National Aeronautics and Space Administration

Fermi

Gamma-ray Space Telescope

www.nasa.gov/fermi

Study of charged cosmic rays with the Fermi Large Area Telescope

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on behalf of the Fermi LAT collaboration

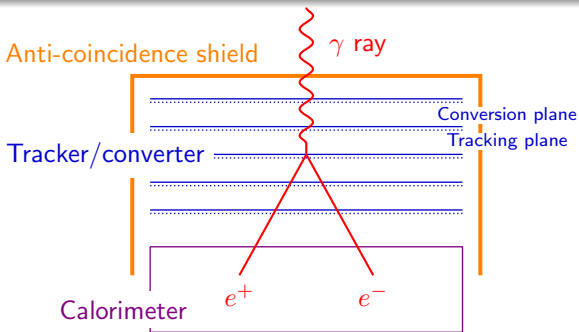CRIS 2015, September 14

The Fermi observatory

Large Area Telescope (LAT)

- ▶ Pair conversion telescope
- ▶ Energy range: 20 MeV − >300 GeV
- ▶ Field of view: ~ 2.4 sr (at 1 GeV)
- ▶ Effective area: ~ 6500 cm^2 on axis (at > 1 GeV)

- ▶ Launched by NASA on 2008 June 11, from Cape Canaveral, Florida
- ▶ Launch vehicle: Delta II Heavy
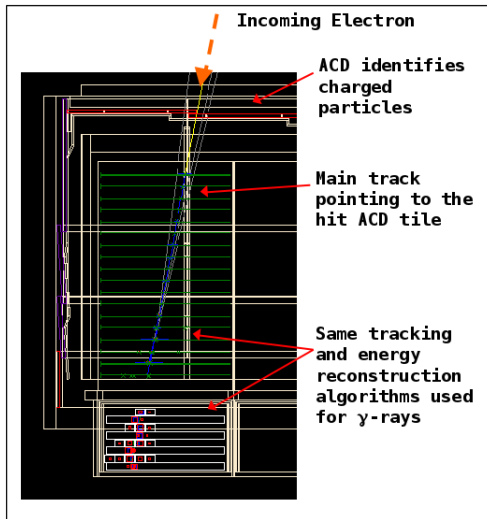- ▶ Orbit: $25.6°$ inclination, 565 km altitude

- ▶ Standard technique for high-energy γ-ray astrophysics
  - ▶ Dominant interaction mechanism for $E > \sim 20 MeV$
  - ▶ Used by past experiment like COS-B and EGRET
- ▶ γ-ray converts in the middle of Tracker/Converter $\rightarrow \gamma$-ray direction
- ▶ Calorimeter absorbs part of the e.m. shower $\rightarrow \gamma$-ray energy
- ▶ No signal in the Anti-coincidence shield $\rightarrow$ charged particle discrimination

- Detector is designed for E. M. showers
    - Naturally including electrons $(e^+ + e^-)$
- Triggering on (almost) every particle that crosses the LAT
- On-board filtering to remove many charged particles
    - Keeps all events with more than 20 GeV in the CAL
    - Prescaled ($\times 250$) unbiased sample of all trigger types
- Event reconstruction assumes a E. M. shower
    - Works fine for electrons
- Electron identification
    - Dedicated event selection
- No charge separation

