The Fermi Large Area Telescope:

Optimizing and then re-optimizing the Science Return

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Jan. 10, 2012

Rossi Prize Lecture

On behalf of the Fermi-LAT Collaboration

Outline

- Intro / History
- Instrument Concept
- Subsystem performance
- Pre-Launch Optimization – maintaining Science Options
- Post Launch Optimization – adjusting to reality & extending capabilities
- Outlook

Gamma-ray Pair Conversion

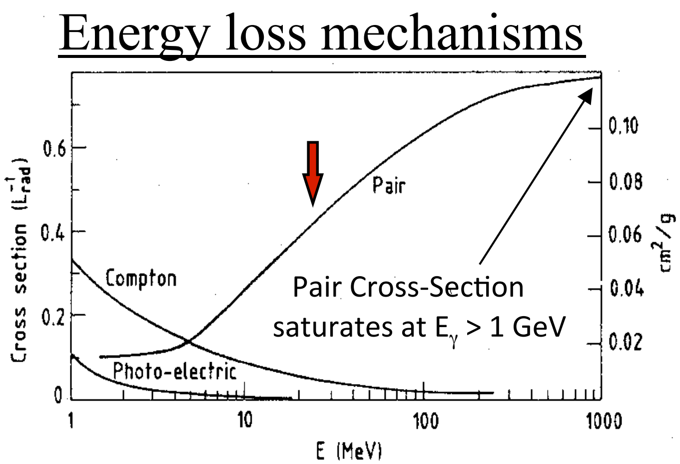
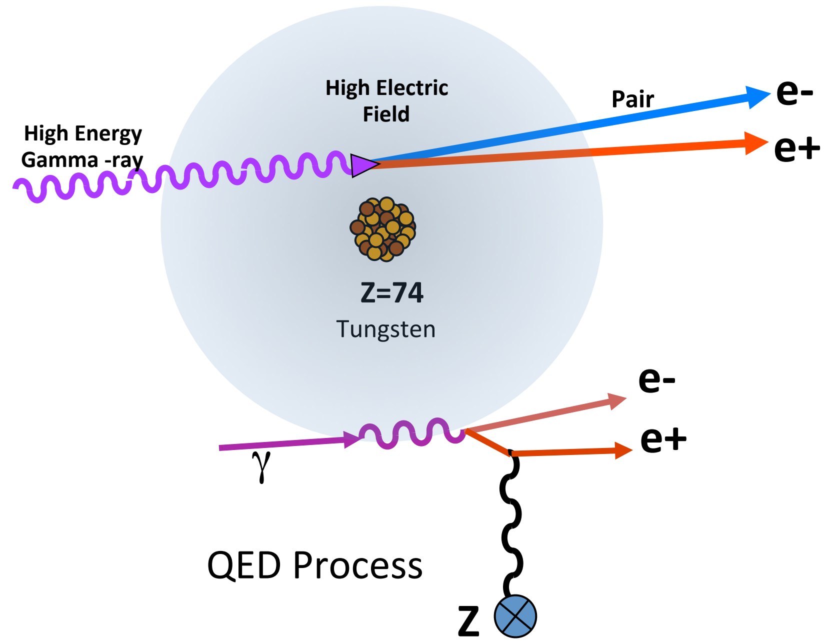
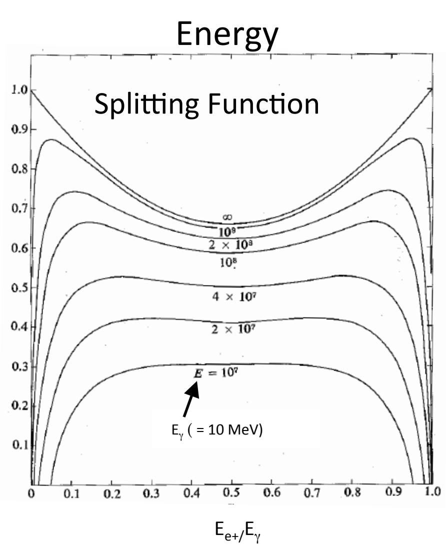


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).



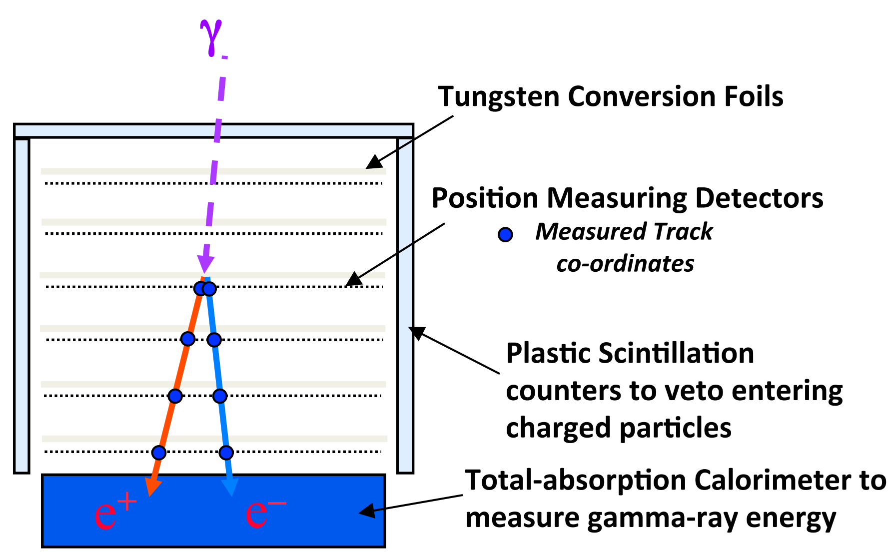


Opening Angle

$$\theta_{Open} \approx \frac{4m_e}{E_\gamma}$$

At 100 MeV

θ_{Open} ~ 1°



Previous Satellite Detectors

- **1967-1968**, OSO-3 Detected Milky Way as an extended γ-ray source

  621 γ-rays
- **1972-1973**, SAS-2,

  ~8,000 γ-rays
- **1975-1982**, COS-B

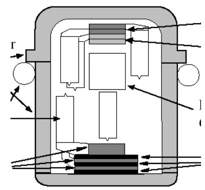
  orbit resulted in a large and variable background of charged particles

  ~200,000 γ-rays
- **1991-2000**, EGRET

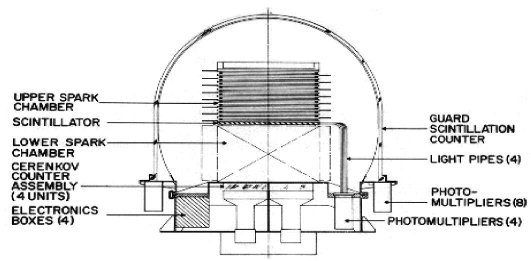
  Large effective area, good PSF, long mission life, excellent background rejection

