The Fermi Large Area Telescope

Eric Charles

Fermi Summer School 2013

Lewes, Delaware

May 29, 2013

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
- IRFs and Instrument Performance (Talk Tomorrow)

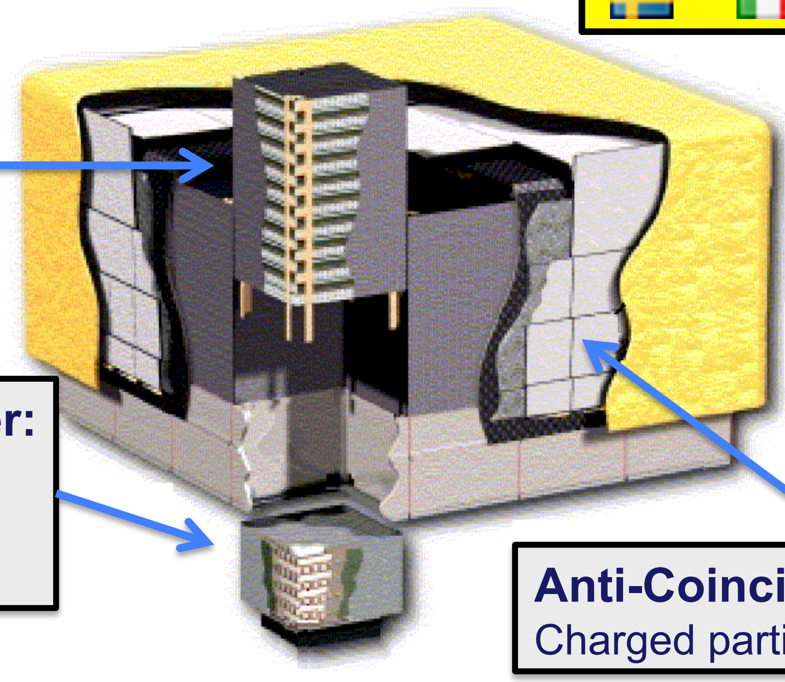
OVERVIEW OF THE LAT &
LAT EVENT PROCESSING

The Fermi Large Area Telescope

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

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International Contributions

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



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

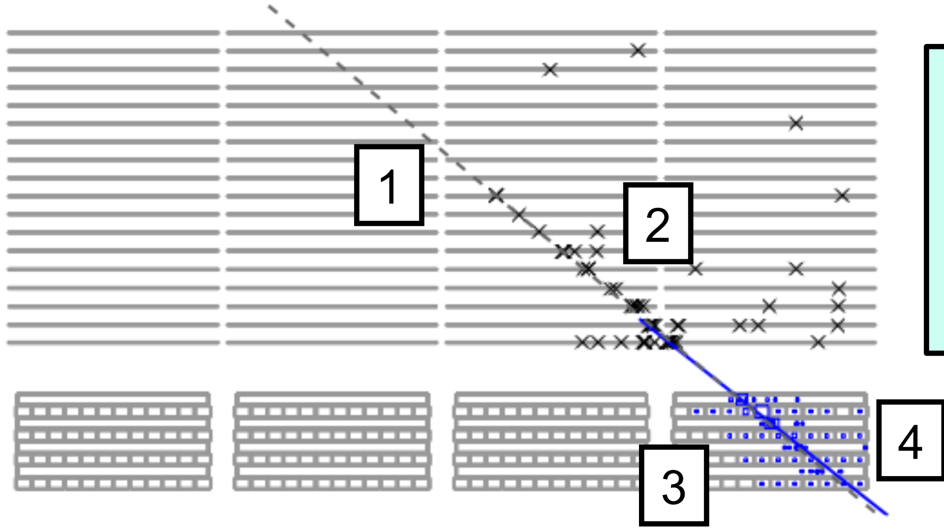
Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
With 2.5 sr Field-of-view LAT sees whole sky every 3 hours

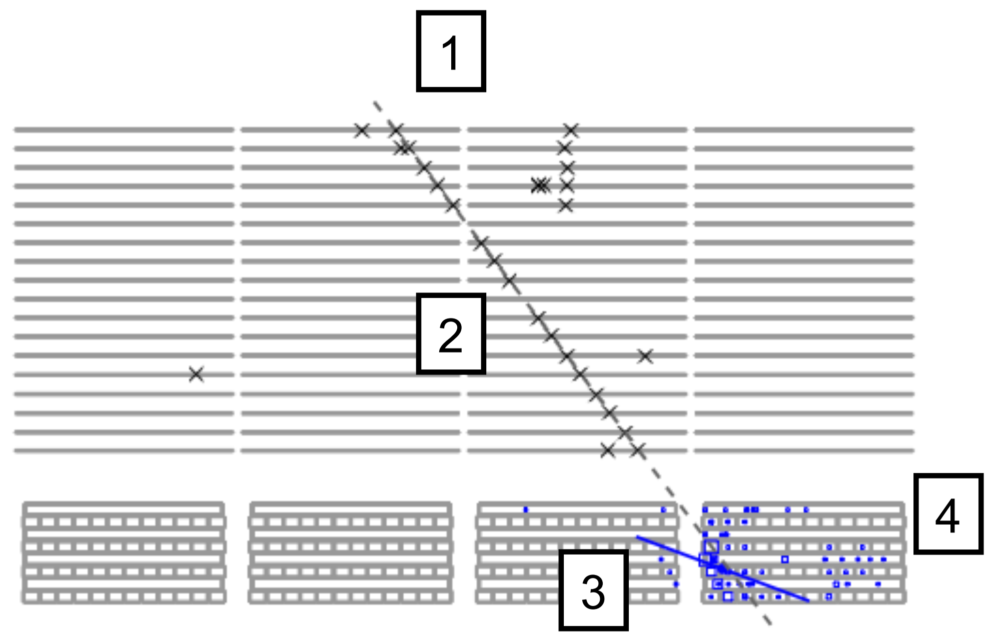
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

The *Fermi* Spacecraft in the Launch Vehicle

LAT Detects Individual γ rays (and Cosmic Rays)