Incoming Electron

ACD identifies charged particles

Main track pointing to the hit ACD tile

Same tracking and energy reconstruction algorithms used for γ-rays

ELECTRON EVENT SELECTION
JUST AN EXAMPLE TO SHOW THE IDEA

Candidate electron
475 GeV deposited energy, 834 GeV reconstructed

Candidate hadron
823 GeV deposited energy, 1 TeV reconstructed
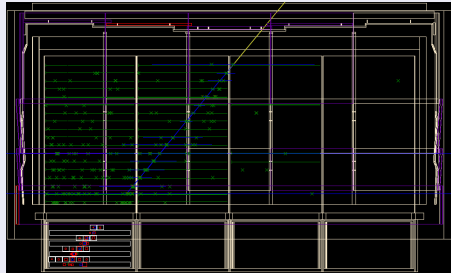
- ▶ Clean main track with extra clusters close to the track (note backsplash from the calorimeter)
- ▶ Relatively few ACD tile hits, mainly in conjunction with the track
- ▶ Well defined (not fully contained) symmetric shower in the calorimeter
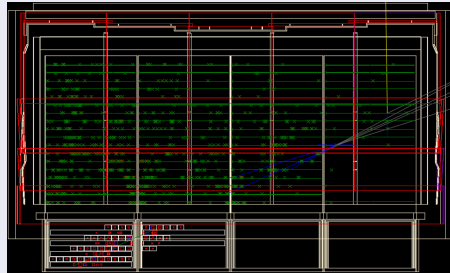
- ▶ Small number of extra clusters around main track, many clusters away from the track
- ▶ Different backsplash topology, large energy deposit per ACD tile
- ▶ Large and asymmetric shower profile in the calorimeter

- ▶ Final event selection by combining these information in Decision Trees
  - ▶ A pretty standard techinque now

"LOW ENERGY" ELECTRONS
BELOW ∼20 GeV

McIlwain L and cutoff rigidity
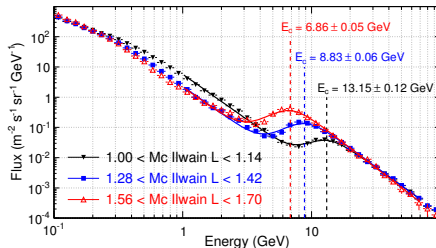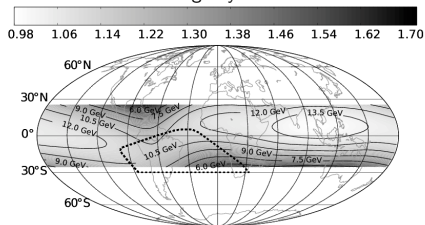
- ▶ Need to take into account the effect of the Geomagnetic field
  - ▶ Rigidity cutoff depends on the detector geomagnetic position
  - ▶ ≈ 7 GeV is the minimum energy accessible in the Fermi orbit
- ▶ Data are divided in independent McIlwain L bins
  - ▶ The cutoff Energy is extracted by fitting the electron flux
  - ▶ For each energy bin we use only the McIlwain L region for which the measured cutoff is below the low edge

Cosmic-ray $e^+ + e^-$ spectrum
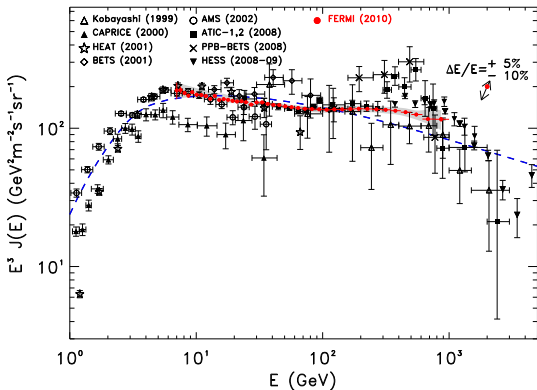
Abdo, A. A. et al.
Phys. Rev. Lett. 102, 181101 (2009)

Ackermann, M. et al.
Phys. Rev. D 82, 092004 (2010)

- ▶ Our first result: spectrum from 7 GeV to 1 TeV
  - ▶ High-energy endpoint mostly limited by crystal saturation in the CAL
  - ▶ Systematic uncertainty dominated by the knowledge of effective geometry factor
- ▶ Spectrum is harder than in pre-Fermi GALPROP model
  - ▶ Can be fitted by a power-law with spectral index in the interval 3.03–3.13

