# Measurement of the high energy cosmic ray electron spectrum with the Fermi Large Area Telescope

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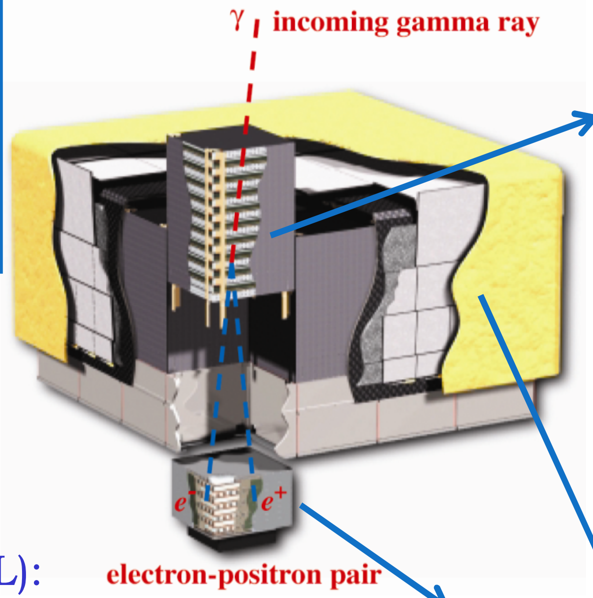
on behalf of the Fermi-LAT Collaboration

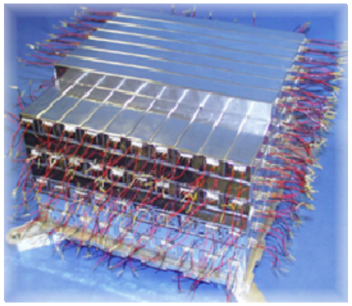
# The Fermi Large Area Telescope (LAT)

**The LAT is a pair conversion γ-ray telescope and is arranged in a 4×4 array of 16 identical towers**



Tracker/Converter (TKR):
- ➢Si-strip detectors
- ➢~ 80 $m^2$ of silicon
- ➢W conversion foils
- ➢1.5 $X_0$ on-axis
- ➢18 X-Y planes
- ➢~ $10^6$ channels
- ➢Highly granular
- ➢High precision tracking

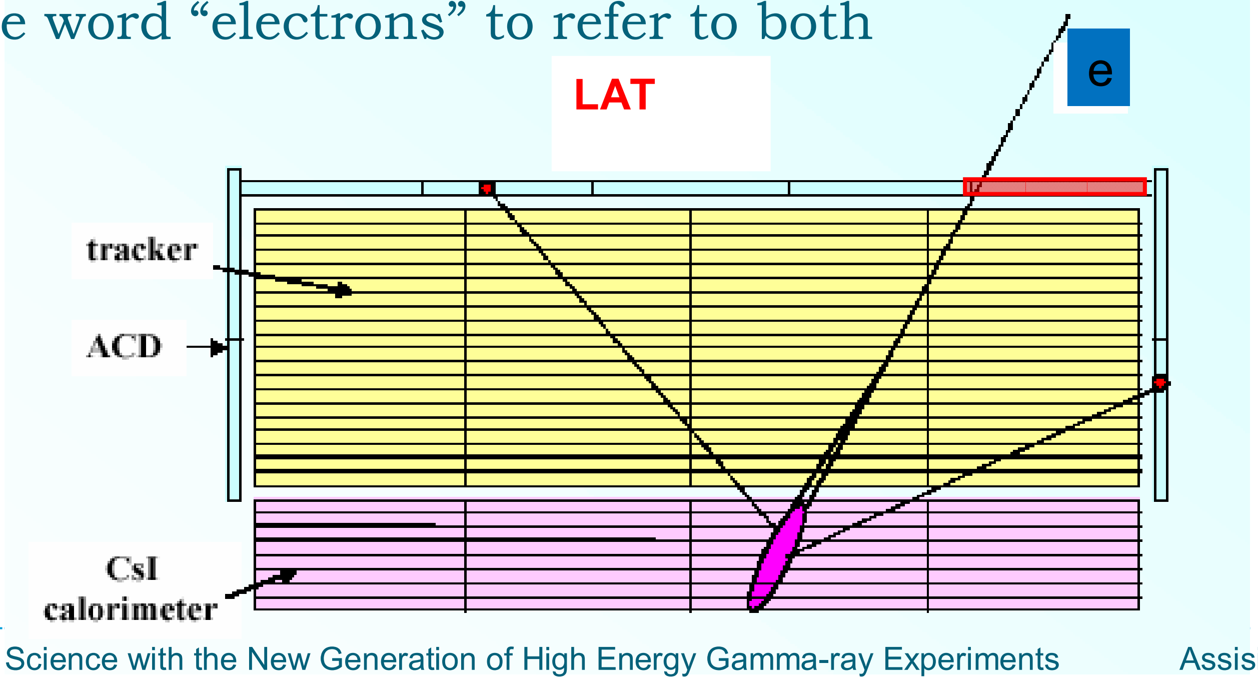
Calorimeter (CAL):
- ➢1536 CsI(Tl) crystals
- ➢8.6 $X_0$ on-axis
- ➢2 PIN-PD per Xtal end
- ➢large dynamic range per crystal (2MeV-60GeV)
- ➢Hodoscopic (8 layers with 12 crystals)



Anti-Coincidence Detector (ACD):
- ➢Segmented (89 tiles)
- ➢Limited self-veto @ high energy
- ➢0.9997 detection efficiency

