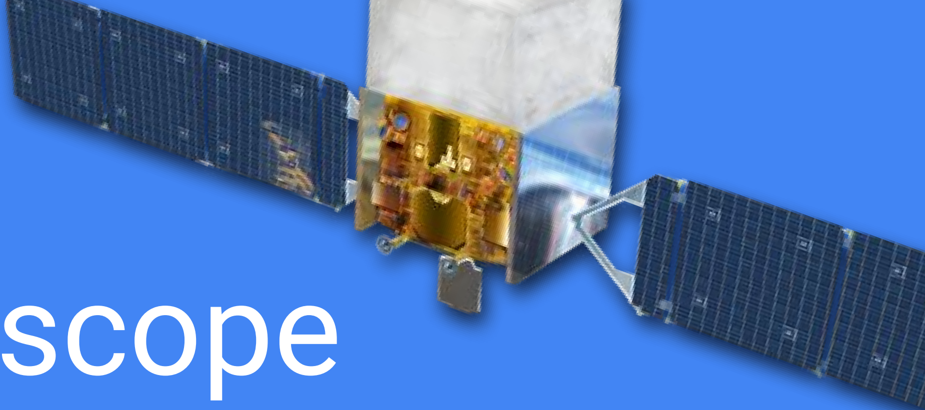


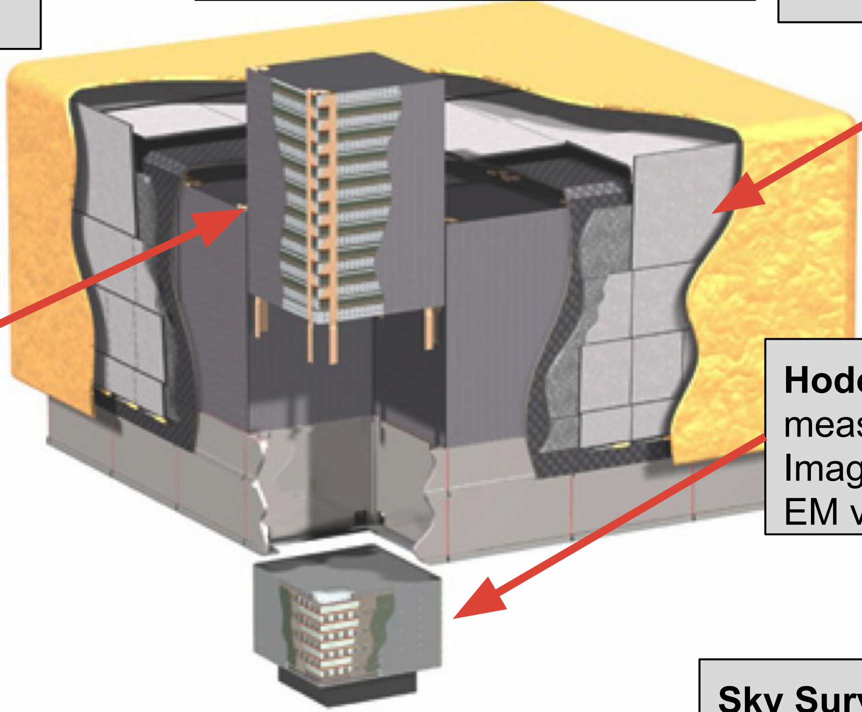
Large Area Telescope Overview

Jeremy S. Perkins (NASA/GSFC)
Slides based on many other people’s work

Fermi-LAT
Modular design with 3 subsystems. Calorimeter and Tracker organized in 4 modules

Public Data Release:
All ɣ-ray data made public within 24 hours (usually less)

Anti-Coincidence Detector:
Charged particle separation



Si-Strip Tracker:
convert ɣ -> e+e-
reconstruct g direction
EM v. hadron separation

Hodoscopic CsI Calorimeter:
measure ɣ energy
Image EM shower
EM v. hadron separation

Trigger and Filter:
Reduce data rate from ~10kHz to 300 - 500 Hz

Sky Survey:
With 2.5 sr Field-of-View LAT sees the sky every 3 hours

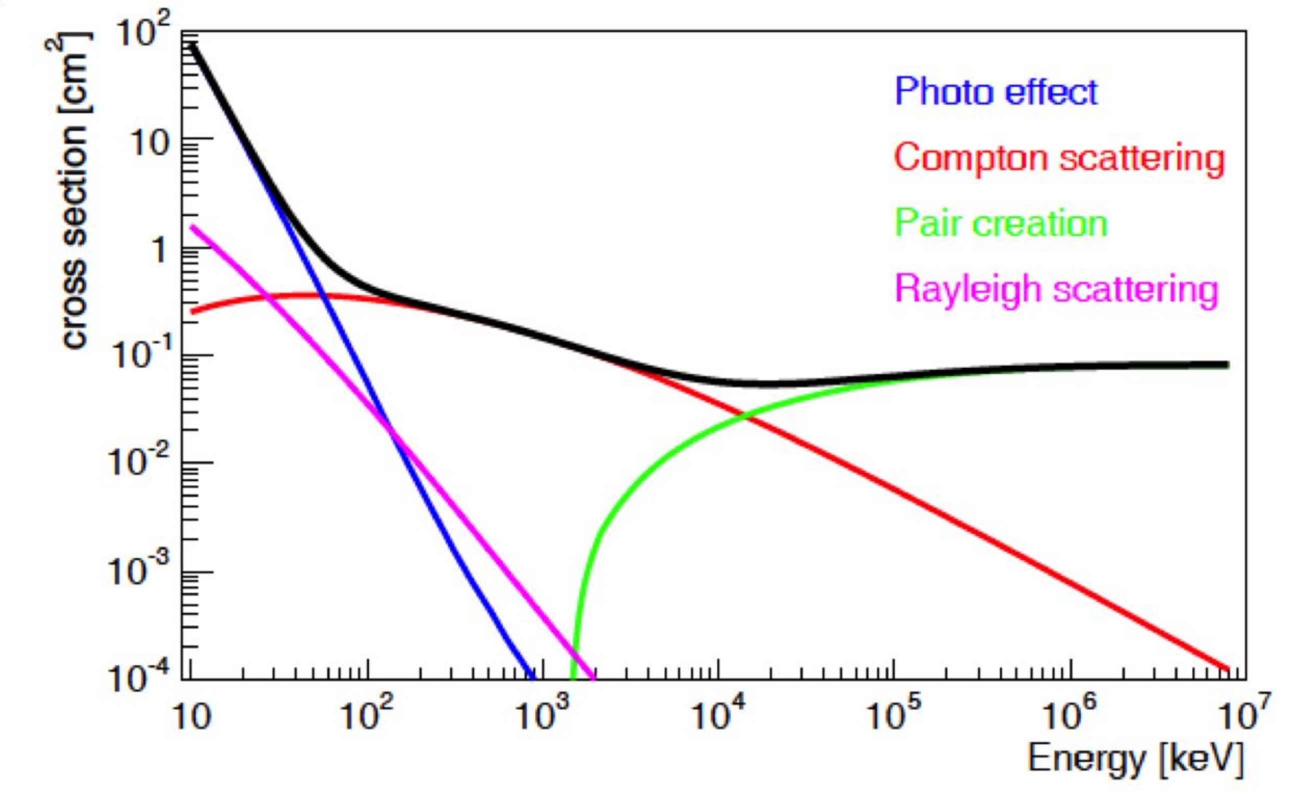
But why is it like this?

With any instrument you build, you have to make choices about the design. You tune your instrument for things like **energy resolution, localization accuracy, flux sensitivity**, and so on.

However, when you build an instrument for flight, there are many other technical limitations you have to take into consideration.

- Mass and spatial dimensions of the observatory is constrained to fit within the launch vehicle/rocket
    - Huge leap in cost if you need to jump to a larger rocket
- Power consumption is limited
    - Need low power electronics
- Data rate is limited by downlink bandwidth to the ground
    - Need efficient onboard filtering and data compression

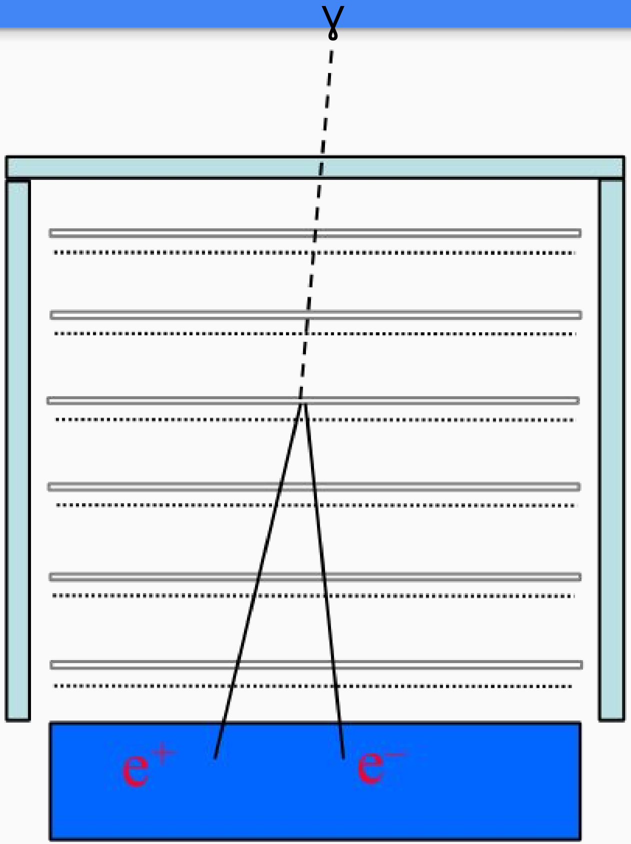
We’re interested in high energy gamma-rays



