Fermi LAT observations of cosmic-ray electrons

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for the Fermi LAT Collaboration

The Fermi Gamma-Ray Space Telescope: launched on June 11, 2008

- **Large Area Telescope (LAT)**
  (20 MeV – >300 GeV)
- **Gamma-ray Burst Monitor (GBM)**
  (8 keV – 40 MeV)

Spacecraft with LAT and GBM before shipping to KSC

LAT collaboration

France
- IN2P3/LLR Ecole Polytechnique
- IN2P3/CENBG Bordeaux
- IN2P3/LPTA Montpellier
- CEA/Saclay
- CESR Toulouse

Germany
- MPI fuer extraterrestr. Physik, Garching

Italy
- INFN Bari, Padova, Perugia, Pisa, Rome, Trieste, Udine
- ASI
- INAF-IASF

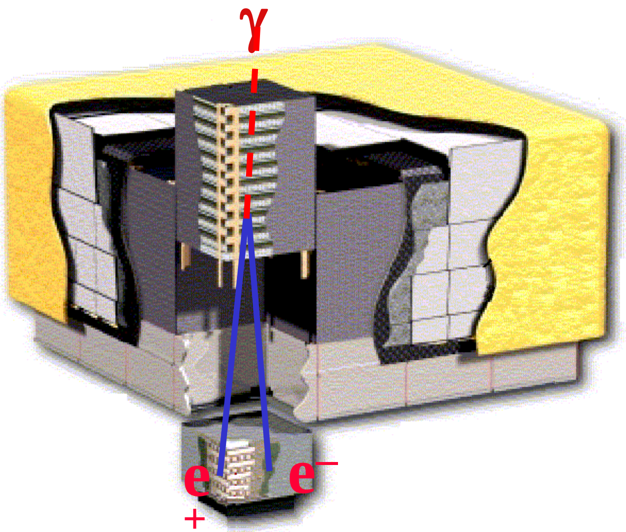
Japan
- Hiroshima University
- ISAS/JAXA
- Tokyo Institute of Technology

Spain
- IEEC-CISC, Barcelona

Sweden
- Royal Institute of Technology (KTH)
- Stockholm University

United States
- Stanford University (HEPL/Physics, SLAC, KIPAC)
- UC Santa Cruz
- Goddard Space Flight Center
- Naval Research Laboratory
- Sonoma State University
- Ohio State University
- University of Washington
- University of Denver
- Purdue University – Calumet

Designed as a gamma-ray instrument, the LAT is a capable detector of high energy cosmic ray electrons



- The LAT is composed of a 4x4 array of identical towers. Each tower has a Tracker and a Calorimeter module. Entire LAT is covered by segmented Anti-Coincidence Detector (ACD)

- The electron data analysis is based on that developed for photons. The main challenge is to identify and separate electrons from all other charged species, mainly CR protons (for gamma-ray analysis this is provided by the Anti-Coincidence Detector)

- The hadron rejection power must be $10^3 – 10^4$ increasing with energy

- Another challenge – assessment of systematic errors : statistical errors are very small

