Validation and Calibration of the Fermi Large Area Telescope Instrument Performance

E Charles and R Rando

on Behalf of the Fermi-LAT Collaboration

Fermi Symposium

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Outline

- Instrument and Event Analysis
- Instrument Response Functions
  - Effective Area (A_{eff})
    - Simulation based A_{eff}, in-flight validation, corrections, error estimates, propagation to science analysis
  - Point Spread Function (PSF)
    - Simulation based PSF, in-flight validation, in-flight PSF, error estimates, propagation to science analysis
  - Energy Dispersion (E_{disp})
    - Simulation based E_{disp}, data validation, effect of ignoring E_{disp} in likelihood fitting
  - Particle Background Contamination
    - Not really an IRF...
- Caveats and Summary
- References and Additional Information

INSTRUMENT AND EVENT ANALYSIS

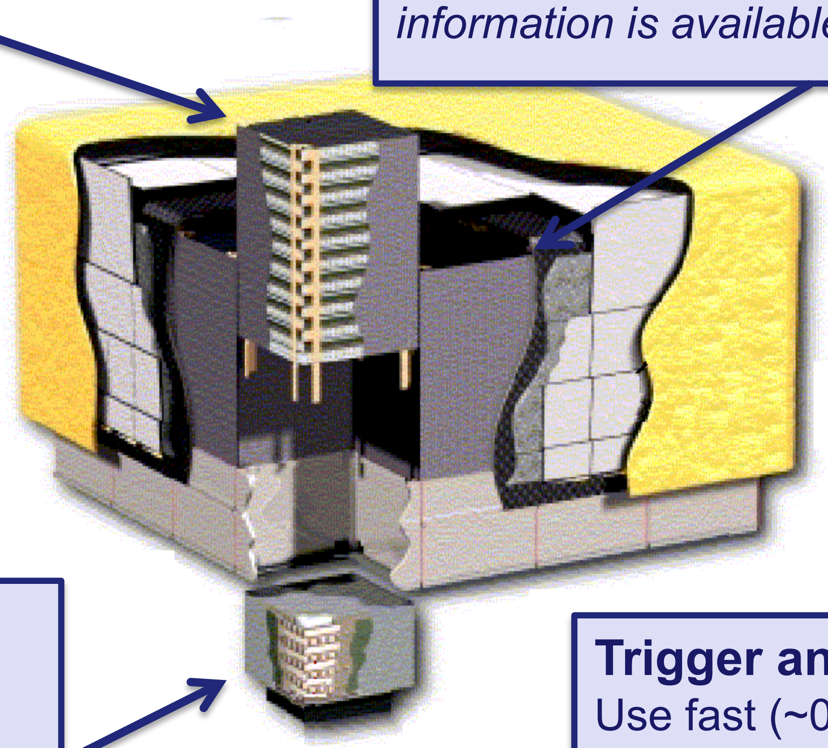
Salient Features of the LAT

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

$PSF_{back} \sim 2x\ PSF_{front}$

Many EM showers start in TKR

Anti-Coincidence Detector (ACD)
Segmented:
less self-veto *when good direction information is available*

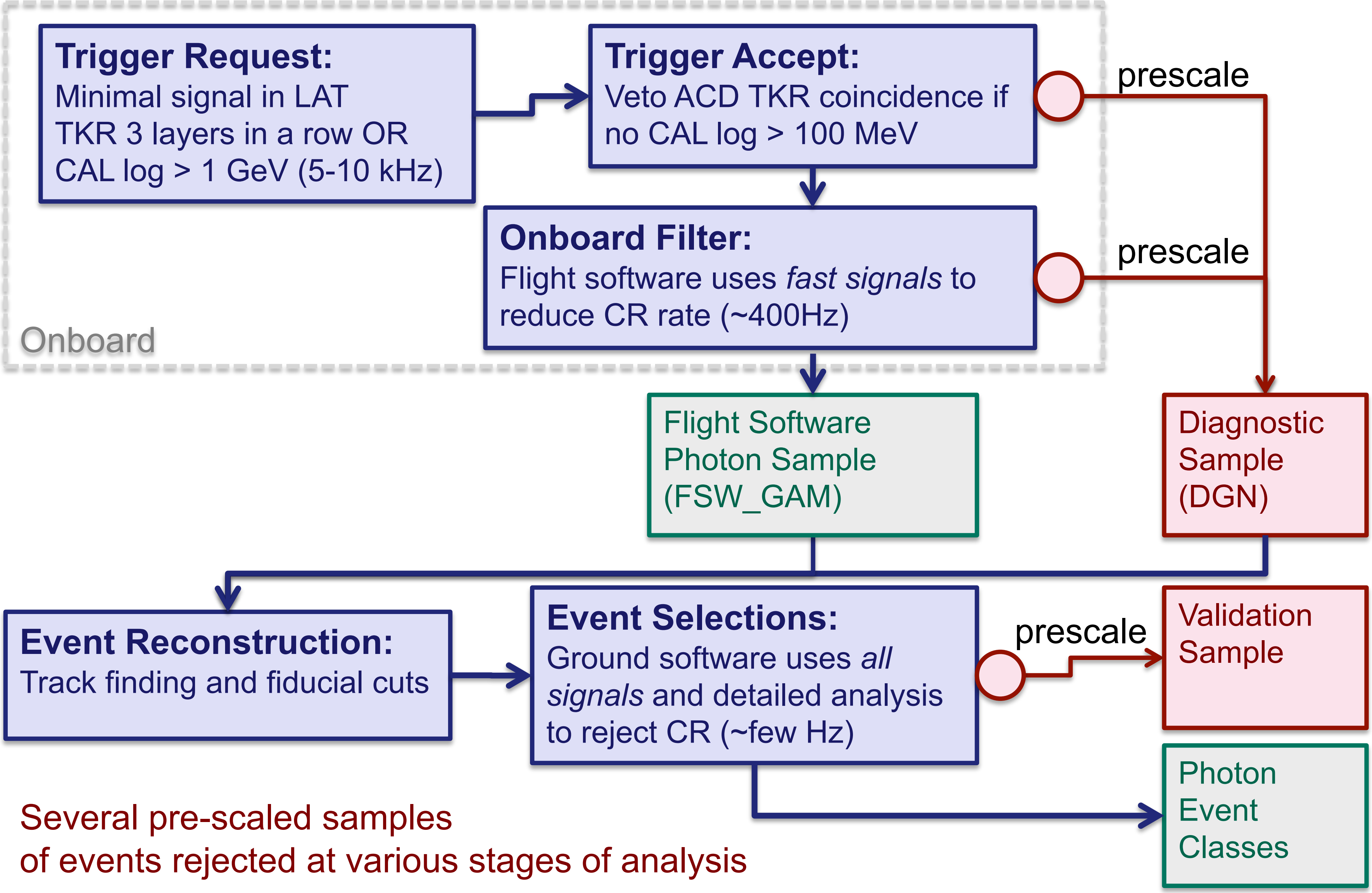


Calorimeter (CAL):
8 layers (8.6 X_o on axis)

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

Overview of the Photon Selection Process



Several pre-scaled samples
of events rejected at various stages of 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.

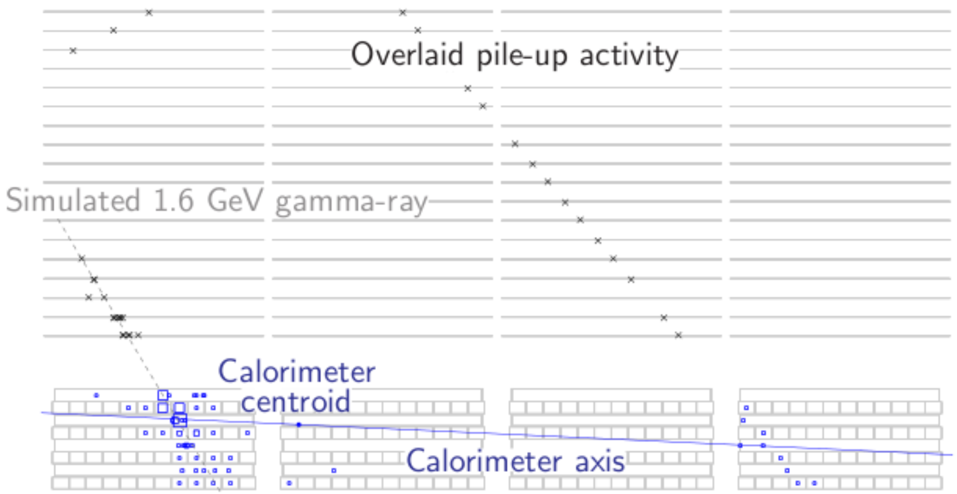
Developed with simulated data.
Simulations validated in beamtests.

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

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

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

Poster: INSTR S2.N1
Ackerman, Atwood, Rando



Event Selections and IRF sets

IRF Set	Details	Public Release Date
P6_V1_[CLASS]	Pre-launch. Simulations validated with beamtests	Superseded before data release
P6_V3_[CLASS]	Post-launch, includes overlays[3]	August 2009
P6_V11_[CLASS]	Includes in flight corrections	May 2011
P7[CLASS]_V6	Pass 7 Event Analysis [4] Includes in flight corrections	(Expected) July 2011

