LAT Performance

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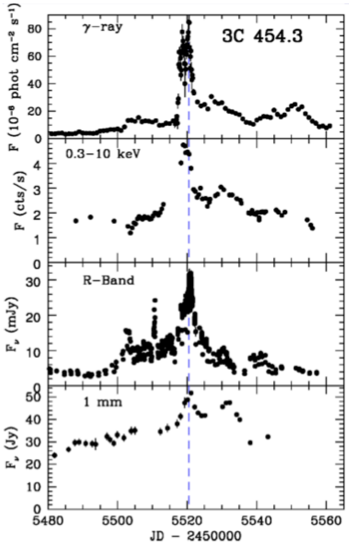
Outline

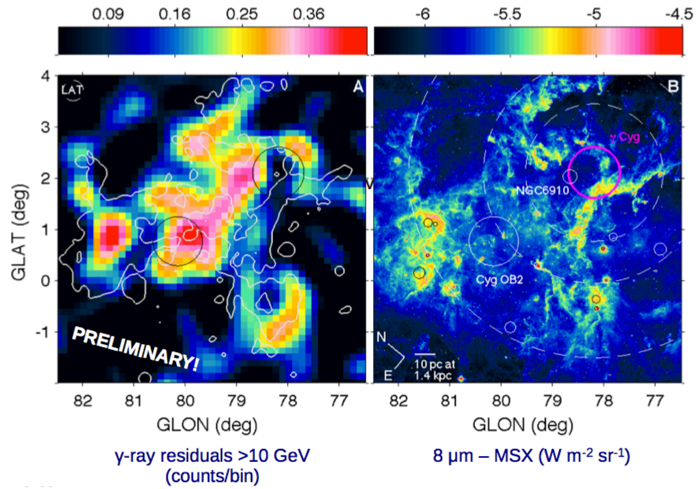
- Optimizing the LAT for Science
- Instrument Response Functions (IRFs)
- Review of LAT Performance and IRF Parameterizations
- Validating and Calibrating the LAT IRFs
- For more detail on the topics presented here see the LAT Performance Paper: **Ackermann et al. 2012,** 2012ApJS..203....4A [arXiv:1206.1896]

Optimizing the LAT for Science

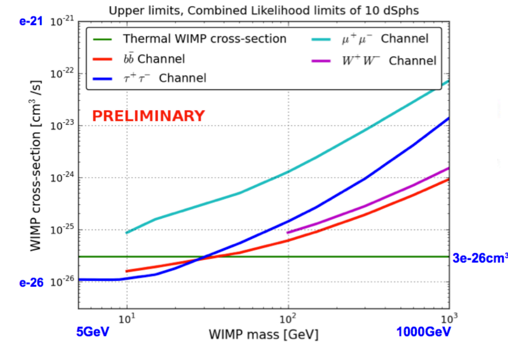
Wide Variety of Analysis Subjects



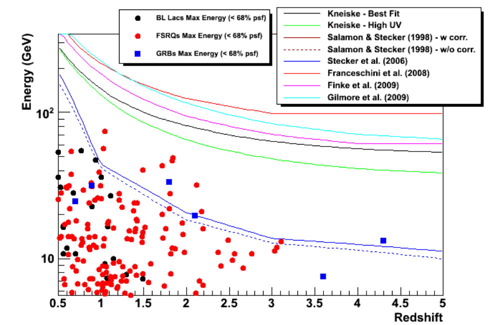
MW Variability



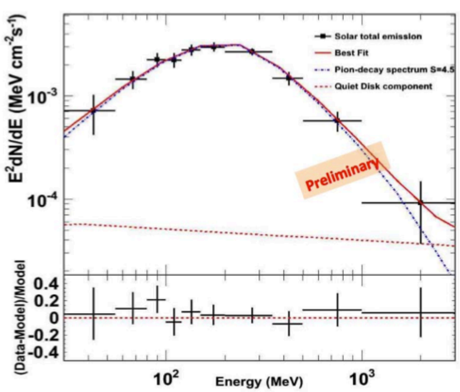
Morphology, Source Extension and Counterpart Identification



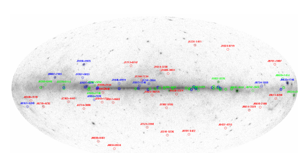
DM Searches

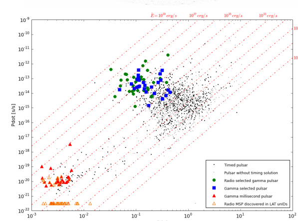


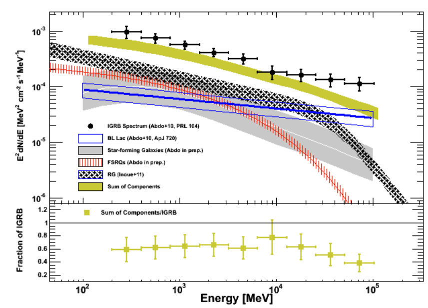
Single Photon Studies



SEDs and Spectral Components



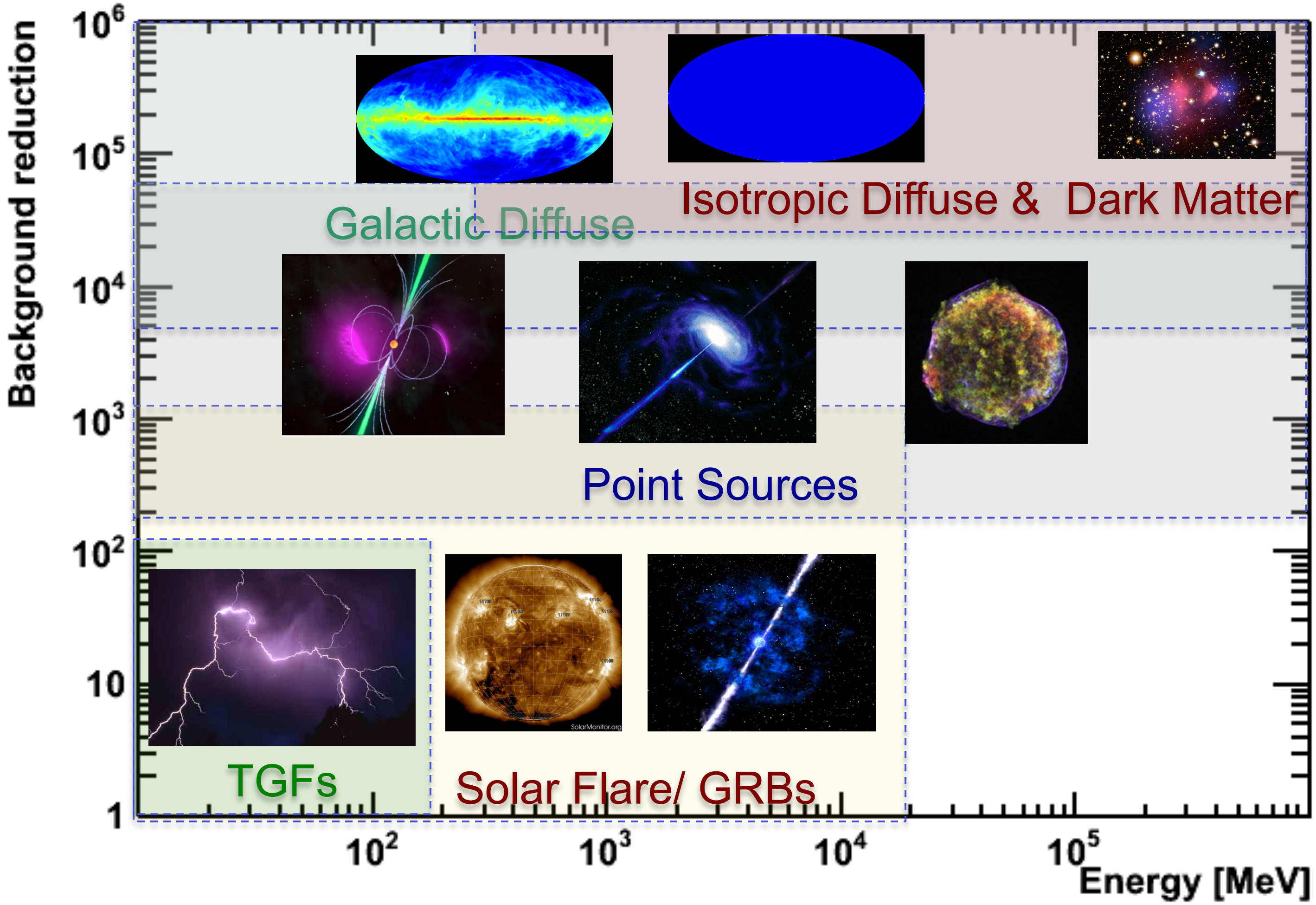




Catalogs, Population Studies and Contribution Estimation

No real "standard" analysis, lots of particular cases.

