LAT Performance

Overview of the Instrument Response Functions

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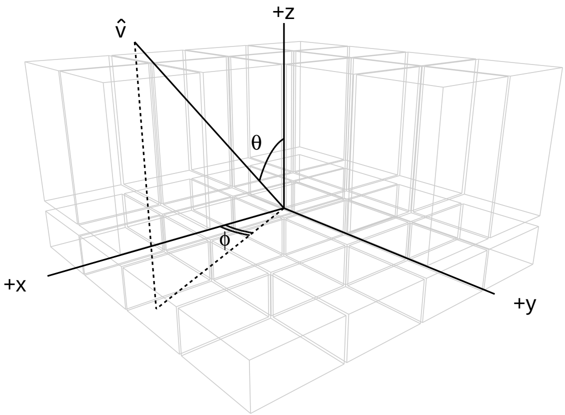
Outline

- Introduction and context.
- The Instrument Response Functions (IRFs):
  - effective area;
  - point-spread function;
  - energy dispersion.
- Systematic uncertainties on the IRFs (time permitting).
- Propagating the systematic uncertainties to high-level science analysis.
- And, of course, more exercises!

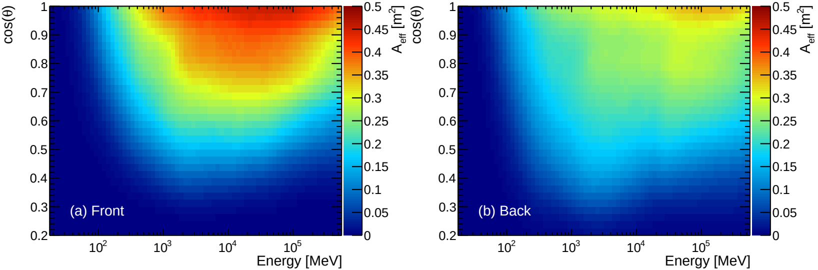
Parametrization of the IRFs

Definition of the coordinate system



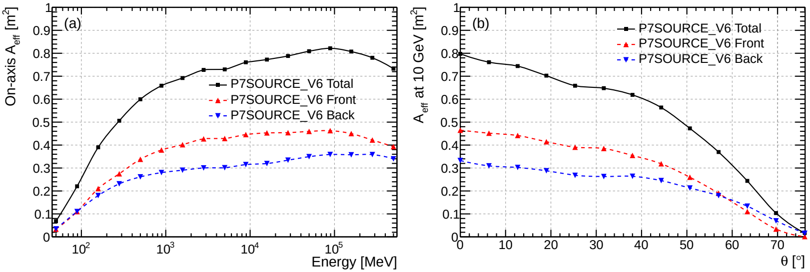
- IRFs parametrized as a function of the energy E and the direction (θ, ϕ) in instrument coordinates.
  - Strong dependence on E and θ, much weaker dependence on ϕ.
- Also: front- and back-converting events treated separately:
  - remember: front and back sections of the TKR have very different performance.

Monte Carlo A_{eff}



- $A_{\text{eff}}(E, \hat{v}, s)$: the product of the geometrical collection area, γ-ray conversion probability, and selection efficiency for a γ ray with energy E and direction $\hat{v}$ in the LAT frame.
- Generating the effective area tables (i.e., 2-dimensional histograms):
  - generate known isotropic incoming flux (with E^{-1} spectrum, i.e., with the same number of events for each logarithmic bin);
  - count how many events pass the selection cuts in each (E_i, θ_j) bin;
  - normalize to input flux.
- Note: we bin events in $\log E$ and $\cos\theta$:
  - ϕ dependence treated as a correction (more on this later);
  - the *ScienceTools* take care of the interpolations for you.

A_{eff} TABLES DERIVATIVES[1] (1/2)



—A_{eff} vs. E (at fixed θ).