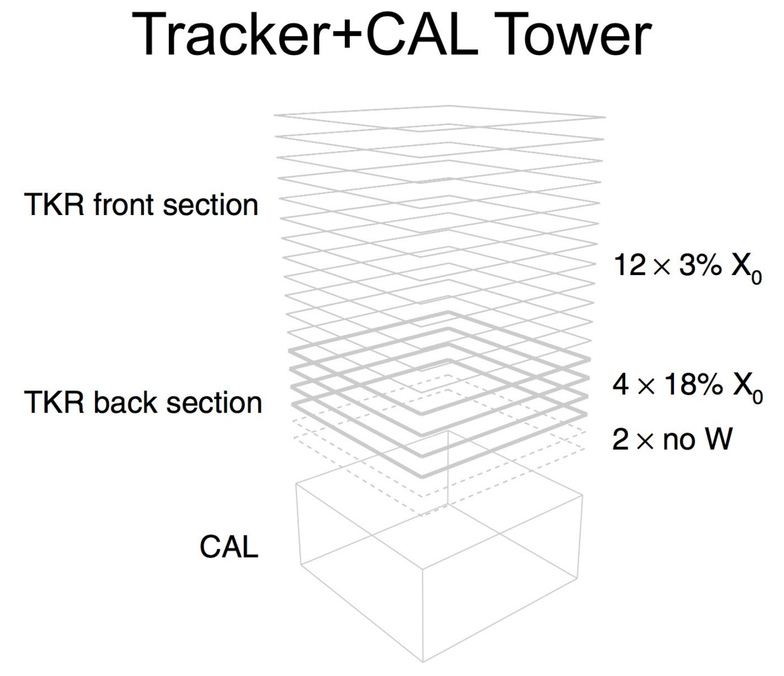
For photons in matter above ~10 MeV, pair conversion is the dominant energy loss mechanism.

So we build a pair production telescope: 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 ɣ-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



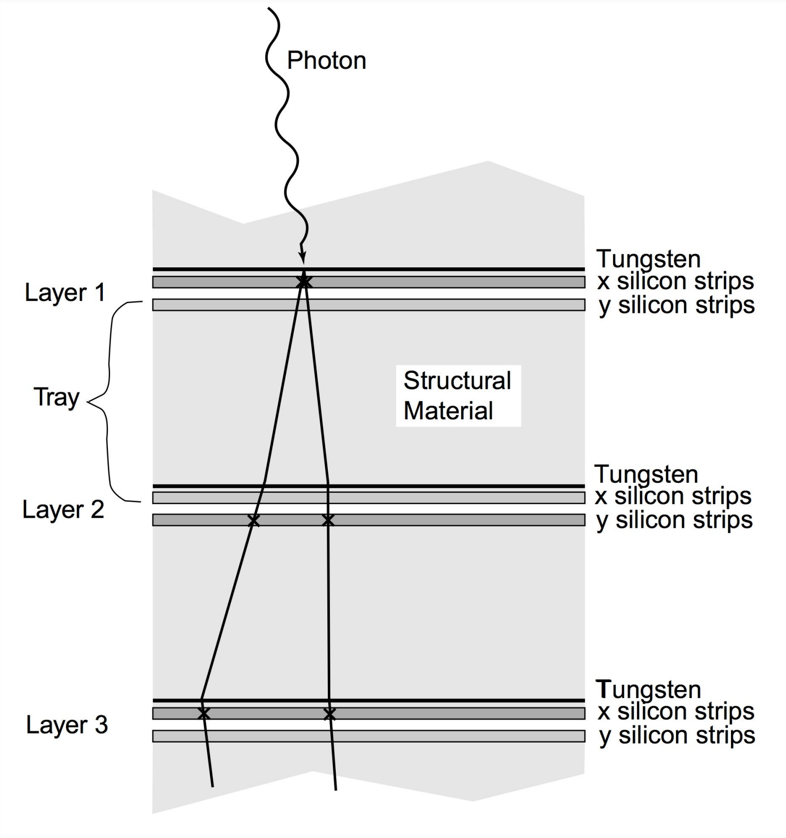
Silicon Tracker (TKR)



- Silicon tracker 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

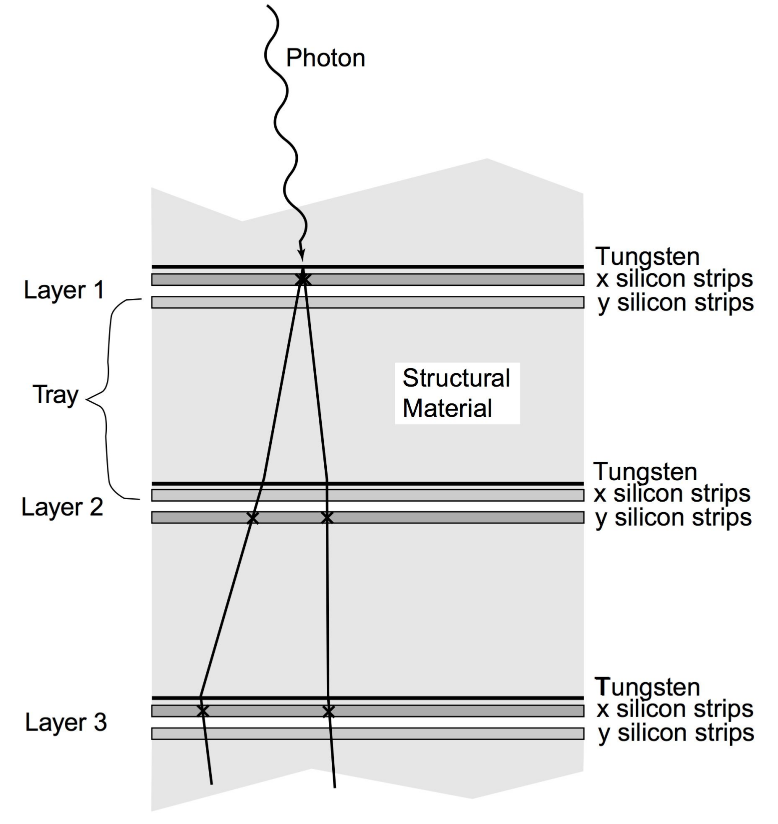
Talk about this in a bit

- Probability of gamma-ray conversion within the detector is proportional to material **radiation length (X_0)** – most γ 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)



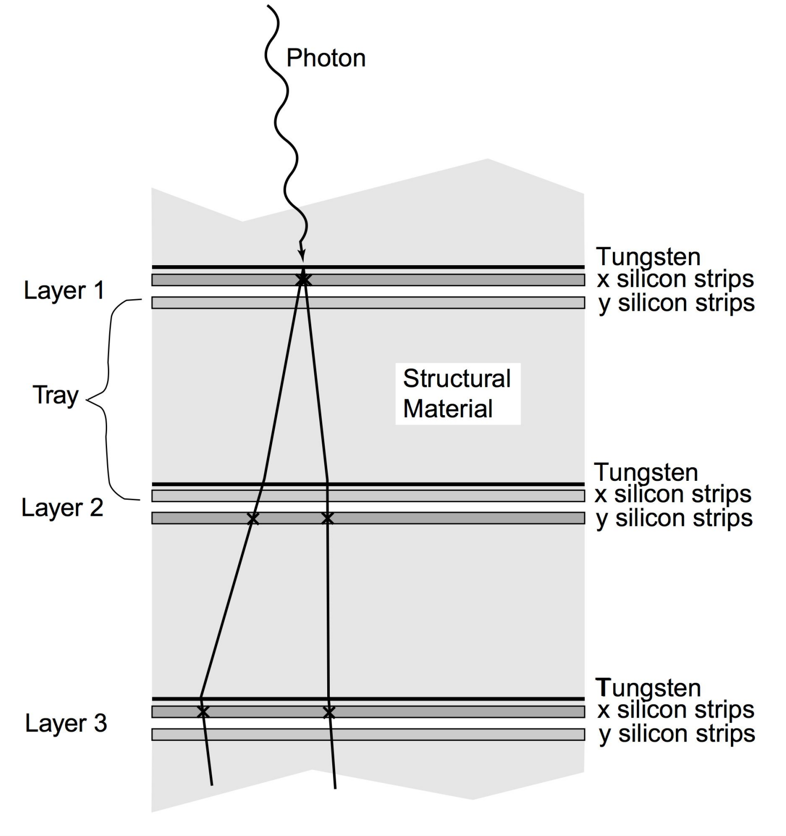
Silicon Tracker

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



Silicon Tracker

- Converter Thickness:
  - We need a reasonable chance for conversion
  - $N(x) = N_0 e^{-\mu X}$
  - $\mu \sim 9/(7X_0)$
  - X_0 = radiation length ~ $1/Z^2$
  - X/X_0 is the number of radiation lengths



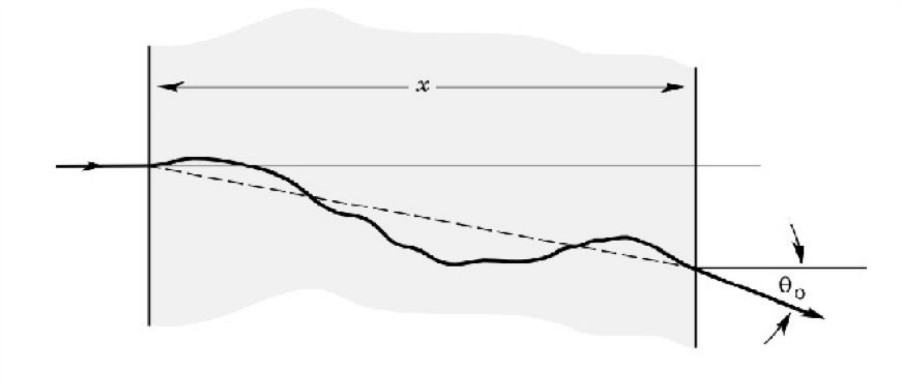
Could just have a really thick converter but need to balance this with multiple scattering in the converter.

