The Fermi Large Area Telescope

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Outline

- Overview of LAT & LAT Event Processing
- Detector Subsystems
  - Silicon Tracker (TKR)
  - CsI Calorimeter (CAL)
  - Anti-coincidence Detector (ACD)
  - Trigger and Filter
- Event Reconstruction
  - Sub-systems reconstruction
  - Event level analysis
- For additional reading here are two excellent references on the LAT
  - **LAT Instrument Paper: Atwood et al. 2009,** 2009ApJ...697.1071A [arXiv:0902.1089]
  - **LAT Performance Paper: Ackermann et al. 2012,** 2012ApJS..203....4A [arXiv:1206.1896]

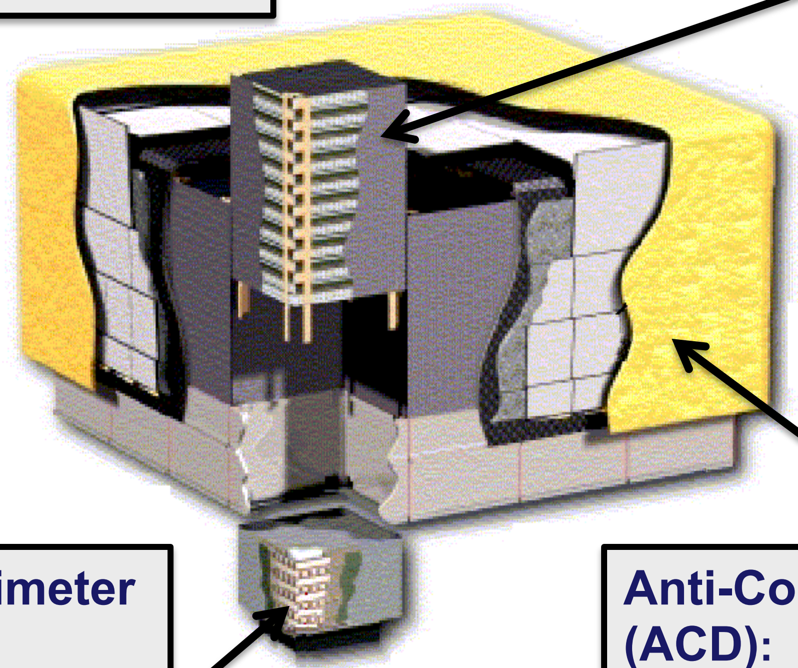
Gamma-ray Space Telescope

Overview of the LAT & LAT Event Processing

The Fermi Large Area Telescope

Fermi-LAT:
Modular design with 3 Subsystems
Calorimeter and Tracker organized in 4x4 modules

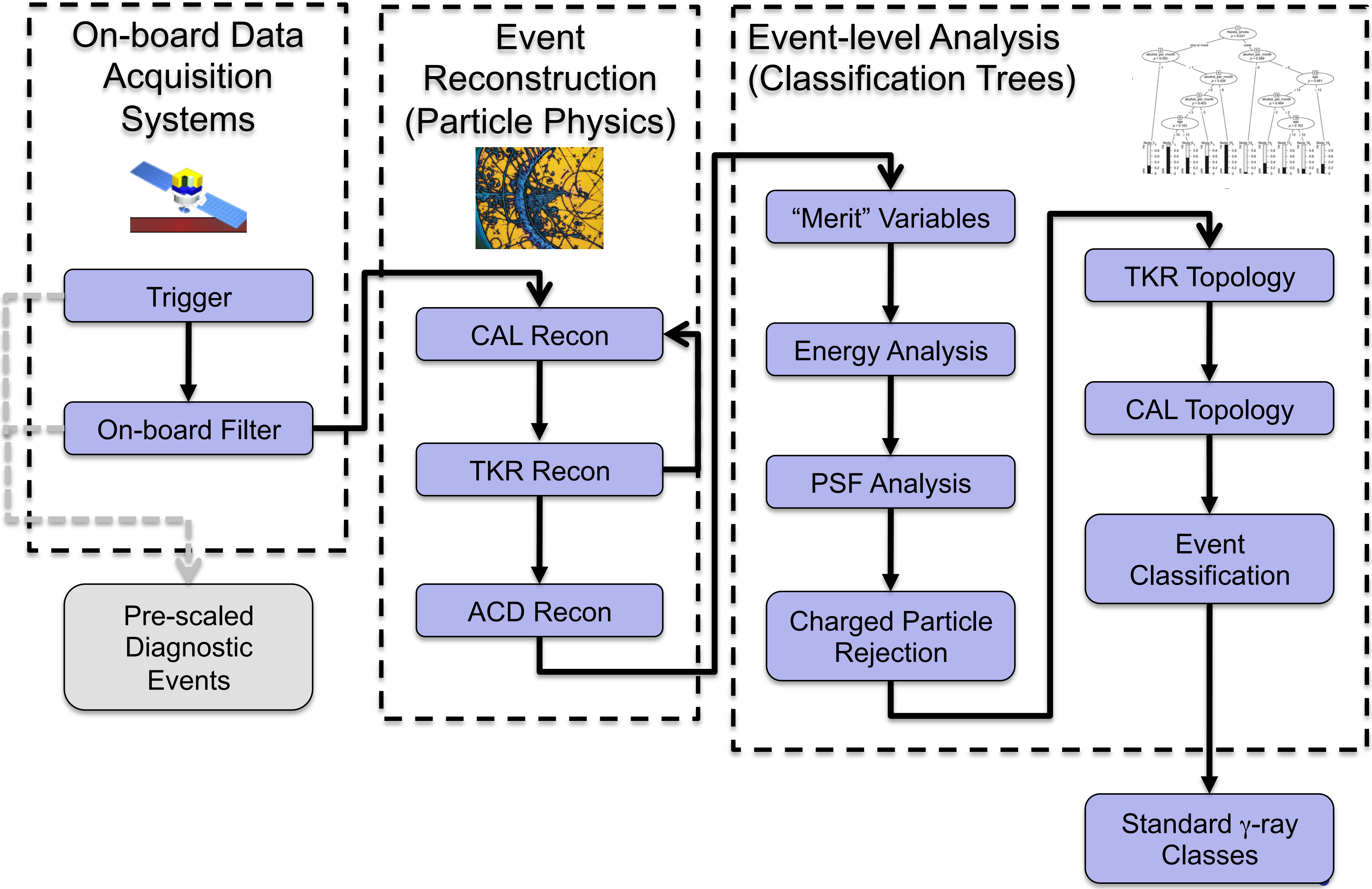
Si-Strip Tracker (TKR):
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation



Hodoscopic CsI Calorimeter (CAL):
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector (ACD):
Charged particle separation

Data Acquisition and Event Analysis



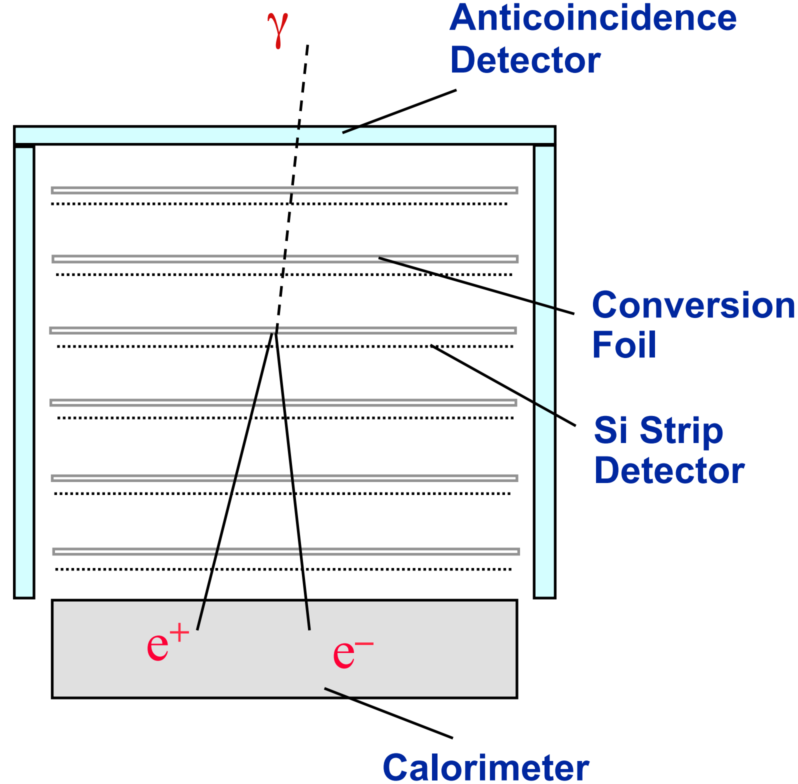
Principle of Operation

- Tungsten foils in the tracker induce **conversions** of gamma rays to e^+/e^- pairs