  $>1.4 \times 10^6$ γ-rays

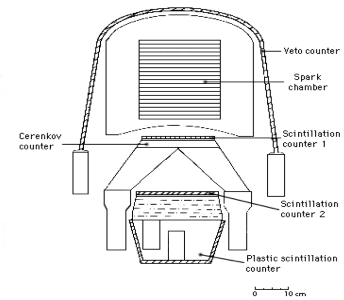
OSO-3



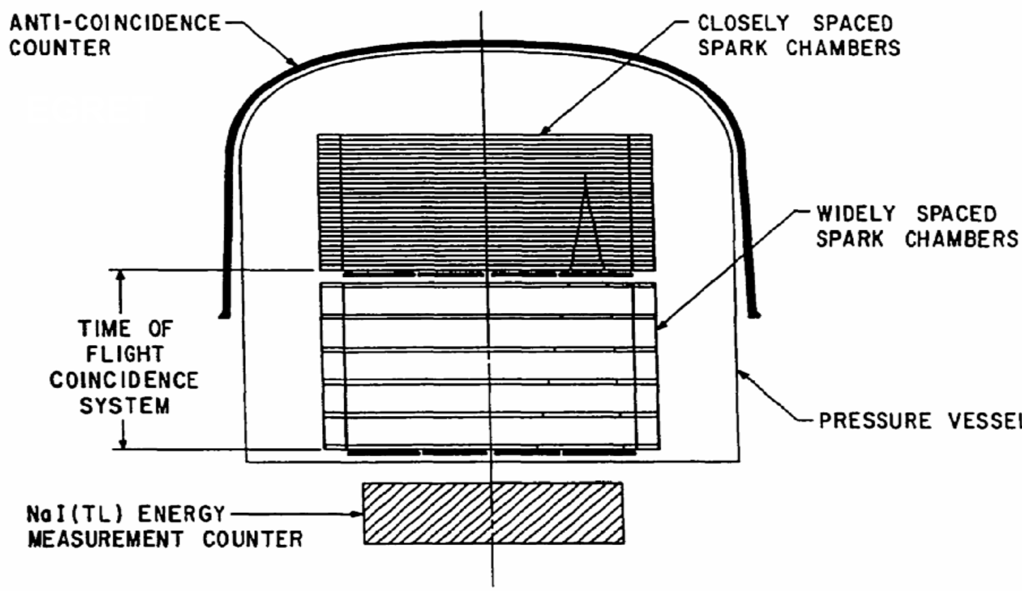
SAS-2



COS-B



EGRET



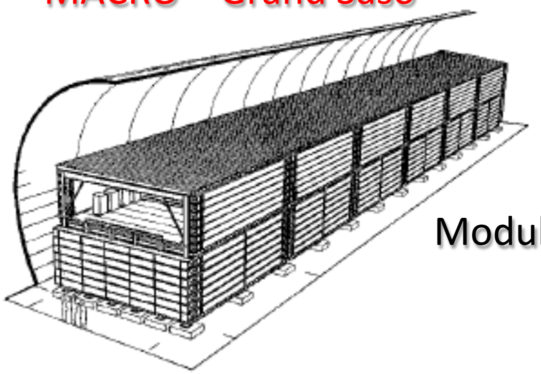
Conception

GLAST was the amalgamation of many ideas and concepts from Experimental Particle Physics in the 1980's and early 1990's

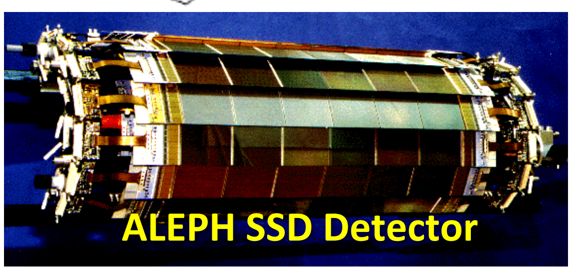
For Space Instruments: Solid State Detectors

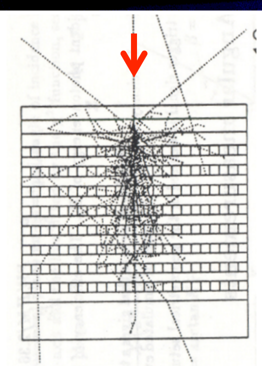
Silicon Strip Detector: SSD

MACRO – Grand Saso



Modularity

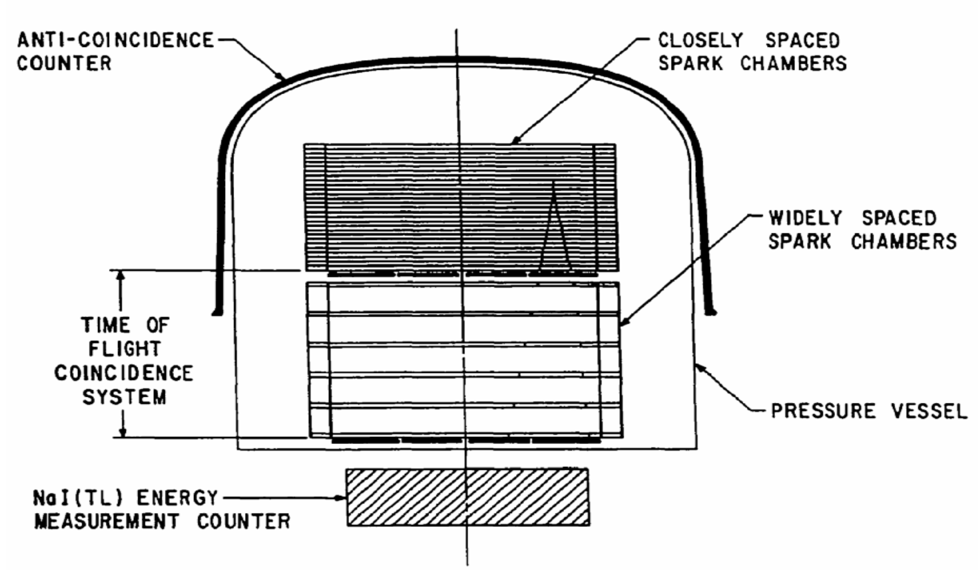




Xtal Calorimeter
Hodoscopic Design

P. Persson – P. Carlsen

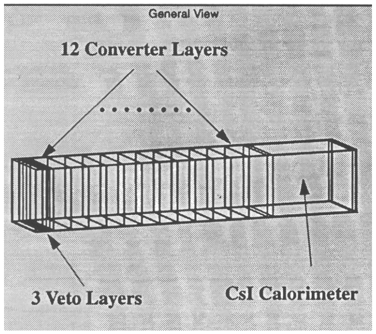
EGRET *onboard CGRO*



Design Steps for GLAST

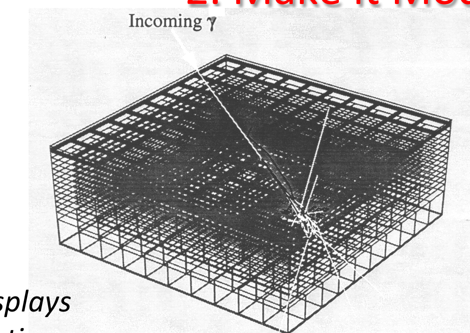
- April, 1991 CGRO (with EGRET on board) Shuttle Launch
- May, 1992 NASA SR & T Proposal Cycle

1. Select the Technologies



Large area SSD systems and CsI Calorimeters resulted from SSC R&D

2. Make it Modular



Another lesson learned in the 1980's: monolithic detectors are inferior to Segmented detectors

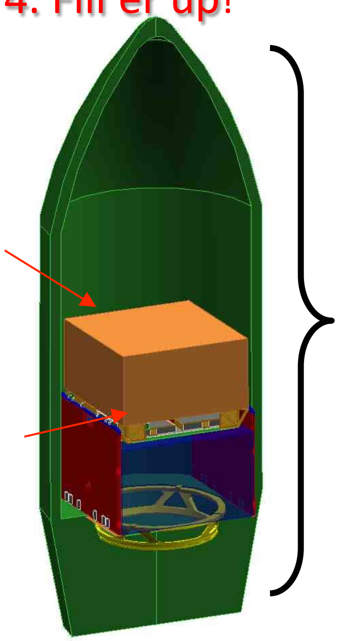
Original GISMO 1 Event Displays from the first GLAST simulations

Cheap, reliable Communication satellite launch vehicle

4. Fill'er up!

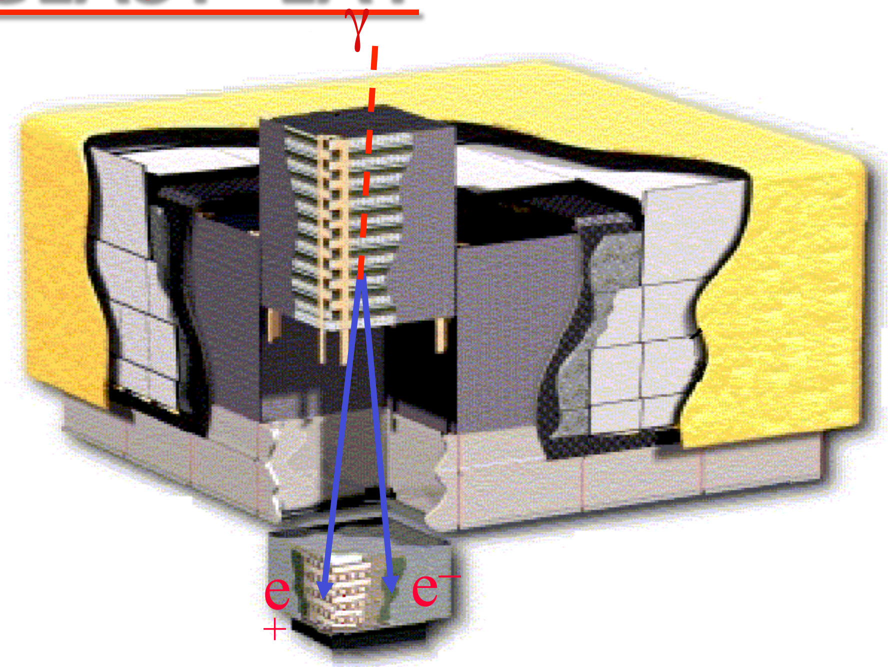
Diameter sets transverse size

Lift capacity to LEO sets depth of Calorimeter



Rocket Payload Fairing

Overview of GLAST- LAT



Tracker: 18 X-Y tracking planes with interleaved W conversion foils.