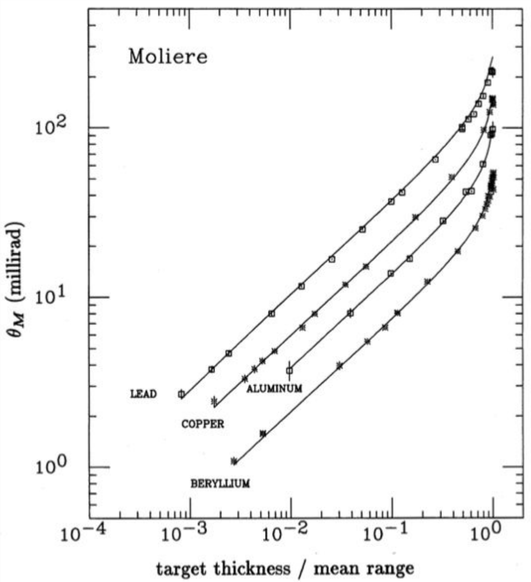
Anything that happens in the converter stays in the converter (i.e. we don't know about it).

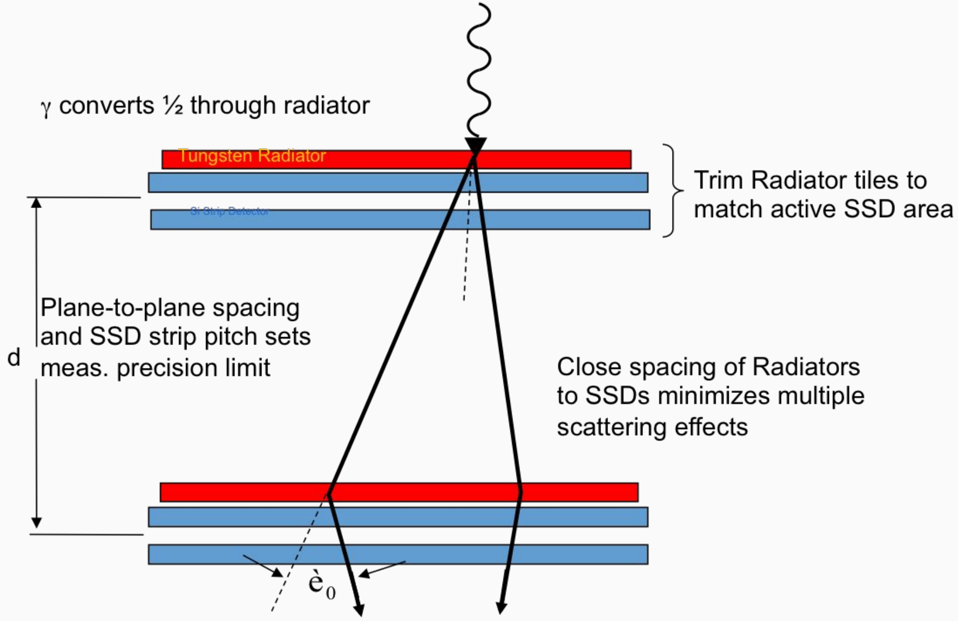
- Multiple Scattering: e^+/e^- undergo repeated elastic Coulomb scattering with nuclei
  - Energy transfer is negligible but each small deviation adds up.
- We can approximate multiple scattering by

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

θ_{MS} in mrad, E_γ in GeV, X in rad. Len.







γ converts ½ through radiator

Trim Radiator tiles to match active SSD area

Plane-to-plane spacing and SSD strip pitch sets meas. precision limit

Close spacing of Radiators to SSDs minimizes multiple scattering effects

Position Resolution (σ) = strip pitch /√(12)

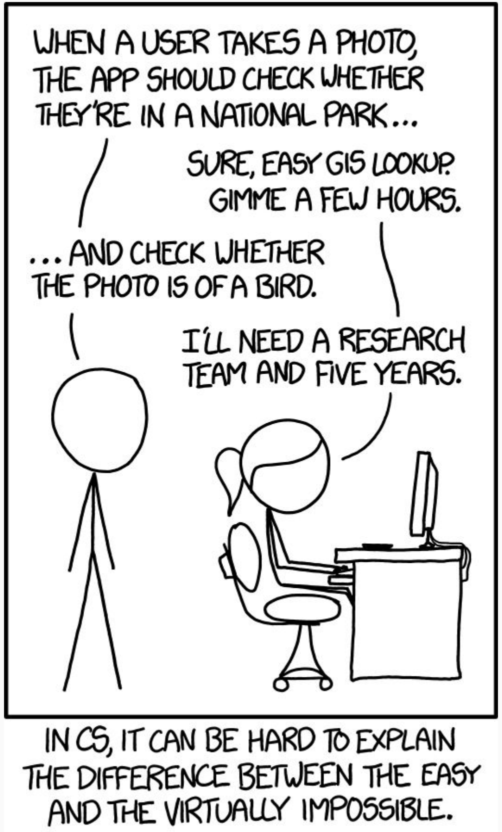
LAT: $\theta_{det} = \sqrt{(2)} * \sigma_{ssd}/d = 228\ \mu m/(32.9mm*\sqrt{(6)}) = 2.8\ mrad = 0.16°$

Silicon Tracker: Best possible resolution for 2 layers

The Perfect Tracker

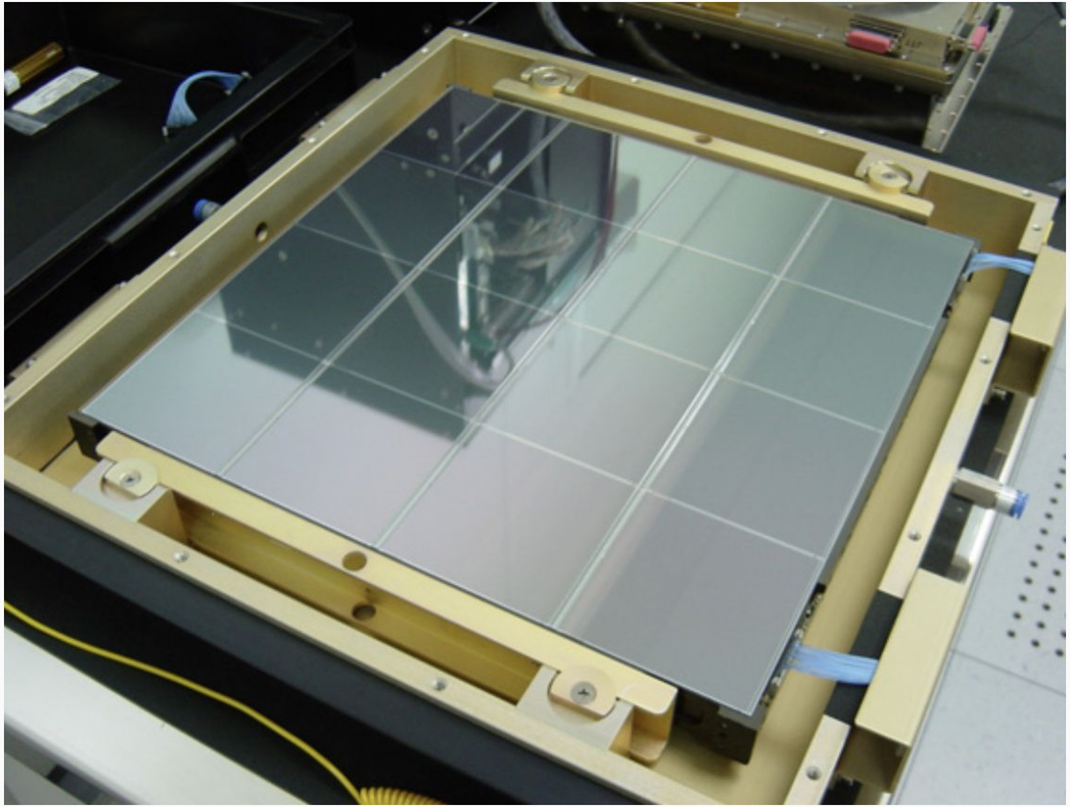
- Infinitesimally thin converter -> minimize multiple scattering
- Infinitely large number of layers -> to allow 100% conversion efficiency
- Infinitesimally small strip pitch -> minimize intrinsic detector resolution

Unfortunately, this kind of instrument is unbuildable, so we have to make choices...



