QUARKS

QUARK MASSES

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A. Introduction:

This note discusses some of the theoretical issues relevant to the determination of quark masses, which are fundamental parameters of the Standard Model of particle physics. Unlike the leptons, quarks are confined inside hadrons and are not observed as physical particles. Quark masses, therefore, cannot be measured directly, but must be determined indirectly through their influence on hadronic properties. Although one often speaks loosely of quark masses as one would of the mass of the electron or muon, any quantitative statement about the value of a quark mass must make careful reference to the particular theoretical framework that is used to define it. It is important to keep this *scheme dependence* in mind when using the quark mass values tabulated in the data Listings.

Historically, the first determinations of quark masses were performed using quark models. The resulting masses only make sense in the limited context of a particular quark model, and cannot be related to the quark mass parameters of the Standard Model. In order to discuss quark masses at a fundamental level, definitions based on quantum field theory must be used, and the purpose of this note is to discuss these definitions and the corresponding determinations of the values of the masses.

B. Mass parameters and the QCD Lagrangian:

The QCD [1] Lagrangian for N_F quark flavors is

$$\mathcal{L} = \sum_{k=1}^{N_F} \overline{q}_k \left(i\not{D} - m_k \right) q_k - \tfrac{1}{4} G_{\mu\nu} G^{\mu\nu} \ , \tag{1}$$

where $\not{D} = \left(\partial_\mu - igA_\mu \right) \gamma^\mu$ is the gauge covariant derivative, A_μ is the gluon field, $G_{\mu\nu}$ is the gluon field strength, m_k is the mass parameter of the k^{th} quark, and q_k is the quark Dirac field. After renormalization, the QCD Lagrangian Eq. (1) gives finite values for physical quantities, such as scattering amplitudes. Renormalization is a procedure that invokes a subtraction scheme to render the amplitudes finite, and requires the introduction of a dimensionful scale parameter μ. The mass parameters in the QCD Lagrangian Eq. (1) depend on the renormalization scheme used to define the theory, and also on the scale parameter μ. The most commonly used renormalization scheme for QCD perturbation theory is the $\overline{\text{MS}}$ scheme.

The QCD Lagrangian has a chiral symmetry in the limit that the quark masses vanish. This symmetry is spontaneously broken by dynamical chiral symmetry breaking, and explicitly broken by the quark masses. The nonperturbative scale of dynamical chiral symmetry breaking, Λ_χ, is around 1 GeV [2]. It is conventional to call quarks heavy if $m > \Lambda_\chi$, so that explicit chiral symmetry breaking dominates (c, b, and t quarks are heavy), and light if $m < \Lambda_\chi$, so that spontaneous chiral symmetry breaking dominates (u, d, and s quarks are light). The determination of light- and heavy-quark masses is considered separately in sections ***D*** and ***E*** below.

At high energies or short distances, nonperturbative effects, such as chiral symmetry breaking, become small, and one can, in principle, determine quark masses by analyzing mass-dependent effects using QCD perturbation theory. Such computations are conventionally performed using the $\overline{\text{MS}}$ scheme at a scale $\mu \gg \Lambda_\chi$, and give the $\overline{\text{MS}}$ "running" mass $\overline{m}(\mu)$. We use the $\overline{\text{MS}}$ scheme when reporting quark masses; one can readily convert these values into other schemes using perturbation theory.

The μ dependence of $\overline{m}(\mu)$ at short distances can be calculated using the renormalization group equation,

$$\mu^2 \frac{\mathrm{d}\overline{m}\,(\mu)}{\mathrm{d}\mu^2} = -\gamma(\overline{\alpha}_s\,(\mu))\ \overline{m}\,(\mu) \,, \tag{2}$$

where γ is the anomalous dimension which is now known to four-loop order in perturbation theory [3,4]. $\overline{\alpha}_s$ is the coupling constant in the $\overline{\text{MS}}$ scheme. Defining the expansion coefficients γ_r by

$$\gamma\left(\overline{\alpha}_s\right) \equiv \sum_{r=1}^{\infty} \gamma_r \left(\frac{\overline{\alpha}_s}{4\pi} \right)^r ,$$

the first four coefficients are given by

$$\begin{aligned}
\gamma_1 &= 4, \\
\gamma_2 &= \frac{202}{3} - \frac{20 N_L}{9}, \\
\gamma_3 &= 1249 + \left(-\frac{2216}{27} - \frac{160}{3}\zeta\,(3) \right) N_L - \frac{140}{81} N_L^2, \\
\gamma_4 &= \frac{4603055}{162} + \frac{135680}{27}\zeta\,(3) - 8800\zeta\,(5) \\
&\quad + \left(-\frac{91723}{27} - \frac{34192}{9}\zeta\,(3) + 880\zeta\,(4) + \frac{18400}{9}\zeta\,(5) \right) N_L \\
&\quad + \left(\frac{5242}{243} + \frac{800}{9}\zeta\,(3) - \frac{160}{3}\zeta\,(4) \right) N_L^2 \\
&\quad + \left(-\frac{332}{243} + \frac{64}{27}\zeta\,(3) \right) N_L^3,
\end{aligned}$$

where N_L is the number of active light quark flavors at the scale μ, *i.e.*, flavors with masses $< \mu$, and ζ is the Riemann zeta function ($\zeta(3) \simeq 1.2020569$, $\zeta(4) \simeq 1.0823232$, and $\zeta(5) \simeq 1.0369278$).

C. Lattice Gauge Theory:

The use of the lattice simulations for *ab initio* determinations of the fundamental parameters of QCD, including the coupling constant and quark masses (except for the top-quark mass), is a very active area of research, with the current emphasis being on the reduction and control of the systematic uncertainties. We now briefly review some of the features of lattice QCD. In this approach, space-time is approximated by a finite, discrete *lattice* of points, and multi-local correlation functions are computed by the numerical evaluation of the corresponding functional integrals. To determine quark masses, one computes a convenient and appropriate set of physical quantities (frequently chosen to be a set of hadronic masses) using lattice QCD for a variety of input values of the quark masses. The true (physical) values of the quark masses are those which correctly reproduce the set of physical quantities being used for calibration.

The values of the quark masses obtained directly in lattice simulations are bare quark masses, with the lattice spacing a as the ultraviolet cut-off. In order for the lattice results to be useful in phenomenology, it is, therefore, necessary to relate the bare quark masses in a lattice formulation of QCD to renormalized masses in some standard renormalization scheme such as $\overline{\text{MS}}$. Provided that both the ultraviolet cut-off a^{-1} and the renormalization scale are much greater than Λ_{QCD}, the bare and renormalized masses can be related in perturbation theory (this is frequently facilitated by the use of chiral Ward identities). However, the coefficients in lattice perturbation theory are often found to be large, and our ignorance of higher-order terms is generally a significant source of systematic uncertainty (although techniques exist which help to resum some of the large higher-order effects). Increasingly, non-perturbative renormalization is used to calculate the relation between the bare and renormalized masses, circumventing the need for lattice perturbation theory.

The precision with which quark masses can be determined in lattice simulations is limited by the available computing resources. There are a number of sources of systematic uncertainty, and there has been considerable progress in recent years in reducing a number of these. Currently, the difficulty of performing a standard error analysis for lattice simulations is due predominantly to two sources of systematic uncertainty:

Quenching: Until recently most of the simulations have been performed in the "quenched" approximation, in which quark vacuum polarization effects are neglected. It is not possible, in general, to quantify the effects of quenching, although there is a folklore that they are of the order of 10 – 15%. Such an estimate is based on a comparison of results from quenched simulations, with experimental measurements for those quantities where this is possible, and with some (partially) unquenched calculations.

Extrapolation towards the Chiral Limit: Increasingly unquenched simulations are being performed, most often with two flavors of sea quarks. The difficulty, however, is that the masses of the u and d quarks (both valence and sea) used in these simulations are much larger than their physical values. The lattice results have, therefore, to be extrapolated as functions of m_u and m_d. Ideally such an extrapolation would be guided by the predictions of chiral perturbation theory, and there are some indications that this may be possible before too long. In general, however, it is likely that the values of m_u and m_d currently used in simulations are too large for the predictions of chiral perturbation theory to be useful. The results quoted below were obtained assuming there will be no major surprises when m_u and m_d are reduced.

In addition, one has to consider the uncertainties due to the fact that the lattice spacing is non-zero (lattice artifacts), and that the volume is not infinite. The former are studied by observing the stability of the results as a is varied, or by using "improved" formulations of lattice QCD. By varying the volume of the lattice one checks that finite-volume effects are indeed small.

D. Light quarks:

For light quarks, one can use the techniques of chiral perturbation theory to extract quark mass ratios. The mass term for light quarks is

$$\overline{\Psi}M\Psi = \overline{\Psi}_L M\Psi_R + \overline{\Psi}_R M\Psi_L, \tag{3}$$

where M is the light quark mass matrix M,

$$M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}, \tag{4}$$

and $\Psi = (u, d, s)$. The mass term $\overline{\Psi}M\Psi$ is the only term in the QCD Lagrangian that mixes left- and right-handed quarks. In the limit $M \to 0$, there is an independent $\text{SU}(3) \times \text{U}(1)$ flavor symmetry for the left- and right-handed quarks. The vector U(1) symmetry is baryon number; the axial U(1) symmetry of the classical theory is broken in the quantum theory, due to the anomaly. The remaining $G_\chi = \text{SU}(3)_L \times \text{SU}(3)_R$ chiral symmetry of the QCD Lagrangian is spontaneously broken to $\text{SU}(3)_V$, which, in the limit $M \to 0$, leads to eight massless Goldstone bosons, the π's, K's, and η.

The symmetry G_χ is only an approximate symmetry, since it is explicitly broken by the quark mass matrix M. The Goldstone bosons acquire masses which can be computed in a systematic expansion in M, in terms of certain unknown nonperturbative parameters of the theory. For example, to first order in M, one finds that [5]

$$\begin{aligned} m^2_{\pi^0} &= B\,(m_u + m_d)\ , \\ m^2_{\pi^\pm} &= B\,(m_u + m_d) + \Delta_{\text{em}}\ , \\ m^2_{K^0} = m^2_{\overline{K}^0} &= B\,(m_d + m_s)\ , \\ m^2_{K^\pm} &= B\,(m_u + m_s) + \Delta_{\text{em}}\ , \\ m^2_\eta &= \frac{1}{3} B\,(m_u + m_d + 4m_s)\ , \end{aligned} \tag{5}$$

with two unknown parameters B and Δ_{em}, the electromagnetic mass difference. From Eq. (5), one can determine the quark mass ratios [5]

$$\begin{aligned} \frac{m_u}{m_d} &= \frac{2m^2_{\pi^0} - m^2_{\pi^+} + m^2_{K^+} - m^2_{K^0}}{m^2_{K^0} - m^2_{K^+} + m^2_{\pi^+}} = 0.56\ , \\ \frac{m_s}{m_d} &= \frac{m^2_{K^0} + m^2_{K^+} - m^2_{\pi^+}}{m^2_{K^0} + m^2_{\pi^+} - m^2_{K^+}} = 20.1\ , \end{aligned} \tag{6}$$

to lowest order in chiral perturbation theory, with an error which will be estimated below. Since the mass ratios extracted using chiral perturbation theory use the symmetry transformation property of M under the chiral symmetry G_χ, it is important to use a renormalization scheme for QCD that does not change this transformation law. Any mass-independent subtraction scheme, such as $\overline{\rm MS}$, is suitable. The ratios of quark masses are scale-independent in such a scheme, and Eq. (6) can be taken to be the ratio of $\overline{\rm MS}$ masses. Chiral perturbation theory cannot determine the overall scale of the quark masses, since it uses only the symmetry properties of M, and any multiple of M has the same G_χ transformation law as M.

The second-order quark-mass term [9]

$$\left(M^\dagger\right)^{-1} \det M^\dagger \tag{7}$$

(which can be generated by instantons) transforms in the same way under G_χ as M. Chiral perturbation theory cannot distinguish between M and $\left(M^\dagger\right)^{-1} \det M^\dagger$; one can make the replacement $M \to M(\lambda) = M + \lambda M \left(M^\dagger M\right)^{-1} \det M^\dagger$ in the chiral Lagrangian,

$$\begin{aligned} M(\lambda) &= \mathrm{diag}\left(m_u(\lambda)\,,\ m_d(\lambda)\,,\ m_s(\lambda)\right) \\ &= \mathrm{diag}\left(m_u + \lambda m_d m_s\,,\ m_d + \lambda m_u m_s\,,\ m_s + \lambda m_u m_d\right), \end{aligned} \tag{8}$$

and leave all observables unchanged.

The combination

$$\left(\frac{m_u}{m_d}\right)^2 + \frac{1}{Q^2}\left(\frac{m_s}{m_d}\right)^2 = 1 \tag{9}$$

where

$$Q^2 = \frac{m_s^2 - \widehat{m}^2}{m_d^2 - m_u^2}, \qquad \widehat{m} = \frac{1}{2}\left(m_u + m_d\right),$$

is insensitive to the transformation in Eq. (8). Eq. (9) gives an ellipse in the $m_u/m_d - m_s/m_d$ plane. The ellipse is well-determined by chiral perturbation theory, but the exact location on the ellipse, and the absolute normalization of the quark masses, has larger uncertainties. Q is determined to be in the range 21–25 from $\eta \to 3\pi$ decay and the electromagnetic contribution to the K^+–K^0 and π^+–π^0 mass differences [10].

Chiral perturbation theory is a systematic expansion in powers of the light quark masses. The typical expansion parameter is $m_K^2/\Lambda_\chi^2 \sim 0.25$ if one uses SU(3) chiral symmetry, and $m_\pi^2/\Lambda_\chi^2 \sim 0.02$ if one uses SU(2) chiral symmetry. Electromagnetic effects at the few percent level also break SU(2) and SU(3) symmetry. The mass formulæ Eq. (5) were derived using SU(3) chiral symmetry, and are expected to have a 25% uncertainty due to second-order corrections.

It is particularly important to determine the quark mass ratio m_u/m_d, since there is no strong CP problem if $m_u = 0$. The chiral symmetry G_χ of the QCD Lagrangian is not enhanced even if $m_u = 0$. [The possible additional axial u-quark number symmetry is anomalous. The only additional symmetry when $m_u = 0$ is CP.] As a result, $m_u = 0$ is not a special value for chiral perturbation theory. One can try and extend the chiral perturbation expansion Eq. (5) to second order in the quark masses M, to get a more accurate determination of the quark mass ratios. However, as we have seen, due to the ambiguity Eq. (8) at second order, one cannot accurately determine m_u/m_d, only the combination Eq. (9).

The absolute normalization of the quark masses can be determined by using methods that go beyond chiral perturbation theory, such as spectral function sum rules for hadronic correlation functions or lattice simulations. In the former approach, one computes a hadron spectral function using QCD perturbation theory, and compares the result with the experimental data. The comparison must necessarily take place at large q^2, where QCD perturbation theory is valid. Quark mass effects are of order m/q, so that the spectral functions are not very sensitive to m at large q^2. The extraction of the absolute value of quark masses is very sensitive to theoretical and experimental uncertainties. The strange quark mass has been extracted from hadronic tau decays using this procedure, since the relevant scale m_τ is large enough for perturbation theory to be valid [11].

Lattice simulations allow for detailed studies of the behavior of hadronic masses and matrix elements as functions of the quark masses. Moreover, the quark masses do not have to take their physical values, but can be varied freely, and chiral perturbation theory applies also for unphysical masses, provided that they are sufficiently light. From such recent studies of pseudoscalar masses and decay constants, the relevant higher-order couplings in the chiral Lagrangian have been estimated, strongly suggesting that $m_u \neq 0$ [6–8]. In order to make this evidence conclusive, the lattice systematic errors must be reduced; in particular, the range of light quark masses should be increased, and the validity of chiral perturbation theory for this range established.

There have been numerous quenched-lattice determinations of the light quark masses, using a variety of formulations of lattice QCD (see, for example, the recent set of results in Refs. [12–22]). Given the different systematic errors in these determinations (*e.g.*, the different lattice formulations of QCD, the use of perturbative and non-perturbative renormalization), the level of agreement is satisfying. There have also been a number of unquenched studies with two flavors of sea quarks, Refs. [16,23,24,25] and results from the APE and MILC Collaborations cited in the review article Ref. 26.

In current lattice simulations, it is the combination $(m_u + m_d)/2$ which can be determined. In the evaluation of m_s, one gets a result which is about 20–25% larger if the ϕ meson is used as input rather than the K meson. This is evidence that the errors due to quenching are significant. It is reassuring that this difference is eliminated or reduced significantly in the cited unquenched studies.

The quark masses for light quarks discussed so far are often referred to as current quark masses. Nonrelativistic quark models use constituent quark masses, which are of order 350 MeV for the u and d quarks. Constituent quark masses model the effects of dynamical chiral symmetry breaking, and are not related to the quark mass parameters m_k of the QCD Lagrangian Eq. (1). Constituent masses are only defined in the context of a particular hadronic model.

E. Heavy quarks:

The masses and decay rates of hadrons containing a single heavy quark, such as the B and D mesons, can be determined using the heavy quark effective theory (HQET) [37]. The theoretical calculations involve radiative corrections computed in perturbation theory with an expansion in $\alpha_s(m_Q)$, and non-perturbative corrections with an expansion in powers of $\Lambda_{\rm QCD}/m_Q$. Due to the asymptotic nature of the QCD perturbation series, the two kinds of corrections are intimately related; renormalon effects in the perturbative expansion are an example of this, which are associated with non-perturbative corrections.

Systems containing two heavy quarks, such as the Υ or J/ψ, are treated using NRQCD [38]. The typical momentum and energy transfers in these systems are $\alpha_s m_Q$, and $\alpha_s^2 m_Q$, respectively, so these bound states are sensitive to scales much smaller than m_Q. However, smeared observables, such as the cross-section for $e^+e^- \to \bar{b}b$, averaged over some range of s that includes several bound state energy levels, are better behaved and only sensitive to scales near m_Q. For this reason, most determinations of the b quark mass using perturbative calculations compare smeared observables with experiment [39,40,41].

Lattice simulations of heavy-quark systems have been performed using effective theories, including HQET and NRQCD, as well as directly in QCD. The systematic uncertainties in the two cases are different, so both approaches contribute to the final results. Simulating the effective theory requires lattice spacings to be fine enough to resolve the size of the hadron, whereas simulating QCD requires much finer lattice spacings, of order the inverse quark mass. For this reason, and because available computing resources limit the lattice spacings which can be used ($a^{-1} \simeq 2-3\,\text{GeV}$), simulations for the b quark using the QCD action are currently done at quark mass values near the c quark, and then extrapolated to the physical b-quark mass. On the other hand, in effective theories, when evaluating non-leading terms in $1/m_b$, one encounters power divergences in $1/a$ which have to be subtracted.

For an observable particle such as the electron, the position of the pole in the propagator is the definition of the particle mass. In QCD, this definition of the quark mass is known as the pole mass. It is known that the on-shell quark propagator has no infrared divergences in perturbation theory [27,28], so this provides a perturbative definition of the quark mass. The pole mass cannot be used to arbitrarily high accuracy because of nonperturbative infrared effects in QCD. The full quark propagator has no pole because the quarks are confined, so that the pole mass cannot be defined outside of perturbation theory.