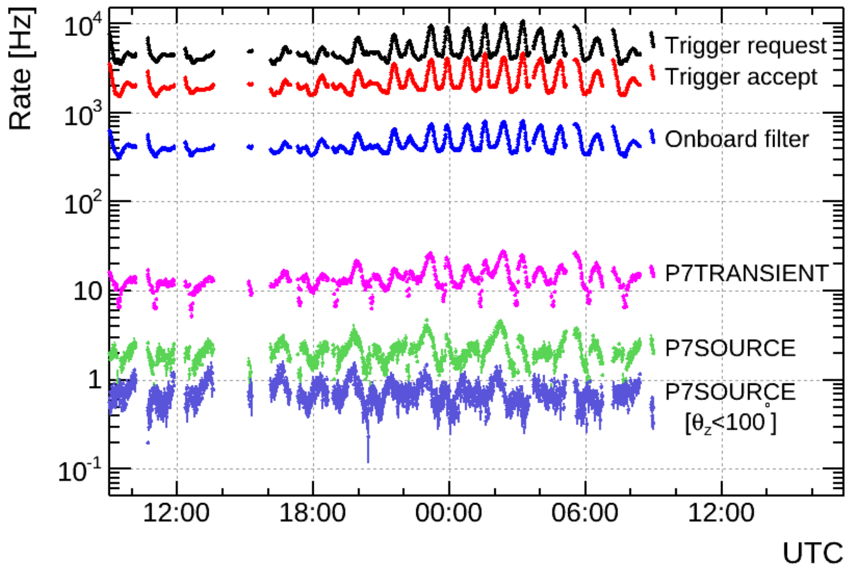
Fermi-LAT Science Covers Huge Phase-Space



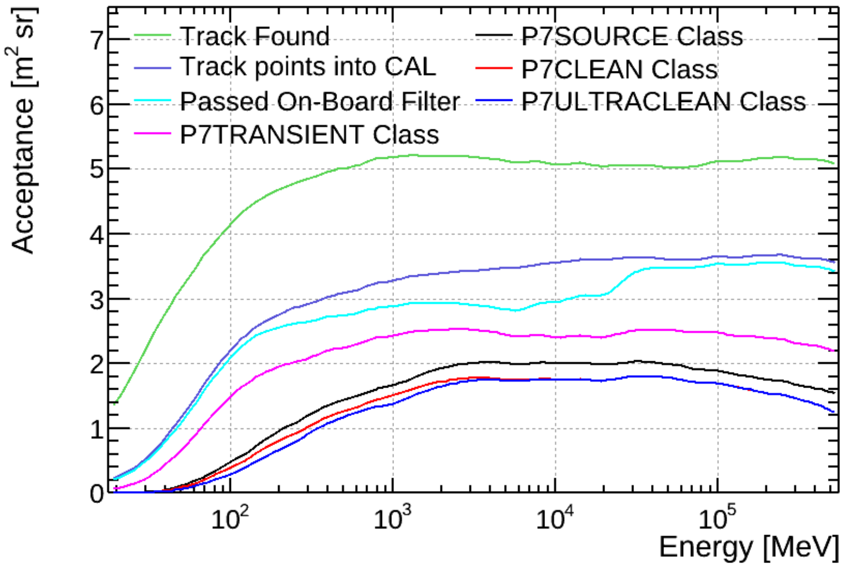
Different data selections for different science cases.

Particle Rate Reduction and Event Selections

Event Rates over 1 Day



Acceptance for Selections

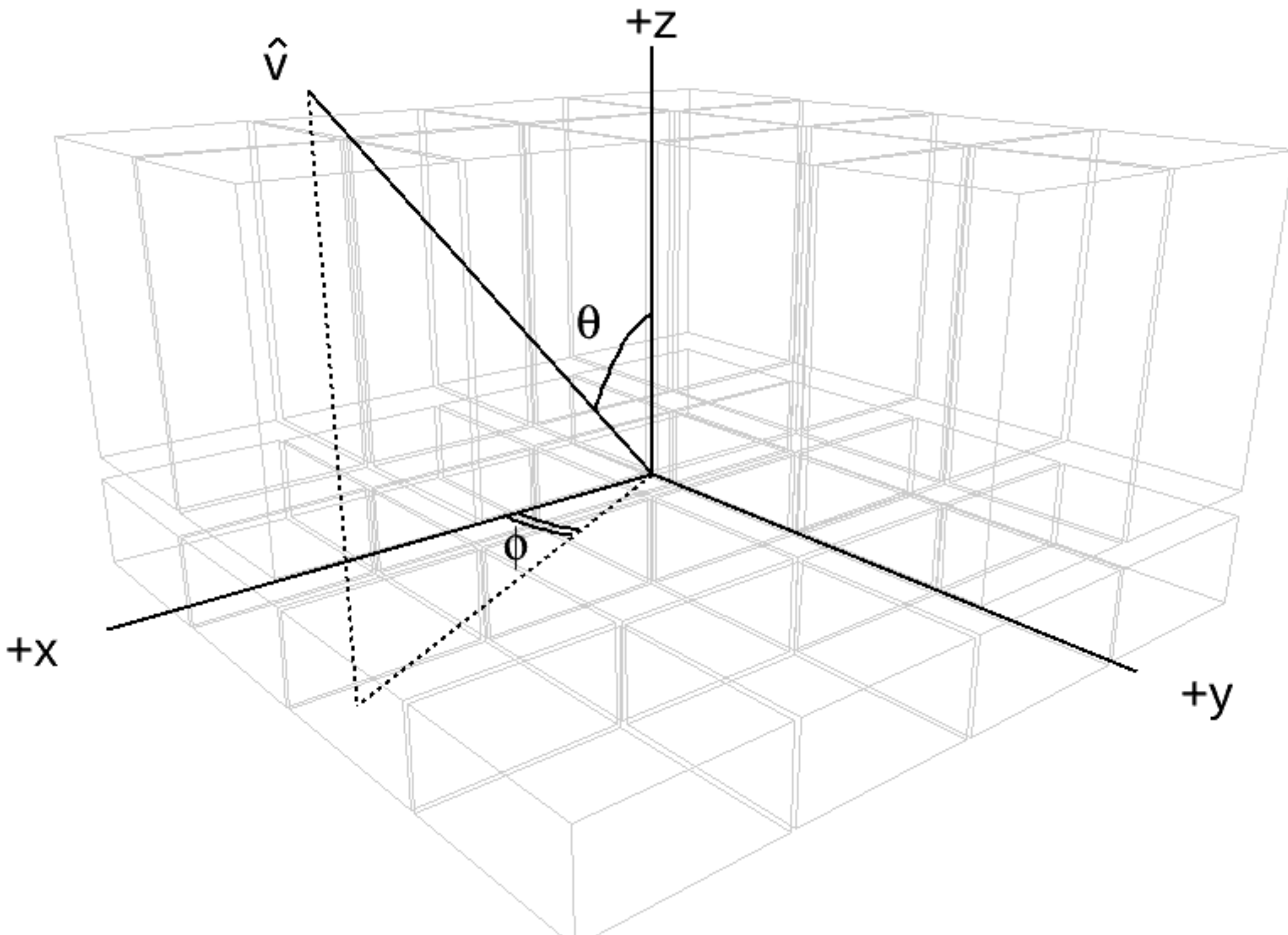


Factor of > 10^5 in bkg. reduction is achieved in several stages.

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

INSTRUMENT RESPONSE FUNCTIONS

LAT Coordinate system



Instrument Response Functions

Measured Energy & Direction

Effective Area

Energy Dispersion

$$R(E', \hat{v}'; E, \hat{v}) = A_{eff}(E, \hat{v}) P(\hat{v}'; E, \hat{v}) D(E'; E, \hat{v})$$

Point-spread Function (PSF)

True Energy & Direction

Expected Count Rate

Source Flux

$$\frac{dM(E', \hat{v}')}{dt} = \int \int R(E', \hat{v}'; E, \hat{v}) F(E, \hat{v}) d\hat{v} dE$$

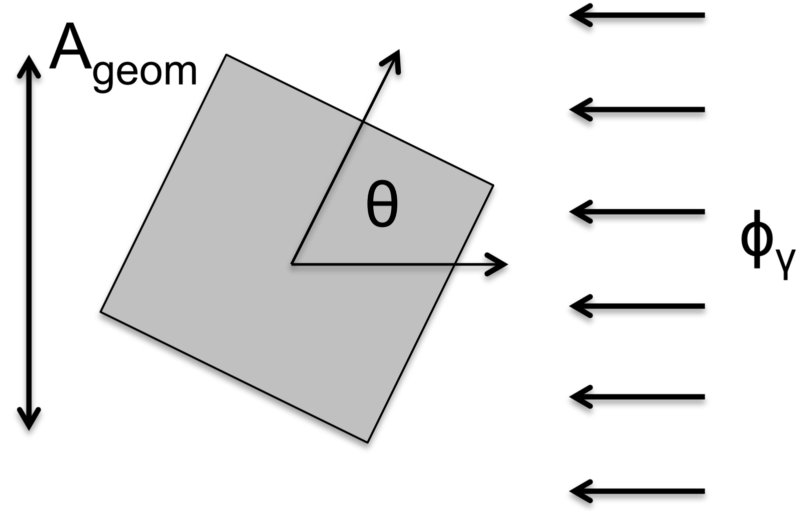
Instrument Response

Instrument Response Functions (IRFs) provide a translation between the true flux of gamma-rays on the sky and measured distribution of energy and direction in the LAT data.

We parameterize our IRFs as a function of gamma-ray energy and its arrival direction in the LAT coordinate system.