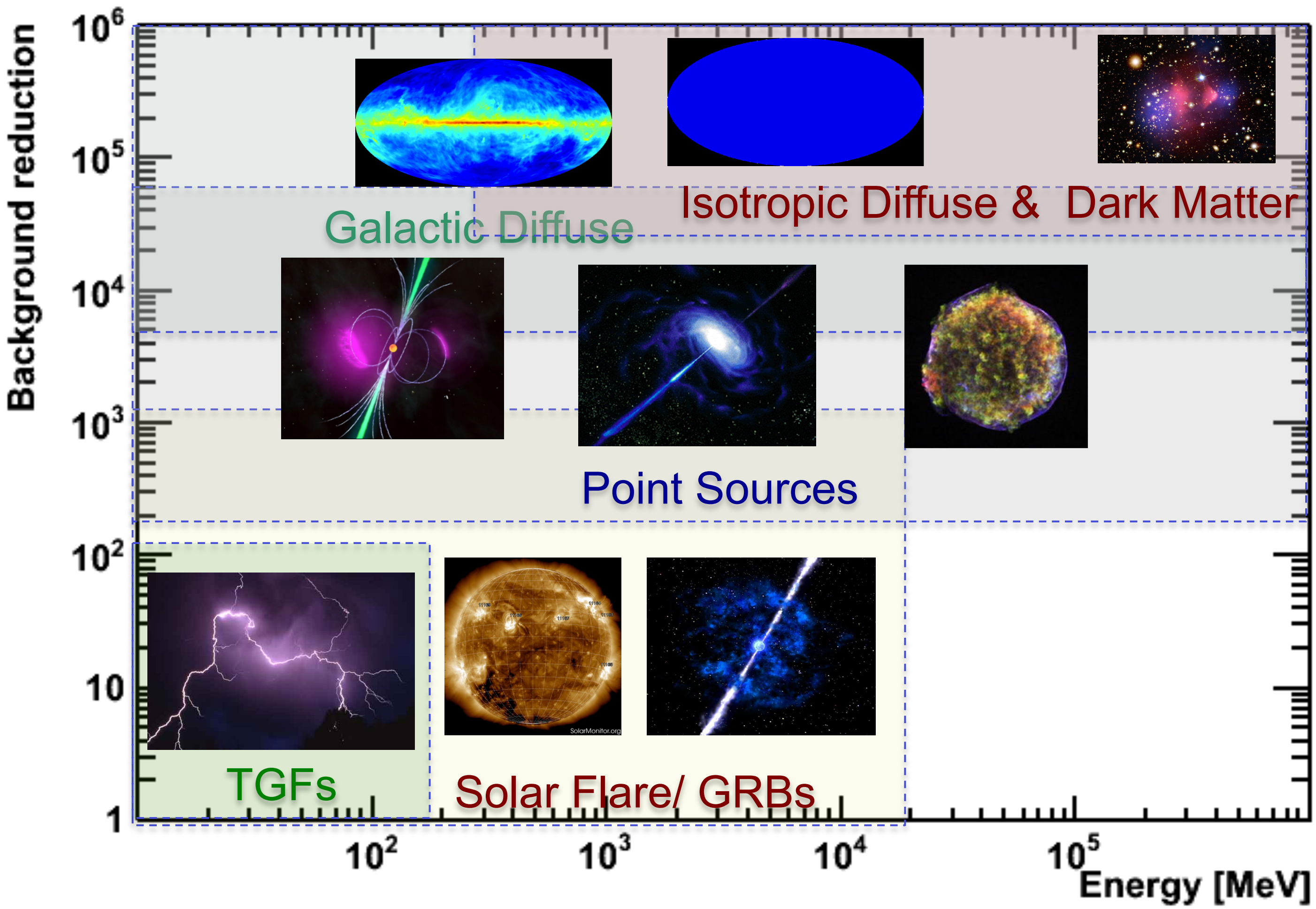


Nearly ideal γ-ray candidate:
1. Starts in middle of TKR
2. Extra hits near track
3. CAL axis aligned with track
4. CAL energy confined near axis



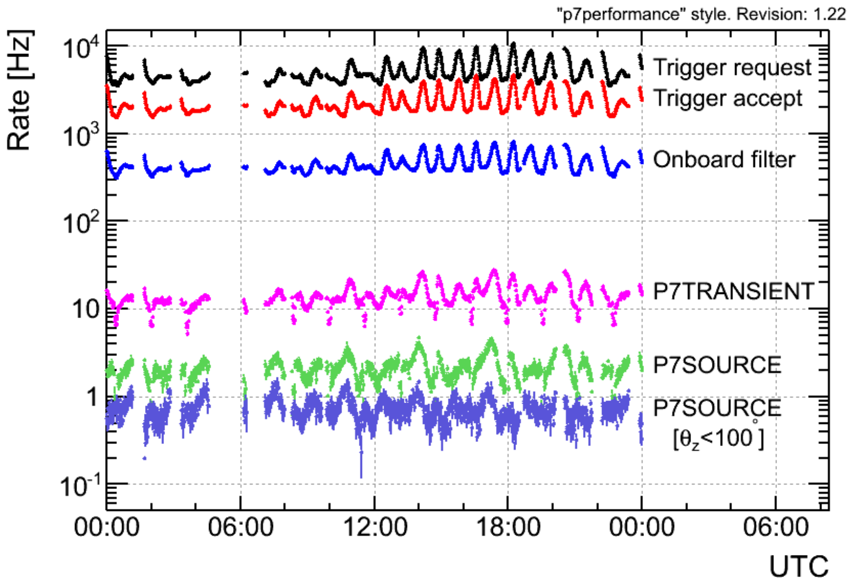
Nearly ideal proton candidate:
1. Starts at top of TKR
2. Few extra hits near track
3. CAL axis not-aligned with track
4. CAL energy “lumpier”
5. Signal in the ACD (not shown)

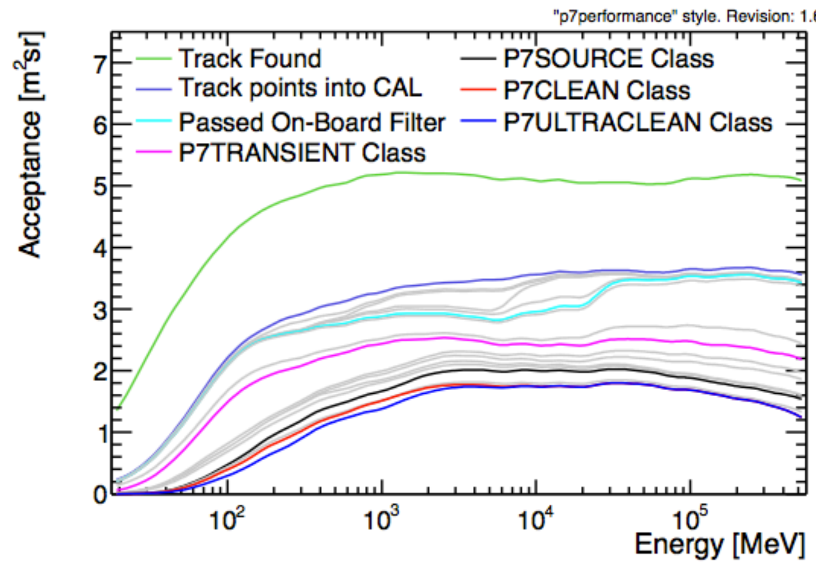
Fermi-LAT Science Covers Huge Phase-Space