The relation between the pole mass m_Q and the $\overline{\rm MS}$ mass $\overline{m}_Q$ is known to three loops [29–33]

$$\begin{aligned} m_Q = \overline{m}_Q(\overline{m}_Q)\Bigg\{1 &+ \frac{4\overline{\alpha}_s(\overline{m}_Q)}{3\pi} \\ &+ \left[-1.0414\sum_k\left(1-\frac{4}{3}\frac{\overline{m}_{Q_k}}{\overline{m}_Q}\right)+13.4434\right]\left[\frac{\overline{\alpha}_s(\overline{m}_Q)}{\pi}\right]^2 \\ &+ \left[0.6527N_L^2-26.655N_L+190.595\right]\left[\frac{\overline{\alpha}_s(\overline{m}_Q)}{\pi}\right]^3\Bigg\}, \end{aligned} \quad (10)$$

where $\overline{\alpha}_s(\mu)$ is the strong interaction coupling constants in the $\overline{\rm MS}$ scheme, and the sum over k extends over the N_L flavors Q_k lighter than Q. The complete mass dependence of the α_s^2 term can be found in Ref. 29; the mass dependence of the α_s^3 term is not known. For the b quark, Eq. (10) reads

$$m_b = \overline{m}_b\,(\overline{m}_b)\,[1+0.09+0.05+0.03]\,, \quad (11)$$

where the contributions from the different orders in α_s are shown explicitly. The two- and three-loop corrections are comparable in size, and have the same sign as the one-loop term. This is a signal of the asymptotic nature of the perturbation series [there is a renormalon in the pole mass]. Such a badly behaved perturbation expansion can be avoided by directly extracting the $\overline{\rm MS}$ mass from data without extracting the pole mass as an intermediate step.

F. Numerical values and caveats:

The quark masses in the Particle Data Group's Listings have been obtained by using a wide variety of methods. Each method involves its own set of approximations and errors. In most cases, the errors are a best guess at the size of neglected higher-order corrections or other uncertainties. The expansion parameters for some of the approximations are not very small (for example, they are $m_K^2/\Lambda_\chi^2 \sim 0.25$ for the chiral expansion, and $\Lambda_{\rm QCD}/m_b \sim 0.1$ for the heavy-quark expansion), so an unexpectedly large coefficient in a neglected higher-order term could significantly alter the results. It is also important to note that the quark mass values can be significantly different in the different schemes.

The heavy quark masses obtained using HQET, QCD sum rules, or lattice gauge theory are consistent with each other if they are all converted into the same scheme. When using the data listings, it is important to remember that the numerical value for a quark mass is meaningless without specifying the particular scheme in which it was obtained.

We have specified all masses in the $\overline{\rm MS}$ scheme. For light quarks, the renormalization scale has been chosen to be $\mu = 2\,\text{GeV}$, and for heavy quarks, the quark mass itself (*i.e.*, we quote $\overline{m}(\mu=\overline{m})$). If necessary, we have converted the values in the original papers using the two-loop formulæ. The light quark masses at 1 GeV are significantly different from those at 2 GeV, $\overline{m}(1\,\text{GeV})/\overline{m}(2\,\text{GeV}) = 1.35$.

From the spread of results, and taking into account the treatment of systematic errors in each of the lattice simulations, we quote as the current best results for the quark masses renormalized in the $\overline{\rm MS}$ scheme at a scale of 2 GeV:

$$\frac{1}{2}\left(\overline{m}_u + \overline{m}_d\right)\Big|_{\mu=2\ \rm GeV} = (4.2 \pm 1.0)\,\rm MeV \quad [\text{Lattice only}],$$

and

$$\overline{m}_s\Big|_{\mu=2\ \rm GeV} = (105 \pm 25)\,\rm MeV \quad [\text{Lattice only}].$$

It should be noted that recent results from simulations with two flavors of sea quarks suggest that the light-quark masses may be in the lower parts of the ranges quoted above (for example Refs. [16,25] find that $m_s \sim 90\,\rm MeV$, with an error of about 7 MeV, and $(m_u + m_d)/2 \sim 3.5\,\rm MeV$, with an error of perhaps 0.3 MeV). As such studies become more widespread, and use a variety of approaches to study and reduce systematic uncertainties, we can confidently expect that the errors quoted above for the best results will decrease significantly.

Continuum determinations of the absolute values of light quark masses have significant systematic uncertainties. The values are consistent with the lattice extractions above. The u- and d-quark masses are in the range

$$1.5\,\rm MeV \le \overline{m}_u\Big|_{\mu=2\ \rm GeV} \le 5\,\rm MeV \quad [\text{Excluding lattice}],$$

$$5\,\rm MeV \le m_d\Big|_{\mu=2\ \rm GeV} \le 9\,\rm MeV \quad [\text{Excluding lattice}].$$

The s-quark mass in more recent determinations tends to be smaller than in older extractions. The newer calculations use both better experimental data and perturbative calculations, which tend to reduce m_s. The continuum extractions give

$$80\,\rm MeV \le \overline{m}_s\Big|_{\mu=2\ \rm GeV} \le 155\,\rm MeV \quad [\text{Excluding lattice}].$$

Using the continuum determinations of the c-quark mass, we quote

$$1\,\rm GeV \le \overline{m}_c\left(\overline{m}_c\right) \le 1.4\,\rm GeV \quad [\text{Excluding lattice}]$$

as a best value. Recent determinations include at least two-loop corrections, and give values consistent with this range. The value $\overline{m}_c\left(\overline{m}_c\right)$ is sensitive to higher-order perturbative corrections, since α_s starts to get large below the charm quark scale.

There are rather few lattice determinations of m_c, as the charm quark is too light for comfortable use of HQET, and yet heavy enough that one must be careful about lattice artifacts. All the results are from quenched simulations, and most are still preliminary. For the best result, we take

$$\overline{m}_c\left(\overline{m}_c\right) = (1.26 \pm 0.13 \pm 0.20)\,\rm GeV \quad [\text{Lattice only}],$$

which is consistent with continuum extractions. The second error of 15% is our estimate of possible quenching effects.

There has been much recent work on the b-quark mass. As a best value from continuum extractions, we quote

$$4\,\rm GeV \le \overline{m}_b\left(\overline{m}_b\right) \le 4.5\,\rm GeV \quad [\text{Excluding lattice}],$$

which is consistent with continuum extractions. The dominant uncertainties in the b-quark mass are the non-perturbative corrections in the B and Υ systems.

As the current best lattice result for $\overline{m}_b$ we take:

$$\overline{m}_b\left(\overline{m}_b\right) = (4.26 \pm 0.15 \pm 0.15)\,\rm GeV \quad [\text{Lattice only}].$$

The second error is our estimate of possible quenching effects (15% on $M_B - \overline{m}_b$).

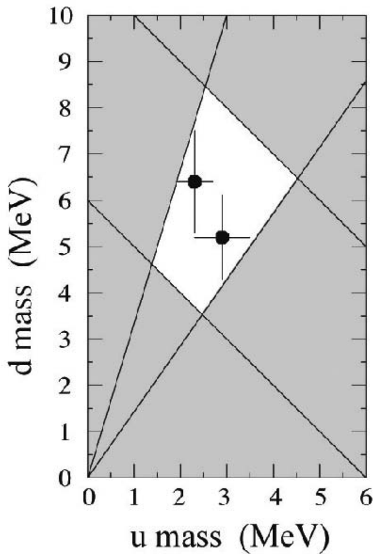

Figure 1: The allowed region (shown in white) for up quark and down quark masses. This region was determined in part from papers reporting values for m_u and m_d (data points shown), and in part from analysis of the allowed ranges of other mass parameters (see Fig. 2). The parameter $(m_u + m_d)/2$ yields the two downward-sloping lines, while m_u/m_d yields the two rising lines originating at (0,0).

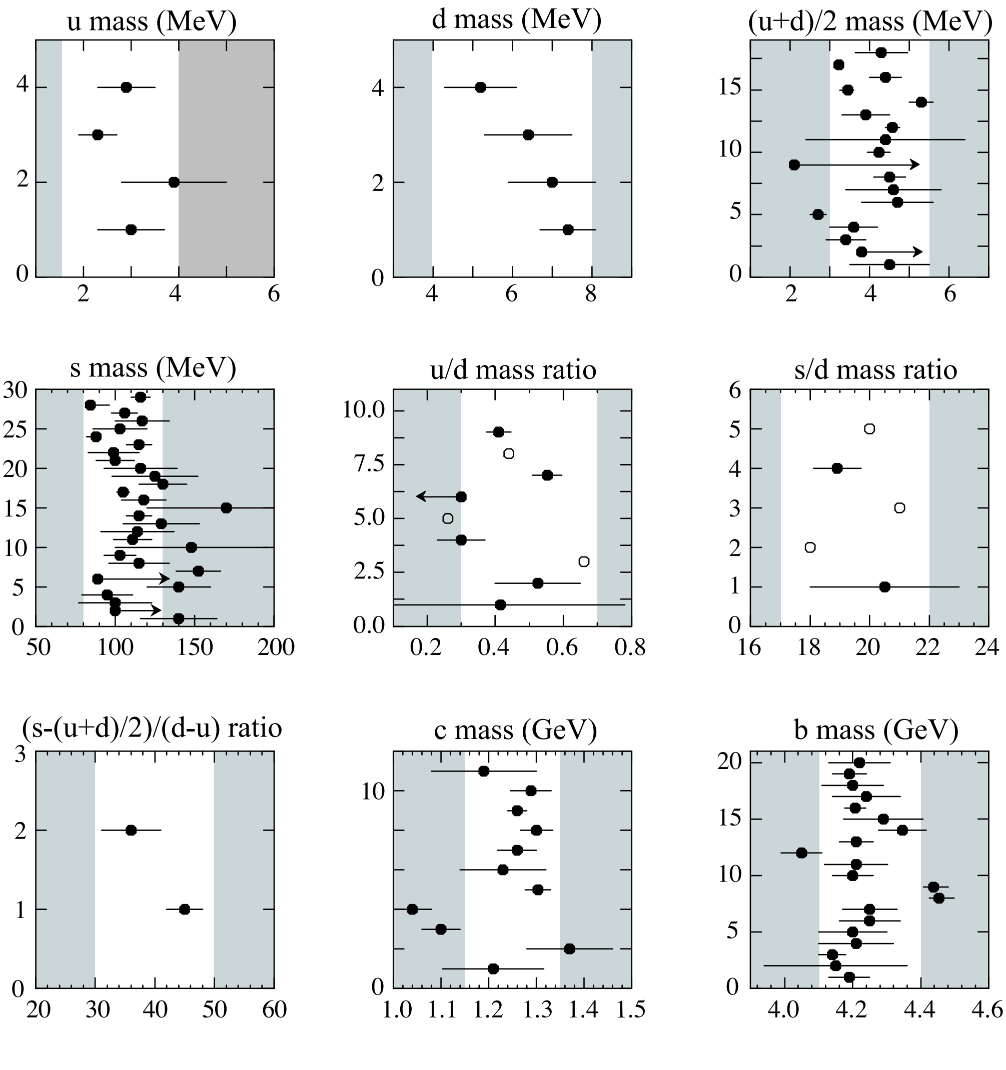

Figure 2. The values of each quark mass parameter taken from the 2004 Data Listings. The most recent data points are at the top of each plot. Points from papers reporting no error bars are open circles. Arrows indicate limits reported. The grey regions indicate values excluded by our evaluations; some regions were determined in part through examination of Fig. 1.

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u

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 1.5 to 4.0 MeV Charge = $\frac{2}{3}$ e $I_z = +\frac{1}{2}$

m_u/m_d = 0.3 to 0.7

d

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass m = 4 to 8 MeV Charge = $-\frac{1}{3}$ e $I_z = -\frac{1}{2}$

m_s/m_d = 17 to 22

$\overline{m} = (m_u + m_d)/2$ = 3.0 to 5.5 MeV

s

$I(J^P) = 0(\frac{1}{2}^+)$

Mass m = 80 to 130 MeV Charge = $-\frac{1}{3}$ e Strangeness = −1

$(m_s - (m_u + m_d)/2)/(m_d - m_u)$ = 30 to 50

LIGHT QUARKS (*u*, *d*, *s*)

OMITTED FROM SUMMARY TABLE

u-QUARK MASS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass- independent subtraction scheme such as $\overline{\text{MS}}$. The ratios m_u/m_d and m_s/m_d are extracted from pion and kaon masses using chiral symmetry. The estimates of *d* and *u* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splittings in hadron masses.

We have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35. The values of "Our Evaluation" were determined in part via Figures 1 and 2.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.5 to 4.0 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.9±0.6	[1] JAMIN	02	THEO	$\overline{\text{MS}}$ scheme
2.3±0.4	[2] NARISON	99	THEO	$\overline{\text{MS}}$ scheme
3.9±1.1	[3] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
3.0±0.7	[4] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme

[1] JAMIN 02 first calculates the strange quark mass from QCD sum rules using the scalar channel, and then combines with the quark mass ratios obtained from chiral perturbation theory to obtain m_u.

[2] NARISON 99 uses sum rules to order α_s^3 for ϕ meson decays to get m_s, and finds m_u by combining with sum rule estimates of m_u+m_d and Dashen's formula.

[3] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_u(1 GeV) = 5.3 ± 1.5 to μ = 2 GeV.

[4] For NARISON 95C, we have rescaled m_u(1 GeV) = 4 ± 1 to μ = 2 GeV.

d-QUARK MASS

See the comment for the *u* quark above.

We have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35. The values of "Our Evaluation" were determined in part via Figures 1 and 2.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
4 to 8 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
5.2±0.9	[5] JAMIN	02	THEO	$\overline{\text{MS}}$ scheme
6.4±1.1	[6] NARISON	99	THEO	$\overline{\text{MS}}$ scheme
7.0±1.1	[7] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
7.4±0.7	[8] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme

[5] JAMIN 02 first calculates the strange quark mass from QCD sum rules using the scalar channel, and then combines with the quark mass ratios obtained from chiral perturbation theory to obtain m_d.
[6] NARISON 99 uses sum rules to order α_s^3 for ϕ meson decays to get m_s, and finds m_d by combining with sum rule estimates of m_u+m_d and Dashen's formula.
[7] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_d(1 GeV) = 9.4 ± 1.5 to μ = 2 GeV.
[8] For NARISON 95C, we have rescaled m_d(1 GeV) = 10 ± 1 to μ = 2 GeV.

$\overline{m} = (m_u+m_d)/2$

See the comments for the u quark above.

We have normalized the $\overline{\rm MS}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35. The values of "Our Evaluation" were determined in part via Figures 1 and 2.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
3.0 to 5.5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.29 ±0.14 ±0.65	[9] AOKI	03	LATT	$\overline{\rm MS}$ scheme
$3.223^{+0.046}_{-0.069}$	[10] AOKI	03B	LATT	$\overline{\rm MS}$ scheme
4.4 ±0.1 ±0.4	[11] BECIREVIC	03	LATT	$\overline{\rm MS}$ scheme
$3.45^{+0.14}_{-0.20}$	[12] ALIKHAN	02	LATT	$\overline{\rm MS}$ scheme
5.3 ±0.3	[13] CHIU	02	LATT	$\overline{\rm MS}$ scheme
3.9 ±0.6	[14] MALTMAN	02	THEO	$\overline{\rm MS}$ scheme
3.9 ±0.6	[15] MALTMAN	01	THEO	$\overline{\rm MS}$ scheme
4.57 ±0.18	[16] AOKI	00	LATT	$\overline{\rm MS}$ scheme
4.4 ±2	[17] GOECKELER	00	LATT	$\overline{\rm MS}$ scheme
4.23 ±0.29	[18] AOKI	99	LATT	$\overline{\rm MS}$ scheme
≥ 2.1	[19] STEELE	99	THEO	$\overline{\rm MS}$ scheme
4.5 ±0.4	[20] BECIREVIC	98	LATT	$\overline{\rm MS}$ scheme
4.6 ±1.2	[21] DOSCH	98	THEO	$\overline{\rm MS}$ scheme
4.7 ±0.9	[22] PRADES	98	THEO	$\overline{\rm MS}$ scheme
2.7 ±0.2	[23] EICKER	97	LATT	$\overline{\rm MS}$ scheme
3.6 ±0.6	[24] GOUGH	97	LATT	$\overline{\rm MS}$ scheme
3.4 ±0.4 ±0.3	[25] GUPTA	97	LATT	$\overline{\rm MS}$ scheme
>3.8	[26] LELLOUCH	97	THEO	$\overline{\rm MS}$ scheme
4.5 ±1.0	[27] BIJNENS	95	THEO	$\overline{\rm MS}$ scheme

[9] AOKI 03 uses quenched lattice simulation of the meson and baryon masses with degenerate light quarks. The extrapolations are done using quenched chiral perturbation theory.
[10] AOKI 03B uses lattice simulation of the meson and baryon masses with two dynamical light quarks. Simulations are performed using the $\mathcal{O}(a)$ improved Wilson action.
[11] BECIREVIC 03 perform quenched lattice computation using the vector and axial Ward identities. Uses $\mathcal{O}(a)$ improved Wilson action and nonperturbative renormalization.
[12] ALIKHAN 02 uses lattice simulation of the meson and baryon masses with two dynamical flavors and degenerate light quarks.
[13] CHIU 02 extracts the average light quark mass from quenched lattice simulations using quenched chiral perturbation theory.
[14] MALTMAN 02 uses finite energy sum rules in the ud and us pseudoscalar channels. Other mass values are also obtained by similar methods.
[15] MALTMAN 01 uses Borel transformed and finite energy sum rules.
[16] AOKI 00 obtain the light quark masses from a quenched lattice simulation of the meson and baryon spectrum with the Wilson quark action.
[17] GOECKELER 00 obtained from a quenched lattice computation of the pseudoscalar meson masses using $\mathcal{O}(a)$ improved Wilson fermions and nonperturbative renormalization.
[18] AOKI 99 obtain the light quark masses from a quenched lattice simulation of the meson spectrum with the staggered quark action employing the regularization independent scheme.
[19] STEELE 99 obtain a bound on the light quark masses by applying the Holder inequality to a sum rule. We have converted their bound of $(m_u+m_d)/2 \geq 3$ MeV at μ=1 GeV to μ=2 GeV.
[20] BECIREVIC 98 compute the quark mass using the Alpha action in the quenched approximation. The conversion from the regularization independent scheme to the $\overline{\rm MS}$ scheme is at NNLO.
[21] DOSCH 98 use sum rule determinations of the quark condensate and chiral perturbation theory to obtain $9.4 \leq (m_u+m_d)$(1 GeV) ≤ 15.7 MeV. We have converted to result to μ=2 GeV.
[22] PRADES 98 uses finite energy sum rules for the axial current correlator.
[23] EICKER 97 use lattice gauge computations with two dynamical light flavors.
[24] GOUGH 97 use lattice gauge computations in the quenched approximation. Correcting for quenching gives $2.1 < \overline{m} < 3.5$ MeV at μ=2 GeV.
[25] GUPTA 97 use Lattice Monte Carlo computations in the quenched approximation. The value for two light dynamic flavors at μ = 2 GeV is 2.7 ± 0.3 ± 0.3 MeV.
[26] LELLOUCH 97 obtain lower bounds on quark masses using hadronic spectral functions.
[27] BIJNENS 95 determines m_u+m_d (1 GeV) = 12 ± 2.5 MeV using finite energy sum rules. We have rescaled this to 2 GeV.

s-QUARK MASS

See the comment for the u quark above.