- 1.5 X0 on-axis
- 9,216 sensors
- 73 m2 of silicon active area 884,736 readout channels
- High-precision tracking, short instrumental dead time

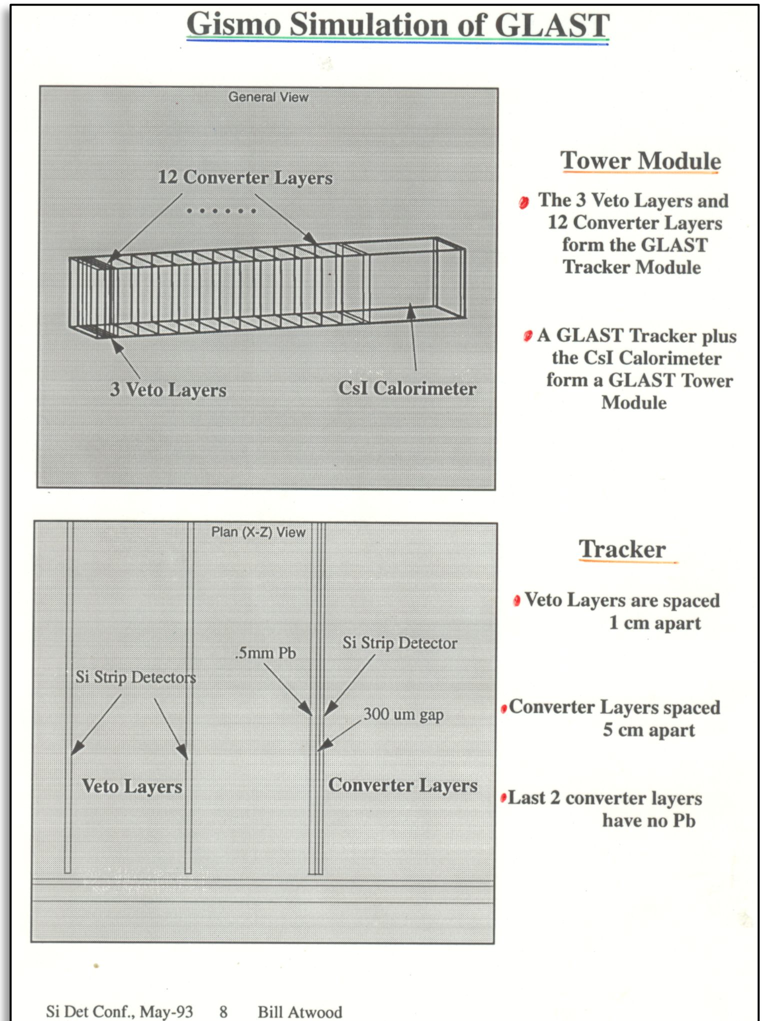
- **Calorimeter:** 1536 CsI(Tl) crystals in 8 layers
  - 8.6 X0 on-axis
  - PIN photodiode readouts
  - Hodoscopic crystal arrangement: 3D Shower Imaging

- **Anticoincidence Detector (ACD):** 89 plastic scintillator tiles
  - Segmentation to reduce "self-veto"
  - Waveshifting Fiber readout to PMTs
- **Electronics System** Includes flexible, robust hardware trigger and software filters.

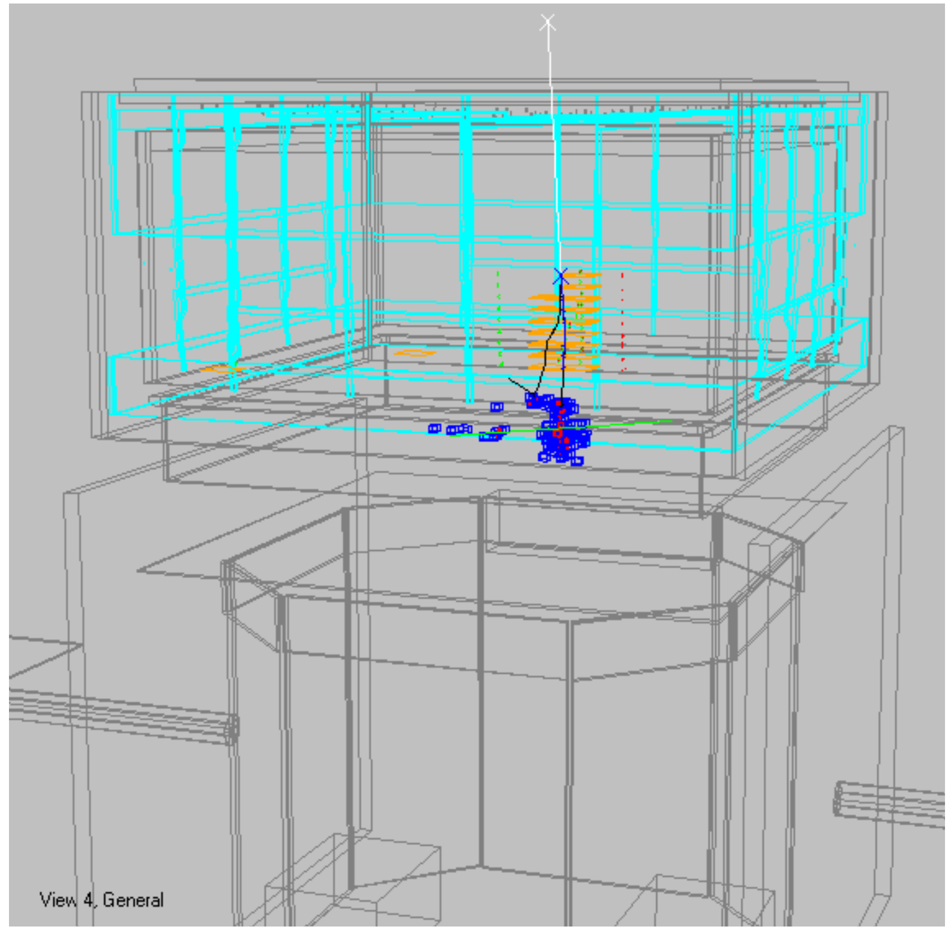
Prelaunch Optimization

- Monte Carlo
  - Complete Physics of particles interacting with Matter
  - Detailed Detector Model (Mass Model)
- All Design concepts/ideas validated by Monte Carlo
- Make the Detector as versatile as possible
  - Trigger
  - Data Acquisition
  - On-board filtering
- Develop Reconstruction *hand-in-hand* with Monte Carlo
- Work began in 1992
  - Get to the finish line – see how it all plays together
  - Iterate to incorporate "lessons learned" from last iteration
- 6 Iterations (Passes) on Reconstruction software
  - Science requirements (SWG Review, 2006) done with Pass 4
  - Launched with Pass 6