Different data selections for different science cases

Particle Rate Reduction





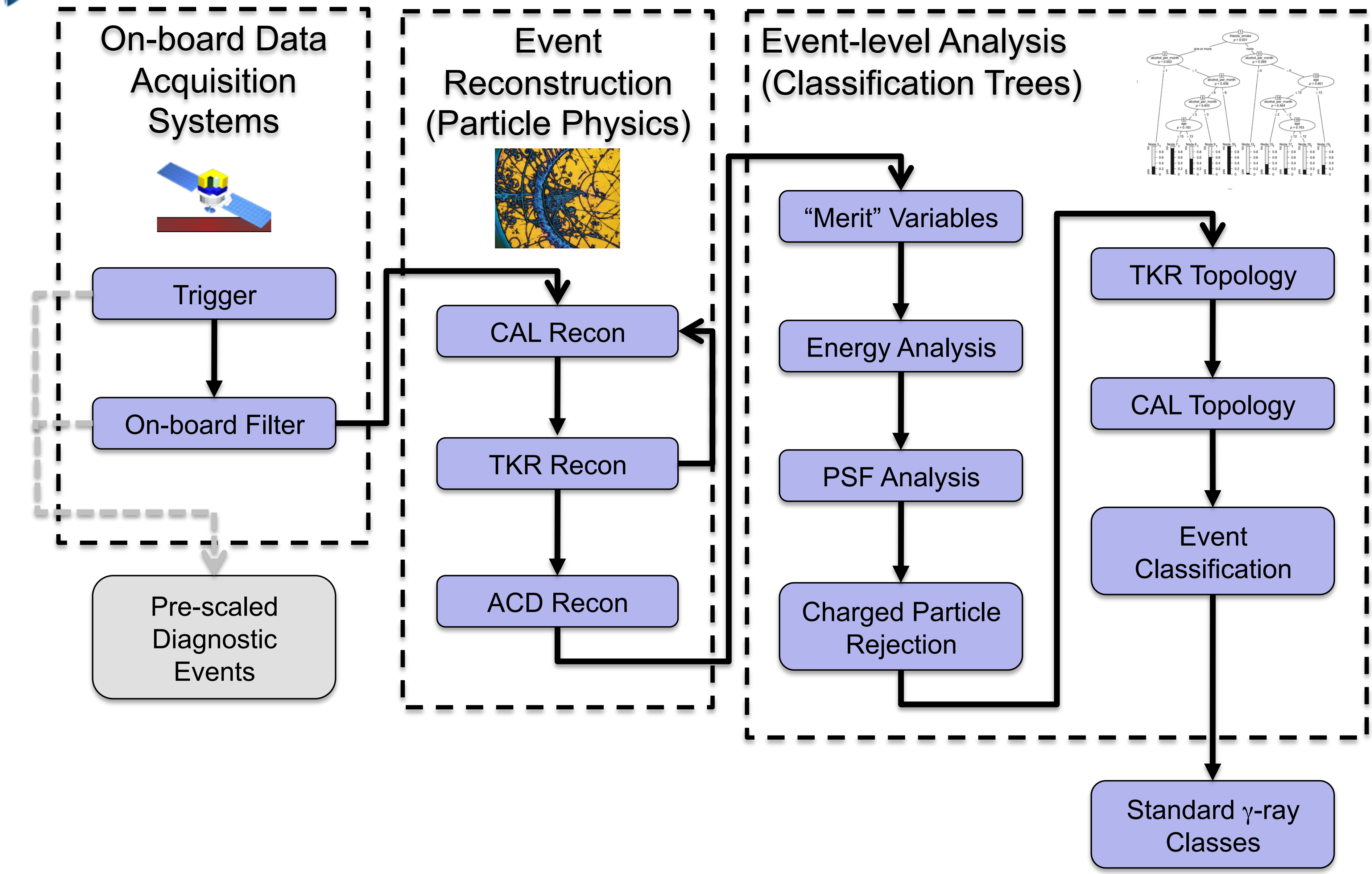
Ackermann et al.: 2012ApJS..203....4A

Factor of > 10^5 in bkg. reduction is achieved in several stages

About 50% γ-ray efficiency inside fiducial volume from 1-100 GeV

Fermi Gamma-ray Space Telescope

Event Analysis



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

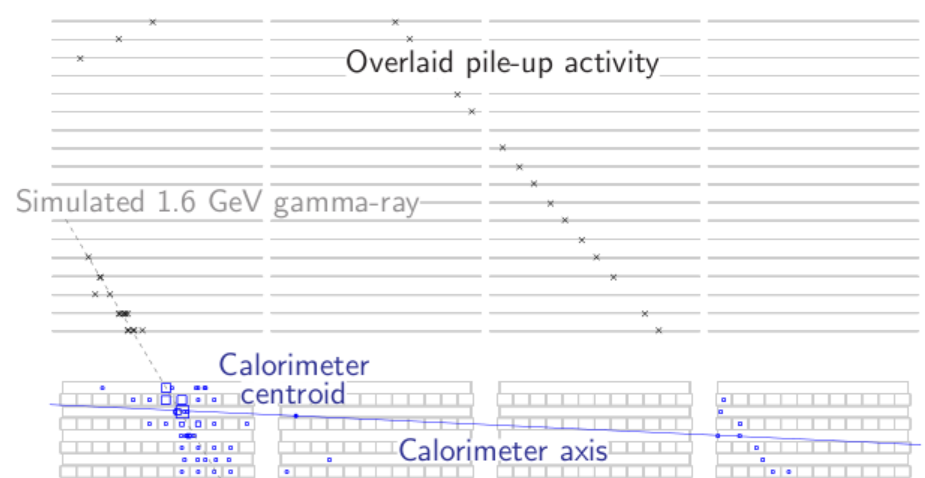
ACD Reconstruction:
Project tracks to ACD, look for reasons to reject event.

Developed with simulated data.
Simulations validated in beamtests.

Only minor changes since launch.
Major rework almost done("Pass 8")

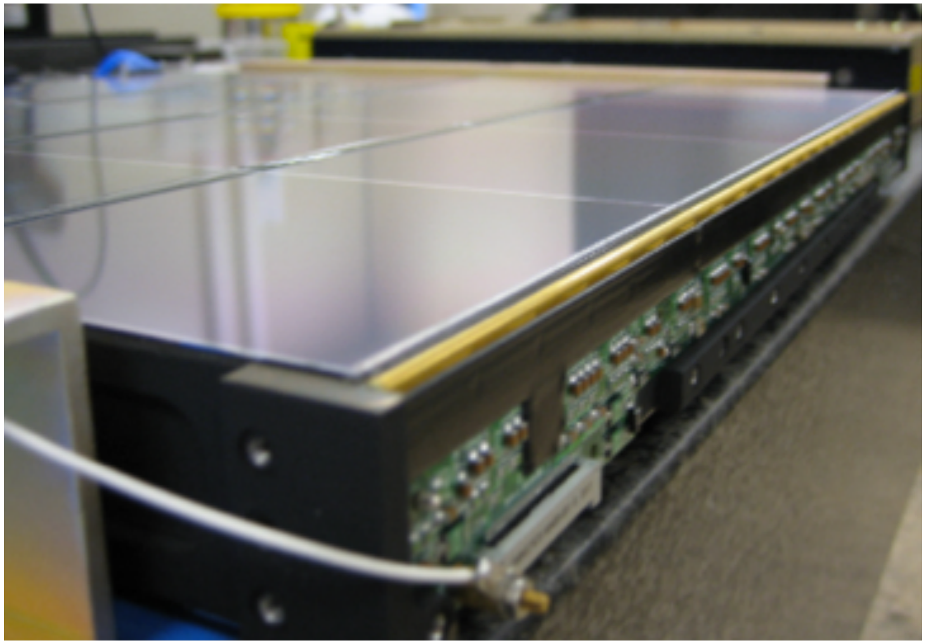
Classification Analysis:
Use combined subsystem information to get best estimates of direction, energy.
Reject particle background and select highest quality events

Reworked post-launch ("Pass 7") to account for effects seen in-flight. Particularly residual cosmic rays signals in the electronics



SILICON TRACKER (TKR)

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

Thickness: 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"

