Pass 8 event analysis of the Fermi Large Area Telescope

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on behalf of the Fermi LAT collaboration

10^{th} Rencontres du Vietnam on Very High Energy Phenomena in the Universe

The Fermi observatory

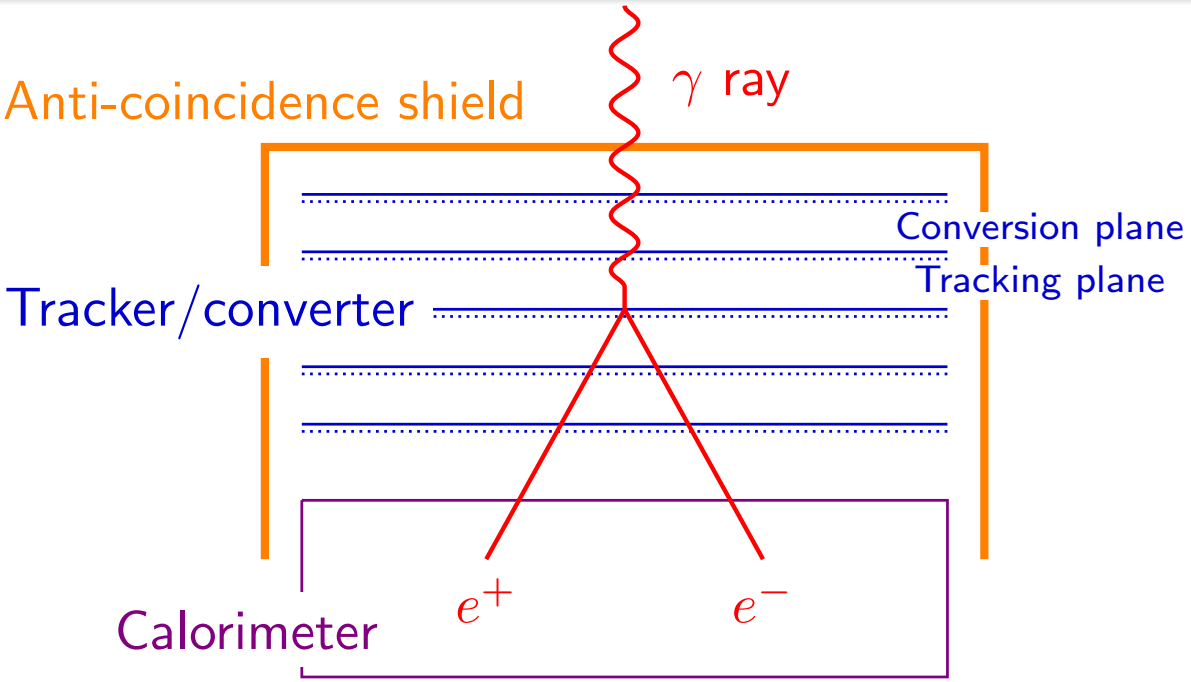
http://fermi.gsfc.nasa.gov/

Large Area Telescope (LAT)

- Pair conversion telescope
- Energy range: 20 MeV – >300 GeV
- Field of view: ~ 2.4 sr (at 1 GeV)
- Effective area: $\sim 6500\ \mathrm{cm}^2$ 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

Detection principle



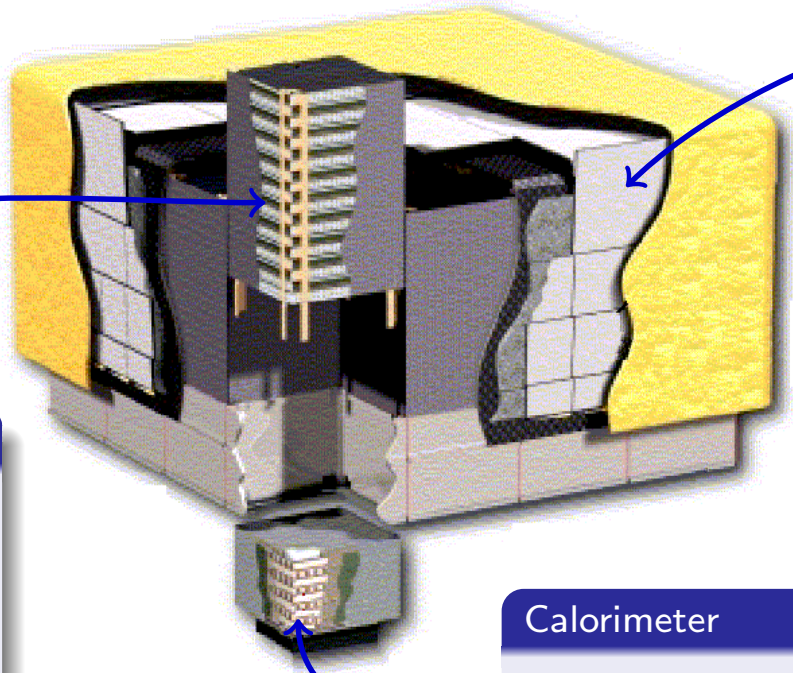
- Standard technique for high-energy γ-ray astrophysics
  - Dominant interaction mechanism for $E >\sim 20 MeV$
  - Used by past experiment like COS-B and EGRET
- γ-ray converts in the middle of Tracker/Converter $\rightarrow$ γ-ray direction
- Calorimeter absorbs part of the e.m. shower $\rightarrow$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

The Large Area Telescope

W. B. Atwood 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)



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

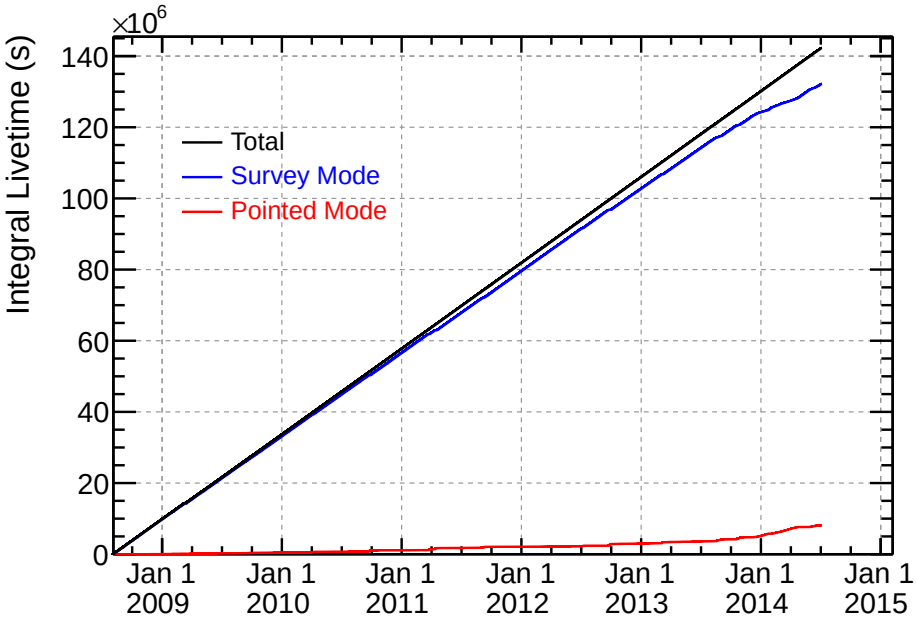
Anti-Coincidence Detector

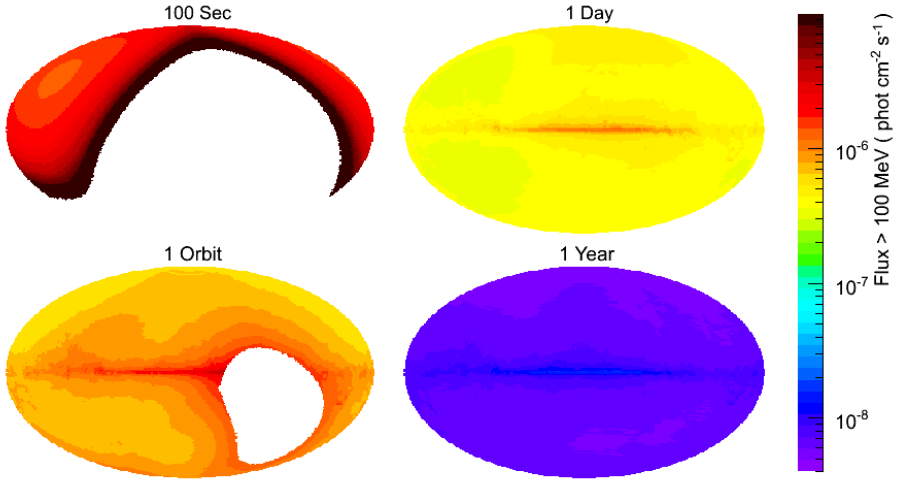
- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

