Fermi LAT Overview

Fermi Summer School
June 2011

Outline

- Overview of LAT & LAT Event Processing
- Detector Subsystems
  - TRK
  - CAL
  - ACD
  - Trigger and Filter
- Event Reconstruction (Talk next week)
  - Sub-systems reconstruction
  - Event level analysis
- IRFs and *ScienceTools* (Talk Friday)

Fermi
Gamma-ray
Space Telescope

OVERVIEW

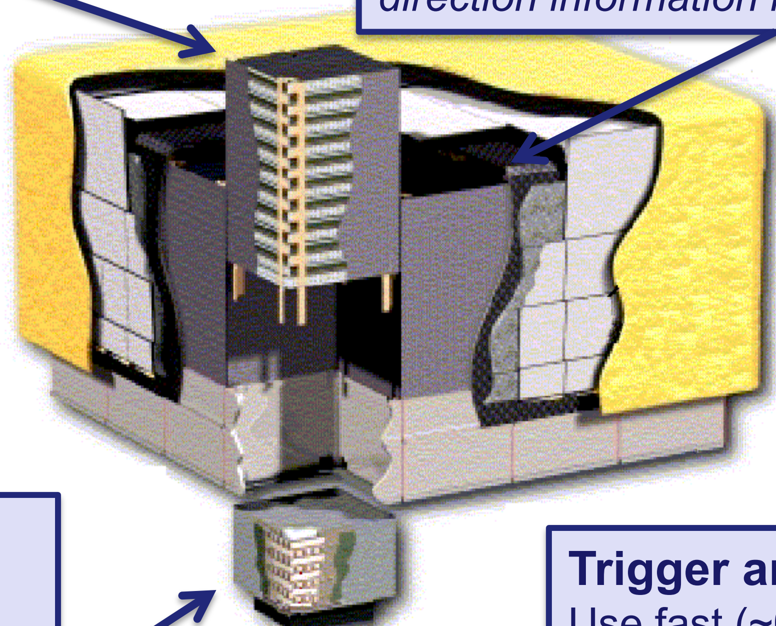
Salient Features of the LAT

Tracker (TKR):
18 Si bi-layers
Front- 12 layers (~60% X_o)
Back- 6 layers (~80% X_o)

Angular resolution ~2x better for front
Many EM showers start in TKR

Anti-Coincidence Detector (ACD):

ε = 0.9997 for MIPs
Segmented: less self-veto *when good direction information is available*

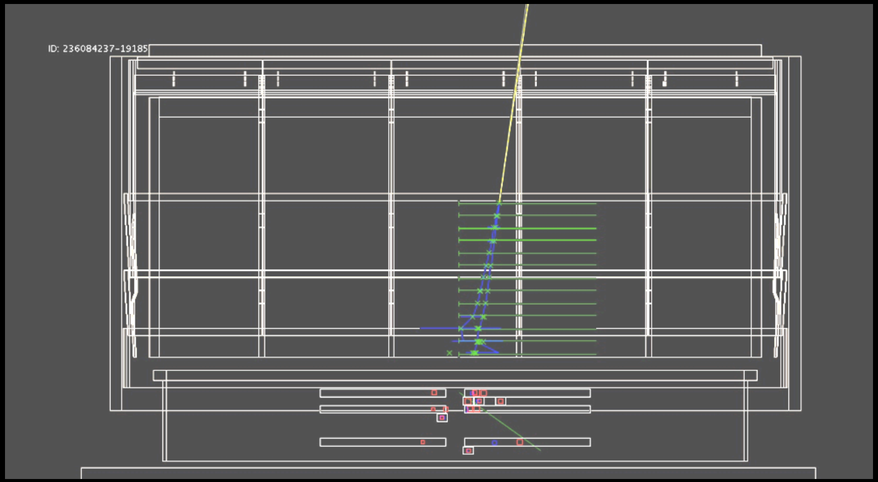


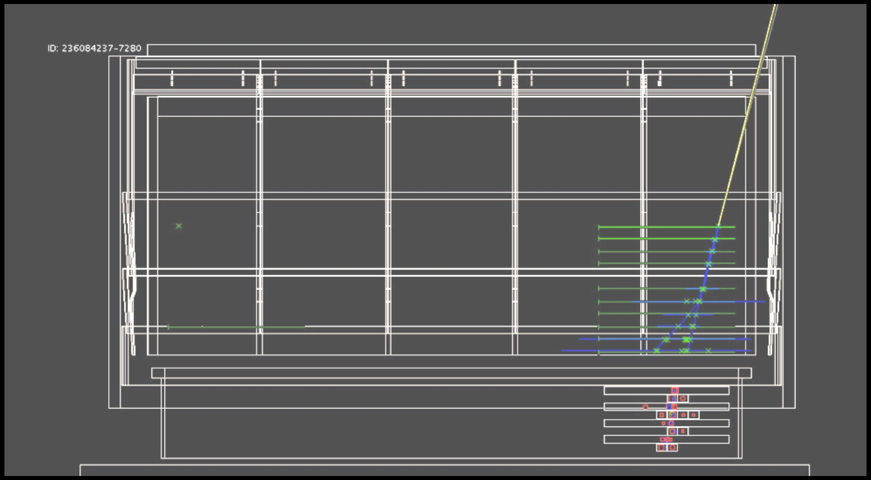
Calorimeter (CAL):
8 layers (8.6 X_o on axis)

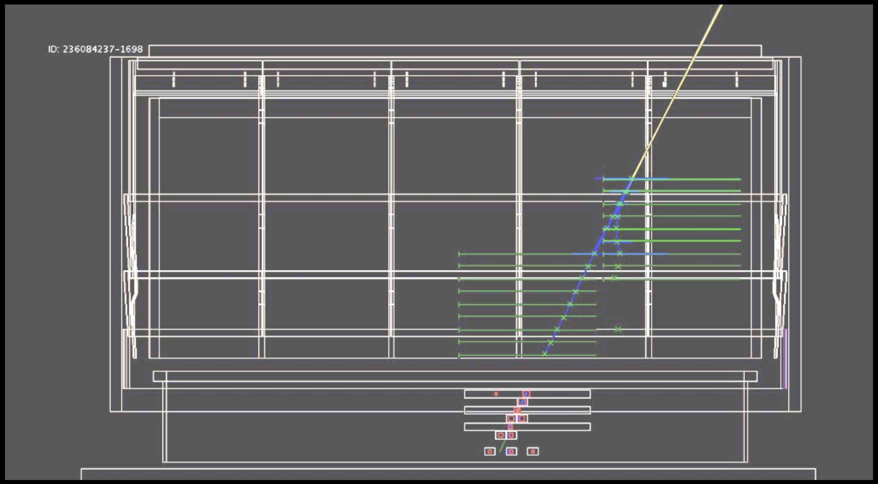
$\Delta E/E$ ~ 5-20%
Hodoscopic, shower profile and *direction* reconstruction above ~200 MeV

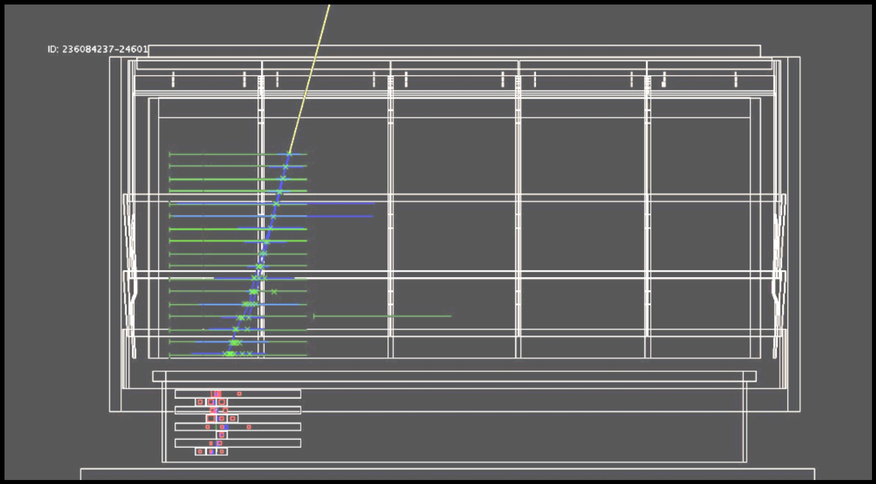
Trigger and Filter
Use fast (~0.1 μs) signals to trigger readout and reject cosmic ray (CR) backgrounds
Ground analysis uses slower (~10μs) shaped signals

