LEPTONS

e

$J = \frac{1}{2}$

e MASS (atomic mass units u)

The primary determination of an electron's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the electron in u; indeed, the recent improvements in the mass determination are not evident when the result is given in MeV. In this datablock we give the result in u, and the following datablock in MeV.

VALUE (10^{-6} u)	DOCUMENT ID		TECN	COMMENT
548.57990945±0.00000024	MOHR	04	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
548.5799092 ±0.0000004	[1] BEIER	02	CNTR	Penning trap
548.5799110 ±0.0000012	MOHR	99	RVUE	1998 CODATA value
548.5799111 ±0.0000012	[2] FARNHAM	95	CNTR	Penning trap
548.579903 ±0.000013	COHEN	87	RVUE	1986 CODATA value

[1] BEIER 02 compares Larmor frequency of the electron bound in a $^{12}C^{5+}$ ion with the cyclotron frequency of a single trapped $^{12}C^{5+}$ ion.
[2] FARNHAM 95 compares cyclotron frequency of trapped electrons with that of a single trapped $^{12}C^{6+}$ ion.

e MASS

2002 CODATA gives the conversion factor from u (atomic mass units, see the above datablock) as 931.494 043 (80). Earlier values use the then-current conversion factor. The conversion error dominates the masses given below.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
0.510998918±0.000000044	MOHR	04	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.510998901±0.000000020	[3,4] BEIER	02	CNTR	Penning trap
0.510998902±0.000000021	MOHR	99	RVUE	1998 CODATA value
0.510998903±0.000000020	[3,5] FARNHAM	95	CNTR	Penning trap
0.510998895±0.000000024	[3] COHEN	87	RVUE	1986 CODATA value
0.5110034 ±0.0000014	COHEN	73	RVUE	1973 CODATA value

[3] Converted to MeV using the 1998 CODATA value of the conversion constant, 931.494013 ± 0.0000037 MeV/u.
[4] BEIER 02 compares Larmor frequency of the electron bound in a $^{12}C^{5+}$ ion with the cyclotron frequency of a single trapped $^{12}C^{5+}$ ion.
[5] FARNHAM 95 compares cyclotron frequency of trapped electrons with that of a single trapped $^{12}C^{6+}$ ion.

$(m_{e^+} - m_{e^-}) / m_{\text{average}}$

A test of *CPT* invariance.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8 \times 10^{-9}$	90	[6] FEE	93	CNTR	Positronium spectroscopy
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-8}$	90	CHU	84	CNTR	Positronium spectroscopy

[6] FEE 93 value is obtained under the assumption that the positronium Rydberg constant is exactly half the hydrogen one.

$\lvert q_{e^+} + q_{e^-} \rvert / e$

A test of *CPT* invariance. See also similar tests involving the proton.

VALUE	DOCUMENT ID		TECN	COMMENT
$<4 \times 10^{-8}$	[7] HUGHES	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-18}$	[8] SCHAEFER	95	THEO	Vacuum polarization
$<1 \times 10^{-18}$	[9] MUELLER	92	THEO	Vacuum polarization

[7] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.
[8] SCHAEFER 95 removes model dependency of MUELLER 92.
[9] MUELLER 92 argues that an inequality of the charge magnitudes would, through higher-order vacuum polarization, contribute to the net charge of atoms.

e MAGNETIC MOMENT ANOMALY

$\mu_e/\mu_B - 1 = (g{-}2)/2$

The CODATA value assumes the $g/2$ values for e^+ and e^- are equal, as required by *CPT*.

VALUE (units 10^{-6})	DOCUMENT ID		TECN	CHG	COMMENT
1159.6521859±0.0000038	MOHR	04	RVUE		2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1159.6521869±0.0000041	MOHR	99	RVUE		1998 CODATA value
1159.652193 ±0.000010	COHEN	87	RVUE		1986 CODATA value
1159.6521884±0.0000043	VANDYCK	87	MRS	−	Single electron
1159.6521879±0.0000043	VANDYCK	87	MRS	+	Single positron

$(g_{e^+} - g_{e^-}) / g_{\text{average}}$

A test of *CPT* invariance.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	COMMENT
− 0.5± 2.1		[10] VANDYCK	87	MRS	Penning trap
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 12	95	[11] VASSERMAN	87	CNTR	Assumes $m_{e^+} = m_{e^-}$
22 ±64		SCHWINBERG	81	MRS	Penning trap

[10] VANDYCK 87 measured $(g_-/g_+)-1$ and we converted it.
[11] VASSERMAN 87 measured $(g_+ - g_-)/(g{-}2)$. We multiplied by $(g{-}2)/g = 1.2 \times 10^{-3}$.

e ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both *T* invariance and *P* invariance.

VALUE (10^{-26} ecm)	CL%	DOCUMENT ID		TECN	COMMENT
0.069± 0.074		REGAN	02	MRS	^{205}Tl beams
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.18 ± 0.12 ±0.10		[12] COMMINS	94	MRS	^{205}Tl beams
− 0.27 ± 0.83		[12] ABDULLAH	90	MRS	^{205}Tl beams
− 14 ± 24		CHO	89	NMR	Tl F molecules
− 1.5 ± 5.5 ±1.5		MURTHY	89		Cesium, no *B* field
− 50 ±110		LAMOREAUX	87	NMR	^{199}Hg
190 ±340	90	SANDARS	75	MRS	Thallium
70 ±220	90	PLAYER	70	MRS	Xenon
< 300	90	WEISSKOPF	68	MRS	Cesium

[12] ABDULLAH 90, COMMINS 94, and REGAN 02 use the relativistic enhancement of a valence electron's electric dipole moment in a high-Z atom.

e^- MEAN LIFE / BRANCHING FRACTION

A test of charge conservation. See the "Note on Testing Charge Conservation and the Pauli Exclusion Principle" following this section in our 1992 edition (Physical Review **D45,** 1 June, Part II (1992), p. VI.10).

Most of these experiments are one of three kinds: Attempts to observe (a) the 255.5 keV gamma ray produced in $e^- \to \nu_e \gamma$, (b) the (K) shell x ray produced when an electron decays without additional energy deposit, e.g., $e^- \to \nu_e \overline{\nu}_e \nu_e$ ("disappearance" experiments), and (c) nuclear de-excitation gamma rays after the electron disappears from an atomic shell and the nucleus is left in an excited state. The last can include both weak boson and photon mediating processes. We use the best $e^- \to \nu_e \gamma$ limit for the Summary Tables.

Note that we use the mean life rather than the half life, which is often reported.

$e \to \nu_e \gamma$ and astrophysical limits

VALUE (yr)	CL%	DOCUMENT ID		TECN	COMMENT
$>4.6 \times 10^{26}$	90	BACK	02	BORX	$e^- \to \nu\gamma$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>3.4 \times 10^{26}$	68	BELLI	00B	DAMA	$e^- \to \nu\gamma$, liquid Xe
$>3.7 \times 10^{25}$	68	AHARONOV	95B	CNTR	$e^- \to \nu\gamma$
$>2.35 \times 10^{25}$	68	BALYSH	93	CNTR	$e^- \to \nu\gamma$, ^{76}Ge detector
$>1.5 \times 10^{25}$	68	AVIGNONE	86	CNTR	$e^- \to \nu\gamma$
$>1 \times 10^{39}$		[13] ORITO	85	ASTR	Astrophysical argument
$>3 \times 10^{23}$	68	BELLOTTI	83B	CNTR	$e^- \to \nu\gamma$

[13] ORITO 85 assumes that electromagnetic forces extend out to large enough distances and that the age of our galaxy is 10^{10} years.

Disappearance and nuclear-de-excitation experiments

VALUE (yr)	CL%	DOCUMENT ID		TECN	COMMENT
$>6.4 \times 10^{24}$	68	[14] BELLI	99B	DAMA	De-excitation of ^{129}Xe
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>4.2 \times 10^{24}$	68	BELLI	99	DAMA	Iodine L-shell disappearance
$>2.4 \times 10^{23}$	90	[15] BELLI	99D	DAMA	De-excitation of ^{127}I (in NaI)
$>4.3 \times 10^{23}$	68	AHARONOV	95B	CNTR	Ge K-shell disappearance
$>2.7 \times 10^{23}$	68	REUSSER	91	CNTR	Ge K-shell disappearance
$>2 \times 10^{22}$	68	BELLOTTI	83B	CNTR	Ge K-shell disappearance

[14] BELLI 99B limit on charge nonconserving e^- capture involving excitation of the 236.1 keV nuclear state of ^{129}Xe; the 90% CL limit is 3.7×10^{24} yr. Less stringent limits for other states are also given.

[15] BELLI 99D limit on charge nonconserving e^- capture involving excitation of the 57.6 keV nuclear state of ^{127}I. Less stringent limits for the other states and for the state of ^{23}Na are also given.

e REFERENCES

MOHR	04	RMP (to be publ.)	P.J. Mohr, B.N. Taylor	(NIST)
physics.nist.gov/constants				
BACK	02	PL B525 29	H.O. Back *et al.*	(BOREXINO/SASSO Collab.)
BEIER	02	PRL 88 011603	T. Beier *et al.*	
REGAN	02	PRL 88 071805	B.C. Regan *et al.*	
BELLI	00B	PR D61 117301	P. Belli *et al.*	(DAMA Collab.)
BELLI	99	PL B460 236	P. Belli *et al.*	(DAMA Collab.)
BELLI	99B	PL B465 315	P. Belli *et al.*	(DAMA Collab.)
BELLI	99D	PR C60 065501	P. Belli *et al.*	(DAMA Collab.)
MOHR	99	JPCRD 28 1713	P.J. Mohr, B.N. Taylor	(NIST)
Also	00	RMP 72 351	P.J. Mohr, B.N. Taylor	(NIST)
AHARONOV	95B	PR D52 3785	Y. Aharonov *et al.*	(SCUC, PNL, ZARA+)
Also	95	PL B353 168	Y. Aharonov *et al.*	(SCUC, PNL, ZARA+)
FARNHAM	95	PRL 75 3598	D.L. Farnham, R.S. van Dyck, P.B. Schwinberg	(WASH)
SCHAEFER	95	PR A51 838	A. Schaefer, J. Reinhardt	(FRAN)
COMMINS	94	PR A50 2960	E.D. Commins *et al.*	
BALYSH	93	PL B298 278	A. Balysh *et al.*	(KIAE, MPIH, SASSO)
FEE	93	PR A48 192	M.S. Fee *et al.*	
HUGHES	92	PRL 69 578	R.J. Hughes, B.I. Deutch	(LANL, AARH)
MUELLER	92	PRL 69 3432	B. Muller, M.H. Thoma	(DUKE)
PDG	92	PR D45, 1 June, Part II	K. Hikasa *et al.*	(KEK, LBL, BOST+)
REUSSER	91	PL B255 143	D. Reusser *et al.*	(NEUC, CIT, PSI)
ABDULLAH	90	PRL 65 2347	K. Abdullah *et al.*	(LBL, UCB)
CHO	89	PRL 63 2559	D. Cho, K. Sangster, E.A. Hinds	(YALE)
MURTHY	89	PRL 63 965	S.A. Murthy *et al.*	(AMHT)
COHEN	87	RMP 59 1121	E.R. Cohen, B.N. Taylor	(RISC, NBS)
LAMOREAUX	87	PRL 59 2275	S.K. Lamoreaux *et al.*	(WASH)
VANDYCK	87	PRL 59 26	R.S. van Dyck, P.B. Schwinberg, H.G. Dehmelt	(WASH)
VASSERMAN	87	PL B198 302	I.B. Vasserman *et al.*	(NOVO)
Also	87B	PL B187 172	I.B. Vasserman *et al.*	(NOVO)
AVIGNONE	86	PR D34 97	F.T. Avignone *et al.*	(PNL, SCUC)
ORITO	85	PRL 54 2457	S. Orito, M. Yoshimura	(TOKY, KEK)
CHU	84	PRL 52 1689	S. Chu, A.P. Mills, J.L. Hall	(BELL, NBS, COLO)
BELLOTTI	83B	PL 124B 435	E. Bellotti *et al.*	(MILA)
SCHWINBERG	81	PRL 47 1679	P.B. Schwinberg, R.S. van Dyck, H.G. Dehmelt	(WASH)
SANDARS	75	PR A11 473	P.G.H. Sandars, D.M. Sternheimer	(OXF, BNL)
COHEN	73	JPCRD 2 664	E.R. Cohen, B.N. Taylor	(RISC, NBS)
PLAYER	70	JPB 3 1620	M.A. Player, P.G.H. Sandars	(OXF)
WEISSKOPF	68	PRL 21 1645	M.C. Weisskopf *et al.*	(BRAN)

μ

$J = \frac{1}{2}$

μ MASS (atomic mass units u)

The primary determination of a muon's mass comes from measuring the ratio of the mass to that of a nucleus, so that the result is obtained in u (atomic mass units). The conversion factor to MeV is more uncertain than the mass of the muon in u. In this datablock we give the result in u, and in the following datablock in MeV.

VALUE (u)	*DOCUMENT ID*		*TECN*	*COMMENT*
0.1134289264±0.0000000030	MOHR	04	RVUE	2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.1134289168±0.0000000034	[1] MOHR	99	RVUE	1998 CODATA value
0.113428913 ±0.000000017	[2] COHEN	87	RVUE	1986 CODATA value

[1] MOHR 99 make use of other 1998 CODATA entries below.
[2] COHEN 87 make use of other 1986 CODATA entries below.

μ MASS

2002 CODATA gives the conversion factor from u (atomic mass units, see the above datablock) as 931.494 043 (80). Earlier values use the then-current conversion factor. The conversion error dominates the masses given below.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
105.6583692±0.0000094	MOHR	04	RVUE		2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
105.6583568±0.0000052	MOHR	99	RVUE		1998 CODATA value
105.658353 ±0.000016	[3] COHEN	87	RVUE		1986 CODATA value
105.658386 ±0.000044	[4] MARIAM	82	CNTR	+	
105.65836 ±0.00026	[5] CROWE	72	CNTR		
105.65865 ±0.00044	[6] CRANE	71	CNTR		

[3] Converted to MeV using the 1998 CODATA value of the conversion constant, 931.494013 ± 0.0000037 MeV/u.

[4] MARIAM 82 give m_μ/m_e = 206.768259(62).

[5] CROWE 72 give m_μ/m_e = 206.7682(5).

[6] CRANE 71 give m_μ/m_e = 206.76878(85).

μ MEAN LIFE τ

Measurements with an error $> 0.001 \times 10^{-6}$ s have been omitted.

VALUE (10^{-6} s)	*DOCUMENT ID*		*TECN*	*CHG*
2.19703 ±0.00004 OUR AVERAGE				
2.197078±0.000073	BARDIN	84	CNTR	+
2.197025±0.000155	BARDIN	84	CNTR	−
2.19695 ±0.00006	GIOVANETTI	84	CNTR	+
2.19711 ±0.00008	BALANDIN	74	CNTR	+
2.1973 ±0.0003	DUCLOS	73	CNTR	+

$\tau_{\mu^+}/\tau_{\mu^-}$ MEAN LIFE RATIO

A test of *CPT* invariance.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
1.000024±0.000078	BARDIN	84	CNTR	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.0008 ±0.0010	BAILEY	79	CNTR	Storage ring
1.000 ±0.001	MEYER	63	CNTR	Mean life μ^+/ μ^-

$(\tau_{\mu^+} - \tau_{\mu^-}) / \tau_{\text{average}}$

A test of *CPT* invariance. Calculated from the mean-life ratio, above.

VALUE	*DOCUMENT ID*
(2±8) × 10^{-5} OUR EVALUATION	

μ/p MAGNETIC MOMENT RATIO

This ratio is used to obtain a precise value of the muon mass and to reduce experimental muon Larmor frequency measurements to the muon magnetic moment anomaly. Measurements with an error $>$ 0.00001 have been omitted. By covention, the minus sign on this ratio is omitted. CODATA values were fitted using their selection of data, plus other data from multiparameter fits.

VALUE	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
3.183345118±0.000000089	MOHR	04	RVUE		2002 CODATA value
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.18334513 ±0.00000039	LIU	99	CNTR	+	HFS in muonium
3.18334539 ±0.00000010	MOHR	99	RVUE		1998 CODATA value
3.18334547 ±0.00000047	COHEN	87	RVUE		1986 CODATA value
3.1833441 ±0.0000017	KLEMPT	82	CNTR	+	Precession strob
3.1833461 ±0.0000011	MARIAM	82	CNTR	+	HFS splitting
3.1833448 ±0.0000029	CAMANI	78	CNTR	+	See KLEMPT 82
3.1833403 ±0.0000044	CASPERSON	77	CNTR	+	HFS splitting
3.1833402 ±0.0000072	COHEN	73	RVUE		1973 CODATA value
3.1833467 ±0.0000082	CROWE	72	CNTR	+	Precession phase

μ MAGNETIC MOMENT ANOMALY

The parity-violating decay of muons in a storage ring is observed. The difference frequency ω_a between the muon spin precision and the orbital angular frequency $(e/m_\mu c)\langle B\rangle$ is measured, as is the free proton NMR frequency ω_p, thus determining the ratio $R{=}\omega_a/\omega_p$. Given the magnetic moment ratio $\lambda{=}\mu_\mu/\mu_p$ (from hyperfine structure in muonium), $(g{-}2)/2 = R/(\lambda{-}R)$.

The new precision results from the Brookhaven MUG2 Collaboration have inspired reevaluation of the theoretical value. Most of the problem concerns the hadronic contributions. Examples of the present uncertainty in this changing field are two theoretical values presented by A. Nyffeler in his theory review at a March 2003 Moriond Conference: 11659167.4 ± 7.5 (had) ±4.0 (light-by-light scattering) ±0.35 (QED + EW) using experimental input from e^+e^- around the ρ (CMD-2), and 11659192.6 ± 5.9 ± 4.0 ± 0.35 from precision τ decay studies (ALEPH).

$\mu_\mu/(e\hbar/2m_\mu){-}1 = (g_\mu{-}2)/2$

VALUE (units 10^{-10})	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
11659203± 7 OUR AVERAGE					
11659204± 7±5	BENNETT	02	MUG2	+	Storage ring
11659202± 14±6	BROWN	01	MUG2	+	Storage ring
11659191± 59	BROWN	00	MUG2	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
11659100± 110	[7] BAILEY	79	CNTR	+	Storage ring
11659360± 120	[7] BAILEY	79	CNTR	−	Storage ring
11659230± 85	[7] BAILEY	79	CNTR	±	Storage ring
11620000±5000	CHARPAK	62	CNTR	+	

[7] BAILEY 79 values recalculated by HUGHES 99 using the COHEN 87 μ/p magnetic moment. The improved MOHR 99 value does not change the result.

$(g_{\mu^+} - g_{\mu^-})$ / g_{average}

A test of CPT invariance.

VALUE (units 10^{-8})	DOCUMENT ID	
−2.6±1.6	BAILEY	79

μ ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both T invariance and P invariance.

VALUE (10^{-19} e cm)	DOCUMENT ID		TECN	CHG	COMMENT
3.7±3.4	[8] BAILEY	78	CNTR	±	Storage ring
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.6±4.5	BAILEY	78	CNTR	+	Storage rings
0.8±4.3	BAILEY	78	CNTR	−	Storage rings

[8] This is the combination of the two BAILEY 78 results given below.

MUON-ELECTRON CHARGE RATIO ANOMALY $q_{\mu^+}/q_{e^-} + 1$

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
(1.1±2.1) × 10^{-9}	[9] MEYER	00	CNTR	+	1s–2s muonium interval

[9] MEYER 00 measure the 1s–2s muonium interval, and then interpret the result in terms of muon-electron charge ratio q_{μ^+}/q_{e^-}.

μ^- DECAY MODES

μ^+ modes are charge conjugates of the modes below.

	Mode			Fraction (Γ_i/Γ)	Confidence level
Γ_1	$e^-\overline{\nu}_e\nu_\mu$			≈ 100%	
Γ_2	$e^-\overline{\nu}_e\nu_\mu\gamma$		[a]	(1.4±0.4) %	
Γ_3	$e^-\overline{\nu}_e\nu_\mu e^+e^-$		[b]	$(3.4\pm0.4)\times10^{-5}$	
	Lepton Family number (LF) violating modes				
Γ_4	$e^-\nu_e\overline{\nu}_\mu$	LF	[c]	< 1.2 %	90%
Γ_5	$e^-\gamma$	LF		$< 1.2 \times 10^{-11}$	90%
Γ_6	$e^-e^+e^-$	LF		$< 1.0 \times 10^{-12}$	90%
Γ_7	$e^-2\gamma$	LF		$< 7.2 \times 10^{-11}$	90%

[a] This only includes events with the γ energy > 10 MeV. Since the $e^-\overline{\nu}_e\nu_\mu$ and $e^-\overline{\nu}_e\nu_\mu\gamma$ modes cannot be clearly separated, we regard the latter mode as a subset of the former.

[b] See the Particle Listings below for the energy limits used in this measurement.

[c] A test of additive vs. multiplicative lepton family number conservation.

μ^- BRANCHING RATIOS

$\Gamma(e^-\overline{\nu}_e\nu_\mu\gamma)/\Gamma_{\text{total}}$ — Γ_2/Γ

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.014 ±0.004		CRITTENDEN	61	CNTR	γ KE > 10 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
	862	BOGART	67	CNTR	γ KE > 14.5 MeV
0.0033±0.0013		CRITTENDEN	61	CNTR	γ KE > 20 MeV
	27	ASHKIN	59	CNTR	

$\Gamma(e^-\overline{\nu}_e\nu_\mu e^+e^-)/\Gamma_{\text{total}}$ — Γ_3/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.4±0.2±0.3	7443	[10] BERTL	85	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
2.2±1.5	7	[11] CRITTENDEN	61	HLBC	+	$E(e^+e^-)$>10 MeV
2	1	[12] GUREVICH	60	EMUL	+	
1.5±1.0	3	[13] LEE	59	HBC	+	

[10] BERTL 85 has transverse momentum cut p_T > 17 MeV/c. Systematic error was increased by us.

[11] CRITTENDEN 61 count only those decays where total energy of either (e^+, e^-) combination is >10 MeV.

[12] GUREVICH 60 interpret their event as either virtual or real photon conversion. e^+ and e^- energies not measured.

[13] In the three LEE 59 events, the sum of energies E(e^+) + E(e^-) + E(e^+) was 51 MeV, 55 MeV, and 33 MeV.

$\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{\text{total}}$ — Γ_4/Γ

Forbidden by the additive conservation law for lepton family number. A multiplicative law predicts this branching ratio to be 1/2. For a review see NEMETHY 81.

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 0.012	90	[14] FREEDMAN	93	CNTR	+	ν oscillation search
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 0.018	90	KRAKAUER	91B	CALO	+	
< 0.05	90	[15] BERGSMA	83	CALO		$\overline{\nu}_\mu e \to \mu^-\overline{\nu}_e$
< 0.09	90	JONKER	80	CALO		See BERGSMA 83
−0.001±0.061		WILLIS	80	CNTR	+	
0.13 ±0.15		BLIETSCHAU	78	HLBC	±	Avg. of 4 values
< 0.25	90	EICHTEN	73	HLBC	+	

[14] FREEDMAN 93 limit on $\overline{\nu}_e$ observation is here interpreted as a limit on lepton family number violation.

[15] BERGSMA 83 gives a limit on the inverse muon decay cross-section ratio $\sigma(\overline{\nu}_\mu e^- \to \mu^-\overline{\nu}_e)/\sigma(\nu_\mu e^- \to \mu^-\nu_e)$, which is essentially equivalent to $\Gamma(e^-\nu_e\overline{\nu}_\mu)/\Gamma_{\text{total}}$ for small values like that quoted.

$\Gamma(e^-\gamma)/\Gamma_{\text{total}}$ — Γ_5/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.2	90	BROOKS	99	SPEC	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.2	90	AHMED	02	SPEC	+	MEGA
< 4.9	90	BOLTON	88	CBOX	+	LAMPF
<100	90	AZUELOS	83	CNTR	+	TRIUMF
< 17	90	KINNISON	82	SPEC	+	LAMPF
<100	90	SCHAAF	80	ELEC	+	SIN

$\Gamma(e^-e^+e^-)/\Gamma_{\text{total}}$ — Γ_6/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-12})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 1.0	90	[16] BELLGARDT	88	SPEC	+	SINDRUM
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 36	90	BARANOV	91	SPEC	+	ARES
< 35	90	BOLTON	88	CBOX	+	LAMPF
< 2.4	90	[16] BERTL	85	SPEC	+	SINDRUM
<160	90	[16] BERTL	84	SPEC	+	SINDRUM
<130	90	[16] BOLTON	84	CNTR		LAMPF

[16] These experiments assume a constant matrix element.

$\Gamma(e^-2\gamma)/\Gamma_{\text{total}}$ — Γ_7/Γ

Forbidden by lepton family number conservation.

VALUE (units 10^{-11})	CL%	DOCUMENT ID		TECN	CHG	COMMENT
< 7.2	90	BOLTON	88	CBOX	+	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 840	90	[17] AZUELOS	83	CNTR	+	TRIUMF
<5000	90	[18] BOWMAN	78	CNTR		DEPOMMIER 77 data

[17] AZUELOS 83 uses the phase space distribution of BOWMAN 78.

[18] BOWMAN 78 assumes an interaction Lagrangian local on the scale of the inverse μ mass.

LIMIT ON $\mu^- \to e^-$ CONVERSION

Forbidden by lepton family number conservation.

$\sigma(\mu^- {}^{32}\text{S} \to e^- {}^{32}\text{S})$ / $\sigma(\mu^- {}^{32}\text{S} \to \nu_\mu {}^{32}\text{P}^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7 \times 10^{-11}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-10}$	90	BADERT...	77	STRC	SIN

$\sigma(\mu^-\text{Cu} \to e^-\text{Cu})$ / $\sigma(\mu^-\text{Cu} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.6 \times 10^{-8}$	90	BRYMAN	72	SPEC

$\sigma(\mu^-\text{Ti} \to e^-\text{Ti})$ / $\sigma(\mu^-\text{Ti} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.3 \times 10^{-12}$	90	[19] DOHMEN	93	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.6 \times 10^{-12}$	90	AHMAD	88	TPC	TRIUMF
$<1.6 \times 10^{-11}$	90	BRYMAN	85	TPC	TRIUMF

[19] DOHMEN 93 assumes $\mu^- \to e^-$ conversion leaves the nucleus in its ground state, a process enhanced by coherence and expected to dominate.

$\sigma(\mu^-\text{Pb} \to e^-\text{Pb})$ / $\sigma(\mu^-\text{Pb} \to \text{capture})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<4.6 \times 10^{-11}$	90	HONECKER	96	SPEC	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4.9 \times 10^{-10}$	90	AHMAD	88	TPC	TRIUMF

LIMIT ON $\mu^- \rightarrow e^+$ CONVERSION

Forbidden by total lepton number conservation.

$\sigma(\mu^- {}^{32}S \rightarrow e^+ {}^{32}Si^*) / \sigma(\mu^- {}^{32}S \rightarrow \nu_\mu {}^{32}P^*)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9 $\times 10^{-10}$	90	BADERT...	80	STRC	SIN
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.5 \times 10^{-9}$	90	BADERT...	78	STRC	SIN

$\sigma(\mu^- {}^{127}I \rightarrow e^+ {}^{127}Sb^*) / \sigma(\mu^- {}^{127}I \rightarrow$ anything)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3 \times 10^{-10}$	90	[20] ABELA	80	CNTR	Radiochemical tech.

[20] ABELA 80 is upper limit for $\mu^- e^+$ conversion leading to particle-stable states of ^{127}Sb. Limit for total conversion rate is higher by a factor less than 4 (G. Backenstoss, private communication).

$\sigma(\mu^-$ Cu $\rightarrow e^+$ Co) / $\sigma(\mu^-$ Cu $\rightarrow \nu_\mu$ Ni)

VALUE	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.6 \times 10^{-8}$	90	BRYMAN	72	SPEC
$<2.2 \times 10^{-7}$	90	CONFORTO	62	OSPK

$\sigma(\mu^-$ Ti $\rightarrow e^+$ Ca) / $\sigma(\mu^-$ Ti $\rightarrow$ capture)

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$<3.6 \times 10^{-11}$	90	1	[21,22] KAULARD	98	SPEC	−	SINDRUM II
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$<1.7 \times 10^{-12}$	90	1	[22,23] KAULARD	98	SPEC	−	SINDRUM II
$<4.3 \times 10^{-12}$	90		[23] DOHMEN	93	SPEC		SINDRUM II
$<8.9 \times 10^{-11}$	90		[21] DOHMEN	93	SPEC		SINDRUM II
$<1.7 \times 10^{-10}$	90		[24] AHMAD	88	TPC		TRIUMF

[21] This limit assumes a giant resonance excitation of the daughter Ca nucleus (mean energy and width both 20 MeV).
[22] KAULARD 98 obtained these same limits using the unified classical analysis of FELDMAN 98.
[23] This limit assumes the daughter Ca nucleus is left in the ground state. However, the probability of this is unknown.
[24] Assuming a giant-resonance-excitation model.

LIMIT ON MUONIUM → ANTIMUONIUM CONVERSION

Forbidden by lepton family number conservation.

$R_g = G_C / G_F$

The effective Lagrangian for the $\mu^+ e^- \rightarrow \mu^- e^+$ conversion is assumed to be

$$\mathcal{L} = 2^{-1/2}\, G_C\, [\overline{\psi}_\mu \gamma_\lambda\, (1-\gamma_5)\, \psi_e]\, [\overline{\psi}_\mu \gamma_\lambda\, (1-\gamma_5)\, \psi_e] + \text{h.c.}$$

The experimental result is then an upper limit on G_C/G_F, where G_F is the Fermi coupling constant.

VALUE	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
< 0.0030	90	1	[25] WILLMANN	99	SPEC	+	μ^+ at 26 GeV/c
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 0.14	90	1	[26] GORDEEV	97	SPEC	+	JINR phasotron
< 0.018	90	0	[27] ABELA	96	SPEC	+	μ^+ at 24 MeV
< 6.9	90		NI	93	CBOX		LAMPF
< 0.16	90		MATTHIAS	91	SPEC		LAMPF
< 0.29	90		HUBER	90B	CNTR		TRIUMF
<20	95		BEER	86	CNTR		TRIUMF
<42	95		MARSHALL	82	CNTR		

[25] WILLMANN 99 quote both probability $P_{M\overline{M}} < 8.3 \times 10^{-11}$ at 90%CL in a 0.1 T field and $R_g = G_C/G_F$.
[26] GORDEEV 97 quote limits on both $f = G_{MM}/GF$ and the probability $W_{MM} < 4.7 \times 10^{-7}$ (90%CL).
[27] ABELA 96 quote both probability $P_{M\overline{M}} < 8 \times 10^{-9}$ at 90% CL and $R_g = G_C/G_F$.

MUON DECAY PARAMETERS

Revised September 2001 by W. Fetscher and H.-J. Gerber (ETH Zürich).

Introduction: All measurements in direct muon decay, $\mu^- \rightarrow e^- + 2$ neutrals, and its inverse, $\nu_\mu + e^- \rightarrow \mu^- +$neutral, are successfully described by the "V-A interaction", which is a particular case of a local, derivative-free, lepton-number-conserving, four fermion interaction [1]. As shown below, within this framework, the Standard Model assumptions, such as the V-A form and the nature of the neutrals (ν_μ and $\bar{\nu}_e$), and hence the doublet assignments $(\nu_e\ e^-)_L$ and $(\nu_\mu\ \mu^-)_L$, have been determined from experiments [2,3]. All considerations on muon decay are valid for the leptonic tau decays $\tau \rightarrow \ell + \nu_\tau + \bar{\nu}_e$ with the replacements $m_\mu \rightarrow m_\tau$, $m_e \rightarrow m_\ell$.

Parameters: The differential decay probability to obtain an $e^\pm$ with (reduced) energy between x and $x + dx$, emitted in the direction $\widehat{\boldsymbol{x}}_3$ at an angle between ϑ and $\vartheta + d\vartheta$ with respect to the muon polarization vector $\boldsymbol{P}_\mu$, and with its spin parallel to the arbitrary direction $\widehat{\boldsymbol{\zeta}}$, neglecting radiative corrections, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\ d\cos\vartheta} =& \frac{m_\mu}{4\pi^3}\, W_{e\mu}^4\, G_F^2\, \sqrt{x^2 - x_0^2} \\ &\times (F_{\rm IS}(x) \pm P_\mu \cos\vartheta\ F_{\rm AS}(x)) \\ &\times \left[1 + \widehat{\boldsymbol{\zeta}} \cdot \boldsymbol{P}_e(x,\vartheta)\right]\ . \end{aligned} \qquad (1)$$

Here, $W_{e\mu} = \max(E_e) = (m_\mu^2 + m_e^2)/2m_\mu$ is the maximum $e^\pm$ energy, $x = E_e/W_{e\mu}$ is the reduced energy, $x_0 = m_e/W_{e\mu} = 9.67 \times 10^{-3}$, and $P_\mu = |\boldsymbol{P}_\mu|$ is the degree of muon polarization. $\widehat{\boldsymbol{\zeta}}$ is the direction in which a perfect polarization-sensitive electron detector is most sensitive. The isotropic part of the spectrum, $F_{\rm IS}(x)$, the anisotropic part $F_{\rm AS}(x)$ and the electron polarization, $\boldsymbol{P}_e(x,\vartheta)$, may be parametrized by the Michel parameters [1,4] ρ, η, ξ, δ, *etc.* These are bilinear combinations of the coupling constants $g^\gamma_{\varepsilon\mu}$, which occur in the matrix element (given below).

If the masses of the neutrinos as well as x_0^2 are neglected, the energy and angular distribution of the electron in the rest frame of a muon ($\mu^\pm$) measured by a polarization insensitive detector, is given by

$$\begin{aligned}\frac{d^2\Gamma}{dx\ d\cos\vartheta} \sim x^2 \cdot \Bigg\{ & 3(1-x) + \frac{2\rho}{3}(4x-3) + 3\eta\ x_0(1-x)/x \\ & \pm P_\mu \cdot \xi \cdot \cos\vartheta \left[1 - x + \frac{2\delta}{3}(4x-3)\right]\Bigg\}\ . \end{aligned} \qquad (2)$$

Here, ϑ is the angle between the electron momentum and the muon spin, and $x \equiv 2E_e/m_\mu$. For the Standard Model coupling, we obtain $\rho = \xi\delta = 3/4$, $\xi = 1$, $\eta = 0$ and the differential decay rate is

$$\frac{d^2\Gamma}{dx\ d\cos\vartheta} = \frac{G_F^2 m_\mu^5}{192\pi^3}\ [3 - 2x \pm P_\mu \cos\vartheta(2x-1)]\ x^2 \quad . \qquad (3)$$

The coefficient in front of the square bracket is the total decay rate.

If only the neutrino masses are neglected, and if the $e^\pm$ polarization is detected, then the functions in Eq. (1) become

$$\begin{aligned} F_{\rm IS}(x) &= x(1-x) + \tfrac{2}{9}\ \rho(4x^2 - 3x - x_0^2) + \eta \cdot x_0(1-x) \\ F_{\rm AS}(x) &= \tfrac{1}{3}\xi\ \sqrt{x^2 - x_0^2} \\ &\quad \times \left[1 - x + \tfrac{2}{3}\delta\Big(4x - 3 + \Big(\sqrt{1 - x_0^2} - 1\Big)\Big)\right] \\ \boldsymbol{P}_e(x,\vartheta) &= P_{{\rm T}_1} \cdot \widehat{\boldsymbol{x}}_1 + P_{{\rm T}_2} \cdot \widehat{\boldsymbol{x}}_2 + P_L \cdot \widehat{\boldsymbol{x}}_3\ . \end{aligned} \qquad (4)$$

Here $\widehat{\boldsymbol{x}}_1$, $\widehat{\boldsymbol{x}}_2$, and $\widehat{\boldsymbol{x}}_3$ are orthogonal unit vectors defined as follows:

$$\widehat{\boldsymbol{x}}_3 \quad \text{is along the } e \text{ momentum } \boldsymbol{p}_e$$

$$\frac{\widehat{\boldsymbol{x}}_3 \times \boldsymbol{P}_\mu}{|\widehat{\boldsymbol{x}}_2 \times \boldsymbol{P}_\mu|} = \widehat{\boldsymbol{x}}_2 \quad \text{is transverse to } \boldsymbol{p}_e \text{ and perpendicular to the "decay plane"}$$

$$\widehat{\boldsymbol{x}}_2 \times \widehat{\boldsymbol{x}}_3 = \widehat{\boldsymbol{x}}_1 \quad \text{is transverse to the } \boldsymbol{p}_e \text{ and in the "decay plane."}$$

The components of $\boldsymbol{P}_e$ then are given by

$$P_{\mathrm{T}_1}(x,\vartheta) = P_\mu \sin\vartheta \cdot F_{\mathrm{T}_1}(x) / \left(F_{\mathrm{IS}}(x) \pm P_\mu \cos\vartheta \cdot F_{\mathrm{AS}}(x)\right)$$
$$P_{\mathrm{T}_2}(x,\vartheta) = P_\mu \sin\vartheta \cdot F_{\mathrm{T}_2}(x) / \left(F_{\mathrm{IS}}(x) \pm P_\mu \cos\vartheta \cdot F_{\mathrm{AS}}(x)\right)$$
$$P_L(x,\vartheta) = \Big(\pm F_{\mathrm{IP}}(x) + P_\mu \cos\vartheta \times F_{\mathrm{AP}}(x)\Big) / \left(F_{\mathrm{IS}}(x) \pm P_\mu \cos\vartheta \cdot F_{\mathrm{AS}}(x)\right) \; ,$$

where

$$F_{\mathrm{T}_1}(x) = \tfrac{1}{12}\Big\{-2\left[\xi'' + 12(\rho - \tfrac{3}{4})\right](1-x)x_0 - 3\eta(x^2 - x_0^2) + \eta''(-3x^2 + 4x - x_0^2)\Big\}$$
$$F_{\mathrm{T}_2}(x) = \tfrac{1}{3}\sqrt{x^2 - x_0^2}\Big\{3\frac{\alpha'}{A}(1-x) + 2\frac{\beta'}{A}\sqrt{1-x_0^2}\Big\}$$
$$F_{\mathrm{IP}}(x) = \tfrac{1}{54}\sqrt{x^2 - x_0^2}\Big\{9\xi'\left(-2x + 2 + \sqrt{1-x_0^2}\right) + 4\xi(\delta - \tfrac{3}{4})(4x - 4 + \sqrt{1-x_0^2})\Big\}$$
$$F_{\mathrm{AP}}(x) = \tfrac{1}{6}\Big\{\xi''(2x^2 - x - x_0^2) + 4(\rho - \tfrac{3}{4})\left(4x^2 - 3x - x_0^2\right) + 2\eta''(1-x)x_0\Big\} \; . \tag{5}$$

For the experimental values of the parameters ρ, ξ, ξ', ξ'', δ, η, η'', α/A, β/A, α'/A, β'/A, which are not all independent, see the Data Listings below. Experiments in the past have also been analyzed using the parameters a, b, c, a', b', c', α/A, β/A, α'/A, β'/A (and $\eta = (\alpha - 2\beta)/2A$), as defined by Kinoshita and Sirlin [5]. They serve as a model-independent summary of all possible measurements on the decay electron (see Listings below). The relations between the two sets of parameters are

$$\rho - \tfrac{3}{4} = \tfrac{3}{4}(-a + 2c)/A \; ,$$
$$\eta = (\alpha - 2\beta)/A \; ,$$
$$\eta'' = (3\alpha + 2\beta)/A \; ,$$
$$\delta - \tfrac{3}{4} = \tfrac{9}{4} \cdot \frac{(a' - 2c')/A}{1 - [a + 3a' + 4(b + b') + 6c - 14c']/A} \; ,$$
$$1 - \xi\frac{\delta}{\rho} = 4\,\frac{[(b + b') + 2(c - c')]/A}{1 - (a - 2c)/A} \; ,$$
$$1 - \xi' = [(a + a') + 4(b + b') + 6(c + c')]/A \; ,$$
$$1 - \xi'' = (-2a + 20c)/A \; ,$$

where

$$A = a + 4b + 6c \; . \tag{6}$$

The differential decay probability to obtain a *left-handed* ν_e with (reduced) energy between y and $y + dy$, neglecting radiative corrections as well as the masses of the electron and of the neutrinos, is given by [6]

$$\frac{d\Gamma}{dy} = \frac{m_\mu^5\, G_F^2}{16\pi^3} \cdot Q_L^{\nu_e} \cdot y^2\Big\{(1-y) - \omega_L \cdot (y - \tfrac{3}{4})\Big\} \; . \tag{7}$$

Here, $y = 2\, E_{\nu_e}/m_\mu$. $Q_L^{\nu_e}$ and ω_L are parameters. ω_L is the neutrino analog of the spectral shape parameter ρ of Michel. Since in the Standard Model, $Q_L^{\nu_e} = 1$, $\omega_L = 0$, the measurement of $d\Gamma/dy$ has allowed a null-test of the Standard Model (see Listings below).

Matrix element: All results in direct muon decay (energy spectra of the electron and of the neutrinos, polarizations, and angular distributions) and in inverse muon decay (the reaction cross section) at energies well below $m_W c^2$ may be parametrized in terms of amplitudes $g^\gamma_{\varepsilon\mu}$ and the Fermi coupling constant G_F, using the matrix element

$$\frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma = S,V,T \\ \varepsilon,\mu = R,L}} g^\gamma_{\varepsilon\mu} \langle \bar{e}_\varepsilon | \Gamma^\gamma | (\nu_e)_n \rangle \langle (\bar{\nu}_\mu)_m | \Gamma_\gamma | \mu_\mu \rangle . \tag{8}$$

We use the notation of Fetscher *et al.* [2], who in turn use the sign conventions and definitions of Scheck [7]. Here, $\gamma = S, V, T$ indicates a scalar, vector, or tensor interaction; and $\varepsilon, \mu = R, L$ indicate a right- or left-handed chirality of the electron or muon. The chiralities n and m of the ν_e and $\bar{\nu}_\mu$ are then determined by the values of γ, ε, and μ. The particles are represented by fields of definite chirality [8].

As shown by Langacker and London [9], explicit lepton-number nonconservation still leads to a matrix element equivalent to Eq. (8). They conclude that it is not possible, even in principle, to test lepton-number conservation in (leptonic) muon decay if the final neutrinos are massless and are not observed.

The ten complex amplitudes $g^\gamma_{\varepsilon\mu}$ (g^T_{RR} and g^T_{LL} are identically zero) and G_F constitute 19 independent (real) parameters to be determined by experiment. The Standard Model interaction corresponds to one single amplitude g^V_{LL} being unity and all the others being zero.

The (direct) muon decay experiments are compatible with an arbitrary mix of the scalar and vector amplitudes g^S_{LL} and g^V_{LL} – in the extreme even with purely scalar $g^S_{LL} = 2$, $g^V_{LL} = 0$. The decision in favour of the Standard Model comes from the quantitative observation of inverse muon decay, which would be forbidden for pure g^S_{LL} [2].

Experimental determination of V−A: In order to determine the amplitudes $g^\gamma_{\varepsilon\mu}$ uniquely from experiment, the following set of equations, where the left-hand sides represent experimental results, has to be solved.

$$a = 16(|g^V_{RL}|^2 + |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 + |g^S_{LR} + 6g^T_{LR}|^2$$
$$a' = 16(|g^V_{RL}|^2 - |g^V_{LR}|^2) + |g^S_{RL} + 6g^T_{RL}|^2 - |g^S_{LR} + 6g^T_{LR}|^2$$
$$\alpha = 8\mathrm{Re}\left\{g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR}) + g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL})\right\}$$

$$\alpha' = 8\text{Im}\left\{g^V_{LR}(g^{S*}_{RL} + 6g^{T*}_{RL}) - g^V_{RL}(g^{S*}_{LR} + 6g^{T*}_{LR})\right\}$$
$$b = 4(|g^V_{RR}|^2 + |g^V_{LL}|^2) + |g^S_{RR}|^2 + |g^S_{LL}|^2$$
$$b' = 4(|g^V_{RR}|^2 - |g^V_{LL}|^2) + |g^S_{RR}|^2 - |g^S_{LL}|^2$$
$$\beta = -4\text{Re}\left\{g^V_{RR}g^{S*}_{LL} + g^V_{LL}g^{S*}_{RR}\right\}$$
$$\beta' = 4\text{Im}\left\{g^V_{RR}g^{S*}_{LL} - g^V_{LL}g^{S*}_{RR}\right\}$$
$$c = \tfrac{1}{2}\left\{|g^S_{RL} - 2g^T_{RL}|^2 + |g^S_{LR} - 2g^T_{LR}|^2\right\}$$
$$c' = \tfrac{1}{2}\left\{|g^S_{RL} - 2g^T_{RL}|^2 - |g^S_{LR} - 2g^T_{LR}|^2\right\}$$

and

$$Q^{\nu_e}_L = 1 - \left\{\tfrac{1}{4}|g^S_{LR}|^2 + \tfrac{1}{4}|g^S_{LL}|^2 + |g^V_{RR}|^2 + |g^V_{RL}|^2 + 3|g^T_{LR}|^2\right\}$$
$$\omega_L = \frac{3}{4}\,\frac{\{|g^S_{RR}|^2 + 4|g^V_{LR}|^2 + |g^S_{RL} + 2g^T_{RL}|^2\}}{|g^S_{RL}|^2 + |g^S_{RR}|^2 + 4|g^V_{LL}|^2 + 4|g^V_{LR}|^2 + 12|g^T_{RL}|^2\}}\ .$$

It has been noted earlier by C. Jarlskog [10], that certain experiments observing the decay electron are especially informative if they yield the V-A values. The complete solution is now found as follows. Fetscher *et al.* [2] introduced four probabilities $Q_{\varepsilon\mu}(\varepsilon, \mu = R, L)$ for the decay of a μ-handed muon into an ε-handed electron and showed that there exist upper bounds on Q_{RR}, Q_{LR}, and Q_{RL}, and a lower bound on Q_{LL}. These probabilities are given in terms of the $g^\gamma_{\varepsilon\mu}$'s by

$$Q_{\varepsilon\mu} = \tfrac{1}{4}|g^S_{\varepsilon\mu}|^2 + |g^V_{\varepsilon\mu}|^2 + 3(1 - \delta_{\varepsilon\mu})|g^T_{\varepsilon\mu}|^2\ , \qquad (9)$$

where $\delta_{\varepsilon\mu} = 1$ for $\varepsilon = \mu$, and $\delta_{\varepsilon\mu} = 0$ for $\varepsilon \neq \mu$. They are related to the parameters a, b, c, a', b', and c' by

$$Q_{RR} = 2(b + b')/A\ ,$$
$$Q_{LR} = [(a - a') + 6(c - c')]/2A\ ,$$
$$Q_{RL} = [(a + a') + 6(c + c')]/2A\ ,$$
$$Q_{LL} = 2(b - b')/A\ , \qquad (10)$$

with $A = 16$. In the Standard Model, $Q_{LL} = 1$ and the others are zero.

Since the upper bounds on Q_{RR}, Q_{LR}, and Q_{RL} are found to be small, and since the helicity of the ν_μ in pion decay is known from experiment [11,12] to very high precision to be -1 [13], the cross section S of *inverse* muon decay, normalized to the V-A value, yields [2]

$$|g^S_{LL}|^2 \leq 4(1 - S) \qquad (11)$$

and

$$|g^V_{LL}|^2 = S\ . \qquad (12)$$

Thus the Standard Model assumption of a pure V-A leptonic charged weak interaction of e and μ is derived (within errors) from experiments at energies far below mass of the $W^\pm$: Eq. (12) gives a lower limit for V-A, and Eqs. (9) and (11) give upper limits for the other four-fermion interactions. The existence of such upper limits may also be seen from $Q_{RR}+Q_{RL} = (1-\xi')/2$ and $Q_{RR}+Q_{LR} = \frac{1}{2}(1+\xi/3-16\ \xi\delta/9)$. Table 1 gives the current experimental limits on the magnitudes of the $g^\gamma_{\varepsilon\mu}$'s.

Limits on the "charge retention" coordinates, as used in the older literature (*e.g.*, Ref. 16), are given by Burkard *et al.* [17].

Table 1. Coupling constants $g^\gamma_{\varepsilon\mu}$. Ninety-percent confidence level experimental limits. The limits on $|g^S_{LL}|$ and $|g^V_{LL}|$ are from Ref. 14, and the others are from Ref. 15. The experimental uncertainty on the muon polarization in pion decay is included. Note that, by definition, $|g^S_{\varepsilon\mu}| \leq 2$, $|g^V_{\varepsilon\mu}| \leq 1$ and $|g^T_{\varepsilon\mu}| \leq 1/\sqrt{3}$.

$\lvert g^S_{RR}\rvert < 0.066$	$\lvert g^V_{RR}\rvert < 0.033$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.125$	$\lvert g^V_{LR}\rvert < 0.060$	$\lvert g^T_{LR}\rvert < 0.036$
$\lvert g^S_{RL}\rvert < 0.424$	$\lvert g^V_{RL}\rvert < 0.110$	$\lvert g^T_{RL}\rvert < 0.122$
$\lvert g^S_{LL}\rvert < 0.550$	$\lvert g^V_{LL}\rvert > 0.960$	$\lvert g^T_{LL}\rvert \equiv 0$

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μ DECAY PARAMETERS

ρ PARAMETER

(V−A) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7518±0.0026		DERENZO	69	RVUE		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.762 ±0.008	170k	[28] FRYBERGER	68	ASPK	+	25–53 MeV e^+
0.760 ±0.009	280k	[28] SHERWOOD	67	ASPK	+	25–53 MeV e^+
0.7503±0.0026	800k	[28] PEOPLES	66	ASPK	+	20–53 MeV e^+

[28] η constrained = 0. These values incorporated into a two parameter fit to ρ and η by DERENZO 69.

η PARAMETER

(V−A) theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
−0.007±0.013 OUR AVERAGE						
−0.007±0.013	5.3M	[29] BURKARD	85B	FIT	+	9–53 MeV e^+
−0.12 ±0.21	6346	DERENZO	69	HBC	+	1.6–6.8 MeV e^+

• • • We do not use the following data for averages, fits, limits, etc. • • •

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
$-0.012\pm0.015\pm0.003$	5.3M	[30] BURKARD	85B	CNTR	+	9–53 MeV e^+
$0.011\pm0.081\pm0.026$	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+
$-0.7\ \pm0.5$	170k	[31] FRYBERGER	68	ASPK	+	25–53 MeV e^+
$-0.7\ \pm0.6$	280k	[31] SHERWOOD	67	ASPK	+	25–53 MeV e^+
$0.05\ \pm0.5$	800k	[31] PEOPLES	66	ASPK	+	20–53 MeV e^+
$-2.0\ \pm0.9$	9213	[32] PLANO	60	HBC	+	Whole spectrum

[29] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[30] $\alpha = \alpha' = 0$ assumed.
[31] ρ constrained $= 0.75$.
[32] Two parameter fit to ρ and η; PLANO 60 discounts value for η.

δ PARAMETER

($V-A$) theory predicts $\delta = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.7486±0.0026±0.0028		[33] BALKE	88	SPEC	+	Surface μ^+'s
• • • We do not use the following data for averages, fits, limits, etc. • • •						
		[34] VOSSLER	69			
$0.752\ \pm0.009$	490k	FRYBERGER	68	ASPK	+	25–53 MeV e^+
$0.782\ \pm0.031$		KRUGER	61			
$0.78\ \ \pm0.05$	8354	PLANO	60	HBC	+	Whole spectrum

[33] BALKE 88 uses $\rho = 0.752 \pm 0.003$.
[34] VOSSLER 69 has measured the asymmetry below 10 MeV. See comments about radiative corrections in VOSSLER 69.

$|(\xi$ PARAMETER$)\times(\mu$ LONGITUDINAL POLARIZATION$)|$

($V-A$) theory predicts $\xi = 1$, longitudinal polarization $= 1$.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.0027±0.0079±0.0030		BELTRAMI	87	CNTR		SIN, π decay in flight
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$1.0013\pm0.0030\pm0.0053$		[35] IMAZATO	92	SPEC	+	$K^+ \rightarrow \mu^+\nu_\mu$
$0.975\ \pm0.015$		AKHMANOV	68	EMUL		140 kG
$0.975\ \pm0.030$	66k	GUREVICH	64	EMUL		See AKHMANOV 68
$0.903\ \pm0.027$		[36] ALI-ZADE	61	EMUL	+	27 kG
$0.93\ \ \pm0.06$	8354	PLANO	60	HBC	+	8.8 kG
$0.97\ \ \pm0.05$	9k	BARDON	59	CNTR		Bromoform target

[35] The corresponding 90% confidence limit from IMAZATO 92 is $|\xi P_\mu| > 0.990$. This measurement is of K^+ decay, not π^+ decay, so we do not include it in an average, nor do we yet set up a separate data block for K results.
[36] Depolarization by medium not known sufficiently well.

$\xi \times (\mu$ LONGITUDINAL POLARIZATION$) \times \delta\ /\ \rho$

VALUE	CL%	DOCUMENT ID		TECN	CHG	COMMENT
>0.99682	90	[37] JODIDIO	86	SPEC	+	TRIUMF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
>0.9966	90	[38] STOKER	85	SPEC	+	μ-spin rotation
>0.9959	90	CARR	83	SPEC	+	11 kG

[37] JODIDIO 86 includes data from CARR 83 and STOKER 85. The value here is from the erratum.
[38] STOKER 85 find $(\xi P_\mu \delta/\rho)$ >0.9955 and >0.9966, where the first limit is from new μ spin-rotation data and the second is from combination with CARR 83 data. In $V-A$ theory, $(\delta/\rho) = 1.0$.

ξ' = LONGITUDINAL POLARIZATION OF e^+

($V-A$) theory predicts the longitudinal polarization $= \pm1$ for $e^\pm$, respectively. We have flipped the sign for e^- so our programs can average.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.00 ±0.04 OUR AVERAGE						
0.998 ± 0.045	1M	BURKARD	85	CNTR	+	Bhabha + annihil
$0.89\ \pm0.28$	29k	SCHWARTZ	67	OSPK	−	Moller scattering
$0.94\ \pm0.38$		BLOOM	64	CNTR	+	Brems. transmiss.
$1.04\ \pm0.18$		DUCLOS	64	CNTR	+	Bhabha scattering
$1.05\ \pm0.30$		BUHLER	63	CNTR	+	Annihilation

ξ'' PARAMETER

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.65±0.36	326k	[39] BURKARD	85	CNTR	+	Bhabha + annihil

[39] BURKARD 85 measure $(\xi''-\xi\xi')/\xi$ and ξ' and set $\xi = 1$.

TRANSVERSE e^+ POLARIZATION IN PLANE OF μ SPIN, e^+ MOMENTUM

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$0.016\pm0.021\pm0.01$	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

TRANSVERSE e^+ POLARIZATION NORMAL TO PLANE OF μ SPIN, e^+ MOMENTUM

Zero if T invariance holds.

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.007±0.022±0.007	5.3M	BURKARD	85B	CNTR	+	Annihil 9–53 MeV

α/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.4± 4.3		[40] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$15\ \ \pm50\ \ \pm14$	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[40] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

α'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
− 0.2± 4.3		[41] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$-47\ \ \pm50\ \ \pm14$	5.3M	[42] BURKARD	85B	CNTR	+	9–53 MeV e^+

[41] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[42] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

β/A

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
3.9± 6.2		[43] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$2\ \ \pm17\ \ \pm6$	5.3M	BURKARD	85B	CNTR	+	9–53 MeV e^+

[43] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

β'/A

Zero if T invariance holds.

VALUE (units 10^{-3})	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
1.5± 6.3		[44] BURKARD	85B	FIT		
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$17\ \ \pm17\ \ \pm6$	5.3M	[45] BURKARD	85B	CNTR	+	9–53 MeV e^+

[44] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.
[45] BURKARD 85B measure e^+ polarizations P_{T_1} and P_{T_2} versus e^+ energy.

a/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<15.9	90	[46] BURKARD	85B	FIT

[46] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

a'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
5.3 ± 4.1	[47] BURKARD	85B	FIT

[47] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$(b'+b)/A$

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<1.04	90	[48] BURKARD	85B	FIT

[48] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<6.4	90	[49] BURKARD	85B	FIT

[49] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

c'/A

This comes from an alternative parameterization to that used in the Summary Table (see the "Note on Muon Decay Parameters" above).

VALUE (units 10^{-3})	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.5 ± 2.0	[50] BURKARD	85B	FIT

[50] Global fit to all measured parameters. Correlation coefficients are given in BURKARD 85B.

$\overline{\eta}$ PARAMETER

$(V-A)$ theory predicts $\overline{\eta} = 0$. $\overline{\eta}$ affects spectrum of radiative muon decay.

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
0.02 ±0.08 OUR AVERAGE					
−0.014±0.090	EICHENBER...	84	ELEC	+	ρ free
+0.09 ±0.14	BOGART	67	CNTR	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
−0.035±0.098	EICHENBER...	84	ELEC	+	ρ=0.75 assumed

μ REFERENCES

MOHR	04	RMP (to be publ.)	P.J. Mohr, B.N. Taylor	(NIST)
physics.nist.gov/constants				
AHMED	02	PR D65 112002	M. Ahmed *et al.*	(MEGA Collab.)
BENNETT	02	PRL 89 101804	G.W. Bennett *et al.*	(Muon(g-2) Collab.)
BROWN	01	PRL 86 2227	H.N. Brown *et al.*	(Muon(g-2) Collab.)
BROWN	00	PR D62 091101R	H.N. Brown *et al.*	(BNL/G-2 Collab.)
MEYER	00	PRL 84 1136	V. Meyer *et al.*	
BROOKS	99	PRL 83 1521	M.L. Brooks *et al.*	(MEGA/LAMPF Collab.)
HUGHES	99	RMP 71 S133	V.W. Hughes, T. Kinoshita	
LIU	99	PRL 82 711	W. Liu *et al.*	(LAMPF Collab.)
MOHR	99	JPCRD 28 1713	P.J. Mohr, B.N. Taylor	(NIST)
Also	00	RMP 72 351	P.J. Mohr, B.N. Taylor	(NIST)
WILLMANN	99	PRL 82 49	L. Willmann *et al.*	
FELDMAN	98	PR D57 3873	G.J. Feldman, R.D. Cousins	
KAULARD	98	PL B422 334	J. Kaulard *et al.*	(SINDRUM-II Collab.)
GORDEEV	97	PAN 60 1164	V.A. Gordeev *et al.*	(PNPI)
		Translated from YAF 60 1291.		
ABELA	96	PRL 77 1950	R. Abela *et al.*	(PSI, ZURI, HEIDH, TBIL+)
HONECKER	96	PRL 76 200	W. Honecker *et al.*	(SINDRUM II Collab.)
DOHMEN	93	PL B317 631	C. Dohmen *et al.*	(PSI SINDRUM-II Collab.)
FREEDMAN	93	PR D47 811	S.J. Freedman *et al.*	(LAMPF E645 Collab.)
NI	93	PR D48 1976	B. Ni *et al.*	(LAMPF Crystal-Box Collab.)
IMAZATO	92	PRL 69 877	J. Imazato *et al.*	(KEK, INUS, TOKY+)
BARANOV	91	SJNP 53 802	V.A. Baranov *et al.*	(JINR)
		Translated from YAF 53 1302.		
KRAKAUER	91B	PL B263 534	D.A. Krakauer *et al.*	(UMD, UCI, LANL)
MATTHIAS	91	PRL 66 2716	B.E. Matthias *et al.*	(YALE, HEIDP, WILL+)
Also	91B	PRL 67 932 erratum	B.E. Matthias *et al.*	(YALE, HEIDP, WILL+)
HUBER	90B	PR D41 2709	T.M. Huber *et al.*	(WYOM, VICT, ARIZ+)
AHMAD	88	PR D38 2102	S. Ahmad *et al.*	(TRIU, VICT, VPI, BRCO+)
Also	87	PRL 59 970	S. Ahmad *et al.*	(TRIU, VPI, VICT, BRCO+)
BALKE	88	PR D37 587	B. Balke *et al.*	(LBL, UCB, COLO, NWES+)
BELLGARDT	88	NP B299 1	U. Bellgardt *et al.*	(SINDRUM Collab.)
BOLTON	88	PR D38 2077	R.D. Bolton *et al.*	(LANL, STAN, CHIC+)
Also	86	PRL 56 2461	R.D. Bolton *et al.*	(LANL, STAN, CHIC+)
Also	86	PRL 57 3241	D. Grosnick *et al.*	(CHIC, LANL, STAN+)
BELTRAMI	87	PL B194 326	I. Beltrami *et al.*	(ETH, SIN, MANZ)
COHEN	87	RMP 59 1121	E.R. Cohen, B.N. Taylor	(RISC, NBS)
BEER	86	PRL 57 671	G.A. Beer *et al.*	(VICT, TRIU, WYOM)
JODIDIO	86	PR D34 1967	A. Jodidio *et al.*	(LBL, NWES, TRIU)
Also	88	PR D37 237 erratum	A. Jodidio *et al.*	(LBL, NWES, TRIU)
BERTL	85	NP B260 1	W. Bertl *et al.*	(SINDRUM Collab.)
BRYMAN	85	PRL 55 465	D.A. Bryman *et al.*	(TRIU, CNRC, BRCO+)
BURKARD	85	PL 150B 242	H. Burkhardt *et al.*	(ETH, SIN, MANZ)
BURKARD	85B	PL 160B 343	H. Burkhardt *et al.*	(ETH, SIN, MANZ)
Also	81B	PR D24 2004	F. Corriveau *et al.*	(ETH, SIN, MANZ)
Also	83B	PL 129B 260	F. Corriveau *et al.*	(ETH, SIN, MANZ)
STOKER	85	PRL 54 1887	D.P. Stoker *et al.*	(LBL, NWES, TRIU)
BARDIN	84	PL 137B 135	G. Bardin *et al.*	(SACL, CERN, BGNA, FIRZ)
BERTL	84	PL 140B 299	W. Bertl *et al.*	(SINDRUM Collab.)
BOLTON	84	PRL 53 1415	R.D. Bolton *et al.*	(LANL, CHIC, STAN+)
EICHENBER...	84	NP A412 523	W. Eichenberger, R. Engfer, A. van der Schaff	
GIOVANETTI	84	PR D29 343	K.L. Giovanetti *et al.*	(WILL)
AZUELOS	83	PRL 51 164	G. Azuelos *et al.*	(MONT, TRIU, BRCO)
Also	77	PRL 39 1113	P. Depommier *et al.*	(MONT, BRCO, TRIU+)
BERGSMA	83	PL 122B 465	F. Bergsma *et al.*	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr *et al.*	(LBL, NWES, TRIU)
KINNISON	82	PR D25 2846	W.W. Kinnison *et al.*	(EFI, STAN, LANL)
Also	79	PRL 42 556	J.D. Bowman *et al.*	(LASL, EFI, STAN)
KLEMPT	82	PR D25 652	E. Klempt *et al.*	(MANZ, ETH)
MARIAM	82	PRL 49 993	F.G. Mariam *et al.*	(YALE, HEIDH, BERN)
MARSHALL	82	PR D25 1174	G.M. Marshall *et al.*	(BRCO)
NEMETHY	81	CNPP 10 147	P. Nemethy, V.W. Hughes	(LBL, YALE)
ABELA	80	PL 95B 318	R. Abela *et al.*	(BASL, KARLK, KARLE)
BADERT...	80	LNC 28 401	A. Badertscher *et al.*	(BERN)
Also	82	NP A377 406	A. Badertscher *et al.*	(BERN)
JONKER	80	PL 93B 203	M. Jonker *et al.*	(CHARM Collab.)
SCHAAF	80	NP A340 249	A. van der Schaaf *et al.*	(ZURI, ETH+)
Also	77	PL 72B 183	H.P. Povel *et al.*	(ZURI, ETH, SIN)
WILLIS	80	PRL 44 522	S.E. Willis *et al.*	(YALE, LBL, LASL+)
Also	80B	PRL 45 1370	S.E. Willis *et al.*	(YALE, LBL, LASL+)
BAILEY	79	NP B150 1	J.M. Bailey	(CERN, DARE, MANZ)
BADERT...	78	PL 79B 371	A. Badertscher *et al.*	(BERN)
BAILEY	78	JPG 4 345	J.M. Bailey	(DARE, BERN, SHEF, MANZ, RMCS+)
Also	79	NP B150 1	J.M. Bailey	(CERN, DARE, MANZ)
BLIETSCHAU	78	NP B133 205	J. Blietschau *et al.*	(Gargamelle Collab.)
BOWMAN	78	PRL 41 442	J.D. Bowman *et al.*	(LASL, IAS, CMU+)
CAMANI	78	PL 77B 326	M. Camani *et al.*	(ETH, MANZ)
BADERT...	77	PRL 39 1385	A. Badertscher *et al.*	(BERN)
CASPERSON	77	PRL 38 956	D.E. Casperson *et al.*	(BERN, HEIDH, LASL+)
DEPOMMIER	77	PRL 39 1113	P. Depommier *et al.*	(MONT, BRCO, TRIU+)
BALANDIN	74	JETP 40 811	M.P. Balandin *et al.*	(JINR)
		Translated from ZETF 67 1631.		
COHEN	73	JPCRD 2 664	E.R. Cohen, B.N. Taylor	(RISC, NBS)
DUCLOS	73	PL 47B 491	J. Duclos, A. Magnon, J. Picard	(SACL)
EICHTEN	73	PL 46B 281	T. Eichten *et al.*	(Gargamelle Collab.)
BRYMAN	72	PRL 28 1469	D.A. Bryman *et al.*	(VPI)
CROWE	72	PR D5 2145	K.M. Crowe *et al.*	(LBL, WASH)
CRANE	71	PRL 27 474	T. Crane *et al.*	(YALE)
DERENZO	69	PR 181 1854	S.E. Derenzo	(EFI)
VOSSLER	69	NC 63A 423	C. Vossler	(EFI)
AKHMANOV	68	SJNP 6 230	V.V. Akhmanov *et al.*	(KIAE)
		Translated from YAF 6 316.		
FRYBERGER	68	PR 166 1379	D. Fryberger	(EFI)
BOGART	67	PR 156 1405	E. Bogart *et al.*	(COLU)
SCHWARTZ	67	PR 162 1306	D.M. Schwartz	(EFI)
SHERWOOD	67	PR 156 1475	B.A. Sherwood	(EFI)
PEOPLES	66	Nevis 147 unpub.	J. Peoples	(COLU)
BLOOM	64	PL 8 87	S. Bloom *et al.*	(CERN)
DUCLOS	64	PL 9 62	J. Duclos *et al.*	(CERN)
GUREVICH	64	PL 11 185	I.I. Gurevich *et al.*	(KIAE)
BUHLER	63	PL 7 368	A. Buhler-Broglin *et al.*	(CERN)
MEYER	63	PR 132 2693	S.L. Meyer *et al.*	(COLU)
CHARPAK	62	PL 1 16	G. Charpak *et al.*	(CERN)
CONFORTO	62	NC 26 261	G. Conforto *et al.*	(INFN, ROMA, CERN)
ALI-ZADE	61	JETP 13 313	S.A. Ali-Zade, I.I. Gurevich, B.A. Nikolsky	
		Translated from ZETF 40 452.		
CRITTENDEN	61	PR 121 1823	R.R. Crittenden, W.D. Walker, J. Ballam	(WISC+)
KRUGER	61	UCRL 9322 unpub.	H. Kruger	(LRL)
GUREVICH	60	JETP 10 225	I.I. Gurevich, B.A. Nikolsky, L.V. Surkova	(ITEP)
		Translated from ZETF 37 318.		
PLANO	60	PR 119 1400	R.J. Plano	(COLU)
ASHKIN	59	NC 14 1266	J. Ashkin *et al.*	(CERN)
BARDON	59	PRL 2 56	M. Bardon, D. Berley, L.M. Lederman	(COLU)
LEE	59	PRL 3 55	J. Lee, N.P. Samios	(COLU)

τ

$J = \frac{1}{2}$

τ discovery paper was PERL 75. $e^+e^- \rightarrow \tau^+\tau^-$ cross-section threshold behavior and magnitude are consistent with pointlike spin-1/2 Dirac particle. BRANDELIK 78 ruled out pointlike spin-0 or spin-1 particle. FELDMAN 78 ruled out $J = 3/2$. KIRKBY 79 also ruled out J=integer, $J = 3/2$.

τ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
$1776.99^{+0.29}_{-0.26}$ OUR AVERAGE					
1775.1 ±1.6 ±1.0	13.3k	[1] ABBIENDI	00A	OPAL	1990–1995 LEP runs
1778.2 ±0.8 ±1.2		ANASTASSOV	97	CLEO	E^{ee}_{cm}= 10.6 GeV
$1776.96^{+0.18}_{-0.21}{}^{+0.25}_{-0.17}$	65	[2] BAI	96	BES	E^{ee}_{cm}= 3.54–3.57 GeV
1776.3 ±2.4 ±1.4	11k	[3] ALBRECHT	92M	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
$1783\ ^{+3}_{-4}$	692	[4] BACINO	78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1777.8 ±0.7 ±1.7	35k	[5] BALEST	93	CLEO	Repl. by ANASTASSOV 97
$1776.9\ ^{+0.4}_{-0.5}$ ±0.2	14	[6] BAI	92	BES	Repl. by BAI 96

[1] ABBIENDI 00A fit τ pseudomass spectrum in $\tau \rightarrow \pi^{\pm} \leq 2\pi^0 \nu_\tau$ and $\tau \rightarrow \pi^{\pm}\pi^+\pi^- \leq 1\pi^0\nu_\tau$ decays. Result assumes m_{ν_τ}=0.

[2] BAI 96 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ at different energies near threshold.

[3] ALBRECHT 92M fit τ pseudomass spectrum in $\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$ decays. Result assumes m_{ν_τ}=0.

[4] BACINO 78B value comes from $e^{\pm}X^{\mp}$ threshold. Published mass 1782 MeV increased by 1 MeV using the high precision $\psi(2S)$ mass measurement of ZHOLENTZ 80 to eliminate the absolute SPEAR energy calibration uncertainty.