Effective Area

- Effective area combines the **geometric cross section** of the LAT with the average **detection efficiency**
- If the LAT was 100% efficient at detecting gamma-rays this would be equal to the projected geometric area of the LAT (A_{geom})
- Product of effective area and flux tells you the number of gamma rays you expect to detect per unit time



$$A_{eff} = A_{geom} \times \text{Efficiency}$$

$$R_\gamma = A_{eff} \times \phi_\gamma$$

PSF and Energy Dispersion

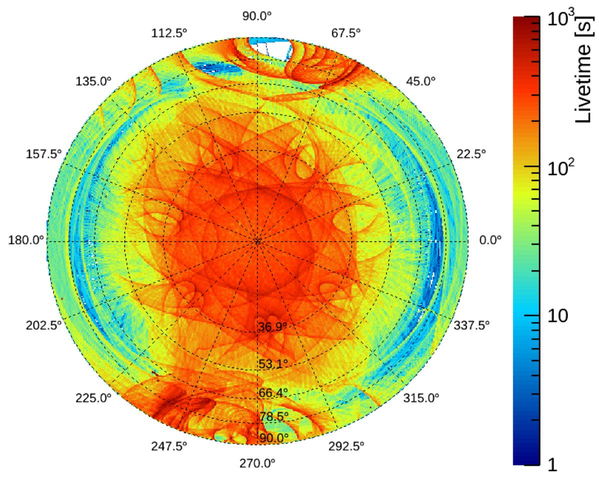
- Whereas the effective area is a scalar the PSF and Energy dispersion are both probability distribution functions (PDFs)
  - **PSF:** Probability to measure an event with direction **v**' given a true direction **v**
  - **EDISP:** Probability to measure an event with energy E' given a true energy E

- We generate the expectations for the measured distribution in E and **v** by performing a convolution of the true source model with each of these PDFs

- Note that the reverse process of deriving the true distribution from the measured one (i.e. deconvolution) can be nontrivial

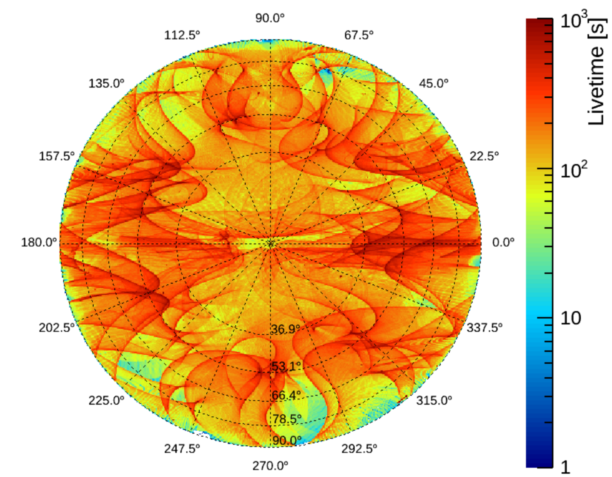
Effects of LAT Pointing

Vela: DEC = -45°, β = -60°

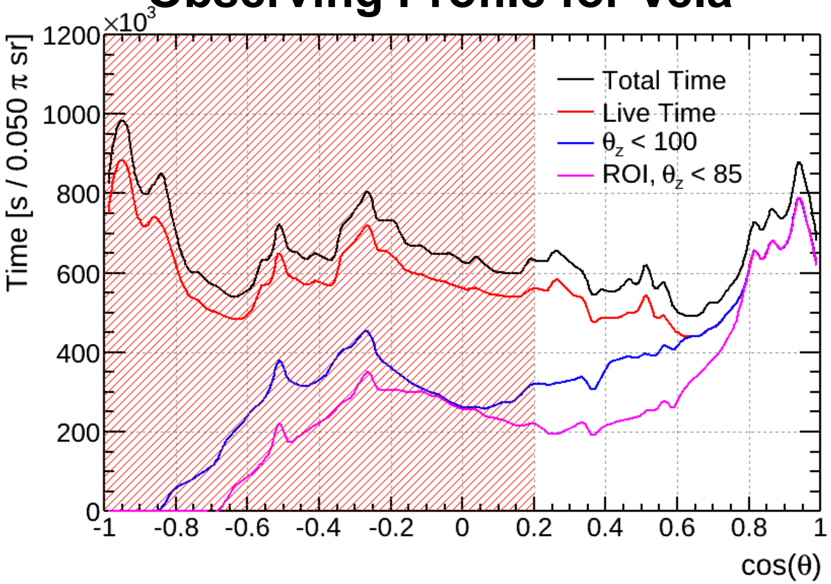


Each point in the sky traces a complicated path in the LAT frame which depends on declination and ecliptic latitude (β)

Crab: DEC = +22°, β = -1°



Observing Profile for Vela



The LAT response depends primarily on the angle w.r.t. the boresight (θ) "Observing profile": observing time as a function of θ

The "effective" instrument response at a point on the celestial sky is computed by weighting the response at each incidence angle by its livetime.

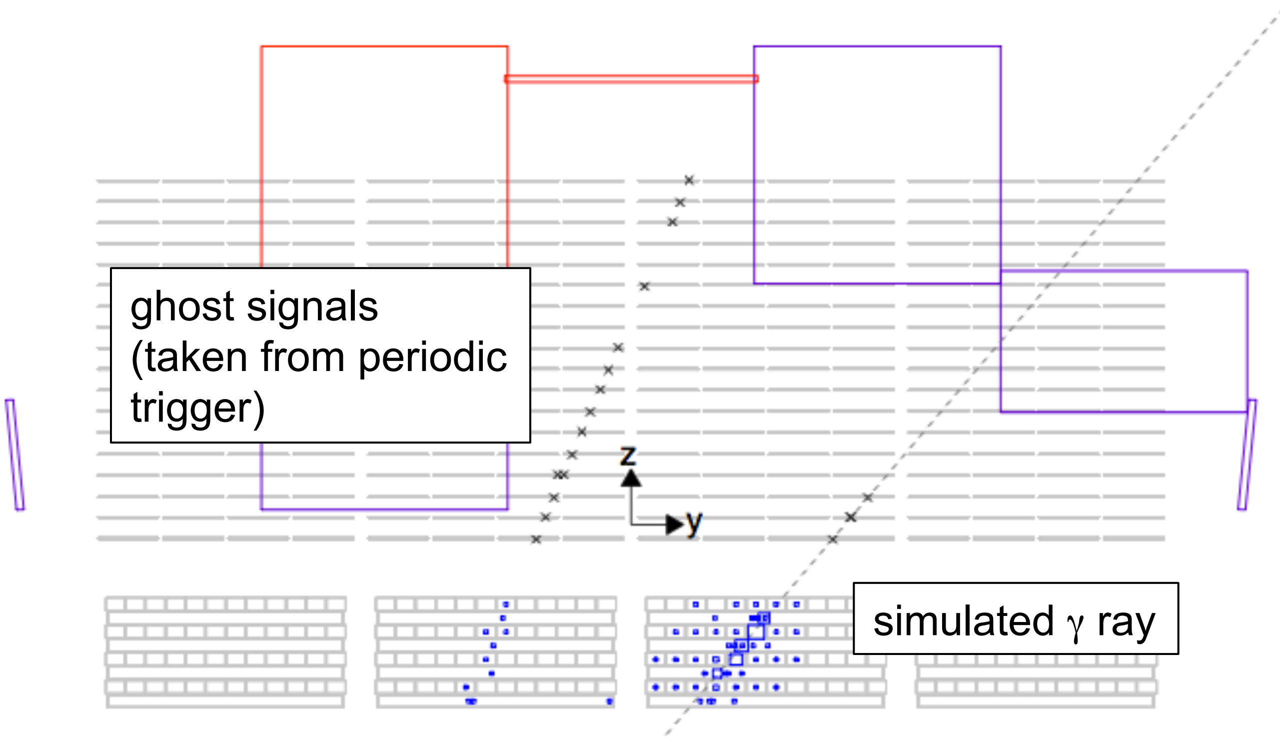
Deriving Instrument Response Functions

- LAT response functions are derived from a detailed MC simulation of the full LAT detector
  - GEANT4 is used to model the propagation of particles in the detector volume – this requires a detailed mass model for all detector components (geometry, material composition, etc.)
  - After simulation of particle interaction we simulate the LAT trigger, filter, and data acquisition
  - Reconstruction and Event analysis are then applied to the simulated data in the same way as flight data

- In practice we produce simulations of an isotropic gamma-ray source in instrument coordinates that spans all energies

- Simulated gamma-rays are then binned in energy and incidence angle and we fit/evaluate the response in each bin

Modeling the Ghost Effect



- The LAT response also depends on pileup effects – ghost signals which are left by out of time events
- We model ghost signals in our simulations by injecting **overlay** events into the MC
- We take overlay events from a library of periodic triggers which sample the quiescent state of the detector

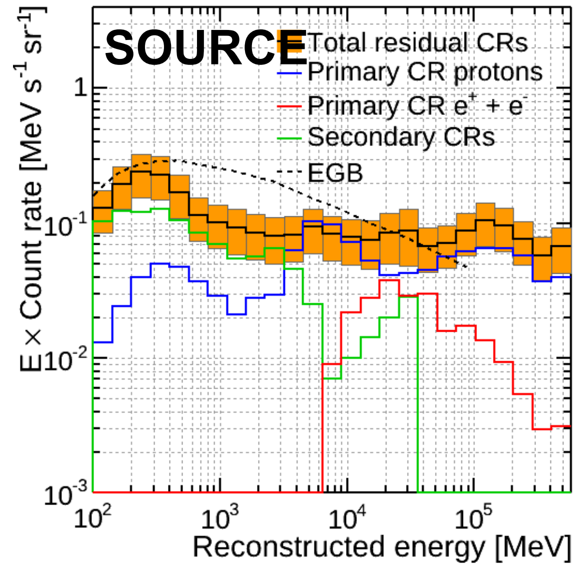
LAT IRF Models and Performance

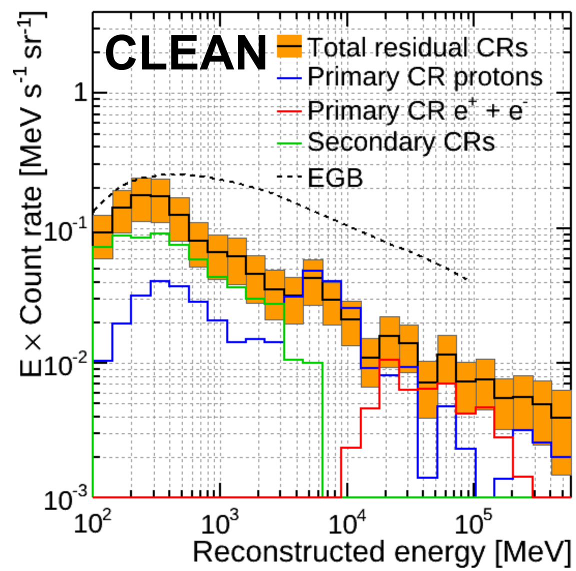
Event Classes

- In order to meet the requirements of different science analyses we provide event classes with different levels of background contamination
  - TRANSIENT: short timescale analysis (< 200 s)
  - SOURCE: point-source analysis and diffuse-source analysis at low latitude
  - CLEAN/ULTRACLEAN: diffuse-source analysis at high latitudes

