The Fermi LAT: highlights after one year in orbit and measurement of the cosmic-ray electron spectrum

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on behalf of the Fermi-LAT collaboration

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OUTLINE

- The observatory.
- Highlights from the first year in orbit.
- The measurement of the high-energy Cosmic-Ray Electron spectrum.
- Conclusions.

Disclaimer: characteristic energies and lengths will be scaled down by a few orders of magnitudes over the next 30 minutes (compared to the last two days).
The observatory

Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–300 GeV
- Huge field of view (≈ 2.4 sr): 20% of the sky at any time, all parts of the sky for 30 minutes every 3 hours.
- Long observation time: 5 years minimum lifetime, 10 planned; 85% duty cycle.

Gamma-ray Burst Monitor (GBM)

- 12 NaI and 2 BGO detectors.
- Energy range: 8 keV–40 MeV.
The Fermi-LAT collaboration

Institutions

- **France**
  - IN2P3, CEA/Saclay

- **Italy**
  - INFN, ASI, INAF

- **Japan**
  - Hiroshima University
  - ISAS/JAXA, RIKEN
  - Tokyo Institute of Technology

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

- **United States**
  - Stanford University (SLAC, KIPAC, and HEPL/Physics)
  - University of California at Santa Cruz, Santa Cruz Institute for Particle Physics
  - Goddard Space Flight Center
  - Naval Research Laboratory
  - Sonoma State University
  - Ohio State University
  - University of Washington
  - Also members from Australia, Germany, Great Britain, Spain.

Sponsoring Agencies

- **France**
  - IN2P3/CNRS, CEA/Saclay

- **Italy**
  - INFN, ASI

- **Japan**
  - MEXT, KEK, JAXA

- **Sweden**
  - K. A. Wallenberg Foundation
  - Swedish Research Council
  - Swedish National Space Board

- **United States**
  - DOE, NASA

Collaboration members

≈ 390 Members (≈ 95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

Construction and operations managed by SLAC, Stanford University
Large Area telescope

- Overall modular design.
- $4 \times 4$ array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by and Anti-Coincidence Detector (ACD).
- *Numerology:* $1.8 \times 1.8$ m$^2$ footprint, 3000 kg weight, 650 W power consumption.
## Large Area Telescope

**Overall modular design.**

- 4 × 4 array of identical towers (each one including a tracker and a calorimeter module).
- Tracker surrounded by and Anti-Coincidence Detector (ACD).
- **Numerology**: 1.8 × 1.8 m² footprint, 3000 kg weight, 650 W power consumption.

### Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 80 m² of silicon active area, 1M readout channels (160 W).
- High-precision tracking, short instrumental dead time.

### Anti-Coincidence Detector

- Segmented (89 tiles) to minimize self-veto at high energy.
- 0.9997 average efficiency (8 fiber ribbons covering gaps between tiles).

### Calorimeter

- 1536 CsI(Tl) crystal; 8.6 radiation lengths on-axis.
- Hodoscopic, 3D shower profile reconstruction for leakage correction.
**Large Area telescope**

- Overall modular design.
- $4 \times 4$ array of identical towers (each one including a tracker and a calorimeter module).
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- *Numerology*: $1.8 \times 1.8 \text{ m}^2$ footprint, 3000 kg weight, 650 W power consumption.

<table>
<thead>
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<th>Parameter</th>
<th>EGRET</th>
<th>Fermi LAT</th>
<th>Design</th>
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<tbody>
<tr>
<td>Peak $A_{\text{eff}}$</td>
<td>1500 cm$^2$</td>
<td>8000 cm$^2$</td>
<td>×4 geometric area</td>
</tr>
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<td>Field of view</td>
<td>0.5 sr</td>
<td>2.4 sr</td>
<td>Aspect ratio (no TOF)</td>
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<td>Angular resolution</td>
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<td>SSD vs. spark chambers</td>
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<td>&lt; 10% @ 0.1–10 GeV</td>
<td>Hodoscopic calorimeter</td>
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<td>Dead time per evt</td>
<td>100 ms</td>
<td>26.5 µs minimum</td>
<td>SSD vs. spark chambers</td>
</tr>
</tbody>
</table>

1. After background rejection.
2. Single photon, 68% containment, on axis.
3. 68% containment, on axis.
The launch
Just turned one year old (in orbit)