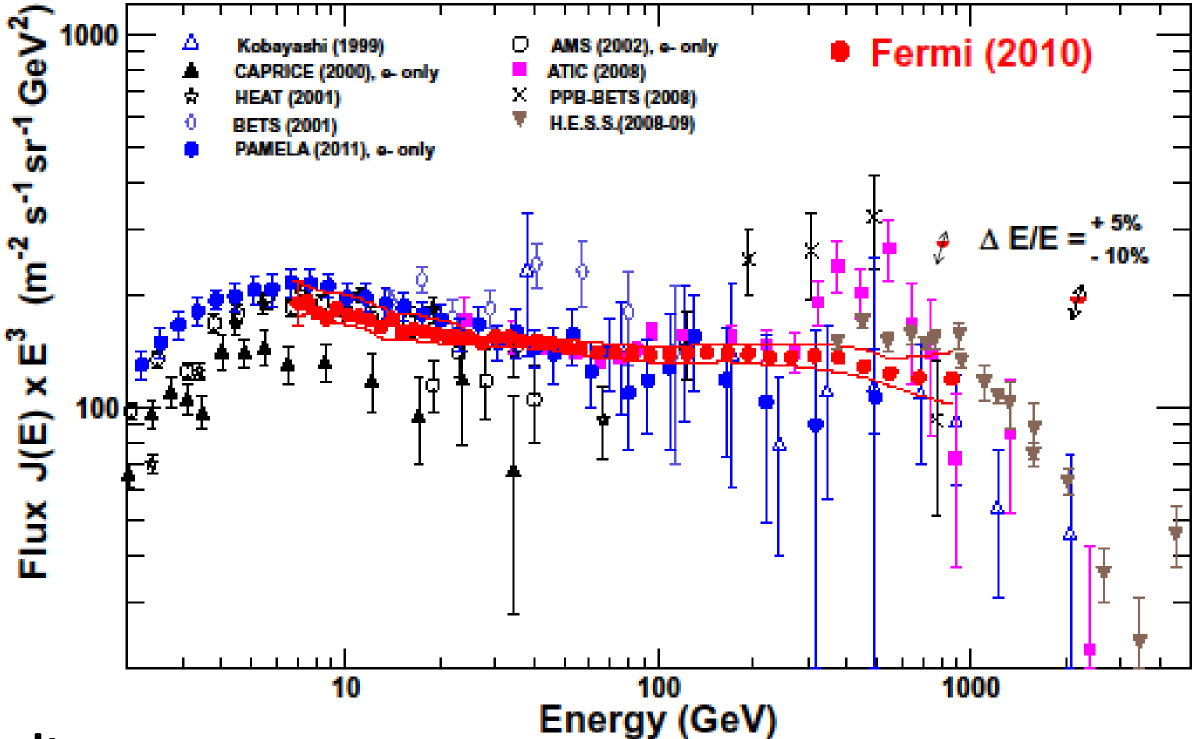
Why electrons?

- Due to their low mass high energy cosmic ray electrons (CRE) lose their energy rapidly (as $-dE/dt \sim E^2$) by synchrotron radiation on Galactic magnetic fields and by inverse Compton scattering on the interstellar radiation field
- The life-time of 1 TeV electron due to these energy losses is ~ 10^5 yr
- The typical distance over which a 1 TeV electron loses half of its energy is ~ 300-400 pc

⇓

- Observation of such HE CRE would imply existence of a nearby source of TeV electrons
- This makes CRE a unique tool for probing nearby Galactic space (to compare: Galactic halo is ~ 40 kpc diameter, ~ 4 kpc thick)

Currently available results on high energy CRE



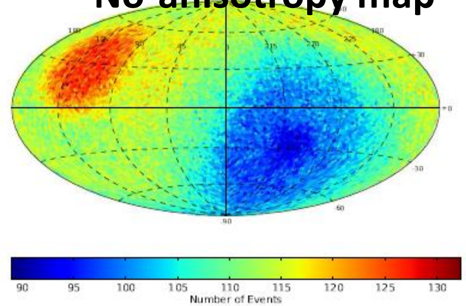
Fermi LAT results:

- PRL 102, 181101, 2009 reported the spectrum from 20 GeV to 1 TeV, taken in the first 6 months of operation. Total statistics 4.7M events. Most cited Fermi LAT paper so far (over 450 times)
- PRD 82, 092004, 2010: spectrum from 7 GeV to 1 TeV, collected in the 1st year. Total statistics 7.95 M events. More than 1000 events in highest energy bin (772 – 1000 GeV)