SEARCH FOR ANISOTROPIES IN $e^- + e^+$

Count map (E > 60 GeV)
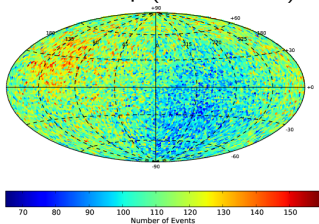
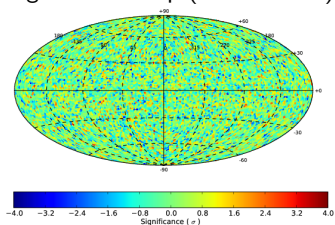
No-anisotropy map (E > 60 GeV)
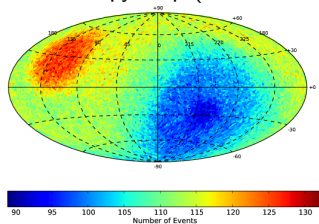
- ▶ Fermi offers large exposure, and complete sky coverage
- ▶ Comparison of the real sky map with *no-anisotropy* one (null hypothesis case)
  - ▶ Accounts for non uniform exposure
  - ▶ Constructed artificially from the actual data set
   - ▶ Avoiding MC usage

Significance map (E > 60 GeV)

- No anisotropy observed in the first year of operation: only upper limits
- Dipole anisotropy is a valuable tool to constrain models
  - 95% confidence level compared with several models
  - Dominance of a single, very bright nearby source is disfavored
  - Dark Matter models predict a smaller effect

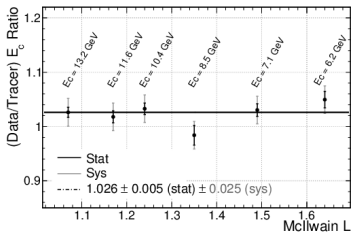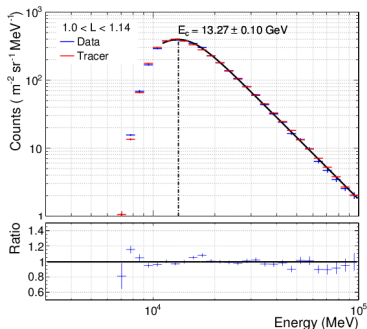Ackermann, M. et al., Phys. Rev. D 82, 092003 (2010)
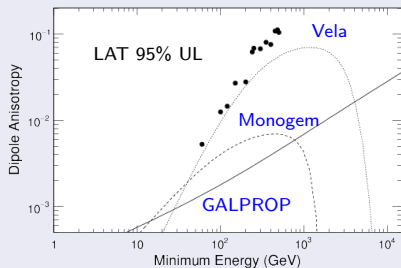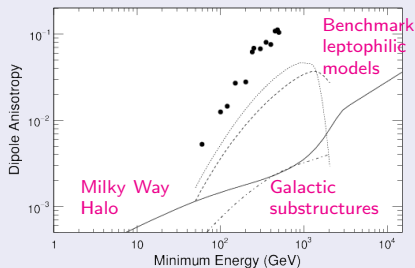
▶ The value for the cutoff rigidity can be predicted using a particle tracing code
  ▶ Using code written by Smart & Shea
    (Final Report, Grant NAG5-8009, 2000)
  ▶ Geomagnetic field described with IGRF model
▶ Comparison of predicted and measured values provides an opportunity to perform an in-fight 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)

Ackermann, M. et al., Astropart. Phys., 35, 346 (2012)

