Pass 8: A comprehensive revision of the Fermi LAT event-level analysis

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on behalf of the Fermi Large Area Telescope Collaboration

Abstract

The event simulation and reconstruction framework developed for the Fermi Large Area Telescope before the launch performed beyond our expectations and proved to be adequate for the science of the first two years. This framework has been regularly updated to reflect the constantly improving knowledge of the detector and of the environment in which it operates. In parallel, a coherent long-term effort is ongoing, aimed at a radical revision of the entire event-level analysis based on the experience gained in the first phase of the mission. The basic ingredients of the new event simulation and reconstruction are in place and ready to serve as input into the new background rejection chain, which is now being developed.

Pass 8 will come close to realizing the full scientific potential of the LAT. The expected improvements include (but are not limited to) greatly reducing the backgrounds, increasing the effective area, arriving at a better understanding of the systematic uncertainties and extending the energy reach of the photon analysis below 100 MeV and above 100 GeV.

Introduction

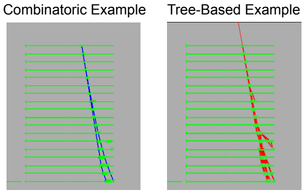
The LAT instrument [1] affords a detailed view of each triggered event. The detector elements and technologies for this mission were selected for their high efficiency, long-term stability and access to fine granularity. This, coupled with a very detailed Monte Carlo simulation, allows pushing the event-level analysis to levels not usually reached in either astro-physics or particle physics. With the Pass-8 software, these benefits are exploited to yield a much improved analysis of the downlinked data. This has been a multi-year effort and we have re-examined and re-done most of the existing algorithms. The results will be increased effective area, reduced point-spread function, lower backgrounds, and extensions in energy, both to the TeV band and to the 10s-of-MeV band.

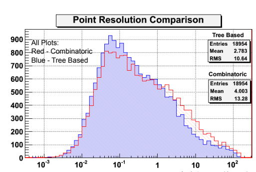
Tracker: Tree-Based Pattern Recognition

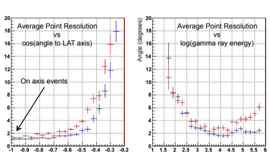
The current reconstruction in the LAT tracker is based on the model of a photon converting into an electron-positron pair that makes two tracks. Thus, the current "combinatoric" pattern-recognition algorithm finds and fits the two tracks representing the electron-positron pair, and then combines them to form a vertex representing the photon. This approach has served us well, but it has at least four weaknesses:

1) To reduce the number of potential hit combinations it uses the reconstructed calorimeter energy centroid and axis to choose the initial hits, and this makes the efficiency of the track finding dependent on the accuracy of the calorimeter reconstruction.
2) The track model includes multiple coulomb scattering, which requires an estimate of the track energy, also derived from the calorimeter.
3) Photon conversions rarely resemble clean two-track events; but, instead they produce multiple hits as the electromagnetic shower begins to develop.
4) High-energy photons converting at angles far off-axis can result in "backsplash"—a large number of randomly hit strips in the lower planes of the tracker. If there are enough of these hits, the track finder can become confused, leading to mis-tracking or even the complete loss of tracks.

Combinatoric Example Tree-Based Example



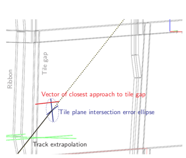


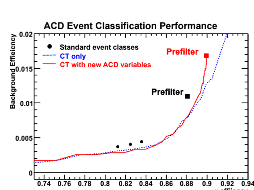


The Pass-8 reconstruction addresses these issues by introducing a global approach, called tree-based tracking, which looks at the photon conversion as a pre-shower process and attempts to model this process by linking hits together into one or more tree-like structures. For each tree, the main branches, roughly, the "longest and straightest", represent the primary electron and positron trajectories; the sub-branches represent associated hits produced as the electron and positron radiate energy in the tracker. The axis of the resulting tree can be found by calculating the moments-of-inertia of its hits. This axis can then be used to associate the trees to a particular cluster in the calorimeter, which allows an estimate of the energy associated with the tree, and a final fit of the tracks.