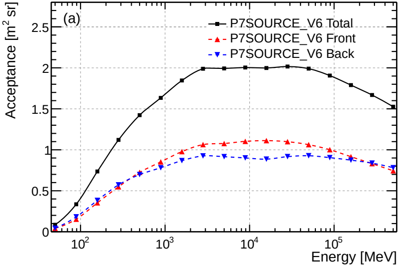
- On-axis A_{eff} increases up $\sim$ 100 GeV.
- $>$ 100 GeV: events are harder to reconstruct (backsplash).

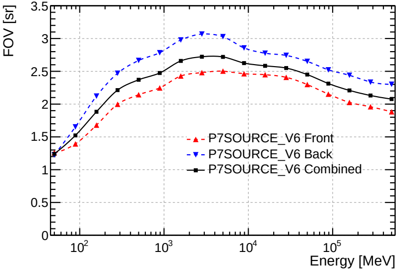
—A_{eff} vs. θ (at fixed E).

- Less cross section as you go off-axis.
- Off-axis events: easier for back-converting events to intercept the CAL.

- Exercise: Why is the effective area decreasing below $\sim$ 1 GeV?

[1] Here and in the following the IRFs are tabulated in correspondence of the markers and the points are smoothly connected





—Acceptance $\mathcal{A}(E)$:

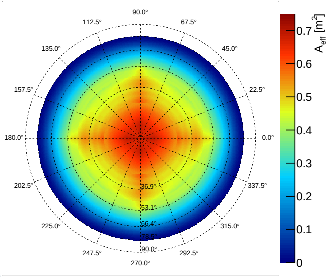
$$\mathcal{A}(E) = \int A_{\mathrm{eff}}(E,\theta,\phi)\, d\Omega$$

— Field of view FoV:

$$\mathrm{FoV}(E) = \frac{\mathcal{A}(E)}{A_{\mathrm{eff}}(E,\theta=0)}$$

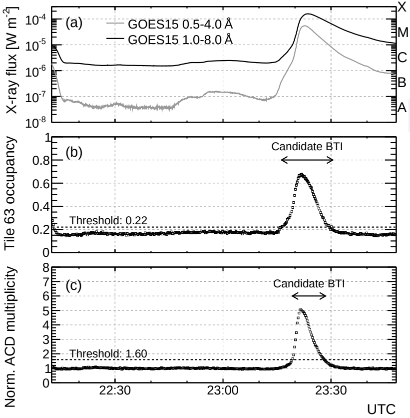
- Exercise: Estimate the high-energy on-axis A_{eff}, the high-energy acceptance and the corresponding FoV with paper and pencil.

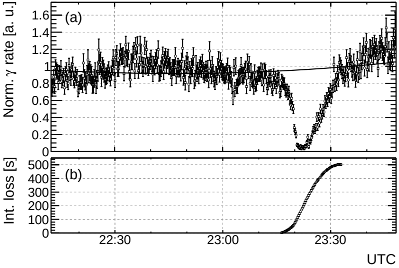
A_{eff} CORRECTIONS



- Correction for livetime dependence:
  - the ghost effect is taken into account *on average* in the MC simulations by *overlaying* a library of out-of-time triggers.
  - but the background rate is dependent on the geomagnetic location of the spacecraft, and tracked by the livetime fraction.
- Correction for the ϕ dependence:
  - treated as a correction on top of the average A_{eff} and included in the FITS files of the IRFs;
  - by default the phi dependence is not used in the *ScienceTools*;
  - generally negligible for long-time observations (see next slide).