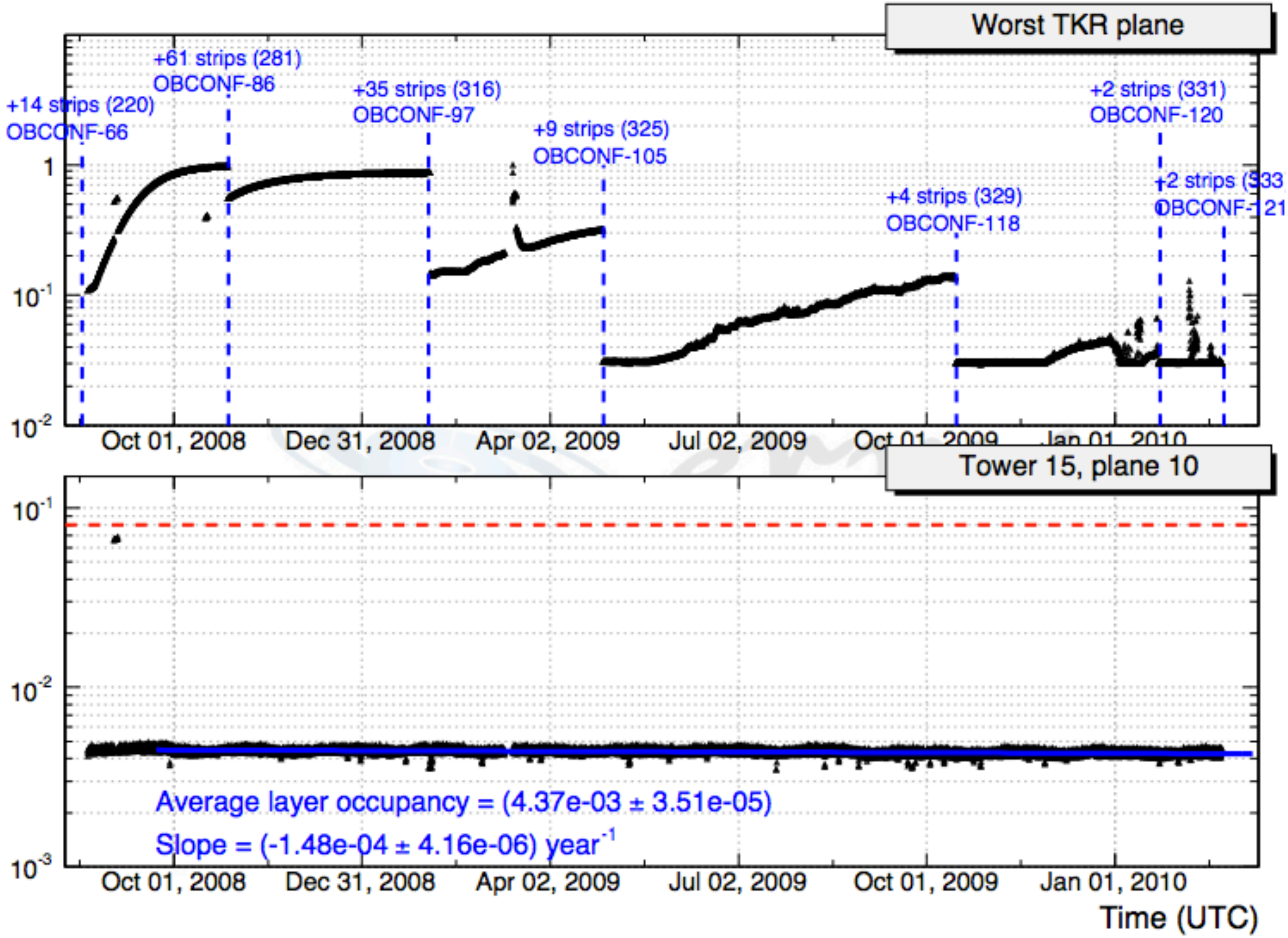
Electronics Calibrations

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

Ground Calibrations

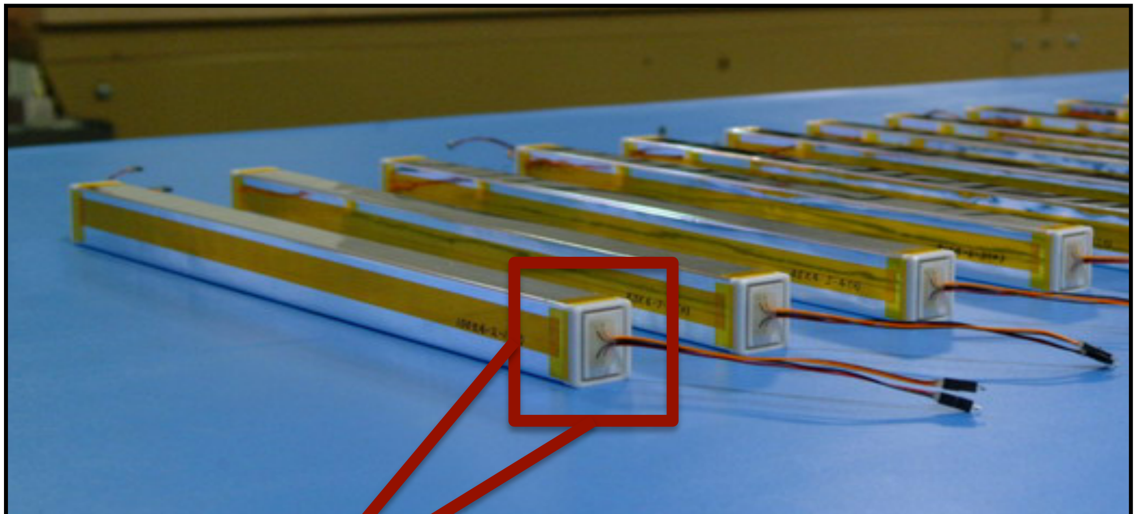
ToT: Convert Time over Threshold (ToT) to MeV equivalent
Module alignment: positional & angular offsets of each Si wafer
LAT-Spacecraft alignment: angular offsets of LAT relative to star trackers