First Monte Carlo of GLAST 1993



Current GEANT 4 Fermi-LAT MC

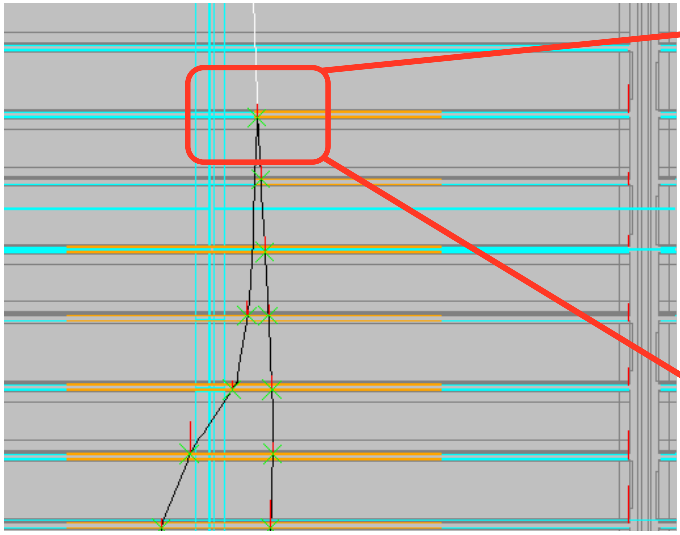


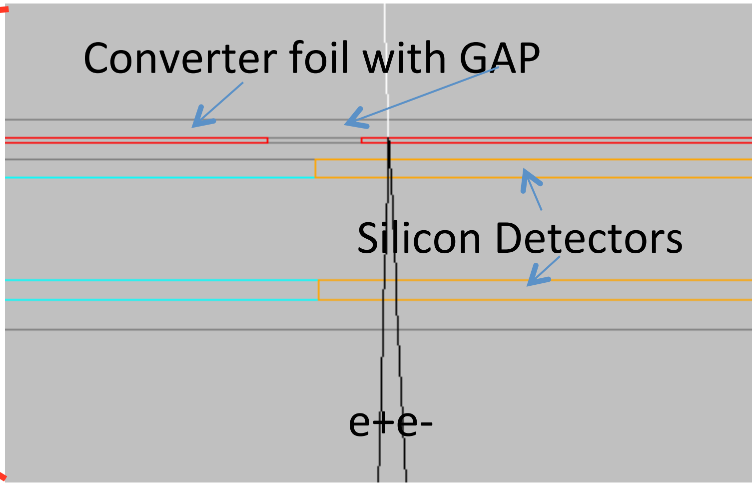
Level of detail greatly increased

- over 50k volumes
- Spacecraft Mass Model
- Detector parametric readouts

Monte Carlo Optimization: Converter Foils

Zoom on Monte Carlo Event





One source of tails on the PSF was identified as events missing the first hits

- Silicon Detectors have a dead margin of 1 mm around the edge
- Leaves 2 mm dead gap between active detector elements (~ 4.5% of Area)
- Events converting above the gaps were a source of tails
- Solution: make converter foils only cover active silicon regions!

More Examples of Pre-Launch Optimizations

For each of these items, a sequence of Monte Carlos were run. This allowed quantitative evaluation of design choices prior to "cutting metal"

Tracker

- Gap between Tracker Tower Modules
- Gap between X and Y silicon layers
- Importance of Tray Closeout material
- Selection of Tray Core material
- Choice of Conversion Foil Thicknesses

Calorimeter

- Depth
- Xtal dimensions
- Light Asymmetry readout for 3rd co-ordinate
- Effect of support structure

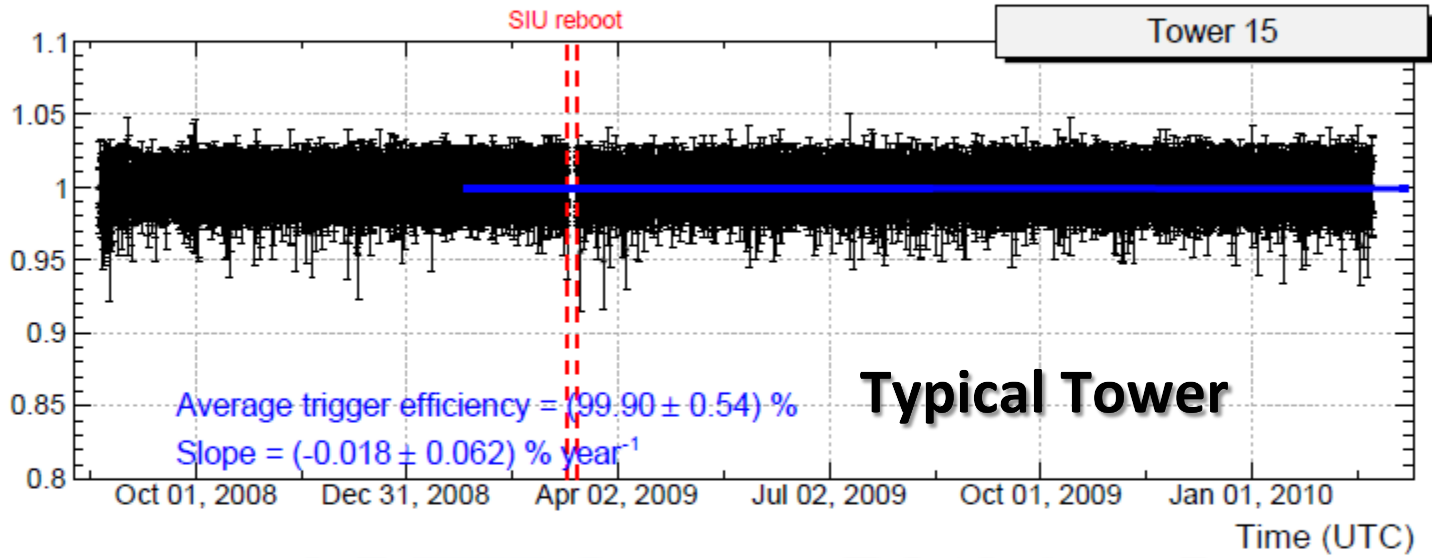
ACD

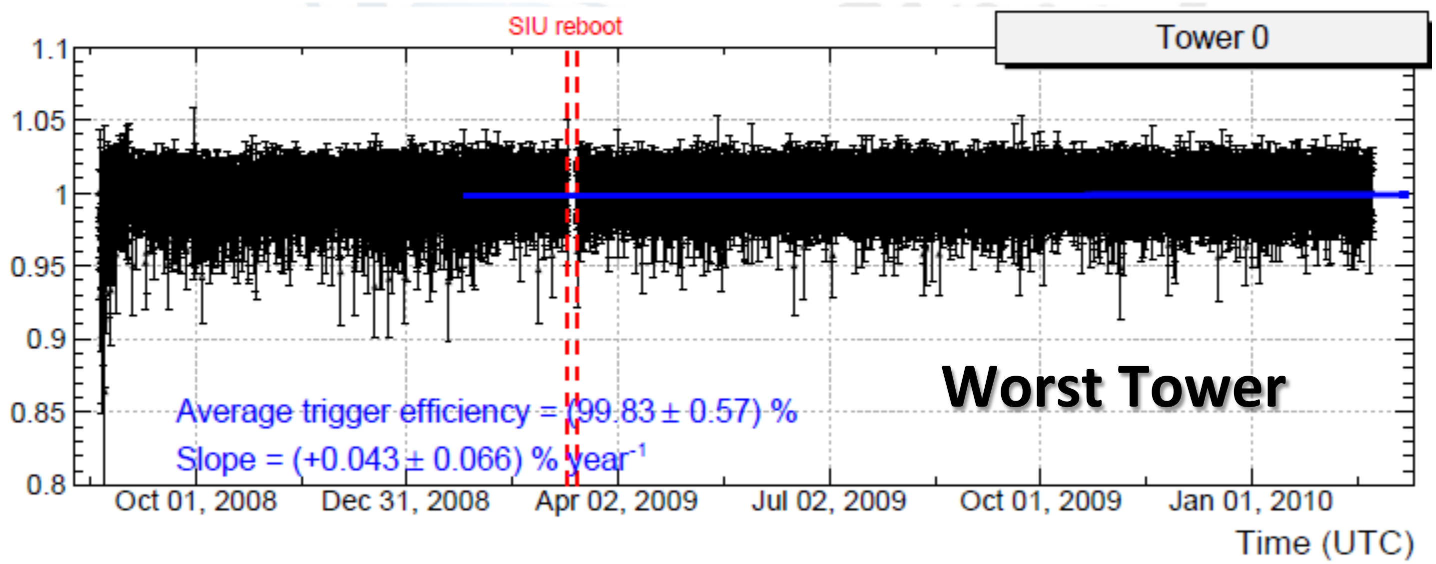
- Segmentation
- Overlaps
- Closing gaps with Ribbons
- Effects of Thermal Blanket & Micro-meteor shield

So… How did it work?
(Post Launch Assessment)