https://xkcd.com/1425/

Tracker Tower

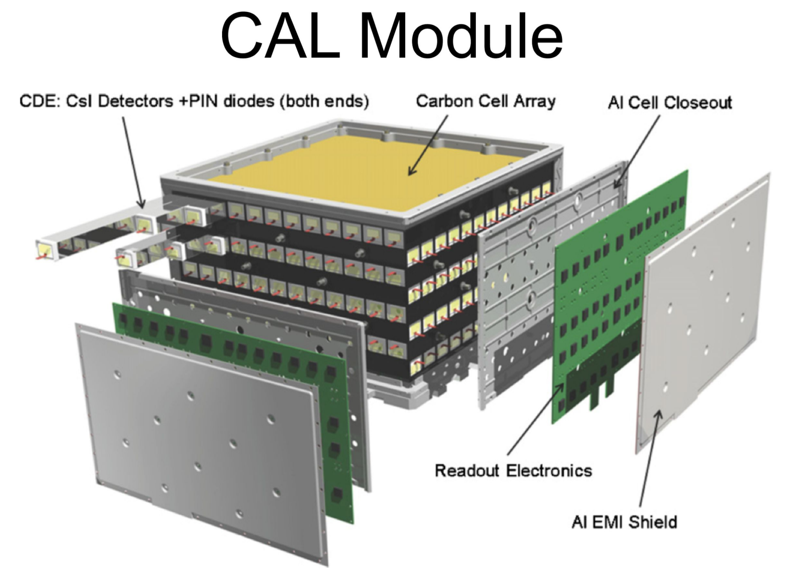


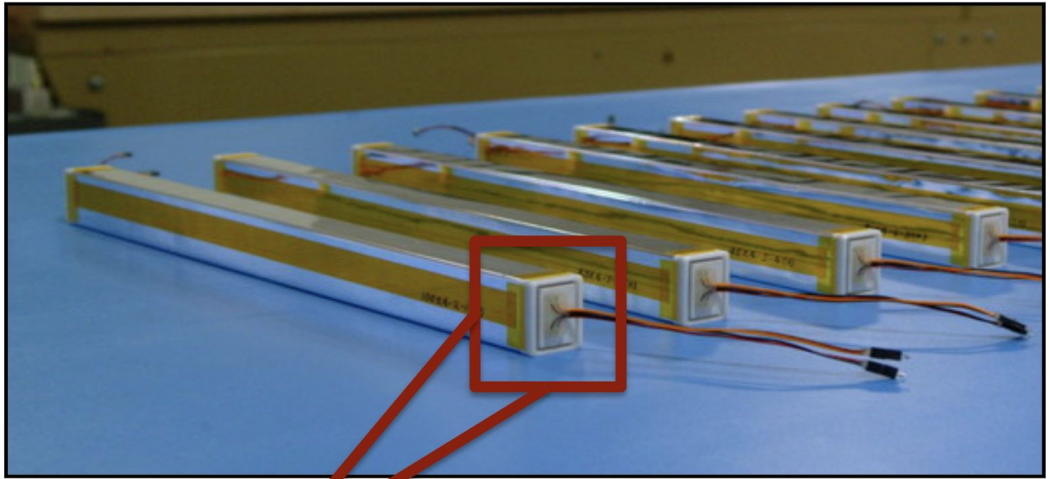
SSD Plane

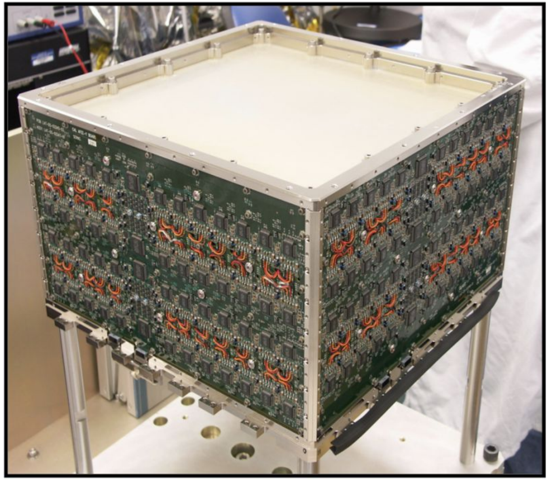
CsI Calorimeter (CAL)

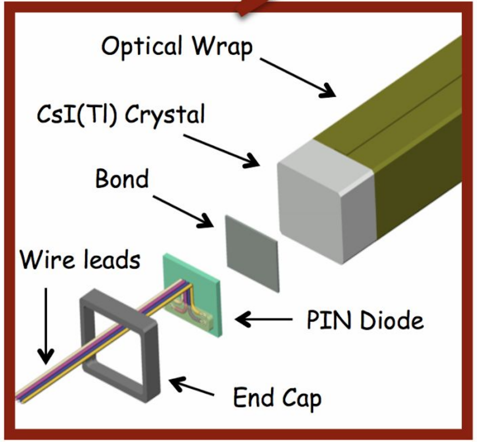
Calorimeter

- 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









Basic detector elements are CsI crystals

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

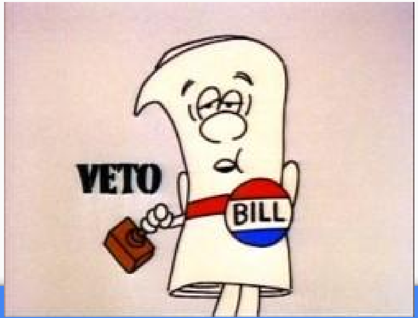
Light readout at both ends, provides measure of longitudinal position to ~cm from light ratio

CAL Imaging

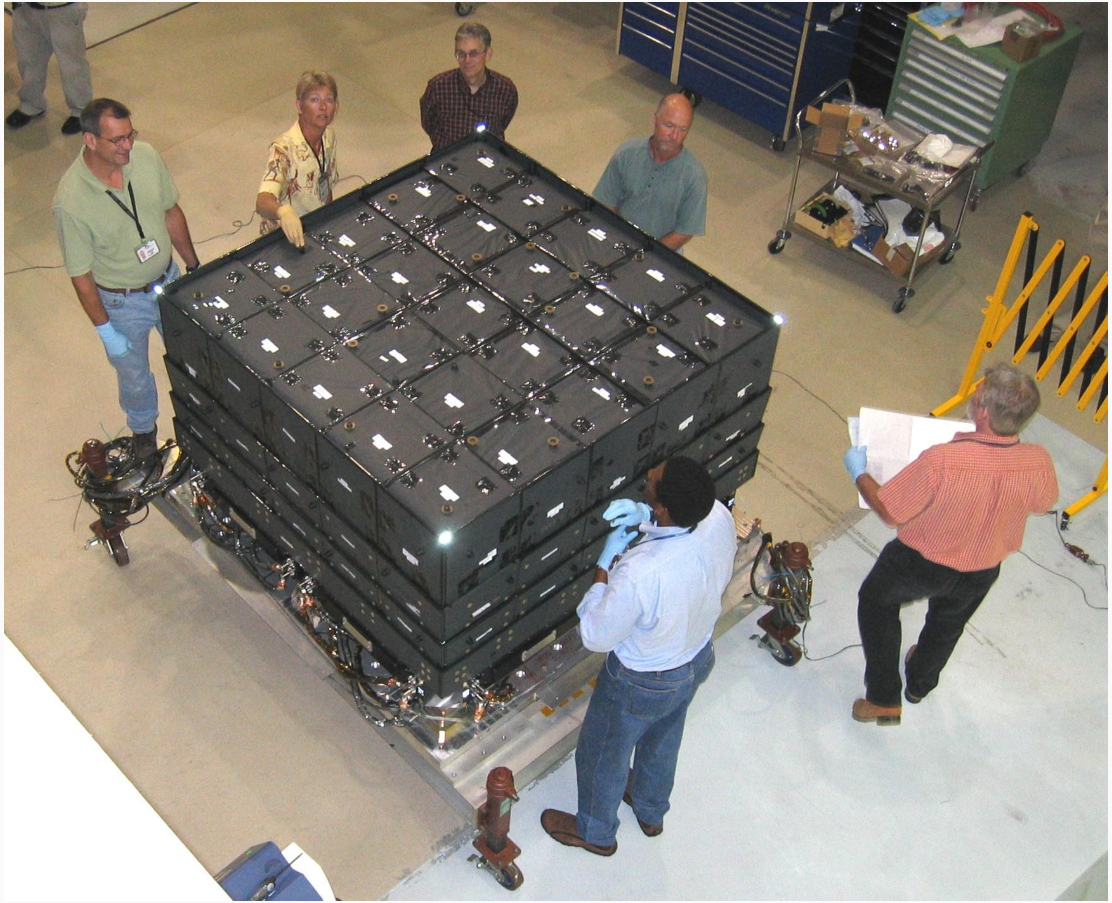
- In addition to measuring shower energy the LAT Calorimeter also has an **imaging capability**
- Asymmetry of light readout at crystal ends can be used to reconstruct a 3-D coordinate for the crystal energy deposition – can be used to build a **3-D image of the EM shower**
- CAL imaging capability is 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)

- 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%)