[5] BALEST 93 fit spectra of minimum kinematically allowed τ mass in events of the type $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\pi^+ n\pi^0 \nu_\tau)(\pi^- m\pi^0 \nu_\tau)$ $n \leq 2$, $m \leq 2$, $1 \leq n+m \leq 3$. If $m_{\nu_\tau} \neq 0$, result increases by $(m^2_{\nu_\tau}/1100\ \mathrm{MeV})$.

[6] BAI 92 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ near threshold using $e\mu$ events.

$(m_{\tau^+} - m_{\tau^-})/m_{\mathrm{average}}$

A test of CPT invariance.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.0 \times 10^{-3}$	90	ABBIENDI	00A	OPAL	1990–1995 LEP runs

τ MEAN LIFE

VALUE (10^{-15} s)	EVTS	DOCUMENT ID		TECN	COMMENT
290.6± 1.1 OUR AVERAGE					
293.2± 2.0± 1.5		ACCIARRI	00B	L3	1991–1995 LEP runs
290.1± 1.5± 1.1		BARATE	97R	ALEP	1989–1994 LEP runs
291.4± 3.0		ABREU	96B	DLPH	1991–1993 LEP runs
289.2± 1.7± 1.2		ALEXANDER	96E	OPAL	1990–1994 LEP runs
289.0± 2.8± 4.0	57.4k	BALEST	96	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
291.2± 2.0± 1.2		BARATE	97I	ALEP	Repl. by BARATE 97R
290.1± 4.0	34k	ACCIARRI	96K	L3	Repl. by ACCIARRI 00B
297 ± 9 ± 5	1671	ABE	95Y	SLD	1992–1993 SLC runs
304 ± 14 ± 7	4100	BATTLE	92	CLEO	E^{ee}_{cm}= 10.6 GeV
301 ± 29	3780	KLEINWORT	89	JADE	E^{ee}_{cm}= 35–46 GeV
288 ± 16 ±17	807	AMIDEI	88	MRK2	E^{ee}_{cm}= 29 GeV
306 ± 20 ±14	695	BRAUNSCH...	88C	TASS	E^{ee}_{cm}= 36 GeV
299 ± 15 ±10	1311	ABACHI	87C	HRS	E^{ee}_{cm}= 29 GeV
295 ± 14 ±11	5696	ALBRECHT	87P	ARG	E^{ee}_{cm}= 9.3–10.6 GeV
309 ± 17 ± 7	3788	BAND	87B	MAC	E^{ee}_{cm}= 29 GeV
325 ± 14 ±18	8470	BEBEK	87C	CLEO	E^{ee}_{cm}= 10.5 GeV
460 ±190	102	FELDMAN	82	MRK2	E^{ee}_{cm}= 29 GeV

τ MAGNETIC MOMENT ANOMALY

The q^2 dependence is expected to be small providing no thresholds are nearby.

$\mu_\tau/(e\hbar/2m_\tau)-1 = (g_\tau-2)/2$

For a theoretical calculation $[(g_\tau-2)/2 = 11773(3)\times 10^{-7}]$, see SAMUEL 91B.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
> −0.052 and < 0.058 (CL = 95%) OUR LIMIT					
> −0.052 and < 0.058	95	ACCIARRI	98E	L3	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> −0.007 and < 0.005	95	[7] GONZALEZ-S...00		RVUE	$e^+e^- \to \tau^+\tau^-$ and $W \to \tau\nu_\tau$
> −0.068 and < 0.065	95	[8] ACKERSTAFF	98N	OPAL	1990–1995 LEP runs
> −0.004 and < 0.006	95	[9] ESCRIBANO	97	RVUE	$Z \to \tau^+\tau^-$ at LEP
<0.01	95	[10] ESCRIBANO	93	RVUE	$Z \to \tau^+\tau^-$ at LEP
<0.12	90	GRIFOLS	91	RVUE	$Z \to \tau\tau\gamma$ at LEP
<0.023	95	[11] SILVERMAN	83	RVUE	$e^+e^- \to \tau^+\tau^-$ at PETRA

[7] GONZALEZ-SPRINBERG 00 use data on tau lepton production at LEP1, SLC, and LEP2, and data from colliders and LEP2 to determine limits. Assume imaginary component is zero.
[8] ACKERSTAFF 98N use $Z \to \tau^+\tau^-\gamma$ events. The limit applies to an average of the form factor for off-shell τ's having p^2 ranging from m_τ^2 to $(M_Z-m_\tau)^2$.
[9] ESCRIBANO 97 use preliminary experimental results.
[10] ESCRIBANO 93 limit derived from $\Gamma(Z \to \tau^+\tau^-)$, and is on the absolute value of the magnetic moment anomaly.
[11] SILVERMAN 83 limit is derived from $e^+e^- \to \tau^+\tau^-$ total cross-section measurements for q^2 up to (37 GeV)^2.

τ ELECTRIC DIPOLE MOMENT (d_τ)

A nonzero value is forbidden by both T invariance and P invariance.

The q^2 dependence is expected to be small providing no thresholds are nearby.

Re(d_τ)

VALUE (10^{-16} $e$cm)	CL%	DOCUMENT ID		TECN	COMMENT
−0.22 to 0.45	95	[12] INAMI	03	BELL	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.6	95	[13] ALBRECHT	00	ARG	E^{ee}_{cm}= 10.4 GeV
> −3.1 and < 3.1	95	ACCIARRI	98E	L3	1991–1995 LEP runs
> −3.8 and < 3.6	95	[14] ACKERSTAFF	98N	OPAL	1990–1995 LEP runs
< 0.11	95	[15,16] ESCRIBANO	97	RVUE	$Z \to \tau^+\tau^-$ at LEP
< 0.5	95	[17] ESCRIBANO	93	RVUE	$Z \to \tau^+\tau^-$ at LEP
< 7	90	GRIFOLS	91	RVUE	$Z \to \tau\tau\gamma$ at LEP
< 1.6	90	DELAGUILA	90	RVUE	$e^+e^- \to \tau^+\tau^-$ E^{ee}_{cm}= 35 GeV

[12] INAMI 03 use $e^+e^- \to \tau^+\tau^-$ events.
[13] ALBRECHT 00 use $e^+e^- \to \tau^+\tau^-$ events. Limit is on the absolute value of Re(d_τ).
[14] ACKERSTAFF 98N use $Z \to \tau^+\tau^-\gamma$ events. The limit applies to an average of the form factor for off-shell τ's having p^2 ranging from m_τ^2 to $(M_Z-m_\tau)^2$.
[15] ESCRIBANO 97 derive the relationship $|d_\tau| = \cot\theta_W\,|d_\tau^W|$ using effective Lagrangian methods, and use a conference result $|d_\tau^W| < 5.8\times10^{-18}$ $e$cm at 95% CL (L. Silvestris, ICHEP96) to obtain this result.
[16] ESCRIBANO 97 use preliminary experimental results.
[17] ESCRIBANO 93 limit derived from $\Gamma(Z \to \tau^+\tau^-)$, and is on the absolute value of the electric dipole moment.

Im(d_τ)

VALUE (10^{-16} $e$cm)	CL%	DOCUMENT ID		TECN	COMMENT
−0.25 to 0.008	95	[18] INAMI	03	BELL	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.8	95	[19] ALBRECHT	00	ARG	E^{ee}_{cm}= 10.4 GeV

[18] INAMI 03 use $e^+e^- \to \tau^+\tau^-$ events.
[19] ALBRECHT 00 use $e^+e^- \to \tau^+\tau^-$ events. Limit is on the absolute value of Im(d_τ).

τ WEAK DIPOLE MOMENT (d_τ^W)

A nonzero value is forbidden by CP invariance.

The q^2 dependence is expected to be small providing no thresholds are nearby.

Re(d_τ^W)

VALUE (10^{-17} $e$cm)	CL%	DOCUMENT ID		TECN	COMMENT
<0.50	95	[20] HEISTER	03F	ALEP	1990–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.0	90	[20] ACCIARRI	98C	L3	1991–1995 LEP runs
<0.56	95	ACKERSTAFF	97L	OPAL	1991–1995 LEP runs
<0.78	95	[21] AKERS	95F	OPAL	Repl. by ACKERSTAFF 97L
<1.5	95	[21] BUSKULIC	95C	ALEP	Repl. by HEISTER 03F
<7.0	95	[21] ACTON	92F	OPAL	$Z \to \tau^+\tau^-$ at LEP
<3.7	95	[21] BUSKULIC	92J	ALEP	Repl. by BUSKULIC 95C

[20] Limit is on the absolute value of the real part of the weak dipole moment.
[21] Limit is on the absolute value of the real part of the weak dipole moment, and applies for $q^2 = m_Z^2$.

Im(d_τ^W)

VALUE (10^{-17} $e$cm)	CL%	DOCUMENT ID		TECN	COMMENT
<1.1	95	[22] HEISTER	03F	ALEP	1990–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.5	95	ACKERSTAFF	97L	OPAL	1991–1995 LEP runs
<4.5	95	[23] AKERS	95F	OPAL	Repl. by ACKERSTAFF 97L

[22] HEISTER 03F limit is on the absolute value of the imaginary part of the weak dipole moment.
[23] Limit is on the absolute value of the imaginary part of the weak dipole moment, and applies for $q^2 = m_Z^2$.

τ WEAK ANOMALOUS MAGNETIC DIPOLE MOMENT (α_τ^W)

Electroweak radiative corrections are expected to contribute at the 10^{-6} level. See BERNABEU 95.

The q^2 dependence is expected to be small providing no thresholds are nearby.

Re(α_τ^W)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.1 × 10^{-3}	95	[24] HEISTER	03F	ALEP	1990–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> −0.0024 and < 0.0025	95	[25] GONZALEZ-S...00		RVUE	$e^+e^- \to \tau^+\tau^-$ and $W \to \tau\nu_\tau$
<4.5 × 10^{-3}	90	[24] ACCIARRI	98C	L3	1991–1995 LEP runs

[24] Limit is on the absolute value of the real part of the weak anomalous magnetic dipole moment.
[25] GONZALEZ-SPRINBERG 00 use data on tau lepton production at LEP1, SLC, and LEP2, and data from colliders and LEP2 to determine limits. Assume imaginary component is zero.

Im(α_τ^W)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.7 × 10^{-3}	95	[26] HEISTER	03F	ALEP	1990–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<9.9 × 10^{-3}	90	[26] ACCIARRI	98C	L3	1991–1995 LEP runs

[26] Limit is on the absolute value of the imaginary part of the weak anomalous magnetic dipole moment.

τ^- DECAY MODES

τ^+ modes are charge conjugates of the modes below. "$h^\pm$" stands for $\pi^\pm$ or $K^\pm$. "ℓ" stands for e or μ. "Neutrals" stands for γ's and/or π^0's.

	Mode		Fraction (Γ_i/Γ)	Scale factor/ Confidence level
	Modes with one charged particle			
Γ_1	particle$^-$ $\geq$ 0 neutrals $\geq 0K^0\nu_\tau$ ("1-prong")		(85.35±0.07) %	S=1.1
Γ_2	particle$^-$ $\geq$ 0 neutrals $\geq 0K_L^0\nu_\tau$		(84.72±0.07) %	S=1.1
Γ_3	$\mu^-\overline{\nu}_\mu\nu_\tau$	[a]	(17.36±0.06) %	
Γ_4	$\mu^-\overline{\nu}_\mu\nu_\tau\gamma$	[b]	(3.6 ±0.4) × 10^{-3}	
Γ_5	$e^-\overline{\nu}_e\nu_\tau$	[a]	(17.84±0.06) %	
Γ_6	$e^-\overline{\nu}_e\nu_\tau\gamma$	[b]	(1.75±0.18) %	
Γ_7	$h^- \geq 0K_L^0\,\nu_\tau$		(12.30±0.11) %	S=1.4
Γ_8	$h^-\nu_\tau$		(11.75±0.11) %	S=1.4
Γ_9	$\pi^-\nu_\tau$	[a]	(11.06±0.11) %	S=1.4
Γ_{10}	$K^-\nu_\tau$	[a]	(6.86±0.23) × 10^{-3}	
Γ_{11}	$h^- \geq$ 1 neutralsν_τ		(36.92±0.14) %	S=1.1
Γ_{12}	$h^-\pi^0\nu_\tau$		(25.87±0.13) %	S=1.1
Γ_{13}	$\pi^-\pi^0\nu_\tau$	[a]	(25.42±0.14) %	S=1.1
Γ_{14}	$\pi^-\pi^0$ non-$\rho(770)\nu_\tau$		(3.0 ±3.2) × 10^{-3}	
Γ_{15}	$K^-\pi^0\nu_\tau$	[a]	(4.50±0.30) × 10^{-3}	
Γ_{16}	$h^- \geq 2\pi^0\nu_\tau$		(10.77±0.15) %	S=1.1
Γ_{17}	$h^-2\pi^0\nu_\tau$		(9.39±0.14) %	S=1.1

Γ_{18}	$h^- 2\pi^0 \nu_\tau$ (ex.K^0)		(9.23 ± 0.14) %	S=1.1
Γ_{19}	$\pi^- 2\pi^0 \nu_\tau$ (ex.K^0)	[a]	(9.17 ± 0.14) %	S=1.1
Γ_{20}	$\pi^- 2\pi^0 \nu_\tau$ (ex.K^0), scalar		$< 9 \times 10^{-3}$	CL=95%
Γ_{21}	$\pi^- 2\pi^0 \nu_\tau$ (ex.K^0), vector		$< 7 \times 10^{-3}$	CL=95%
Γ_{22}	$K^- 2\pi^0 \nu_\tau$ (ex.K^0)	[a]	$(5.8 \pm2.3) \times 10^{-4}$	
Γ_{23}	$h^- \geq 3\pi^0 \nu_\tau$		(1.37 ± 0.11) %	S=1.1
Γ_{24}	$h^- 3\pi^0 \nu_\tau$		(1.21 ± 0.10) %	
Γ_{25}	$\pi^- 3\pi^0 \nu_\tau$ (ex.K^0)	[a]	(1.08 ± 0.10) %	
Γ_{26}	$K^- 3\pi^0 \nu_\tau$ (ex.K^0, η)	[a]	$(3.8 \ ^{+2.2}_{-2.0}) \times 10^{-4}$	
Γ_{27}	$h^- 4\pi^0 \nu_\tau$ (ex.K^0)		$(1.6 \pm0.6) \times 10^{-3}$	
Γ_{28}	$h^- 4\pi^0 \nu_\tau$ (ex.K^0,η)	[a]	$(1.0 \ ^{+0.6}_{-0.5}) \times 10^{-3}$	
Γ_{29}	$K^- \geq 0\pi^0 \ \geq 0K^0 \ \geq 0\gamma \ \nu_\tau$		(1.56 ± 0.04) %	
Γ_{30}	$K^- \geq 1$ (π^0 or K^0 or γ) ν_τ		$(8.74\pm0.35) \times 10^{-3}$	
	Modes with K^0's			
Γ_{31}	K^0_S(particles)$^- \nu_\tau$		$(9.2 \pm0.4) \times 10^{-3}$	S=1.1
Γ_{32}	$h^- \overline{K}^0 \nu_\tau$		(1.05 ± 0.04) %	S=1.1
Γ_{33}	$\pi^- \overline{K}^0 \nu_\tau$	[a]	$(8.9 \pm0.4) \times 10^{-3}$	S=1.1
Γ_{34}	$\pi^- \overline{K}^0$ (non-$K^*(892)^-$)ν_τ		$< 1.7 \times 10^{-3}$	CL=95%
Γ_{35}	$K^- K^0 \nu_\tau$	[a]	$(1.54\pm0.16) \times 10^{-3}$	
Γ_{36}	$K^- K^0 \geq 0\pi^0 \nu_\tau$		$(3.09\pm0.24) \times 10^{-3}$	
Γ_{37}	$h^- \overline{K}^0 \pi^0 \nu_\tau$		$(5.2 \pm0.4) \times 10^{-3}$	
Γ_{38}	$\pi^- \overline{K}^0 \pi^0 \nu_\tau$	[a]	$(3.7 \pm0.4) \times 10^{-3}$	
Γ_{39}	$\overline{K}^0 \rho^- \nu_\tau$		$(2.2 \pm0.5) \times 10^{-3}$	
Γ_{40}	$K^- K^0 \pi^0 \nu_\tau$	[a]	$(1.55\pm0.20) \times 10^{-3}$	
Γ_{41}	$\pi^- \overline{K}^0 \geq 1\pi^0 \nu_\tau$		$(3.2 \pm1.0) \times 10^{-3}$	
Γ_{42}	$\pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau$		$(2.6 \pm2.4) \times 10^{-4}$	
Γ_{43}	$K^- K^0 \pi^0 \pi^0 \nu_\tau$		$< 1.6 \times 10^{-4}$	CL=95%
Γ_{44}	$\pi^- K^0 \overline{K}^0 \nu_\tau$		$(1.59\pm0.29) \times 10^{-3}$	S=1.1
Γ_{45}	$\pi^- K^0_S K^0_S \nu_\tau$	[a]	$(2.4 \pm0.5) \times 10^{-4}$	
Γ_{46}	$\pi^- K^0_S K^0_L \nu_\tau$	[a]	$(1.10\pm0.28) \times 10^{-3}$	S=1.1
Γ_{47}	$\pi^- K^0 \overline{K}^0 \pi^0 \nu_\tau$		$(3.1 \pm2.3) \times 10^{-4}$	
Γ_{48}	$\pi^- K^0_S K^0_S \pi^0 \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=95%
Γ_{49}	$\pi^- K^0_S K^0_L \pi^0 \nu_\tau$		$(3.1 \pm1.2) \times 10^{-4}$	
Γ_{50}	$K^0 h^+ h^- h^- \geq 0$ neutrals ν_τ		$< 1.7 \times 10^{-3}$	CL=95%
Γ_{51}	$K^0 h^+ h^- h^- \nu_\tau$		$(2.3 \pm2.0) \times 10^{-4}$	
	Modes with three charged particles			
Γ_{52}	$h^- h^- h^+ \geq 0$ neutrals $\geq 0K^0_L \nu_\tau$		(15.19 ± 0.07) %	S=1.1
Γ_{53}	$h^- h^- h^+ \geq 0$ neutrals ν_τ (ex. $K^0_S \to \pi^+\pi^-$) ("3-prong")		(14.57 ± 0.07) %	S=1.1
Γ_{54}	$h^- h^- h^+ \nu_\tau$		(10.01 ± 0.09) %	S=1.2
Γ_{55}	$h^- h^- h^+ \nu_\tau$ (ex.K^0)		(9.65 ± 0.09) %	S=1.2
Γ_{56}	$h^- h^- h^+ \nu_\tau$ (ex.K^0,ω)		(9.60 ± 0.09) %	S=1.2
Γ_{57}	$\pi^- \pi^+ \pi^- \nu_\tau$		(9.47 ± 0.10) %	S=1.2
Γ_{58}	$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)		(9.16 ± 0.10) %	S=1.2
Γ_{59}	$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0), non-axial vector		< 2.4 %	CL=95%
Γ_{60}	$\pi^- \pi^+ \pi^- \nu_\tau$ (ex.K^0,ω)	[a]	(9.12 ± 0.10) %	S=1.2
Γ_{61}	$h^- h^- h^+ \geq 1$ neutrals ν_τ		(5.19 ± 0.10) %	S=1.3
Γ_{62}	$h^- h^- h^+ \geq 1$ neutrals ν_τ (ex. $K^0_S \to \pi^+\pi^-$)		(4.92 ± 0.09) %	S=1.3
Γ_{63}	$h^- h^- h^+ \pi^0 \nu_\tau$		(4.53 ± 0.09) %	S=1.3
Γ_{64}	$h^- h^- h^+ \pi^0 \nu_\tau$ (ex.K^0)		(4.35 ± 0.09) %	S=1.3
Γ_{65}	$h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0, ω)		(2.62 ± 0.09) %	S=1.2
Γ_{66}	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		(4.37 ± 0.09) %	S=1.3
Γ_{67}	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)		(4.25 ± 0.09) %	S=1.3
Γ_{68}	$\pi^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0,ω)	[a]	(2.51 ± 0.09) %	S=1.2
Γ_{69}	$h^- \rho \pi^0 \nu_\tau$			
Γ_{70}	$h^- \rho^+ h^- \nu_\tau$			
Γ_{71}	$h^- \rho^- h^+ \nu_\tau$			
Γ_{72}	$h^- h^- h^+ 2\pi^0 \nu_\tau$		$(5.5 \pm0.4) \times 10^{-3}$	
Γ_{73}	$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0)		$(5.4 \pm0.4) \times 10^{-3}$	
Γ_{74}	$h^- h^- h^+ 2\pi^0 \nu_\tau$ (ex.K^0,ω,η)	[a]	$(1.1 \pm0.4) \times 10^{-3}$	
Γ_{75}	$h^- h^- h^+ 3\pi^0 \nu_\tau$	[a]	$(2.3 \pm0.8) \times 10^{-4}$	S=1.5
Γ_{76}	$K^- h^+ h^- \geq 0$ neutrals ν_τ		$(6.9 \pm0.4) \times 10^{-3}$	S=1.3
Γ_{77}	$K^- h^+ \pi^- \nu_\tau$ (ex.K^0)		$(4.8 \pm0.4) \times 10^{-3}$	S=1.5
Γ_{78}	$K^- h^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)		$(1.07\pm0.22) \times 10^{-3}$	
Γ_{79}	$K^- \pi^+ \pi^- \geq 0$ neutrals ν_τ		$(5.0 \pm0.4) \times 10^{-3}$	S=1.3
Γ_{80}	$K^- \pi^+ \pi^- \geq 0\pi^0 \nu_\tau$ (ex.K^0)		$(3.9 \pm0.4) \times 10^{-3}$	S=1.3
Γ_{81}	$K^- \pi^+ \pi^- \nu_\tau$		$(3.8 \pm0.4) \times 10^{-3}$	S=1.6
Γ_{82}	$K^- \pi^+ \pi^- \nu_\tau$ (ex.K^0)	[a]	$(3.3 \pm0.4) \times 10^{-3}$	S=1.6

Γ_{83}	$K^- \rho^0 \nu_\tau \to K^- \pi^+ \pi^- \nu_\tau$		$(1.6 \pm0.6) \times 10^{-3}$	
Γ_{84}	$K^- \pi^+ \pi^- \pi^0 \nu_\tau$		$(1.18\pm0.25) \times 10^{-3}$	
Γ_{85}	$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0)		$(6.5 \pm2.4) \times 10^{-4}$	
Γ_{86}	$K^- \pi^+ \pi^- \pi^0 \nu_\tau$ (ex.K^0,η)	[a]	$(5.9 \pm2.4) \times 10^{-4}$	
Γ_{87}	$K^- \pi^+ K^- \geq 0$ neut. ν_τ		$< 9 \times 10^{-4}$	CL=95%
Γ_{88}	$K^- K^+ \pi^- \geq 0$ neut. ν_τ		$(1.97\pm0.18) \times 10^{-3}$	S=1.1
Γ_{89}	$K^- K^+ \pi^- \nu_\tau$	[a]	$(1.55\pm0.07) \times 10^{-3}$	
Γ_{90}	$K^- K^+ \pi^- \pi^0 \nu_\tau$	[a]	$(4.2 \pm1.6) \times 10^{-4}$	S=1.1
Γ_{91}	$K^- K^+ K^- \geq 0$ neut. ν_τ		$< 2.1 \times 10^{-3}$	CL=95%
Γ_{92}	$K^- K^+ K^- \nu_\tau$		$< 3.7 \times 10^{-5}$	CL=90%
Γ_{93}	$\pi^- K^+ \pi^- \geq 0$ neut. ν_τ		$< 2.5 \times 10^{-3}$	CL=95%
Γ_{94}	$e^- e^- e^+ \overline{\nu}_e \nu_\tau$		$(2.8 \pm1.5) \times 10^{-5}$	
Γ_{95}	$\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau$		$< 3.6 \times 10^{-5}$	CL=90%
	Modes with five charged particles			
Γ_{96}	$3h^- 2h^+ \geq 0$ neutrals ν_τ (ex. $K^0_S \to \pi^-\pi^+$) ("5-prong")		$(1.00\pm0.06) \times 10^{-3}$	
Γ_{97}	$3h^- 2h^+ \nu_\tau$ (ex.K^0)	[a]	$(8.2 \pm0.6) \times 10^{-4}$	
Γ_{98}	$3h^- 2h^+ \pi^0 \nu_\tau$ (ex.K^0)	[a]	$(1.81\pm0.27) \times 10^{-4}$	
Γ_{99}	$3h^- 2h^+ 2\pi^0 \nu_\tau$		$< 1.1 \times 10^{-4}$	CL=90%
	Miscellaneous other allowed modes			
Γ_{100}	$(5\pi)^- \nu_\tau$		$(8.0 \pm0.7) \times 10^{-3}$	
Γ_{101}	$4h^- 3h^+ \geq 0$ neutrals ν_τ ("7-prong")		$< 2.4 \times 10^{-6}$	CL=90%
Γ_{102}	$X^-(S{=}-1)\nu_\tau$		(2.91 ± 0.08) %	S=1.1
Γ_{103}	$K^*(892)^- \geq 0$ neutrals $\geq 0K^0_L \nu_\tau$		(1.42 ± 0.18) %	S=1.4
Γ_{104}	$K^*(892)^- \nu_\tau$		(1.29 ± 0.05) %	
Γ_{105}	$K^*(892)^0 K^- \geq 0$ neutrals ν_τ		$(3.2 \pm1.4) \times 10^{-3}$	
Γ_{106}	$K^*(892)^0 K^- \nu_\tau$		$(2.1 \pm0.4) \times 10^{-3}$	
Γ_{107}	$\overline{K}^*(892)^0 \pi^- \geq 0$ neutrals ν_τ		$(3.8 \pm1.7) \times 10^{-3}$	
Γ_{108}	$\overline{K}^*(892)^0 \pi^- \nu_\tau$		$(2.2 \pm0.5) \times 10^{-3}$	
Γ_{109}	$(\overline{K}^*(892)\pi)^- \nu_\tau \to \pi^- \overline{K}^0 \pi^0 \nu_\tau$		$(1.0 \pm0.4) \times 10^{-3}$	
Γ_{110}	$K_1(1270)^- \nu_\tau$		$(4.7 \pm1.1) \times 10^{-3}$	
Γ_{111}	$K_1(1400)^- \nu_\tau$		$(1.7 \pm2.6) \times 10^{-3}$	S=1.7
Γ_{112}	$K^*(1410)^- \nu_\tau$		$(1.5 \ ^{+1.4}_{-1.0}) \times 10^{-3}$	
Γ_{113}	$K^*_0(1430)^- \nu_\tau$		$< 5 \times 10^{-4}$	CL=95%
Γ_{114}	$K^*_2(1430)^- \nu_\tau$		$< 3 \times 10^{-3}$	CL=95%
Γ_{115}	$a_0(980)^- \geq 0$ neutrals ν_τ			
Γ_{116}	$\eta \pi^- \nu_\tau$		$< 1.4 \times 10^{-4}$	CL=95%
Γ_{117}	$\eta \pi^- \pi^0 \nu_\tau$	[a]	$(1.74\pm0.24) \times 10^{-3}$	
Γ_{118}	$\eta \pi^- \pi^0 \pi^0 \nu_\tau$		$(1.5 \pm0.5) \times 10^{-4}$	
Γ_{119}	$\eta K^- \nu_\tau$	[a]	$(2.7 \pm0.6) \times 10^{-4}$	
Γ_{120}	$\eta K^*(892)^- \nu_\tau$		$(2.9 \pm0.9) \times 10^{-4}$	
Γ_{121}	$\eta K^- \pi^0 \nu_\tau$		$(1.8 \pm0.9) \times 10^{-4}$	
Γ_{122}	$\eta \overline{K}^0 \pi^- \nu_\tau$		$(2.2 \pm0.7) \times 10^{-4}$	
Γ_{123}	$\eta \pi^+ \pi^- \pi^- \geq 0$ neutrals ν_τ		$< 3 \times 10^{-3}$	CL=90%
Γ_{124}	$\eta \pi^- \pi^+ \pi^- \nu_\tau$		$(2.3 \pm0.5) \times 10^{-4}$	
Γ_{125}	$\eta a_1(1260)^- \nu_\tau \to \eta \pi^- \rho^0 \nu_\tau$		$< 3.9 \times 10^{-4}$	CL=90%
Γ_{126}	$\eta \eta \pi^- \nu_\tau$		$< 1.1 \times 10^{-4}$	CL=95%
Γ_{127}	$\eta \eta \pi^- \pi^0 \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=95%
Γ_{128}	$\eta'(958) \pi^- \nu_\tau$		$< 7.4 \times 10^{-5}$	CL=90%
Γ_{129}	$\eta'(958) \pi^- \pi^0 \nu_\tau$		$< 8.0 \times 10^{-5}$	CL=90%
Γ_{130}	$\phi \pi^- \nu_\tau$		$< 2.0 \times 10^{-4}$	CL=90%
Γ_{131}	$\phi K^- \nu_\tau$		$< 6.7 \times 10^{-5}$	CL=90%
Γ_{132}	$f_1(1285) \pi^- \nu_\tau$		$(5.8 \pm2.3) \times 10^{-4}$	
Γ_{133}	$f_1(1285) \pi^- \nu_\tau \to \eta \pi^- \pi^+ \pi^- \nu_\tau$		$(1.3 \pm0.4) \times 10^{-4}$	
Γ_{134}	$\pi(1300)^- \nu_\tau \to (\rho\pi)^- \nu_\tau \to (3\pi)^- \nu_\tau$		$< 1.0 \times 10^{-4}$	CL=90%
Γ_{135}	$\pi(1300)^- \nu_\tau \to ((\pi\pi)_{S-\text{wave}} \pi)^- \nu_\tau \to (3\pi)^- \nu_\tau$		$< 1.9 \times 10^{-4}$	CL=90%
Γ_{136}	$h^- \omega \geq 0$ neutrals ν_τ		(2.38 ± 0.08) %	
Γ_{137}	$h^- \omega \nu_\tau$	[a]	(1.94 ± 0.07) %	
Γ_{138}	$h^- \omega \pi^0 \nu_\tau$	[a]	$(4.4 \pm0.5) \times 10^{-3}$	
Γ_{139}	$h^- \omega 2\pi^0 \nu_\tau$		$(1.4 \pm0.5) \times 10^{-4}$	
Γ_{140}	$2h^- h^+ \omega \nu_\tau$		$(1.20\pm0.22) \times 10^{-4}$	

Lepton Family number (LF), Lepton number (L), or Baryon number (B) violating modes

L means lepton number violation (*e.g.* $\tau^- \to e^+\pi^-\pi^-$). Following common usage, LF means lepton family violation *and not* lepton number violation (*e.g.* $\tau^- \to e^-\pi^+\pi^-$). B means baryon number violation.

Γ_{141}	$e^-\gamma$	LF	$< 2.7 \times 10^{-6}$	CL=90%
Γ_{142}	$\mu^-\gamma$	LF	$< 1.1 \times 10^{-6}$	CL=90%
Γ_{143}	$e^-\pi^0$	LF	$< 3.7 \times 10^{-6}$	CL=90%
Γ_{144}	$\mu^-\pi^0$	LF	$< 4.0 \times 10^{-6}$	CL=90%
Γ_{145}	$e^-K^0_S$	LF	$< 9.1 \times 10^{-7}$	CL=90%
Γ_{146}	$\mu^-K^0_S$	LF	$< 9.5 \times 10^{-7}$	CL=90%
Γ_{147}	$e^-\eta$	LF	$< 8.2 \times 10^{-6}$	CL=90%
Γ_{148}	$\mu^-\eta$	LF	$< 9.6 \times 10^{-6}$	CL=90%
Γ_{149}	$e^-\rho^0$	LF	$< 2.0 \times 10^{-6}$	CL=90%
Γ_{150}	$\mu^-\rho^0$	LF	$< 6.3 \times 10^{-6}$	CL=90%
Γ_{151}	$e^-K^*(892)^0$	LF	$< 5.1 \times 10^{-6}$	CL=90%
Γ_{152}	$\mu^-K^*(892)^0$	LF	$< 7.5 \times 10^{-6}$	CL=90%
Γ_{153}	$e^-\overline{K}^*(892)^0$	LF	$< 7.4 \times 10^{-6}$	CL=90%
Γ_{154}	$\mu^-\overline{K}^*(892)^0$	LF	$< 7.5 \times 10^{-6}$	CL=90%
Γ_{155}	$e^-\phi$	LF	$< 6.9 \times 10^{-6}$	CL=90%
Γ_{156}	$\mu^-\phi$	LF	$< 7.0 \times 10^{-6}$	CL=90%
Γ_{157}	$e^-e^+e^-$	LF	$< 2.9 \times 10^{-6}$	CL=90%
Γ_{158}	$e^-\mu^+\mu^-$	LF	$< 1.8 \times 10^{-6}$	CL=90%
Γ_{159}	$e^+\mu^-\mu^-$	LF	$< 1.5 \times 10^{-6}$	CL=90%
Γ_{160}	$\mu^-e^+e^-$	LF	$< 1.7 \times 10^{-6}$	CL=90%
Γ_{161}	$\mu^+e^-e^-$	LF	$< 1.5 \times 10^{-6}$	CL=90%
Γ_{162}	$\mu^-\mu^+\mu^-$	LF	$< 1.9 \times 10^{-6}$	CL=90%
Γ_{163}	$e^-\pi^+\pi^-$	LF	$< 2.2 \times 10^{-6}$	CL=90%
Γ_{164}	$e^+\pi^-\pi^-$	L	$< 1.9 \times 10^{-6}$	CL=90%
Γ_{165}	$\mu^-\pi^+\pi^-$	LF	$< 8.2 \times 10^{-6}$	CL=90%
Γ_{166}	$\mu^+\pi^-\pi^-$	L	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{167}	$e^-\pi^+K^-$	LF	$< 6.4 \times 10^{-6}$	CL=90%
Γ_{168}	$e^-\pi^-K^+$	LF	$< 3.8 \times 10^{-6}$	CL=90%
Γ_{169}	$e^+\pi^-K^-$	L	$< 2.1 \times 10^{-6}$	CL=90%
Γ_{170}	$e^-K^0_SK^0_S$	LF	$< 2.2 \times 10^{-6}$	CL=90%
Γ_{171}	$e^-K^+K^-$	LF	$< 6.0 \times 10^{-6}$	CL=90%
Γ_{172}	$e^+K^-K^-$	L	$< 3.8 \times 10^{-6}$	CL=90%
Γ_{173}	$\mu^-\pi^+K^-$	LF	$< 7.5 \times 10^{-6}$	CL=90%
Γ_{174}	$\mu^-\pi^-K^+$	LF	$< 7.4 \times 10^{-6}$	CL=90%
Γ_{175}	$\mu^+\pi^-K^-$	L	$< 7.0 \times 10^{-6}$	CL=90%
Γ_{176}	$\mu^-K^0_SK^0_S$	LF	$< 3.4 \times 10^{-6}$	CL=90%
Γ_{177}	$\mu^-K^+K^-$	LF	$< 1.5 \times 10^{-5}$	CL=90%
Γ_{178}	$\mu^+K^-K^-$	L	$< 6.0 \times 10^{-6}$	CL=90%
Γ_{179}	$e^-\pi^0\pi^0$	LF	$< 6.5 \times 10^{-6}$	CL=90%
Γ_{180}	$\mu^-\pi^0\pi^0$	LF	$< 1.4 \times 10^{-5}$	CL=90%
Γ_{181}	$e^-\eta\eta$	LF	$< 3.5 \times 10^{-5}$	CL=90%
Γ_{182}	$\mu^-\eta\eta$	LF	$< 6.0 \times 10^{-5}$	CL=90%
Γ_{183}	$e^-\pi^0\eta$	LF	$< 2.4 \times 10^{-5}$	CL=90%
Γ_{184}	$\mu^-\pi^0\eta$	LF	$< 2.2 \times 10^{-5}$	CL=90%
Γ_{185}	$\overline{p}\gamma$	L,B	$< 3.5 \times 10^{-6}$	CL=90%
Γ_{186}	$\overline{p}\pi^0$	L,B	$< 1.5 \times 10^{-5}$	CL=90%
Γ_{187}	$\overline{p}2\pi^0$	L,B	$< 3.3 \times 10^{-5}$	CL=90%
Γ_{188}	$\overline{p}\eta$	L,B	$< 8.9 \times 10^{-6}$	CL=90%
Γ_{189}	$\overline{p}\pi^0\eta$	L,B	$< 2.7 \times 10^{-5}$	CL=90%
Γ_{190}	e^- light boson	LF	$< 2.7 \times 10^{-3}$	CL=95%
Γ_{191}	μ^- light boson	LF	$< 5 \times 10^{-3}$	CL=95%

[*a*] Basis mode for the τ.

[*b*] See the Particle Listings below for the energy limits used in this measurement.

CONSTRAINED FIT INFORMATION

An overall fit to 65 branching ratios uses 128 measurements and one constraint to determine 31 parameters. The overall fit has a $\chi^2 = 62.5$ for 98 degrees of freedom.

The following *off-diagonal* array elements are the correlation coefficients $\langle\delta x_i \delta x_j\rangle/(\delta x_i \cdot \delta x_j)$, in percent, from the fit to the branching fractions, $x_i \equiv \Gamma_i/\Gamma_{total}$. The fit constrains the x_i whose labels appear in this array to sum to one.

	x_3	x_5	x_9	x_{10}	x_{13}	x_{15}	x_{19}	x_{22}	x_{25}	x_{26}
x_5	3									
x_9	−5	−5								
x_{10}	0	0	−20							
x_{13}	−13	−13	−25	1						
x_{15}	0	0	1	−3	−22					
x_{19}	−13	−14	−25	0	−36	4				
x_{22}	0	0	1	−2	5	−21	−16			
x_{25}	−8	−8	−15	0	−18	5	−24	3		
x_{26}	0	0	1	−2	5	−19	3	−13	−22	
x_{28}	−4	−4	−7	0	−10	0	−12	0	−7	0
x_{33}	−1	−2	−13	0	−3	1	−8	1	−1	1
x_{35}	0	0	−4	−1	2	−12	−1	−8	2	−8
x_{38}	−2	−2	−2	0	−5	3	−5	2	−9	2
x_{40}	−1	−1	0	−1	2	−16	1	−11	−1	−10
x_{45}	0	0	−2	0	0	0	0	0	0	0
x_{46}	−2	−2	−2	0	−4	1	−4	1	−2	1
x_{60}	−1	−1	−2	0	−4	0	−3	0	−2	0
x_{68}	−1	−1	−3	0	−3	0	−4	0	−2	0
x_{74}	0	0	0	0	0	0	0	0	0	0
x_{75}	0	0	0	0	0	0	0	0	0	0
x_{82}	0	0	0	0	0	0	0	0	0	0
x_{86}	0	0	0	0	0	0	0	0	0	0
x_{89}	0	0	0	0	0	0	0	0	0	0
x_{90}	0	0	0	0	0	0	0	0	0	0
x_{97}	0	0	−1	0	−1	0	−1	0	0	0
x_{98}	0	0	0	0	0	0	0	0	0	0
x_{117}	−1	−1	−1	0	−2	0	−2	0	−1	0
x_{119}	0	0	0	0	0	−3	0	−2	−2	−2
x_{137}	−1	−1	−2	0	−3	0	−3	0	−1	0
x_{138}	−1	−1	−1	0	−2	0	−2	0	−1	0

	x_{28}	x_{33}	x_{35}	x_{38}	x_{40}	x_{45}	x_{46}	x_{60}	x_{68}	x_{74}
x_{33}	−1									
x_{35}	0	−5								
x_{38}	−1	−7	0							
x_{40}	0	−2	−15	−19						
x_{45}	0	−2	−1	−2	0					
x_{46}	−1	−12	−4	−10	−3	−3				
x_{60}	−1	−7	−3	3	2	0	0			
x_{68}	−1	4	2	−5	−2	0	0	−47		
x_{74}	2	1	0	1	0	0	0	−8	−7	
x_{75}	0	0	0	0	0	0	0	−3	−3	0
x_{82}	0	−1	0	0	0	0	0	−31	−1	0
x_{86}	0	0	0	0	0	0	0	2	−14	0
x_{89}	0	0	0	0	0	0	0	−3	−1	0
x_{90}	0	0	0	0	0	0	0	−6	−1	−1
x_{97}	0	0	0	0	0	0	0	−1	−1	0
x_{98}	0	0	0	0	0	0	0	0	0	0
x_{117}	−14	0	0	0	0	0	0	−1	−1	−14
x_{119}	0	0	−1	0	−2	0	0	0	0	0
x_{137}	−1	1	1	−3	−1	0	0	−23	−29	−3
x_{138}	−1	1	0	1	0	0	0	−9	−10	−44

	x_{75}	x_{82}	x_{86}	x_{89}	x_{90}	x_{97}	x_{98}	x_{117}	x_{119}	x_{137}
x_{82}	0									
x_{86}	0	−14								
x_{89}	0	−11	1							
x_{90}	0	6	−47	−1						
x_{97}	0	0	0	0	0					
x_{98}	0	0	0	0	0	−19				
x_{117}	0	0	0	0	0	0	0			
x_{119}	0	0	−6	0	0	0	0	0		
x_{137}	−1	−2	2	0	2	0	0	0	0	
x_{138}	−1	−1	0	0	−1	0	0	0	0	−4

τ BRANCHING FRACTIONS

Revised April 2004 by K.G. Hayes (Hillsdale College).

The constrained fit to τ branching fractions: The Lepton Summary Table and the List of τ-Decay Modes contain branching fractions for 109 conventional τ-decay modes and upper limits on the branching fractions for 27 other conventional τ-decay modes. Of the 109 modes with branching fractions, 79 are derived from a constrained fit to τ branching fraction data. The goal of the constrained fit is to make optimal use of the experimental data to determine τ branching fractions. For example, the branching fractions for the decay modes $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ are determined mostly from experimental measurements of the branching fractions for $\tau^- \to h^-h^-h^+\nu_\tau$ and $\tau^- \to h^-h^-h^+\pi^0\nu_\tau$ and recent measurements of exclusive branching fractions for 3-prong modes containing charged kaons and 0 or 1 π^0's.

Branching fractions from the constrained fit are derived from a set of basis modes. The basis modes form an exclusive set whose branching fractions are constrained to sum exactly to one. The set of selected basis modes expands as branching fraction measurements for new τ-decay modes are published. The number of basis modes has expanded from 12 in the year 1994 fit to 31 in the 2002 and 2004 fits. The 31 basis modes selected for the 2004 fit are listed in Table 1. See the 1996 edition of this *Review* [1] for a complete description of our notation for naming τ-decay modes and the selection of the basis modes. For each edition since the 1996 edition, the changes in the selected basis modes from the previous edition are described in the τ Branching Fractions Review.

In selecting the basis modes, assumptions and choices must be made. For example, we assume the decays $\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau$ and $\tau^- \to \pi^+K^-K^- \geq 0\pi^0\nu\tau$ have negligible branching fractions. This is consistent with standard model predictions for τ decay, although the experimental limits for these branching fractions are not very stringent. The 95% confidence level upper limits for these branching fractions in the current Listings are $B(\tau^- \to \pi^-K^+\pi^- \geq 0\pi^0\nu_\tau) < 0.25\%$ and $B(\tau^- \to \pi^+K^-K^- \geq 0\pi^0\nu_\tau) < 0.09\%$, values not so different from measured branching fractions for allowed 3-prong modes containing charged kaons. Although our usual goal is to impose as few theoretical constraints as possible so that the world averages and fit results can be used to test the theoretical constraints (*i.e.*, we do not make use of the theoretical constraint

Table 1: Basis modes for the 2004 fit to τ branching fraction data.

$e^-\overline{\nu}_e\nu_\tau$	$K^-K^0\pi^0\nu_\tau$
$\mu^-\overline{\nu}_\mu\nu_\tau$	$\pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0, ω)
$\pi^-\nu_\tau$	$\pi^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0, ω)
$\pi^-\pi^0\nu_\tau$	$K^-\pi^+\pi^-\nu_\tau$ (ex. K^0)
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	$K^-\pi^+\pi^-\pi^0\nu_\tau$ (ex. K^0, η)
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	$K^-K^+\pi^-\nu_\tau$
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	$K^-K^+\pi^-\pi^0\nu_\tau$
$K^-\nu_\tau$	$h^-h^-h^+2\pi^0\nu_\tau$ (ex. K^0, ω, η)
$K^-\pi^0\nu_\tau$	$h^-h^-h^+3\pi^0\nu_\tau$
$K^-2\pi^0\nu_\tau$ (ex. K^0)	$3h^-2h^+\nu_\tau$ (ex. K^0)
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	$3h^-2h^+\pi^0\nu_\tau$ (ex. K^0)
$\pi^-\overline{K}^0\nu_\tau$	$h^-\omega\nu_\tau$
$\pi^-\overline{K}^0\pi^0\nu_\tau$	$h^-\omega\pi^0\nu_\tau$
$\pi^-K^0_SK^0_S\nu_\tau$	$\eta\pi^-\pi^0\nu_\tau$
$\pi^-K^0_SK^0_L\nu_\tau$	$\eta K^-\nu_\tau$
$K^-K^0\nu_\tau$	

from lepton universality on the ratio of the τ-leptonic branching fractions $B(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)/\ B(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = 0.9726$), the experimental challenge to identify charged prongs in 3-prong τ decays is sufficiently difficult that experimenters have been forced to make these assumptions when measuring the branching fractions of the allowed decays.

There are several recently measured modes with small but well-measured (> 2.5 sigma from zero) branching fractions [2] which cannot be expressed in terms of the selected basis modes and are therefore left out of the fit:

$$B(\tau^- \to \pi^-K^0_SK^0_L\pi^0\nu_\tau) = (3.1 \pm 1.2) \times 10^{-4}$$
$$B(\tau^- \to h^-\omega\pi^0\pi^0\nu_\tau) = (1.4 \pm 0.5) \times 10^{-4}$$
$$B(\tau^- \to 2h^-h^+\omega\nu_\tau) = (1.20 \pm 0.22) \times 10^{-4}$$

plus the $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\gamma$ components of the branching fractions

$$B(\tau^- \to \eta\pi^-\pi^+\pi^-\nu_\tau) = (2.3 \pm 0.5) \times 10^{-4}\ ,$$
$$B(\tau^- \to \eta\pi^-\pi^0\pi^0\nu_\tau) = (1.5 \pm 0.5) \times 10^{-4}\ ,$$
$$B(\tau^- \to \eta\overline{K}^0\pi^-\nu_\tau) = (2.2 \pm 0.7) \times 10^{-4}\ .$$

The sum of these excluded branching fractions is $(0.08 \pm 0.01)\%$. This is near our goal of 0.1% for the internal consistency of the τ Listings for this edition, and thus for simplicity we do not include these small branching fraction decay modes in the basis set.

Begininng with the 2002 edition, the fit algorithm has been improved to allow for correlations between branching fraction measurements used in the fit. In this edition, correlations between measurements contained in Refs. [3,4,5,6] have been included. In the τ Listings, the correlation coefficients are listed in the footnote for each measurement. Sometimes experimental papers contain correlation coefficients between measurements using only statistical errors without including systematic errors. We usually cannot make use of these correlation coefficients.

The constrained fit has a χ^2 of 62.5 for 99 degrees of freedom. Only one of the year 2004 basis mode branching fractions shifted by more than 1 sigma from its 2002 value: $B(\tau^- \to K^-\pi^+\pi^-\nu_\tau(\text{ex. }K^0))$ changed from $(0.28 \pm 0.05)\%$ to $(0.33 \pm 0.04)\%$.

Overconsistency of Leptonic Branching Fraction Measurements: To minimize the effects of older experiments which often have larger systematic errors and sometimes make assumptions that have later been shown to be invalid, we exclude old measurements in decay modes which contain at least several newer data of much higher precision. As a rule, we exclude those experiments with large errors which together would contribute no more than 5% of the weight in the average. This procedure leaves six measurements for $B_e \equiv B(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ and five measurements for $B_\mu \equiv B(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)$. For both B_e and B_μ, the six measurements are considerably more consistent with each other than should be expected from the quoted errors on the individual measurements. The χ^2 from the calculation of the average of the selected measurements is 0.49 for B_e and 0.09 for B_μ.

References

1. R.M. Barnett *et al.* (Particle Data Group), *Review of Particle Physics*, Phys. Rev. **D54**, 1 (1996).
2. See the τ Listings for references.
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5. A. Anastassov *et al.* (**CLEO** Collaboration), Phys. Rev. **D55**, 2559 (1997) and Phys. Rev. **D58**, 119903 (1998) (erratum).
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τ^- BRANCHING RATIOS

$\Gamma(\text{particle}^- \geq 0\text{ neutrals} \geq 0K^0\nu_\tau(\text{"1-prong"}))/\Gamma_{\text{total}}$ — Γ_1/Γ

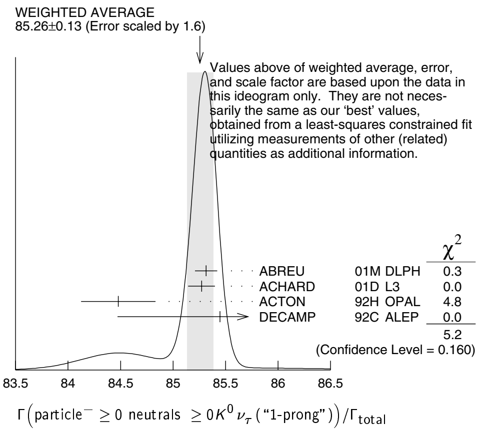
$\Gamma_1/\Gamma = (\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{22}+\Gamma_{25}+\Gamma_{26}+\Gamma_{28}+\Gamma_{33}+\Gamma_{35}+\Gamma_{38}+\Gamma_{40}+2\Gamma_{45}+\Gamma_{46}+0.708\Gamma_{117}+0.715\Gamma_{119}+0.09\Gamma_{137}+0.09\Gamma_{138})/\Gamma$

The charged particle here can be e, μ, or hadron. In many analyses, the sum of the topological branching fractions (1, 3, and 5 prongs) is constrained to be unity. Since the 5-prong fraction is very small, the measured 1-prong and 3-prong fractions are highly correlated and cannot be treated as independent quantities in our overall fit. We arbitrarily choose to use the 3-prong fraction in our fit, and leave the 1-prong fraction out. We do, however, use these 1-prong measurements in our average below. The measurements used only for the average are marked "avg," whereas "f&a" marks a result used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
85.35 ±0.07 OUR FIT Error includes scale factor of 1.1.					
85.26 ±0.13 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.					
85.316±0.093±0.049	avg	78k	[27] ABREU	01M DLPH	1992–1995 LEP runs
85.274±0.105±0.073	avg		[28] ACHARD	01D L3	1992–1995 LEP runs
84.48 ±0.27 ±0.23	avg		ACTON	92H OPAL	1990–1991 LEP runs
85.45 $^{+0.69}_{-0.73}$ ±0.65	f&a		DECAMP	92C ALEP	1989–1990 LEP runs

[27] The correlation coefficients between this measurement and the ABREU 01M measurements of $B(\tau \to$ 3-prong) and $B(\tau \to$ 5-prong) are −0.98 and −0.08 respectively.

[28] The correlation coefficients between this measurement and the ACHARD 01D measurements of $B(\tau \to$ "3-prong") and $B(\tau \to$ "5-prong") are −0.978 and −0.082 respectively.



$\Gamma(\text{particle}^- \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\text{total}}$ — Γ_2/Γ

$\Gamma_2/\Gamma = (\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10}+\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{22}+\Gamma_{25}+\Gamma_{26}+\Gamma_{28}+0.6569\Gamma_{33}+0.6569\Gamma_{35}+0.6569\Gamma_{38}+0.6569\Gamma_{40}+1.0985\Gamma_{45}+0.3139\Gamma_{46}+0.708\Gamma_{117}+0.715\Gamma_{119}+0.09\Gamma_{137}+0.09\Gamma_{138})/\Gamma$

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
84.72±0.07 OUR FIT Error includes scale factor of 1.1.					
85.1 ±0.4 OUR AVERAGE					
85.6 ±0.6 ±0.3	avg	3300	[29] ADEVA	91F L3	E^{ee}_{cm}= 88.3–94.3 GeV
84.9 ±0.4 ±0.3	avg		BEHREND	89B CELL	E^{ee}_{cm}= 14–47 GeV
84.7 ±0.8 ±0.6	avg		[30] AIHARA	87B TPC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
86.4 ±0.3 ±0.3			ABACHI	89B HRS	E^{ee}_{cm}= 29 GeV
87.1 ±1.0 ±0.7			[31] BURCHAT	87 MRK2	E^{ee}_{cm}= 29 GeV
87.2 ±0.5 ±0.8			SCHMIDKE	86 MRK2	E^{ee}_{cm}= 29 GeV
84.7 ±1.1 $^{+1.6}_{-1.3}$		169	[32] ALTHOFF	85 TASS	E^{ee}_{cm}= 34.5 GeV
86.1 ±0.5 ±0.9			BARTEL	85F JADE	E^{ee}_{cm}= 34.6 GeV
87.8 ±1.3 ±3.9			[33] BERGER	85 PLUT	E^{ee}_{cm}= 34.6 GeV
86.7 ±0.3 ±0.6			FERNANDEZ	85 MAC	E^{ee}_{cm}= 29 GeV

[29] Not independent of ADEVA 91F $\Gamma(h^- h^- h^+ \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\text{total}}$ value.

[30] Not independent of AIHARA 87B $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, and $/\Gamma_{\text{total}}$ values.

[31] Not independent of SCHMIDKE 86 value (also not independent of BURCHAT 87 value for $\Gamma(h^- h^- h^+ \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\text{total}}$.

[32] Not independent of ALTHOFF 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$, $\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{\text{total}}$, $/\Gamma_{\text{total}}$, and $\Gamma(h^- h^- h^+ \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\text{total}}$ values.

[33] Not independent of (1-prong + $0\pi^0$) and (1-prong + $\geq 1\pi^0$) values.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{\text{total}}$ — Γ_3/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
17.36 ±0.06 OUR FIT					
17.33 ±0.06 OUR AVERAGE					
17.34 ±0.09 ±0.06	f&a	31.4k	ABBIENDI	03 OPAL	1990–1995 LEP runs
17.342±0.110±0.067	f&a	21.5k	[34] ACCIARRI	01F L3	1991–1995 LEP runs
17.325±0.095±0.077	f&a	27.7k	ABREU	99X DLPH	1991–1995 LEP runs
17.37 ±0.08 ±0.18	avg		[35] ANASTASSOV	97 CLEO	E^{ee}_{cm}= 10.6 GeV
17.31 ±0.11 ±0.05	f&a	20.7k	BUSKULIC	96C ALEP	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
17.02 ±0.19 ±0.24		6586	ABREU	95T DLPH	Repl.. by ABREU 99X
17.36 ±0.27		7941	AKERS	95I OPAL	Repl. by ABBIENDI 03
17.6 ±0.4 ±0.4		2148	ADRIANI	93M L3	Repl. by ACCIARRI 01F
17.4 ±0.3 ±0.5			[36] ALBRECHT	93G ARG	E^{ee}_{cm}= 9.4–10.6 GeV
17.35 ±0.41 ±0.37	f&a		DECAMP	92C ALEP	1989–1990 LEP runs
17.7 ±0.8 ±0.4		568	BEHREND	90 CELL	E^{ee}_{cm}= 35 GeV
17.4 ±1.0		2197	ADEVA	88 MRKJ	E^{ee}_{cm}= 14–16 GeV
17.7 ±1.2 ±0.7			AIHARA	87B TPC	E^{ee}_{cm}= 29 GeV

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
18.3 ±0.9 ±0.8		BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
18.6 ±0.8 ±0.7	558	[37] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
12.9 ±1.7 $^{+0.7}_{-0.5}$		ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
18.0 ±0.9 ±0.5	473	[37] ASH 85B	MAC	E^{ee}_{cm}= 29 GeV
18.0 ±1.0 ±0.6		[38] BALTRUSAIT...85	MRK3	E^{ee}_{cm}= 3.77 GeV
19.4 ±1.6 ±1.7	153	BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
17.6 ±2.6 ±2.1	47	BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV
17.8 ±2.0 ±1.8		BERGER 81B	PLUT	E^{ee}_{cm}= 9–32 GeV

[34] The correlation coefficient between this measurement and the ACCIARRI 01F measurement of B($\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$) is 0.08.

[35] The correlation coefficients between this measurement and the ANASTASSOV 97 measurements of B($e\overline{\nu}_e\nu_\tau$), B($\mu\overline{\nu}_\mu\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$), B($h^-\nu_\tau$), and B($h^-\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$) are 0.50, 0.58, 0.50, and 0.08 respectively.

[36] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and ALBRECHT 93G $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{total}$ values.

[37] Modified using B($e^-\overline{\nu}_e\nu_\tau$)/B("1 prong") and B("1 prong") ,= 0.855.

[38] Error correlated with BALTRUSAITIS 85 $e\nu\overline{\nu}$ value.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma_{total}$ — Γ_4/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.361±0.016±0.035		[39] BERGFELD 00	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.30 ±0.04 ±0.05	116	[40] ALEXANDER 96S	OPAL	1991–1994 LEP runs
0.23 ±0.10	10	[41] WU 90	MRK2	E^{ee}_{cm}= 29 GeV

[39] BERGFELD 00 impose requirements on detected γ's corresponding to a τ-rest-frame energy cutoff $E^*_\gamma > 10$ MeV. For $E^*_\gamma > 20$ MeV, they quote $(3.04 \pm 0.14 \pm 0.30)\times 10^{-3}$.

[40] ALEXANDER 96S impose requirements on detected γ's corresponding to a τ-rest-frame energy cutoff E_γ >20 MeV.

[41] WU 90 reports $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) = 0.013 \pm 0.006$, which is converted to $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma_{total}$ using $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau\gamma)/\Gamma_{total} = 17.35\%$. Requirements on detected γ's correspond to a τ rest frame energy cutoff E_γ > 37 MeV.

$\Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma_{total}$ — Γ_5/Γ

To minimize the effect of experiments with large systematic errors, we exclude experiments which together would contribute 5% of the weight in the average.

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
17.84 ±0.06 OUR FIT				
17.81 ±0.06 OUR AVERAGE				
17.806±0.104±0.076	24.7k	[42] ACCIARRI 01F	L3	1991–1995 LEP runs
17.81 ±0.09 ±0.06	33.1k	ABBIENDI 99H	OPAL	1991–1995 LEP runs
17.877±0.109±0.110	23.3k	ABREU 99X	DLPH	1991–1995 LEP runs
17.76 ±0.06 ±0.17		[43] ANASTASSOV 97	CLEO	E^{ee}_{cm}= 10.6 GeV
17.79 ±0.12 ±0.06	20.6k	BUSKULIC 96C	ALEP	1991–1993 LEP runs
18.09 ±0.45 ±0.45		DECAMP 92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
17.78 ±0.10 ±0.09	25.3k	ALEXANDER 96D	OPAL	Repl. by ABBIENDI 99H
17.51 ±0.23 ±0.31	5059	ABREU 95T	DLPH	Repl.. by ABREU 99X
17.9 ±0.4 ±0.4	2892	ADRIANI 93M	L3	Repl. by ACCIARRI 01F
17.5 ±0.3 ±0.5		[44] ALBRECHT 93G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
17.97 ±0.14 ±0.23	3970	AKERIB 92	CLEO	Repl. by ANASTASSOV 97
19.1 ±0.4 ±0.6	2960	[45] AMMAR 92	CLEO	E^{ee}_{cm}= 10.5–10.9 GeV
17.0 ±0.5 ±0.6	1.7k	ABACHI 90	HRS	E^{ee}_{cm}= 29 GeV
18.4 ±0.8 ±0.4	644	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
16.3 ±0.3 ±3.2		JANSSEN 89	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
18.4 ±1.2 ±1.0		AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
19.1 ±0.8 ±1.1		BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
16.8 ±0.7 ±0.9	515	[45] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
20.4 ±3.0 $^{+1.4}_{-0.9}$		ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
17.8 ±0.9 ±0.6	390	[45] ASH 85B	MAC	E^{ee}_{cm}= 29 GeV
18.2 ±0.7 ±0.5		[46] BALTRUSAIT...85	MRK3	E^{ee}_{cm}= 3.77 GeV
13.0 ±1.9 ±2.9		BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
18.3 ±2.4 ±1.9	60	BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV
16.0 ±1.3	459	[47] BACINO 78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV

[42] The correlation coefficient between this measurement and the ACCIARRI 01F measurement of B($\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau$) is 0.08.

[43] The correlation coefficients between this measurement and the ANASTASSOV 97 measurements of B($\mu\overline{\nu}_\mu\nu_\tau$), B($\mu\overline{\nu}_\mu\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$), B($h^-\nu_\tau$), and B($h^-\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$) are 0.50, −0.42, 0.48, and −0.39 respectively.

[44] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ and ALBRECHT 93G $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)/\Gamma^2_{total}$ values.

[45] Modified using B($e^-\overline{\nu}_e\nu_\tau$)/B("1 prong") and B("1 prong") ,= 0.855.

[46] Error correlated with BALTRUSAITIS 85 $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma_{total}$.

[47] BACINO 78B value comes from fit to events with $e^\pm$ and one other nonelectron charged prong.

$\Gamma(e^-\overline{\nu}_e\nu_\tau\gamma)/\Gamma_{total}$ — Γ_6/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
1.75±0.06±0.17	[48] BERGFELD 00	CLEO	E^{ee}_{cm}= 10.6 GeV

[48] BERGFELD 00 impose requirements on detected γ's corresponding to a τ-rest-frame energy cutoff $E^*_\gamma > 10$ MeV.

$\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — Γ_3/Γ_5

Standard Model prediction including mass effects is 0.9726.

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		DOCUMENT ID	TECN	COMMENT
0.974 ±0.004 OUR FIT				
0.978 ±0.011 OUR AVERAGE				
0.9777±0.0063±0.0087	f&a	[49] ANASTASSOV 97	CLEO	E^{ee}_{cm}= 10.6 GeV
0.997 ±0.035 ±0.040	f&a	ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[49] The correlation coefficients between this measurement and the ANASTASSOV 97 measurements of B($\mu\overline{\nu}_\mu\nu_\tau$), B($e\overline{\nu}_e\nu_\tau$), B($h^-\nu_\tau$), and B($h^-\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$) are 0.58, −0.42, 0.07, and 0.45 respectively.

$\Gamma(h^- \geq 0K^0_L\,\nu_\tau)/\Gamma_{total}$ — Γ_7/Γ

$\Gamma_7/\Gamma = (\Gamma_9+\Gamma_{10}+\frac{1}{2}\Gamma_{33}+\frac{1}{2}\Gamma_{35}+\Gamma_{45})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
12.30±0.11 OUR FIT Error includes scale factor of 1.4.					
12.44±0.14 OUR AVERAGE					
12.44±0.11±0.11	f&a	15k	[50] BUSKULIC 96	ALEP	1991–1993 LEP run
12.47±0.26±0.43	f&a	2967	[51] ACCIARRI 95	L3	1992 LEP run
12.4 ±0.7 ±0.7	f&a	283	[52] ABREU 92N	DLPH	1990 LEP run
12.98±0.44±0.33	f&a		[53] DECAMP 92C	ALEP	1989–1990 LEP runs
12.1 ±0.7 ±0.5	f&a	309	ALEXANDER 91D	OPAL	1990 LEP run
11.3 ±0.5 ±0.8	avg	798	[54] FORD 87	MAC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
11.7 ±0.6 ±0.8			[55] ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
12.3 ±0.9 ±0.5		1338	BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
11.1 ±1.1 ±1.4			[56] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
12.3 ±0.6 ±1.1		328	[57] BARTEL 86D	JADE	E^{ee}_{cm}= 34.6 GeV
13.0 ±2.0 ±4.0			BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
11.2 ±1.7 ±1.2		34	[58] BEHREND 83C	CELL	E^{ee}_{cm}= 34 GeV

[50] BUSKULIC 96 quote 11.78 ± 0.11 ± 0.13 We add 0.66 to undo their correction for unseen K^0_L and modify the systematic error accordingly.

[51] ACCIARRI 95 with 0.65% added to remove their correction for $\pi^- K^0_L$ backgrounds.

[52] ABREU 92N with 0.5% added to remove their correction for $K^*(892)^-$ backgrounds.

[53] DECAMP 92C quote B($h^- \geq 0K^0_L \geq 0\,(K^0_S \rightarrow \pi^+\pi^-)\,\nu_\tau$) = 13.32 ± 0.44 ± 0.33. We subtract 0.35 to correct for their inclusion of the K^0_S decays.

[54] FORD 87 result for B($\pi^-\nu_\tau$) with 0.67% added to remove their K^- correction and adjusted for 1992 B("1 prong").

[55] Not independent of ALBRECHT 92D $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$, $\Gamma(\mu^-\overline{\nu}_\mu\nu_\tau) \times \Gamma(e^-\overline{\nu}_e\nu_\tau)$, and $\Gamma(h^- \geq 0K^0_L\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ values.

[56] BURCHAT 87 with 1.1% added to remove their correction for K^- and $K^*(892)^-$ backgrounds.

[57] BARTEL 86D result for B($\pi^-\nu_\tau$) with 0.59% added to remove their K^- correction and adjusted for 1992 B("1 prong").

[58] BEHREND 83C quote B($\pi^-\nu_\tau$) = 9.9 ± 1.7 ± 1.3 after subtracting 1.3 ± 0.5 to correct for B($K^-\nu_\tau$).

$\Gamma(h^-\nu_\tau)/\Gamma_{total}$ — $\Gamma_8/\Gamma = (\Gamma_9+\Gamma_{10})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID	TECN	COMMENT
11.75±0.11 OUR FIT Error includes scale factor of 1.4.				
11.65±0.21 OUR AVERAGE Error includes scale factor of 1.9.				
11.98±0.13±0.16	f&a	ACKERSTAFF 98M	OPAL	1991–1995 LEP runs
11.52±0.05±0.12	f&a	[59] ANASTASSOV 97	CLEO	E^{ee}_{cm}= 10.6 GeV

[59] The correlation coefficients between this measurement and the ANASTASSOV 97 measurements of B($\mu\overline{\nu}_\mu\nu_\tau$), B($e\overline{\nu}_e\nu_\tau$), B($\mu\overline{\nu}_\mu\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$), and B($h^-\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$) are 0.50, 0.48, 0.07, and 0.63 respectively.

$\Gamma(h^-\nu_\tau)/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ — $\Gamma_8/\Gamma_5 = (\Gamma_9+\Gamma_{10})/\Gamma_5$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		DOCUMENT ID	TECN	COMMENT
0.659 ±0.007 OUR FIT Error includes scale factor of 1.4.				
0.6484±0.0041±0.0060	**avg**	[60] ANASTASSOV 97	CLEO	E^{ee}_{cm}= 10.6 GeV

[60] The correlation coefficients between this measurement and the ANASTASSOV 97 measurements of B($\mu\overline{\nu}_\mu\nu_\tau$), B($e\overline{\nu}_e\nu_\tau$), B($\mu\overline{\nu}_\mu\nu_\tau$)/B($e\overline{\nu}_e\nu_\tau$), and B($h^-\nu_\tau$) are 0.08, −0.39, 0.45, and 0.63 respectively.

$\Gamma(\pi^-\nu_\tau)/\Gamma_{total}$ — Γ_9/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
11.06±0.11 OUR FIT	Error includes scale factor of 1.4.					
11.07±0.18 OUR AVERAGE						
11.06±0.11±0.14	avg		[61] BUSKULIC	96	ALEP	LEP 1991–1993 data
11.7 ±0.4 ±1.8	f&a	1138	BLOCKER	82D	MRK2	E^{ee}_{cm}= 3.5–6.7 GeV

[61] Not independent of BUSKULIC 96 $B(h^-\nu_\tau)$ and $B(K^-\nu_\tau)$ values.

$\Gamma(K^-\nu_\tau)/\Gamma_{total}$ — Γ_{10}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.686±0.023 OUR FIT					
0.685±0.023 OUR AVERAGE					
0.658±0.027±0.029		[62] ABBIENDI	01J	OPAL	1990–1995 LEP runs
0.696±0.025±0.014	2032	BARATE	99K	ALEP	1991–1995 LEP runs
0.85 ±0.18	27	ABREU	94K	DLPH	LEP 1992 Z data
0.66 ±0.07 ±0.09	99	BATTLE	94	CLEO	$E^{ee}_{cm}\approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.72 ±0.04 ±0.04	728	BUSKULIC	96	ALEP	Repl. by BARATE 99K
0.59 ±0.18	16	MILLS	84	DLCO	E^{ee}_{cm}= 29 GeV
1.3 ±0.5	15	BLOCKER	82B	MRK2	E^{ee}_{cm}= 3.9–6.7 GeV

[62] The correlation coefficient between this measurement and the ABBIENDI 01J $B(\tau^-\to K^-\geq 0\pi^0\ \geq 0K^0\ \geq 0\gamma\ \nu_\tau)$ is 0.60.

$\Gamma(h^-\geq 1\,\text{neutrals}\,\nu_\tau)/\Gamma_{total}$ — Γ_{11}/Γ

$\Gamma_{11}/\Gamma = (\Gamma_{13}+\Gamma_{15}+\Gamma_{19}+\Gamma_{22}+\Gamma_{25}+\Gamma_{26}+\Gamma_{28}+0.157\Gamma_{33}+0.157\Gamma_{35}+0.157\Gamma_{38}+0.157\Gamma_{40}+0.0985\Gamma_{45}+0.708\Gamma_{117}+0.715\Gamma_{119}+0.09\Gamma_{137}+0.09\Gamma_{138})/\Gamma$

VALUE (%)	DOCUMENT ID		TECN	COMMENT
36.92±0.14 OUR FIT	Error includes scale factor of 1.1.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
36.14±0.33±0.58	[63] AKERS	94E	OPAL	1991–1992 LEP runs
38.4 ±1.2 ±1.0	[64] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
42.7 ±2.0 ±2.9	BERGER	85	PLUT	E^{ee}_{cm}= 34.6 GeV

[63] Not independent of ACKERSTAFF 98M $B(h^-\pi^0\nu_\tau)$ and $B(h^-\geq 2\pi^0\nu_\tau)$ values.
[64] BURCHAT 87 quote for $B(\pi^\pm\geq 1\ \text{neutral}\,\nu_\tau) = 0.378\pm0.012\pm0.010$. We add 0.006 to account for contribution from $(K^{*-}\nu_\tau)$ which they fixed at BR = 0.013.