- Interleaved Si Layers record hits left by the e^+/e^- pair as it passes through the tracker and measure the particle **trajectory**

- Calorimeter measures the gamma-ray **energy** from the amount of scintillation light produced by the electromagnetic shower

- Anticoincidence detector provides a **veto** against charged particles which enter the LAT



SILICON TRACKER (TKR)

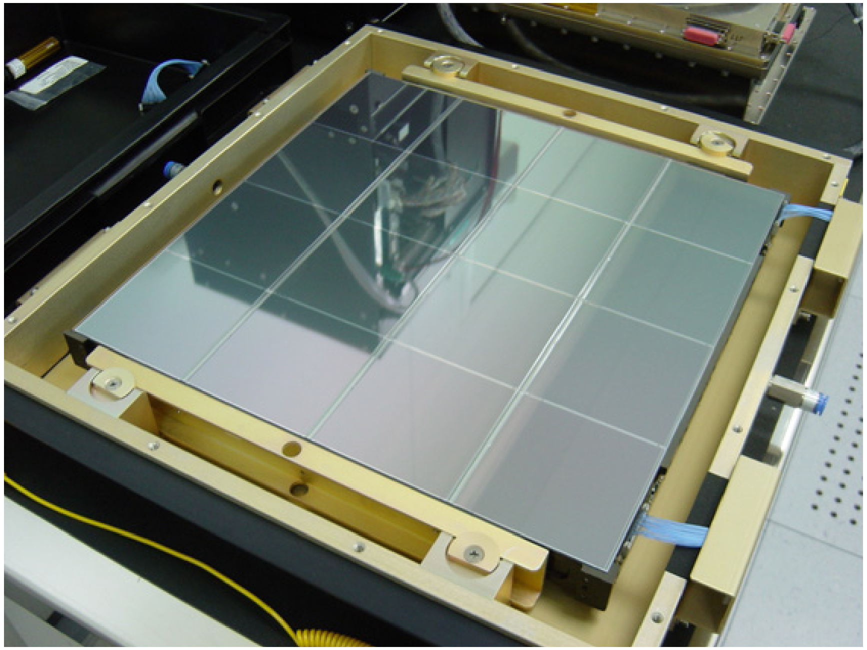
Silicon Tracker

- Silicon tracker is the primary subsystem for **direction** reconstruction
- Tracker is organized in 4 identical towers
- Each tower contains 18 bi-layers, (x,y planes) with silicon strip detectors (SSDs) of thickness 400 μm and pitch 256 μm
- Silicon layers are divided into **Front** and **Back** sections by thickness of associated conversion foils
  - Front: 12 Layers thin (0.03 X_0) Tungsten
  - Back: 4 Layers thick (0.12 X_0) Tungsten
  - 2 Layers no Tungsten

Tracker+CAL Tower

Images of the Silicon Tracker

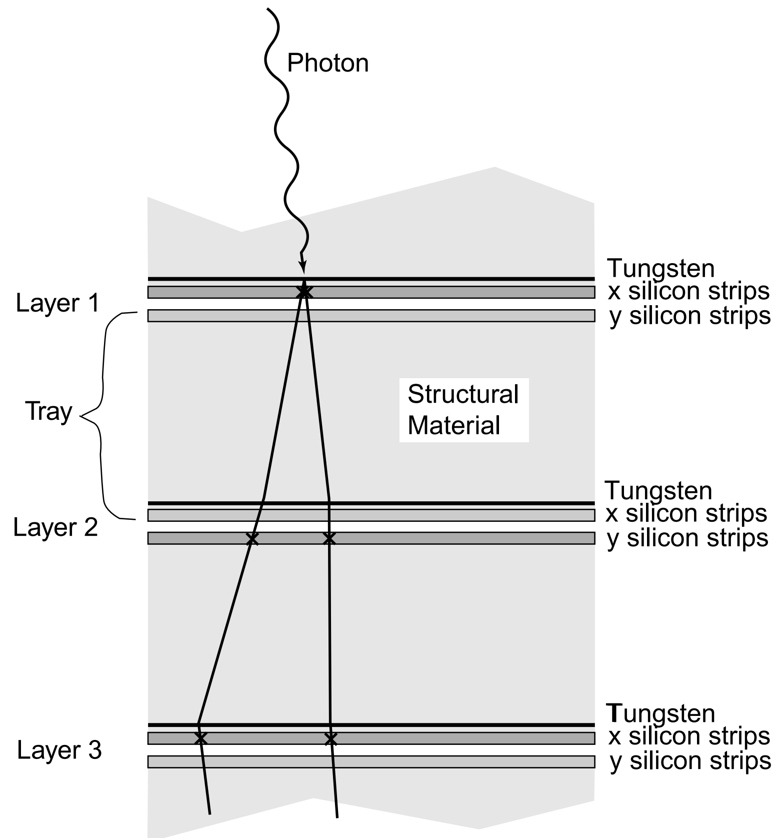
Silicon Strip Plane



1x Tracker Tower

Operating the Tracker

- Probability of gamma-ray conversion within the detector is proportional to material **radiation length (X_0)** – most gamma rays convert in tungsten foils (which have high X_0 relative to other components of the LAT)
- The e^+/e^- pair produces hits in X/Y SSDs below each converter which can be used to reconstruct a 3-D coordinate (cluster) for that particle
- Using clusters from adjacent planes we can reconstruct a particle trajectory
- SSDs in the LAT tracker are extremely efficient (~99.9%) and have very low noise (~10^{-6} noise occupancy)



Tradeoffs in Tracker Design

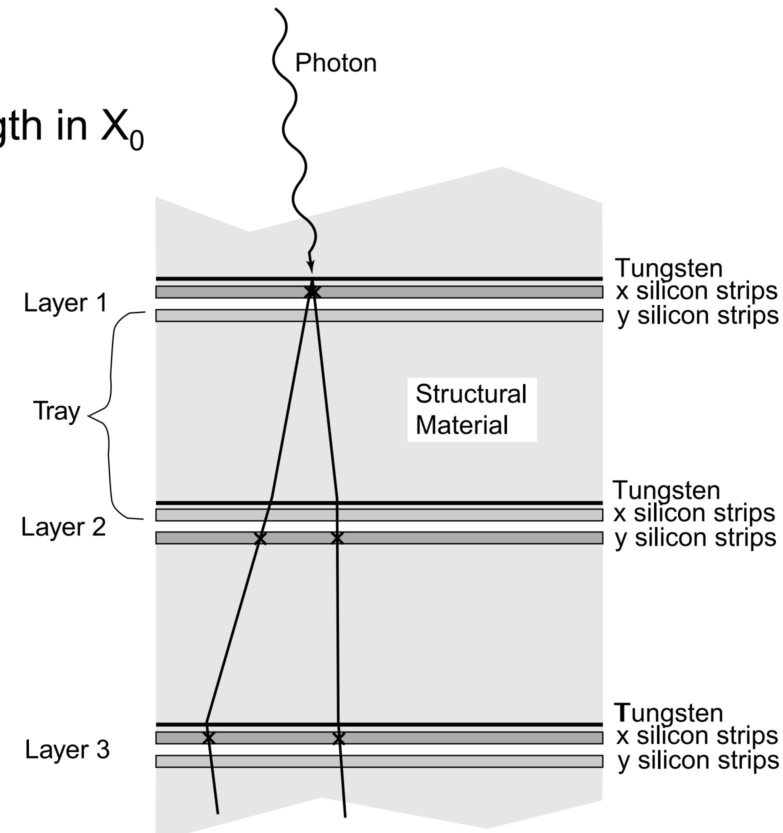
- Tracker angular resolution is limited by **multiple scattering** at low energies and **strip pitch** at high energies

Radiation Length in X_0

$$\theta_{MS} = \frac{13.6}{E_\gamma/2}\sqrt{X}(1+.038\ln(X))$$

Gamma-ray Energy in MeV

- Tracker design is a tradeoff between FoV, PSF, and effective area
  - Large X_0 provides high conversion efficiency (effective area) but worse PSF
  - Larger spacing between tracker planes improves PSF but decreases FoV
- Front and Back sections provide a balance between conversion efficiency and good PSF
  - Back PSF is ~2x worse than Front PSF due to larger radiator thickness but provides the same conversion efficiency in only 4 layers

