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

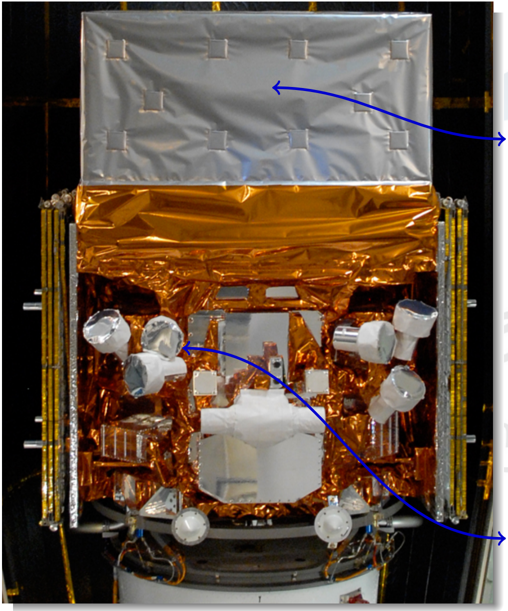
SOCoR, Trondheim
June 18, 2009

Outline

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

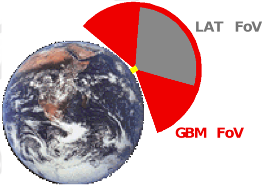
Disclaimer: characteristic energies and lengths will be scaled down by a few orders of magnitudes over the next 30 minutes (compared to the last two days).

The observatory



Large Area Telescope (LAT)

- Pair conversion telescope.
- Energy range: 20 MeV–> 300 GeV
- Huge field of view ($\approx$ 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

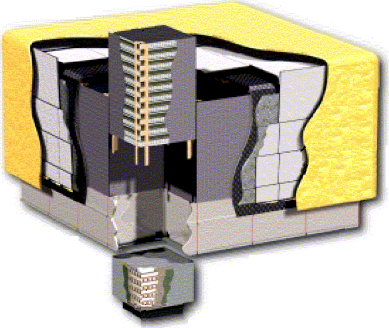
$\approx$ 390 Members ($\approx$ 95 Affiliated Scientists, 68 Postdocs, and 105 Graduate Students)

Construction and operations managed by SLAC, Stanford University

The Large Area Telescope

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 m^2 footprint, 3000 kg weight, 650 W power consumption.



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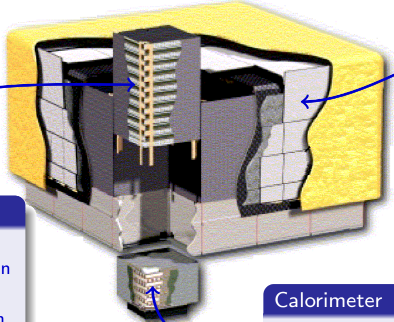

Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis.
- 10k sensors, 80 m^2 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.

The Large Area Telescope

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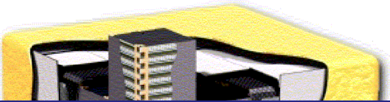


Parameter	EGRET	Fermi LAT	Design
Energy range	20 MeV–30 GeV	20 MeV–> 300 GeV	Hodoscopic calorimeter, segmented ACD
Peak A_{eff}[1]	1500 cm^2	8000 cm^2	$\times$4 geometric area
Field of view	0.5 sr	2.4 sr	Aspect ratio (no TOF)
Angular resolution[2]	5.8° @ 100 MeV	3.5° @ 100 MeV $<$ 0.15° @ 10 GeV	SSD vs. spark chambers
Energy resolution[3]	10%	$<$ 10% @ 0.1–10 GeV	Hodoscopic calorimeter
Dead time per evt	100 ms	26.5 μs minimum	SSD vs. spark chambers

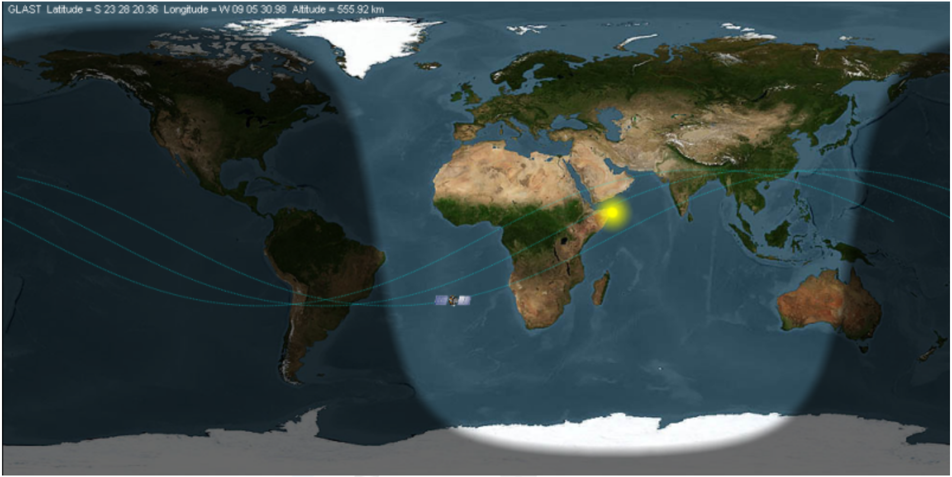
[1] After background rejection.
[2] Single photon, 68% containment, on axis.
[3] 68% containment, on axis.

The launch
Just turned one year old (in orbit)