$\Gamma(h^-\pi^0\nu_\tau)/\Gamma_{total}$ — $\Gamma_{12}/\Gamma = (\Gamma_{13}+\Gamma_{15})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
25.87±0.13 OUR FIT	Error includes scale factor of 1.1.				
25.76±0.15 OUR AVERAGE					
25.89±0.17±0.29		ACKERSTAFF	98M	OPAL	1991–1995 LEP runs
25.76±0.15±0.13	31k	BUSKULIC	96	ALEP	LEP 1991–1993 data
25.05±0.35±0.50	6613	ACCIARRI	95	L3	1992 LEP run
25.87±0.12±0.42	51k	[65] ARTUSO	94	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
25.98±0.36±0.52		[66] AKERS	94E	OPAL	Repl. by ACKERSTAFF 98M
22.9 ±0.8 ±1.3	283	[67] ABREU	92N	DLPH	E^{ee}_{cm}= 88.2–94.2 GeV
23.1 ±0.4 ±0.9	1249	[68] ALBRECHT	92Q	ARG	E^{ee}_{cm}= 10 GeV
25.02±0.64±0.88	1849	DECAMP	92C	ALEP	1989–1990 LEP runs
22.0 ±0.8 ±1.9	779	ANTREASYAN	91	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
22.6 ±1.5 ±0.7	1101	BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
23.1 ±1.9 ±1.6		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV

[65] ARTUSO 94 reports the combined result from three independent methods, one of which (23% of the $\tau^-\to h^-\pi^0\nu_\tau$) is normalized to the inclusive one-prong branching fraction, taken as 0.854 ± 0.004. Renormalization to the present value causes negligible change.
[66] AKERS 94E quote $(26.25\pm0.36\pm0.52)\times10^{-2}$; we subtract 0.27% from their number to correct for $\tau^-\to h^-K^0_L\nu_\tau$.
[67] ABREU 92N with 0.5% added to remove their correction for $K^*(892)^-$ backgrounds.
[68] ALBRECHT 92Q with 0.5% added to remove their correction for $\tau^-\to K^*(892)^-\nu_\tau$ background.

$\Gamma(\pi^-\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{13}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
25.42±0.14 OUR FIT	Error includes scale factor of 1.1.					
25.31±0.18 OUR AVERAGE						
25.30±0.15±0.13	avg		[69] BUSKULIC	96	ALEP	LEP 1991–1993 data
25.36±0.44	avg		[70] ARTUSO	94	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
21.5 ±0.4 ±1.9		4400	[71,72] ALBRECHT	88L	ARG	E^{ee}_{cm}= 10 GeV
23.0 ±1.3 ±1.7		582	ADLER	87B	MRK3	E^{ee}_{cm}= 3.77 GeV
25.8 ±1.7 ±2.5			[73] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
22.3 ±0.6 ±1.4		629	[72] YELTON	86	MRK2	E^{ee}_{cm}= 29 GeV

[69] Not independent of BUSKULIC 96 $B(h^-\pi^0\nu_\tau)$ and $B(K^-\pi^0\nu_\tau)$ values.
[70] Not independent of ARTUSO 94 $B(h^-\pi^0\nu_\tau)$ and BATTLE 94 $B(K^-\pi^0\nu_\tau)$ values.
[71] The authors divide by $(\Gamma_3+\Gamma_5+\Gamma_9+\Gamma_{10})/\Gamma = 0.467$ to obtain this result.
[72] Experiment had no hadron identification. Kaon corrections were made, but insufficient information is given to permit their removal.
[73] BURCHAT 87 value is not independent of YELTON 86 value. Nonresonant decays included.

$\Gamma(\pi^-\pi^0\,\text{non-}\rho(770)\nu_\tau)/\Gamma_{total}$ — Γ_{14}/Γ

VALUE (%)	DOCUMENT ID		TECN	COMMENT
0.3 ±0.1 ±0.3	[74] BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV

[74] BEHREND 84 assume a flat nonresonant mass distribution down to the $\rho(770)$ mass, using events with mass above 1300 to set the level.

$\Gamma(K^-\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{15}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.450±0.030 OUR FIT					
0.449±0.034 OUR AVERAGE					
0.444±0.026±0.024	923	BARATE	99K	ALEP	1991–1995 LEP runs
0.51 ±0.10 ±0.07	37	BATTLE	94	CLEO	$E^{ee}_{cm}\approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.52 ±0.04 ±0.05	395	BUSKULIC	96	ALEP	Repl. by BARATE 99K

$\Gamma(h^-\geq 2\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{16}/Γ

$\Gamma_{16}/\Gamma = (\Gamma_{19}+\Gamma_{22}+\Gamma_{25}+\Gamma_{26}+\Gamma_{28}+0.157\Gamma_{33}+0.157\Gamma_{35}+0.157\Gamma_{38}+0.157\Gamma_{40}+0.0985\Gamma_{45}+0.319\Gamma_{117}+0.322\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
10.77±0.15 OUR FIT	Error includes scale factor of 1.1.					
10.0 ±0.4 OUR AVERAGE						
9.91±0.31±0.27	f&a		ACKERSTAFF	98M	OPAL	1991–1995 LEP runs
12.0 ±1.4 ±2.5	f&a		[75] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
9.89±0.34±0.55			[76] AKERS	94E	OPAL	Repl. by ACKERSTAFF 98M
14.0 ±1.2 ±0.6		938	[77] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
13.9 ±2.0 $^{+1.9}_{-2.2}$			[78] AIHARA	86E	TPC	E^{ee}_{cm}= 29 GeV

[75] Error correlated with BURCHAT 87 $\Gamma(\rho^-\nu_e)/\Gamma(\text{total})$ value.
[76] AKERS 94E not independent of AKERS 94E $B(h^-\geq 1\pi^0\nu_\tau)$ and $B(h^-\pi^0\nu_\tau)$ measurements.
[77] No independent of BEHREND 90 $\Gamma(h^-2\pi^0\nu_\tau(\text{exp. }K^0))$ and $\Gamma(h^-\geq 3\pi^0\nu_\tau)$.
[78] AIHARA 86E (TPC) quote $B(2\pi^0\pi^-\nu_\tau) + 1.6B(3\pi^0\pi^-\nu_\tau) + 1.1B(\pi^0\eta\pi^-\nu_\tau)$.

$\Gamma(h^-2\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{17}/Γ

$\Gamma_{17}/\Gamma = (\Gamma_{19}+\Gamma_{22}+0.157\Gamma_{33}+0.157\Gamma_{35})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
9.39±0.14 OUR FIT	Error includes scale factor of 1.1.				
9.48±0.13±0.10	12k	[79] BUSKULIC	96	ALEP	LEP 1991–1993 data

[79] BUSKULIC 96 quote $9.29\pm0.13\pm0.10$. We add 0.19 to undo their correction for $\tau^-\to h^-K^0\nu_\tau$.

$\Gamma(h^-2\pi^0\nu_\tau(\text{ex.}K^0))/\Gamma_{total}$ — Γ_{18}/Γ

$\Gamma_{18}/\Gamma = (\Gamma_{19}+\Gamma_{22})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. f&a marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
9.23±0.14 OUR FIT	Error includes scale factor of 1.1.					
9.08±0.34 OUR AVERAGE						
8.88±0.37±0.42	f&a	1060	ACCIARRI	95	L3	1992 LEP run
8.96±0.16±0.44	avg		[80] PROCARIO	93	CLEO	$E^{ee}_{cm}\approx$ 10.6 GeV
10.38±0.66±0.82	f&a	809	[81] DECAMP	92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •						
5.7 ±0.5 $^{+1.7}_{-1.0}$		133	[82] ANTREASYAN	91	CBAL	E^{ee}_{cm}= 9.4–10.6 GeV
10.0 ±1.5 ±1.1		333	[83] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
8.7 ±0.4 ±1.1		815	[84] BAND	87	MAC	E^{ee}_{cm}= 29 GeV
6.2 ±0.6 ±1.2			[85] GAN	87	MRK2	E^{ee}_{cm}= 29 GeV
6.0 ±3.0 ±1.8			BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV

[80] PROCARIO 93 entry is obtained from $B(h^-2\pi^0\nu_\tau)/B(h^-\pi^0\nu_\tau)$ using ARTUSO 94 result for $B(h^-\pi^0\nu_\tau)$.
[81] We subtract 0.0015 to account for $\tau^-\to K^*(892)^-\nu_\tau$ contribution.
[82] ANTREASYAN 91 subtract 0.001 to account for the $\tau^-\to K^*(892)^-\nu_\tau$ contribution.
[83] BEHREND 90 subtract 0.002 to account for the $\tau^-\to K^*(892)^-\nu_\tau$ contribution.
[84] BAND 87 assume $B(\pi^-3\pi^0\nu_\tau) = 0.01$ and $B(\pi^-\pi^0\eta\nu_\tau) = 0.005$.
[85] GAN 87 analysis use photon multiplicity distribution.

$\Gamma\big(h^- 2\pi^0 \nu_\tau (\text{ex.}K^0)\big)/\Gamma\big(h^- \pi^0 \nu_\tau\big)$ — Γ_{18}/Γ_{12}

$\Gamma_{18}/\Gamma_{12} = (\Gamma_{19}+\Gamma_{22})/(\Gamma_{13}+\Gamma_{15})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.357±0.006 OUR FIT	Error includes scale factor of 1.1.		
0.342±0.006±0.016	[86] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[86] PROCARIO 93 quote 0.345 ± 0.006 ± 0.016 after correction for 2 kaon backgrounds assuming $B(K^{*-} \nu_\tau)$=1.42 ± 0.18% and $B(h^- K^0 \pi^0 \nu_\tau)$=0.48 ± 0.48%. We multiply by 0.990 ± 0.010 to remove these corrections to $B(h^- \pi^0 \nu_\tau)$.

$\Gamma\big(\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0)\big)/\Gamma_{\text{total}}$ — Γ_{19}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID	TECN	COMMENT
9.17±0.14 OUR FIT	Error includes scale factor of 1.1.			
9.21±0.13±0.11	**avg**	[87] BUSKULIC 96	ALEP	LEP 1991–1993 data

[87] Not independent of BUSKULIC 96 $B(h^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$ and $B(K^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$ values.

$\Gamma\big(\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0), \text{scalar}\big)/\Gamma\big(\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0)\big)$ — Γ_{20}/Γ_{19}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.094	95	[88] BROWDER 00	CLEO	4.7 fb^{-1} E^{ee}_{cm}= 10.6 GeV

[88] Model-independent limit from structure function analysis on contribution to $B(\tau^- \to \pi^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$ from scalars.

$\Gamma\big(\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0), \text{vector}\big)/\Gamma\big(\pi^- 2\pi^0 \nu_\tau (\text{ex.}K^0)\big)$ — Γ_{21}/Γ_{19}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.073	95	[89] BROWDER 00	CLEO	4.7 fb^{-1} E^{ee}_{cm}= 10.6 GeV

[89] Model-independent limit from structure function analysis on contribution to $B(\tau^- \to \pi^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$ from vectors.

$\Gamma\big(K^- 2\pi^0 \nu_\tau (\text{ex.}K^0)\big)/\Gamma_{\text{total}}$ — Γ_{22}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.058±0.023 OUR FIT				
0.058±0.024 OUR AVERAGE				
0.056±0.020±0.015	131	BARATE 99K	ALEP	1991–1995 LEP runs
0.09 ±0.10 ±0.03	3	[90] BATTLE 94	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.08 ±0.02 ±0.02	59	BUSKULIC 96	ALEP	Repl. by BARATE 99K

[90] BATTLE 94 quote 0.14 ± 0.10 ± 0.03 or < 0.3% at 90% CL. We subtract (0.05 ± 0.02)% to account for $\tau^- \to K^- (K^0 \to \pi^0 \pi^0)\nu_\tau$ background.

$\Gamma\big(h^- \geq 3\pi^0 \nu_\tau\big)/\Gamma_{\text{total}}$ — Γ_{23}/Γ

$\Gamma_{23}/\Gamma = (\Gamma_{25}+\Gamma_{26}+\Gamma_{28}+0.157\Gamma_{38}+0.157\Gamma_{40}+0.0985\Gamma_{45}+0.319\Gamma_{117}+0.322\Gamma_{119})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
1.37±0.11 OUR FIT	Error includes scale factor of 1.1.			
1.53±0.40±0.46	186	DECAMP 92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.2 ±1.0 ±1.0		BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV

$\Gamma\big(h^- 3\pi^0 \nu_\tau\big)/\Gamma_{\text{total}}$ — Γ_{24}/Γ

$\Gamma_{24}/\Gamma = (\Gamma_{25}+\Gamma_{26}+0.157\Gamma_{38}+0.157\Gamma_{40}+0.322\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.21±0.10 OUR FIT					
1.22±0.10 OUR AVERAGE					
1.24±0.09±0.11	f&a	2.3k	[91] BUSKULIC 96	ALEP	LEP 1991–1993 data
1.70±0.24±0.38	f&a	293	ACCIARRI 95	L3	1992 LEP run
1.15±0.08±0.13	avg		[92] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.0\ ^{+1.4}_{-0.1}\ ^{+1.1}_{-0.1}$			[93] GAN 87	MRK2	E^{ee}_{cm}= 29 GeV

[91] BUSKULIC 96 quote $B(h^- 3\pi^0 \nu_\tau (\text{ex. } K^0))$ = 1.17 ± 0.09 ± 0.11. We add 0.07 to remove their correction for K^0 backgrounds.

[92] PROCARIO 93 entry is obtained from $B(h^- 3\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau)$ using ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$.

[93] Highly correlated with GAN 87 $\Gamma(\eta\pi^- \pi^0 \nu_\tau)/\Gamma_{\text{total}}$ value. Authors quote $B(\pi^\pm 3\pi^0 \nu_\tau) + 0.67 B(\pi^\pm \eta \pi^0 \nu_\tau)$ = 0.047 ± 0.010 ± 0.011.

$\Gamma\big(h^- 3\pi^0 \nu_\tau\big)/\Gamma\big(h^- \pi^0 \nu_\tau\big)$ — Γ_{24}/Γ_{12}

$\Gamma_{24}/\Gamma_{12} = (\Gamma_{25}+\Gamma_{26}+0.157\Gamma_{38}+0.157\Gamma_{40}+0.322\Gamma_{119})/(\Gamma_{13}+\Gamma_{15})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.047±0.004 OUR FIT	Error includes scale factor of 1.1.		
0.044±0.003±0.005	[94] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[94] PROCARIO 93 quote 0.041 ± 0.003 ± 0.005 after correction for 2 kaon backgrounds assuming $B(K^{*-} \nu_\tau)$=1.42 ± 0.18% and $B(h^- K^0 \pi^0 \nu_\tau)$=0.48 ± 0.48%. We add 0.003 ± 0.003 and multiply the sum by 0.990 ± 0.010 to remove these corrections.

$\Gamma\big(\pi^- 3\pi^0 \nu_\tau (\text{ex.}K^0)\big)/\Gamma_{\text{total}}$ — Γ_{25}/Γ

VALUE (%)	DOCUMENT ID
1.08±0.10 OUR FIT	

$\Gamma\big(K^- 3\pi^0 \nu_\tau (\text{ex.}K^0, \eta)\big)/\Gamma_{\text{total}}$ — Γ_{26}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{0.038^{+0.022}_{-0.020}}$ **OUR FIT**				
0.037±0.021±0.011	22	BARATE 99K	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.05 ±0.13		[95] BUSKULIC 94E	ALEP	Repl. by BARATE 99K

[95] BUSKULIC 94E quote $B(K^- \geq 0\pi^0 \geq 0K^0 \nu_\tau) - [B(K^- \nu_\tau) + B(K^- \pi^0 \nu_\tau) + B(K^- K^0 \nu_\tau) + B(K^- \pi^0 \pi^0 \nu_\tau) + B(K^- \pi^0 K^0 \nu_\tau)]$ = 0.05 ± 0.13% accounting for common systematic errors in BUSKULIC 94E and BUSKULIC 94F measurements of these modes. We assume $B(K^- \geq 2K^0 \nu_\tau)$ and $B(K^- \geq 4\pi^0 \nu_\tau)$ are negligible.

$\Gamma\big(h^- 4\pi^0 \nu_\tau (\text{ex.}K^0)\big)/\Gamma_{\text{total}}$ — Γ_{27}/Γ

$\Gamma_{27}/\Gamma = (\Gamma_{28}+0.319\Gamma_{117})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.16±0.06 OUR FIT				
0.16±0.06 OUR AVERAGE				
0.16±0.04±0.09	232	[96] BUSKULIC 96	ALEP	LEP 1991–1993 data
0.16±0.05±0.05		[97] PROCARIO 93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[96] BUSKULIC 96 quote result for $\tau^- \to h^- \geq 4\pi^0 \nu_\tau$. We assume $B(h^- \geq 5\pi^0 \nu_\tau)$ is negligible.

[97] PROCARIO 93 quotes $B(h^- 4\pi^0 \nu_\tau)/B(h^- \pi^0 \nu_\tau)$ =0.006 ± 0.002 ± 0.002. We multiply by the ARTUSO 94 result for $B(h^- \pi^0 \nu_\tau)$ to obtain $B(h^- 4\pi^0 \nu_\tau)$. PROCARIO 93 assume $B(h^- \geq 5\ \pi^0 \nu_\tau)$ is small and do not correct for it.

$\Gamma\big(h^- 4\pi^0 \nu_\tau (\text{ex.}K^0,\eta)\big)/\Gamma_{\text{total}}$ — Γ_{28}/Γ

VALUE (%)	DOCUMENT ID
$\mathbf{0.10^{+0.06}_{-0.05}}$ **OUR FIT**	

$\Gamma\big(K^- \geq 0\pi^0 \geq 0K^0 \geq 0\gamma\ \nu_\tau\big)/\Gamma_{\text{total}}$ — Γ_{29}/Γ

$\Gamma_{29}/\Gamma = (\Gamma_{10}+\Gamma_{15}+\Gamma_{22}+\Gamma_{26}+\Gamma_{35}+\Gamma_{40}+0.715\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.56 ±0.04 OUR FIT					
1.53 ±0.04 OUR AVERAGE					
1.528±0.039±0.040	f&a		[98] ABBIENDI 01J	OPAL	1990–1995 LEP runs
1.520±0.040±0.041	avg	4006	[99] BARATE 99K	ALEP	1991–1995 LEP runs
1.54 ±0.24	f&a		ABREU 94K	DLPH	LEP 1992 Z data
1.70 ±0.12 ±0.19	f&a	202	[100] BATTLE 94	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
1.6 ±0.4 ±0.2	f&a	35	AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
1.71 ±0.29	f&a	53	MILLS 84	DLCO	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.70 ±0.05 ±0.06		1610	[101] BUSKULIC 96	ALEP	Repl. by BARATE 99K

[98] The correlation coefficient between this measurement and the ABBIENDI 01J $B(\tau^- \to K^- \nu_\tau)$ is 0.60.

[99] Not independent of BARATE 99K $B(K^- \nu_\tau)$, $B(K^- \pi^0 \nu_\tau)$, $B(K^- 2\pi^0 \nu_\tau (\text{ex. } K^0))$, $B(K^- 3\pi^0 \nu_\tau (\text{ex. } K^0))$, $B(K^- K^0 \nu_\tau)$, and $B(K^- K^0 \pi^0 \nu_\tau)$ values.

[100] BATTLE 94 quote 1.60 ± 0.12 ± 0.19. We add 0.10 ± 0.02 to correct for their rejection of $K^0_S \to \pi^+ \pi^-$ decays.

[101] Not independent of BUSKULIC 96 $B(K^- \nu_\tau)$, $B(K^- \pi^0 \nu_\tau)$, $B(K^- 2\pi^0 \nu_\tau)$, $B(K^- K^0 \nu_\tau)$, and $B(K^- K^0 \pi^0 \nu_\tau)$ values.

$\Gamma\big(K^- \geq 1\ (\pi^0 \text{ or } K^0 \text{ or } \gamma)\ \nu_\tau\big)/\Gamma_{\text{total}}$ — Γ_{30}/Γ

$\Gamma_{30}/\Gamma = (\Gamma_{15}+\Gamma_{22}+\Gamma_{26}+\Gamma_{35}+\Gamma_{40}+0.715\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.874±0.035 OUR FIT					
0.86 ±0.05 OUR AVERAGE					
0.869±0.031±0.034	avg		[102] ABBIENDI 01J	OPAL	1990–1995 LEP runs
0.69 ±0.25	avg		[103] ABREU 94K	DLPH	LEP 1992 Z data
$1.2\ \pm 0.5\ ^{+0.2}_{-0.4}$	f&a	9	AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV

[102] Not independent of ABBIENDI 01J $B(\tau^- \to K^- \nu_\tau)$ and $B(\tau^- \to K^- \geq 0\pi^0 \geq 0K^0 \geq 0\gamma\ \nu_\tau)$ values.

[103] Not independent of ABREU 94K $B(K^- \nu_\tau)$ and $B(K^- \geq 0\ \text{neutrals}\,\nu_\tau)$ measurements.

$\Gamma\big(K^0_S (\text{particles})^- \nu_\tau\big)/\Gamma_{\text{total}}$ — Γ_{31}/Γ

$\Gamma_{31}/\Gamma = (\frac{1}{2}\Gamma_{33}+\frac{1}{2}\Gamma_{35}+\frac{1}{2}\Gamma_{38}+\frac{1}{2}\Gamma_{40}+\Gamma_{45}+\Gamma_{46})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.92 ±0.04 OUR FIT	Error includes scale factor of 1.1.			
0.97 ±0.07 OUR AVERAGE				
0.970±0.058±0.062	929	BARATE 98E	ALEP	1991–1995 LEP runs
0.97 ±0.09 ±0.06	141	AKERS 94G	OPAL	E^{ee}_{cm}= 88–94 GeV

$\Gamma(h^- \overline{K}^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{32}/\Gamma = (\Gamma_{33}+\Gamma_{35})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
1.05 ±0.04 OUR FIT Error includes scale factor of 1.1.					
0.90 ±0.07 OUR AVERAGE					
1.01 ±0.11 ±0.07	avg	555	[104] BARATE 98E	ALEP	1991–1995 LEP runs
0.855±0.036±0.073	f&a	1242	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[104] Not independent of BARATE 98E $B(\tau^- \to \pi^- \overline{K}^0 \nu_\tau)$ and $B(\tau^- \to K^- K^0 \nu_\tau)$ values.

$\Gamma(\pi^- \overline{K}^0 \nu_\tau)/\Gamma_{total}$ — Γ_{33}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.89 ±0.04 OUR FIT Error includes scale factor of 1.1.					
0.88 ±0.05 OUR AVERAGE Error includes scale factor of 1.2.					
0.933±0.068±0.049	f&a	377	ABBIENDI 00C	OPAL	1991–1995 LEP runs
0.928±0.045±0.034	f&a	937	[105] BARATE 99K	ALEP	1991–1995 LEP runs
0.855±0.117±0.066	avg	509	[106] BARATE 98E	ALEP	1991–1995 LEP runs
0.704±0.041±0.072	avg		[107] COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
0.95 ±0.15 ±0.06	f&a		[108] ACCIARRI 95F	L3	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.79 ±0.10 ±0.09		98	[109] BUSKULIC 96	ALEP	Repl. by BARATE 99K

[105] BARATE 99K measure K^0's by detecting K^0_L's in their hadron calorimeter.
[106] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays. Not independent of BARATE 98E $B(K^0 \text{particles}^- \nu_\tau)$ value.
[107] Not independent of COAN 96 $B(h^- K^0 \nu_\tau)$ and $B(K^- K^0 \nu_\tau)$ measurements.
[108] ACCIARRI 95F do not identify π^-/K^- and assume $B(K^- K^0 \nu_\tau) = (0.29 \pm 0.12)\%$.
[109] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

$\Gamma(\pi^- \overline{K}^0 (\text{non-}K^*(892)^-) \nu_\tau)/\Gamma_{total}$ — Γ_{34}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.17	95	ACCIARRI 95F	L3	1991–1993 LEP runs

$\Gamma(K^- K^0 \nu_\tau)/\Gamma_{total}$ — Γ_{35}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.154±0.016 OUR FIT				
0.158±0.017 OUR AVERAGE				
0.162±0.021±0.011	150	[110] BARATE 99K	ALEP	1991–1995 LEP runs
0.158±0.042±0.017	46	[111] BARATE 98E	ALEP	1991–1995 LEP runs
0.151±0.021±0.022	111	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.26 ±0.09 ±0.02	13	[112] BUSKULIC 96	ALEP	Repl. by BARATE 99K

[110] BARATE 99K measure K^0's by detecting K^0_L's in their hadron calorimeter.
[111] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays.
[112] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

$\Gamma(K^- K^0 \geq 0\pi^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{36}/\Gamma = (\Gamma_{35}+\Gamma_{40})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.309±0.024 OUR FIT				
0.330±0.055±0.039	124	ABBIENDI 00C	OPAL	1991–1995 LEP runs

$\Gamma(h^- \overline{K}^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{37}/\Gamma = (\Gamma_{38}+\Gamma_{40})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.52 ±0.04 OUR FIT					
0.50 ±0.06 OUR AVERAGE Error includes scale factor of 1.2.					
0.446±0.052±0.046	avg	157	[113] BARATE 98E	ALEP	1991–1995 LEP runs
0.562±0.050±0.048	f&a	264	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[113] Not independent of BARATE 98E $B(\tau^- \to \pi^- \overline{K}^0 \pi^0 \tau)$ and $B(\tau^- \to K^- K^0 \pi^0 \nu_\tau)$ values.

$\Gamma(\pi^- \overline{K}^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{38}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.37 ±0.04 OUR FIT					
0.36 ±0.04 OUR AVERAGE					
0.347±0.053±0.037	f&a	299	[114] BARATE 99K	ALEP	1991–1995 LEP runs
0.294±0.073±0.037	f&a	142	[115] BARATE 98E	ALEP	1991–1995 LEP runs
0.417±0.058±0.044	avg		[116] COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
0.41 ±0.12 ±0.03	f&a		[117] ACCIARRI 95F	L3	1991–1993 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.32 ±0.11 ±0.05		23	[118] BUSKULIC 96	ALEP	Repl. by BARATE 99K

[114] BARATE 99K measure K^0's by detecting K^0_L's in their hadron calorimeter.
[115] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays.
[116] Not independent of COAN 96 $B(h^- K^0 \pi^0 \nu_\tau)$ and $B(K^- K^0 \pi^0 \nu_\tau)$ measurements.
[117] ACCIARRI 95F do not identify π^-/K^- and assume $B(K^- K^0 \pi^0 \nu_\tau) = (0.05 \pm 0.05)\%$.
[118] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

$\Gamma(\overline{K}^0 \rho^- \nu_\tau)/\Gamma_{total}$ — Γ_{39}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
0.22 ±0.05 OUR AVERAGE			
0.250±0.057±0.044	[119] BARATE 99K	ALEP	1991–1995 LEP runs
0.188±0.054±0.038	[120] BARATE 98E	ALEP	1991–1995 LEP runs

[119] BARATE 99K measure K^0's by detecting K^0_L's in hadron calorimeter. They determine the $\overline{K}^0 \rho^-$ fraction in $\tau^- \to \pi^- \overline{K}^0 \pi^0 \nu_\tau$ decays to be $(0.72 \pm 0.12 \pm 0.10)$ and multiply their $B(\pi^- \overline{K}^0 \pi^0 \nu_\tau)$ measurement by this fraction to obtain the quoted result.
[120] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays. They determine the $\overline{K}^0 \rho^-$ fraction in $\tau^- \to \pi^- \overline{K}^0 \pi^0 \nu_\tau$ decays to be $(0.64 \pm 0.09 \pm 0.10)$ and multiply their $B(\pi^- \overline{K}^0 \pi^0 \nu_\tau)$ measurement by this fraction to obtain the quoted result.

$\Gamma(K^- K^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{40}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.155±0.020 OUR FIT				
0.144±0.023 OUR AVERAGE				
0.143±0.025±0.015	78	[121] BARATE 99K	ALEP	1991–1995 LEP runs
0.152±0.076±0.021	15	[122] BARATE 98E	ALEP	1991–1995 LEP runs
0.145±0.036±0.020	32	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.10 ±0.05 ±0.03	5	[123] BUSKULIC 96	ALEP	Repl. by BARATE 99K

[121] BARATE 99K measure K^0's by detecting K^0_L's in their hadron calorimeter.
[122] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays.
[123] BUSKULIC 96 measure K^0's by detecting K^0_L's in their hadron calorimeter.

$\Gamma(\pi^- \overline{K}^0 \geq 1\pi^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{41}/\Gamma = (\Gamma_{38}+\Gamma_{42})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.324±0.074±0.066	148	ABBIENDI 00C	OPAL	1991–1995 LEP runs

$\Gamma(\pi^- \overline{K}^0 \pi^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{42}/Γ

VALUE (units 10^{-3})	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
0.26±0.24			[124] BARATE 99R	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.66	95	17	[125] BARATE 99K	ALEP	1991–1995 LEP runs
0.58±0.33±0.14		5	[126] BARATE 98E	ALEP	1991–1995 LEP runs

[124] BARATE 99R combine the BARATE 98E and BARATE 99K measurements to obtain this value.
[125] BARATE 99K measure K^0's by detecting K^0_L's in their hadron calorimeter.
[126] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays.

$\Gamma(K^- K^0 \pi^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{43}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.16 × 10^{-3}	95	[127] BARATE 99R	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.18 × 10^{-3}	95	[128] BARATE 99K	ALEP	1991–1995 LEP runs
<0.39 × 10^{-3}	95	[129] BARATE 98E	ALEP	1991–1995 LEP runs

[127] BARATE 99R combine the BARATE 98E and BARATE 99K bounds to obtain this value.
[128] BARATE 99K measure K^0's by detecting K^0_L's in hadron calorimeter.
[129] BARATE 98E reconstruct K^0's by using $K^0_S \to \pi^+\pi^-$ decays.

$\Gamma(\pi^- K^0 \overline{K}^0 \nu_\tau)/\Gamma_{total}$ — $\Gamma_{44}/\Gamma = (2\Gamma_{45}+\Gamma_{46})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
0.159±0.029 OUR FIT Error includes scale factor of 1.1.					
0.153±0.030±0.016	**avg**	74	[130] BARATE 98E	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.31 ±0.12 ±0.04			[131] ACCIARRI 95F	L3	1991–1993 LEP runs

[130] BARATE 98E obtain this value by adding twice their $B(\pi^- K^0_S K^0_S \nu_\tau)$ value to their $B(\pi^- K^0_S K^0_L \nu_\tau)$ value.
[131] ACCIARRI 95F assume $B(\pi^- K^0_S K^0_S \nu) = B(\pi^- K^0_S K^0_L \nu) = 1/2 B(\pi^- K^0_S K^0_L \nu)$.

$\Gamma(\pi^- K^0_S K^0_S \nu_\tau)/\Gamma_{total}$ — Γ_{45}/Γ

Bose-Einstein correlations might make the mixing fraction different than 1/4.

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.024±0.005 OUR FIT				
0.024±0.005 OUR AVERAGE				
0.026±0.010±0.005	6	BARATE 98E	ALEP	1991–1995 LEP runs
0.023±0.005±0.003	42	COAN 96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(\pi^- K^0_S K^0_L \nu_\tau)/\Gamma_{total}$ — Γ_{46}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.110±0.028 OUR FIT	Error includes scale factor of 1.1.			
0.101±0.023±0.013	68	BARATE 98E	ALEP	1991–1995 LEP runs

$\Gamma(\pi^- K^0 \overline{K}^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{47}/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
$(0.31\pm0.23)\times10^{-3}$	[132] BARATE 99R	ALEP	1991–1995 LEP runs

[132] BARATE 99R combine BARATE 98E $\Gamma(\pi^- K^0_S K^0_S \pi^0 \nu_\tau)/\Gamma_{total}$ and $\Gamma(\pi^- K^0_S K^0_L \pi^0 \nu_\tau)/\Gamma_{total}$ measurements to obtain this value.

$\Gamma(\pi^- K^0_S K^0_S \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{48}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.020	95	BARATE 98E	ALEP	1991–1995 LEP runs

$\Gamma(\pi^- K^0_S K^0_L \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{49}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.031±0.011±0.005	11	BARATE 98E	ALEP	1991–1995 LEP runs

$\Gamma(K^0 h^+ h^- h^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{50}/Γ

VALUE (%)	CL%	DOCUMENT ID	TECN	COMMENT
<0.17	95	TSCHIRHART 88	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.27	90	BELTRAMI 85	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(K^0 h^+ h^- h^- \nu_\tau)/\Gamma_{total}$ — Γ_{51}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.023±0.019±0.007	6	[133] BARATE 98E	ALEP	1991–1995 LEP runs

[133] BARATE 98E reconstruct K^0's using $K^0_S \to \pi^+\pi^-$ decays.

$\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals } \geq 0K^0_L \nu_\tau)/\Gamma_{total}$ — Γ_{52}/Γ

$\Gamma_{52}/\Gamma = (0.3431\Gamma_{33}+0.3431\Gamma_{35}+0.3431\Gamma_{38}+0.3431\Gamma_{40}+0.4307\Gamma_{45}+0.6861\Gamma_{46}+\Gamma_{60}+\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{82}+\Gamma_{86}+\Gamma_{89}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.9101\Gamma_{137}+0.9101\Gamma_{138})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
15.19± 0.07 OUR FIT	Error includes scale factor of 1.1.			
14.8 ± 0.4 OUR AVERAGE				
14.4 ± 0.6 ±0.3		ADEVA 91F	L3	E^{ee}_{cm}= 88.3–94.3 GeV
15.0 ± 0.4 ±0.3		BEHREND 89B	CELL	E^{ee}_{cm}= 14–47 GeV
15.1 ± 0.8 ±0.6		AIHARA 87B	TPC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
13.5 ± 0.3 ±0.3		ABACHI 89B	HRS	E^{ee}_{cm}= 29 GeV
12.8 ± 1.0 ±0.7		[134] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
12.1 ± 0.5 ±1.2		RUCKSTUHL 86	DLCO	E^{ee}_{cm}= 29 GeV
12.8 ± 0.5 ±0.8	1420	SCHMIDKE 86	MRK2	E^{ee}_{cm}= 29 GeV
$15.3 \pm 1.1 {}^{+1.3}_{-1.6}$	367	ALTHOFF 85	TASS	E^{ee}_{cm}= 34.5 GeV
13.6 ± 0.5 ±0.8		BARTEL 85F	JADE	E^{ee}_{cm}= 34.6 GeV
12.2 ± 1.3 ±3.9		[135] BERGER 85	PLUT	E^{ee}_{cm}= 34.6 GeV
13.3 ± 0.3 ±0.6		FERNANDEZ 85	MAC	E^{ee}_{cm}= 29 GeV
24 ± 6	35	BRANDELIK 80	TASS	E^{ee}_{cm}= 30 GeV
32 ± 5	692	[136] BACINO 78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
35 ±11		[136] BRANDELIK 78	DASP	Assumes $V-A$ decay
18 ± 6.5	33	[136] JAROS 78	MRK1	E^{ee}_{cm} > 6 GeV

[134] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[135] Not independent of BERGER 85 $\Gamma(\mu^- \overline{\nu}_\mu \nu_\tau)/\Gamma_{total}$, $\Gamma(e^- \overline{\nu}_e \nu_\tau)/\Gamma_{total}$, $\Gamma(h^- \geq 1 \text{ neutrals} \nu_\tau)/\Gamma_{total}$, and $\Gamma(h^- \geq 0K^0_L \nu_\tau)/\Gamma_{total}$, and therefore not used in the fit.

[136] Low energy experiments are not in average or fit because the systematic errors in background subtraction are judged to be large.

$\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau \text{ (ex. } K^0_S \to \pi^+\pi^-)(\text{"3-prong"}))/\Gamma_{total}$ — Γ_{53}/Γ

$\Gamma_{53}/\Gamma = (\Gamma_{60}+\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{82}+\Gamma_{86}+\Gamma_{89}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.9101\Gamma_{137}+0.9101\Gamma_{138})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
14.57 ±0.07 OUR FIT	Error includes scale factor of 1.1.				
14.59 ±0.08 OUR AVERAGE	Error includes scale factor of 1.1.				
14.569±0.093±0.048	f&a	23k	[137] ABREU 01M	DLPH	1992–1995 LEP runs
14.556±0.105±0.076	f&a		[138] ACHARD 01D	L3	1992–1995 LEP runs
14.96 ±0.09 ±0.22	f&a	10.4k	AKERS 95Y	OPAL	1991–1994 LEP runs
14.22 ±0.10 ±0.37	avg		[139] BALEST 95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
15.26 ±0.26 ±0.22			ACTON 92H	OPAL	Repl. by AKERS 95Y
13.3 ±0.3 ±0.8			[140] ALBRECHT 92D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
$14.35 {}^{+0.40}_{-0.45} \pm0.24$			DECAMP 92C	ALEP	1989–1990 LEP runs

[137] The correlation coefficients between this measurement and the ABREU 01M measurements of B($\tau \to$ 1-prong) and B($\tau \to$ 5-prong) are −0.98 and −0.08 respectively.

[138] The correlation coefficients between this measurement and the ACHARD 01D measurements of B($\tau \to$ "1-prong") and B($\tau \to$ "5-prong") are −0.978 and −0.19 respectively.

[139] Not independent of BALEST 95C $B(h^- h^- h^+ \nu_\tau)$ and $B(h^- h^- h^+ \pi^0 \nu_\tau)$ values, and BORTOLETTO 93 $B(h^- h^- h^+ 2\pi^0 \nu_\tau)/B(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau)$ value.

[140] This ALBRECHT 92D value is not independent of their $\Gamma(\mu^- \overline{\nu}_\mu \nu_\tau)\Gamma(e^- \overline{\nu}_e \nu_\tau)/\Gamma^2_{total}$ value.

$\Gamma(h^- h^- h^+ \nu_\tau)/\Gamma_{total}$ — Γ_{54}/Γ

$\Gamma_{54}/\Gamma = (0.3431\Gamma_{33}+0.3431\Gamma_{35}+\Gamma_{60}+\Gamma_{82}+\Gamma_{89}+0.0221\Gamma_{137})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
10.01±0.09 OUR FIT	Error includes scale factor of 1.2.				
9.8 ±0.6 OUR AVERAGE	Error includes scale factor of 4.4. See the ideogram below.				
7.6 ±0.1 ±0.5	avg	7.5k	[141] ALBRECHT 96E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
9.92±0.10±0.09	f&a	11.2k	[142] BUSKULIC 96	ALEP	LEP 1991–1993 data
9.49±0.36±0.63	f&a		DECAMP 92C	ALEP	1989–1990 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
8.7 ±0.7 ±0.3		694	[143] BEHREND 90	CELL	E^{ee}_{cm}= 35 GeV
7.0 ±0.3 ±0.7		1566	[144] BAND 87	MAC	E^{ee}_{cm}= 29 GeV
6.7 ±0.8 ±0.9			[145] BURCHAT 87	MRK2	E^{ee}_{cm}= 29 GeV
6.4 ±0.4 ±0.9			[146] RUCKSTUHL 86	DLCO	E^{ee}_{cm}= 29 GeV
7.8 ±0.5 ±0.8		890	SCHMIDKE 86	MRK2	E^{ee}_{cm}= 29 GeV
8.4 ±0.4 ±0.7		1255	[146] FERNANDEZ 85	MAC	E^{ee}_{cm}= 29 GeV
9.7 ±2.0 ±1.3			BEHREND 84	CELL	E^{ee}_{cm}= 14,22 GeV

[141] ALBRECHT 96E not independent of ALBRECHT 93C $\Gamma(h^- h^- h^+ \nu_\tau \text{(ex. } K^0) \times \Gamma(\text{particle}^- \geq 0 \text{ neutrals } \geq 0 K^0_L \nu_\tau)/\Gamma^2_{total}$ value.

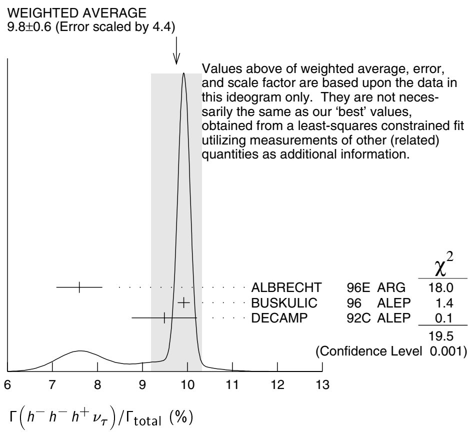
[142] BUSKULIC 96 quote $B(h^- h^- h^+ \nu_\tau \text{(ex. } K^0)) = 9.50 \pm 0.10 \pm 0.11$. We add 0.42 to remove their K^0 correction and reduce the systematic error accordingly.

[143] BEHREND 90 subtract 0.3% to account for the $\tau^- \to K^*(892)^- \nu_\tau$ contribution to measured events.

[144] BAND 87 subtract for charged kaon modes; not independent of FERNANDEZ 85 value.

[145] BURCHAT 87 value is not independent of SCHMIDKE 86 value.

[146] Value obtained by multiplying paper's $R = B(h^- h^- h^+ \nu_\tau)/B(\text{3-prong})$ by B(3-prong) = 0.143 and subtracting 0.3% for $K^*(892)$ background.



$\Gamma(h^- h^- h^+ \nu_\tau \text{(ex.} K^0))/\Gamma_{total}$ — Γ_{55}/Γ

$\Gamma_{55}/\Gamma = (\Gamma_{60}+\Gamma_{82}+\Gamma_{89}+0.0221\Gamma_{137})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID	TECN	COMMENT
9.65±0.09 OUR FIT	Error includes scale factor of 1.2.				
9.57±0.11 OUR AVERAGE					
9.50±0.10±0.11	avg	11.2k	[147] BUSKULIC 96	ALEP	LEP 1991–1993 data
9.87±0.10±0.24	avg		[148] AKERS 95Y	OPAL	1991–1994 LEP runs
9.51±0.07±0.20	f&a	37.7k	BALEST 95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[147] Not independent of BUSKULIC 96 $B(h^- h^- h^+ \nu_\tau)$ value.

[148] Not independent of AKERS 95Y $B(h^- h^- h^+ \geq 0 \text{ neutrals} \nu_\tau \text{ (ex. } K^0_S \to \pi^+\pi^-))$ and $B(h^- h^- h^+ \nu_\tau \text{(ex. } K^0))/B(h^- h^- h^+ \geq 0 \text{ neutrals} \nu_\tau \text{ (ex. } K^0_S \to \pi^+\pi^-))$ values.

$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0))/\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^+\pi^-)$ ("3-prong")) Γ_{55}/Γ_{53}

$\Gamma_{55}/\Gamma_{53} = (\Gamma_{60}+\Gamma_{82}+\Gamma_{89}+0.0221\Gamma_{137})/(\Gamma_{60}+\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{82}+\Gamma_{86}+\Gamma_{89}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.9101\Gamma_{137}+0.9101\Gamma_{138})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.662±0.006 OUR FIT	Error includes scale factor of 1.3.			
0.660±0.004±0.014	AKERS	95Y	OPAL	1991–1994 LEP runs

$\Gamma(h^- h^- h^+ \nu_\tau (\text{ex.} K^0,\omega))/\Gamma_{\text{total}}$ $\Gamma_{56}/\Gamma = (\Gamma_{60}+\Gamma_{82}+\Gamma_{89})/\Gamma$

VALUE (%)	DOCUMENT ID
9.60±0.09 OUR FIT	Error includes scale factor of 1.2.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau)/\Gamma_{\text{total}}$ $\Gamma_{57}/\Gamma = (0.3431\Gamma_{33}+\Gamma_{60}+0.0221\Gamma_{137})/\Gamma$

VALUE (%)	DOCUMENT ID
9.47±0.10 OUR FIT	Error includes scale factor of 1.2.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau (\text{ex.} K^0))/\Gamma_{\text{total}}$ $\Gamma_{58}/\Gamma = (\Gamma_{60}+0.0221\Gamma_{137})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
9.16±0.10 OUR FIT	Error includes scale factor of 1.2.				
9.13±0.05±0.46	43k	[149] BRIERE	03	CLE3	E^{ee}_{cm}= 10.6 GeV

[149] 47% correlated with BRIERE 03 $\tau^- \to K^-\pi^+\pi^-\nu_\tau$ and 71% correlated with $\tau^- \to K^- K^+ \pi^- \nu_\tau$ because of a common 5% normalization error.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau (\text{ex.} K^0)$, non-axial vector$)/\Gamma(\pi^-\pi^+\pi^-\nu_\tau (\text{ex.} K^0))$ $\Gamma_{59}/\Gamma_{58} = \Gamma_{59}/(\Gamma_{60}+0.0221\Gamma_{137})$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.261	95	[150] ACKERSTAFF	97R	OPAL	1992–1994 LEP runs

[150] Model-independent limit from structure function analysis on contribution to B($\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ (ex. K^0)) from non-axial vectors.

$\Gamma(\pi^-\pi^+\pi^-\nu_\tau (\text{ex.} K^0,\omega))/\Gamma_{\text{total}}$ Γ_{60}/Γ

VALUE (%)	DOCUMENT ID
9.12±0.10 OUR FIT	Error includes scale factor of 1.2.

$\Gamma(h^- h^- h^+ \geq 1 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ Γ_{61}/Γ

$\Gamma_{61}/\Gamma = (0.3431\Gamma_{38}+0.3431\Gamma_{40}+0.4307\Gamma_{45}+0.6861\Gamma_{46}+\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{86}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.888\Gamma_{137}+0.9101\Gamma_{138})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.19±0.10 OUR FIT	Error includes scale factor of 1.3.				
• • • We do not use the following data for averages, fits, limits, etc. • • •					
5.6 ±0.7 ±0.3	352	[151] BEHREND	90	CELL	E^{ee}_{cm}= 35 GeV
4.2 ±0.5 ±0.9	203	[152] ALBRECHT	87L	ARG	E^{ee}_{cm}= 10 GeV
6.1 ±0.8 ±0.9		[153] BURCHAT	87	MRK2	E^{ee}_{cm}= 29 GeV
7.6 ±0.4 ±0.9		[154,155] RUCKSTUHL	86	DLCO	E^{ee}_{cm}= 29 GeV
4.7 ±0.5 ±0.8	530	[156] SCHMIDKE	86	MRK2	E^{ee}_{cm}= 29 GeV
5.6 ±0.4 ±0.7		[155] FERNANDEZ	85	MAC	E^{ee}_{cm}= 29 GeV
6.2 ±2.3 ±1.7		BEHREND	84	CELL	E^{ee}_{cm}= 14,22 GeV

[151] BEHREND 90 value is not independent of BEHREND 90 B($3h\nu_\tau \geq 1$ neutrals) + B(5-prong).
[152] ALBRECHT 87L measure the product of branching ratios B($3\pi^\pm\pi^0\nu_\tau$) B(($e\overline{\nu}$ or $\mu\overline{\nu}$ or π or K or ρ)ν_τ) = 0.029 and use the PDG 86 values for the second branching ratio which sum to 0.69 ± 0.03 to get the quoted value.
[153] BURCHAT 87 value is not independent of SCHMIDKE 86 value.
[154] Contributions from kaons and from $>1\pi^0$ are subtracted. Not independent of (3-prong + $0\pi^0$) and (3-prong + $\geq 0\pi^0$) values.
[155] Value obtained using paper's R = B($h^- h^- h^+ \nu_\tau$)/B(3-prong) and current B(3-prong) = 0.143.
[156] Not independent of SCHMIDKE 86 $h^- h^- h^+ \nu_\tau$ and $h^- h^- h^+ (\geq 0\pi^0)\nu_\tau$ values.

$\Gamma(h^- h^- h^+ \geq 1 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^+\pi^-))/\Gamma_{\text{total}}$ Γ_{62}/Γ

$\Gamma_{62}/\Gamma = (\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{86}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.888\Gamma_{137}+0.9101\Gamma_{138})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
4.92±0.09 OUR FIT	Error includes scale factor of 1.3.					
5.07±0.24 OUR AVERAGE						
5.09±0.10±0.23	avg		[157] AKERS	95Y	OPAL	1991–1994 LEP runs
4.95±0.29±0.65	f&a	570	DECAMP	92C	ALEP	1989–1990 LEP runs

[157] Not independent of AKERS 95Y B($h^- h^- h^+ \geq 0$ neutralsν_τ (ex. $K^0_S \to \pi^+\pi^-$)) and B($h^- h^- h^+ \geq 0$ neutralsν_τ (ex. K^0))/B($h^- h^- h^+ \geq 0$ neutralsν_τ (ex. $K^0_S \to \pi^+\pi^-$)) values.

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{63}/Γ

$\Gamma_{63}/\Gamma = (0.3431\Gamma_{38}+0.3431\Gamma_{40}+\Gamma_{68}+\Gamma_{86}+\Gamma_{90}+0.231\Gamma_{119}+0.888\Gamma_{137}+0.0221\Gamma_{138})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.53±0.09 OUR FIT	Error includes scale factor of 1.3.				
4.45±0.09±0.07	6.1k	[158] BUSKULIC	96	ALEP	LEP 1991–1993 data

[158] BUSKULIC 96 quote B($h^- h^- h^+ \pi^0 \nu_\tau$ (ex. K^0)) = 4.30 ± 0.09 ± 0.09. We add 0.15 to remove their K^0 correction and reduce the systematic error accordingly.

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma_{\text{total}}$ Γ_{64}/Γ

$\Gamma_{64}/\Gamma = (\Gamma_{68}+\Gamma_{86}+\Gamma_{90}+0.231\Gamma_{119}+0.888\Gamma_{137}+0.0221\Gamma_{138})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
4.35±0.09 OUR FIT	Error includes scale factor of 1.3.				
4.23±0.06±0.22	7.2k	BALEST	95C	CLEO	$E^{ee}_{\text{cm}} \approx$ 10.6 GeV

$\Gamma(h^- h^- h^+ \pi^0 \nu_\tau (\text{ex. } K^0,\omega))/\Gamma_{\text{total}}$ $\Gamma_{65}/\Gamma = (\Gamma_{68}+\Gamma_{86}+\Gamma_{90}+0.231\Gamma_{119})/\Gamma$

VALUE (%)	DOCUMENT ID
2.62±0.09 OUR FIT	Error includes scale factor of 1.2.

$\Gamma(\pi^-\pi^+\pi^-\pi^0\nu_\tau)/\Gamma_{\text{total}}$ $\Gamma_{66}/\Gamma = (0.3431\Gamma_{38}+\Gamma_{68}+0.888\Gamma_{137}+0.0221\Gamma_{138})/\Gamma$

VALUE (%)	DOCUMENT ID
4.37±0.09 OUR FIT	Error includes scale factor of 1.3.

$\Gamma(\pi^-\pi^+\pi^-\pi^0\nu_\tau (\text{ex.} K^0))/\Gamma_{\text{total}}$ $\Gamma_{67}/\Gamma = (\Gamma_{68}+0.888\Gamma_{137}+0.0221\Gamma_{138})/\Gamma$

VALUE (%)	DOCUMENT ID		TECN	COMMENT
4.25±0.09 OUR FIT	Error includes scale factor of 1.3.			
4.19±0.10±0.21	[159] EDWARDS	00A	CLEO	4.7 fb^{-1} E^{ee}_{cm}= 10.6 GeV

[159] EDWARDS 00A quote (4.19 ± 0.10) × 10^{-2} with a 5% systematic error.

$\Gamma(\pi^-\pi^+\pi^-\pi^0\nu_\tau (\text{ex.} K^0,\omega))/\Gamma_{\text{total}}$ Γ_{68}/Γ

VALUE (%)	DOCUMENT ID
2.51±0.09 OUR FIT	Error includes scale factor of 1.2.

$\Gamma(h^-\rho\pi^0\nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ Γ_{69}/Γ_{63}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.30 ±0.04 ±0.02	393	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(h^-\rho^+ h^-\nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ Γ_{70}/Γ_{63}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.10 ±0.03 ±0.04	142	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(h^-\rho^- h^+\nu_\tau)/\Gamma(h^- h^- h^+ \pi^0 \nu_\tau)$ Γ_{71}/Γ_{63}

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.26 ±0.05 ±0.01	370	ALBRECHT	91D	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{72}/Γ

$\Gamma_{72}/\Gamma = (0.4307\Gamma_{45}+\Gamma_{74}+0.236\Gamma_{117}+0.888\Gamma_{138})/\Gamma$

VALUE (%)	DOCUMENT ID
0.55±0.04 OUR FIT	

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma_{\text{total}}$ Γ_{73}/Γ

$\Gamma_{73}/\Gamma = (\Gamma_{74}+0.236\Gamma_{117}+0.888\Gamma_{138})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.54±0.04 OUR FIT					
0.50±0.07±0.07	1.8k	BUSKULIC	96	ALEP	LEP 1991–1993 data

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.} K^0))/\Gamma(h^- h^- h^+ \geq 0 \text{ neutrals} \geq 0 K^0_L \nu_\tau)$ Γ_{73}/Γ_{52}

$\Gamma_{73}/\Gamma_{52} = (\Gamma_{74}+0.236\Gamma_{117}+0.888\Gamma_{138})/(0.3431\Gamma_{33}+0.3431\Gamma_{35}+0.3431\Gamma_{38}+0.3431\Gamma_{40}+0.4307\Gamma_{45}+0.6861\Gamma_{46}+\Gamma_{60}+\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{82}+\Gamma_{86}+\Gamma_{89}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.9101\Gamma_{137}+0.9101\Gamma_{138})$

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.0355±0.0028 OUR FIT				
0.034 ±0.002 ±0.003	668	BORTOLETTO93	CLEO	$E^{ee}_{\text{cm}} \approx$ 10.6 GeV

$\Gamma(h^- h^- h^+ 2\pi^0 \nu_\tau (\text{ex.} K^0,\omega,\eta))/\Gamma_{\text{total}}$ Γ_{74}/Γ

VALUE (%)	DOCUMENT ID
0.11±0.04 OUR FIT	

$\Gamma(h^- h^- h^+ 3\pi^0 \nu_\tau)/\Gamma_{\text{total}}$ Γ_{75}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.023 ±0.008 OUR FIT	Error includes scale factor of 1.5.				
0.023 ±0.005 OUR AVERAGE					
0.022 ±0.003 ±0.004	139	ANASTASSOV	01	CLEO	E^{ee}_{cm}= 10.6 GeV
0.11 ±0.04 ±0.05	440	[160] BUSKULIC	96	ALEP	LEP 1991–1993 data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.0285±0.0056±0.0051	57	ANDERSON	97	CLEO	Repl. by ANASTASSOV 01

[160] BUSKULIC 96 state their measurement is for B($h^- h^- h^+ \geq 3\pi^0 \nu_\tau$). We assume that B($h^- h^- h^+ \geq 4\pi^0 \nu_\tau$) is very small.

$\Gamma(K^- h^+ h^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{\text{total}}$ $\Gamma_{76}/\Gamma = (0.3431\Gamma_{35}+0.3431\Gamma_{40}+\Gamma_{82}+\Gamma_{86}+\Gamma_{89}+\Gamma_{90}+0.285\Gamma_{119})/\Gamma$

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
0.69±0.04 OUR FIT	Error includes scale factor of 1.3.				
<0.6	90	AIHARA	84C	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^- h^+ \pi^- \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ $\Gamma_{77}/\Gamma = (\Gamma_{82}+\Gamma_{89})/\Gamma$

VALUE (%)	DOCUMENT ID
0.48±0.04 OUR FIT Error includes scale factor of 1.5.	

$\Gamma(K^- h^+ \pi^- \nu_\tau (\text{ex.}K^0))/\Gamma(\pi^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))$ $\Gamma_{77}/\Gamma_{58} = (\Gamma_{82}+\Gamma_{89})/(\Gamma_{60}+0.0221\Gamma_{137})$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
5.2 ±0.4 OUR FIT Error includes scale factor of 1.6.					
5.44±0.21±0.53	7.9k	RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(K^- h^+ \pi^- \pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ $\Gamma_{78}/\Gamma = (\Gamma_{86}+\Gamma_{90}+0.231\Gamma_{119})/\Gamma$

VALUE (%)	DOCUMENT ID
0.107±0.022 OUR FIT	

$\Gamma(K^- h^+ \pi^- \pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma(\pi^- \pi^+ \pi^- \pi^0 \nu_\tau (\text{ex.}K^0))$ $\Gamma_{78}/\Gamma_{67} = (\Gamma_{86}+\Gamma_{90}+0.231\Gamma_{119})/(\Gamma_{68}+0.888\Gamma_{137}+0.0221\Gamma_{138})$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
2.5 ±0.5 OUR FIT					
2.61±0.45±0.42	719	RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(K^- \pi^+ \pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ $\Gamma_{79}/\Gamma = (0.3431\Gamma_{35}+0.3431\Gamma_{40}+\Gamma_{82}+\Gamma_{86}+0.285\Gamma_{119})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.50±0.04 OUR FIT Error includes scale factor of 1.3.					
$\mathbf{0.58^{+0.15}_{-0.13}\pm0.12}$	20	[161] BAUER	94	TPC	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$0.22^{+0.16}_{-0.13}\pm0.05$	9	[162] MILLS	85	DLCO	E^{ee}_{cm}= 29 GeV

[161] We multiply 0.58% by 0.20, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

[162] Error correlated with MILLS 85 ($K K \pi \nu$) value. We multiply 0.22% by 0.23, the relative systematic error quoted by MILLS 85, to obtain obtain the systematic error.

$\Gamma(K^- \pi^+ \pi^- \geq 0\pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ $\Gamma_{80}/\Gamma = (\Gamma_{82}+\Gamma_{86}+0.231\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID		TECN	COMMENT
0.39 ±0.04 OUR FIT Error includes scale factor of 1.3.					
0.30 ±0.05 OUR AVERAGE					
0.343±0.073±0.031	f&a	ABBIENDI	00D	OPAL	1990–1995 LEP runs
0.275±0.064	avg	[163] BARATE	98	ALEP	1991–1995 LEP runs

[163] Not independent of BARATE 98 $\Gamma(\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau)/\Gamma_{total}$ and $\Gamma(\tau^- \rightarrow K^- \pi^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ values.

$\Gamma(K^- \pi^+ \pi^- \nu_\tau)/\Gamma_{total}$ $\Gamma_{81}/\Gamma = (0.3431\Gamma_{35}+\Gamma_{82})/\Gamma$

VALUE (%)	DOCUMENT ID
0.38±0.04 OUR FIT Error includes scale factor of 1.6.	

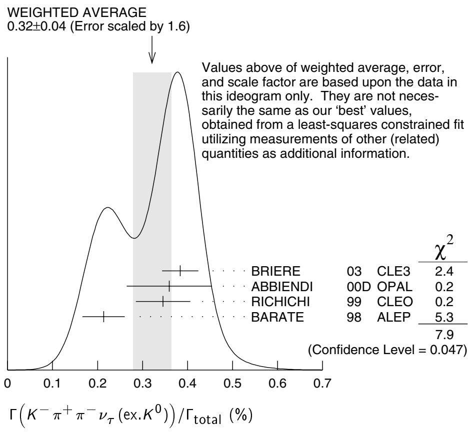
$\Gamma(K^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ Γ_{82}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
0.33 ±0.04 OUR FIT Error includes scale factor of 1.6.						
0.32 ±0.04 OUR AVERAGE Error includes scale factor of 1.6. See the ideogram below.						
0.384±0.014±0.038	f&a	3.5k	[164] BRIERE	03	CLE3	E^{ee}_{cm}= 10.6 GeV
0.360±0.082±0.048	avg		ABBIENDI	00D	OPAL	1990–1995 LEP runs
0.346±0.023±0.056	avg	158	[165] RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV
0.214±0.037±0.029	f&a		BARATE	98	ALEP	1991–1995 LEP runs

[164] 47% correlated with BRIERE 03 $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ and 34% correlated with $\tau^- \rightarrow K^- K^+ \pi^- \nu_\tau$ because of a common 5% normalization error.

[165] Not independent of RICHICHI 99 $\Gamma(\tau^- \rightarrow K^- h^+ \pi^- \nu_\tau (\text{ex.}K^0))/\Gamma(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))$, $\Gamma(\tau^- \rightarrow K^- K^+ \pi^- \nu_\tau)/\Gamma(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))$ and BALEST 95C $\Gamma(\tau^- \rightarrow h^- h^- h^+ \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ values.



$\Gamma(K^- \rho^0 \nu_\tau \rightarrow K^- \pi^+ \pi^- \nu_\tau)/\Gamma(K^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))$ Γ_{83}/Γ_{82}

VALUE	DOCUMENT ID		TECN	COMMENT
0.48±0.14±0.10	[166] ASNER	00B	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.39±0.14	[167] BARATE	99R	ALEP	1991–1995 LEP runs

[166] ASNER 00B assume $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ (ex. K^0) decays proceed only through $K\rho$ and $K^*\pi$ intermediate states. They assume the resonance structure of $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ (ex. K^0) decays is dominated by $K_1(1270)^-$ and $K_1(1400)^-$ resonances, and assume $B(K_1(1270) \rightarrow K^*(892)\pi) = (16 \pm 5)\%$, $B(K_1(1270) \rightarrow K\rho) = (42 \pm 6)\%$, and $B(K_1(1400) \rightarrow K\rho) = 0$.

[167] BARATE 99R assume $\tau^- \rightarrow K^- \pi^+ \pi^- \nu_\tau$ (ex. K^0) decays proceed only through $K\rho$ and $K^*\pi$ intermediate states. The quoted error is statistical only.

$\Gamma(K^- \pi^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ $\Gamma_{84}/\Gamma = (0.3431\Gamma_{40}+\Gamma_{86}+0.231\Gamma_{119})/\Gamma$

VALUE (units 10^{-4})	DOCUMENT ID
11.8±2.5 OUR FIT	

$\Gamma(K^- \pi^+ \pi^- \pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ $\Gamma_{85}/\Gamma = (\Gamma_{86}+0.231\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
6.5±2.4 OUR FIT					
7.0±2.5 OUR AVERAGE					
7.5±2.6±1.8	avg	[168] RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV
6.1±3.9±1.8	f&a	BARATE	98	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<17	95	ABBIENDI	00D	OPAL	1990–1995 LEP runs

[168] Not independent of RICHICHI 99 $\Gamma(\tau^- \rightarrow K^- h^+ \pi^- \nu_\tau (\text{ex.}K^0))/\Gamma(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))$, $\Gamma(\tau^- \rightarrow K^- K^+ \pi^- \nu_\tau)/\Gamma(\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau (\text{ex.}K^0))$ and BALEST 95C $\Gamma(\tau^- \rightarrow h^- h^- h^+ \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ values.

$\Gamma(K^- \pi^+ \pi^- \pi^0 \nu_\tau (\text{ex.}K^0,\eta))/\Gamma_{total}$ Γ_{86}/Γ

Test of lepton family number conservation.

VALUE (units 10^{-4})	DOCUMENT ID
5.9±2.4 OUR FIT	

$\Gamma(K^- \pi^+ K^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ Γ_{87}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	95	BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^- K^+ \pi^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ $\Gamma_{88}/\Gamma = (\Gamma_{89}+\Gamma_{90})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
0.197±0.018 OUR FIT Error includes scale factor of 1.1.						
0.203±0.031 OUR AVERAGE						
0.159±0.053±0.020	f&a		ABBIENDI	00D	OPAL	1990–1995 LEP runs
0.238±0.042	avg		[169] BARATE	98	ALEP	1991–1995 LEP runs
$0.15^{+0.09}_{-0.07}\pm0.03$	f&a	4	[170] BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

[169] Not independent of BARATE 98 $\Gamma(\tau^- \rightarrow K^- K^+ \pi^- \nu_\tau)/\Gamma_{total}$ and $\Gamma(\tau^- \rightarrow K^- K^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ values.

[170] We multiply 0.15% by 0.20, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$\Gamma(K^- K^+ \pi^- \nu_\tau)/\Gamma_{total}$ Γ_{89}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
0.155±0.007 OUR FIT						
0.154±0.009 OUR AVERAGE						
0.155±0.006±0.009	f&a	932	[171] BRIERE	03	CLE3	E^{ee}_{cm}= 10.6 GeV
0.087±0.056±0.040	avg		ABBIENDI	00D	OPAL	1990–1995 LEP runs
0.145±0.013±0.028	avg	2.3k	[172] RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV
0.163±0.021±0.017	f&a		BARATE	98	ALEP	1991–1995 LEP runs
$0.22\ ^{+0.17}_{-0.11}$ ±0.05	f&a	9	[173] MILLS	85	DLCO	E^{ee}_{cm}= 29 GeV

[171] 71% correlated with BRIERE 03 $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and 34% correlated with $\tau \to K^-\pi^+\pi^-\nu_\tau$ because of a common 5% normalization error.

[172] Not independent of RICHICHI 99 $\Gamma(\tau^- \to K^- K^+ \pi^- \nu_\tau)/\Gamma(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0))$ and BALEST 95C $\Gamma(\tau^- \to h^- h^- h^+ \nu_\tau(\text{ex.}K^0))/\Gamma_{total}$ values.

[173] Error correlated with MILLS 85 ($K\pi\pi\pi^0\nu$) value. We multiply 0.22% by 0.23, the relative systematic error quoted by MILLS 85, to obtain obtain the systematic error.

$\Gamma(K^- K^+ \pi^- \nu_\tau)/\Gamma(\pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0))$ $\Gamma_{89}/\Gamma_{58} = \Gamma_{89}/(\Gamma_{60}+0.0221\Gamma_{137})$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.69±0.08 OUR FIT Error includes scale factor of 1.1.					
1.60±0.15±0.30	2.3k	RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(K^- K^+ \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ Γ_{90}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (units 10^{-4})		CL%	EVTS	DOCUMENT ID		TECN	COMMENT
4.2±1.6 OUR FIT Error includes scale factor of 1.1.							
4.4±1.8 OUR AVERAGE Error includes scale factor of 1.1.							
3.3±1.8±0.7	avg		158	[174] RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV
7.5±2.9±1.5	f&a			BARATE	98	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<27		95		ABBIENDI	00D	OPAL	1990–1995 LEP runs

[174] Not independent of RICHICHI 99 $\Gamma(\tau^- \to K^- K^+ \pi^- \nu_\tau)/\Gamma(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau(\text{ex.}K^0))$ and BALEST 95C $\Gamma(\tau^- \to h^- h^- h^+ \nu_\tau(\text{ex.}K^0))/\Gamma_{total}$ values.

$\Gamma(K^- K^+ \pi^- \pi^0 \nu_\tau)/\Gamma(\pi^-\pi^+\pi^-\pi^0\nu_\tau(\text{ex.}K^0))$ $\Gamma_{90}/\Gamma_{67} = \Gamma_{90}/(\Gamma_{68}+0.888\Gamma_{137}+0.0221\Gamma_{138})$

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
1.0 ±0.4 OUR FIT Error includes scale factor of 1.1.					
0.79±0.44±0.16	158	[175] RICHICHI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

[175] RICHICHI 99 also quote a 95%CL upper limit of 0.0157 for this measurement.

$\Gamma(K^- K^+ K^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ Γ_{91}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.21	95	BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(K^- K^+ K^- \nu_\tau)/\Gamma_{total}$ Γ_{92}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.7\times10^{-5}$	90	BRIERE	03	CLE3	E^{ee}_{cm}= 10.6 GeV
$<1.9\times10^{-4}$	90	BARATE	98	ALEP	1991–1995 LEP runs

$\Gamma(\pi^- K^+ \pi^- \geq 0 \text{ neut. } \nu_\tau)/\Gamma_{total}$ Γ_{93}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.25	95	BAUER	94	TPC	E^{ee}_{cm}= 29 GeV

$\Gamma(e^- e^- e^+ \overline{\nu}_e \nu_\tau)/\Gamma_{total}$ Γ_{94}/Γ

VALUE (units 10^{-5})	EVTS	DOCUMENT ID		TECN	COMMENT
2.8±1.4±0.4	5	ALAM	96	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^- e^- e^+ \overline{\nu}_\mu \nu_\tau)/\Gamma_{total}$ Γ_{95}/Γ

VALUE (units 10^{-5})	CL%	DOCUMENT ID		TECN	COMMENT
<3.6	90	ALAM	96	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(3h^- 2h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{ex. } K^0_S \to \pi^-\pi^+)(\text{"5-prong"}))/\Gamma_{total}$ Γ_{96}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average. $\Gamma_{96}/\Gamma = (\Gamma_{97}+\Gamma_{98})/\Gamma$

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
0.100±0.006 OUR FIT						
0.111±0.008 OUR AVERAGE Error includes scale factor of 1.1.						
0.115±0.013±0.006	f&a	112	[176] ABREU	01M	DLPH	1992–1995 LEP runs
0.170±0.022±0.026	f&a		[177] ACHARD	01D	L3	1992–1995 LEP runs
0.119±0.013±0.008	avg	119	[178] ACKERSTAFF	99E	OPAL	1991–1995 LEP runs
0.097±0.005±0.011	f&a	419	GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV
0.102±0.029	f&a	13	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •						
0.26 ±0.06 ±0.05			ACTON	92H	OPAL	E^{ee}_{cm}= 88.2–94.2 GeV
$0.10\ ^{+0.05}_{-0.04}$ ±0.03			DECAMP	92C	ALEP	1989–1990 LEP runs
0.16 ±0.13 ±0.04			BEHREND	89B	CELL	E^{ee}_{cm}= 14–47 GeV
0.3 ±0.1 ±0.2			BARTEL	85F	JADE	E^{ee}_{cm}= 34.6 GeV
0.13 ±0.04		10	BELTRAMI	85	HRS	Repl. by BYLSMA 87
0.16 ±0.08 ±0.04		4	BURCHAT	85	MRK2	E^{ee}_{cm}= 29 GeV
1.0 ±0.4		10	BEHREND	82	CELL	Repl. by BEHREND 89B

[176] The correlation coefficients between this measurement and the ABREU 01M measurements of B($\tau \to$ 1-prong) and B($\tau \to$ 3-prong) are −0.08 and −0.08 respectively.