ACD: From Distances to Sigmas

Linking the found tracks to responses in the ACD tiles is critical in identifying and removing background events. Doing this to first order – does a track intersect a particular ACD tile? – is not difficult. More challenging is to assess by how many standard deviations (sigmas) a track has missed a hit tile. This requires the propagation of not only the track parameters but their associated errors (the covariance matrix) through the 3D detector geometry. In Pass 8 this has been done and yields improved associations with a lower error rate, and results in better background rejection with higher efficiency for retaining gamma-ray events.





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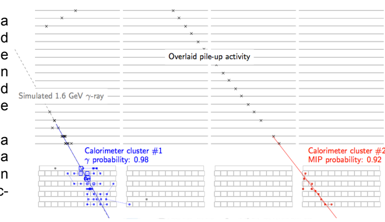
Calorimeter: Clustering, Moments and More

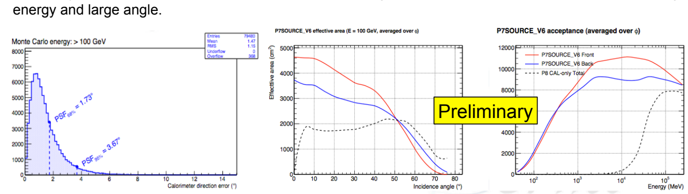
Due to time and resource limitations, the calorimeter analysis was by far the least developed at the time of launch. The expedient of simply by-passing a clustering stage and considering all hit crystals to be part of the same energy deposition was used. Shortly after the launch it became clear that residual pile-up signals away from the gamma-ray shower can introduce substantial errors in the measurement of the energy, centroid and direction of the shower itself, the most direct consequence being a loss of effective area due to gamma-rays misclassified as background.

Pass 8 remedies this situation by using a minimal-spanning-tree algorithm [2] to find and identify groups of crystals belonging to the same deposition. The position and direction information for each cluster can be matched with the tracker information to enhance the event-level background rejection.

In addition, classifying the clusters using a dedicated multivariate analysis allows for a fuller exploitation of the topological information where needed in the subsequent reconstruction steps.



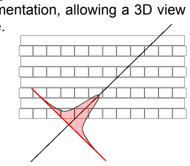
Finally, these calorimeter clusters, taken by themselves, are now demonstrated to provide imaging of the sky at high energy (more than ~10 GeV), albeit with worse image resolution (at the level of 1°). In fact, provided that the necessary background rejection power can be achieved, the calorimeter can be effectively operated as a standalone instrument, with a large potential increase in the effective area at high energy and large angle.

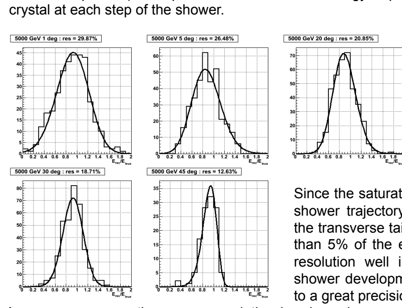


Calorimeter: Energy Reach

Limitations in total weight dictated that the LAT calorimeter be only 8.6 radiation lengths in depth. This leads to large shower leakage out the back above ~50GeV, with similarly large event-to-event fluctuations in energy deposition. The solution to this problem was a high degree of segmentation, allowing a 3D view of the shower, which has allowed for event-to-event compensation for leakage.

This shower-fitting technique is based on a detailed description of the shower development in the calorimeter (including both longitudinal and transverse profiles), that predicts the fraction of energy deposited in each crystal at each step of the shower.





Since launch, this technique has proven to work well up to 1 TeV, when crystal signals start to saturate (the saturation level for one crystal is about 70 GeV). When a crystal signal saturates, it is almost useless for energy reconstruction. Since the saturated crystals correspond to the core along the shower trajectory, the shower-fitting technique must rely on the transverse tails of the shower, which usually contains less than 5% of the energy. In order to provide a usable energy resolution well into the TeV band, the description of the shower development inside the calorimeter has been refined to a great precision.

As a consequence, the energy resolution has been improved below 1 TeV and the shower-fit technique works now up to 5 TeV when, on average, the non-saturated deposited energy only accounts for about 5% of the gamma energy.

References

1. Atwood, W. B. et al., *The Large Area Telescope on the Fermi Gamma-ray Space Telescope Mission*, ApJ, **697**, 1071 (2009).
2. Mavromanolakis, G., *Calorimeter clustering with minimal spanning trees*, arXiv:physics/040939v2

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