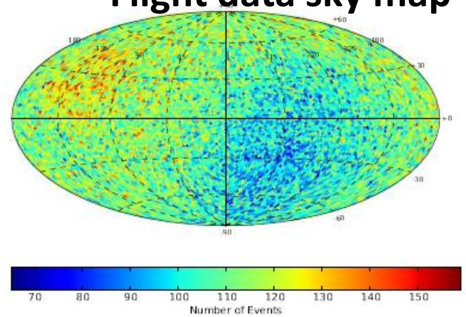
CR Electrons Anisotropy

Ackermann et al., Fermi LAT Collaboration, Phys Rev D82, 092003, 2009

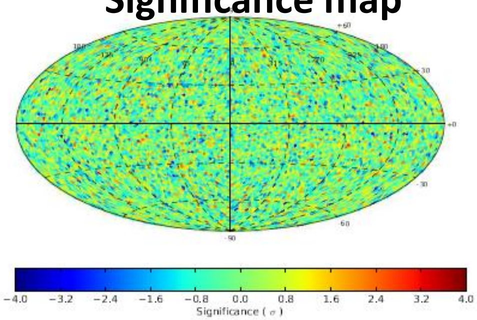
No-anisotropy map



Flight data sky map



Significance map

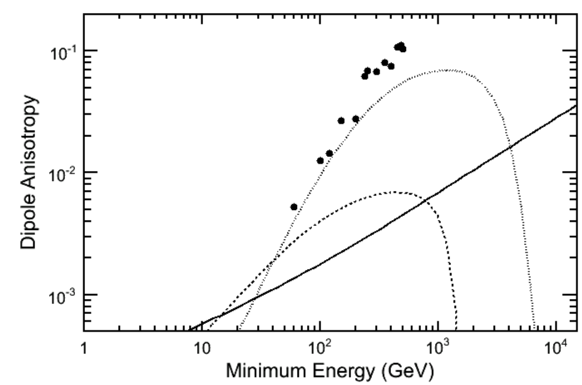


✓ **Search for CR electrons anisotropy provides an information on:**

- **Local CR sources and their distribution in space**
- **propagation environment**
- **heliospheric effects**
- **presence of dark matter clumps producing $e^+ e^-$**

✓ **Result:**

- **More than 1.6 million electron events with energy above 60 GeV have been analyzed on anisotropy**
- **Upper limit for the dipole anisotropy has been set to 0.5 – 5% (depending on the energy)**
- **Upper limit on fractional anisotropic excess ranges from a fraction to about one percent (depending on the minimum energy and the anisotropy's angular scale)**
- **Our upper limits lie roughly on or above the predicted anisotropies**

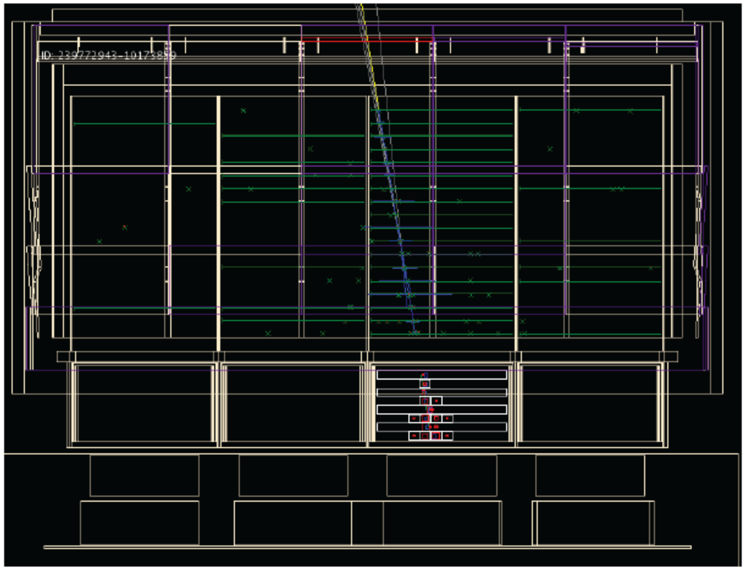


Dipole anisotropy vs. minimum energy. Solid line: Galprop spectrum, dashed line – Monogem, dotted line – Vela Circles: Fermi LAT 95 % CL data