Calorimeter

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

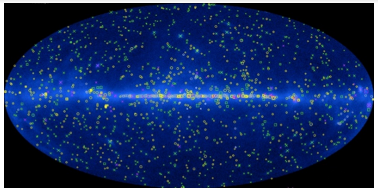
Status of the LAT



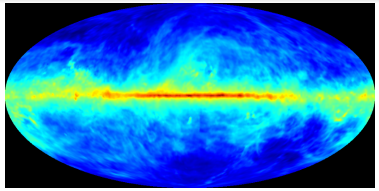


- LAT is healthy and continuously collecting data
  - More than 99% up-time collecting science data (out of the SAA)
- Primary mode is sky survey
  - Scan entire sky every 3 hours
  - 1 orbit rock north, 1 orbit rock south
  - LAT boresight stays away from the Earth
- More time in pointed mode in the last $\sim$ year
  - Autonomous Repoint Request and Target of Opportunity
  - To favor specific science targets

The complexity of the γ-ray sky


Resolved sources

+


Galactic diffuse

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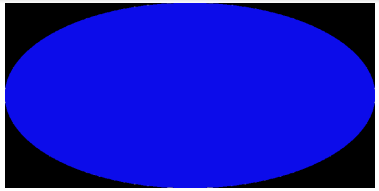
Isotropic diffuse

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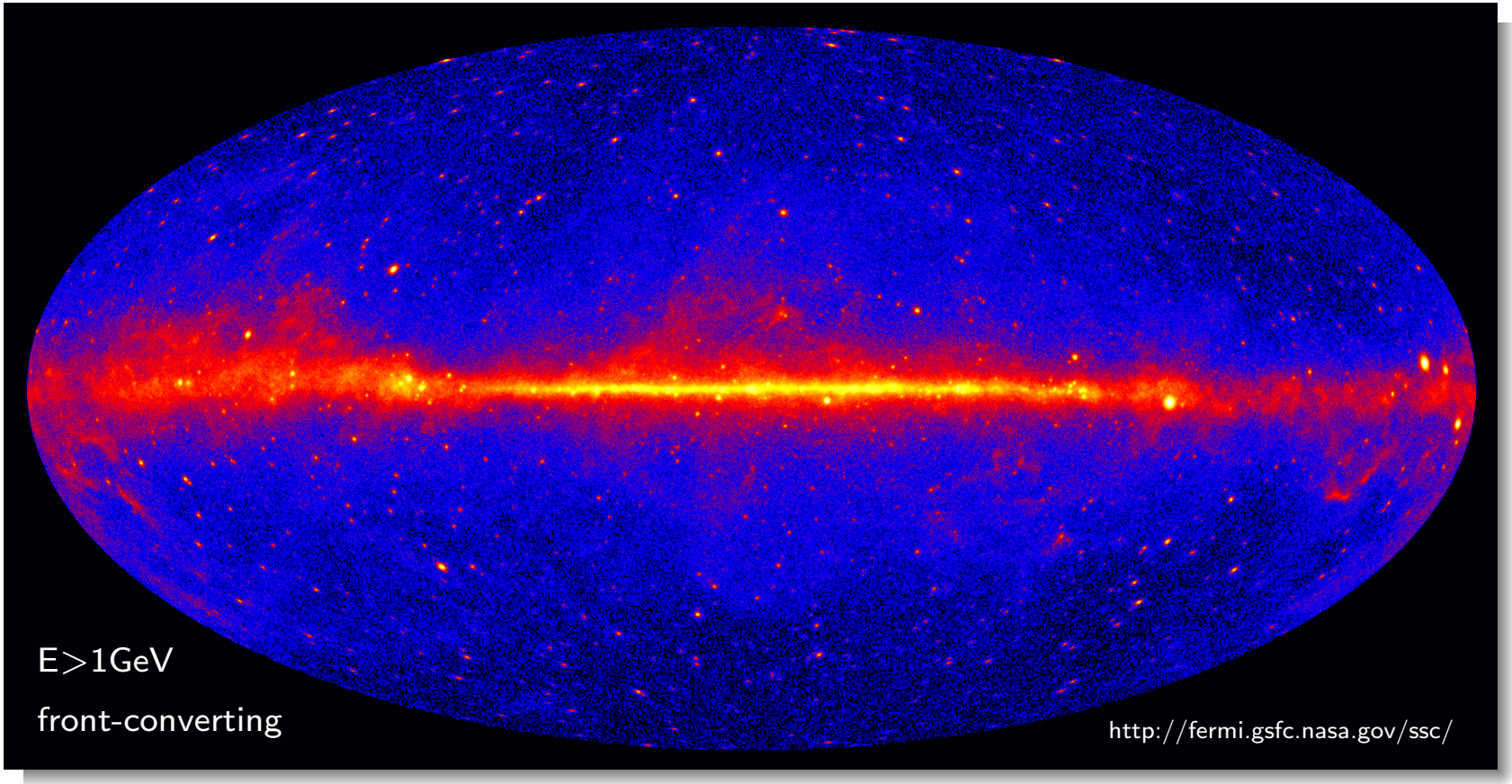


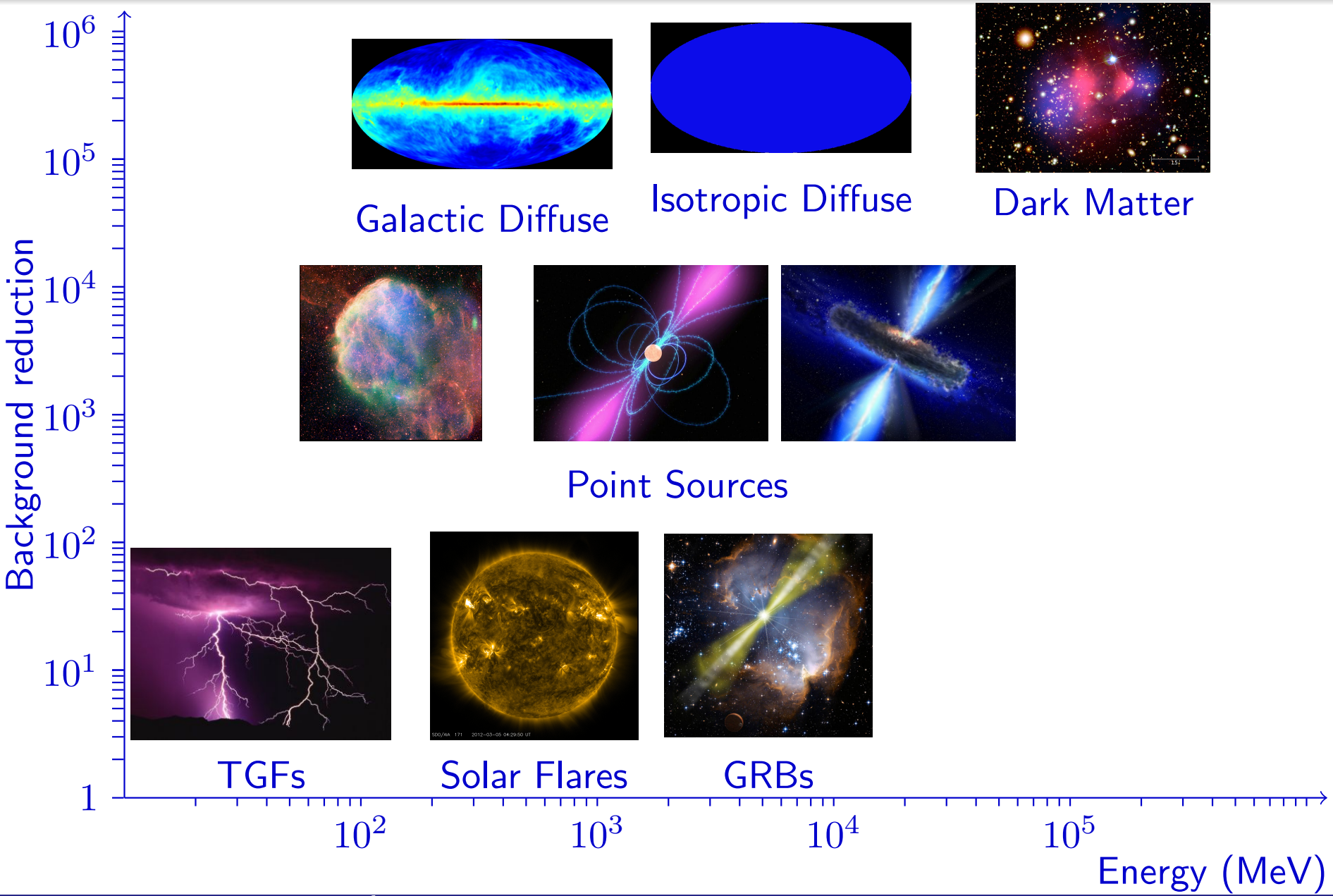
+ Local sources:
Sun
Earth
Moon

+ New Physics (DM search)