Single Event Gallery







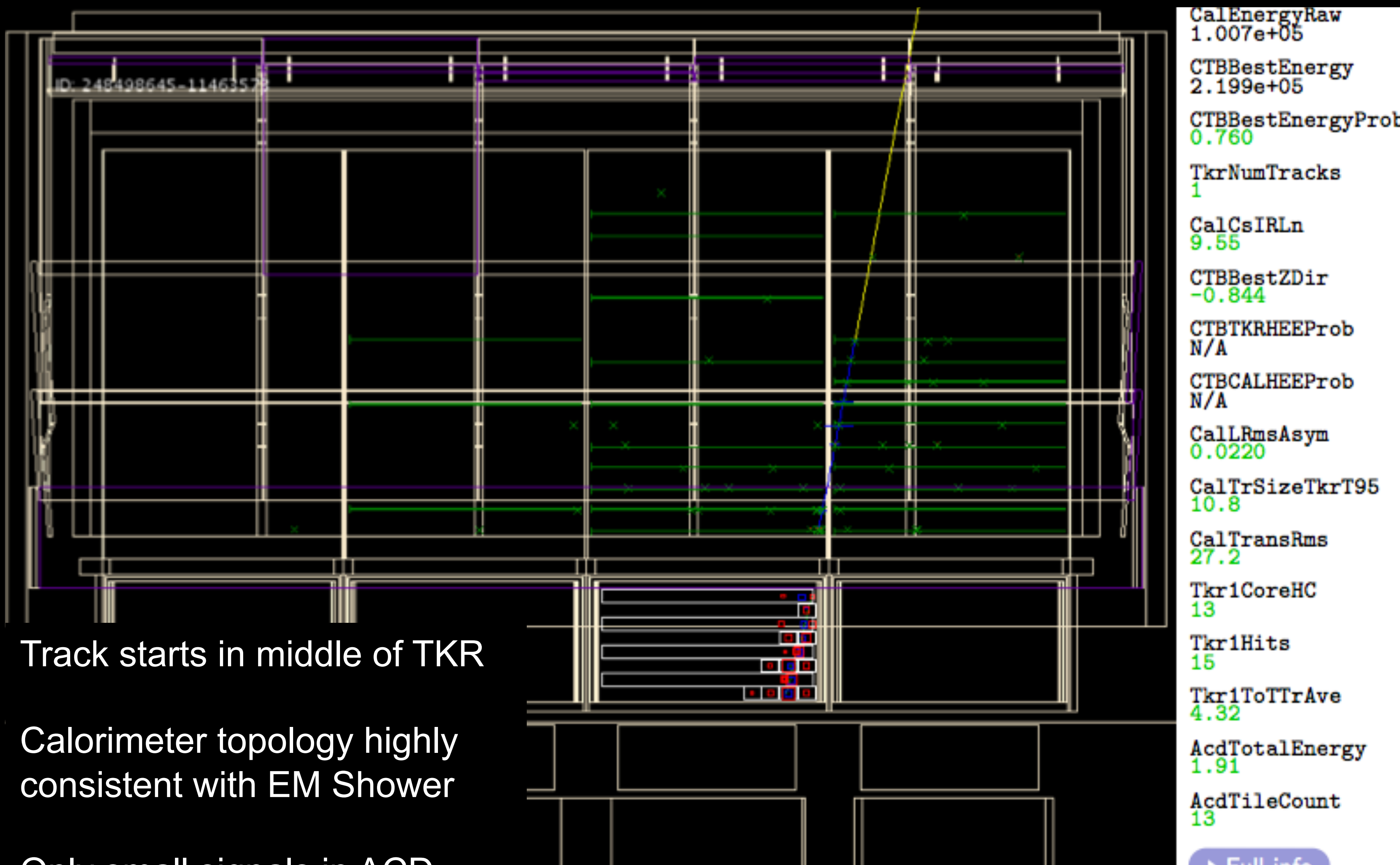


Green Lines = Strip hits , Green Crosses = TKR hits on track, Blue lines = TKR trajectories

Grey Boxes = CAL log hits , Red crosses = Reconstructed CAL energy deposits

Yellow Line = Incoming photon direction

A good photon event

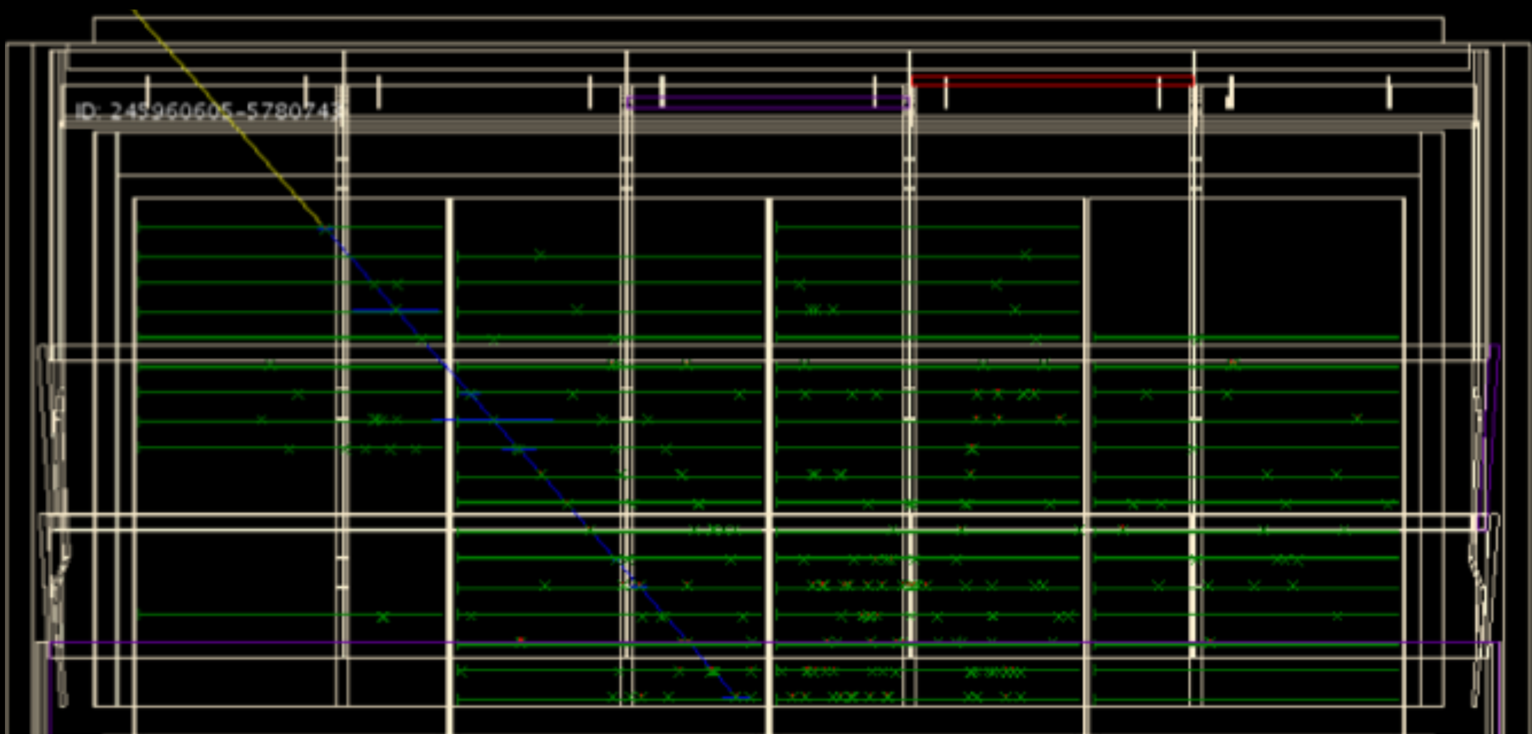


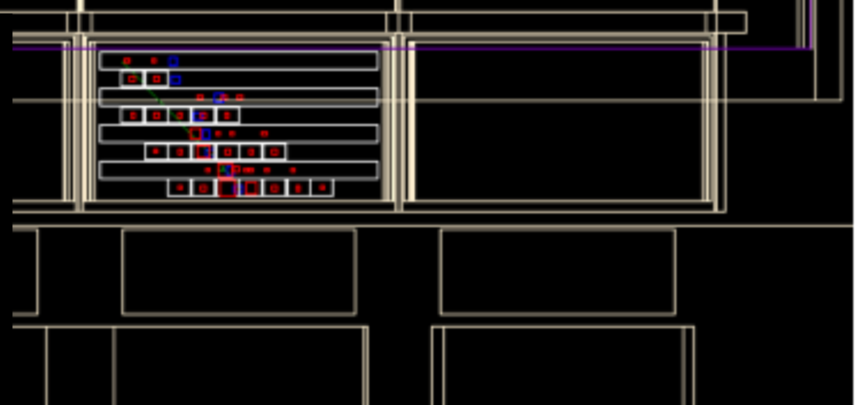
Track starts in middle of TKR

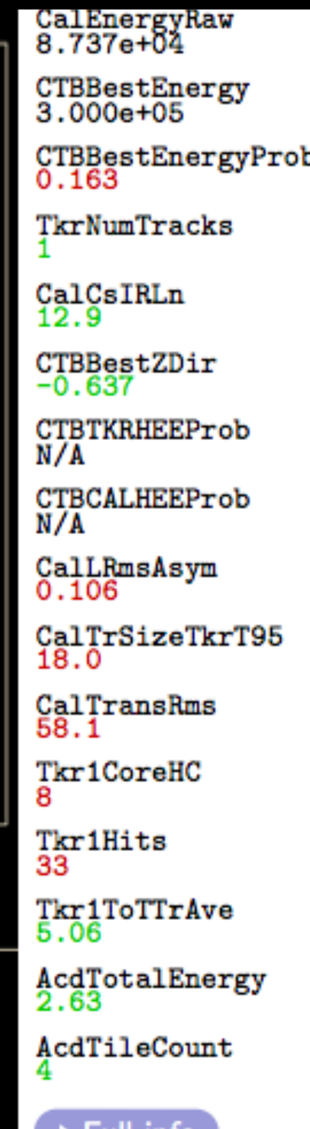
Calorimeter topology highly consistent with EM Shower