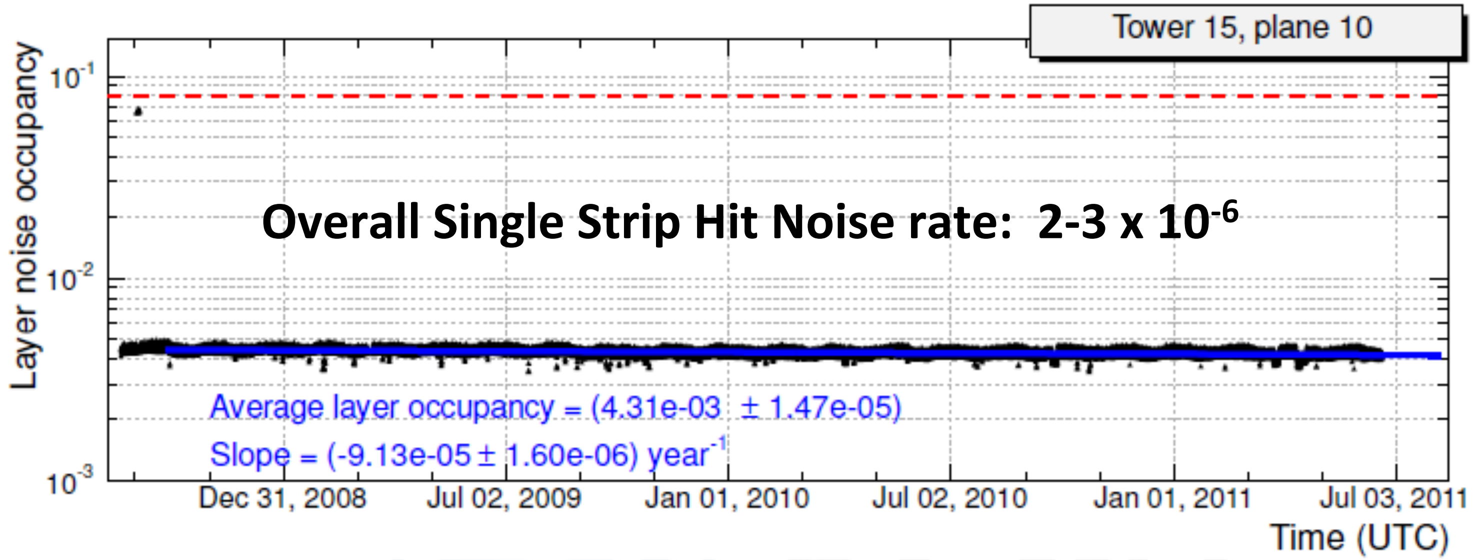
- Technology Choices
- Can we do Science?
- What did we miss? A prelude to re-optimization

Tracker: Single-hit Efficiency ~ 100%





Tracker: Noise Occupancy



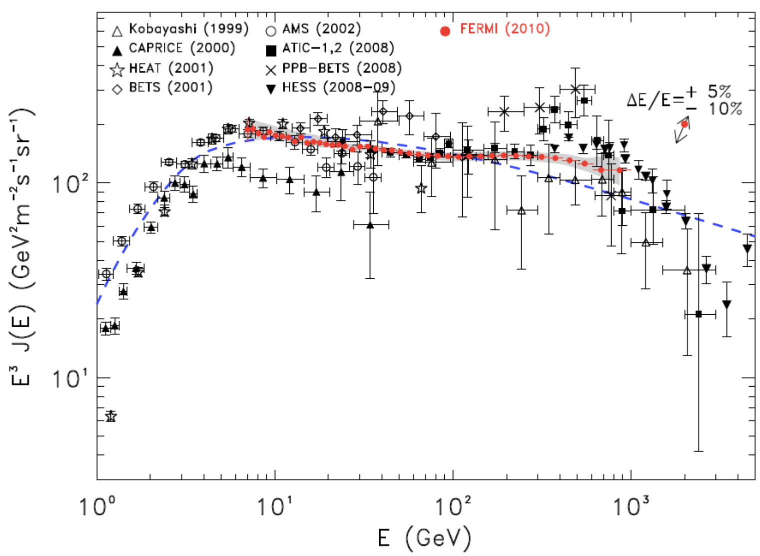
Calorimeter & ACD

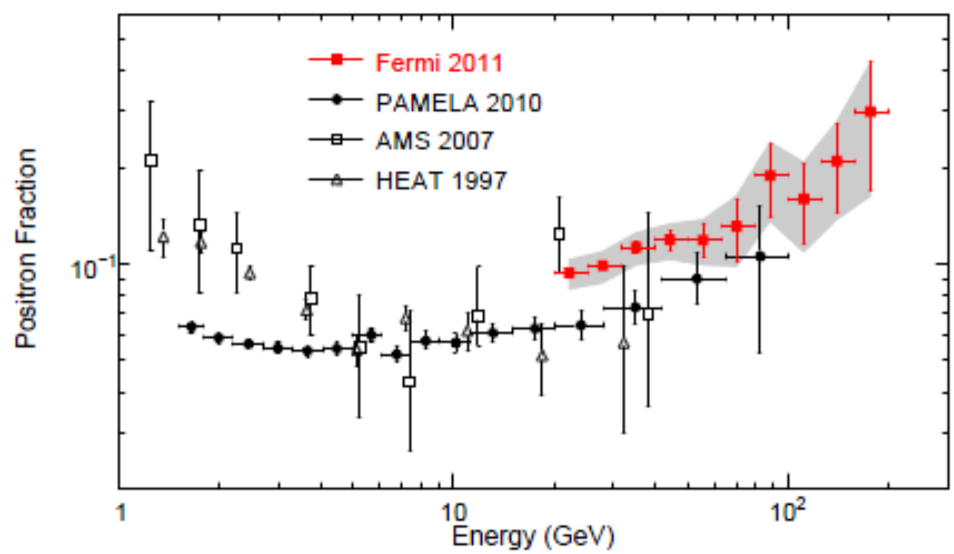
- Aging at the few % level seen (yellowing of Xtals and Plastic Scintillators)
- 2 Calorimeter Channels now bad
- No ACD Channels bad

Extension to Other Science

How Fermi got to measure the High-energy Electron Spectrum

- Gamma-ray detectors are electron detectors too!
- Flexible Trigger allows acquisition of events above 20 GeV with no Filtering
- Reconstruction software – essentially the same – except require the logical complement of an ACD Veto!





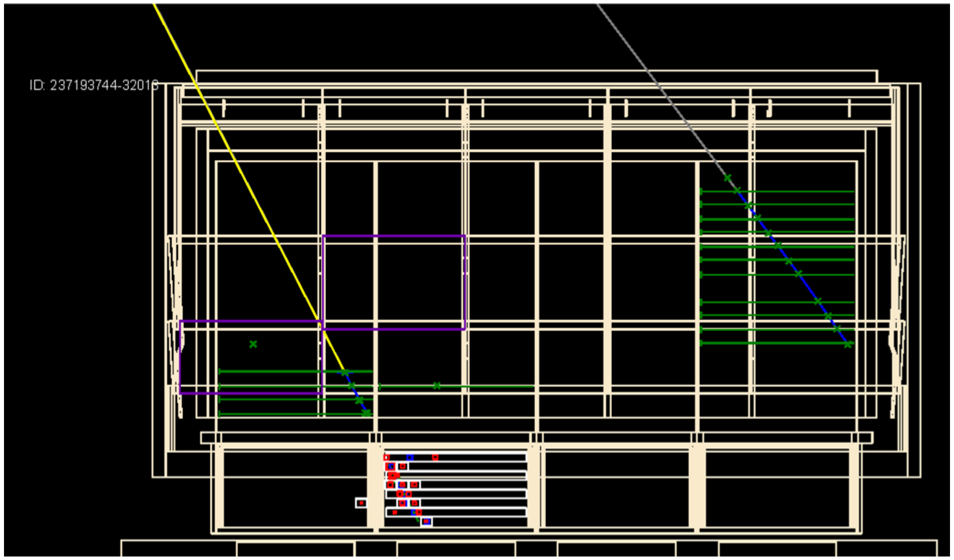
Post Launch Optimizations

- What was missed in the modeling prior to Launch?
- The first update to the Monte Carlo / Reconstruction: Pass 7
- The full re-write of Reconstruction accounting for real Flight Data experience: Pass 8