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

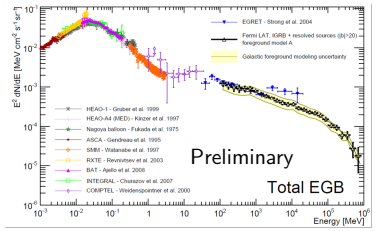
Fermi-LAT Science

Different data selection for different science cases

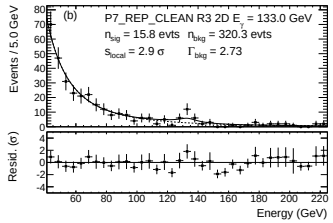


Fermi-LAT Science

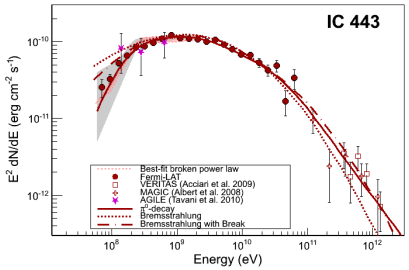
Just a few examples. Several other talks show detailed results



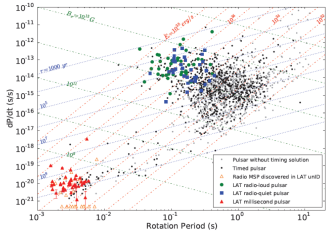
Isotropic Diffuse



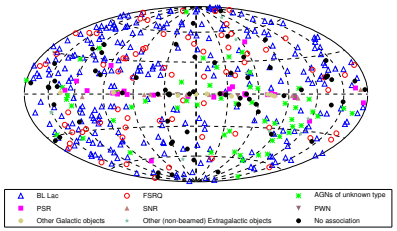
GC line search



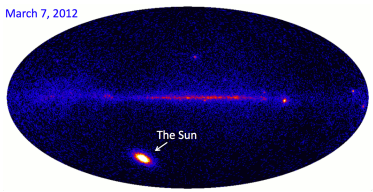
SNR

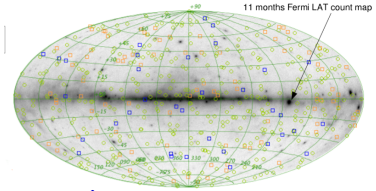


2^{nd} Pulsar Cat.



1^{st} Hard source Cat.





1^{st} GRB Cat.

SF March 7, 2012

Background reduction

10^6 10^5 10^4 10^3 10^2 10^1 1

10^2 10^3 10^4 10^5

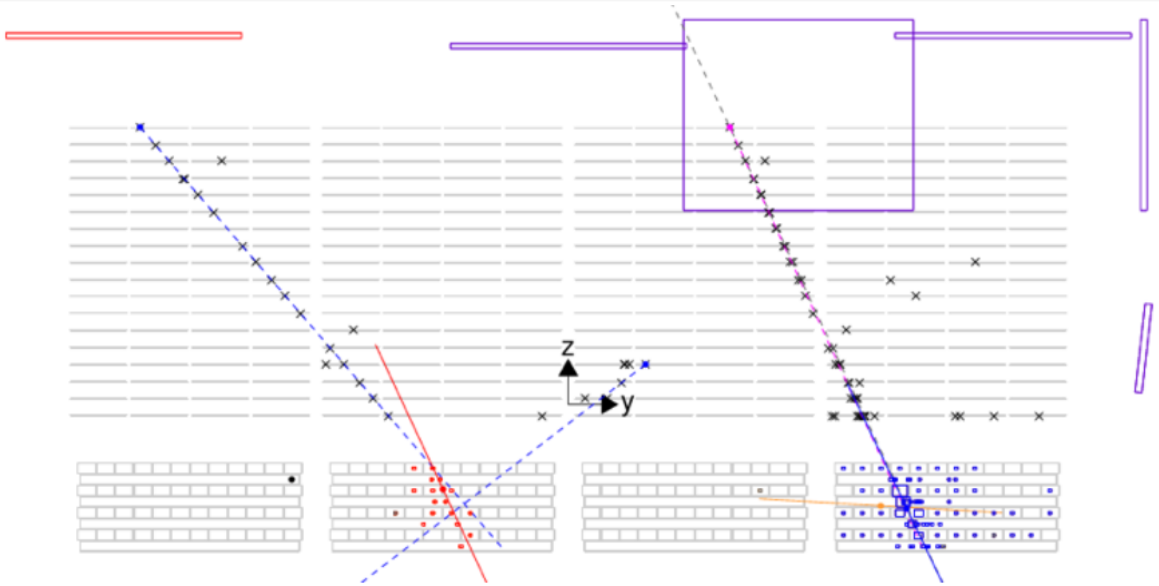
Energy (MeV)

The new event reconstruction: Pass 8

W. B. Atwood et al, 2012 Fermi Symposium proceedings, arXiv:1303.3514

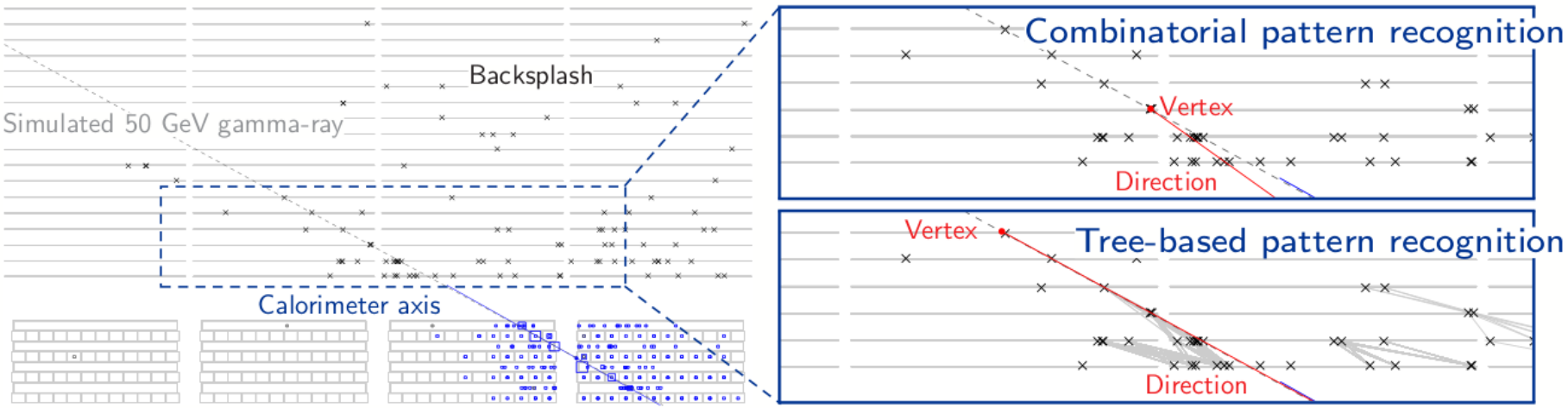
- Event analysis is periodically updated
  - Each iteration of the event analysis is called "Pass"
  - Pass 7 is the current analysis distributed to the community
- Pass 8 is a unique opportunity to exploit the experience of several years of operation in space
- Extensive review of all the reconstruction algorithms
  - TKR Recon: new tree-based pattern recognition
  - ACD Recon: using covariant errors and fast signal
  - CAL Recon: multiple clusters, improved shower profile fit
- Performance improvement:
  - Larger acceptance
  - Better PSF at high energy
  - Wider energy range
  - Better control of systematic uncertainty
- Effectively a "new" LAT