Launch

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

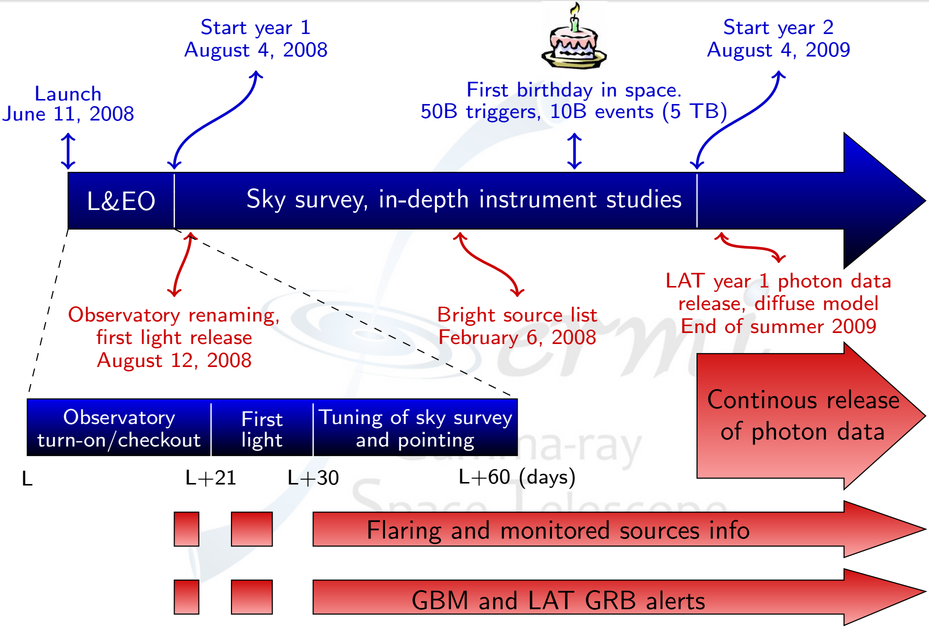
Fermi in orbit

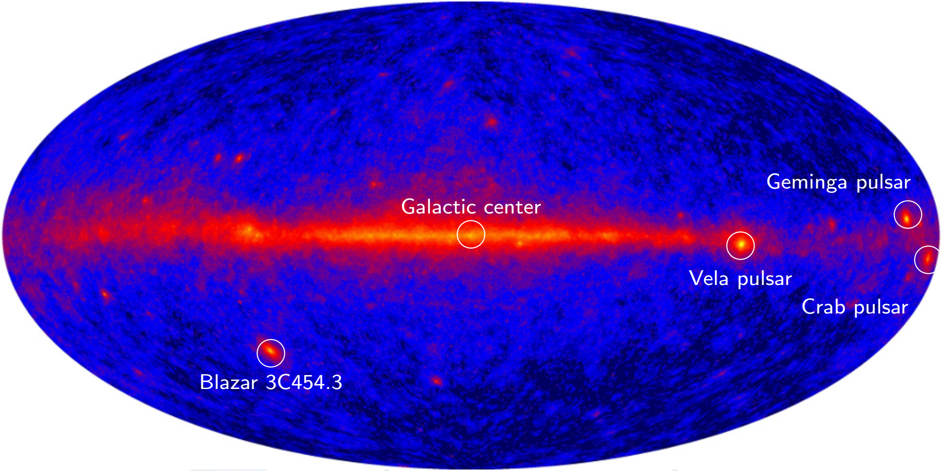


- Track the satellite:

  http://observatory.tamu.edu:8080/Trakker
- Watch Fermi as it orbits over you home town:

  http://www.nasa.gov/mission_pages/GLAST/news/glast_online.html

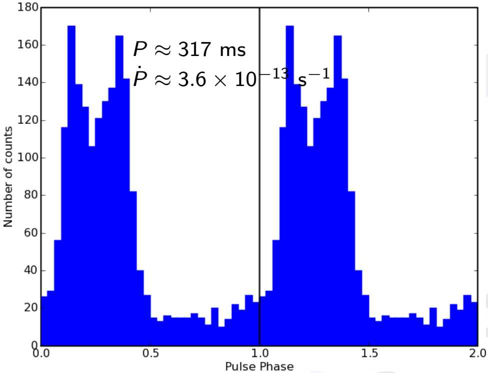

Start year 1
August 4, 2008
Start year 2
August 4, 2009
Launch
June 11, 2008
First birthday in space.
50B triggers, 10B events (5 TB)
L&EO
Sky survey, in-depth instrument studies
Observatory renaming,
first light release
August 12, 2008
Bright source list
February 6, 2008
LAT year 1 photon data
release, diffuse model
End of summer 2009
Observatory
turn-on/checkout
First
light
Tuning of sky survey
and pointing
Continous release
of photon data
L
L+21
L+30
L+60 (days)
Flaring and monitored sources info
GBM and LAT GRB alerts

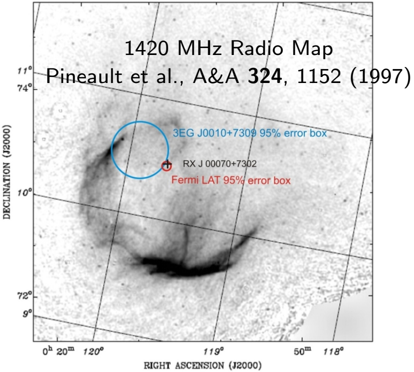


- Released on August 26, 2009, combines four days of observing time (equivalent to ≈ 1 year of observation with EGRET).

The first Gamma-ray only pulsar

Abdo, A. A. et al. 2008, Science, **322**, 1218

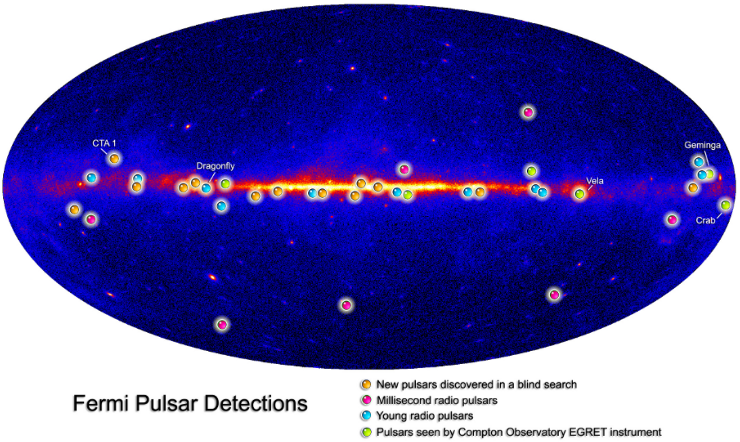




- Radio-quiet pulsar in Super-Nova Remnant CTA1.
  - Abdo et al., Science Express, 16 October 2008, 1$^{\text{st}}$ Fermi Publication.
- Quick discovery made possible by:
  - Large leap in instrument capabilities;
  - New analysis technique (Atwood et al. 2008).

The pulsing sky

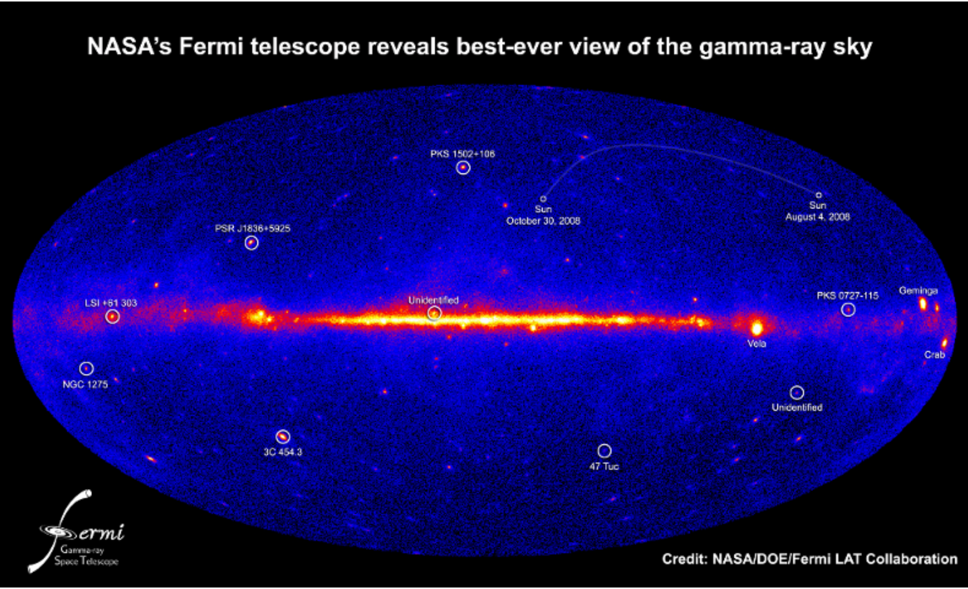
http://www.nasa.gov/mission_pages/GLAST/news/dozen_pulsars.html