[177] The correlation coefficients between this measurement and the ACHARD 01D measurements of B($\tau \to$ "1-prong") and B($\tau \to$ "3-prong") are −0.082 and −0.19 respectively.

[178] Not independent of ACKERSTAFF 99E B($\tau^- \to 3h^- 2h^+ \nu_\tau$(ex. K^0)) and B($\tau^- \to 3h^- 2h^+ \pi^0 \nu_\tau$(ex. K^0)) measurements.

$\Gamma(3h^- 2h^+ \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ Γ_{97}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.082±0.006 OUR FIT					
0.076±0.007 OUR AVERAGE					
0.091±0.014±0.006	97	ACKERSTAFF	99E	OPAL	1991–1995 LEP runs
0.080±0.011±0.013	58	BUSKULIC	96	ALEP	LEP 1991–1993 data
0.077±0.005±0.009	295	GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV
0.064±0.023±0.01	12	ALBRECHT	88B	ARG	E^{ee}_{cm}= 10 GeV
0.051±0.020	7	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.067±0.030	5	[179] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[179] The error quoted is statistical only.

$\Gamma(3h^- 2h^+ \pi^0 \nu_\tau (\text{ex.}K^0))/\Gamma_{total}$ Γ_{98}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.0181±0.0027 OUR FIT					
0.0172±0.0027 OUR AVERAGE					
0.017 ±0.002 ±0.002	231	ANASTASSOV	01	CLEO	E^{ee}_{cm}= 10.6 GeV
0.027 ±0.018 ±0.009	23	ACKERSTAFF	99E	OPAL	1991–1995 LEP runs
0.018 ±0.007 ±0.012	18	BUSKULIC	96	ALEP	LEP 1991–1993 data
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.019 ±0.004 ±0.004	31	GIBAUT	94B	CLEO	Repl. by ANASTASSOV 01
0.051 ±0.022	6	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV
0.067 ±0.030	5	[180] BELTRAMI	85	HRS	Repl. by BYLSMA 87

[180] The error quoted is statistical only.

$\Gamma(3h^- 2h^+ 2\pi^0 \nu_\tau)/\Gamma_{total}$ Γ_{99}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.011	90	GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma((5\pi)^- \nu_\tau)/\Gamma_{total}$ Γ_{100}/Γ

$\Gamma_{100}/\Gamma = (\Gamma_{28}+\Gamma_{45}+\Gamma_{74}+\Gamma_{97}+0.553\Gamma_{117}+0.888\Gamma_{138})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		DOCUMENT ID		TECN	COMMENT
0.80±0.07 OUR FIT					
0.61±0.06±0.08	**avg**	[181] GIBAUT	94B	CLEO	E^{ee}_{cm}= 10.6 GeV

[181] Not independent of GIBAUT 94B B($3h^- 2h^+ \nu_\tau$), PROCARIO 93 B($h^- 4\pi^0 \nu_\tau$), and BORTOLETTO 93 B($2h^- h^+ 2\pi^0 \nu_\tau$)/B("3prong") measurements. Result is corrected for η contributions.

$\Gamma(4h^- 3h^+ \geq 0 \text{ neutrals } \nu_\tau (\text{"7-prong"}))/\Gamma_{total}$ Γ_{101}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.4\times10^{-6}$	90	EDWARDS	97B	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.8\times10^{-5}$	95	ACKERSTAFF	97J	OPAL	1990–1995 LEP runs
$<2.9\times10^{-4}$	90	BYLSMA	87	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(X^-(S{=}-1)\nu_\tau)/\Gamma_{\rm total}$

$\Gamma_{102}/\Gamma = (\Gamma_{10}+\Gamma_{15}+\Gamma_{22}+\Gamma_{26}+\Gamma_{33}+\Gamma_{38}+\Gamma_{82}+\Gamma_{86}+\Gamma_{119})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

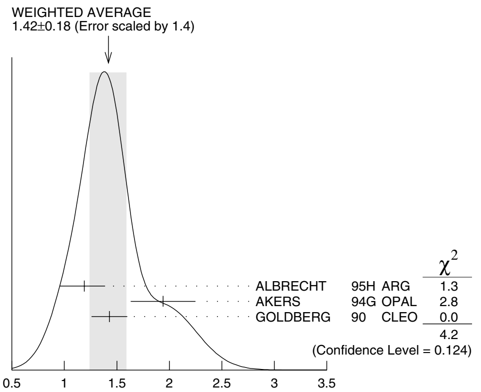
VALUE (%)		DOCUMENT ID	TECN	COMMENT
2.91±0.08 OUR FIT		Error includes scale factor of 1.1.		
2.87±0.12	avg	[182] BARATE 99R	ALEP	1991–1995 LEP runs

[182] BARATE 99R perform a combined analysis of all ALEPH LEP1 data on τ branching fraction measurements for decay modes having total strangeness equal to -1.

$\Gamma(K^*(892)^- \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\rm total}$ — Γ_{103}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
1.42±0.18 OUR AVERAGE		Error includes scale factor of 1.4. See the ideogram below.		
$1.19\pm0.15^{+0.13}_{-0.18}$	104	ALBRECHT 95H	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
1.94±0.27±0.15	74	[183] AKERS 94G	OPAL	$E^{ee}_{\rm cm}$= 88–94 GeV
1.43±0.11±0.13	475	[184] GOLDBERG 90	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.9 GeV

[183] AKERS 94G reject events in which a K^0_S accompanies the $K^*(892)^-$. We do not correct for them.
[184] GOLDBERG 90 estimates that 10% of observed $K^*(892)$ are accompanied by a π^0.



$\Gamma(K^*(892)^- \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma_{\rm total}$ — Γ_{103}/Γ

$\Gamma(K^*(892)^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{104}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
1.29 ±0.05 OUR AVERAGE				
1.326±0.063		BARATE 99R	ALEP	1991–1995 LEP runs
1.11 ±0.12		[185] COAN 96	CLEO	$E^{ee}_{\rm cm}\approx$ 10.6 GeV
1.42 ±0.22 ±0.09		[186] ACCIARRI 95F	L3	1991–1993 LEP runs
$1.23\pm0.21^{+0.11}_{-0.21}$	54	[187] ALBRECHT 88L	ARG	$E^{ee}_{\rm cm}$= 10 GeV
1.9 ±0.3 ±0.4	44	[188] TSCHIRHART 88	HRS	$E^{ee}_{\rm cm}$= 29 GeV
1.5 ±0.4 ±0.4	15	[189] AIHARA 87C	TPC	$E^{ee}_{\rm cm}$= 29 GeV
1.3 ±0.3 ±0.3	31	YELTON 86	MRK2	$E^{ee}_{\rm cm}$= 29 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.39 ±0.09 ±0.10		[190] BUSKULIC 96	ALEP	Repl. by BARATE 99R
1.45 ±0.13 ±0.11	273	[191] BUSKULIC 94F	ALEP	Repl. by BUSKULIC 96
1.7 ±0.7	11	DORFAN 81	MRK2	$E^{ee}_{\rm cm}$= 4.2–6.7 GeV

[185] Not independent of COAN 96 B($\pi^-\overline{K}^0\nu_\tau$) and BATTLE 94 B($K^-\pi^0\nu_\tau$) measurements. $K\pi$ final states are consistent with and assumed to originate from $K^*(892)^-$ production.
[186] This result is obtained from their B($\pi^-\overline{K}^0\nu_\tau$) assuming all those decays originate in $K^*(892)^-$ decays.
[187] The authors divide by $\Gamma_2/\Gamma = 0.865$ to obtain this result.
[188] Not independent of TSCHIRHART 88 $\Gamma(\tau^- \to h^-\overline{K}^0 \geq 0\text{ neutrals} \geq 0K^0_L\nu_\tau)/\Gamma$(total).
[189] Decay π^- identified in this experiment, is assumed in the others.
[190] Not independent of BUSKULIC 96 B($\pi^-\overline{K}^0\nu_\tau$) and B($K^-\pi^0\nu_\tau$) measurements.
[191] BUSKULIC 94F obtain this result from BUSKULIC 94F B($\overline{K}^0\pi^-\nu_\tau$) and BUSKULIC 94E B($K^-\pi^0\nu_\tau$) assuming all of those decays originate in $K^*(892)^-$ decays.

$\Gamma(K^*(892)^-\nu_\tau)/\Gamma(\pi^-\pi^0\nu_\tau)$ — Γ_{104}/Γ_{13}

VALUE	DOCUMENT ID	TECN	COMMENT
0.075±0.027	[192] ABREU 94K	DLPH	LEP 1992 Z data

[192] ABREU 94K quote B($\tau^-\to K^*(892)^-\nu_\tau$)B($K^*(892)^-\to K^-\pi^0$)/B($\tau^-\to\rho^-\nu_\tau$) $= 0.025\pm0.009$. We divide by B($K^*(892)^-\to K^-\pi^0$) $= 0.333$ to obtain this result.

$\Gamma(K^*(892)^0K^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{\rm total}$ — Γ_{105}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.32±0.08±0.12	119	GOLDBERG 90	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.9 GeV

$\Gamma(K^*(892)^0K^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{106}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.21 ±0.04 OUR AVERAGE				
0.213±0.048		[193] BARATE 98	ALEP	1991–1995 LEP runs
0.20 ±0.05 ±0.04	47	ALBRECHT 95H	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[193] BARATE 98 measure the $K^-(\rho^0\to\pi^+\pi^-)$ fraction in $\tau^-\to K^-\pi^+\pi^-\nu_\tau$ decays to be (35 ± 11)% and derive this result from their measurement of $\Gamma(\tau^-\to K^-\pi^+\pi^-\nu_\tau)/\Gamma_{\rm total}$ assuming the intermediate states are all $K^-\rho$ and $K^-K^*(892)^0$.

$\Gamma(\overline{K}^*(892)^0\pi^- \geq 0\text{ neutrals }\nu_\tau)/\Gamma_{\rm total}$ — Γ_{107}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.38±0.11±0.13	105	GOLDBERG 90	CLEO	$E^{ee}_{\rm cm}$= 9.4–10.9 GeV

$\Gamma(\overline{K}^*(892)^0\pi^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{108}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.22 ±0.05 OUR AVERAGE				
0.209±0.058		[194] BARATE 98	ALEP	1991–1995 LEP runs
0.25 ±0.10 ±0.05	27	ALBRECHT 95H	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[194] BARATE 98 measure the $K^-K^*(892)^0$ fraction in $\tau^-\to K^-K^+\pi^-\nu_\tau$ decays to be (87 ± 13)% and derive this result from their measurement of $\Gamma(\tau^-\to K^-K^+\pi^-\nu_\tau)/\Gamma_{\rm total}$.

$\Gamma((\overline{K}^*(892)\pi)^-\nu_\tau \to \pi^-\overline{K}^0\pi^0\nu_\tau)/\Gamma_{\rm total}$ — Γ_{109}/Γ

VALUE (%)	DOCUMENT ID	TECN	COMMENT
0.10 ±0.04 OUR AVERAGE			
0.097±0.044±0.036	[195] BARATE 99K	ALEP	1991–1995 LEP runs
0.106±0.037±0.032	[196] BARATE 98E	ALEP	1991–1995 LEP runs

[195] BARATE 99K measure K^0's by detecting K^0_L's in their hadron calorimeter. They determine the $\overline{K}^0\rho^-$ fraction in $\tau^-\to\pi^-\overline{K}^0\pi^0\nu_\tau$ decays to be $(0.72\pm0.12\pm0.10)$ and multiply their B($\pi^-\overline{K}^0\pi^0\nu_\tau$) measurement by one minus this fraction to obtain the quoted result.
[196] BARATE 98E reconstruct K^0's using $K^0_S\to\pi^+\pi^-$ decays. They determine the $\overline{K}^0\rho^-$ fraction in $\tau^-\to\pi^-\overline{K}^0\pi^0\nu_\tau$ decays to be $(0.64\pm0.09\pm0.10)$ and multiply their B($\pi^-\overline{K}^0\pi^0\nu_\tau$) measurement by one minus this fraction to obtain the quoted result.

$\Gamma(K_1(1270)^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{110}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.47±0.11 OUR AVERAGE				
0.48±0.11		BARATE 99R	ALEP	1991–1995 LEP runs
$0.41^{+0.41}_{-0.35}\pm0.10$	5	[197] BAUER 94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[197] We multiply 0.41% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$\Gamma(K_1(1400)^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{111}/Γ

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
0.17±0.26 OUR AVERAGE		Error includes scale factor of 1.7.		
0.05±0.17		BARATE 99R	ALEP	1991–1995 LEP runs
$0.76^{+0.40}_{-0.33}\pm0.20$	11	[198] BAUER 94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[198] We multiply 0.76% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error.

$[\Gamma(K_1(1270)^-\nu_\tau)+\Gamma(K_1(1400)^-\nu_\tau)]/\Gamma_{\rm total}$ — $(\Gamma_{110}+\Gamma_{111})/\Gamma$

VALUE (%)	EVTS	DOCUMENT ID	TECN	COMMENT
$\mathbf{1.17^{+0.41}_{-0.37}\pm0.29}$	16	[199] BAUER 94	TPC	$E^{ee}_{\rm cm}$= 29 GeV

[199] We multiply 1.17% by 0.25, the relative systematic error quoted by BAUER 94, to obtain the systematic error. Not independent of BAUER 94 B($K_1(1270)^-\nu_\tau$) and BAUER 94 B($K_1(1400)^-\nu_\tau$) measurements.

$\Gamma(K_1(1270)^-\nu_\tau)/[\Gamma(K_1(1270)^-\nu_\tau)+\Gamma(K_1(1400)^-\nu_\tau)]$ — $\Gamma_{110}/(\Gamma_{110}+\Gamma_{111})$

VALUE	DOCUMENT ID	TECN	COMMENT
0.69±0.15 OUR AVERAGE			
0.71±0.16±0.11	[200] ABBIENDI 00D	OPAL	1990–1995 LEP runs
0.66±0.19±0.13	[201] ASNER 00B	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

[200] ABBIENDI 00D assume the resonance structure of $\tau^-\to K^-\pi^+\pi^-\nu_\tau$ decays is dominated by the $K_1(1270)^-$ and $K_1(1400)^-$ resonances.
[201] ASNER 00B assume the resonance structure of $\tau^-\to K^-\pi^+\pi^-\nu_\tau$ (ex. K^0) decays is dominated by $K_1(1270)^-$ and $K_1(1400)^-$ resonances.

$\Gamma(K^*(1410)^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{112}/Γ

VALUE (units 10^{-3})	DOCUMENT ID	TECN	COMMENT
$\mathbf{1.5^{+1.4}_{-1.0}}$	BARATE 99R	ALEP	1991–1995 LEP runs

$\Gamma(K^*_0(1430)^-\nu_\tau)/\Gamma_{\rm total}$ — Γ_{113}/Γ

VALUE (units 10^{-3})	CL%	DOCUMENT ID	TECN	COMMENT
<0.5	95	BARATE 99R	ALEP	1991–1995 LEP runs

$\Gamma(K_2^*(1430)^- \nu_\tau)/\Gamma_{total}$ — Γ_{114}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<0.3	95		TSCHIRHART	88	HRS	E^{ee}_{cm}= 29 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<0.33	95		[202] ACCIARRI	95F	L3	1991–1993 LEP runs
<0.9	95	0	DORFAN	81	MRK2	E^{ee}_{cm}= 4.2–6.7 GeV

[202] ACCIARRI 95F quote $B(\tau^- \to K^*(1430)^- \to \pi^- \overline{K}^0 \nu_\tau) < 0.11\%$. We divide by $B(K^*(1430)^- \to \pi^- \overline{K}^0) = 0.33$ to obtain the limit shown.

$\Gamma(a_0(980)^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total} \times B(a_0(980) \to K^0 K^-)$ — $\Gamma_{115}/\Gamma \times B$

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
<2.8	90	GOLDBERG	90	CLEO	E^{ee}_{cm}= 9.4–10.9 GeV

$\Gamma(\eta \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{116}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
< 1.4	95	0	BARTELT	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 6.2	95		BUSKULIC	97C	ALEP	1991–1994 LEP runs
< 3.4	95		ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
< 90	95		ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
<140	90		BEHREND	88	CELL	E^{ee}_{cm}= 14–46.8 GeV
<180	95		BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV
<250	90	0	COFFMAN	87	MRK3	E^{ee}_{cm}= 3.77 GeV
510 ±100±120		65	DERRICK	87	HRS	E^{ee}_{cm}= 29 GeV
<100	95		GAN	87B	MRK2	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{117}/Γ

VALUE (%)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
0.174±0.024 OUR FIT						
0.173±0.024 OUR AVERAGE						
0.18 ±0.04 ±0.02			BUSKULIC	97C	ALEP	1991–1994 LEP runs
0.17 ±0.02 ±0.02		125	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<1.10	95		ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV
<2.10	95		BARINGER	87	CLEO	E^{ee}_{cm}= 10.5 GeV
$4.20\ ^{+0.70}_{-1.20}$ ±1.60			[203] GAN	87	MRK2	E^{ee}_{cm}= 29 GeV

[203] Highly correlated with GAN 87 $\Gamma(\pi^- 3\pi^0 \nu_\tau)/\Gamma(\text{total})$ value.

$\Gamma(\eta \pi^- \pi^0 \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{118}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.5±0.5		30	[204] ANASTASSOV	01	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

1.4±0.6±0.3		15	[205] BERGFELD	97	CLEO	Repl. by ANASTASSOV 01
< 4.3	95		ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
<120	95		ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

[204] Weighted average of BERGFELD 97 and ANASTASSOV 01 value of $(1.5 \pm 0.6 \pm 0.3) \times 10^{-4}$ obtained using η's reconstructed from $\eta \to \pi^+ \pi^- \pi^0$ decays.

[205] BERGFELD 97 reconstruct η's using $\eta \to \gamma\gamma$ decays.

$\Gamma(\eta K^- \nu_\tau)/\Gamma_{total}$ — Γ_{119}/Γ

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
2.7±0.6 OUR FIT						
2.7±0.6 OUR AVERAGE						
$2.9^{+1.3}_{-1.2}$±0.7			BUSKULIC	97C	ALEP	1991–1994 LEP runs
2.6±0.5±0.5		85	BARTELT	96	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<4.7	95		ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(\eta K^*(892)^- \nu_\tau)/\Gamma_{total}$ — Γ_{120}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.90±0.80±0.42	25	BISHAI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\eta K^- \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{121}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.77±0.56±0.71	36	BISHAI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\eta \overline{K}^0 \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{122}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.20±0.70±0.22	15	[206] BISHAI	99	CLEO	E^{ee}_{cm}= 10.6 GeV

[206] We multiply the BISHAI 99 measurement $B(\tau^- \to \eta K^0_S \pi^- \nu_\tau) = (1.10 \pm 0.35 \pm 0.11) \times 10^{-4}$ by 2 to obtain the listed value.

$\Gamma(\eta \pi^+ \pi^- \pi^- \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{123}/Γ

VALUE (%)	CL%	DOCUMENT ID		TECN	COMMENT
<0.3	90	ABACHI	87B	HRS	E^{ee}_{cm}= 29 GeV

$\Gamma(\eta \pi^- \pi^+ \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{124}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
2.3±0.5	170	[207] ANASTASSOV	01	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

$3.4^{+0.6}_{-0.5}$±0.6	89	[208] BERGFELD	97	CLEO	Repl. by ANASTASSOV 01

[207] Weighted average of BERGFELD 97 and ANASTASSOV 01 measurements using η's reconstructed from $\eta \to \pi^+ \pi^- \pi^0$ and $\eta \to 3\pi^0$ decays.

[208] BERGFELD 97 reconstruct η's using $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$ decays.

$\Gamma(\eta a_1(1260)^- \nu_\tau \to \eta \pi^- \rho^0 \nu_\tau)/\Gamma_{total}$ — Γ_{125}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<3.9 × 10⁻⁴	90	BERGFELD	97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\eta \eta \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{126}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1	95	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<83	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\eta \eta \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{127}/Γ

VALUE (units 10^{-4})	CL%	DOCUMENT ID		TECN	COMMENT
< 2.0	95	ARTUSO	92	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<90	95	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(\eta'(958) \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{128}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7.4 × 10⁻⁵	90	BERGFELD	97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\eta'(958) \pi^- \pi^0 \nu_\tau)/\Gamma_{total}$ — Γ_{129}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<8.0 × 10⁻⁵	90	BERGFELD	97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\phi \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{130}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.0 × 10⁻⁴	90	[209] AVERY	97	CLEO	E^{ee}_{cm}= 10.6 GeV

• • • We do not use the following data for averages, fits, limits, etc. • • •

<3.5 × 10⁻⁴	90	ALBRECHT	95H	ARG	E^{ee}_{cm}= 9.4–10.6 GeV

[209] AVERY 97 limit varies from $(1.2–2.0) \times 10^{-4}$ depending on decay model assumptions.

$\Gamma(\phi K^- \nu_\tau)/\Gamma_{total}$ — Γ_{131}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<6.7 × 10⁻⁵	90	[210] AVERY	97	CLEO	E^{ee}_{cm}= 10.6 GeV

[210] AVERY 97 limit varies from $(5.4–6.7) \times 10^{-5}$ depending on decay model assumptions.

$\Gamma(f_1(1285) \pi^- \nu_\tau)/\Gamma_{total}$ — Γ_{132}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
$5.8^{+1.4}_{-1.3}$±1.8	54	BERGFELD	97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(f_1(1285) \pi^- \nu_\tau \to \eta \pi^- \pi^+ \pi^- \nu_\tau)/\Gamma(\eta \pi^- \pi^+ \pi^- \nu_\tau)$ — $\Gamma_{133}/\Gamma_{124}$

VALUE	DOCUMENT ID		TECN	COMMENT
0.55±0.14	BERGFELD	97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\pi(1300)^- \nu_\tau \to (\rho\pi)^- \nu_\tau \to (3\pi)^- \nu_\tau)/\Gamma_{total}$ — Γ_{134}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.0 × 10⁻⁴	90	ASNER	00	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\pi(1300)^- \nu_\tau \to ((\pi\pi)_{S-wave} \pi)^- \nu_\tau \to (3\pi)^- \nu_\tau)/\Gamma_{total}$ — Γ_{135}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<1.9 × 10⁻⁴	90	ASNER	00	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(h^- \omega \geq 0 \text{ neutrals } \nu_\tau)/\Gamma_{total}$ — Γ_{136}/Γ

$\Gamma_{136}/\Gamma = (\Gamma_{137}+\Gamma_{138})/\Gamma$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
2.38±0.08 OUR FIT						
1.65±0.3 ±0.2	**avg**	1513	ALBRECHT	88M	ARG	$E^{ee}_{cm} \approx$ 10 GeV

$\Gamma(h^-\omega\nu_\tau)/\Gamma_{total}$ — Γ_{137}/Γ

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE (%)		EVTS	DOCUMENT ID		TECN	COMMENT
1.94±0.07 OUR FIT						
1.92±0.07 OUR AVERAGE						
1.91±0.07±0.06	f&a	5803	BUSKULIC	97C	ALEP	1991–1994 LEP runs
1.95±0.07±0.11	avg	2223	[211] BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
1.60±0.27±0.41	f&a	139	BARINGER	87	CLEO	$E^{ee}_{cm} =$ 10.5 GeV

[211] Not independent of BALEST 95C B($\tau^- \rightarrow h^-\omega\nu_\tau$)/B($\tau^- \rightarrow h^-h^-h^+\pi^0\nu_\tau$) value.

$\Gamma(h^-\omega\nu_\tau)/\Gamma(h^-h^-h^+\pi^0\nu_\tau\,(\text{ex.}K^0))$ — Γ_{137}/Γ_{64}

$\Gamma_{137}/\Gamma_{64} = \Gamma_{137}/(\Gamma_{68}+\Gamma_{86}+\Gamma_{90}+0.231\Gamma_{119}+0.888\Gamma_{137}+0.0221\Gamma_{138})$

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.446±0.015 OUR FIT					
0.453±0.019 OUR AVERAGE					
0.431±0.033	2350	[212] BUSKULIC	96	ALEP	LEP 1991–1993 data
0.464±0.016±0.017	2223	[213] BALEST	95C	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.37 ±0.05 ±0.02	458	[214] ALBRECHT	91D	ARG	$E^{ee}_{cm} =$ 9.4–10.6 GeV

[212] BUSKULIC 96 quote the fraction of $\tau \rightarrow h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0) decays which originate in a $h^-\omega$ final state = 0.383 ± 0.029. We divide this by the $\omega(782) \rightarrow \pi^+\pi^-\pi^0$ branching fraction (0.888).

[213] BALEST 95C quote the fraction of $\tau^- \rightarrow h^-h^-h^+\pi^0\nu_\tau$ (ex. K^0) decays which originate in a $h^-\omega$ final state equals 0.412 ± 0.014 ± 0.015. We divide this by the $\omega(782) \rightarrow \pi^+\pi^-\pi^0$ branching fraction (0.888).

[214] ALBRECHT 91D quote the fraction of $\tau^- \rightarrow h^-h^-h^+\pi^0\nu_\tau$ decays which originate in a $\pi^-\omega$ final state equals 0.33 ± 0.04 ± 0.02. We divide this by the $\omega(782) \rightarrow \pi^+\pi^-\pi^0$ branching fraction (0.888).

$\Gamma(h^-\omega\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{138}/Γ

VALUE (%)	EVTS	DOCUMENT ID		TECN	COMMENT
0.44±0.05 OUR FIT					
0.43±0.06±0.05	7283	BUSKULIC	97C	ALEP	1991–1994 LEP runs

$\Gamma(h^-\omega 2\pi^0\nu_\tau)/\Gamma_{total}$ — Γ_{139}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.4 ±0.4 ±0.3	53	ANASTASSOV	01	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.89^{+0.74}_{-0.67}\pm0.40$	19	ANDERSON	97	CLEO	Repl. by ANASTASSOV 01

$\Gamma(h^-\omega\pi^0\nu_\tau)/\Gamma(h^-h^-h^+ \geq 0\,\text{neutrals} \geq 0K^0_L\nu_\tau)$ — Γ_{138}/Γ_{52}

$\Gamma_{138}/\Gamma_{52} = \Gamma_{138}/(0.3431\Gamma_{33}+0.3431\Gamma_{35}+0.3431\Gamma_{38}+0.3431\Gamma_{40}+0.4307\Gamma_{45}+0.6861\Gamma_{46}+\Gamma_{60}+\Gamma_{68}+\Gamma_{74}+\Gamma_{75}+\Gamma_{82}+\Gamma_{86}+\Gamma_{89}+\Gamma_{90}+0.285\Gamma_{117}+0.285\Gamma_{119}+0.9101\Gamma_{137}+0.9101\Gamma_{138})$

Data marked "avg" are highly correlated with data appearing elsewhere in the Listings, and are therefore used for the average given below but not in the overall fits. "f&a" marks results used for the fit and the average.

VALUE		EVTS	DOCUMENT ID		TECN	COMMENT
0.0286±0.0031 OUR FIT						
0.028 ±0.003 ±0.003	**avg**	430	[215] BORTOLETTO	93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

[215] Not independent of BORTOLETTO 93 $\Gamma(\tau^- \rightarrow h^-\omega\pi^0\nu_\tau)/\Gamma(\tau^- \rightarrow h^-h^-h^+2\pi^0\nu_\tau(\text{ex.}K^0))$ value.

$\Gamma(h^-\omega\pi^0\nu_\tau)/\Gamma(h^-h^-h^+2\pi^0\nu_\tau\,(\text{ex.}K^0))$ — Γ_{138}/Γ_{73}

$\Gamma_{138}/\Gamma_{73} = \Gamma_{138}/(\Gamma_{74}+0.236\Gamma_{117}+0.888\Gamma_{138})$

VALUE	DOCUMENT ID		TECN	COMMENT
0.81±0.08 OUR FIT				
0.81±0.06±0.06	BORTOLETTO	93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV

$\Gamma(2h^-h^+\omega\nu_\tau)/\Gamma_{total}$ — Γ_{140}/Γ

VALUE (units 10^{-4})	EVTS	DOCUMENT ID		TECN	COMMENT
1.2 ±0.2 ±0.1	110	ANASTASSOV	01	CLEO	$E^{ee}_{cm} =$ 10.6 GeV

$\Gamma(e^-\gamma)/\Gamma_{total}$ — Γ_{141}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<2.7 × 10^{-6}	90	EDWARDS	97	CLEO	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.1 \times 10^{-4}$	90	ABREU	95U	DLPH	1990–1993 LEP runs
$<1.2 \times 10^{-4}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$<2.0 \times 10^{-4}$	90	KEH	88	CBAL	$E^{ee}_{cm} =$ 10 GeV
$<6.4 \times 10^{-4}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

$\Gamma(\mu^-\gamma)/\Gamma_{total}$ — Γ_{142}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 1.1 × 10^{-6}	90	AHMED	00	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 3.0 \times 10^{-6}$	90	EDWARDS	97	CLEO	
$< 6.2 \times 10^{-5}$	90	ABREU	95U	DLPH	1990–1993 LEP runs
$< 0.42 \times 10^{-5}$	90	BEAN	93	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
$< 3.4 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$<55 \times 10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

$\Gamma(e^-\pi^0)/\Gamma_{total}$ — Γ_{143}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 3.7 × 10^{-6}	90	BONVICINI	97	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 17 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$< 14 \times 10^{-5}$	90	KEH	88	CBAL	$E^{ee}_{cm} =$ 10 GeV
$<210 \times 10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

$\Gamma(\mu^-\pi^0)/\Gamma_{total}$ — Γ_{144}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 4.0 × 10^{-6}	90	BONVICINI	97	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 4.4 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$<82 \times 10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

$\Gamma(e^-K^0_S)/\Gamma_{total}$ — Γ_{145}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.1 × 10^{-7}	90	CHEN	02C	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.3 \times 10^{-3}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

$\Gamma(\mu^-K^0_S)/\Gamma_{total}$ — Γ_{146}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.5 × 10^{-7}	90	CHEN	02C	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.0 \times 10^{-3}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

$\Gamma(e^-\eta)/\Gamma_{total}$ — Γ_{147}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 8.2 × 10^{-6}	90	BONVICINI	97	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 6.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$<24 \times 10^{-5}$	90	KEH	88	CBAL	$E^{ee}_{cm} =$ 10 GeV

$\Gamma(\mu^-\eta)/\Gamma_{total}$ — Γ_{148}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<9.6 × 10^{-6}	90	BONVICINI	97	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<7.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV

$\Gamma(e^-\rho^0)/\Gamma_{total}$ — Γ_{149}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 2.0 × 10^{-6}	90	BLISS	98	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.42 \times 10^{-5}$	90	[216] BARTELT	94	CLEO	Repl. by BLISS 98
$< 1.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$<37 \times 10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

[216] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-\rho^0)/\Gamma_{total}$ — Γ_{150}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
< 6.3 × 10^{-6}	90	BLISS	98	CLEO	$E^{ee}_{cm} =$ 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.57 \times 10^{-5}$	90	[217] BARTELT	94	CLEO	Repl. by BLISS 98
$< 2.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	$E^{ee}_{cm} =$ 10 GeV
$<44 \times 10^{-5}$	90	HAYES	82	MRK2	$E^{ee}_{cm} =$ 3.8–6.8 GeV

[217] BARTELT 94 assume phase space decays.

$\Gamma(e^- K^*(892)^0)/\Gamma_{total}$ — Γ_{151}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<5.1 × 10⁻⁶	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.63 \times 10^{-5}$	90	[218] BARTELT	94	CLEO	Repl. by BLISS 98
$<3.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV

[218] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- K^*(892)^0)/\Gamma_{total}$ — Γ_{152}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.5 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.94 \times 10^{-5}$	90	[219] BARTELT	94	CLEO	Repl. by BLISS 98
$<4.5 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV

[219] BARTELT 94 assume phase space decays.

$\Gamma(e^- \overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{153}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.4 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1.1 \times 10^{-5}$	90	[220] BARTELT	94	CLEO	Repl. by BLISS 98

[220] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \overline{K}^*(892)^0)/\Gamma_{total}$ — Γ_{154}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.5 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.87 \times 10^{-5}$	90	[221] BARTELT	94	CLEO	Repl. by BLISS 98

[221] BARTELT 94 assume phase space decays.

$\Gamma(e^- \phi)/\Gamma_{total}$ — Γ_{155}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.9 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^- \phi)/\Gamma_{total}$ — Γ_{156}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<7.0 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^- e^+ e^-)/\Gamma_{total}$ — Γ_{157}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 2.9 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.33 \times 10^{-5}$	90	[222] BARTELT	94	CLEO	Repl. by BLISS 98
$< 1.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$< 2.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
$<40 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

[222] BARTELT 94 assume phase space decays.

$\Gamma(e^- \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{158}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 1.8 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.36 \times 10^{-5}$	90	[223] BARTELT	94	CLEO	Repl. by BLISS 98
$< 1.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$< 2.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
$<33 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

[223] BARTELT 94 assume phase space decays.

$\Gamma(e^+ \mu^- \mu^-)/\Gamma_{total}$ — Γ_{159}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.5 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.35 \times 10^{-5}$	90	[224] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<1.6 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[224] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- e^+ e^-)/\Gamma_{total}$ — Γ_{160}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 1.7 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.34 \times 10^{-5}$	90	[225] BARTELT	94	CLEO	Repl. by BLISS 98
$< 1.4 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$< 2.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
$<44 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

[225] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+ e^- e^-)/\Gamma_{total}$ — Γ_{161}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.5 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.34 \times 10^{-5}$	90	[226] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.4 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<1.6 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[226] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \mu^+ \mu^-)/\Gamma_{total}$ — Γ_{162}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$< 1.9 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 0.43 \times 10^{-5}$	90	[227] BARTELT	94	CLEO	Repl. by BLISS 98
$< 1.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$< 1.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9
$<49 \times 10^{-5}$	90	HAYES	82	MRK2	E^{ee}_{cm}= 3.8–6.8 GeV

[227] BARTELT 94 assume phase space decays.

$\Gamma(e^- \pi^+ \pi^-)/\Gamma_{total}$ — Γ_{163}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<2.2 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.44 \times 10^{-5}$	90	[228] BARTELT	94	CLEO	Repl. by BLISS 98
$<2.7 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<6.0 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[228] BARTELT 94 assume phase space decays.

$\Gamma(e^+ \pi^- \pi^-)/\Gamma_{total}$ — Γ_{164}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<1.9 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.44 \times 10^{-5}$	90	[229] BARTELT	94	CLEO	Repl. by BLISS 98
$<1.8 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<1.7 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[229] BARTELT 94 assume phase space decays.

$\Gamma(\mu^- \pi^+ \pi^-)/\Gamma_{total}$ — Γ_{165}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<8.2 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.74 \times 10^{-5}$	90	[230] BARTELT	94	CLEO	Repl. by BLISS 98
$<3.6 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<3.9 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[230] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+ \pi^- \pi^-)/\Gamma_{total}$ — Γ_{166}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<3.4 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.69 \times 10^{-5}$	90	[231] BARTELT	94	CLEO	Repl. by BLISS 98
$<6.3 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<3.9 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[231] BARTELT 94 assume phase space decays.

$\Gamma(e^- \pi^+ K^-)/\Gamma_{total}$ — Γ_{167}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
$<6.4 \times 10^{-6}$	90	BLISS	98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<0.77 \times 10^{-5}$	90	[232] BARTELT	94	CLEO	Repl. by BLISS 98
$<2.9 \times 10^{-5}$	90	ALBRECHT	92K	ARG	E^{ee}_{cm}= 10 GeV
$<5.8 \times 10^{-5}$	90	BOWCOCK	90	CLEO	E^{ee}_{cm}= 10.4–10.9

[232] BARTELT 94 assume phase space decays.

$\Gamma(e^-\pi^-K^+)/\Gamma_{total}$ Γ_{168}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.8 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<0.46 \times 10^{-5}$	90	[233] BARTELT 94	CLEO	Repl. by BLISS 98
$<5.8 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E^{ee}_{cm}= 10.4–10.9

[233] BARTELT 94 assume phase space decays.

$\Gamma(e^+\pi^-K^-)/\Gamma_{total}$ Γ_{169}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.1 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<0.45 \times 10^{-5}$	90	[234] BARTELT 94	CLEO	Repl. by BLISS 98
$<2.0 \times 10^{-5}$	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
$<4.9 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E^{ee}_{cm}= 10.4–10.9

[234] BARTELT 94 assume phase space decays.

$\Gamma(e^-K^0_SK^0_S)/\Gamma_{total}$ Γ_{170}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<2.2 $\times 10^{-6}$	90	CHEN 02C	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^-K^+K^-)/\Gamma_{total}$ Γ_{171}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.0 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^+K^-K^-)/\Gamma_{total}$ Γ_{172}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.8 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^-\pi^+K^-)/\Gamma_{total}$ Γ_{173}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 7.5 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 0.87 \times 10^{-5}$	90	[235] BARTELT 94	CLEO	Repl. by BLISS 98
$<11 \times 10^{-5}$	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
$< 7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E^{ee}_{cm}= 10.4–10.9

[235] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-\pi^-K^+)/\Gamma_{total}$ Γ_{174}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.4 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.5 \times 10^{-5}$	90	[236] BARTELT 94	CLEO	Repl. by BLISS 98
$<7.7 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E^{ee}_{cm}= 10.4–10.9

[236] BARTELT 94 assume phase space decays.

$\Gamma(\mu^+\pi^-K^-)/\Gamma_{total}$ Γ_{175}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<7.0 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2.0 \times 10^{-5}$	90	[237] BARTELT 94	CLEO	Repl. by BLISS 98
$<5.8 \times 10^{-5}$	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV
$<4.0 \times 10^{-5}$	90	BOWCOCK 90	CLEO	E^{ee}_{cm}= 10.4–10.9

[237] BARTELT 94 assume phase space decays.

$\Gamma(\mu^-K^0_SK^0_S)/\Gamma_{total}$ Γ_{176}/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<3.4 $\times 10^{-6}$	90	CHEN 02C	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^-K^+K^-)/\Gamma_{total}$ Γ_{177}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<15 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^+K^-K^-)/\Gamma_{total}$ Γ_{178}/Γ

Test of lepton number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.0 $\times 10^{-6}$	90	BLISS 98	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^-\pi^0\pi^0)/\Gamma_{total}$ Γ_{179}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<6.5 $\times 10^{-6}$	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^-\pi^0\pi^0)/\Gamma_{total}$ Γ_{180}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<14 $\times 10^{-6}$	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^-\eta\eta)/\Gamma_{total}$ Γ_{181}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<35 $\times 10^{-6}$	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^-\eta\eta)/\Gamma_{total}$ Γ_{182}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<60 $\times 10^{-6}$	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^-\pi^0\eta)/\Gamma_{total}$ Γ_{183}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<24 $\times 10^{-6}$	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\mu^-\pi^0\eta)/\Gamma_{total}$ Γ_{184}/Γ

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<22 $\times 10^{-6}$	90	BONVICINI 97	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\overline{p}\gamma)/\Gamma_{total}$ Γ_{185}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 3.5 $\times 10^{-6}$	90	GODANG 99	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<29 \times 10^{-5}$	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV

$\Gamma(\overline{p}\pi^0)/\Gamma_{total}$ Γ_{186}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<15 $\times 10^{-6}$	90	GODANG 99	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<66 \times 10^{-5}$	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV

$\Gamma(\overline{p}2\pi^0)/\Gamma_{total}$ Γ_{187}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<33 $\times 10^{-6}$	90	GODANG 99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(\overline{p}\eta)/\Gamma_{total}$ Γ_{188}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
< 8.9 $\times 10^{-6}$	90	GODANG 99	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<130 \times 10^{-5}$	90	ALBRECHT 92K	ARG	E^{ee}_{cm}= 10 GeV

$\Gamma(\overline{p}\pi^0\eta)/\Gamma_{total}$ Γ_{189}/Γ

Test of lepton number and baryon number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<27 $\times 10^{-6}$	90	GODANG 99	CLEO	E^{ee}_{cm}= 10.6 GeV

$\Gamma(e^-\text{ light boson})/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ Γ_{190}/Γ_5

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.015	95	[238] ALBRECHT 95G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.018	95	[239] ALBRECHT 90E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
<0.040	95	[240] BALTRUSAIT..85	MRK3	E^{ee}_{cm}= 3.77 GeV

[238] ALBRECHT 95G limit holds for bosons with mass < 0.4 GeV. The limit rises to 0.036 for a mass of 1.0 GeV, then falls to 0.006 at the upper mass limit of 1.6 GeV.

[239] ALBRECHT 90E limit applies for spinless boson with mass < 100 MeV, and rises to 0.050 for mass = 500 MeV.

[240] BALTRUSAITIS 85 limit applies for spinless boson with mass < 100 MeV.

$\Gamma(\mu^-\text{ light boson})/\Gamma(e^-\overline{\nu}_e\nu_\tau)$ Γ_{191}/Γ_5

Test of lepton family number conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.026	95	[241] ALBRECHT 95G	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.033	95	[242] ALBRECHT 90E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
<0.125	95	[243] BALTRUSAIT..85	MRK3	E^{ee}_{cm}= 3.77 GeV

[241] ALBRECHT 95G limit holds for bosons with mass < 1.3 GeV. The limit rises to 0.034 for a mass of 1.4 GeV, then falls to 0.003 at the upper mass limit of 1.6 GeV.

[242] ALBRECHT 90E limit applies for spinless boson with mass < 100 MeV, and rises to 0.071 for mass = 500 MeV.

[243] BALTRUSAITIS 85 limit applies for spinless boson with mass < 100 MeV.

τ-DECAY PARAMETERS

τ-LEPTON DECAY PARAMETERS

Written April 2002 by A. Stahl (DESY).

The purpose of the measurements of the decay parameters (*i.e.,* Michel parameters) of the τ is to determine the structure (spin and chirality) of the current mediating its decays.

Leptonic Decays: The Michel parameters are extracted from the energy spectrum of the charged daughter lepton $\ell = e, \mu$ in the decays $\tau \to \ell\nu_\ell\nu_\tau$. Ignoring radiative corrections, neglecting terms of order $(m_\ell/m_\tau)^2$ and $(m_\tau/\sqrt{s})^2$, and setting the neutrino masses to zero, the spectrum in the laboratory frame reads

$$\frac{d\Gamma}{dx} = \frac{G_{\tau\ell}^2\ m_\tau^5}{192\ \pi^3} \times$$
$$\left\{ f_0\left(x\right) + \rho f_1\left(x\right) + \eta \frac{m_\ell}{m_\tau} f_2\left(x\right) - P_\tau \left[\xi g_1\left(x\right) + \xi\delta g_2\left(x\right)\right] \right\}\ , \quad (1)$$

with

$$f_0\left(x\right) = 2 - 6\,x^2 + 4\,x^3$$
$$f_1\left(x\right) = -\frac{4}{9} + 4\,x^2 - \frac{32}{9}\,x^3 \qquad g_1\left(x\right) = -\frac{2}{3} + 4\,x - 6\,x^2 + \frac{8}{3}\,x^3$$
$$f_2\left(x\right) = 12\left(1-x\right)^2 \qquad g_2\left(x\right) = \frac{4}{9} - \frac{16}{3}\,x + 12\,x^2 - \frac{64}{9}\,x^3\ .$$

The integrated decay width is given by

$$\Gamma = \frac{G_{\tau\ell}^2\ m_\tau^5}{192\ \pi^3}\left(1 + 4\,\eta\ \frac{m_\ell}{m_\tau}\right)\ . \quad (2)$$

The situation is similar to muon decays $\mu \to e\nu_e\nu_\mu$. The generalized matrix element with the couplings $g_{\varepsilon\mu}^\gamma$ and their relations to the Michel parameters ρ, η, ξ, and δ have been described in the "Note on Muon Decay Parameters". The Standard Model expectations are 3/4, 0, 1, and 3/4, respectively. For more details, see Ref. 1.

Hadronic Decays: In the case of hadronic decays $\tau \to h\nu_\tau$, with $h = \pi$, ρ, or a_1, the ansatz is restricted to purely vectorial currents. The matrix element is

$$\frac{G_{\tau h}}{\sqrt{2}} \sum_{\lambda=R,L} g_\lambda\ \langle\ \overline{\Psi}_\omega(\nu_\tau)\ |\ \gamma^\mu\ |\ \Psi_\lambda(\tau)\ \rangle\quad J_\mu^h \quad (3)$$

with the hadronic current J_μ^h. The neutrino chirality ω is uniquely determined from λ. The spectrum depends only on a single parameter ξ_h

$$\frac{d\Gamma}{d\vec{x}} = f\left(\vec{x}\right) + \xi_h P_\tau g\left(\vec{x}\right)\ , \quad (4)$$

with f and g being channel-dependent functions of the observables $\vec{x}$ (see Ref. 2). The parameter ξ_h is related to the couplings through

$$\xi_h = \left|g_L\right|^2 - \left|g_R\right|^2\ . \quad (5)$$

ξ_h is the negative of the chirality of the τ neutrino in these decays. In the Standard Model, $\xi_h = 1$. Also included are measurements of the neutrino helicity which coincide with ξ_h, if the neutrino is massless (ASNER 00, ACKERSTAFF 97R, AKERS 95P, ALBRECHT 93C, and ALBRECHT 90I).

Combination of Measurements: The individual measurements are combined, taking into account the correlations between the parameters. There is one fit, assuming universality between the two leptonic decays, and between all hadronic decays and a second fit without these assumptions. These are the values labeled 'OUR FIT' in the tables. The measurements show good agreement with the Standard Model. The χ^2 values with respect to the Standard model predictions are 24.1 for 41 degrees of freedom and 26.8 for 56 degrees of freedom, respectively. The correlations are reduced through this combination to less than 20%, with the exception of ρ and η which are correlated by +23%, for the fit with universality and by +70% for $\tau \to \mu\nu_\mu\nu_\tau$.

Model-independent Analysis: From the Michel parameters, limits can be derived on the couplings $g_{\varepsilon\lambda}^\kappa$ without further module assumptions. In the Standard model $g_{LL}^V = 1$ (leptonic decays), and $g_L = 1$ (hadronic decays) and all other couplings vanish. First, the partial decay widths have to be compared to the Standard Model predictions to derive limits on the normalization of the couplings $A_x = G_{\tau x}^2/G_F^2$ with Fermi's constant G_F:

$$A_e = 1.0012 \pm 0.0053\ ,$$
$$A_\mu = 0.981 \pm 0.018\ ,$$
$$A_\pi = 1.018 \pm 0.012\ . \quad (6)$$

Then limits on the couplings (95% CL) can be extracted (see Ref. 3 and Ref. 4). Without the assumption of universality, the limits given in Table 1 are derived.

Model-dependent Interpretation: More stringent limits can be derived assuming specific models. For example, in the framework of a two Higgs doublet model, the measurements correspond to a limit of $m_{H^\pm} > 1.9$ GeV $\times \tan\beta$ on the mass of the charged Higgs boson, or a limit of 253 GeV on the mass of the second W boson in left-right symmetric models for arbitrary mixing (both 95% CL). See Ref. 4 and Ref. 5.

Footnotes and References

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Table 1: Coupling constants $g^{\gamma}_{\varepsilon\mu}$. 95% confidence level experimental limits. The limits include the quoted values of A_e, A_μ, and A_π and assume $A_\rho = A_{a_1} = 1$.

$\tau \to e\nu_e\nu_\tau$		
$\lvert g^S_{RR}\rvert < 0.70$	$\lvert g^V_{RR}\rvert < 0.17$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.99$	$\lvert g^V_{LR}\rvert < 0.13$	$\lvert g^T_{LR}\rvert < 0.082$
$\lvert g^S_{RL}\rvert < 2.01$	$\lvert g^V_{RL}\rvert < 0.52$	$\lvert g^T_{RL}\rvert < 0.51$
$\lvert g^S_{LL}\rvert < 2.01$	$\lvert g^V_{LL}\rvert < 1.005$	$\lvert g^T_{LL}\rvert \equiv 0$
$\tau \to \mu\nu_\mu\nu_\tau$		
$\lvert g^S_{RR}\rvert < 0.72$	$\lvert g^V_{RR}\rvert < 0.18$	$\lvert g^T_{RR}\rvert \equiv 0$
$\lvert g^S_{LR}\rvert < 0.95$	$\lvert g^V_{LR}\rvert < 0.12$	$\lvert g^T_{LR}\rvert < 0.079$
$\lvert g^S_{RL}\rvert < 2.01$	$\lvert g^V_{RL}\rvert < 0.52$	$\lvert g^T_{RL}\rvert < 0.51$
$\lvert g^S_{LL}\rvert < 2.01$	$\lvert g^V_{LL}\rvert < 1.005$	$\lvert g^T_{LL}\rvert \equiv 0$
$\tau \to \pi\nu_\tau$		
$\lvert g^V_R\rvert < 0.15$	$\lvert g^V_L\rvert > 0.992$	
$\tau \to \rho\nu_\tau$		
$\lvert g^V_R\rvert < 0.10$	$\lvert g^V_L\rvert > 0.995$	
$\tau \to a_1\nu_\tau$		
$\lvert g^V_R\rvert < 0.16$	$\lvert g^V_L\rvert > 0.987$	

ρ^τ(e or μ) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.745±0.008 OUR FIT				
0.749±0.008 OUR AVERAGE				
0.742±0.014±0.006	81k	HEISTER 01E	ALEP	1991–1995 LEP runs
0.775±0.023±0.020	36k	ABREU 00L	DLPH	1992–1995 runs
0.781±0.028±0.018	46k	ACKERSTAFF 99D	OPAL	1990–1995 LEP runs
0.762±0.035	54k	ACCIARRI 98R	L3	1991–1995 LEP runs
0.731±0.031		[244] ALBRECHT 98	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.72 ±0.09 ±0.03		[245] ABE 97O	SLD	1993–1995 SLC runs
0.747±0.010±0.006	55k	ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.79 ±0.10 ±0.10	3732	FORD 87B	MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.71 ±0.09 ±0.03	1426	BEHRENDS 85	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.735±0.013±0.008	31k	AMMAR 97B	CLEO	Repl. by ALEXANDER 97F
0.794±0.039±0.031	18k	ACCIARRI 96H	L3	Repl. by ACCIARRI 98R
0.732±0.034±0.020	8.2k	[246] ALBRECHT 95	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.738±0.038		[247] ALBRECHT 95C	ARG	Repl. by ALBRECHT 98
0.751±0.039±0.022		BUSKULIC 95D	ALEP	Repl. by HEISTER 01E
0.742±0.035±0.020	8000	ALBRECHT 90E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[244] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 98, ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

[245] ABE 97O assume $\eta^\tau = 0$ in their fit. Letting η^τ vary in the fit gives a ρ^τ value of $0.69 \pm 0.13 \pm 0.05$.

[246] Value is from a simultaneous fit for the ρ^τ and η^τ decay parameters to the lepton energy spectrum. Not independent of ALBRECHT 90E ρ^τ(e or μ) value which assumes η^τ=0. Result is strongly correlated with ALBRECHT 95C.

[247] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E.

ρ^τ(e) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.747±0.010 OUR FIT				
0.744±0.010 OUR AVERAGE				
0.747±0.019±0.014	44k	HEISTER 01E	ALEP	1991–1995 LEP runs
0.744±0.036±0.037	17k	ABREU 00L	DLPH	1992–1995 runs
0.779±0.047±0.029	25k	ACKERSTAFF 99D	OPAL	1990–1995 LEP runs
0.68 ±0.04 ±0.07		[248] ALBRECHT 98	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.71 ±0.14 ±0.05		ABE 97O	SLD	1993–1995 SLC runs
0.747±0.012±0.004	34k	ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.735±0.036±0.020	4.7k	[249] ALBRECHT 95	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.79 ±0.08 ±0.06	3230	[250] ALBRECHT 93G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.64 ±0.06 ±0.07	2753	JANSSEN 89	CBAL	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.62 ±0.17 ±0.14	1823	FORD 87B	MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.60 ±0.13	699	BEHRENDS 85	CLEO	e^+e^- near $\Upsilon(4S)$
0.72 ±0.10 ±0.11	594	BACINO 79B	DLCO	$E^{ee}_{\rm cm}$= 3.5–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.732±0.014±0.009	19k	AMMAR 97B	CLEO	Repl. by ALEXANDER 97F
0.793±0.050±0.025		BUSKULIC 95D	ALEP	Repl. by HEISTER 01E
0.747±0.045±0.028	5106	ALBRECHT 90E	ARG	Repl. by ALBRECHT 95

[248] ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

[249] ALBRECHT 95 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(h^+h^-h^+(\pi^0)\overline{\nu}_\tau)$ and their charged conjugates.

[250] ALBRECHT 93G use tau pair events of the type $\tau^-\tau^+ \to (\mu^-\overline{\nu}_\mu\nu_\tau)(e^+\nu_e\overline{\nu}_\tau)$ and their charged conjugates.

ρ^τ(μ) PARAMETER

($V-A$) theory predicts $\rho = 0.75$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.763±0.020 OUR FIT				
0.770±0.022 OUR AVERAGE				
0.776±0.045±0.019	46k	HEISTER 01E	ALEP	1991–1995 LEP runs
0.999±0.098±0.045	22k	ABREU 00L	DLPH	1992–1995 runs
0.777±0.044±0.016	27k	ACKERSTAFF 99D	OPAL	1990–1995 LEP runs
0.69 ±0.06 ±0.06		[251] ALBRECHT 98	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
0.54 ±0.28 ±0.14		ABE 97O	SLD	1993–1995 SLC runs
0.750±0.017±0.045	22k	ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
0.76 ±0.07 ±0.08	3230	ALBRECHT 93G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.734±0.055±0.027	3041	ALBRECHT 90E	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV
0.89 ±0.14 ±0.08	1909	FORD 87B	MAC	$E^{ee}_{\rm cm}$= 29 GeV
0.81 ±0.13	727	BEHRENDS 85	CLEO	e^+e^- near $\Upsilon(4S)$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.747±0.048±0.044	13k	AMMAR 97B	CLEO	Repl. by ALEXANDER 97F
0.693±0.057±0.028		BUSKULIC 95D	ALEP	Repl. by HEISTER 01E

[251] ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

ξ^τ(e or μ) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.985±0.030 OUR FIT				
0.981±0.031 OUR AVERAGE				
0.986±0.068±0.031	81k	HEISTER 01E	ALEP	1991–1995 LEP runs
0.929±0.070±0.030	36k	ABREU 00L	DLPH	1992–1995 runs
0.98 ±0.22 ±0.10	46k	ACKERSTAFF 99D	OPAL	1990–1995 LEP runs
0.70 ±0.16	54k	ACCIARRI 98R	L3	1991–1995 LEP runs
1.03 ±0.11		[252] ALBRECHT 98	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
1.05 ±0.35 ±0.04		[253] ABE 97O	SLD	1993–1995 SLC runs
1.007±0.040±0.015	55k	ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.94 ±0.21 ±0.07	18k	ACCIARRI 96H	L3	Repl. by ACCIARRI 98R
0.97 ±0.14		[254] ALBRECHT 95C	ARG	Repl. by ALBRECHT 98
1.18 ±0.15 ±0.16		BUSKULIC 95D	ALEP	Repl. by HEISTER 01E
0.90 ±0.15 ±0.10	3230	[255] ALBRECHT 93G	ARG	$E^{ee}_{\rm cm}$= 9.4–10.6 GeV

[252] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 98, ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

[253] ABE 97O assume $\eta^\tau = 0$ in their fit. Letting η^τ vary in the fit gives a ξ^τ value of $1.02 \pm 0.36 \pm 0.05$.

[254] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 95C uses events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(h^+h^-h^+\overline{\nu}_\tau)$ and their charged conjugates.

[255] ALBRECHT 93G measurement determines $\lvert\xi^\tau\rvert$ for the case $\xi^\tau(e) = \xi^\tau(\mu)$, but the authors point out that other LEP experiments determine the sign to be positive.

ξ^τ(e) PARAMETER

($V-A$) theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID	TECN	COMMENT
0.994±0.040 OUR FIT				
1.00 ±0.04 OUR AVERAGE				
1.011±0.094±0.038	44k	HEISTER 01E	ALEP	1991–1995 LEP runs
1.01 ±0.12 ±0.05	17k	ABREU 00L	DLPH	1992–1995 runs
1.13 ±0.39 ±0.14	25k	ACKERSTAFF 99D	OPAL	1990–1995 LEP runs
1.11 ±0.20 ±0.08		[256] ALBRECHT 98	ARG	$E^{ee}_{\rm cm}$= 9.5–10.6 GeV
1.16 ±0.52 ±0.06		ABE 97O	SLD	1993–1995 SLC runs
0.979±0.048±0.016	34k	ALEXANDER 97F	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.03 ±0.23 ±0.09		BUSKULIC 95D	ALEP	Repl. by HEISTER 01E

[256] ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

$\xi^\tau(\mu)$ PARAMETER

$(V-A)$ theory predicts $\xi = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.030±0.059 OUR FIT					
1.06 ±0.06 OUR AVERAGE					
1.030±0.120±0.050	46k	HEISTER	01E	ALEP	1991–1995 LEP runs
1.16 ±0.19 ±0.06	22k	ABREU	00L	DLPH	1992–1995 runs
0.79 ±0.41 ±0.09	27k	ACKERSTAFF	99D	OPAL	1990–1995 LEP runs
1.26 ±0.27 ±0.14		[257] ALBRECHT	98	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.75 ±0.50 ±0.14		ABE	97O	SLD	1993–1995 SLC runs
1.054±0.069±0.047	22k	ALEXANDER	97F	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.23 ±0.22 ±0.10		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

[257] ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

$\eta^\tau(e$ or $\mu)$ PARAMETER

$(V-A)$ theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.013±0.020 OUR FIT					
0.015±0.021 OUR AVERAGE					
0.012±0.026±0.004	81k	HEISTER	01E	ALEP	1991–1995 LEP runs
−0.005±0.036±0.037		ABREU	00L	DLPH	1992–1995 runs
0.027±0.055±0.005	46k	ACKERSTAFF	99D	OPAL	1990–1995 LEP runs
0.27 ±0.14	54k	ACCIARRI	98R	L3	1991–1995 LEP runs
−0.13 ±0.47 ±0.15		ABE	97O	SLD	1993–1995 SLC runs
−0.015±0.061±0.062	31k	AMMAR	97B	CLEO	E^{ee}_{cm}= 10.6 GeV
0.03 ±0.18 ±0.12	8.2k	ALBRECHT	95	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.25 ±0.17 ±0.11	18k	ACCIARRI	96H	L3	Repl. by ACCIARRI 98R
−0.04 ±0.15 ±0.11		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

$\eta^\tau(\mu)$ PARAMETER

$(V-A)$ theory predicts $\eta = 0$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.094±0.073 OUR FIT					
0.17 ±0.15 OUR AVERAGE Error includes scale factor of 1.2.					
0.160±0.150±0.060	46k	HEISTER	01E	ALEP	1991–1995 LEP runs
0.72 ±0.32 ±0.15		ABREU	00L	DLPH	1992–1995 runs
−0.59 ±0.82 ±0.45		[258] ABE	97O	SLD	1993–1995 SLC runs
0.010±0.149±0.171	13k	[259] AMMAR	97B	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.010±0.065±0.001	27k	[260] ACKERSTAFF	99D	OPAL	1990–1995 LEP runs
−0.24 ±0.23 ±0.18		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

[258] Highly correlated (corr. = 0.92) with ABE 97O $\rho^\tau(\mu)$ measurement.

[259] Highly correlated (corr. = 0.949) with AMMAR 97B $\rho^\tau(\mu)$ value.

[260] ACKERSTAFF 99D result is dominated by a constraint on η^τ from the OPAL measurements of the τ lifetime and B($\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$) assuming lepton universality for the total coupling strength.

$(\delta\xi)^\tau(e$ or $\mu)$ PARAMETER

$(V-A)$ theory predicts $(\delta\xi) = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.746±0.021 OUR FIT					
0.744±0.022 OUR AVERAGE					
0.776±0.045±0.024	81k	HEISTER	01E	ALEP	1991–1995 LEP runs
0.779±0.070±0.028	36k	ABREU	00L	DLPH	1992–1995 runs
0.65 ±0.14 ±0.07	46k	ACKERSTAFF	99D	OPAL	1990–1995 LEP runs
0.70 ±0.11	54k	ACCIARRI	98R	L3	1991–1995 LEP runs
0.63 ±0.09		[261] ALBRECHT	98	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.88 ±0.27 ±0.04		[262] ABE	97O	SLD	1993–1995 SLC runs
0.745±0.026±0.009	55k	ALEXANDER	97F	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.81 ±0.14 ±0.06	18k	ACCIARRI	96H	L3	Repl. by ACCIARRI 98R
0.65 ±0.12		[263] ALBRECHT	95C	ARG	Repl. by ALBRECHT 98
0.88 ±0.11 ±0.07		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

[261] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 98, ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

[262] ABE 97O assume $\eta^\tau = 0$ in their fit. Letting η^τ vary in the fit gives a $(\rho\xi)^\tau$ value of $0.87 \pm 0.27 \pm 0.04$.

[263] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E. ALBRECHT 95C uses events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)\,(h^+h^-h^+\overline{\nu}_\tau)$ and their charged conjugates.

$(\delta\xi)^\tau(e)$ PARAMETER

$(V-A)$ theory predicts $(\delta\xi) = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.734±0.028 OUR FIT					
0.731±0.029 OUR AVERAGE					
0.778±0.066±0.024	44k	HEISTER	01E	ALEP	1991–1995 LEP runs
0.85 ±0.12 ±0.04	17k	ABREU	00L	DLPH	1992–1995 runs
0.72 ±0.31 ±0.14	25k	ACKERSTAFF	99D	OPAL	1990–1995 LEP runs
0.56 ±0.14 ±0.06		[264] ALBRECHT	98	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.85 ±0.43 ±0.08		ABE	97O	SLD	1993–1995 SLC runs
0.720±0.032±0.010	34k	ALEXANDER	97F	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.11 ±0.17 ±0.07		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

[264] ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

$(\delta\xi)^\tau(\mu)$ PARAMETER

$(V-A)$ theory predicts $(\delta\xi) = 0.75$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.778±0.037 OUR FIT					
0.79 ±0.04 OUR AVERAGE					
0.786±0.066±0.028	46k	HEISTER	01E	ALEP	1991–1995 LEP runs
0.86 ±0.13 ±0.04	22k	ABREU	00L	DLPH	1992–1995 runs
0.63 ±0.23 ±0.05	27k	ACKERSTAFF	99D	OPAL	1990–1995 LEP runs
0.73 ±0.18 ±0.10		[265] ALBRECHT	98	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
0.82 ±0.32 ±0.07		ABE	97O	SLD	1993–1995 SLC runs
0.786±0.041±0.032	22k	ALEXANDER	97F	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.71 ±0.14 ±0.06		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

[265] ALBRECHT 98 use tau pair events of the type $\tau^-\tau^+ \to (\ell^-\overline{\nu}_\ell\nu_\tau)(\pi^+\pi^0\overline{\nu}_\tau)$, and their charged conjugates.

$\xi^\tau(\pi)$ PARAMETER

$(V-A)$ theory predicts $\xi^\tau(\pi) = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.993±0.022 OUR FIT					
0.994±0.023 OUR AVERAGE					
0.994±0.020±0.014	27k	HEISTER	01E	ALEP	1991–1995 LEP runs
0.81 ±0.17 ±0.02		ABE	97O	SLD	1993–1995 SLC runs
1.03 ±0.06 ±0.04	2.0k	COAN	97	CLEO	E^{ee}_{cm}= 10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.987±0.057±0.027		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E
0.95 ±0.11 ±0.05		[266] BUSKULIC	94D	ALEP	1990+1991 LEP run

[266] Superseded by BUSKULIC 95D.

$\xi^\tau(\rho)$ PARAMETER

$(V-A)$ theory predicts $\xi^\tau(\rho) = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.994±0.008 OUR FIT					
0.994±0.009 OUR AVERAGE					
0.987±0.012±0.011	59k	HEISTER	01E	ALEP	1991–1995 LEP runs
0.99 ±0.12 ±0.04		ABE	97O	SLD	1993–1995 SLC runs
0.995±0.010±0.003	66k	ALEXANDER	97F	CLEO	E^{ee}_{cm}= 10.6 GeV
1.022±0.028±0.030	1.7k	[267] ALBRECHT	94E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1.045±0.058±0.032		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E
1.03 ±0.11 ±0.05		[268] BUSKULIC	94D	ALEP	1990+1991 LEP run

[267] ALBRECHT 94E measure the square of this quantity and use the sign determined by ALBRECHT 90I to obtain the quoted result.

[268] Superseded by BUSKULIC 95D.

$\xi^\tau(a_1)$ PARAMETER

$(V-A)$ theory predicts $\xi^\tau(a_1) = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
1.001±0.027 OUR FIT					
1.002±0.028 OUR AVERAGE					
1.000±0.016±0.024	35k	[269] HEISTER	01E	ALEP	1991–1995 LEP runs
1.02 ±0.13 ±0.03	17.2k	ASNER	00	CLEO	E^{ee}_{cm}= 10.6 GeV
1.29 ±0.26 ±0.11	7.4k	[270] ACKERSTAFF	97R	OPAL	1992–1994 LEP runs
$0.85\ ^{+0.15}_{-0.17}\ \pm0.05$		ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
$1.25\ \pm0.23\ ^{+0.15}_{-0.08}$	7.5k	ALBRECHT	93C	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1.08\ ^{+0.46}_{-0.41}\ ^{+0.14}_{-0.25}$	2.6k	[271] AKERS	95P	OPAL	Repl. by ACKERSTAFF 97R
0.937±0.116±0.064		BUSKULIC	95D	ALEP	Repl. by HEISTER 01E

[269] HEISTER 01E quote $1.000 \pm 0.016 \pm 0.013 \pm 0.020$ where the errors are statistical, systematic, and an uncertainty due to the final state model. We combine the systematic error and model uncertainty.

[270] ACKERSTAFF 97R obtain this result with a model independent fit to the hadronic structure functions. Fitting with the model of Kuhn and Santamaria (ZPHY **C48**, 445 (1990)) gives $0.87 \pm 0.16 \pm 0.04$, and with the model of of Isgur *et al.* (PR **D39**,1357 (1989)) they obtain $1.20 \pm 0.21 \pm 0.14$.

[271] AKERS 95P obtain this result with a model independent fit to the hadronic structure functions. Fitting with the model of Kuhn and Santamaria (ZPHY **C48**, 445 (1990)) gives $0.87 \pm 0.27^{+0.05}_{-0.06}$, and with the model of of Isgur *et al.* (PR **D39**,1357 (1989)) they obtain $1.10 \pm 0.31^{+0.13}_{-0.14}$.

ξ^{τ} (all hadronic modes) PARAMETER

$(V-A)$ theory predicts $\xi^{\tau} = 1$.

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
0.995±0.007 OUR FIT					
0.997±0.007 OUR AVERAGE					
0.992±0.007±0.008	102k	[272] HEISTER	01E	ALEP	1991–1995 LEP runs
0.997±0.027±0.011	39k	[273] ABREU	00L	DLPH	1992–1995 runs
1.02 ±0.13 ±0.03	17.2k	[274] ASNER	00	CLEO	E^{ee}_{cm}= 10.6 GeV
1.032±0.031	37k	[275] ACCIARRI	98R	L3	1991–1995 LEP runs
0.93 ±0.10 ±0.04		ABE	97O	SLD	1993–1995 SLC runs
1.29 ±0.26 ±0.11	7.4k	[276] ACKERSTAFF	97R	OPAL	1992–1994 LEP runs
0.995±0.010±0.003	66k	[277] ALEXANDER	97F	CLEO	E^{ee}_{cm}= 10.6 GeV
1.03 ±0.06 ±0.04	2.0k	[278] COAN	97	CLEO	E^{ee}_{cm}= 10.6 GeV
1.017±0.039		[279] ALBRECHT	95C	ARG	E^{ee}_{cm}= 9.5–10.6 GeV
1.25 ±0.23 $^{+0.15}_{-0.08}$	7.5k	[280] ALBRECHT	93C	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
0.970±0.053±0.011	14k	[281] ACCIARRI	96H	L3	Repl. by ACCIARRI 98R
1.08 $^{+0.46}_{-0.41}$ $^{+0.14}_{-0.25}$	2.6k	[282] AKERS	95P	OPAL	Repl. by ACKERSTAFF 97R
1.006±0.032±0.019		[283] BUSKULIC	95D	ALEP	Repl. by HEISTER 01E
1.022±0.028±0.030	1.7k	[284] ALBRECHT	94E	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
0.99 ±0.07 ±0.04		[285] BUSKULIC	94D	ALEP	1990+1991 LEP run

[272] HEISTER 01E quote 0.992 ± 0.007 ± 0.006 ± 0.005 where the errors are statistical, systematic, and an uncertainty due to the final state model. We combine the systematic error and model uncertainty. They use $\tau \to \pi \nu_\tau$, $\tau \to K \nu_\tau$, $\tau \to \rho \nu_\tau$, and $\tau \to a_1 \nu_\tau$ decays.

[273] ABREU 00L use $\tau^- \to h^- \geq 0\pi^0 \nu_\tau$ decays.

[274] ASNER 00 use $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ decays.

[275] ACCIARRI 98R use $\tau \to \pi \nu_\tau$, $\tau \to K \nu_\tau$, and $\tau \to \rho \nu_\tau$ decays.

[276] ACKERSTAFF 97R use $\tau \to a_1 \nu_\tau$ decays.

[277] ALEXANDER 97F use $\tau \to \rho \nu_\tau$ decays.

[278] COAN 97 use $h^+ h^-$ energy correlations.

[279] Combined fit to ARGUS tau decay parameter measurements in ALBRECHT 95C, ALBRECHT 93G, and ALBRECHT 94E.

[280] Uses $\tau \to a_1 \nu_\tau$ decays. Replaced by ALBRECHT 95C.