What was not in the Models

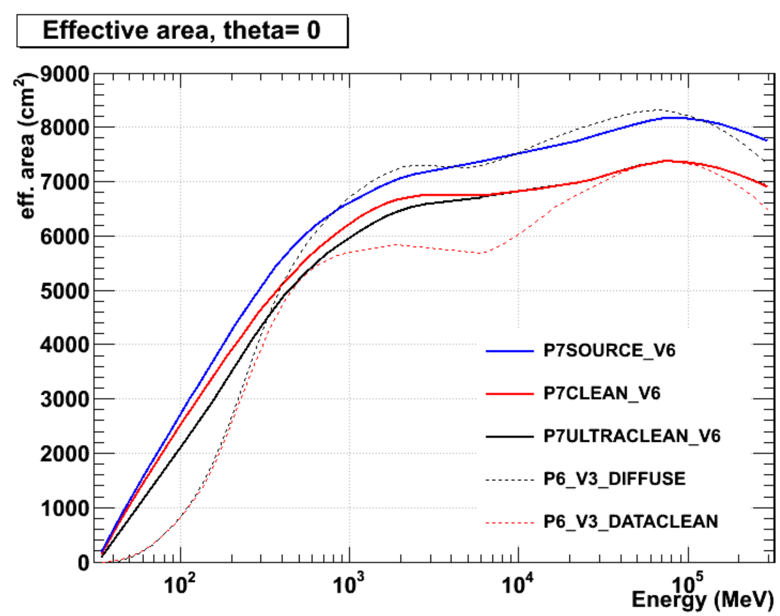
- Major: inclusion of the finite (~ 10 μsec) persistence of the detector responses. This lead to "Ghost" tracks in otherwise good events
- Minor: details of the background fluxes

One-Event Display showing the presences of a Ghost track. These tracks are out of time with respect to the triggering events and as such can be identified using the fast Trigger information provided by each tower.



Pass 7: Include Missing Effects in the Monte Carlo

- First step to in account for the effect of ghost tracks is to include this in the Monte Carlo.
  - Use unbiased Periodic Triggers as the background on which to superimpose the Monte Carlo event
  - Re-assess impact on Reconstruction Analysis
- Include updates to Calibrations
- Include cleaner Event Classes
- Reprocess data-to-date
  - Just started – expect completion Summer, 2012



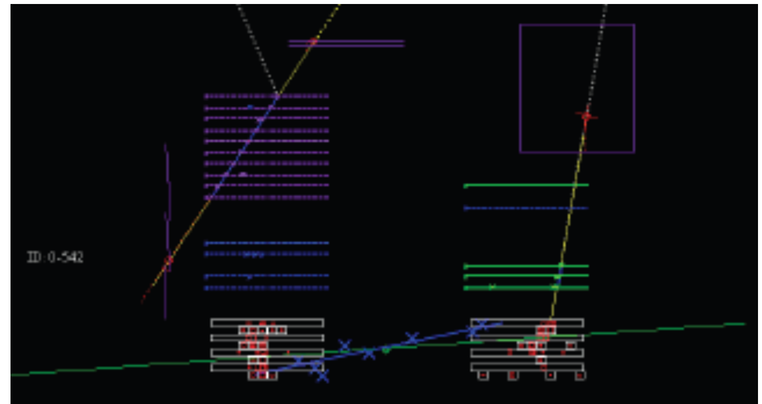
Pass 8: the Future

- Lessons learned from real data were incorporated into the Monte Carlo in Pass 7. The Reconstruction was not changed for Pass 7.
- It was clear that a *grounds-up* re-write based on this updated knowledge of the detector could make large improvements.
- This was not a small undertaking and has been underway since early 2010
- The re-write includes all of the Subsystems: Calorimeter, Tracker, and ACD.

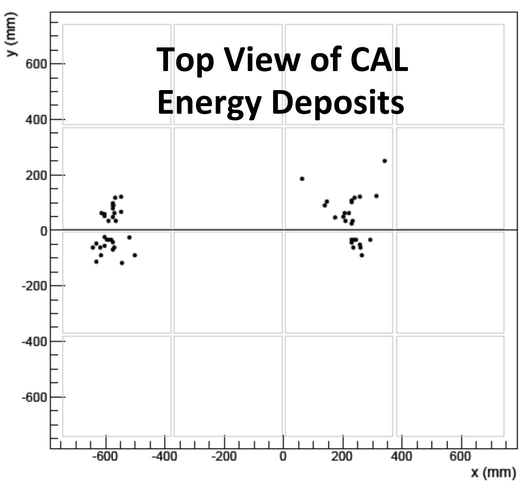
Pass 8: Calorimeter Analysis

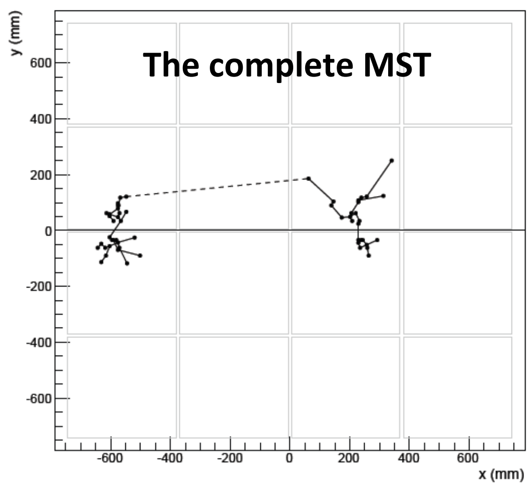
Clustering Analysis using Minimal Spanning Trees (MSTs)

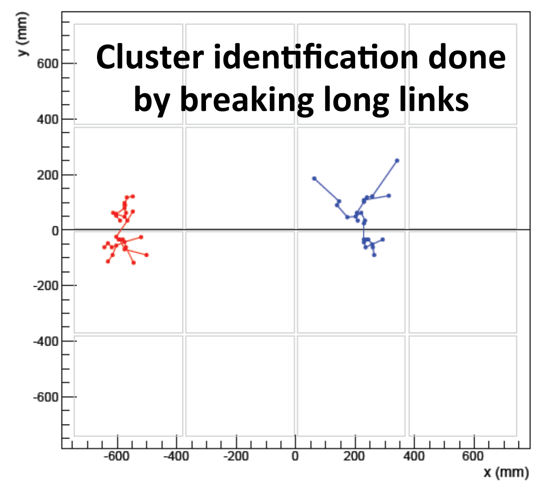
- Through Pass 7 – no clustering analysis for CAL
- Present of CAL Ghosts caused event loss
- No Multi-Photon capability
- The MST approach was selected as the best option for this critical CAL Pattern Recognition stage