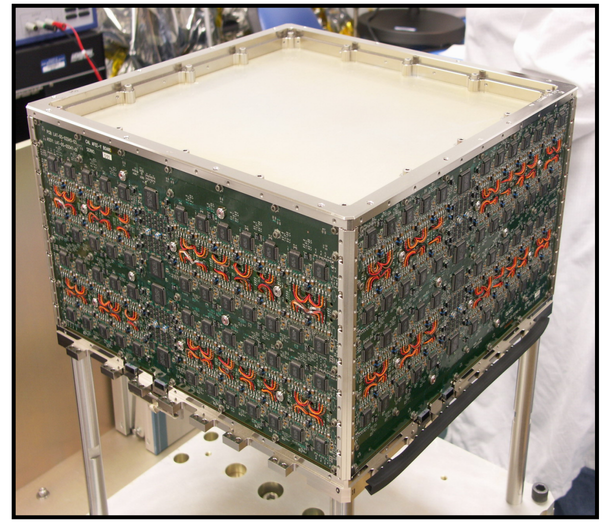
Trending: masking TKR channels

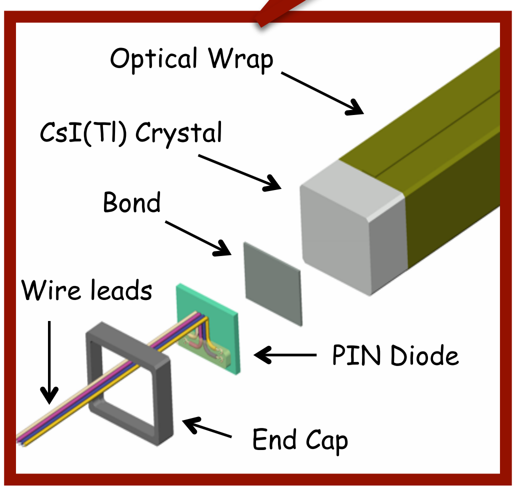


CsI Calorimeter

Images of the CAL







12 * 8 * 16 logs

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

4 readout ranges (2 MeV –70 GeV) for each crystal

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

Ground Calibrations

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

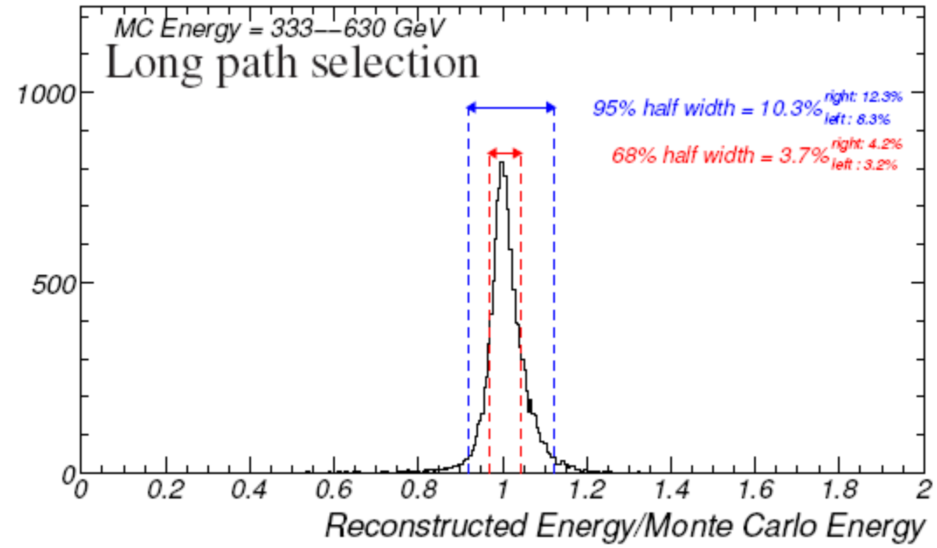
Improving the energy resolution for specific case

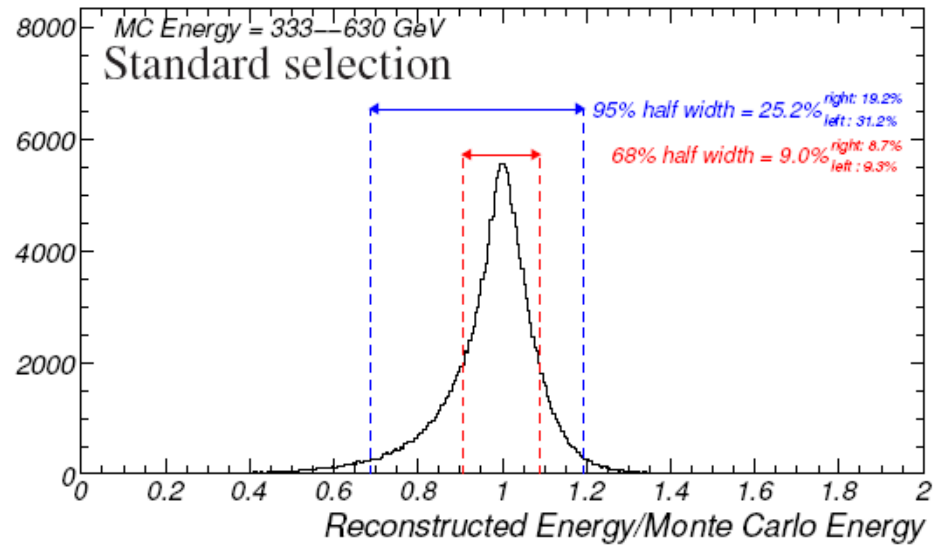
The calorimeter energy resolution improves substantially if catch more of the shower in the CAL

On axis = 8.6 X_0 of material in CAL

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

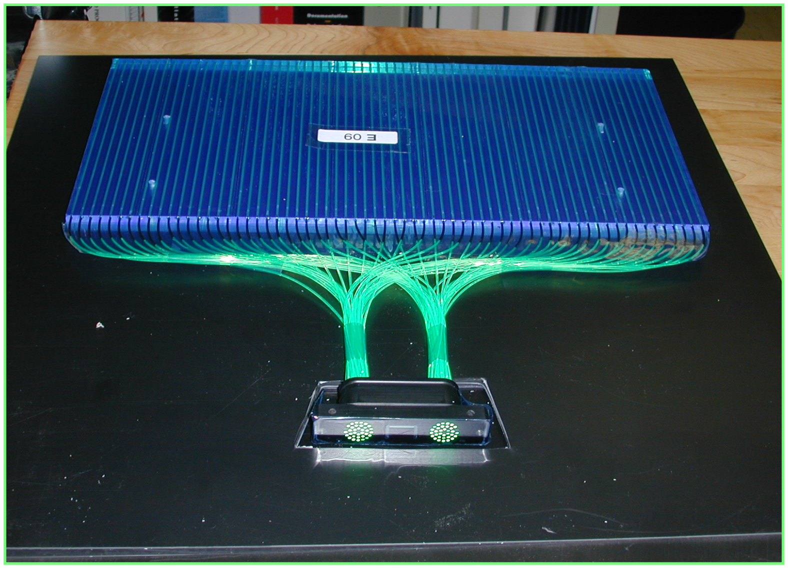
For e^+e^- spectra, much higher statistics, can make special selection of events with long path in CAL





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 photoelectrons)
Ribbons (~3-8 photoelectrons)

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

Ground 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.
Efficient above about 10-30 MeV
Generates Trigger Request

CAL-HI: High Energy CAL

Any single CAL channel has energy about 1 GeV.
Efficient above about 5-10 GeV
Generates Trigger Request

CAL-LO: Low Energy CAL

Any single CAL channel has energy about 100 MeV.
Efficient above about 0.5-1 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	Read?	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?