Only small signals in ACD

A Marginal Event





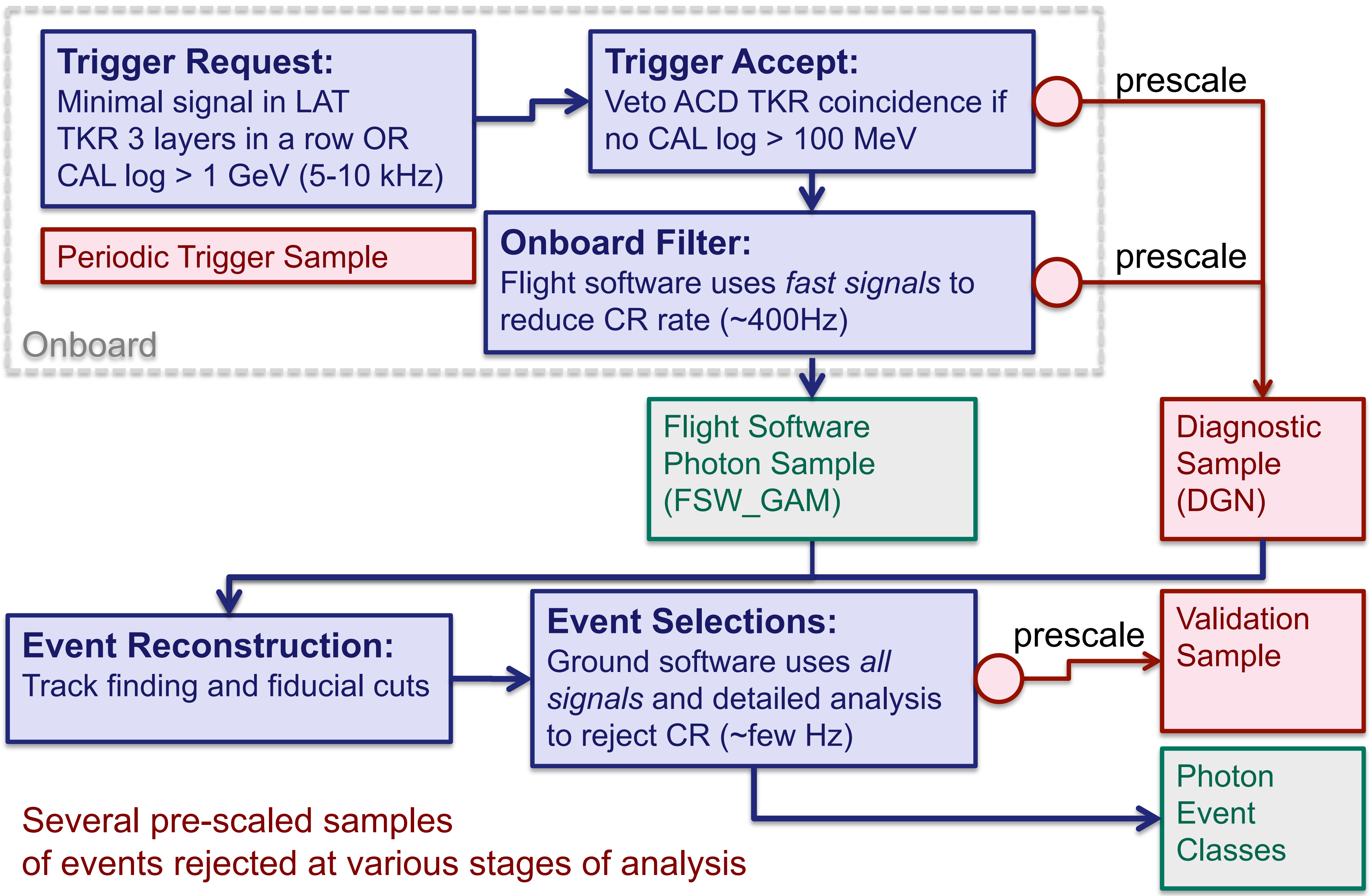


Track starts near edge of TKR

CAL topology larger transverse spread than average EM shower

Large signal in ACD, but away from main track

Overview of the Photon Selection Process



Instrument Response Functions

- **Provide a description of the instrument**
- **Done in context of likelihood fit**
  - **Can extract information needed for aperture photometry**

Effective Area:
Area x efficiency for physicists
Aperture size x effic. for astronomers

$A_{eff}(E,\theta,\phi)$

Point Spread Function
Direction resolution for physicists
Image resolution for astronomers

$P(\theta', \phi' ; E, \theta, \phi) = P(\delta \mathbf{v} ; E, \mathbf{v})$

Energy Dispersion
Energy resolution for physicists
Spectral resolution for astronomers

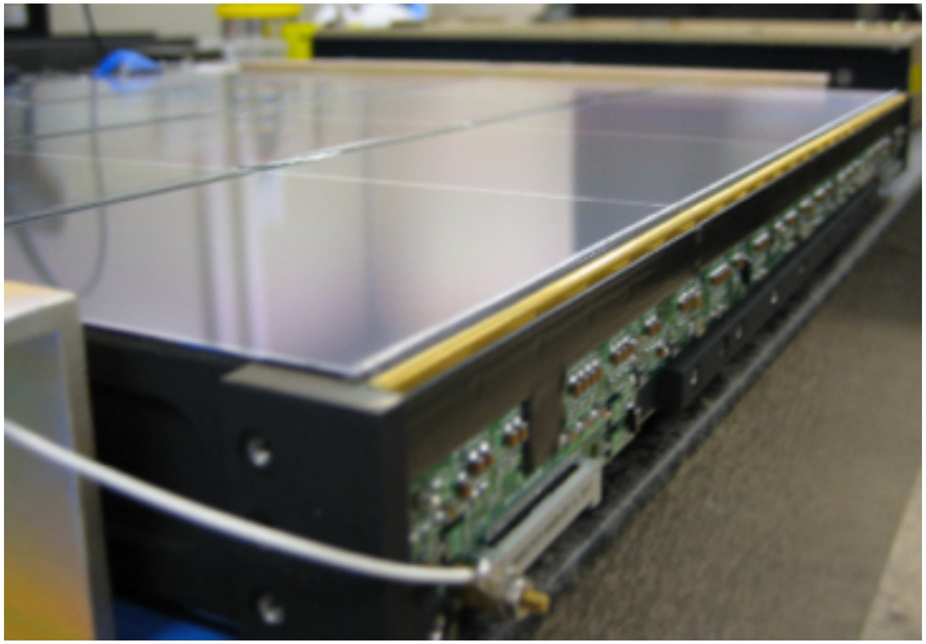
$D(E' ; E,\theta,\phi) = D(\Delta E/E ; E,\theta,\phi)$

Residual Particle Background
Not really an IRF, absorbed into template for isotropic γ-ray flux

$\nu F(\nu)$ or $E\, dN(E)/dE$

SILICON TRACKER

Images of the TKR



18 bi-layers, (x,y planes)

12 Layers thin (0.03 X_0) Tungsten
4 Layers thick (0.12 X_0) Tungsten
2 Layers no Tungsten

Width: 400μm, Pitch 256 μm
Point Resolution ~ pitch / sqrt(12)

TKR Roles

- **Primary Roles:**
  - **Direction reconstruction**
  - **Main event trigger**
- **Other roles:**
  - **Projection to CAL, ACD**
  - **Background rejection**
    - **pair-conversion**
      - **conversion vertex found?**
    - **(pre-)shower topology, e^+e^- versus hadrons**
    - **specific backgrounds**
      - **backsplash from CAL**
      - **Up-going heavy ions stopping in TKR**

Operating the TKR

Timing

Digital hold and delay counters, offset shaping time constants. "Set and forget"

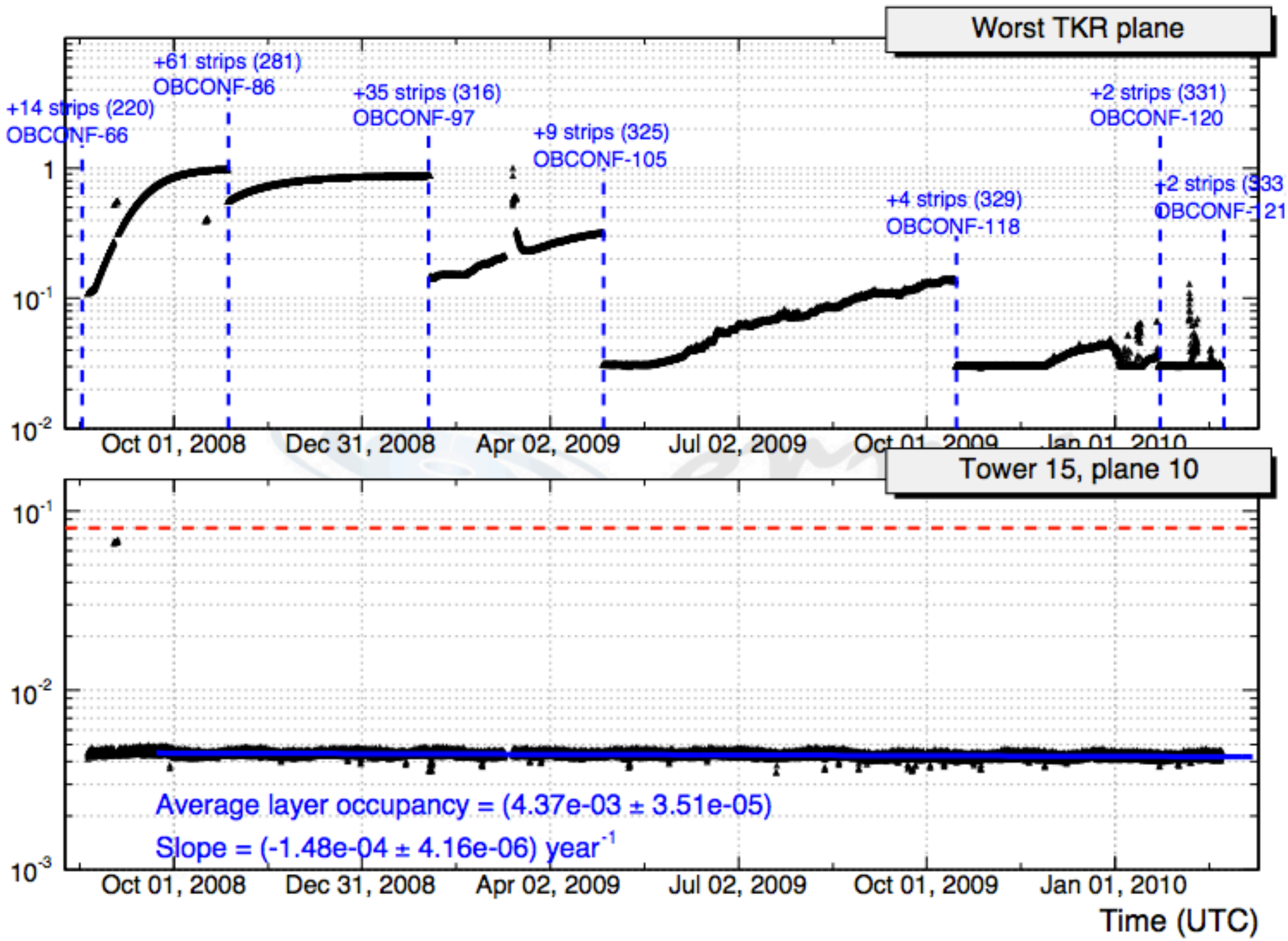
Electronics Calibrations

Threshold: tune each readout section to trigger at about 0.25 x MIP
Noise Occupancy: identify and mask off bad channels