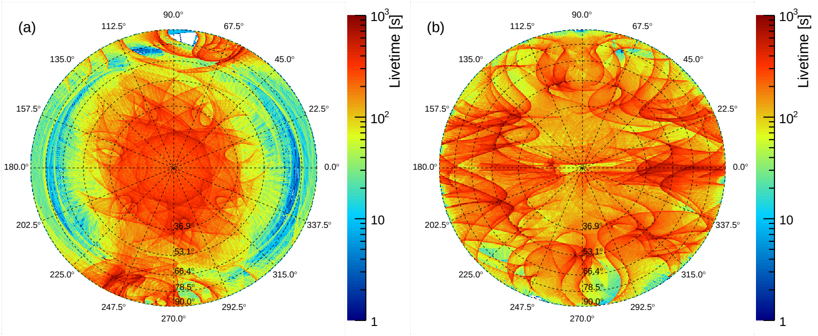
A_{eff} AND SOLAR FLARES



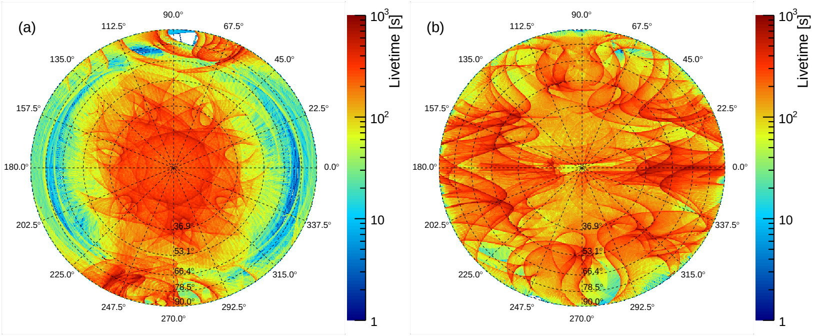


- During the brightest solar flares hard X-rays cause spurious activity in the ACD;
  - this causes otherwise reconstructable photons to be tagged as charged particles;
  - the IRFs do not adequately describe the instrument during these intervals.

Can you guess what these are?



Can you guess what these are?



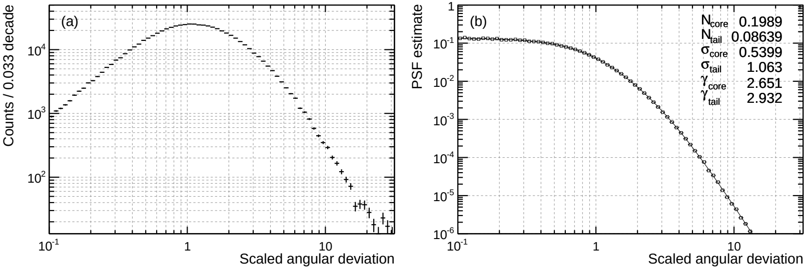
- Livetime maps in instrument coordinates.
- Credits: Eric Charles[2]
  - check them out at `http://apod.nasa.gov/apod/ap120504.html`.
- Take-away message: *things that average out in long-term observations do not necessarily do so on short timescales.*

[2] If you were here last year you would have met him in person.

- $P(\hat{v}'; E, \hat{v}, s)$: the probability density to reconstruct an incident direction $\hat{v}'$ for a gamma ray with $(E, \hat{v})$ in a given event selection.
- For a given point (E, θ) in the LAT phase space the PSF is not a single number (like $A_{\rm eff}$) but rather a p.d.f.:
  - need a functional form to parametrize it;
  - for the Monte Carlo PSF we use the sum of two King functions.