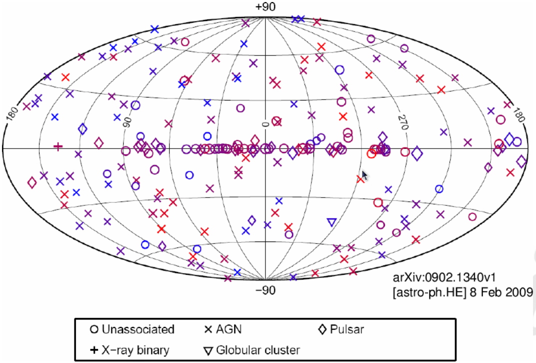


- Press release on January 6, 2009.
  - 12 gamma-ray only pulsars discovered plus 18 radio loud.
- $\approx$ 50 pulsars observed to date.

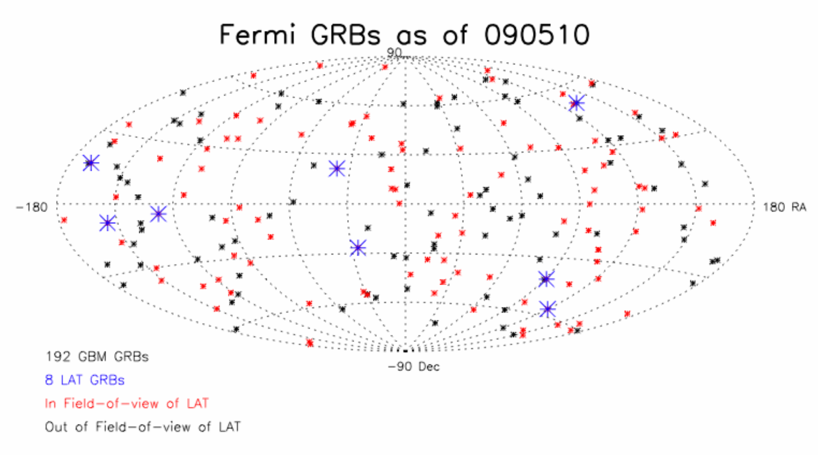
THREE-MONTHS GAMMA-RAY SKY MAP

HTTP://WWW.NASA.GOV/MISSION_PAGES/GLAST/NEWS/GAMMARAY_BEST.HTML

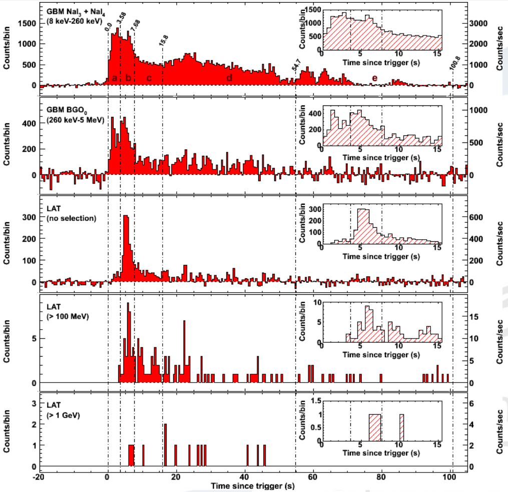




- Based on three months of data (2.8M events above 100 MeV).
- Only sources with C.L. $> 10\sigma$ over this period; includes location, significance, flux, variability, association.
  - Not a catalog—not complete, not flux-limited, not uniform.
- 205 sources (EGRET detected 31 sources above 10σ)
  - 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).

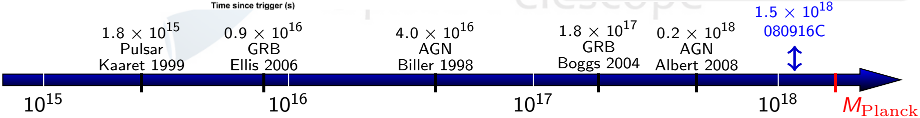


Light curve

- 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 2nd peak moving at later times as energy increases.

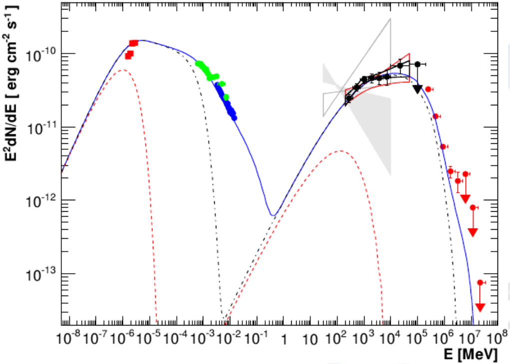
Large fluence, $z = 4.35$ implying:

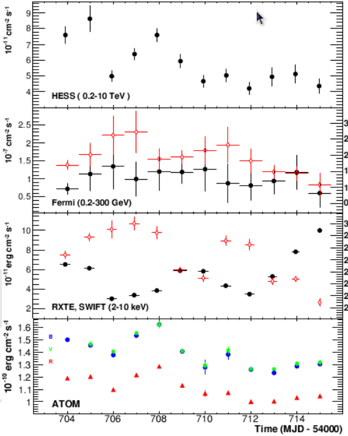
- Largest apparent energy release ever observed: $E_{iso} = 8.8 \times 10^{54}$ erg $\approx 4.9\ M_\odot$.
- Largest bulk Lorenz factor: $\Gamma_{min} = 809 \pm 20$.
- Most stringent limit on the Lorenz invariance mass scale: $M_{QG} > 1.5 \times 10^{18}$ GeV.



Multi-wavelength campaign on PKS 2155-304

Aharonian, F. et al. 2009, ApJL, **696**, L150





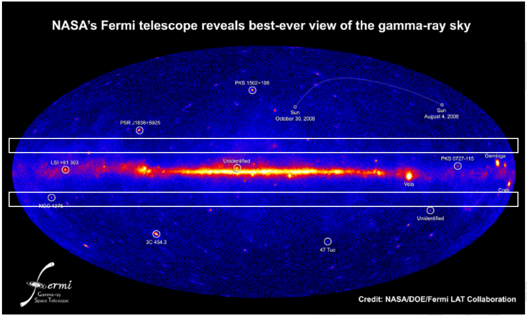
- Simultaneous observations:

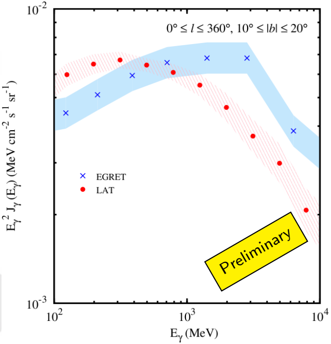
  Fermi-LAT, H.E.S.S., RXTE, Swift, ATOM ($\approx$ 11 days).