Focus

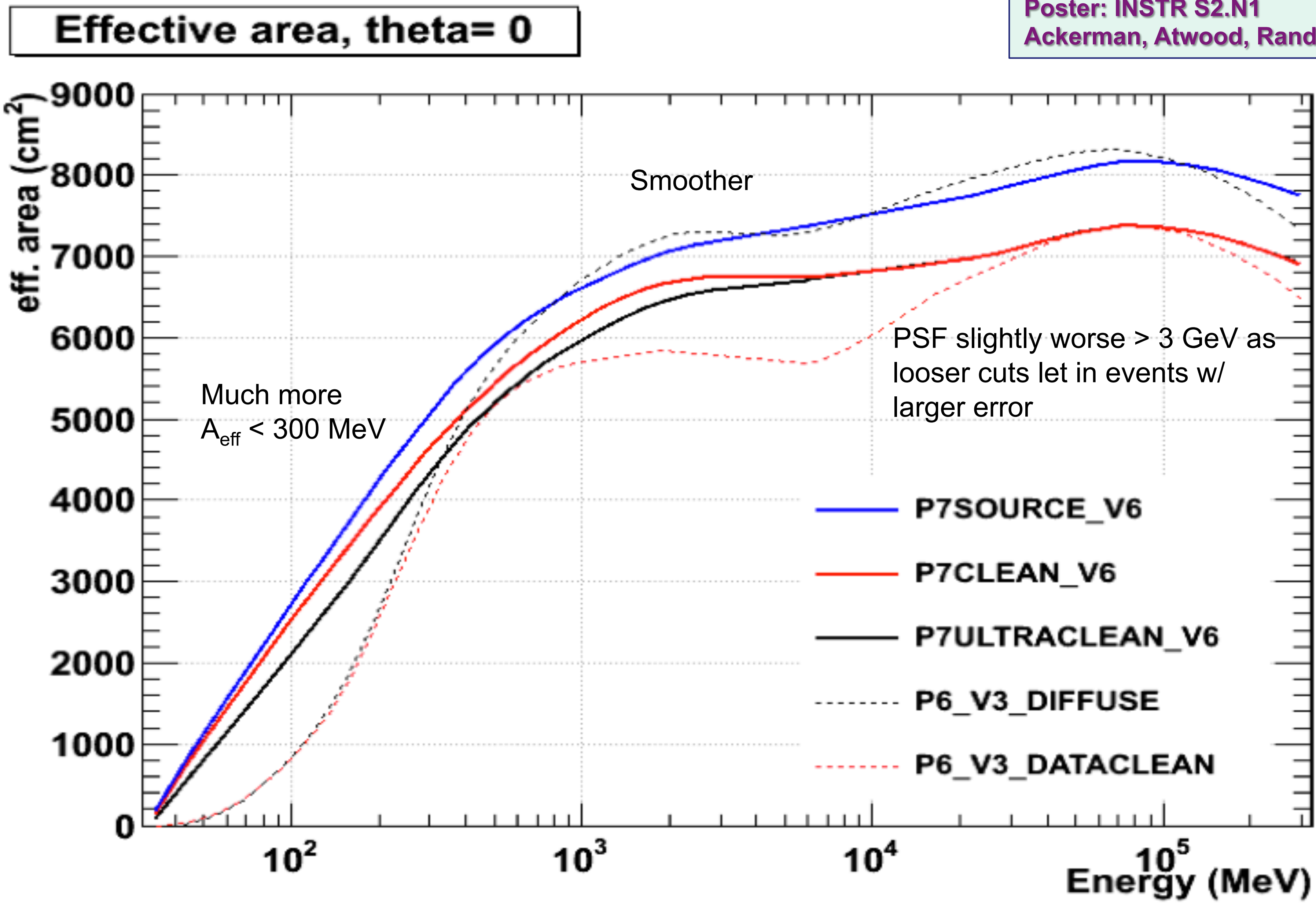
Pass 7 Event Class	Purpose	Pass6 equivalent
LAT Low Energy (LLE)[5]	xspec type analysis of short transients (GRBs, Flares)	None
Transient	Analysis of short transients (GRBs, Flares)	P6_v3_transient (event class >= 1)
Source	2nd LAT catalog, analysis of point sources	P6_v3_diffuse (event class >= 3)
Clean	Study of extended sources & diffuse gamma-ray emission	P6_v3_dataclean (event class >= 4)
UltraClean	Analysis of the extra-galactic gamma-ray background	None

Talk: V. Pelassa

Focus

Comparison of Pass 6 and Pass 7

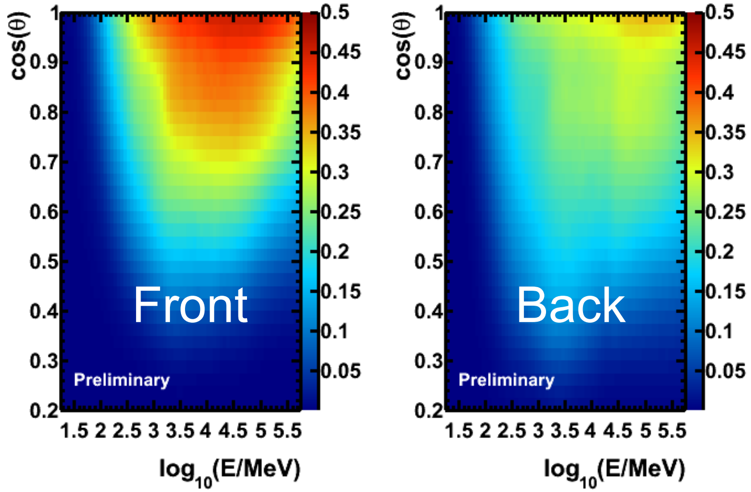
Poster: INSTR S2.N1
Ackerman, Atwood, Rando



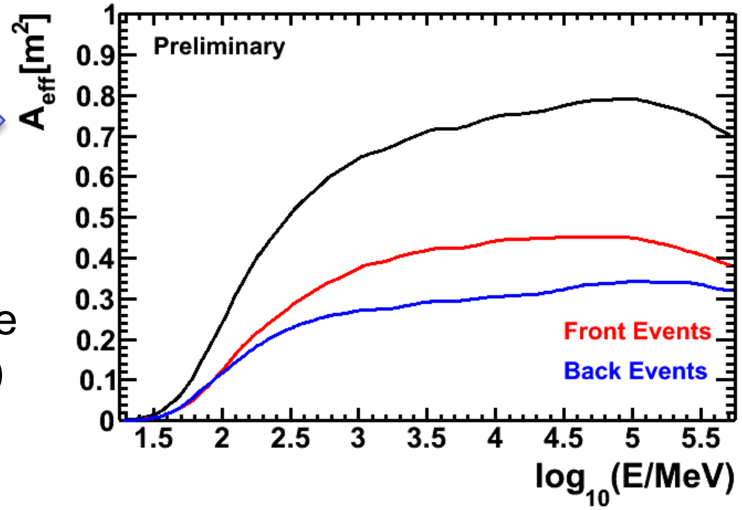
INSTRUMENT RESPONSE FUNCTIONS

Monte Carlo Based A_{eff}

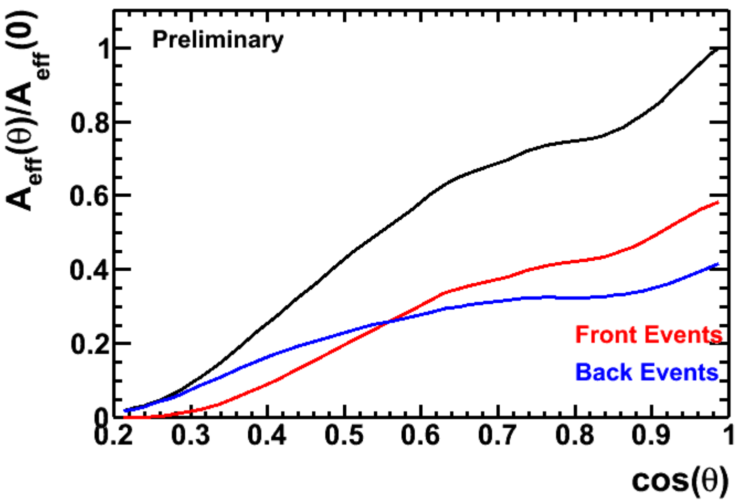
A_{eff} (cosθ,E) tables: generate uniform event set and count how many pass cuts



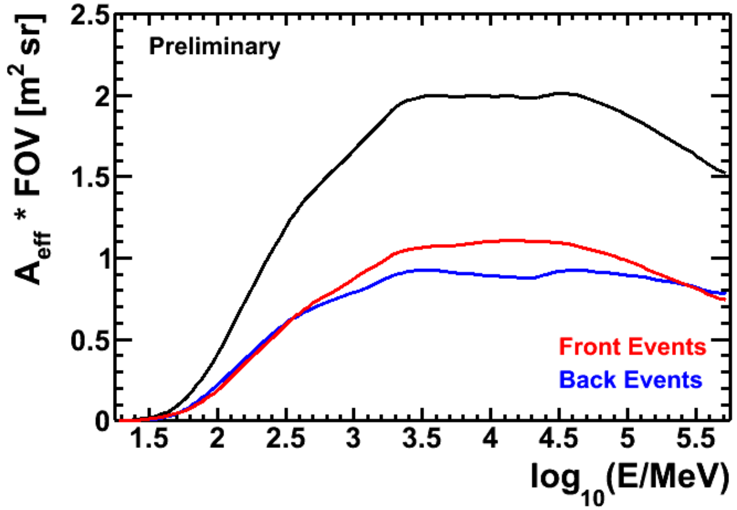
Slice in cosθ
E dependence
A_{eff}(E;cosθ=1)



Slice in Energy
cosθ dependence
A_{eff}(cosθ;E=1GeV)



Integrate over cosθ
Acceptance A(E)



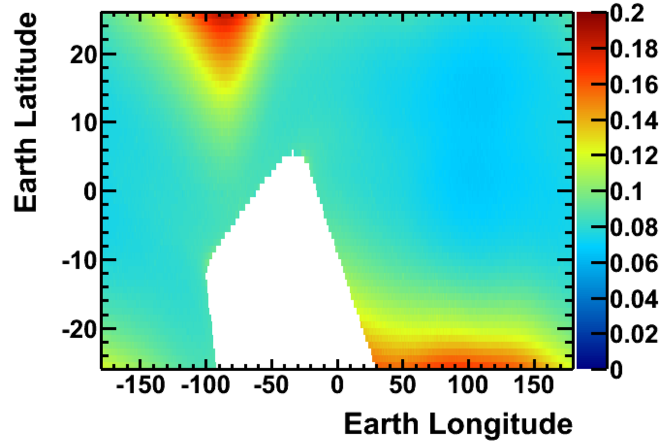
Deadtime fraction Corrections to A_{eff}

- Residual signals from cosmic rays contaminate events
  - can cause us to reject good photons
  - addressed by "*overlay*" technique
    - merge periodic triggers with photon simulations [3]

- Procedure only accurate on average
  - orbital variations in CR rates (right) -> variations in A_{eff}

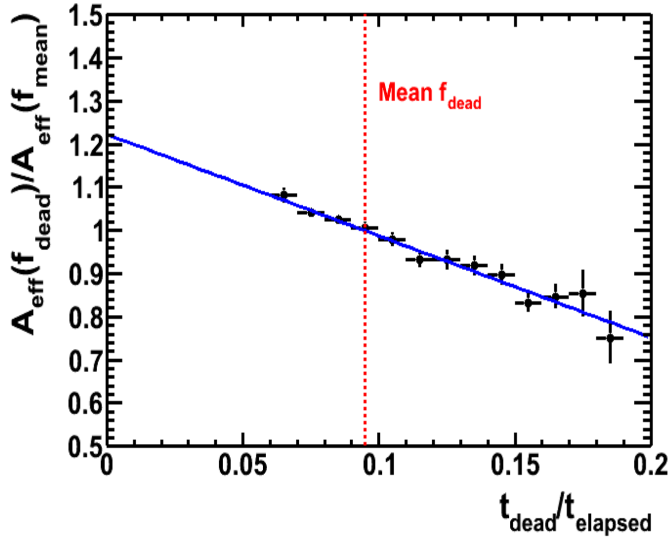
- f_{dead} = fraction of time the LAT reading out events, trigger off
  - good tracer of the particle rates and induced loss of A_{eff}
  - already in spacecraft history files

- Measure $A_{eff}(f_{dead}, E)$ and include as refinement in IRFs.