Offline Calibrations

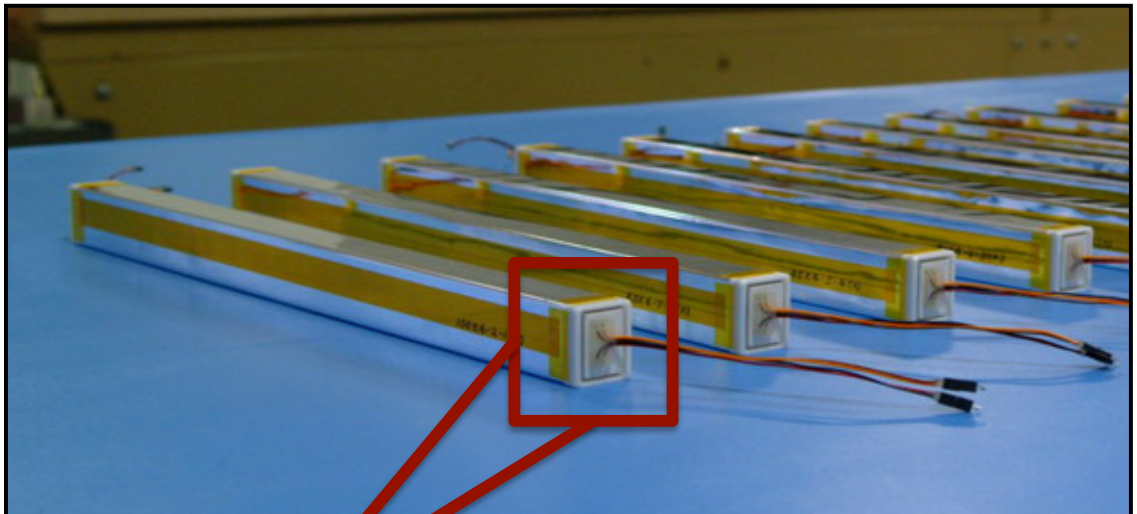
ToT: Convert Time over Threshold (ToT) to MeV equivalent
Module alignment: positional & angular offsets of each Si wafer
LAT-Spacecraft alignment: angular offsets of LAT relative to start trackers

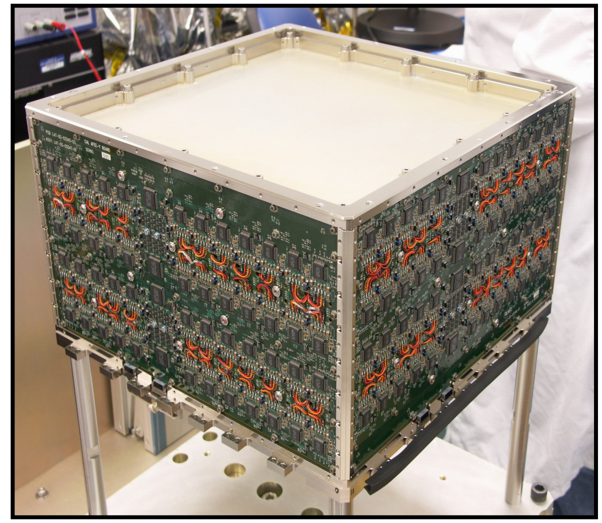
Trending: masking TKR channels

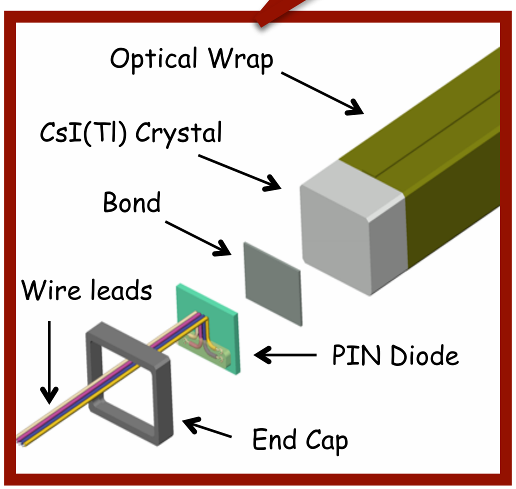


CsI Calorimeter

Images of the CAL







12 * 8 * 16 logs

Light readout at both ends, get long. position to ~cm from light ration

4 readout ranges (2 MeV – 100 GeV)

CAL Roles

- **Primary Roles:**
  - **Energy reconstruction**
  - **Contributes to event trigger**
- **Other Roles:**
  - **"Energy Flow" axis at high energy**
    - **Seeds tracker pattern-recognition in complicated events**
  - **Background rejection**
    - **Shower topology e^+e^- versus hadrons**
    - **Specific backgrounds**
      - **Up-going particles**
      - **Backsplash**
  - **Projection to ACD**

Operating the CAL

Timing

Digital hold and delay counters, offset shaping time constants. "Set and forget"

Electronics Calibrations

Pedestals: electronic signal in absence of physics
Thresholds: provide hardware triggers at 100MeV, 1GeV
Zero-suppression: provide readout threshold at 2MeV

Offline Calibrations

Proton/ MIP: convert signal to MeV (MIP as reference)
Asymmetry: position information along length of crystal from light asymmetry
Inter-range: cross calibrate readout ranges

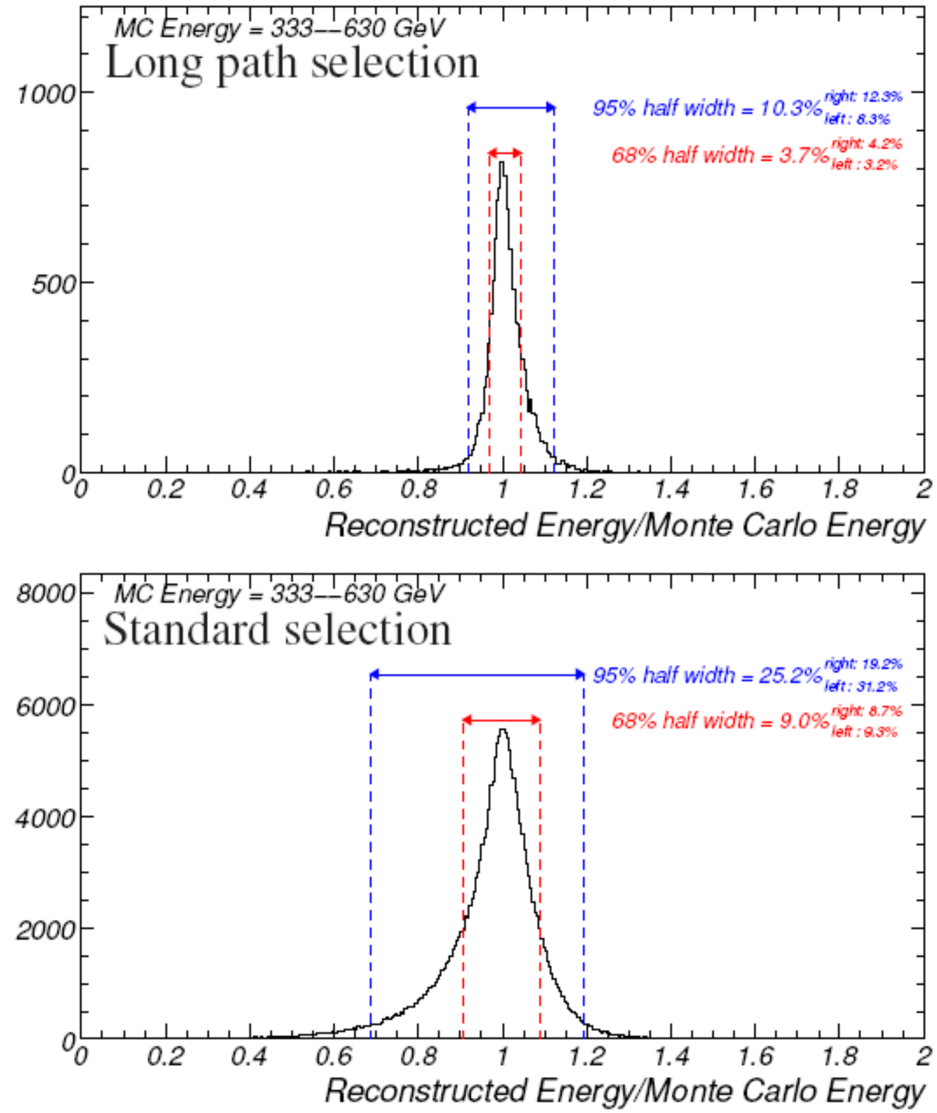
Improving the energy resolution for specific case

The calorimeter energy resolution improves substantially if catch more of the shower in the CAL

On axis = 8.6 X_0 of material in CAL

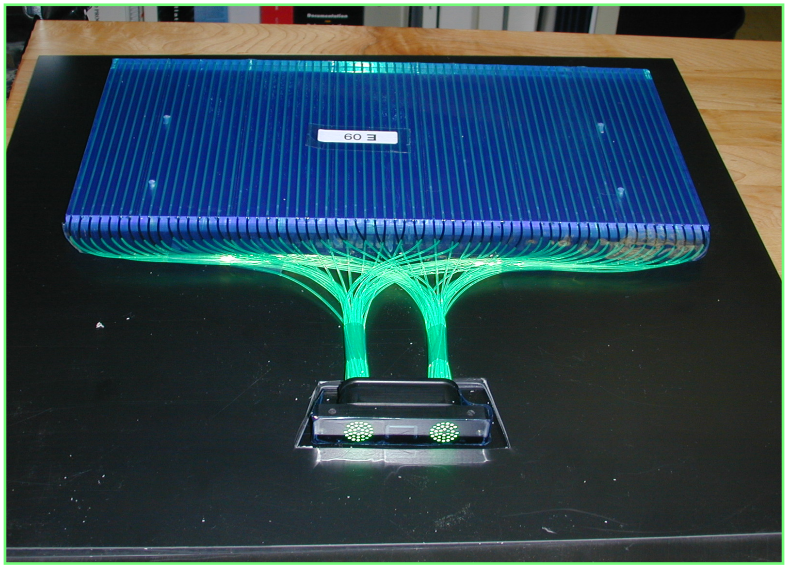
At 500 GeV -> significant leakage out the back of the CAL

For e^+e^- spectra, much higher statistics, can make special selection of events with long path in CAL



ANTI-COINCIDENCE DETECTOR

Images of the ACD



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

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

2 readout ranges
< 0-8 MIP (Standard)
> 8-1000 MIP (Heavy Ions)

ACD Roles

- **Primary Roles:**
  - **Offline background rejection**
  - **Hardware & onboard filter veto**
- **Other Roles**
  - **Identifying Heavy Ion (C,N,O + up) calibration events**

Operating the ACD

Timing

Digital hold and delay counters, offset shaping time constants. "Set and forget"

Electronics Calibrations

Electronics pedestals
Zero Suppression: provide readout threshold at pedestal + 5x electronics noise
Thresholds: provide hardware veto at 0.4 x MIP, 30 x MIP

Offline Calibrations

MIP Calibration: Convert pulse height to MeV equivalent (MIP as reference)
Carbon Calibration: Convert large pulses to MeV equivalent (C as reference)
Inter-range calibration: Match readout in low (< 8 MIPs) to high (> 8 MIPs) range

TRIGGER AND FILTER

Roles of the Trigger and Filter

- **Primary Role:**
  - **Trigger readout of the LAT**
  - **Hardware trigger: Reduce readout rate to be manageable**
    - **From 5-10 kHz down 1-2 kHz**
  - **Onboard filter: Reduce downlink rate**
    - **From 1-2 kHz down to 300-500 Hz**
- **Other Roles:**
  - **Provide calibration and diagnostic samples**
    - **MIPs, Heavy Ions, periodic triggers, leaked prescalers**

Hardware Trigger Components

TKR: Tracker 3 in a row

Three consecutive tracker layers have a signal.
Active above about 10-30 MeV
Generates Trigger Request

CAL-HI: High Energy CAL

Any single CAL channel has energy about 1 GeV.
Active above about 10 GeV
Generates Trigger Request

CAL-LO: Low Energy CAL

Any single CAL channel has energy about 100 MeV.
Active above about 1 GeV

ROI: ACD Veto

TKR && ACD tile in tracker ROI has signal above 0.4 x MIP.