[281] ACCIARRI 96H use $\tau \to \pi \nu_\tau$, $\tau \to K \nu_\tau$, and $\tau \to \rho \nu_\tau$ decays.

[282] AKERS 95P use $\tau \to a_1 \nu_\tau$ decays.

[283] BUSKULIC 95D use $\tau \to \pi \nu_\tau$, $\tau \to \rho \nu_\tau$, and $\tau \to a_1 \nu_\tau$ decays.

[284] ALBRECHT 94E measure the square of this quantity and use the sign determined by ALBRECHT 90I to obtain the quoted result. Uses $\tau \to a_1 \nu_\tau$ decays. Replaced by ALBRECHT 95C.

[285] BUSKULIC 94D use $\tau \to \pi \nu_\tau$ and $\tau \to \rho \nu_\tau$ decays. Superseded by BUSKULIC 95D.

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Heavy Charged Lepton Searches

Charged Heavy Lepton MASS LIMITS

Sequential Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

These experiments assumed that a fourth generation $L^{\pm}$ decayed to a fourth generation ν_L (or L^0) where ν_L was stable, or that $L^{\pm}$ decays to a light ν_ℓ via mixing.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited leptons, *i.e.* $\ell^* \to \ell\gamma$. See the "WIMPs and other Particle Searches" section for heavy charged particle search limits in which the charged particle could be a lepton.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>100.8	95	ACHARD	01B	L3	Decay to νW
>101.9	95	ACHARD	01B	L3	$m_L - m_{L^0} > 15$ GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 81.5	95	ACKERSTAFF	98C	OPAL	Assumed $m_{L^{\pm}} - m_{L^0} > 8.4$ GeV
> 80.2	95	ACKERSTAFF	98C	OPAL	$m_{L^0} > m_{L^{\pm}}$ and $L^{\pm} \to \nu W$
< 48 or > 61	95	[1] ACCIARRI	96G	L3	
> 63.9	95	ALEXANDER	96P	OPAL	Decay to massless ν's
> 63.5	95	BUSKULIC	96S	ALEP	$m_L - m_{L^0} > 7$ GeV
> 65	95	BUSKULIC	96S	ALEP	Decay to massless ν's
none 10–225		[2] AHMED	94	CNTR	H1 Collab. at HERA
none 12.6–29.6	95	KIM	91B	AMY	Massless ν assumed
> 44.3	95	AKRAWY	90G	OPAL	
none 0.5–10	95	[3] RILES	90	MRK2	For $(m_{L^0}$-$m_{L^0})>$ 0.25–0.4GeV
> 8		[4] STOKER	89	MRK2	For $(m_{L^+} - m_{L^0})$= 0.4 GeV
> 12		[4] STOKER	89	MRK2	For m_{L^0}=0.9 GeV
none 18.4–27.6	95	[5] ABE	88	VNS	
> 25.5	95	[6] ADACHI	88B	TOPZ	
none 1.5–22.0	95	BEHREND	88C	CELL	
> 41	90	[7] ALBAJAR	87B	UA1	
> 22.5	95	[8] ADEVA	85	MRKJ	
> 18.0	95	[9] BARTEL	83	JADE	
none 4–14.5	95	[10] BERGER	81B	PLUT	
> 15.5	95	[11] BRANDELIK	81	TASS	
> 13.		[12] AZIMOV	80		
> 16.	95	[13] BARBER	80B	CNTR	
> 0.490		[14] ROTHE	69	RVUE	

[1] ACCIARRI 96G assumes LEP result that the associated neutral heavy lepton mass > 40 GeV.
[2] The AHMED 94 limits are from a search for neutral and charged sequential heavy leptons at HERA via the decay channels $L^- \to e\gamma$, $L^- \to \nu W^-$, $L^- \to eZ$; and $L^0 \to \nu\gamma$, $L^0 \to e^- W^+$, $L^- \to \nu Z$, where the W decays to $\ell\nu_\ell$, or to jets, and Z decays to $\ell^+\ell^-$ or jets.
[3] RILES 90 limits were the result of a special analysis of the data in the case where the mass difference $m_{L^-} - m_{L^0}$ was allowed to be quite small, where L^0 denotes the neutrino into which the sequential charged lepton decays. With a slightly reduced $m_{L^{\pm}}$ range, the mass difference extends to about 4 GeV.
[4] STOKER 89 (Mark II at PEP) gives bounds on charged heavy lepton (L^+) mass for the generalized case in which the corresponding neutral heavy lepton (L^0) in the SU(2) doublet is not of negligible mass.
[5] ABE 88 search for L^+ and $L^- \to$ hadrons looking for acoplanar jets. The bound is valid for $m_\nu < 10$ GeV.
[6] ADACHI 88B search for hadronic decays giving acoplanar events with large missing energy. $E_{cm}{}^{ee} = 52$ GeV.
[7] Assumes associated neutrino is approximately massless.
[8] ADEVA 85 analyze one-isolated-muon data and sensitive to τ <10 nanosec. Assume B(lepton) = 0.30. E_{cm} = 40–47 GeV.
[9] BARTEL 83 limit is from PETRA e^+e^- experiment with average $E_{cm} = 34.2$ GeV.
[10] BERGER 81B is DESY DORIS and PETRA experiment. Looking for $e^+e^- \to L^+L^-$.
[11] BRANDELIK 81 is DESY-PETRA experiment. Looking for $e^+e^- \to L^+L^-$.
[12] AZIMOV 80 estimated probabilities for $M + N$ type events in $e^+e^- \to L^+L^-$ deducing semi-hadronic decay multiplicities of L from e^+e^- annihilation data at $E_{cm} = (2/3)m_L$. Obtained above limit comparing these with e^+e^- data (BRANDELIK 80).
[13] BARBER 80B looked for $e^+e^- \to L^+L^-$, $L \to \nu_L^+$X with MARK-J at DESY-PETRA.
[14] ROTHE 69 examines previous data on μ pair production and π and K decays.

Stable Charged Heavy Lepton ($L^{\pm}$) MASS LIMITS

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*
>102.6	95	ACHARD	01B	L3
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 28.2	95	[15] ADACHI	90C	TOPZ
none 18.5–42.8	95	AKRAWY	90O	OPAL
> 26.5	95	DECAMP	90F	ALEP
none m_μ–36.3	95	SODERSTROM	90	MRK2

[15] ADACHI 90C put lower limits on the mass of stable charged particles with electric charge Q satisfying $2/3 < Q/e < 4/3$ and with spin 0 or 1/2. We list here the special case for a stable charged heavy lepton.

Charged Long-Lived Heavy Lepton MASS LIMITS

VALUE (GeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •							
>102.0	95		ABBIENDI	03L	OPAL		pair produced in e^+e^-
> 0.1		0	[16] ANSORGE	73B	HBC	$-$	Long-lived
none 0.55–4.5			[17] BUSHNIN	73	CNTR	$-$	Long-lived
none 0.2–0.92			[18] BARNA	68	CNTR	$-$	Long-lived
none 0.97–1.03			[18] BARNA	68	CNTR	$-$	Long-lived

[16] ANSORGE 73B looks for electron pair production and electron-like Bremsstrahlung.
[17] BUSHNIN 73 is SERPUKHOV 70 GeV p experiment. Masses assume mean life above 7×10^{-10} and 3×10^{-8} respectively. Calculated from cross section (see "Charged Quasi-Stable Lepton Production Differential Cross Section" below) and 30 GeV muon pair production data.
[18] BARNA 68 is SLAC photoproduction experiment.

Doubly-Charged Heavy Lepton MASS LIMITS

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 1–9 GeV	90	[19] CLARK	81	SPEC	++

[19] CLARK 81 is FNAL experiment with 209 GeV muons. Bounds apply to μ_P which couples with full weak strength to muon. See also section on "Doubly-Charged Lepton Production Cross Section."

Doubly-Charged Lepton Production Cross Section (μN Scattering)

VALUE (cm^2)	*EVTS*	*DOCUMENT ID*		*TECN*	*CHG*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<6. \times 10^{-38}$	0	[20] CLARK	81	SPEC	++

[20] CLARK 81 is FNAL experiment with 209 GeV muon. Looked for μ^+ nucleon $\to \overline{\mu}_P^0$X, $\overline{\mu}_P^0 \to \mu^+\mu^-\overline{\nu}_\mu$ and $\mu^+ n \to \mu_P^{++}$X, $\mu_P^{++} \to 2\mu^+\nu_\mu$. Above limits are for $\sigma\times$BR taken from their mass-dependence plot figure 2.

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Neutrinos

OMITTED FROM SUMMARY TABLE

ELECTRON, MUON, AND TAU NEUTRINO LISTINGS

Revised July 2003 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

The following Listings concern measurements of the properties of neutrinos produced in association with $e^{\pm}$, $\mu^{\pm}$, and $\tau^{\pm}$. Nearly all of the measurements, all of which so far are upper limits, actually concern superpositions of the mass eigenstates ν_i, which are in turn related to the weak eigenstates ν_ℓ, via the neutrino mixing matrix

$$|\nu_\ell\rangle = \sum_i U_{\ell i}\,|\nu_i\rangle \quad . \tag{1}$$

In the analogous case of quark mixing via the CKM matrix, the smallness of the off-diagonal terms (small mixing angles) permits a "dominant eigenstate" approximation. Previous editions of this Review have assumed that the dominant eigenstate paradigm applies to neutrinos as well. However, the present results of neutrino oscillation searches suggest that the mixing matrix contains two large mixing angles. We can therefore no longer associate any particular state $|\nu_i\rangle$ with any particular lepton label e, μ, or τ. Nevertheless, neutrinos are produced in weak decays with a definite lepton flavor, and are typically detected by the charged current weak interaction again associated with a specific lepton flavor. The listings that follow are separated into the three associated charged lepton categories.

Measured quantities (mass-squared, magnetic moments, mean lifetimes, *etc.*) all depend upon the mixing parameters $|U_{\ell i}|^2$, but to some extent also on experimental conditions (energy resolution). Most of these observables, in particular mass-squared, cannot distinguish between Dirac and Majorana neutrinos and are unaffected by CP phases.

Direct neutrino mass measurements are usually based on the analysis of the kinematics of charged particles (leptons, pions) emitted together with neutrinos (flavor states) in various weak decays. The most sensitive neutrino mass measurement to date, involving electron type neutrinos, is based on fitting the shape of the beta spectrum. The quantity $m_{\nu_e}^{2(\text{eff})} = \sum_i |U_{ei}|^2 m_{\nu_i}^2$ is determined or constrained, where the sum is over all mass eigenvalues m_{ν_i} that are too close together to be resolved experimentally. If the energy resolution is better than $\Delta m_{ij}^2 \equiv m_{\nu_i}^2 - m_{\nu_j}^2$, the corresponding heavier m_{ν_i} and mixing parameter could be determined by fitting the resulting spectral anomaly (step or kink).

A limit on $m_{\nu_e}^{2(\text{eff})}$ implies an *upper* limit on the *minimum* value $m_{\nu_{\min}}^2$ of $m_{\nu_i}^2$, independent of the mixing parameters U_{ei}: $m_{\nu_{\min}}^2 \le m_{\nu_e}^{2(\text{eff})}$. However, if and when the study of neutrino oscillations provides us with the values of *all* neutrino mass-squared differences Δm_{ij}^2 and the mixing parameters $|U_{ei}|^2$, then the individual neutrino mass squares $m_{\nu_j}^2 = m_{\nu_e}^{2(\text{eff})} - \sum_i |U_{ei}|^2 \Delta m_{ij}^2$ can be determined. If only the $|\Delta m_{ij}^2|$ are known, a limit on $m_{\nu_e}^{(\text{eff})}$ from beta decay may be used to define an *upper* limit on the *maximum* value $m_{\nu_{\max}}$ of m_{ν_i}: $m_{\nu_{\max}}^2 \le m_{\nu_e}^{2(\text{eff})} + \sum_{i<j} |\Delta m_{ij}^2|$.

The analysis of the low energy beta decay of tritium yields the most stringent limit on $m_{\nu_e}^{(\text{eff})}$ to date (where $m_{\nu_e}^{(\text{eff})} \equiv \sqrt{m_{\nu_e}^{2(\text{eff})}}$). Unphysical negative $m_{\nu_e}^{2(\text{eff})}$ fits, caused by an as yet not understood event excess near the spectrum endpoint, are sometimes encountered. In Ref. 1 two analyses which either exclude the spectral anomaly by choice of the analysis energy window or by using one of four data sets yield an acceptable $m_{\nu_e}^{2(\text{eff})}$ fit and a $m_{\nu_e}^{(\text{eff})}$ limit of 2.8 eV. Ref. 2 reports a $m_{\nu_e}^{(\text{eff})}$ limit of 2.5 eV by introducing an *a priori* chosen parameterization of the anomalous near-endpoint events into the spectral analysis.

In analogous way, by measuring the muon momentum in the pion decay $\pi^+ \to \mu^+ + \nu_\mu$ one constrains the quantity $m_{\nu_\mu}^{2(\text{eff})} = \sum_i |U_{\mu i}|^2 m_{\nu_i}^2$, where the sum is again over all m_{ν_i} that cannot be resolved experimentally. Obviously, the true $m_{\nu_\mu}^{2(\text{eff})}$ cannot be larger than the *maximum* value of $m_{\nu_i}^2$. As pointed out above, this maximum could be restricted by the tritium beta decay, provided *all* neutrino mass-squared differences $|\Delta m_{ij}^2|$ are known. The most sensitive measurement is $m_{\nu_\mu}^{(\text{eff})} < 170$ keV [3], more than four orders of magnitude less stringent than the tritium experiments.

Similar remarks can be made about $m_{\nu_\tau}^{2(\text{eff})}$ constrained by the shape of the spectrum of decay products of the τ lepton. Again, the true $m_{\nu_\tau}^{2(\text{eff})}$ cannot exceed the *maximum* $m_{\nu_i}^2$ value, which could be constrained by *both* $m_{\nu_e}^{2(\text{eff})}$ and $m_{\nu_\mu}^{2(\text{eff})}$ values or limits, provided the corresponding $|\Delta m_{ij}^2|$ are known. The most stringent limit on $m_{\nu_\tau}^{(\text{eff})}$, 18.2 MeV [4], is yet another two orders of magnitude less sensitive than the $m_{\nu_\mu}^{(\text{eff})}$ limit. The different sensitivities of the current experiments regarding $m_{\nu_\tau}^{(\text{eff})}$, $m_{\nu_\mu}^{(\text{eff})}$, and $m_{\nu_e}^{(\text{eff})}$ are relevant, however, only if the oscillation searches, reported below, can be regarded as an reliable source of all $|\Delta m_{ij}^2|$ values.

The spread of arrival times of the neutrinos from SN1987A, coupled with the measured neutrino energies, provides a time-of-flight limit on a quantity similar to $m_{\nu_e}^{(\rm eff)}$. This statement, clothed in various degrees of sophistication, has been the basis for a very large number of papers. The resulting limits, however, are no longer competitive with the limits from the tritium beta decay.

Another constraint has been obtained recently from the analysis of the cosmic microwave background anisotropy ([5]), combined with the galaxy redshift surveys and other data. The constrained quantity is the sum of the neutrino masses, $\sum_i m_{\nu_i} \leq 0.7$ eV. Discussion concerning the model dependence of this limit is continuing.

References

1. Ch. Weinheimer *et al.*, Phys. Lett. **B460**, 219 (1999); Phys. Lett. **B464**, 352 (1999) (*erratum*).
2. M. Lobashev *et al.*, Phys. Lett. **B460**, 227 (1999).
3. K.A. Assamagan *et al.*, Phys. Rev. **D53**, 6065 (1996).
4. R. Barate *et al.*, Eur. Phys. J. **C2**, 395 (1998).
5. N. Spergel *et al.*, Astrophys. J. Supp. **148**, 175 (2003).

ν_e

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with e^+ or e^-. See Note on "Electron, muon, and tau neutrino listings."

$\overline{\nu}$ MASS

Those limits given below for $\overline{\nu}$ mass that come from the kinematics of $^3{\rm H}\beta^-\overline{\nu}$ decay are the square roots of limits for $m_{\nu_e}^{2(\rm eff)}$. These are obtained from the measurements reported in the Listings for "$\overline{\nu}$ Mass Squared," below.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 3 OUR EVALUATION					
< 5.7	95	[1] LOREDO	02	ASTR	SN1987A
< 2.5	95	[2] LOBASHEV	99	SPEC	^{3}H β decay
< 2.8	95	[3] WEINHEIMER	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 4.35	95	[4] BELESEV	95	SPEC	^{3}H β decay
<12.4	95	[5] CHING	95	SPEC	^{3}Hβ decay
<92	95	[6] HIDDEMANN	95	SPEC	^{3}H β decay
15^{+32}_{-15}		HIDDEMANN	95	SPEC	^{3}H β decay
<19.6	95	KERNAN	95	ASTR	SN 1987A
< 7.0	95	[7] STOEFFL	95	SPEC	^{3}H β decay
< 7.2	95	[8] WEINHEIMER	93	SPEC	^{3}H β decay
<11.7	95	[9] HOLZSCHUH	92B	SPEC	^{3}H β decay
<13.1	95	[10] KAWAKAMI	91	SPEC	^{3}H β decay
< 9.3	95	[11] ROBERTSON	91	SPEC	^{3}H β decay
<14	95	AVIGNONE	90	ASTR	SN 1987A
<16		SPERGEL	88	ASTR	SN 1987A
17 to 40		[12] BORIS	87	SPEC	^{3}Hβ decay

[1] LOREDO 02 updates LOREDO 89.

[2] LOBASHEV 99 report a new measurement which continues the work reported in BELESEV 95. This limit depends on phenomenological fit parameters used to derive their best fit to m_ν^2, making unambiguous interpretation difficult. See the footnote under "$\overline{\nu}$ Mass Squared."

[3] WEINHEIMER 99 presents two analyses which exclude the spectral anomaly and result in an acceptable m_ν^2. We report the most conservative limit, but the other (< 2.7 eV) is nearly the same. See the footnote under "$\overline{\nu}$ Mass Squared."

[4] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. A fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly) plus a monochromatic line 7–15 eV below the endpoint yields $m_\nu^2 = -4.1 \pm 10.9$ eV^2, leading to this Bayesian limit.

[5] CHING 95 quotes results previously given by SUN 93; no experimental details are given. A possible explanation for consistently negative values of m_ν^2 is given.

[6] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. Bayesian limit calculated from the weighted mean $m_\nu^2 = 221 \pm 4244$ eV^2 from the two runs listed below.

[7] STOEFFL 95 (LLNL) result is the Bayesian limit obtained from the m_ν^2 errors given below but with m_ν^2 set equal to 0. The anomalous endpoint accumulation leads to a value of m_ν^2 which is negative by more than 5 standard deviations.

[8] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium β spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[9] HOLZSCHUH 92B (Zurich) result is obtained from the measurement $m_\nu^2 = -24 \pm 48 \pm 61$ (1σ errors), in eV^2, using the PDG prescription for conversion to a limit in m_ν.

[10] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid. This result is the Bayesian limit obtained from the m_ν^2 limit with the errors combined in quadrature. This was also done in ROBERTSON 91, although the authors report a different procedure.

[11] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that m_ν lies between 17 and 40 eV. However, the probability of a positive m^2 is only 3% if statistical and systematic error are combined in quadrature.

[12] See also comment in BORIS 87B and erratum in BORIS 88.

$\overline{\nu}$ MASS SQUARED

Given troubling systematics which result in improbably negative estimators of $m_{\nu_e}^{2(\rm eff)}$ in many experiments, we use only WEINHEIMER 99 and LOBASHEV 99 for our average, as discussed above in the Note on the "Electron, muon, and tau neutrino listings."

VALUE (eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
− 2.5± 3.3 OUR AVERAGE					
− 1.9± 3.4± 2.2		[13] LOBASHEV	99	SPEC	^{3}H β decay
− 3.7± 5.3± 2.1		[14] WEINHEIMER	99	SPEC	^{3}H β decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
− 22 ± 4.8		[15] BELESEV	95	SPEC	^{3}H β decay
129 ±6010		[16] HIDDEMANN	95	SPEC	^{3}H β decay
313 ±5994		[16] HIDDEMANN	95	SPEC	^{3}H β decay
−130 ± 20 ±15	95	[17] STOEFFL	95	SPEC	^{3}H β decay
− 31 ± 75 ±48		[18] SUN	93	SPEC	^{3}Hβ decay
− 39 ± 34 ±15		[19] WEINHEIMER	93	SPEC	^{3}H β decay
− 24 ± 48 ±61		[20] HOLZSCHUH	92B	SPEC	^{3}H β decay
− 65 ± 85 ±65		[21] KAWAKAMI	91	SPEC	^{3}H β decay
−147 ± 68 ±41		[22] ROBERTSON	91	SPEC	^{3}H β decay

[13] LOBASHEV 99 report a new measurement which continues the work reported in BELESEV 95. The data were corrected for electron trapping effects in the source, eliminating the dependence of the fitted neutrino mass on the fit interval. The analysis assuming a pure beta spectrum yields significantly negative fitted $m_\nu^2 \approx -(20\text{–}10)$ eV^2. This problem is attributed to a discrete spectral anomaly of about 6×10^{-11} intensity with a time-dependent energy of 5–15 eV below the endpoint. The data analysis accounts for this anomaly by introducing two extra phenomenological fit parameters resulting in a best fit of $m_\nu^2 = -1.9 \pm 3.4 \pm 2.2$ eV^2 which is used to derive a neutrino mass limit. However, the introduction of phenomenological fit parameters which are correlated with the derived m_ν^2 limit makes unambiguous interpretation of this result difficult.

[14] WEINHEIMER 99 is a continuation of the work reported in WEINHEIMER 93 . Using a lower temperature of the frozen tritium source eliminated the dewetting of the T_2 film, which introduced a dependence of the fitted neutrino mass on the fit interval in the earlier work. An indication for a spectral anomaly reported in LOBASHEV 99 has been seen, but its time dependence does not agree with LOBASHEV 99. Two analyses, which exclude the spectral anomaly either by choice of the analysis interval or by using a particular data set which does not exhibit the anomaly, result in acceptable m_ν^2 fits and are used to derive the neutrino mass limit published by the authors. We list the most conservative of the two.

[15] BELESEV 95 (Moscow) use an integral electrostatic spectrometer with adiabatic magnetic collimation and a gaseous tritium sources. This value comes from a fit to a normal Kurie plot above 18300–18350 eV (to avoid a low-energy anomaly), including the effects of an apparent peak 7–15 eV below the endpoint.

[16] HIDDEMANN 95 (Munich) experiment uses atomic tritium embedded in a metal-dioxide lattice. They quote measurements from two data sets.

[17] STOEFFL 95 (LLNL) uses a gaseous source of molecular tritium. An anomalous pileup of events at the endpoint leads to the negative value for m_ν^2. The authors acknowledge that "the negative value for the best fit of m_ν^2 has no physical meaning" and discuss possible explanations for this effect.

[18] SUN 93 uses a tritiated hydrocarbon source. See also CHING 95.

[19] WEINHEIMER 93 (Mainz) is a measurement of the endpoint of the tritium β spectrum using an electrostatic spectrometer with a magnetic guiding field. The source is molecular tritium frozen onto an aluminum substrate.

[20] HOLZSCHUH 92B (Zurich) source is a monolayer of tritiated hydrocarbon.

[21] KAWAKAMI 91 (Tokyo) experiment uses tritium-labeled arachidic acid.

[22] ROBERTSON 91 (LANL) experiment uses gaseous molecular tritium. The result is in strong disagreement with the earlier claims by the ITEP group [LUBIMOV 80, BORIS 87 (+ BORIS 88 erratum)] that m_ν lies between 17 and 40 eV. However, the probability of a positive m_ν^2 is only 3% if statistical and systematic error are combined in quadrature.

ν MASS

These are measurement of m_ν (in contrast to $m_{\overline{\nu}}$, given above). The masses can be different for a Dirac neutrino in the absence of *CPT* invariance. The possible distinction between ν and $\overline{\nu}$ properties is usually ignored elsewhere in these Listings.

VALUE (eV)	CL%	DOCUMENT ID		TECN	COMMENT
$<$ 460	68	YASUMI	94	CNTR	^{163}Ho decay
$<$ 225	95	SPRINGER	87	CNTR	^{163}Ho decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< \; 4.5 \times 10^5$	90	CLARK	74	ASPK	K_{e3} decay
$<$4100	67	BECK	68	CNTR	^{22}Na decay

ν CHARGE

VALUE (units: electron charge)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-14}$	[23] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$	[24] RAFFELT	99	ASTR	Solar cooling
$<2 \times 10^{-15}$	[25] BARBIELLINI	87	ASTR	SN 1987A
$<1 \times 10^{-13}$	BERNSTEIN	63	ASTR	Solar energy losses

[23] This RAFFELT 99 limit applies to all neutrino flavors which are light enough ($<$5 keV) to be emitted from globular-cluster red giants.
[24] This RAFFELT 99 limit is derived from the helioseismological limit on a new energy-loss channel of the Sun, and applies to all neutrino flavors which are light enough ($<$1 keV) to be emitted from the sun.
[25] Precise BARBIELLINI 87 limit depends on assumptions about the intergalactic or galactic magnetic fields and about the direct distance and time through the field.

ν MEAN LIFE

Measures $\left[\sum |U_{\ell j}|^2 \; \Gamma_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. In most cases the limit pertains to any decaying neutrino. See footnotes for qualifications and exceptions.

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[26] BILLER	98	ASTR	m_ν= 0.05–1 eV
		[27] COWSIK	89	ASTR	m_ν = 1–50 MeV
		[28] RAFFELT	89	RVUE	$\overline{\nu}$ (Dirac, Majorana)
		[29] RAFFELT	89B	ASTR	
$>$278	90	[30] LOSECCO	87B	IMB	
$> \; 1.1 \times 10^{25}$		[31] HENRY	81	ASTR	m_ν= 16–20 eV
$> 10^{22}$–10^{23}		[32] KIMBLE	81	ASTR	m_ν= 10–100 eV

[26] BILLER 98 use the observed TeV γ-ray spectra to set limits on the mean life of any radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/\mathrm{B}_\gamma > 0.15 \times 10^{21}$ s at 0.05 eV, $> 1.2 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where B_γ is the branching ratio to photons.
[27] COWSIK 89 use observations of supernova SN 1987A to set the limit for the lifetime of a neutrino with $1 < m < 50$ MeV decaying through $\nu_H \rightarrow \nu e e$ to be $\tau > 4 \times 10^{15}$ $\exp(-m/5\text{ MeV})$ s.
[28] RAFFELT 89 uses KYULDJIEV 84 to obtain $\tau m^3 > 3 \times 10^{18}$ s eV^3 (based on $\overline{\nu} e^-$ cross sections). The bound is not valid if electric and magnetic transition moments are equal for Dirac neutrinos.
[29] RAFFELT 89B analyze stellar evolution and exclude the region $3 \times 10^{12} < \tau m^3 < 3 \times 10^{21}$ s eV^3.
[30] LOSECCO 87B assumes observed rate of 2.1 SNU (solar neutrino units) comes from sun while 7.0 ± 3.0 is theory.
[31] HENRY 81 uses UV flux from clusters of galaxies to find limit for radiative decay.
[32] KIMBLE 81 uses extreme UV flux limits.

ν (MEAN LIFE) / MASS

Measures $\left[\sum |U_{ej}|^2 \; \Gamma_j \; m_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. For many of the ASTR papers (RAFFELT 85 excepted), the limit applies to any ν in the indicated mass range.

VALUE (s/eV)	CL%	DOCUMENT ID		TECN	COMMENT
$>$ 7 $\times 10^9$		[33] RAFFELT	85	ASTR	
$>$ 300	90	[34] REINES	74	CNTR	$\overline{\nu}$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$> \; 8.7 \times 10^{-5}$	99	[35] BANDYOPA...	03	FIT	nonradiative decay
$\geq$ 4200	90	[36] DERBIN	02B	CNTR	Solar pp and Be ν
$> \; 2.8 \times 10^{-5}$	99	[37] JOSHIPURA	02B	FIT	nonradiative decay
$> \; 2.8 \times 10^{15}$		[38,39] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
$> \; 6.4$	90	[40] KRAKAUER	91	CNTR	ν at LAMPF
$> \; 6.3 \times 10^{15}$		[39,41] CHUPP	89	ASTR	$m_\nu < 20$ eV
$> \; 1.7 \times 10^{15}$		[39] KOLB	89	ASTR	$m_\nu < 20$ eV
$> \; 8.3 \times 10^{14}$		[42] VONFEILIT...	88	ASTR	
$>$ 22	68	[43] OBERAUER	87		$\overline{\nu}_R$ (Dirac)
$>$ 38	68	[43] OBERAUER	87		$\overline{\nu}$ (Majorana)
$>$ 59	68	[43] OBERAUER	87		$\overline{\nu}_L$ (Dirac)
$>$ 30	68	KETOV	86	CNTR	$\overline{\nu}$ (Dirac)
$>$ 20	68	KETOV	86	CNTR	$\overline{\nu}$ (Majorana)
$> \; 2 \; \times 10^{21}$		[44] STECKER	80	ASTR	m_ν= 10–100 eV

[33] RAFFELT 85 limit is from solar x- and γ-ray fluxes. Limit depends on ν flux from pp, now established from GALLEX and SAGE to be $>$ 0.5 of expectation.
[34] REINES 74 looked for ν of nonzero mass decaying to a neutral of lesser mass + γ. Used liquid scintillator detector near fission reactor. Finds lab lifetime 6×10^7 s or more. Above value of (mean life)/mass assumes average effective neutrino energy of 0.2 MeV. To obtain the limit 6×10^7 s REINES 74 assumed that the full $\overline{\nu}$ reactor flux could be responsible for yielding decays with photon energies in the interval 0.1 MeV – 0.5 MeV. This represents some overestimate so their lower limit is an over-estimate of the lab lifetime (VOGEL 84). If so, OBERAUER 87 may be comparable or better.
[35] The ratio of the lifetime over the mass derived by BANDYOPADHYAY 03 is for ν_2. They obtained this result using the following solar-neutrino data: total rates measured in Cl and Ga experiments, the Super-Kamiokande's zenith-angle spectra, and SNO's day and night spectra. They assumed that ν_1 is the lowest mass, stable or nearly stable neutrino state and ν_2 decays through nonradiative Majoron emission process, $\nu_2 \rightarrow \overline{\nu}_1 + J$, or through nonradiative process with all the final state particles being sterile. The best fit is obtained in the region of the LMA solution.
[36] DERBIN 02B (also BACK 03B) obtained this bound from the results of background measurements with Counting Test Facility (the prototype of the Borexino detector). The laboratory gamma spectrum is given as $dN_\gamma/d\cos\theta = (1/2)\,(1 + \alpha\cos\theta)$ with α=0 for a Majorana neutrino, and α varying to -1 to 1 for a Dirac neutrino. The listed bound is for the case of α=0. The most conservative bound 1.5×10^3 s eV^{-1} is obtained for the case of α=-1.
[37] The ratio of the lifetime over the mass derived by JOSHIPURA 02B is for ν_2. They obtained this result from the total rates measured in all solar neutrino experiments. They assumed that ν_1 is the lowest mass, stable or nearly stable neutrino state and ν_2 decays through nonradiative process like Majoron emission decay, $\nu_2 \rightarrow \nu'_1 + J$ where ν'_1 state is sterile. The exact limit depends on the specific solution of the solar neutrino problem. The quoted limit is for the LMA solution.
[38] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.
[39] Nonobservation of γ's in coincidence with ν's from SN 1987A.
[40] KRAKAUER 91 quotes the limit $\tau/m_\nu > (0.3a^2 + 9.8a + 15.9)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).
[41] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.
[42] Model-dependent theoretical analysis of SN 1987A neutrinos.
[43] OBERAUER 87 bounds are from comparison of observed and expected rate of reactor neutrinos.
[44] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

$|(\mathrm{v} - c)\,/c|$ (v $\equiv$ ν VELOCITY)

Expected to be zero for massless neutrino, but tests also whether photons and neutrinos have the same limiting velocity in vacuum.

VALUE (units 10^{-8})	EVTS	DOCUMENT ID		TECN	COMMENT
$<$1	17	[45] STODOLSKY	88	ASTR	SN 1987A
$<$0.2		[46] LONGO	87	ASTR	SN 1987A

[45] STODOLSKY 88 result based on $<$10 hr between $\overline{\nu}$ detection in IMB and KAMI detectors and beginning of light signal. Inclusion of the problematic 5 neutrino events from Mont Blanc (four hours later) does not change the result.
[46] LONGO 87 argues that uncertainty between light and neutrino transit times is $\pm$3 hr, ignoring Mont Blanc events.

ν MAGNETIC MOMENT

Must vanish for a purely chiral massless Dirac neutrino. A massive Dirac or Majorana neutrino can have a transition magnetic moment connecting one mass eigenstate to another one. The experimental limits below usually cannot distinguish between the true (diagonal, in mass) magnetic moment and a transition magnetic moment. The value of the magnetic moment for the standard SU(2)$\times$U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2})$ $= (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_\nu < 3$ eV, it follows that for the extended standard electroweak theory, $\mu_\nu < 1 \times 10^{-18}\ \mu_B$. Current experiments are not yet challenging this limit. There is considerable controversy over the validity of many of the claimed upper limits on the magnetic moment from the astrophysical data. For example, VOLOSHIN 90 states that "in connection with the astrophysical limits on μ_ν, ... there is by now a general consensus that contrary to the initial claims (BARBIERI 88, LATTIMER 88, GOLDMAN 88, NOTZOLD 88), essentially no better than quoted limits (from previous constraints) can be derived from detection of the neutrino flux from the supernova SN1987A." See VOLOSHIN 88 and VOLOSHIN 88C.

VALUE ($10^{-10}\ \mu_B$)	CL%	DOCUMENT ID		TECN	COMMENT
$<$ 1.0	90	[47] DARAKTCH...	03		Reactor $\overline{\nu}_e$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 5.5	90	[48] BACK	03B	CNTR	Solar pp and Be ν
$<$ 1.3	90	[49] LI	03B	CNTR	Reactor $\overline{\nu}_e$

< 2	90	[50] GRIMUS	02 FIT	solar + reactor (Majorana ν)
< 0.01–0.04		[51] AYALA	99 ASTR	$\nu_L \to \nu_R$ in SN 1987A
< 1.5	90	[52] BEACOM	99 SKAM	ν spectrum shape
< 0.03		[53] RAFFELT	99 ASTR	Red giant luminosity
< 4		[54] RAFFELT	99 ASTR	Solar cooling
< 0.62		[55] ELMFORS	97 COSM	Depolarization in early universe plasma
< 1.9	95	[56] DERBIN	93 CNTR	Reactor $\overline{\nu}e \to \overline{\nu}e$
< 2.4	90	[57] VIDYAKIN	92 CNTR	Reactor $\overline{\nu}e \to \overline{\nu}e$
<10.8	90	[58] KRAKAUER	90 CNTR	LAMPF $\nu e \to \nu e$
< 0.02		[59] RAFFELT	90 ASTR	Red giant luminosity
< 0.1		[60] RAFFELT	89B ASTR	Cooling helium stars
		[61] FUKUGITA	88 COSM	Primordial magn. fields
$\leq .3$		[60] RAFFELT	88B ASTR	He burning stars
< 0.11		[60] FUKUGITA	87 ASTR	Cooling helium stars
< 0.1–0.2		MORGAN	81 COSM	^{4}He abundance
< 0.85		BEG	78 ASTR	Stellar plasmons
< 0.6		[62] SUTHERLAND	76 ASTR	Red giants + degenerate dwarfs
< 1		BERNSTEIN	63 ASTR	Solar cooling
<14		COWAN	57 CNTR	Reactor $\overline{\nu}$

[47] Search for non-standard $\overline{\nu}_e$-e scattering component at Bugey nuclear reactor. Full kinematical event reconstruction by use of TPC. Most stringent laboratory limit on magnetic moment.

[48] BACK 03B obtained this bound from the results of background measurements with Counting Test Facility (the prototype of the Borexino detector). Standard Solar Model flux was assumed. This μ_ν can be different from the reactor μ_ν in certain oscillation scenarios (see BEACOM 99).

[49] LI 03B used Ge detector in active shield near nuclear reactor to test for nonstandard $\overline{\nu}_e$-e scattering.

[50] GRIMUS 02 obtain stringent bounds on all Majorana neutrino transition moments from a simultaneous fit of LMA-MSW oscillation parameters and transition moments to global solar neutrino data + reactor data. Using only solar neutrino data, a 90% CL bound of $6.3 \times 10^{-10} \mu_B$ is obtained.

[51] AYALA 99 improves the limit of BARBIERI 88.

[52] BEACOM 99 obtain the limit using the shape, but not the absolute magnitude which is affected by oscillations, of the solar neutrino spectrum obtained by Superkamiokande (825 days). This μ_ν can be different from the reactor μ_ν in certain oscillation scenarios.

[53] RAFFELT 99 is an update of RAFFELT 90. This limit applies to all neutrino flavors which are light enough ($<$ 5 keV) to be emitted from globular-cluster red giants. This limit pertains equally to electric dipole moments and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

[54] RAFFELT 99 is essentially an update of BERNSTEIN 63, but is derived from the helioseismological limit on a new energy-loss channel of the Sun. This limit applies to all neutrino flavors which are light enough ($<$1 keV) to be emitted from the Sun. This limit pertains equally to electric dipole and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

[55] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[56] DERBIN 93 determine the cross section for 0.6–2.0 MeV electron energy as $(1.28 \pm 0.63) \times \sigma_{\text{weak}}$. However, the (reactor on − reactor off)/(reactor off) is only $\sim 1/100$.

[57] VIDYAKIN 92 limit is from a $e\overline{\nu}_e$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[58] KRAKAUER 90 experiment fully reported in ALLEN 93.

[59] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[60] Significant dependence on details of stellar models.

[61] FUKUGITA 88 find magnetic dipole moments of any two neutrino species are bounded by $\mu < 10^{-16}$ $[10^{-9}\ G/B_0]$ where B_0 is the present-day intergalactic field strength.

[62] We obtain above limit from SUTHERLAND 76 using their limit $f < 1/3$.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared. While the straight-forward definition of a neutrino charge radius has been proven to be gauge-dependent and, hence, unphysical (LEE 77C), there have been recent attempts to define a physically observable neutrino charge radius (BERNABEU 00, BERNABEU 02). The issue is still controversial (FUJIKAWA 03, BERNABEU 03). A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
-2.97 to 4.14	90	[63] AUERBACH	01 LSND	$\nu_e e \to \nu_e e$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.9 $\pm$2.7		ALLEN	93 CNTR	LAMPF $\nu e \to \nu e$
< 2.3	95	MOURAO	92 ASTR	HOME/KAM2 ν rates
< 7.3	90	[64] VIDYAKIN	92 CNTR	Reactor $\overline{\nu}e \to \overline{\nu}e$
1.1 $\pm$2.3		ALLEN	91 CNTR	Repl. by ALLEN 93
		[65] GRIFOLS	89B ASTR	SN 1987A

[63] AUERBACH 01 measure $\nu_e e$ elastic scattering with LSND detector. The cross section agrees with the Standard Model expectation, including the charge and neutral current interference. The 90% CL applies to the range shown.

[64] VIDYAKIN 92 limit is from a $e\overline{\nu}$ elastic scattering experiment. No experimental details are given except for the cross section from which this limit is derived. Signal/noise was 1/10. The limit uses $\sin^2\theta_W = 0.23$ as input.

[65] GRIFOLS 89B sets a limit of $\langle r^2 \rangle < 0.2 \times 10^{-32}$ cm^2 for right-handed neutrinos.

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ν_μ

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with μ^+ or μ^-. See Note on "Electron, muon, and tau neutrino listings."

ν MASS

In the context of some models, it is possible that this weighted sum over mass eigenstates is the same as for the neutrinos produced in τ decay.

In some of the ASTR and COSM papers listed below, the authors did not distinguish between weak and mass eigenstates.

OUR EVALUATION is based on OUR AVERAGE for the $\pi^\pm$ mass and the ASSAMAGAN 96 value for the muon momentum for the π^+ decay at rest. The limit is calculated using the unified classical analysis of FELDMAN 98 for a Gaussian distribution near a physical boundary. WARNING: since $m^{2(\text{eff})}_{\nu_\mu}$ is calculated from the differences of large numbers, it and the corresponding limits are extraordinarily sensitive to small changes in the pion mass, the decay muon momentum, and their errors. For example, the limits obtained using the JECKELMANN 94, LENZ 98, and the weighted averages are 0.15, 0.29, and 0.19 MeV, respectively.

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
<0.19 (CL = 90%) OUR EVALUATION					
<0.17	90	[1] ASSAMAGAN	96	SPEC	$m_\nu^2 = -0.016 \pm 0.023$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.15		[2] DOLGOV	95	COSM	Nucleosynthesis
<0.48		[3] ENQVIST	93	COSM	Nucleosynthesis
<0.3		[4] FULLER	91	COSM	Nucleosynthesis
<0.42		[4] LAM	91	COSM	Nucleosynthesis
<0.50	90	[5] ANDERHUB	82	SPEC	$m_\nu^2 = -0.14 \pm 0.20$
<0.65	90	CLARK	74	ASPK	$K_{\mu3}$ decay

[1] ASSAMAGAN 96 measurement of p_μ from $\pi^+ \to \mu^+ \nu$ at rest combined with JECKELMANN 94 Solution B pion mass yields $m_\nu^2 = -0.016 \pm 0.023$ with corresponding Bayesian limit listed above. If Solution A is used, $m_\nu^2 = -0.143 \pm 0.024$ MeV^2. Replaces ASSAMAGAN 94.

[2] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits.

[3] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, $\sim$ 1 s.

[4] Assumes neutrino lifetime >1 s. For Dirac neutrinos only. See also ENQVIST 93.

[5] ANDERHUB 82 kinematics is insensitive to the pion mass.

$m_\nu - m_{\overline{\nu}}$

Test of *CPT* for a Dirac neutrino. (Not a very strong test.)

VALUE (MeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.45	90	CLARK	74	ASPK	$K_{\mu3}$ decay

ν (MEAN LIFE) / MASS

Measures $\left[\sum |U_{\ell j}|^2\, \Gamma_j\, m_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. Most of these limits apply to any ν within the indicated mass range.

VALUE (s/eV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
>15.4	90		[6] KRAKAUER	91	CNTR	ν_μ, $\overline{\nu}_\mu$ at LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •						
			[7] BILLER	98	ASTR	m_ν= 0.05–1 eV
$> 2.8 \times 10^{15}$			[8,9] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
none 10^{-12} – 5×10^4			[10] DODELSON	92	ASTR	m_ν=1–300 keV
$> 6.3 \times 10^{15}$			[9,11] CHUPP	89	ASTR	$m_\nu < 20$ eV
$> 1.7 \times 10^{15}$			[9] KOLB	89	ASTR	$m_\nu < 20$ eV
$> 3.3 \times 10^{14}$			[12,13] VONFEILIT...	88	ASTR	
> 0.11	90	0	[14] FRANK	81	CNTR	$\nu\overline{\nu}$ LAMPF
			[15] HENRY	81	ASTR	m_ν= 16–20 eV
			[16] KIMBLE	81	ASTR	m_ν= 10–100 eV
			[17] REPHAELI	81	ASTR	m_ν= 30–150 eV
			[18] DERUJULA	80	ASTR	m_ν= 10–100 eV
$> 2 \times 10^{21}$			[19] STECKER	80	ASTR	m_ν= 10–100 eV
$> 1.0 \times 10^{-2}$	90	0	[14] BLIETSCHAU	78	HLBC	ν_μ, CERN GGM
$> 1.7 \times 10^{-2}$	90	0	[14] BLIETSCHAU	78	HLBC	$\overline{\nu}_\mu$, CERN GGM
$> 2.2 \times 10^{-3}$	90	0	[14] BARNES	77	DBC	ν, ANL 12-ft
$> 3. \times 10^{-3}$	90	0	[14] BELLOTTI	76	HLBC	ν, CERN GGM
$> 1.3 \times 10^{-2}$	90	1	[14] BELLOTTI	76	HLBC	$\overline{\nu}$, CERN GGM

[6] KRAKAUER 91 quotes the limit $\tau/m_{\nu_1} > (0.75a^2 + 21.65a + 26.3)$ s/eV, where a is a parameter describing the asymmetry in the neutrino decay defined as $dN_\gamma/d\cos\theta = (1/2)(1 + a\cos\theta)$ The parameter $a = 0$ for a Majorana neutrino, but can vary from -1 to 1 for a Dirac neutrino. The bound given by the authors is the most conservative (which applies for $a = -1$).

[7] BILLER 98 use the observed TeV γ-ray spectra to set limits on the mean life of a radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/\text{B}_\gamma > 0.15 \times 10^{21}$ s at 0.05 eV, $> 1.2 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where B_γ is the branching ratio to photons.

[8] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.

[9] Nonobservation of γ's in coincidence with ν's from SN 1987A. Results should be divided by the $\nu \to \gamma X$ branching ratio.

[10] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.

[11] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.

[12] Model-dependent theoretical analysis of SN 1987A neutrinos.

[13] Limit applies to ν_τ also.

[14] These experiments look for $\nu_k \to \nu_j \gamma$ or $\overline{\nu}_k \to \overline{\nu}_j \gamma$.

[15] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.

[16] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.

[17] REPHAELI 81 consider the effect of radiative neutrino decay on neutral H in early universe based on M31 HI. They conclude $\tau > 10^{24}$ s.

[18] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.

[19] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m_\nu = 20$ eV.

ν CHARGE

VALUE (units: electron charge)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-14}$	[20] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$	[21] RAFFELT	99	ASTR	Solar cooling

[20] This RAFFELT 99 limit applies to all neutrinos which are light enough (<5 kEV) to be emitted from globular-cluster red giants.

[21] This RAFFELT 99 limit is derived from the helioseismological limit on a new energy-loss channel of the Sun, and applies to all neutrinos which are light enough (<1 keV) to be emitted from the sun.

$|(v - c)/c|$ ($v \equiv \nu$ VELOCITY)

Expected to be zero for massless neutrino, but also tests whether photons and neutrinos have the same limiting velocity in vacuum.

VALUE (units 10^{-4})	CL%	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •							
<0.4	95	9800	KALBFLEISCH	79	SPEC		
<2.0	99	77	ALSPECTOR	76	SPEC	0	>5 GeV ν
<4.0	99	26	ALSPECTOR	76	SPEC	0	<5 GeV ν

ν MAGNETIC MOMENT

Must vanish for a purely chiral massless Dirac neutrino. A massive Dirac or Majorana neutrino can have a transition magnetic moment connecting one mass eigenstate to another one. The experimental limits below usually cannot distinguish between the true (diagonal, in mass) magnetic moment and a transition magnetic moment. The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.2 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_\nu < 0.19$ MeV, it follows that for the extended standard electroweak theory, $\mu_\nu < 6 \times 10^{-14}\ \mu_B$.

VALUE ($10^{-10}\ \mu_B$)	CL%	DOCUMENT ID		TECN	COMMENT
< 6.8	90	[22] AUERBACH	01	LSND	$\nu_e e$ scatt.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 2	90	[23] GRIMUS	02	FIT	solar + reactor (Majorana ν)
< 0.03		[24] RAFFELT	99	ASTR	Red giant luminosity
< 4		[25] RAFFELT	99	ASTR	Solar cooling
< 0.62		[26] ELMFORS	97	COSM	Depolarization in early universe plasma
< 30	90	VILAIN	95B	CHM2	$\nu_\mu e \to \nu_\mu e$
<100	95	[27] DORENBOS...	91	CHRM	$\nu_\mu e \to \nu_\mu e$
< 8.5	90	AHRENS	90	CNTR	$\nu_\mu e \to \nu_\mu e$
< 7.4	90	[28] KRAKAUER	90	CNTR	LAMPF (ν_μ, $\overline{\nu}_\mu$) e elast.
< 0.02		[29] RAFFELT	90	ASTR	Red giant luminosity
< 0.1		[30] RAFFELT	89B	ASTR	Cooling helium stars
< 0.11		[30,31] FUKUGITA	87	ASTR	Cooling helium stars
< 0.0006		[32] NUSSINOV	87	ASTR	Cosmic EM backgrounds
< 0.85		[31] BEG	78	ASTR	Stellar plasmons
< 81		[33] KIM	74	RVUE	$\overline{\nu}_\mu e \to \overline{\nu}_\mu e$
< 1		[34] BERNSTEIN	63	ASTR	Solar cooling

[22] AUERBACH 01 limit is based on the LSND ν_e and ν_μ electron scattering measurements. The limit is slightly more stringent than KRAKAUER 90.

[23] GRIMUS 02 obtain stringent bounds on all Majorana neutrino transition moments from a simultaneous fit of LMA-MSW oscillation parameters and transition moments to global solar neutrino data + reactor data. Using only solar neutrino data, a 90% CL bound of $6.3 \times 10^{-10} \mu_B$ is obtained.

[24] RAFFELT 99 is an update of RAFFELT 90. This limit applies to all neutrino flavors which are light enough (< 5 keV) to be emitted from globular-cluster red giants. This limit pertains equally to electric dipole moments and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

[25] RAFFELT 99 is essentially an update of BERNSTEIN 63, but is derived from the helioseismological limit on a new energy-loss channel of the Sun. This limit applies to all neutrino flavors which are light enough (<1 keV) to be emitted from the Sun. This limit pertains equally to electric dipole and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.

[26] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[27] DORENBOSCH 91 corrects an incorrect statement in DORENBOSCH 89 that the ν magnetic moment is $< 1 \times 10^{-9}$ at the 95%CL. DORENBOSCH 89 measures both $\nu_\mu e$ and $\overline{\nu} e$ elastic scattering and assume $\mu(\nu) = \mu(\overline{\nu})$.

[28] KRAKAUER 90 experiment fully reported in ALLEN 93.

[29] RAFFELT 90 limit applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.

[30] Significant dependence on details of stellar properties.

[31] If m_ν < 10 keV.

[32] For m_ν = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\mu \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for m_ν > 16 eV and $< 6 \times 10^{-14}$ for m_ν > 4 eV.

[33] KIM 74 is a theoretical analysis of $\overline{\nu}_\mu$ reaction data.

[34] If m_ν < 1 keV.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared. While the straight-forward definition of a neutrino charge radius has been proven to be gauge-dependent and, hence, unphysical (LEE 77C), there have been recent attempts to define a physically observable neutrino charge radius (BERNABEU 00, BERNABEU 02). The issue is still controversial (FUJIKAWA 03, BERNABEU 03). A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.68, > −0.53	90	[35] HIRSCH	03		νe scat.
< |0.6|	90	VILAIN	95B	CHM2	νe elastic scat.
−1.1±1.0		[36] AHRENS	90	CNTR	νe elastic scat.
−0.3±1.5		[36] DORENBOS...	89	CHRM	νe elastic scat.

[35] Based on analysis of CCFR 98 results. Limit is on $\langle r_V^2 \rangle + \langle r_A^2 \rangle$. The CHARM II and E734 at BNL results are reanalyzed, and weaker bounds on the charge radius squared than previously published are obtained. The NuTeV result is discussed; when tentatively interpreted as ν_μ charge radius it implies $\langle r_V^2 \rangle + \langle r_A^2 \rangle = (4.20 \pm 1.64) \times 10^{-33}$ cm^2.

[36] Result is obtained from reanalysis given in ALLEN 91, followed by our reduction to obtain 1 σ errors.

ν_μ REFERENCES

BERNABEU	03	hep-ph/0303202	J. Bernabeu, J. Papavassiliou, J. Vidal	
FUJIKAWA	03	hep-ph/0303188	K. Fujikawa, R. Shrock	
HIRSCH	03	PR D67 033005	M. Hirsch *et al.*	
BERNABEU	02	PRL 89 101802	J. Bernabeu, J. Papavassiliou, J. Vidal	
Also	02B	PRL 89 229902 (erratum)	J. Bernabeu, J. Papavassiliou, J. Vidal	
GRIMUS	02	NP B648 376	W. Grimus *et al.*	
AUERBACH	01	PR D63 112001	L.B. Auerbach *et al.*	(LSND Collab.)
BERNABEU	00	PR D62 113012	J. Bernabeu *et al.*	
RAFFELT	99	PRPL 320 319	G.G. Raffelt	
BILLER	98	PRL 80 2992	S.D. Biller *et al.*	(WHIPPLE Collab.)
FELDMAN	98	PR D57 3873	G.J. Feldman, R.D. Cousins	
LENZ	98	PL B416 50	S. Lenz *et al.*	
ELMFORS	97	NP B503 3	P. Elmfors *et al.*	
ASSAMAGAN	96	PR D53 6065	K.A. Assamagan *et al.*	(PSI, ZURI, VILL+)
DOLGOV	95	PR D51 4129	A.D. Dolgov, K. Kainulainen, I.Z. Rothstein	(MICH+)
VILAIN	95B	PL B345 115	P. Vilain *et al.*	(CHARM II Collab.)
ASSAMAGAN	94	PL B335 231	K.A. Assamagan *et al.*	(PSI, ZURI, VILL+)
JECKELMANN	94	PL B335 326	B. Jeckelmann, P.F.A. Goudsmit, H.J. Leisi	(WABRN+)
ALLEN	93	PR D47 11	R.C. Allen *et al.*	(UCI, LANL, ANL+)
DOLGOV	93	PRL 71 476	A.D. Dolgov, I.Z. Rothstein	(MICH)
ENQVIST	93	PL B301 376	K. Enqvist, H. Uibo	(NORD)
BLUDMAN	92	PR D45 4720	S.A. Bludman	(CFPA)
DODELSON	92	PRL 68 2572	S. Dodelson, J.A. Frieman, M.S. Turner	(FNAL+)
ALLEN	91	PR D43 R1	R.C. Allen *et al.*	(UCI, LANL, UMD)
DORENBOS...	91	ZPHY C51 142	J. Dorenbosch *et al.*	(CHARM Collab.)
FULLER	91	PR D43 3136	G.M. Fuller, R.A. Malaney	(UCSD)
KRAKAUER	91	PR D44 R6	D.A. Krakauer *et al.*	(LAMPF E225 Collab.)
LAM	91	PR D44 3345	W.P. Lam, K.W. Ng	(AST)
AHRENS	90	PR D41 3297	L.A. Ahrens *et al.*	(BNL, BROW, HIRO+)
KRAKAUER	90	PL B252 177	D.A. Krakauer *et al.*	(LAMPF E225 Collab.)
RAFFELT	90	PRL 64 2856	G.G. Raffelt	(MPIM)
CHUPP	89	PRL 62 505	E.L. Chupp, W.T. Vestrand, C. Reppin	(UNH, MPIM)
DORENBOS...	89	ZPHY C41 567	J. Dorenbosch *et al.*	(CHARM Collab.)
KOLB	89	PRL 62 509	E.W. Kolb, M.S. Turner	(CHIC, FNAL)
RAFFELT	89B	APJ 336 61	G. Raffelt, D. Dearborn, J. Silk	(UCB, LLL)
VONFEILIT...	88	PL B200 580	F. von Feilitzsch, L. Oberauer	(MUNT)
FUKUGITA	87	PR D36 3817	M. Fukugita, S. Yazaki	(KYOTU, TOKY)
NUSSINOV	87	PR D36 2278	S. Nussinov, Y. Rephaeli	(TELA)
ANDERHUB	82	PL 114B 76	H.B. Anderhub *et al.*	(ETH, SIN)
FRANK	81	PR D24 2001	J.S. Frank *et al.*	(LASL, YALE, MIT+)
HENRY	81	PRL 47 618	R.C. Henry, P.D. Feldman	(JHU)
KIMBLE	81	PRL 46 80	R. Kimble, S. Bowyer, P. Jakobsen	(UCB)
REPHAELI	81	PL 106B 73	Y. Rephaeli, A.S. Szalay	(UCSB, CHIC)
DERUJULA	80	PRL 45 942	A. De Rujula, S.L. Glashow	(MIT, HARV)
FUJIKAWA	80	PRL 45 963	K. Fujikawa, R. Shrock	(STON)
STECKER	80	PRL 45 1460	F.W. Stecker	(NASA)
KALBFLEISCH	79	PRL 43 1361	G.R. Kalbfleisch *et al.*	(FNAL, PURD, BELL)
BEG	78	PR D17 1395	M.A.B. Beg, W.J. Marciano, M. Ruderman	(ROCK+)
BLIETSCHAU	78	NP B133 205	J. Blietschau *et al.*	(Gargamelle Collab.)
BARNES	77	PRL 38 1049	V.E. Barnes *et al.*	(PURD, ANL)
LEE	77C	PR D16 1444	B.W. Lee, R.E. Shrock	(STON)
ALSPECTOR	76	PRL 36 837	J. Alspector *et al.*	(BNL, PURD, CIT+)
BELLOTTI	76	LNC 17 553	E. Bellotti *et al.*	(MILA)
CLARK	74	PR D9 533	A.R. Clark *et al.*	(LBL)
KIM	74	PR D9 3050	J.E. Kim, V.S. Mathur, S. Okubo	(ROCH)
BERNSTEIN	63	PR 132 1227	J. Bernstein, M. Ruderman, G. Feinberg	(NYU+)

ν_τ

$J = \frac{1}{2}$

The following results are obtained using neutrinos associated with τ^+ or τ^-. See Note on "Electron, muon, and tau neutrino listings."

The ν_τ was directly observed by the DONUT Collaboration (KODAMA 01). Existence indirectly established from τ decay data combined with ν reaction data. See for example FELDMAN 81. ALBRECHT 92Q rules out $J = 3/2$ by establishing that the ρ^- is not in a pure H_ρ=−1 helicity state in $\tau^- \rightarrow \rho^- \nu_\tau$.

ν MASS

In the context of some models, it is possible that this weighted sum over mass eigenstates is the same as for the neutrinos produced in μ decay.

In some of the ASTR and COSM papers listed below, the authors did not distinguish between weak and mass eigenstates.

VALUE (MeV)	*CL%*	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 18.2	95		[1] BARATE	98F	ALEP	1991–1995 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 28	95		[2] ATHANAS	00	CLEO	E^{ee}_{cm} = 10.6 GeV
< 27.6	95		[3] ACKERSTAFF	98T	OPAL	1990–1995 LEP runs
< 30	95	473	[4] AMMAR	98	CLEO	E^{ee}_{cm} = 10.6 GeV
< 60	95		[5] ANASTASSOV	97	CLEO	E^{ee}_{cm} = 10.6 GeV
< 0.37 or >22			[6] FIELDS	97	COSM	Nucleosynthesis
< 68	95		[7] SWAIN	97	THEO	m_τ, τ_τ, τ partial widths
< 29.9	95		[8] ALEXANDER	96M	OPAL	1990–1994 LEP runs
<149			[9] BOTTINO	96	THEO	π, μ, τ leptonic decays
<1 or >25			[10] HANNESTAD	96C	COSM	Nucleosynthesis
< 71	95		[11] SOBIE	96	THEO	m_τ, τ_τ, B($\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$)
< 24	95	25	[12] BUSKULIC	95H	ALEP	1991–1993 LEP runs
< 0.19			[13] DOLGOV	95	COSM	Nucleosynthesis
< 3			[14] SIGL	95	ASTR	SN 1987A
< 0.4 or > 30			[15] DODELSON	94	COSM	Nucleosynthesis
< 0.1 or > 50			[16] KAWASAKI	94	COSM	Nucleosynthesis
155–225			[17] PERES	94	THEO	π,K,μ,τ weak decays
< 32.6	95	113	[18] CINABRO	93	CLEO	$E^{ee}_{cm} \approx$ 10.6 GeV
< 0.3 or > 35			[19] DOLGOV	93	COSM	Nucleosynthesis
< 0.74			[20] ENQVIST	93	COSM	Nucleosynthesis
< 31	95	19	[21] ALBRECHT	92M	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
< 0.3			[22] FULLER	91	COSM	Nucleosynthesis
< 0.5 or > 25			[23] KOLB	91	COSM	Nucleosynthesis
< 0.42			[22] LAM	91	COSM	Nucleosynthesis

[1] BARATE 98F result based on kinematics of 2939 $\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$ and 52 $\tau^- \rightarrow 3\pi^-2\pi^+(\pi^0)\nu_\tau$ decays. If possible 2.5% excited a_1 decay is included in 3-prong sample analysis, limit increases to 19.2 MeV.

[2] ATHANAS 00 bound comes from analysis of $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ decays.

[3] ACKERSTAFF 98T use $\tau \rightarrow 5\pi^\pm\nu_\tau$ decays to obtain a limit of 43.2 MeV (95%CL). They combine this with ALEXANDER 96M value using $\tau \rightarrow 3h^\pm\nu_\tau$ decays to obtain quoted limit.

[4] AMMAR 98 limit comes from analysis of $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \rightarrow 2\pi^-\pi^+2\pi^0\nu_\tau$ decay modes.

[5] ANASTASSOV 97 derive limit by comparing their m_τ measurement (which depends on m_{ν_τ}) to BAI 96 m_τ threshold measurement.

[6] FIELDS 97 limit for a Dirac neutrino. For a Majorana neutrino the mass region < 0.93 or >31 MeV is excluded. These bounds assume N_ν <4 from nucleosynthesis; a wider excluded region occurs with a smaller N_ν upper limit.

[7] SWAIN 97 derive their limit from the Standard Model relationships between the tau mass, lifetime, branching fractions for $\tau^- \rightarrow e^-\overline{\nu}_e\nu_\tau$, $\tau^- \rightarrow \mu^-\overline{\nu}_\mu\nu_\tau$, $\tau^- \rightarrow \pi^-\nu_\tau$, and $\tau^- \rightarrow K^-\nu_\tau$, and the muon mass and lifetime by assuming lepton universality and using world average values. Limit is reduced to 48 MeV when the CLEO τ mass measurement (BALEST 93) is included; see CLEO's more recent m_{ν_τ} limit (ANASTASSOV 97). Consideration of mixing with a fourth generation heavy neutrino yields $\sin^2\theta_L < 0.016$ (95%CL).

[8] ALEXANDER 96M bound comes from analyses of $\tau^- \rightarrow 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \rightarrow h^-h^-h^+\nu_\tau$ decays.

[9] BOTTINO 96 assumes three generations of neutrinos with mixing, finds consistency with massless neutrinos with no mixing based on 1995 data for masses, lifetimes, and leptonic partial widths.
[10] HANNESTAD 96C limit is on the mass of a Majorana neutrino. This bound assumes $N_\nu < 4$ from nucleosynthesis. A wider excluded region occurs with a smaller N_ν upper limit. This paper is the corrected version of HANNESTAD 96; see the erratum: HANNESTAD 96B.
[11] SOBIE 96 derive their limit from the Standard Model relationship between the tau mass, lifetime, and leptonic branching fraction, and the muon mass and lifetime, by assuming lepton universality and using world average values.
[12] BUSKULIC 95H bound comes from a two-dimensional fit of the visible energy and invariant mass distribution of $\tau \to 5\pi(\pi^0)\nu_\tau$ decays. Replaced by BARATE 98F.
[13] DOLGOV 95 removes earlier assumptions (DOLGOV 93) about thermal equilibrium below T_{QCD} for wrong-helicity Dirac neutrinos (ENQVIST 93, FULLER 91) to set more stringent limits. DOLGOV 96 argues that a possible window near 20 MeV is excluded.
[14] SIGL 95 exclude massive Dirac or Majorana neutrinos with lifetimes between 10^{-3} and 10^8 seconds if the decay products are predominantly γ or e^+e^-.
[15] DODELSON 94 calculate constraints on ν_τ mass and lifetime from nucleosynthesis for 4 generic decay modes. Limits depend strongly on decay mode. Quoted limit is valid for all decay modes of Majorana neutrinos with lifetime greater than about 300 s. For Dirac neutrinos limits change to < 0.3 or > 33.
[16] KAWASAKI 94 excluded region is for Majorana neutrino with lifetime >1000 s. Other limits are given as a function of ν_τ lifetime for decays of the type $\nu_\tau \to \nu_\mu \phi$ where ϕ is a Nambu-Goldstone boson.
[17] PERES 94 used PDG 92 values for parameters to obtain a value consistent with mixing. Reexamination by BOTTINO 96 which included radiative corrections and 1995 PDG parameters resulted in two allowed regions, $m_3 < 70$ MeV and 140 MeV $m_3 < 149$ MeV.
[18] CINABRO 93 bound comes from analysis of $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ and $\tau^- \to 2\pi^-\pi^+2\pi^0\nu_\tau$ decay modes.
[19] DOLGOV 93 assumes neutrino lifetime >100 s. For Majorana neutrinos, the low mass limit is 0.5 MeV. KAWANO 92 points out that these bounds can be overcome for a Dirac neutrino if it possesses a magnetic moment. See also DOLGOV 96.
[20] ENQVIST 93 bases limit on the fact that thermalized wrong-helicity Dirac neutrinos would speed up expansion of early universe, thus reducing the primordial abundance. FULLER 91 exploits the same mechanism but in the older calculation obtains a larger production rate for these states, and hence a lower limit. Neutrino lifetime assumed to exceed nucleosynthesis time, ~ 1 s.
[21] ALBRECHT 92M reports measurement of a slightly lower τ mass, which has the effect of reducing the ν_τ mass reported in ALBRECHT 88B. Bound is from analysis of $\tau^- \to 3\pi^-2\pi^+\nu_\tau$ mode.
[22] Assumes neutrino lifetime >1 s. For Dirac neutrinos. See also ENQVIST 93.
[23] KOLB 91 exclusion region is for Dirac neutrino with lifetime >1 s; other limits are given.

ν (MEAN LIFE) / MASS

Measures $\left[\sum |U_{\ell j}|^2 \Gamma_j m_j\right]^{-1}$, where the sum is over mass eigenstates which cannot be resolved experimentally. Most of these limits apply to any ν within the indicated mass range.

VALUE (s/eV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[24] DOLGOV	99	COSM	
	[25] BILLER	98	ASTR	m_ν= 0.05–1 eV
$>1 \times 10^{14}$	[26] SIGL	95	ASTR	$m_\nu >$ few MeV
$>2.8 \times 10^{15}$	[27,28] BLUDMAN	92	ASTR	$m_\nu < 50$ eV
$< 10^{-12}$ or $> 5 \times 10^4$	[29] DODELSON	92	ASTR	m_ν=1–300 keV
	[30] GRANEK	91	COSM	Decaying L^0
	[31] WALKER	90	ASTR	m_ν= 0.03 – ~ 2 MeV
$>6.3 \times 10^{15}$	[28,32] CHUPP	89	ASTR	$m_\nu < 20$ eV
$>1.7 \times 10^{15}$	[28] KOLB	89	ASTR	$m_\nu < 20$ eV
	[33] TERASAWA	88	COSM	m_μ= 30–70 MeV
	[34] KAWASAKI	86	COSM	m_ν >10 MeV
	[35] LINDLEY	85	COSM	$m_\nu >$ 10 MeV
	[36] BINETRUY	84	COSM	$m_\nu \sim$ 1 MeV
	[37] SARKAR	84	COSM	m_ν= 10–100 MeV
	[38] HENRY	81	ASTR	m_ν= 16–20 eV
	[39] KIMBLE	81	ASTR	m_ν= 10–100 eV
	[40] REPHAELI	81	ASTR	m_ν= 30–150 eV
	[41] DERUJULA	80	ASTR	m_ν= 10–100 eV
$>2 \times 10^{21}$	[42] STECKER	80	ASTR	m_ν= 10–100 eV
	[43] DICUS	78	COSM	m_ν= 0.5–30 MeV
$<3 \times 10^{-11}$	[44] FALK	78	ASTR	m_ν <10 MeV
	[45] COWSIK	77	ASTR	

[24] DOLGOV 99 places limits in the (Majorana) τ-associated ν mass-lifetime plane based on nucleosynthesis. Results would be considerably modified if neutrino oscillations exist.
[25] BILLER 98 use the observed TeV γ-ray spectra to set limits on the mean life of a radiatively decaying neutrino between 0.05 and 1 eV. Curve shows $\tau_\nu/B_\gamma > 0.15\times10^{21}$ s at 0.05 eV, $> 1.2 \times 10^{21}$ s at 0.17 eV, $> 3 \times 10^{21}$ s at 1 eV, where B_γ is the branching ratio to photons.
[26] SIGL 95 exclude 1 s $\lesssim \tau \lesssim 10^8$ s for MeV-mass τ neutrinos from SN 1987A decaying radiatively, and eliminates the lower limit using other published results.
[27] BLUDMAN 92 sets additional limits by this method for higher mass ranges. Cosmological limits are also obtained.
[28] Nonobservation of γ's in coincidence with ν's from SN 1987A. Results should be divided by the $\nu \to \gamma X$ branching ratio.
[29] DODELSON 92 range is for wrong-helicity keV mass Dirac ν's from the core of neutron star in SN 1987A decaying to ν's that would have interacted in KAM2 or IMB detectors.
[30] GRANEK 91 considers heavy neutrino decays to $\gamma\nu_L$ and $3\nu_L$, where $m_{\nu_L} <$100 keV. Lifetime is calculated as a function of heavy neutrino mass, branching ratio into $\gamma\nu_L$, and m_{ν_L}.
[31] WALKER 90 uses SN 1987A γ flux limits after 289 days to find $\langle m/\tau\rangle > 1.1\times10^{15}$ eV s.
[32] CHUPP 89 should be multiplied by a branching ratio (about 1) and a detection efficiency (about 1/4), and pertains to radiative decay of any neutrino to a lighter or sterile neutrino.
[33] TERASAWA 88 finds only $10^2 < \tau < 10^4$ allowed for 30–70 MeV ν's from primordial nucleosynthesis.
[34] KAWASAKI 86 concludes that light elements in primordial nucleosynthesis would be destroyed by radiative decay of neutrinos with 10 MeV$<m_\nu<$1 GeV unless $\tau \lesssim 10^4$ s.
[35] LINDLEY 85 considers destruction of cosmologically-produced light elements, and finds $\tau < 2 \times 10^3$ s for 10 MeV $<m_\nu<$100 MeV. See also LINDLEY 79.
[36] BINETRUY 84 finds $\tau < 10^8$ s for neutrinos in a radiation-dominated universe.
[37] SARKAR 84 finds $\tau <$ 20 s at m_ν=10 MeV, with higher limits for other m_ν, and claims that all masses between 1 MeV and 50 MeV are ruled out.
[38] HENRY 81 uses UV flux from clusters of galaxies to find $\tau > 1.1 \times 10^{25}$ s for radiative decay.
[39] KIMBLE 81 uses extreme UV flux limits to find $\tau > 10^{22}$–10^{23} s.
[40] REPHAELI 81 consider ν decay γ effect on neutral H in early universe; based on M31 HI concludes $\tau > 10^{24}$ s.
[41] DERUJULA 80 finds $\tau > 3 \times 10^{23}$ s based on CDM neutrino decay contribution to UV background.
[42] STECKER 80 limit based on UV background; result given is $\tau > 4 \times 10^{22}$ s at $m = 20$ eV.
[43] DICUS 78 considers effect of ν decay photons on light-element production, and finds lifetime must be less than "hours." See also DICUS 77.
[44] FALK 78 finds lifetime constraints based on supernova energetics.
[45] COWSIK 77 considers variety of scenarios. For neutrinos produced in the big bang, present limits on optical photon flux require $\tau > 10^{23}$ s for $m_\nu \sim 1$ eV. See also COWSIK 79 and GOLDMAN 79.