Mean f_{dead} (color scale) as a function of orbit position

Poster: INSTR S2.N1
Ackerman, Atwood, Rando
Poster: INSTR S2.N9
EC et. al.



A_{eff} variation with deadtime at 3.3 GeV

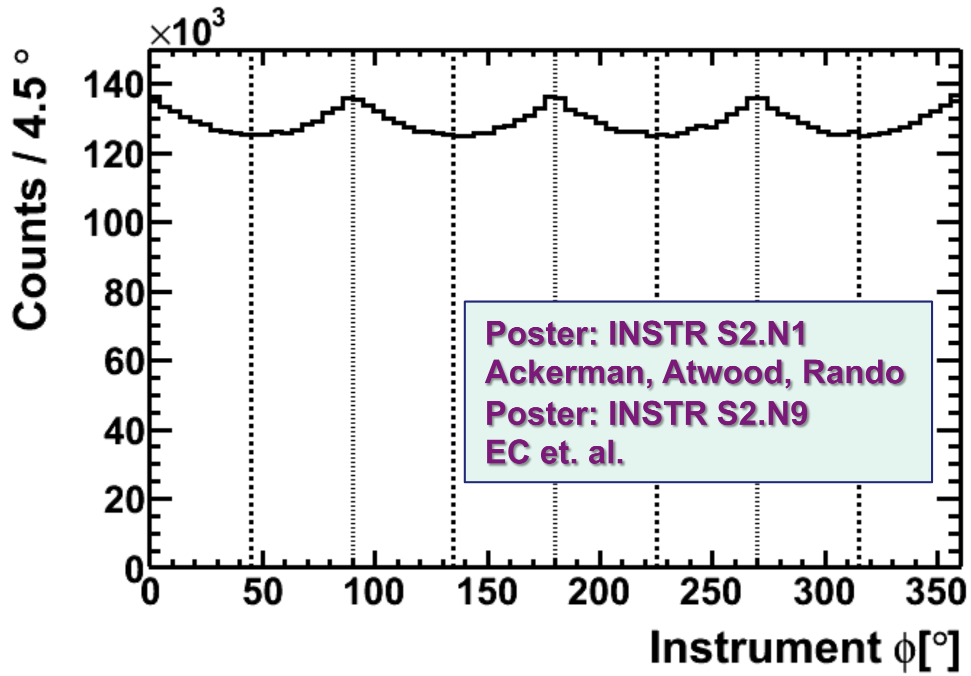
$A_{eff}(f_{dead})$ Modeling

1) Fit for slope at in log(E) bin (right)
2) Parameterize slope as a function of log(E)

ϕ dependence A_{eff} Correction

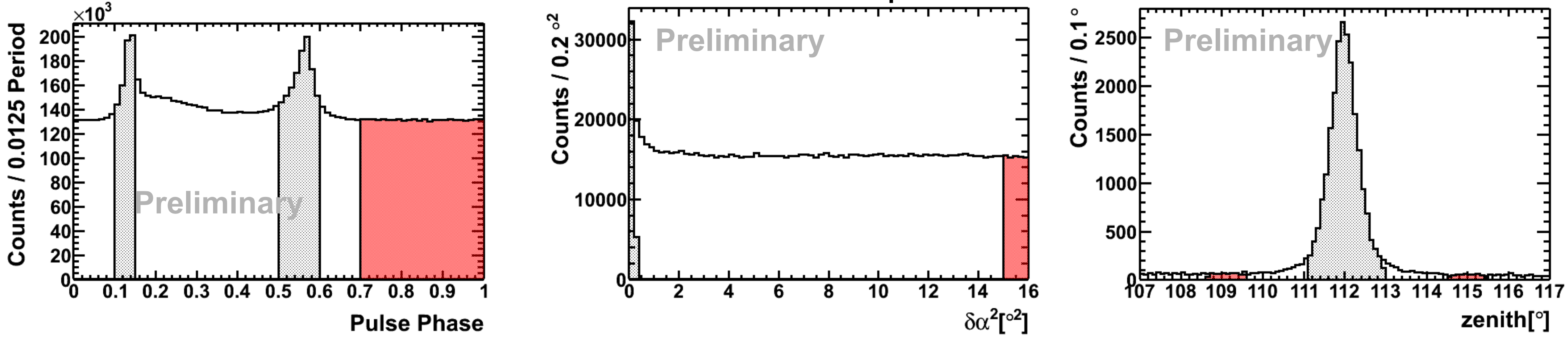
- Simulations show ~5% $A_{eff}(\phi)$ variation
  - Four-fold symmetry of LAT reduces effect to question of corners vs. sides of LAT
  - Confirmed in flight data
- By default we integrate it out in data treatment
  - Short term observations and particularly pointed-mode can favor particular ϕ values
- Parameterize $\Delta A_{eff}(\phi \mid \log(E), \cos\theta)$ using Monte Carlo and include as refinement to IRFs

Available in updated IRFs
but not used by default



Flight Data Calibration Samples

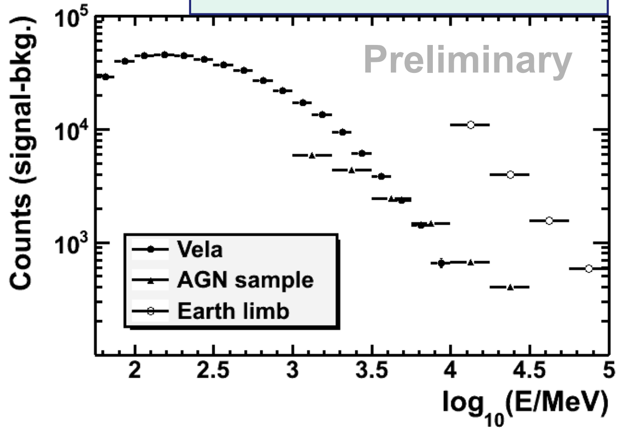
Vela | AGN sample | Earth limb



Calibration samples showing signal (grey) and background (red) regions for the **P7TRANSIENT** event class
These are used as starting point for testing **P7SOURCE** event selection criteria

Poster: INSTR S2.N6
Bregeon, Monzani & EC
Poster: INSTR S2.N9
EC et. al.

Calibration Sample	Method
Vela pulsar (2 years) 15° ROI, $q_{z,vela} > 90°$ Very clean bkg. subtraction but cuts off around 3 GeV	Phase-gated
30 Bright, isolated AGN (2 years) 6° ROI, $q_z > 105°$, E > 800MeV Need small PSF for bkg. subtraction	Aperture
Earth limb (200 limb-pointed orbits) E > 8 GeV Difficult to model earth limb emission below ~ 10 GeV.	Zenith Angle cut



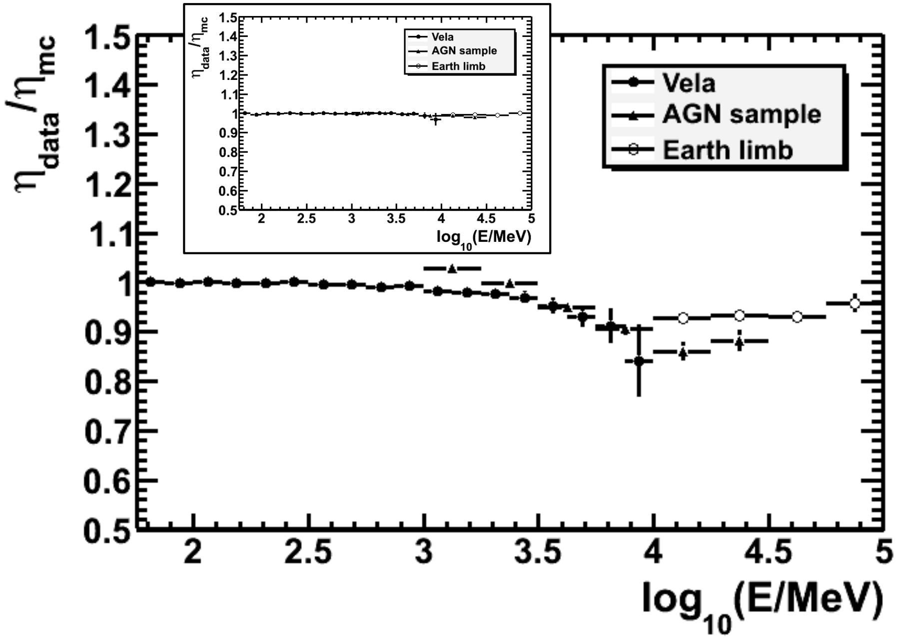
Statistics of the calibrations samples after background subtraction

Validation and Calibration of A_{eff}

•Compare efficiency of each step of event selection between flight data and Monte Carlo using calibration samples

•In Pass 6 one piece of event selection showed significant disagreement around 10 GeV (plot on right)

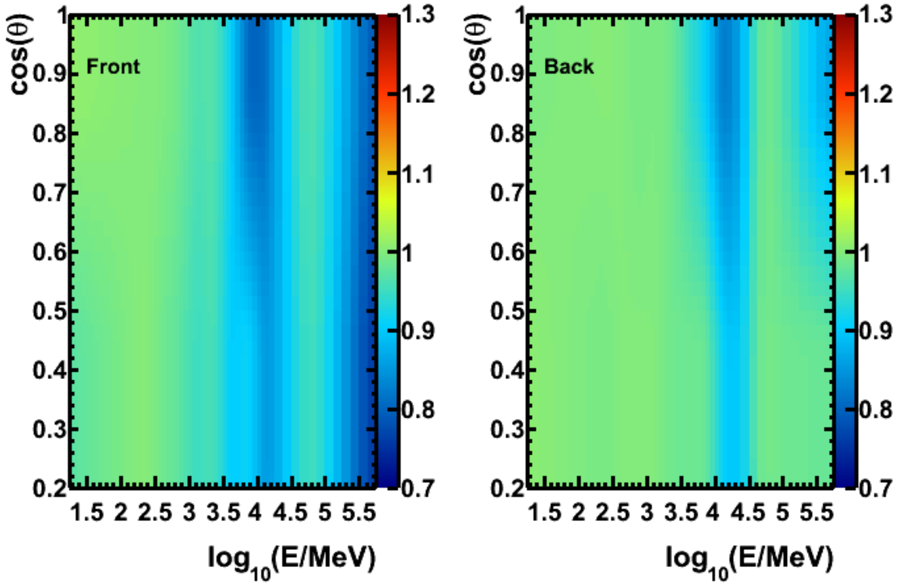
  •Traced back to issues with using CAL direction and centroid information