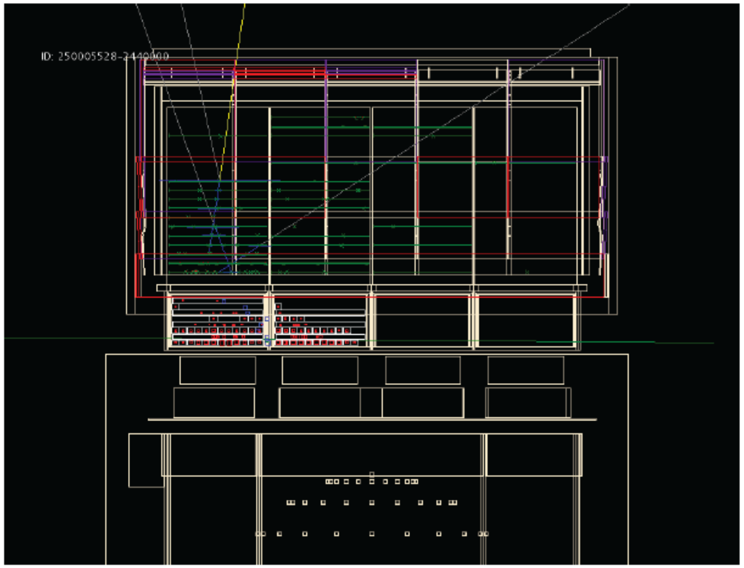
Electron Event Selection in Fermi LAT analysis

- All the LAT subsystems – tracker, calorimeter and ACD contribute to the event selection
- Event selection is based on the difference between electromagnetic and hadronic event topologies in the instrument