ν MAGNETIC MOMENT

Must vanish for a purely chiral massless Dirac neutrino. A massive Dirac or Majorana neutrino can have a transition magnetic moment connecting one mass eigenstate to another one. The experimental limits below usually cannot distinguish between the true (diagonal, in mass) magnetic moment and a transition magnetic moment.

The value of the magnetic moment for the standard SU(2)×U(1) electroweak theory extended to include massive neutrinos (see FUJIKAWA 80) is $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = (3.20 \times 10^{-19}) m_\nu \mu_B$ where m_ν is in eV and $\mu_B = e\hbar/2m_e$ is the Bohr magneton. Given the upper bound $m_\nu <$ 18 MeV, it follows that for the extended standard electroweak theory, $\mu_\nu < 6 \times 10^{-12} \mu_B$.

Most of the astrophysical limits pertain to any neutrino.

VALUE (μ_B)	CL%	DOCUMENT ID		TECN	COMMENT
$<3.9 \times 10^{-7}$	90	[46] SCHWIENHO...	01	DONU	$\nu_\tau e^- \to \nu_\tau e^-$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2 \times 10^{-10}$	90	[47] GRIMUS	02	FIT	solar + reactor (Majorana ν)
$<8.0 \times 10^{-6}$	90	[48] TANIMOTO	00	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<3 \times 10^{-12}$		[49] RAFFELT	99	ASTR	Red giant luminosity
$<4 \times 10^{-10}$		[50] RAFFELT	99	ASTR	Solar cooling
$<4.4 \times 10^{-6}$	90	ABREU	97J	DLPH	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$<3.3 \times 10^{-6}$	90	[51] ACCIARRI	97Q	L3	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$<6.2 \times 10^{-11}$		[52] ELMFORS	97	COSM	Depolarization in early universe plasma
$<2.7 \times 10^{-6}$	95	[53] ESCRIBANO	97	RVUE	$\Gamma(Z \to \nu\nu)$ at LEP
$<5.5 \times 10^{-6}$	90	GOULD	94	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$ at LEP
$<5.4 \times 10^{-7}$	90	[54] COOPER-...	92	BEBC	$\nu_\tau e^- \to \nu_\tau e^-$
$\gtrsim 10^{-8}$		[55] KAWANO	92	ASTR	Primodial ^{4}He abundance
$<5.6 \times 10^{-6}$	90	DESHPANDE	91	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<2 \times 10^{-12}$		[56] RAFFELT	90	ASTR	Red giant luminosity
$<1 \times 10^{-11}$		[57] RAFFELT	89B	ASTR	Cooling helium stars
$<4. \times 10^{-6}$	90	[58] GROTCH	88	RVUE	$e^+e^- \to \nu\overline{\nu}\gamma$
$<1.1 \times 10^{-11}$		[57,59] FUKUGITA	87	ASTR	Cooling helium stars
$<6 \times 10^{-14}$		[60] NUSSINOV	87	ASTR	Cosmic EM backgrounds
$<8.5 \times 10^{-11}$		[59] BEG	78	ASTR	Stellar plasmons

[46] SCHWIENHORST 01 quote an experimental sensitivity of 4.9×10^{-7}.
[47] GRIMUS 02 obtain stringent bounds on all Majorana neutrino transition moments from a simultaneous fit of LMA-MSW oscillation parameters and transition moments to global solar neutrino data + reactor data. Using only solar neutrino data, a 90% CL bound of $6.3 \times 10^{-10} \mu_B$ is obtained.
[48] TANIMOTO 00 combined $e^+e^- \to \nu\overline{\nu}\gamma$ data from VENUS, TOPAZ, and AMY.
[49] RAFFELT 99 is an update of RAFFELT 90. This limit applies to all neutrino flavors which are light enough (< 5 keV) to be emitted from globular-cluster red giants. This limit pertains equally to electric dipole moments and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.
[50] RAFFELT 99 is derived from the helioseismological limit on a new energy-loss channel of the Sun. This limit applies to all neutrino flavors which are light enough (<1 keV) to be emitted from the Sun. This limit pertains equally to electric dipole and magnetic transition moments, and it applies to both Dirac and Majorana neutrinos.
[51] ACCIARRI 97Q result applies to both direct and transition magnetic moments and for q^2=0.
[52] ELMFORS 97 calculate the rate of depolarization in a plasma for neutrinos with a magnetic moment and use the constraints from a big-bang nucleosynthesis on additional degrees of freedom.

[53] Applies to absolute value of magnetic moment.
[54] COOPER-SARKAR 92 assume $f_{D_s}/f_\pi = 2$ and D_s, $\overline{D}_s$ production cross section = 2.6 μb to calculate ν flux.
[55] KAWANO 92 lower limit is that needed to circumvent ^{4}He production if m_ν is between 5 and $\sim$ 30 MeV/c^2.
[56] RAFFELT 90 limit valid if m_ν < 5 keV. It applies for a diagonal magnetic moment of a Dirac neutrino, or for a transition magnetic moment of a Majorana neutrino. In the latter case, the same analysis gives $< 1.4 \times 10^{-12}$. Limit at 95%CL obtained from δM_c.
[57] Significant dependence on details of stellar properties.
[58] GROTCH 88 combined data from MAC, ASP, CELLO, and Mark J.
[59] If m_ν < 10 keV.
[60] For m_ν = 8–200 eV. NUSSINOV 87 examines transition magnetic moments for $\nu_\tau \rightarrow \nu_e$ and obtain $< 3 \times 10^{-15}$ for m_ν < 16 eV and $< 6 \times 10^{-14}$ for m_ν > 4 eV.

ν ELECTRIC DIPOLE MOMENT

VALUE (ecm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<5.2 × 10^{-17}	95	[61] ESCRIBANO	97	RVUE	$\Gamma(Z \rightarrow \nu\nu)$ at LEP

[61] Applies to absolute value of electric dipole moment.

ν CHARGE

VALUE (units: electron charge)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-14}$	[62] RAFFELT	99	ASTR	Red giant luminosity
$<6 \times 10^{-14}$	[63] RAFFELT	99	ASTR	Solar cooling
$<4 \times 10^{-4}$	[64] BABU	94	RVUE	BEBC beam dump
$<3 \times 10^{-4}$	[65] DAVIDSON	91	RVUE	SLAC electron beam dump

[62] This RAFFELT 99 limit applies to all neutrino flavors which are light enough (<5 keV) to be emitted from globular-cluster red giants.
[63] This RAFFELT 99 limit is derived from the helioseismological limit on a new energy-loss channel of the Sun, and applies to all neutrino flavors which are light enough (<1 keV) to be emitted from the sun.
[64] BABU 94 use COOPER-SARKAR 92 limit on ν magnetic moment to derive quoted result.
[65] DAVIDSON 91 use data from early SLAC electron beam dump experiment to derive charge limit as a function of neutrino mass.

NONSTANDARD CONTRIBUTIONS TO NEUTRINO SCATTERING

We report limits on the so-called neutrino charge radius squared. While the straight-forward definition of a neutrino charge radius has been proven to be gauge-dependent and, hence, unphysical (LEE 77C), there have been recent attempts to define a physically observable neutrino charge radius (BERNABEU 00, BERNABEU 02). The issue is still controversial (FUJIKAWA 03, BERNABEU 03). A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	*CL%*	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<9.9 and > −8.2	90	[66] HIRSCH	03	anomalous $e^+e^- \rightarrow \nu\overline{\nu}\gamma$

[66] Results of LEP-2 are interpreted as limits on the axial-vector charge radius squared of a Majorana ν_τ. Slightly weaker limits for both vector and axial-vector charge radius squared are obtained for the Dirac case, and somewhat weaker limits are obtained from the analysis of lower energy data (LEP-1.5 and TRISTAN).

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Number of Neutrino Types and Sum of Neutrino Masses

The neutrinos referred to in this section are those of the Standard SU(2)×U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m < m_Z/2$. The limits are on the number of neutrino mass eigenstates, including ν_1, ν_2, and ν_3.

THE NUMBER OF LIGHT NEUTRINO TYPES FROM COLLIDER EXPERIMENTS

Revised August 2001 by D. Karlen (Carleton University).

The most precise measurements of the number of light neutrino types, N_ν, come from studies of Z production in e^+e^- collisions. The invisible partial width, $\Gamma_{\rm inv}$, is determined by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{\rm SM} = 1.991 \pm 0.001$, is used instead of $(\Gamma_\nu)_{\rm SM}$ to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM} \quad . \qquad (1)$$

The combined result from the four LEP experiments is $N_\nu = 2.984 \pm 0.008$ [1].

In the past, when only small samples of Z decays had been recorded by the LEP experiments and by the Mark II at SLC, the uncertainty in N_ν was reduced by using Standard Model fits to the measured hadronic cross sections at several center-of-mass energies near the Z resonance. Since this method is much more dependent on the Standard Model, the approach described above is favored.

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy e^+e^- colliders by measuring the cross section of the process $e^+e^- \to \nu\overline{\nu}\gamma$. The ASP, CELLO, MAC, MARK J, and VENUS experiments observed a total of 3.9 events above background [2], leading to a 95% CL limit of $N_\nu < 4.8$. This process has a much larger cross section at center-of-mass energies near the Z mass and has been measured at LEP by the ALEPH, DELPHI, L3, and OPAL experiments [3]. These experiments have observed several thousand such events, and the combined result is $N_\nu = 3.00 \pm 0.08$. The same process has also been measured by the LEP experiments at much higher center-of-mass energies, between 130 and 208 GeV, in searches for new physics [4]. Combined, the measured cross section is 0.982 ± 0.012 (stat) of that expected for three light neutrino generations [5].

Experiments at $p\overline{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \to \ell^\pm\nu$ to $Z \to \ell^+\ell^-$ events [6]. This involved a calculation that assumed Standard Model values for the total W width and the ratio of W and Z leptonic partial widths, and used an estimate of the ratio of Z to W production cross sections. Now that the Z width is very precisely known from the LEP experiments, the approach is now one of those used to determine the W width.

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Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value $\Gamma_\nu/\Gamma_\ell = 1.9908 \pm 0.0015$.

VALUE	DOCUMENT ID		TECN	COMMENT
2.994±0.012 OUR EVALUATION	Combined fit to all LEP data.			
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.00 ±0.05	[1] LEP	92	RVUE	

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \to \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the E^{ee}_{cm} range 88–209 GeV.

VALUE	DOCUMENT ID		TECN	COMMENT
2.92±0.07 OUR AVERAGE				
2.86 ± 0.09	HEISTER	03C	ALEP	$\sqrt{s}$=189–209 GeV
2.69±0.13±0.11	ABBIENDI,G	00D	OPAL	1998 LEP run
2.84±0.15±0.14	ABREU	00Z	DLPH	1997–1998 LEP runs
3.01±0.08	ACCIARRI	99R	L3	1991–1998 LEP runs
2.89±0.32±0.19	ABREU	97J	DLPH	1993–1994 LEP runs
2.68±0.20±0.20	BUSKULIC	93L	ALEP	1990–1991 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.1 ±0.6 ±0.1	ADAM	96C	DLPH	$\sqrt{s}$ = 130, 136 GeV

Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 3.3	[2] BARGER	03C	COSM	
$1.4 < N_\nu < 6.8$	[3] CROTTY	03	COSM	
< 3.6	[4] CYBURT	03	COSM	
$1.9 < N_\nu < 7.0$	[5] HANNESTAD	03B	COSM	
$1.9 < N_\nu < 6.6$	[3] PIERPAOLI	03	COSM	
$2 < N_\nu < 4$	LISI	99		BBN
< 4.3	OLIVE	99		BBN
< 4.9	COPI	97		Cosmology
< 3.6	HATA	97B		High D/H quasar abs.
< 4.0	OLIVE	97		BBN; high ^{4}He and ^{7}Li
< 4.7	CARDALL	96B		Cosmology, High D/H quasar abs.
< 3.9	FIELDS	96		Cosmology, BBN; high ^{4}He and ^{7}Li
< 4.5	KERNAN	96		Cosmology, High D/H quasar abs.
< 3.6	OLIVE	95		BBN; ≥ 3 massless ν
< 3.3	WALKER	91		Cosmology
< 3.4	OLIVE	90		Cosmology
< 4	YANG	84		Cosmology
< 4	YANG	79		Cosmology
< 7	STEIGMAN	77		Cosmology
	PEEBLES	71		Cosmology
<16	[6] SHVARTSMAN	69		Cosmology
	HOYLE	64		Cosmology

[2] Limit on the number of neutrino types based on combination of WMAP data and big-bang nucleosynthesis. The limit from WMAP data alone is 8.3. See also KNELLER 01. $N_\nu \geq 3$ is assumed to compute the limit.
[3] 95% confidence level range on the number of neutrino flavors from WMAP data combined with other CMB measurements, the 2dfGRS data, and HST data.
[4] Limit on the number of neutrino types based on ^{4}He abundance assuming a baryon density fixed by the WMAP data. Limit relaxes to 5.2 if D/H is used instead of ^{4}He. See also CYBURT 01. $N_\nu \geq 3$ is assumed to compute the limit.
[5] 95% confidence level range on the number of neutrino flavors from WMAP data combined with other CMB measurements, the 2dfGRS data, HST data, and SN1a data.
[6] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

VALUE	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
<20	[7] OLIVE	81C	COSM
<20	[7] STEIGMAN	79	COSM

[7] Limit varies with strength of coupling. See also WALKER 91.

Revised April 1998 by K.A. Olive (University of Minnesota).

The limits on low mass ($m_\nu \lesssim 1$ MeV) neutrinos apply to $m_{\rm tot}$ given by

$$m_{\rm tot} = \sum_\nu (g_\nu/2) m_\nu \ ,$$

where g_ν is the number of spin degrees of freedom for ν plus $\overline{\nu}$: $g_\nu = 4$ for neutrinos with Dirac masses; $g_\nu = 2$ for Majorana neutrinos. Stable neutrinos in this mass range make a contribution to the total energy density of the Universe which is given by

$$\rho_\nu = m_{\rm tot} n_\nu = m_{\rm tot} (3/11) n_\gamma \ ,$$

where the factor 3/11 is the ratio of (light) neutrinos to photons. Writing $\Omega_\nu = \rho_\nu/\rho_c$, where ρ_c is the critical energy density of the Universe, and using $n_\gamma = 412$ cm^{-3}, we have

$$\Omega_\nu h^2 = m_{\rm tot}/(94 \ {\rm eV}) \ .$$

Therefore, a limit on $\Omega_\nu h^2$ such as $\Omega_\nu h^2 < 0.25$ gives the limit

$$m_{\rm tot} < 24 \ {\rm eV} \ .$$

The limits on high mass ($m_\nu > 1$ MeV) neutrinos apply separately to each neutrino type.

Limit on Total ν MASS, $m_{\rm tot}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\rm tot}$. For other limits, see SZALAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
< 1.0	[8] HANNESTAD	03B	COSM	
< 0.7	[9] SPERGEL	03	COSM	WMAP
< 1.8	[10] ELGAROY	02	ASTR	2dF Galaxy Redshift Survey
< 0.9	[11] LEWIS	02	COSM	
< 4.2	[12] WANG	02	COSM	CMB
< 2.7	[13] FUKUGITA	00	COSM	
< 5.5	[14] CROFT	99	ASTR	Ly α power spec
<180	SZALAY	74	COSM	
<132	COWSIK	72	COSM	
<280	MARX	72	COSM	
<400	GERSHTEIN	66	COSM	

[8] Constrains the fractional contribution of neutrinos to the total matter density in the Universe from WMAP data combined with other CMB measurements, the 2dfGRS data, HST data, and SN1a data.

[9] Constrains the fractional contribution of neutrinos to the total matter density in the Universe from WMAP data combined with other CMB measurements, the 2dfGRS data, and Lyman α data. The limit does not noticeably change if the Lyman α data are not used.

[10] ELGAROY 02 constrains the fractional contribution of neutrinos to the total matter density in the Universe from the power spectrum of fluctuations derived from the 2 Degree Field Galaxy Redshift Survey. Assumes $\Omega_{\rm matter} < 0.5$ and a spectral index of 1.0. Limit softens to $m_\nu < 2.2$ eV for n=1.0 ± 0.1.

[11] LEWIS 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB, HST Key project, 2dF galaxy redshift survey, supernovae type Ia, and BBN.

[12] WANG 02 constrains the total mass of neutrinos from the power spectrum of fluctuations derived from the CMB and other cosmological data sets such as galaxy clustering and the Lyman α forest.

[13] FUKUGITA 00 is a limit on neutrino masses from structure formation. The constraint is based on the clustering scale σ_8 and the COBE normalization and leads to a conservative limit of 0.9 eV assuming 3 nearly degenerate neutrinos. The quoted limit is on the sum of the light neutrino masses.

[14] CROFT 99 result based on the power spectrum of the Ly α forest. If $\Omega_{\rm matter} < 0.5$, the limit is improved to $m_\nu < 2.4$ ($\Omega_{\rm matter}$/0.17–1) eV.

Limits on MASSES of Light Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (eV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<100–200	[15] OLIVE	82	COSM	Dirac ν
<200–2000	[15] OLIVE	82	COSM	Majorana ν

[15] Depending on interaction strength G_R where $G_R < G_F$.

Limits on MASSES of Heavy Stable Right-Handed ν (with necessarily suppressed interaction strengths)

VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
> 10	[16] OLIVE	82	COSM	G_R/G_F <0.1
>100	[16] OLIVE	82	COSM	G_R/G_F <0.01

[16] These results apply to heavy Majorana neutrinos and are summarized by the equation: m_ν >1.2 GeV (G_F/G_R). The bound saturates, and if G_R is too small no mass range is allowed.

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SCHRAMM 84 PL 141B 337 D.N. Schramm, G. Steigman (FNAL, BART)
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Double-β Decay

OMITTED FROM SUMMARY TABLE

LIMITS FROM NEUTRINOLESS DOUBLE-β DECAY

Revised September 2003 by P. Vogel (Caltech) and A. Piepke (University of Alabama).

Neutrinoless double-beta ($0\nu\beta\beta$) decay, if observed, would signal violation of the total lepton number conservation. The process can be mediated by an exchange of a light Majorana neutrino, or by an exchange of other particles. However, the existence of $0\nu\beta\beta$-decay requires Majorana neutrino mass, no matter what the actual mechanism is. As long as only a limit on the lifetime is available, limits on the effective Majorana neutrino mass, and on the lepton-number violating right-handed current can be obtained, independently on the actual mechanism. These limits are listed in the next three tables. In the following we *assume* that the exchange of light Majorana neutrinos ($m_{\nu_i} \le \mathcal{O}(10 \ {\rm MeV})$) contributes dominantly to the decay rate.

Besides a dependence on the phase space ($G^{0\nu}$) and the nuclear matrix element ($M^{0\nu}$), the observable $0\nu\beta\beta$-decay rate is proportional to the square of the effective Majorana mass ($\langle m_{\beta\beta}\rangle$), $(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_{\beta\beta}\rangle|^2$, with $\langle m_{\beta\beta}\rangle = \sum_i U^2_{ei} m_{\nu_i}$. The sum contains, in general, complex CP phases in U^2_{ei}, i.e., cancelations may occur. For three neutrino flavors there are three physical phases for Majorana neutrinos and one for Dirac neutrinos. The two additional Majorana phases affect only total lepton number violating processes. Given the general 3×3 mixing matrix for Majorana neutrinos, one can construct other analogous lepton number violating quantities, $\sum_i U_{\ell i} U_{\ell' i} m_{\nu_i}$. However, these are currently much less constrained than $\langle m_{\beta\beta}\rangle$.

Nuclear structure calculations are needed to deduce $\langle m_{\beta\beta}\rangle$ from the decay rate. While $G^{0\nu}$ can be calculated reliably, the computation of $M^{0\nu}$ is subject to considerable uncertainty. If the spread among different ways of evaluating the nuclear matrix elements is taken as a measure of error, then there is a factor of $\sim$3 uncertainty in the derived $\langle m_{\beta\beta}\rangle$ values.

The particle physics quantities to be determined are thus nuclear model-dependent, so the half-life measurements are listed first. Where possible, we reference the nuclear matrix elements used in the subsequent analysis. Since rates for the more conventional $2\nu\beta\beta$ decay serve to calibrate the nuclear theory, results for this process are also given.

Neutrino oscillation experiments yield strong evidence that at least some neutrinos are massive. However, these findings shed no light on the mass hierarchy, the absolute neutrino mass values or the properties of neutrinos under CP conjugation (Dirac or Majorana). The atmospheric neutrino anomaly implies $\Delta m^2_{atm} \sim (2-3) \times 10^{-3}$ eV^2 and a large mixing angle $\sin^2\theta_{atm} \approx \sin^2\theta_{23} \approx 0.5$. Oscillations of solar ν_e and reactor $\bar{\nu}_e$ neutrinos lead to the unique 'LMA solution' with $\Delta m^2_{sol} \sim 7 \times 10^{-5}$ eV^2 and $\sin^2\theta_{sol} \approx \sin^2\theta_{12} \approx 0.3$. The investigation of reactor $\bar{\nu}_e$ at 1 km baseline indicates that electron type neutrinos couple only weakly to the third mass eigenstate with $\sin^2\theta_{13} < 0.03$. The so called 'LSND evidence' for oscillations at short baseline requires $\Delta m^2 \sim 0.2 - 2$ eV^2 and small mixing.

Based on these results (and neglecting the not yet confirmed LSND signal): $|\langle m_{\beta\beta}\rangle|^2 \approx |\cos^2\theta_{sol}\ m_1 + e^{i\alpha_1}\ \sin^2\theta_{sol}\ m_2 + e^{i\alpha_2}\ \sin^2\theta_{13}\ m_3|^2$, with α_1, α_2 denoting CP phases. The apparent smallness of $\sin^2\theta_{13}$ thus effectively shields $\langle m_{\beta\beta}\rangle$ from one of the CP phases. Given the present knowledge of the neutrino oscillation parameters, both of the Δm^2 values and of the mixing angles, one can derive the relation between the effective Majorana mass and the mass of the lightest neutrino, as illustrated in Fig. 1. The contribution of possible sterile neutrinos has been neglected.

If the neutrinoless double-beta decay is observed, it will be possible to fix a *range* of absolute values of the masses m_{ν_i}. However, if direct neutrino mass measurements, e.g. using beta decay (which is sensitive to $m^{2(\mathrm{eff})}_{\nu_e} = \sum_i |U_{ei}|^2 m^2_{\nu_i}$), also yield positive results, we may learn something about the otherwise

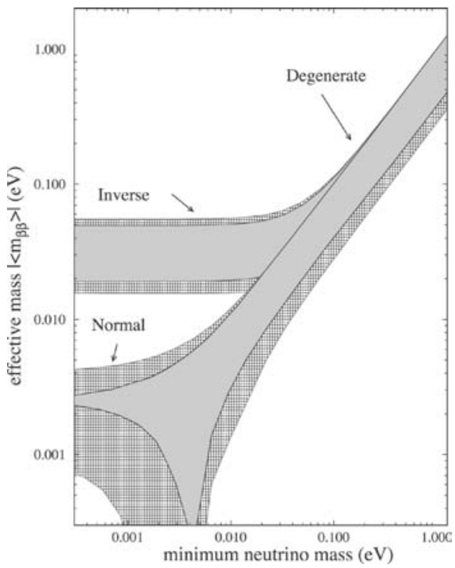

Figure 1: Dependence of the effective Majorana mass $\langle m_{\beta\beta}\rangle$ derived from the rate of neutrinoless double-beta decay $(1/T^{0\nu}_{1/2} \sim |\langle m_{\beta\beta}\rangle|^2)$ on the absolute mass of the lightest neutrino. The arrows indicate the three possible neutrino mass patterns or "hierarchies." The curves are based on the 'LMA solution,' $\Delta m^2_{sol} = 7 \times 10^{-5}$ eV^2, $\sin^2\theta_{sol} = 0.3$, and $\Delta m^2_{atm} = 2.4 \times 10^{-3}$ eV^2, $\theta_{13} = 0$. The cross-hatched region is covered if one σ errors on these oscillation parameters are included.

inaccessible CP phases. To do so we have to assume that the Majorana mass is responsible for the decay and that the calculations of $M^{0\nu}$ will be improved. Unlike the direct neutrino mass measurements, however, a limit on $\langle m_{\beta\beta}\rangle$ does not allow one to constrain the individual mass values m_{ν_i} even when the mass differences Δm^2 are known.

Depending on the pattern of neutrino mass, $0\nu\beta\beta$-decay may be driven by the small Δm^2_{sol}, "normal hierarchy" in Fig. 1 ($\langle m_{\beta\beta}\rangle \sim \sin^2\theta_{sol}\sqrt{\Delta m^2_{sol}} \sim 5$ meV), or by the larger Δm^2_{atm}, "inverse hierarchy" in Fig. 1 ($\langle m_{\beta\beta}\rangle \sim \sqrt{\Delta m^2_{atm}} \sim 50$ meV). In the so called "degenerate" scenario an overall mass offset exists and $\langle m_{\beta\beta}\rangle$ is relatively large.

Neutrino oscillation data imply the existence of a *lower limit* for the Majorana neutrino mass for some of the mass patterns. Several new double-beta searches have been proposed to probe the interesting $\langle m_{\beta\beta}\rangle$ mass range.

If lepton-number violating right-handed current weak interactions exist, the $0\nu\beta\beta$ decay rate also depends on the quantities $\langle\eta\rangle = \eta\sum_i U_{ei}V_{ei}$ and $\langle\lambda\rangle = \lambda\sum_i U_{ei}V_{ei}$, where V_{lj} is a matrix analogous to U_{lj} but describing the mixing with the hypothetical right-handed neutrinos and the coupling constants η and λ characterize the strength of the corresponding right-right and right-left weak interactions. The $\langle\eta\rangle$ and $\langle\lambda\rangle$ vanish for massless or unmixed neutrinos due to the unitarity of the generalized mixing matrix containing both the U and V matrices. The limits on $\langle\eta\rangle$ are of order 10^{-8}, while the limits on $\langle\lambda\rangle$ are of order 10^{-6}. The reader is cautioned that a number of earlier experiments did not distinguish between η and λ. In addition, see the section on Majoron searches for additional limits set by these experiments.

Half-life Measurements and Limits for Double-β Decay

In all cases of double-beta decay, (Z,A) $\rightarrow$ (Z+2,A) $+ 2e^-$ $+$ (0 or 2)$\overline{\nu}_e$. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported. For 2ν decay, which is well established, only measured half-lives are reported.

$t_{1/2}$(10^{21} yr)	CL%	ISOTOPE		TRANSITION	METHOD	DOCUMENT ID	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
$>$ 210	90	^{130}Te	0ν		Cryog. det.	[1] ARNABOLDI	03
$>$ 31	90	^{130}Te	0ν	$0^+ \to 2^+$	Cryog. det.	[2] ARNABOLDI	03
$0.61 \pm 0.14 ^{+0.29}_{-0.35}$	90	^{130}Te	2ν		Cryog. det.	[3] ARNABOLDI	03
$>$ 110	90	^{128}Te	0ν		Cryog. det.	[4] ARNABOLDI	03
$(0.029 ^{+0.004}_{-0.003})$		^{116}Cd	2ν		^{116}CdWO$_4$ scint.	[5] DANEVICH	03
$>$ 170	90	^{116}Cd	0ν		^{116}CdWO$_4$ scint.	[6] DANEVICH	03
$>$ 29	90	^{116}Cd	0ν	$0^+ \to 2^+$	^{116}CdWO$_4$ scint.	[7] DANEVICH	03
$>$ 14	90	^{116}Cd	0ν	$0^+ \to 0^+_1$	^{116}CdWO$_4$ scint.	[8] DANEVICH	03
$>$ 6	90	^{116}Cd	0ν	$0^+ \to 0^+_2$	^{116}CdWO$_4$ scint.	[9] DANEVICH	03
$>$15700	90	^{76}Ge	0ν		Enriched HPGe	[10] AALSETH	02B
$>$ 58	90	^{134}Xe	0ν		Liquid Xe Scint.	[11] BERNABEI	02D
$>$ 1200	90	^{136}Xe	0ν		Liquid Xe Scint.	[12] BERNABEI	02D
$15000 ^{+168000}_{-\ \ 7500}$		^{76}Ge	0ν		Enriched HPGe	[13] KLAPDOR-K...	02D
$(7.2 \pm 0.9 \pm 1.8)$E-3		^{100}Mo	2ν		Liq. Ar ioniz.	[14] ASHITKOV	01
$>$ 4.9	90	^{100}Mo	0ν		Liq. Ar ioniz.	[15] ASHITKOV	01
$>$ 1.3	90	^{160}Gd	0ν		Gd$_2$SiO$_5$:Ce	[16] DANEVICH	01
$>$ 1.3	90	^{160}Gd	0ν	$0^+ \to 2^+$	Gd$_2$SiO$_5$:Ce	[17] DANEVICH	01
$0.59 ^{+0.17}_{-0.11} \pm 0.06$		^{100}Mo	0ν+2ν	$0^+ \to 0^+_1$	Ge coinc.	[18] DEBRAECKEL...	01
$>$ 55	90	^{100}Mo	$0\nu,\langle m_\nu\rangle$		ELEGANT V	[19] EJIRI	01
$>$ 42	90	^{100}Mo	$0\nu,\langle\lambda\rangle$		ELEGANT V	[19] EJIRI	01
$>$ 49	90	^{100}Mo	$0\nu,\langle\eta\rangle$		ELEGANT V	[19] EJIRI	01
$>$19000	90	^{76}Ge	0ν		Enriched HPGe	[20] KLAPDOR-K...	01
$1.55 \pm 0.001 ^{+0.19}_{-0.15}$	90	^{76}Ge	2ν		Enriched HPGe	[21] KLAPDOR-K...	01
(9.4 ± 3.2)E-3	90	^{96}Zr	0ν+2ν		Geochem	[22] WIESER	01
$0.042 ^{+0.033}_{-0.013}$		^{48}Ca	2ν		Ge spectrometer	[23] BRUDANIN	00
$0.021 ^{+0.008}_{-0.004} \pm 0.002$		^{96}Zr	2ν		NEMO-2	[24] ARNOLD	99
$>$ 1.0	90	^{96}Zr	0ν		NEMO-2	[24] ARNOLD	99
$(8.3 \pm 1.0 \pm 0.7)$E-2		^{82}Se	2ν		NEMO-2	[25] ARNOLD	98
$>$ 9.5	90	^{82}Se	0ν		NEMO-2	[26] ARNOLD	98
$>$ 2.8	90	^{82}Se	0ν	$0^+ \to 2^+$	NEMO-2	[27] ARNOLD	98
$(7.6 ^{+2.2}_{-1.4})$E-3		^{100}Mo	2ν		Si(Li)	[28] ALSTON-...	97
$(6.82 ^{+0.38}_{-0.53} \pm 0.68)$E-3		^{100}Mo	2ν		TPC	[29] DESILVA	97
$(6.75 ^{+0.37}_{-0.42} \pm 0.68)$E-3		^{150}Nd	2ν		TPC	[30] DESILVA	97
$>$ 1.2	90	^{150}Nd	0ν		TPC	[31] DESILVA	97
$1.77 \pm 0.01 ^{+0.13}_{-0.11}$		^{76}Ge	2ν		Enriched HPGe	[32] GUENTHER	97
$(3.75 \pm 0.35 \pm 0.21)$E-2		^{116}Cd	2ν	$0^+ \to 0^+$	NEMO 2	[33] ARNOLD	96
$0.043 ^{+0.024}_{-0.011} \pm 0.014$		^{48}Ca	2ν		TPC	[34] BALYSH	96
0.79 ± 0.10		^{130}Te	0ν+2ν		Geochem	[35] TAKAOKA	96
$0.61 ^{+0.18}_{-0.11}$		^{100}Mo	0ν+2ν	$0^+ \to 0^+_1$	γ in HPGe	[36] BARABASH	95
$(9.5 \pm 0.4 \pm 0.9)$E-3		^{100}Mo	2ν		NEMO 2	DASSIE	95
$>$ 0.6	90	^{100}Mo	0ν	$0^+ \to 0^+_1$	NEMO 2	DASSIE	95
$0.026 ^{+0.009}_{-0.005}$		^{116}Cd	2ν	$0^+ \to 0^+$	ELEGANT IV	EJIRI	95
$0.017 ^{+0.010}_{-0.005} \pm 0.0035$		^{150}Nd	2ν	$0^+ \to 0^+$	TPC	ARTEMEV	93
0.039 ± 0.009		^{96}Zr	0ν+2ν		Geochem	KAWASHIMA	93
2.7 ± 0.1		^{130}Te	0ν+2ν		Geochem	BERNATOW...	92
7200 ± 400		^{128}Te	0ν+2ν		Geochem	[37] BERNATOW...	92
$>$ 27	68	^{82}Se	0ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
$0.108 ^{+0.026}_{-0.006}$		^{82}Se	2ν	$0^+ \to 0^+$	TPC	ELLIOTT	92
2.0 ± 0.6		^{238}U	0ν+2ν		Radiochem	[38] TURKEVICH	91
$>$ 9.5	76	^{48}Ca	0ν		CaF$_2$ scint.	YOU	91
$0.12 \pm 0.01 \pm 0.04$	68	^{82}Se	0ν+2ν		Geochem.	[39] LIN	88
$0.75 \pm 0.03 \pm 0.23$	68	^{130}Te	0ν+2ν		Geochem.	[40] LIN	88
1800 ± 700	68	^{128}Te	0ν+2ν		Geochem.	[41] LIN	88B
2.60 ± 0.28		^{130}Te	0ν+2ν		Geochem	[42] KIRSTEN	83

[1] Supersedes ALESSANDRELLO 00. Array of TeO$_2$ crystals in high resolution cryogenic calorimeter. Some enriched in ^{130}Te. Ground state to ground state decay.

[2] Decay into first excited state of daughter nucleus.

[3] Two neutrino decay into ground state. Relatively large error mainly due to uncertainties in background determination. Reported value is shorter than the geochemical measurements of KIRSTEN 83 and BERNATOWICZ 92 but in agreement with LIN 88 and TAKAOKA 96.

[4] Supersedes ALESSANDRELLO 00. Array of TeO$_2$ crystals in high resolution cryogenic calorimeter. Some enriched in ^{128}Te. Ground state to ground state decay.

[5] Calorimetric measurement of 2ν ground state decay of ^{116}Cd using enriched CdWO$_4$ scintillators. Agrees with EJIRI 95 and ARNOLD 96. Supersedes DANEVICH 00.

[6] Limit on 0ν decay of ^{116}Cd using enriched CdWO$_4$ scintillators. Supersedes DANEVICH 00.

[7] Limit on 0ν decay of ^{116}Cd into first excited 2^+ state of daughter nucleus using enriched CdWO$_4$ scintillators. Supersedes DANEVICH 00.

[8] Limit on 0ν decay of ^{116}Cd into first excited 0^+ state of daughter nucleus using enriched CdWO$_4$ scintillators. Supersedes DANEVICH 00.

[9] Limit on 0ν decay of ^{116}Cd into second excited 0^+ state of daughter nucleus using enriched CdWO$_4$ scintillators. Supersedes DANEVICH 00.

[10] AALSETH 02B limit is based on 117 mol·yr of data using enriched Ge detectors. Background reduction by means of pulse shape analysis is applied to part of the data set. Reported limit is slightly less restrictive than that in KLAPDOR-KLEINGROTHAUS 01 However, it excludes part of the allowed half-life range reported in KLAPDOR-KLEINGROTHAUS 01B for the same nuclide.

[11] BERNABEI 02D report a limit for the 0ν, $0^+ \rightarrow 0^+$ decay of ^{134}Xe, present in the source at 17%, by considering the maximum number of events for this mode compatible with the fitted smooth background.

[12] BERNABEI 02D report a limit for the 0ν, $0^+ \rightarrow 0^+$ decay of ^{136}Xe, by considering the maximum number of events for this mode compatible with the fitted smooth background. The quoted sensitivity is 450×10^{21} yr. The Feldman and Cousins method is used to obtain the quoted limit.

[13] KLAPDOR-KLEINGROTHAUS 02D is an expanded version of KLAPDOR-KLEINGROTHAUS 01B. The authors re-evaluate the data collected by the Heidelberg-Moscow experiment (KLAPDOR-KLEINGROTHAUS 01) and present a more detailed description of their analysis of an excess of counts at the energy expected for neutrinoless double-beta decay. They interpret this excess, which has a significance of 2.2 to 3.1 σ depending on the data analysis, as evidence for the observation of Lepton Number violation and violation of Baryon minus Lepton Number. The analysis has been criticized by AALSETH 02 and others. The criticisms have been addressed in KLAPDOR-KLEINGROTHAUS 02. See also KLAPDOR-KLEINGROTHAUS 02B.

[14] ASHITKOV 01 result for 2ν of ^{100}Mo is in agreement with other determinations of that halflife.

[15] ASHITKOV 01 result for 0ν of ^{100}Mo is less stringent than EJIRI 01.

[16] DANEVICH 01 place limit on 0ν decay of ^{160}Gd using Gd$_2$SiO$_5$:Ce crystal scintillators. The limit is more stringent than KOBAYASHI 95.

[17] DANEVICH 01 place limits on 0ν decay of ^{160}Gd into excited 2^+ state of daughter nucleus using Gd$_2$SiO$_5$:Ce crystal scintillators.

[18] DEBRAECKELEER 01 performed an inclusive measurement of the $\beta\beta$ decay into the second excited state of the daughter nucleus. A novel coincidence technique counting the de-excitation photons is employed. The result agrees with BARABASH 95.

[19] EJIRI 01 uses tracking calorimeter and isotopically enriched passive source. Efficiencies were calculated assuming $\langle m_\nu\rangle$, $\langle\lambda\rangle$, or $\langle\eta\rangle$ driven decay. This is a continuation of EJIRI 96 which it supersedes.

[20] KLAPDOR-KLEINGROTHAUS 01 is a continuation of the work published in BAUDIS 99. Isotopically enriched Ge detectors are used in calorimetric measurement. The most stringent bound is derived from the data set in which pulse-shape analysis has been used to reduce background. Exposure time is 35.5 kg y. Supersedes BAUDIS 99 as most stringent result.

[21] KLAPDOR-KLEINGROTHAUS 01 is a measurement of the $\beta\beta 2\nu$-decay rate with higher statistics than GUENTHER 97. The reported value has a worse systematic error than their previous result.

[22] WIESER 01 reports an inclusive geochemical measurement of ^{96}Zr $\beta\beta$ half life. Their result agrees within 2σ with ARNOLD 99 but only marginally, within 3σ, with KAWASHIMA 93.

[23] BRUDANIN 00 determine the 2ν halflife of ^{48}Ca. Their value is less accurate than BALYSH 96.

[24] ARNOLD 99 measure directly the 2ν decay of Zr for the first time, using the NEMO-2 tracking detector and an isotopically enriched source. The lifetime is more accurate than the geochemical result of KAWASHIMA 93.

[25] ARNOLD 98 measure the 2ν decay of ^{82}Se by comparing the spectra in an enriched and natural selenium source using the NEMO-2 tracking detector. The measured half-life is in agreement, perhaps slightly shorter, than ELLIOTT 92.

[26] ARNOLD 98 determine the limit for 0ν decay to the ground state of ^{82}Se using the NEMO-2 tracking detector. The half-life limit is in agreement, but less stringent, than ELLIOTT 92.

[27] ARNOLD 98 determine the limit for 0ν decay to the excited 2^+ state of ^{82}Se using the NEMO-2 tracking detector.

[28] ALSTON-GARNJOST 97 report evidence for 2ν decay of ^{100}Mo. This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.

[29] DESILVA 97 result for 2ν decay of ^{100}Mo is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.

[30] DESILVA 97 result for 2ν decay of ^{150}Nd is in marginal agreement with ARTEMEV 93. It has smaller errors.

[31] DESILVA 97 do not explain whether their efficiency for 0ν decay of ^{150}Nd was calculated under the assumption of a $\langle m_\nu\rangle$, $\langle\lambda\rangle$, or $\langle\eta\rangle$ driven decay.

[32] GUENTHER 97 half-life for the 2ν decay of ^{76}Ge is not in good agreement with the previous measurements of BALYSH 94, AVIGNONE 91, and MILEY 90.

[33] ARNOLD 96 measure the 2ν decay of ^{116}Cd. This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.

[34] BALYSH 96 measure the 2ν decay of ^{48}Ca, using a passive source of enriched ^{48}Ca in a TPC.

[35] TAKAOKA 96 measure the geochemical half-life of ^{130}Te. Their value is in disagreement with the quoted values of BERNATOWICZ 92 and KIRSTEN 83; but agrees with several other unquoted determinations, e.g., MANUEL 91.

[36] BARABASH 95 cannot distinguish 0ν and 2ν, but it is inferred indirectly that the 0ν mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92).

[37] BERNATOWICZ 92 finds ^{128}Te/^{130}Te activity ratio from slope of ^{128}Xe/^{132}Xe vs ^{130}Xe/^{132}Xe ratios during extraction, and normalizes to lead-dated ages for the ^{130}Te lifetime. The authors state that their results imply that "(a) the double beta decay of ^{128}Te has been firmly established and its half-life has been determined ... without any ambiguity due to trapped Xe interferences... (b) Theoretical calculations ... underestimate the [long half-lives of ^{128}Te ^{130}Te] by 1 or 2 orders of magnitude, pointing to a real suppression in the 2ν decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models predict a *ratio* of 2ν decay widths ... in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray ^{128}Xe production corrections.

[38] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the ^{238}U transition in the same range as deduced for ^{130}Te and ^{76}Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

[39] Result agrees with direct determination of ELLIOTT 92.

[40] Inclusive half life inferred from mass spectroscopic determination of abundance of $\beta\beta$-decay product ^{130}Te in mineral kitkaite (NiTeSe). Systematic uncertainty reflects variations in U-Xe gas-retention-age derived from different uranite samples. Agrees with geochemical determination of TAKAOKA 96 and direct measurement of ARNABOLDI 03. Inconsistent with results of KIRSTEN 83 and BERNATOWICZ 92.

[41] Ratio of inclusive double beta half lives of ^{128}Te and ^{130}Te determined from minerals melonite ($NiTe_2$) and altaite (PbTe) by means of mass spectroscopic measurement of abundance of $\beta\beta$-decay products. As gas-retention-age could not be determined the authors use half life of ^{130}Te (LIN 88) to infer the half life of ^{128}Te. No estimate of the systematic uncertainty of this method is given. The directly determined half life ratio agrees with BERNATOWICZ 92. However, the inferred ^{128}Te half life disagrees with KIRSTEN 83 and BERNATOWICZ 92.

[42] KIRSTEN 83 reports "2σ" error. References are given to earlier determinations of the ^{130}Te lifetime.

$\langle m_\nu \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double-β Decay

$\langle m_\nu \rangle = |\Sigma\, U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to n and where n = number of neutrino generations, and ν_j is a Majorana neutrino. Note that U^2_{ej}, not $|U_{ej}|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

VALUE (eV)	*CL%*	*ISOTOPE*	*TRANSITION*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •						
< 1.1–2.6	90	^{130}Te		Cryog. det.	[43] ARNABOLDI	03
< 1.5–1.7	90	^{116}Cd	0ν	$^{116}CdWO_4$ scint.	[44] DANEVICH	03
< 0.33–1.35	90			Enriched HPGe	[45] AALSETH	02B
<2.9	90	^{136}Xe	0ν	Liquid Xe Scint.	[46] BERNABEI	02D
$0.39^{+0.17}_{-0.28}$		^{76}Ge	0ν	Enriched HPGe	[47] KLAPDOR-K...	02D
< 2.1–4.8	90	^{100}Mo	0ν	ELEGANT V	[48] EJIRI	01
< 0.35	90	^{76}Ge		Enriched HPGe	[49] KLAPDOR-K...	01
<23	90	^{96}Zr		NEMO-2	[50] ARNOLD	99
< 1.1–1.5		^{128}Te		Geochem	[51] BERNATOW...	92
<5	68	^{82}Se		TPC	[52] ELLIOTT	92
<8.3	76	^{48}Ca	0ν	CaF_2 scint.	YOU	91

[43] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.

[44] Limit for $\langle m_\nu \rangle$ is based on the nuclear matrix elements of STAUDT 90 and ARNOLD 96. Supersedes DANEVICH 00.

[45] AALSETH 02B reported range of limits on $\langle m_\nu \rangle$ reflects the spread of theoretical nuclear matrix elements. Excludes part of allowed mass range reported in KLAPDOR-KLEINGROTHAUS 01B.

[46] BERNABEI 02D limit is based on the matrix elements of SIMKOVIC 02. The range of neutrino masses based on a variety of matrix elements is 1.1–2.9 eV.

[47] KLAPDOR-KLEINGROTHAUS 02D is a detailed description of the analysis of the data collected by the Heidelberg-Moscow experiment, previously presented in KLAPDOR-KLEINGROTHAUS 01B. Matrix elements in STAUDT 90 have been used. See the footnote in the preceding table for further details. See also KLAPDOR-KLEINGROTHAUS 02B.

[48] The range of the reported $\langle m_\nu \rangle$ values reflects the spread of the nuclear matrix elements. On axis value assuming $\langle\lambda\rangle$=$\langle\eta\rangle$=0.

[49] KLAPDOR-KLEINGROTHAUS 01 uses the calculation by STAUDT 90. Using several other models in the literature could worsen the limit up to 1.2 eV. This is the most stringent experimental bound on m_ν. It supersedes BAUDIS 99B.

[50] ARNOLD 99 limit based on the nuclear matrix elements of STAUDT 90.

[51] BERNATOWICZ 92 finds these majorana neutrino mass limits assuming that the measured geochemical decay width is a limit on the 0ν decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.

[52] ELLIOTT 92 uses the matrix elements of HAXTON 84.

Limits on Lepton-Number Violating ($V+A$) Current Admixture

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle\lambda\rangle = \lambda \sum U_{ej} V_{ej}$ and $\langle\eta\rangle = \eta \sum U_{ej} V_{ej}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

$\langle\lambda\rangle$ (10^{-6})	*CL%*	$\langle\eta\rangle$ (10^{-8})	*CL%*	*ISOTOPE*	*METHOD*	*DOCUMENT ID*	
• • • We do not use the following data for averages, fits, limits, etc. • • •							
< 1.6–2.4	90	< 0.9–5.3	90	^{130}Te	Cryog. det.	[53] ARNABOLDI	03
<2.2	90	<2.5	90	^{116}Cd	$^{116}CdWO_4$ scint.	[54] DANEVICH	03
< 3.2–4.7	90	< 2.4–2.7	90	^{100}Mo	ELEGANT V	[55] EJIRI	01
<1.1	90	<0.64	90	^{76}Ge	Enriched HPGe	[56] GUENTHER	97
<4.4	90	<2.3	90	^{136}Xe	TPC	[57] VUILLEUMIER	93
		<5.3		^{128}Te	Geochem	[58] BERNATOW...	92

[53] Supersedes ALESSANDRELLO 00. Cryogenic calorimeter search. Reported a range reflecting uncertainty in nuclear matrix element calculations.

[54] Limits for $\langle\lambda\rangle$ and $\langle\eta\rangle$ are based on nuclear matrix elements of STAUDT 90. Supersedes DANEVICH 00.

[55] The range of the reported $\langle\lambda\rangle$ and $\langle\eta\rangle$ values reflects the spread of the nuclear matrix elements. On axis value assuming $\langle m_\nu\rangle$=0 and $\langle\lambda\rangle$=$\langle\eta\rangle$=0, respectively.

[56] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.

[57] VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit 2.6×10^{23} y at 90%CL.

[58] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the 0ν width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on η. Further details of the experiment are given in BERNATOWICZ 93.

Double-β Decay REFERENCES

ARNABOLDI	03	PL B557 167	C. Arnaboldi *et al.*	
DANEVICH	03	PR C68 035501	F.A. Danevich *et al.*	
AALSETH	02	MPL A17 1475	C.E. Aalseth *et al.*	
AALSETH	02B	PR D65 092007	C.E. Aalseth *et al.*	(IGEX Collab.)
BERNABEI	02D	PL B546 23	R. Bernabei *et al.*	(DAMA Collab.)
KLAPDOR-K...	02	hep-ph/0205228	H.V. Klapdor-Kleingrothaus	
KLAPDOR-K...	02B	JINRRC 110 57	H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina	
KLAPDOR-K...	02D	FP 32 1181	H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina	
SIMKOVIC	02	hep-ph/0204278	F. Simkovic, P. Domin, A. Faessler	
ASHITKOV	01	JETPL 74 529 Translated from ZETFP 74 601.	V.D. Ashitkov *et al.*	
DANEVICH	01	NP A694 375	F.A. Danevich *et al.*	
DEBRAECKEL...	01	PRL 86 3510	L. De Braeckeleer *et al.*	
EJIRI	01	PR C63 065501	H. Ejiri *et al.*	
KLAPDOR-K...	01	EPJ A12 147	H.V. Klapdor-Kleingrothaus *et al.*	
KLAPDOR-K...	01B	MPL A16 2409	H.V. Klapdor-Kleingrothaus *et al.*	
WIESER	01	PR C64 024308	M.E. Wieser, J.R. De Laeter	
ALESSAND...	00	PL B486 13	A. Alessandrello *et al.*	
BRUDANIN	00	PL B495 63	V.B. Brudanin *et al.*	
DANEVICH	00	PR C62 045501	F.A. Danevich *et al.*	
ARNOLD	99	NP A658 299	R. Arnold *et al.*	(NEMO Collab.)
BAUDIS	99	PR D59 022001	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
BAUDIS	99B	PRL 83 41	L. Baudis *et al.*	(Heidelberg-Moscow Collab.)
ARNOLD	98	NP A636 209	R. Arnold *et al.*	(NEMO-2 Collab.)
ALSTON-...	97	PR C55 474	M. Alston-Garnjost *et al.*	(LBL, MTHO+)
DESILVA	97	PR C56 2451	A. de Silva *et al.*	(UCI)
GUENTHER	97	PR D55 54	M. Gunther *et al.*	(Heidelberg-Moscow Collab.)
ARNOLD	96	ZPHY C72 239	R. Arnold *et al.*	(BCEN, CAEN, JINR+)
BALYSH	96	PRL 77 5186	A. Balysh *et al.*	(KIAE, UCI, CIT)
EJIRI	96	NP A611 85	H. Ejiri *et al.*	(OSAK)
TAKAOKA	96	PR C53 1557	N. Takaoka, Y. Motomura, K. Nagao	(KYUSH, OKAY)
ARNOLD	95	JETPL 61 170 Translated from ZETFP 61 168.	R.G. Arnold *et al.*	(NEMO Collab.)
BALYSH	95	PL B356 450	A. Balysh *et al.*	(Heidelberg-Moscow Collab.)
BARABASH	95	PL B345 408	A.S. Barabash *et al.*	(ITEP, SCUC, PNL+)
DASSIE	95	PR D51 2090	D. Dassie *et al.*	(NEMO Collab.)
EJIRI	95	JPSJ 64 339	H. Ejiri *et al.*	(OSAK, KIEV)
KOBAYASHI	95	NP A586 457	M. Kobayashi, M. Kobayashi	(KEK, SAGA)
BALYSH	94	PL B322 176	A. Balysh *et al.*	(Heidelberg-Moscow Collab.)
ARTEMEV	93	JETPL 58 262 Translated from ZETFP 58 256.	V.A. Artemiev *et al.*	(ITEP, INRM)
BERNATOW...	93	PR C47 806	T. Bernatowicz *et al.*	(WUSL, TATA)
KAWASHIMA	93	PR C47 R2452	A. Kawashima, K. Takahashi, A. Masuda	(TOKYC+)
VUILLEUMIER	93	PR D48 1009	J.C. Vuilleumier *et al.*	(NEUC, CIT, VILL)
BALYSH	92	PL B283 32	A. Balysh *et al.*	(MPIH, KIAE, SASSO)
BERNATOW...	92	PRL 69 2341	T. Bernatowicz *et al.*	(WUSL, TATA)
BLUM	92	PL B275 506	D. Blum *et al.*	(NEMO Collab.)
ELLIOTT	92	PR C46 1535	S.R. Elliott *et al.*	(UCI)
AVIGNONE	91	PL B256 559	F.T. Avignone *et al.*	(SCUC, PNL, ITEP+)
EJIRI	91	PL B258 17	H. Ejiri *et al.*	(OSAK)
MANUEL	91	JPG 17 S221	O.K. Manuel	(MISSR)
SUHONEN	91	NP A535 509	J. Suhonen, S.B. Khadkikar, A. Faessler	(JYV+)
TURKEVICH	91	PRL 67 3211	A. Turkevich, T.E. Economou, G.A. Cowan	(CHIC+)
YOU	91	PL B265 53	K. You *et al.*	(BHEP, CAST+)
MILEY	90	PRL 65 3092	H.S. Miley *et al.*	(SCUC, PNL)
STAUDT	90	EPL 13 31	A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus	
MUTO	89	ZPHY A334 187	K. Muto, E. Bender, H.V. Klapdor	(TINT, MPIH)
LIN	88	NP A481 477	W.J. Lin *et al.*	
LIN	88B	NP A481 484	W.J. Lin *et al.*	
BOEHM	87	Massive Neutrinos Cambridge Univ. Press, Cambridge	F. Bohm, P. Vogel	(CIT)
TOMODA	87	PL B199 475	T. Tomoda, A. Faessler	(TUBIN)
HAXTON	84	PPNP 12 409	W.C. Haxton, G.J. Stevenson	
KIRSTEN	83	PRL 50 474	T. Kirsten, H. Richter, E. Jessberger	(MPIH)

UNDERSTANDING TWO-FLAVOR OSCILLATION PARAMETERS AND LIMITS

Revised March 2002 by D.E. Groom (LBNL).

As discussed in Boris Kayser's Review "Neutrino Mass, Mixing, and Flavor Change," there are several conditions under which the two-neutrino mixing approximation is valid. Many results have been published with this assumption, whether it is valid or not. In this context, and in the context of vacuum oscillations, the probability that a neutrino with original flavor ℓ, for example, oscillates into a flavor $\ell\,'$ over a distance L in vacuum is given by

$$\begin{aligned} P(\nu_\ell \to \nu_{\ell'}) &= \sin^2 2\theta \sin^2(\Delta m^2_{ij} L/4\hbar c E) \\ &= \sin^2 2\theta \sin^2(1.27 \Delta m^2_{ij}(\mathrm{eV}^2)\, L(\mathrm{km})/E(\mathrm{GeV})) \end{aligned} \qquad (1)$$

where we assume that mass eigenstates i and j are involved. Although this equation is frequently quoted and is used in Monte Carlo calculations, the function is badly behaved for arguments larger than about one, where it oscillates more and more rapidly between $\sin^2 2\theta = P$ and $\sin^2 2\theta = 0$ as the argument increases. It is difficult to relate this function to the exclusion curves in the literature.

In a real experiment, E, and sometimes L, have some spread due to various effects, but in a subset of these experiments there is a well-defined $\langle L/E\rangle$ about which the events distribute. It is instructive to make a toy model in which $b \equiv 1.27L/E$ has a Gaussian distribution with standard deviation σ_b about a central value b_0. The convolution of this Gaussian with P as given in Eq. (1) is analytic, with the result

$$\langle P\rangle = \tfrac{1}{2}\sin^2 2\theta[1 - \cos(2b_0\Delta m^2_{ij})\exp(-2\sigma_b^2(\Delta m^2_{ij})^2)] \ . \qquad (2)$$

The value of $\langle P\rangle$ is set by the experiment. For example, if 230 interactions of the expected flavor are detected and none of the wrong flavor are seen, then $P = 0.010$ at the 90% CL (slightly subject to one's way of calculating the CL). Then with fixed $\langle P\rangle$ we can find $\sin^2 2\theta$ as a function of Δm^2_{ij}. This function is shown in Fig. 1(a) and (c) for particular parameter choices. The resulting parameter exclusion region boundary has the following features:

(1) For large Δm^2_{ij} the fast oscillations are completely washed out by the resolution, and $\sin^2 2\theta = 2\langle P\rangle$ in this limit;

(2) the maximum excursion of the curve to the left is to $\sin^2 2\theta = \langle P\rangle$ if the resolution is very good, and somewhat smaller if it is not. This "bump" to the left occurs at $\Delta m^2_{ij} = \pi/2b_0$;

(3) For large $\sin^2 2\theta$, $\Delta m^2_{ij} \approx \sqrt{\langle P\rangle}/(b_0\sqrt{\sin^2 2\theta})$; and, consequently,

   (a) the nearly straight-line segment at the bottom is described by $\Delta m^2_{ij} \approx \langle P\rangle/b_0\sqrt{\sin^2 2\theta}$

   (b) the intercept at $\sin^2 2\theta = 1$ is at $\Delta m^2_{ij} = \sqrt{\langle P\rangle}/b_0 = \sqrt{\langle P\rangle}/1.27\langle L/E\rangle$.

The intercept for large Δm^2_{ij} is a measure of running time and backgrounds, while the intercept at $\sin^2 2\theta = 1$ also depends upon $\langle L/E\rangle$. The wiggles depend upon the experimental

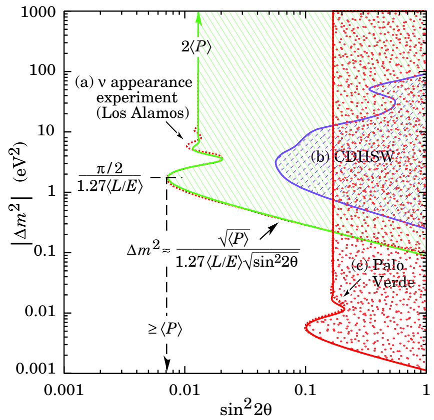

Figure 1: Neutrino oscillation parameter ranges excluded by three experiments. The dotted line in (a) is from an older Los Alamos appearance experiment (DURKIN 88), while the solid line is obtained from Eq. (2) using the parameters $\langle P\rangle = 0.0065$, $\Delta m^2 = 0.095$ eV^2 at $\sin^2 2\theta = 1$, and $\sigma_b/b_0 = 0.23$; (b) is a disappearance experiment with the flux obtained from the data in a long detector (DYDAK 84); and for (c) the Palo Verde reactor experiment result (BOEHM 01) is shown by the dotted line. In this experiment the flux at production is known. The solid line is calculated from Eq. (2) using $\langle P\rangle = 0.084$, $\Delta m^2 = 0.0011$ eV^2 at $\sin^2 2\theta = 1$, and $\sigma_b/b_0 = 0.3$. The experiments have been chosen for illustrative purposes, and none represents a current best limit. See full-color version on color pages at end of book.

features such as the size of the source, the neutrino energy distribution, detector resolution (L and E), and analysis details. Aside from such details, the two intercepts completely describe the exclusion region: For large Δm^2_{ij}, $\sin^2 2\theta$ is constant and equal to $2\langle P\rangle$, and for large $\sin^2 2\theta$ the slope and intercept are known. For these reasons, it is (nearly) sufficient to summarize the results of an experiment by stating the two intercepts, as is done in our Listings in cases where two-neutrino analyses of this sort have been published.

While there is no reason for such a naïve 3-parameter function to describe all real experiments, the function actually does give a remarkably good description of *some* experimental results, underscoring the usefulness of the way we report results in the Listings. In example (a) in Fig. 1, the dotted curve shows the result obtained in an old Los Alamos appearance experiment (DURKIN 88). DURKIN 88 reports $\Delta m^2 = 0.11$ eV^2 for maximal mixing and $\sin^2 2\theta = 2 \times 0.070$ for large Δm^2. The solid curve is obtained using Eq. (2), with parameters $\langle P\rangle = 0.0065$, $\Delta m^2 = 0.095$ eV^2 at $\sin^2 2\theta = 1$, and $\sigma_b/b_0 = 0.23$.

If a positive effect is claimed, then the excluded region is replaced by an allowed band. However, in a real experiment there is usually other information, such as estimators of L and E for each event. The likelihood function is formed using this event-by-event information. The CL is not uniform along the allowed band, resulting in "islands" of high confidence.

In a "disappearance" experiment, one looks for the attenuation of the initial lepton eigenstate ν_ℓ beam in transit to a detector, where the ν_ℓ flux is measured. (We label such experiments as $\nu_\ell \not\to \nu_\ell$.) In the two-neutrino mixing approximation, the probability that a lepton eigenstate remains unscathed from the production point to the detector is given by

$$P(\nu_\ell \to \nu_\ell) = 1 - P(\nu_\ell \to \nu_{\ell'}) \ , \qquad (3)$$

where mixing occurs between the ν_ℓ and $\nu_{\ell'}$, with $P(\nu_\ell \to \nu_{\ell'})$ given by Eq. (1) or Eq. (2).

The disappearance of a small fraction of the "right-flavor" neutrinos in such an experiment can go unobserved because of statistical fluctuations—if 100 events are expected and 95 events are observed, nothing is proven.* For this reason, disappearance experiments usually cannot establish small-probability (small $\sin^2 2\theta$) mixing.

Disappearance experiments fall into several classes:

(1) Those in which attenuation or oscillation of the beam neutrino flux is measured in the apparatus itself (two detectors, or a "long" detector). Above some minimum Δm^2_{ij} the equilibrium is established upstream, and there is no change in intensity over the length of the apparatus. As a result, sensitivity is lost at high Δm^2_{ij}, as can be seen by the CDHSW curve, Fig. 1(b) (DYDAK 84). Such experiments have not been competitive for a long time. However, a new generation of long-baseline experiments will use this strategy to advantage.

(2) Accelerator and reactor experiments in which the beam neutrino flux is known, from theory or from other measurements. Although such experiments cannot establish very small $\sin^2 2\theta$ mixing, they can establish small limits on Δm^2_{ij} for large $\sin^2 2\theta$ because L/E can be very large. Results of the Palo Verde experiment (BOEHM 01) are shown by the dotted curve (c) in Fig. 1. The solid curve has been calculated via Eq. (2), with parameters $\langle P\rangle = 0.084$, $\Delta m^2 = 0.0011$ eV^2 at $\sin^2 2\theta = 1$ (very nearly the values reported in BOEHM 01), and $\sigma_b/b_0 = 0.3$.

(3) Atmospheric neutrino experiments, in which ν_e and ν_μ are detected over a large range of L (the diameter of the earth). This is a subset of (1) above, and the resulting curves, in this case showing a positive effect, are similar.

This discussion has so far been limited to "vacuum oscillations," where the mixing probability is described Eq. (1). In the solar neutrino case it is likely that interactions between the neutrinos and solar electrons affect the oscillation probability ("matter oscillations," the MSW effect). This effect is described in the Review "Neutrino Mass, Mixing, and Flavor Change," by Boris Kayser. In this situation the formalism discussed above is not applicable.

* In contrast, if 5 golden "wrong-flavor" events are seen among 100 "right-flavor" events, a great deal is learned.

Eq. (1) depends on the mixing angle only through $\sin^2 2\theta$, giving the false impression that physically distinct possibilities map one-to-one onto the interval [0,1] in $\sin^2 2\theta$.† The relationship between mass eigenstates, *e.g.*, ν_1, ν_2, and weak eigenstates, *e.g.*, ν_e, ν_μ, is given by

$$\begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} \ . \qquad (4)$$

By convention, we can take ν_2 always heavier than ν_1, *i.e.*, $\Delta m^2_{21} = m^2_2 - m^2_1 > 0$, without a loss of generality. The $\theta \to 0$ limit is relevant when there is no mixing and ν_e is lighter, while $\theta \to \pi/2$ is needed to describe the possibility where ν_e is heavier with no mixing. Therefore, θ needs to be varied between 0 and $\pi/2$, which makes $\sin^2 2\theta$ fold at 1 back down to 0. In the case of oscillation in vacuum, θ and $\pi/2 - \theta$ happen to give identical oscillation probabilities, even though they are physically inequivalent. In this case, the use of $\sin^2 2\theta$ is misleading, but acceptable from practical point of view. In presence of matter effects, even the oscillation probabilities are different, and $\sin^2 2\theta$ is not an appropriate parameter in oscillation parameter plots. One common choice is $\tan^2\theta$, because it can cover the whole range of $0 \le \theta \le \pi/2$, while showing the same probabilities for $\theta \leftrightarrow \pi/2 - \theta$ in the absence of matter effects as a reflection symmetry around $\tan^2\theta = 1$ if plotted on log scale.‡

Neutrino Mixing

INTRODUCTION TO NEUTRINO MIXING LISTINGS

Based on the discussion in the previous review "Understanding Two-Flavor Oscillation Parameters and Limits" by Don Groom, most results in the neutrino mixing listings are presented as Δm^2 limits (or ranges) for $\sin^2 2\theta = 1$, and $\sin^2 2\theta$ limits (or ranges) for large Δm^2. Together, they summarize most of the information contained in the usual Δm^2 vs $\sin^2 2\theta$ plots in the experiments' papers. The neutrino mixing listings are divided into four sub-sections:

(A) Accelerator neutrino experiments: shows Δm^2 and $\sin^2 2\theta$ limits for, successively, $\nu_e \to \nu_\tau$ and $\overline{\nu}_e \to \overline{\nu}_\tau$ appearance, $\nu_e \not\to \nu_e$ disappearance, $\nu_\mu \to \nu_e$, $\overline{\nu}_\mu \to \overline{\nu}_e$, $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ appearance, and $\nu_\mu \not\to \nu_\mu$ and $\overline{\nu}_\mu \not\to \overline{\nu}_\mu$ disappearance. They are all limits, except for the positive $\nu_\mu \not\to \nu_\mu$ signal from the K2K collaboration reported in AHN 03.

(B) Reactor $\overline{\nu}_e$ disappearance experiments: has Δm^2 and $\sin^2 2\theta$ limits for $\overline{\nu}_e \not\to \overline{\nu}_e$ disappearance, together with the ratios of measured to expected rates of events. It also contains

† For example, see G.L. Fogli, E. Lisi, and D. Montanino, Phys. Rev. **D54**, 2048 (1996), and A. de Gouvêa, A. Friedland, and H. Murayama, Phys. Lett. **B490**, 125 (2000)

‡ This discussion of the $\pi/4 \le \theta \le \pi/2$ region was contributed by H. Murayama.

the positive signal from the KamLAND collaboration (EGUCHI 03).

(C) Atmospheric neutrino observations: lists the ratio of measured to expect ν_μ rate, the double ratio of measured ν_μ/ν_e rates over expected, and the up/down ratio of measured over expected for both ν_μ and ν_e. It also gives Δm^2 and $\sin^2 2\theta$ limits for $\nu_e \leftrightarrow \nu_\mu$ and $\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu$, as well as the Kamiokande, SuperKamiokande and MACRO measurements of both $\sin^2 2\theta$ and Δm^2 for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, together with limits on ν_μ oscillations to a sterile neutrino.

(D) Solar ν experiments: is organized differently, showing first the results from radiochemical experiments and moving then to results of ^{8}B fluxes from elastic scattering, charged current and neutral current. From these, the solar fluxes for all three neutrino flavors combined and for only ν_μ and ν_τ are derived and listed. The day/night asymmetry for ^{8}B is also listed. Finally, the Kamiokande limit on the "hep" ν_e flux from the sun as measured in elastic scattering is given.

(A) Accelerator neutrino experiments

$\nu_e \rightarrow \nu_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.77	90	[1] ARMBRUSTER	98	KARM	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 5.9	90	[2] ASTIER	01B	NOMD	CERN SPS
< 7.5	90	[3] ESKUT	01	CHRS	CERN SPS
<17	90	NAPLES	99	CCFR	FNAL
<44	90	TALEBZADEH	87	HLBC	BEBC
< 9	90	USHIDA	86C	EMUL	FNAL

[1] ARMBRUSTER 98 use KARMEN detector with ν_e from muon decay at rest and observe ^{12}C(ν_e,e^-)^{12}N$_{gs}$. This is a disappearance experiment which is almost insensitive to $\nu_e \rightarrow \nu_\mu$ oscillation. Results are presented as limits to $\nu_e \rightarrow \nu_\tau$ oscillation, although the (non)oscillation could be to a non-visible flavor. A three-flavor analysis is also presented.

[2] ASTIER 01B searches for the appearance of ν_τ with the NOMAD detector at CERN's SPS. The limit is based on an oscillation probability $< 0.74 \times 10^{-2}$, whereas the quoted sensitivity was 1.1×10^{-2}. The limit was obtained following the statistical prescriptions of FELDMAN 98. See also the footnote to ESKUT 01.

[3] ESKUT 01 searches for the appearance of the ν_τ with the CHORUS detector at CERN's SPS. The limit is obtained following the statistical prescriptions in JUNK 99. The limit would have been 6 eV^2 if the prescriptions in FELDMAN 98 had been followed, as they were in ASTIER 01B.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.015	90	[4] ASTIER	01B	NOMD	CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.052	90	[5] ESKUT	01	CHRS	CERN SPS
<0.21	90	NAPLES	99	CCFR	FNAL
<0.338	90	[6] ARMBRUSTER	98	KARM	
<0.36	90	TALEBZADEH	87	HLBC	BEBC
<0.25	90	[7] USHIDA	86C	EMUL	FNAL

[4] ASTIER 01B limit is based on an oscillation probability $< 0.74 \times 10^{-2}$, whereas the quoted sensitivity was 1.1×10^{-2}. The limit was obtained following the statistical prescriptions of FELDMAN 98. See also the footnote to ESKUT 01.