In-flight A_{eff} Correction

1. Pass 7:
   we loosened the cut (top inset)

2. P6_V11:
   we scaled the A_{eff} tables using ratio of η_{data}/η_{mc} (lower plot)



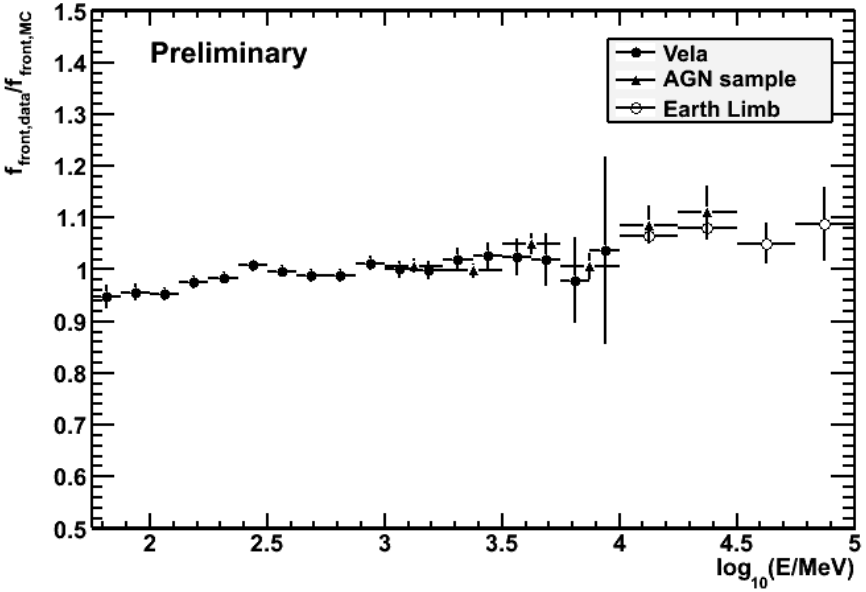
Error Estimates on A_{eff}

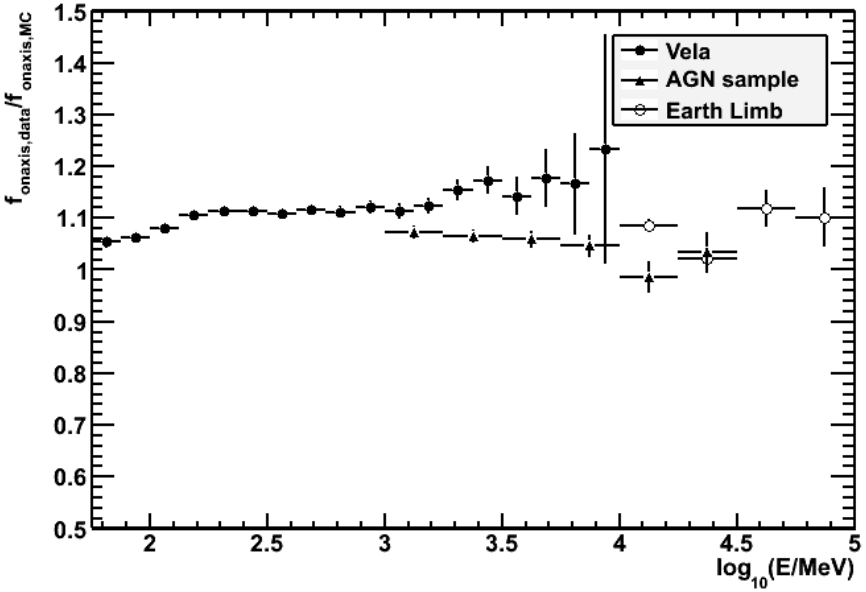
- Consistency checks also provide estimate of how well we understand the instrument

- Flux from conversions in right side v. left side, even layer v. odd layers, etc…

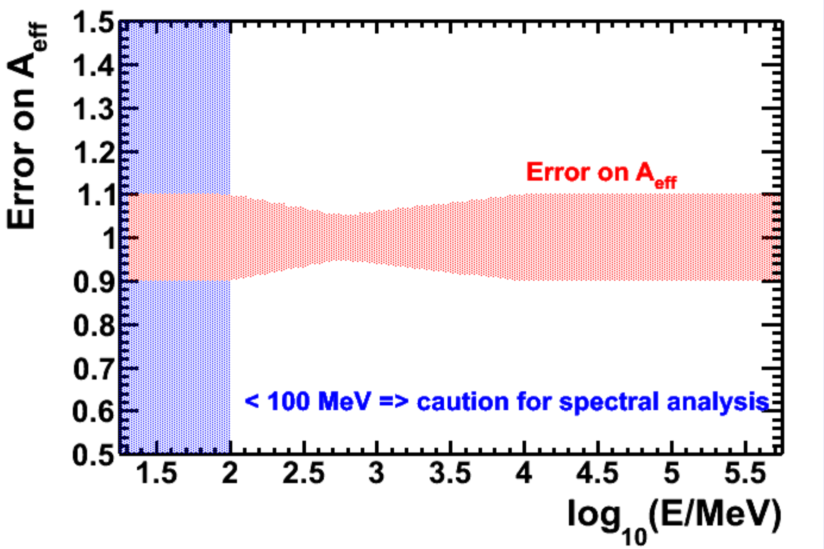
- Largest inconsistencies in Data v. Monte Carlo comparisons
    - front v. back conversions (top)
    - on-axis v. off-axis pointing (bottom)
    - effects are correlated

- Larger than other uncertainties on A_{eff}
    - Assign ½ of difference as systematic bound on combined A_{eff} (roughly)

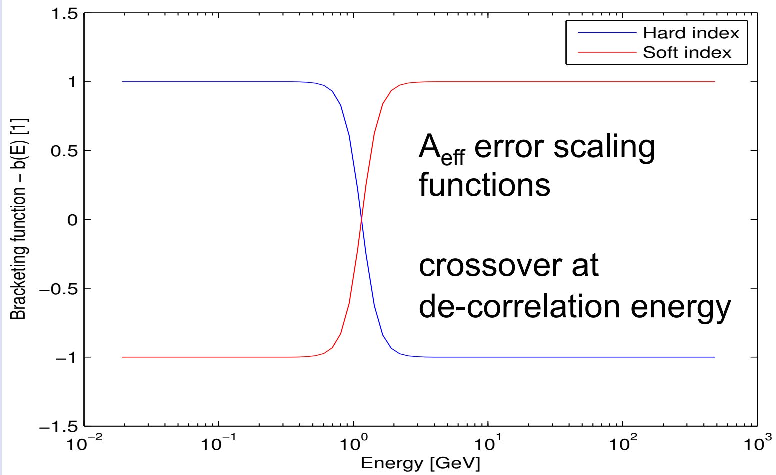


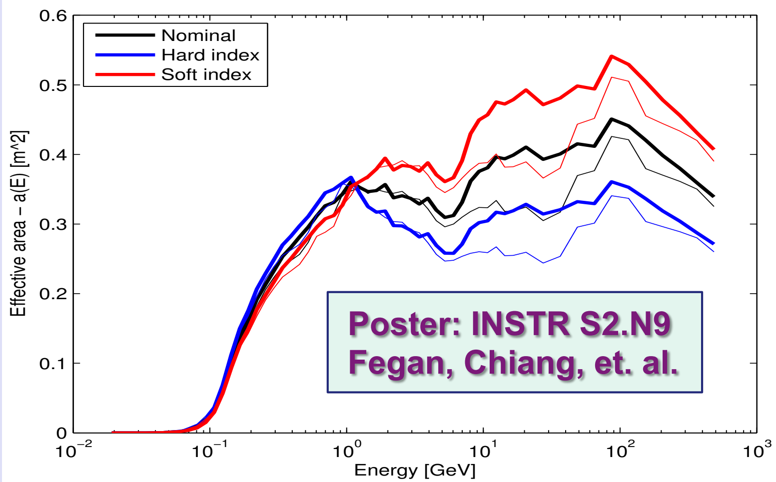


Errors and Propagation of Errors on A_{eff}

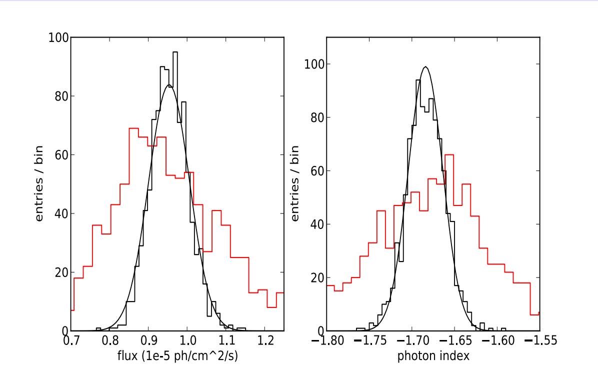


Uncertainty bands on A_{eff} as a function of energy. These estimates are based on the consistency checks from the previous slide.





A) Bracketing IRFs. Generate A_{eff} curves which fit within systematic errors and maximize the error on measured quantities (e.g. the spectral index). Represents worst case.



B) Bootstrap analysis. Mimic plausible A_{eff} by re-sampling data with weighting factors. Bayesian, equiv. treatment of syst. and stat. errors.