Flight event display



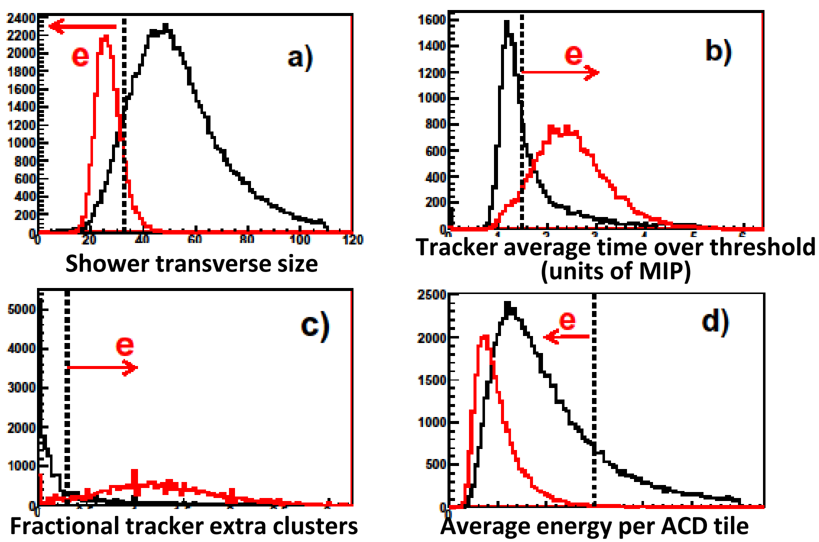
Electron candidate, 844 GeV



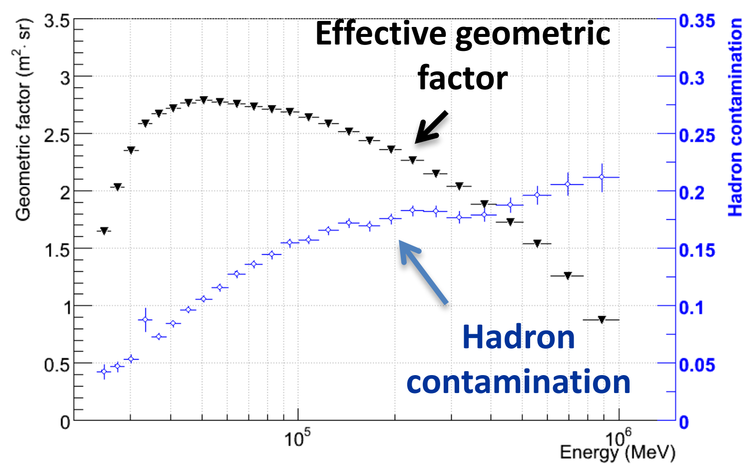
Background event, 765 GeV

Electron event selection (cont.)

- Electron event selection is a complicated, highly-optimized process that utilizes numerous physical variables from all LAT subsystems, as well as combined variables calculated with the Classification Tree method
- Most of the selections are energy dependent or scaled with the energy
- The most powerful separators between electromagnetic and hadronic events are the lateral distributions of the shower image



Histograms of selected variable distributions for the electron (red) and proton (black) events

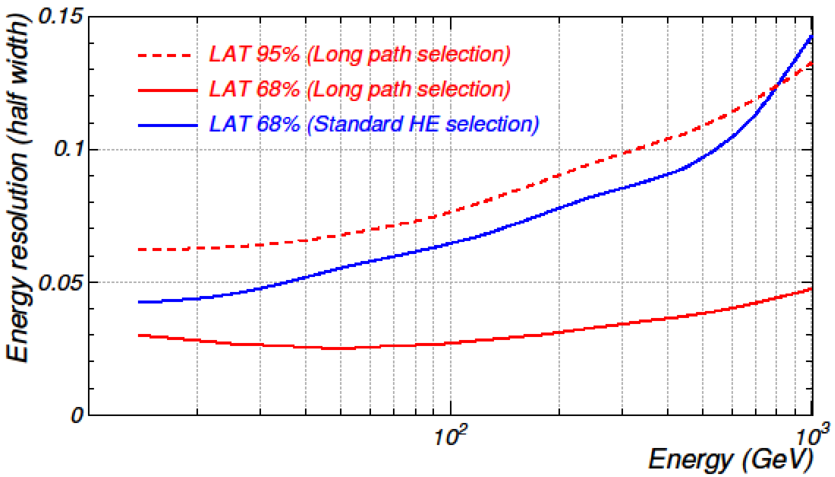


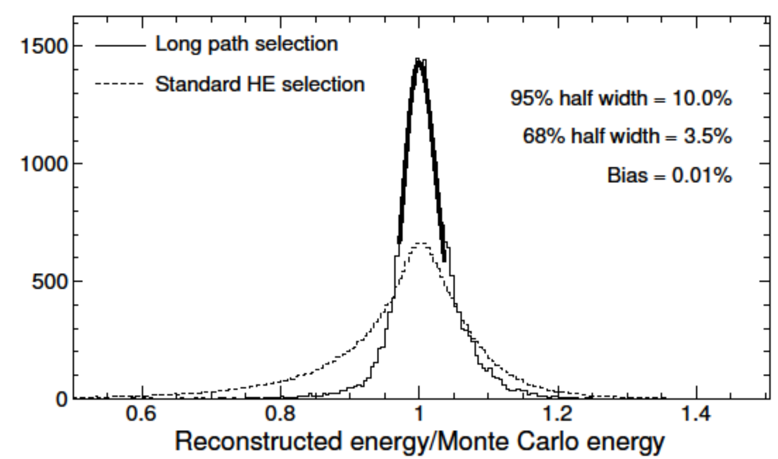
Remark: Residual Hadron contamination rate is subtracted from the rate of electron candidate events

Energy resolution

• 6% at 20 GeV, gradually increasing to 13% at 1 TeV (half width for 68% event containment)

• Selecting of the events with long paths in the calorimeter (> 12 X_0 ; average path length ~16 X_0), the energy resolution becomes better than 5% up to 1 TeV





Comparison of standard and "long path" analysis

Systematic uncertainties

• Very high event counting statistics → our result is dominated by systematic uncertainties.