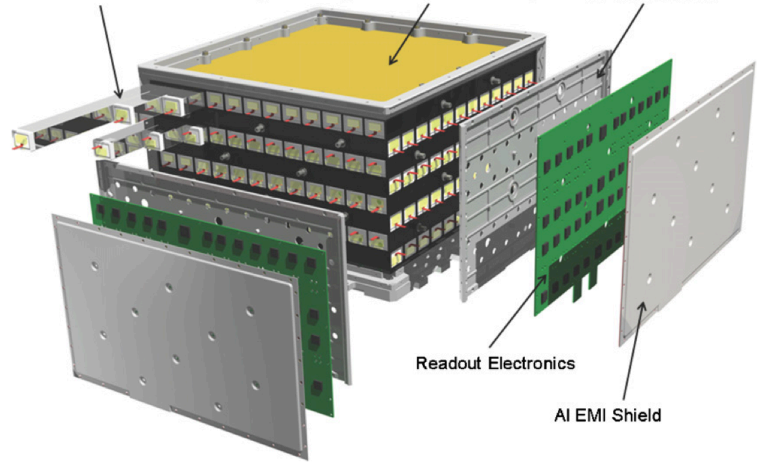


CsI Calorimeter (CAL)

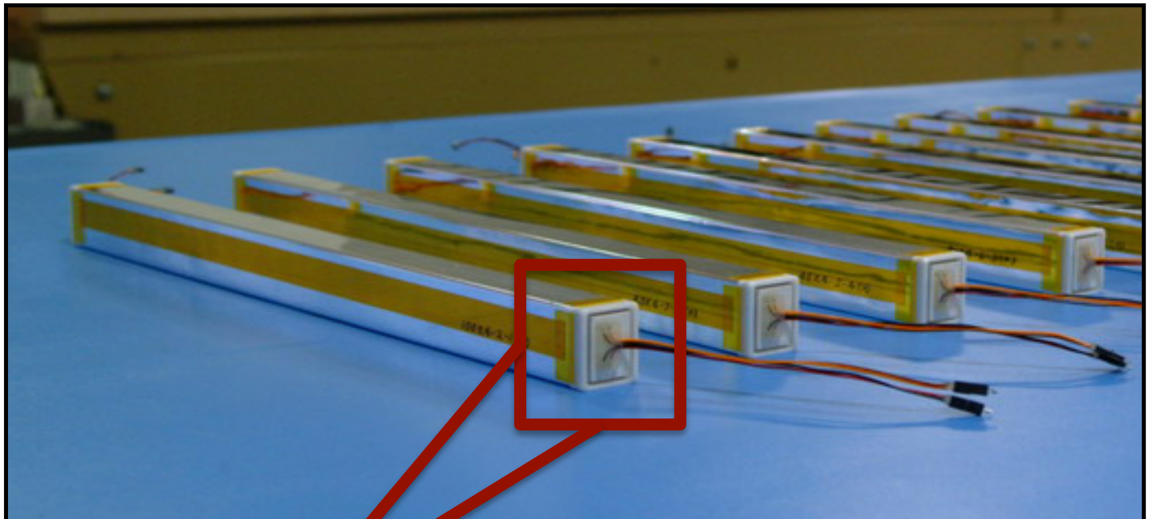
Calorimeter

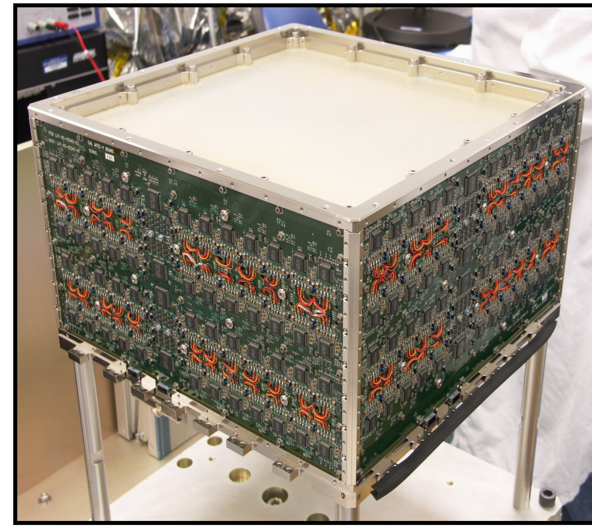
- Calorimeter is the primary subsystem for **energy** reconstruction
- Total radiation length of 8.6 X_0 on-axis (versus 1.5 X_0 for tracker)
  - Large radiation length needed to induce an electromagnetic shower
  - At high energies many showers are still not fully contained
- Each CAL module is composed of segmented CsI crystals arranged in orthogonal layers
- Relativistic charged particles produce scintillation light in the CAL crystals which is collected by PIN diodes at either end

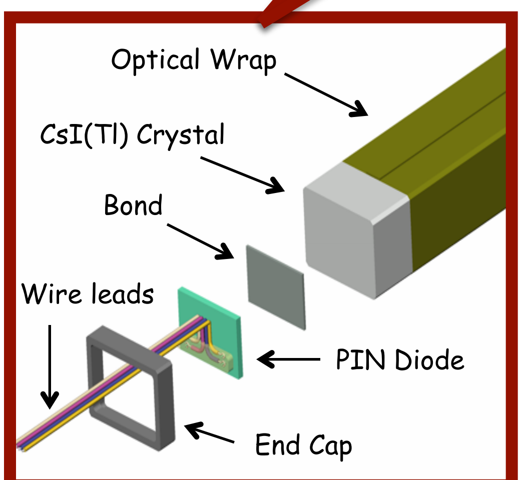
CAL Module



Images of the Calorimeter







Basic detector elements are CsI crystals

Each CAL module contains 8 layers of 12 crystals arranged in alternating orthogonal layers

Light readout at both ends, provides measure of long. position to ~cm from light ratio

CAL Imaging

- In addition to measuring shower energy the LAT Calorimeter also has an **imaging** capability
- Asymmetry of light readout at crystal ends can be used to reconstruct a 3-D coordinate for the crystal energy deposition – can be used to build a 3-D image of the EM shower
- CAL imaging capability is important for many aspects of event reconstruction
  - Major axis of CAL shower provides a seed direction for track reconstruction in the TKR
  - Helps in evaluation of leakage correction for energy reconstruction
  - Consistency between track and CAL directions – very important parameter for background rejection
  - Shower Topology – another useful background rejection parameter; EM showers are generally smoother and more confined along the particle trajectory than hadronic showers

ANTI-COINCIDENCE DETECTOR (ACD)

Anticoincidence Detector

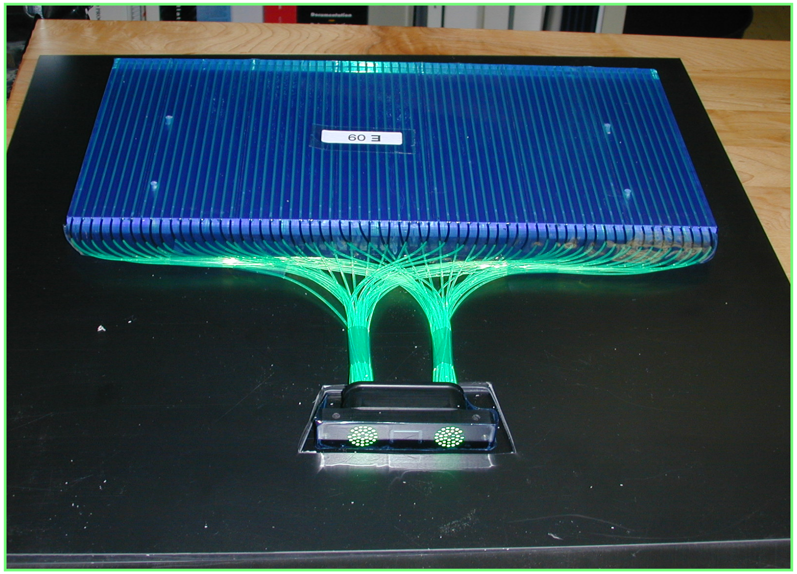
- Primary subsystem for rejection of charged cosmic rays
  - Veto at hardware-level for trigger and onboard filter
  - ACD information also used in offline reconstruction to identify CR events

- Cosmic-ray shield around the four sides and top of the LAT
  - 89 plastic scintillating tiles
  - 8 ribbons to cover remaining gaps