Monte Carlo Based PSF

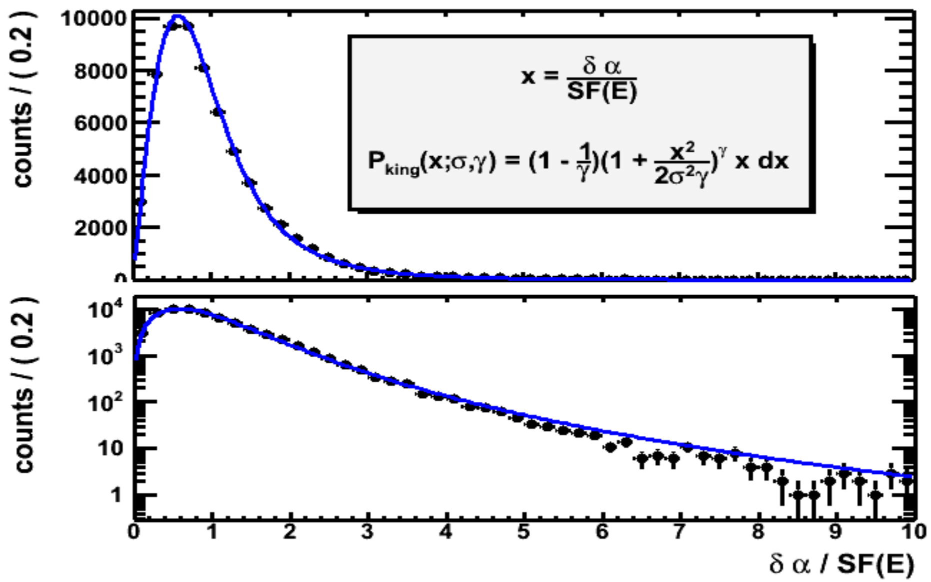
1) PSF scales w/ Energy

$SF(E) = (c_0 + c_1(E/100MeV)^{\gamma})^{1/2}$

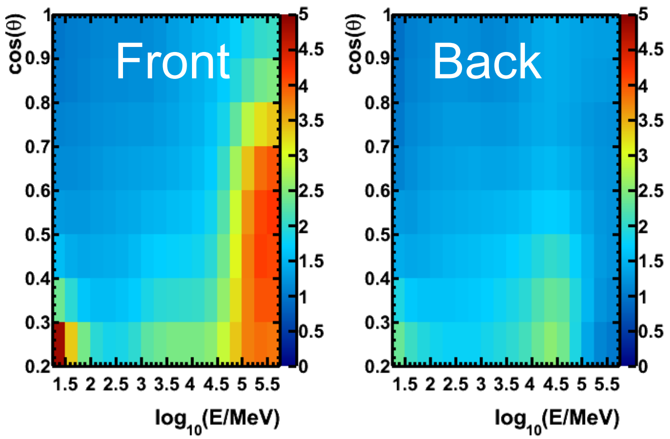
c_0, c_1, γ differ for front/back

2) Fit scaled deviation $x = \delta\alpha/SF(E)$ with King function in each log(E) and cos(θ) bin

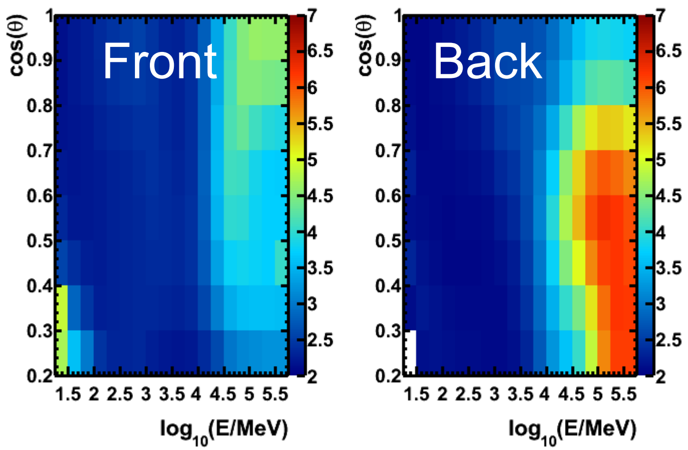
NB: Multi-faceted behavior across LAT bandpass and incident angles



Fit of PSF (on axis, 5 GeV) to Double King function

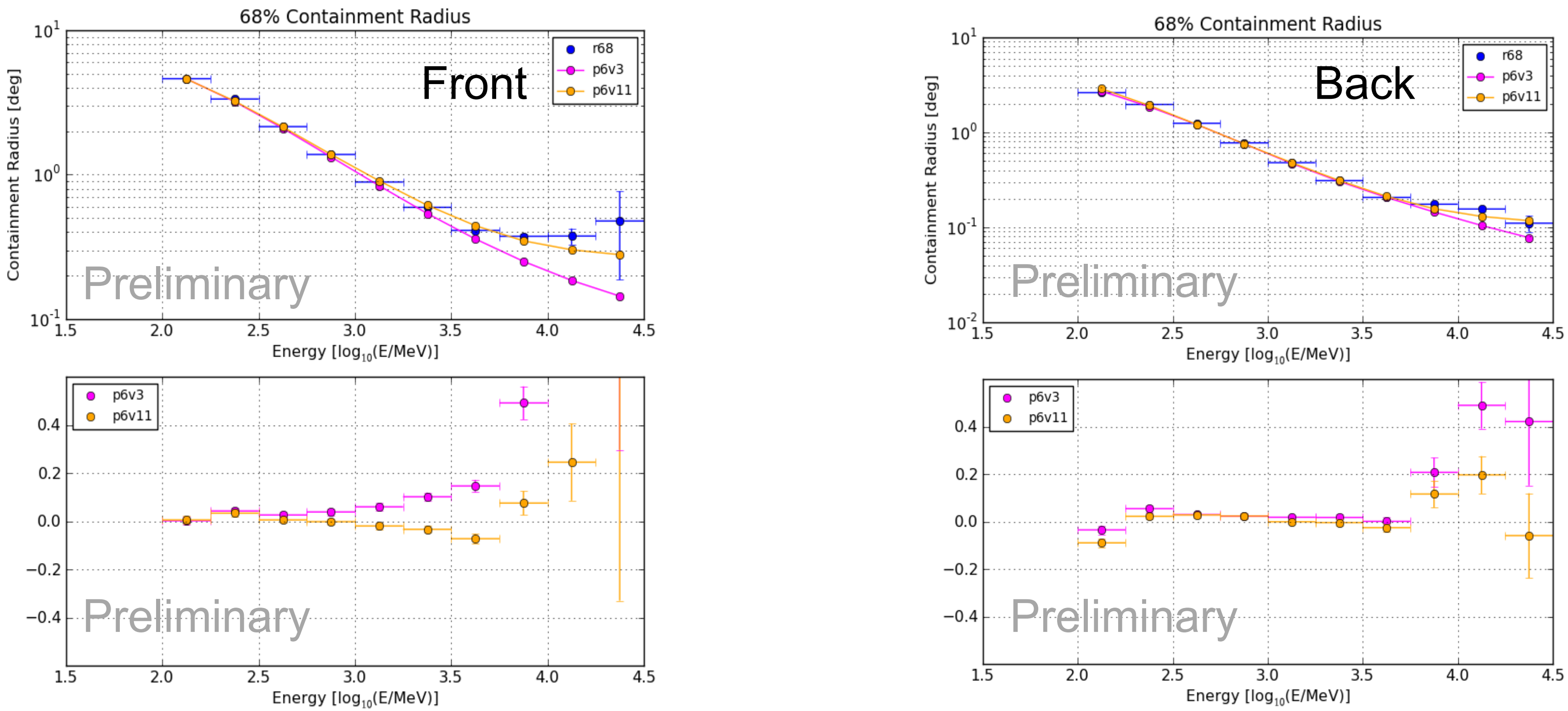


Scaled R68%



Ratio of R95% to R68%

Validation and Calibration of PSF



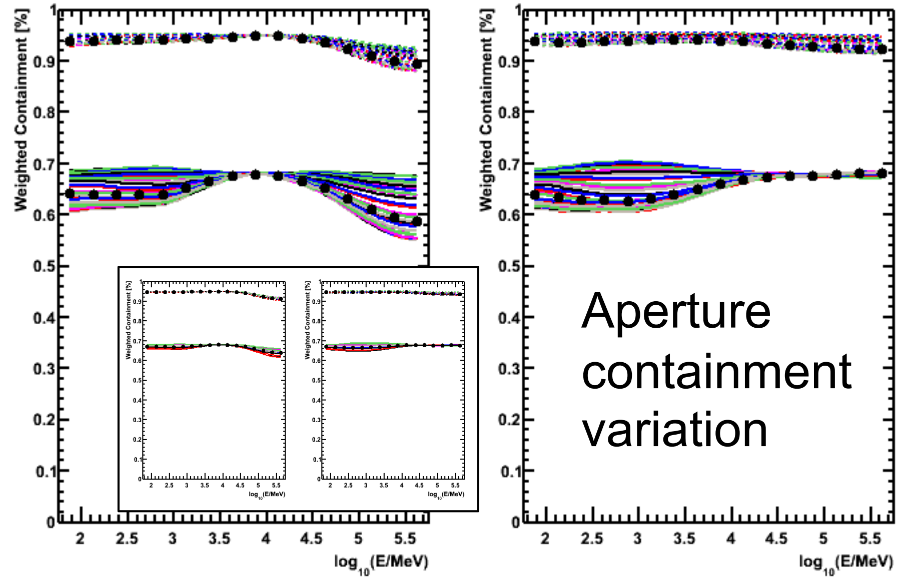
- Monte Carlo underestimates PSF above ~1 GeV

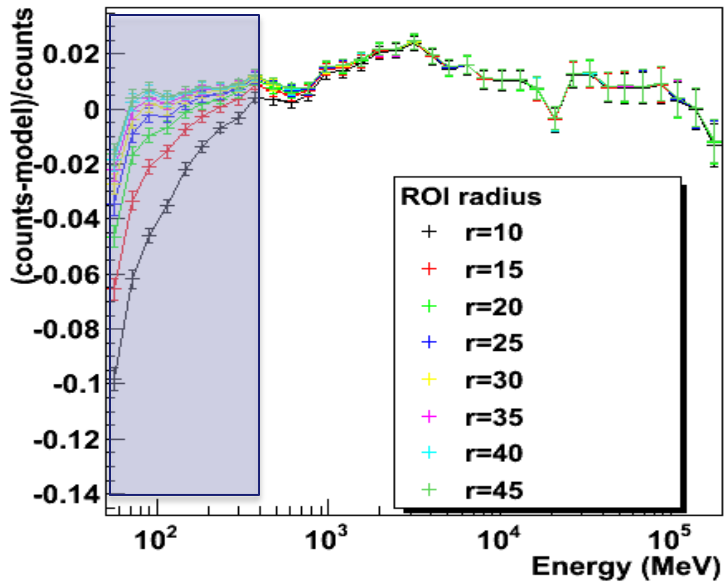
Poster: INSTR S2.N25
Roth, Rando & Wood

- P6V11 and P7 in-flights PSF based on study of bright AGN with ~11 months of data
  - Not enough statistics to study θ-dependence: Average it out
- Use phase-subtracted pulsar and AGN samples to compare containment to Monte Carlo based (P6V3) and flight-data based (P6V11) PSFs