Launched on June 11, 2008 from the Kennedy Space Center.
Launch vehicle: Delta 2920H-10.
Circular orbit, 565 km altitude, 25.6° inclination.
Fermi in orbit

- Track the satellite: http://observatory.tamu.edu:8080/Trakker
- Watch Fermi as it orbits over your home town: http://www.nasa.gov/mission_pages/GLAST/news/glast_online.html

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1 YEAR SCIENCE OPERATION TIMELINE

Launch June 11, 2008

Start year 1
August 4, 2008

First birthday in space.
50B triggers, 10B events (5 TB)

Start year 2
August 4, 2009

L&EO Sky survey, in-depth instrument studies

Observatory renaming,
first light release
August 12, 2008

Bright source list
February 6, 2008

LAT year 1 photon data
release, diffuse model
End of summer 2009

Observatory turn-on/checkout
First light
Tuning of sky survey and pointing

L L+21 L+30 L+60 (days)

Continous release of photon data

Flaring and monitored sources info

GBM and LAT GRB alerts
Released on August 26, 2009, combines four days of observing time (equivalent to \( \approx 1 \) year of observation with EGRET).
The first Gamma-ray only pulsar

\[ P \approx 317 \text{ ms} \]
\[ \dot{P} \approx 3.6 \times 10^{-13} \text{ s}^{-1} \]


Quick discovery made possible by:
- Large leap in instrument capabilities;
- New analysis technique (Atwood et al. 2008).

- 12 gamma-ray only pulsars discovered plus 18 radio loud.
- ≈ 50 pulsars observed to date.
NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky
Based on three months of data (2.8M events above 100 MeV).

- Only sources with C.L. $>10\sigma$ over this period; includes location, significance, flux, variability, association.
  - Not a catalog—not complete, not flux-limited, not uniform.

- 205 sources (EGRET detected 31 sources above $10\sigma$)
  - Only 60 clearly associated with 3EG catalog—the sky changes!
Performance roughly consistent with expectations.
- GBM: $\approx 250$ bursts/year ($\approx 1/2$ in the LAT field of view).
- LAT: $\approx 10$ bursts/year (8 bursts detected so far).
GRB 080916C

Light curve
- 145 photons above 100 MeV, 14 photons above 1 GeV, highest energy photon 13 GeV.
- First low-energy peak not observed by the LAT.
- Bulk of the 2\textsuperscript{nd} peak moving at later times as energy increases.

Large fluence, $z = 4.35$ implying:
- Largest apparent energy release ever observed: $E_{\text{iso}} = 8.8 \times 10^{54}$ erg $\approx 4.9 M_\odot$.
- Largest bulk Lorenz factor: $\Gamma_{\text{min}} = 809 \pm 20$.
- Most stringent limit on the Lorenz invariance mass scale: $M_{\text{QG}} > 1.5 \times 10^{18}$ GeV.
Simultaneous observations:
Fermi-LAT, H.E.S.S., RXTE, Swift, ATOM (≈ 11 days).
Relatively small variability (≈ 30%), optical/VHE flux and X-ray/HE spectral index correlations.
4.5 months of data, $10^\circ \leq |b| \leq 20^\circ$ (minimize the effect of uncertainties on the CR propagation and gas distribution).

- Lower latitudes: large scale DGE.
- Higher latitudes: instrumental background and DGE model.

The EGRET all-sky excess is not confirmed.
4.5 months of data, $10^\circ \leq |b| \leq 20^\circ$ (minimize the effect of uncertainties on the CR propagation and gas distribution).

- Lower latitudes: large scale DGE.
- Higher latitudes: instrumental background and DGE model.

- The EGRET all-sky excess is not confirmed.
- Fermi data well reproduced by an a-priori DE model.
Not only gamma rays

- All events with energy (measured on board) greater than 20 GeV are down-linked to ground.
- Peak geometric factor (or \textit{aperture}) close to $3 \text{ m}^2 \text{ sr}$.
- $\approx 10$ million of electrons per year above 20 GeV.
- Challenges connected with energy reconstruction and background rejection largely in common with the standard photon analysis.
- Cannot distinguish the charge sign ($\textit{electrons}$ are really $e^+ + e^-$ hereafter.)
Event topology

Candidate electron
475 GeV raw energy, 834 GeV reconstructed

- Clean main track with extra clusters close to the track (note backsplash from the calorimeter).
- Relatively few ACD tile hits, mainly in conjunction with the track.

