THE CALORIMETER OF THE FERMI LARGE AREA TELESCOPE

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on behalf of the Fermi LAT collaboration

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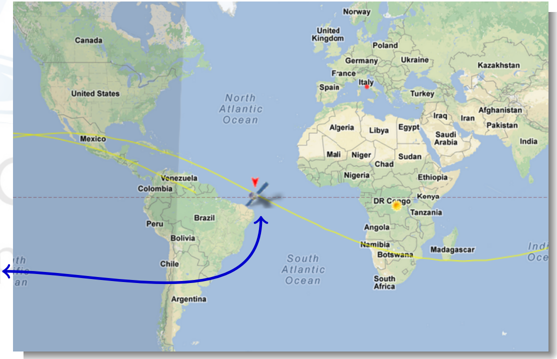
THE FERMI OBSERVATORY

HTTP://FERMI.GSFC.NASA.GOV/

Large Area Telescope (LAT)

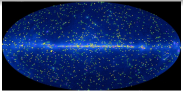
- Pair conversion telescope
- Energy range: 20 MeV – $>$300 GeV
- Field of view: ~ 2.4 sr (at 1 GeV)
- Effective area: $\sim 8000\ \mathrm{cm}^2$ on axis (at > 1 GeV)



- Launched by NASA on 2008 June 11
- Almost circular orbit, at 565 km altitude and 25.6° inclination

Fermi Science target

The γ-ray sky above ~ 20 MeV



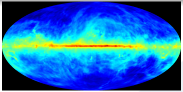
Resolved sources:

point-like vs. extended

stable vs. variable

bright vs. faint

+



Galactic diffuse:

Cosmic-ray interactions with

the interstellar medium

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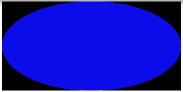

Isotropic diffuse

Unresolved sources

Truly diffuse emission

Residual cosmic-rays

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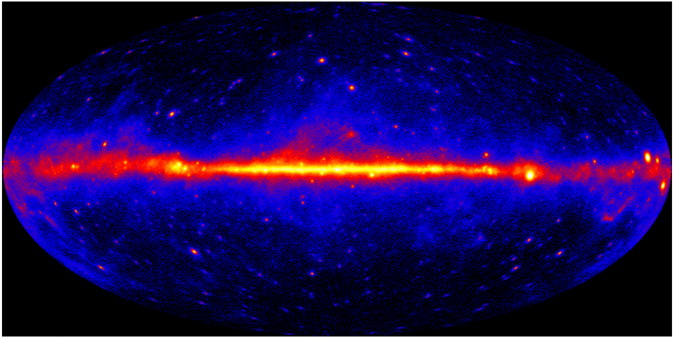


+ Local sources:

Sun

Earth

Moon

+ New Physics (DM search)

▶ Cosmic-ray $e^- + e^+$: spectra & anisotropy

SCIENCE REQUIREMENTS AND CONSTRAINTS
A SHORT SUMMARY

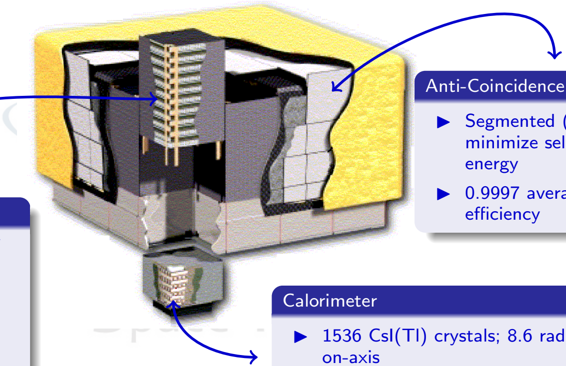
- Fermi sources generally have a $E^{\sim -2}$ power-law spectrum
  - Need of a moderate energy resolution
  - Energy over-estimation is dangerous
  - Need large collecting area for high energy
- We want to be able to measure precisely spectral features (cutoff, lines)
- We want a broad energy range
  - Very hard to have a uniform detector response in the whole energy range
- We want to study source variability
  - Need relatively "fast" detectors
    - Also important to reduce pile-up effects
  - Need large field–of–view
- Operation in orbit imposes very stringent limits on:
  - Lateral size
    - Launcher dimensions: $\sim 1.8 \times 1.8\ \mathrm{m}^2$ for the LAT
  - Mass budget:
    - Calorimeter depth (once the footprint is fixed)
    - 3000 kg for Fermi, ~ 1400 kg for the CAL
  - Power budget:
    - 650 W for the LAT, ~ 60 W for the CAL