Errors and Propagation of Errors on PSF

- Effect of uncertainties on PSF on source fitting depends on source and source environment
  - Nearby source for confusion
  - Relative level of diffuse and isotropic background
- Estimate bias and spread on aperture containment when ignoring θ-dependence
  - ~10% spread on 12-hour times scales
  - ~2% on 2year times scales (inset)
- Estimate effect on likelihood fit using "Toy" Monte Carlo
  - Simulate event with one PSF, fit with another. Effect < 2% independent of size of Region Of Interest above 500 MeV





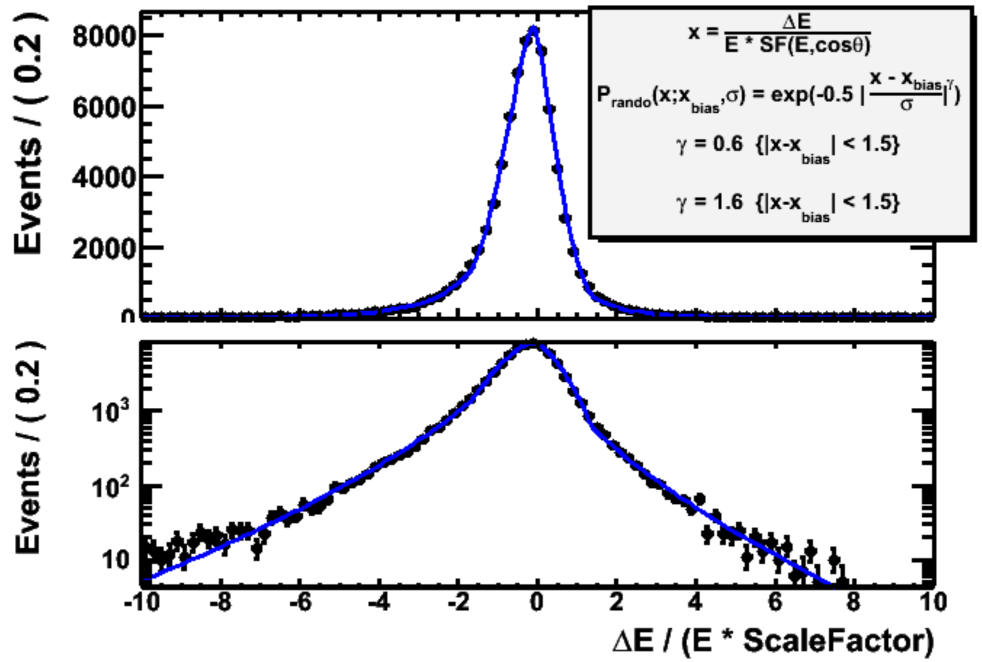
Monte Carlo Based E_{disp}

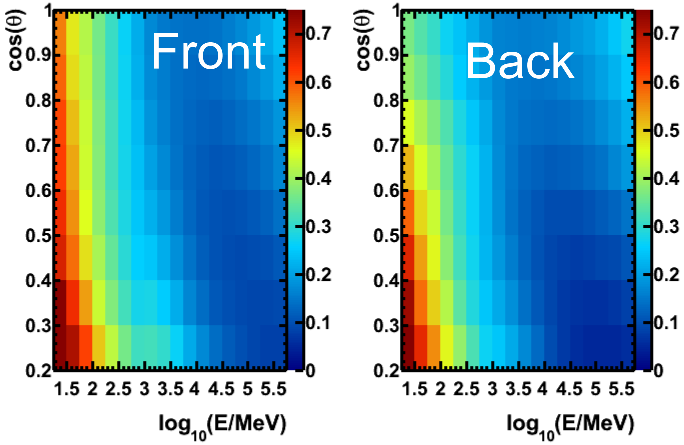
1) E_{disp} scales w/ log(E), cos(θ)

SF(E, cos(θ)) -> paraboloid

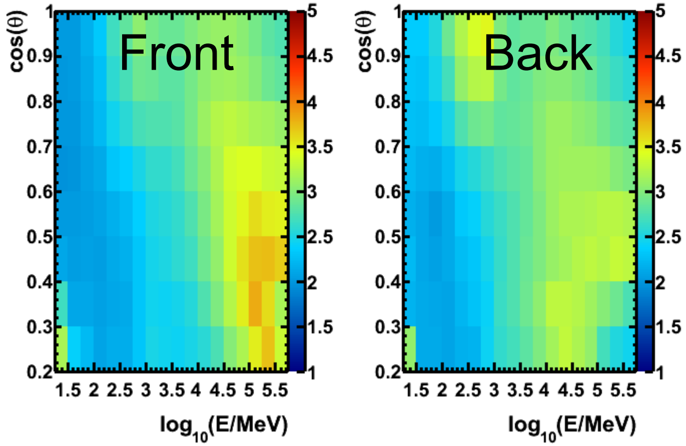
2) Fit scaled deviation $x = \Delta E/(E*SF(E))$ with Rando function in each log(E) and cos(θ) bin

NB: As with PSF, multi-faceted behavior across LAT bandpass and incident angles





Scaled R68%

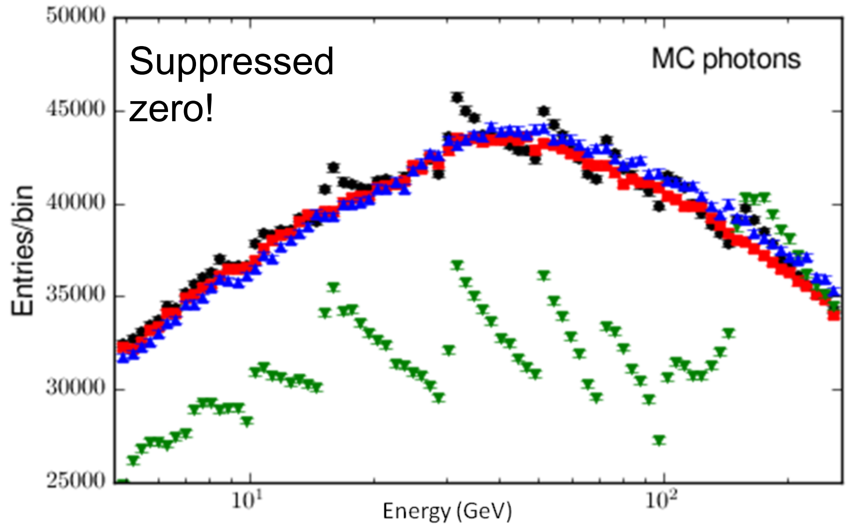


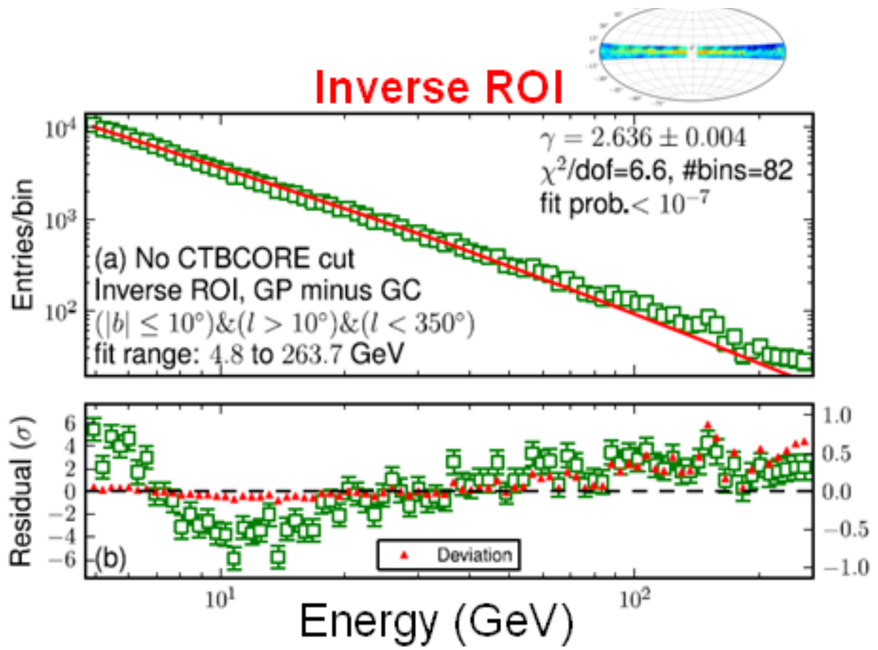
Ratio of R95% to R68%

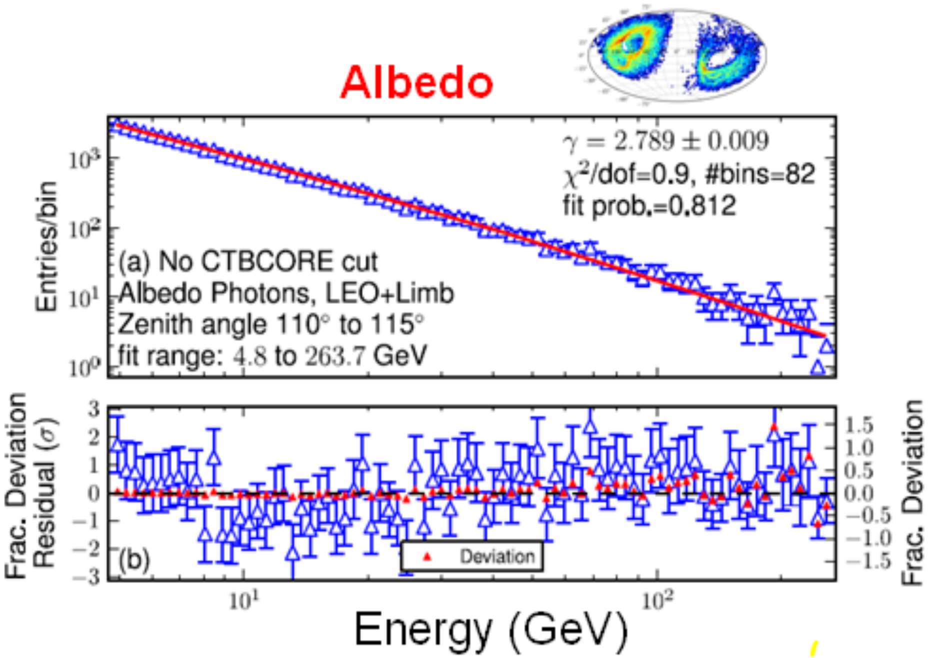
Spectral Artifacts

- Narrow (~1/5 decade) artifacts at the 2-3% level
  - Traced to 1 (of 3 possible) energy estimates
  - Removed in Pass 7