- Each event class has its own set of response functions (effective area, PSF, and energy dispersion) – these are found in the CALDB of the ScienceTools

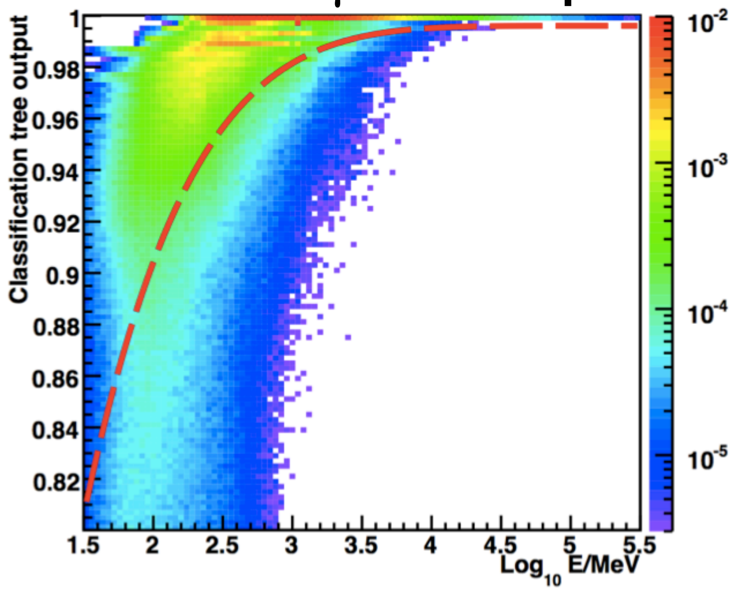
- In general the event class influences the PSF and EDISP response as well as the effective area





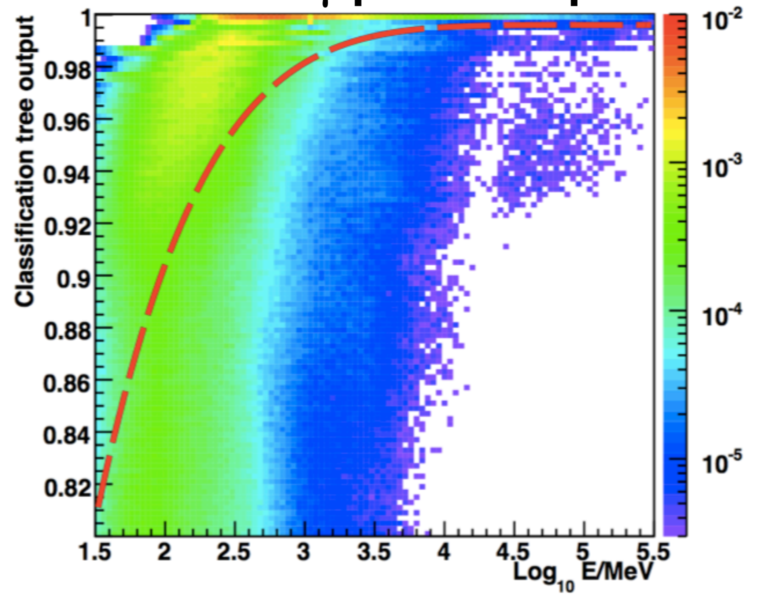
Tuning Cuts for Background Reduction

X v. E for γ-rich sample



Energy dependent cut rejects 5% of event at all energies.

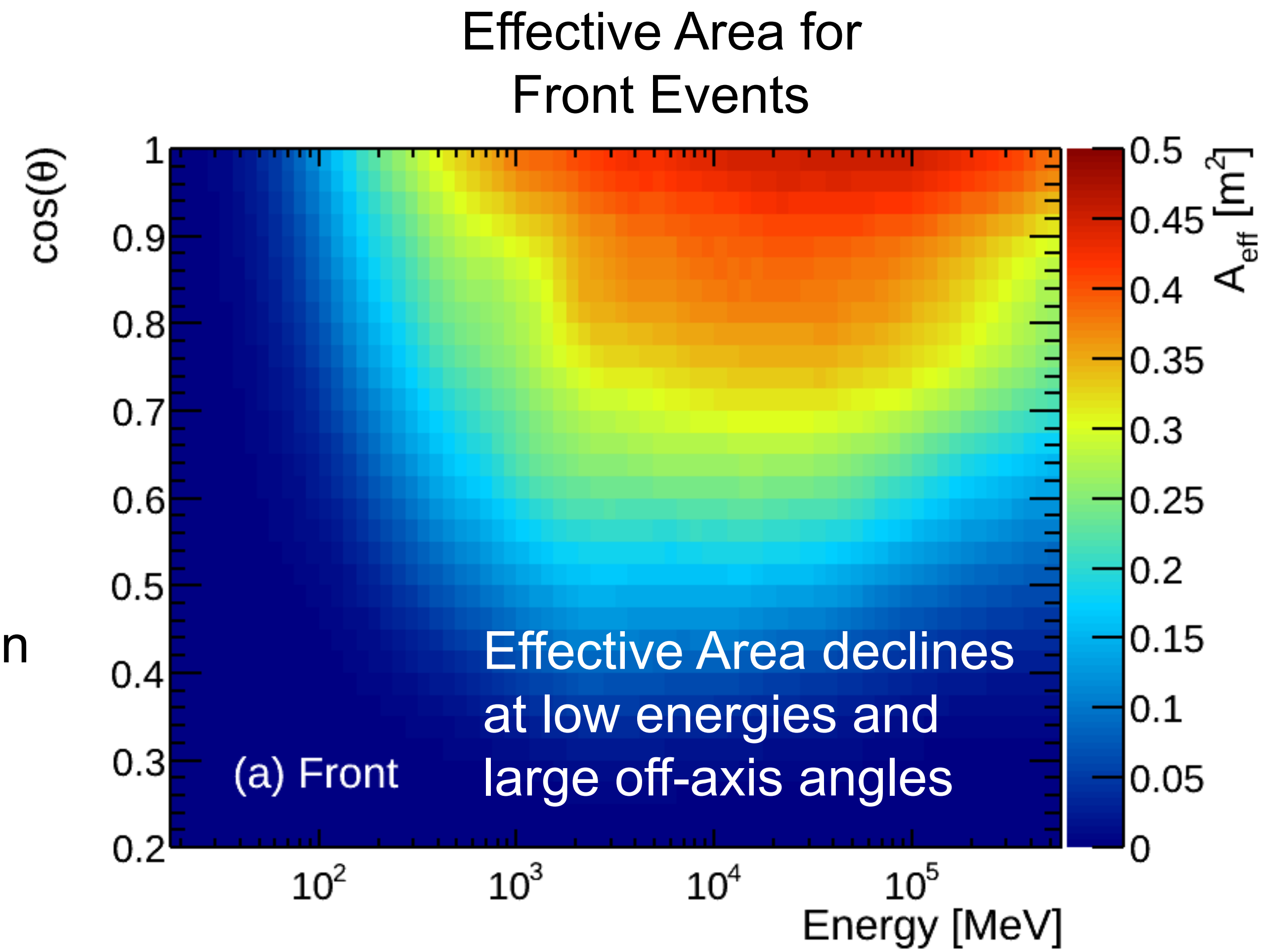
X v. E for γ-poor sample



Cut rejects larger fraction of events.

P7SOURCE, P7CLEAN and P7ULTRACLEAN were developed w/ flight data
Too much background to use this method for P7TRANSIENT.

