Pass 8: Toward the Full Realization of the Fermi-LAT Scientific Potential

W. Atwood
Santa Cruz Institute for Particle Physics, University of California, Santa Cruz
A. Albert
The Ohio State University
L. Baldini and M. Tinivella
Università di Pisa and INFN-Sezione di Pisa
J. Bregeon, M. Pesce-Rollins, and C. Sgrò
INFN-Sezione di Pisa
P. Brueá
LLR, Ecole polytechnique, IN2P3/CNRS
E. Charles, A. Drlica-Wagner, A. Franckowiak, T. Jogler, L. Rochester, T. Usher, and M. Wood
SLAC National Accelerator Laboratory
J. Cohen-Tanugi
Laboratoire Univers et Particules de Montpellier, Université Montpellier 2, CNRS/IN2P3
S. Zimmer
The Oskar Klein Centre for Cosmoparticle Physics
for the Fermi-LAT Collaboration

The event selection developed for the Fermi Large Area Telescope before launch has been periodically updated to reflect the constantly improving knowledge of the detector and the environment in which it operates. Pass 7, released to the public in August 2011, represents the most recent major iteration of this incremental process. In parallel, the LAT team has undertaken a coherent long-term effort aimed at a radical revision of the entire event-level analysis, based on the experience gained in the prime phase of the mission. This includes virtually every aspect of the data reduction process, from the simulation of the detector to the event reconstruction and the background rejection. The potential improvements include (but are not limited to) a significant reduction in background contamination coupled with an increased effective area, a better point-spread function, a better understanding of the systematic uncertainties and an extension of the energy reach for the photon analysis below 100 MeV and above a few hundred GeV.

We present an overview of the work that has been done or is ongoing and the prospects for the near future.

1. Introduction

The current Large Area Telescope (LAT) event-level analysis framework was largely developed before launch using Monte Carlo simulations through a series of iterations that, for historical reasons, we call Passes. Pass 6 was released at launch, and was followed in August 2011 by Pass 7, which mitigates the impact of some of the limitations of its predecessor. We refer the reader to [Atwood et al. 2009] for a description of the LAT instrument and to [Ackermann et al. 2012] for detailed information about the associated Instrument Response Functions (IRFs).

Though the current simulation and reconstruction framework has served adequately the science of the prime phase of the mission, on-orbit experience with the fully integrated detector has revealed some neglected and overlooked issues—primarily the effect of the instrumental pile-up (hereafter ghost events or ghost signals, see [Ackermann et al. 2012] for more details). Not long after launch, opportunities for clear improvements, with the potential to greatly extend the LAT science capabilities, were identified in the three main areas of the event-level analysis: (i) Monte Carlo simulation of the detector, (ii) event reconstruction and (iii) background rejection [Rochester et al. 2010]. These improvements are now being deployed in a systematic and coherent fashion in the context of the Pass-8 iteration of the LAT event-level analysis.

2. Event Reconstruction

The event reconstruction is so far the single development area where most of the effort has been put since the Pass-8 project started at the end of 2009. In this section we review the main improvements we have implemented at the reconstruction level for each of the three LAT subsystems: tracker, calorimeter and Anti-Coincidence Detector (ACD).
2.1. Tracker Reconstruction

The conceptual model underlying the current reconstruction in the LAT tracker is that a photon converts to produce an electron-positron pair and that the electron and positron make hits in the tracker, which can be followed from the point of conversion to their exit from the tracker. The present tracker reconstruction code uses a track-by-track combinatoric pattern-recognition algorithm to find and fit the two tracks representing the electron-positron pair, and then combines them to form a vertex representing the photon conversion point.

This approach is problematic in four general areas. First, the track-following algorithm needs an initial direction to start the track following and hit attachment. To reduce the number of potential hit combinations it uses the reconstructed calorimeter energy centroid and axis of energy flow to choose the initial hits, and this makes the efficiency of the track finding dependent on the accuracy of the calorimeter reconstruction (as we shall see in Section 2.2, the presence of ghost signals in the calorimeter exacerbates the situation). Second, the track model includes multiple Coulomb scattering, which requires an estimate of the track energy, also derived from the calorimeter. Third, electrons and positrons interact readily in the material comprising the tracker (in particular the converter foils and silicon), with the result that photon conversions rarely resemble clean two-track events; instead they produce multiple hits as the electromagnetic shower begins to develop. Finally, large energy deposits in the calorimeter, particularly from high-energy photons far off-axis, can result in “backsplash” — particles moving upwards from the calorimeter causing a large number of randomly hit strips in the lower planes of the tracker. As the number of backsplash hits increases the current track finding can become confused, particularly if the initial position and direction estimates from the calorimeter are not accurate. For photons that convert in the back (lower part) of the tracker, where the real gamma-ray track can feature as few as three hits in each orthogonal view, the potential to drown out real signal in a sea of spurious hits is large.

These features combine to produce three main effects: the loss of the events that fail to reconstruct at all, the migration of events from the core of the Point-Spread Function (PSF) to the tails because of poorly reconstructed tracks and increased confusion often resulting in mislabeling good gamma ray events as background.