Match conditions starting from top, x = Don't care

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

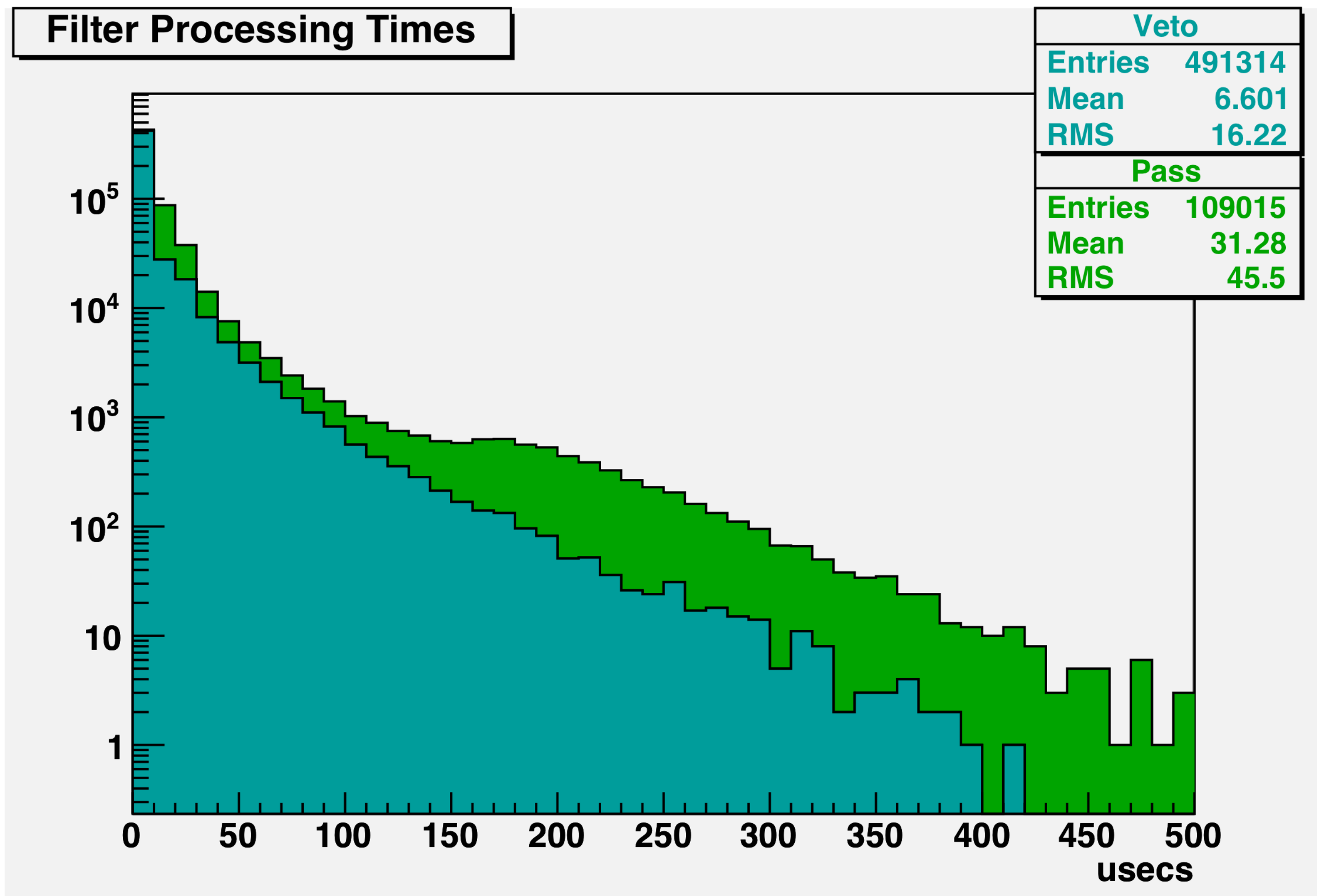
ACD
- Checks that ACD information is consistent with the energy in the CAL
- Rejects 9% of total events in the nominal configuration

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



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.

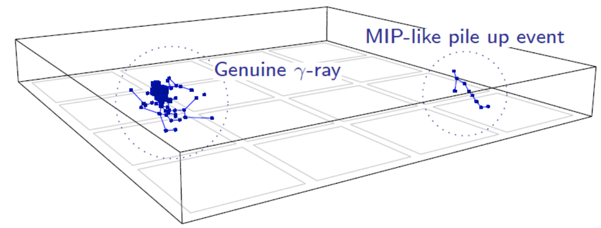
Reconstruction:
Developed with simulated data.
Simulations validated in beamtests.

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

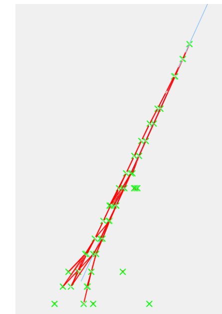
Event Classification:
Developed with simulated + flight data
Validated primarily with flight data