[5] ESKUT 01 limit obtained following the statistical prescriptions in JUNK 99. The limit would have been 0.03 if the prescriptions in FELDMAN 98 had been followed, as they were in ASTIER 01B.

[6] See footnote in preceding table (ARMBRUSTER 98) for further details, and see the paper for a plot showing allowed regions. A three-flavor analysis is also presented here.

[7] USHIDA 86C published result is $\sin^2 2\theta < 0.12$. The quoted result is corrected for a numerical mistake incurred in calculating the expected number of ν_e CC events, normalized to the total number of neutrino interactions (3886) rather than to the total number of ν_μ CC events (1870).

$\overline{\nu}_e \rightarrow \overline{\nu}_\tau$

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.7	90	[8] FRITZE	80	HYBR	BEBC CERN SPS

[8] Authors give P($\nu_e \rightarrow \nu_\tau$) <0.35, equivalent to above limit.

$\nu_e \not\rightarrow \nu_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.18	90	[9] HAMPEL	98	GALX	^{51}Cr source
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<40	90	[10] BORISOV	96	CNTR	IHEP-JINR detector
<14.9	90	BRUCKER	86	HLBC	15-ft FNAL
< 8	90	BAKER	81	HLBC	15-ft FNAL
<56	90	DEDEN	81	HLBC	BEBC CERN SPS
<10	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<2.3 OR >8	90	NEMETHY	81B	CNTR	LAMPF

[9] HAMPEL 98 analyzed the GALLEX calibration results with ^{51}Cr neutrino sources and updates the BAHCALL 95 analysis result. They also gave 95% and 99% CL limits of < 0.2 and < 0.22, respectively.

[10] BORISOV 96 exclusion curve extrapolated to obtain this value; however, it does not have the right curvature in this region.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<7 × 10^{-2}	90	[11] ERRIQUEZ	81	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	[12] HAMPEL	98	GALX	^{51}Cr source
<0.115	90	[13] BORISOV	96	CNTR	$\Delta(m^2) = 175$ eV^2
<0.54	90	BRUCKER	86	HLBC	15-ft FNAL
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<0.3	90	[11] DEDEN	81	HLBC	BEBC CERN SPS

[11] Obtained from a Gaussian centered in the unphysical region.

[12] HAMPEL 98 analyzed the GALLEX calibration results with ^{51}Cr neutrino sources and updates the BAHCALL 95 analysis result. They also gave 95% and 99% CL limits of < 0.45 and < 0.56, respectively.

[13] BORISOV 96 sets less stringent limits at large $\Delta(m^2)$, but exclusion curve does not have clear asymptotic behavior.

$\nu_e \rightarrow (\overline{\nu}_e)_L$

This is a limit on lepton family-number violation and total lepton-number violation. $(\overline{\nu}_e)_L$ denotes a hypothetical left-handed $\overline{\nu}_e$. The bound is quoted in terms of $\Delta(m^2)$, $\sin(2\theta)$, and α, where α denotes the fractional admixture of $(V+A)$ charged current.

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.14	90	[14] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<7	90	[15] COOPER	82	HLBC	BEBC CERN SPS

[14] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$.

[15] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.032	90	[16] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.05	90	[17] COOPER	82	HLBC	BEBC CERN SPS

[16] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$.

[17] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\nu_\mu \rightarrow \nu_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.09	90	ANGELINI	86	HLBC	BEBC CERN PS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.4	90	ASTIER	03	NOMD	CERN SPS
<2.4	90	AVVAKUNOV	02	NTEV	NUTEV FNAL
		[18] AGUILAR	01	LSND	$\nu\mu \rightarrow \nu_e$ osc.prob.
0.03 to 0.3	95	[19] ATHANASSO...	98	LSND	$\nu_\mu \rightarrow \nu_e$
<2.3	90	[20] LOVERRE	96		CHARM/CDHS
<0.9	90	VILAIN	94C	CHM2	CERN SPS
<0.1	90	BLUMENFELD	89	CNTR	
<1.3	90	AMMOSOV	88	HLBC	SKAT at Serpukhov
<0.19	90	BERGSMA	88	CHRM	
		[21] LOVERRE	88	RVUE	
<2.4	90	AHRENS	87	CNTR	BNL AGS
<1.8	90	BOFILL	87	CNTR	FNAL
<2.2	90	[22] BRUCKER	86	HLBC	15-ft FNAL
<0.43	90	AHRENS	85	CNTR	BNL AGS E734
<0.20	90	BERGSMA	84	CHRM	
<1.7	90	ARMENISE	81	HLBC	GGM CERN PS
<0.6	90	BAKER	81	HLBC	15-ft FNAL
<1.7	90	ERRIQUEZ	81	HLBC	BEBC CERN PS
<1.2	95	BLIETSCHAU	78	HLBC	GGM CERN PS
<1.2	95	BELLOTTI	76	HLBC	GGM CERN PS

[18] AGUILAR 01 is the final analysis of the LSND full data set. Search is made for the $\nu_\mu \rightarrow \nu_e$ oscillations using ν_μ from π^+ decay in flight by observing beam-on electron events from $\nu_e \mathrm{C} \rightarrow e^- X$. Present analysis results in 8.1 ± 12.2 ± 1.7 excess events in the 60<E_e < 200 MeV energy range, corresponding to oscillation probability of 0.10 ± 0.16 ± 0.04%. This is consistent, though less significant, with the previous result of ATHANASSOPOULOS 98, which it supersedes. The present analysis uses selection criteria developed for the decay at rest region, and is less effective in removing the background above 60 MeV than ATHANASSOPOULOS 98.

[19] ATHANASSOPOULOS 98 is a search for the $\nu_\mu \rightarrow \nu_e$ oscillations using ν_μ from π^+ decay in flight. The 40 observed beam-on electron events are consistent with $\nu_e \mathrm{C} \rightarrow e^- \mathrm{X}$; the expected background is 21.9 ± 2.1. Authors interpret this excess as evidence for an oscillation signal corresponding to oscillations with probability (0.26 ± 0.10 ± 0.05)%. Although the significance is only 2.3 σ, this measurement is an important and consistent cross check of ATHANASSOPOULOS 96 who reported evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations from μ^+ decay at rest. See also ATHANASSOPOULOS 98B.

[20] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[21] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.

[22] 15ft bubble chamber at FNAL.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
< 1.4	90	ASTIER	03	NOMD	CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 1.6	90	AVVAKUNOV	02	NTEV	NUTEV FNAL
		[23] AGUILAR	01	LSND	$\nu\mu \rightarrow \nu_e$ osc.prob.
0.5 to 30	95	[24] ATHANASSO...	98	LSND	$\nu_\mu \rightarrow \nu_e$
< 3.0	90	[25] LOVERRE	96		CHARM/CDHS
< 9.4	90	VILAIN	94C	CHM2	CERN SPS
< 5.6	90	[26] VILAIN	94C	CHM2	CERN SPS
< 16	90	BLUMENFELD	89	CNTR	
< 2.5	90	AMMOSOV	88	HLBC	SKAT at Serpukhov
< 8	90	BERGSMA	88	CHRM	$\Delta(m^2) \geq 30$ eV^2
		[27] LOVERRE	88	RVUE	
< 10	90	AHRENS	87	CNTR	BNL AGS
< 15	90	BOFILL	87	CNTR	FNAL
< 20	90	[28] ANGELINI	86	HLBC	BEBC CERN PS
20 to 40		[29] BERNARDI	86B	CNTR	$\Delta(m^2)$=5–10
< 11	90	[30] BRUCKER	86	HLBC	15-ft FNAL
< 3.4	90	AHRENS	85	CNTR	BNL AGS E734
<240	90	BERGSMA	84	CHRM	
< 10	90	ARMENISE	81	HLBC	GGM CERN PS
< 6	90	BAKER	81	HLBC	15-ft FNAL
< 10	90	ERRIQUEZ	81	HLBC	BEBC CERN PS
< 4	95	BLIETSCHAU	78	HLBC	GGM CERN PS
< 10	95	BELLOTTI	76	HLBC	GGM CERN PS

[23] AGUILAR 01 is the final analysis of the LSND full data set of the search for the $\nu_\mu \rightarrow \nu_e$ oscillations. See footnote in preceding table for further details.

[24] ATHANASSOPOULOS 98 report (0.26 ± 0.10 ± 0.05)% for the oscillation probability; the value of $\sin^2 2\theta$ for large Δm^2 is deduced from this probability. See footnote in preceding table for further details, and see the paper for a plot showing allowed regions. If effect is due to oscillation, it is most likely to be intermediate $\sin^2 2\theta$ and Δm^2. See also ATHANASSOPOULOS 98B.

[25] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

[26] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming CP conservation.

[27] LOVERRE 88 reports a less stringent, indirect limit based on theoretical analysis of neutral to charged current ratios.

[28] ANGELINI 86 limit reaches 13×10^{-3} at $\Delta(m^2) \approx 2$ eV^2.

[29] BERNARDI 86B is a typical fit to the data, assuming mixing between two species. As the authors state, this result is in conflict with earlier upper bounds on this type of neutrino oscillations.

[30] 15ft bubble chamber at FNAL.

$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.055	90	[31] ARMBRUSTER	02	KAR2	Liquid Sci. calor.
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<2.6	90	AVVAKUNOV	02	NTEV	NUTEV FNAL
0.03–0.05		[32] AGUILAR	01	LSND	LAMPF
0.05–0.08	90	[33] ATHANASSO...	96	LSND	LAMPF
0.048–0.090	80	[34] ATHANASSO...	95		
<0.07	90	[35] HILL	95		
<0.9	90	VILAIN	94C	CHM2	CERN SPS
<0.14	90	[36] FREEDMAN	93	CNTR	LAMPF
<3.1	90	BOFILL	87	CNTR	FNAL
<2.4	90	TAYLOR	83	HLBC	15-ft FNAL
<0.91	90	[37] NEMETHY	81B	CNTR	LAMPF
<1	95	BLIETSCHAU	78	HLBC	GGM CERN PS

[31] ARMBRUSTER 02 is the final analysis of the KARMEN 2 data for 17.7 m distance from the ISIS stopped pion and muon neutrino source. It is a search for $\overline{\nu}_e$, detected by the inverse β-decay reaction on protons and ^{12}C. 15 candidate events are observed, and 15.8 ± 0.5 background events are expected, hence no oscillation signal is detected. The results exclude large regions of the parameter area favored by the LSND experiment.

[32] AGUILAR 01 is the final analysis of the LSND full data set. It is a search for $\overline{\nu}_e$ 30 m from LAMPF beam stop. Neutrinos originate mainly for π^+ decay at rest. $\overline{\nu}_e$ are detected through $\overline{\nu}_e p \rightarrow e^+ n$ (20<E_{e^+} < 60 MeV) in delayed coincidence with $np \rightarrow d\gamma$. AUthors observe 87.9 ± 22.4 ± 6.0 total excess events. The observation is attributed to $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations with the oscillation probability of 0.264 ± 0.067 ± 0.045%, consistent with the previously published result. Taking into account all constraints, the most favored allowed region of oscillation parameters is a band of $\Delta(m^2)$ from 0.2–2.0 eV^2. Supersedes ATHANASSOPOULOS 95, ATHANASSOPOULOS 96, and ATHANASSOPOULOS 98.

[33] ATHANASSOPOULOS 96 is a search for $\overline{\nu}_e$ 30 m from LAMPF beam stop. Neutrinos originate mainly from π^+ decay at rest. $\overline{\nu}_e$ could come from either $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ or $\nu_e \rightarrow \overline{\nu}_e$; our entry assumes the first interpretation. They are detected through $\overline{\nu}_e p \rightarrow e^+ n$ (20 MeV <E_{e^+} <60 MeV) in delayed coincidence with $np \rightarrow d\gamma$. Authors observe 51 ± 20 ± 8 total excess events over an estimated background 12.5 ± 2.9. ATHANASSOPOULOS 96B is a shorter version of this paper.

[34] ATHANASSOPOULOS 95 error corresponds to the 1.6σ band in the plot. The expected background is 2.7 ± 0.4 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)$%. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[35] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[36] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. FREEDMAN 93 replaces DURKIN 88.

[37] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.0011	90	AVVAKUNOV	02	NTEV	NUTEV FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0017	90	[38] ARMBRUSTER	02	KAR2	Liquid Sci. calor.
0.0053 ± 0.0013 ± 0.009		[39] AGUILAR	01	LSND	LAMPF
0.0062 ± 0.0024 ± 0.0010		[40] ATHANASSO...	96	LSND	LAMPF
0.003–0.012	80	[41] ATHANASSO...	95		
<0.006	90	[42] HILL	95		
<4.8	90	VILAIN	94C	CHM2	CERN SPS
<5.6	90	[43] VILAIN	94C	CHM2	CERN SPS
<0.024	90	[44] FREEDMAN	93	CNTR	LAMPF
<0.04	90	BOFILL	87	CNTR	FNAL
<0.013	90	TAYLOR	83	HLBC	15-ft FNAL
<0.2	90	[45] NEMETHY	81B	CNTR	LAMPF
<0.004	95	BLIETSCHAU	78	HLBC	GGM CERN PS

[38] ARMBRUSTER 02 is the final analysis of the KARMEN 2 data. See footnote in the preceding table for further details, and the paper for the exclusion plot.

[39] AGUILAR 01 is the final analysis of the LSND full data set. The deduced oscillation probability is 0.264 ± 0.067 ± 0.045%; the value of $\sin^2 2\theta$ for large $\Delta(m^2)$ is twice this probability (although these values are excluded by other constraints). See footnote in preceding table for further details, and the paper for a plot showing allowed regions. Supersedes ATHANASSOPOULOS 95, ATHANASSOPOULOS 96, and ATHANASSOPOULOS 98.

[40] ATHANASSOPOULOS 96 reports (0.31 ± 0.12 ± 0.05)% for the oscillation probability; the value of $\sin^2 2\theta$ for large $\Delta(m^2)$ should be twice this probability. See footnote in preceding table for further details, and see the paper for a plot showing allowed regions.

[41] ATHANASSOPOULOS 95 error corresponds to the 1.6σ band in the plot. The expected background is 2.7 ± 0.4 events. Corresponds to an oscillation probability of $(0.34^{+0.20}_{-0.18} \pm 0.07)$%. For a different interpretation, see HILL 95. Replaced by ATHANASSOPOULOS 96.

[42] HILL 95 is a report by one member of the LSND Collaboration, reporting a different conclusion from the analysis of the data of this experiment (see ATHANASSOPOULOS 95). Contrary to the rest of the LSND Collaboration, Hill finds no evidence for the neutrino oscillation $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ and obtains only upper limits.

[43] VILAIN 94C limit derived by combining the ν_μ and $\overline{\nu}_\mu$ data assuming CP conservation.

[44] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \rightarrow e^+ n$. FREEDMAN 93 replaces DURKIN 88.

[45] In reaction $\overline{\nu}_e p \rightarrow e^+ n$.

$\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_e(\overline{\nu}_e)$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.075	90	BORODOV...	92	CNTR	BNL E776
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.6	90	[46] ROMOSAN	97	CCFR	FNAL

[46] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<1.8	90	[47] ROMOSAN	97	CCFR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3.8	90	[48] MCFARLAND	95	CCFR	FNAL
<3	90	BORODOV...	92	CNTR	BNL E776

[47] ROMOSAN 97 uses wideband beam with a 0.5 km decay region.

[48] MCFARLAND 95 state that "This result is the most stringent to date for $250 < \Delta(m^2) < 450$ eV^2 and also excludes at 90%CL much of the high $\Delta(m^2)$ region favored by the recent LSND observation." See ATHANASSOPOULOS 95 and ATHANASSOPOULOS 96.

$\nu_\mu \to \nu_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
< 0.6	90	[49] ESKUT	01	CHRS	CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.7	90	[50] ASTIER	01B	NOMD	CERN SPS
< 1.4	90	[51] ALTEGOER	98B	NOMD	CERN SPS
< 1.5	90	[52] ESKUT	98	CHRS	CERN SPS
< 1.1	90	[53] ESKUT	98B	CHRS	CERN SPS
< 3.3	90	[54] LOVERRE	96		CHARM/CDHS
< 1.4	90	MCFARLAND	95	CCFR	FNAL
< 4.5	90	BATUSOV	90B	EMUL	FNAL
<10.2	90	BOFILL	87	CNTR	FNAL
< 6.3	90	BRUCKER	86	HLBC	15-ft FNAL
< 0.9	90	USHIDA	86C	EMUL	FNAL
< 4.6	90	ARMENISE	81	HLBC	GGM CERN SPS
< 3	90	BAKER	81	HLBC	15-ft FNAL
< 6	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
< 3	90	USHIDA	81	EMUL	FNAL

[49] ESKUT 01 limit obtained following the statistical prescriptions in JUNK 99. The limit would have been 0.5 eV^2 if the prescriptions in FELDMAN 98 had been followed, as they were in ASTIER 01B.

[50] ASTIER 01B limit is based on an oscillation probability $< 1.63 \times 10^{-4}$, whereas the quoted sensitivity was 2.5×10^{-4}. The limit was obtained following the statistical prescriptions of FELDMAN 98. See also the footnote to ESKUT 01.

[51] ALTEGOER 98B is the NOMAD 1995 data sample result, searching for events with $\tau^- \to e^- \nu_\tau \overline{\nu}_e$, hadron$^-$ ν_τ, or $\pi^-\pi^+\pi^-$ decay modes using classical CL approach of FELDMAN 98.

[52] ESKUT 98 search for events with one μ^- with indication of a kink from τ^- decay in the nuclear emulsion. No candidates were found in a 31,423 event subsample.

[53] ESKUT 98B search for $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$ or $h^- \nu_\tau \overline{\nu}_\mu$, where h^- is a negatively charged hadron. The μ^- sample is somewhat larger than in ESKUT 98, which this result supersedes. Bayesian limit.

[54] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.00033	90	[55] ASTIER	01B	NOMD	CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.00068	90	[56] ESKUT	01	CHRS	CERN SPS
<0.0042	90	[57] ALTEGOER	98B	NOMD	CERN SPS
<0.0035	90	[58] ESKUT	98	CHRS	CERN SPS
<0.0018	90	[59] ESKUT	98B	CHRS	CERN SPS
<0.006	90	[60] LOVERRE	96		CHARM/CDHS
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.06	90	BATUSOV	90B	EMUL	FNAL
<0.34	90	BOFILL	87	CNTR	FNAL
<0.088	90	BRUCKER	86	HLBC	15-ft FNAL
<0.004	90	USHIDA	86C	EMUL	FNAL
<0.11	90	BALLAGH	84	HLBC	15-ft FNAL
<0.017	90	ARMENISE	81	HLBC	GGM CERN SPS
<0.06	90	BAKER	81	HLBC	15-ft FNAL
<0.05	90	ERRIQUEZ	81	HLBC	BEBC CERN SPS
<0.013	90	USHIDA	81	EMUL	FNAL

[55] ASTIER 01B limit is based on an oscillation probability $< 1.63 \times 10^{-4}$, whereas the quoted sensitivity was 2.5×10^{-4}. The limit was obtained following the statistical prescriptions of FELDMAN 98. See also the footnote to ESKUT 01.

[56] ESKUT 01 limit obtained following the statistical prescriptions in JUNK 99. The limit would have been 0.00040 if the prescriptions in FELDMAN 98 had been followed, as they were in ASTIER 01B.

[57] ALTEGOER 98B is the NOMAD 1995 data sample result, searching for events with $\tau^- \to e^- \nu_\tau \overline{\nu}_e$, hadron$^-$ ν_τ, or $\pi^-\pi^+\pi^-$ decay modes using classical CL approach of FELDMAN 98.

[58] ESKUT 98 search for events with one μ^- with indication of a kink from τ^- decay in the nuclear emulsion. No candidates were found in a 31,423 event subsample.

[59] ESKUT 98B search for $\tau^- \to \mu^- \nu_\tau \overline{\nu}_\mu$ or $h^- \nu_\tau \overline{\nu}_\mu$, where h^- is a negatively charged hadron. The μ^- sample is somewhat larger than in ESKUT 98, which this result supersedes. Bayesian limit.

[60] LOVERRE 96 uses the charged-current to neutral-current ratio from the combined CHARM (ALLABY 86) and CDHS (ABRAMOWICZ 86) data from 1986.

$\overline{\nu}_\mu \to \overline{\nu}_\tau$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<2.2	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<1.4	90	MCFARLAND	95	CCFR	FNAL
<6.5	90	BOFILL	87	CNTR	FNAL
<7.4	90	TAYLOR	83	HLBC	15-ft FNAL

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<4.4 $\times 10^{-2}$	90	ASRATYAN	81	HLBC	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0081	90	MCFARLAND	95	CCFR	FNAL
<0.15	90	BOFILL	87	CNTR	FNAL
<8.8 $\times 10^{-2}$	90	TAYLOR	83	HLBC	15-ft FNAL

$\nu_\mu(\overline{\nu}_\mu) \to \nu_\tau(\overline{\nu}_\tau)$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<1.5	90	[61] GRUWE	93	CHM2	CERN SPS

[61] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \to \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE (units 10^{-3})	CL%	DOCUMENT ID		TECN	COMMENT
<8	90	[62] GRUWE	93	CHM2	CERN SPS

[62] GRUWE 93 is a search using the CHARM II detector in the CERN SPS wide-band neutrino beam for $\nu_\mu \to \nu_\tau$ and $\overline{\nu}_\mu \to \overline{\nu}_\tau$ oscillations signalled by quasi-elastic ν_τ and $\overline{\nu}_\tau$ interactions followed by the decay $\tau \to \nu_\tau \pi$. The maximum sensitivity in $\sin^2 2\theta$ ($< 6.4 \times 10^{-3}$ at the 90% CL) is reached for $\Delta(m^2) \simeq 50$ eV^2.

$\nu_\mu \not\to \nu_\mu$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
>0.0015 AND < 0.0039	90	[63] AHN	03	K2K	KEK to Super-K
• • • We do not use the following data for averages, fits, limits, etc. • • •					
< 0.29 OR >22	90	BERGSMA	88	CHRM	
<7	90	BELIKOV	85	CNTR	Serpukhov
<8.0 OR >1250	90	STOCKDALE	85	CNTR	
<0.29 OR >22	90	BERGSMA	84	CHRM	
<0.23 OR >100	90	DYDAK	84	CNTR	
<13 OR >1500	90	STOCKDALE	84	CNTR	
<8.0	90	BELIKOV	83	CNTR	

[63] K2K is a 250 km long-baseline disappearance experiment. The result indicates neutrino oscillations. The measured oscillation parameters are consistent with the ones suggested by atmospheric neutrino observations.

$\sin^2(2\theta)$ for $\Delta(m^2) = 0.003$ eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 0.35	90	[64] AHN	03	K2K	KEK to Super-K

[64] K2K is a 250 km long-baseline disappearance experiment. The result indicates neutrino oscillations. The measured oscillation parameters are consistent with the ones suggested by atmospheric neutrino observations.

$\sin^2(2\theta)$ for $\Delta(m^2) = 100$eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[65] STOCKDALE	85	CNTR	FNAL
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	90	[66] BERGSMA	88	CHRM	
<0.07	90	[67] BELIKOV	85	CNTR	Serpukhov
<0.27	90	[66] BERGSMA	84	CHRM	CERN PS
<0.1	90	[68] DYDAK	84	CNTR	CERN PS
<0.02	90	[69] STOCKDALE	84	CNTR	FNAL
<0.1	90	[70] BELIKOV	83	CNTR	Serpukhov

[65] This bound applies for $\Delta(m^2) = 100$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $8 < \Delta(m^2) < 1250$ eV^2.

[66] This bound applies for $\Delta(m^2) = 0.7$–9. eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.28 < \Delta(m^2) < 22$ eV^2.

[67] This bound applies for a wide range of $\Delta(m^2) > 7$ eV^2. For some values of $\Delta(m^2)$, the value is less stringent; the least restrictive, nontrivial bound occurs approximately at $\Delta(m^2) = 300$ eV^2 where $\sin^2(2\theta) < 0.13$ at CL = 90%.

[68] This bound applies for $\Delta(m^2) = 1.$–10. eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $0.23 < \Delta(m^2) < 90$ eV^2.

[69] This bound applies for $\Delta(m^2) = 110$ eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $13 < \Delta(m^2) < 1500$ eV^2.

[70] Bound holds for $\Delta(m^2) = 20$–1000 eV^2.

$\overline{\nu}_\mu \not\to \overline{\nu}_\mu$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN
<7 OR >1200 OUR LIMIT				
<7 OR >1200	90	STOCKDALE	85	CNTR

$\sin^2(2\theta)$ for 190 eV^2 $< \Delta(m^2) <$ 320 eV^2

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.02	90	[71] STOCKDALE	85	CNTR	FNAL

[71] This bound applies for $\Delta(m^2)$ between 190 and 320 or = 530 eV^2. Less stringent bounds apply for other $\Delta(m^2)$; these are nontrivial for $7 < \Delta(m^2) <$1200 eV^2.

$\nu_\mu \to (\overline{\nu}_e)_L$

See note above for $\nu_e \to (\overline{\nu}_e)_L$ limit

$\alpha\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
<0.16	90	[72] FREEDMAN	93	CNTR	LAMPF
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.7	90	[73] COOPER	82	HLBC	BEBC CERN SPS

[72] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$ is almost a factor of 100 less sensitive.

[73] COOPER 82 states that existing bounds on V+A currents require α to be small.

$\alpha^2\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
<0.001	90	[74] COOPER	82	HLBC	BEBC CERN SPS
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.07	90	[75] FREEDMAN	93	CNTR	LAMPF

[74] COOPER 82 states that existing bounds on V+A currents require α to be small.

[75] FREEDMAN 93 is a search at LAMPF for $\overline{\nu}_e$ generated from any of the three neutrino types ν_μ, $\overline{\nu}_\mu$, and ν_e which come from the beam stop. The $\overline{\nu}_e$'s would be detected by the reaction $\overline{\nu}_e p \to e^+ n$. The limit on $\Delta(m^2)$ is better than the CERN BEBC experiment, but the limit on $\sin^2\theta$

(B) Reactor $\overline{\nu}_e$ disappearance experiments

In most cases, the reaction $\overline{\nu}_e p \to e^+ n$ is observed at different distances from one or more reactors in a complex.

Events (Observed/Expected) from Reactor $\overline{\nu}_e$ Experiments

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.611±0.085±0.041	[76] EGUCHI	03	KLND	Japanese react ∼ 180 km
1.01 ±0.024±0.053	[77] BOEHM	01		Palo Verde react. 0.75–0.89 km
1.04 ±0.03 ±0.08	[78] BOEHM	00C		Palo Verde react. 0.75–0.89 km
1.01 ±0.028±0.027	[79] APOLLONIO	99	CHOZ	Chooz reactors 1 km
0.987±0.006±0.037	[80] GREENWOOD	96		Savannah River, 18.2 m
0.988±0.004±0.05	ACHKAR	95	CNTR	Bugey reactor, 15 m
0.994±0.010±0.05	ACHKAR	95	CNTR	Bugey reactor, 40 m
0.915±0.132±0.05	ACHKAR	95	CNTR	Bugey reactor, 95 m
0.987±0.014±0.027	[81] DECLAIS	94	CNTR	Bugey reactor, 15 m
0.985±0.018±0.034	KUVSHINN...	91	CNTR	Rovno reactor
1.05 ±0.02 ±0.05	VUILLEUMIER	82		Gösgen reactor
0.955±0.035±0.110	[82] KWON	81		$\overline{\nu}_e p \to e^+ n$
0.89 ±0.15	[82] BOEHM	80		$\overline{\nu}_e p \to e^+ n$
0.38 ±0.21	[83,84] REINES	80		
0.40 ±0.22	[83,84] REINES	80		

[76] EGUCHI 03 observe reactor neutrino disappearance at ∼ 180 km baseline to various Japanese nuclear power reactors. See the footnote in the following table for further details, and the paper for the inclusion/exclusion plot.

[77] BOEHM 01 search for neutrino oscillations at 0.75 and 0.89 km distance from the Palo Verde reactors.

[78] BOEHM 00C search for neutrino oscillations at 0.75 and 0.89 km distance from the Palo Verde reactors.

[79] APOLLONIO 99, APOLLONIO 98 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e p \to e^+ n$ in Gd-loaded scintillator target. APOLLONIO 99 supersedes APOLLONIO 98. See also APOLLONIO 03 for detailed description.

[80] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River.

[81] DECLAIS 94 result based on integral measurement of neutrons only. Result is ratio of measured cross section to that expected in standard *V-A* theory. Replaced by ACHKAR 95.

[82] KWON 81 represents an analysis of a larger set of data from the same experiment as BOEHM 80.

[83] REINES 80 involves comparison of neutral- and charged-current reactions $\overline{\nu}_e d \to n p \overline{\nu}_e$ and $\overline{\nu}_e d \to n n e^+$ respectively. Combined analysis of reactor $\overline{\nu}_e$ experiments was performed by SILVERMAN 81.

[84] The two REINES 80 values correspond to the calculated $\overline{\nu}_e$ fluxes of AVIGNONE 80 and DAVIS 79 respectively.

$\overline{\nu}_e \not\to \overline{\nu}_e$

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$

VALUE (eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
>8 × 10^{-6}	95	[85] EGUCHI	03	KLND	Japanese react ∼ 180 km
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.0011	90	[86] BOEHM	01		Palo Verde react. 0.75–0.89 km
<0.0011	90	[87] BOEHM	00		Palo Verde react. 0.8 km
<0.0007	90	[88] APOLLONIO	99	CHOZ	Chooz reactors 1 km
<0.01	90	[89] ACHKAR	95	CNTR	Bugey reactor
<0.0075	90	[90] VIDYAKIN	94		Krasnoyarsk reactors
<0.04	90	[91] AFONIN	88	CNTR	Rovno reactor
<0.014	68	[92] VIDYAKIN	87		$\overline{\nu}_e p \to e^+ n$
<0.019	90	[93] ZACEK	86		Gösgen reactor

[85] EGUCHI 03 observe reactor neutrino disappearance at ∼ 180 km baseline to various Japanese nuclear power reactors. This is the lower limit on the mass difference spread, unlike all other entries in this table. Observation is consistent with neutrino oscillations, with mass-mixing and mixing-angle parameters in the Large Mixing Angle Solution region of the solar neutrino problem.

[86] BOEHM 01, a continuation of BOEHM 00, is a disappearance search for neutrino oscillations at 0.75 and 0.89 km distance from the Palo Verde reactors. Result is less restrictive than APOLLONIO 99.

[87] BOEHM 00 is a disappearance search for neutrino oscillations at 0.75 and 0.89 km distance from Palo Verde reactors. The detection reaction is $\overline{\nu}_e p \to e^+ n$ in a segmented Gd loaded scintillator target. Result is less restrictive than APOLLONIO 99.

[88] APOLLONIO 99 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. They use $\overline{\nu}_e p \to e^+ n$ in Gd-loaded scintillator target. APOLLONIO 99 supersedes APOLLONIO 98. This is the most sensitive search in terms of $\Delta(m^2)$ for $\overline{\nu}_e$ disappearance. See also APOLLONIO 03 for detailed description.

[89] ACHKAR 95 bound is for L=15, 40, and 95 m.

[90] VIDYAKIN 94 bound is for L=57.0 m, 57.6 m, and 231.4 m. Supersedes VIDYAKIN 90.

[91] AFONIN 86 and AFONIN 87 also give limits on $\sin^2(2\theta)$ for intermediate values of $\Delta(m^2)$. (See also KETOV 92). Supersedes AFONIN 87, AFONIN 86, AFONIN 85, AFONIN 83, and BELENKII 83.

[92] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.

[93] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m.

$\sin^2(2\theta)$ for "Large" $\Delta(m^2)$

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
>0.4	95	[94] EGUCHI	03	KLND	Japanese react ∼ 180 km
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.17	90	[95] BOEHM	01		Palo Verde react. 0.75–0.89 km
<0.21	90	[96] BOEHM	00		Palo Verde react. 0.8 km
<0.10	90	[97] APOLLONIO	99	CHOZ	Chooz reactors 1 km
<0.24	90	[98] GREENWOOD	96		
<0.04	90	[98] GREENWOOD	96		For $\Delta(m^2)$ = 1.0 eV^2
<0.02	90	[99] ACHKAR	95	CNTR	For $\Delta(m^2)$ = 0.6 eV^2
<0.087	68	[100] VYRODOV	95	CNTR	For $\Delta(m^2)$ >2 eV^2
<0.15	90	[101] VIDYAKIN	94		For $\Delta(m^2) > 5.0 \times 10^{-2}$ eV^2
<0.2	90	[102] AFONIN	88	CNTR	$\overline{\nu}_e p \to e^+ n$
<0.14	68	[103] VIDYAKIN	87		$\overline{\nu}_e p \to e^+ n$
<0.21	90	[104] ZACEK	86		$\overline{\nu}_e p \to e^+ n$
<0.19	90	[105] ZACEK	85		Gösgen reactor
<0.16	90	[106] GABATHULER	84		$\overline{\nu}_e p \to e^+ n$

[94] EGUCHI 03 observe reactor neutrino disappearance at ∼ 180 km baseline to various Japanese nuclear power reactors. This is the lower limit on $\sin^2 2\theta$, unlike all other entries in this table. It is based on the observed rate only; consideration of the spectrum shape results in somewhat more restrictive limit. Observation is consistent with neutrino oscillations, with mass-mixing and mixing-angle parameters in the Large Mixing Angle Solution region of the solar neutrino problem.

[95] BOEHM 01 search for neutrino oscillations at 0.75 and 0.89 km distance from the Palo Verde reactors. Continuation of BOEHM 00.

[96] BOEHM 00 search for neutrino oscillations at 0.75 and 0.89 km distance from Palo Verde reactors.

[97] APOLLONIO 99 search for neutrino oscillations at 1.1 km fixed distance from Chooz reactors. See also APOLLONIO 03 for detailed description.

[98] GREENWOOD 96 search for neutrino oscillations at 18 m and 24 m from the reactor at Savannah River by observing $\overline{\nu}_e p \to e^+ n$ in a Gd loaded scintillator target. Their region of sensitivity in $\Delta(m^2)$ and $\sin^2 2\theta$ is already excluded by ACHKAR 95.

[99] ACHKAR 95 bound is from data for L=15, 40, and 95 m distance from the Bugey reactor.

[100] The VYRODOV 95 bound is from data for L=15 m distance from the Bugey-5 reactor.

[101] The VIDYAKIN 94 bound is from data for L=57.0 m, 57.6 m, and 231.4 m from three reactors in the Krasnoyarsk Reactor complex.

[102] Several different methods of data analysis are used in AFONIN 88. We quote the most stringent limits. Different upper limits on $\sin^2 2\theta$ apply at intermediate values of $\Delta(m^2)$. Supersedes AFONIN 87, AFONIN 85, and BELENKII 83.

[103] VIDYAKIN 87 bound is for L = 32.8 and 92.3 m distance from two reactors.

[104] This bound is from data for L=37.9 m, 45.9 m, and 64.7 m distance from Gosgen reactor.

[105] ZACEK 85 gives two sets of bounds depending on what assumptions are used in the data analysis. The bounds in figure 3(a) of ZACEK 85 are progressively poorer for large $\Delta(m^2)$ whereas those of figure 3(b) approach a constant. We list the latter. Both sets of bounds use combination of data from 37.9, 45.9, and 64.7m distance from reactor. ZACEK 85 states "Our experiment excludes this area (the oscillation parameter region allowed by the Bugey data, CAVAIGNAC 84) almost completely, thus disproving the indications of neutrino oscillations of CAVAIGNAC 84 with a high degree of confidence."

[106] This bound comes from a combination of the VUILLEUMIER 82 data at distance 37.9m from Gosgen reactor and new data at 45.9m.

(C) Atmospheric neutrino observations

Neutrinos and antineutrinos produced in the atmosphere induce μ-like and e-like events in underground detectors. The ratio of the numbers of the two kinds of events is defined as μ/e. It has the advantage that systematic effects, such as flux uncertainty, tend to cancel, for both experimental and theoretical values of the ratio. The "ratio of the ratios" of experimental to theoretical μ/e, $R(\mu/e)$, or that of experimental to theoretical μ/total, $R(\mu/\text{total})$ with total $= \mu + e$, is reported below. If the actual value is not unity, the value obtained in a given experiment may depend on the experimental conditions.

$R(\mu/e)$ = (Measured Ratio μ/e) / (Expected Ratio μ/e)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.64 \pm 0.11 \pm 0.06$	[107] ALLISON	99	SOU2	Calorimeter
$0.61 \pm 0.03 \pm 0.05$	[108] FUKUDA	98	SKAM	sub-GeV
$0.66 \pm 0.06 \pm 0.08$	[109] FUKUDA	98E	SKAM	multi-GeV
	[110] FUKUDA	96B	KAMI	Water Cherenkov
$1.00 \pm 0.15 \pm 0.08$	[111] DAUM	95	FREJ	Calorimeter
$0.60^{+0.06}_{-0.05} \pm 0.05$	[112] FUKUDA	94	KAMI	sub-GeV
$0.57^{+0.08}_{-0.07} \pm 0.07$	[113] FUKUDA	94	KAMI	multi-Gev
	[114] BECKER-SZ...	92B	IMB	Water Cherenkov

[107] ALLISON 99 result is based on an exposure of 3.9 kton yr, 2.6 times the exposure reported in ALLISON 97, and replaces that result.

[108] FUKUDA 98 result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained e-like events with 0.1 GeV/$c < p_e$ and μ-like events with 0.2 GeV/$c < p_\mu$, both having a visible energy $<$ 1.33 GeV. These criteria match the definition used by FUKUDA 94.

[109] FUKUDA 98E result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained single-ring events with visible energy $>$ 1.33 GeV and partially contained events. All partially contained events are classified as μ-like.

[110] FUKUDA 96B studied neutron background in the atmospheric neutrino sample observed in the Kamiokande detector. No evidence for the background contamination was found.

[111] DAUM 95 results are based on an exposure of 2.0 kton yr which includes the data used by BERGER 90B. This ratio is for the contained and semicontained events. DAUM 95 also report $R(\mu/e) = 0.99 \pm 0.13 \pm 0.08$ for the total neutrino induced data sample which includes upward going stopping muons and horizontal muons in addition to the contained and semicontained events.

[112] FUKUDA 94 result is based on an exposure of 7.7 kton yr and updates the HIRATA 92 result. The analyzed data sample consists of fully-contained e-like events with $0.1 < p_e < 1.33$ GeV/c and fully-contained μ-like events with $0.2 < p_\mu < 1.5$ GeV/c.

[113] FUKUDA 94 analyzed the data sample consisting of fully contained events with visible energy $>$ 1.33 GeV and partially contained μ-like events.

[114] BECKER-SZENDY 92B reports the fraction of nonshowering events (mostly muons from atmospheric neutrinos) as $0.36 \pm 0.02 \pm 0.02$, as compared with expected fraction $0.51 \pm 0.01 \pm 0.05$. After cutting the energy range to the Kamiokande limits, BEIER 92 finds $R(\mu/e)$ very close to the Kamiokande value.

$R(\nu_\mu)$ = (Measured Flux of ν_μ) / (Expected Flux of ν_μ)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.72 \pm 0.026 \pm 0.13$	[115] AMBROSIO	01	MCRO	upward through-going
$0.57 \pm 0.05 \pm 0.15$	[116] AMBROSIO	00	MCRO	upgoing partially contained
$0.71 \pm 0.05 \pm 0.19$	[117] AMBROSIO	00	MCRO	downgoing partially contained + upgoing stopping
$0.74 \pm 0.036 \pm 0.046$	[118] AMBROSIO	98	MCRO	Streamer tubes
	[119] CASPER	91	IMB	Water Cherenkov
	[120] AGLIETTA	89	NUSX	
0.95 ± 0.22	[121] BOLIEV	81		Baksan
0.62 ± 0.17	CROUCH	78		Case Western/UCI

[115] AMBROSIO 01 result is based on the upward through-going muon tracks with $E_\mu > 1$ GeV. The data came from three different detector configurations, but the statistics is largely dominated by the full detector run, from May 1994 to December 2000. The total live time, normalized to the full detector configuration, is 6.17 years. The first error is the statistical error, the second is the systematic error, dominated by the theoretical error in the predicted flux.

[116] AMBROSIO 00 result is based on the upgoing partially contained event sample. It came from 4.1 live years of data taking with the full detector, from April 1994 to February 1999. The average energy of atmospheric muon neutrinos corresponding to this sample is 4 GeV. The first error is statistical, the second is the systematic error, dominated by the 25% theoretical error in the rate (20% in the flux and 15% in the cross section, added in quadrature). Within statistics, the observed deficit is uniform over the zenith angle.

[117] AMBROSIO 00 result is based on the combined samples of downgoing partially contained events and upgoing stopping events. These two subsamples could not be distinguished due to the lack of timing information. The result came from 4.1 live years of data taking with the full detector, from April 1994 to February 1999. The average energy of atmospheric muon neutrinos corresponding to this sample is 4 GeV. The first error is statistical, the second is the systematic error, dominated by the 25% theoretical error in the rate (20% in the flux and 15% in the cross section, added in quadrature). Within statistics, the observed deficit is uniform over the zenith angle.

[118] AMBROSIO 98 result is for all nadir angles and updates AHLEN 95 result. The lower cutoff on the muon energy is 1 GeV. In addition to the statistical and systematic errors, there is a Monte Carlo flux error (theoretical error) of ± 0.13. With a neutrino oscillation hypothesis, the fit either to the flux or zenith distribution independently yields $\sin^2 2\theta = 1.0$ and $\Delta(m^2) \sim$ a few times 10^{-3} eV^2. However, the fit to the observed zenith distribution gives a maximum probability for χ^2 of only 5% for the best oscillation hypothesis.

[119] CASPER 91 correlates showering/nonshowering signature of single-ring events with parent atmospheric-neutrino flavor. They find nonshowering ($\approx \nu_\mu$ induced) fraction is $0.41 \pm 0.03 \pm 0.02$, as compared with expected 0.51 ± 0.05 (syst).

[120] AGLIETTA 89 finds no evidence for any anomaly in the neutrino flux. They define ρ = (measured number of ν_e's)/(measured number of ν_μ's). They report $\rho(\text{measured}) = \rho(\text{expected}) = 0.96^{+0.32}_{-0.28}$.

[121] From this data BOLIEV 81 obtain the limit $\Delta(m^2) \leq 6 \times 10^{-3}$ eV^2 for maximal mixing, $\nu_\mu \not\to \nu_\mu$ type oscillation.

$R(\mu/\text{total})$ = (Measured Ratio μ/total) / (Expected Ratio μ/total)

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.1^{+0.07}_{-0.12} \pm 0.11$	[122] CLARK	97	IMB	multi-GeV

[122] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cherenkov detector with visible energy $>$ 0.95 GeV.

$N_{\text{up}}(\mu)/N_{\text{down}}(\mu)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.52^{+0.07}_{-0.06} \pm 0.01$	[123] FUKUDA	98E	SKAM	multi-GeV

[123] FUKUDA 98E result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained single-ring μ-like events with visible energy $>$ 1.33 GeV and partially contained events. All partially contained events are classified as μ-like. Upward-going events are those with $-1 <$ cos (zenith angle) < -0.2 and downward-going events with those with $0.2 <$ cos (zenith angle) < 1. FUKUDA 98E result strongly deviates from an expected value of $0.98 \pm 0.03 \pm 0.02$.

$N_{\text{up}}(e)/N_{\text{down}}(e)$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$0.84^{+0.14}_{-0.12} \pm 0.02$	[124] FUKUDA	98E	SKAM	multi-GeV

[124] FUKUDA 98E result is based on an exposure of 25.5 kton yr. The analyzed data sample consists of fully-contained single-ring e-like events with visible energy $>$ 1.33 GeV. Upward-going events are those with $-1 <$ cos (zenith angle) < -0.2 and downward-going events are those with $0.2 <$ cos (zenith angle) < 1. FUKUDA 98E result is compared to an expected value of $1.01 \pm 0.06 \pm 0.03$.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_e \leftrightarrow \nu_\mu$)

For a review see BAHCALL 89.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.6	90	[125] OYAMA	98	KAMI	$\Delta(m^2) > 0.1$ eV^2
<0.5		[126] CLARK	97	IMB	$\Delta(m^2) > 0.1$ eV^2
>0.55	90	[127] FUKUDA	94	KAMI	$\Delta(m^2) = 0.007$–0.08 eV^2
<0.47	90	[128] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2
<0.14	90	LOSECCO	87	IMB	$\Delta(m^2) = 0.00011$ eV^2

[125] OYAMA 98 obtained this result by an analysis of upward-going muons in Kamiokande. The data sample used is essentially the same as that used by HATAKEYAMA 98.

[126] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cherenkov detector with visible energy $>$ 0.95 GeV.

[127] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[128] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_e \leftrightarrow \nu_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<560	90	[129] OYAMA	98	KAMI
<980		[130] CLARK	97	IMB
$700 < \Delta(m^2) < 7000$	90	[131] FUKUDA	94	KAMI
<150	90	[132] BERGER	90B	FREJ

[129] OYAMA 98 obtained this result by an analysis of upward-going muons in Kamiokande. The data sample used is essentially the same as that used by HATAKEYAMA 98.

[130] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cherenkov detector with visible energy $>$ 0.95 GeV.

[131] FUKUDA 94 obtained this result by a combined analysis of sub- and multi-GeV atmospheric neutrino events in Kamiokande.

[132] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<0.9	99	[133] SMIRNOV	94	THEO	$\Delta(m^2) > 3 \times 10^{-4}$ eV^2
<0.7	99	[133] SMIRNOV	94	THEO	$\Delta(m^2) < 10^{-11}$ eV^2

[133] SMIRNOV 94 analyzed the data from SN 1987A using stellar-collapse models. They also give less stringent upper limits on $\sin^2 2\theta$ for $10^{-11} < \Delta(m^2) < 3 \times 10^{-7}$ eV^2 and $10^{-5} < \Delta(m^2) < 3 \times 10^{-4}$ eV^2. The same results apply to $\overline{\nu}_e \leftrightarrow \overline{\nu}_\tau$, ν_μ, and ν_τ.

$\sin^2(2\theta)$ for given $\Delta(m^2)$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.45	90	[134] AMBROSIO	03	MCRO	$\Delta(m^2)$= 0.00025–0.009 eV^2
>0.77	90	[135] AMBROSIO	03	MCRO	$\Delta(m^2)$= 0.0006–0.007 eV^2
>0.8	90	[136] AMBROSIO	01	MCRO	$\Delta(m^2)$= 0.0006–0.015 eV^2
>0.82	90	[137] AMBROSIO	01	MCRO	$\Delta(m^2)$= 0.001–0.006 ev^2
>0.25	90	[138] AMBROSIO	00	MCRO	$\Delta(m^2) > 3 \times 10^{-4}$ eV^2
>0.4	90	[139] FUKUDA	99C	SKAM	$\Delta(m^2)$= 0.001–0.1 eV^2
>0.7	90	[140] FUKUDA	99D	SKAM	$\Delta(m^2)$= 0.0015–0.015 eV^2
>0.82	90	[141] AMBROSIO	98	MCRO	$\Delta(m^2) \sim 0.0025$ eV^2
>0.82	90	[142] FUKUDA	98C	SKAM	$\Delta(m^2)$ = 0.0005–0.006 eV^2
>0.3	90	[143] HATAKEYAMA	98	KAMI	$\Delta(m^2)$= 0.00055–0.14 eV^2
>0.73	90	[144] HATAKEYAMA	98	KAMI	$\Delta(m^2)$= 0.004–0.025 eV^2
<0.7		[145] CLARK	97	IMB	$\Delta(m^2) >$ 0.1 eV^2
>0.65	90	[146] FUKUDA	94	KAMI	$\Delta(m^2)$ = 0.005–0.03 eV^2
<0.5	90	[147] BECKER-SZ...	92	IMB	$\Delta(m^2)$= 1–2 $\times 10^{-4}$ eV^2
<0.6	90	[148] BERGER	90B	FREJ	$\Delta(m^2) > 1$ eV^2

[134] AMBROSIO 03 obtained this result on the basis of the ratio $R=N_{low}/N_{high}$, where N_{low} and N_{high} are the number of upward through-going muon events with reconstructed neutrino energy <30 GeV and >130 GeV, respectively. The data came from the full detector run started in 1994. The method of FELDMAN 98 is used to obtain the limits.

[135] AMBROSIO 03 obtained this result by using the ratio R and the angular distribution of the upward through-going muons. R is given by N_{low}/N_{high}, where N_{low} and N_{high} are the number of events with reconstructed neutrino energy <30 and >130 GeV, respectively. The angular distribution is reported in AMBROSIO 01. The method of FELDMAN 98 is used to obtain the limits.

[136] AMBROSIO 01 result is based on the angular distribution of upward through-going muon tracks with $E_\mu > 1$ GeV. The data came from three different detector configurations, but the statistics is largely dominated by the full detector run, from May 1994 to December 2000. The total live time, normalized to the full detector configuration, is 6.17 years. The best fit is obtained outside the physical region. The method of FELDMAN 98 is used to obtain the limits.

[137] AMBROSIO 01 result is based on the angular distribution and normalization of upward through-going muon tracks with $E_\mu > 1$ GeV. The best fit is obtained outside the physical region. The method of FELDMAN 98 is used to obtain the limits. See the previous footnote.

[138] AMBROSIO 00 obtained this result by using the upgoing partially contained event sample and the combined samples of downgoing partially contained events and upgoing stopping events. These data came from 4.1 live years of data taking with the full detector, from April 1994 to February 1999. The average energy of atmospheric muon neutrinos corresponding to these samples is 4 GeV. The maximum of the χ^2 probability (97%) occurs at maximal mixing and $\Delta(m^2)$=(1$\sim$ 20) $\times 10^{-3}$ eV^2.

[139] FUKUDA 99C obtained this result from a total of 537 live days of upward through-going muon data in Super-Kamiokande between April 1996 to January 1998. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muons is (1.74 ± 0.07 ± 0.02)$\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The zenith-angle dependence of the flux does not agree with no-oscillation predictions. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99C obtained the best fit at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=5.9 $\times 10^{-3}$ eV^2. FUKUDA 99C also reports 68% and 99% confidence-level allowed regions for the same hypothesis.

[140] FUKUDA 99D obtained this result from a simultaneous fitting to zenith angle distributions of upward-stopping and through-going muons. The flux of upward-stopping muons of minimum energy of 1.6 GeV measured between April 1996 and January 1998 is (0.39 ± 0.04 ± 0.02)$\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (0.73 ± 0.16 (theoretical error))$\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The flux of upward through-going muons is taken from FUKUDA 99C. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99D obtained the best fit in the physical region at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.9 $\times 10^{-3}$ eV^2. FUKUDA 99D also reports 68% and 99% confidence-level allowed regions for the same hypothesis. FUKUDA 99D further reports the result of the oscillation analysis using the zenith-angle dependence of upward-stopping/through-going flux ratio. The best fit in the physical region is obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.1 $\times 10^{-3}$ eV^2.

[141] AMBROSIO 98 result is only 17% probable at maximum because of relatively low flux for $\cos\theta < -0.8$.

[142] FUKUDA 98C obtained this result by an analysis of 33.0 kton yr atmospheric-neutrino data which include the 25.5 kton yr data used by FUKUDA 98 (sub-GeV) and FUKUDA 98E (multi-GeV). Inside the physical region, the best fit was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=2.2$\times 10^{-3}$ eV^2. In addition, FUKUDA 98C gave the 99% confidence interval, $\sin^2 2\theta > 0.73$ and $3\times 10^{-4} < \Delta(m^2) < 8.5\times 10^{-3}$ eV^2. FUKUDA 98C also tested the $\nu_\mu \rightarrow \nu_e$ hypothesis, and concluded that it is not favored.

[143] HATAKEYAMA 98 obtained this result from a total of 2456 live days of upward-going muon data in Kamiokande between December 1985 and May 1995. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muon is (1.94 ± 0.10$^{+0.07}_{-0.06}$) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (2.46 ± 0.54 (theoretical error)) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, the best fit inside the physical region was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.2 $\times 10^{-3}$ eV^2.

[144] HATAKEYAMA 98 obtained this result from a combined analysis of Kamiokande's contained events (FUKUDA 94) and upward-going muon events. The best fit was obtained at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=1.3 $\times 10^{-2}$ eV^2.

[145] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cherenkov detector with visible energy > 0.95 GeV.

[146] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[147] BECKER-SZENDY 92 uses upward-going muons to search for atmospheric ν_μ oscillations. The fraction of muons which stop in the detector is used to search for deviations in the expected spectrum. No evidence for oscillations is found.

[148] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \leftrightarrow \nu_\tau$)

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •				
25< $\Delta(m^2)$ <900	90	[149] AMBROSIO	03	MCRO
60< $\Delta(m^2)$ <700	90	[150] AMBROSIO	03	MCRO
60< $\Delta(m^2)$ <1500	90	[151] AMBROSIO	01	MCRO
100< $\Delta(m^2)$ <600	90	[152] AMBROSIO	01	MCRO
> 35	90	[153] AMBROSIO	00	MCRO
100< $\Delta(m^2)$ < 5000	90	[154] FUKUDA	99C	SKAM
150< $\Delta(m^2)$ < 1500	90	[155] FUKUDA	99D	SKAM
50< $\Delta(m^2)$ < 600	90	[156] AMBROSIO	98	MCRO
50< $\Delta(m^2)$ < 600	90	[157] FUKUDA	98C	SKAM
55< $\Delta(m^2)$ < 5000	90	[158] HATAKEYAMA	98	KAMI
400< $\Delta(m^2)$ < 2300	90	[159] HATAKEYAMA	98	KAMI
<1500		[160] CLARK	97	IMB
500 < $\Delta(m^2)$ < 2500	90	[161] FUKUDA	94	KAMI
< 350	90	[162] BERGER	90B	FREJ

[149] AMBROSIO 03 obtained this result on the basis of the ratio $R=N_{low}/N_{high}$, where N_{low} and N_{high} are the number of upward through-going muon events with reconstructed neutrino energy <30 GeV and >130 GeV, respectively. The data came from the full detector run started in 1994. The method of FELDMAN 98 is used to obtain the limits.

[150] AMBROSIO 03 obtained this result by using the ratio R and the angular distribution of the upward through-going muons. R is given by N_{low}/N_{high}, where N_{low} and N_{high} are the number of events with reconstructed neutrino energy <30 and >130 GeV, respectively. The angular distribution is reported in AMBROSIO 01. The method of FELDMAN 98 is used to obtain the limits.

[151] AMBROSIO 01 result is based on the angular distribution of upward through-going muon tracks with $E_\mu > 1$ GeV. The data came from three different detector configurations, but the statistics is largely dominated by the full detector run, from May 1994 to December 2000. The total live time, normalized to the full detector configuration, is 6.17 years. The best fit is obtained outside the physical region. The method of FELDMAN 98 is used to obtain the limits.

[152] AMBROSIO 01 result is based on the angular distribution and normalization of upward through-going muon tracks with $E_\mu > 1$ GeV. The best fit is obtained outside the physical region. The method of FELDMAN 98 is used to obtain the limits. See the previous footnote.

[153] AMBROSIO 00 obtained this result by using the upgoing partially contained event sample and the combined samples of downgoing partially contained events and upgoing stopping events. These data came from 4.1 live years of data taking with the full detector, from April 1994 to February 1999. The average energy of atmospheric muon neutrinos corresponding to these samples is 4 GeV. The maximum of the χ^2 probability (97%) occurs at maximal mixing and $\Delta(m^2)$=(1$\sim$ 20) $\times 10^{-3}$ eV^2.

[154] FUKUDA 99C obtained this result from a total of 537 live days of upward through-going muon data in Super-Kamiokande between April 1996 to January 1998. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muon is (1.74 ± 0.07 ± 0.02)$\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The zenith-angle dependence of the flux does not agree with no-oscillation predictions. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99C obtained the best fit at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=5.9 $\times 10^{-3}$ eV^2. FUKUDA 99C also reports 68% and 99% confidence-level allowed regions for the same hypothesis.

[155] FUKUDA 99D obtained this result from a simultaneous fitting to zenith angle distributions of upward-stopping and through-going muons. The flux of upward-stopping muons of minimum energy of 1.6 GeV measured between April 1996 and January 1998 is (0.39 ± 0.04 ± 0.02)$\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (0.73 ± 0.16 (theoretical error))$\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. The flux of upward through-going muons is taken from FUKUDA 99C. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, FUKUDA 99D obtained the best fit in the physical region at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.9 $\times 10^{-3}$ eV^2. FUKUDA 99D also reports 68% and 99% confidence-level allowed regions for the same hypothesis. FUKUDA 99D further reports the result of the oscillation analysis using the zenith-angle dependence of upward-stopping/through-going flux ratio. The best fit in the physical region is obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.1 $\times 10^{-3}$ eV^2.

[156] AMBROSIO 98 result is only 17% probable at maximum because of relatively low flux for $\cos\theta < -0.8$.

[157] FUKUDA 98C obtained this result by an analysis of 33.0 kton yr atmospheric-neutrino data which include the 25.5 kton yr data used by FUKUDA 98 (sub-GeV) and FUKUDA 98E (multi-GeV). Inside the physical region, the best fit was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=2.2$\times 10^{-3}$ eV^2. In addition, FUKUDA 98C gave the 99% confidence interval, $\sin^2 2\theta > 0.73$ and $3\times 10^{-4} < \Delta(m^2) < 8.5\times 10^{-3}$ eV^2. FUKUDA 98C also tested the $\nu_\mu \rightarrow \nu_e$ hypothesis, and concluded that it is not favored.

[158] HATAKEYAMA 98 obtained this result from a total of 2456 live days of upward-going muon data in Kamiokande between December 1985 and May 1995. With a threshold of $E_\mu > 1.6$ GeV, the observed flux of upward through-going muon is (1.94 ± 0.10$^{+0.07}_{-0.06}$) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. This is compared to the expected flux of (2.46 ± 0.54 (theoretical error)) $\times 10^{-13}$ cm^{-2} s^{-1} sr^{-1}. For the $\nu_\mu \rightarrow \nu_\tau$ hypothesis, the best fit inside the physical region was obtained at $\sin^2 2\theta$=1.0 and $\Delta(m^2)$=3.2 $\times 10^{-3}$ eV^2.

[159] HATAKEYAMA 98 obtained this result from a combined analysis of Kamiokande's contained events (FUKUDA 94) and upward-going muon events. The best fit was obtained at $\sin^2 2\theta$=0.95 and $\Delta(m^2)$=1.3 $\times 10^{-2}$ eV^2.

[160] CLARK 97 obtained this result by an analysis of fully contained and partially contained events in the IMB water-Cherenkov detector with visible energy > 0.95 GeV.

[161] FUKUDA 94 obtained this result by a combined analysis of sub-and multi-GeV atmospheric neutrino events in Kamiokande.

[162] BERGER 90B uses the Frejus detector to search for oscillations of atmospheric neutrinos. Bounds are for both neutrino and antineutrino oscillations.

$\Delta(m^2)$ for $\sin^2(2\theta) = 1$ ($\nu_\mu \rightarrow \nu_s$)

ν_s means ν_τ or any sterile (noninteracting) ν.

VALUE (10^{-5} eV^2)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
<3000 (or <550)	90	[163] OYAMA	89	KAMI	Water Cherenkov
< 4.2 or > 54.	90	BIONTA	88	IMB	Flux has ν_μ, $\overline{\nu}_\mu$, ν_e, and $\overline{\nu}_e$

[163] OYAMA 89 gives a range of limits, depending on assumptions in their analysis. They argue that the region $\Delta(m^2) = (100\text{–}1000) \times 10^{-5}$ eV^2 is not ruled out by any data for large mixing.

Search for $\nu_\mu \rightarrow \nu_s$

VALUE	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[164] AMBROSIO	01	MCRO	matter effects
	[165] FUKUDA	00	SKAM	neutral currents + matter effects

[164] AMBROSIO 01 tested the pure 2-flavor $\nu_\mu \rightarrow \nu_s$ hypothesis using matter effects which change the shape of the zenith-angle distribution of upward through-going muons. With maximum mixing and $\Delta(m^2)$ around 0.0024 eV^2, the $\nu_\mu \rightarrow \nu_s$ oscillation is disfavored with 99% confidence level with respect to the $\nu_\mu \rightarrow \nu_\tau$ hypothesis.

[165] FUKUDA 00 tested the pure 2-flavor $\nu_\mu \rightarrow \nu_s$ hypothesis using three complementary atmospheric-neutrino data samples. With this hypothesis, zenith-angle distributions are expected to show characteristic behavior due to neutral currents and matter effects. In the $\Delta(m^2)$ and $\sin^2 2\theta$ region preferred by the Super-Kamiokande data, the $\nu_\mu \rightarrow \nu_s$ hypothesis is rejected at the 99% confidence level, while the $\nu_\mu \rightarrow \nu_\tau$ hypothesis consistently fits all of the data sample.

(D) Solar ν Experiments

SOLAR NEUTRINOS

Revised November 2003 by K. Nakamura (KEK, High Energy Accelerator Research Organization, Japan).

1. Introduction

The Sun is a main-sequence star at a stage of stable hydrogen burning. It produces an intense flux of electron neutrinos as a consequence of nuclear fusion reactions whose combined effect is

$$4p \rightarrow {}^4\text{He} + 2e^+ + 2\nu_e. \tag{1}$$

Positrons annihilate with electrons. Therefore, when considering the solar thermal energy generation, a relevant expression is

$$4p + 2e^- \rightarrow {}^4\text{He} + 2\nu_e + 26.73\ \text{MeV} - E_\nu\ , \tag{2}$$

where E_ν represents the energy taken away by neutrinos, with an average value being $\langle E_\nu \rangle \sim 0.6$ MeV. The neutrino-producing reactions which are at work inside the Sun are enumerated in the first column in Table 1. The second column in Table 1 shows abbreviation of these reactions. The energy spectrum of each reaction is shown in Fig. 1.

Observation of solar neutrinos directly addresses the theory of stellar structure and evolution, which is the basis of the standard solar model (SSM). The Sun as a well-defined neutrino source also provides extremely important opportunities to investigate nontrivial neutrino properties such as nonzero mass and mixing, because of the wide range of matter density and the great distance from the Sun to the Earth.

A pioneering solar neutrino experiment by Davis and collaborators using ^{37}Cl started in the late 1960's. From the very beginning of the solar-neutrino observation [1], it was recognized that the observed flux was significantly smaller than the SSM prediction, provided nothing happens to the electron neutrinos after they are created in the solar interior. This deficit has been called "the solar-neutrino problem."

In spite of the challenges by the chlorine and gallium radiochemical experiments (GALLEX, SAGE, and GNO) and water-Cherenkov experiments (Kamiokande and Super-Kamiokande), the solar-neutrino problem had persisted for more than 30 years. However, there have been remarkable developments in the past few years and now the solar-neutrino problem has been finally solved.

In 2001, the initial result from SNO (Sudbury Neutrino Observatory) [2], a water Cherenkov detector with heavy water, on the solar-neutrino flux measured via charged-current (CC) reaction, $\nu_e d \rightarrow e^- pp$, combined with the Super-Kamiokande's high-statistics flux measurement via νe elastic scattering [3], provided direct evidence for flavor conversion of solar neutrinos [2]. Later in 2002, SNO's measurement of the neutral-current (NC) rate, $\nu d \rightarrow \nu pn$, and the updated CC result further strengthened this conclusion [4].

The most probable explanation which can also solve the solar-neutrino problem is neutrino oscillation. At this stage, the LMA (large mixing angle) solution was the most promising. However, at 3σ confidence level, LOW (low probability or low mass) and/or VAC (vacuum) solutions were allowed depending on the method of analysis (see Sec. 3.6). LMA and LOW are solutions of neutrino oscillation in matter [5,6] and VAC is a solution of neutrino oscillation in vacuum. Subsequently, experiments have excluded vacuum oscillations and there exists strong evidence that matter effects are required in the solution to the solar-neutrino problem.

In December 2002, KamLAND (Kamioka Liquid Scintillator Anti-Neutrino Detector), a terrestrial $\bar{\nu}_e$ disappearance experiment using reactor neutrinos, observed clear evidence of neutrino oscillation with the allowed parameter region overlapping with the parameter region of the LMA solution [7]. Assuming CPT invariance, this result directly implies that the true solution of the solar ν_e oscillation has been determined to be LMA. A combined analysis of all the solar-neutrino data and KamLAND data significantly constrained the allowed parameter region. Inside the LMA region, the allowed region splits into two bands with higher Δm^2 and lower Δm^2.

More recently, in September, 2003, SNO reported [8] results on solar-neutrino fluxes observed with NaCl added in heavy water: this improved the sensitivity for the detection of the NC reaction. A global analysis of all the solar neutrino data combined with the KamLAND data further reduced the allowed region to the lower Δm^2 band with the best fit point of $\Delta m^2 = 7.1 \times 10^{-5}$ eV^2 and $\theta = 32.5$ degrees [8].

2. Solar Model Predictions

A standard solar model is based on the standard theory of stellar evolution. A variety of input information is needed in the evolutionary calculations. The most elaborate SSM, BP2000 [9], is presented by Bahcall *et al.* who define their SSM as the solar model which is constructed with the best available physics and input data. Though they used no helioseismological constraints in defining the SSM, the calculated sound speed as a function of the solar radius shows an excellent agreement with the helioseismologically determined sound speed to a precision of 0.1% rms throughout essentially the entire Sun. This greatly strengthens the confidence in the solar model. The BP2000 predictions [9] for the flux and contributions to the event rates in chlorine and gallium solar-neutrino experiments from each neutrino-producing reaction are listed in Table 1. The solar-neutrino spectra shown in Fig. 1 also resulted from the BP2000 calculations [9].

Other recent solar-model predictions for solar-neutrino fluxes were given by Turck-Chieze *et al.* [10] Their model is based on the standard theory of stellar evolution where the best physics available is adopted, but some fundamental inputs such as the *pp* reaction rate and the heavy-element abundance in the Sun are seismically adjusted within the commonly estimated errors aiming at reducing the residual differences between the helioseismologically-determined and the model-calculated sound speeds. Their predictions for the event rates in chlorine and gallium solar-neutrino experiments as well as ^{8}B solar-neutrino flux are shown in the last line in Table 2, where the BP2000 predictions [9] are also shown in the same format. As is apparent from this table, the predictions of the two models are remarkably consistent.

The SSM predicted ^{8}B solar-neutrino flux is proportional to the low-energy cross section factor $S_{17}(0)$ for the ^{7}Be(p,γ)^{8}B reaction. The BP2000 [9] and Turck-Chieze *et al.* [10] models adopted $S_{17}(0) = 19^{+4}_{-2}$ eV·b. Inspired by the recent precise measurement of the low-energy cross section for the ^{7}Be(p,γ)^{8}B reaction by Junghans *et al.* [11], Bahcall *et al.* [12] calculated the (BP2000 + New ^{8}B) SSM predictions using $S_{17}(0) = (22.3 \pm 0.9)$ eV·b. The results are: a ^{8}B solar-neutrino flux of $5.93(1.00^{+0.14}_{-0.15}) \times 10^6$ cm^{-2} s^{-1}, a chlorine capture rate of $8.59^{+1.1}_{-1.2}$ SNU, and a gallium capture rate of 130^{+9}_{-7} SNU.

Table 1: Neutrino-producing reactions in the Sun (first column) and their abbreviations (second column). The neutrino fluxes and event rates in chlorine and gallium solar-neutrino experiments predicted by Bahcall, Pinsonneault and Basu [9] are listed in the third, fourth, and fifth columns respectively.

Reaction	Abbr.	BP2000 [9] Flux (cm^{-2} s^{-1})	Cl (SNU*)	Ga (SNU*)
$pp \rightarrow d\,e^+\,\nu$	*pp*	$5.95(1.00^{+0.01}_{-0.01}) \times 10^{10}$	—	69.7
$pe^-p \rightarrow d\,\nu$	*pep*	$1.40(1.00^{+0.015}_{-0.015}) \times 10^8$	0.22	2.8
^{3}He $p \rightarrow {}^4$He $e^+\nu$	*hep*	9.3×10^3	0.04	0.1
^{7}Be $e^- \rightarrow {}^7$Li $\nu + (\gamma)$	^{7}Be	$4.77(1.00^{+0.10}_{-0.10}) \times 10^9$	1.15	34.2
^{8}B $\rightarrow {}^8$Be* $e^+\nu$	^{8}B	$5.05(1.00^{+0.20}_{-0.16}) \times 10^6$	5.76	12.1
^{13}N $\rightarrow {}^{13}$C $e^+\nu$	^{13}N	$5.48(1.00^{+0.21}_{-0.17}) \times 10^8$	0.09	3.4
^{15}O $\rightarrow {}^{15}$N $e^+\nu$	^{15}O	$4.80(1.00^{+0.25}_{-0.19}) \times 10^8$	0.33	5.5
^{17}F $\rightarrow {}^{17}$O $e^+\nu$	^{17}F	$5.63(1.00^{+0.25}_{-0.25}) \times 10^6$	0.0	0.1
Total			$7.6^{+1.3}_{-1.1}$	128^{+9}_{-7}

* 1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

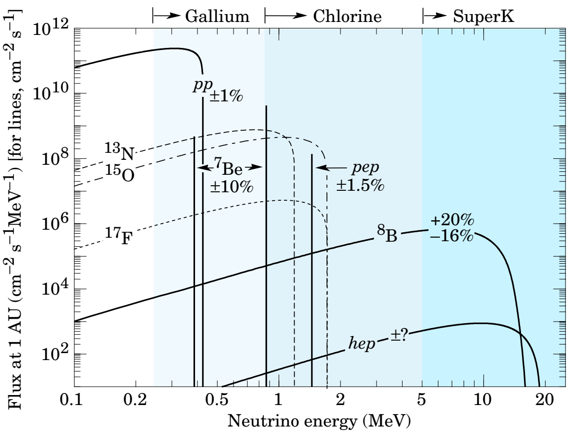

Figure 1: The solar neutrino spectrum predicted by the standard solar model. The neutrino fluxes from continuum sources are given in units of number cm^{-2}s^{-1}MeV^{-1} at one astronomical unit, and the line fluxes are given in number cm^{-2}s^{-1}. Spectra for the *pp* chain, shown by the solid curves, are courtesy of J.N. Bahcall (2001). Spectra for the CNO chain are shown by the dotted curves, and are also courtesy of J.N. Bahcall (1995). See full-color version on color pages at end of book.