- Segmented design minimizes self-veto effect -- shower backsplash from the CAL can be distinguished from genuine cosmic-ray events

- Very high detection efficiency (~99.97%)

Images of the ACD

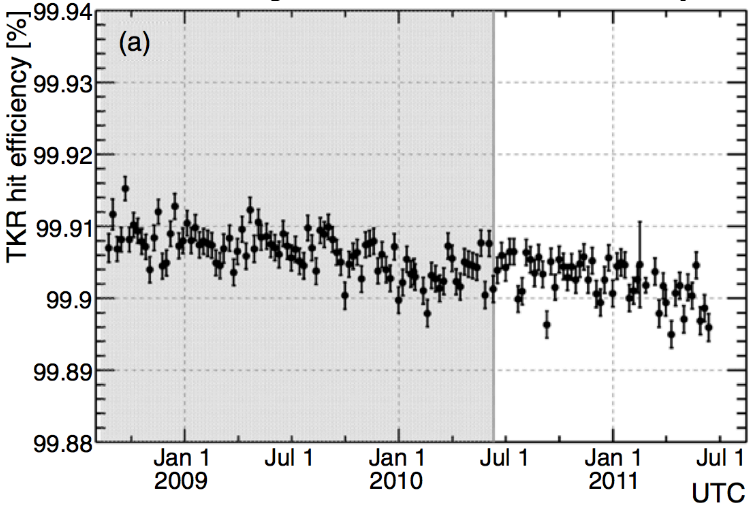


89 Tiles (25 + 4 * 16)
8 Ribbons to cover gaps

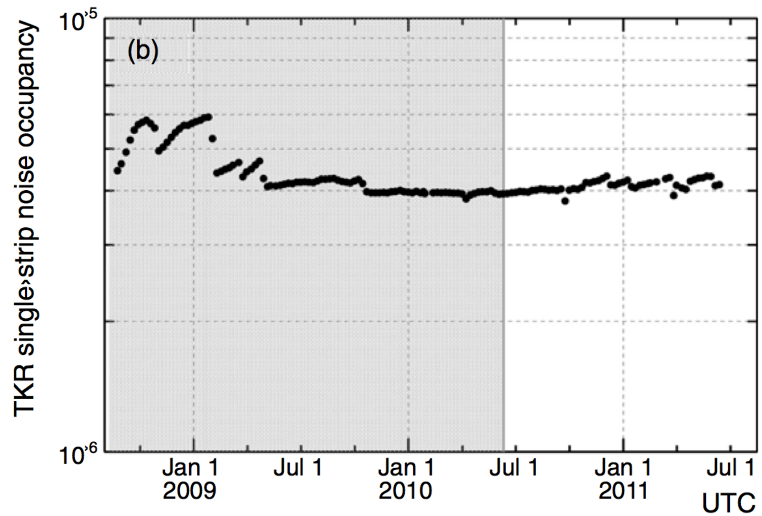
2 PMT for each tile/ ribbon
Tiles (~20 photoelectrons)
Ribbons (~3-8 photoelectrons)