Transverse shower size: 23.2 mm
Fractional extra clusters: 1.48
Average ACD tile energy: 2.46 MeV
Energy reconstruction quality: 0.73

Candidate hadron
823 GeV raw energy, 1 TeV reconstructed

- Small number of extra clusters around main track, many clusters away from the track.
- Different backsplash topology, large energy deposit per ACD tile.

Transverse shower size: 34.4 mm
Fractional extra clusters: 0.17
Average ACD tile energy: 10.2 MeV
Energy reconstruction quality: 0.15
Candidate electron
475 GeV raw energy, 834 GeV reconstructed

- Clean main track with extra clusters close to the track (note backsplash from the calorimeter).
- Relatively few ACD tile hits, mainly in conjunction with the track.
- Well defined (not fully contained) symmetric shower in the calorimeter.

Candidate hadron
823 GeV raw energy, 1 TeV reconstructed

- Small number of extra clusters around main track, many clusters away from the track.
- Different backsplash topology, large energy deposit per ACD tile.
- Large and asymmetric shower profile in the calorimeter.

Transverse shower size: 23.2 mm
Fractional extra clusters: 1.48
Average ACD tile energy: 2.46 MeV
Energy reconstruction quality: 0.73

Transverse shower size: 34.4 mm
Fractional extra clusters: 0.17
Average ACD tile energy: 10.2 MeV
Energy reconstruction quality: 0.15
Three main steps, in which all the subsystems contribute.

- Basic quality cuts (requiring ACD signal to remove gammas)
- Event topology in the tracker, calorimeter and ACD.
- Classification tree analysis:
  - input variables for the CT analysis carefully selected;
  - boost at high energy obtained by means of an explicitly energy-dependent cut.
Data/Monte Carlo comparison routinely performed for:
- all variables involved in the selection;
- at different stages of the selection.

Residual discrepancies propagated to the spectrum for each energy bin and included into the systematics.
Event selection: figures of merit

▶ Peak geometric factor of 2.8 \( m^2 \) sr, 2 \( m^2 \) sr at 300 GeV.
▶ Estimated residual hadron contamination \( \approx 5-20\% \);
  ▶ subtracted from the candidate electrons.
▶ Trade-off between electron efficiency, residual contamination and control of systematic uncertainties.
Validated with the Calibration Unit beam tests up to 280 GeV.

- Excellent agreement over the whole (energy, angle, position) phase space.
- We have a solid ground in extrapolating to 1 TeV.

Our energy dispersion is adequate for the measurement.

- Candidate electrons traverse 12.5 $X_0$ on average.
Shower profile: Monte Carlo vs. beam test
Electron beams, on axis

Energy Profile (Beam P = 10 GeV/c, Theta = 0)

Layer number

Energy peak (MeV)

0 1 2 3 4 5 6 7

Layer number

Energy peak (MeV)

200 400 600 800 1000 1200

Energy Profile (Beam P = 20 GeV/c, Theta = 0)

Layer number

Energy peak (MeV)

0 1 2 3 4 5 6 7

Layer number

Energy peak (MeV)

500 1000 1500 2000 2500

Energy Profile (Beam P = 50 GeV/c, Theta = 0)

Layer number

Energy peak (MeV)

0 1 2 3 4 5 6 7

Layer number

Energy peak (MeV)

1000 2000 3000 4000 5000

Energy Profile (Beam P = 100 GeV/c, Theta = 0)

Layer number

Energy peak (MeV)

0 1 2 3 4 5 6 7

Layer number

Energy peak (MeV)

2000 4000 6000 8000 10000 12000

Energy Profile (Beam P = 200 GeV/c, Theta = 0)

Layer number

Energy peak (MeV)

0 1 2 3 4 5 6 7

Layer number

Energy peak (MeV)

5000 10000 15000 20000 25000

Energy Profile (Beam P = 280 GeV/c, Theta = 0)

Layer number

Energy peak (MeV)

0 1 2 3 4 5 6 7

Layer number

Energy peak (MeV)

5000 10000 15000 20000 25000 30000
The measured spectrum


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Unprecedented statistics (4 M electrons above 20 GeV, > 400 in the last bin).

Does not follow the conventional wisdom $E^{-3.3}$ power law ($E^{-3.0}$–$E^{-3.1}$ instead).
Interpretation: Quick Review

### Pulsars
Grasso et. al 2009

### Dark matter annihilation (or decay)
Bergström et. al 2009

### Secondary production in the CR sources
Blasi 2009

### Source stochasticity
Grasso et. al 2009
Interpretation: quick review

Pulsars
Grasso et. al 2009

Dark matter annihilation (or decay)
Bergström et. al 2009

Bottomline

▶ The CR $e^+ + e^-$ spectrum by itself is not enough to rule out any of the models.