We have normalized the $\overline{\rm MS}$ masses at a renormalization scale of μ = 2 GeV. Results quoted in the literature at μ = 1 GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	DOCUMENT ID		TECN	COMMENT
80 to 130 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
116 ± 6 ± 0.65	[28] AOKI	03	LATT	$\overline{\rm MS}$ scheme
$84.5^{+12}_{-1.7}$	[29] AOKI	03B	LATT	$\overline{\rm MS}$ scheme
106 ± 2 ± 8	[30] BECIREVIC	03	LATT	$\overline{\rm MS}$ scheme
117 ±17	[31] GAMIZ	03	THEO	$\overline{\rm MS}$ scheme
103 ±17	[32] GAMIZ	03	THEO	$\overline{\rm MS}$ scheme
88^{+3}_{-6}	[33] ALIKHAN	02	LATT	$\overline{\rm MS}$ scheme
115 ± 8	[34] CHIU	02	LATT	$\overline{\rm MS}$ scheme
99 ±16	[35] JAMIN	02	THEO	$\overline{\rm MS}$ scheme
100 ±12	[36] MALTMAN	02	THEO	$\overline{\rm MS}$ scheme
116^{+20}_{-25}	[37] CHEN	01B	THEO	$\overline{\rm MS}$ scheme
125 ±27	[38] KOERNER	01	THEO	$\overline{\rm MS}$ scheme
130 ±15	[39] AOKI	00	LATT	$\overline{\rm MS}$ scheme
105 ± 4	[40] GOECKELER	00	LATT	$\overline{\rm MS}$ scheme
118 ±14	[41] AOKI	99	LATT	$\overline{\rm MS}$ scheme
170^{+44}_{-55}	[42] BARATE	99R	ALEP	$\overline{\rm MS}$ scheme
115 ± 8	[43] MALTMAN	99	THEO	$\overline{\rm MS}$ scheme
129 ±24	[44] NARISON	99	THEO	$\overline{\rm MS}$ scheme
114 ±23	[45] PICH	99	THEO	$\overline{\rm MS}$ scheme
111 ±12	[46] BECIREVIC	98	LATT	$\overline{\rm MS}$ scheme
148 ±48	[47] CHETYRKIN	98	THEO	$\overline{\rm MS}$ scheme
103 ±10	[48] CUCCHIERI	98	LATT	$\overline{\rm MS}$ scheme
115 ±19	[49] DOMINGUEZ	98	THEO	$\overline{\rm MS}$ scheme
152.4±14.1	[50] CHETYRKIN	97	THEO	$\overline{\rm MS}$ scheme
≥ 89	[51] COLANGELO	97	THEO	$\overline{\rm MS}$ scheme
140 ±20	[52] EICKER	97	LATT	$\overline{\rm MS}$ scheme
95 ±16	[53] GOUGH	97	LATT	$\overline{\rm MS}$ scheme
100 ±21 ±10	[54] GUPTA	97	LATT	$\overline{\rm MS}$ scheme
>100	[55] LELLOUCH	97	THEO	$\overline{\rm MS}$ scheme
140 ±24	[56] JAMIN	95	THEO	$\overline{\rm MS}$ scheme

[28] AOKI 03 uses quenched lattice simulation of the meson and baryon masses with degenerate light quarks. The extrapolations are done using quenched chiral perturbation theory. Determines $m_s=113.8 \pm 2.3^{+5.8}_{-2.9}$ using K mass as input and $m_s=142.3 \pm 5.8^{+22}_{-0}$ using ϕ mass as input. We have performed a weighted average of these values.
[29] AOKI 03B uses lattice simulation of the meson and baryon masses with two dynamical light quarks. Simulations are performed using the $\mathcal{O}(a)$ improved Wilson action.
[30] BECIREVIC 03 perform quenched lattice computation using the vector and axial Ward identities. Uses $\mathcal{O}(a)$ improved Wilson action and nonperturbative renormalization. They also quote $\overline{m}/m_s$=24.3 ± 0.2 ± 0.6.
[31] GAMIZ 03 determines m_s from SU(3) breaking in the τ hadronic width. The value of V_{us} is chosen to satisfy CKM unitarity.
[32] GAMIZ 03 determines m_s from SU(3) breaking in the τ hadronic width. The value of V_{us} is taken from the PDG.
[33] ALIKHAN 02 uses lattice simulation of the meson and baryon masses with two dynamical flavors and degenerate light quarks. The above value uses the K-meson mass to determine m_s. If the ϕ meson is used, the number changes to 90^{+5}_{-10}.
[34] CHIU 02 extracts the strange quark mass from quenched lattice simulations using quenched chiral perturbation theory.
[35] JAMIN 02 calculates the strange quark mass from QCD sum rules using the scalar channel.
[36] MALTMAN 02 uses finite energy sum rules in the ud and us pseudoscalar channels. Other mass values are also obtained by similar methods.
[37] CHEN 01B uses an analysis of the hadronic spectral function in τ decay.
[38] KOERNER 01 obtain the s quark mass of $m_s(m_\tau)$ = 130 ± 27(exp) ±9(thy) MeV from an analysis of Cabibbo suppressed τ decays. We have converted this to μ = 2 GeV.
[39] AOKI 00 obtain the light quark masses from a quenched lattice simulation of the meson and baryon spectrum with the Wilson quark action. We have averaged their results of m_s= 115.6 ± 2.3 and m_s= 143.7 ± 5.8 obtained using m_K and m_ϕ, respectively, to normalize the spectrum.
[40] GOECKELER 00 obtained from a quenched lattice computation of the pseudoscalar meson masses using $\mathcal{O}(a)$ improved Wilson fermions and nonperturbative renormalization.
[41] AOKI 99 obtain the light quark masses from a quenched lattice simulation of the meson spectrum with the Staggered quark action employing the regularization independent scheme. We have averaged their results of m_s=106.0 ± 7.1 and m_s=129 ± 12 obtained using m_K and m_ϕ, respectively, to normalize the spectrum.
[42] BARATE 99R obtain the strange quark mass from an analysis of the observed mass spectra in τ decay. We have converted their value of $m_s(m_\tau)= 176^{+46}_{-57}$ MeV to μ=2 GeV.
[43] MALTMAN 99 determines the strange quark mass using finite energy sum rules.
[44] NARISON 99 uses sum rules to order α_s^3 for ϕ meson decays.
[45] PICH 99 obtain the s-quark mass from an analysis of the moments of the invariant mass distribution in τ decays.
[46] BECIREVIC 98 compute the quark mass using the Alpha action in the quenched approximation. The conversion from the regularization independent scheme to the $\overline{\rm MS}$ scheme is at NNLO.
[47] CHETYRKIN 98 uses spectral moments of hadronic τ decays to determine m_s(1 GeV)=200 ± 70 MeV. We have rescaled the result to μ=2 GeV.

[48] CUCCHIERI 98 obtains the quark mass using a quenched lattice computation of the hadronic spectrum.
[49] DOMINGUEZ 98 uses hadronic spectral function sum rules (to four loops, and including dimension six operators) to determine $m_s(1\text{ GeV}) < 155 \pm 25$ MeV. We have rescaled the result to μ=2 GeV.
[50] CHETYRKIN 97 obtains 205.5 ± 19.1 MeV at μ=1 GeV from QCD sum rules including fourth-order QCD corrections. We have rescaled the result to 2 GeV.
[51] COLANGELO 97 is QCD sum rule computation. We have rescaled $m_s(1\text{ GeV}) > 120$ to $\mu = 2$ GeV.
[52] EICKER 97 use lattice gauge computations with two dynamical light flavors.
[53] GOUGH 97 use lattice gauge computations in the quenched approximation. Correcting for quenching gives $54 < m_s < 92$ MeV at μ=2 GeV.
[54] GUPTA 97 use Lattice Monte Carlo computations in the quenched approximation. The value for two light dynamical flavors at $\mu = 2$ GeV is 68 ± 12 ± 7 MeV.
[55] LELLOUCH 97 obtain lower bounds on quark masses using hadronic spectral functions.
[56] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled $m_s(1\text{ GeV}) = 189 \pm 32$ to $\mu = 2$ GeV.

LIGHT QUARK MASS RATIOS

u/d MASS RATIO

VALUE	DOCUMENT ID		TECN	COMMENT
0.3 to 0.7 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.410±0.036	[57] NELSON	03	LATT	$\overline{MS}$ scheme
0.44	[58] GAO	97	THEO	$\overline{MS}$ scheme
0.553±0.043	[59] LEUTWYLER	96	THEO	Compilation
<0.3	[60] CHOI	92	THEO	
0.26	[61] DONOGHUE	92	THEO	
0.30 ±0.07	[62] DONOGHUE	92B	THEO	
0.66	[63] GERARD	90	THEO	
0.4 to 0.65	[64] LEUTWYLER	90B	THEO	
0.05 to 0.78	[65] MALTMAN	90	THEO	

[57] NELSON 03 computes coefficients in the order p^4 chiral Lagrangian using a lattice calculation with three dynamical flavors. The ratio m_u/m_d is obtained by combining this with the chiral perturbation theory computation of the meson masses to order p^4.
[58] GAO 97 uses electromagnetic mass splittings of light mesons.
[59] LEUTWYLER 96 uses a combined fit to $\eta \rightarrow 3\pi$ and $\psi' \rightarrow J/\psi\ (\pi,\eta)$ decay rates, and the electromagnetic mass differences of the π and K.
[60] CHOI 92 result obtained from the decays $\psi(2S) \rightarrow J/\psi(1S)\pi$ and $\psi(2S) \rightarrow J/\psi(1S)\eta$, and a dilute instanton gas estimate of some unknown matrix elements.
[61] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.
[62] DONOGHUE 92B computes quark mass ratios using $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$, and an estimate of L_{14} using Weinberg sum rules.
[63] GERARD 90 uses large N and η-η' mixing.
[64] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine L_7.
[65] MALTMAN 90 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Uses a criterion of "maximum reasonableness" that certain coefficients which are expected to be of order one are ≤ 3.

s/d MASS RATIO

VALUE	DOCUMENT ID		TECN	COMMENT
17 to 22 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.0	[66] GAO	97	THEO	$\overline{MS}$ scheme
18.9±0.8	[67] LEUTWYLER	96	THEO	Compilation
21	[68] DONOGHUE	92	THEO	
18	[69] GERARD	90	THEO	
18 to 23	[70] LEUTWYLER	90B	THEO	

[66] GAO 97 uses electromagnetic mass splittings of light mesons.
[67] LEUTWYLER 96 uses a combined fit to $\eta \rightarrow 3\pi$ and $\psi' \rightarrow J/\psi\ (\pi,\eta)$ decay rates, and the electromagnetic mass differences of the π and K.
[68] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.
[69] GERARD 90 uses large N and η-η' mixing.
[70] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine L_7.

$(m_s - \overline{m})/(m_d - m_u)$ MASS RATIO

$\overline{m} \equiv (m_u + m_d)/2$

VALUE	DOCUMENT ID		TECN
30 to 50 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[71] ANISOVICH	96	THEO
36±5	[72] NEFKENS	92	THEO
45±3	[73] NEFKENS	92	THEO

[71] ANISOVICH 96 find Q=22.7 ± 0.8 with $Q^2 \equiv (m_s^2 - \overline{m}^2)/(m_d^2 - m_s^2)$ from $\eta \rightarrow \pi^+\pi^-\pi^0$ decay using dispersion relations and chiral perturbation theory.
[72] NEFKENS 92 result is from an analysis of meson masses, mixing, and decay.
[73] NEFKENS 92 result is from an analysis of of baryon masses.

LIGHT QUARKS (u, d, s) REFERENCES

AOKI	03	PR D67 034503	S. Aoki *et al.*	(CP-PACS Collab.)
AOKI	03B	PR D68 054502	S. Aoki *et al.*	(CP-PACS Collab.)
BECIREVIC	03	PL B558 69	D. Becirevic, V. Lubicz, C. Tarantino	
GAMIZ	03	JHEP 0301 060	E. Gamiz *et al.*	
NELSON	03	PRL 90 021601	D. Nelson, G.T. Fleming, G.W. Kilcup	
ALIKHAN	02	PR D65 054505	A. Ali Khan *et al.*	(CP-PACS Collab.)
Also	03	PR D67 059901 (erratum)	A. Ali Khan *et al.*	(CP-PACS Collab.)
CHIU	02	PL B538 298	T.-W. Chiu, T.-H. Hsieh	
JAMIN	02	EPJ C24 237	M. Jamin, J.A. Oller, A. Pich	
MALTMAN	02	PR D65 074013	K. Maltman, J. Kambor	
CHEN	01B	EPJ C22 31	S. Chen *et al.*	
KOERNER	01	EPJ C20 259	J.G. Koerner, F. Krajewski, A.A. Pivovarov	
MALTMAN	01	PL B517 332	K. Maltman, J. Kambor	
AOKI	00	PRL 84 238	S. Aoki *et al.*	(CP-PACS Collab.)
GOECKELER	00	PR D62 054504	M. Goeckeler *et al.*	
AOKI	99	PRL 82 4392	S. Aoki *et al.*	(JLQCD Collab.)
BARATE	99R	EPJ C11 599	R. Barate *et al.*	(ALEPH Collab.)
MALTMAN	99	PL B462 195	K. Maltman	
NARISON	99	PL B466 345	S. Narison	
PICH	99	JHEP 9910 004	A. Pich, J. Prades	
STEELE	99	PL B451 201	T.G. Steele, K. Kostuik, J. Kwan	
BECIREVIC	98	PL B444 401	D. Becirevic *et al.*	
CHETYRKIN	98	NP B533 473	K.G. Chetyrkin, J.H. Kuehn, A.A. Pivovarov	
CUCCHIERI	98	PL B422 212	A. Chucchieri *et al.*	
DOMINGUEZ	98	PL B425 193	C.A. Dominguez, L. Pirovano, K. Schilcher	
DOSCH	98	PL B417 173	H.G. Dosch, S. Narison	
PRADES	98	NPBPS 64 253	J. Prades	
CHETYRKIN	97	PL B404 337	K.G. Chetyrkin, D. Pirjol, K. Schilcher	
COLANGELO	97	PL B408 340	P. Colangelo *et al.*	
EICKER	97	PL B407 290	N. Eicker *et al.*	(SESAM Collab.)
GAO	97	PR D56 4115	D.-N. Gao, B.A. Li, M.-L. Yan	
GOUGH	97	PRL 79 1622	B. Gough *et al.*	
GUPTA	97	PR D55 7203	R. Gupta, T. Bhattacharya	
LELLOUCH	97	PL B414 195	L. Lellouch, E. de Rafael, J. Taron	
ANISOVICH	96	PL B375 335	A.V. Anisovich, H. Leutwyler	
LEUTWYLER	96	PL B378 313	H. Leutwyler	
BIJNENS	95	PL B348 226	J. Bijnens, J. Prades, E. de Rafael	(NORD, BOHR+)
JAMIN	95	ZPHY C66 633	M. Jamin, M. Munz	(HEIDT, MUNT)
NARISON	95C	PL B358 113	S. Narison	(MONP)
CHOI	92	PL B292 159	K.W. Choi	(UCSD)
DONOGHUE	92	PRL 69 3444	J.F. Donoghue, B.R. Holstein, D. Wyler	(MASA+)
DONOGHUE	92B	PR D45 892	J.F. Donoghue, D. Wyler	(MASA, ZURI, UCSBT)
NEFKENS	92	CNPP 20 221	B.M.K. Nefkens, G.A. Miller, I. Slaus	(UCLA+)
GERARD	90	MPL A5 391	J.M. Gerard	(MPIM)
LEUTWYLER	90B	NP B337 108	H. Leutwyler	(BERN)
MALTMAN	90	PL B234 158	K. Maltman, T. Goldman, Stephenson Jr.	(YORKC+)

c

$I(J^P) = 0(\frac{1}{2}^+)$

Charge = $\frac{2}{3}$ e Charm = +1

c-QUARK MASS

The c-quark mass corresponds to the "running" mass m_c ($\mu = m_c$) in the $\overline{MS}$ scheme. We have converted masses in other schemes to the $\overline{MS}$ scheme using two-loop QCD perturbation theory with $\alpha_s(\mu{=}m_c) = 0.39$. The range 1.0–1.4 GeV for the $\overline{MS}$ mass corresponds to 1.47–1.83 GeV for the pole mass (see the "Note on Quark Masses").

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
1.15 to 1.35 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1.19 ±0.11	[1] EIDEMULLER	03	THEO	$\overline{MS}$ scheme
1.289±0.043	[2] ERLER	03	THEO	$\overline{MS}$ scheme
1.26 ±0.02	[3] ZYABLYUK	03	THEO	$\overline{MS}$ scheme
1.26 ±0.04 ±0.12	[4] BECIREVIC	02	LATT	$\overline{MS}$ scheme
1.301±0.034	[5] ROLF	02	LATT	$\overline{MS}$ scheme
1.23 ±0.09	[6] EIDEMULLER	01	THEO	$\overline{MS}$ scheme
1.304±0.027	[7] KUHN	01	THEO	$\overline{MS}$ scheme
1.04 ±0.04	[8] MARTIN	01	THEO	$\overline{MS}$ scheme
1.1 ±0.04	[9] NARISON	01B	THEO	$\overline{MS}$ scheme
1.37 ±0.09	[10] PENARROCHA	01	THEO	$\overline{MS}$ scheme
1.210±0.070±0.080	[11] PINEDA	01	THEO	$\overline{MS}$ scheme
1.3 ±0.3 ±0.3	[12] ASTIER	00D	NOMD	
1.79 ±0.38	[13] VILAIN	99	THEO	$\overline{MS}$ scheme

[1] EIDEMULLER 03 determines m_b and m_c using QCD sum rules.
[2] ERLER 03 determines m_b and m_c using QCD sum rules. Includes recent BES data.
[3] ZYABLYUK 03 determines m_c by using QCD sum rules in the pseudoscalar channel and comparing with the η_c mass.
[4] BECIREVIC 02 uses Monte-Carlo calculations of lattice Ward identities and the D_s mass. The authors estimate an error of about 5% for use of the quenched approximation, not included in systematic error of 0.12.
[5] ROLF 02 determines m_c from a quenched lattice calculation of the D_s mass. The error estimate is for all systematics except the quenched approximation, including lattice spacing effects, finite volume effects, excited states contamination, rounding errors, and the scale uncertainty. The authors estimate the uncertainty due to the quenched approximation may be about 3%.
[6] EIDEMULLER 01 result is QCD sum rule analysis of charmonium using NRQCD at next-to-next-to-leading order.
[7] KUHN 01 uses an analysis of the e^+e^- total cross section to hadrons.
[8] MARTIN 01 obtain a pole mass of 1.33–1.4 GeV from an analysis of R, the rate for $e^+e^- \rightarrow$ hadrons. We have converted this to the $\overline{MS}$ scheme using the two-loop formula.
[9] NARISON 01B uses pseudoscalar sum rules in the B and D meson channels.
[10] PENARROCHA 01 result is from an analysis of the BES-II e^+e^- data using finite energy sum rules.
[11] PINEDA 01 uses the $\Upsilon(1S)$ system and the B-D mass difference to determine m_c. The errors are due to theory, and the uncertainty in λ_1 and m_b.
[12] Study of opposite sign dimuon events.
[13] VILAIN 99 obtain the charm quark mass from an analysis of charm production in neutrino scattering.

c-QUARK REFERENCES

EIDEMULLER	03	PR D67 113002	M. Eidemuller	
ERLER	03	PL B558 125	J. Erler, M. Luo	
ZYABLYUK	03	JHEP 0301 081	K.N. Zyablyuk	(ITEP)
BECIREVIC	02	PL B524 115	D. Beciveric, V. Lubicz, G. Martinelli	
ROLF	02	JHEP 0212 007	J. Rolf, S. Sint	
EIDEMULLER	01	PL B498 203	M. Eidemueller, M. Jamin	
KUHN	01	NP B619 588	J.H. Kuhn, M. Steinhauser	
MARTIN	01	EPJ C19 681	A.D. Martin, J. Outhwaite, M.G. Ryskin	
NARISON	01B	PL B520 115	S. Narison	
PENARROCHA	01	PL B515 291	J. Penarrocha, K. Schilcher	
PINEDA	01	JHEP 0106 022	A. Pineda	
ASTIER	00D	PL B486 35	P. Astier *et al.*	(CERN NOMAD Collab.)
VILAIN	99	EPJ C11 19	P. Vilain *et al.*	(CHARM II Collab.)

b

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= -\frac{1}{3}\,e$ Bottom $= -1$

b-QUARK MASS

The first value is the "running mass" $\overline{m}_b(\mu = \overline{m}_b)$ in the $\overline{\text{MS}}$ scheme, and the second value is the $1S$ mass, which is half the mass of the $\Upsilon(1S)$ in perturbation theory. For a review of different quark mass definitions and their properties, see EL-KHADRA 02. The $1S$ mass is better suited for use in analyzing B decays than the $\overline{\text{MS}}$ mass because it gives a stable perturbative expansion. We have converted masses in other schemes to the $\overline{\text{MS}}$ mass and $1S$ mass using two-loop QCD perturbation theory with $\alpha_s(\mu = \overline{m}_b) = 0.22$. The range 4.1–4.4 for the $\overline{\text{MS}}$ mass corresponds to 4.6–4.9 for the $1S$ mass and 4.7–5.0 GeV for the pole mass.