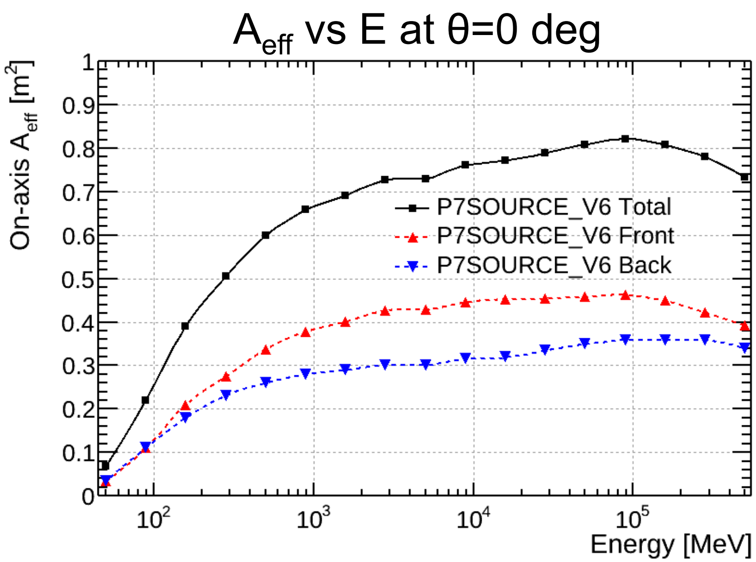
Effective Area

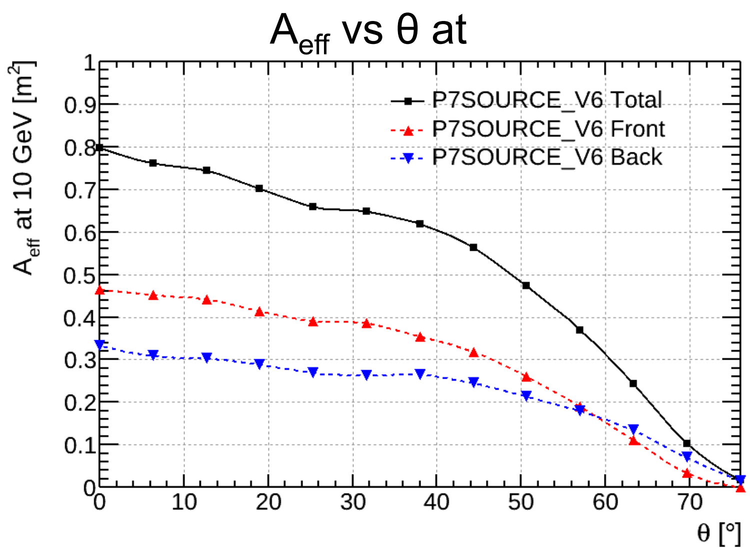


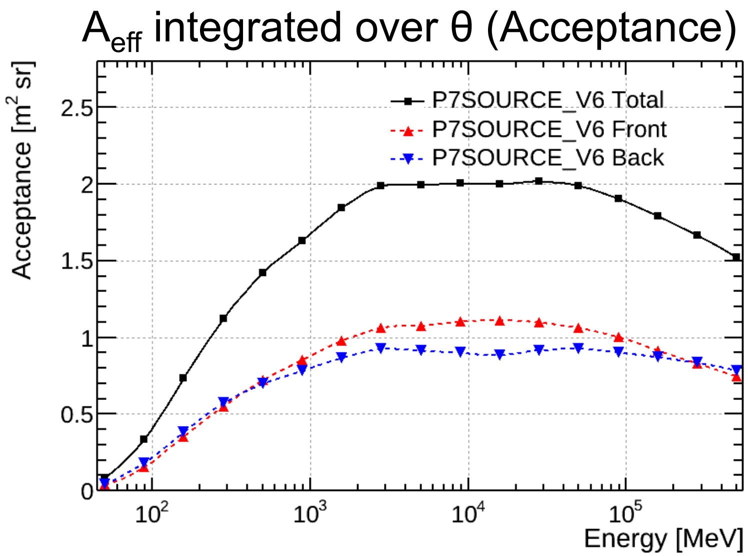
Inclination Angle

Gamma-ray Energy

Effective Area

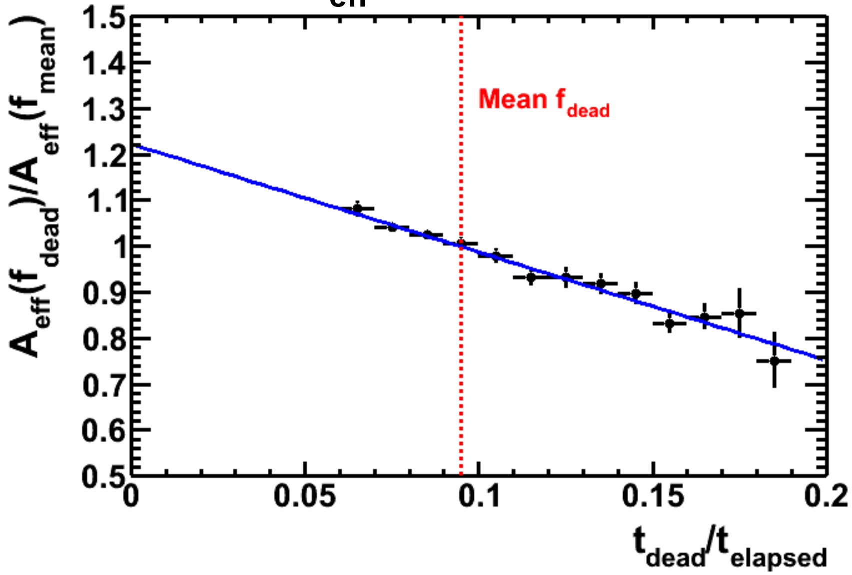




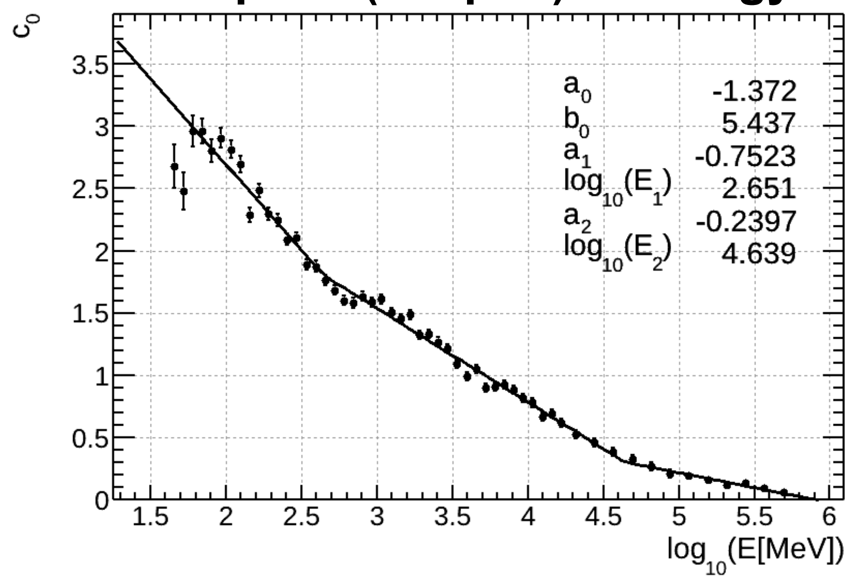


Post Launch MC-Based corrections to A_{eff}

A_{eff} v. Deadtime

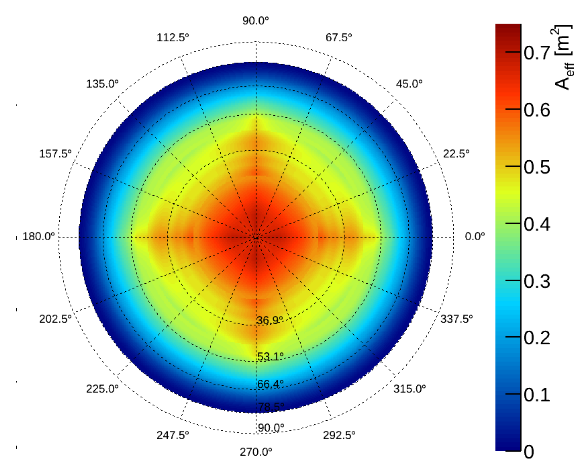


Slope of (left plot) v. Energy



A_{eff} is affected by ghost signals and correlates with trigger rate and "deadtime fraction".
"Overlay" periodic triggers from flight data on MC events to estimate scale of effect as a function of energy.

ϕ dependence map @ 10GeV



LAT Point-Spread Function

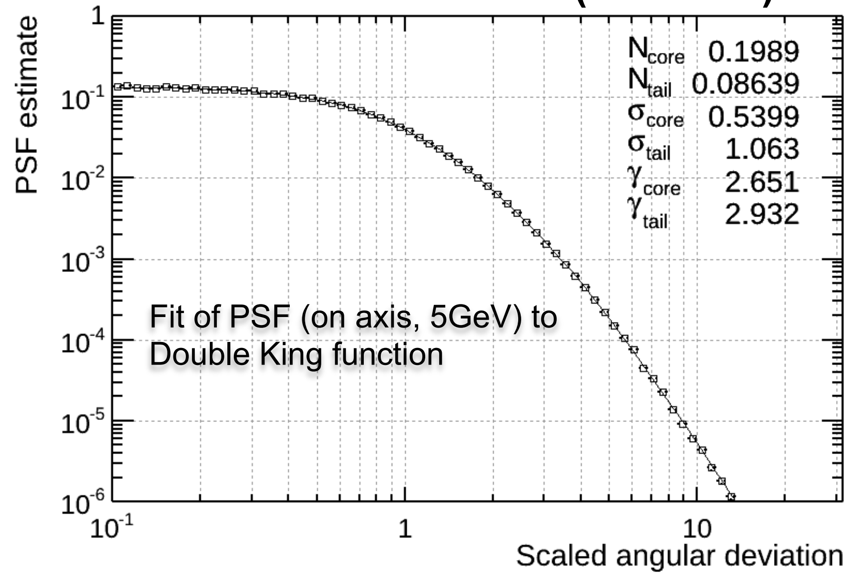
- We parameterize the LAT PSF as a double King function
- We use a King function instead of a gaussian to model the tails of the PSF –the King function reduces to a Gaussian in the limit that γ goes to infinity
- In order to remove the large variation of the PSF with energy we fit the IRFs in a dimensionless parameter (scaled angular deviation)
- We store the representation of the PSF as FITS tables with dimension of energy and inclination angle for the King function parameters (σ,γ)

King Function

$$K(x,\sigma,\gamma) = \frac{1}{\sigma^2}\left(1-\frac{1}{\gamma}\right)\left(1+\frac{x^2}{2\sigma^2\gamma}\right)^{-\gamma}$$

$$P(x,E) = f_{core}K(x,\sigma_{core}(E),\gamma_{core}(E)) + (1-f_{core})K(x,\sigma_{tail}(E),\gamma_{tail}(E))$$

MC PSF Distribution (E=5 GeV)