THE LARGE AREA TELESCOPE

ATWOOD, W. B. ET AL. 2009, APJ, 697, 1071

Large Area telescope

- Overall modular design
- 4×4 array of identical towers (each one including a tracker and a calorimeter module)
- Tracker surrounded by an Anti-Coincidence Detector (ACD)



Anti-Coincidence Detector

- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

Tracker

- Silicon strip detectors, W conversion foils; 1.5 radiation lengths on-axis
- 10k sensors, 73 m^2 of silicon active area, 1M readout channels
- High-precision tracking, short dead time

Calorimeter

- 1536 CsI(Tl) crystals; 8.6 radiation lengths on-axis
- Hodoscopic, 3D shower profile reconstruction for leakage correction

CALORIMETER MODULE OVERVIEW

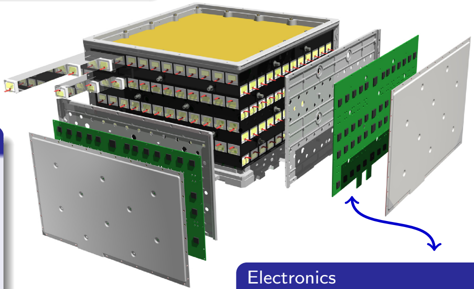
GROVE, J. E. AND JOHNSON, W. N. 2010, PROC. OF SPIE, 7732, 77320J

Imaging Calorimeter

- Energy-profile fitting improves energy resolution
- Shower shape helps background rejection
- CAL-only events (direction reconstruction)

Mechanics

- Carbon composite cell structure
- Al base plate and side cell closeouts



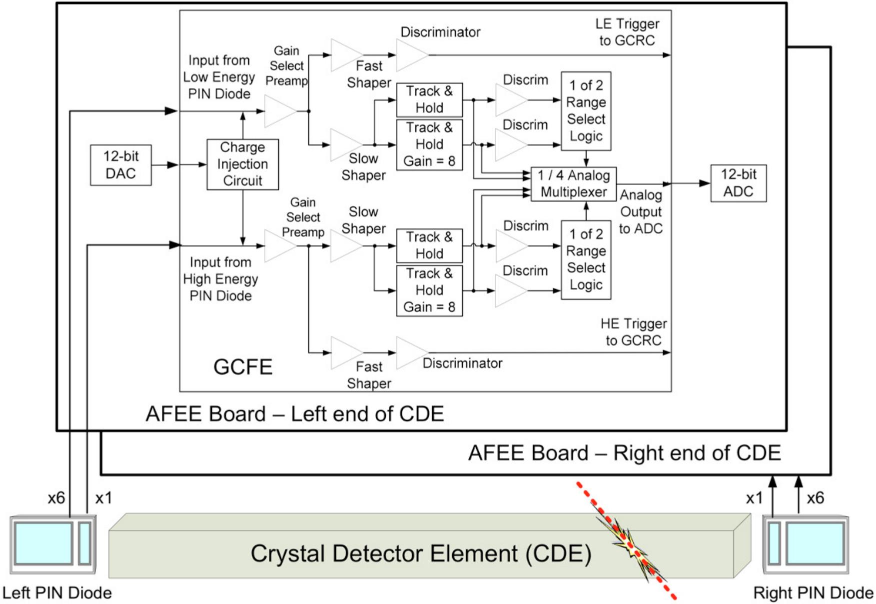
Detector Element

- 8 layers of 12 CsI(Tl) crystals
- Crystal dimensions 27 × 20 × 326 mm
  - Moliere radius is 38 mm
  - Radiation length is 19 mm
- Alternating orthogonal layers
- Dual PIN photodiode on each end of crystals
  - 3D position