$\overline{\text{MS}}$ *MASS* (GeV)	*1S MASS* (GeV)	*DOCUMENT ID*		*TECN*
4.1 to 4.4 OUR EVALUATION of $\overline{\text{MS}}$ Mass				
4.6 to 4.9 OUR EVALUATION of $1S$ Mass				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.22 ±0.09	4.74 ± 0.10	[1] BAUER	03	THEO
4.19 ±0.05	4.66 ± 0.05	[2] BORDES	03	THEO
4.20 ±0.09	4.67 ± 0.10	[3] CORCELLA	03	THEO
4.24 ±0.10	4.72 ± 0.11	[4] EIDEMULLER	03	THEO
4.207±0.031	4.682 ± 0.035	[5] ERLER	03	THEO
4.33 ±0.06 ±0.10	4.82 ± 0.07 ± 0.11	[6] MAHMOOD	03	THEO
4.346±0.070	4.837 ± 0.078	[7] PENIN	02	THEO
3.95 ±0.57	4.40 ± 0.63	[8] ABBIENDI	01S	OPAL
4.21 ±0.05	4.69 ± 0.06	[9] KUHN	01	THEO
4.05 ±0.06	4.51 ± 0.07	[10] NARISON	01B	THEO
4.210±0.090±0.025	4.69 ± 0.100 ± 0.028	[11] PINEDA	01	THEO
4.7 ±0.74	5.23 ± 0.82	[12] BARATE	00V	ALEP
4.20 ±0.06	4.71 ± 0.03	[13] HOANG	00	THEO
$4.437^{+0.045}_{-0.029}$	$4.938^{+0.050}_{-0.032}$	[14] LUCHA	00	THEO
$4.454^{+0.045}_{-0.029}$	$4.957^{+0.050}_{-0.032}$	[14] PINEDA	00	THEO
4.25 ±0.08	4.73 ± 0.09	[15] BENEKE	99	THEO
$3.8\ ^{+0.77}_{-2.0}$	$4.23^{+0.86}_{-2.0}$	[16] BRANDENB...	99	
4.25 ±0.09	4.73 ± 0.10	[17] HOANG	99	THEO
4.2 ±0.1	4.67 ± 0.11	[18] MELNIKOV	99	THEO
4.21 ±0.11	4.69 ± 0.12	[19] PENIN	99	THEO
3.91 ±0.67	4.35 ± 0.75	[20] ABREU	98I	DLPH
4.14 ±0.04	4.61 ± 0.05	[21] KUEHN	98	THEO
4.15 ±0.05 ±0.20	4.62 ± 0.06 ± 0.22	[22] GIMENEZ	97	LATT
4.19 ±0.06	4.66 ± 0.07	[23] JAMIN	97	THEO
4.16 ±0.32 ±0.60	4.63 ± 0.36 ± 0.67	[24] RODRIGO	97	THEO

[1] BAUER 03 determine the b quark mass by a global fit to B decay observables. The experimental data includes lepton energy and hadron invariant mass moments in semileptonic $B \to X_c \ell \nu_\ell$ decay, and the inclusive photon spectrum in $B \to X_s \gamma$ decay. The theoretical expressions used are of order $1/\text{m}^3$, and $\alpha_s^2 \beta_0$.

[2] BORDES 03 determines m_b using QCD finite energy sum rules to order α_s^2.

[3] CORCELLA 03 determines $\overline{m}_b$ using sum rules computed to order α_s^2. Includes charm quark mass effects.

[4] EIDEMULLER 03 determines $\overline{m}_b$ and $\overline{m}_c$ using QCD sum rules.

[5] ERLER 03 determines $\overline{m}_b$ and $\overline{m}_c$ using QCD sum rules. Includes recent BES data.

[6] MAHMOOD 03 determines m_b^{1S} by a fit to the lepton energy moments in $B \to X_c \ell \nu_\ell$ decay. The theoretical expressions used are of order $1/\text{m}^3$ and $\alpha_s^2 \beta_0$. We have converted their result to the $\overline{\text{MS}}$ scheme.

[7] PENIN 02 determines $\overline{m}_b$ from the spectrum of the Υ system.

[8] ABBIENDI 01S find $\overline{m}_b$ (M_Z) to be 2.67 ± 0.4 GeV from an analysis of $Z \to b$ decays.

[9] KUHN 01 uses an analysis of the $e^+ e^-$ total cross section to hadrons.

[10] NARISON 01B uses pseudoscalar sum rules in the B and D meson channels.

[11] PINEDA 01 uses the $\Upsilon(1S)$ system to determine the quark mass. The errors are due to theory, and the uncertainty in α_s.

[12] BARATE 00V obtain the b quark mass $\overline{m}_b(M_Z)$ = 3.27 ± 0.22(stat) ±0.22(exp) ±0.38(had) ±0.16(thy) from an analysis of event shape variables in Z decays. We have converted this to $\mu = \overline{m}_b$.

[13] HOANG 00 uses a NNLO calculation of the vacuum polarization function to determine spectral moments of the masses and electronic decay widths of the Υ mesons.

[14] LUCHA 00, PINEDA 00 obtain the b-quark mass from a perturbative calculation of the Υ spectrum and decay widths to order α_s^4.

[15] BENEKE 99 uses a calculation of the $b\overline{b}$ production cross section and the mass of the Υ meson at NNLO.

[16] BRANDENBURG 99 obtain a b-quark mass of $\overline{m}_b(M_Z)$= $2.56 \pm 0.27^{+0.28}_{-0.38}{}^{+0.49}_{-1.48}$ from a study of three-jet events at the Z. We have converted this to $\mu = \overline{m}_b$.

[17] HOANG 99 uses a NNLO calculation of the vacuum polarization function to determine spectral moments of the masses and electronic decay widths of the Υ mesons.

[18] MELNIKOV 99 compute the quark mass using Υ sum rules at NNLO.

[19] PENIN 99 compute the quark mass using Υ sum rules at NNLO.

[20] ABREU 98I determines the $\overline{\text{MS}}$ mass $\overline{m}_b$ = 2.67 ± 0.25 ± 0.34 ± 0.27 GeV at $\mu = M_Z$ from three jet heavy quark production at LEP. ABREU 98I have rescaled the result to $\mu = \overline{m}_b$ using α_s=0.118 ± 0.003.

[21] KUEHN 98 uses a calculation of the vacuum polarization function, including resumming threshold effects, to determine spectral moments of the masses of the Υ mesons. We have converted their extracted value of 4.75 ± 0.04 for the pole mass to the $\overline{\text{MS}}$ scheme.

[22] GIMENEZ 97 uses lattice computations of the B-meson propagator and the B-meson binding energy $\overline{\Lambda}$ in the HQET. Their systematic (second) error for the $\overline{\text{MS}}$ mass is an estimate of the effects of higher-order corrections in the matching of the HQET operators (renormalon effects).

[23] JAMIN 97 apply the QCD moment method to the Υ system. They also find a pole mass of 4.60 ± 0.02.

[24] RODRIGO 97 determines the $\overline{\text{MS}}$ mass $\overline{m}_b$ = 2.85 ± 0.22 ± 0.20 ± 0.36 GeV at $\mu = M_Z$ from three jet heavy quark production at LEP. We have rescaled the result.

b-QUARK REFERENCES

BAUER	03	PR D67 054012	C.W. Bauer *et al.*	
BORDES	03	PL B562 81	J. Bordes, J. Penarrocha, K. Schilcher	
CORCELLA	03	PL B554 133	G. Corcella, A.H. Hoang	
EIDEMULLER	03	PR D67 113002	M. Eidemuller	
ERLER	03	PL B558 125	J. Erler, M. Luo	
MAHMOOD	03	PR D67 072001	A.H. Mahmood *et al.*	(CLEO Collab.)
EL-KHADRA	02	ARNPS 52 201	A.X. El-Khadra, M. Luke	
PENIN	02	PL B538 335	A. Penin, M. Steinhauser	
ABBIENDI	01S	EPJ C21 411	G. Abbiendi *et al.*	(OPAL Collab.)
KUHN	01	NP B619 588	J.H. Kuhn, M. Steinhauser	
NARISON	01B	PL B520 115	S. Narison	
PINEDA	01	JHEP 0106 022	A. Pineda	
BARATE	00V	EPJ C18 1	R. Barate *et al.*	(ALEPH Collab.)
HOANG	00	PR D61 034005	A.H .Hoang	
LUCHA	00	PR D62 097501	W. Lucha, F.F. Schoeberl	
PINEDA	00	PR D61 077505	A. Pineda, F.J. Yndurain	
BENEKE	99	PL B471 233	M. Beneke, A. Signer	
BRANDENB...	99	PL B468 168	A. Brandenburg *et al.*	
HOANG	99	PR D59 014039	A.H. Hoang	
MELNIKOV	99	PR D59 114009	K. Melnikov, A. Yelkhovsky	
PENIN	99	NP B549 217	A.A. Penin, A.A. Pivovarov	
ABREU	98I	PL B418 430	P. Abreu *et al.*	(DELPHI Collab.)
KUEHN	98	NP B534 356	J.H. Kuehn, A.A. Penin, A.A. Pivovarov	
GIMENEZ	97	PL B393 124	V. Gimenez, G. Martinelli, C.T. Sachrajda	
JAMIN	97	NP B507 334	M. Jamin, A. Pich	
RODRIGO	97	PRL 79 193	G. Rodrigo, A. Santamaria, M.S. Bilenky	

t

$I(J^P) = 0(\frac{1}{2}^+)$

Charge $= \frac{2}{3}\,e$ Top $= +1$

THE TOP QUARK

Updated January 2004 by M. Mangano (CERN) and T. Trippe (LBNL).

A. Introduction: The top quark is the $Q = 2/3$, $T_3 = +1/2$ member of the weak-isospin doublet containing the bottom quark (see our review on the "Standard Model of Electroweak Interactions" for more information). This note summarizes its currently measured properties, and provides a discussion of the experimental and theoretical issues involved in the determination of its parameters (mass, production cross section, decay branching ratios, *etc.*).

B. Top quark production at the Tevatron: All direct measurements of top quark production and decay have been made by the CDF and DØ experiments at the Fermilab Tevatron collider in $p\overline{p}$ collisions. The first observations and studies have been performed during the so-called run I, at $\sqrt{s} = 1.8$ TeV, completed in 1996. Most of the results in this note refer to analyses of these data. A new period of data-taking, the run II, started in 2001 at $\sqrt{s} = 1.96$ TeV. All analyses from run II are still only preliminary and yet unpublished [1]. The main body of this note will therefore only quote results relative to the run I data, with some highlights of current run II results included in an Appendix.

In hadron collisions, top quarks are produced dominantly in pairs from the QCD processes $q\overline{q} \to t\overline{t}$ and $gg \to t\overline{t}$. At 1.8 TeV (1.96 TeV), the production cross section [2] in these channels is expected to be approximately 5 pb (6.5 pb) for $m_t = 175$ GeV/c^2, with a 90% (85%) contribution from $q\overline{q}$ annihilation. Smaller contributions are expected from electroweak single-top production mechanisms, namely $q\overline{q}' \to W^* \to t\overline{b}$ and $qg \to q't\overline{b}$, the latter mediated by virtual-W exchange ("W-gluon fusion"). The combined rate of these processes at 1.8 TeV is approximately 2.5 pb at $m_t = 175$ GeV/c^2 (see Ref. 3 and references therein). The expected contribution of these channels is further reduced relative to the dominant pair-production mechanisms because of larger backgrounds and poor detection efficiency.

With a mass above the Wb threshold, the decay width of the top quark is expected to be dominated by the two-body channel $t \to Wb$. Neglecting terms of order m_b^2/m_t^2, α_s^2 and those of order $(\alpha_s/\pi)m_W^2/m_t^2$, this is predicted in the Standard Model to be [4]:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{M_W^2}{m_t^2}\right)^2\left(1+2\frac{M_W^2}{m_t^2}\right)\left[1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right]. \quad (1)$$

The use of G_F in this equation accounts for the largest part of the one-loop electroweak radiative corrections, providing an expression accurate to better than 2%. The width increases with mass, going for example from 1.02 GeV/c^2 at $m_t = 160$ GeV/c^2 to 1.56 GeV/c^2 at $m_t = 180$ GeV/c^2 (we used $\alpha_S(\mathrm{M_Z}) = 0.118$). With such a correspondingly short lifetime, the top quark is expected to decay before top-flavored hadrons or $t\overline{t}$-quarkonium bound states can form [5]. The order α_s^2 QCD corrections to Γ_t have also been calculated [6], thereby improving the overall theoretical accuracy to better than 1%.

In top decay, the Ws and Wd final states are expected to be suppressed relative to Wb by the square of the CKM matrix elements V_{ts} and V_{td}, whose values can be estimated under the assumption of unitarity of the three-generation CKM matrix to be less than 0.043 and 0.014, respectively (see our review "The Cabibbo-Kobayashi-Maskawa Mixing Matrix" in the current edition for more information). Typical final states for the leading pair-production process therefore belong to three classes:

A. $t\overline{t} \to W\,b\,W\,\overline{b} \to q\,\overline{q}'\,b\,q''\,\overline{q}'''\,\overline{b}$,

B. $t\overline{t} \to W\,b\,W\,\overline{b} \to q\,\overline{q}'\,b\,\ell\,\overline{\nu}_\ell\,\overline{b} + \overline{\ell}\,\nu_\ell\,b\,q\,\overline{q}'\,\overline{b}$,

C. $t\overline{t} \to W\,b\,W\,\overline{b} \to \overline{\ell}\,\nu_\ell\,b\,\ell'\,\overline{\nu}_{\ell'}\,\overline{b}$,

where A, B, and C are referred to as the all-jets, lepton + jets, and dilepton channels, respectively. While ℓ in the above processes refers to e, μ, or τ, throughout the rest of this article, the meaning of ℓ is restricted to an observed e or μ.

The final state quarks can emit radiation and will eventually evolve into jets of hadrons. The precise number of jets reconstructed by the detectors varies event by event, as it depends on the decay kinematics, as well as on the precise definition of jet used in the analysis. (Additional gluon radiation can also be emitted from the initial states.) The transverse momenta of the neutrinos are reconstructed via the large imbalance in detected transverse momentum of the event (missing E_T).

The observation of $t\overline{t}$ pairs has been reported in all of the above decay modes. As discussed below, the production and decay properties of the top quark extracted from the above three decay channels are all consistent with each other within experimental uncertainty. In particular, the $t \to Wb$ decay mode is supported through the reconstruction of the $W \to jj$ invariant mass in the $\ell\nu_\ell b\overline{b}jj$ final state [7].

The extraction of top-quark properties from Tevatron data requires a good understanding of the production and decay mechanisms of the top, as well as of the large background processes. Because only leading order QCD calculations are available for most of the relevant processes (W+3 and 4 jets, or WW+2 jets), theoretical estimates of the backgrounds have large uncertainties. While this limitation affects estimates of the overall $t\overline{t}$ production rates, it is believed that the LO determination of the event kinematics and of the fraction of W + multi-jet events containing b quarks is relatively accurate. In particular, for the background one expects the E_T spectrum of jets to fall rather steeply, the jet direction to peak at small angles to the beams, and the fraction of events with b quarks to be of the order of a few percent. On the contrary, for the top signal, the b fraction is $\sim$ 100% and the jets are rather energetic, since they come from the decay of a massive object. It is therefore possible to improve the S/B ratio either by requiring the presence of a b quark, or by selecting very energetic and central kinematic configurations.

A detailed study of control samples with features similar to those of the relevant backgrounds, but free from possible top contamination, is required to provide a reliable check on background estimates.

C. Measured top properties: Current measurements of top properties based on the run I data use an integrated luminosity of 109 pb^{-1} for CDF and 125 pb^{-1} for DØ. DØ and CDF determine the $t\overline{t}$ cross section $\sigma_{t\overline{t}}$ from their number of observed top candidates, estimated background, $t\overline{t}$ acceptance, and integrated luminosity, assuming the Standard-Model decay $t \to Wb$ with unity branching ratio. Table 1 shows the measured cross sections from DØ and CDF along with the range of theoretical expectations, evaluated at the m_t values used by the experiments in calculating their acceptances. The DØ values we quote [9] reflect the final analysis of the run I data, and are adjusted to the current DØ value of the top mass. The agreement of both DØ and CDF $t\overline{t}$ cross sections with theory supports the hypothesis that the excess of events over background in all of these channels can be attributed to $t\overline{t}$ production.

More precise measurements of the top production cross section will test current understanding of the production mechanisms.This is important for the extrapolation to higher energies of colliders such as the LHC, where the larger expected cross section will permit more extensive studies [15]. The results

Table 1: Cross section for $t\overline{t}$ production in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV from DØ ($m_t = 172.1$ GeV/c^2), CDF ($m_t = 175$ GeV/c^2), and theory.