How we can distinguish e^+ and e^-

- ▶ The LAT doesn't carry a magnet on-board
  - ▶ We can not directly discriminate particle charge
- ▶ The only magnet we can use is provided by the Earth
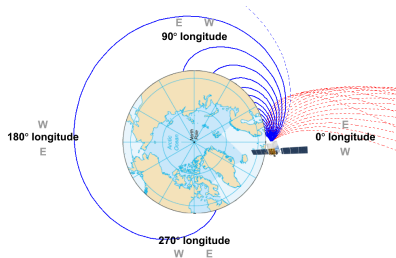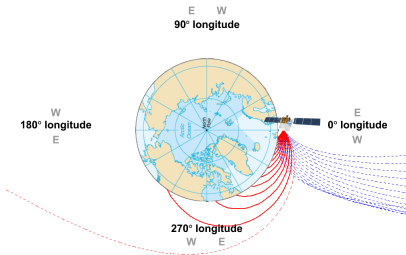
- ▶ The solid Earth surrounded by its magnetic field blocks some of the particle trajectories
  - ▶ Continuous lines in the figures above
- ▶ There are regions in which only one of the two particle types is permitted
  - ▶ Pure e^+ region in the West direction & Pure e^- region in the East direction
- ▶ Particle trajectories are numerically traced in geomagnetic field
 - ▶ Region boundaries vary with energy and LAT position in the orbit
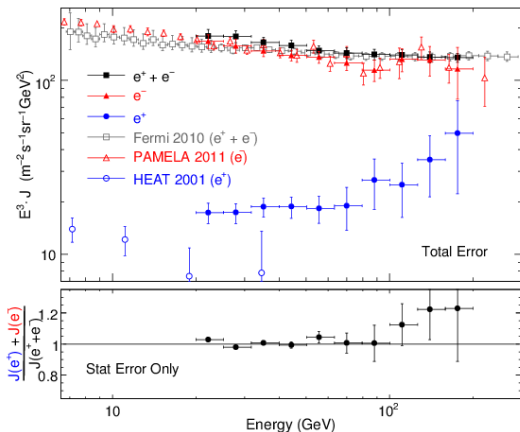
- ▶ Three regions used in this analysis: $e^+ + e^-$, e^-, e^+
  - ▶ Smaller e^-–only and e^+–only as energy increases
    - ▶ This limits the highest energy
- ▶ Useful data only when the LAT is looking down at the Earth (non–survey mode)
  - ▶ ~39 days of livetime, up to April 2011

- ▶ Positron fraction can be calculated from e^+ and e^- spectra
- ▶ It increases with energy from 20 to 200 GeV
  - ▶ First independend confirmation of PAMELA result
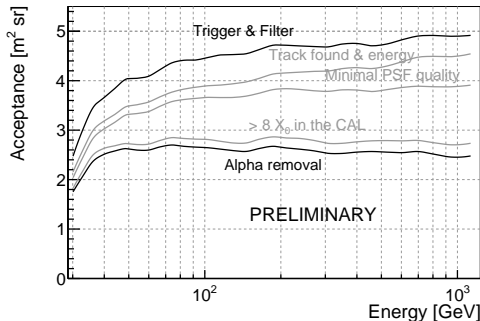
Ackermann, M. et al., Phys. Rev. Lett. 108, 011103 (2012)

- Pass 8 is a complete rework of the entire event level analysis
  - Simulation, reconstruction, background rejection, analysis methods
- Effectively a new instrument, with superior performance
- Data processing pipeline switched to Pass 8 on 24 June 2015
  - FSSC now serving Pass 8 data

- Tree-based tracking pattern recognition
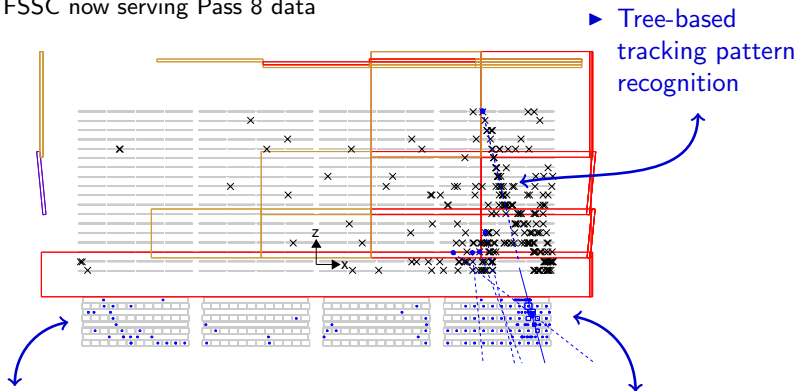
- Calorimeter clustering to handle "ghost" events
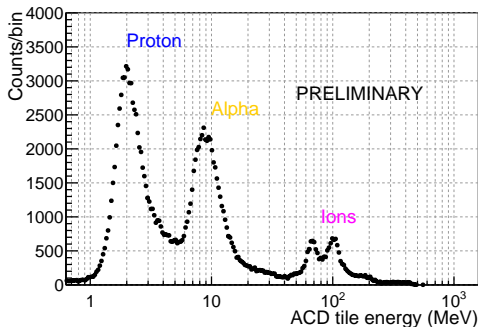
- Improved shower profile fit for energy reconstruction