▶ The other pieces of the puzzle: positron and antiproton ratios, gammas, neutrinos.

▶ Fermi has the unique perspective of being able to probe models in gamma rays, as well.
Sensitivity for the integral large-scale dipole anisotropy.

The plot includes the main instrumental effects:

- Energy-dependent effective geometry factor;
- Instrumental dead time and duty cycle;
- On board filter.

Room for improvements with a better event selection!
Conclusions

- Fermi is performing extremely well.
  - First-year (in sky survey mode) just finished.
- Wealth of results in gamma-ray astrophysics:
  - Some $\approx 50$ pulsars detected (a fair fraction only in gamma rays), many flaring active galaxies observed, 8 GRBs, EGRET GeV excess in diffuse gamma not confirmed.
- First high-statistics measurement of cosmic-ray electron spectrum from 20 GeV to 1 TeV.
  - Harder spectral index than conventional models;
  - Several different interpretations possible, future observations from Fermi-LAT and other instruments will help finding the answer:
    - Improved statistics and systematics, larger energy range, anisotropies in the electron arrival directions, connection with diffuse gamma.
Five hardware trigger primitives (at the tower level).

- **TKR**: three $x$-$y$ tracker planes hit in a row.
- **CAL_{LO}**: single log with more than 100 MeV.
- **CAL_{HI}**: single log with more than 1 GeV.
- **ROI**: MIP signal in a ACD tiles close to a triggering tower.
- **CNO**: heavy ion signal in the ACD.

Upon L1 trigger the entire detector is read out.

Need onboard filtering to fit the data volume within the allocated bandwidth.

- **GAMMA**: rough onboard photon selection.
  - All events with raw energy greater than 20 GeV downlinked.
  - Primary source of high-energy $e^+ e^-$.  
- **HIP**: heavy ions for CAL calibration.
- **DGN**: prescaled ($\times 250$) unbiased sample of all trigger types.
  - Source of low-energy $e^+ e^-$, decent statistics up to 100 GeV.
- **MIP**: straight tracks for alignment (only in dedicated runs).
Monte Carlo validation with flight data
CT combined electron probability above 150 GeV

- Two different CT ensembles (based on TKR and CAL).
  - Each one providing an event based electron probability.
  - Combined with the general (energy-dependent) scheme

\[ \rho_{\text{comb}} = k \sqrt{\rho_{\text{tkr}} \cdot \rho_{\text{cal}}}/(\log E - \log E_0) \]
 Gamma-ray contamination

- Conservative estimate from the EGRET all-sky average gamma-ray intensity.
  - Galactic background not an issue (spectral index -2.7).
  - Extra-galactic background falls like $E^{-2.1}$.
- Naive extrapolation yields a $\gamma/(e^+ + e^-)$ of 20% at 1 TeV.
  - Does not take into account the EBL absorption.
- When corrected for the relative acceptance, this translates into a 2% gamma contamination at 1 TeV (not subtracted).
Energy resolution: validation with beam test
Electrons at 45°

Beam = 20 GeV Peak = 19.7 GeV Resolution = 2.8%

Beam = 50 GeV Peak = 50.1 GeV Resolution = 2%

Beam = 99.7 GeV Peak = 99.9 GeV Resolution = 2%

Beam = 196 GeV Peak = 199 GeV Resolution = 2.5%

20 GeV, 45°

50 GeV, 45°

100 GeV, 45°

200 GeV, 45°
Shower profile: Monte Carlo vs. flight data

After the electron selection, integrated over all angles

Measured energy: 246−291 GeV

Layer number
0 1 2 3 4 5 6 7 8
Average layer energy (GeV)
0 20 40 60 80 100
Monte Carlo
Flight data

Measured energy: 346−415 GeV

Layer number
0 1 2 3 4 5 6 7 8
Average layer energy (GeV)
0 20 40 60 80 100
Monte Carlo
Flight data

Measured energy: 503−615 GeV

Layer number
0 1 2 3 4 5 6 7 8
Average layer energy (GeV)
0 20 40 60 80 100
Monte Carlo
Flight data

Measured energy: 772−1000 GeV

Layer number
0 1 2 3 4 5 6 7 8
Average layer energy (GeV)
0 20 40 60 80 100
Monte Carlo
Flight data
Shower profile: flight data
After the electron selection, integrated over all angles

Showers of different energies look different in the detectors (i.e. can be distinguished).