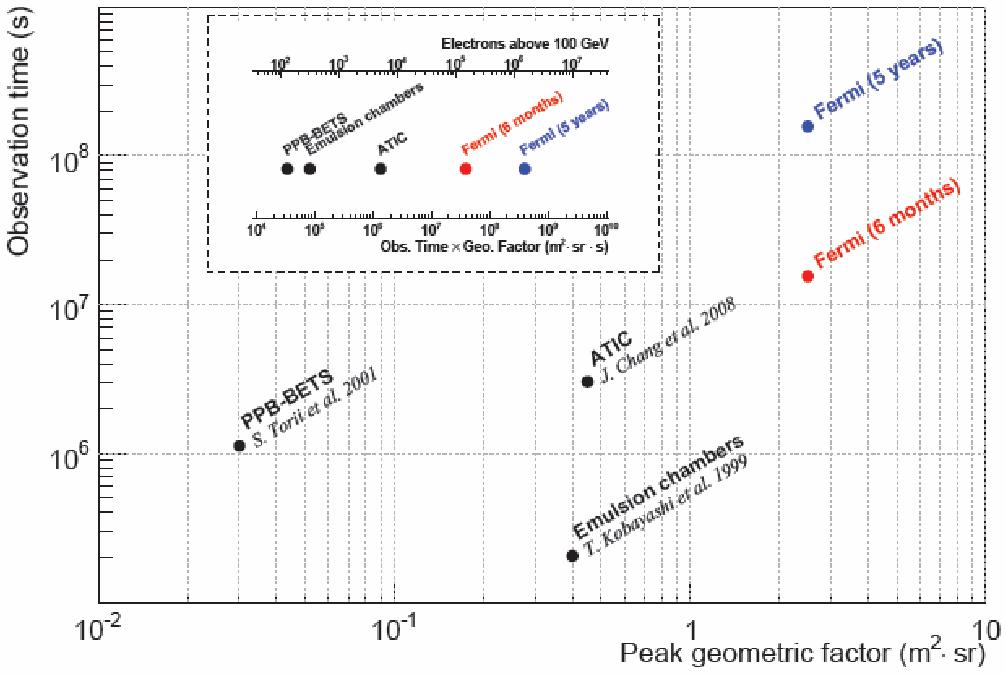
# The LAT is an electron telescope!

- Gamma-ray detection:
  - Look for an electromagnetic cascade
  - Reject charged particles
- Electron detection:
  - Also an electromagnetic cascade! (Loosen charge veto, tighten the other cuts)
  - Fermi-LAT does not distinguish between $e^-$ and $e^+$, we use the word “electrons” to refer to both



# The LAT as an electron observatory

- Both photons and electrons (positrons) interact in the matter generating EM showers
  - the LAT is also an $e^+/e^-$ detector!
- Huge field of view:
  - the LAT observes 20% of the sky at any time
  - all parts of the sky are observed for 30 minutes every 3 hours
- Huge observation time:
  - mission lifetime: 5yr planned, 10yr expected
  - ~85% duty cycle in 9 months (SAA) + 8%instrument dead time
- High efficiency for electrons above 20GeV
  - on board filter records events with energy deposits larger than 20GeV

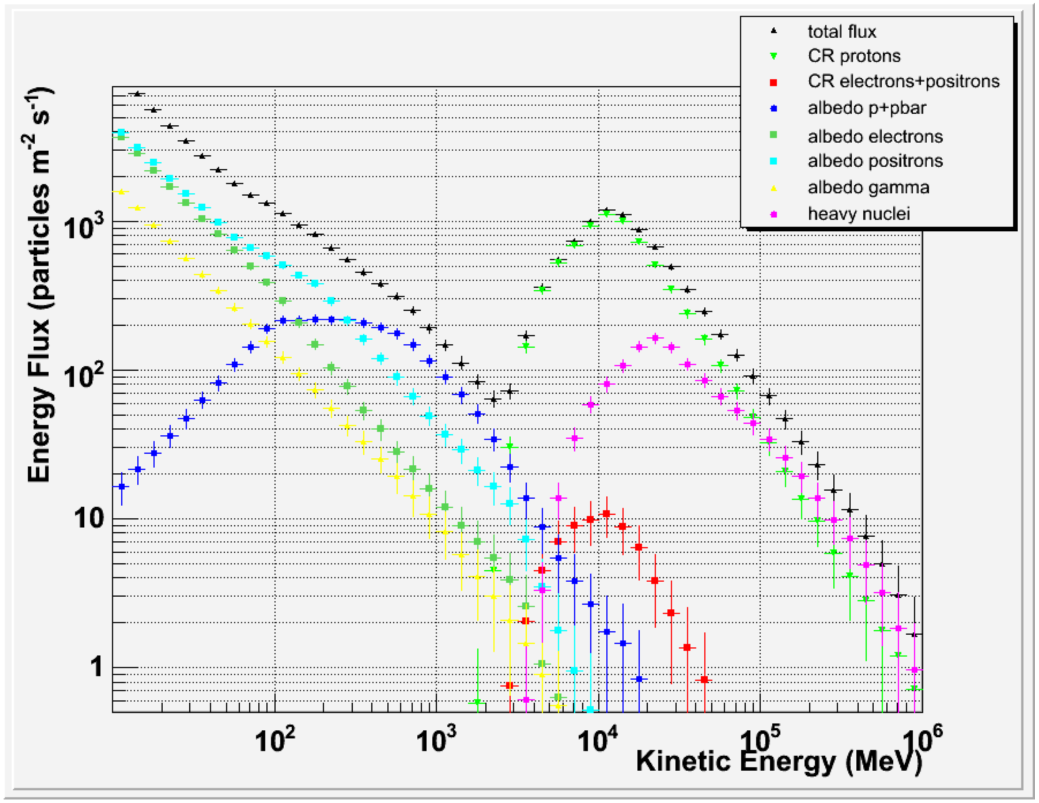


# LAT Trigger and Filter

- **Five hardware trigger primitives (at the tower level)**
  - **TKR:** 3 x + 3 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:** the purpose is to select $\gamma$-ray candidates and events that deposit at least 20 GeV in the CAL
    - High energy events, including electrons, are available for analysis on the ground
  - **Heavy Ions:** the purpose is to perform calibration on high-energy scales;
  - **Diagnostic:** the purpose is to select an unbiased event sample for filter and background performance studies
  - **MIP:** the purpose is to select non interacting charged particles (protons)