▶ Similar strategy as before:
  ▶ A few simple cut to require a minimum event quality and remove not well simulated event topology
  ▶ Decision Trees to remove the bulk of hadronic contamination
    ▶ Based on roughly the same topological information as before

▶ Moving to the TMVA package for classifiers
  ▶ Boosted Decision Trees (BDT) provide the best performance
  ▶ Several combination of training setting under study

▶ Basic quality cuts:
  ▶ At least a reconstructed track and 5 GeV of energy deposition in the CAL
  ▶ A loose selection on the PSF quality (using the same handle as in γ-ray analysis)
  ▶ At least 8 radiation lengths in the CAL

▶ Field of view is limited to $60°$

A NEW ANALYSIS FOR COSMIC RAY ELECTRONS

▶ Similar strategy as before:
  ▶ A few simple cut to require a minimum event quality and remove not well simulated event topology
  ▶ Decision Trees to remove the bulk of hadronic contamination
    ▶ Based on roughly the same topological information as before

▶ Moving to the TMVA package for classifiers
  ▶ Boosted Decision Trees (BDT) provide the best performance
  ▶ Several combination of training setting under study

▶ Alpha and ions removal:
  ▶ Relatively easy to separate using, e.g., the pulse height information in the ACD and the tracker
  ▶ Their hadronic interactions are comparatively hard to simulate
  ▶ A set of simple cuts bring down their contamination to a negligible level

► Similar strategy as before:
  ► A few simple cut to require a minimum event quality and remove not well simulated event topology
  ► Decision Trees to remove the bulk of hadronic contamination
    ► Based on roughly the same topological information as before
► Moving to the TMVA package for classifiers
  ► Boosted Decision Trees (BDT) provide the best performance
  ► Several combination of training setting under study
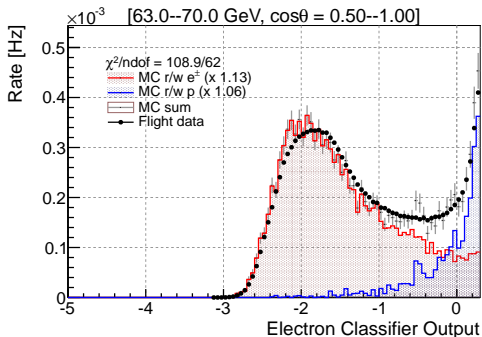
► Template fitting of the BDT output
  ► Fitting only normalization
  ► Testing the data-MC agreement
  ► Estimating signal directly from the fit
 ► Estimating the residual background correction
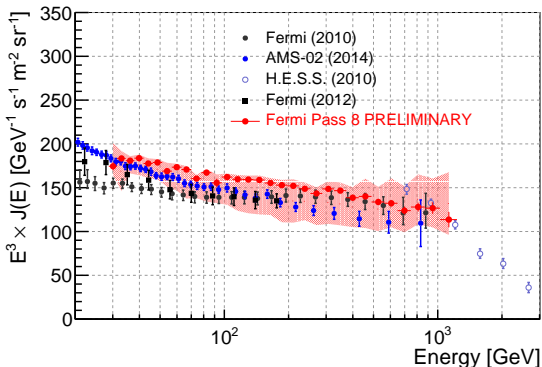
- ▶ Shaded region includes the maximum variation changing the CT efficiency from 90% to 20%
- ▶ Effect of absolute energy scale uncertainty not included