Electronics

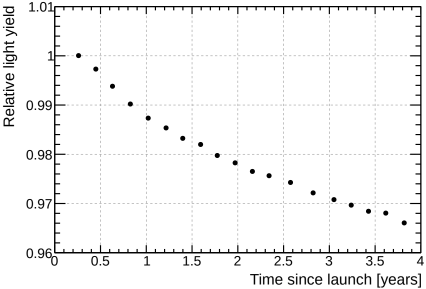
- Electronics boards attached to each side
- Minimize space, passive/empty volumes
- Low power per channel ASICs
- Large dynamic range (2 MeV – 70 GeV) is demanding

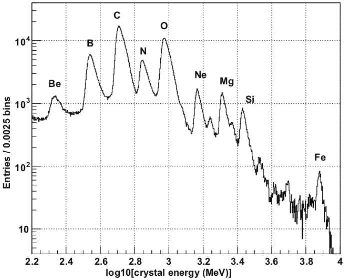
CAL CRYSTAL READOUT



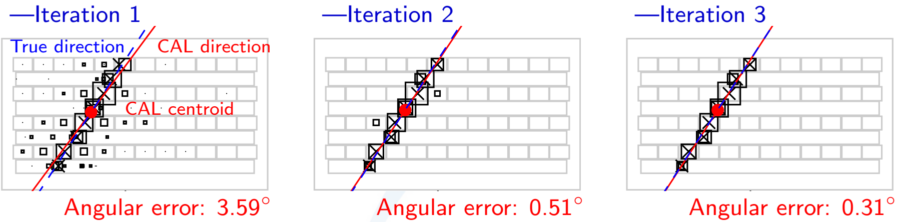
ON-ORBIT PERFORMANCE AND CALIBRATION

- The calorimeter is alive and all channels are working as expected
  - Except 3 noisy channels out of 6144 (no impact on science performance)
- Periodic triggers (at 2 Hz) for pedestal monitoring
- Charge injection to correct for the electronics non-linearities
- Non-interacting protons for low energy calibration
- Protons and heavy nuclei for inter-range calibration
- Non-interacting heavy nuclei for light asymmetry (using tracker information)
- Crystal light yield attenuation due to radiation damage ($\sim -1\%$/year as expected)





Calorimeter Direction reconstruction

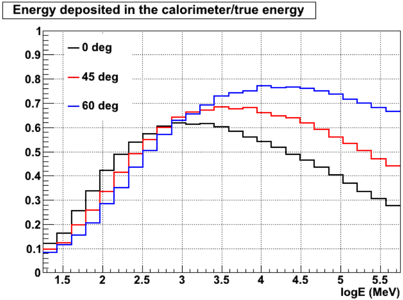


- The calorimeter direction is determined through a three-dimensional moments analysis:
  - Principal axes of the energy deposit determined by diagonalizing the corresponding inertia tensor
  - Iterative process in which the calorimeter hits far from the axis are progressively discarded
- Calorimeter axis can be used in
  - event reconstruction, to seed the track finding
  - event selection, via CAL-Track matching
  - event direction, for events without good tracks

ENERGY RECONSTRUCTION METHODS

Very large phase space: from ~ 20 MeV to > 300 GeV; up to $\sim 70^\circ$ wrt to vertical axis

- E$<\sim 1$ GeV
  - A large fraction of the energy is deposited in the tracker (1.4 X_0)
  - We use both the calorimeter and tracker information (nb of hits)
- E$>\sim 1$ GeV
  - The energy loss in the tracker becomes smaller than the leakage behind the calorimeter
  - At large E, the leakage becomes very important