The shower maximum at 1 TeV is at $11.5 \, X_0$ (candidate electrons traverse $\approx 12.5 \, X_0$).
Energy reconstruction quality

0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
0 200 400 600 800
301−412 GeV

▶ Probability of good energy reconstruction: diagnostic output of our energy analysis.

▶ A CT is trained to identify events in the core of the energy dispersion.
Distribution of the **probability of good energy reconstruction** provided by the standard energy classification tree analysis.

Events above 400 GeV at two different stages of the selection.
Uncertainty in our knowledge of the geometry factor.

- Data/Monte Carlo agreement extensively studied for each single variable involved in the selection (bin by bin).
- All the residual discrepancies mapped and propagated to the actual spectrum.
- Ranging from a few % to $\approx 20\%$ depending on energy.

Normalization of the primary proton spectrum.

- Affecting the electron spectrum through the subtraction of the residual hadron contamination.

LAT absolute calibration of the energy scale.

- Unlike the other terms does not introduce energy-dependent modifications of the spectrum.
- From beam test data, calibration and flight data, the systematic uncertainty on the absolute energy is (+5%, -10%).
Evaluation of the Systematic Uncertainties

- If the data/MC agreement was perfect, the actual spectrum would not depend on the cut values.
EVALUATION OF THE SYSTEMATIC UNCERTAINTIES

**Data**

**Monte Carlo**

Evaluating the systematics

- In real life data/MC discrepancies introduce such a dependence.
Evaluation of the systematic uncertainties

The induced variations in the spectrum effectively map the data/MC discrepancies.

The induced variations in the spectrum effectively map the data/MC discrepancies.
Model adapted from Chang et al. 2008:
- broken power law with $\Gamma = -3.1$ below 1 TeV, $-4.5$ above;
- harder ($\Gamma = -1.5$) feature with break at 620 GeV.
Energy resolution and spectral features

**Energy resolution**

- ATIC (2008)
- Fermi (2009)
- Model, no smear
- Model, $\Delta E/E = 12\%$ (1 $\sigma$)

**Model adapted from Chang et al. 2008:**
- Broken power law with $\Gamma = -3.1$ below 1 TeV, $-4.5$ above;
- Harder ($\Gamma = -1.5$) feature with break at 620 GeV.

- 12% is a conservative estimation for Fermi in the 100s GeV.
Model adapted from Chang et al. 2008:
- broken power law with $\Gamma = -3.1$ below 1 TeV, $-4.5$ above;
- harder ($\Gamma = -1.5$) feature with break at 620 GeV.

12% is a conservative estimation for Fermi in the 100s GeV.
Significance of the bump around $\approx 500$ GeV

- It crucially depends on the point-to-point correlation matrix between the systematic errors $C_{ij} = \left\langle \Delta_i^{\text{sys}} \Delta_j^{\text{sys}} \right\rangle$:
  - $C_{ij} \propto 1 \quad \forall i, j$: the spectrum moves up/down rigidly (i);
  - $C_{ij} \propto \delta_{ij}$: the systematic errors are bin-wise independent, i.e. can be summed in quadrature with the statistical errors (ii);
- We have different sources of systematic errors:
  - uncertainty in the overall energy scale: (i) to a good approximation;
  - uncertainty in the overall background flux: $C_{ij} \propto f(E) \quad \forall i, j$;
  - data/Monte Carlo discrepancies through the selection cuts: somehow in between (i) and (ii), with terms very far from diagonal presumably small.
- Detailed analysis underway (not trivial, but can be done).
  - Will not change the best values for the model parameters, but might affect the exclusion contours.
Measurements of anisotropies: systematics
Far from being exhaustive

Raw TKR trigger rate
- Terrestrial coordinates (South Atlantic Anomaly clearly visible).
- Fermi does not take science data within the SAA polygon.

Exposure map
- In galactic coordinates, for gammas, after three months of mission.
- It will not be very different for the electrons and for longer time periods.

- $\approx 25\%$ disuniformity in the exposure (mainly due to the SAA).
- Measuring a $0.1\%$ anisotropy requires a knowledge of the exposure map at the $\approx 0.1\%$ level.