- ▶ We have evidence that at least a significant part of the difference with our 2010 result is due to "ghost" signal
    - ▶ This was not taken into account in the acceptance in our first analysis
    - ▶ Subsequent studies (e.g. the control region in the positron analysis) suggest an overestimation of acceptance by 10–15% at ∼10 GeV
    - ▶ Pass 8 is designed to be less sensitive to "ghost"

SENSITIVITY TO ANISOTROPY

- ▶ The final goal is the search for local sources of $e^+ + e^-$
- ▶ Anisotropy analysis is still statistics limited
  - ▶ Upper limits improves with time
- ▶ With 7 years of Pass 8 data we may be able to exclude the case of a single dominant source
- ▶ Here a simple exercise based on a toy-MC and reasonable response functions:
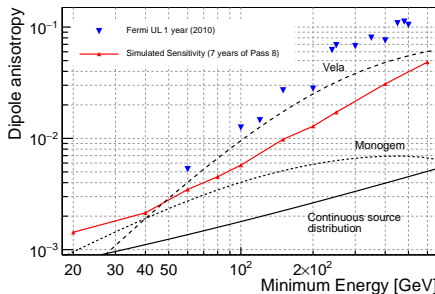

Credits N. Di Lalla

PROTON ANALYSIS

▶ The goal is to reconstruct a spectrum in an energy range that can join space-baced and balloon measurement

▶ Similar strategy as for electron analysis
  ▶ A few cut to remove obvious background
  ▶ A BDT for the final selection
▶ Here an example of how alpha and heavier ions are identified and removed $\longrightarrow$

▶ With a few additional difficulties
  ▶ No energy reconstruction for single events
    ▶ Need to unfold the energy distribution
    ▶ Here the LAT's response using proton simulations $\longrightarrow$
  ▶ Uncertainties on hadronic simulation to be studied

CONCLUSIONS
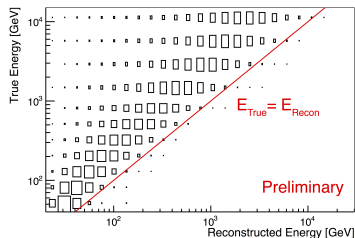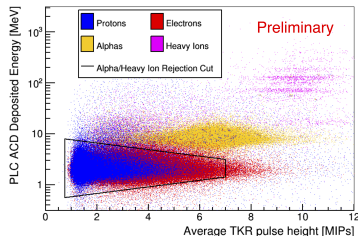
- Cosmic-ray studies with the Fermi-LAT have been quite successful
  - Inclusive $e^+ + e^-$ spectrum from 7 GeV to 1 TeV
  - Upper limits on anisotropies in the arrival directions above 60 GeV
  - Particle tracing in Earth's magnetic field
    - Charge discrimination and test of instrument calibration

- New analysis in progress with the new Pass 8 event-level analysis
  - New reconstruction, improved MC simulation, new analysis tools etc...
  - About $\times 6$ more data available
  - Focusing on the high-energy extension (> 1.2 TeV)
 - Working on particle tracing for low energies (< 30 GeV)