Point-Spread Function

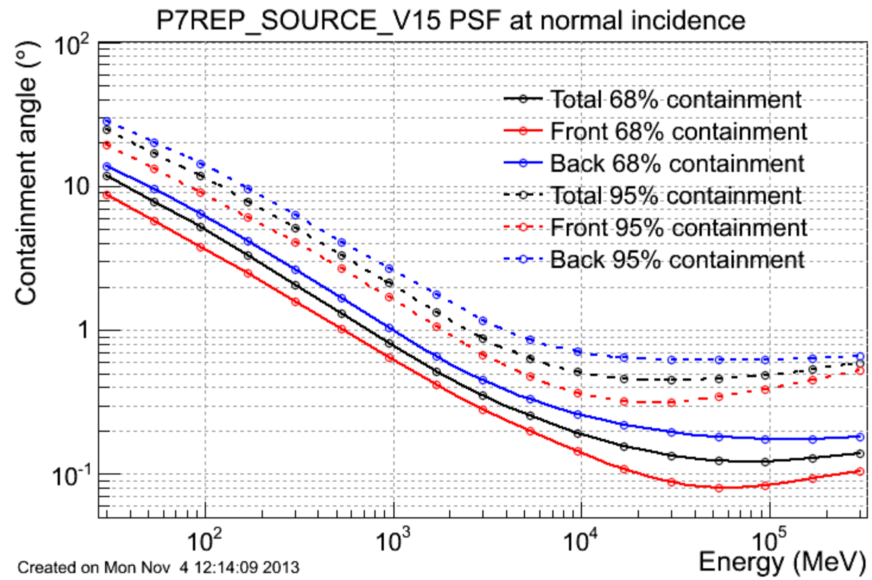
- LAT PSF approximately scales as the sum of two terms combined in quadrature

Multiple Scattering

$$\theta_{PSF} \propto \sqrt{(\theta_{MS}\ E^{-\beta})^2 + \theta_{IP}^2}$$

Instrument Pitch

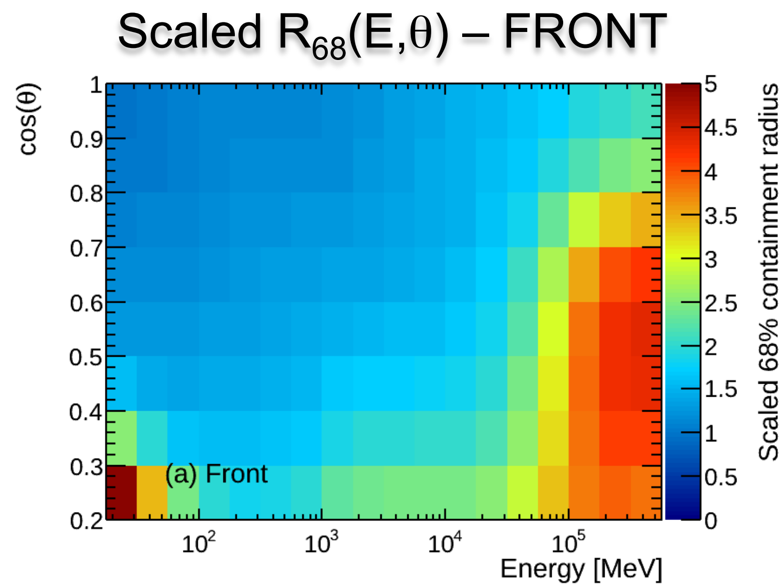
- At low energies multiple scattering dominates and the PSF improves as $\sim E^{-0.8}$
- At high energies the SSD pitch dominates and the PSF is approximately constant with energy
- Due to larger thickness of conversion foils the Back PSF is ~2x larger than the Front PSF

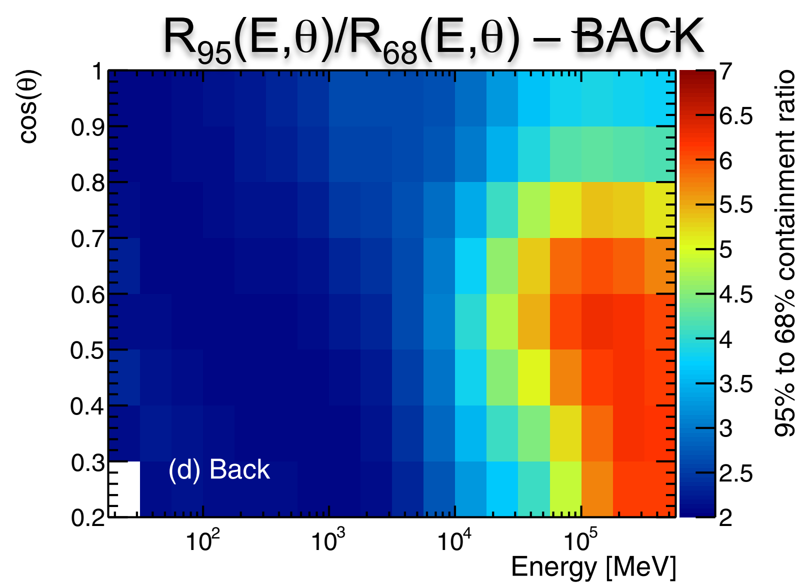


Point-Spread Function

- LAT PSF is generally better on-axis but variation with incidence angle is much smaller than with energy

- At high energies > 10 GeV the tails of the PSF are substantially larger due to CAL backsplash effect – this will be partially mitigated in Pass8



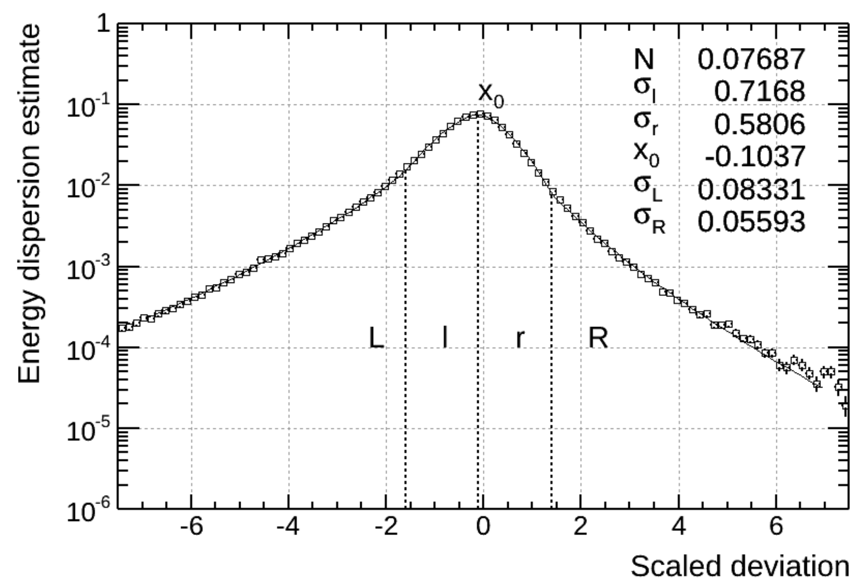


Energy Dispersion

- We use a piece-wise function to to fit independently the low and high energy part of the energy dispersion
- LAT energy dispersion is highly non-gaussian and asymmetric with a low energy tail that is generally larger than the high energy one
- Fitting is performed in a dimensionless variable (scaled deviation) which removes the first order dependence on energy and inclination angle
- As for the PSF we store the energy dispersion representation using FITS tables of the function parameters versus energy and inclination

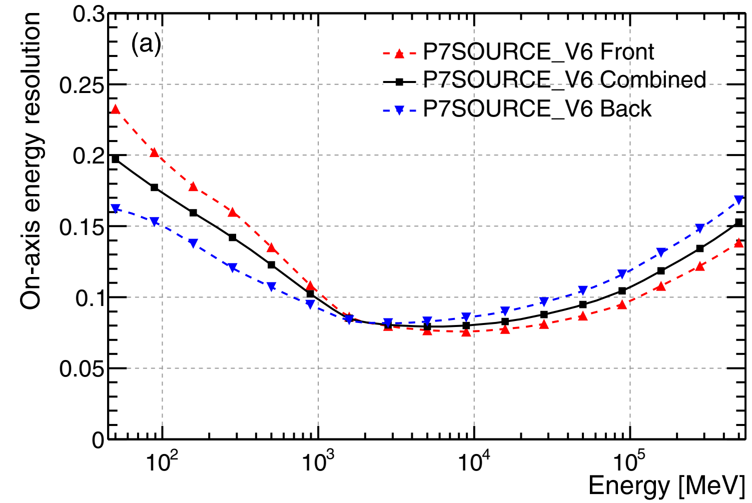
$$R(x, x_0, \sigma, \gamma) = N \exp\left(-\frac{1}{2}\left|\frac{x - x_0}{\sigma}\right|^{\gamma}\right)$$

$$D(x) = \begin{cases} N_L R(x, x_0, \sigma_L, \gamma_L) & \text{if } (x - x_0) < -\tilde{x} \\ N_l R(x, x_0, \sigma_l, \gamma_l) & \text{if } (x - x_0) \in [-\tilde{x}, 0] \\ N_r R(x, x_0, \sigma_r, \gamma_r) & \text{if } (x - x_0) \in [0, \tilde{x}] \\ N_R R(x, x_0, \sigma_R, \gamma_R) & \text{if } (x - x_0) > \tilde{x}. \end{cases}$$