LAT Detector Trending and Stability

Average TKR hit efficiency



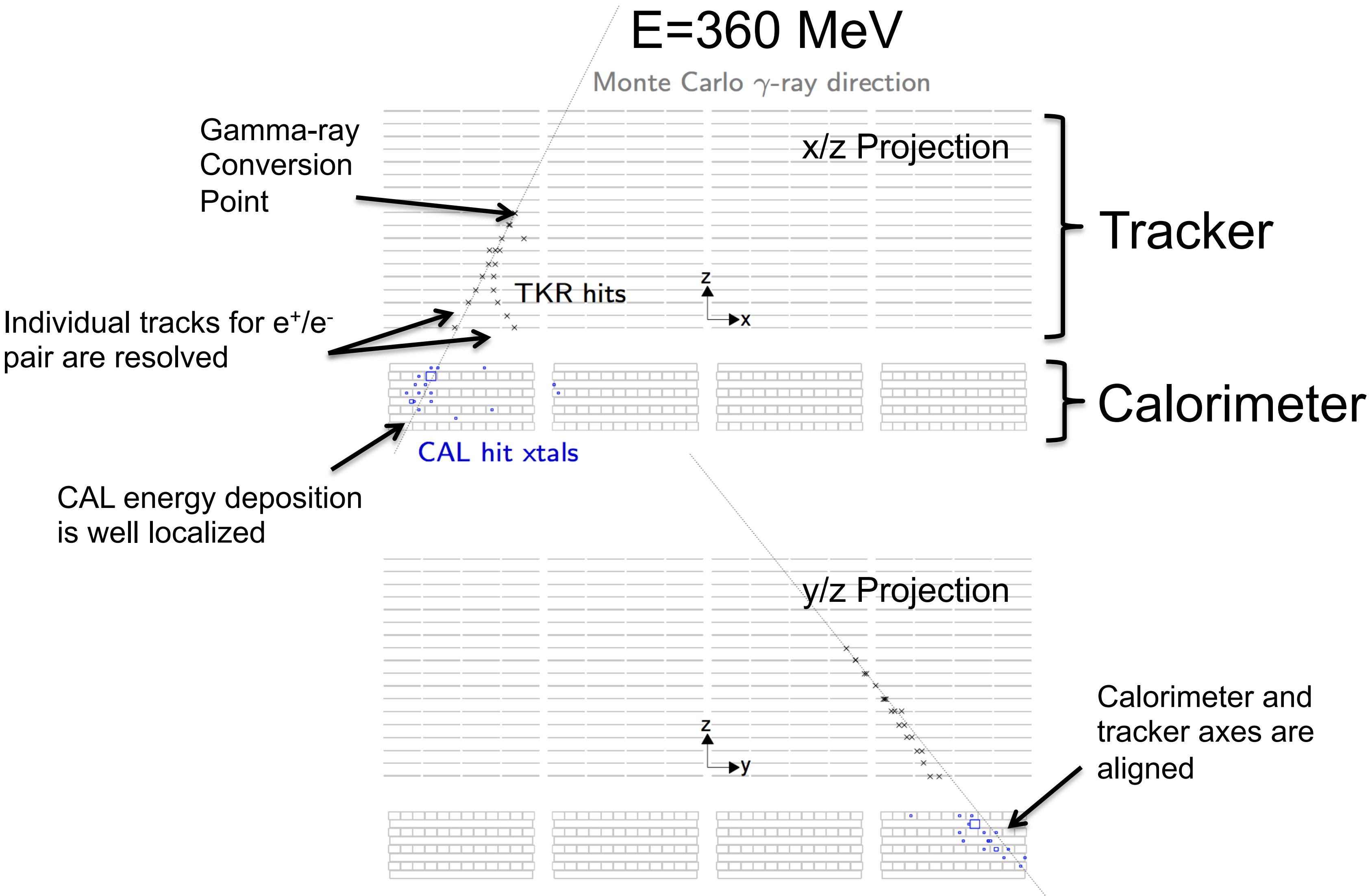
Average TKR noise occupancy



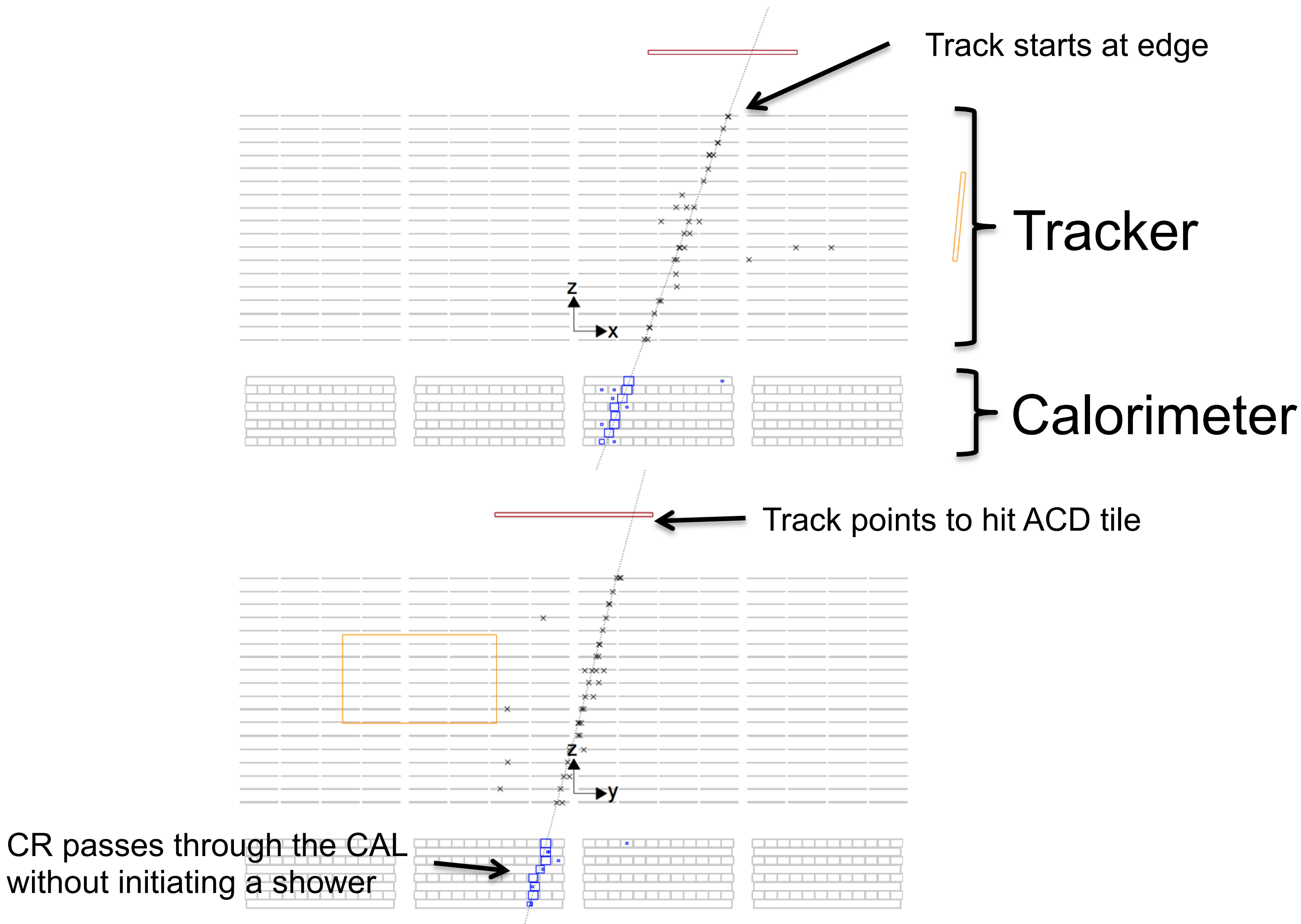
- The LAT detectors are extraordinarily stable vs. time – trending of most performance metrics (e.g. TKR efficiency) show changes less than 1% over many years
- Largest change in LAT response is degradation of CAL light yield by ~1% per year from radiation damage – note that this is fully corrected for in the energy reconstruction

Some Real Event Displays

Gamma-ray Event Display

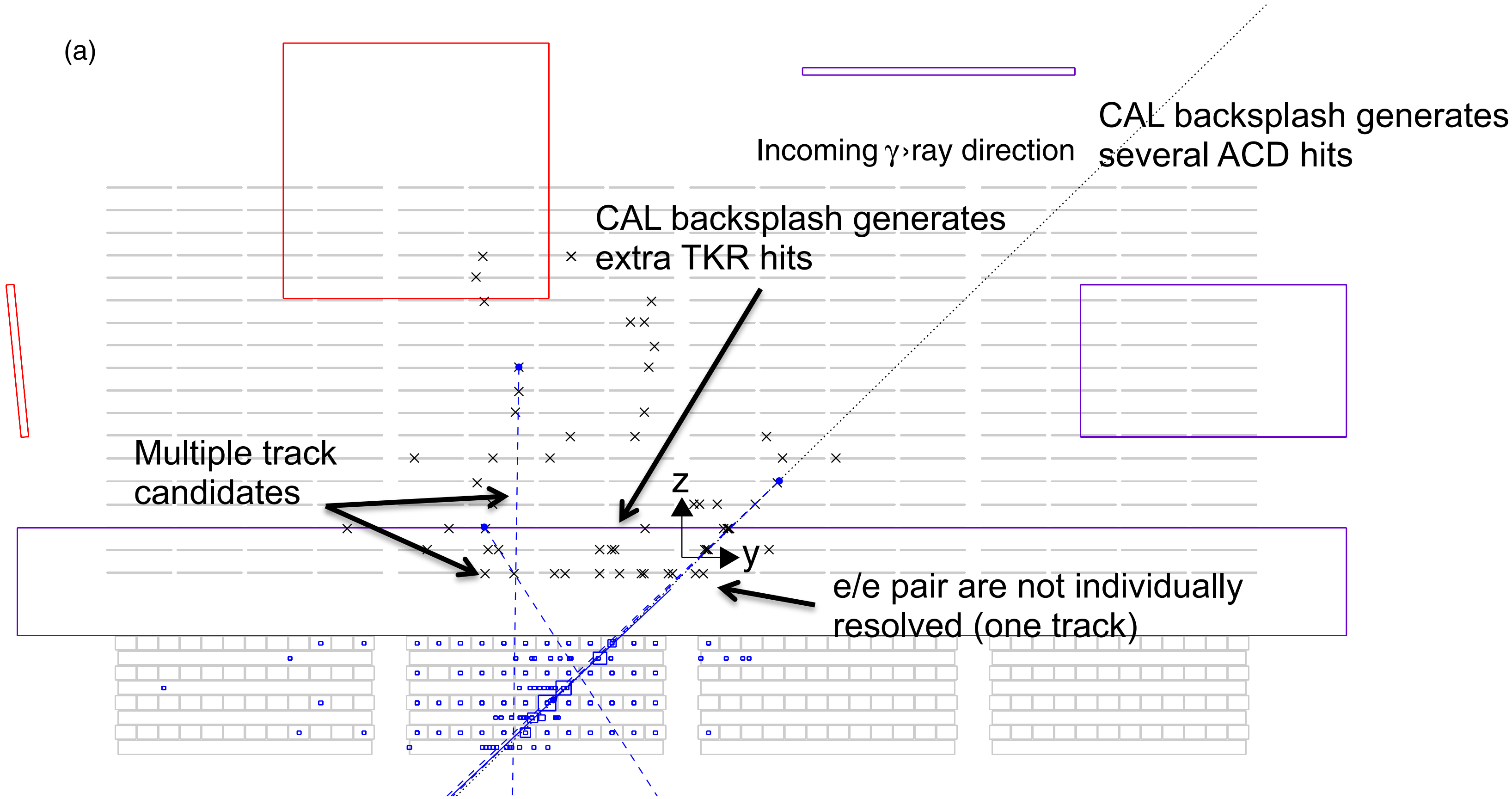


Cosmic-Ray Event Display



High Energy Gamma-ray Event Display

E = 27 GeV gamma ray



Trigger and Filter

Trigger and Filter

- In an ideal instrument we would record every event and perform all analysis offline
- The hardware trigger and filters are needed to reduce the data rate to a manageable level before offline analysis
  - Every readout incurs instrument deadtime (26.5 μs)
  - Need to further reduce data volume to fit within finite downlink bandwidth
- General Goals of Trigger/Filter Design
  - Keep a very high efficiency for gamma-ray events
  - Minimize the background rate (without impacting gamma efficiency)
- Trigger is also used to collect extra diagnostic events with a prescale (i.e. accept only 1 out of N events)

Trigger Primitives

- Each subsystem produces a set of trigger primitives that indicate when a certain condition in that detector is met
- Relevant trigger primitives for gamma-rays
  - **TKR**: At least three consecutive tracker layer pairs (x+y) with a signal
  - **CAL_LO**: Any CAL channel > 100 MeV
  - **CAL_HI**: Any CAL channel > 1 GeV
  - **ROI**: Coincidence between TKR trigger and neighboring ACD Tile w/ energy > 0.4 MIP (indicates probable background event)
- Trigger primitives are based on faster electronics (~1 μs) than used for the full detector readout (~10 μs) in order to minimize impact of instrument pileup

Trigger Engines

Engine	PERIODIC	CAL_HI	CAL_LO	TKR	ROI	CNO	Prescale	Average Rate (Hz)
3	1	×	×	×	×	×	0	2
4	0	×	1	1	1	1	0	200
5	0	×	×	×	×	1	250	5
6	0	1	×	×	×	0	0	100
7	0	0	×	1	0	0	0	1500
8	0	0	1	0	0	0	0	400[a]
9	0	0	1	1	1	0	0	700
10	0	0	0	1	1	0	50	100