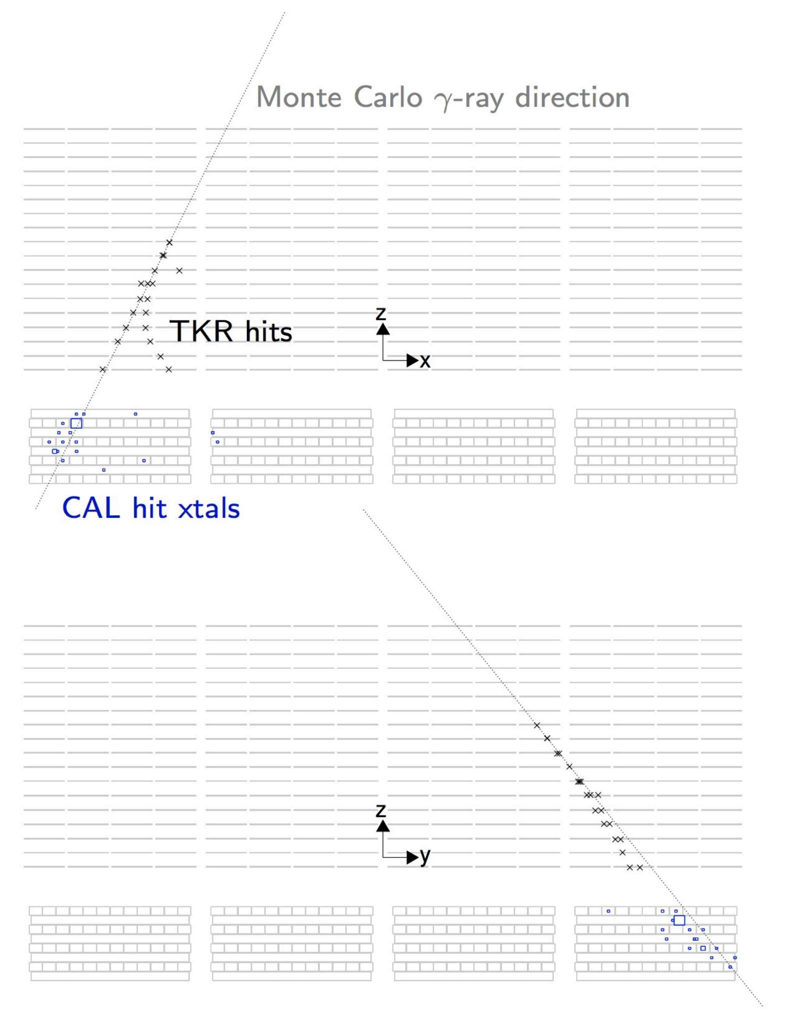


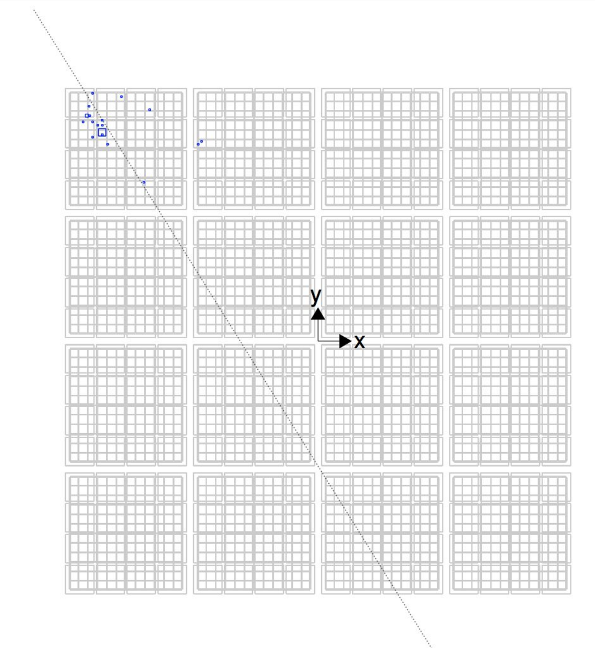
Curved ACD Tile



ACD from above

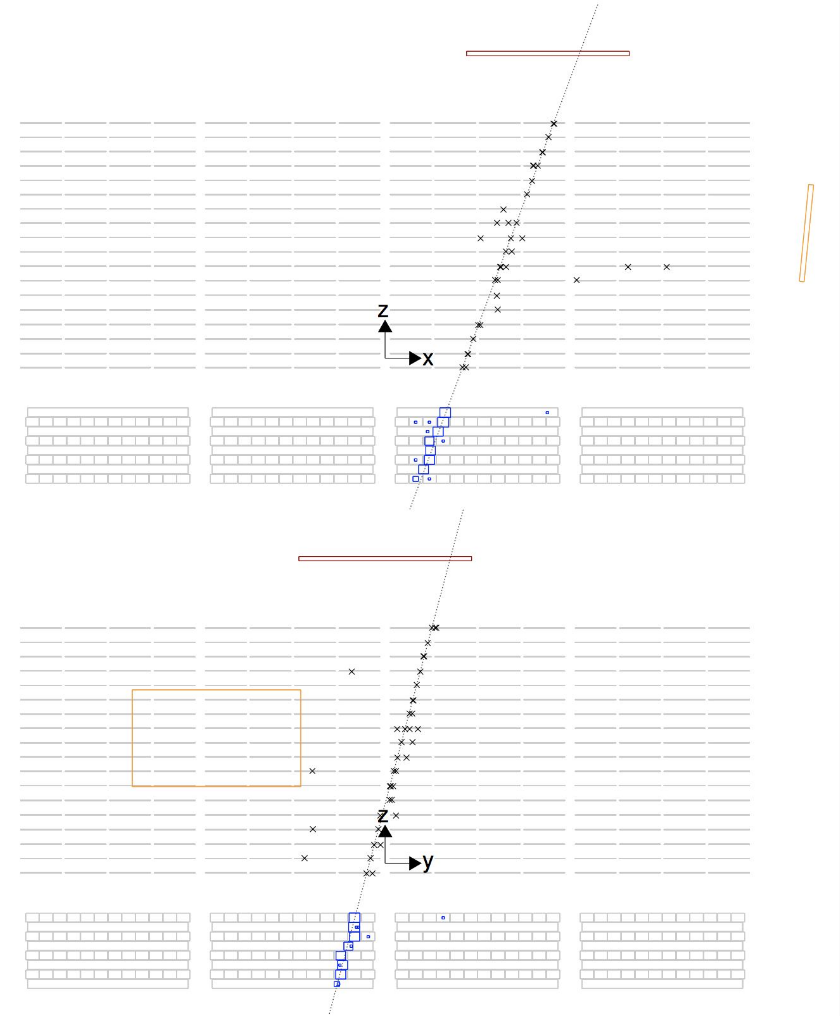
Real Event Displays

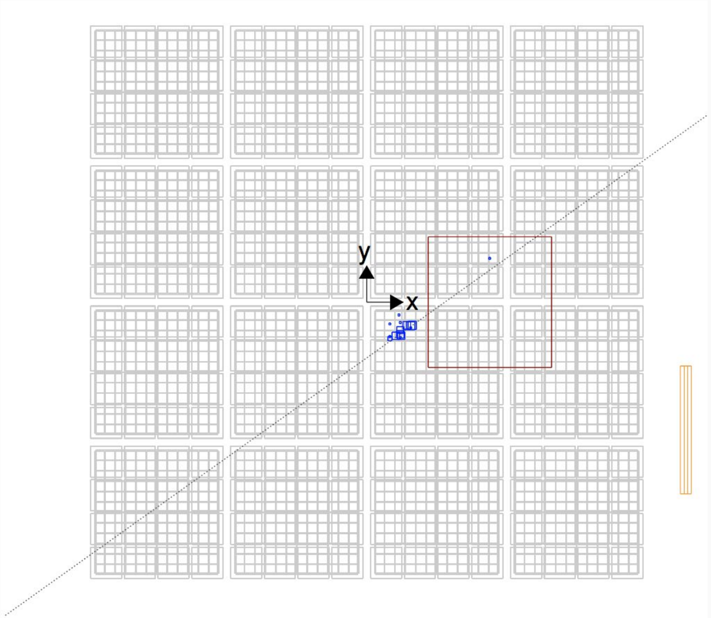




360 MeV ɣ-ray

- Two clear tracks
- Tracks point to energy deposits in the CAL
- No ACD hit tiles
- Tracks start in the middle of the instrument
- CAL energy deposits well localized





Background Event

- One Track
- Track points to an ACD hit
- Track starts in edge of TKR
- No shower in CAL

ɣ-ray

bably)

- Lots of CAL back-spash
- Tracks point everywhere
- Many hits in the ACD
- We can still get the energy and direction correct

Trigger, Filter, and Event Reconstruction

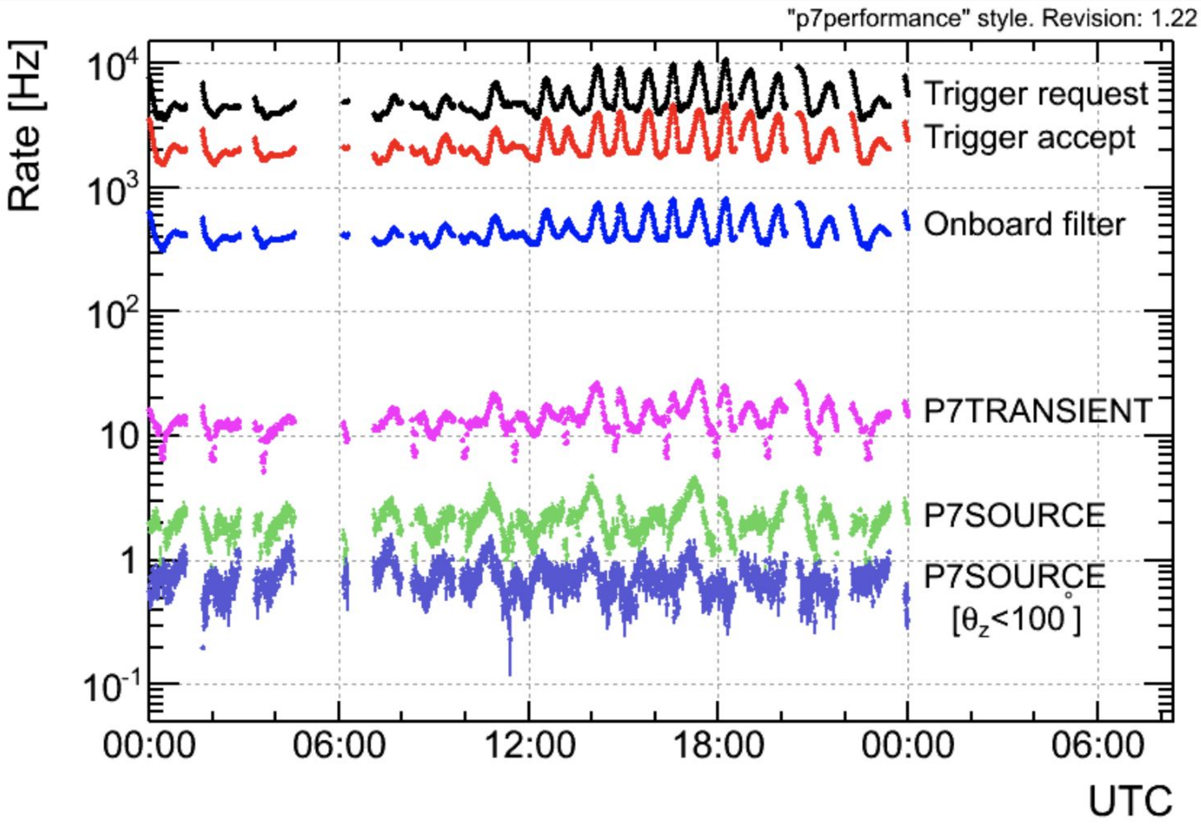
Trigger and Filter

- 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)

Onboard Filter

- Onboard filter provides an additional level of data reduction at hardware level
    - Needed to keep data volume within downlink bandwith (~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