The gamma-ray energy is reconstructed via two different algorithms

a) A parametric correction
  - Use energy centroid depth along the showed axis
  - Corrects for energy losses
  - Best at *low energy*

b) A shower profile fit
  - Uses a shower axis as reference
  - Full 3D fit of energy deposition
  - Best at *high energy*

SHOWER PROFILE FIT

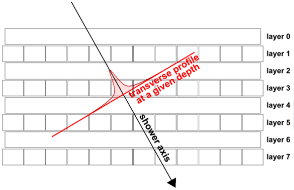
PH. BRUEL 2012 J. PHYS.: CONF. SER. 404 012033

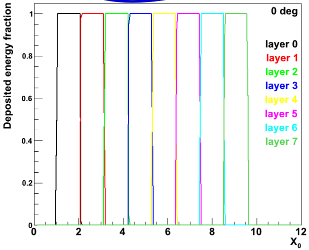
- The principle: fit the energy deposit in each layer
  - $g(\alpha,\beta,E)$ is to constrain the α and β to be close to their average

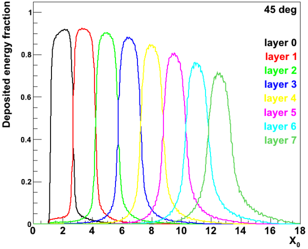
$$\chi^2(\alpha,\beta,E) = \sum_{i=0}^{8} \frac{(E_{meas,i} - E_{pred,i}(\alpha,\beta,E))^2}{\delta E^2} + g(\alpha,\beta,E)$$

- Need a precise modeling of the shower development through the CAL layers
  - $f_i(t)$ is the fraction of energy deposited in layer i
  - For off-axis photons the energy at a given t is shared between layers

$$E_{pred,i}(\alpha,\beta,E) = \int_0^\infty f_i(t) \times E\,\frac{(\beta t)^{\alpha-1}\beta e^{-\beta t}}{\Gamma(\alpha)}dt$$

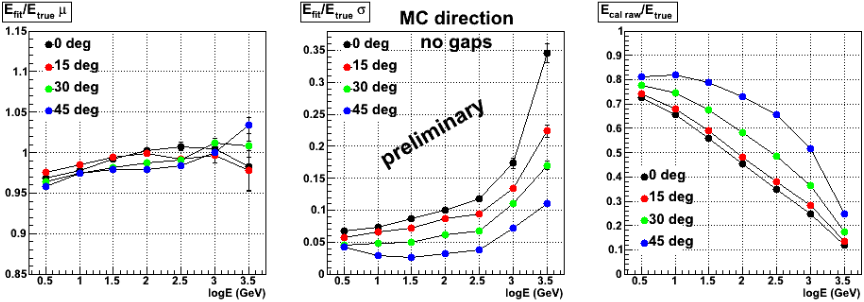






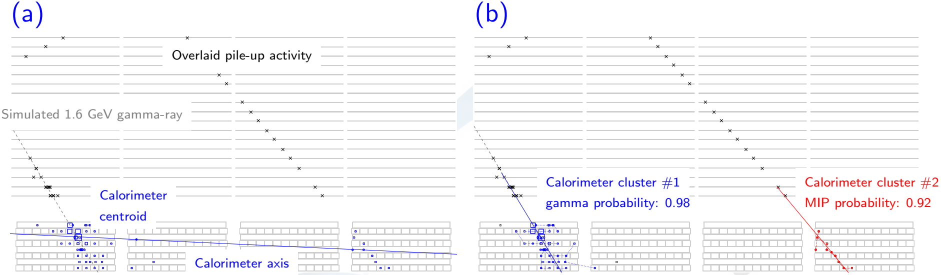
SHOWER PROFILE PERFORMANCE

PH. BRUEL 2012 J. PHYS.: CONF. SER. 404 012033



- An improved version of the algorithm is under development
- Good energy resolution up to ~ 1 TeV
- Above 1 TeV, the energy resolution is degraded, because of crystal saturation and poor containment
- The energy measurement depends on the precision of the direction given by the tracker, but bad events can be rejected by using the χ^2 of the fit
- No large over-estimation of the energy