CNO: ACD Heavy Ion (C,N,O)

ACD tile in tracker ROI has signal above 30 x MIP.

Periodic: 2 Hz cyclic
Min. bias instrument sample

Software: FSW trigger
Calibrations & bookkeeping

External:
Really shouldn't happen on orbit

Hardware Trigger Logic

#	EXT	SOL	PER	CNO	CHI	CLO	TKR	ROI	?	Comment
0	1	x	x	x	x	x	x	x	Y	Error
1	0	0	x	x	x	x	0	1	Y	Error
2	0	1	x	x	x	x	x	x	Y	Error
3	0	0	1	x	x	x	x	x	Y	Cyclic
4	0	0	0	1	x	1	1	1	Y	CNO
5	0	0	0	1	x	x	x	x	%250	CNO Veto
6	0	0	0	0	1	x	x	x	Y	CAL HI
7	0	0	0	0	0	x	1	0	Y	TKR &!ROI
8	0	0	0	0	0	1	0	0	Y	Error
9	0	0	0	0	0	1	1	1	Y	Splash?
10	0	0	0	0	0	0	1	1	%50	MIP?

ACD Region of Interest definitions

FSW Onboard Filter

GEM
- Uses only information contained in the Trigger contribution
- Rejects 47% of total events in nominal configuration

CAL
- Calculates the energy in the event before applying cuts
- No cuts currently applied at this stage, High Energy Pass is 2% of total events

ACD
- Checks that ACD information is consistent with the energy in the CAL
- Rejects 9% of total events in the nominal configuration

DIR
- Reassembles event into a form that allows further processing
- At this point can veto events with TEM error events (Though they're leaked)

ATF
- Fast technique to match TKR and ACD information using gross topology
- Rejects 2% of total events in the nominal configuration

TKR
- Full 2D track reconstruction matched to ACD tile hits
- Rejects 7% of total events in the nominal configuration

OBF optimized for speed

GEM

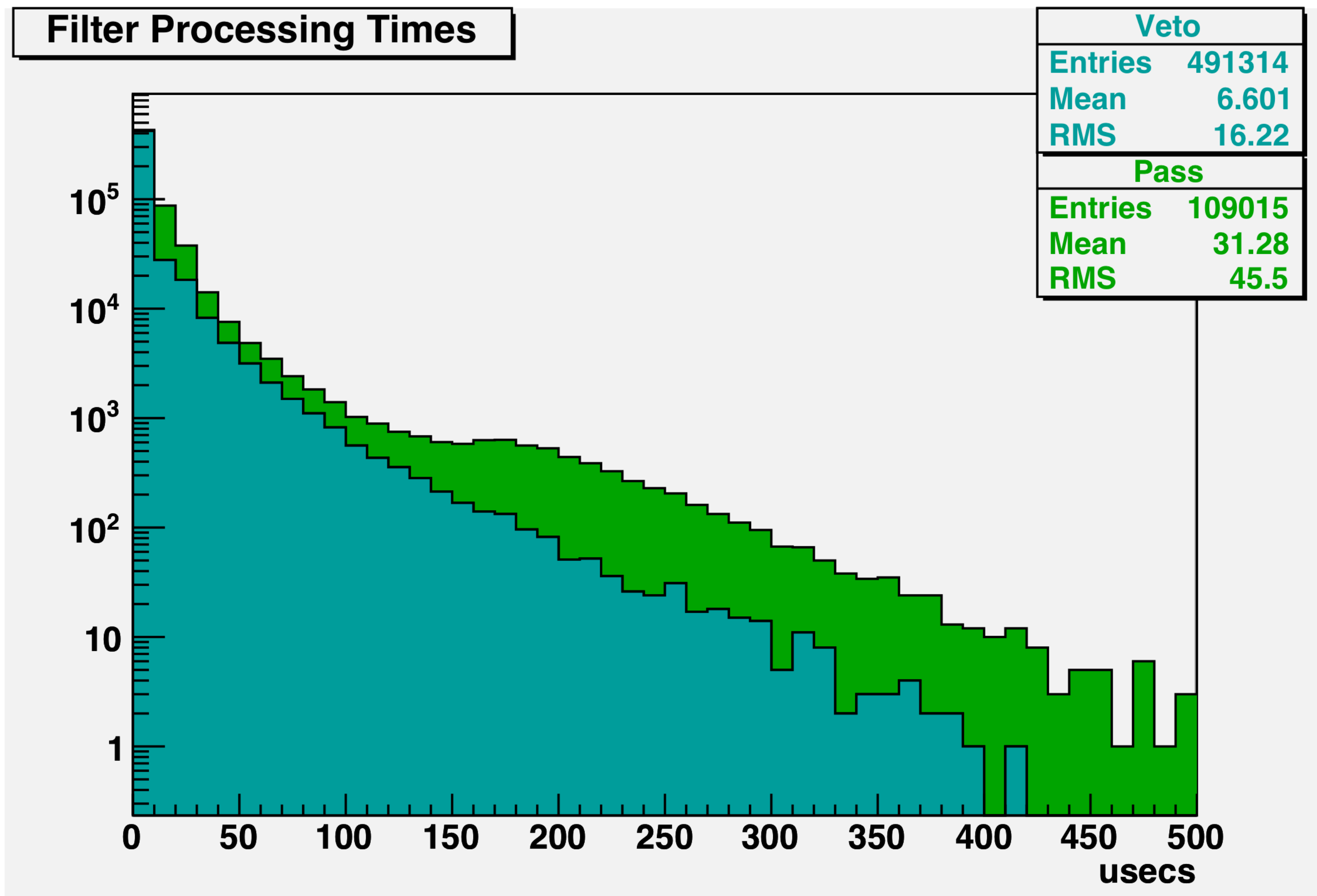
CAL

ACD

DIR

ATF

TKR



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.

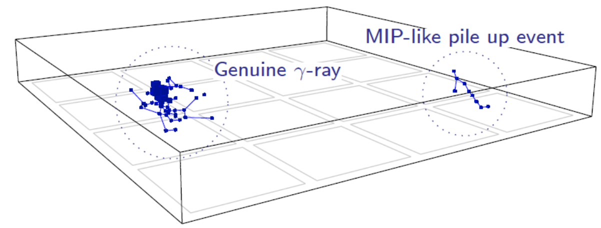
Reconstruction:
Developed with simulated data.
Simulations validated in beamtests.

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

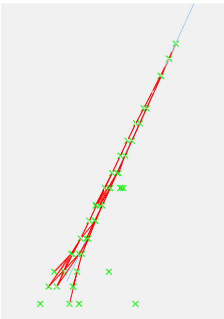
Event Classification:
Developed with simulated + flight data
Validated primarily with flight data

CAL Reconstruction



- Apply per-crystal calibration
- Clustering: group hits into clusters (TBD)
  - Up to now treat whole CAL as single cluster
- Moments analysis
  - Iterative procedure, minimize RMS w.r.t. shower axis
    - Cluster centroid (x,y,z)
    - Cluster axis (v_x,v_y,v_z)
    - Cluster moments and spread
      - Transverse, longitudinal RMS
- Energy Reconstruction (Multiple Methods)
  - Parametric correction for leakage out sides and gaps
  - Fit to cluster profile
  - Likelihood fit for event energy

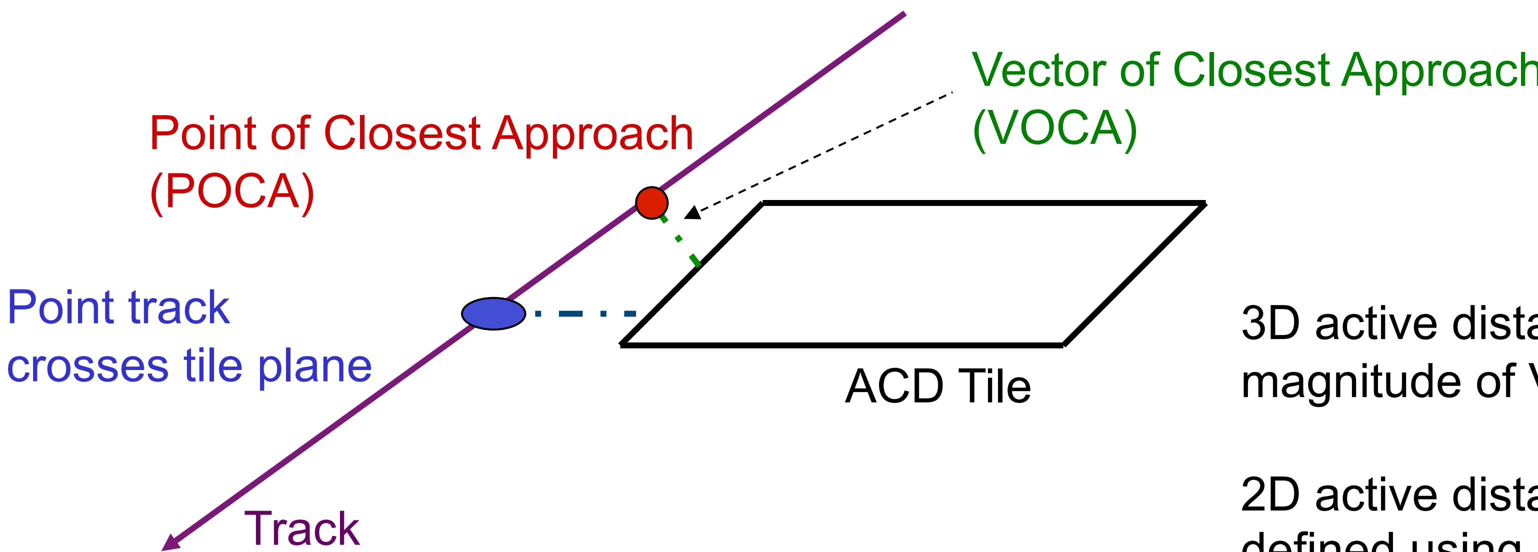
TKR Reconstruction



- Hit clustering
  - combine adjacent hit strips in clusters
- Start with CAL direction, if available
  - useful seed for high energy events, which are complicated
- Combinatoric search for straight(ish) lines
- Propagate lines to next plane, add hits as possible
- Kalman fit/filter technique
  - Combine information (hits) with loss of information (multiple scattering)
    - Requires energy estimate to handle multiple scattering
- Order tracks by “quality”
  - Favor longest, straightest track
    - Most likely to come from event origin
- Vertexing: try to combine 2 best tracks into single item