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

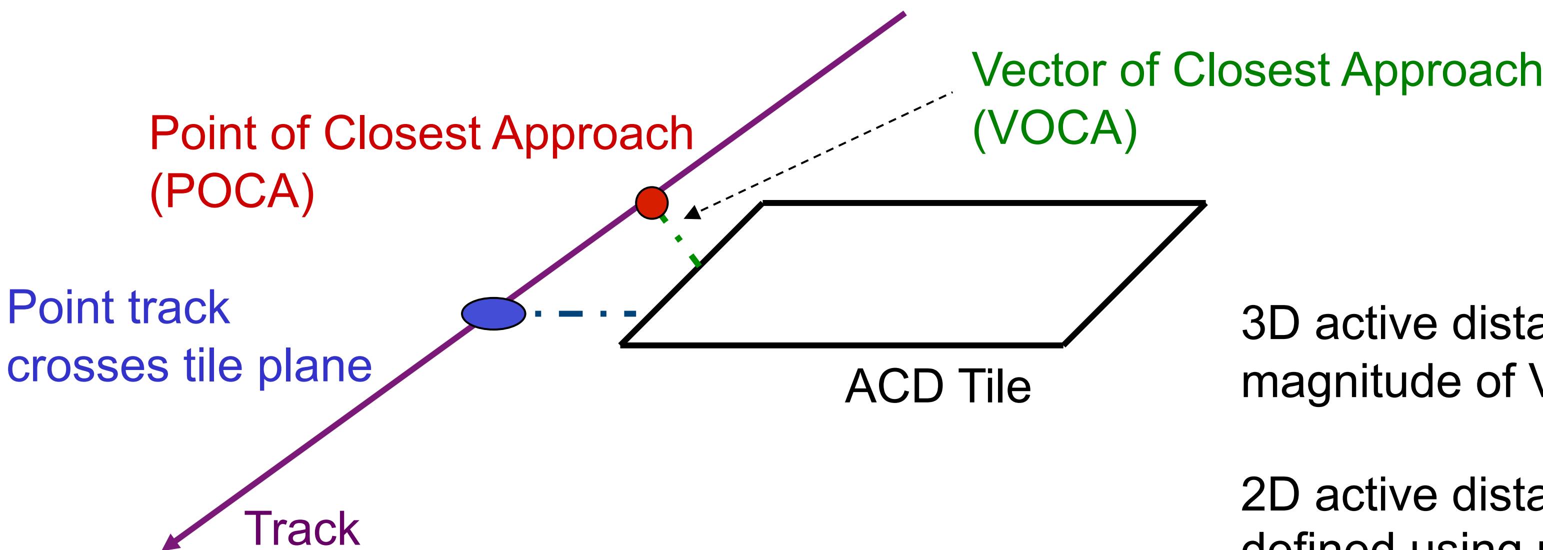
TKR Reconstruction



- 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

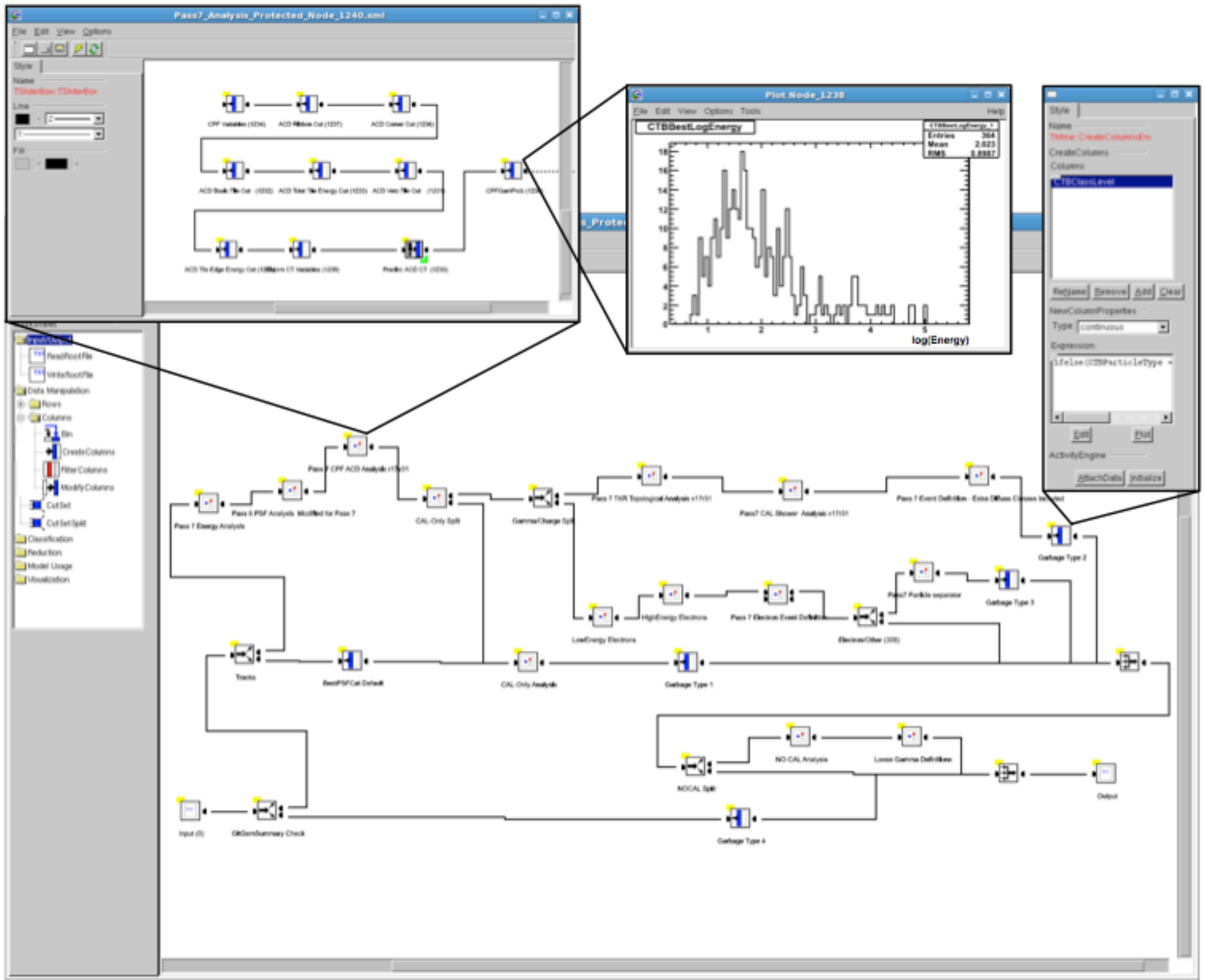
- **Apply tile calibrations**
- **Look for reason to veto event**
  - **Track extrapolation to ACD hit?**
  - **Compare ACD energy to CAL energy**
    - **Catches events where TKR direction is bad**



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

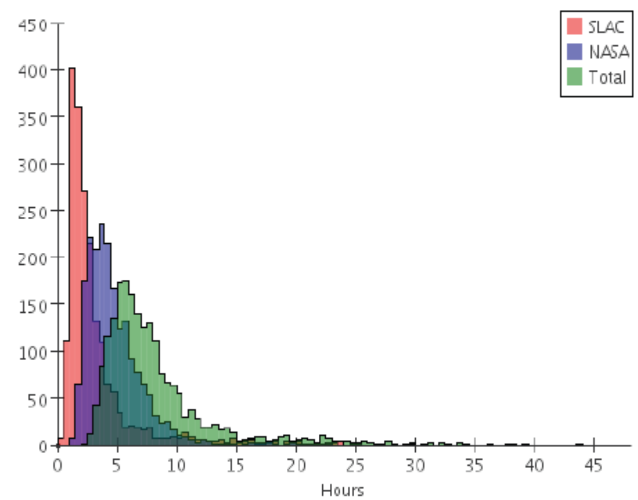
ASP Sky Monitor Process

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

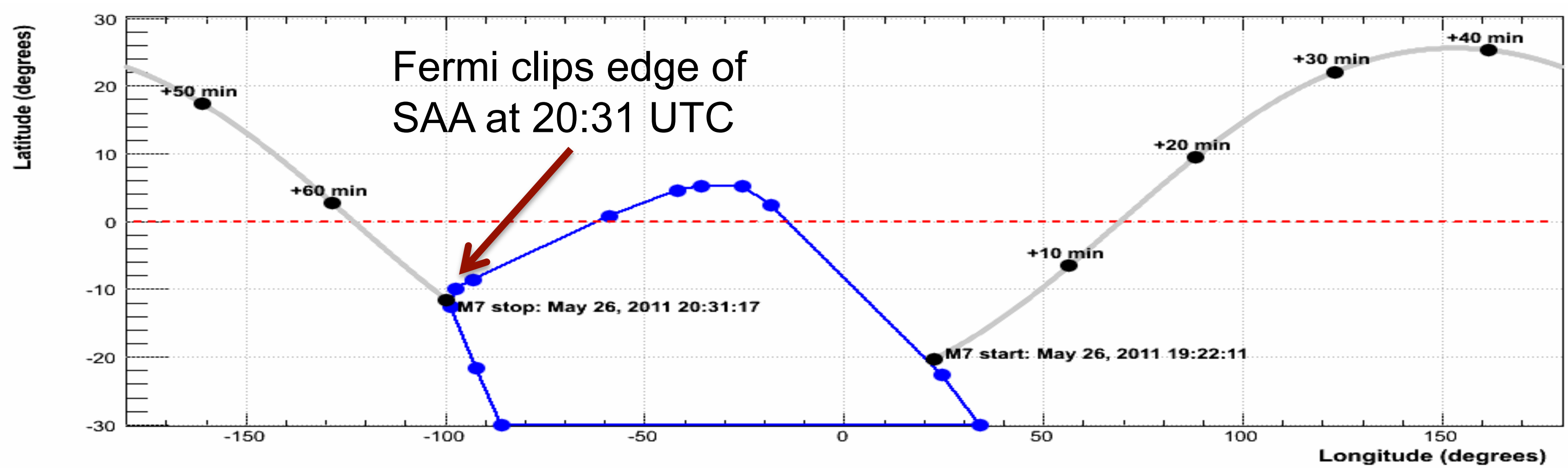
We require 150-200 cores processing full time to keep up with data