Main motivation for Pass 8



- Event reconstruction was designed, before launch, for a one particle in the LAT at a time
- In flight we studied the fraction of events accompanied by *ghost* signals...
  - Small, but not negligible
  - *Persistence* time of electronic signal in the detector is of the order of $\sim 10\ \mu s$
  - Can cause good γ-ray to be misclassified as background (with loss in effective area)
- Pass 7 mitigates the effect of ghosts
  - Periodic trigger are used to sample out-of-time event
- Pass 8 seeks to remove them at the reconstruction level

A new TKR reconstruction in Pass 8



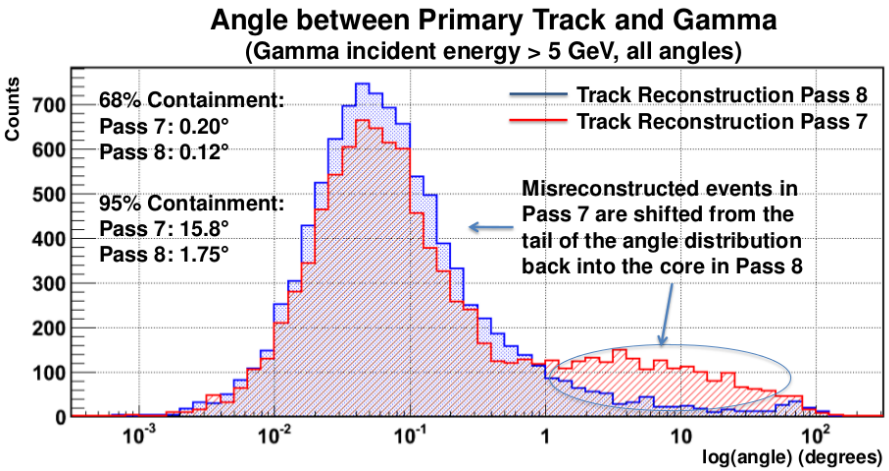
Current framework – track-by-track combinatorial pattern recognition:

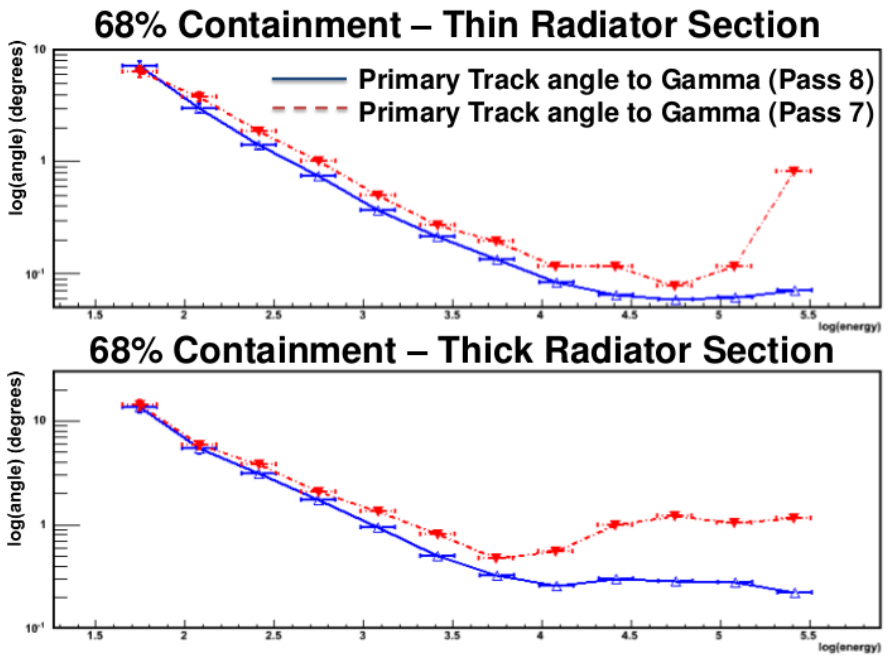
- Returns the optimum trajectory for each track
- Need a good "seed": strong dependence on the CAL
- Track confusion and errors in high-multiplicity events

Pass 8 – global tree-based approach to track finding:

- Reduce mistracking, improve the high-energy Point Spread Function (PSF)
- Provide additional information for the background rejection
- No dependence on CAL

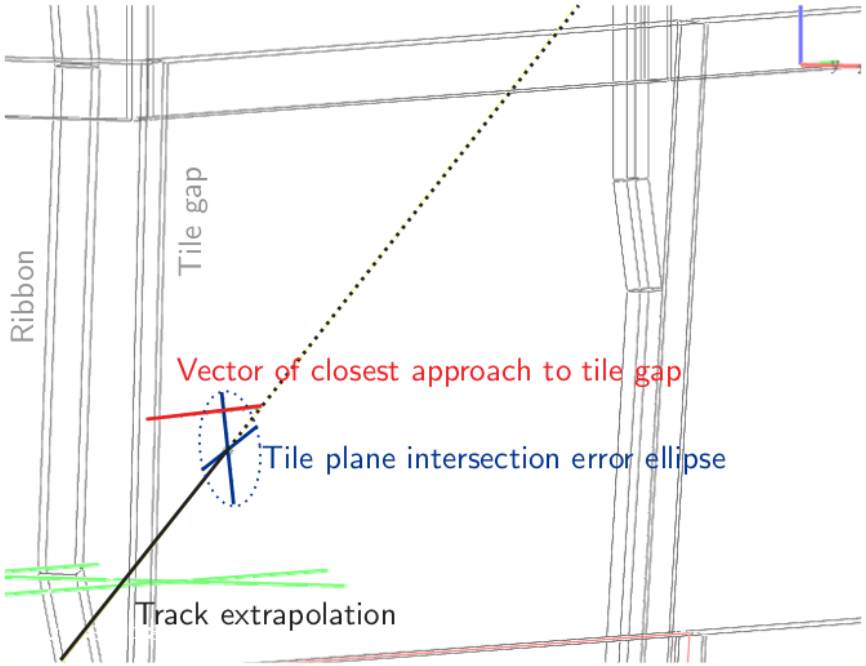
Improved tracking performance





- The intrinsic resolution of the Track Reconstruction is set by the physics of the detector
- The effective resolution is impacted by mis-reconstruction of events
  - A problem as the incident gamma energy increases
- The Tree-Based Tracking is able to better associate Tracker hits that belong to a common source
  - The "tail" of the PSF is highly suppressed

New ACD reconstruction in Pass 8



- The ACD is responsible for providing 0.9997% rejection power for singly charged particles entering the top or sides of the LAT
- Must avoid self-vetoes from the backsplash of energetic gamma-rays

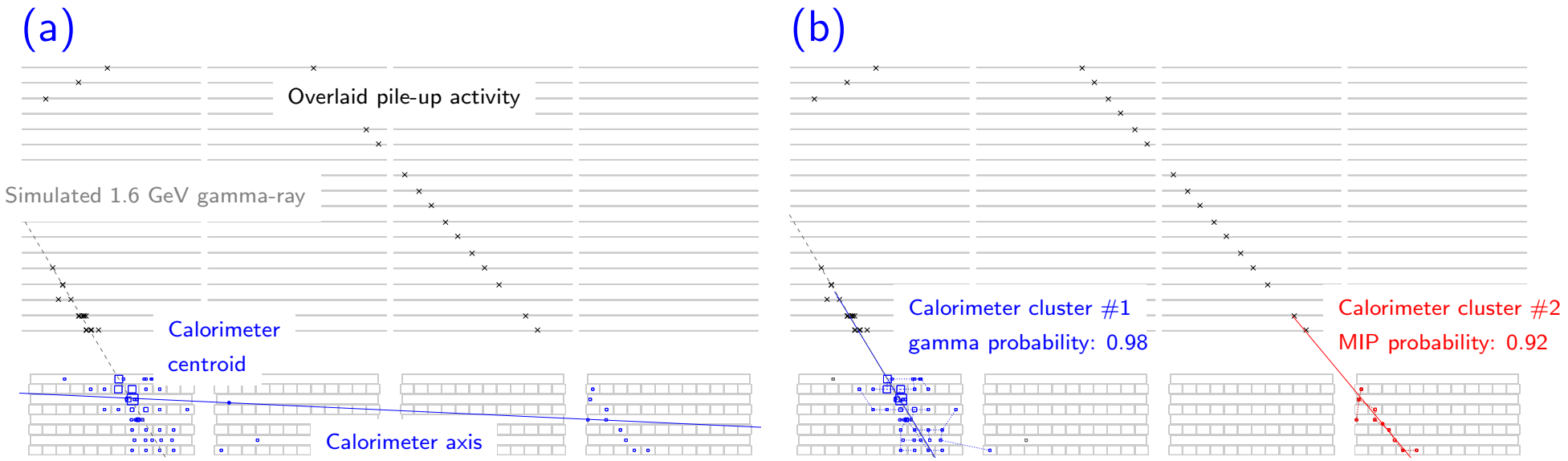
Current framework – track/tile association in physical distance:

- Explicit energy dependent cuts
- Susceptible to global pile-up at low energy

Pass 8 – track and cluster/tile association based on covariant error propagation:

- Improved background rejection
- Use trigger veto to suppress pile-up

CAL Clustering introduced in Pass 8



(a) In the current framework all hits in CAL are considered part of a single shower

- Background rejection suffers when event multiplicity > 1
- Small efficiency loss (accounted for in the Instrument Response Functions)

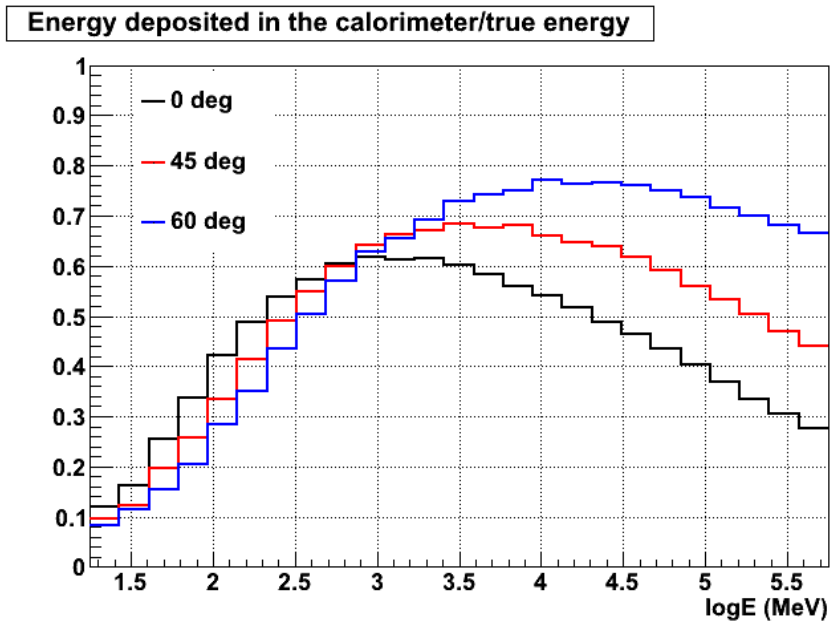
(b) We added clustering stage at the beginning of the reconstruction chain

- Separate the pile-up activity from the genuine gamma-ray signal
- Provide topology information to the following reconstruction steps

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 (No. 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



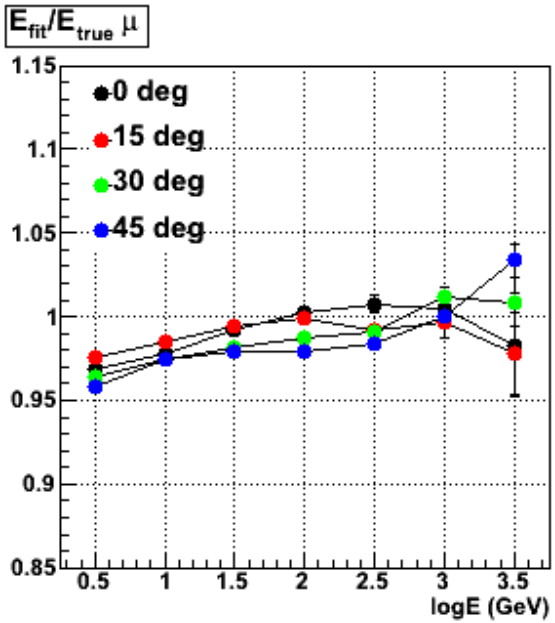
The gamma-ray energy is reconstructed via two different algorithms

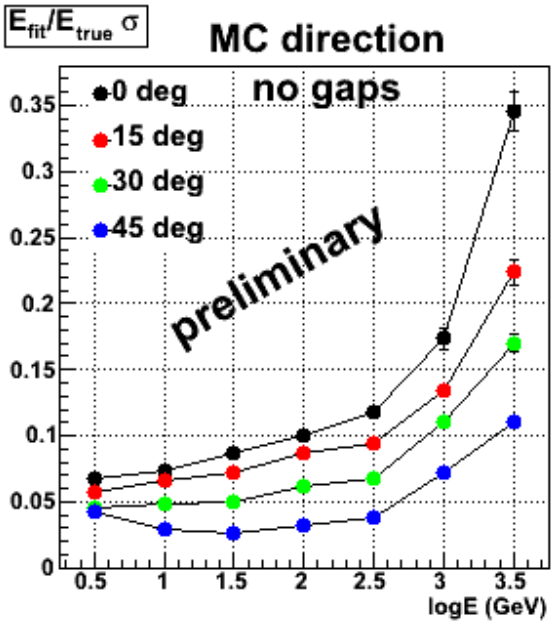
a) A parametric correction
- Use energy centroid depth along the showed axis
- Corrects for energy losses
- Best at *low energy*

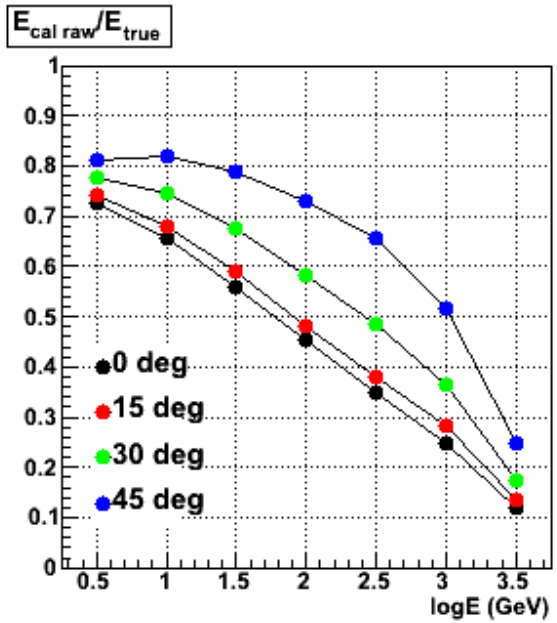
b) A shower profile fit
- Uses a shower axis as reference
- Full 3D fit of energy deposition
- Best at *high energy*

Shower profile fit performance

Ph. Bruel 2012 J. Phys.: Conf. Ser. 404 012033



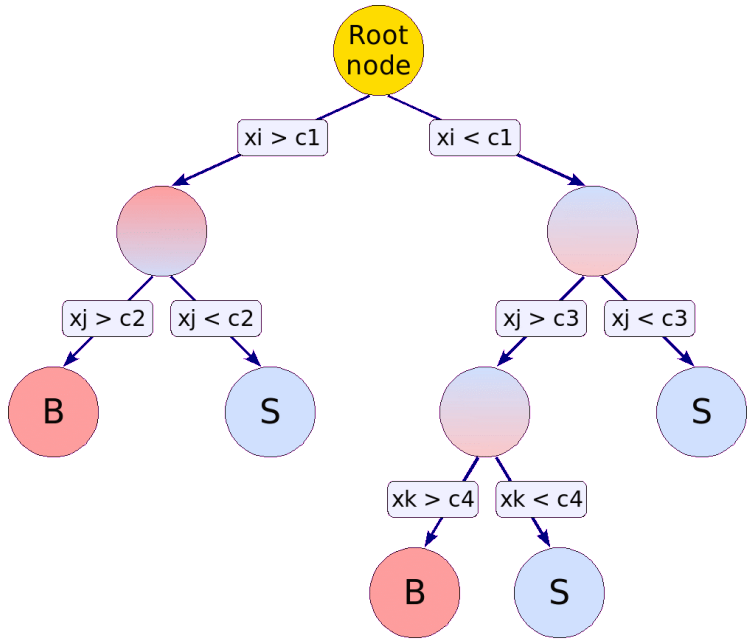




- Good energy resolution up to ~ 1 TeV
  - Thanks to the fine segmentation of CAL
- Above 1 TeV, the energy resolution is degraded, because of crystal saturation and poor containment
- The energy measurement depends on the precision of the direction given by the tracker, but bad events can be rejected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