# On-orbit environment simulation

- A full Monte Carlo simulation of the on-orbit environment has been developed:
  - fluxes in the model fit previous experimental data
  - effects of Earth magnetic field included
- The on-orbit model has been used for:
  - optimize the event selection
    - identify quantities sensitive to discriminate between EM and hadronic showers
    - provide the background sample for event selection
  - verify simulation with flight data
    - data/MC comparison with realistic fluxes
  - calculate residual hadron background



# Cosmic ray electron simulation

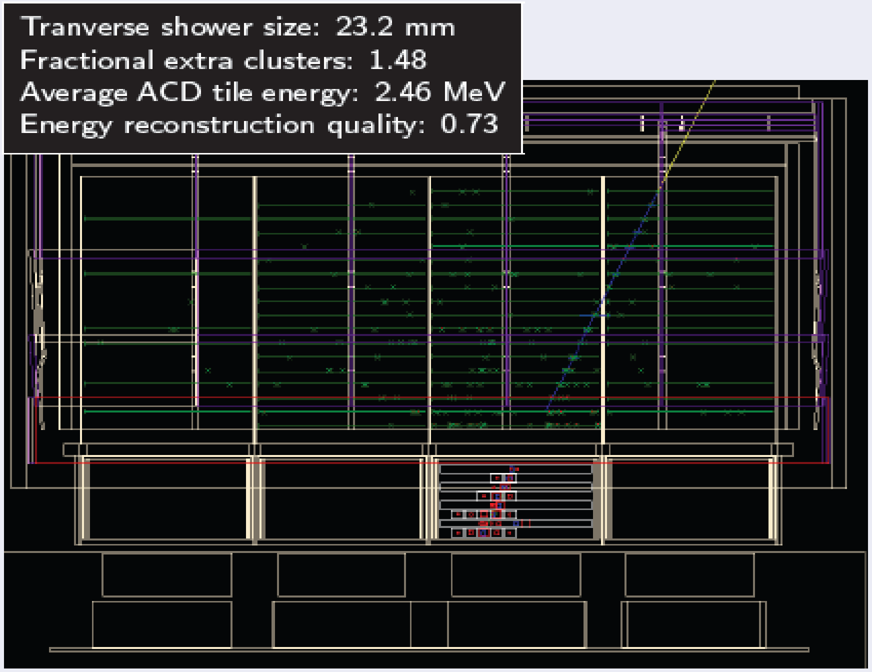
- A dedicated electron simulation has been also implemented
  - isotropic flux
  - dN/dE ~1/E
- The electron sample has been used for:
  - optimize the event selection
    - provide the signal sample for event selection
  - evaluate the LAT performance and response function
    - geometric factor
      - ☐ includes selection efficiency
    - energy dispersion
      - ☐ smearing matrix used for flux deconvolution

# Event selection

- The electron selection essentially relies on the LAT capability to discriminate electromagnetic (EM) from hadronic showers based on their longitudinal and lateral development, as measured by both the TKR and CAL detectors
  - EM showers start developing in the TKR, while most of the energy is absorbed in the CAL
  - The measurement of the lateral shower development is a powerful discriminator between more compact EM showers and wider hadronic showers
- The selection must find the best trade-off between hadron rejection power and electron identification efficiency
- The event selection follows three main steps:
  - Basic quality cuts (requiring ACD signal to remove gammas)
  - Event topology in the tracker, calorimeter and ACD
  - Classification tree analysis:
    - Separate analysis for tracker and calorimeter
    - Combined at the end to boost the rejection at high energy
    - Energy dependent

# Event topology

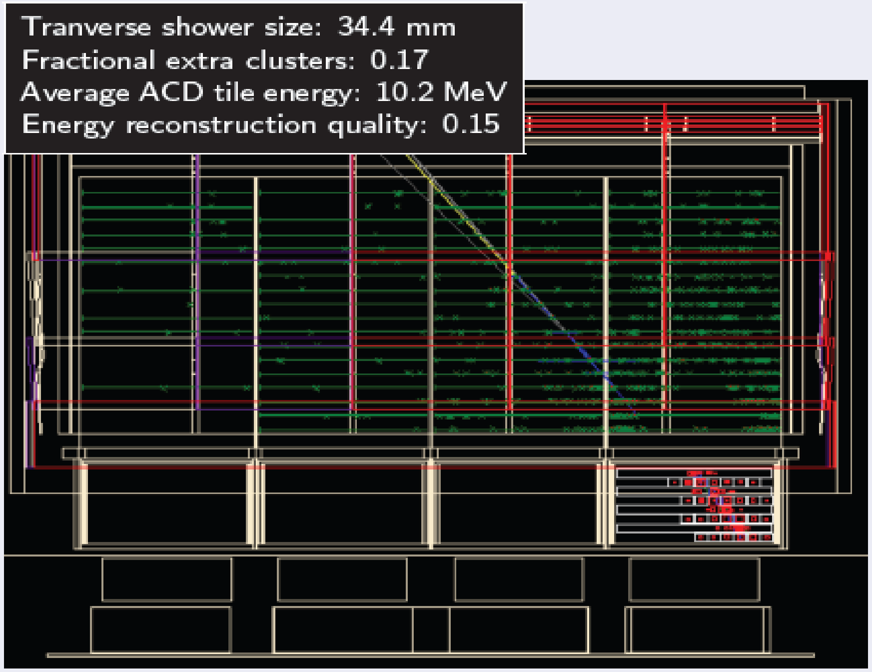
**Candidate electron**
**475 GeV raw energy, 834 GeV reconstructed**



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

- Well defined (not fully contained) symmetric shower in the calorimeter.
- 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**



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

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

# Basic quality cuts

- Quality cuts:
  - Gamma Filter
  - Trigger coincidence from ACD, TKR and CAL
  - at least one ACD tile fired
  - at least 20GeV deposited in the CAL
  - path length of at least $7X_0$ in the CAL
  - at least one reconstructed track in the TKR with angle <72° with respect to the LAT *z*-axis
  - angle with local zenith <105° to reject Earth albedo particles