- Relatively small variability ($\approx$ 30%), optical/VHE flux and X-ray/HE spectral index correlations.

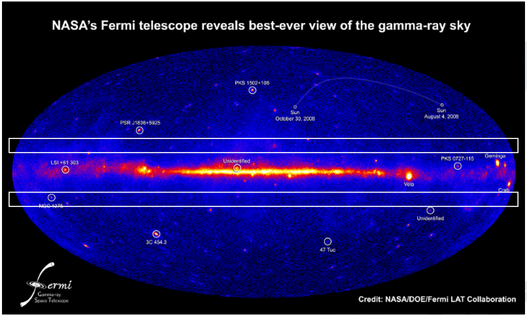
Diffuse gamma: non-GeV excess

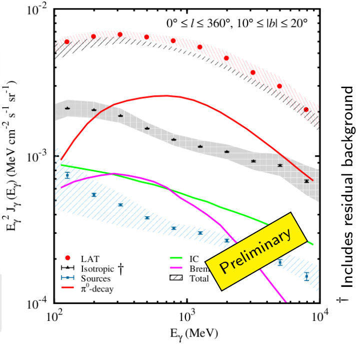
Submitted to PRL





- 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.

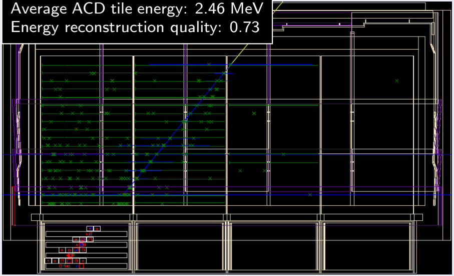
The LAT as an electron detector

Not only gamma rays

- All events with energy (measured on board) greater than 20 GeV are down-linked to ground.
- Peak geometric factor (or *aperture*) close to 3 m^2 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 (*electrons* are really $e^+ + e^-$ hereafter.)

Candidate electron
475 GeV raw energy, 834 GeV reconstructed

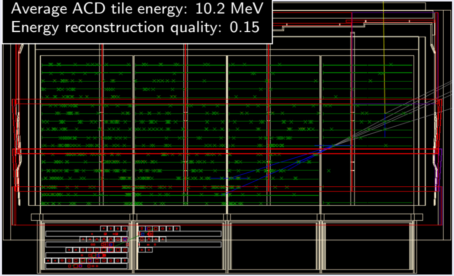
Transverse shower size: 23.2 mm
Fractional extra clusters: 1.48
Average ACD tile energy: 2.46 MeV
Energy reconstruction quality: 0.73



- 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.

Candidate hadron
823 GeV raw energy, 1 TeV reconstructed

Transverse shower size: 34.4 mm
Fractional extra clusters: 0.17
Average ACD tile energy: 10.2 MeV
Energy reconstruction quality: 0.15



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

Event topology

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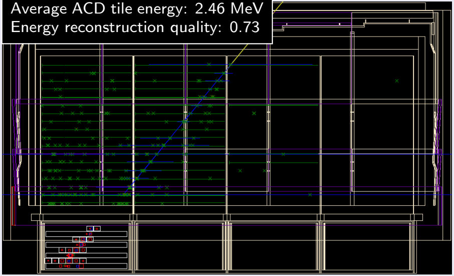

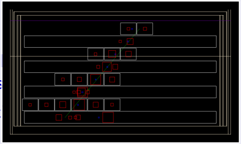

- Clean main track wit
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- Relatively few ACD t
  conjunction with the
- Well defined (not fully contained) symmetric shower in the calorimeter.

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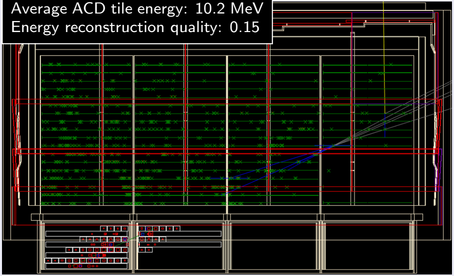
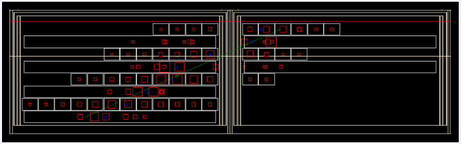
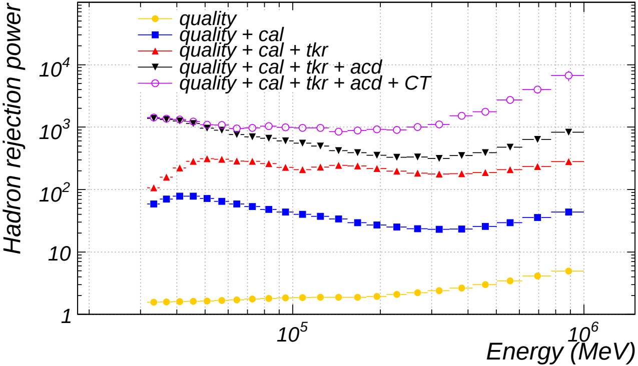




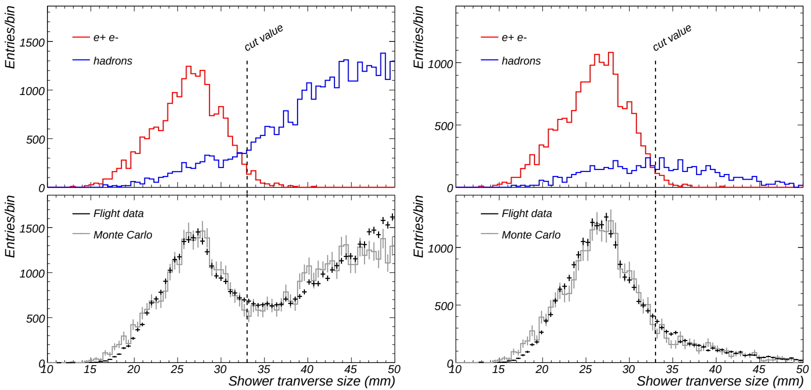
- Large and asymmetric shower profile in the calorimeter.

Event selection: rejection power



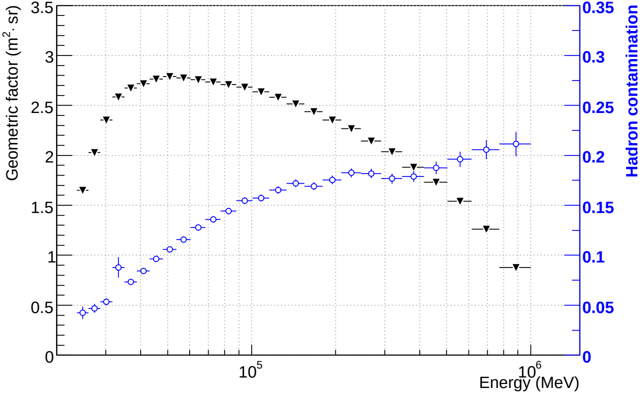
- Three main steps, in which *all* the subsystems contribute.
  - Basic quality cuts (requiring ACD signal to remove gammas)
  - Event topology in the tracker, calorimeter and ACD.
  - Classification tree analysis:
    - input variables for the CT analysis carefully selected;
    - boost at high energy obtained by means of an explicitly energy-dependent cut.