ACD Reconstruction

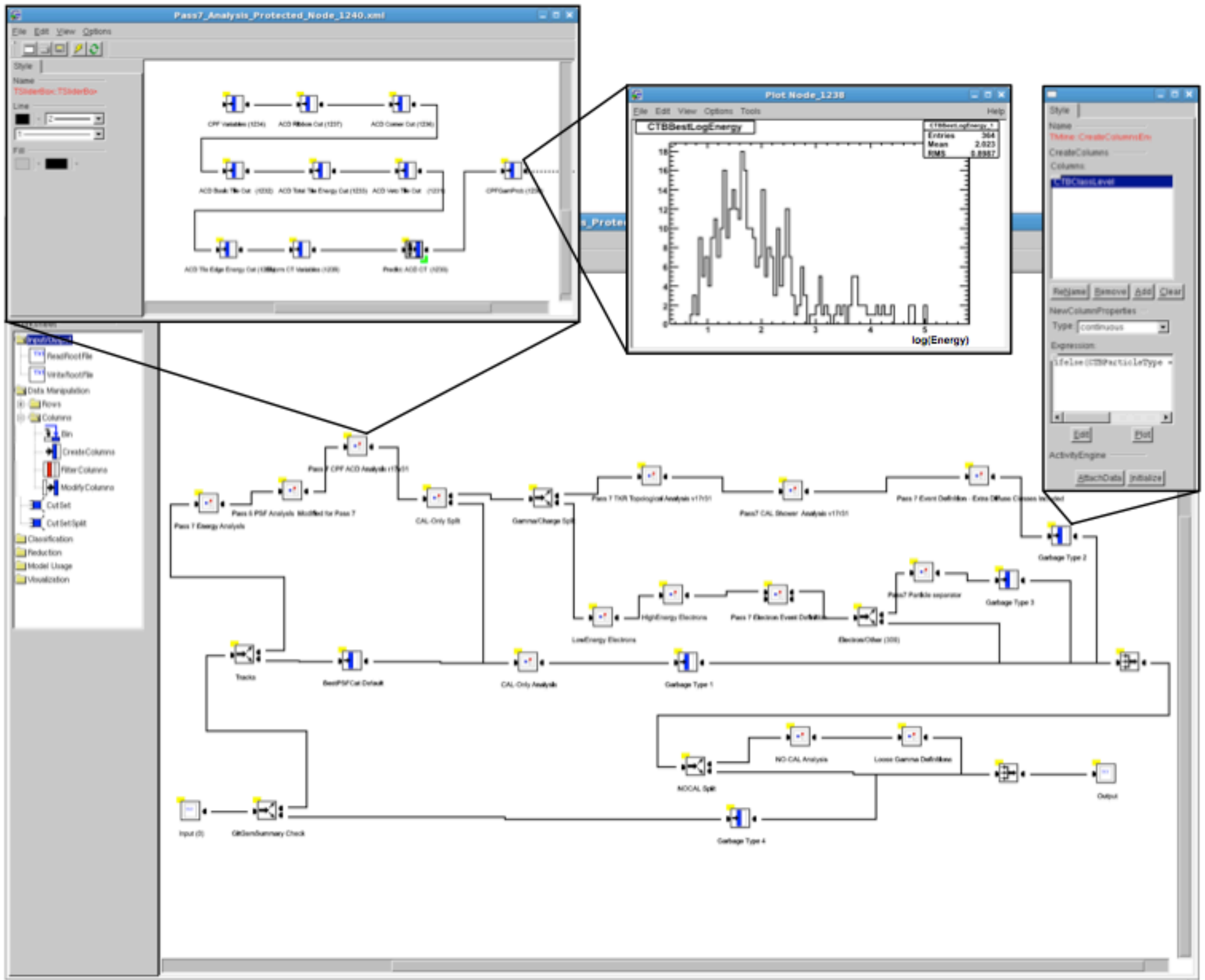
- **Apply tile calibrations**
- **Look for reason to veto event**
  - **Track extrapolation to ACD hit?**
  - **Compare ACD energy to CAL energy**
    - **Catches events where TKR direction is bad**



3D active distance is magnitude of VOCA

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

Event Level Analysis



Complex multivariate analysis

Uses Classification Trees (CT) in conjunction with cuts

30+ individual cuts, in addition to CTs

Broken into many sub-sections

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."

Data Processing Pipeline

Deliveries/Runs processing status

Delivery		FASTCopy		HalfPipe	Runs				L1Proc				GRB Search
Id	Time (UTC)	Proc	Logs	Proc	Id - Start MET	Status	Intent		Proc	Status	Logs	Data Mon	Proc
90610007	Jun/10/2009 13:20:37		3										
90610006	Jun/10/2009 10:07:08		2 15		266315949	InProgress	nomSciOps			Running	101 299	Di | Me | Cal	
					266309972 R	InProgress	nomSciOps			InProgress	2 4109	FM | Di | Re | Me | Cal	
90610005	Jun/10/2009 08:47:52		6 15		266309972 R	InProgress	nomSciOps			InProgress			
					266303988 R	Complete	nomSciOps			Running			
90610004	Jun/10/2009 07:16:51		19		266303988 R	Complete	nomSciOps			Running	223 2 1 3885	FM | Di | Re | Me | Cal	
					266297989	Complete	nomSciOps			Running	606	FM | Di | Cal	
					266291944	Complete	nomSciOps			Running	4 378	Di | Cal	

GRB Alerts

Trigger Time		GRB		Processing		Data
UTC	MET	Name	Notice	Prompt	Afterglow	
Jun/10/2009 07:54:28	266313268	GRB090610329	SWIFT			266309972

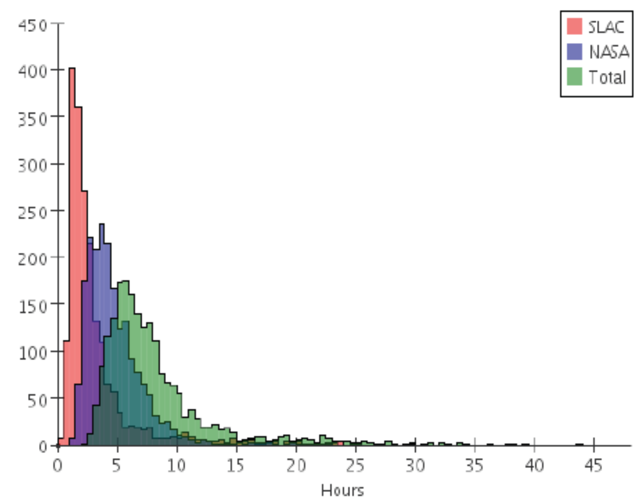
ASP Sky Monitor Process

Processing (UTC)	PGWave	DRP	Data	Data Start (UTC)	Frequency
Jun/10/2009 03:30:42			Pgwave Drp	Jun/09/2009 18:00:00	six_hours
Jun/10/2009 01:58:26			Pgwave Drp	Jun/09/2009 00:00:00	daily
Jun/09/2009 23:29:49			Pgwave Drp	Jun/09/2009 12:00:00	six_hours
Jun/09/2009 17:04:47			Pgwave Drp	Jun/03/2009 00:00:00	weekly
Jun/09/2009 14:40:35			Pgwave Drp	Jun/09/2009 06:00:00	six_hours
Jun/09/2009 06:59:22			Pgwave Drp	Jun/09/2009 00:00:00	six_hours
Jun/08/2009 21:20:28			Pgwave Drp	Jun/08/2009 18:00:00	six_hours
Jun/08/2009 19:48:25			Pgwave Drp	Jun/08/2009 00:00:00	daily

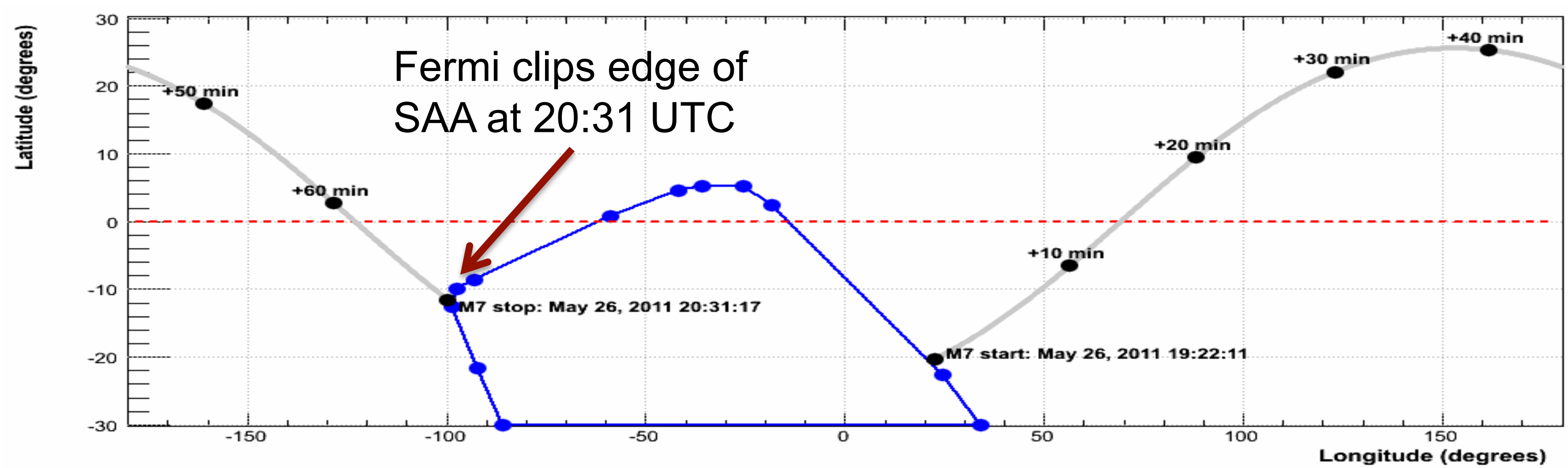
We require 150-200 cores processing full time to keep up with data