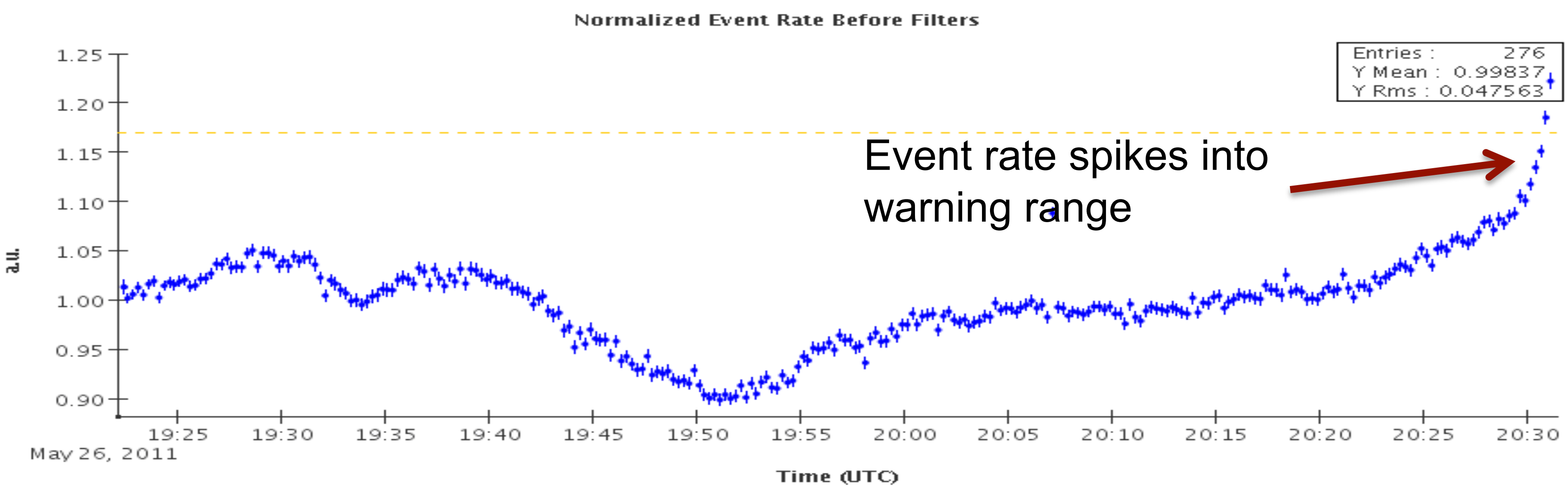
Done in a pipeline which does all the bookkeeping

Pipeline also does routine science analysis and GRB searches

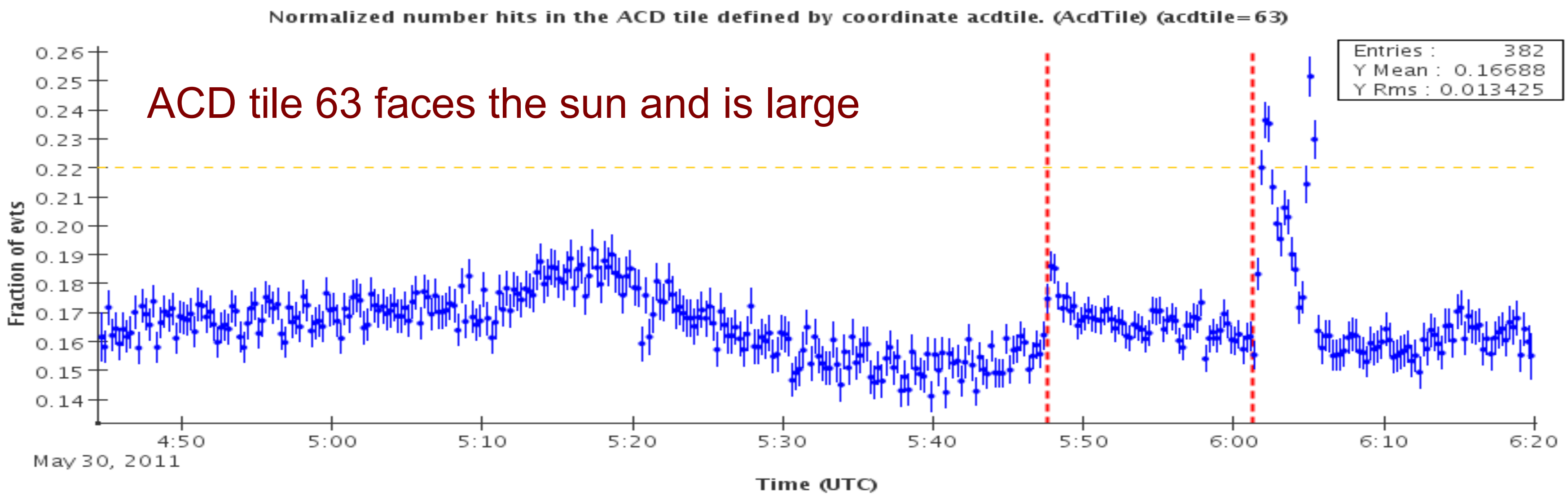


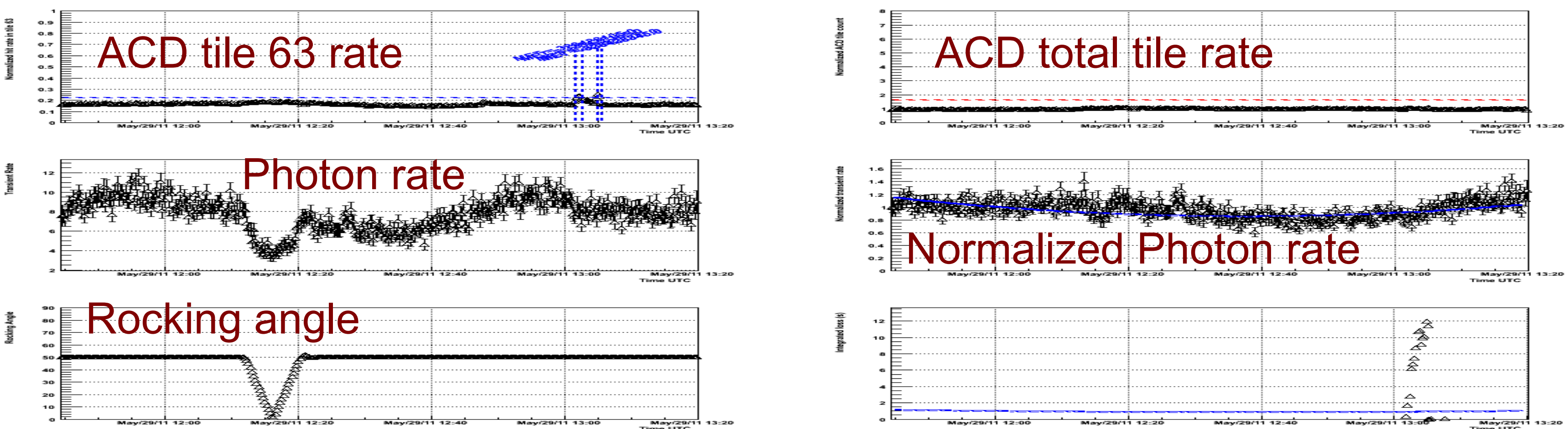
Data Monitoring: Rates & Orbit





Data Monitoring: Solar Flare





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