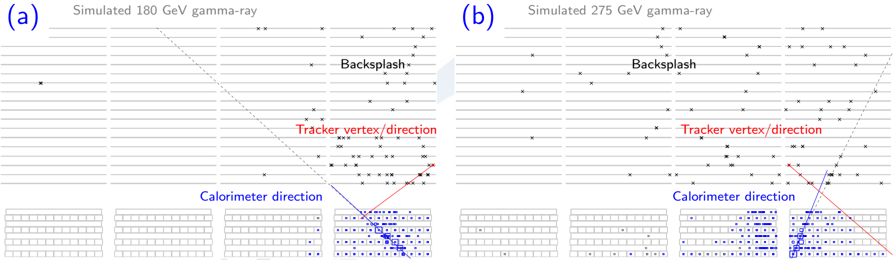
NEW RECONSTRUCTION (PASS8): CAL CLUSTERING



(a) In the current framework all hits in CAL are considered part of a single shower
  - Background rejection suffers instrumental pile-up
  - Small efficiency loss (accounted for in the Instrument Response Functions)

(b) We added clustering stage at the beginning of the reconstruction chain
  - Separate the pile-up activity from the genuine gamma-ray signal
  - Provide topology information to the following reconstruction steps

New reconstruction (Pass8): CAL-Only events



- Events with no usable tracker direction information:
  - (a) a γ-ray converting in the calorimeter and
  - (b) a γ-ray converting in the tracker being mistracked due to the backsplash
- Currently removed from the photon sample
- Dedicated analysis to recover these events
  - Increase aeff at high energy
  - Background rejection is more difficult
  - Need to evaluate real performance

SUMMARY

- The Fermi Large Area Telescope has proven to be an excellent telescope for gamma rays above ∼20 MeV
- The LAT calorimeter works as designed. Thanks to its hodoscopic segmentation it provides :
  - Good energy resolution up to 300 GeV, still acceptable at 1 TeV and beyond, despite its modest $8.6X_0$ depth
  - Good background rejection capabilities
  - Good direction measurement ($\sim 2^\circ$ above 20 GeV)
- Current re-writing of the reconstruction software (Pass8) to improve the instrument performance, taking into account the real data experience, including the extension of the energy reach up to 3 TeV

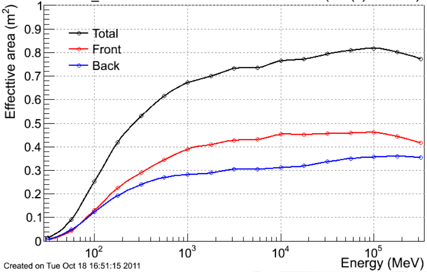
- Looking forward: Fermi continues to survey the sky! NASA Senior Review recommended extending operations through 2016, at least
- Remember, Fermi data are publicly available
  - Get data and analysis software at Fermi Science Support Center
    - `http://fermi.gsfc.nasa.gov/ssc/`

EXTRA

INSTRUMENT RESPONSE FUNCTION

http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

P7SOURCE_V6 effective area at normal incidence (cos(θ) > 0.975)



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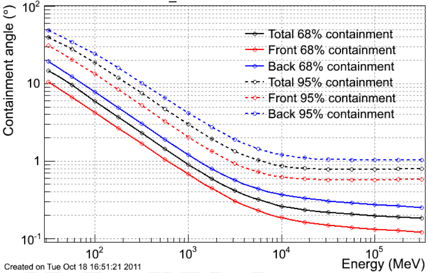
P7SOURCE_V6 PSF at normal incidence



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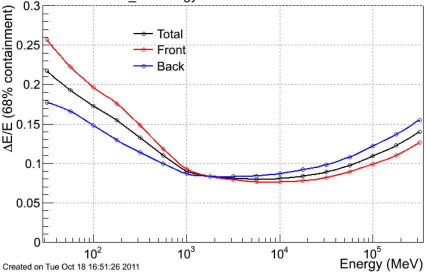
P7SOURCE_V6 energy resolution at normal incidence