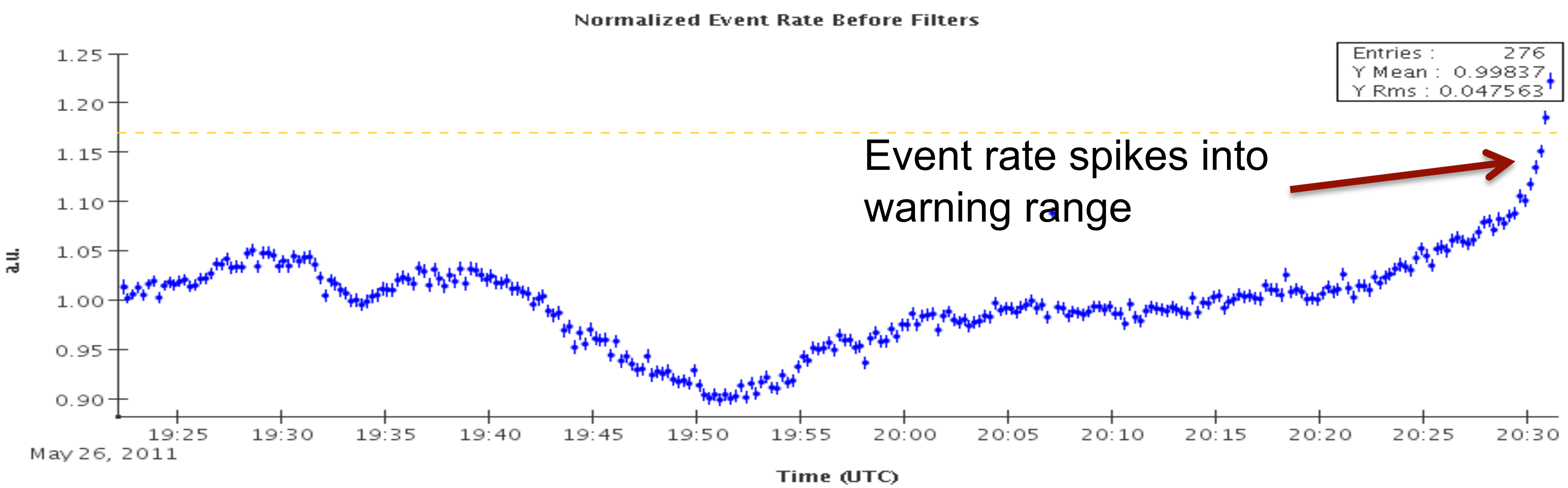
Done in a pipeline which does all the bookkeeping

Pipeline also does routine science analysis and GRB searches

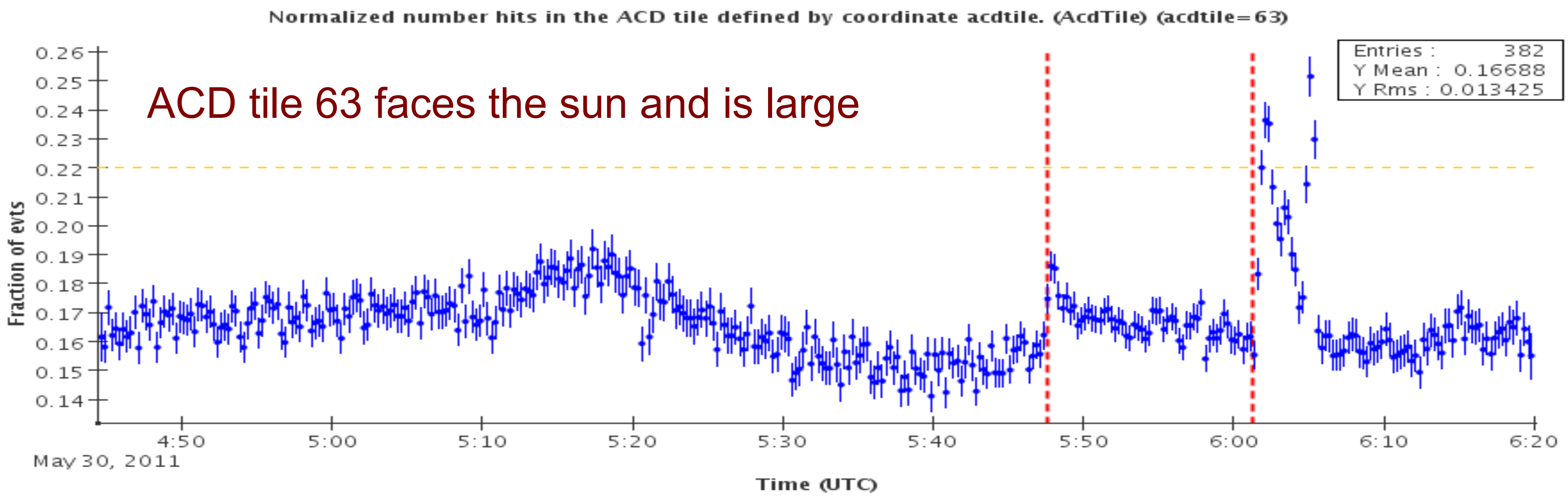


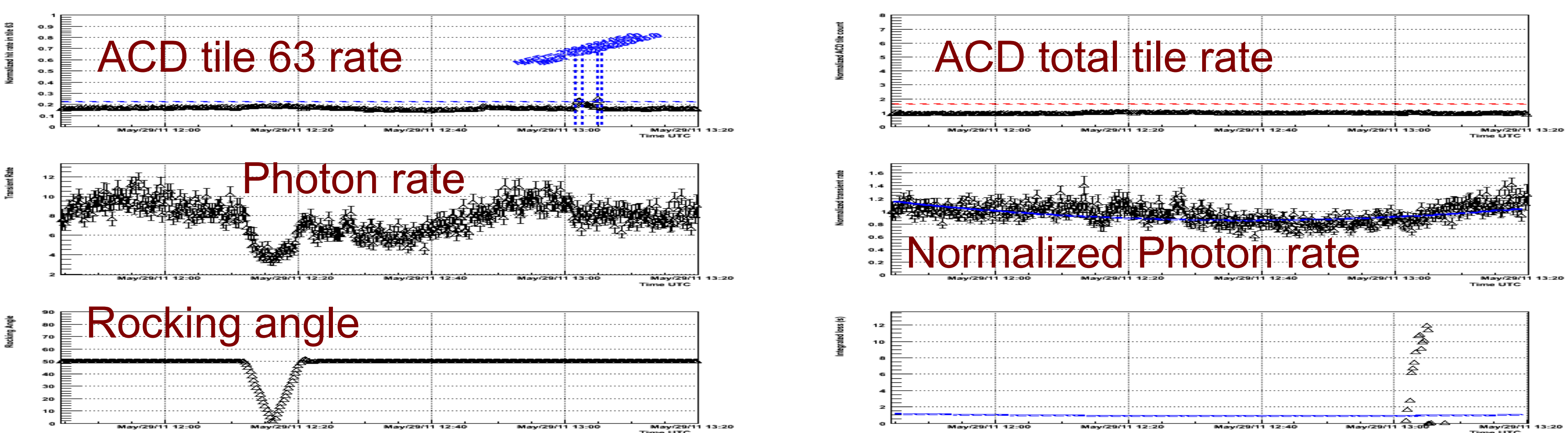
Data Monitoring: Rates & Orbit





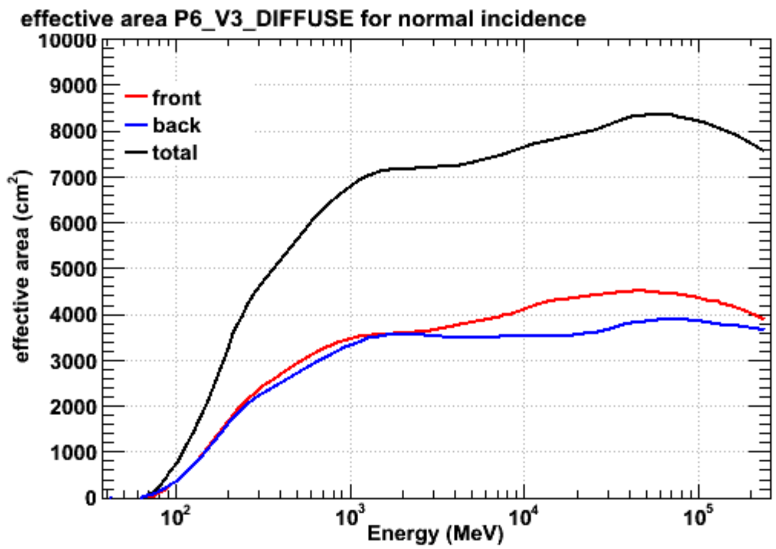
Data Monitoring: Solar Flare

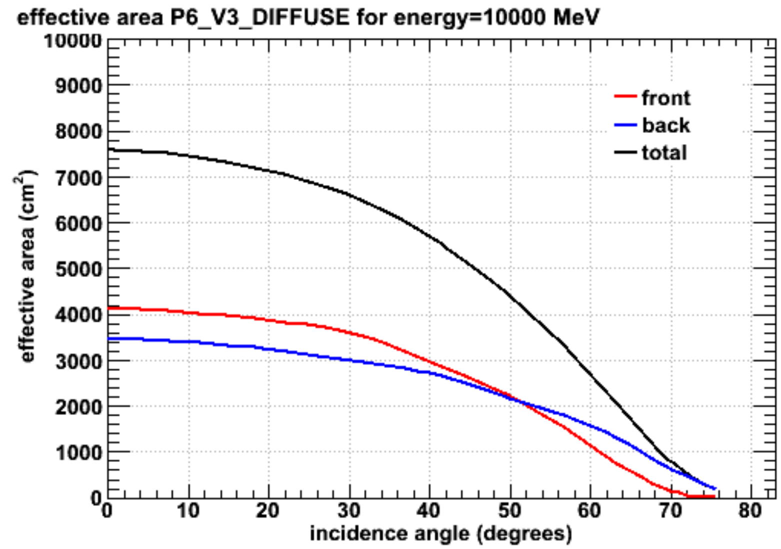




IRFs and ScienceTools

Effective Area (A_{eff})