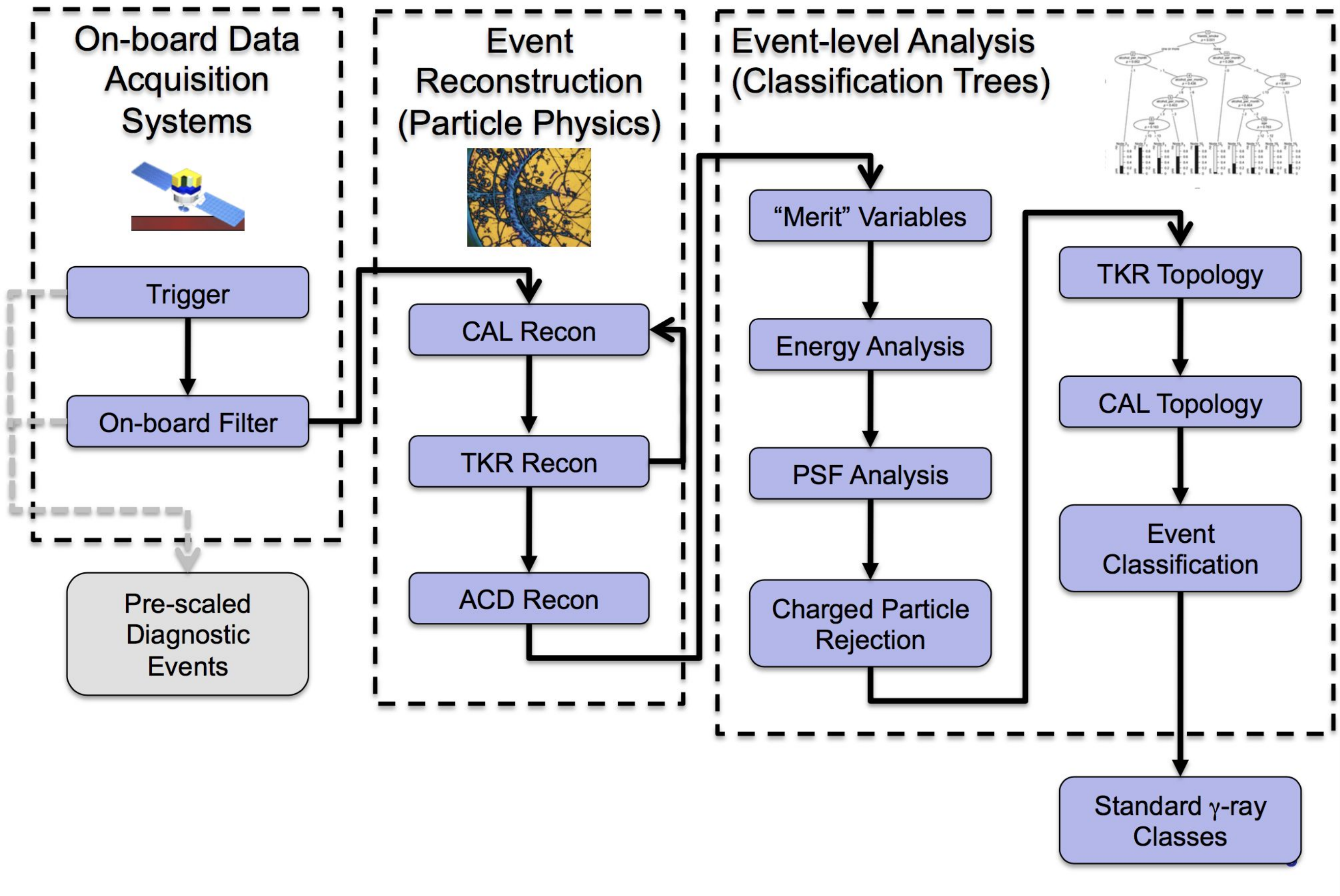
Trigger Rate (~2 kHz)

↓

Downlink Rate (~400 Hz)

↓

Celestial Gamma Rate (~0.5 Hz)



On-board Data Acquisition Systems

Trigger

On-board Filter

Pre-scaled Diagnostic Events

Event Reconstruction (Particle Physics)

CAL Recon

TKR Recon

ACD Recon

Event-level Analysis (Classification Trees)

“Merit” Variables

Energy Analysis

PSF Analysis

Charged Particle Rejection

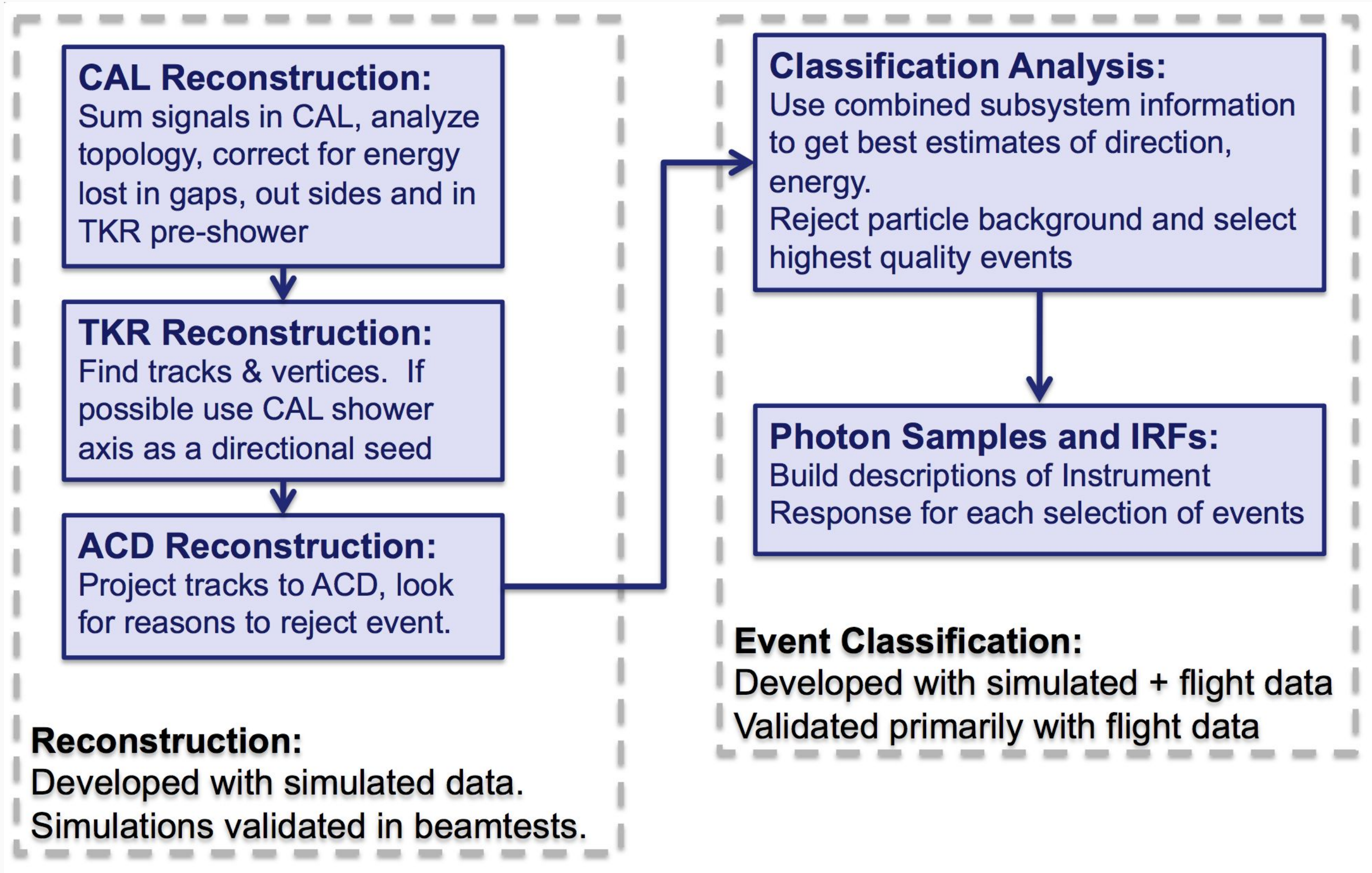
TKR Topology

CAL Topology

Event Classification

Standard γ-ray Classes

Data Acquisition and Event Analysis



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.

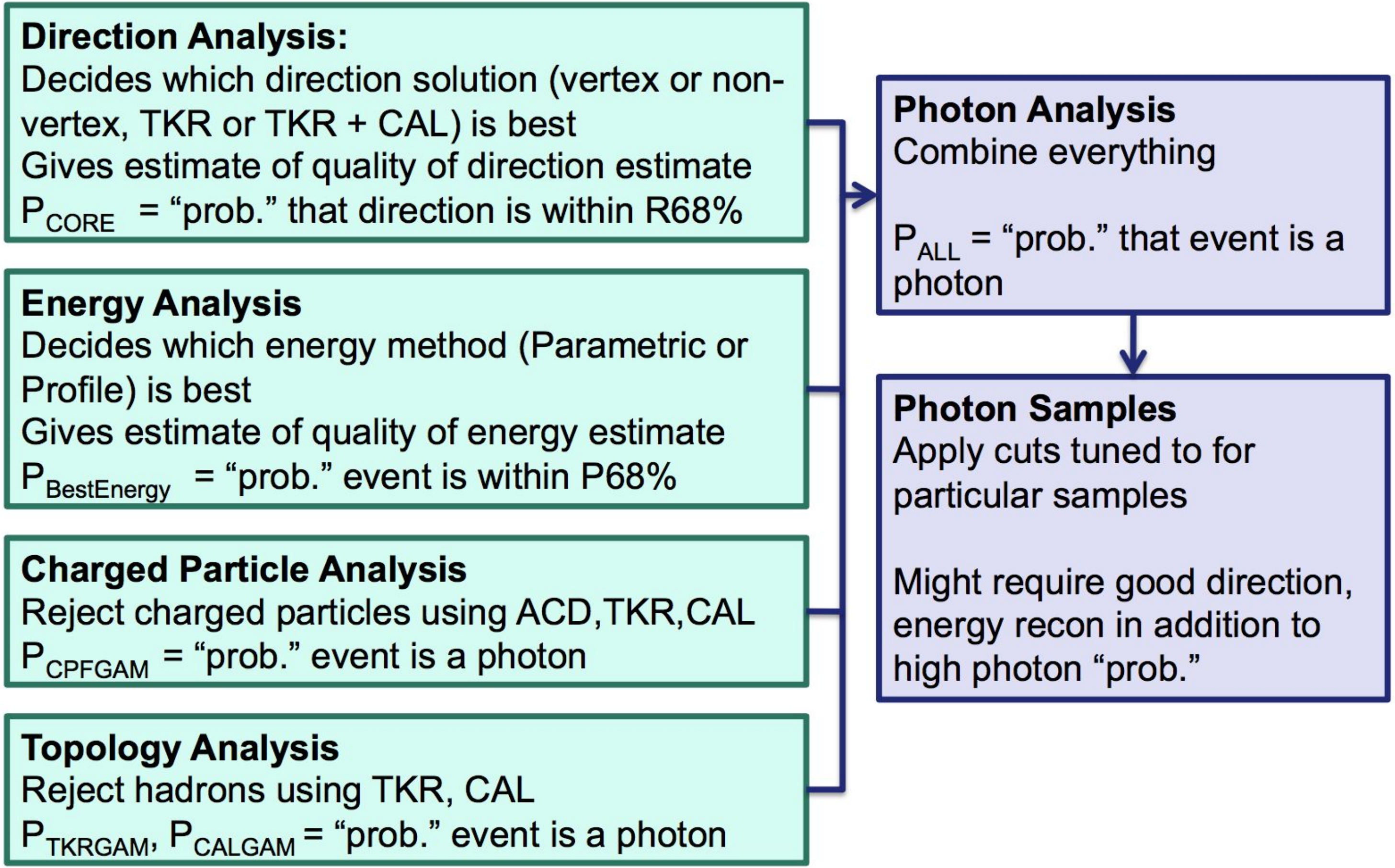
Classification Analysis:
Use combined subsystem information to get best estimates of direction, energy.
Reject particle background and select highest quality events