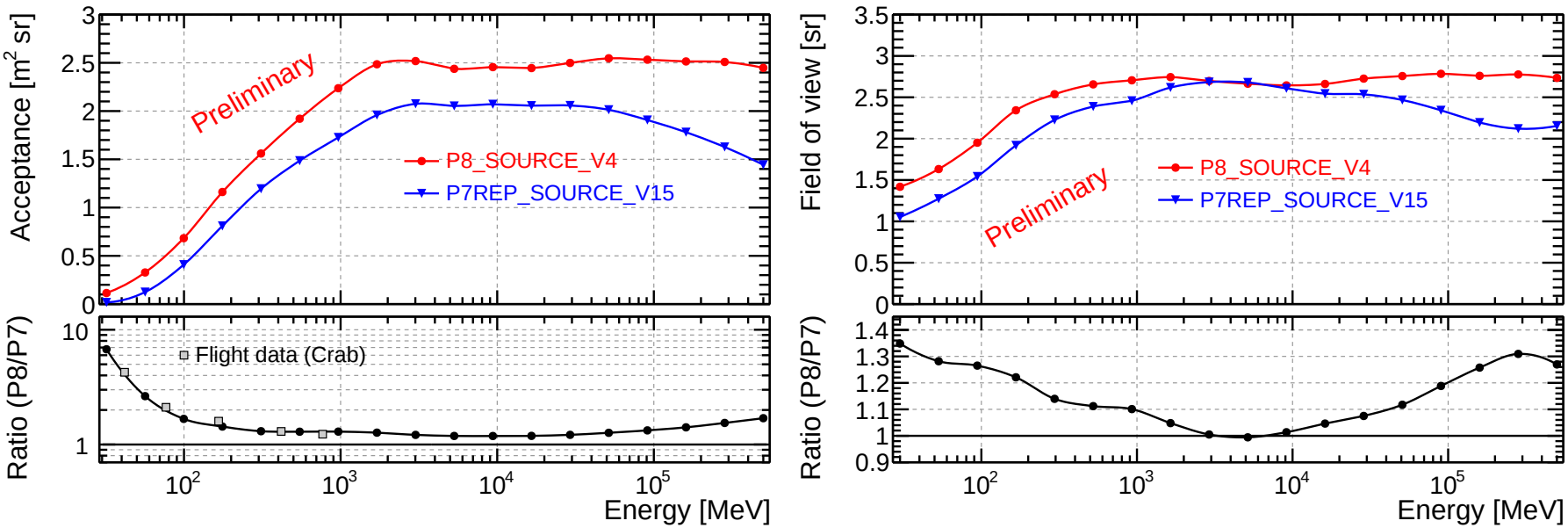
Event Classification

- The final stage of the analysis chain is the event classification:
  - Identify particle type (i.e. select γ, e^+/e^-, etc.)
  - Assess the quality of the reconstructed direction and energy
- LAT analysis make extensive use of multivariate classification technique
  - Very successful in Pass 7
  - Exploiting the TMVA package (`http://tmva.sourceforge.net`)
  - Boosted Decision Trees (BDT) provide the best performance



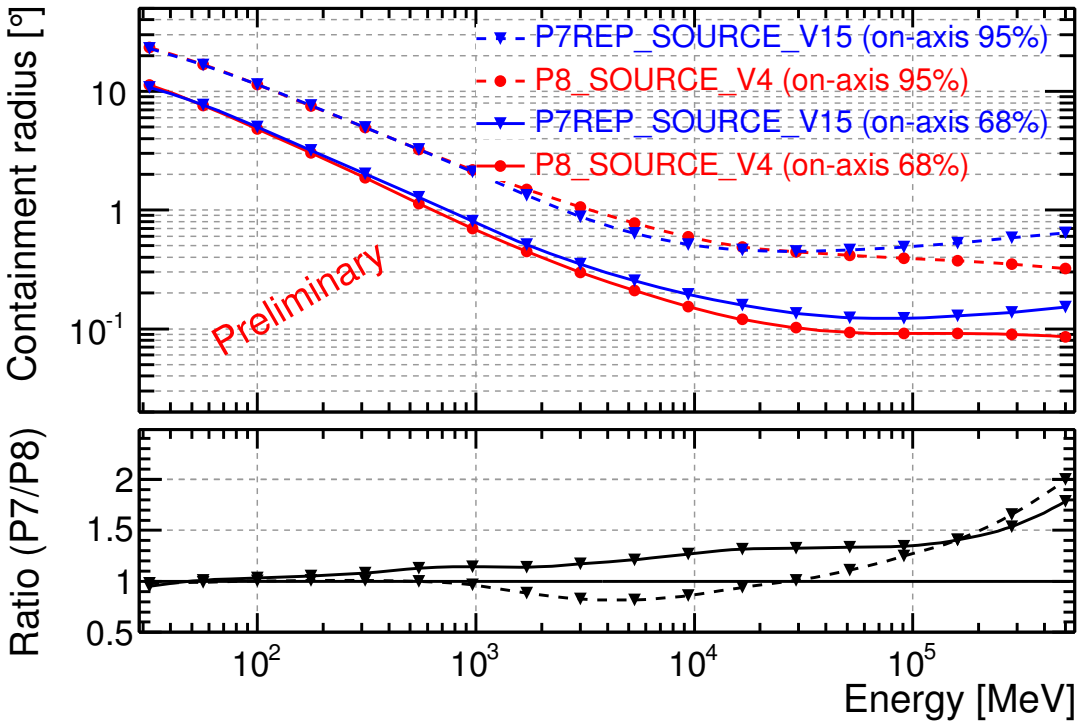
- Decision Tree:
  - Sequential application of cuts splits the data into nodes, where the final nodes classify an event as Signal or Background
  - Well known in "data mining", becoming popular in Physics

Acceptance improvement



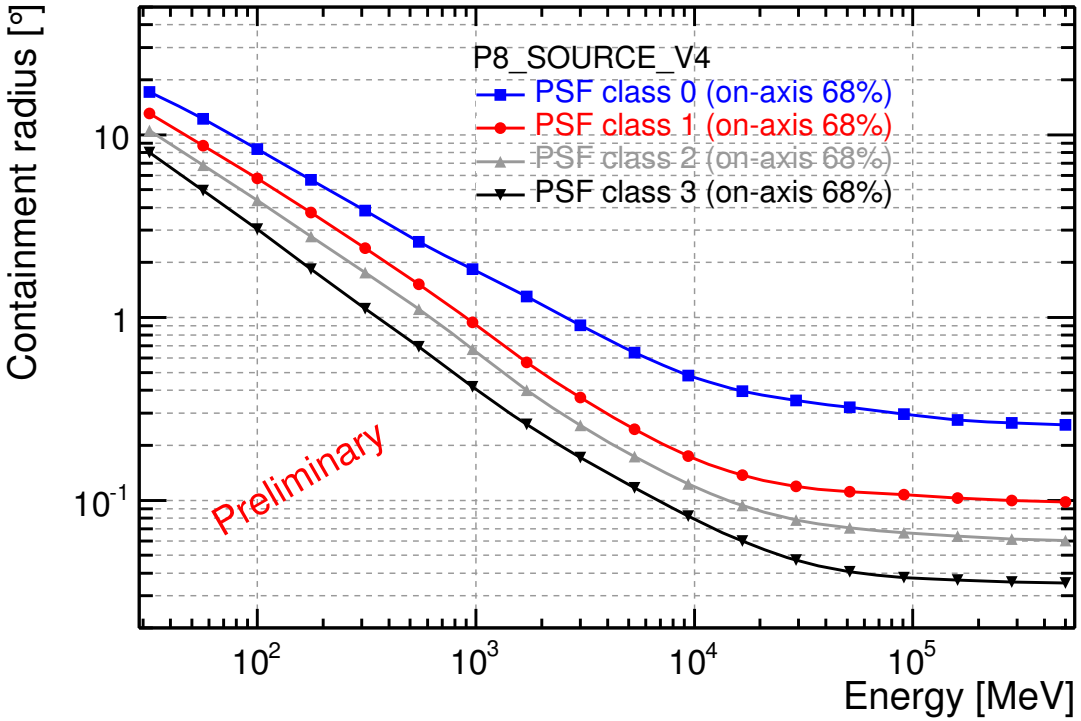
- Preliminary event class for source analysis
- Substantial increase in acceptance ($> \times 2$) below 100 MeV
- About 25% improvement at high energy
- Larger field of view in the entire energy range
- Potential for dramatic improvement in time-domain high-energy astronomy