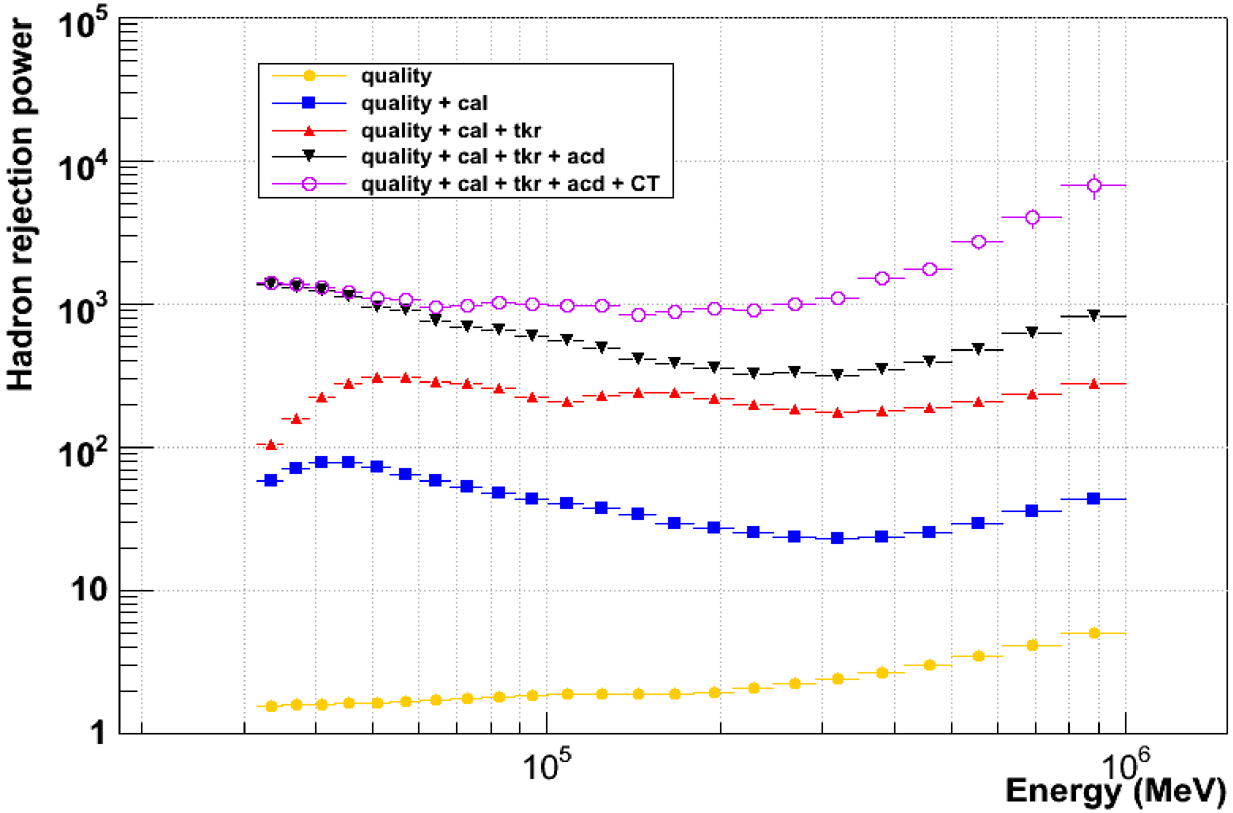
# Topology cuts

- ACD:
  - energy deposit in the ACD tiles consistent with a single charged particle
- TKR:
  - most TKR clusters must be located in the region around the main track
  - average Time Over Threshold (TOT) larger than the expected value for a single charged particles
- CAL:
  - narrow energy distribution in the CsI crystals around the shower axis

# Classification tree analysis

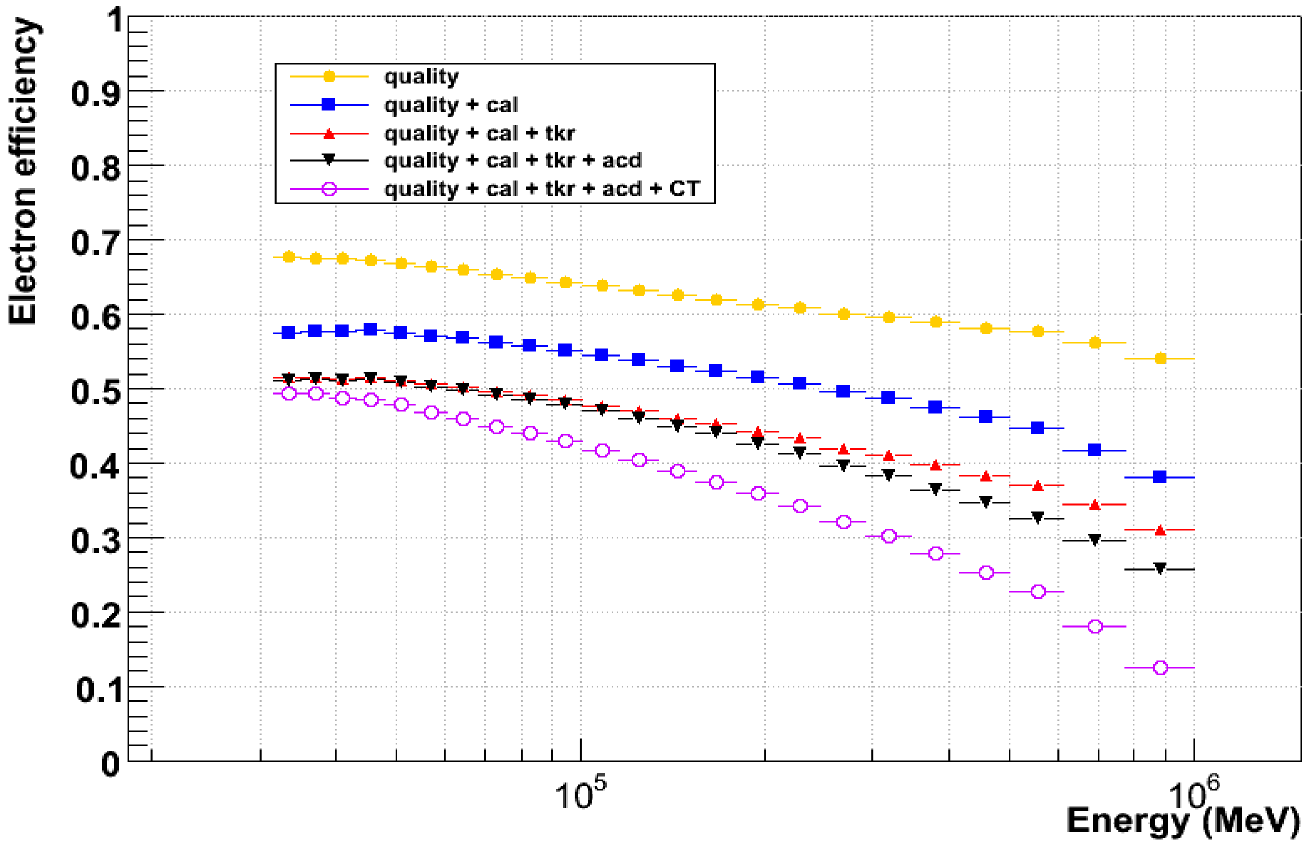
- Two classification trees are built to distinguish between EM and hadronic events
  - A first CT is based on the TKR variables
  - A second CT is based on the CAL variables
- The TKR and CAL electron probabilities are combined
- An energy dependent selection is performed