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

You have to simulate *everything*

- Active material (Si, CsI, Plastic)
- Inactive material
    - Tungsten
    - Carbon Fiber
    - Glue
    - Cables
    - Tape
    - Closeouts
    - Brackets
    - Alignment fixtures
    - Nuts, bolts,...



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

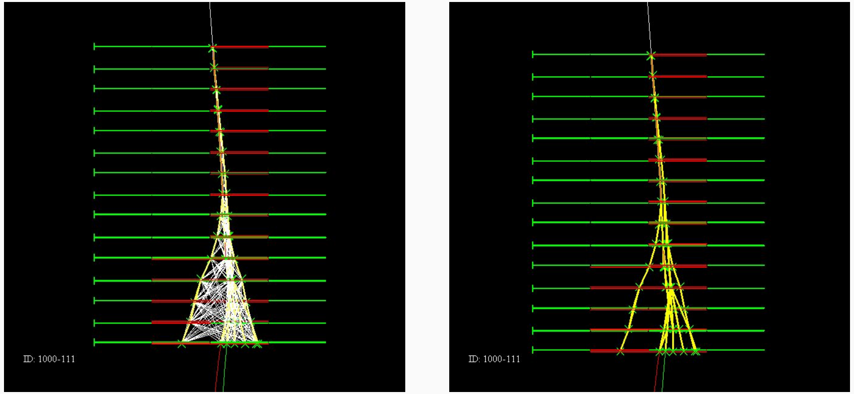
Photon Analysis
Combine everything

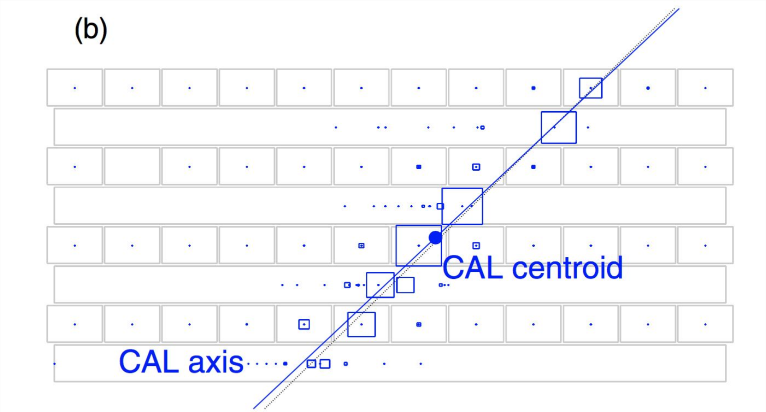
P_{ALL} = “prob.” that event is a photon

Photon Samples
Apply cuts tuned to for particular samples

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

- Tree based pattern recognition in the Tracker (in 3D!)
  - Basically finds x-y points and then connects them with links
  - Biases the direction to be similar to the direction determined from the CAL (reduces the number of options to a manageable number)
  - Builds the 'tree' from the top down
  - Direction is found by looking at the 'straightest branch' in the tree.
- Look for clusters of events in the CAL then performs a moments analysis on each cluster to determine its centroid, direction, and so on
- Look for a reason to veto the event in the ACD
  - Track extrapolation to an ACD hit?
  - Compare ACD energy to CAL energy (catches events where TKR direction is bad)



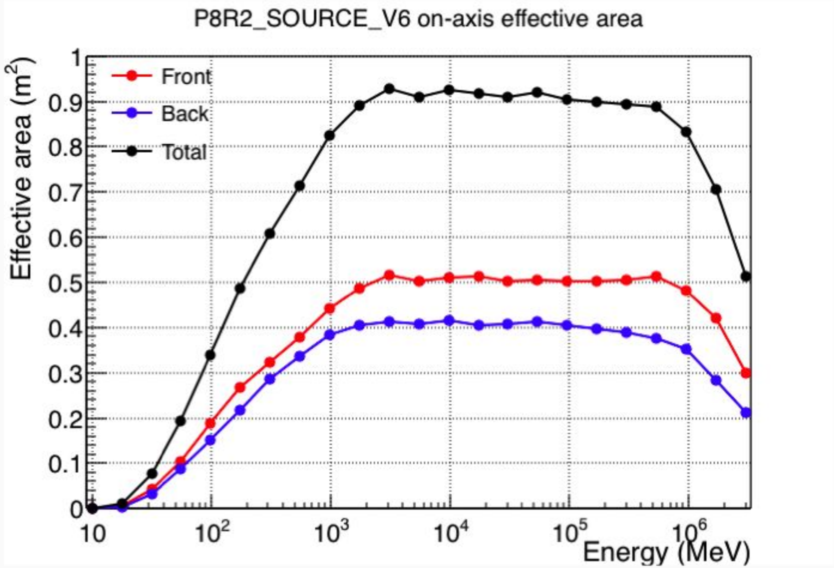


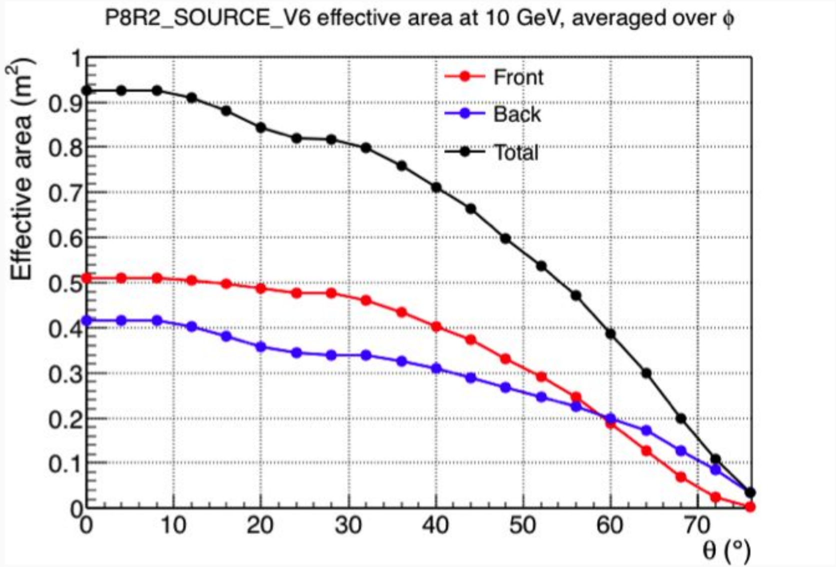
Pass 8 reconstruction

Detector Properties: IRFs

Detector Properties

- Every Detector has specific measurable characteristics that include:
    - Angular Resolution: how well can we reconstruct a photon’s direction.
    - Time Resolution: how well can we measure the photon’s arrival time.
    - Energy Resolution: how well can we measure the energy of the photon.
    - Field of View: how much of the sky can we see at any one time.
    - Effective Area: how big and efficient is the detector.
    - Energy Range: what energies can we detect.