• Careful analysis of contributions to the systematic uncertainty:

- uncertainty in knowledge of the LAT response (mainly the effective geometric factor, 5-20% increasing with energy)

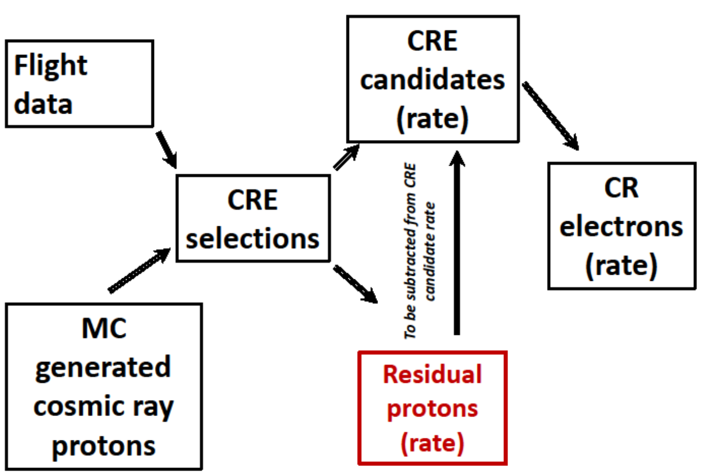
- uncertainty of residual hadron contamination (< 5%). Recently published data on the broken proton spectrum (Pamela, CREAM, ATIC) require to check the effect of the proton spectral break on our reconstructed electron spectrum.

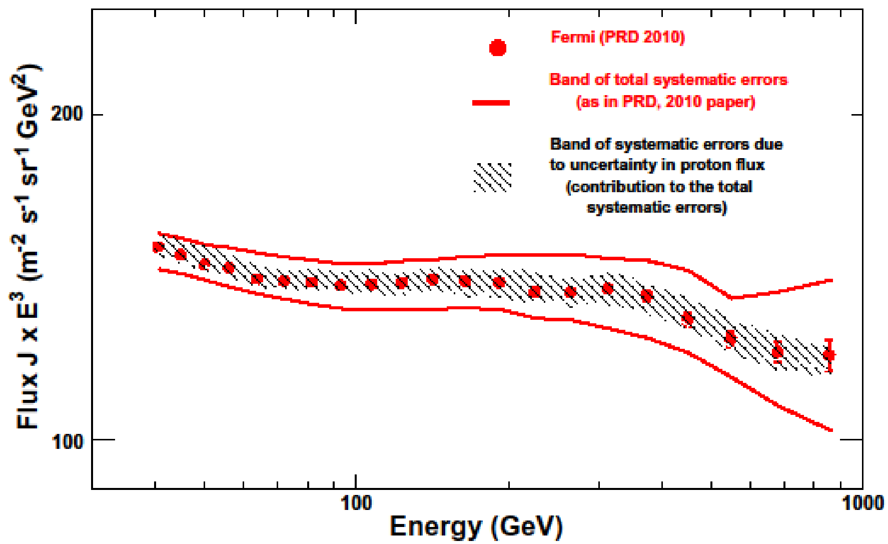
• Uncertainty in absolute energy scale (+5-10%) is constant with energy and can imply only a rigid shift of the entire spectrum

Correction for the residual hadron contamination with the use of new proton data

- Accurate calculation of the residual (hadron) background assumes good knowledge of the proton spectrum.
- We re-calculated the correction for the background (residual hadrons) with the use of the new proton data with the spectral break at 200-300 GeV and found that its effect on the shape of reconstructed CRE spectrum is negligible (see dashed band on the plot, corresponding to the highest and lowest proton spectra). The upper edge of the dashed band corresponds to the ATIC proton spectrum (index 2.75 below 300 GeV, 2.65 above)