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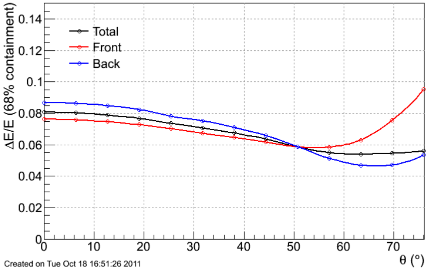
P7SOURCE_V6 energy resolution at 10 GeV



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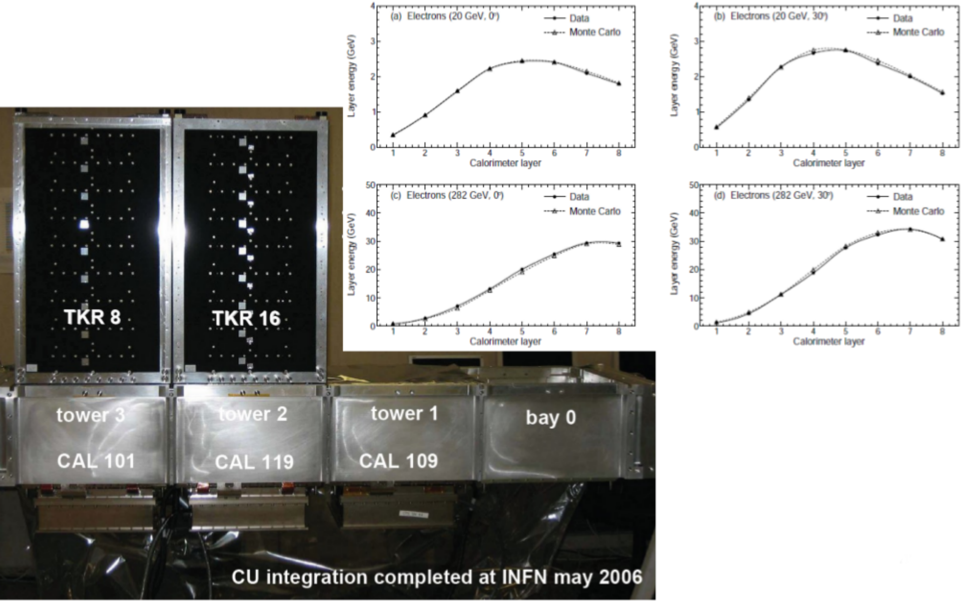
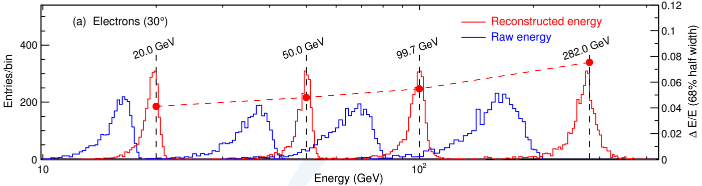
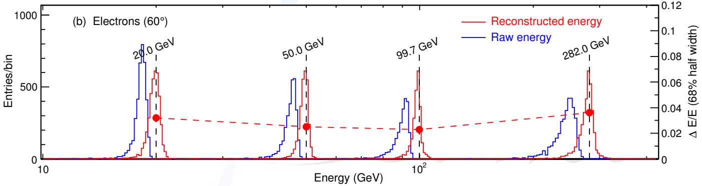
BEAM TEST RESULTS