The new Point Spread Function



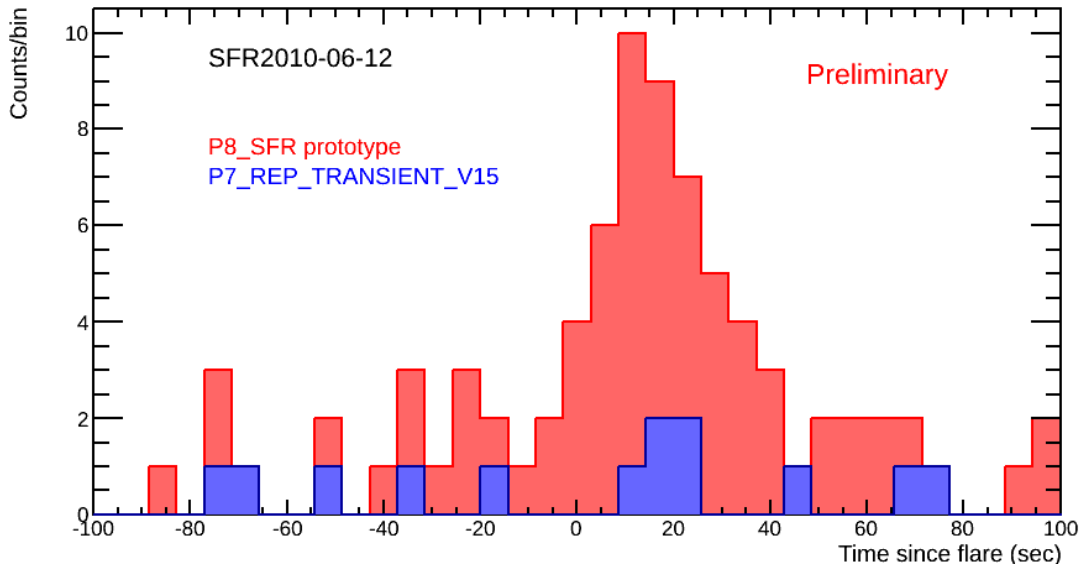
- Preliminary event class for source analysis
- Better angular resolution at high energy
  - Thanks to the new tracking algorithm
- Preliminary study indicates a better agreement with in-flight PSF
- Improvements in high-energy source analysis

Selecting event with better PSF



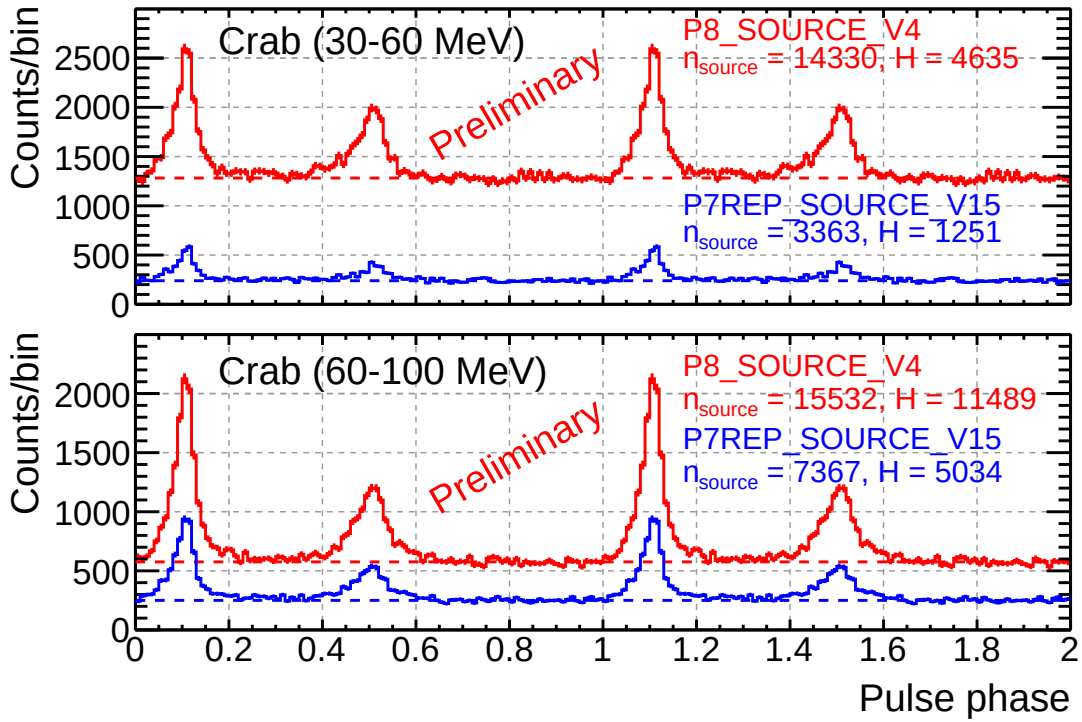
- Different sub-classes with progressively better PSF can be identified
  - Here 4 equal-acceptance cases are shown
- Selection based on event-by-event PSF quality estimator
  - Beyond the existing Front/Back conversion types
- Selection can be optimized for specific cases
  - Removing the worst case(s)
  - Combining pdf in your fit
  - etc...

Dedicated selection for peculiar sources



- Specialized event class for Solar flares
  - Transient phenomena that doesn't require large background rejection
- Alleviate the pile-up effect often present during impulsive Solar flares
- Increase the number of Solar flares sample for localization study

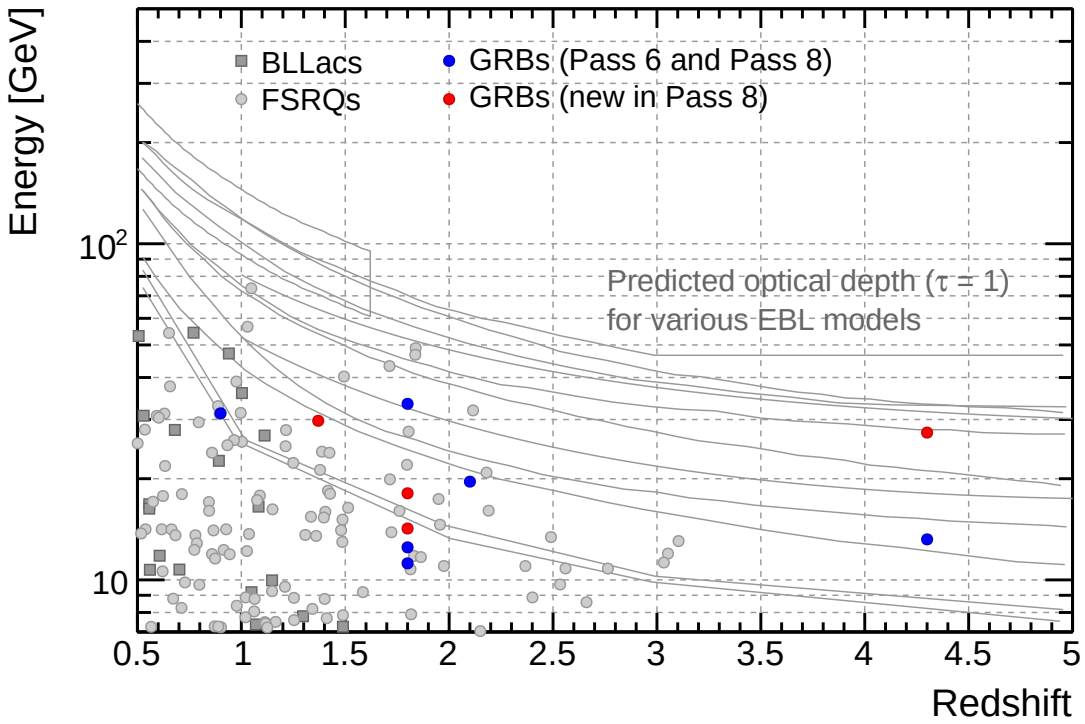
Pass 8 at work: low energy



- Pulse profiles for the Crab pulsar below 100 MeV (2 years of data)
  - Increase in total number of events is consistent with Monte Carlo prediction of acceptance
  - Large increase in H-test significance; particularly exciting for faint pulsars
- Substantially improved sensitivity for time-domain astronomy
  - Blind and epoch-folding pulsar searches
  - Transient searches (novae, blazar flares, etc.)