Event selection: validation with flight data
Shower transverse size above 150 GeV

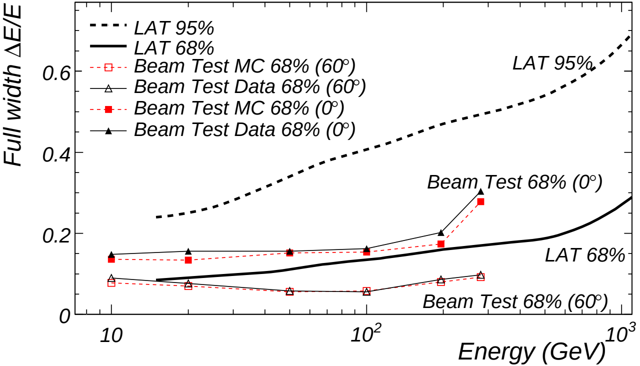


- Data/Monte Carlo comparison routinely performed for:
  - all variables involved in the selection;
  - at different stages of the selection.
- Residual discrepancies propagated to the spectrum *for each energy bin* and included into the systematics.

Event selection: figures of merit

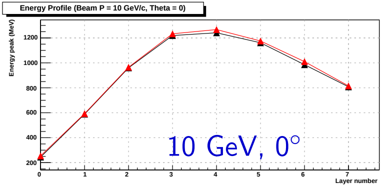


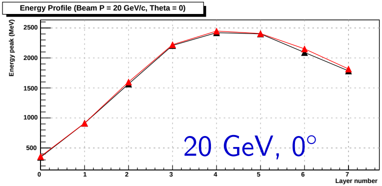
- Peak geometric factor of 2.8 m^2 sr, 2 m^2 sr at 300 GeV.
- Estimated residual hadron contamination ≈ 5–20%;
  - subtracted from the candidate electrons.
- Trade-off between electron efficiency, residual contamination and control of systematic uncertainties.

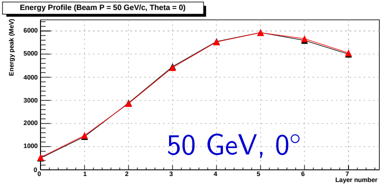


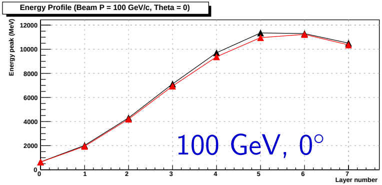
- Validated with the Calibration Unit beam tests up to 280 GeV.
  - Excellent agreement over the whole (energy, angle, position) phase space.
  - We have a solid ground in extrapolating to 1 TeV.
- Our energy dispersion is adequate for the measurement.
  - Candidate electrons traverse 12.5 X_0 on average.

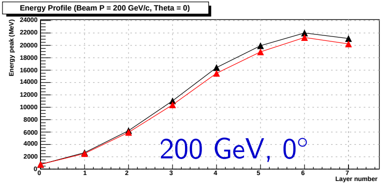
Shower profile: Monte Carlo vs. beam test
Electron beams, on axis

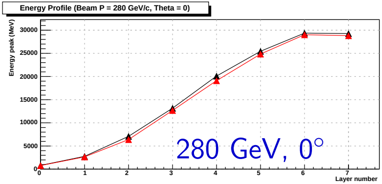


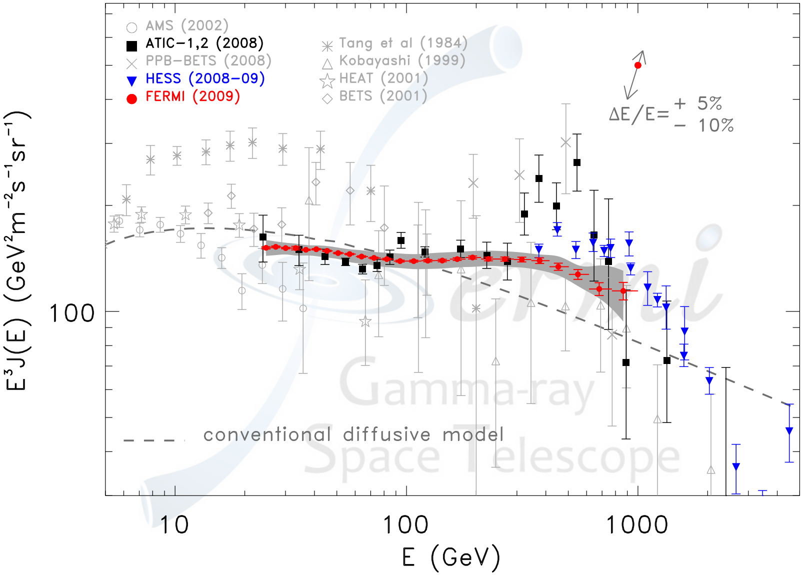




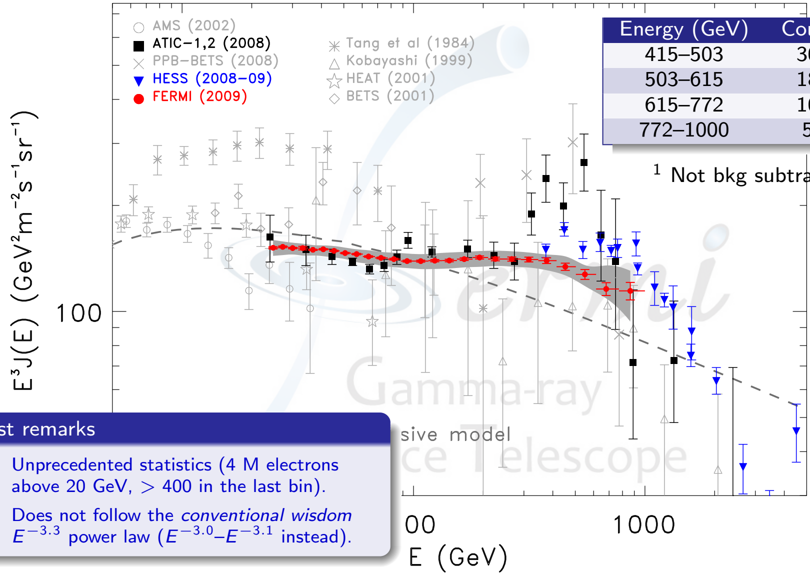








AMS (2002)
ATIC−1,2 (2008)
PPB−BETS (2008)
HESS (2008−09)
FERMI (2009)
Tang et al (1984)
Kobayashi (1999)
HEAT (2001)
BETS (2001)
ΔE/E= + 5% − 10%
conventional diffusive model
$E^3J(E)$ (GeV^{2}m^{-2}s^{-1}sr^{-1})
100
10
100
1000
E (GeV)
Gamma-ray Space Telescope



Energy (GeV)	Counts[1]
415–503	3036
503–615	1839
615–772	1039
772–1000	544

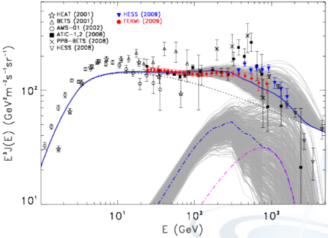
[1] Not bkg subtracted.