Hadron background removal in Fermi LAT CRE analysis





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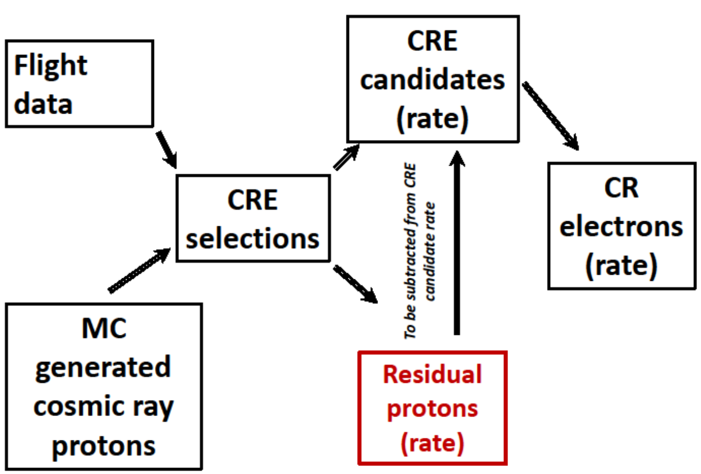
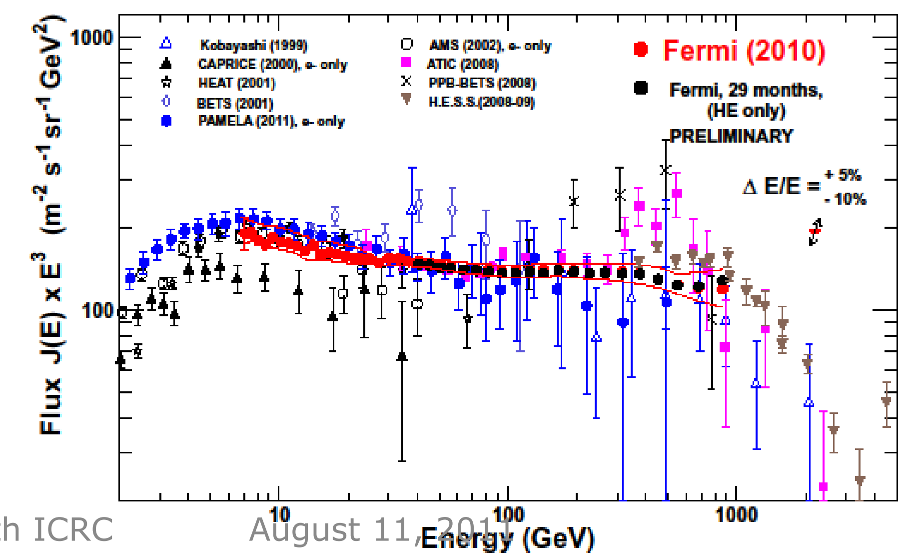
Hadron background removal in Fermi LAT CRE analysis



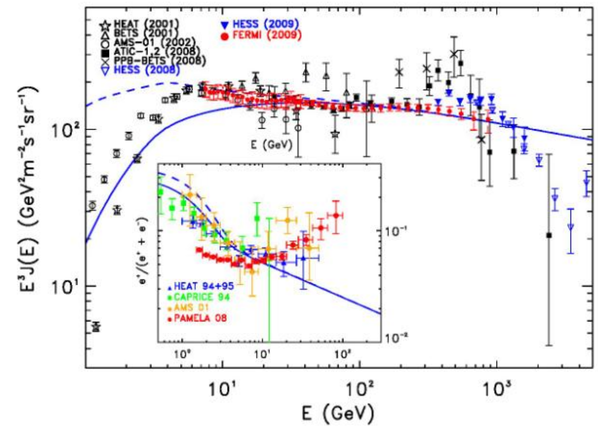


Interpretation

<u>Conventional (pre-Fermi) model</u>: $e^+ + e^-$ spectrum consists of dominating "primary" (produced in quasi-uniformly distributed distant astrophysical sources, thought to be SNR) e^-, plus contribution from "secondary" e^+ and e^-, produced in interactions of cosmic rays with interstellar matter

- We were rather successful to fit our first spectrum published in PRL paper (20 GeV – 1 TeV) with a single component (single power law fit).