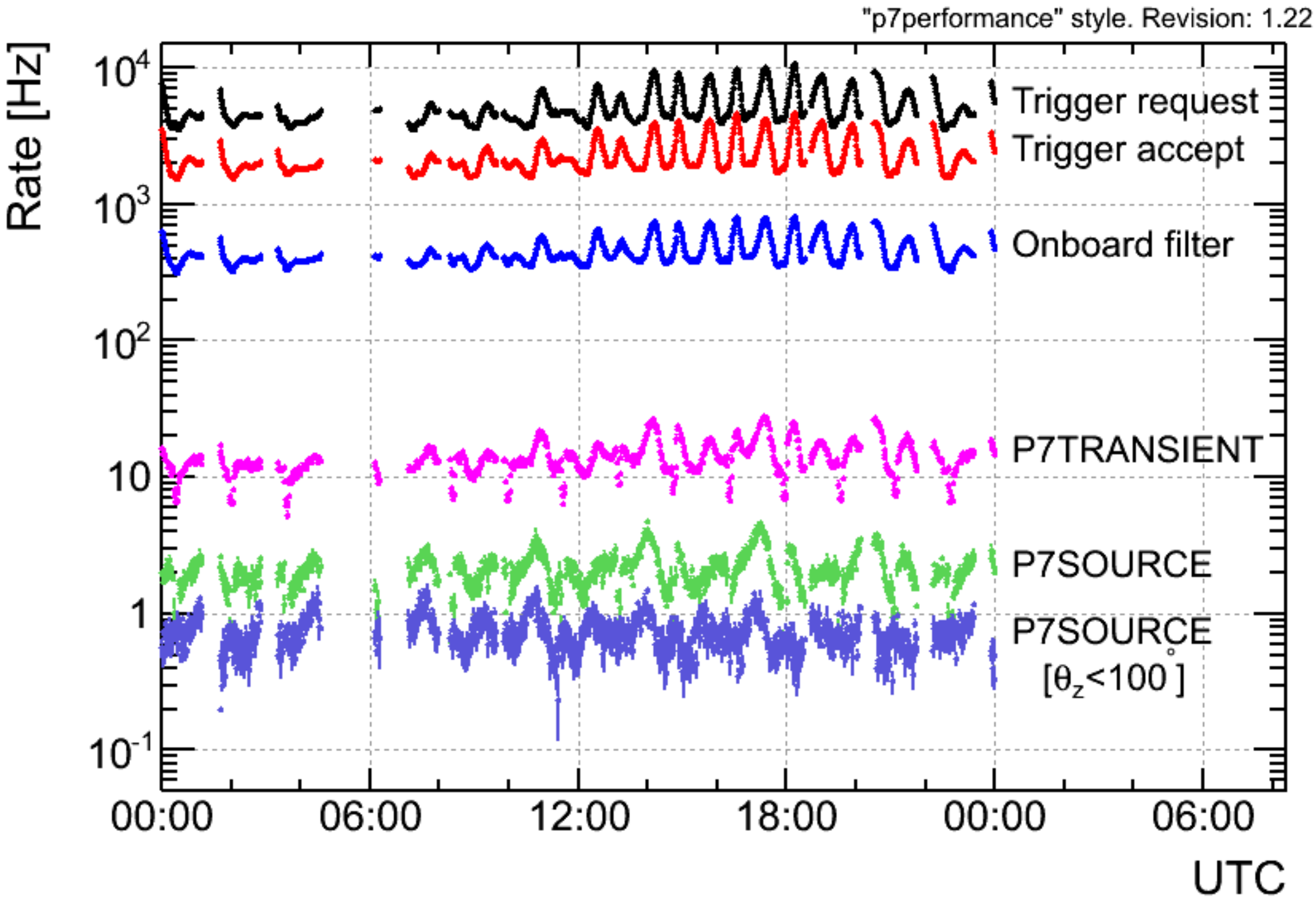
1: required, 0: excluded, x: ignore

- Trigger engines use logical combinations of the trigger primitives to form a final trigger decision that initiates readout
- Relevant trigger engines for gamma rays
  - **Engine 6**: Accept all events w/ > 1 GeV in a xtal (CAL_HI) – important for trigger efficiency at high energies
  - **Engine 7**: Accept events with a track (TKR) and no ACD (ROI)
  - **Engine 9**: Accepts events with TKR && ROI && CAL_LO – increases efficiency for events with backsplash

Onboard Filter

- Onboard filter provides an additional level of data reduction at hardware level
  - Needed to keep data volume within downlink bandwidth (~ 1 Mb/s)
  - Uses all available event information (ACD+CAL+TKR) to identify whether an event is a candidate gamma-ray
- Multiple Filters applied in parallel
  - **GAMMA**: Select gamma-ray events
  - **HIP**: Select heavy ion events for CAL calibration
  - **DIAGNOSTIC**: Select unbiased sample of all trigger types – used to monitor trigger/filter efficiency
- Final downlink rate is **300-500 Hz**

Particle Rate Reduction



Trigger Rate (~2 kHz)

↓

Downlink Rate (~400 Hz)

↓

Celestial Gamma Rate (~0.5 Hz)

EVENT RECONSTRUCTION

Event Reconstruction and Selection

CAL Reconstruction:
Sum signals in CAL, analyze topology, correct for energy lost in gaps, out sides and in TKR pre-shower

TKR Reconstruction:
Find tracks & vertices. If possible use CAL shower axis as a directional seed

ACD Reconstruction:
Project tracks to ACD, look for reasons to reject event.

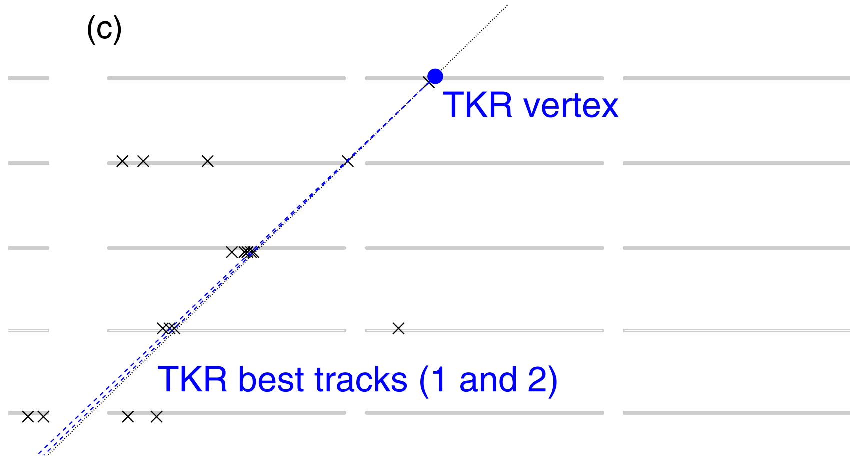
Reconstruction:
Developed with simulated data.
Simulations validated in beamtests.

Classification Analysis:
Use combined subsystem information to get best estimates of direction, energy.
Reject particle background and select highest quality events

Photon Samples and IRFs:
Build descriptions of Instrument Response for each selection of events

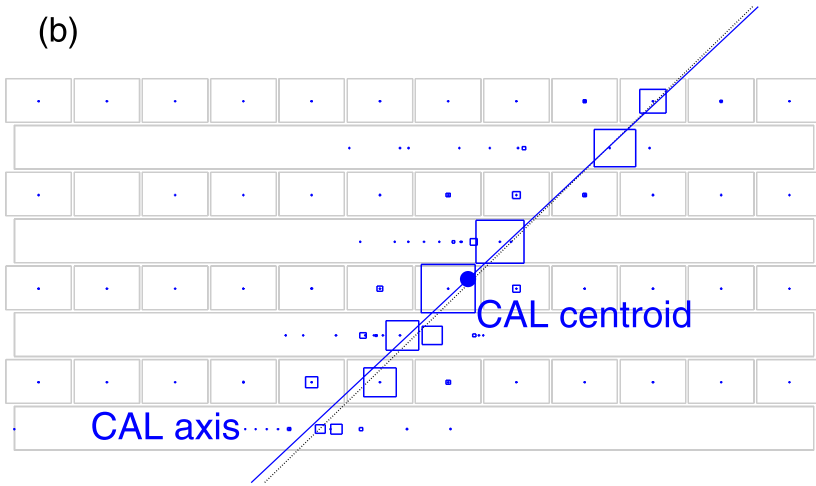
Event Classification:
Developed with simulated + flight data
Validated primarily with flight data