$\sigma_{t\overline{t}}(pb)$	Source	Ref.	Method
2.8 ± 2.1	DØ	[8,9]	e + jets/topological
5.6 ± 3.7	DØ	[8,9]	μ + jets/topological
6.0 ± 3.6	DØ	[8,9]	e + jets/soft μ b-tag
11.3 ± 6.6	DØ	[8,9]	μ + jets/soft μ b-tag
5.1 ± 1.9	DØ	[8,9]	all ℓ + jets combined
6.0 ± 3.2	DØ	[8,9]	$\ell\ell + e\nu$
7.3 ± 3.2	DØ	[9,10]	all jets
5.7 ± 1.6	DØ	[9,10]	all combined
$5.2 - 6.2$	Theory	[2]	$m_t = 172.1$ GeV/c^2
5.1 ± 1.5	CDF	[11,14]	ℓ + jets/vtx b-tag
9.2 ± 4.3	CDF	[11,14]	ℓ + jets/soft ℓ b-tag
$8.4^{+4.5}_{-3.5}$	CDF	[12,14]	$\ell\ell$
$7.6^{+3.5}_{-2.7}$	CDF	[13,14]	all jets
$6.5^{+1.7}_{-1.4}$	CDF	[14]	all combined
$4.5 - 5.7$	Theory	[2]	$m_t = 175$ GeV/c^2

of preliminary analyses of the run II data are given in the Appendix: the current statistical and systematic uncertainties are still too large to draw any conclusion. With the expected improvements once larger samples have been collected, discrepancies in rate between theory and data would be quite exciting, and might indicate the presence of exotic production or decay channels, as predicted in certain models. Such new sources of top would lead to a modification of kinematic distributions such as the invariant mass of the top pair or the transverse momentum of the top quark. Studies by CDF of the former [16] and of the latter [17] distributions, show no deviation from expected QCD behavior. DØ [18] also finds these kinematic distributions consistent with Standard Model expectations.

The top mass has been measured in the lepton + jets and dilepton channels by both DØ and CDF, and in the all-jets channel by CDF. At present, the most precise measurements come from the lepton + jets channel, with four or more jets and large missing E_T. In this channel, each event is subjected to a two-constraint kinematic fit to the hypothesis $t\overline{t} \to W^+ b W^- \overline{b} \to \ell \, \nu_\ell \, q \, \overline{q}' \, b \, \overline{b}$, assuming that the four highest E_T jets are the quarks from $t\overline{t}$ decay. The shape of the distribution of fitted top masses from these events is compared to templates expected from a mixture of background and signal distributions for a series of assumed top masses. This comparison yields values of the likelihood as a function of top mass, from which a best value of the top mass and its uncertainty can be obtained. The results are shown in Table 2. The systematic uncertainty (second uncertainty shown) is comparable to the statistical uncertainty, and is primarily due to uncertainties in the jet energy scale and in the Monte Carlo modeling.

Less precise determinations of the top mass come from the dilepton channel with two or more jets and large missing E_T, and from the all-jets channel. In the dilepton channel, a kinematically constrained fit is not possible because there are two missing neutrinos, so experiments must use other mass estimators than the reconstructed top mass. In principle, any quantity which is correlated with the top mass can be used as such an estimator. The DØ method uses the fact that if a value for m_t is assumed, the $t\overline{t}$ system can be reconstructed (up to a four-fold ambiguity). They compare the resulting kinematic configurations to expectations from $t\overline{t}$ production, and obtain an m_t-dependent weight curve for each event, which they histogram in five bins to obtain four shape-sensitive quantities as their multidimensional mass estimator. This method yields a significant increase in precision over one-dimensional estimators. CDF has employed a similar method, thereby reducing their previous systematic uncertainty in the $\ell\ell$ + jets channel by a factor of two. DØ and CDF obtain the top mass and uncertainty from these mass estimators using the same type of template likelihood method as for the lepton + jets channel. CDF also measures the mass in the all-jets channel using events with six or more jets, at least one of which is tagged as a b jet through the detection of a secondary vertex.

Table 2: Top mass measurements from DØ and CDF.

m_t (GeV/c^2)	Source	Ref.	Method
$173.3 \pm 5.6 \pm 5.5$	DØ	[18]	ℓ + jets
$(180.1 \pm 3.6 \pm 4.0)$ †	DØ	[19]	ℓ + jets
$168.4 \pm 12.3 \pm 3.6$	DØ	[20]	$\ell\ell$
$172.1 \pm 5.2 \pm 4.9$	DØ	[18]	DØ comb.
$176.1 \pm 5.1 \pm 5.3$	CDF	[21–23]	ℓ + jets
$167.4 \pm 10.3 \pm 4.8$	CDF	[21]	$\ell\ell$
$186.0 \pm 10.0 \pm 5.7$	CDF	[13,21]	all jets
176.1 ± 6.6	CDF	[21,23]	CDF comb.
$174.3 \pm 3.2 \pm 4.0$ *	DØ & CDF	[24]	PDG best

† DØ finds a significantly improved preliminary result for the mass, using the same data as for the Ref. 18 result, but analyzed using a method similar to that of their dilepton analysis. This value is not used in the "DØ combined" mass of 172.1 GeV/c^2, nor in the "PDG best" (DØ & CDF combined) mass.

* PDG uses this Top Averaging Group result as its best value. In spite of the new ℓ+jets CDF result [23], this average, given in Ref. 24, still applies within rounding errors.

As seen in Table 2, all results are in good agreement with a unique mass for the top quark, giving further support to the hypothesis that these events are due to $t\overline{t}$ production. The Top Averaging Group, a joint CDF/DØ working group, produced the combined CDF/DØ average top mass in Table 2, taking into account correlations between systematic uncertainties in different measurements. They assume that the uncertainty in jet energy scale is completely correlated within CDF and within DØ but uncorrelated between the two experiments, and that the signal model and Monte Carlo generator uncertainties are completely correlated between all measurements. The uncertainties from uranium noise and multiple interactions relate only to DØ and are assumed completely correlated between their two measurements. The uncertainty on the background model is taken to be completely correlated between the CDF and the DØ ℓ+jets measurements, and similarly for the $\ell\ell$ measurements. The Particle Data Group uses this combined top mass, $m_t = 174.3 \pm 5.1$ GeV/c^2 (statistical and systematic uncertainties combined in quadrature), as our PDG best value.

Given the experimental technique used to extract the top mass, these mass values should be taken as representing the top *pole mass* (see our review "Note on Quark Masses" in the current edition for more information).

With a smaller uncertainty on the top mass, and with improved measurements of other electroweak parameters, it will be possible to get important constraints on the value of the Higgs mass. Current global fits performed within the Standard Model and its minimal supersymmetric extension provide indications for a relatively light Higgs (see the review "H^0 Indirect Mass Limits from Electroweak Analysis" in the Particle Listings of the current edition for more information).

Other properties of top decays are being studied. CDF reports a direct measurement of the $t \to Wb$ branching ratio [25]. Their result, obtained by comparing the number of events with 0, 1 and 2 tagged b jets and using the known b-tagging efficiency, is: $R = \mathrm{B}(t \to Wb)/\sum_{q=d,s,b}\mathrm{B}(t \to Wq) = 0.94^{+0.31}_{-0.24}$, or as a lower limit, $R > 0.56$ at 95% CL. Assuming that non-W decays of top can be neglected, that only three generations of fermions exist, and that the CKM matrix is unitary, they extract a CKM matrix-element $|V_{tb}| = 0.97^{+0.16}_{-0.12}$ or $|V_{tb}| > 0.75$ at 95% CL. A more direct measurement of the Wtb coupling constant will be possible when enough data are accumulated to detect the less frequent single-top production processes, such as $q\overline{q}' \to W^* \to t\overline{b}$ (a.k.a. s-channel W exchange) and $qb \to q't$ via W exchange (a.k.a. Wg fusion). The cross sections for these processes are proportional to $|V_{tb}|^2$, and there is no assumption needed on the number of families or the unitarity of the CKM matrix in the extraction of $|V_{tb}|$. CDF [26] gives 95% CL limits of 15.8 and 15.4 pb for the single-top production rates in the s-channel and Wg-fusion channels, respectively, while DØ [27] gives 17 and 22 pb, respectively. Comparison with the expected Standard Model rates of 0.73 ± 0.10 pb and 1.70 ± 0.30 pb, respectively, shows that far better statistics will be required before significant measurements can be achieved. For the prospects of these measurements at the LHC, see [15].

Both CDF and DØ have searched for non-Standard Model top decays [28,29], particularly those expected in supersymmetric models. These studies search for $t \to H^+b$, followed by $H^+ \to \tau\nu$ or $c\overline{s}$. The $t \to H^+b$ branching ratio is a minimum at $\tan\beta = \sqrt{m_t/m_b} \simeq 6$ and is large in the region of either $\tan\beta \ll 6$ or $\tan\beta \gg 6$. In the former range $H^+ \to c\overline{s}$ is the dominant decay, while $H^+ \to \tau\nu$ dominates in the latter range. These studies are based either on direct searches for these final states, or on top disappearance. In the standard lepton + jets or dilepton cross section analyses, the charged Higgs decays are not detected as efficiently as $t \to W^{\pm}b$, primarily because the selection criteria are optimized for the standard decays, and because of the absence of energetic isolated leptons in the Higgs decays. With a significant $t \to H^+b$ contribution, this would give rise to measured cross sections lower than the prediction from the Standard Model (assuming that non-Standard contributions to $t\overline{t}$ production are negligible). More details, and the results of these studies, can be found in the review "Search for Higgs bosons" and in the "H^+ Mass Limits" section of the Higgs Particle Listings of the current edition.

CDF reports a search for flavor changing neutral current (FCNC) decays of the top quark $t \to q\gamma$ and $t \to qZ$ [30], for which the Standard Model predicts such small rates that their observation here would indicate new physics. They assume that one top decays via FCNC while the other decays via Wb. For the $t \to q\gamma$ search, they examine two signatures, depending on whether the W decays leptonically or hadronically. For leptonic W decay, the signature is $\gamma\ell$ and missing E_T and two or more jets, while for hadronic W decay, it is γ plus four or more jets, one with a secondary vertex b tag. They observe one event ($\mu\gamma$) with an expected background of less than half an event, giving an upper limit on the top branching ratio of $\mathrm{B}(t \to q\gamma) < 3.2\%$ at 95% CL.

For the $t \to qZ$ FCNC search, they look for $Z \to \mu\mu$ or ee and $W \to$ hadrons, giving a Z + four jets signature. They observe one $\mu\mu$ event with an expected background of 1.2 events, giving an upper limit on the top branching ratio of $\mathrm{B}(t \to qZ) < 33\%$ at 95% CL. Both the γ and Z limits are non-background subtracted (i.e. conservative) estimates.

Indirect constraints on FCNC couplings of the top quark can be obtained from single-top production in e^+e^- collisions, via the process $e^+e^- \to \gamma, Z^* \to t\overline{q}$ and its charge-conjugate ($q = u, c$). Limits on the cross section for this reaction have been updated by ALEPH [31] and OPAL [32]. When interpreted in terms of top decay branching ratios [15,33], these limits lead to bounds of $\mathrm{B}(t \to qZ) < 0.17$ and < 0.137, respectively, which are stronger than the direct CDF limit.

Studies of the decay angular distributions allow a direct analysis of the V–A nature of the Wtb coupling, and provide information on the relative coupling of longitudinal and transverse W bosons to the top quark. In the Standard Model, the fraction of decays to longitudinally polarized W bosons is expected to be $\mathcal{F}_0^{\mathrm{SM}} = x/(1+x)$, $x = m_t^2/2M_W^2$ ($\mathcal{F}_0^{\mathrm{SM}} \sim 70\%$ for $m_t = 175$ GeV/c^2). Deviations from this value would bring into question the validity of the Higgs mechanism of spontaneous symmetry breaking. CDF has recently measured $\mathcal{F}_0^{\mathrm{SM}} = 0.91 \pm 0.37_{\mathrm{stat}} \pm 0.13_{\mathrm{syst}}$ [34], in agreement with the expectations.

DØ has studied $t\bar{t}$ spin correlation [35]. Top quark pairs produced at the Tevatron are expected to be unpolarized but to have correlated spins. Since top quarks decay before hadronizing, their spins are transmitted to their decay daughters. Spin correlation is studied by analyzing the joint decay angular distribution of one t daughter and one $\bar{t}$ daughter. The sensitivity to top spin is greatest when the daughters are charged leptons or d-type quarks, in which case, the joint distribution is

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(cos\theta_+)d(cos\theta_-)} = \frac{1+\kappa cos\theta_+ cos\theta_-}{4}, \qquad (2)$$

where θ_+ and θ_- are the angles of the daughters in the top rest frames with respect to a particular quantization axis, the optimal off-diagonal basis [36]. In this basis, the Standard Model predicts maximum correlation with $\kappa = 0.88$ at the Tevatron. DØ analyzes their six dilepton events and obtains a likelihood as a function of κ which weakly favors the Standard Model ($\kappa = 0.88$) over no correlation ($\kappa = 0$) or anticorrelation ($\kappa = -1$, as would be expected for $t\bar{t}$ produced via an intermediate scalar). They quote a limit $\kappa > -0.25$ at 68% CL. With improved statistics, an observation of $t\bar{t}$ spin correlation could yield a lower limit on $|V_{tb}|$, independent of the assumption of three quark families [37].

Appendix. First Results from run II: Preliminary measurements of the top properties determined from run II data have been reported at several Conferences [1]. First results for the top mass have been shown by CDF. In the lepton plus four jets channel with at least one secondary vertex b-tagged jet CDF obtains a value of $m_t = 177.5^{+12.7}_{-9.4}(stat) \pm 7.1(syst)\,\mathrm{GeV/c^2}$ (22 candidate events). In the dilepton channel, CDF found a preliminary value of $m_t = 175.0^{+17.4}_{-16.9}(stat) \pm 7.9(syst)\,\mathrm{GeV/c^2}$ (6 candidate events). Results for the production cross-section have been given by both experiments, and are collected in Table Table 3. The uncertainties are still rather large when compared to those achieved in run I, and the rates are consistent both with the measurements at lower energy, and with the theoretical predictions [2].

Table 3: Cross section for $t\bar{t}$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV from DØ ($m_t = 172.1$ GeV/c^2), CDF ($m_t = 175$ GeV/c^2), and theory. CSIP refers to a "counted signed-impact-parameter" determination of secondary vertices. The first uncertainty is statistical, the second systematical, and the third uncertainty quoted by DØ reflects the luminosity uncertainty (included in CDF's systematics). Luminosities quoted in pb^{-1}.

$\sigma_{t\bar{t}}(pb)$	Source	Lum.	Method
$8.7\ ^{+6.4}_{-4.7}\ ^{+2.7}_{-2.0} \pm 0.9$	DØ	90–107	$\ell\ell$
$7.4\ ^{+4.4}_{-3.6}\ ^{+2.1}_{-1.6} \pm 0.7$	DØ	45	ℓ+jets, CSIP
$10.8\ ^{+4.9}_{-4.0}\ ^{+2.1}_{-2.0} \pm 1.1$	DØ	45	ℓ+jets/vtx b-tag
$4.6\ ^{+3.1}_{-2.7}\ ^{+2.1}_{-2.0} \pm 0.5$	DØ	92	ℓ+jets/topological
$11.4\ ^{+4.1}_{-3.5}\ ^{+2.0}_{-1.8} \pm 1.1$	DØ	92	ℓ+jets/soft μ b-tag
$8.0\ ^{+2.4}_{-2.1}\ ^{+1.7}_{-1.5} \pm 0.8$	DØ	92	ℓ+jets combined
$8.1\ ^{+2.2}_{-2.0}\ ^{+1.6}_{-1.4} \pm 0.8$	DØ	90–107	Dilepton and ℓ+jets combined
$7.6\ ^{+3.8}_{-3.1}\ ^{+1.5}_{-1.9}$	CDF	126	$\ell\ell$
$7.3 \pm 3.4\ \pm 1.7$	CDF	126	ℓ+track
$5.3 \pm 1.9\ \pm 0.9$	CDF	57	ℓ+jets/vtx b-tag
$5.1 \pm 1.8\ \pm 2.1$	CDF	126	ℓ+jets/H_T
$5.8 - 7.4$	Theory [2]		$m_t = 175$ GeV/c^2

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t-Quark Mass in $p\overline{p}$ Collisions

The t quark has been observed. Its mass is sufficiently high that decay is expected to occur before hadronization. OUR EVALUATION is an AVERAGE which incorporates correlations between systematic errors of the five different measurements. The average was done by a joint CDF/DØ working group and is reported in DEMORTIER 99, an FNAL Technical Memo. They report $174.3 \pm 3.2 \pm 4.0$ GeV, which yields "OUR EVALUATION" when statistical and systematic errors are combined. When the most recent CDF lepton + jets result is combined with the other CDF and DØ results, the combined result given as "OUR EVALUATION" is unchanged from the DEMORTIER 99 result after rounding.

For earlier search limits see the *Review of Particle Physics*, Phys. Rev. **D54**,1 (1996).

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
174.3 ± 5.1 OUR EVALUATION			
176.1 ± 5.1 ± 5.3	[1] AFFOLDER 01	CDF	lepton + jets
167.4 ± 10.3 ± 4.8	[2,3] ABE 99B	CDF	dilepton
168.4 ± 12.3 ± 3.6	[4] ABBOTT 98D	D0	dilepton
173.3 ± 5.6 ± 5.5	[4] ABBOTT 98F	D0	lepton + jets
186 ± 10 ± 5.7	[2,5] ABE 97R	CDF	6 or more jets
• • • We do not use the following data for averages, fits, limits, etc. • • •			
176.1 ± 6.6	[6] AFFOLDER 01	CDF	lepton + jets, dileptons, all-jets
172.1 ± 5.2 ± 4.9	[7] ABBOTT 99G	D0	di-lepton, lepton+jets
176.0 ± 6.5	[3,8] ABE 99B	CDF	dilepton, lepton+jets, and all jets
175.9 ± 4.8 ± 5.3	[2,9] ABE 98E	CDF	lepton + jets
161 ± 17 ± 10	[2] ABE 98F	CDF	dilepton
172.1 ± 5.2 ± 4.9	[10] BHAT 98B	RVUE	dilepton and lepton+jets
173.8 ± 5.0	[11] BHAT 98B	RVUE	dilepton, lepton+jets, and all jets
173.3 ± 5.6 ± 6.2	[4] ABACHI 97E	D0	lepton + jets
$199 \, ^{+19}_{-21} \pm 22$	ABACHI 95	D0	lepton + jets
176 ± 8 ± 10	ABE 95F	CDF	lepton + b-jet
$174 \pm 10 \, ^{+13}_{-12}$	ABE 94E	CDF	lepton + b-jet

[1] AFFOLDER 01 result uses lepton + jets topology. It is based on $\sim 106\ \mathrm{pb}^{-1}$ of data at $\sqrt{s} = 1.8$ TeV.
[2] Result is based on $109 \pm 7\ \mathrm{pb}^{-1}$ of data at $\sqrt{s} = 1.8$ TeV.
[3] See AFFOLDER 01 for details of systematic error re-evaluation.
[4] Result is based on $125 \pm 7\ \mathrm{pb}^{-1}$ of data at $\sqrt{s} = 1.8$ TeV.
[5] ABE 97R result is based on the first observation of all hadronic decays of $t\overline{t}$ pairs. Single b-quark tagging with jet-shape variable constraints was used to select signal enriched multi-jet events. The updated systematic error is listed. See AFFOLDER 01, appendix C.
[6] AFFOLDER 01 is obtained by combining the measurements in the lepton + jets [AFFOLDER 01], all-jets [ABE 97R, ABE 99B], and dilepton [ABE 99B] decay topologies.
[7] ABBOTT 99G result is obtained by combining the D0 result m_t (GeV) $= 168.4 \pm 12.3 \pm 3.6$ from 6 di-lepton events (see also ABBOTT 98D) and m_t (GeV) $= 173.3 \pm 5.6 \pm 5.5$ from lepton+jet events (ABBOTT 98F).
[8] ABE 99B result is obtained by combining the CDF results of m_t (GeV)$=167.4 \pm 10.3 \pm 4.8$ from 8 dilepton events, m_t (GeV)$=175.9 \pm 4.8 \pm 5.3$ from lepton+jet events (ABE 98E), and m_t (GeV)$=186.0 \pm 10.0 \pm 5.7$ from all-jet events (ABE 97R). The systematic errors in the latter two measurements are changed in this paper.
[9] The updated systematic error is listed. See AFFOLDER 01, appendix C.
[10] BHAT 98B result is obtained by combining the DØ results of m_t(GeV)$=168.4 \pm 12.3 \pm 3.6$ from 6 dilepton events and m_t(GeV)$=173.3 \pm 5.6 \pm 5.5$ from 77 lepton+jet events.
[11] BHAT 98B result is obtained by combining the DØ results from dilepton and lepton+jet events, and the CDF results (ABE 99B) from dilepton, lepton+jet events, and all-jet events.