First remarks

- 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).

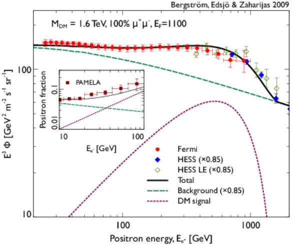
Pulsars

Grasso et. al 2009



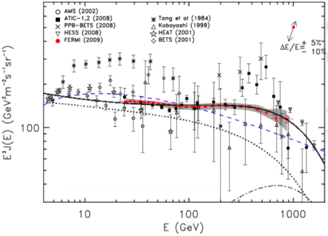
Dark matter annihilation (or decay)

Bergström et. al 2009



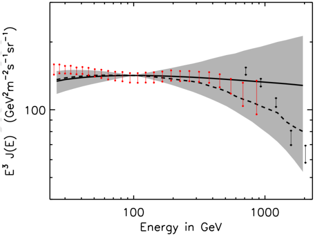
Secondary production in the CR sources

Blasi 2009



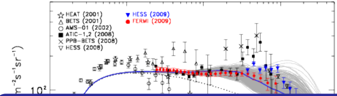
Source stocasticity

Grasso et. al 2009



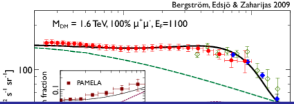
Pulsars

Grasso et. al 2009



Dark matter annihilation (or decay)

Bergström et. al 2009



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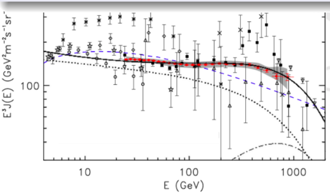
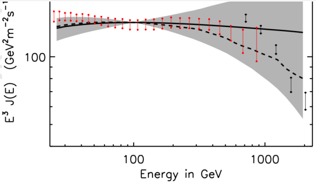
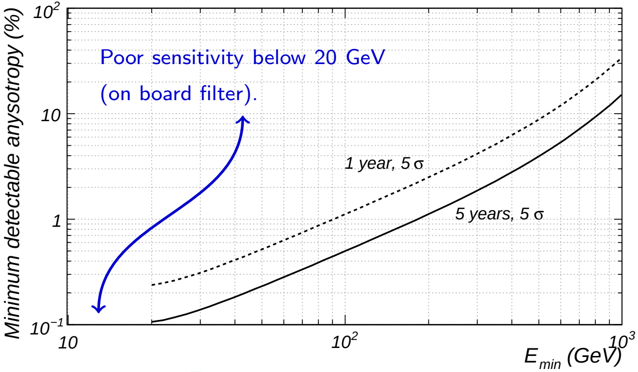
Bottomline

- 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.

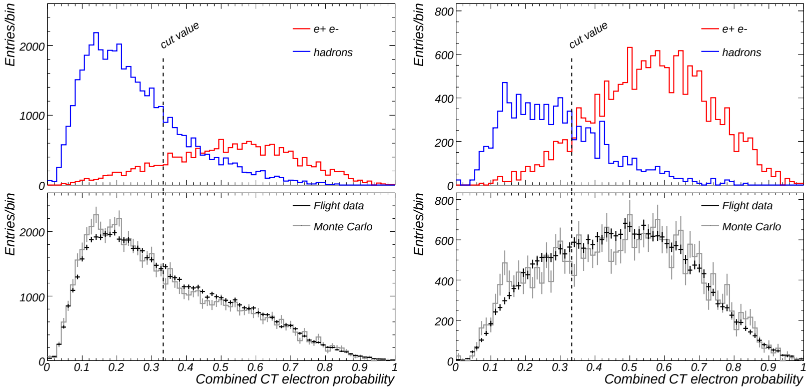
Spare slides

Trigger and filter

- 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).

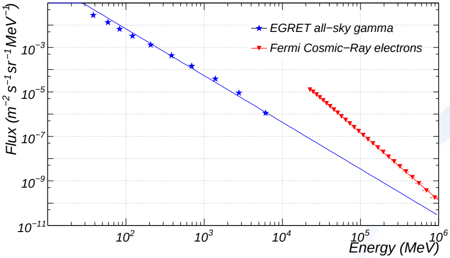
Monte Carlo validation with flight data

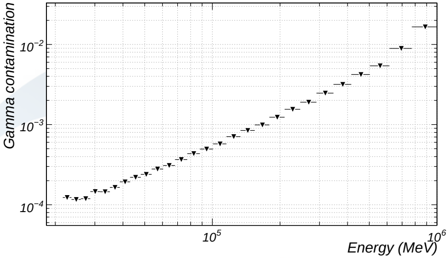
CT combined electron probability above 150 GeV



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

$$p_{\rm comb} = k\sqrt{p_{\rm tkr} \cdot p_{\rm cal}}/(\log E - \log E_0)$$

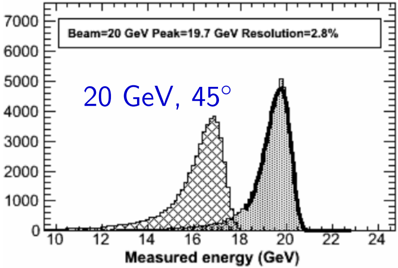


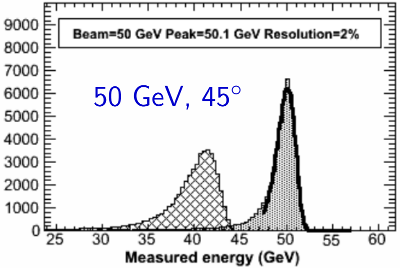


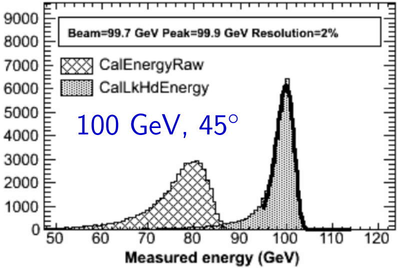
- Conservative estimate from the EGRET all-sky average gamma-ray intensity.
  - Galactic background not an issue (spectral index -2.7).
  - Extra-galactic background falls like $E^{-2.1}$
- Naive extrapolation yields a $\gamma/(e^{+}+e^{-})$ of 20% at 1 TeV.
  - Does not take into account the EBL absorption.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