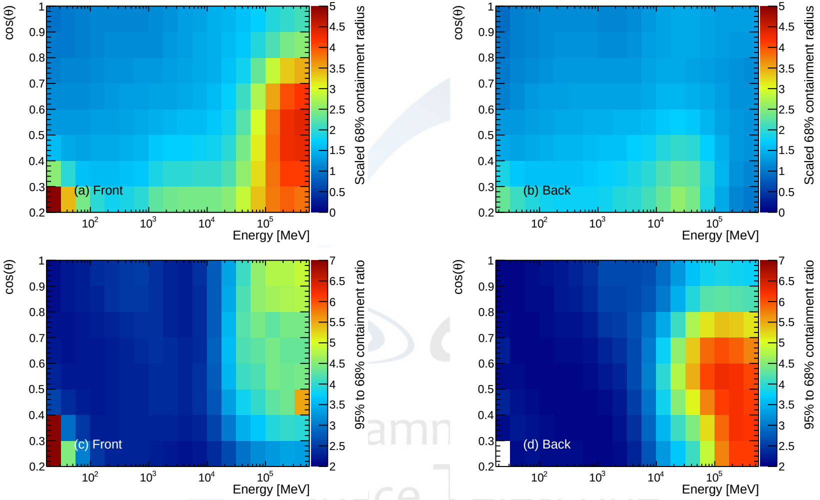
$$K(x, \sigma, \gamma) = \frac{1}{2\pi\sigma^2}\left(1 - \frac{1}{\gamma}\right) \cdot \left[1 + \frac{1}{2\gamma} \cdot \frac{x^2}{\sigma^2}\right]^{-\gamma}$$

- The PSF varies by orders of magnitude across the LAT energy range:
  - at low energy it is dominated by multiple Coulomb scattering in the W conversion foils (which scales like E^{-1});
  - at high energy it is determined by the TKR strip pitch and lever arm.
- Exercise: Estimate the asymptotic high-energy PSF for front- and back-converting events. Why are they different?
- Exercise: Estimate the rollover energy of the transition between the two regimes.



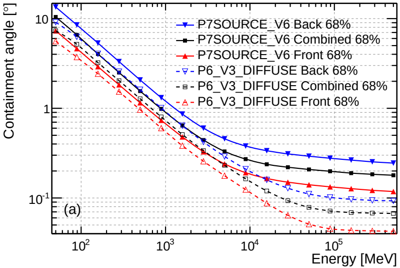
- PSF tables are generated with the same MC sample used for A_{eff}:
  - calculate $\delta v = |\mathbf{v}' - \mathbf{v}|$ event by event.
- First step: prescaling takes care of the PSF energy dependence:
  - Scaling function: $S_P(E) = \sqrt{\left[c_0 \cdot \left(\frac{E}{100\ \text{MeV}}\right)^{-\beta}\right]^2 + c_1^2}$.
  - Scaled angular deviation: $x = \delta v / S_P(E)$.
- x histogram is converted into a p.d.f. wrt solid angle and fitted with a double King function.
- In the FITS files of the IRFs we store the $S_P(E)$ parameters and the fit parameters.

Scaled angular deviation behavior



- A lot of richness in the (E, θ) plane.
  - remember: we prescale in energy, not in inclination angle.
  - (And we neglect the ϕ dependence of the PSF.)

In-flight PSF

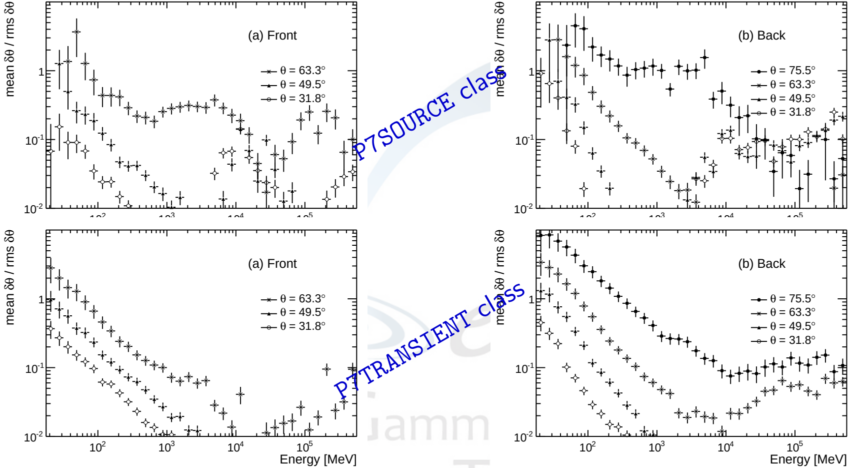


- Monte Carlo prediction for the width of the core of the PSF is underpredicted above a few GeV;
  - we think we understand the root cause and can mitigate it to a large extent (massive data reprocessing undergoing to demonstrate that).
- For the time being we derive the PSF directly from flight data, by means of a stacking analysis of selected point sources:
  - the statistics do not allow to determine the θ dependence;
  - the in-flight PSF is really a PSF averaged over the FoV;
  - (which is perfectly adequate for most long-time observations).
  - Also: in-flight PSF uses a single King function (does not match the 95% containmebt very well).