Indirect t-Quark Mass from Standard Model Electroweak Fit

"OUR EVALUATION" below is from the fit to electroweak data described in the "Electroweak Model and Constraints on New Physics" section of this Review. This fit result does not include direct measurements of m_t.

The RVUE values are based on the data described in the footnotes. RVUE's published before 1994 and superseded analyses are now omitted. For more complete listings of earlier results, see the 1994 edition (Physical Review **D50** 1173 (1994)).

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{178.1^{+10.4}_{-\ 8.3}}$ **OUR EVALUATION**			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$162 \pm 15 \, ^{+25}_{-\ 5}$	[12] ABBIENDI 01A	OPAL	Z parameters
170.7 ± 3.8	[13] FIELD 00	RVUE	Z parameters without b-jet + Direct
$171.2^{+\ 3.7}_{-\ 3.8}$	[14] FIELD 99	RVUE	Z parameters without $b$jet + Direct
$172.0^{+\ 5.8}_{-\ 5.7}$	[15] DEBOER 97B	RVUE	Electroweak + Direct
$157 \, ^{+16}_{-12}$	[16] ELLIS 96C	RVUE	Z parameters, m_W, low energy
$175 \pm 11 \, ^{+17}_{-19}$	[17] ERLER 95	RVUE	Z parameters, m_W, low energy
$180 \pm 9^{+19}_{-21} \mp 2.6 \pm 4.8$	[18] MATSUMOTO 95	RVUE	
$157 \, ^{+36}_{-48} \, ^{+19}_{-20}$	[19] ABREU 94	DLPH	Z parameters
$158 \, ^{+32}_{-40} \pm 19$	[20] ACCIARRI 94	L3	Z parameters
$190 \, ^{+39}_{-48} \, ^{+12}_{-14}$	[21] ARROYO 94	CCFR	ν_μ iron scattering
$184 \, ^{+25}_{-29} \, ^{+17}_{-18}$	[22] BUSKULIC 94	ALEP	Z parameters
153 ± 15	[23] ELLIS 94B	RVUE	Electroweak
$177 \pm 9 \, ^{+16}_{-20}$	[24] GURTU 94	RVUE	Electroweak
$174 \, ^{+11}_{-13} \, ^{+17}_{-18}$	[25] MONTAGNA 94	RVUE	Electroweak
$171 \pm 12 \, ^{+15}_{-21}$	[26] NOVIKOV 94B	RVUE	Electroweak
$160 \, ^{+50}_{-60}$	[27] ALITTI 92B	UA2	m_W, m_Z

[12] ABBIENDI 01A result is from fit with free α_s when m_H is fixed to 150 GeV. The second errors are for m_H= 90 GeV (lower) and 1000 GeV (upper). The fit also finds $\alpha_s = 0.125 \pm 0.005^{+0.004}_{-0.001}$.
[13] FIELD 00 result updates FIELD 99 by using the 1998 EW data (CERN-EP/99-15). Only the lepton asymmetry data are used together with the direct measurement constraint m_t=173.8 ± 5.0 GeV, $\alpha_s(m_Z) = 0.12$, and $1/\alpha(m_Z) = 128.896$. The result is from a two parameter fit with free m_t and m_H, yielding also m_H=$38.0^{+30.5}_{-19.8}$ GeV.

[14] FIELD 99 result is from the two-parameter fit with free m_t and m_H, yielding also m_H= $47.2^{+29.8}_{-24.5}$ GeV. Only the lepton and charm-jet asymmetry data are used together with the direct measurement constraint m_t= 173.8 ± 5.0 GeV, and $1/\alpha(m_Z)$= 128.896.

[15] DEBOER 97B result is from the five-parameter fit which varies m_Z, m_t, m_H, α_s, and $\alpha(m_Z)$ under the constraints: m_t=175 ± 6 GeV, $1/\alpha(m_Z)$=128.896 ± 0.09. They found m_H=141^{+140}_{-77} GeV and $\alpha_s(m_Z)$=0.1197 ± 0.0031.

[16] ELLIS 96C result is a the two-parameter fit with free m_t and m_H, yielding also m_H=65^{+117}_{-37} GeV.

[17] ERLER 95 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding $\alpha_s(m_Z)$ = 0.127(5)(2).

[18] MATSUMOTO 95 result is from fit with free m_t to Z parameters, M_W, and low-energy neutral-current data. The second error is for $m_H = 300^{+700}_{-240}$ GeV, the third error is for $\alpha_s(m_Z)$ = 0.116 ± 0.005, the fourth error is for $\delta\alpha_{\rm had}$ = 0.0283 ± 0.0007.

[19] ABREU 94 value is for $\alpha_s(m_Z)$ constrained to 0.123 ± 0.005. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[20] ACCIARRI 94 value is for $\alpha_s(m_Z)$ constrained to 0.124 ± 0.006. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[21] ARROYO 94 measures the ratio of the neutral-current and charged-current deep inelastic scattering of ν_μ on an iron target. By assuming the SM electroweak correction, they obtain $1-m^2_W/m^2_Z$ = 0.2218 ± 0.0059, yielding the quoted m_t value. The second error corresponds to $m_H = 300^{+700}_{-240}$ GeV.

[22] BUSKULIC 94 result is from fit with free α_s. The second error is from m_H=300^{+700}_{-240} GeV.

[23] ELLIS 94B result is fit to electroweak data available in spring 1994, including the 1994 A_{LR} data from SLD. m_t and m_H are two free parameters of the fit for $\alpha_s(m_Z)$ = 0.118 ± 0.007 yielding m_t above, and $m_H = 35^{+70}_{-22}$ GeV. ELLIS 94B also give results for fits including constraints from CDF's direct measurement of m_t and CDF's and DØ 's production cross-section measurements. Fits excluding the A_{LR} data from SLD are also given.

[24] GURTU 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z)$ = 0.125 ± $0.005^{+0.003}_{-0.001}$. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP, M_W, νN, and SLD electroweak data available in spring 1994.

[25] MONTAGNA 94 result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z)$ = 0.124. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Errors in $\alpha(m_Z)$ and m_b are taken into account in the fit. Uses LEP, SLC, and M_W/M_Z data available in spring 1994.

[26] NOVIKOV 94B result is from fit with free m_t and $\alpha_s(m_Z)$, yielding m_t above and $\alpha_s(m_Z)$ = 0.125 ± 0.005 ± 0.002. The second errors correspond to $m_H = 300^{+700}_{-240}$ GeV. Uses LEP and CDF electroweak data available in spring 1994.

[27] ALITTI 92B assume m_H = 100 GeV. The 95%CL limit is m_t < 250 GeV for m_H < 1 TeV.

t DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$W q (q = b, s, d)$			
Γ_2	$W b$			
Γ_3	$\ell \nu_\ell$ anything		[a,b] (9.4±2.4) %	
Γ_4	$\tau \nu_\tau b$			
Γ_5	$\gamma q (q=u,c)$		[c] < 5.9 $\times 10^{-3}$	95%

$\Delta T = 1$ weak neutral current ($T1$) modes

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_6	$Z q (q=u,c)$	$T1$	[d] < 13.7 %	95%

[a] ℓ means e or μ decay mode, not the sum over them.

[b] Assumes lepton universality and W-decay acceptance.

[c] This limit is for $\Gamma(t \to \gamma q)/\Gamma(t \to W b)$.

[d] This limit is for $\Gamma(t \to Z q)/\Gamma(t \to W b)$.

t BRANCHING RATIOS

$\Gamma(W b)/\Gamma(W q (q = b, s, d))$ — Γ_2/Γ_1

VALUE	DOCUMENT ID	TECN
$\mathbf{0.94^{+0.26}_{-0.21}{}^{+0.17}_{-0.12}}$	[28] AFFOLDER 01C	CDF

[28] AFFOLDER 01C measures the top-quark decay width ratio R= $\Gamma(W b)/\Gamma(W q)$, where q is a d, s, or b quark, by using the number of events with multiple b tags. The first error is statistical and the second systematic. A numerical integration of the likelihood function gives R> 0.61 (0.56) at 90% (95%) CL. By assuming three generation unitarity, $|V_{tb}|$= $0.97^{+0.16}_{-0.12}$ or $|V_{tb}|$ > 0.78 (0.75) at 90% (95%) CL is obtained. The result is based on 109 pb^{-1} of data at $\sqrt{s}$= 1.8 TeV.

$\Gamma(\ell \nu_\ell \text{anything})/\Gamma_{\rm total}$ — Γ_3/Γ

VALUE	DOCUMENT ID	TECN
0.094±0.024	[29] ABE 98X	CDF

[29] ℓ means e or μ decay mode, not the sum. Assumes lepton universality and W-decay acceptance.

$\Gamma(\tau \nu_\tau b)/\Gamma_{\rm total}$ — Γ_4/Γ

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[30] ABE 97V	CDF	$\ell\tau$ + jets

[30] ABE 97V searched for $t\bar{t} \to (\ell\nu_\ell)(\tau\nu_\tau) b\bar{b}$ events in 109 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV. They observed 4 candidate events where one expects ∼ 1 signal and ∼ 2 background events. Three of the four observed events have jets identified as b candidates.

$\Gamma(\gamma q (q=u,c))/\Gamma_{\rm total}$ — Γ_5/Γ

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.0059	95	[31] CHEKANOV 03	ZEUS	B($t \to \gamma u$)
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.041	95	[32] ACHARD 02J	L3	B($t \to \gamma c$ or γu)
<0.032	95	[33] ABE 98G	CDF	$t\bar{t} \to (W b)(\gamma c$ or $\gamma u)$

[31] CHEKANOV 03 looked for single top production via FCNC in the reaction $e^\pm p \to e^\pm (t$ or $\bar{t})$ X in 130.1 pb^{-1} of data at $\sqrt{s}$=300–318 GeV. No evidence for top production and its decay into bW was found. The result is obtained for m_t=175 GeV when B(γc)=B(Zq)=0, where q is a u or c quark. Bounds on the effective t-u-γ and t-u-Z couplings are found in their Fig. 4. The conversion to the constraint listed is from private communication, E. Gallo, January 2004.

[32] ACHARD 02J looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 634 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to a bound on the top-quark decay branching fraction B(γq), where q is a u or c quark. The bound assumes B(Zq)=0 and is for m_t= 175 GeV; bounds for m_t=170 GeV and 180 GeV and B(Zq) ≠ 0 are given in Fig. 5 and Table 7.

[33] ABE 98G looked for $t\bar{t}$ events where one t decays into $q\gamma$ while the other decays into bW. The quoted bound is for $\Gamma(\gamma q)/\Gamma(W b)$.

$\Gamma(Z q (q=u,c))/\Gamma_{\rm total}$ — Γ_6/Γ

Test for ΔT=1 weak neutral current. Allowed by higher-order electroweak interaction.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<0.137	95	[34] ACHARD 02J	L3	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.14	95	[35] HEISTER 02Q	ALEP	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.137	95	[36] ABBIENDI 01T	OPAL	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<0.17	95	[37] BARATE 00S	ALEP	$e^+e^- \to \bar{t}c$ or $\bar{t}u$
<0.33	95	[38] ABE 98G	CDF	$t\bar{t} \to (W b)(Z c$ or $Z u)$

[34] ACHARD 02J looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 634 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to a bound on the top-quark decay branching fraction B(Zq), where q is a u or c quark. The bound assumes B(γq)=0 and is for m_t= 175 GeV; bounds for m_t=170 GeV and 180 GeV and B(γq) ≠0 are given in Fig. 5 and Table 7. Table 6 gives constraints on t-c-e-e four-fermi contact interactions.

[35] HEISTER 02Q looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 214 pb^{-1} of data at $\sqrt{s}$= 204–209 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction B(Zq), where q is a u or c quark. The bound assumes B(γq)=0 and is for m_t= 174 GeV. Bounds on the effective t- (c or u)-γ and t- (c or u)- Z couplings are given in their Fig. 2.

[36] ABBIENDI 01T looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 600 pb^{-1} of data at $\sqrt{s}$= 189–209 GeV. No deviation from the SM is found, which leads to bounds on the branching fractions B(Zq) and B(γq), where q is a u or c quark. The result is obtained for m_t= 174 GeV. The upper bound becomes 9.7% (20.6%))) for m_t= 169 (179) GeV. Bounds on the effective t- (c or u)-γ and t- (c or u)-Z couplings are given in their Fig. 4.

[37] BARATE 00S looked for single top production via FCNC in the reaction $e^+e^- \to \bar{t}c$ or $\bar{t}u$ in 411 pb^{-1} of data at c.m. energies between 189 and 202 GeV. No deviation from the SM is found, which leads to a bound on the branching fraction. The bound assumes B(γq)=0. Bounds on the effective t- (c or u)-γ and t- (c or u)-Z couplings are given in their Fig. 4.

[38] ABE 98G looked for $t\bar{t}$ events where one t decays into three jets and the other decays into qZ with $Z \to \ell\ell$. The quoted bound is for $\Gamma(Zq)/\Gamma(W b)$.

t Decay Vertices

VALUE	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
0.91±0.37±0.13	[39] AFFOLDER 00B	CDF	F_0=$W_L/(W_L+W_T)$
0.11±0.15	[39] AFFOLDER 00B	CDF	B($t \to W_+ b$)

[39] AFFOLDER 00B studied the angular distribution of leptonic decays of W bosons in $t \to W b$ events. The ratio F_0 is the fraction of the helicity zero (longitudinal) W bosons in the decaying top quark rest frame. The first error is statistical and the second systematic. B($t \to W_+ b$) is the fraction of positive helicity (right-handed) positive charge W bosons in the top quark decays. It is obtained by assuming the Standard Model value of F_0.

Single t-Quark Production Cross Section in $p\bar{p}$ Collisions

Direct probes of the tbW coupling and possible new physics

VALUE (pb)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
<18	95	[40] ACOSTA 02	CDF	$p\bar{p} \to tb + X$
<13	95	[41] ACOSTA 02	CDF	$p\bar{p} \to tqb + X$
<17	95	[42,43] ABAZOV 01C	D0	$p\bar{p} \to tb + X$
<22	95	[43,44] ABAZOV 01C	D0	$p\bar{p} \to tqb + X$
<39	95	[42] ABBOTT 01B	D0	$p\bar{p} \to tb + X$
<58	95	[44] ABBOTT 01B	D0	$p\bar{p} \to tqb + X$

[40] ACOSTA 02 bounds the cross section for single top-quark production via the s-channel W-exchange process, $q' \overline{q} \rightarrow t \overline{b}$. It is based on $\sim 106\ \text{pb}^{-1}$ of data at $\sqrt{s}$=1.8 TeV.

[41] ACOSTA 02 bounds the cross section for single top-quark production via the t-channel W-exchange process, $q' g \rightarrow q t \overline{b}$. It is based on $\sim 106\ \text{pb}^{-1}$ of data at $\sqrt{s}$=1.8 TeV.

[42] Result bounds the cross section for single top-quark production via the s-channel process $q' \overline{q} \rightarrow W' \rightarrow t b$. It is based on $\sim 90\ \text{pb}^{-1}$ of data at $\sqrt{s}$= 1.8 TeV.

[43] ABAZOV 01C results updates those of ABBOTT 01B by making use of arrays of neural networks to separate signals from backgrounds.