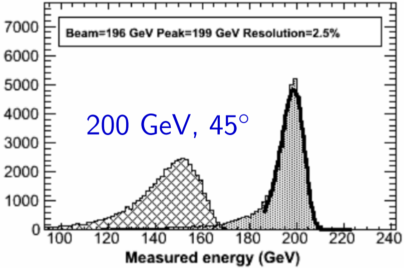
Energy resolution: validation with beam test

Electrons at 45°



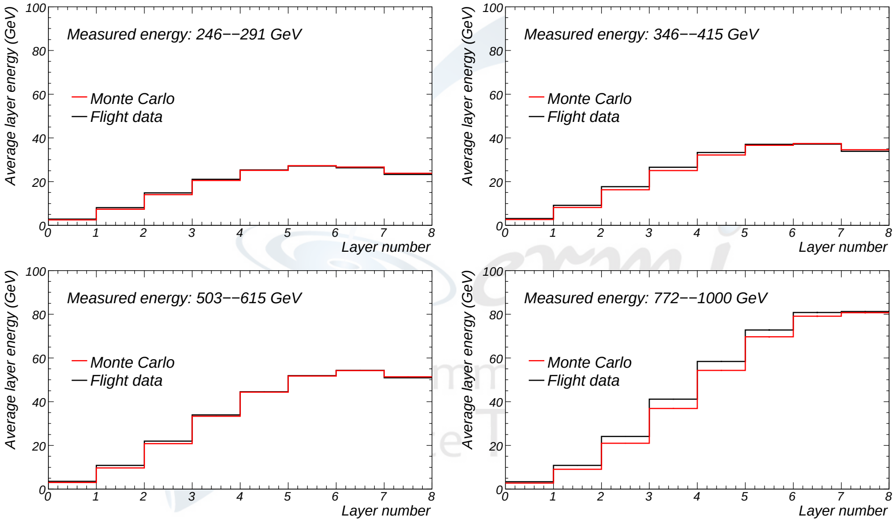






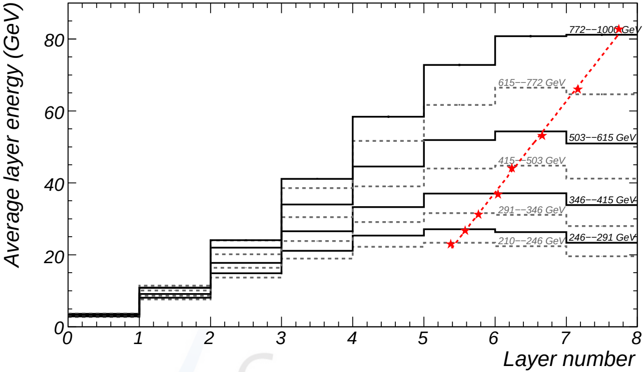
Shower profile: Monte Carlo vs. flight data

After the electron selection, integrated over all angles



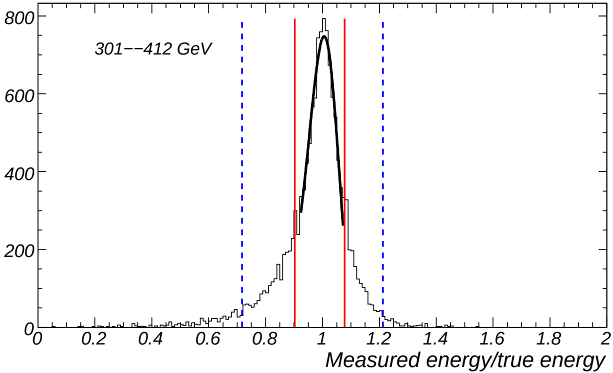
Shower profile: flight data

After the electron selection, integrated over all angles

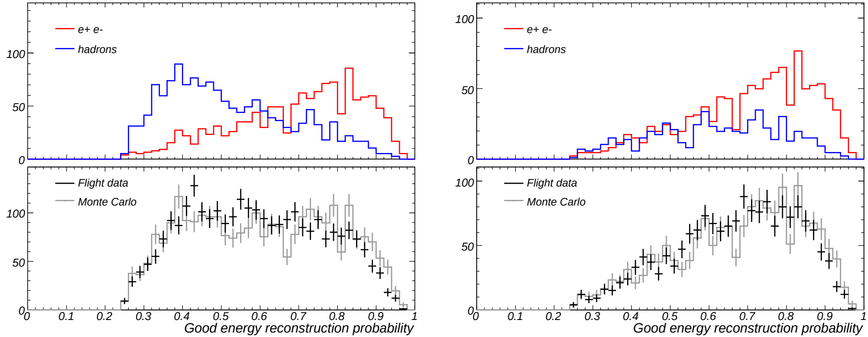


- Showers of different energies look different in the detectors (i.e. can be distinguished).
- The shower maximum at 1 TeV is at 11.5 X_0 (candidate electrons traverse $\approx$ 12.5 X_0).

Energy reconstruction quality



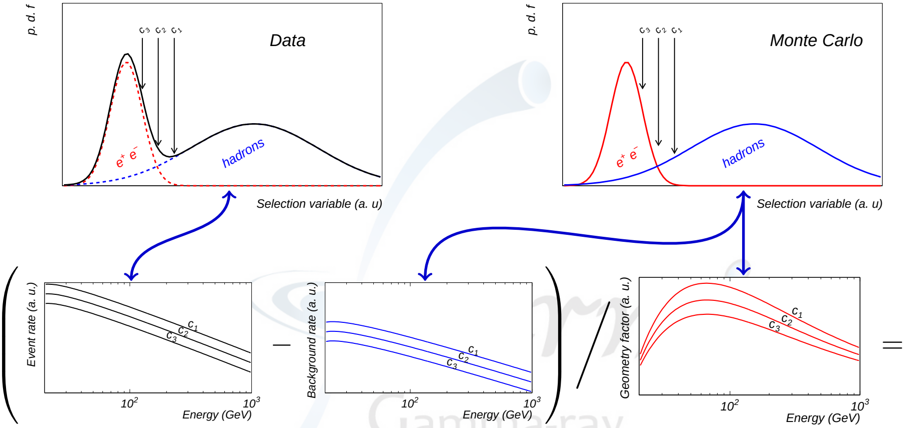
- *Probability of good energy reconstruction*: diagnostic output of our energy analysis.
  - A CT is trained to identify events in the core of the energy dispersion.

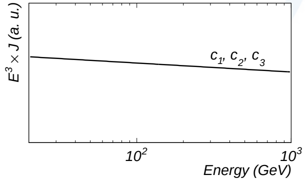


- Distribution of the *probability of good energy reconstruction* provided by the standard energy classification tree analysis.
- Events above 400 GeV at two different stages of the selection.