# Hadron rejection power



- The hadron rejection power is better than $10^3$ up to 200GeV and rises to ~$10^4$ at 1TeV, compensating for the increasing hadron/electron flux ratio

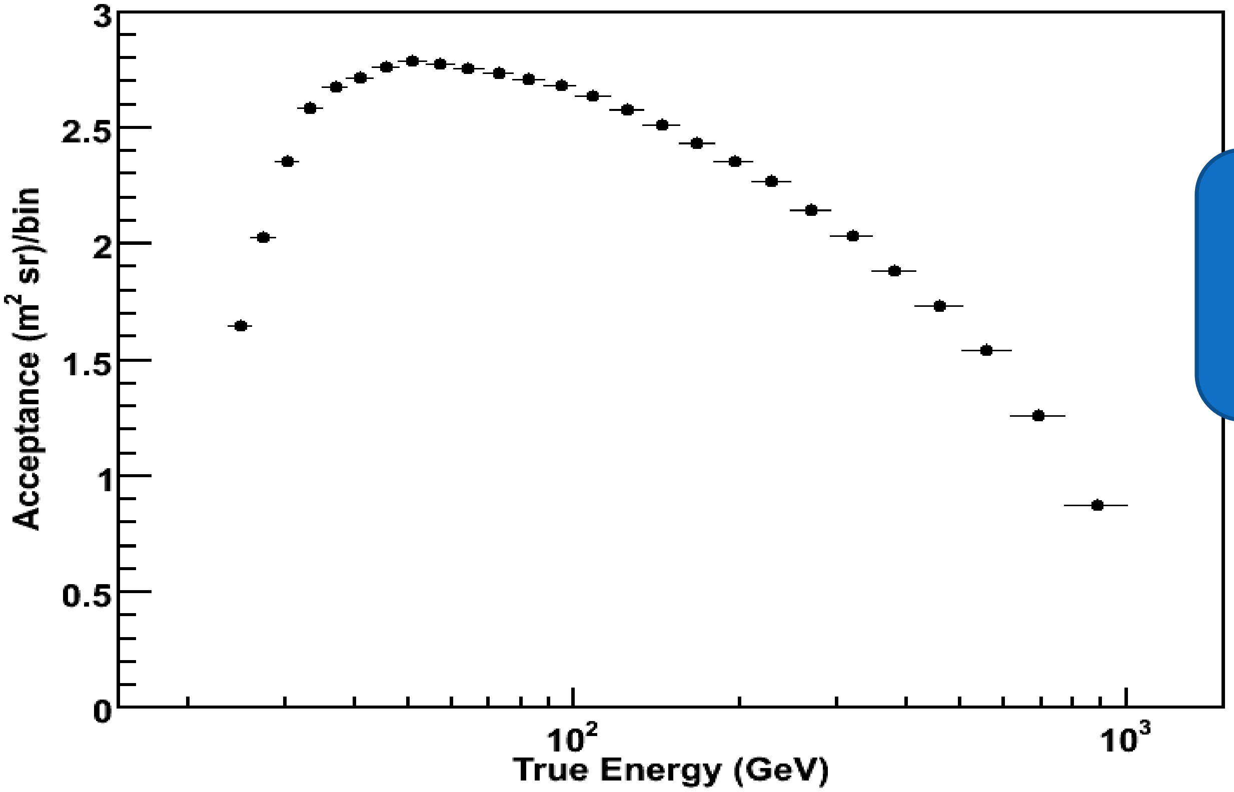
# Electron identification efficiency



- The efficiency is defined as the fraction of events passing the on board filter that are identified as electrons