Fisheye effect

- Definition: bias in the reconstruction γ-ray directions toward the LAT boresight.
- Why does that happen?
  - Particles scattering toward the LAT boresight are more likely to trigger the instrument and be reconstructed;
  - especially true at low energy and large angles.
- Is it an important effect?
  - Generally not;
  - this is only a systematic bias in instrument coordinates;
  - over long integration time any source is typically seen at all angles;
  - *our PSF parametrization includes the broadening due to the fisheye effect.*
  - It is potentially important for short observations!
- How do you *measure* it?

$$\hat{\phi} = \frac{\hat{z} \times \hat{v}}{|\hat{z} \times \hat{v}|} \quad \hat{\theta} = \frac{\hat{\phi} \times \hat{v}}{|\hat{\phi} \times \hat{v}|} \quad \delta\theta = -\sin^{-1}\left(\hat{\theta} \cdot (\hat{v}' - \hat{v})\right)$$

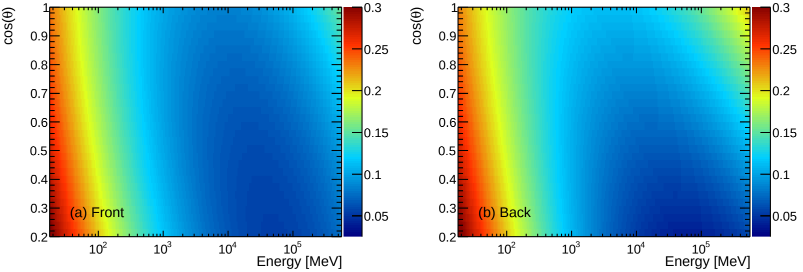


- Typically smaller than 1;
  - except for very low energies and very large angles;
  - and especially for the `TRANSIENT` class.

Energy Dispersion

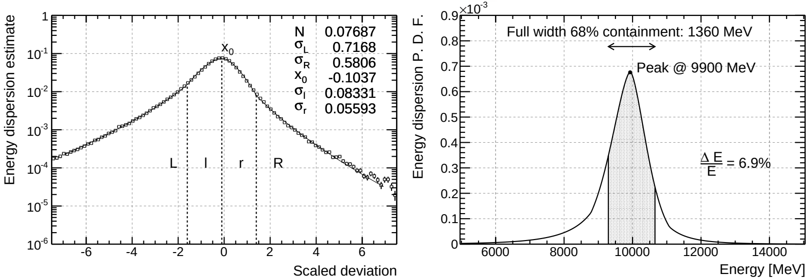
- $D(E'; E, \hat{v}, s)$: the probability density to measure an event energy E' for a gamma ray with $(E, \hat{v})$ in the event selection s.
- Parametrization strategy similar to that of the PSF in many respects.
- Unlike the PSF, the energy dispersion is ignored by default in the standard likelihood fitting:
  - negligible effect in many situations—except for energies below 100 MeV;
  - *ScienceTools* can now be told to take it into account.
  - Is it important? This will be the subject of our hands-on session.
- Energy dispersion prescaling:
  - scaling function: $S_D(E, \theta) = c_0(\log_{10} E)^2 + c_1(\cos\theta)^2 + c_2 \log_{10} E + c_3 \cos\theta + c_4 \log_{10} E \cos\theta + c_5$;
  - scaled energy deviation: $x = (E' - E)/(E S_D(E, \theta))$.
- Fitting of the scaled variable:
  - 4 piecewise Rando functions: $R(x, x_0, \sigma, \gamma) = N \exp\left(-\frac{1}{2}\left|\frac{x - x_0}{\sigma}\right|^{\gamma}\right)$;
  - fit parameters stored in the FITS files of the IRFs.