Pass 8 at work: high energy

W. B. Atwood et al. 2013 ApJ 774 76, arXiv:1307.3037



- Re-analysis of the prompt phase of GRBs with measured redshift in the first LAT GRB catalog
- 4 photons above 10 GeV previously discarded are recovered in Pass 8.
- Stronger limit on energy density of optical/UV extragalactic background light

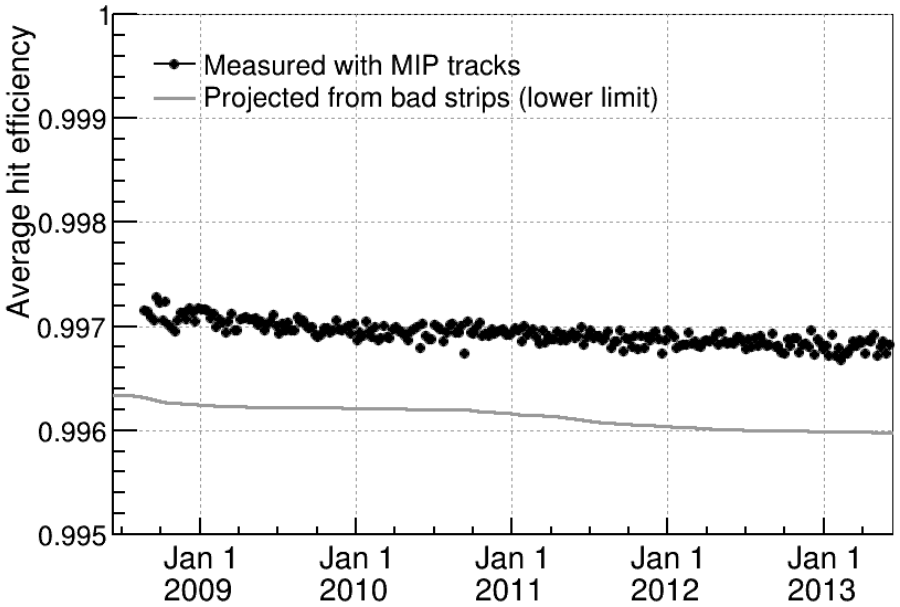
Conclusions

- About 6 years of excellent gamma-ray data thanks to the Fermi Large Area Telescope
  - NASA Senior Review recommended extending operations through 2018 (next review in 2016)
  - All subsystem working properly, no performance degradation
- New Pass 8 gamma-ray analysis will enhance instrument performance of full mission data set
  - We are currently working on final validation of Pass 8 analysis
- Planning more news on scientific result at next Fermi Symposium
  - Nagoya, October 20 - 24, 2014
  - `http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2014/`

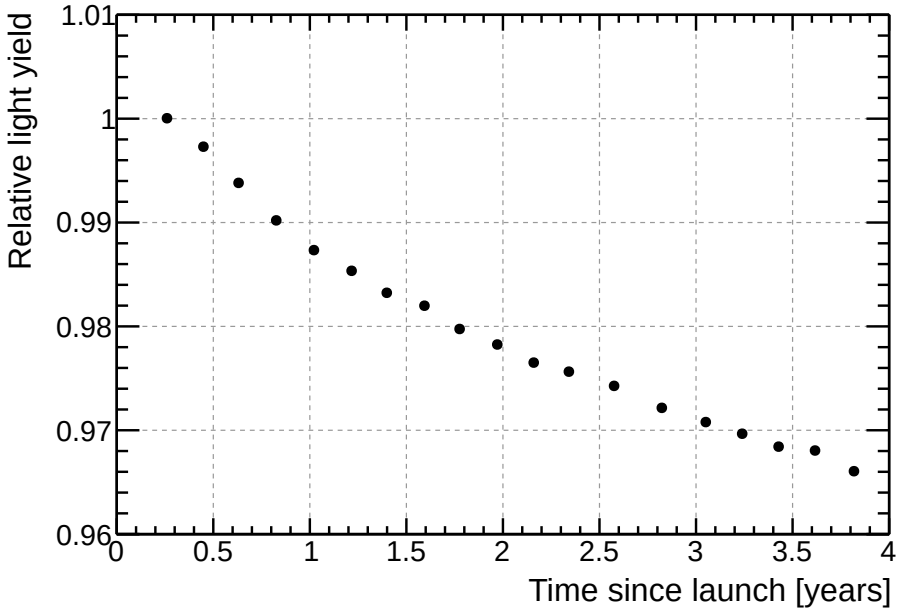
EXTRA

Status of the subsystems

Tracker hit efficiency



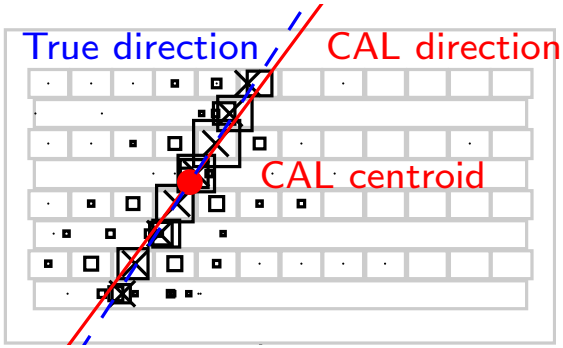
Calorimeter crystals light yield



- Instrument performance continuously monitored and calibrations periodically updated
  - Dedicated runs (for charge injection), periodic triggers (at 2 Hz) and cosmic rays data
- Tracker performance are stable
  - Efficiency well above specification
  - Less than 2% increase in channel noise
- Calorimeter light yield decrease as expected
  - Effect of radiation exposure ($\sim -1\%$/year)

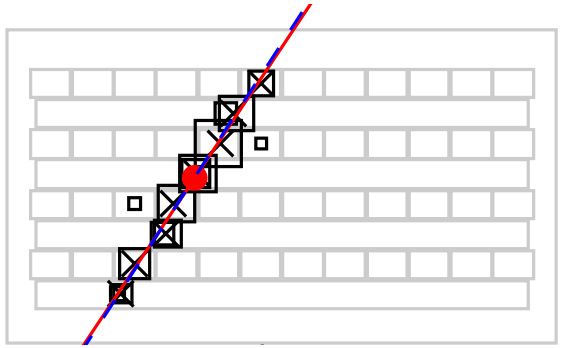
Calorimeter Direction reconstruction

—Iteration 1



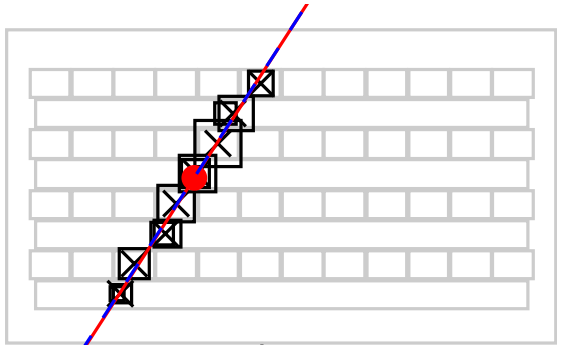
Angular error: 3.59°

—Iteration 2



Angular error: 0.51°

—Iteration 3



Angular error: 0.31°

- 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