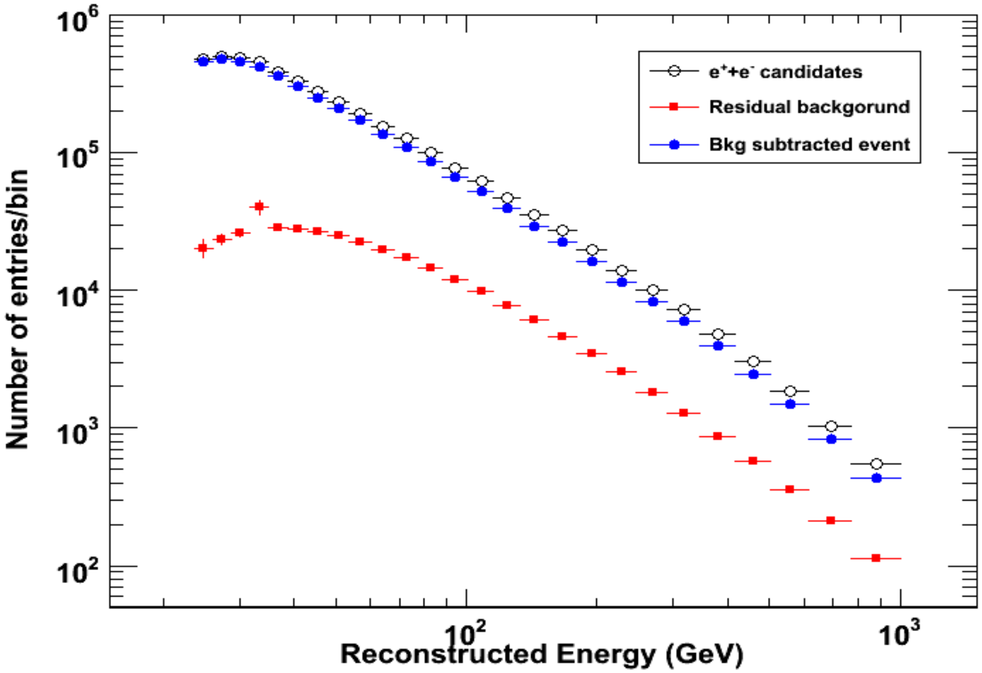
# Effective geometry factor

$$\mathrm{G.F.} = \frac{\text{rate of selected events } [\mathrm{s}^{-1}]}{\text{incident flux } [\mathrm{m}^{-2}\mathrm{sr}^{-1}\mathrm{s}^{-1}]}$$



- 2.8 $m^2$sr @ 50 GeV
- 2 $m^2$sr @ 300 GeV
- ~ 1 $m^2$sr @ 1 TeV

# Observed count spectrum



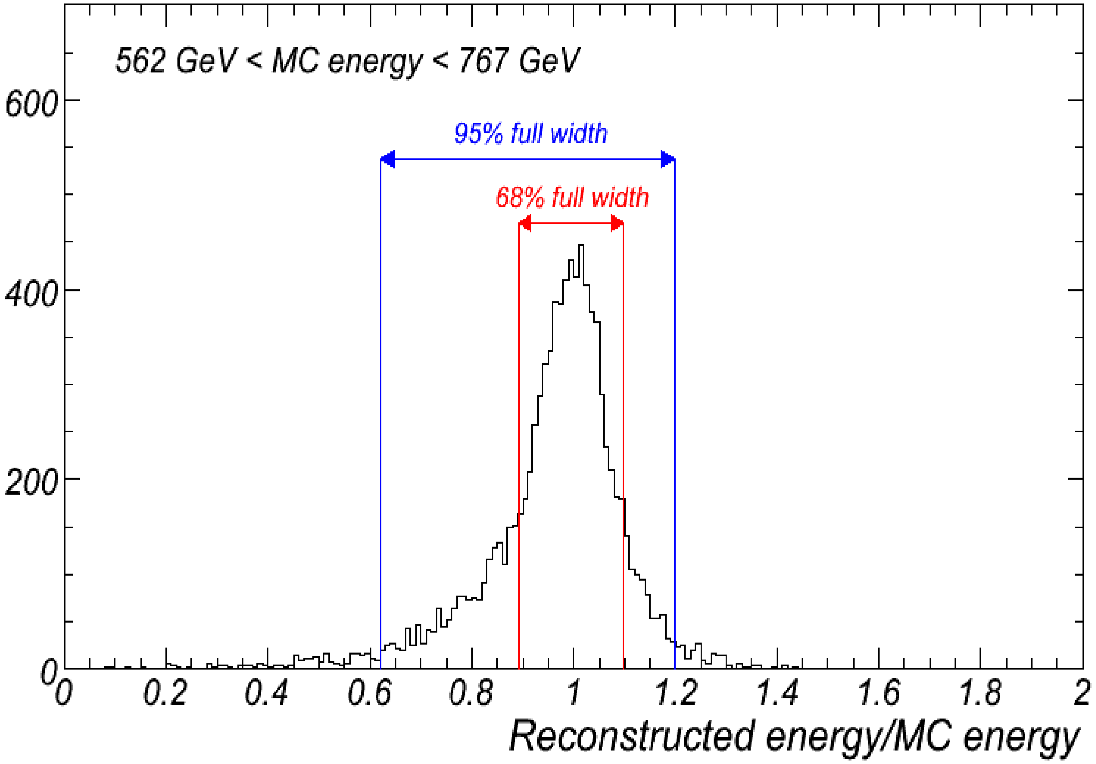
- Data collected in the first six months of operation
  - 4 M candidate electron events above 20 GeV
  - 544 events before background subtraction in the last energy bin
- The residual hadronic background has been estimated from the average rate of hadrons that survive electron selection in the simulations