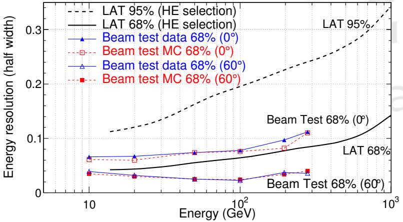


CU integration completed at INFN may 2006

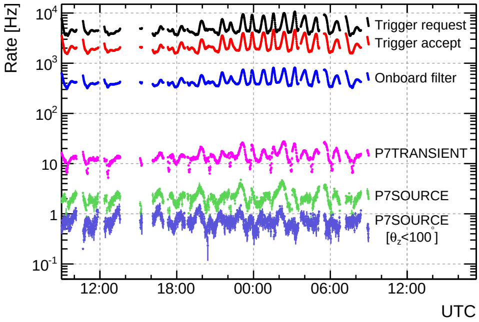
BEAM TEST RESULT II







TRIGGER

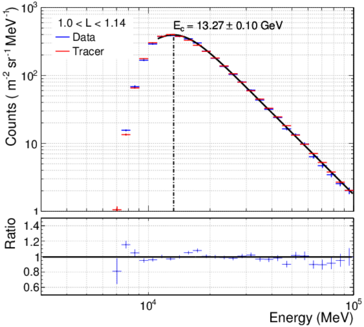


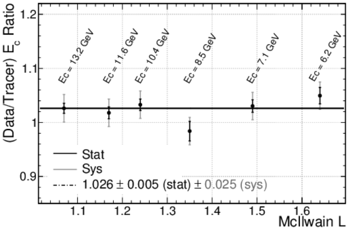
- Triggering on (almost) all the charged particle that crosses the LAT (∼2 kHz)
- Programmable on-board filter to fit the data volume into the allocated bandwidth (∼1.5 Mb/s average).
- Most of the ∼400 Hz of events passing the gamma filter and downlinked to ground are actually charged-particle background

- All subsystems contribute to the L1 hardware trigger:
  - `TKR`: three consecutive TKR x-y planes hit in a row
  - `CAL LO`: single CAL log with more than 100 MeV (adjustable)
  - `CAL HI`: single CAL log with more than 1 GeV (adjustable)
  - `ROI`: MIP signal in the ACD tiles close to the triggering TKR tower
  - `CNO`: signal in one of the ACD tiles compatible with a heavy

IN-FLIGHT ENERGY SCALE CALIBRATION

EXPLOITING THE $e^- + e^+$ GEOMAGNETIC RIGIDITY CUTOFF

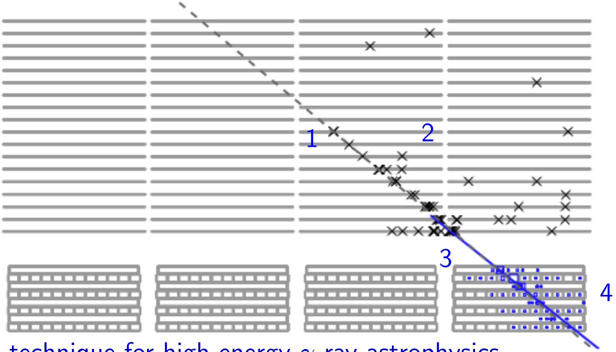




- The value for the cutoff rigidity can be predicted using a particle tracing code
    - Using code written by Smart & Shea (Final Report, Grant NAG5-8009, 2000)
    - Cross checks on the fidelity of the geomagnetic field model have been performed using rigidity measurements from other satellites such as SAMPEX and HEAO-3
- Comparison of predicted and measured values provides an opportunity to perform an in-fight verification
- By using different McIlwain L intervals we obtain several calibration points from 6 to 13 GeV
    - The energy scale is known within 5% (in this energy range)

Details in: Astropart. Phys., 35, 346 (2012)

THE TECHNIQUE: PAIR PRODUCTION



- Standard technique for high-energy γ-ray astrophysics
  - Dominant interaction mechanism for $E >\sim 20MeV$
  - Used by past experiment like COS-B and EGRET
- Here an example of a nearly ideal γ-ray candidate:
  1. γ-ray converts in the middle of TKR
  2. 1 or more tracks found (with a few extra hits near the track)
  3. CAL axis aligned with track
  4. CAL energy confined near axis