- Photons from Galactic Plane and Earth Limb as control sample
  - Wider (1/2 decade) variation at the 5% level







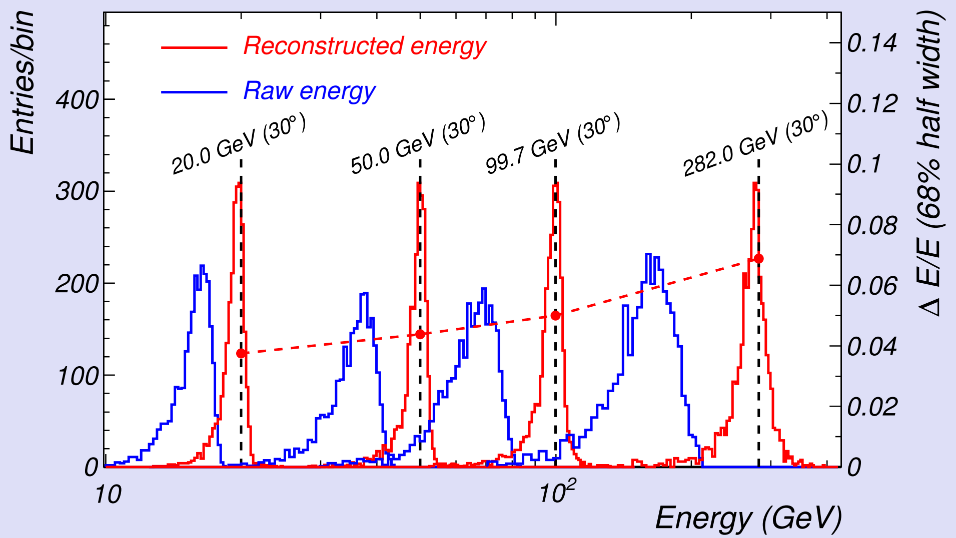
Energy Measurement Validations

- No adequate celestial calibration sources
  - Stat. error on Vela cut-off < 5%

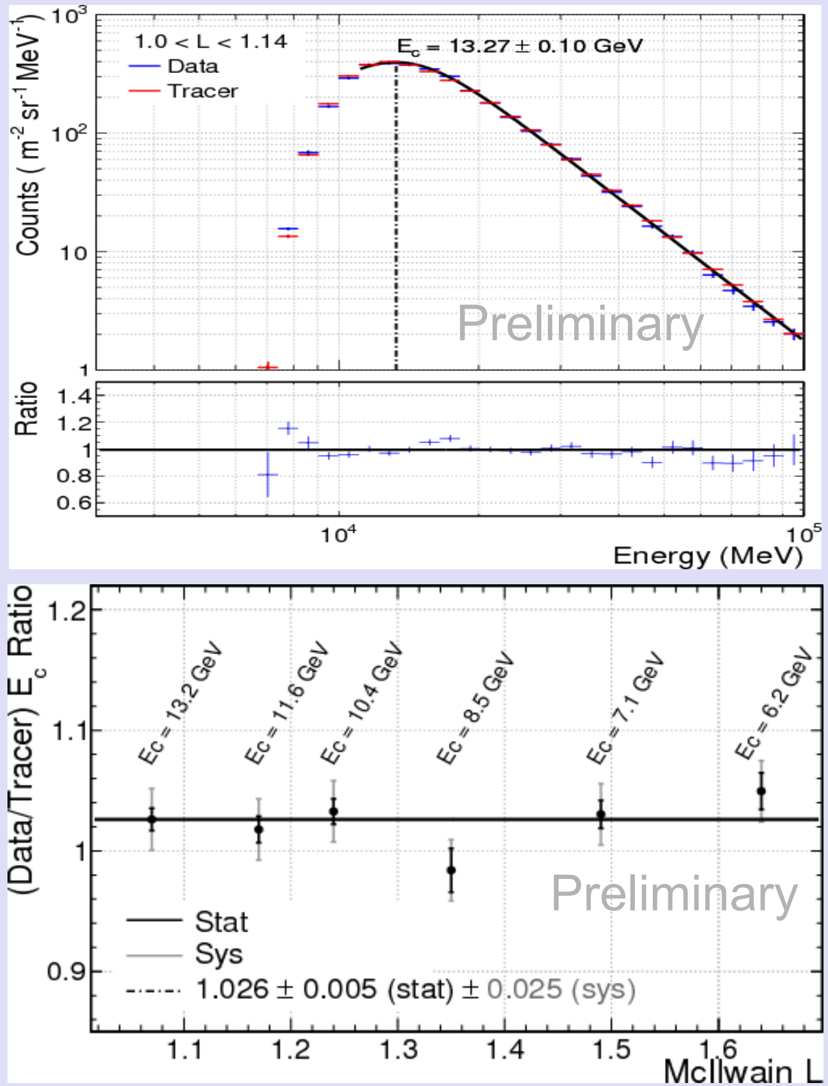
- Geomagnetic cutoff of e+e- spectra well studied and very sharp
  - Varies from 6-13 GeV around LAT orbit

Poster: INSTR S2.N21
Pesce-Rollins

- Rely on beamtest data (below) for other energies



Energy scale and resolution measurements from 20-200 GeV using the Calibration Unit in e- beam



Measurement of absolute Energy scale between 6-13 GeV using e^+e^- spectra and Earth's Geomagnetic cutoff

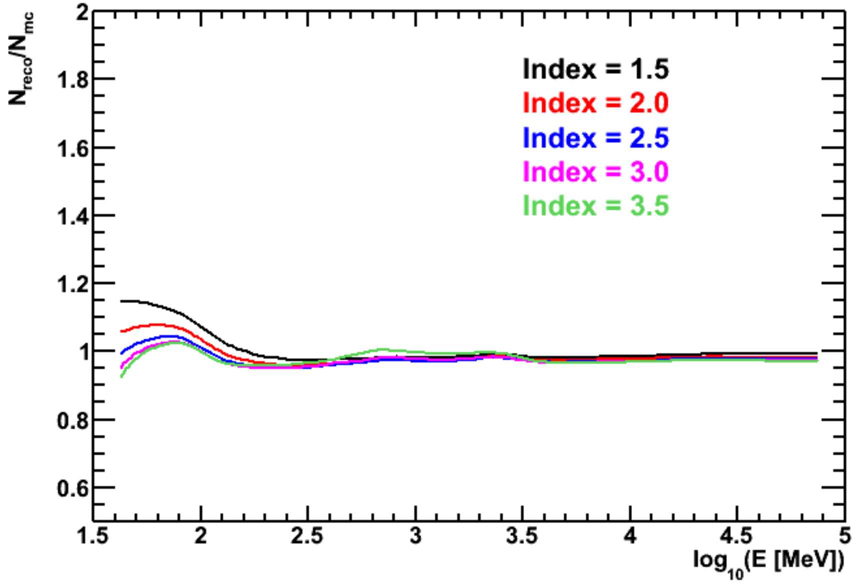
Errors and Propagation of Errors on E_{disp}

•*ScienceTools* do not account for E_{disp} in fitting

•This induced bias is < 2% across most of spectral range

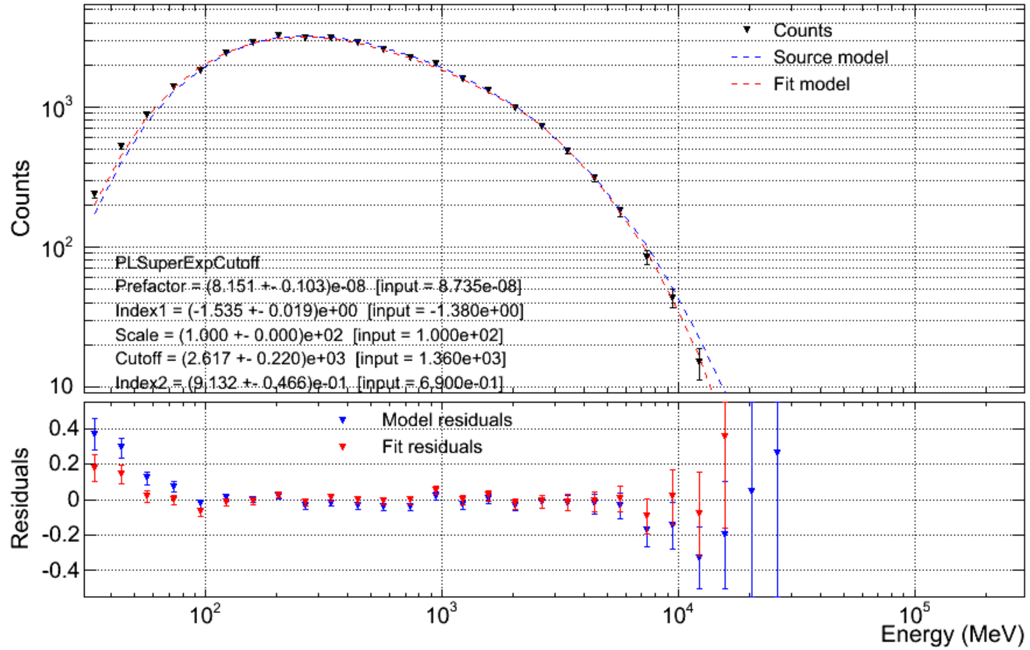
•Below 200 MeV where Aeff rises steeply, effect is larger and depends on spectral index

•Biases in this part of spectrum can pull index, flux and cutoff (as seen in the "Toy" Monte Carlo simulation of Vela)