TKR Reconstruction



- Hit clustering: combine adjacent hit strips into clusters
- Perform combinatoric search over adjacent cluster pairs to construct track candidates
  - Start with CAL direction (useful for high energy events with many hits)
  - Build a track by successively adding clusters from the next layer
  - Track direction derived from Kalman fit that incorporates expected error introduced at each layer from multiple scattering
- Order tracks by “quality”
  - Favor longest, straightest track
- Vertexing: try to combine 2 best tracks into single item

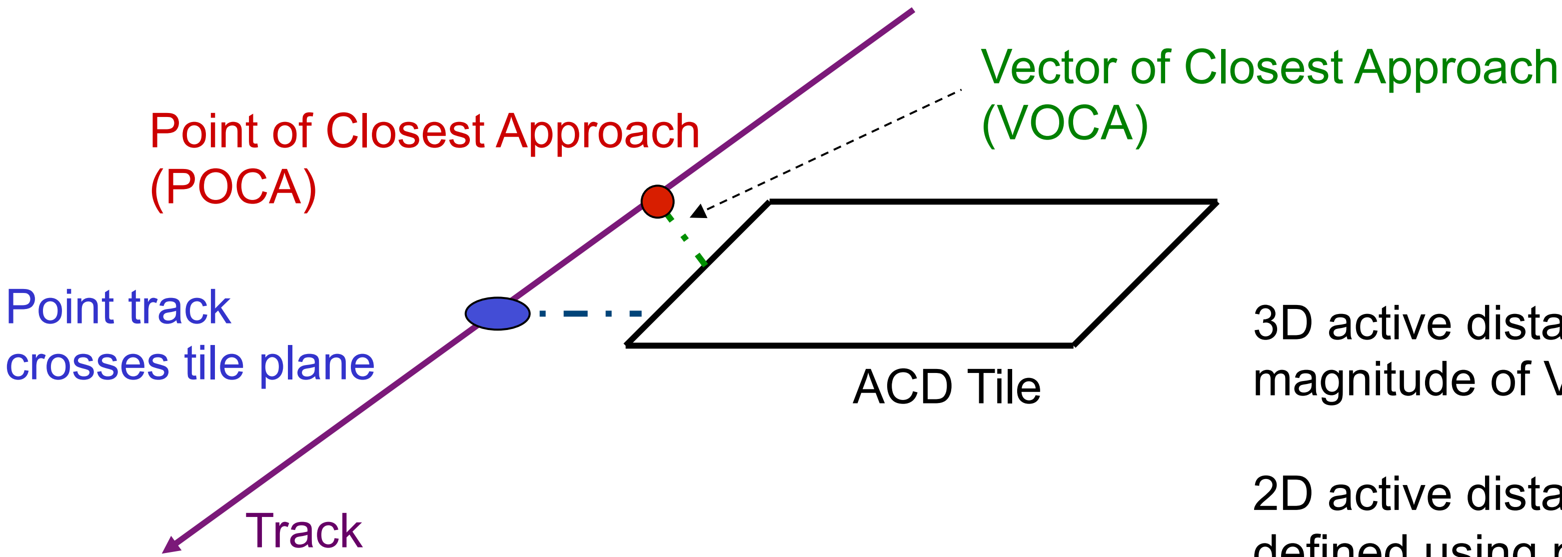
CAL Reconstruction



- Apply per-crystal calibration
- Apply Moments analysis to derive the following quantities
  - Cluster centroid (x,y,z)
  - Cluster axis (v_x,v_y,v_z)
  - Cluster 2nd moments (RMS)
- Energy Reconstruction (Multiple Methods)
  - Parametric correction for leakage out sides and gaps
  - Fit to energy deposition in CAL with EM shower profile

ACD Reconstruction

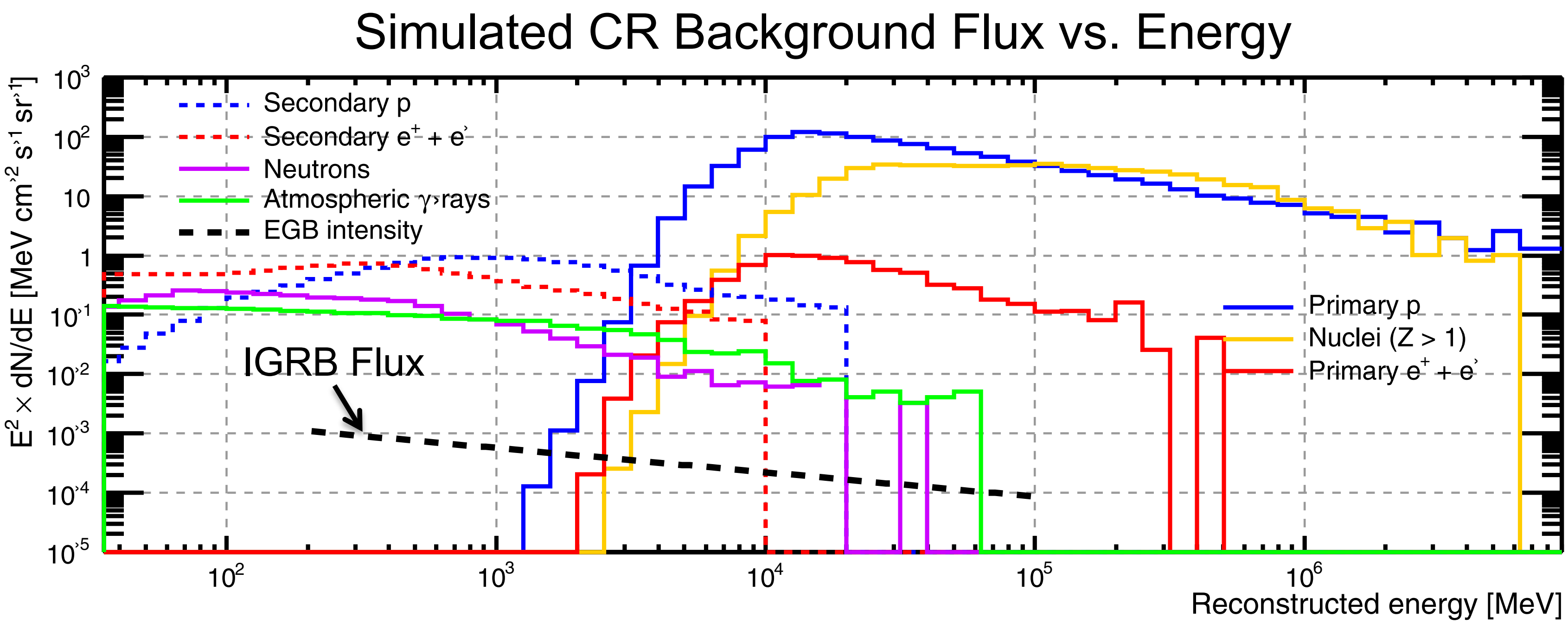
- Apply tile calibrations
- Look for reason to veto event
  - Track extrapolation to ACD hit?
  - Compare ACD energy to CAL energy
    - Catches events where TKR direction is bad



3D active distance is magnitude of VOCA

2D active distance is defined using point track crosses tile plane

Background Rejection

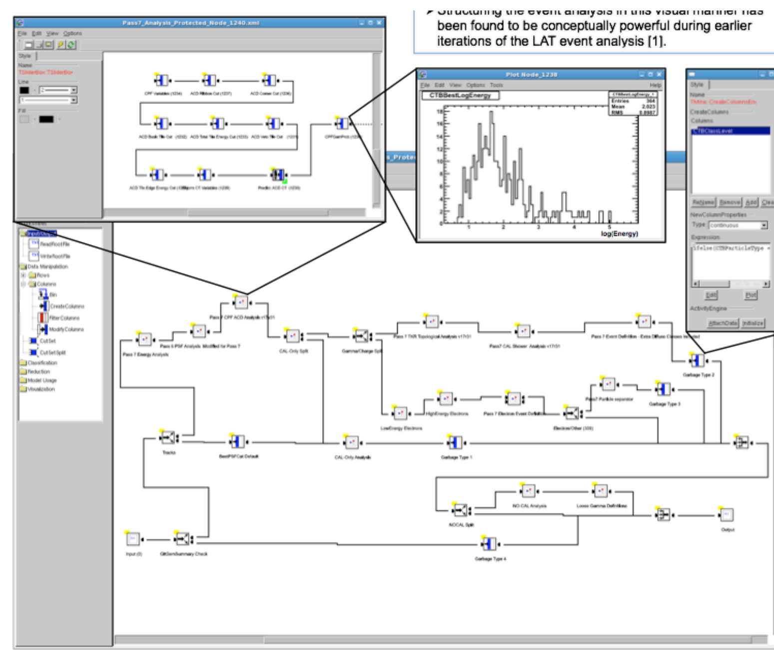


- LAT is subject to a large flux of both primary and secondary CRs which is a background for studies of the gamma-ray sky
- We generally require a rejection factor 10^3-10^6 to reach acceptable background contamination for point-source analysis (e.g. SOURCE class)