3. Solar Neutrino Experiments

So far, seven solar-neutrino experiments have published results. The most recent published results on the average event rates or flux from these experiments are listed in Table 2 and compared to the two recent solar-model predictions.

3.1. Radiochemical Experiments

Radiochemical experiments exploit electron neutrino absorption on nuclei followed by their decay through orbital electron capture. Produced Auger electrons are counted.

The Homestake chlorine experiment in USA uses the reaction

$$^{37}\text{Cl} + \nu_e \rightarrow {}^{37}\text{Ar} + e^- \quad \text{(threshold 814 keV)}. \qquad (3)$$

Three gallium experiments (GALLEX and GNO at Gran Sasso in Italy and SAGE at Baksan in Russia) use the reaction

$$^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^- \quad \text{(threshold 233 keV)}. \qquad (4)$$

The produced ^{37}Ar and ^{71}Ge atoms are both radioactive, with half lives ($\tau_{1/2}$) of 34.8 days and 11.43 days, respectively. After an exposure of the detector for two to three times $\tau_{1/2}$, the reaction products are chemically extracted and introduced into a low-background proportional counter, where they are counted for a sufficiently long period to determine the exponentially decaying signal and a constant background.

Solar-model calculations predict that the dominant contribution in the chlorine experiment comes from ^{8}B neutrinos, but

Table 2: Recent results from the seven solar-neutrino experiments and a comparison with standard solar-model predictions. Solar model calculations are also presented. The first and the second errors in the experimental results are the statistical and systematic errors, respectively.

	$^{37}Cl \rightarrow ^{37}Ar$ (SNU)	$^{71}Ga \rightarrow ^{71}Ge$ (SNU)	^{8}B ν flux ($10^6 cm^{-2}s^{-1}$)
Homestake			
(CLEVELAND 98)[13]	$2.56 \pm 0.16 \pm 0.16$	—	—
GALLEX			
(HAMPEL 99)[14]	—	$77.5 \pm 6.2^{+4.3}_{-4.7}$	—
GNO			
(ALTMANN 00)[15]	—	$65.8^{+10.2+3.4}_{-\ 9.6-3.6}$	—
SAGE			
(ABDURASHI...02)[16]	—	$70.8^{+5.3+3.7}_{-5.2-3.2}$	—
Kamiokande			
(FUKUDA 96)[17]	—	—	$2.80 \pm 0.19 \pm 0.33^{\dagger}$
Super-Kamiokande			
(FUKUDA 02)[18]	—	—	$2.35 \pm 0.03^{+0.07}_{-0.06}{}^{\dagger}$
SNO (pure D_2O)			
(AHMAD 02)[4]	—	—	$1.76^{+0.06}_{-0.05} \pm 0.09^{\ddagger}$
	—	—	$2.39^{+0.24}_{-0.23} \pm 0.12^{\dagger}$
	—	—	$5.09^{+0.44+0.46}_{-0.43-0.43}{}^{*}$
SNO (NaCl in D_2O)			
(AHMED 03)[8]	—	—	$1.59^{+0.08+0.06}_{-0.07-0.08}{}^{\ddagger}$
	—	—	$2.21^{+0.31}_{-0.26} \pm 0.10^{\dagger}$
	—	—	$5.21 \pm 0.27 \pm 0.38^{*}$
(BAHCALL 01)[9]	$7.6^{+1.3}_{-1.1}$	128^{+9}_{-7}	$5.05(1.00^{+0.20}_{-0.16})$
(TURCK-CHIEZE 01)[10]	7.44 ± 0.96	127.8 ± 8.6	4.95 ± 0.72

* Flux measured via the neutral-current reaction.

† Flux measured via νe elastic scattering.

‡ Flux measured via the charged-current reaction.

^{7}Be, *pep*, ^{13}N, and ^{15}O neutrinos also contribute. At present, the most abundant *pp* neutrinos can be detected only in gallium experiments. Even so, according to the solar-model calculations, almost half of the capture rate in the gallium experiments is due to other solar neutrinos.

The Homestake chlorine experiment was the first to attempt the observation of solar neutrinos. Initial results obtained in 1968 showed no events above background with upper limit for the solar-neutrino flux of 3 SNU [1]. After introduction of an improved electronics system which discriminates signal from background by measuring the rise time of the pulses from proportional counters, a finite solar-neutrino flux has been observed since 1970. The solar-neutrino capture rate shown in Table 2 is a combined result of 108 runs between 1970 and 1994 [13]. It is only about 1/3 of the BP2000 prediction [9].

GALLEX presented the first evidence of *pp* solar-neutrino observation in 1992 [19]. Here also, the observed capture rate is significantly less than the SSM prediction. SAGE initially reported very low capture rate, $20^{+15}_{-20} \pm 32$ SNU, with a 90% confidence-level upper limit of 79 SNU [20]. Later, SAGE observed similar capture rate to that of GALLEX [21]. Both GALLEX and SAGE groups tested the overall detector response with intense man-made ^{51}Cr neutrino sources, and observed good agreement between the measured ^{71}Ge production rate and that predicted from the source activity, demonstrating the reliability of these experiments. The GALLEX Collaboration formally finished observations in early 1997. Since April, 1998, a newly defined collaboration, GNO (Gallium Neutrino Observatory) resumed the observations.

3.2 Kamiokande and Super-Kamiokande

Kamiokande and Super-Kamiokande in Japan are real-time experiments utilizing νe scattering

$$\nu_x + e^- \rightarrow \nu_x + e^- \tag{5}$$

in a large water-Cherenkov detector. It should be noted that the reaction Eq. (5) is sensitive to all active neutrinos, $x = e$, μ, and τ. However, the sensitivity to ν_μ and ν_τ is much smaller than the sensitivity to ν_e, $\sigma(\nu_{\mu,\tau}e) \approx 0.16\,\sigma(\nu_e e)$. The solar-neutrino flux measured via νe scattering is deduced assuming no neutrino oscillations.

These experiments take advantage of the directional correlation between the incoming neutrino and the recoil electron. This feature greatly helps the clear separation of the solar-neutrino signal from the background. Due to the high thresholds (7 MeV in Kamiokande and 5 MeV at present in Super-Kamiokande) the experiments observe pure ^{8}B solar neutrinos because *hep* neutrinos contribute negligibly according to the SSM.

The Kamiokande-II Collaboration started observing ^{8}B solar neutrinos at the beginning of 1987. Because of the strong directional correlation of νe scattering, this result gave the first direct evidence that the Sun emits neutrinos [22] (no directional information is available in radiochemical solar-neutrino experiments). The observed solar-neutrino flux was also significantly less than the SSM prediction. In addition, Kamiokande-II obtained the energy spectrum of recoil electrons and the fluxes separately measured in the daytime and nighttime. The Kamiokande-II experiment came to an end at the beginning of 1995.

Super-Kamiokande is a 50-kton second-generation solar-neutrino detector, which is characterized by a significantly larger counting rate than the first-generation experiments. This experiment started observation in April 1996. The solar-neutrino flux was measured as a function of zenith angle and recoil-electron energy [18]. The average solar-neutrino flux was smaller than, but consistent with, the Kamiokande-II result [17]. The observed day-night asymmetry was $A_{\rm DN} = \dfrac{\rm Day - Night}{0.5(\rm Day + Night)} = -0.021 \pm 0.020^{+0.013}_{-0.012}$. No indication of spectral distortion was observed.

In November 2001, Super-Kamiokande suffered from an accident in which substantial number of photomultiplier tubes were lost. The detector was rebuilt within a year with about half of the original number of photomultiplier tubes. The experiment with the detector before the accident is now called Super-Kamiokande-I, and that after the accident is called Super-Kamiokande-II.

3.3 SNO

In 1999, a new real time solar-neutrino experiment, SNO, in Canada started observation. This experiment uses 1000 tons of ultra-pure heavy water (D_2O) contained in a spherical acrylic vessel, surrounded by an ultra-pure H_2O shield. SNO measures ^{8}B solar neutrinos via the reactions

$$\nu_e + d \to e^- + p + p \tag{6}$$

and

$$\nu_x + d \to \nu_x + p + n, \tag{7}$$

as well as νe scattering, Eq. (5). The CC reaction, Eq. (6), is sensitive only to electron neutrinos, while the NC reaction, Eq. (7), is sensitive to all active neutrinos.

The Q-value of the CC reaction is -1.4 MeV and the electron energy is strongly correlated with the neutrino energy. Thus, the CC reaction provides an accurate measure of the shape of the ^{8}B solar-neutrino spectrum. The contributions from the CC reaction and νe scattering can be distinguished by using different cos $\theta_\odot$ distributions where $\theta_\odot$ is the angle of the electron momentum with respect to the direction from the Sun to the Earth. While the νe scattering events have a strong forward peak, CC events have an approximate angular distribution of $1 - 1/3\ \cos\theta_\odot$.

The threshold of the NC reaction is 2.2 MeV. In the pure D_2O, the signal of the NC reaction is neutron capture in deuterium, producing a 6.25-MeV γ-ray. In this case, the capture efficiency is low and the deposited energy is close to the detection threshold of 5 MeV. In order to enhance both the capture efficiency and the total γ-ray energy (8.6 MeV), 2 tons of NaCl were added to the heavy water in the second phase of the experiment. In addition, installation of discrete ^{3}He neutron counters is planned for the NC measurement in the third phase.

In 2001, SNO published the initial results on the measurement of the ^{8}B solar-neutrino flux via CC reaction [2]. The electron energy spectrum and the $\cos\theta_\odot$ distribution were also measured. The spectral shape of the electron energy was consistent with the expectations for an undistorted ^{8}B solar-neutrino spectrum.

SNO also measured the ^{8}B solar-neutrino flux via νe scattering. Though the latter result had poor statistics, it was consistent with the high-statistics Super-Kamiokande result. Thus, the SNO group compared their CC result with Super-Kamiokande's νe scattering result, and obtained evidence of an active non-ν_e component in the solar-neutrino flux, as further described in Sec. 3.5.

Later, in April, 2002, SNO reported the first result on the ^{8}B solar-neutrino flux measurement via NC reaction [4]. The total flux measured via NC reaction was consistent with the solar-model predictions (see Table 2). Also, the SNO's CC and νe scattering results were updated [4]. These results were consistent with the earlier results [2].

Further, the day and night energy spectra were measured and the day-night asymmetry of the ν_e flux measured with CC events was presented [23]. Assuming an undistorted ^{8}B spectrum, the asymmetry was $A_{\rm DN} = \dfrac{\text{Day} - \text{Night}}{0.5(\text{Day} + \text{Night})} = -0.140 \pm 0.063^{+0.015}_{-0.014}$. With an additional constraint of no asymmetry for the total flux of active neutrinos, the asymmetry was found to be $-0.070 \pm 0.049^{+0.013}_{-0.012}$.

The SNO Collaboration made a global analysis (see Sect. 3.6) of the SNO's day and night energy spectra together with the data from other solar-neutrino experiments. The results strongly favored the LMA solution, with the LOW solution allowed at 99.5% confidence level [23]. (In most of the similar global analyses, the VAC solution was also allowed at $99.9 \sim 99.73\%$ confidence level, see Sect. 3.6.) For the LMA solution (and also for the LOW solution), the maximal mixing was excluded at $> 3\sigma$.

Recently, in September, 2003, SNO has released the results of solar-neutrino flux measurements with dissolved NaCl in the heavy water. The results from the "salt phase" are described in Sect. 5.

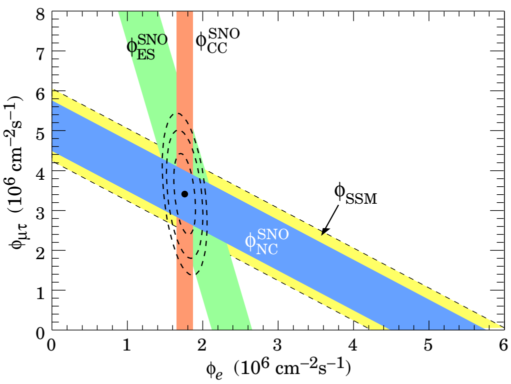

Figure 2: Fluxes of ^{8}B solar neutrinos, $\phi(\nu_e)$, and $\phi(\nu_{\mu\ \text{or}\ \tau})$, deduced from the SNO's charged-current (CC), ν_e elastic scattering (ES), and neutral-current (NC) results for pure D_2O. The standard solar model prediction [9] is also shown. The bands represent the 1σ error. The contours show the 68%, 95%, and 99% joint probability for $\phi(\nu_e)$ and $\phi(\nu_{\mu\ \text{or}\ \tau})$. This figure is courtesy of K.T. Lesko (LBNL). See full-color version on color pages at end of book.

3.4 Comparison of Experimental Results with Solar-Model Predictions

It is clear from Table 2 that the results from all the solar-neutrino experiments, except the SNO's NC result, indicate significantly less flux than expected from the BP2000 SSM [9] and the Turck-Chieze *et al.* solar model [10].

There has been a consensus that a consistent explanation of all the results of solar-neutrino observations is unlikely within the framework of astrophysics using the solar-neutrino spectra given by the standard electroweak model. Many authors made solar model-independent analyses constrained by the observed solar luminosity [24–28], where they attempted to fit the measured solar-neutrino capture rates and ^{8}B flux with normalization-free, undistorted energy spectra. All these attempts only obtained solutions with very low probabilities.

The data therefore suggest that the solution to the solar-neutrino problem requires nontrivial neutrino properties.

3.5 Evidence for Solar Neutrino Oscillations

Denoting the ^{8}B solar-neutrino flux obtained by the SNO's CC measurement as $\phi^{\rm CC}_{\rm SNO}(\nu_e)$ and that obtained by the Super-Kamiokande νe scattering as $\phi^{\rm ES}_{\rm SK}(\nu_x)$, $\phi^{\rm CC}_{\rm SNO}(\nu_e) = \phi^{\rm ES}_{\rm SK}(\nu_x)$ is expected for the standard neutrino physics. However, SNO's initial data [2] indicated

$$\phi^{\rm ES}_{\rm SK}(\nu_x) - \phi^{\rm CC}_{\rm SNO}(\nu_e) = (0.57 \pm 0.17) \times 10^6 \ {\rm cm}^{-2}{\rm s}^{-1}. \qquad (8)$$

The significance of the difference was $> 3\sigma$, implying direct evidence for the existence of a non-ν_e active neutrino flavor component in the solar-neutrino flux. A natural and most probable explanation of neutrino flavor conversion is neutrino oscillation. Note that both the SNO [2] and Super-Kamiokande [3] flux results were obtained by assuming the standard ^{8}B neutrino spectrum shape. This assumption was justified by the measured energy spectra in both of the experiments.

The SNO's results for pure D_2O, reported in 2002 [4], provided stronger evidence for neutrino oscillation than Eq. (8). The fluxes measured with CC, ES and NC events were

$$\phi^{\rm CC}_{\rm SNO}(\nu_e) = (1.76^{+0.06}_{-0.05} \pm 0.09) \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}\ , \qquad (9)$$

$$\phi^{\rm ES}_{\rm SNO}(\nu_x) = (2.39^{+0.24}_{-0.23} \pm 0.12) \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}\ , \qquad (10)$$

$$\phi^{\rm NC}_{\rm SNO}(\nu_x) = (5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}) \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}\ . \qquad (11)$$

Eq. (11) is a mixing-independent result and therefore tests solar models. It shows very good agreement with the ^{8}B solar-neutrino flux predicted by the BP2000 SSM [9] and that predicted by Turck-Chieze *et al.* model [10]. The fluxes $\phi(\nu_e)$ and $\phi(\nu_{\mu\ {\rm or}\ \tau})$ deduced from these results were remarkably consistent as can be seen in Fig. 2. The resultant flux of non-ν_e active neutrinos, $\phi(\nu_{\mu\ {\rm or}\ \tau})$, was

$$\phi(\nu_{\mu\ {\rm or}\ \tau}) = \left(3.41^{+0.66}_{-0.64}\right) \times 10^6 {\rm cm}^{-2}{\rm s}^{-1} \qquad (12)$$

where the statistical and systematic errors were added in quadrature. This $\phi(\nu_{\mu\ {\rm or}\ \tau})$ was 5.3 σ above 0.

3.6. Pre-KamLAND Global Analyses of the Solar Neutrino Data

A global analysis of the solar-neutrino data essentially uses all the independent solar-neutrino data that are available when the analysis is made to determine the globally allowed regions in terms of two neutrino oscillations either in vacuum or in matter. A number of pre-SNO global analyses of the solar-neutrino data yielded various solutions. (For example, see Ref. [29].) With the SNO's CC and NC measurements, various global analyses [30–36] showed that LMA was the most favored solution, but either or both of the two other solutions, LOW (low probability or low mass) and VAC (vacuum), were marginally allowed at $99.9 \sim 99.73\%$ confidence level. These global analyses mostly differ in the statistical treatment of the data.

Typical parameter values [34] corresponding to these solutions are

- LMA: $\Delta m^2 = 5.5 \times 10^{-5}$ eV^2, $\tan^2\theta = 0.42$
- LOW: $\Delta m^2 = 7.3 \times 10^{-8}$ eV^2, $\tan^2\theta = 0.67$
- VAC: $\Delta m^2 = 6.5 \times 10^{-10}$ eV^2, $\tan^2\theta = 1.33$.

It should be noted that all these solutions have large mixing angles. SMA (small mixing angle) solution (typical parameter values [34] are $\Delta m^2 = 5.2 \times 10^{-6}$ eV^2 and $\tan^2\theta = 1.1 \times 10^{-3}$) was once favored, but after SNO it was excluded at $> 3\sigma$ [30–36].

4. KamLAND and Combined Oscillation Analysis

KamLAND is a 1-kton ultra-pure liquid scintillator detector located at the old Kamiokande's site in Japan. Although the ultimate goal of KamLAND is observation of ^{7}Be solar neutrinos with much lower energy threshold, the initial phase of the experiment is a long baseline (flux-weighted average distance of ~ 180 km) neutrino oscillation experiment using $\bar{\nu}_e$'s emitted from power reactors. The reaction $\bar{\nu}_e + p \to e^+ + n$ is used to detect reactor $\bar{\nu}_e$'s and delayed coincidence with 2.2 MeV γ-ray from neutron capture on a proton is used to reduce the backgrounds.

With the reactor $\bar{\nu}_e$'s energy spectrum (< 8 MeV) and an analysis threshold of 2.6 MeV, this experiment has a sensitive Δm^2 range down to $\sim 10^{-5}$ eV^2. Therefore, if the LMA solution is the real solution of the solar neutrino problem, KamLAND should observe reactor $\bar{\nu}_e$ disappearance, assuming CPT invariance.

The first KamLAND results [7] with live time of 145 days were reported in December 2002. The ratio of observed to expected (assuming no neutrino oscillation) number of events was

$$\frac{N_{\rm obs} - N_{\rm BG}}{N_{\rm NoOsc}} = 0.611 \pm 0.085 \pm 0.041. \qquad (13)$$

with obvious notation. This result shows clear evidence of event deficit expected from neutrino oscillation. The 95% confidence level allowed regions shown in Fig. 3 are obtained from the oscillation analysis with the observed event rates and positron spectrum shape. In this figure, the allowed region for the LMA solution from a global analysis [34] of the solar-neutrino data is also shown. There are two bands of regions allowed by both solar and KamLAND data. The LOW and VAC solutions are excluded by the KamLAND results.

A combined global solar and KamLAND analysis shows that the LMA is a unique solution to the solar neutrino problem with $> 5\sigma$ confidence level [37]. The 99% confidence

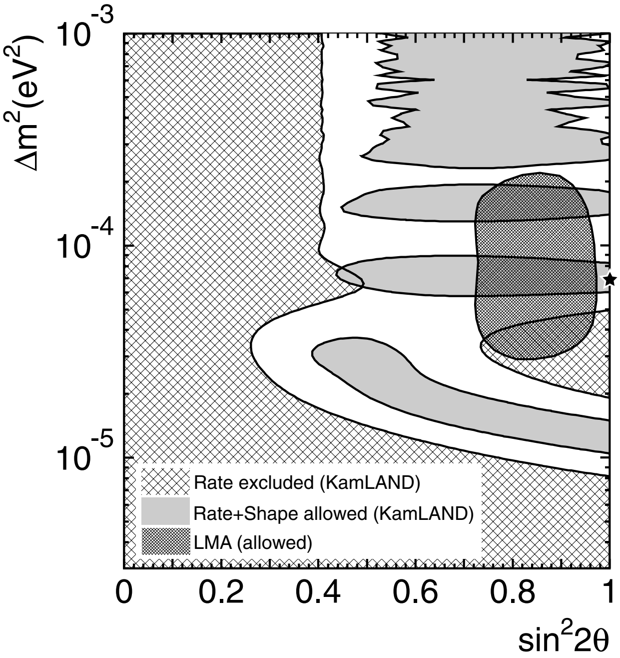

Figure 3: Excluded regions of neutrino oscillation parameters for the rate analysis and allowed regions for the combined rate and shape analysis from KamLAND at 95% confidence level. The 95% confidence-level allowed region of the LMA solution taken from a global analysis by Fogli *et al.* [34] is also shown. The star shows the best fit to the KamLAND data in the physical region: $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 6.9 \times 10^{-5}$ eV^2. All regions look identical under $\theta \leftrightarrow (\pi/2 - \theta)$ except for the LMA region from solar-neutrino experiments. This figure is courtesy of K. Inoue (Tohoku University).

level allowed region from combined analyses [37–45] splits into two subregions. At $> 3\sigma$ these subregions become connected.

5. SNO Salt Phase Results

The SNO Collaboration recently reported the total ^{8}B solar-neutrino flux measured via NC reaction with NaCl dissolved in the detector heavy water [8]. The accuracy in the flux measurement has improved compared to the previous measurements thanks to the enhanced sensitivity to NC reactions (see Table 2). These results further constrain the allowed region of the LMA solution (see Fig. 4). A global analysis of the solar-neutrino data combined with the KamLAND data has shrunk the allowed region to the lower Δm^2 band at 99% confidence level with the best fit point at $\Delta m^2 = 7.1^{+1.2}_{-0.6} \times 10^{-5}$ eV^2 and $\theta = 32.5^{+2.4}_{-2.3}$ degrees [8]. The maximal mixing is now excluded at $> 5\sigma$ confidence level [8]. Other combined analyses give consistent results [46–51].

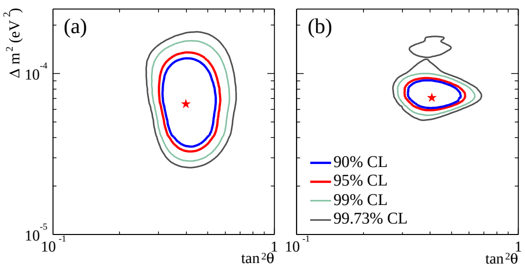

Figure 4: Global neutrino oscillation contours given by the SNO Collaboration assuming that the ^{8}B neutrino flux is free and the *hep* neutrino flux is fixed. (a) Solar global analysis. (b) Solar global + KamLAND. For details, see Ref. [8]. See full-color version on color pages at end of book.

6. Future Prospects

Now that the solar-neutrino problem has been essentially solved, what are the future prospects of the solar-neutrino experiments?

From the particle-physics point of view, precise determination of the oscillation parameters and search for non-standard physics such as a small admixture of a sterile component in the solar-neutrino flux will be still of interest. To determine Δm^2 more precisely, further KamLAND exposure to the reactor neutrinos will be most powerful [46,53]. More precise NC measurements by SNO will contribute in reducing the uncertainty of the mixing angle [51,53]. Measurements of the pp flux to an accuracy comparable to the quoted accuracy ($\pm$1%) of the SSM calculation will significantly improve the precision of the mixing angle [46,53].

An important task of the future solar neutrino experiments is further tests of the SSM by measuring monochromatic ^{7}Be neutrinos and fundamental *pp* neutrinos. The ^{7}Be neutrino flux will be measured by a new experiment, Borexino, at Gran Sasso via νe scattering in 300 tons of ultra-pure liquid scintillator with a detection threshold as low as 250 keV. KamLAND will also observe ^{7}Be neutrinos if the detection threshold can be lowered to a level similar to that of Borexino.

For the detection of *pp* neutrinos, various ideas for the detection scheme have been presented. However, no experiments have been approved yet, and extensive R&D efforts are still needed for any of these ideas to prove its feasibility.

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ν_e Capture Rates from Radiochemical Experiments

1 SNU (Solar Neutrino Unit) = 10^{-36} captures per atom per second.

VALUE (SNU)	DOCUMENT ID		TECN	COMMENT
$70.8\ ^{+\ 5.3}_{-\ 5.2}\ ^{+3.7}_{-3.2}$	[166] ABDURASHI...	02	SAGE	$^{71}Ga \to {}^{71}Ge$
$65.8\ ^{+10.2}_{-\ 9.6}\ ^{+3.4}_{-3.6}$	[167] ALTMANN	00	GNO	$^{71}Ga \to {}^{71}Ge$
$74.1\ ^{+\ 6.7}_{-\ 6.8}$	[168] ALTMANN	00	GNO	GNO + GALX combined
$77.5 \pm 6.2\ ^{+4.3}_{-4.7}$	[169] HAMPEL	99	GALX	$^{71}Ga \to {}^{71}Ge$
$2.56 \pm 0.16 \pm 0.16$	[170] CLEVELAND	98	HOME	$^{37}Cl \to {}^{37}Ar$

[166] ABDURASHITOV 02 report a combined analysis of 92 runs of the SAGE solar-neutrino experiment during the period January 1990 through December 2001, and updates the ABDURASHITOV 99B result. A total of 406.4 ^{71}Ge events were observed. No evidence was found for temporal variations of the neutrino capture rate over the entire observation period.

[167] ALTMANN 00 report the first result from the GNO solar-neutrino experiment (GNO I), which is the successor project of GALLEX. Experimental technique of GNO is essentially the same as that of GALLEX. The run data cover the period 20 May 1998 through 12 January 2000.

[168] Combined result of GALLEX I+II+III+IV (HAMPEL 99) and GNO I. The indicated errors include systematic errors.

[169] HAMPEL 99 report the combined result for GALLEX I+II+III+IV (65 runs in total), which update the HAMPEL 96 result. The GALLEX IV result (12 runs) is 118.4 ± 17.8 ± 6.6 SNU. (HAMPEL 99 discuss the consistency of partial results with the mean.) The GALLEX experimental program has been completed with these runs. The total run data cover the period 14 May 1991 through 23 January 1997. A total of 300 ^{71}Ge events were observed.

[170] CLEVELAND 98 is a detailed report of the ^{37}Cl experiment at the Homestake Mine. The average solar neutrino-induced ^{37}Ar production rate from 108 runs between 1970 and 1994 updates the DAVIS 89 result.

ϕ_{ES} (^{8}B)

^{8}B solar-neutrino flux measured via νe elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to ν_μ, ν_τ due to the cross-section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.16\sigma(\nu_e e)$. If the ^{8}B solar-neutrino flux involves nonelectron flavor active neutrinos, their contribution to the flux is ~ 0.16 times of ν_e.

VALUE (10^6 cm^{-2}s^{-1})	DOCUMENT ID		TECN	COMMENT
$2.35^{+0.07}_{-0.06}$ OUR AVERAGE				
$2.39^{+0.24}_{-0.23} \pm 0.12$	[171] AHMAD	02	SNO	average flux
$2.35 \pm 0.03^{+0.07}_{-0.06}$	[172] FUKUDA	02	SKAM	average flux
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$2.39 \pm 0.34^{+0.16}_{-0.14}$	[173] AHMAD	01	SNO	average flux
$2.80 \pm 0.19 \pm 0.33$	[174] FUKUDA	96	KAMI	average flux
2.70 ± 0.27	[174] FUKUDA	96	KAMI	day flux
$2.87^{+0.27}_{-0.26}$	[174] FUKUDA	96	KAMI	night flux

[171] AHMAD 02 reports the ^{8}B solar-neutrino flux measured via νe elastic scattering above the kinetic energy threshold of 5 MeV. The data correspond to 306.4 live days with SNO between November 2, 1999 and May 28, 2001, and updates AHMAD 01 results.

[172] FUKUDA 02 results are for 1496 live days with Super-Kamiokande between May 31, 1996 and July 15, 2002, and replace FUKUDA 01 results. The analysis threshold is 5 MeV except for the first 280 live days (6.5 MeV).

[173] AHMAD 01 reports the ^{8}B solar-neutrino flux measured via νe elastic scattering above the kinetic energy threshold of 6.75 MeV. The data correspond to 241 live days with SNO between November 2, 1999 and January 15, 2001.

[174] FUKUDA 96 results are for a total of 2079 live days with Kamiokande II and III from January 1987 through February 1995, covering the entire solar cycle 22, with threshold $E_e > 9.3$ MeV (first 449 days), > 7.5 MeV (middle 794 days), and > 7.0 MeV (last 836 days). These results update the HIRATA 90 result for the average ^{8}B solar-neutrino flux and HIRATA 91 result for the day-night variation in the ^{8}B solar-neutrino flux. The total data sample was also analyzed for short-term variations: within experimental errors, no strong correlation of the solar-neutrino flux with the sunspot numbers was found.

ϕ_{CC} (^{8}B)

^{8}B solar-neutrino flux measured with charged-current reaction which is sensitive exclusively to ν_e.

VALUE (10^6 cm^{-2}s^{-1})	DOCUMENT ID		TECN	COMMENT
$1.76^{+0.06}_{-0.05} \pm 0.09$	[175] AHMAD	02	SNO	average flux
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$1.75 \pm 0.07^{+0.12}_{-0.11} \pm 0.05$	[176] AHMAD	01	SNO	average flux

[175] AHMAD 02 reports the SNO result of the ^{8}B solar-neutrino flux measured with charged-current reaction on deuterium, $\nu_e d \to ppe^-$, above the kinetic energy threshold of 5 MeV. The data correspond to 306.4 live days with SNO between November 2, 1999 and May 28, 2001, and updates AHMAD 01 results.

[176] AHMAD 01 reports the first SNO result of the ^{8}B solar-neutrino flux measured with the charged-current reaction on deuterium, $\nu_e d \to ppe^-$, above the kinetic energy threshold of 6.75 MeV. The data correspond to 241 live days with SNO between November 2, 1999 and January 15, 2001.

ϕ_{NC} (^{8}B)

^{8}B solar neutrino flux measured with neutral-current reaction, which is equally sensitive to ν_e, ν_μ, and ν_τ.

VALUE (10^6 cm^{-2}s^{-1})	DOCUMENT ID		TECN	COMMENT
$5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$	[177] AHMAD	02	SNO	average flux

[177] AHMAD 02 reports the first SNO result of the ^{8}B solar-neutrino flux measured with the neutral-current reaction on deuterium, $\nu_\ell d \to np\nu_\ell$, above the neutral-current reaction threshold of 2.2 MeV. The data correspond to 306.4 live days with SNO between November 2, 1999 and May 28, 2001.

$\phi_{\nu_\mu+\nu_\tau}$ (^{8}B)

Nonelectron-flavor active neutrino component (ν_μ and ν_τ) in the ^{8}B solar-neutrino flux.

VALUE (10^6 cm^{-2}s^{-1})	DOCUMENT ID		TECN	COMMENT
$3.41 \pm 0.45^{+0.48}_{-0.45}$	[178] AHMAD	02	SNO	Derived from SNO ϕ_{CC}, ϕ_{ES}, and ϕ_{NC}
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.69 ± 1.13	[179] AHMAD	01		Derived from SNO+SuperKam, water Cherenkov

[178] AHMAD 02 deduced the nonelectron-flavor active neutrino component (ν_μ and ν_τ) in the ^{8}B solar-neutrino flux, by combining the charged-current result, the νe elastic-scattering result and the neutral-current result.

[179] AHMAD 01 deduced the nonelectron-flavor active neutrino component (ν_μ and ν_τ) in the ^{8}B solar-neutrino flux, by combining the SNO charged-current result (AHMAD 01) and the Super-Kamiokande νe elastic-scattering result (FUKUDA 01).

Total Flux of Active ^{8}B Solar Neutrinos

Total flux of active neutrinos (ν_e, ν_μ, and ν_τ).

VALUE (10^6 cm^{-2}s^{-1})	DOCUMENT ID		TECN	COMMENT
$5.09^{+0.44}_{-0.43}{}^{+0.46}_{-0.43}$	[180] AHMAD	02	SNO	Direct measurement from ϕ_{NC}
5.44 ± 0.99	[181] AHMAD	01		Derived from SNO+SuperKam, water Cherenkov

[180] AHMAD 02 determined the total flux of active ^{8}B solar neutrinos by directly measuring the neutral-current reaction, $\nu_\ell d \to np\nu_\ell$, which is equally sensitive to ν_e, ν_μ, and ν_τ.

[181] AHMAD 01 deduced the total flux of active ^{8}B solar neutrinos by combining the SNO charged-current result (AHMAD 01) and the Super-Kamiokande νe elastic-scattering result (FUKUDA 01).

Day-Night Asymmetry (^{8}B)

$A = (\phi_{\text{night}} - \phi_{\text{day}}) / \phi_{\text{average}}$

VALUE	DOCUMENT ID		TECN	COMMENT
$0.14 \pm 0.063^{+0.015}_{-0.014}$	[182] AHMAD	02B	SNO	Derived from SNO ϕ_{CC}
$0.07 \pm 0.049^{+0.013}_{-0.012}$	[183] AHMAD	02B	SNO	Constraint of no ϕ_{NC} asymmetry
$0.021 \pm 0.020^{+0.013}_{-0.012}$	[184] FUKUDA	02	SKAM	Based on ϕ_{ES}

[182] AHMAD 02B results are based on the charged-current interactions recorded between November 2, 1999 and May 28, 2001, with the day and night live times of 128.5 and 177.9 days, respectively.

[183] AHMAD 02B results are derived from the charged-current interactions, neutral-current interactions, and νe elastic scattering, with the total flux of active neutrinos constrained to have no asymmetry. The data were recorded between November 2, 1999 and May 28, 2001, with the day and night live times of 128.5 and 177.9 days, respectively.

[184] FUKUDA 02 results are for 1496 live days with Super-Kamiokande between May 31, 1996 and July 15, 2002, and replace FUKUDA 01 results. The analysis threshold is 5 MeV except for the first 280 live days (6.5 MeV).

ϕ_{ES} (hep)

hep solar-neutrino flux measured via νe elastic scattering. This process is sensitive to all active neutrino flavors, but with reduced sensitivity to ν_μ, ν_τ due to the cross-section difference, $\sigma(\nu_{\mu,\tau} e) \sim 0.16\sigma(\nu_e e)$. If the hep solar-neutrino flux involves nonelectron flavor active neutrinos, their contribution to the flux is ~ 0.16 times of ν_e.

VALUE (10^3 cm^{-2}s^{-1})	CL%	DOCUMENT ID		TECN
<40	90	[185] FUKUDA	01	SKAM

[185] FUKUDA 01 result is obtained from the recoil electron energy window of 18–21 MeV, and the obtained 90% confidence level upper limit is 4.3 times the BP2000 Standard-Solar-Model prediction.

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Heavy Neutral Leptons, Searches for

(A) Heavy Neutral Leptons

Stable Neutral Heavy Lepton MASS LIMITS

Note that LEP results in combination with REUSSER 91 exclude a fourth stable neutrino with $m <$ 2400 GeV.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>45.0	95	ABREU	92B	DLPH	Dirac
>39.5	95	ABREU	92B	DLPH	Majorana
>44.1	95	ALEXANDER	91F	OPAL	Dirac
>37.2	95	ALEXANDER	91F	OPAL	Majorana
none 3–100	90	SATO	91	KAM2	Kamiokande II
>42.8	95	[1] ADEVA	90S	L3	Dirac
>34.8	95	[1] ADEVA	90S	L3	Majorana
>42.7	95	DECAMP	90F	ALEP	Dirac

[1] ADEVA 90S limits for the heavy neutrino apply if the mixing with the charged leptons satisfies $|U_{1j}|^2 + |U_{2j}|^2 + |U_{3j}|^2 > 6.2\times10^{-8}$ at $m_{L^0} = 20$ GeV and $> 5.1\times10^{-10}$ for $m_{L^0} = 40$ GeV.

Heavy Neutral Lepton MASS LIMITS

Limits apply only to heavy lepton type given in comment at right of data Listings. See review above for description of types.

See the "Quark and Lepton Compositeness, Searches for" Listings for limits on radiatively decaying excited neutral leptons, *i.e.* $\nu^* \to \nu\gamma$.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>101.3	95	ACHARD	01B	L3	Dirac coupling to e
>101.5	95	ACHARD	01B	L3	Dirac coupling to μ
> 90.3	95	ACHARD	01B	L3	Dirac coupling to τ
> 89.5	95	ACHARD	01B	L3	Majorana coupling to e
> 90.7	95	ACHARD	01B	L3	Majorana coupling to μ
> 80.5	95	ACHARD	01B	L3	Majorana coupling to τ
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 76.0	95	ABBIENDI	00I	OPAL	Majorana, coupling to e
> 88.0	95	ABBIENDI	00I	OPAL	Dirac, coupling to e
> 76.0	95	ABBIENDI	00I	OPAL	Majorana, coupling to μ
> 88.1	95	ABBIENDI	00I	OPAL	Dirac, coupling to μ
> 53.8	95	ABBIENDI	00I	OPAL	Majorana, coupling to τ
> 71.1	95	ABBIENDI	00I	OPAL	Dirac, coupling to τ
> 76.5	95	ABREU	99O	DLPH	Dirac coupling to e
> 79.5	95	ABREU	99O	DLPH	Dirac coupling to μ
> 60.5	95	ABREU	99O	DLPH	Dirac coupling to τ
> 63	95	[2,3] BUSKULIC	96S	ALEP	Dirac
> 54.3	95	[2,4] BUSKULIC	96S	ALEP	Majorana

[2] BUSKULIC 96S requires the decay length of the heavy lepton to be $<$ 1 cm, limiting the square of the mixing angle $|U_{\ell j}|^2$ to 10^{-10}.
[3] BUSKULIC 96S limit for mixing with τ. Mass is $>$ 63.6 GeV for mixing with e or μ.
[4] BUSKULIC 96S limit for mixing with τ. Mass is $>$ 55.2 GeV for mixing with e or μ.

Astrophysical Limits on Neutrino MASS for $m_\nu > 1$ GeV

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
none 60–115		[5] FARGION	95	ASTR	Dirac
none 9.2–2000		[6] GARCIA	95	COSM	Nucleosynthesis
none 26–4700		[6] BECK	94	COSM	Dirac
none 6 – hundreds		[7,8] MORI	92B	KAM2	Dirac neutrino
none 24 – hundreds		[7,8] MORI	92B	KAM2	Majorana neutrino
none 10–2400	90	[9] REUSSER	91	CNTR	HPGe search
none 3–100	90	SATO	91	KAM2	Kamiokande II
		[10] ENQVIST	89	COSM	
none 12–1400		[6] CALDWELL	88	COSM	Dirac ν
none 4–16	90	[6,7] OLIVE	88	COSM	Dirac ν
none 4–35	90	OLIVE	88	COSM	Majorana ν
>4.2 to 4.7		SREDNICKI	88	COSM	Dirac ν
>5.3 to 7.4		SREDNICKI	88	COSM	Majorana ν
none 20–1000	95	[6] AHLEN	87	COSM	Dirac ν
>4.1		GRIEST	87	COSM	Dirac ν

[5] FARGION 95 bound is sensitive to assumed ν concentration in the Galaxy. See also KONOPLICH 94.
[6] These results assume that neutrinos make up dark matter in the galactic halo.
[7] Limits based on annihilations in the sun and are due to an absence of high energy neutrinos detected in underground experiments.
[8] MORI 92B results assume that neutrinos make up dark matter in the galactic halo. Limits based on annihilations in earth are also given.
[9] REUSSER 91 uses existing $\beta\beta$ detector (see FISHER 89) to search for CDM Dirac neutrinos.
[10] ENQVIST 89 argue that there is no cosmological upper bound on heavy neutrinos.

(B) Other Bounds from Nuclear and Particle Decays

Limits on $|U_{ex}|^2$ as Function of m_{ν_x}

Peak and kink search tests

Limits on $|U_{ex}|^2$ as function of m_{ν_j}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1 × 10⁻⁷	90	[11] BRITTON	92B	CNTR	50 MeV $< m_{\nu_x} <$ 130 MeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=20 MeV
$<5 \times 10^{-7}$	90	DELEENER-...	91		m_{ν_x}=40 MeV
$<3 \times 10^{-7}$	90	DELEENER-...	91		m_{ν_x}=60 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=80 MeV
$<1 \times 10^{-6}$	90	DELEENER-...	91		m_{ν_x}=100 MeV
$<5 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=60 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=80 MeV
$<3 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=100 MeV
$<1 \times 10^{-6}$	90	AZUELOS	86	CNTR	m_{ν_x}=120 MeV
$<2 \times 10^{-7}$	90	AZUELOS	86	CNTR	m_{ν_x}=130 MeV
$<1 \times 10^{-4}$	90	[12] BRYMAN	83B	CNTR	m_{ν_x}=5 MeV
$<1.5 \times 10^{-6}$	90	BRYMAN	83B	CNTR	m_{ν_x}=53 MeV
$<1 \times 10^{-5}$	90	BRYMAN	83B	CNTR	m_{ν_x}=70 MeV
$<1 \times 10^{-4}$	90	BRYMAN	83B	CNTR	m_{ν_x}=130 MeV
$<1 \times 10^{-4}$	68	[13] SHROCK	81	THEO	m_{ν_x}=10 MeV
$<5 \times 10^{-6}$	68	[13] SHROCK	81	THEO	m_{ν_x}=60 MeV
$<1 \times 10^{-5}$	68	[14] SHROCK	80	THEO	m_{ν_x}=80 MeV
$<3 \times 10^{-6}$	68	[14] SHROCK	80	THEO	m_{ν_x}=160 MeV

[11] BRITTON 92B is from a search for additional peaks in the e^+ spectrum from $\pi^+ \to e^+\nu_e$ decay at TRIUMF. See also BRITTON 92.
[12] BRYMAN 83B obtain upper limits from both direct peak search and analysis of B($\pi \to e\nu$)/B($\pi \to \mu\nu$). Latter limits are not listed, except for this entry (i.e. — we list the most stringent limits for given mass).
[13] Analysis of $(\pi^+ \to e^+\nu_e)/(\pi^+ \to \mu^+\nu_\mu)$ and $(K^+ \to e^+\nu_e)/(K^+ \to \mu^+\nu_\mu)$ decay ratios.
[14] Analysis of $(K^+ \to e^+\nu_e)$ spectrum.

Kink search in nuclear β decay

High-sensitivity follow-up experiments show that indications for a neutrino with mass 17 keV (Simpson, Hime, and others) were not valid. Accordingly, we no longer list the experiments by these authors and some others which made positive claims of 17 keV neutrino emission. Complete listings are given in the 1994 edition (Physical Review **D50** 1173 (1994)) and in the 1998 edition (The European Physical Journal **C3** 1 (1998)). We list below only the best limits on $|U_{ex}|^2$ for each m_{ν_x}. See WIETFELDT 96 for a comprehensive review.

VALUE (units 10^{-3})	*CL%*	m_{ν_j} (keV)	*ISOTOPE*	*METHOD*	*DOCUMENT ID*

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 4–20	90	700–3500	^{38m}K	Trap	[15] TRINCZEK 03
< 9–116	95	1–0.1	^{187}Re	cryog.	[16] GALEAZZI 01
< 1	95	10–90	^{35}S	Mag spect	[17] HOLZSCHUH 00
< 4	95	14–17	^{241}Pu	Electrostatic spec	[18] DRAGOUN 99
< 1	95	4–30	^{63}Ni	Mag spect	[19] HOLZSCHUH 99
< 10–40	90	370–640	^{37}Ar	EC ion recoil	[20] HINDI 98
< 10	95	1	^{3}H	SPEC	[21] HIDDEMANN 95
< 6	95	2	^{3}H	SPEC	[21] HIDDEMANN 95
< 2	95	3	^{3}H	SPEC	[21] HIDDEMANN 95
< 0.7	99	16.3–16.6	^{3}H	Prop chamber	[22] KALBFLEISCH 93
< 2	95	13–40	^{35}S	Si(Li)	[23] MORTARA 93
< 0.73	95	17	^{63}Ni	Mag spect	OHSHIMA 93
< 1.0	95	10–24	^{63}Ni	Mag spect	KAWAKAMI 92
< 0.9–2.5	90	1200–6800	^{20}F	beta spectrum	[24] DEUTSCH 90
< 8	90	80	^{35}S	Mag spect	[25] APALIKOV 85
< 1.5	90	60	^{35}S	Mag spect	APALIKOV 85
< 3.0	90	5–50		Mag spect	MARKEY 85
< 0.62	90	48	^{35}S	Si(Li)	OHI 85
< 0.90	90	30	^{35}S	Si(Li)	OHI 85
< 4	90	140	^{64}Cu	Mag spect	[26] SCHRECK... 83
< 8	90	440	^{64}Cu	Mag spect	[26] SCHRECK... 83
<100	90	0.1–3000		THEO	[27] SHROCK 80
< 0.1	68	80		THEO	[28] SHROCK 80

[15] TRINCZEK 03 is a search for admixture of heavy neutrino to ν_e, in contrast to $\overline{\nu}_e$ used in many other searches. Full kinematic reconstruction of the neutrino momentum by use of a magneto optical trap.

[16] GALEAZZI 01 use an cryogenic microcalorimeter to search for mass 50–1000 eV neutrino admixtures using the ^{187}Re beta spectrum with 2.4 keV endpoint. They derive limits for the admixture of heavy neutrinos, ranging from 9×10^{-3} for mass 1 keV to 0.116 for mass 100 eV. This is a significant improvement with respect to HIDDEMANN 95, especially for masses below $\sim$ 500 MeV, where the limit is about a factor of $\sim$ 2 higher.

[17] HOLZSCHUH 00 use an iron-free β spectrometer to measure the ^{35}S β decay spectrum. An analysis of the spectrum in the energy range 56–173 keV is used to derive limits for the admixture of heavy neutrinos. This extends the range of neutrino masses explored in HOLZSCHUH 99.

[18] DRAGOUN 99 analyze the β decay spectrum of ^{241}Pu in the energy range 0.2–9.2 keV to derive limits for the admixture of heavy neutrinos. It is not competitive with HOLZSCHUH 99.

[19] HOLZSCHUH 99 use an iron-free β spectrometer to measure the ^{63}Niβ decay spectrum. An analysis of the spectrum in the energy rage 33–67.8 keV is used to derive limits for the admixture of heavy neutrinos.

[20] HINDI 98 obtain a limit on heavy neutrino admixture from EC decay of ^{37}Ar by measuring the time-of-flight distribution of the recoiling ions in coincidence with x-rays or Auger electrons. The authors report upper limit for $|U_{ex}|^2$ of $\approx$ 3% for m_{ν_x}=500 keV, 1% for m_{ν_x}=550 keV, 2% for m_{ν_x}=600 keV, and 4% for m_X=650 keV. Their reported limits for $m_{\nu_x} \le$ 450 keV are inferior to the limits of SCHRECKENBACH 83.

[21] In the beta spectrum from tritium β decay nonvanishing or mixed $m_{\overline{\nu}_1}$ state in the mass region 0.01–4 keV. For m_{ν_x} <1 keV, their upper limit on $|U_{ex}|^2$ becomes less

[22] KALBFLEISCH 93 extends the 17 keV neutrino search of BAHRAN 92, using an improved proportional chamber to which a small amount of ^{3}H is added. Systematics are significantly reduced, allowing for an improved upper limit. The authors give a 99% confidence limit on $|U_{ex}|^2$ as a function of m_{ν_x} in the range from 13.5 keV to 17.5 keV. See also the related papers BAHRAN 93, BAHRAN 93B, and BAHRAN 95 on theoretical aspects of beta spectra and fitting methods for heavy neutrinos.

[23] MORTARA 93 limit is from study using a high-resolution solid-state detector with a superconducting solenoid. The authors note that "The sensitivity to neutrino mass is verified by measurement with a mixed source of ^{35}S and ^{14}C, which artificially produces a distortion in the beta spectrum similar to that expected from the massive neutrino."

[24] DEUTSCH 90 search for emission of heavy $\overline{\nu}_e$ in super-allowed beta decay of ^{20}F by spectral analysis of the electrons.

[25] This limit was taken from the figure 3 of APALIKOV 85; the text gives a more restrictive limit of 1.7×10^{-3} at CL = 90%.

[26] SCHRECKENBACH 83 is a combined measurement of the β^+ and β^- spectrum.

[27] SHROCK 80 was a retroactive analysis of data on several superallowed β decays to search for kinks in the Kurie plot.

[28] Application of test to search for kinks in β decay Kurie plots.

Searches for Decays of Massive ν

Limits on $|U_{ex}|^2$ as function of m_{ν_x}

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.5\times10^{-3}$	95	ACHARD 01	L3	m_{ν_x}=80 GeV
$<2\times10^{-2}$	95	ACHARD 01	L3	m_{ν_x}=175 GeV
<0.3	95	ACHARD 01	L3	m_{ν_x}=200 GeV
$<4\times10^{-3}$	95	ACCIARRI 99K	L3	m_{ν_x}=80 GeV
$<5\times10^{-2}$	95	ACCIARRI 99K	L3	m_{ν_x}= 175 GeV
$<2\times10^{-5}$	95	[29] ABREU 97I	DLPH	m_{ν_x}=6 GeV
$<3\times10^{-5}$	95	[29] ABREU 97I	DLPH	m_{ν_x}=50 GeV
$<1.8\times10^{-3}$	90	[30] HAGNER 95	MWPC	m_{ν_h} = 1.5 MeV
$<2.5\times10^{-4}$	90	[30] HAGNER 95	MWPC	m_{ν_h} = 4 MeV
$<4.2\times10^{-3}$	90	[30] HAGNER 95	MWPC	m_{ν_h} = 9 MeV
$<1\times10^{-5}$	90	[31] BARANOV 93		m_{ν_x}=100 MeV
$<1\times10^{-6}$	90	[31] BARANOV 93		m_{ν_x}= 200 MeV
$<3\times10^{-7}$	90	[31] BARANOV 93		m_{ν_x}= 300 MeV
$<2\times10^{-7}$	90	[31] BARANOV 93		m_{ν_x}=400 MeV
$<6.2\times10^{-8}$	95	ADEVA 90S	L3	m_{ν_x}=20 GeV
$<5.1\times10^{-10}$	95	ADEVA 90S	L3	m_{ν_x}=40 GeV
all values ruled out	95	[32] BURCHAT 90	MRK2	m_{ν_x} < 19.6 GeV
$<1\times10^{-10}$	95	[32] BURCHAT 90	MRK2	m_{ν_x}= 22 GeV
$<1\times10^{-11}$	95	[32] BURCHAT 90	MRK2	m_{ν_x}= 41 GeV
all values ruled out	95	DECAMP 90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1\times10^{-13}$	95	DECAMP 90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5\times10^{-3}$	90	AKERLOF 88	HRS	m_{ν_x}=1.8 GeV
$<2\times10^{-5}$	90	AKERLOF 88	HRS	m_{ν_x}=4 GeV
$<3\times10^{-6}$	90	AKERLOF 88	HRS	m_{ν_x}=6 GeV
$<1.2\times10^{-7}$	90	BERNARDI 88	CNTR	m_{ν_x}=100 MeV
$<1\times10^{-8}$	90	BERNARDI 88	CNTR	m_{ν_x}=200 MeV
$<2.4\times10^{-9}$	90	BERNARDI 88	CNTR	m_{ν_x}=300 MeV
$<2.1\times10^{-9}$	90	BERNARDI 88	CNTR	m_{ν_x}=400 MeV
$<2\times10^{-2}$	68	[33] OBERAUER 87		m_{ν_x}=1.5 MeV
$<8\times10^{-4}$	68	[33] OBERAUER 87		m_{ν_x}=4.0 MeV
$<8\times10^{-3}$	90	BADIER 86	CNTR	m_{ν_x}=400 MeV
$<8\times10^{-5}$	90	BADIER 86	CNTR	m_{ν_x}=1.7 GeV
$<8\times10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_x}=100 MeV
$<4\times10^{-8}$	90	BERNARDI 86	CNTR	m_{ν_x}=200 MeV
$<6\times10^{-9}$	90	BERNARDI 86	CNTR	m_{ν_x}=400 MeV
$<3\times10^{-5}$	90	DORENBOS... 86	CNTR	m_{ν_x}=150 MeV
$<1\times10^{-6}$	90	DORENBOS... 86	CNTR	m_{ν_x}=500 MeV
$<1\times10^{-7}$	90	DORENBOS... 86	CNTR	m_{ν_x}=1.6 GeV
$<7\times10^{-7}$	90	[34] COOPER-... 85	HLBC	m_{ν_x}=0.4 GeV
$<8\times10^{-8}$	90	[34] COOPER-... 85	HLBC	m_{ν_x}=1.5 GeV
$<1\times10^{-2}$	90	[35] BERGSMA 83B	CNTR	m_{ν_x}=10 MeV
$<1\times10^{-5}$	90	[35] BERGSMA 83B	CNTR	m_{ν_x}=110 MeV
$<6\times10^{-7}$	90	[35] BERGSMA 83B	CNTR	m_{ν_x}=410 MeV
$<1\times10^{-5}$	90	GRONAU 83		m_{ν_x}=160 MeV
$<1\times10^{-6}$	90	GRONAU 83		m_{ν_x}=480 MeV

[29] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.

[30] HAGNER 95 obtain limits on heavy neutrino admixture from the decay $\nu_h \rightarrow \nu_e e^+ e^-$ at a nuclear reactor for the ν_h mass range 2–9 MeV.

[31] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron. The limits are not as good as those achieved earlier by BERGSMA 83 and BERNARDI 86, BERNARDI 88.

[32] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

[33] OBERAUER 87 bounds from search for $\nu \rightarrow \nu' e e$ decay mode using reactor (anti)neutrinos.

[34] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, x is not equal to 3, i.e. ν_x cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, x is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

[35] BERGSMA 83B also quote limits on $|U_{e3}|^2$ where the index 3 refers to the mass eigenstate dominantly coupled to the τ. Those limits were based on assumptions about the D_s mass and $D_s \rightarrow \tau \nu_\tau$ branching ratio which are no longer valid. See COOPER-SARKAR 85.

Limits on Coupling of μ to ν_x as Function of m_{ν_x}

Peak search test

Limits on B(π (or K) $\rightarrow \mu \nu_x$).

VALUE	CL%	EVTS	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
			[36] ASTIER 02	NOMD	$\pi \rightarrow \mu X$ for m_X=33.9 MeV
$<6.0\times10^{-10}$	95	0	[37] DAUM 00	CNTR	$\pi \rightarrow \mu x$, for m_X=33.905 MeV
			[38] FORMAGGIO 00	CNTR	$\pi \rightarrow \mu x$, for m_X=33.905 MeV
<0.22	90		[39] ASSAMAGAN 98	SILI	m_{ν_x}= 0.53 MeV
<0.029	90		[39] ASSAMAGAN 98	SILI	m_{ν_x}= 0.75 MeV
<0.016	90		[39] ASSAMAGAN 98	SILI	m_{ν_x}= 1.0 MeV
$<4\text{–}6\times10^{-5}$			[40] BRYMAN 96	CNTR	m_{ν_x} = 30–33.91 MeV
$\sim 1\times10^{-16}$			[41] ARMBRUSTER 95	KARM	m_{ν_x} = 33.9 MeV
$<4\times10^{-7}$	95		[42] BILGER 95	LEPS	$m_{\overline{\nu}_x}$ = 33.9 MeV
$<7\times10^{-8}$	95		[42] BILGER 95	LEPS	m_{ν_x} = 33.9 MeV
$<2.6\times10^{-8}$	95		[42] DAUM 95B	TOF	m_{ν_x} = 33.9 MeV
$<2\times10^{-2}$	90		DAUM 87		m_{ν_x}=1 MeV
$<1\times10^{-3}$	90		DAUM 87		m_{ν_x}=2 MeV
$<6\times10^{-5}$	90		DAUM 87		3 MeV < m_{ν_x} < 19.5 MeV

$<3 \times 10^{-2}$	90	[43] MINEHART	84	m_{ν_x}=2 MeV
$<1 \times 10^{-3}$	90	[43] MINEHART	84	m_{ν_x}=4 MeV
$<3 \times 10^{-4}$	90	[43] MINEHART	84	m_{ν_x}=10 GeV
$<5 \times 10^{-6}$	90	[44] HAYANO	82	m_{ν_x}=330 MeV
$<1 \times 10^{-4}$	90	[44] HAYANO	82	m_{ν_x}=70 MeV
$<9 \times 10^{-7}$	90	[44] HAYANO	82	m_{ν_x}=250 MeV
$<1 \times 10^{-1}$	90	[43] ABELA	81	m_{ν_x}=4 MeV
$<7 \times 10^{-5}$	90	[43] ABELA	81	m_{ν_x}=10.5 MeV
$<2 \times 10^{-4}$	90	[43] ABELA	81	m_{ν_x}=11.5 MeV
$<2 \times 10^{-5}$	90	[43] ABELA	81	m_{ν_x}=16–30 MeV

[36] ASTIER 02 search for anomalous pion decay into a 33.9 MeV neutral particle. No evidence was found and the sensitivity to the branching ratio B($\pi \rightarrow \mu X$)·B($X \rightarrow \nu e^+ e^-$) is as low as 3.7×10^{-15}, depending on the X lifetime.
[37] DAUM 00 search for anomalous pion decay into a 33.9 MeV neutral particle that might be responsible for the time-distribution anomaly observed by the KARMEN Collaboration.
[38] FORMAGGIO 00 search for anomalous pion decay into a 33.9 MeV neutral particle Q^0 that might be responsible for the time-distribution anomaly observed by the KARMEN Collaboration. In the E815 (NuTeV) experiment at Fermilab no evidence was found, with sensitivity for the pion branching ratio B($\pi \rightarrow \mu Q^0$)·B($Q^0 \rightarrow$ visible) as low as 10^{-13}.
[39] ASSAMAGAN 98 obtain a limit on heavy neutrino admixture from π^+ decay essentially at rest, by measuring with good resolution the momentum distribution of the muons. However, the search uses an ad hoc shape correction. The authors report upper limit for $|U_{\mu x}|^2$ of 0.22 for $m_\nu = 0.53$ MeV, 0.029 for $m_\nu = 0.75$ MeV, and 0.016 for $m_\nu = 1.0$ MeV at 90%CL.
[40] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay.
[41] ARMBRUSTER 95 study the reactions ^{12}C(ν_e,e^-) ^{12}N and ^{12}C(ν,ν') ^{12}C* induced by neutrinos from π^+ and μ^+ decay at the ISIS neutron spallation source at the Rutherford-Appleton laboratory. An anomaly in the time distribution can be interpreted as the decay $\pi^+ \rightarrow \mu^+ \nu_x$, where ν_x is a neutral weakly interacting particle with mass $\approx$ 33.9 MeV and spin 1/2. The lower limit to the branching ratio is a function of the lifetime of the new massive neutral particle, and reaches a minimum of a few $\times 10^{-16}$ for $\tau_x \sim 5$ s.
[42] From experiments of π^+ and π^- decay in flight at PSI, to check the claim of the KARMEN Collaboration quoted above (ARMBRUSTER 95).
[43] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.
[44] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.

Peak search test

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$< 1\text{–}10 \times 10^{-4}$		[45] BRYMAN	96	CNTR	m_{ν_x} = 30–33.91 MeV
$<2 \times 10^{-5}$	95	[46] ASANO	81		m_{ν_x}=70 MeV
$<3 \times 10^{-6}$	95	[46] ASANO	81		m_{ν_x}=210 MeV
$<3 \times 10^{-6}$	95	[46] ASANO	81		m_{ν_x}=230 MeV
$<6 \times 10^{-6}$	95	[47] ASANO	81		m_{ν_x}=240 MeV
$<5 \times 10^{-7}$	95	[47] ASANO	81		m_{ν_x}=280 MeV
$<6 \times 10^{-6}$	95	[47] ASANO	81		m_{ν_x}=300 MeV
$<1 \times 10^{-2}$	95	CALAPRICE	81		m_{ν_x}=7 MeV
$<3 \times 10^{-3}$	95	[48] CALAPRICE	81		m_{ν_x}=33 MeV
$<1 \times 10^{-4}$	68	[49] SHROCK	81	THEO	m_{ν_x}=13 MeV
$<3 \times 10^{-5}$	68	[49] SHROCK	81	THEO	m_{ν_x}=33 MeV
$<6 \times 10^{-3}$	68	[50] SHROCK	81	THEO	m_{ν_x}=80 MeV
$<5 \times 10^{-3}$	68	[50] SHROCK	81	THEO	m_{ν_x}=120 MeV

[45] BRYMAN 96 search for massive unconventional neutrinos of mass m_{ν_x} in π^+ decay. They interpret the result as an upper limit for the admixture of a heavy sterile or otherwise
[46] $K^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.
[47] Analysis of experiment on $K^+ \rightarrow \mu^+ \nu_\mu \nu_x \overline{\nu}_x$ decay.
[48] $\pi^+ \rightarrow \mu^+ \nu_\mu$ peak search experiment.
[49] Analysis of magnetic spectrometer experiment, bubble chamber experiment, and emulsion experiment on $\pi^+ \rightarrow \mu^+ \nu_\mu$ decay.
[50] Analysis of magnetic spectrometer experiment on $K \rightarrow \mu$, ν_μ decay.

Peak Search in Muon Capture

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	*DOCUMENT ID*		*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<1 \times 10^{-1}$	DEUTSCH	83	m_{ν_x}=45 MeV
$<7 \times 10^{-3}$	DEUTSCH	83	m_{ν_x}=70 MeV
$<1 \times 10^{-1}$	DEUTSCH	83	m_{ν_x}=85 MeV

Searches for Decays of Massive ν

Limits on $|U_{\mu x}|^2$ as function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5 \times 10^{-7}$	90	[51] VAITAITIS	99	CCFR	m_{ν_x}=0.28 GeV
$<8 \times 10^{-8}$	90	[51] VAITAITIS	99	CCFR	m_{ν_x}=0.37 GeV
$<5 \times 10^{-7}$	90	[51] VAITAITIS	99	CCFR	m_{ν_x}= 0.50 GeV
$<6 \times 10^{-8}$	90	[51] VAITAITIS	99	CCFR	m_{ν_x}= 1.50 GeV
$<2 \times 10^{-5}$	95	[52] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[52] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<3 \times 10^{-6}$	90	GALLAS	95	CNTR	m_{ν_x} = 1 GeV
$<3 \times 10^{-5}$	90	[53] VILAIN	95C	CHM2	m_{ν_x} = 2 GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 GeV
all values ruled out	95	[54] BURCHAT	90	MRK2	m_{ν_x} < 19.6 GeV
$<1 \times 10^{-10}$	95	[54] BURCHAT	90	MRK2	m_{ν_x} = 22 GeV
$<1 \times 10^{-11}$	95	[54] BURCHAT	90	MRK2	m_{ν_x} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-3}$	90	AKERLOF	88	HRS	m_{ν_x}=1.8 GeV
$<2 \times 10^{-5}$	90	AKERLOF	88	HRS	m_{ν_x}=4 GeV
$<3 \times 10^{-6}$	90	AKERLOF	88	HRS	m_{ν_x}=6 GeV
$<1 \times 10^{-7}$	90	BERNARDI	88	CNTR	m_{ν_x}=200 MeV
$<3 \times 10^{-9}$	90	BERNARDI	88	CNTR	m_{ν_x}=300 MeV
$<4 \times 10^{-4}$	90	[55] MISHRA	87	CNTR	m_{ν_x}=1.5 GeV
$<4 \times 10^{-3}$	90	[55] MISHRA	87	CNTR	m_{ν_x}=2.5 GeV
$<0.9 \times 10^{-2}$	90	[55] MISHRA	87	CNTR	m_{ν_x}=5 GeV
<0.1	90	[55] MISHRA	87	CNTR	m_{ν_x}=10 GeV
$<8 \times 10^{-4}$	90	BADIER	86	CNTR	m_{ν_x}=600 MeV
$<1.2 \times 10^{-5}$	90	BADIER	86	CNTR	m_{ν_x}=1.7 GeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_x}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_x}=350 MeV
$<1 \times 10^{-6}$	90	DORENBOS...	86	CNTR	m_{ν_x}=500 MeV
$<1 \times 10^{-7}$	90	DORENBOS...	86	CNTR	m_{ν_x}=1600 MeV
$<0.8 \times 10^{-5}$	90	[56] COOPER-...	85	HLBC	m_{ν_x}=0.4 GeV
$<1.0 \times 10^{-7}$	90	[56] COOPER-...	85	HLBC	m_{ν_x}=1.5 GeV

[51] VAITAITIS 99 search for $L^0_\mu \rightarrow \mu X$. See paper for rather complicated limit as function of m_{ν_x}.
[52] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity except at 3.5 GeV, where the limit is the same as at 6 GeV.
[53] VILAIN 95C is a search for the decays of heavy isosinglet neutrinos produced by neutral current neutrino interactions. Limits were quoted for masses in the range from 0.3 to 24 GeV. The best limit is listed above.
[54] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.
[55] See also limits on $|U_{3x}|$ from WENDT 87.
[56] COOPER-SARKAR 85 also give limits based on model-dependent assumptions for ν_τ flux. We do not list these. Note that for this bound to be nontrivial, x is not equal to 3, i.e. ν_x cannot be the dominant mass eigenstate in ν_τ since m_{ν_3} <70 MeV (ALBRECHT 85I). Also, of course, x is not equal to 1 or 2, so a fourth generation would be required for this bound to be nontrivial.

Limits on $|U_{\tau x}|^2$ as a Function of m_{ν_x}

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-2}$	90	[57] ORLOFF	02	CHRM	m_{ν_x}=45 MeV
$<1.4 \times 10^{-4}$	90	[57] ORLOFF	02	CHRM	m_{ν_x}=180 MeV
<0.025	90	ASTIER	01		m_{ν_x}=45 MeV
<0.002	90	ASTIER	01		m_{ν_x}=140 MeV
$<2 \times 10^{-5}$	95	[58] ABREU	97I	DLPH	m_{ν_x}=6 GeV
$<3 \times 10^{-5}$	95	[58] ABREU	97I	DLPH	m_{ν_x}=50 GeV
$<6.2 \times 10^{-8}$	95	ADEVA	90S	L3	m_{ν_x}=20 GeV
$<5.1 \times 10^{-10}$	95	ADEVA	90S	L3	m_{ν_x}=40 GeV
all values ruled out	95	[59] BURCHAT	90	MRK2	m_{ν_x} < 19.6 GeV
$<1 \times 10^{-10}$	95	[59] BURCHAT	90	MRK2	m_{ν_x} = 22 GeV
$<1 \times 10^{-11}$	95	[59] BURCHAT	90	MRK2	m_{ν_x} = 41 GeV
all values ruled out	95	DECAMP	90F	ALEP	m_{ν_x}= 25.0–42.7 GeV
$<1 \times 10^{-13}$	95	DECAMP	90F	ALEP	m_{ν_x}= 42.7–45.7 GeV
$<5 \times 10^{-2}$	80	AKERLOF	88	HRS	m_{ν_x}=2.5 GeV
$<9 \times 10^{-5}$	80	AKERLOF	88	HRS	m_{ν_x}=4.5 GeV

[57] ORLOFF 02 use the negative result of a search for neutral particles decaying into two electrons performed by CHARM to get these limits for a mostly isosinglet heavy neutrino.
[58] ABREU 97I long-lived ν_x analysis. Short-lived analysis extends limit to lower masses with decreasing sensitivity.
[59] BURCHAT 90 includes the analyses reported in JUNG 90, ABRAMS 89C, and WENDT 87.

Limits on $|U_{ax}|^2$

Where $a = e$, μ from ρ parameter in μ decay.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<1 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_x}=10 GeV
$<2 \times 10^{-3}$	68	SHROCK	81B	THEO	m_{ν_x}=40 MeV
$<4 \times 10^{-2}$	68	SHROCK	81B	THEO	m_{ν_x}=70 MeV

Limits on $|U_{1j} \times U_{2j}|$ as Function of m_{ν_j}

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<3 \times 10^{-5}$	90	[60] BARANOV	93		m_{ν_j}= 80 MeV
$<3 \times 10^{-6}$	90	[60] BARANOV	93		m_{ν_j}= 160 MeV
$<6 \times 10^{-7}$	90	[60] BARANOV	93		m_{ν_j}= 240 MeV
$<2 \times 10^{-7}$	90	[60] BARANOV	93		m_{ν_j}= 320 MeV
$<9 \times 10^{-5}$	90	BERNARDI	86	CNTR	m_{ν_j}=25 MeV
$<3.6 \times 10^{-7}$	90	BERNARDI	86	CNTR	m_{ν_j}=100 MeV
$<3 \times 10^{-8}$	90	BERNARDI	86	CNTR	m_{ν_j}=200 MeV
$<6 \times 10^{-9}$	90	BERNARDI	86	CNTR	m_{ν_j}=350 MeV
$<1 \times 10^{-2}$	90	BERGSMA	83B	CNTR	m_{ν_j}=10 MeV
$<1 \times 10^{-5}$	90	BERGSMA	83B	CNTR	m_{ν_j}=140 MeV
$<7 \times 10^{-7}$	90	BERGSMA	83B	CNTR	m_{ν_j}=370 MeV

[60] BARANOV 93 is a search for neutrino decays into $e^+ e^- \nu_e$ using a beam dump experiment at the 70 GeV Serpukhov proton synchrotron.

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