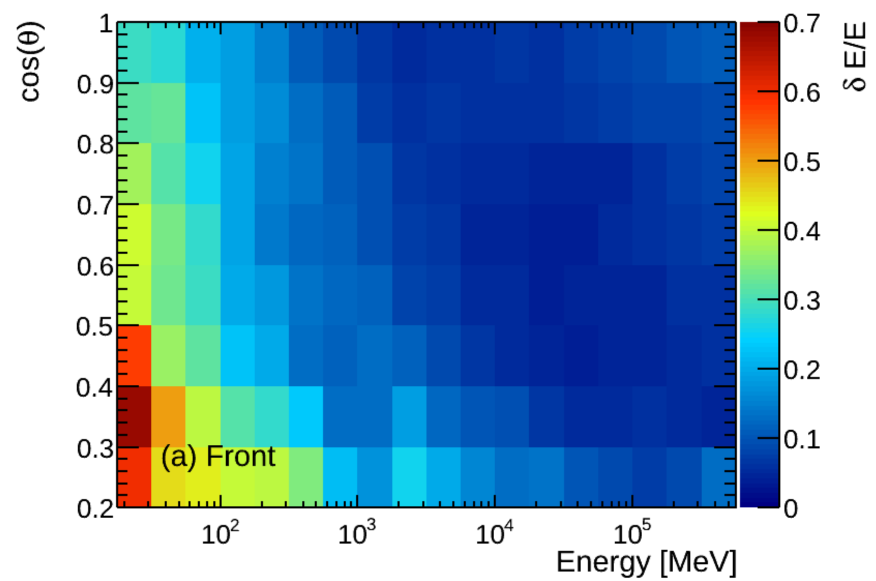


Energy Dispersion

- Behavior of energy dispersion over LAT phase space is quite different than for the PSF
- Variation with energy is much smaller and not monotonically improving with energy
- At high energies the energy dispersion actually improves off-axis due to larger path length through the CAL

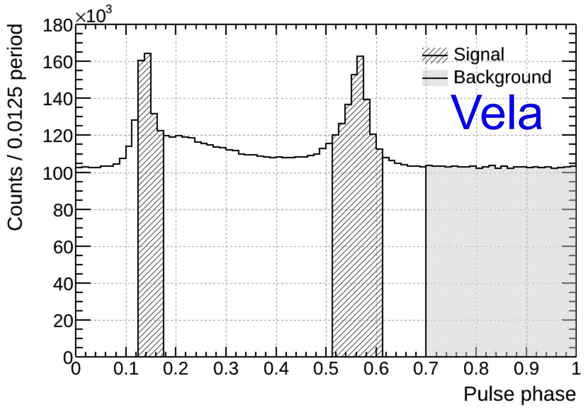


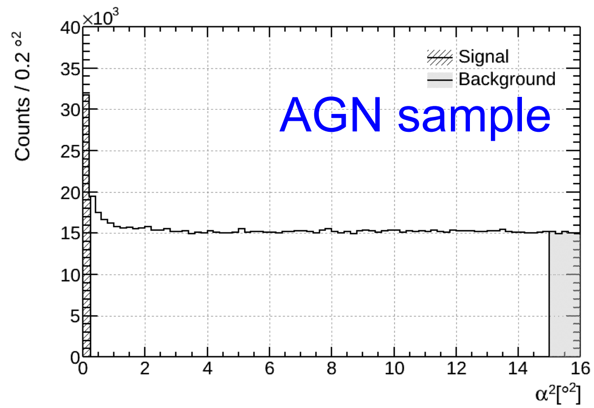
68% δE / E v. E, θ

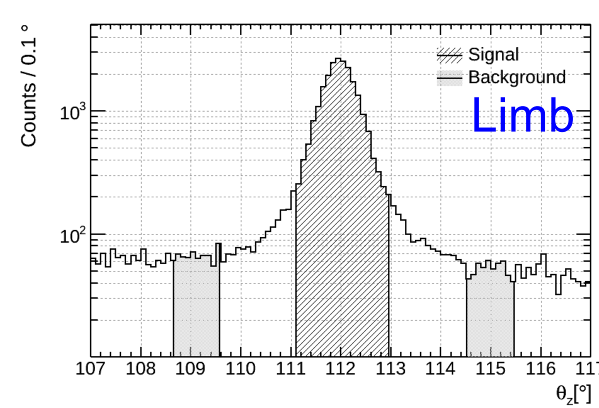


Validating and Calibrating the IRFs

Flight Data Calibration Samples

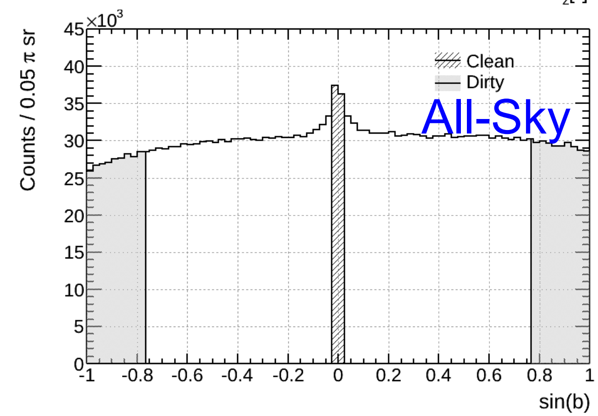


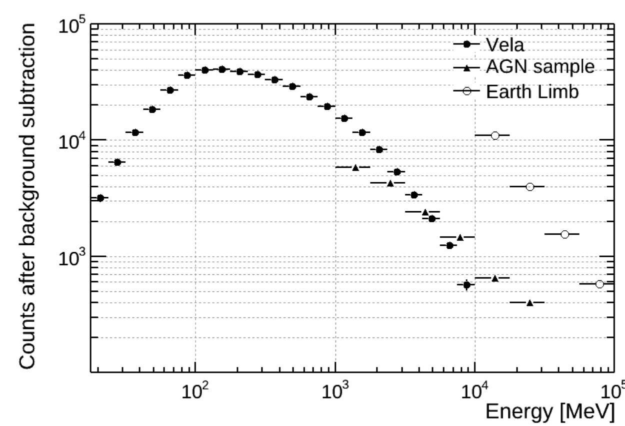




Shown for P7TRANSIENT event class

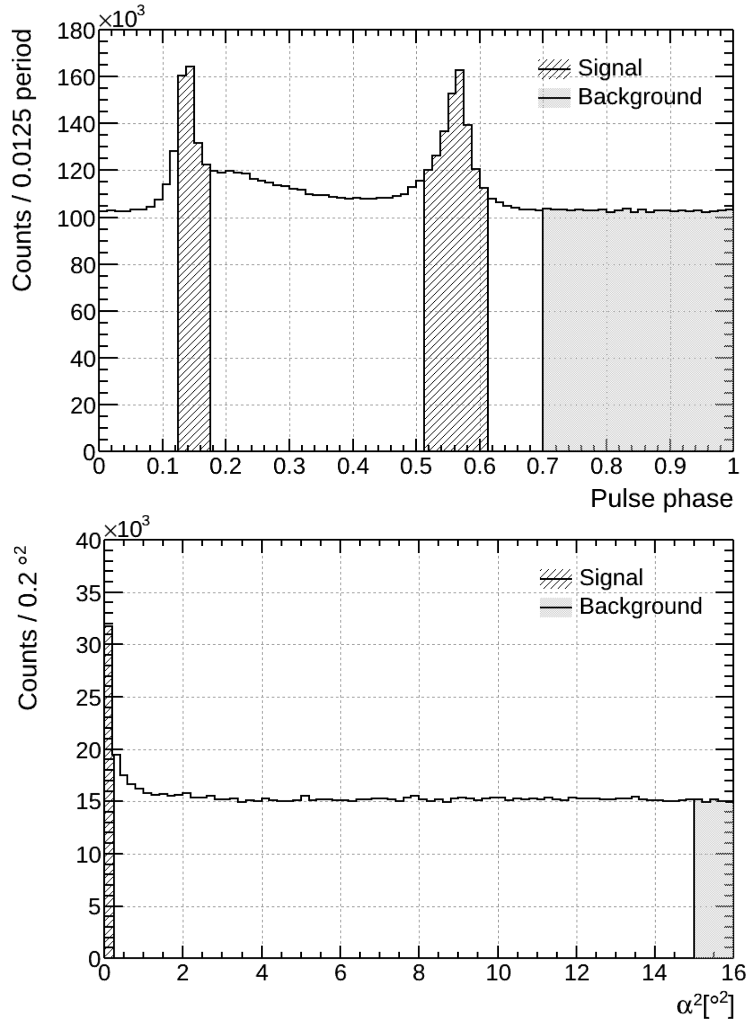
Calibration Sample	Method
Vela pulsar (2 years) 15° ROI, $q_{z,vela}$ > 85° Very clean bkg. subtraction but cuts off around 3 GeV	Phase-gated
76 Bright, isolated AGN (2 years) 6° ROI, q_z > 100°, E > 1 GeV Need small PSF for bkg. subtraction	Aperture
Earth limb (200 limb-pointed orbits) E > 10 GeV Difficult to model earth limb emission below ~ 10 GeV.	Zenith Angle cut
All Sky E > 10 GeV (also prescaled samples at lower E) Useful for optimizing selections, but not precise	Latitude