Energy dispersion scaling function



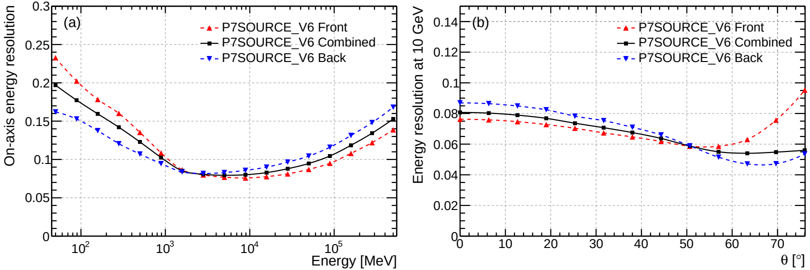
- Again, a lot of richness as a function of E and θ.
- Beware: the value of the scaling function at a particular energy/angle is not the energy resolution at that energy/angle;
  - (the two things are obviously related to each other, though, as both represent the width of the energy dispersion.)
- We define the energy resolution as the half width of the energy window containing $34\% + 34\%$ (i.e., 68%) of the energy dispersion on both sides of its MPV, divided by the MPV itself.

Scaled deviation and energy dispersion



- Note that the low-energy tail is relatively more prominent than the high-energy one.
- Exercise: If you had to choose, would you prefer a pronounced low-energy or high-energy tail?

Energy resolution



—Energy resolution vs E:

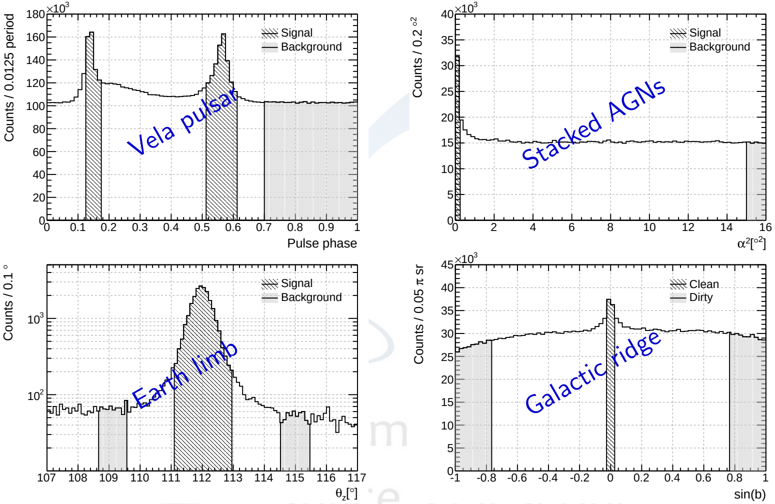
- sweet spot between $\sim$ 1–100 GeV;
- low energy: energy deposited in the TKR not negligible anymore;
- high-energy: shower leakage becoming dominant.

— Energy resolution vs. θ:

- energy resolution improves at large angle (more path length in the CAL);
- more pronounced at very high energy (above 100 GeV);
- behavior above 60° off axis irrelevant (no acceptance there).

Validation of the IRFs

VALIDATION DATA SAMPLES

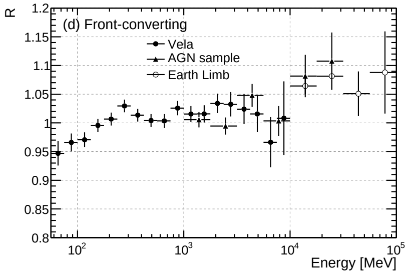


- We have plenty of flight data for validation purposes:
  - different sources and background subtraction methods allow to extract clean photon samples across most of the LAT phase space.