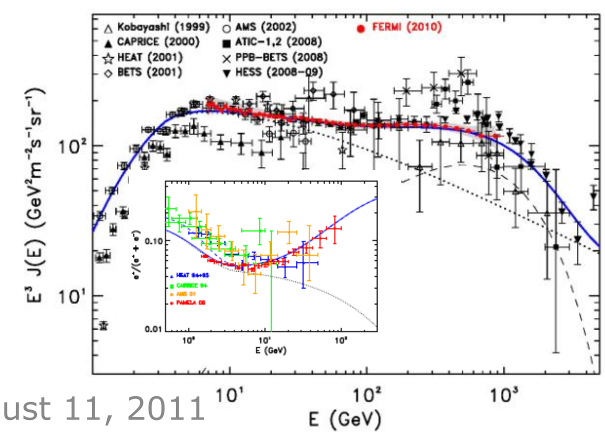
- With our new spectrum extended down to 7 GeV we tested many combinations of injection spectra, diffusion models and solar modulation. It appears that the spectral flattening at 20-100 GeV and the softening at ~ 500 GeV cannot be satisfactory fitted by the single component model.



- Positron fraction, reported by Pamela and recently confirmed by Fermi LAT (see talk of *Justin Vandenbroucke in this conference)* cannot be reproduced as well

<u>Conclusion:</u> Fermi LAT electron spectrum cannot be explained within conventional single-component model

Introduction of an additional component of the CRE flux: it is assumed that there is a source of HE $e^+ + e^-$ with hard spectrum, providing equal amount of e^+ and e^-, in order to satisfy raising with energy positron ratio. This component can be astrophysical or "exotic", such as e.g. dark matter clump



Future perspectives in CRE analysis with Fermi LAT

1. We expect important new results from Fermi LAT on CRE with the use of the new Fermi LAT analysis called Pass 8, currently under development. It will have an improved event pattern recognition, better agreement between the flight data and Monte Carlo, correction for the "ghost" events, improved efficiency to gamma-rays, etc. It will also have improved energy reconstruction at high energy with the goal to extend the energy range up to few TeV.

2. Detailed spectral structure. It was reported in our PRD paper that in our analysis the energy resolution can be significantly improved by selecting events with longer path in the LAT, e.g. selection of events with pathlength more than $12X_0$ in the calorimeter ($16\ X_0$ in average for the whole LAT). This approach provides energy resolution better than 5%, but the statistics reduces by a factor of ~20. With the new Pass 8 analysis and 3+ years of LAT operation we hope to have a reliable reconstruction of the spectral shape. The expected statistics (with "long path" analysis) in a 100-GeV-wide bin at 1 TeV is ~100 electrons per 3 years

3. Spectrum above 1 TeV. The HESS experiment reported a spectral fall at around 1 TeV with the change of the slope from 3.0 to 4.1. This is a fundamental issue, and LAT will be able to study the CRE spectrum above 1 TeV with Pass 8 analysis. Expected statistics from 1 to 3 TeV is ~3,500 electrons for 3 years if the spectral index does not change (~2,800 if the spectral index above 1 TeV is 4.1 as reported by HESS)

4. CRE anisotropy. We already published anisotropy limits on the CRE flux. Currently the Fermi LAT sensitivity is approaching the range expected by the theoretical models, both for dark matter and for pulsars.

Stay tuned!

THANK YOU FOR YOUR ATTENTION !