# From counts to flux

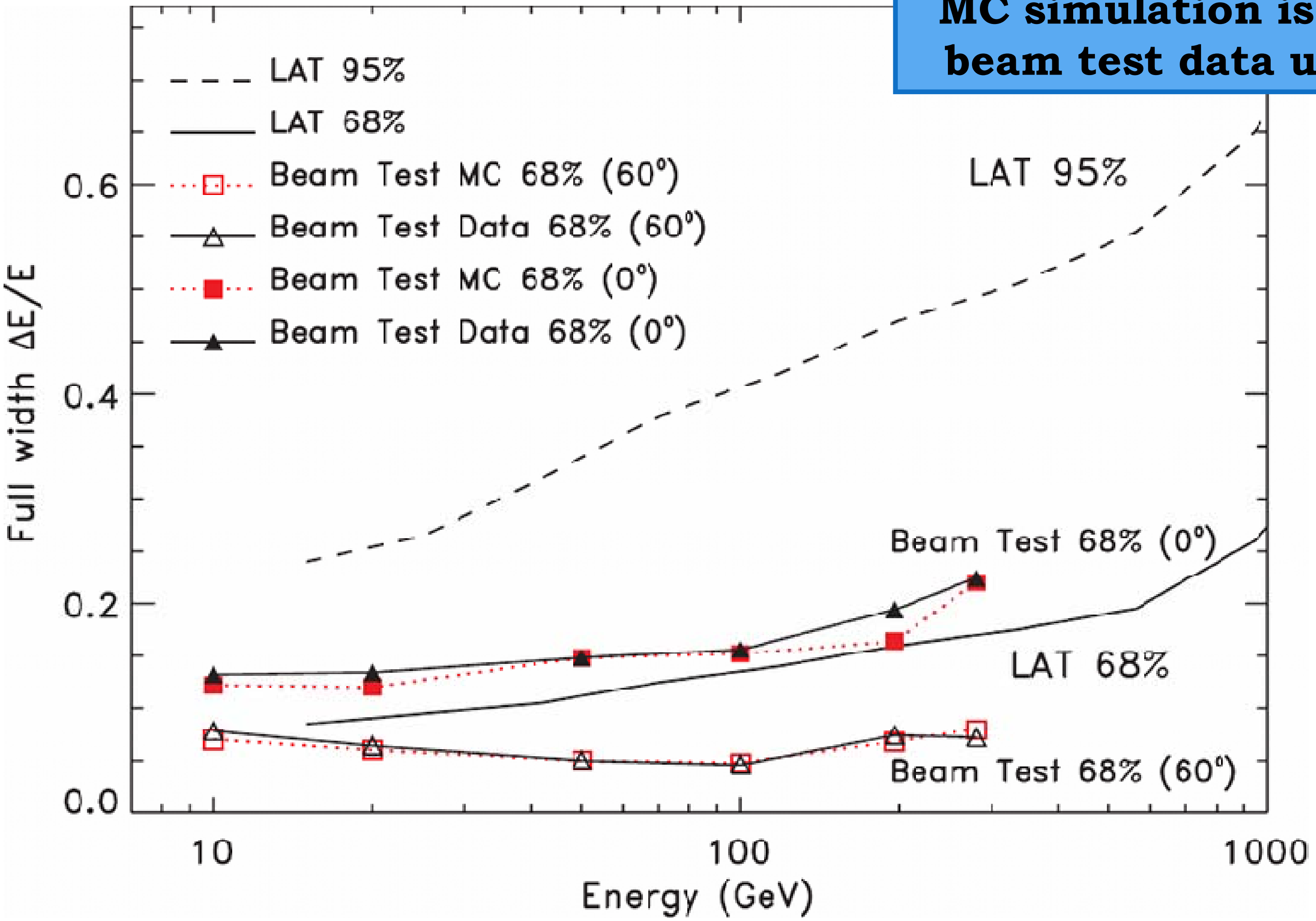
- The electron/positron flux is evaluated by correcting the observed number of events with the instrument response function
- In absence of energy dispersion (i.e. the true and the reconstructed energy are the same) the flux could be evaluated simply by dividing the number of observed counts by the detector acceptance
- On the other hand, to include the finite energy dispersion effect the flux is evaluated using a deconvolution (unfolding) method
  - In the present analysis we used a Bayesian unfolding method

# Energy resolution (1)

- Energy dispersion must be taken into account when reconstructing the true electron flux from the observed one
- It is estimated studying the ratio reconstructed energy/true energy
  - energy resolution = full width of the smallest window that contains 68% of events



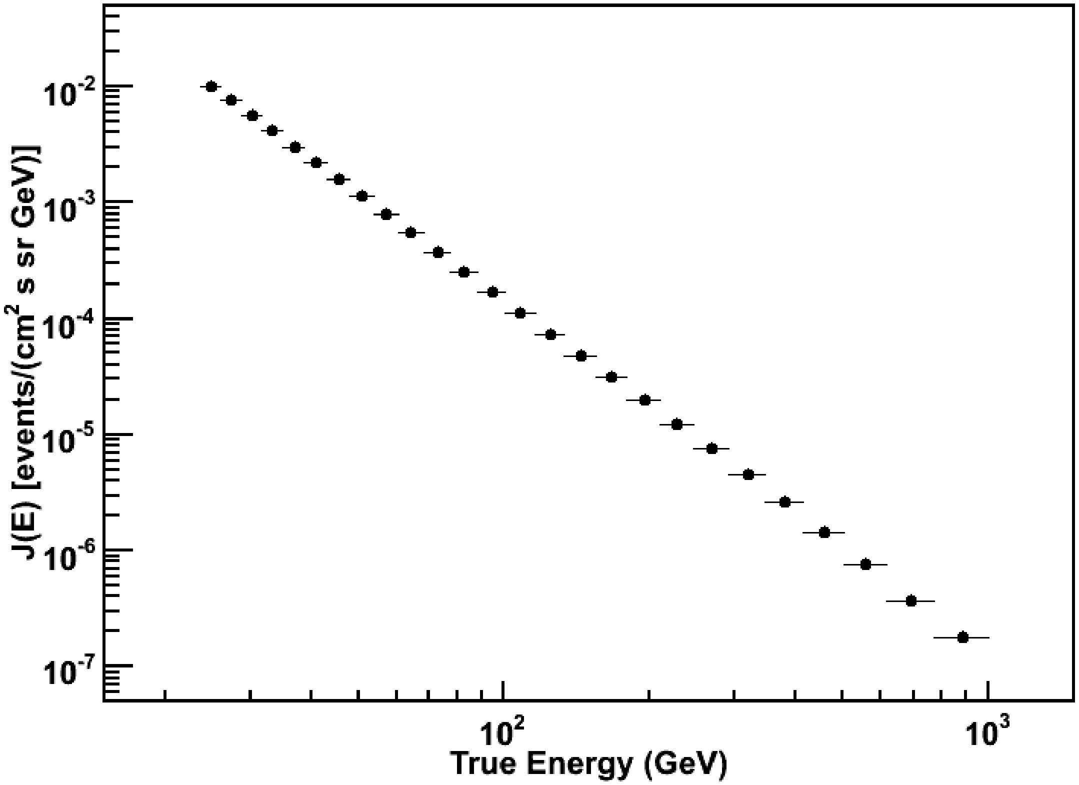
# Energy resolution (2)



