Measurements of high-energy cosmic-ray electrons with Fermi LAT

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Fermi Gamma-ray Space Telescope was launched on June 11, 2008. Launched as GLAST, renamed to Fermi after 3 months of successful operation.

There are two possible outcomes: If the result confirms the hypothesis, then you've made a measurement. If the result is contrary to the hypothesis, then you've made a discovery. “ Enrico Fermi
Fermi Gamma-ray Space Telescope

Two instruments onboard Fermi:

✓ Large Area Telescope LAT
  • main instrument, gamma-ray telescope, 20 MeV - >300 GeV energy range
  • scanning (main) mode - 20% of the sky all the time; all parts of sky for ~30 min. every 3 hours
  • ~ 2.4 sr field of view, 8000 cm² effective area above 1 GeV
  • good energy (5-10%) and spatial (~3° at 100 MeV and <0.1° at 1 GeV) resolution

✓ GLAST Burst Monitor GBM
LAT as a 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)

- Although the LAT was designed to detect photons, it was recognized early in its design that the LAT is a capable detector of high energy electrons too

- 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

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

- Another challenge – assessment of systematic errors: statistical errors will be very small
Electron event selection – basic principles

- Electron event selection is a complicated, highly-optimized process that utilizes numerous physical variables from all 3 LAT subsystems, as well as combined variables calculated with the Classification Tree method (later BDT).
- 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.

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

Effective geometric factor

Hadron contamination rate is subtracted from the rate of electron candidate events.
Event energy reconstruction and validation (2008-2009)

- Based on the algorithms developed for the LAT photon analysis
- Extended to 1 TeV for the electron analysis
- Validated in extensive beam tests (SLAC, CERN, GSI). Practically unbiased

Agreement between MC and beam test data up to 280 GeV gives us a solid ground to rely on simulations for extended energy range.
Systematic uncertainties: critical aspect of our analysis

• 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%)

• Uncertainty in absolute energy scale (+5-10%)
Fermi LAT electron+positron spectrum – first result

- Total statistics 4.7M events, taken in the first 6 months of operation
- Noticeable deviation from single power law spectrum: Number of papers published on the interpretation of Pamela and Fermi results
- Still one of the most cited Fermi LAT papers
2010: Measurement of the spectrum below 20 GeV

- Requires consideration of the shielding effect of the Earth’s magnetic field
- Important for understanding the solar modulation of the IS electron flux
- Extended down to 7 GeV, lowest geomagnetic cutoff energy accessible to the Fermi satellite
- The lowest energy of primary electrons that can be measured strongly depends on the satellite geomagnetic position

Approach:
- all data are divided in 10 intervals of McIlwain L parameters
- for each interval only events with $E > 1.15 \times E_c$ are used for the analysis to minimize the effect of geomagnetic cutoff (1.15 is a safety padding)
- the cutoff energy $E_c$ for each interval is determined from our data
Fermi LAT electron+positron spectrum 7 GeV – 1 TeV

Data collected for the first 12 months of operation
• Total statistics 7.95 M electron candidate events
• More than 1000 events in highest energy bin (772 – 1000 GeV)
2010: High statistics and excellent direction reconstruction: CRE Anisotropy

Approach: M. Ackermann et al., PRD 82, 092003 (2010)

• statistical comparison of “no anisotropy” sky map of electron counts with the flight data.

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
2012: Cosmic Ray Positrons

Approach: use the Earth’s Magnetic Field to Distinguish $e^+$ and $e^-$

- Pure $e^+$ region in the west, and pure $e^-$ region in the east
- The regions vary with particle energy and the Fermi-LAT position
- To locate these regions, we use a code written by Smart, D. F. and Shea, M. A.* which numerically calculates a particle's trajectory in the most up-to-date geomagnetic field model (IGRF2010)

Slide courtesy of Warit Mitthumsiri
2012: Cosmic Ray Positrons. The Result

M. Ackermann et al., PRL 108, 011103 (2012)

- Some systematic uncertainties cancel in ratio calculation
- Error bars = statistical errors, and the grey band = total errors
- The e\(^+\) fraction is increasing with energy, consistent with PAMELA results
Challenging analysis:

- Only ~35% of the shower is contained in the calorimeter
- Significant fraction of the crystals along the shower axis are saturated

- Improved event selection and background rejection
- Improved low-energy analysis
- Careful assessment of systematic errors (acceptance, contamination, IVC, energy measurement)
- Including events with saturated crystals
- Removal of ghost (off-time) events

Result: improved acceptance, PSF, energy measurement
2017: 3\textsuperscript{rd} Fermi LAT paper on CRE.
Spectrum from 7 GeV to 2 TeV

- The best fit by broken power-law with break energy of $47 \pm 6$ GeV and spectral indices below and above the break of $3.21 \pm 0.02$ and $3.11 \pm 0.02$, respectively
- Cutoff for $E_c < 1.8$ TeV is excluded with 95\% C.L.
- Around 1000 events in each of 3 highest energy bin
- Some tension with AMS and CALET results at intermediate energies, which is currently unexplained, likely due to unaccounted systematic errors

- $\sim 850K$ events in LE spectrum
- $\sim 15.5M$ events in HE spectrum
2017: Update on CRE Anisotropy
S. Abdollahi et al., PRL 118, 091103 (2017)

- No dipole at the level of $10^{-3}$
- Limits improved 3x wrt previous LAT results
- Best current limits

Search for the proton arrival anisotropy is under way

Slide courtesy of Luca Latronico and Nicola Mazziotta
SUMMARY

CRE Inclusive spectrum

2008, before Fermi

CRE Origin still unclear

2020+

Ratio at around 1 TeV and above?

Spectral structure in TeV range?