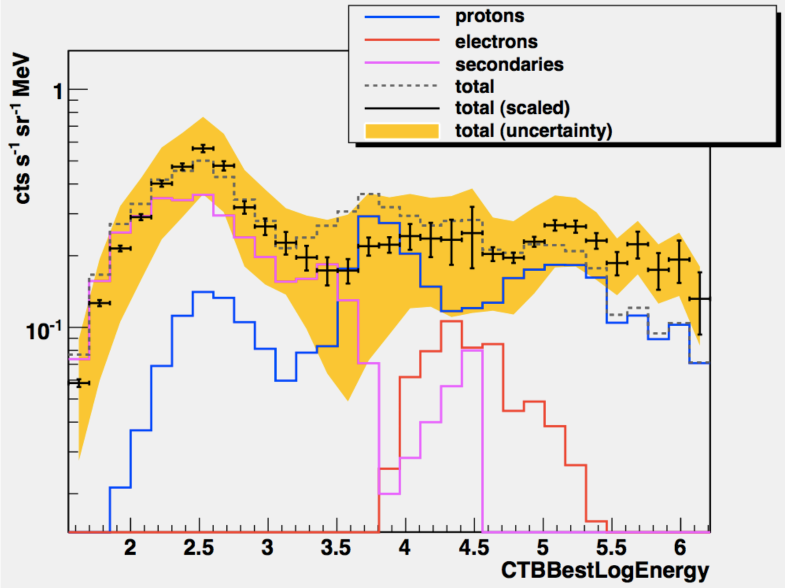

```
Index  = (-1.53 +- 0.19)e+00
  [Input = -1.38]

Cutoff = ( 2.61 +- 0.22)e+03
 [Input = 1.36 e+03]
```

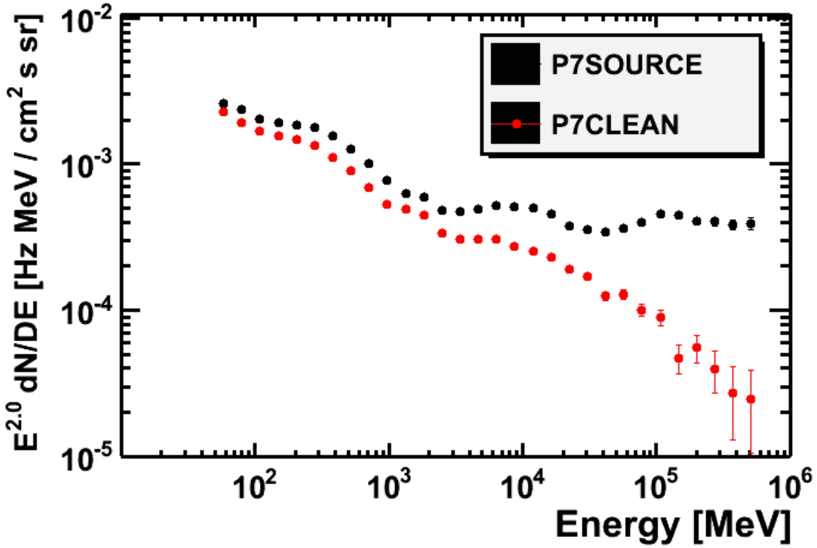


Particle Background Contamination

•Estimated particle background contamination from massive (> 10^{11} events) simulation of particle background
- •Uncertainties in input spectra
- •High Bkg. rejection means we are exploring extreme tails of distribution
  - •Challenging accuracy of simulation



•Note: particle background contamination is absorbed into isotropic template in *ScienceTools* analysis
- •Use cleaner event classes to cross-check results



Variability

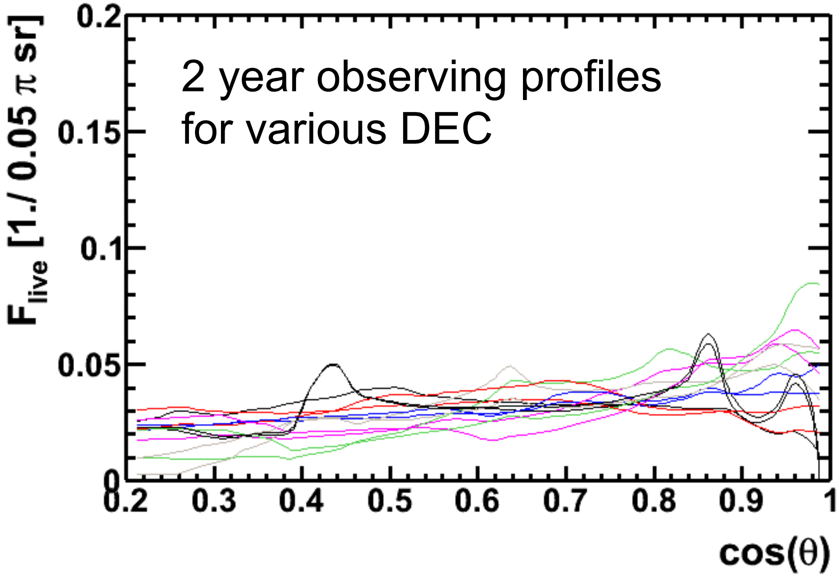
•Lots of variation in IRFs across the LAT field of view

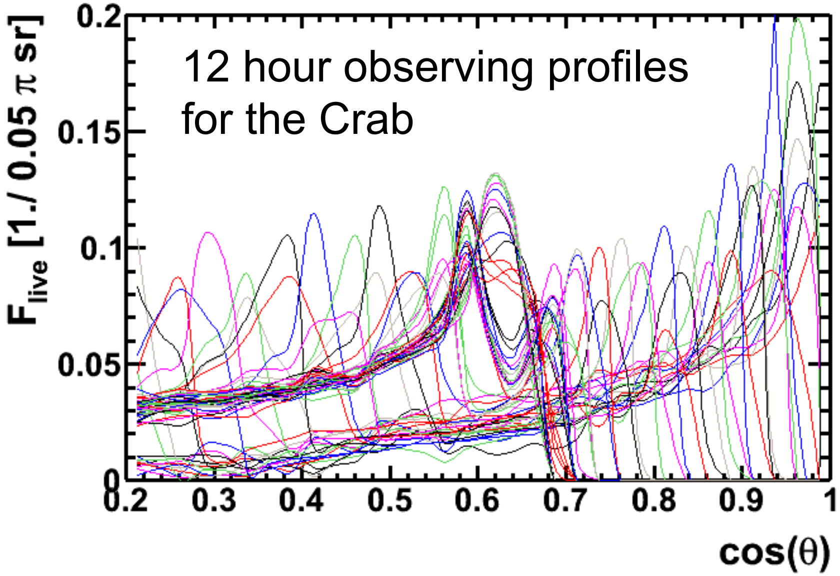
•Largest uncertainties in IRFs are correlated with incident angle w.r.t. LAT boresight (θ)

•IRFs validations are most accurate for long term averages

- •On short times scales $T_{live}(\cos(\theta))$ can be very non-uniform

•Best advice: use diffuse emission and or nearby sources as control sample when doing variability studies





Event Selections and IRF sets revisited

- The LAT team has included the flight data derived corrections as well as the largest 2nd order effects into the Pass 7 data as the P7 IRF sets
- We have also applied these to Pass 6 "Diffuse" class data, as the P6_V11_DIFFUSE IRF set
  - We expect this to be the *LAST* Pass 6 IRF release
- The table below summarizes the releases IRF sets
  - These cover all publications since public data release

IRF Sets	A_{eff} Model	PSF Model	Energy Estimate	Status
P6_V3_[CLASS]	Overlays	Monte Carlo	3 Methods	Public
P6_V11_[CLASS] (Diffuse only)	Overlays ϕ, f_{dead} dependence (§1) A_{eff} correction (§4)	In-Flight (no θ dependence)	3 Methods	In Release process (May 2011)
P7[CLASS]_V6	Overlays ϕ , f_{dead} dependence(§1)	In-Flight (no θ dependence)	2 Methods Unbiasing	Release Date July 2011

CAVEATS AND SUMMARY

Caveats and Recommendations

- LAT has a very large bandpass and FOV
  - IRFs can vary by > 10x for different regimes
- A_{eff} changes rapidly below 100 MeV
  - Can cause errors in spectral analysis, especially when ignoring E_{disp}
- PSF above 3GeV is somewhat larger in-flight than in simulation
  - In-flight PSF has less detail (but more fidelity)
- LAT IRFs and *ScienceTools* are optimized for *long-term* analysis of *point sources*.
  - Some 2nd order effects are averaged out of IRFs by default
    - $A_{eff}(\phi)$, $A_{eff}(f_{dead})$, PSF(θ)
    - Use caution (and control sources) with variability analysis
- When possible use nearby, well understood, sources as controls for instrumental artifacts

Summary

- LAT team has performed detailed and systematic studies of instrument using flight data
  - Developed new calibration techniques for LAT bandpass
  - Some surprises on orbit, now largely understood
    - Particle pile-up
    - 2nd order effects of pointing strategy and variations across FOV
- Greatly improved understanding of instrument since launch
  - Becoming truly a precision instrument
    - Errors < 10% for many types of measurements

REFERENCES AND ADDITIONAL INFORMATION

References and More Information

Papers and Proceedings:

LAT Instrument Paper	[arXiv:0902.1089] Atwood et. al.
On-Orbit Calibration Paper	[arXiv:0904.2226] Abdo et. al.
On-Orbit Performance Update	[axXiv:0907.626] Rando
CRE Electron Full Paper	[arXiv:] Abdo et. al.

Symposium Posters & Talks:

Pass 7 Event Analysis Poster	[Instr S2.N1] Ackerman, Atwood and Rando
A_{eff} Validation Poster	[Instr S2.N9] Charles et. al.
On-Orbit PSF Poster	[Instr S2.N25] Roth, Rando and Wood
Calibration Data Sets	[Instr S2.N6] Bregeon, Monzani and Charles
Systematic Errors from A_{eff}	[Instr S2.N13] Fegan et. al.
Absolute Energy Scale	[Instr S2.N21] Pesce-Rollins
LAT Low Energy (LLE) Talk	V. Pelassa talk upcoming in this session
LAT Low Energy (LLE) Poster	[SolarSystem S2.N2] Omodei et. al.

The Future: Pass 8

Symposium Posters on Pass 8:

Pass 8 Overview	[Instr S2.N3] Baldini et. al.
Calibration Data Sets	[Instr S2.N6] Bregeon, Monzani and Charles
Tree Based Track-Finding	[Instr S2.N29] Usher
TKR Readout	[Instr S2.N23] Rochester
CAL-Based Event Analysis	[Instr S2.N2] Baldini et. al.
MST CAL Clustering	[Instr S2.N26] Sgro et. al.
Cluster Classification	[Instr S2.N22] Pesce-Rollins et. al.
TMine Multivariate Analysis Tool	[Instr S2.N11] Drlica-Wagner and Charles