< 100 MeV limited by 3-in a row requirement

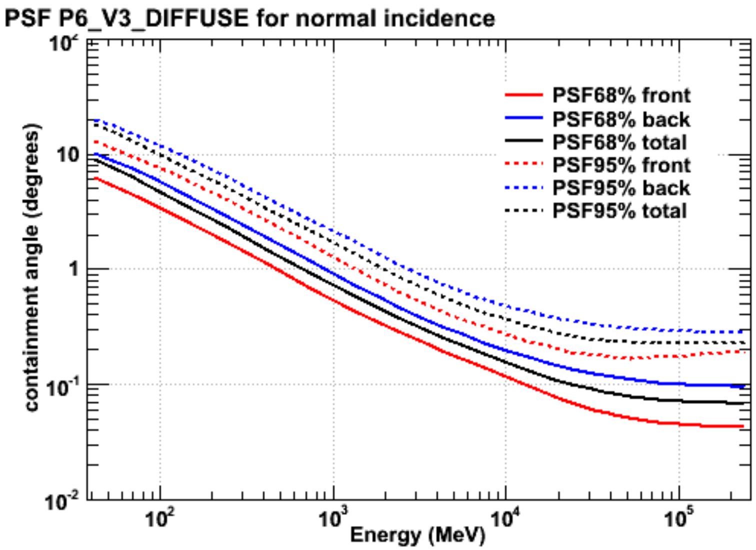
< 1 GeV limited discriminating information

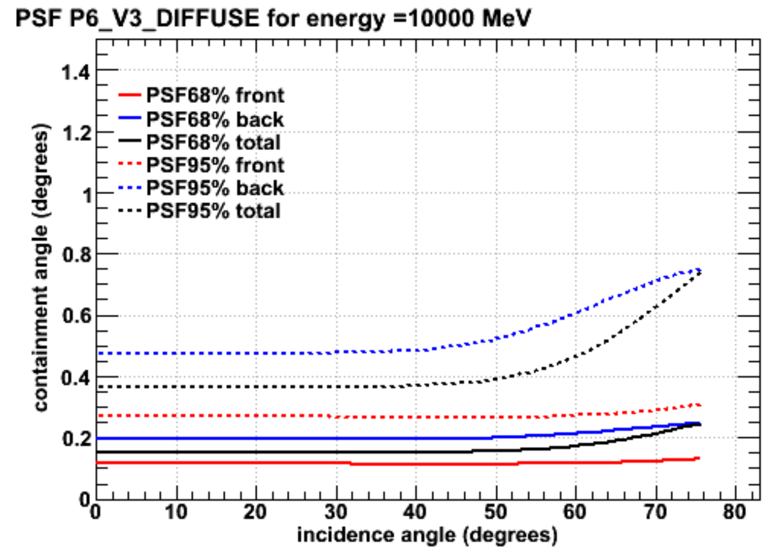
> 100 GeV self-veto from backsplash

Off-axis: more material, less cross section

Shift from front/back events as we go off-axis

Point Spread Function (P)





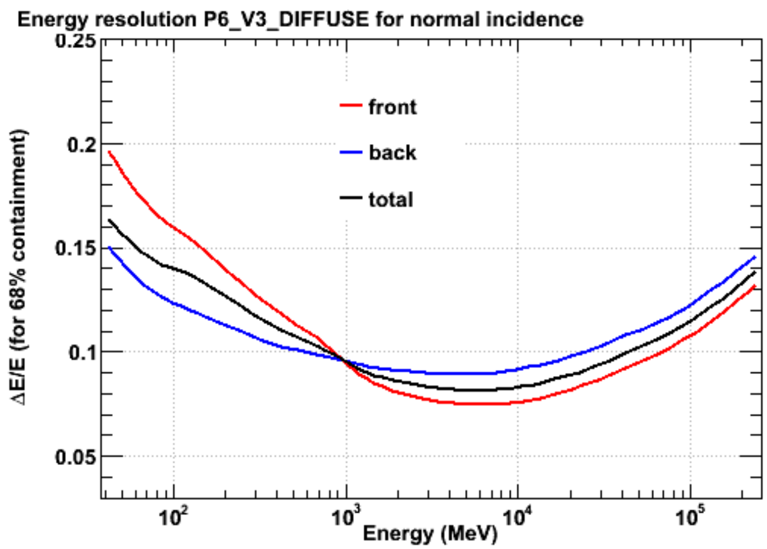
Low energy: dominated by MS

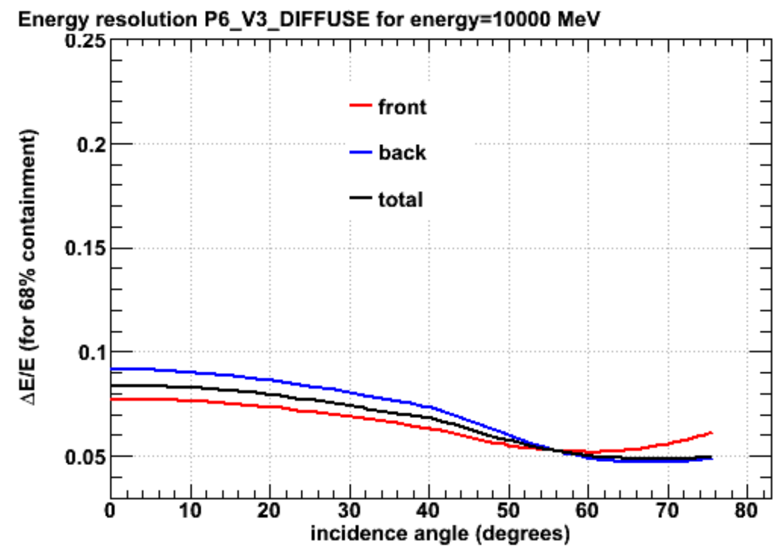
High energy: dominated by strip pitch

Off-axis: more material, more MS at low energy

More pattern recognition confusion off-axis at high energy

Energy Dispersion (D)





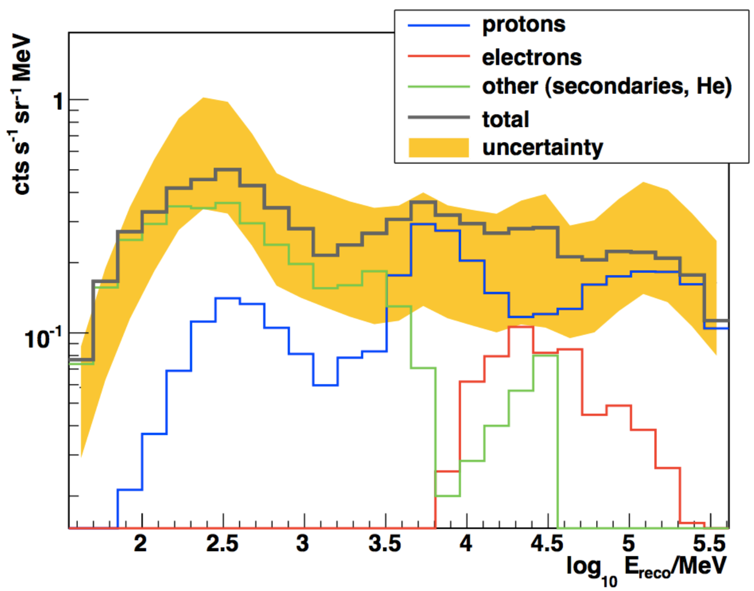
Low energy: energy lost in TKR

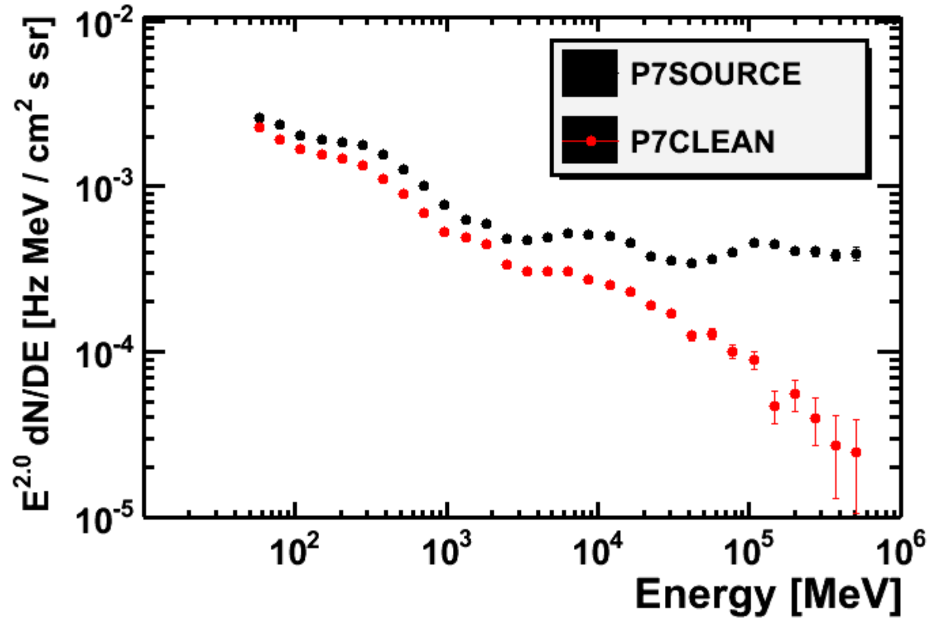
High energy: energy lost out back of CAL

Off-axis: more material, more MS at low energy

More pattern recognition confusion off-axis at high energy

Particle Background Contamination





Estimate particle background leakage from very large MC simulations

Need to generate 10^9 events to have ~few hundred passing cuts

Fit for isotropic component in sky with different event samples

Sky does not change, difference is instrumental

SUMMARY

Talking Points

- **The LAT is a particle physics detector we've shot into space**
  - **We analyze individual events (one photon at a time) with high energy physics techniques to get photon sample**
  - **Lots of hard work to get (RA,DEC,E) behind the curtain**
    - **Challenging, interesting, extremely useful. Great opportunities for experts**
- **Huge variations in response to different types of events**
  - **Bandpass = 4-5 decades in energy (< 20MeV to > 300 GeV)**
  - **Field of View = 2.4 sr (some response up to 70° off-axis)**
    - **Understanding instrumental effects can be very hard**