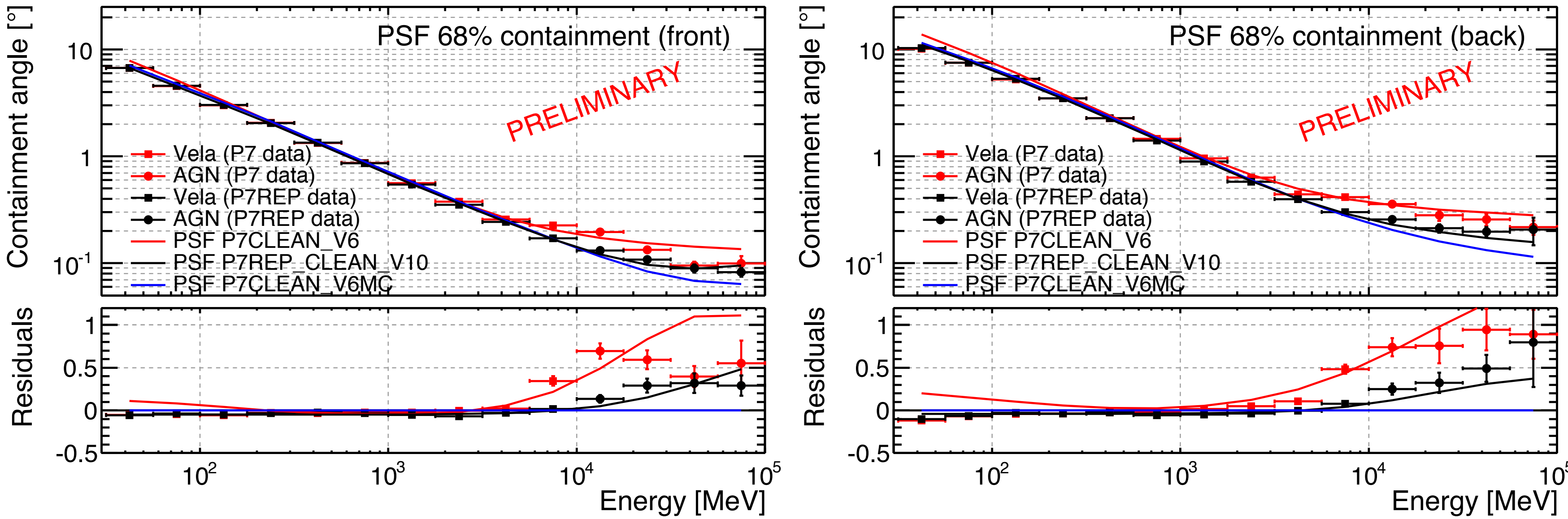


Validation and Calibration of the PSF

- To validate the PSF we use the Vela at low energies (< 10 GeV) and a sample of high latitude AGN at high energies (> 10 GeV)
- Since these sources have well-measured positions at other wavelengths we can measure the 'true' direction error of each gamma ray
- At each energy we construct the cumulative distribution of the gamma-ray excess and find the radius containing X % of the distribution



Validation and Calibration of the PSF

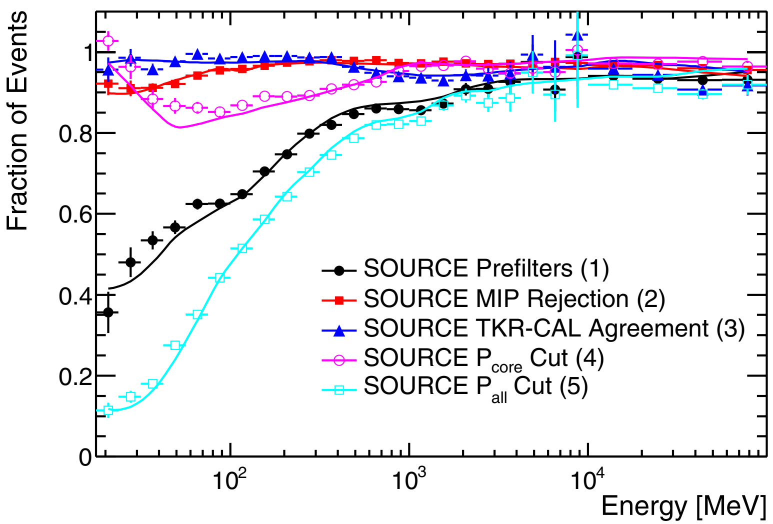


- One of the largest discrepancies seen in the IRFs after launch was in the high energy PSF which was systematically broader than predicted by the MC above ~1 GeV – this necessitated the creation of an in-flight PSF which was fit to our PSF calibration samples (Vela and AGN)
- The P7REP data release was generated with updated CAL calibrations that improved the PSF relative to the P7 release and eliminated most of this discrepancy
- We developed a new in-flight PSF model for P7REP to fit the remaining residuals above ~10 GeV

Validation and Calibration of Effective Area

- A useful way to check the consistency of our effective area model is to look at cut efficiency on a pure gamma-ray sample
- Cut efficiency analysis
  - Evaluate the ratio vs. energy (η_{data}) of events passing two selections where one selection is a subset of the other (e.g. SOURCE and TRANSIENT)
  - Evaluate the same ratio from MC (η_{MC})
  - If the MC is consistent with data then $R=\eta_{data}/\eta_{MC}$ should be equal to 1

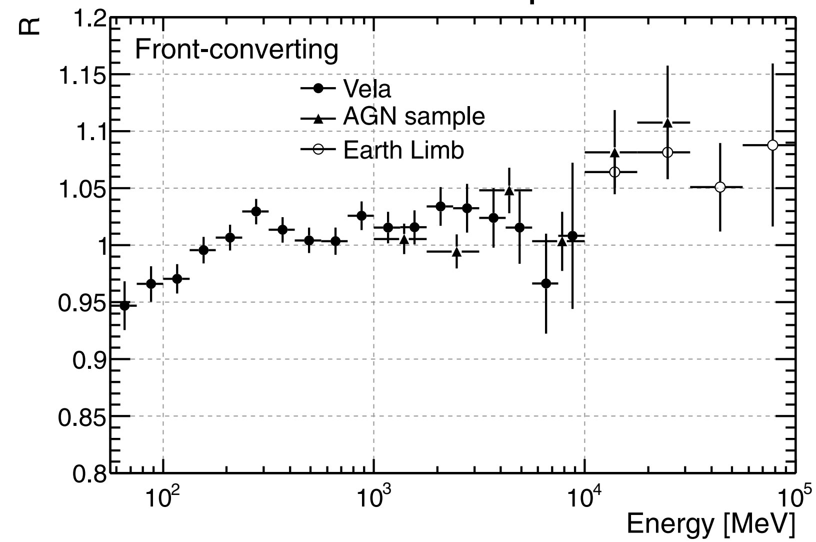
TRANSIENT to SOURCE Efficiency



Validation and Calibration of Effective Area

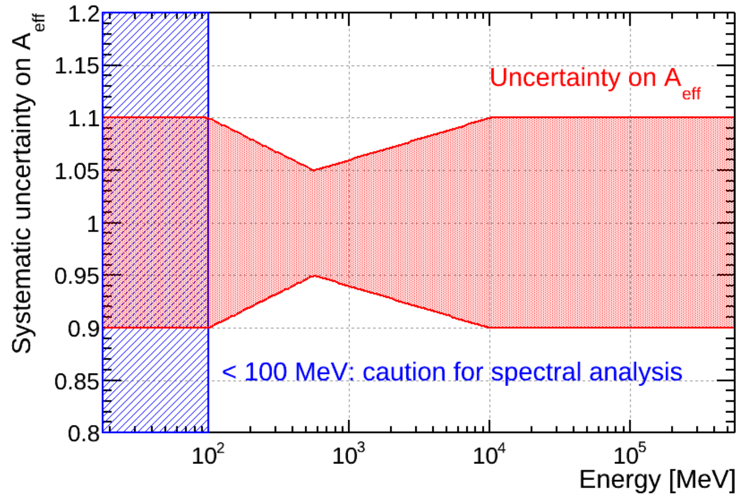
- We generally find very a good agreement in the efficiency ratio for most selections (< 2-3% residuals over the whole LAT energy range)
- Largest discrepancy observed in the fraction of front-converting events
- We attempt to correct for this discrepancy in the P7REP IRFs by applying a symmetric correction on the Front/Back ratio
- We use the magnitude of the front/back discrepancy versus energy to set the width of the systematic error envelope

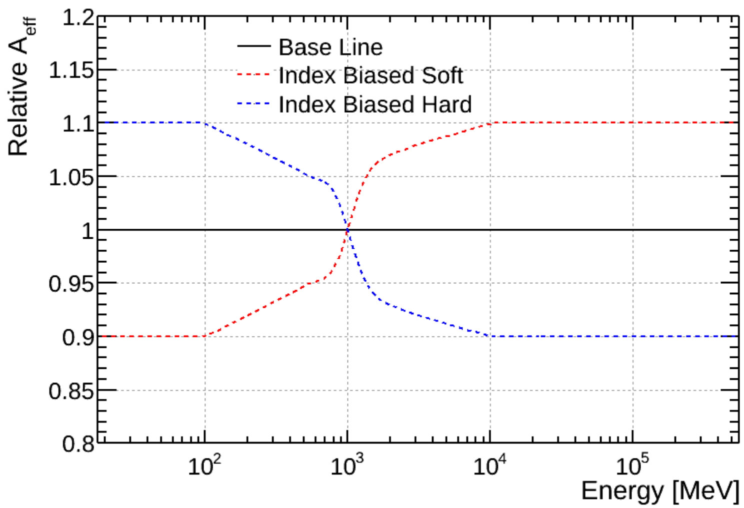
Ratio of Front-converting Event Fraction to MC Expectation



Assessing Systematic Errors in Analysis

- We define a conservative systematic error by drawing a symmetric envelope that encompasses the largest residual we observe in the effective area validation at each energy
- There are many ways to use this envelope to test the impact of systematics on your analysis – see e.g. discussion of bracketing IRFs in the Performance Paper
- Note that instrumental systematics are only one component of the total systematic error – astrophysical uncertainties in modeling the sky can be as large or larger than instrumental systematics
  - Unmodeled point sources
  - Errors in the isotropic and galactic diffuse templates





Summary

- LAT data is used to study a many topics in the γ-ray sky
  - Flexibility is need to account for many types of analysis
  - Huge amount of instrumental phase space to calibrate
- Validation studies with gamma-ray calibration samples verify that the IRFs provide a good description of the instrument
  - Residuals in effective area and PSF models are generally at the level of 2-3%
  - We conservatively assess the systematic error on effective area at 5-10% between 100 MeV and 300 GeV
- Current analysis and IRFs provide tremendous potential
- Work is ongoing to expand energy range, improve performance, and reduce systematic errors (Pass8)