An event with a Ghost in both the CAL and Tracker

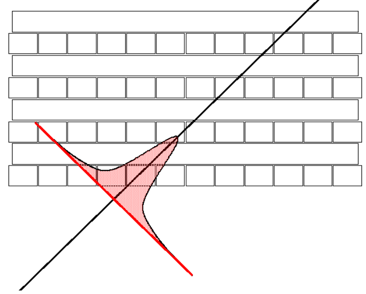




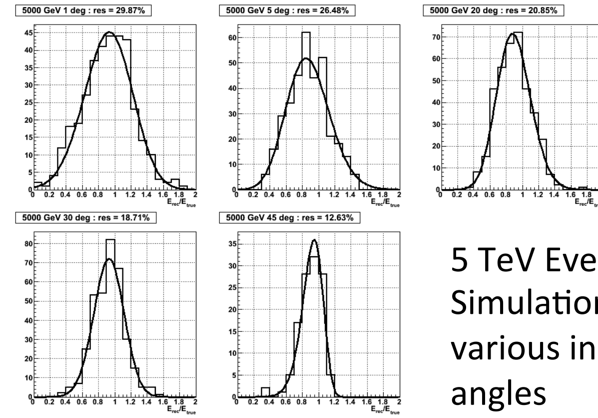


Extension to the TeV Band

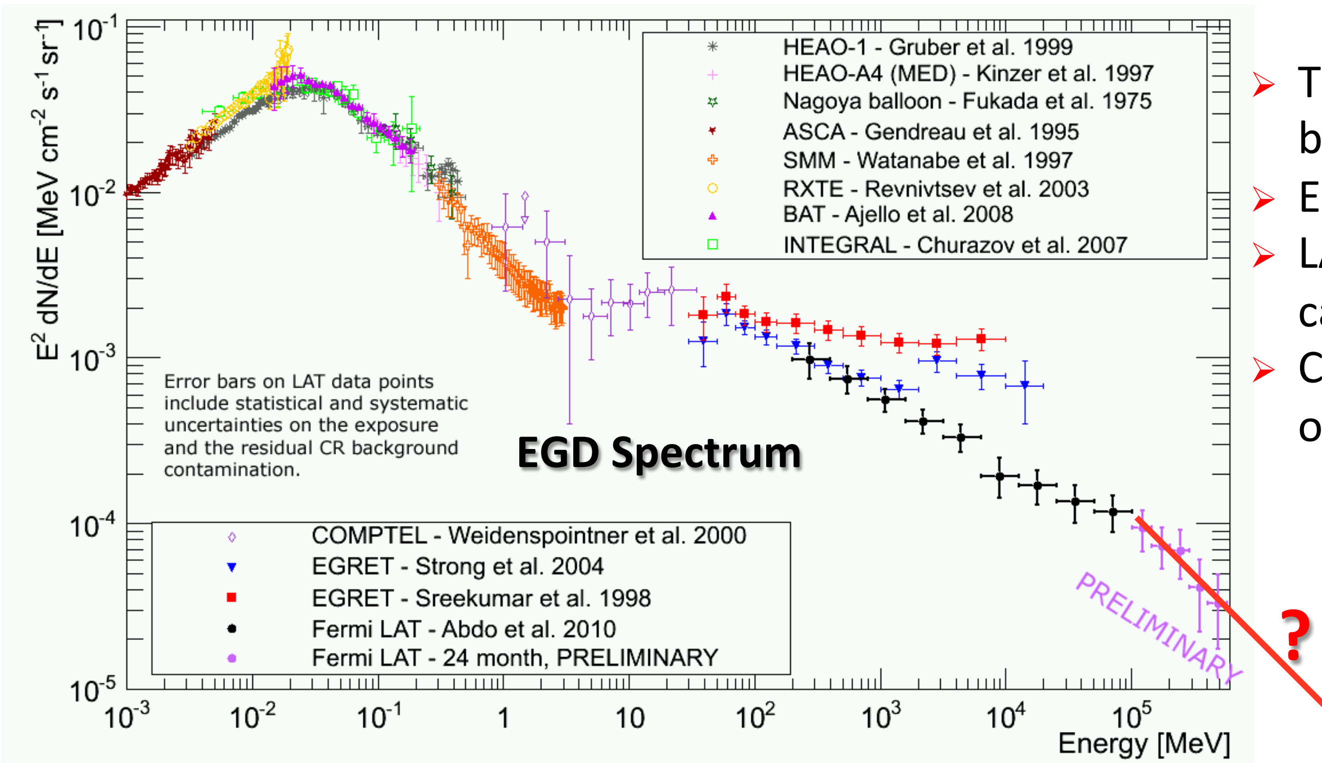
Illustration of Shower Profile along shower axis



- 3D Shower Imaging allows for a detailed fit to the shower shape.
- Fit allows compensation for leakage and for saturated crystals
- Good energy resolution is achieved even at > 50% leakage



5 TeV Event Simulations at various incident angles



- Too few photons in TeV band for most sources
- EGD is a major exception
- LAT is the only instrument capable of measuring EGD
- Current LAT EGD meas. out to ~ 500 GeV

? What happens here?

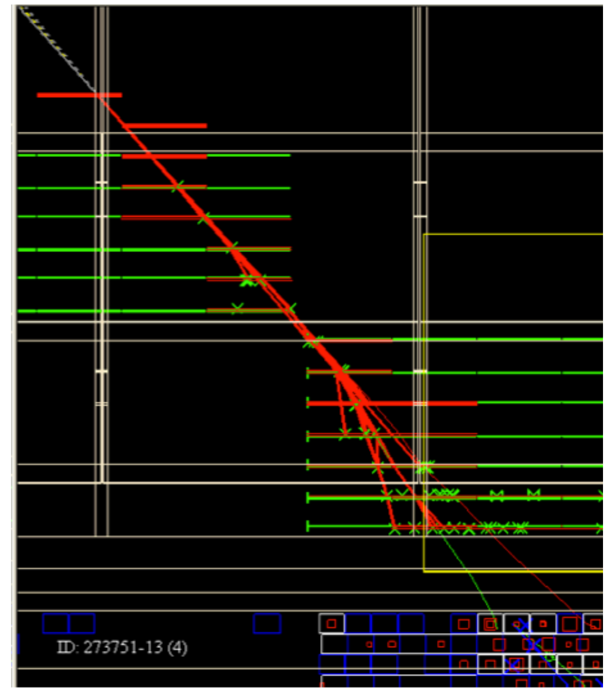
Pass 8: Tracker Analysis

What and Why

- Replace Combinatoric Pattern Recognition with Tree based algorithm.
- More efficiently captures beginning of EM shower.
- Reduces mis-tracking particularly at large incident angles and at high energy.

Science Impacts

- Less noise in the sky – a darker field and hence increased sensitivity for faint objects
- Better capture of the initial pair vertex and hence location of conversion. This is vital to isolate conversion within the silicon detectors.
- Improves PSF core and reduces tails



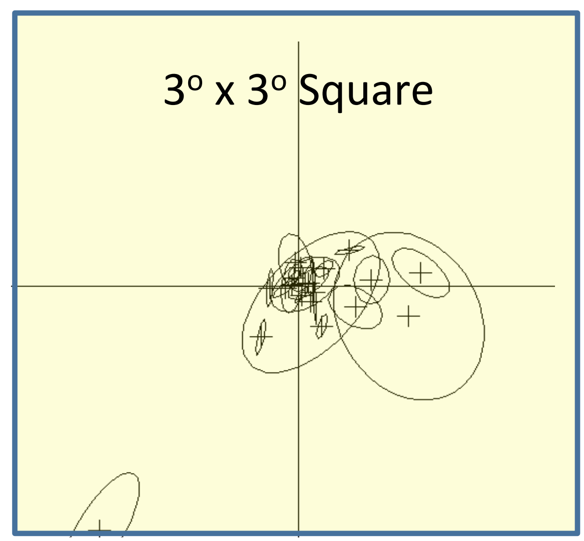
Reducing mis-tracking effectively darkens the sky and faint sources are more easily resolved.

Exploiting the Full Power of LAT Tracking: Covariant Errors

- Current analyses assess the angular resolution of each event generically taking into account the incident angle on the LAT and the reconstructed energy. This is captured by the functional form of the PSF (IRF).
- IRFs average over all the various possibilities of missed hits (due mostly to gaps), mix of conversion plane types crossed, etc.
- Detailed fit to each event yields both the direction of the incoming gamma-ray and the full error matrix for the event.
- Applying the event-by-event errors should better resolve sources by essentially providing a better estimate of the weight.
- Effort made from the start to get the Kalman Fit Errors correct.

Error Ellipses from a 5-GeV Point Source

The relative areas of these ellipses shows the event-to-event variations possible