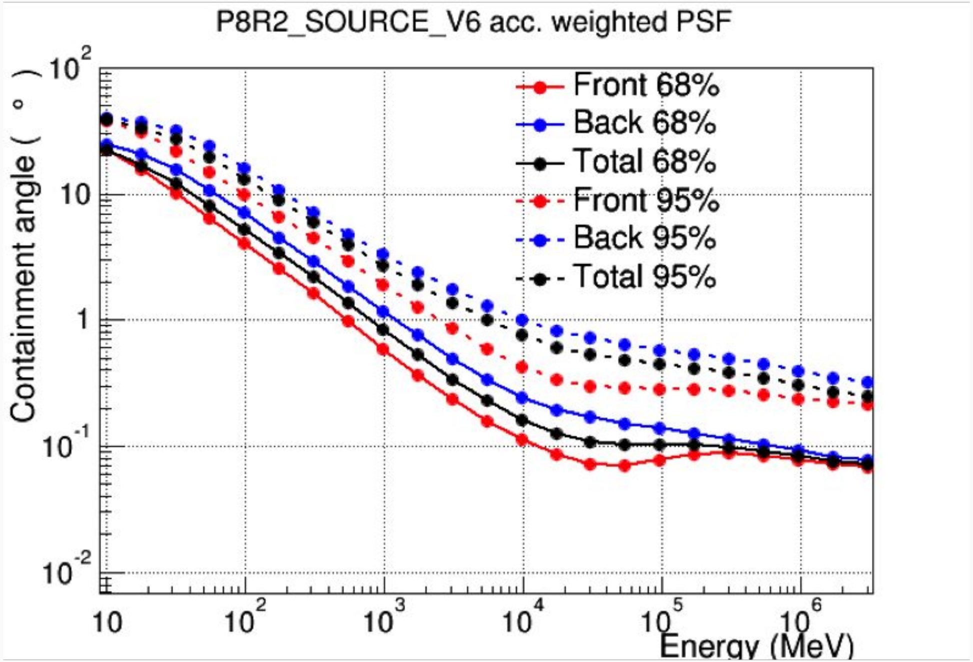

P8R2_SOURCE_V6 on-axis effective area


P8R2_SOURCE_V6 effective area at 10 GeV, averaged over ϕ

Aeff = Aphysical * Efficiency
Flux * Aeff = number of detected gammas

- Effecive area rises rapidly up to 1 GeV
- Useful data collected out to 65 - 70 degrees from the LAT boresight

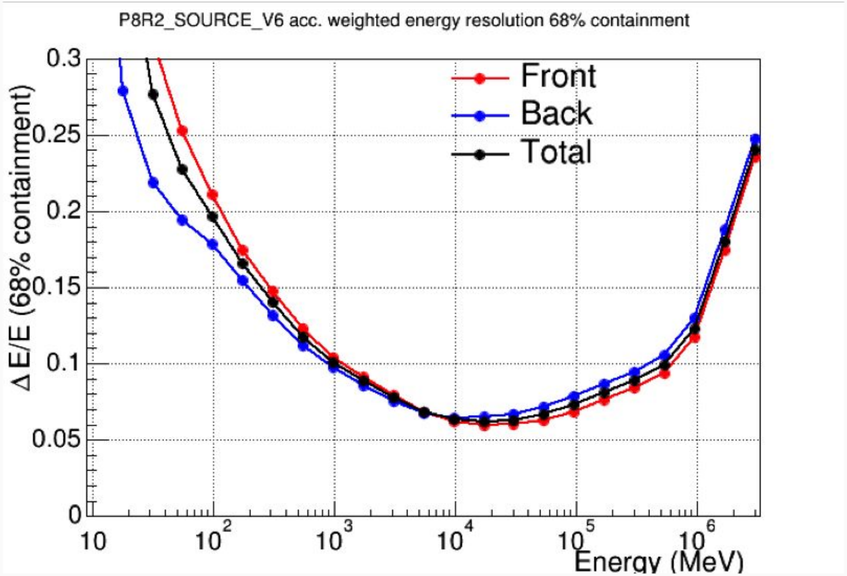
Effective Area



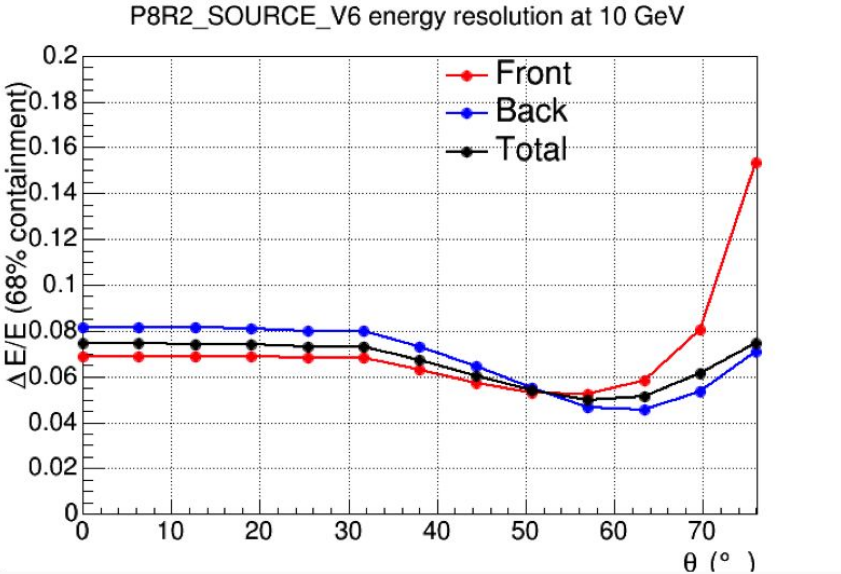
Characterized by angular radius that contains the 68% and 95% of the gamma-rays

- Angular resolution rapidly improves with increasing energy.
- Improved sensitivity (less background): greatly improved source confusion - particularly for hard spectrum sources

P8R2_SOURCE_V6 acc. weighted energy resolution 68% containment



P8R2_SOURCE_V6 energy resolution at 10 GeV



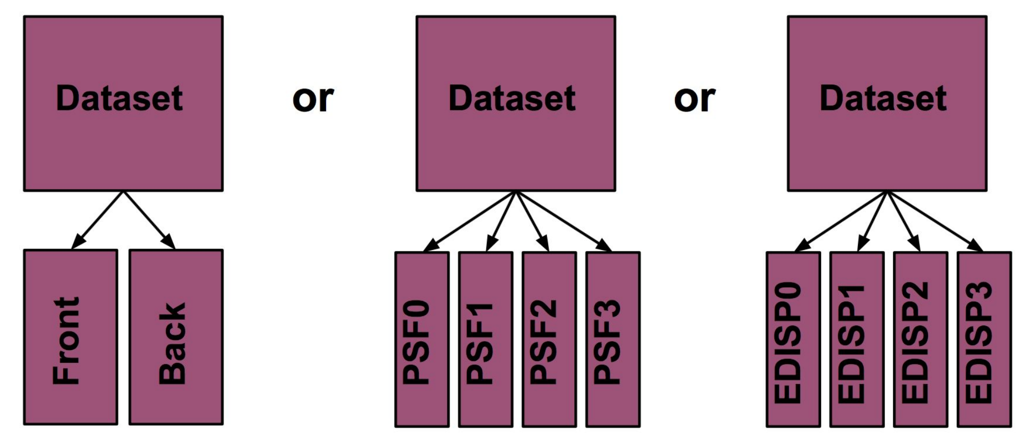
- Energy resolution improves for large theta at high energies

Energy Resolution

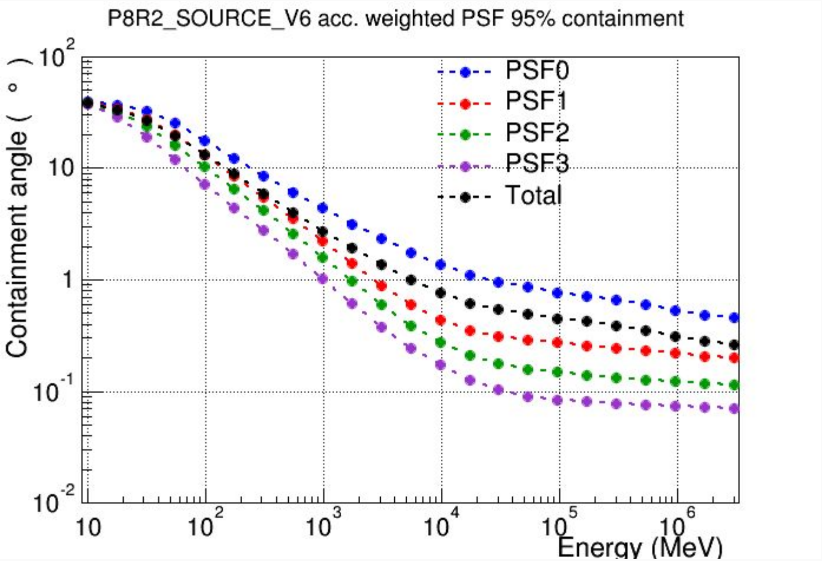
Event Types

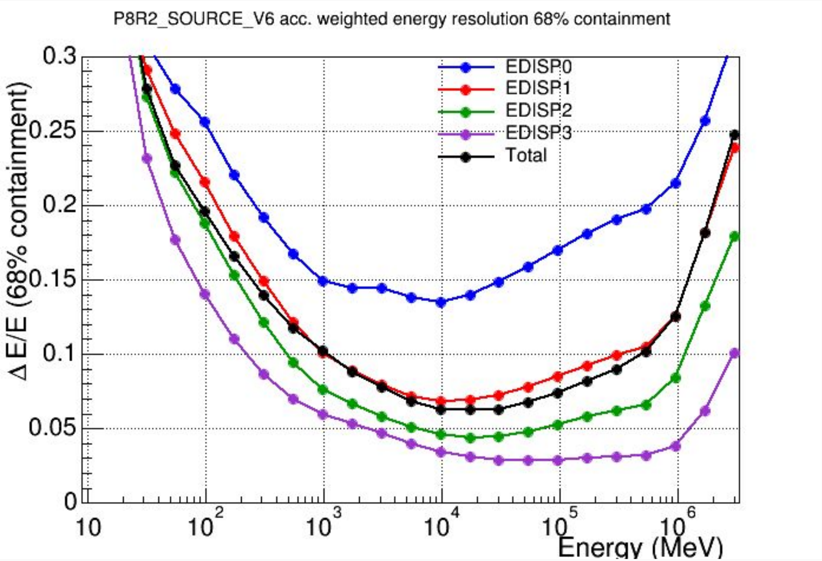
Pass 8 introduces a generalization of the conversion type classification in the form of *event types*. In addition to the conversion type partition, Pass 8 defines two additional partitions:

- PSF event type: using an event-level quantity indicating the quality of the reconstructed direction, the data is divided into quartiles, from the lowest quality quartile (PSF0) to the best quality quartile (PSF3)
- EDISP event type: same as PSF except that the event-level quantity used to partition the data indicates the quality of the energy reconstruction.



The likelihood function can be generalized to take advantage of these types and pretty much **everyone** should be doing an event type analysis now (we'll show you how).





Discussion Point: How/when should you use event types?

Summary