[44] Result bounds the cross section for single top-quark production via the t-channel W-exchange process $q' g \rightarrow q t b$. It is based on $\sim 90\ \text{pb}^{-1}$ of data at $\sqrt{s}$= 1.8 TeV.

t-Quark REFERENCES

CHEKANOV	03	PL B559 153	S. Chekanov *et al.*	(ZEUS Collab.)
ACHARD	02J	PL B549 290	P. Achard *et al.*	(L3 Collab.)
ACOSTA	02	PR D65 091102	D. Acosta *et al.*	(CDF Collab.)
HEISTER	02Q	PL B543 173	A. Heister *et al.*	(ALEPH Collab.)
ABAZOV	01C	PL B517 282	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	01A	EPJ C19 587	G. Abbiendi *et al.*	(OPAL Collab.)
ABBIENDI	01T	PL B521 181	G. Abbiendi *et al.*	(OPAL Collab.)
ABBOTT	01B	PR D63 031101	B. Abbott *et al.*	(D0 Collab.)
AFFOLDER	01	PR D63 032003	T. Affolder *et al.*	(CDF Collab.)
AFFOLDER	01C	PRL 86 3233	T. Affolder *et al.*	(CDF Collab.)
AFFOLDER	00B	PRL 84 216	T. Affolder *et al.*	(CDF Collab.)
BARATE	00S	PL B494 33	S. Barate *et al.*	(ALEPH Collab.)
FIELD	00	PR D61 013010	J.H. Field	
ABBOTT	99G	PR D60 052001	B. Abbott *et al.*	(D0 Collab.)
ABE	99B	PRL 82 271	F. Abe *et al.*	(CDF Collab.)
Also	99G	PRL 82 2808 (erratum)	F. Abe *et al.*	(CDF Collab.)
DEMORTIER	99	FNAL-TM-2084	L. Demortier *et al.*	(CDF/D0 Working Group)
FIELD	99	MPL A14 1815	J.H. Field	
ABBOTT	98D	PRL 80 2063	B. Abbott *et al.*	(D0 Collab.)
ABBOTT	98F	PR D58 052001	B. Abbott *et al.*	(D0 Collab.)
ABE	98E	PRL 80 2767	F. Abe *et al.*	(CDF Collab.)
ABE	98F	PRL 80 2779	F. Abe *et al.*	(CDF Collab.)
ABE	98G	PRL 80 2525	F. Abe *et al.*	(CDF Collab.)
ABE	98X	PRL 80 2773	F. Abe *et al.*	(CDF Collab.)
BHAT	98B	IJMP A13 5113	P.C. Bhat, H.B. Prosper, S.S. Snyder	
ABACHI	97E	PRL 79 1197	S. Abachi *et al.*	(D0 Collab.)
ABE	97R	PRL 79 1992	F. Abe *et al.*	(CDF Collab.)
ABE	97V	PRL 79 3585	F. Abe *et al.*	(CDF Collab.)
DEBOER	97B	ZPHY C75 627	W. de Boer *et al.*	
ELLIS	96C	PL B389 321	J. Ellis, G.L. Fogli, E. Lisi	(CERN, BARI)
ABACHI	95	PRL 74 2632	S. Abachi *et al.*	(D0 Collab.)
ABE	95F	PRL 74 2626	F. Abe *et al.*	(CDF Collab.)
ERLER	95	PR D52 441	J. Erler, P. Langacker	(PENN)
MATSUMOTO	95	MPL A10 2553	S. Matsumoto	(KEK)
ABE	94E	PR D50 2966	F. Abe *et al.*	(CDF Collab.)
Also	94F	PRL 73 225	F. Abe *et al.*	(CDF Collab.)
ABREU	94	NP B418 403	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	94	ZPHY C62 551	M. Acciarri *et al.*	(L3 Collab.)
ARROYO	94	PRL 72 3452	C.G. Arroyo *et al.*	(COLU, CHIC, FNAL+)
BUSKULIC	94	ZPHY C62 539	D. Buskulic *et al.*	(ALEPH Collab.)
ELLIS	94B	PL B333 118	J. Ellis, G.L. Fogli, E. Lisi	(CERN, BARI)
GURTU	94	MPL A9 3301	A. Gurtu	(TATA)
MONTAGNA	94	PL B335 484	G. Montagna *et al.*	(INFN, PAVI, CERN+)
NOVIKOV	94B	MPL A9 2641	V.A. Novikov *et al.*	(GUEL, CERN, ITEP)
PDG	94	PR D50 1173	L. Montanet *et al.*	(CERN, LBL, BOST+)
ALITTI	92B	PL B276 354	J. Alitti *et al.*	(UA2 Collab.)

b' (4^{th} Generation) Quark, Searches for

MASS LIMITS for b' (4^{th} Generation) Quark or Hadron in $p\overline{p}$ Collisions

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>190	95	[1] ACOSTA	03	CDF	quasi-stable b'
>199	95	[2] AFFOLDER	00	CDF	NC: $b' \rightarrow bZ$
>128	95	[3] ABACHI	95F	D0	$\ell\ell$ + jets, ℓ + jets
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>148	95	[4] ABE	98N	CDF	NC: $b' \rightarrow bZ$ +decay vertex
> 96	95	[5] ABACHI	97D	D0	NC: $b' \rightarrow b\gamma$
> 75	95	[6] MUKHOPAD...	93	RVUE	NC: $b' \rightarrow b\ell\ell$
> 85	95	[7] ABE	92	CDF	CC: $\ell\ell$
> 72	95	[8] ABE	90B	CDF	CC: e + μ
> 54	95	[9] AKESSON	90	UA2	CC: e + jets + missing E_T
> 43	95	[10] ALBAJAR	90B	UA1	CC: μ + jets
> 34	95	[11] ALBAJAR	88	UA1	CC: e or μ + jets

[1] ACOSTA 03 looked for long-lived fourth generation quarks in the data sample of 90 pb^{-1} of $\sqrt{s}$=1.8 TeV $p\overline{p}$ collisions by using the muon-like penetration and anomalously high ionization energy loss signature. The corresponding lower mass bound for the charge (2/3)e quark (t') is 220 GeV. The t' bound is higher than the b' bound because t' is more likely to produce charged hadrons than b'. The 95% CL upper bounds for the production cross sections are given in their Fig. 3.

[2] AFFOLDER 00 looked for b' that decays in to b+Z. The signal searched for is $bbZZ$ events where one Z decays into e^+e^- or $\mu^+\mu^-$ and the other Z decays hadronically. The bound assumes B($b' \rightarrow bZ$)= 100%. Between 100 GeV and 199 GeV, the 95%CL upper bound on $\sigma(b' \rightarrow \overline{b}')\times$B^2($b' \rightarrow bZ$) is also given (see their Fig. 2).

[3] ABACHI 95F bound on the top-quark also applies to b' and t' quarks that decay predominantly into W. See FROGGATT 97.

[4] ABE 98N looked for $Z \rightarrow e^+e^-$ decays with displaced vertices. Quoted limit assumes B($b' \rightarrow bZ$)=1 and $c\tau_{b'}$=1 cm. The limit is lower than m_Z+m_b ($\sim$ 96 GeV) if $c\tau$> 22 cm or $c\tau$< 0.009 cm. See their Fig. 4.

[5] ABACHI 97D searched for b' that decays mainly via FCNC. They obtained 95%CL upper bounds on B($b'\overline{b}' \rightarrow \gamma$+ 3 jets) and B($b'\overline{b}' \rightarrow 2\gamma$+ 2 jets), which can be interpreted as the lower mass bound $m_{b'}$ >m_Z+m_b.

[6] MUKHOPADHYAYA 93 analyze CDF dilepton data of ABE 92G in terms of a new quark decaying via flavor-changing neutral current. The above limit assumes B($b' \rightarrow b\ell^+\ell^-$)=1%. For an exotic quark decaying only via virtual Z [B($b\ell^+\ell^-$) = 3%], the limit is 85 GeV.

[7] ABE 92 dilepton analysis limit of >85 GeV at CL=95% also applies to b' quarks, as discussed in ABE 90B.

[8] ABE 90B exclude the region 28–72 GeV.

[9] AKESSON 90 searched for events having an electron with p_T > 12 GeV, missing momentum > 15 GeV, and a jet with E_T > 10 GeV, $|\eta|$ < 2.2, and excluded $m_{b'}$ between 30 and 69 GeV.

[10] For the reduction of the limit due to non-charged-current decay modes, see Fig. 19 of ALBAJAR 90B.

[11] ALBAJAR 88 study events at E_{cm} = 546 and 630 GeV with a muon or isolated electron, accompanied by one or more jets and find agreement with Monte Carlo predictions for the production of charm and bottom, without the need for a new quark. The lower mass limit is obtained by using a conservative estimate for the $b'\overline{b}'$ production cross section and by assuming that it cannot be produced in W decays. The value quoted here is revised using the full $O(\alpha_s^3)$ cross section of ALTARELLI 88.

MASS LIMITS for b' (4^{th} Generation) Quark or Hadron in e^+e^- Collisions

Search for hadrons containing a fourth-generation $-1/3$ quark denoted b'.

The last column specifies the assumption for the decay mode (CC denotes the conventional charged-current decay) and the event signature which is looked for.

VALUE (GeV)	CL%	DOCUMENT ID		TECN	COMMENT
>46.0	95	[12] DECAMP	90F	ALEP	any decay
• • • We do not use the following data for averages, fits, limits, etc. • • •					
		[13] ADRIANI	93G	L3	Quarkonium
>44.7	95	ADRIANI	93M	L3	$\Gamma(Z)$
>45	95	ABREU	91F	DLPH	$\Gamma(Z)$
none 19.4–28.2	95	ABE	90D	VNS	Any decay; event shape
>45.0	95	ABREU	90D	DLPH	B(CC) = 1; event shape
>44.5	95	[14] ABREU	90D	DLPH	$b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$, $\tau^-\nu$
>40.5	95	[15] ABREU	90D	DLPH	$\Gamma(Z \rightarrow$ hadrons)
>28.3	95	ADACHI	90	TOPZ	B(FCNC)=100%; isol. γ or 4 jets
>41.4	95	[16] AKRAWY	90B	OPAL	Any decay; acoplanarity
>45.2	95	[16] AKRAWY	90B	OPAL	B(CC) = 1; acoplanarity
>46	95	[17] AKRAWY	90J	OPAL	$b' \rightarrow \gamma$ + any
>27.5	95	[18] ABE	89E	VNS	B(CC) =1; μ, e
none 11.4–27.3	95	[19] ABE	89G	VNS	B($b' \rightarrow b\gamma$) > 10%; isolated γ
>44.7	95	[20] ABRAMS	89C	MRK2	B(CC)= 100%; isol. track
>42.7	95	[20] ABRAMS	89C	MRK2	B(bg)= 100%; event shape
>42.0	95	[20] ABRAMS	89C	MRK2	Any decay; event shape
>28.4	95	[21,22] ADACHI	89C	TOPZ	B(CC) =1; μ
>28.8	95	[23] ENO	89	AMY	B(CC) $\gtrsim$ 90%; μ, e
>27.2	95	[23,24] ENO	89	AMY	any decay; event shape
>29.0	95	[23] ENO	89	AMY	B($b' \rightarrow bg$) $\gtrsim$ 85%; event shape
>24.4	95	[25] IGARASHI	88	AMY	μ,e
>23.8	95	[26] SAGAWA	88	AMY	event shape
>22.7	95	[27] ADEVA	86	MRKJ	μ
>21		[28] ALTHOFF	84C	TASS	R, event shape
>19		[29] ALTHOFF	84I	TASS	Aplanarity

[12] DECAMP 90F looked for isolated charged particles, for isolated photons, and for four-jet final states. The modes $b' \rightarrow bg$ for B($b' \rightarrow bg$) > 65% $b' \rightarrow b\gamma$ for B($b' \rightarrow b\gamma$) > 5% are excluded. Charged Higgs decay were not discussed.

[13] ADRIANI 93G search for vector quarkonium states near Z and give limit on quarkonium-Z mixing parameter δm^2 <(10–30) GeV^2 (95%CL) for the mass 88–94.5 GeV. Using Richardson potential, a 1S ($b'\overline{b}'$) state is excluded for the mass range 87.7–94.7 GeV. This range depends on the potential choice.

[14] ABREU 90D assumed m_{H^-} < $m_{b'}$ − 3 GeV.

[15] Superseded by ABREU 91F.

[16] AKRAWY 90B search was restricted to data near the Z peak at E_{cm} = 91.26 GeV at LEP. The excluded region is between 23.6 and 41.4 GeV if no H^+ decays exist. For charged Higgs decays the excluded regions are between (m_{H^+} + 1.5 GeV) and 45.5 GeV.

[17] AKRAWY 90J search for isolated photons in hadronic Z decay and derive B($Z \rightarrow b'\overline{b}'$)·B($b' \rightarrow \gamma$X)/B($Z \rightarrow$ hadrons) < 2.2×10^{-3}. Mass limit assumes B($b' \rightarrow \gamma$X) > 10%.

[18] ABE 89E search at E_{cm} = 56–57 GeV at TRISTAN for multihadron events with a spherical shape (using thrust and acoplanarity) or containing isolated leptons.

[19] ABE 89G search was at E_{cm} = 55–60.8 GeV at TRISTAN.

[20] If the photonic decay mode is large (B($b' \rightarrow b\gamma$) > 25%), the ABRAMS 89C limit is 45.4 GeV. The limit for for Higgs decay ($b' \rightarrow cH^-$, $H^- \rightarrow \overline{c}s$) is 45.2 GeV.

[21] ADACHI 89C search was at E_{cm} = 56.5–60.8 GeV at TRISTAN using multi-hadron events accompanying muons.

[22] ADACHI 89C also gives limits for any mixture of CC and bg decays.

[23] ENO 89 search at E_{cm} = 50–60.8 at TRISTAN.

[24] ENO 89 considers arbitrary mixture of the charged current, bg, and $b\gamma$ decays.

[25] IGARASHI 88 searches for leptons in low-thrust events and gives $\Delta R(b')$ < 0.26 (95% CL) assuming charged current decay, which translates to $m_{b'}$ > 24.4 GeV.

[26] SAGAWA 88 set limit σ(top) < 6.1 pb at CL=95% for top-flavored hadron production from event shape analyses at E_{cm} = 52 GeV. By using the quark parton model cross-section formula near threshold, the above limit leads to lower mass bounds of 23.8 GeV for charge $-1/3$ quarks.

[27] ADEVA 86 give 95%CL upper bound on an excess of the normalized cross section, ΔR, as a function of the minimum c.m. energy (see their figure 3). Production of a pair of 1/3 charge quarks is excluded up to $E_{cm} = 45.4$ GeV.
[28] ALTHOFF 84C narrow state search sets limit $\Gamma(e^+ e^-)$B(hadrons) <2.4 keV CL = 95% and heavy charge 1/3 quark pair production m >21 GeV, CL = 95%.
[29] ALTHOFF 84I exclude heavy quark pair production for 7 $<m<$19 GeV (1/3 charge) using aplanarity distributions (CL = 95%).

REFERENCES FOR Searches for (Fourth Generation) b' Quark

ACOSTA	03	PRL 90 131801	D. Acosta *et al.*	(CDF Collab.)
AFFOLDER	00	PRL 84 835	A. Affolder *et al.*	(CDF Collab.)
ABE	98N	PR D58 051102	F. Abe *et al.*	(CDF Collab.)
ABACHI	97D	PRL 78 3818	S. Abachi *et al.*	(D0 Collab.)
FROGGATT	97	ZPHY C73 333	C.D. Froggatt, D.J. Smith, H.B. Nielsen	(GLAS+)
ABACHI	95F	PR D52 4877	S. Abachi *et al.*	(D0 Collab.)
ADRIANI	93G	PL B313 326	O. Adriani *et al.*	(L3 Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani *et al.*	(L3 Collab.)
MUKHOPAD...	93	PR D48 2105	B. Mukhopadhyaya, D.P. Roy	(TATA)
ABE	92	PRL 68 447	F. Abe *et al.*	(CDF Collab.)
Also	92G	PR D45 3921	F. Abe *et al.*	(CDF Collab.)
ABE	92G	PR D45 3921	F. Abe *et al.*	(CDF Collab.)
ABREU	91F	NP B367 511	P. Abreu *et al.*	(DELPHI Collab.)
ABE	90B	PRL 64 147	F. Abe *et al.*	(CDF Collab.)
ABE	90D	PL B234 382	K. Abe *et al.*	(VENUS Collab.)
ABREU	90D	PL B242 536	P. Abreu *et al.*	(DELPHI Collab.)
ADACHI	90	PL B234 197	I. Adachi *et al.*	(TOPAZ Collab.)
AKESSON	90	ZPHY C46 179	T. Akesson *et al.*	(UA2 Collab.)
AKRAWY	90B	PL B236 364	M.Z. Akrawy *et al.*	(OPAL Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy *et al.*	(OPAL Collab.)
ALBAJAR	90B	ZPHY C48 1	C. Albajar *et al.*	(UA1 Collab.)
DECAMP	90F	PL B236 511	D. Decamp *et al.*	(ALEPH Collab.)
ABE	89E	PR D39 3524	K. Abe *et al.*	(VENUS Collab.)
ABE	89G	PRL 63 1776	K. Abe *et al.*	(VENUS Collab.)
ABRAMS	89C	PRL 63 2447	G.S. Abrams *et al.*	(Mark II Collab.)
ADACHI	89C	PL B229 427	I. Adachi *et al.*	(TOPAZ Collab.)
ENO	89	PRL 63 1910	S. Eno *et al.*	(AMY Collab.)
ALBAJAR	88	ZPHY C37 505	C. Albajar *et al.*	(UA1 Collab.)
ALTARELLI	88	NP B308 724	G. Altarelli *et al.*	(CERN, ROMA, ETH)
IGARASHI	88	PRL 60 2359	S. Igarashi *et al.*	(AMY Collab.)
SAGAWA	88	PRL 60 93	H. Sagawa *et al.*	(AMY Collab.)
ADEVA	86	PR D34 681	B. Adeva *et al.*	(Mark-J Collab.)
ALTHOFF	84C	PL 138B 441	M. Althoff *et al.*	(TASSO Collab.)
ALTHOFF	84I	ZPHY C22 307	M. Althoff *et al.*	(TASSO Collab.)

Free Quark Searches

FREE QUARK SEARCHES

The basis for much of the theory of particle scattering and hadron spectroscopy is the construction of the hadrons from a set of fractionally charged constituents (quarks). A central but unproven hypothesis of this theory, Quantum Chromodynamics, is that quarks cannot be observed as free particles but are confined to mesons and baryons.

Experiments show that it is at best difficult to "unglue" quarks. Accelerator searches at increasing energies have produced no evidence for free quarks, while only a few cosmic-ray and matter searches have produced uncorroborated events.

This compilation is only a guide to the literature, since the quoted experimental limits are often only indicative. Reviews can be found in Refs. 1–3.

References

1. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
2. L. Lyons, Phys. Reports **129**, 225 (1985).
3. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).

Quark Production Cross Section — Accelerator Searches

X-SECT (cm^2)	CHG ($e/3$)	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<1.3E−36	±2	45–84	130–172	$e^+ e^-$	0	ABREU	97D	DLPH
<2.E−35	+2	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
<1.E−35	+4	250	1800	$p\overline{p}$	0	[1] ABE	92J	CDF
<3.8E−28			14.5A	^{28}Si–Pb	0	[2] HE	91	PLAS
<3.2E−28			14.5A	^{28}Si–Cu	0	[2] HE	91	PLAS
<1.E−40	±1,2	<10		$p,\nu,\overline{\nu}$	0	BERGSMA	84B	CHRM
<1.E−36	±1,2	<9	200	μ	0	AUBERT	83C	SPEC
<2.E−10	±2,4	1–3	200	p	0	[3] BUSSIERE	80	CNTR
<5.E−38	+1,2	>5	300	p	0	[4,5] STEVENSON	79	CNTR
<1.E−33	±1	<20	52	$p p$	0	BASILE	78	SPEC
<9.E−39	±1,2	<6	400	p	0	[4] ANTREASYAN	77	SPEC
<8.E−35	+1,2	<20	52	$p p$	0	[6] FABJAN	75	CNTR
<5.E−38	−1,2	4–9	200	p	0	NASH	74	CNTR
<1.E−32	+2,4	4–24	52	$p p$	0	ALPER	73	SPEC
<5.E−31	+1,2,4	<12	300	p	0	LEIPUNER	73	CNTR
<6.E−34	±1,2	<13	52	$p p$	0	BOTT	72	CNTR
<1.E−36	−4	4	70	p	0	ANTIPOV	71	CNTR
<1.E−35	±1,2	2	28	p	0	[7] ALLABY	69B	CNTR
<4.E−37	−2	<5	70	p	0	[3] ANTIPOV	69	CNTR
<3.E−37	−1,2	2–5	70	p	0	[7] ANTIPOV	69B	CNTR
<1.E−35	+1,2	<7	30	p	0	DORFAN	65	CNTR
<2.E−35	−2	< 2.5–5	30	p	0	[8] FRANZINI	65B	CNTR
<5.E−35	+1,2	<2.2	21	p	0	BINGHAM	64	HLBC
<1.E−32	+1,2	<4.0	28	p	0	BLUM	64	HBC
<1.E−35	+1,2	<2.5	31	p	0	[8] HAGOPIAN	64	HBC
<1.E−34	+1	<2	28	p	0	LEIPUNER	64	CNTR
<1.E−33	+1,2	<2.4	24	p	0	MORRISON	64	HBC

[1] ABE 92J flux limits decrease as the mass increases from 50 to 500 GeV.
[2] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3.
[3] Hadronic or leptonic quarks.
[4] Cross section cm^2/GeV^2.
[5] 3×10^{-5} <lifetime $< 1 \times 10^{-3}$ s.
[6] Includes BOTT 72 results.
[7] Assumes isotropic cm production.
[8] Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X-SECT ($cm^2 sr^{-1} GeV^{-1}$)	CHG $e/3$	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<4.E−36	−2,4	1.5–6	70	p	0	BALDIN	76	CNTR
<2.E−33	±4	5–20	52	$p p$	0	ALBROW	75	SPEC
<5.E−34	<7	7–15	44	$p p$	0	JOVANOV...	75	CNTR
<5.E−35			20	γ	0	[9] GALIK	74	CNTR
<9.E−35	−1,2		200	p	0	NASH	74	CNTR
<4.E−36	−4	2.3–2.7	70	p	0	ANTIPOV	71	CNTR
<3.E−35	±1,2	<2.7	27	p	0	ALLABY	69B	CNTR
<7.E−38	−1,2	<2.5	70	p	0	ANTIPOV	69B	CNTR

[9] Cross section in cm^2/sr/equivalent quanta.