Event Level Analysis

- The event-level analysis uses classification trees (CTs) in conjunction with cuts to distinguish gamma-ray events from CR background
- Designed with many branches that use different cuts/CTs depending on event topology (front vs. back, vertex vs. no vertex, etc.)
- CTs are also used to augment the gamma-ray reconstruction
  - Choose between different reconstruction algorithms for energy and direction
  - Assess the quality of reconstruction on an event-wise basis (CTBCORE, BestEnergyProb)

Visualization of Event Analysis Breakdown



Outputs of the event level analysis

Direction Analysis:
Decides which direction solution (vertex or non-vertex, TKR or TKR + CAL) is best
Gives estimate of quality of direction estimate
P_{CORE} = "prob." that direction is within R68%

Energy Analysis
Decides which energy method (Parametric or Profile) is best
Gives estimate of quality of energy estimate
$P_{BestEnergy}$ = "prob." event is within P68%

Charged Particle Analysis
Reject charged particles using ACD,TKR,CAL
P_{CPFGAM} = "prob." event is a photon

Topology Analysis
Reject hadrons using TKR, CAL
P_{TKRGAM}, P_{CALGAM} = "prob." event is a photon

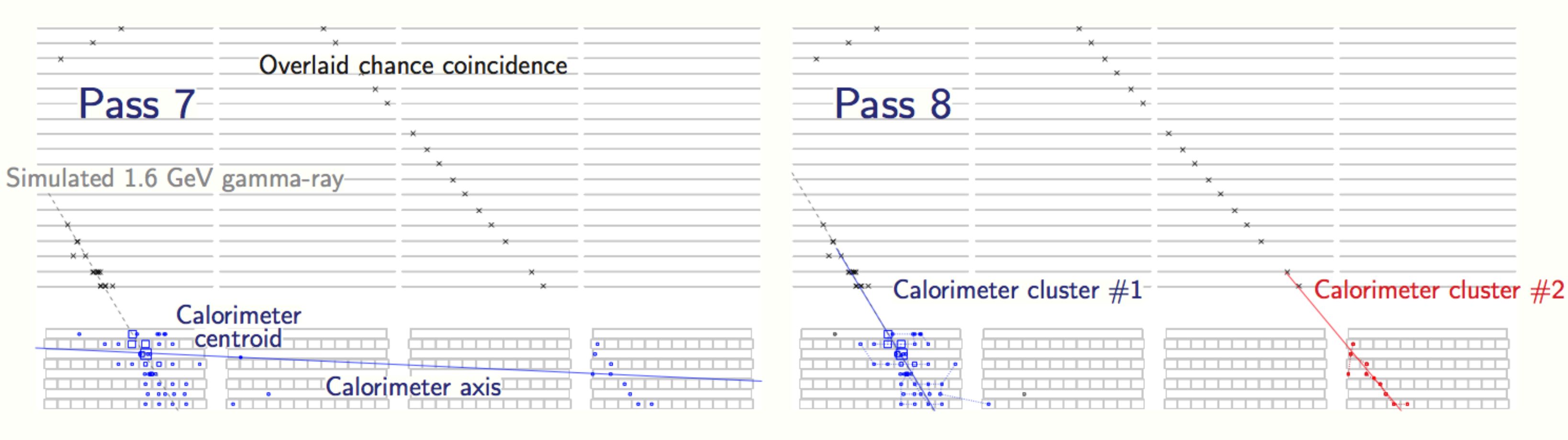
Photon Analysis
Combine everything

P_{ALL} = "prob." that event is a photon

Photon Samples
Apply cuts tuned to for particular samples

Might require good direction, energy recon in addition to high photon "prob."

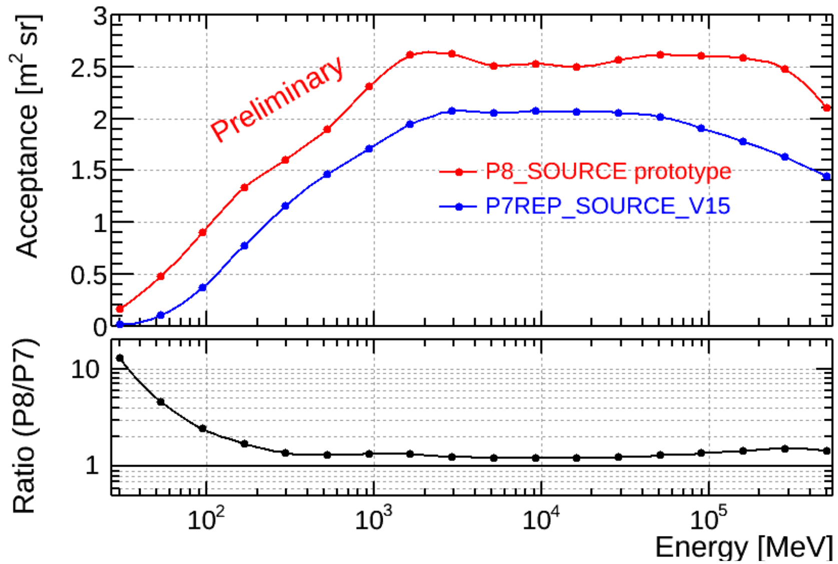
A Preview of the Future with Pass8

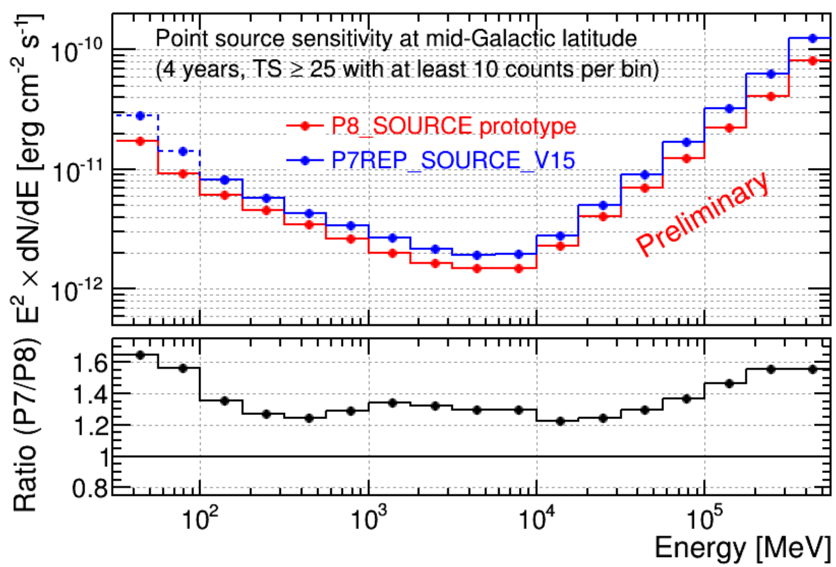


- The current P7REP data release uses reconstruction algorithms that were developed prior to launch
- Pass8 is a comprehensive revision of the entire LAT analysis chain based on experience gained from operating the LAT in orbit
  - Tree-based track reconstruction
  - Clustering algorithm applied to remove pileup activity in CAL
  - New energy reconstruction with improved handling of CAL saturation – extends energy reach of LAT to > 1 TeV

Pass8 Performance

- Prototype Pass8 SOURCE class demonstrates a substantial improvement in performance over the Pass7 SOURCE class
  - Increase in acceptance at all energies (> 2x below 100 MeV)
  - 30-40% improvement in point-source sensitivity between 1 and 10 GeV
- Preparation of Pass8 is on-going and the public release is tentatively scheduled for mid-2015





Summary

- The LAT is a particle physics detector we've shot into space
  - Uses well-established detector technologies from particle physics (SSDs, crystal EM CAL, etc.)
  - Many tradeoffs made in the design in order to have good performance over a large phase space in energy (< 20MeV to > 300 GeV) and incidence angle (0 to >70 deg)
  - Combining information from all three subsystems is critical to achieving the LAT performance objectives
- The LAT event reconstruction and analysis distills a huge amount of information about each event into a small number of quantities (E,RA,DEC)
- For the user (data analyst) we fold all of the complexity of the LAT into the instrument response functions (IRFs) – these will be discussed in more detail tomorrow