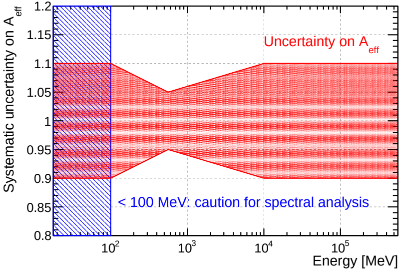
Effective area validation

- There is no astrophysical source whose flux is perfectly known.
- But the effective area is essentially a measure of the selection efficiency:
  - can study the efficiency cut by cut;
  - (remember: this includes *all the selection steps*: from triggering and filtering to the definition of the event classes).
- Compare the cut efficiency on Monte Carlo and flight data sets.
- Also: devise and perform consistency checks:
  - e.g., do events split themselves between front and back as predicted by the Monte Carlo simulations?

An important consistency check



- Fraction of events converting in the front section of the TKR relative to the MC prediction:
  - sensitive to possible inaccuracies in our description of the detector materials and geometry.
- This is one of the most significant discrepancies observed when comparing flight data with Monte Carlo simulations;
  - and the most important piece of information for estimating the uncertainties of our effective area.



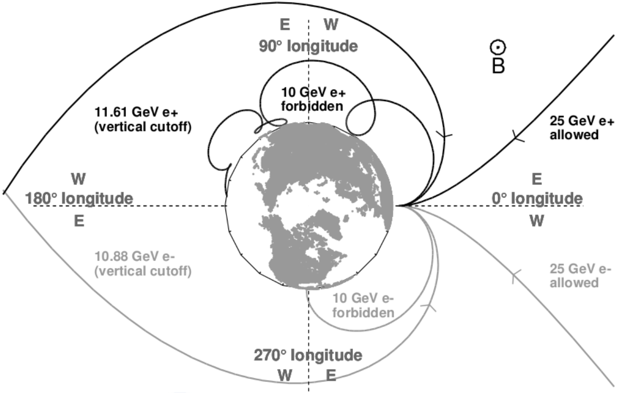
- Summary of our understanding of the effective area.
  - Below 100 MeV the worsening of the energy resolution, coupled with the steep falling of the effective are make the effect of the energy dispersion potentially noticeable.
- Note that this is just an error envelope:
  - no information about what type of deviation we might expect within the uncertainty band.
- Point-to-point correlations?
  - Yes: strong correlation on energy scales much lower than half a decade (look at the previous slide).

PSF validation

- In many respects easier than $A_{\rm eff}$: we have point sources at *known* (from other wavelengths) locations:
  - most notably pulsars and AGNs;
  - which is what we use to derive the in-flight PSF;
  - caveat: in some cases a deviation from a point source (e.g., a halo) is the physical effect we are searching for.
- Compare the measured 68% and 95% PSF containment radii for selected point sources with the PSF parametrization:
  - do it for on-axis and off axis events: this tells you how much of the PSF richness we are really capturing in our representation.
- Remember: by default you are using a PSF parametrization averaged over the LAT field of view:
  - for short-time observations this might be an issue!

Energy measurement validation

- Two very different aspects of the validation of the energy measurement:
  - energy dispersion (event by event fluctuations around true value);
  - absolute energy scale (common systematic error).
- Suppose you are studying a strong γ-ray line:
  - the uncertainty in the energy dispersion determines how the line looks smeared in the detector;
  - the uncertainty in the absolute energy scale determines the offset in the peak position.
- This is where things get really tricky in terms of in-flight validation:
  - there is no astrophysical γ-ray source with a sharp feature at a perfectly known energy.
- We do have many pieces of information anyway: ground tests, beam tests, measurement of the CRE geomagnetic cutoff.
- We understand the energy resolution at the $\sim 10\%$ level...
  - negligible in most practical situations.
- ...and the absolute scale within $+2/-5\%$.