Quark Flux — Accelerator Searches

The definition of FLUX depends on the experiment

(a) is the ratio of measured free quarks to predicted free quarks if there is no "confinement."
(b) is the probability of fractional charge on nuclear fragments. Energy is in GeV/nucleon.
(c) is the 90%CL upper limit on fractionally-charged particles produced per interaction.
(d) is quarks per collision.
(e) is inclusive quark-production cross-section ratio to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$.
(f) is quark flux per charged particle.
(g) is the flux per ν-event.
(h) is quark yield per π^- yield.
(i) is 2-body exclusive quark-production cross-section ratio to $\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$.

FLUX		CHG ($e/3$)	MASS (GeV)	ENRGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<1.6E−3	b	see note		200	^{32}S–Pb	0	[10] HUENTRUP	96	PLAS
<6.2E−4	b	see note		10.6	^{32}S–Pb	0	[10] HUENTRUP	96	PLAS
<0.94E−4	e	±2	2–30	88–94	$e^+ e^-$	0	AKERS	95R	OPAL
<1.7E−4	e	±2	30–40	88–94	$e^+ e^-$	0	AKERS	95R	OPAL
<3.6E−4	e	±4	5–30	88–94	$e^+ e^-$	0	AKERS	95R	OPAL
<1.9E−4	e	±4	30–45	88–94	$e^+ e^-$	0	AKERS	95R	OPAL
<2.E−3	e	+1	5–40	88–94	$e^+ e^-$	0	[11] BUSKULIC	93C	ALEP
<6.E−4	e	+2	5–30	88–94	$e^+ e^-$	0	[11] BUSKULIC	93C	ALEP
<1.2E−3	e	+4	15–40	88–94	$e^+ e^-$	0	[11] BUSKULIC	93C	ALEP
<3.6E−4	i	+4	5.0–10.2	88–94	$e^+ e^-$	0	BUSKULIC	93C	ALEP
<3.6E−4	i	+4	16.5–26.0	88–94	$e^+ e^-$	0	BUSKULIC	93C	ALEP
<6.9E−4	i	+4	26.0–33.3	88–94	$e^+ e^-$	0	BUSKULIC	93C	ALEP
<9.1E−4	i	+4	33.3–38.6	88–94	$e^+ e^-$	0	BUSKULIC	93C	ALEP
<1.1E−3	i	+4	38.6–44.9	88–94	$e^+ e^-$	0	BUSKULIC	93C	ALEP
<1.6E−4	b	see note		see note		0	[12] CECCHINI	93	PLAS
	b	4,5,7,8		2.1A	^{16}O	0,2,0,6	[13] GHOSH	92	EMUL
<6.4E−5	g	1			$\nu,\overline{\nu}$	1	[14] BASILE	91	CNTR
<3.7E−5	g	2			$\nu,\overline{\nu}$	0	[14] BASILE	91	CNTR
<3.9E−5	g	1			$\nu,\overline{\nu}$	1	[15] BASILE	91	CNTR
<2.8E−5	g	2			$\nu,\overline{\nu}$	0	[15] BASILE	91	CNTR
<1.9E−4	c			14.5A	^{28}Si–Pb	0	[16] HE	91	PLAS
<3.9E−4	c			14.5A	^{28}Si–Cu	0	[16] HE	91	PLAS
<1.E−9	c	±1,2,4		14.5A	^{16}O–Ar	0	MATIS	91	MDRP
<5.1E−10	c	±1,2,4		14.5A	^{16}O–Hg	0	MATIS	91	MDRP
<8.1E−9	c	±1,2,4		14.5A	Si–Hg	0	MATIS	91	MDRP
<1.7E−6	c	±1,2,4		60A	^{16}O–Hg	0	MATIS	91	MDRP
<3.5E−7	c	±1,2,4		200A	^{16}O–Hg	0	MATIS	91	MDRP
<1.3E−6	c	±1,2,4		200A	S–Hg	0	MATIS	91	MDRP
<5E−2	e	2	19–27	52–60	$e^+ e^-$	0	ADACHI	90C	TOPZ
<5E−2	e	4	<24	52–60	$e^+ e^-$	0	ADACHI	90C	TOPZ

<1.E−4	e	+2	<3.5	10	e^+e^-	0	BOWCOCK 89B	CLEO
<1.E−6	d	±1,2		60	^{16}O–Hg	0	CALLOWAY 89	MDRP
<3.5E−7	d	±1,2		200	^{16}O–Hg	0	CALLOWAY 89	MDRP
<1.3E−6	d	±1,2		200	S–Hg	0	CALLOWAY 89	MDRP
<1.2E−10	d	±1	1	800	p–Hg	0	MATIS 89	MDRP
<1.1E−10	d	±2	1	800	p–Hg	0	MATIS 89	MDRP
<1.2E−10	d	±1	1	800	p–N_2	0	MATIS 89	MDRP
<7.7E−11	d	±2	1	800	p–N_2	0	MATIS 89	MDRP
<6.E−9	h	−5	0.9–2.3	12	p	0	NAKAMURA 89	SPEC
<5.E−5	g	1,2	<0.5		$\nu,\overline{\nu}d$	0	ALLASIA 88	BEBC
<3.E−4	b	See note		14.5	^{16}O–Pb	0	[17] HOFFMANN 88	PLAS
<2.E−4	b	See note		200	^{16}O–Pb	0	[18] HOFFMANN 88	PLAS
<8E−5	b	19,20,22,23		200A			GERBIER 87	PLAS
<2.E−4	a	±1,2	<300	320	$\overline{p}p$	0	LYONS 87	MLEV
<1.E−9	c	±1,2,4,5		14.5	^{16}O–Hg	0	SHAW 87	MDRP
<3.E−3	d	−1,2,3,4,6	<5	2	Si–Si	0	[19] ABACHI 86C	CNTR
<1.E−4	e	±1,2,4	<4	10	e^+e^-	0	ALBRECHT 85G	ARG
<6.E−5	b	±1,2	1	540	$p\overline{p}$	0	BANNER 85	UA2
<5.E−3	e	−4	1–8	29	e^+e^-	0	AIHARA 84	TPC
<1.E−2	e	±1,2	1–13	29	e^+e^-	0	AIHARA 84B	TPC
<2.E−4	b	±1		72	^{40}Ar	0	[20] BARWICK 84	CNTR
<1.E−4	e	±2	<0.4	1.4	e^+e^-	0	BONDAR 84	OLYA
<5.E−1	e	±1,2	<13	29	e^+e^-	0	GURYN 84	CNTR
<3.E−3	b	±1,2	<2	540	$p\overline{p}$	0	BANNER 83	CNTR
<1.E−4	b	±1,2		106	^{56}Fe	0	LINDGREN 83	CNTR
<3.E−3	b	$>\lvert\pm 0.1\rvert$		74	^{40}Ar	0	[20] PRICE 83	PLAS
<1.E−2	e	±1,2	<14	29	e^+e^-	0	MARINI 82B	CNTR
<8.E−2	e	±1,2	<12	29	e^+e^-	0	ROSS 82	CNTR
<3.E−4	e	±2	1.8–2	7	e^+e^-	0	WEISS 81	MRK2
<5.E−2	e	+1,2,4,5	2–12	27	e^+e^-	0	BARTEL 80	JADE
<2.E−5	g	1,2			ν	0	[14,15] BASILE 80	CNTR
<3.E−10	f	±2,4	1–3	200	p	0	[21] BOZZOLI 79	CNTR
<6.E−11	f	±1	<21	52	pp	0	BASILE 78	SPEC
<5.E−3	g				ν_μ	0	BASILE 78B	CNTR
<2.E−9	f	±1	<26	62	pp	0	BASILE 77	SPEC
<7.E−10	f	+1,2	<20	52	p	0	[22] FABJAN 75	CNTR
		+1,2	>4.5		γ	0	[14,15] GALIK 74	CNTR
		+1,2	>1.5	12	e^-	0	[14,15] BELLAMY 68	CNTR
		+1,2	>0.9		γ	0	[15] BATHOW 67	CNTR
		+1,2	>0.9	6	γ	0	[15] FOSS 67	CNTR

[10] HUENTRUP 96 quote 95% CL limits for production of fragments with charge differing by as much as ±1/3 (in units of e) for charge $6 \le Z \le 10$.

[11] BUSKULIC 93C limits for inclusive quark production are more conservative if the ALEPH hadronic fragmentation function is assumed.

[12] CECCHINI 93 limit at 90%CL for $23/3 \le Z \le 40/3$, for 16A GeV O, 14.5A Si, and 200A S incident on Cu target. Other limits are 2.3×10^{-4} for $17/3 \le Z \le 20/3$ and 1.2×10^{-4} for $20/3 \le Z \le 23/3$.

[13] GHOSH 92 reports measurement of spallation fragment charge based on ionization in emulsion. Out of 650 measured tracks, 2 were consistent with charge $5e/3$, and 4 with $7e/3$.

[14] Hadronic quark.

[15] Leptonic quark.

[16] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3, and correspond to cross-section limits of 380μb (Pb) and 320μb (Cu).

[17] The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of $e/3$.

[18] The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of $e/3$.

[19] Flux limits and mass range depend on charge.

[20] Bound to nuclei.

[21] Quark lifetimes $> 1 \times 10^{-8}$ s.

[22] One candidate m <0.17 GeV.

Quark Flux — Cosmic Ray Searches

Shielding values followed with an asterisk indicate altitude in km. Shielding values not followed with an asterisk indicate sea level in kg/cm^2.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	CHG ($e/3$)	MASS (GeV)	SHIELDING	EVTS	DOCUMENT ID	TECN
< 9.2E−15	±1		3800	0	[23] AMBROSIO 00C	MCRO
<2.1E−15	±1			0	MORI 91	KAM2
<2.3E−15	±2			0	MORI 91	KAM2
<2.E−10	±1,2		0.3	0	WADA 88	CNTR
	±4		0.3	12	[24] WADA 88	CNTR
	±4		0.3	9	[25] WADA 86	CNTR
<1.E−12	±2,3/2		−70.	0	[26] KAWAGOE 84B	PLAS
<9.E−10	±1,2		0.3	0	WADA 84B	CNTR
<4.E−9	±4		0.3	7	WADA 84B	CNTR
<2.E−12	±1,2,3		−0.3 *	0	MASHIMO 83	CNTR
<3.E−10	±1,2		0.3	0	MARINI 82	CNTR
<2.E−11	±1,2			0	MASHIMO 82	CNTR
<8.E−10	±1,2		0.3	0	[26] NAPOLITANO 82	CNTR
				3	[27] YOCK 78	CNTR
<1.E−9				0	[28] BRIATORE 76	ELEC
<2.E−11	+1			0	[29] HAZEN 75	CC
<2.E−10	+1,2			0	KRISOR 75	CNTR
<1.E−7	+1,2			0	[29,30] CLARK 74B	CC
<3.E−10	+1	>20		0	KIFUNE 74	CNTR
<8.E−11	+1			0	[29] ASHTON 73	CNTR
<2.E−8	+1,2			0	HICKS 73B	CNTR
<5.E−10	+4		2.8 *	0	BEAUCHAMP 72	CNTR
<1.E−10	+1,2			0	[29] BOHM 72B	CNTR
<1.E−10	+1,2		2.8 *	0	COX 72	ELEC
<3.E−10	+2			0	CROUCH 72	CNTR
<3.E−8			7	0	[28] DARDO 72	CNTR
<4.E−9	+1			0	[29] EVANS 72	CC
<2.E−9		>10		0	[28] TONWAR 72	CNTR
<2.E−10	+1		2.8 *	0	CHIN 71	CNTR
<3.E−10	+1,2			0	[29] CLARK 71B	CC
<1.E−10	+1,2			0	[29] HAZEN 71	CC
<5.E−10	+1,2		3.5 *	0	BOSIA 70	CNTR
	+1,2	<6.5		1	[29] CHU 70	HLBC
<2.E−9	+1			0	FAISSNER 70B	CNTR
<2.E−10	+1,2		0.8 *	0	KRIDER 70	CNTR
<5.E−11	+2			4	CAIRNS 69	CC
<8.E−10	+1,2	<10		0	FUKUSHIMA 69	CNTR
	+2			1	[29,31] MCCUSKER 69	CC
<1.E−10		>5	1.7,3.6	0	[28] BJORNBOE 68	CNTR
<1.E−8	±1,2,4		6.3,.2 *	0	[26] BRIATORE 68	CNTR
<3.E−8		>2		0	FRANZINI 68	CNTR
<9.E−11	±1,2			0	GARMIRE 68	CNTR
<4.E−10	±1			0	HANAYAMA 68	CNTR
<3.E−8		>15		0	KASHA 68	OSPK
<2.E−10	+2			0	KASHA 68B	CNTR
<2.E−10	+4			0	KASHA 68C	CNTR
<2.E−10	+2		6	0	BARTON 67	CNTR
<2.E−7	+4		0.008,0.5 *	0	BUHLER 67	CNTR
<5.E−10	1,2		0.008,0.5 *	0	BUHLER 67B	CNTR
<4.E−10	+1,2			0	GOMEZ 67	CNTR
<2.E−9	+2			0	KASHA 67	CNTR
<2.E−10	+2		220	0	BARTON 66	CNTR
<2.E−9	+1,2		0.5 *	0	BUHLER 66	CNTR
<3.E−9	+1,2			0	KASHA 66	CNTR
<2.E−9	+1,2			0	LAMB 66	CNTR
<2.E−8	+1,2	>7	2.8 *	0	DELISE 65	CNTR
<5.E−8	+2	>2.5	0.5 *	0	MASSAM 65	CNTR
<2.E−8	+1		2.5 *	0	BOWEN 64	CNTR
<2.E−7	+1		0.8	0	SUNYAR 64	CNTR

[23] AMBROSIO 00C limit is below 11×10^{-15} for $0.25 < q/e < 0.5$, and is changing rapidly near q/e=2/3, where it is 2×10^{-14}.

[24] Distribution in celestial sphere was described as anisotropic.

[25] With telescope axis at zenith angle 40° to the south.

[26] Leptonic quarks.

[27] Lifetime $> 10^{-8}$ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.

[28] Time delayed air shower search.

[29] Prompt air shower search.

[30] Also $e/4$ and $e/6$ charges.

[31] No events in subsequent experiments.

Quark Density — Matter Searches

For a review, see SMITH 89.

QUARKS/ NUCLEON	CHG ($e/3$)	MASS (GeV)	MATERIAL/METHOD	EVTS	DOCUMENT ID
<4.7E−21	±1,2		silicone oil drops	0	MAR 96
<8.E−22	+2		Si/infrared photoionization	0	PERERA 93
<5.E−27	±1,2		sea water/levitation	0	HOMER 92
<4.E−20	±1,2		meteorites/mag. levitation	0	JONES 89
<1.E−19	±1,2		various/spectrometer	0	MILNER 87
<5.E−22	±1,2		W/levitation	0	SMITH 87
<3.E−20	+1,2		org liq/droplet tower	0	VANPOLEN 87
<6.E−20	−1,2		org liq/droplet tower	0	VANPOLEN 87
<3.E−21	±1		Hg drops-untreated	0	SAVAGE 86
<3.E−22	±1,2		levitated niobium	0	SMITH 86
<2.E−26	±1,2		^{4}He/levitation	0	SMITH 86B
<2.E−20	>±1	0.2–250	niobium+tungs/ion	0	MILNER 85
<1.E−21	±1		levitated niobium	0	SMITH 85
	+1,2	<100	niobium/mass spec	0	KUTSCHERA 84
<5.E−22			levitated steel	0	MARINELLI 84
<9.E−20	± <13		water/oil drop	0	JOYCE 83
<2.E−21	$>\lvert\pm 1/2\rvert$		levitated steel	0	LIEBOWITZ 83
<1.E−19	±1,2		photo ion spec	0	VANDESTEEG 83
<2.E−20			mercury/oil drop	0	[32] HODGES 81
1.E−20	+1		levitated niobium	4	[33] LARUE 81
1.E−20	−1		levitated niobium	4	[33] LARUE 81
<1.E−21			levitated steel	0	MARINELLI 80B
<6.E−16			helium/mass spec	0	BOYD 79
1.E−20	+1		levitated niobium	2	[33] LARUE 79
<4.E−28			earth+/ion beam	0	OGOROD... 79
<5.E−15	+1		tungs./mass spec	0	BOYD 78
<5.E−16	+3	<1.7	hydrogen/mass spec	0	BOYD 78B
<1.E−21	±2,4		water/ion beam	0	LUND 78
<6.E−15	>1/2		levitated tungsten	0	PUTT 78
<1.E−22			metals/mass spec	0	SCHIFFER 78
<5.E−15			levitated tungsten ox	0	BLAND 77
<3.E−21			levitated iron	0	GALLINARO 77

2.E−21	−1		levitated niobium	1	[33] LARUE	77
4.E−21	+1		levitated niobium	2	[33] LARUE	77
<1.E−13	+3	<7.7	hydrogen/mass spec	0	MULLER	77
<5.E−27			water+/ion beam	0	OGOROD...	77
<1.E−21			lunar+/ion spec	0	STEVENS	76
<1.E−15	+1	<60	oxygen+/ion spec	0	ELBERT	70
<5.E−19			levitated graphite	0	MORPURGO	70
<5.E−23			water+/atom beam	0	COOK	69
<1.E−17	±1,2		levitated graphite	0	BRAGINSK	68
<1.E−17			water+/uv spec	0	RANK	68
<3.E−19	±1		levitated iron	0	STOVER	67
<1.E−10			sun/uv spec	0	[34] BENNETT	66
<1.E−17	+1,2		meteorites+/ion beam	0	CHUPKA	66
<1.E−16	±1		levitated graphite	0	GALLINARO	66
<1.E−22			argon/electrometer	0	HILLAS	59
	−2		levitated oil	0	MILLIKAN	10

[32] Also set limits for $Q = \pm e/6$.
[33] Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.
[34] Limit inferred by JONES 77B.

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