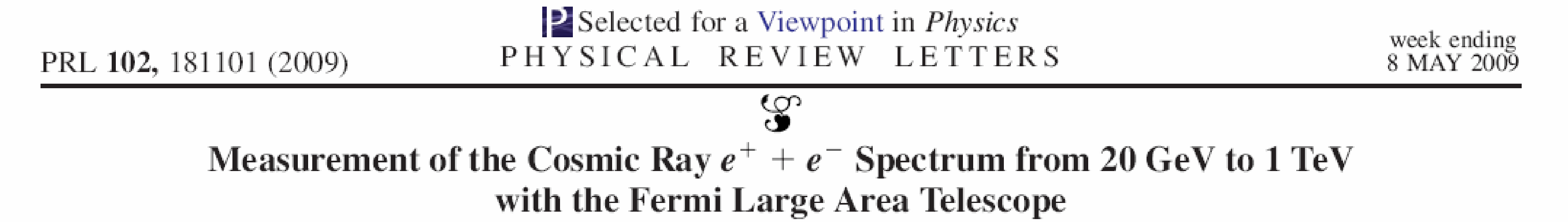
**MC simulation is validated by beam test data up to 280GeV**

# Electron (+positron) flux

The Fermi-LAT electron+positron spectrum can be fitted by a simple power law with spectral index close to 3



# The high energy electron spectrum



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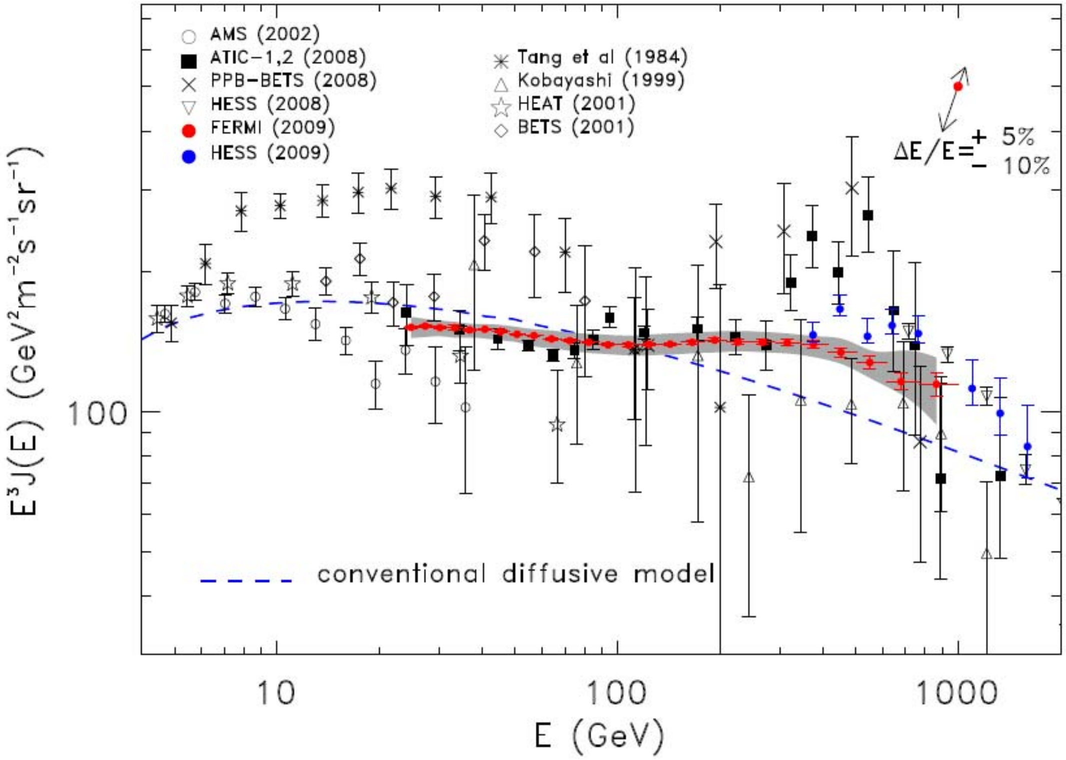
## Measurement of the Cosmic Ray $e^+ + e^-$ Spectrum from 20 GeV to 1 TeV with the Fermi Large Area Telescope



# Interpretation of the Fermi-LAT results

- Anomalous features in the electron spectrum are excluded
- The electron spectrum is harder than the one expected from conventional diffusive models (GALPROP based on pre-Fermi data)
  - Possible interpretations:
    - harder electron spectrum at the source
      - ☐ GALPROP assumes a source electron spectrum with $\gamma$=2.54 above 4 GeV and a diffusive coefficient ~$E^{1/3}$
    - presence of a local source of high energy electrons and positron with injection spectrum $J(E) \sim E^{-\gamma}\exp(-E/E_{cut})$
      - ☐ this interpretation allows also to explain the increase in the $e^+/(e^+ + e^-)$ ratio observed by PAMELA above 10GeV

# Conclusions

- The Fermi LAT is a powerful high-energy electron detector
  - Large geometric factor and observation time in the multi-100 GeV energy range
- Hadron rejection power and energy reconstruction are the key issues
  - Very detailed Monte Carlo simulation framework including all the relevant aspects of the detector
  - Extensively validated at beam tests and with flight data
  - Background rejection and energy resolution well under control and perfectly adequate for the measurement
- The Fermi LAT provides a measurement of the cosmic ray electron spectrum up to 1 TeV