Sources of systematic errors

- 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 $\simeq$ 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%)

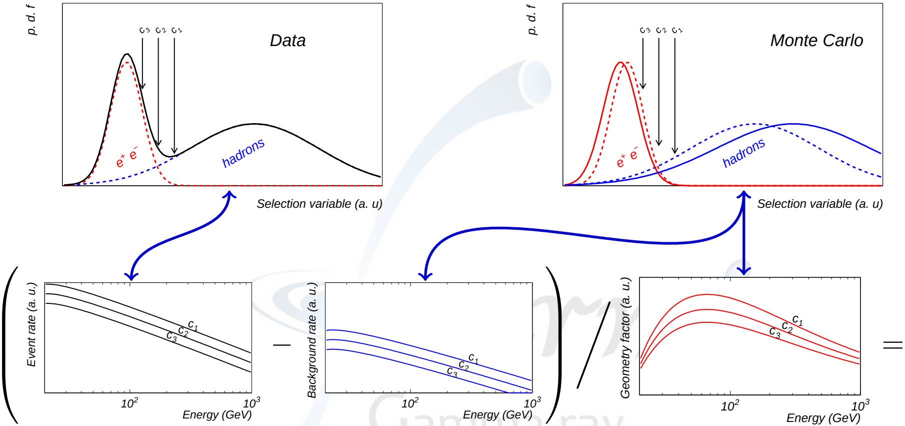


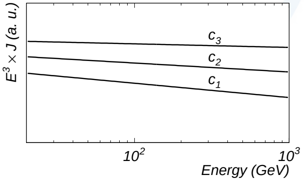


Evaluating the systematics

- If the data/MC agreement was perfect, the actual spectrum would not depend on the cut values.

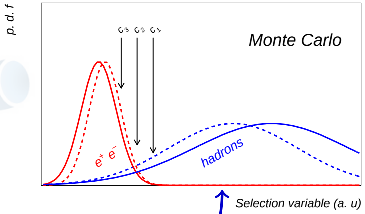
Evaluation of the systematic uncertainties

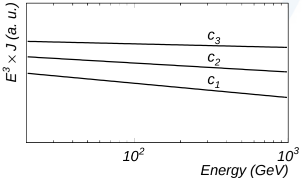




Evaluating the systematics

- In real life data/MC discrepancies introduce such a dependence.

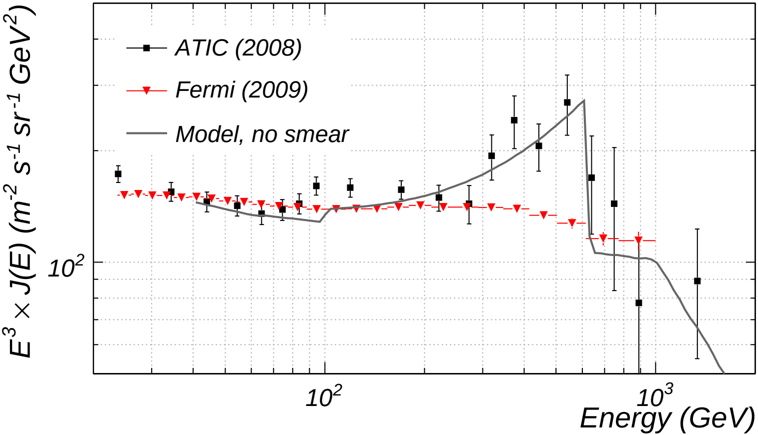




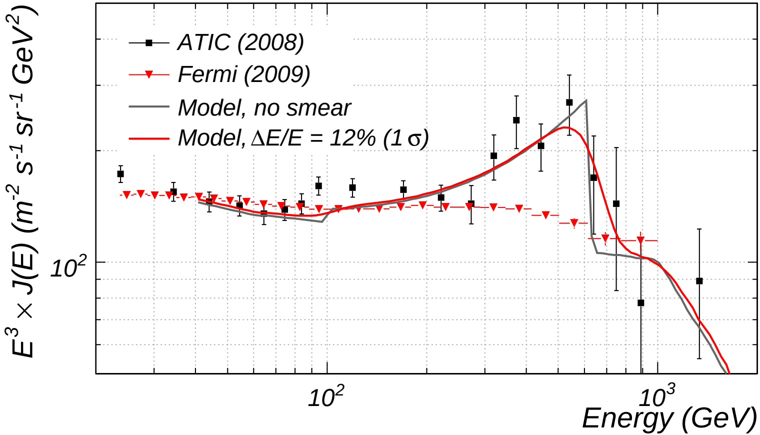
Evaluating the systematics

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

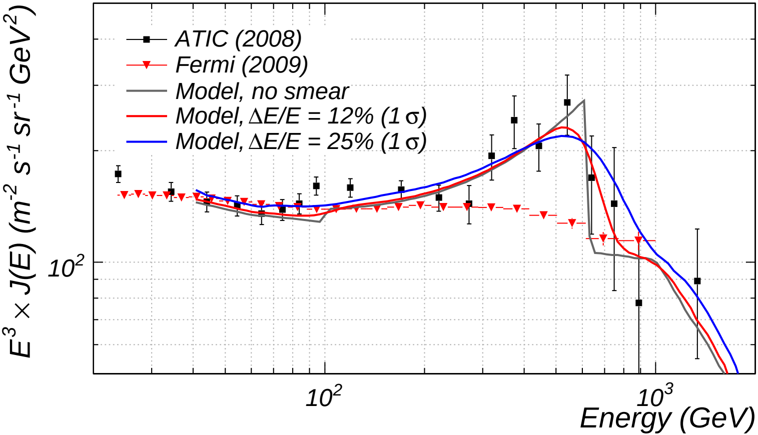
Energy resolution and spectral features



- 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.



- 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.



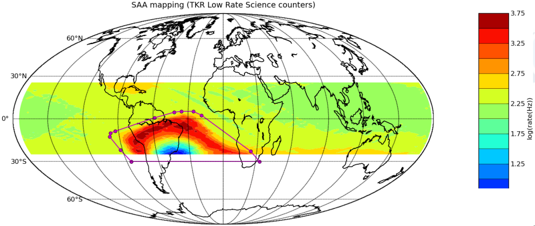
- Model adapted from Chang et al. 2008:
  - broken power law with $\Gamma = -3.1$ below 1 TeV, -4.5 above;
  - harder ($\Gamma = -1.5$) feature with break at 620 GeV.
- 12% is a conservative estimation for Fermi in the 100s GeV.

Significance of the bump around ≈ 500 GeV

- It crucially depends on the point-to-point correlation matrix between the systematic errors $C_{ij} = \left\langle \Delta_i^{\rm sys} \Delta_j^{\rm sys} \right\rangle$:
  - $C_{ij} \propto 1 \quad \forall i,j$: 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.

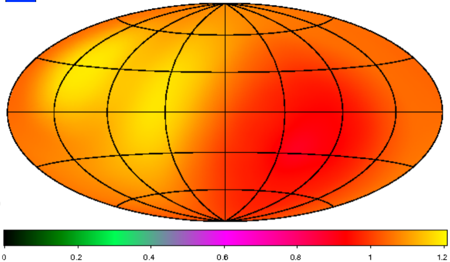
Measurements of anisotropies: systematics

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.