Spare slides
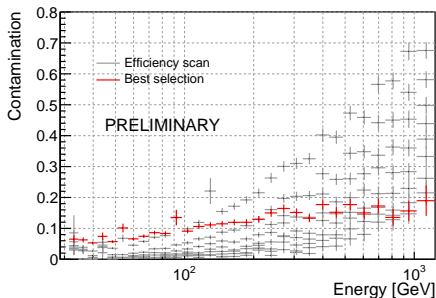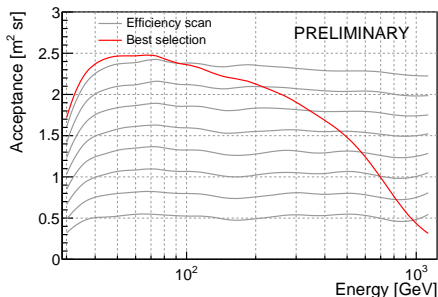
- ▶ Testing the stability of the spectrum in this very wide range
  - ▶ Spectrum variation likely relate to data-MC disagreement
- ▶ Form 90% to 20%, (almost) energy-independent
  - ▶ Maybe a too wide...
- ▶ Average acceptance (after cuts) for this scan shown on the left
- ▶ "Best" cut can be evaluated using the MC-based ROC, as the point in which the slope goes above a defined threshold
- ▶ Bottom plot shows the corresponding residual contamination
 - ▶ Can be very large at high energy
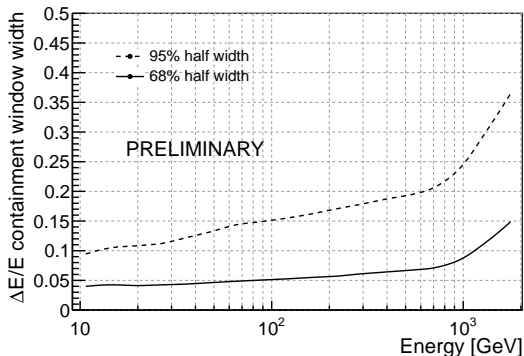
- ▶ After a complete selection, including a cut on a classifier
- ▶ Integrating all the field of view

▶ 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

$$E_{pred,i}(\alpha, \beta, E) = \int_0^\infty f_i(t) \times E \frac{(\beta t)^{\alpha-1} \beta e^{-\beta t}}{\Gamma(\alpha)} dt$$
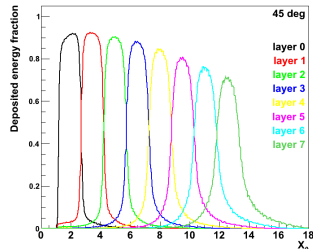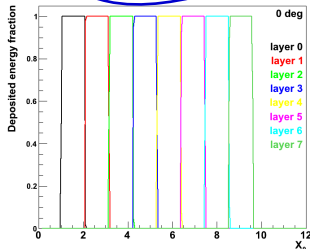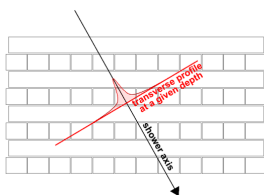
Status of the LAT
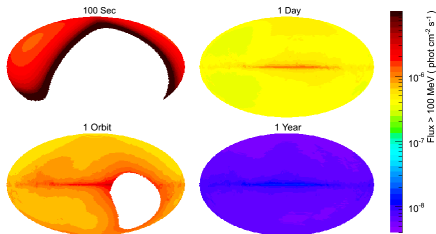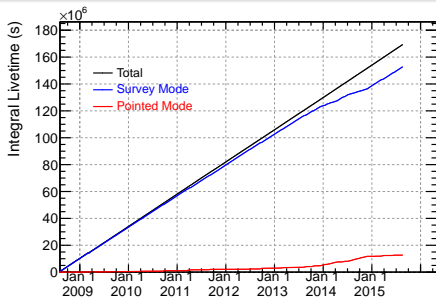
- ▶ LAT is healthy and continuously collecting data
  - ▶ More than 99% up-time collecting science data (out of the SAA)
- ▶ Primary mode is sky survey
  - ▶ Scan entire sky every 3 hours
  - ▶ 1 orbit rock north, 1 orbit rock south
  - ▶ LAT boresight stays away from the Earth
- ▶ More time in pointed mode in ~ 2014
  - ▶ Autonomous Repoint Request and Target of Opportunity
  - ▶ To favor specific science targets (e.g. Galactic Center)