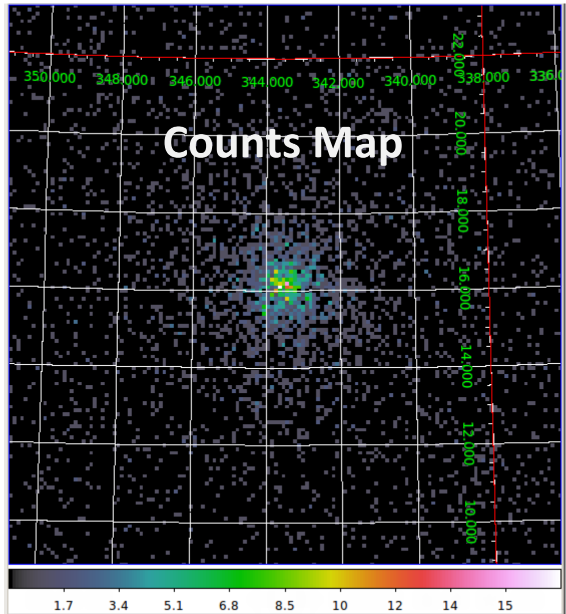


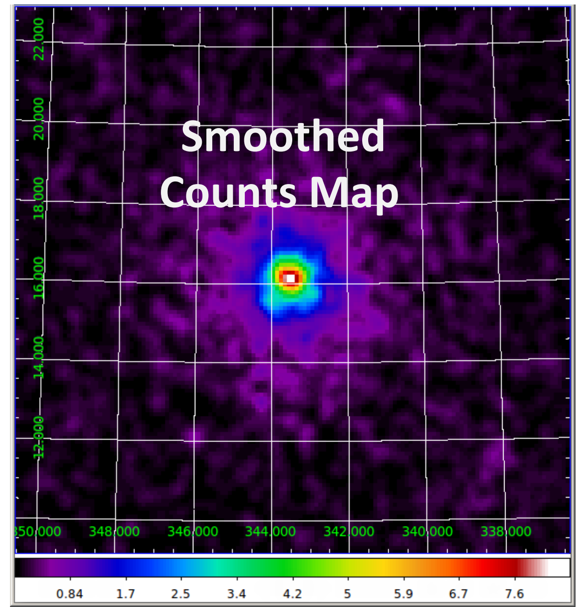
A new view of the Sky using Covariance

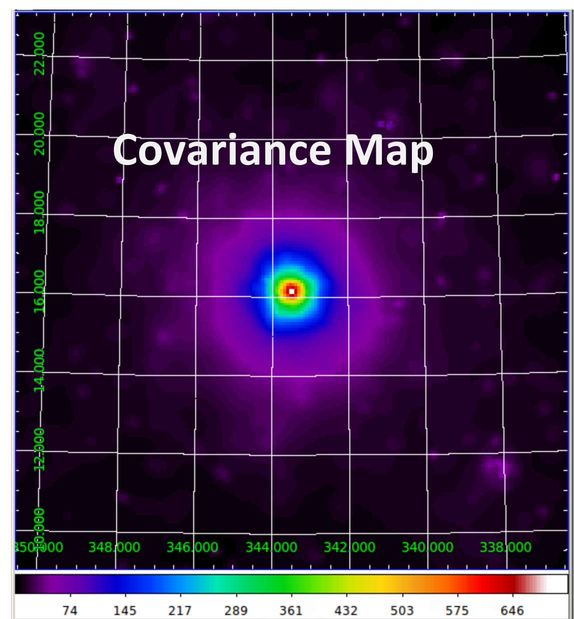
The AGN 3C454.3
E > 100 MeV

Smoothed Counts Map done with a Gaussian Kernel

Covariance Map: 2D Gaussian smoothing using covariant errors







Question: Will covariant image analysis of AGNs finally reveal Pair Halos?

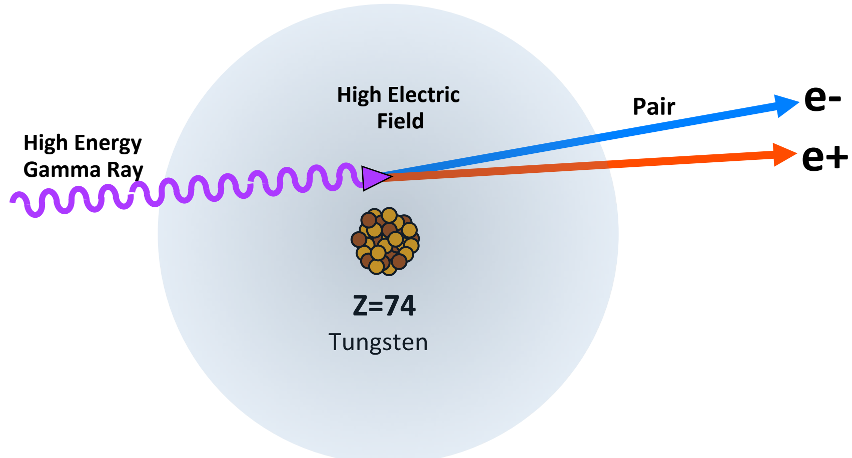
Summary & Conclusions

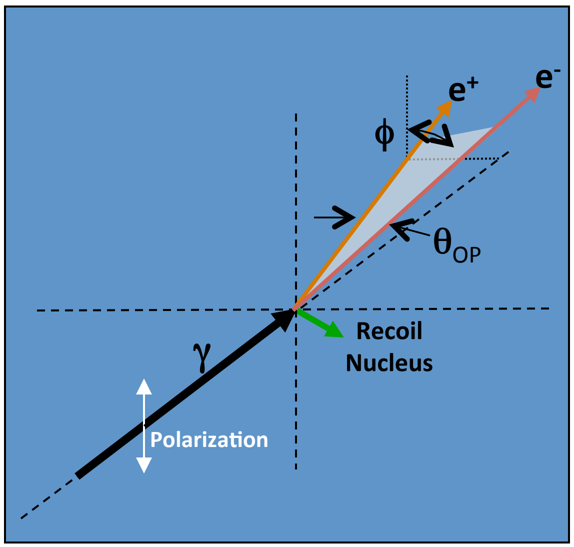
- Careful optimization during the design and construction of the LAT resulted in a great instrument !
- Technology choices resulted in an instrument which has negligible down time spent on remedying problems and calibrations.
- After 3+ years of operation, deterioration in performance is nil.
- Flexibility of Trigger and Data Acquisition have allowed for high energy science outside of gamma-ray astronomy.
- Continuing efforts to extend and optimize science return promise an even more productive future.
- We can all look forward to many more years of Fermi!

Backup

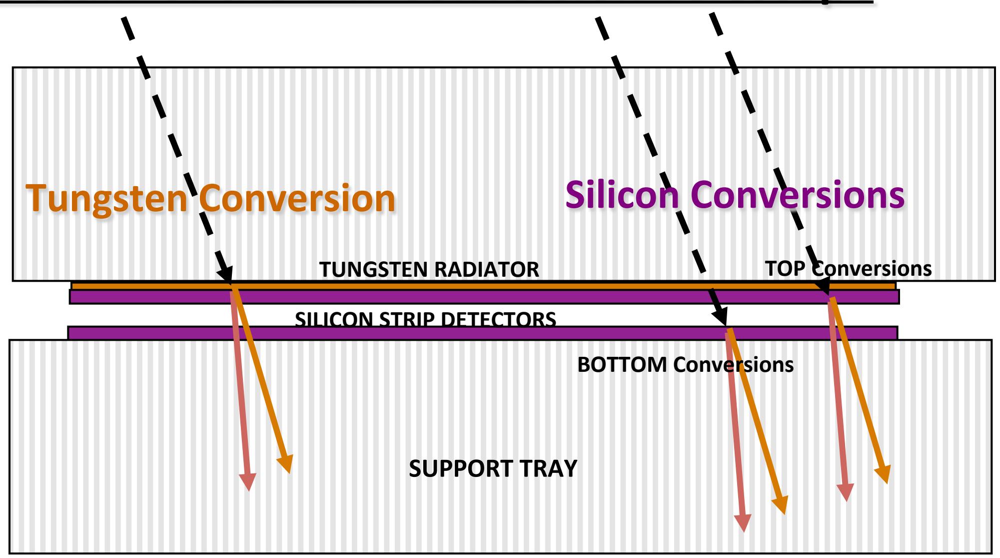
Detailed Vertex Topology: Polarization?

If the incident Gamma Ray is linearly polarized, the plane of the e+,e- pair shows a modulation in azimuth, ϕ, about the direction of the Gamma Ray..





Details of the LAT Conversion Telescope



First 12 LAT Bi-Planes

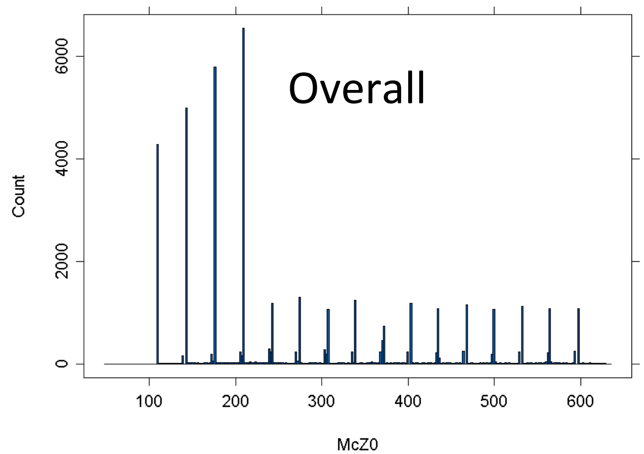
Radiator = 2.8% (68% Convert Here)

Silicon = 2 x .4% (**20% Convert Here**)

Trays = .5% (12% Convert Here)

Separation of Silicon Conversions

Monte Carlo location of conversions



The reconstruction places the start of the track in the middle of the lower SSD measuring plane or in the middle of the tungsten radiator above the upper SSD measuring plane.

Tray Level