- The power-law spectrum of primary CRs is effectively shielded by the magnetic field of the Earth;
  - the effect depends on the position of the LAT across the orbit.
- The cutoff energy can be predicted by means of a model of the magnetic field and a ray-tracing code:
  - several calibration point between ~ 5 and ~ 15 GeV.

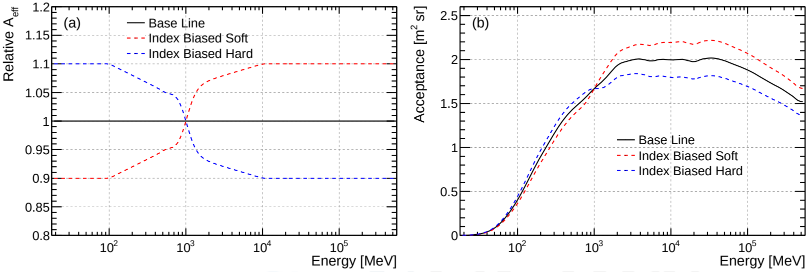
Propagating systematic uncertainties.

A_{eff} BRACKETING FUNCTIONS

- Scale A_{eff} by the product of the relative error $\epsilon(E) = \frac{\delta A_{\text{eff}}(E)}{A_{\text{eff}}(E)}$ (see slide 25) and an arbitrary bracketing function $B(E)$:
  - $A'_{\text{eff}}(E, \theta) = A_{\text{eff}}(E, \theta) \cdot (1 + \epsilon(E)B(E))$.
  - Creating modified A_{eff} curves is as easy as opening the A_{eff} FITS files, doing some multiplications and saving new files.
- The most appropriate choice of the bracketing function depends on the quantity we're interested in:
  - $B(E) = \pm 1$ maximizes/minimizes A_{eff} within its uncertainty band leaving the spectral index $\sim$ unaffected.
- Note: the public Galactic and isotropic diffuse emission models are fit to the data using the standard effective area tables:
  - need to rescale the diffuse models by the inverse of $B(E)$ to ensure the expected numbers of counts are unchanged.
- Basic idea: repeat the analysis with a family of modified A_{eff} curves and see how the measured quantities change:
  - use the maximal changes to estimate the systematic errors.
- On a separate note: modified IRFs can be used with *gtobssim* too.

A_{eff} BRACKETING FUNCTION EXAMPLE

MAXIMIZING THE EFFECT ON THE SPECTRAL INDEX IN A POWER-LAW FIT



- Use a function that changes sign at the pivot (or decorrelation) energy (i.e., the energy at which the fitted index and normalization are uncorrelated):
  - for example $B(E) = \pm \tanh\left(\frac{1}{k}\log(E/E_0)\right)$;
  - $k = 0.13$ corresponds to smoothing over twice the LAT energy resolution.

PSF and edisp bracketing functions

- The PSF and energy dispersion being probability density functions, using bracketing IRFs is more tricky;
  - you have to modify the appropriate parameters in a self-consistent way to generate families of reasonable IRFs;
  - (e.g., wider or narrower PSF and energy dispersion, offset in the absolute energy scale).
  - the way the IRFs are parametrized and stored in the FITS files of the IRFs is not always optimal for that.
- But it can be done with a little bit of thought!
- Exercise: Evaluate (with paper and pencil) how an error ϵ in the absolute energy scale affects the measured flux for a power-law spectrum assuming $A_{\rm eff}$ is constant.

- The LAT is a complicated instrument:
  - performance figures vary a lot across the phase space;
  - there's a lot going on behind the scenes as you run a typical science analysis.
- The LAT team has put a huge effort into understanding the instrument and is continuing to do so:
  - the IRFs are being regularly updated and released to the public.
- Propagating the systematic uncertainties to high-level science analysis can be tricky:
  - Wouldn't it be nice if it was possible to produce a table with all the numbers that you need for your preferred analysis?
  - Unfortunately that's impossible: the answer can be given only on a case-by-case basis.