2.1.1. Tree-based Tracking

The Pass-8 reconstruction addresses these issues by introducing a global approach, called tree-based tracking, which looks at the conversion in the tracker as the start of a shower and attempts to model this process by linking hits together into one or more tree-like structures. For each tree, the primary and secondary branches, defined as the two longest and straightest, represent the primary electron and positron trajectories (if unique) and sub-branches represent associated hits as the electron and positron radiate energy traversing the tracker. Once the tree has been constructed, its axis can be found by calculating the moments of inertia of the associated hits, with the mass of each hit taken as a function of the length and straightness of its branch. The axis can then be used to associate the tree to a particular cluster in the calorimeter, which allows an estimate of the energy associated with the tree. Once an energy is available, up to two tracks can be extracted, and fit, from the tree by associating the hits along the primary and secondary branches. As the tracks are extracted, they are fit using a Kalman Filter technique which accounts for multiple scattering but also allows for kinks which exceed deviations expected from multiple scattering and with each track given half the energy from the associated cluster. The fit tracks incorporate the best information about the axis of the tree, and provide the best resolution on the direction of the photon.

Tests with Monte Carlo simulations and flight data show that the new tracker pattern recognition has the potential to significantly reduce the fraction of mis-tracked event and provide a 15–20% increase of the high-energy acceptance, with even larger improvement in the off-axis effective area, especially for photons converting in the lower part of the tracker.

2.1.2. Vertexing

If more than one track is produced from a given tree, then an attempt is made to combine the two tracks into the vertex expected in a pair conversion. The track association in the vertexing stage exploits both the distance of closest approach of the projected tracks (typically 1 mm or less for genuine pair conversions) and the number of layers that separate the heads of the tracks (either 0 or 1). The track fitting yields not only track parameters, but also the associated errors (see Section 5.3 for more details). Accordingly, when the tracks are combined to form the vertex, these errors are used to properly weight the contributions of each track. The resulting vertex generally yields the best information on the photon direction.

Since the multiple Coulomb scattering scales as $E^{-1}$, the weights input to the vertexing (in the scattering-dominated regime) are proportional to the square of the assigned track energies. Unfortunately the LAT has very limited ability to determine the individual track energies, since the energy deposits in the calorimeter associated with the individual tracks usually overlap. In the context of Pass 8 the strategy to determine the energy ordering of the tracks has been
completely reworked and we anticipate that the improvement achieved over the current ordering scheme will be reflected in a better overall PSF.

2.2. Calorimeter Reconstruction

Just as for the tracker, the calorimeter reconstruction has been extensively revisited at all levels—from the crystal simulation (where, e.g., unaccounted-for end effects in the light collection proved to have noticeable consequences on the high-level science performance) to the energy and direction reconstruction and the background-rejection algorithms.

2.2.1. Clustering

The single most radical change is the abandonment of the single-particle paradigm common to the pre-Pass-8 event-level analysis and the introduction of a clustering stage in the calorimeter. In the Pass-6 and Pass-7 event reconstruction we treat the energy deposit in the calorimeter as a monolithic entity, with all the hit crystals grouped together. In a low occupancy environment such as the one in which Fermi operates, this approach proved to be adequate to support the science analysis of the prime phase of the mission. However residual ghost signals away from the gamma-ray shower (and therefore easily distinguishable from it, in principle) can introduce substantial errors in the measurement of the energy, centroid and direction of the shower itself. Since the matching between the tracker and the calorimeter is one of the main inputs to the background rejection, this results in a net loss of effective area from genuine gamma-ray events misclassified as background\(^2\).

In Pass 8 we have introduced a clustering stage in the calorimeter aimed at identifying the ghost signals and recovering the aforementioned loss in effective area. This presents some unique challenges, mostly connected with the fact that the LAT is designed to trigger on events over a huge field of view and therefore the calorimeter is seldom projective. We therefore decided to take advantage of the intrinsically three-dimensional calorimeter readout and exploit a Minimum Spanning Tree (MST) construction—a concept borrowed from graph theory with a long standing connection with clustering applications.

Tests performed on Monte Carlo simulations and flight data clearly confirm the effectiveness of this approach, indicating a 5–10% increase in the effective area above \(\sim 1\) GeV and, potentially, a much larger effect below a few hundred MeV, where the energy in the ghost signal can be of the same order of magnitude or larger than that of the triggering gamma-ray.

2.2.2. Energy Reconstruction

The other crucial calorimeter-related development area is the energy reconstruction at very high energy. Above a few GeV our workhorse reconstruction method is a three-dimensional profile fit to the calorimeter layer energies. This approach proved to be nearly optimal up to \(1\) TeV, where the average energy-release per crystal at the shower maximum starts exceeding the dynamic range of the readout electronics and saturation becomes an issue.

In order to overcome this limitation, the profile fit has been extensively reworked by breaking up the layer contributions into individual crystal energies. Monte Carlo simulations indicate that the energy deposits in the saturated channels can be recovered to some extent by using the information from the nearby (non-saturated) crystals, achieving a decent energy resolution up to \(\sim 3\) TeV [Bruel 2012].

2.3. ACD Reconstruction

The ACD reconstruction has been fully re-written in the context of Pass 8. The first major improvement comes from the novel incorporation of calorimeter information when associating incident particle direction with energy deposition in the ACD. Directional information derived from calorimeter clusters is now propagated to the ACD in addition to tracks derived from the tracker. This additional calorimeter information is particularly important for identifying background events at high energies or large incident angles, which are more susceptible to tracking errors. In these cases, the calorimeter provides the more robust directional information.

The second major improvement is to utilize event-by-event directional uncertainties when associating tracks and clusters with energy depositions in the ACD. Previously, the ACD reconstruction scaled the tracking uncertainty in an ad hoc manner based on an estimate of the total event energy. However, widely varying event topologies can lead to large differences in the quality of directional reconstruction for events of the same energy (see Section \[\text{III} \] \text{C}). Capturing this information in the event-by-event uncertainties provides substantially more information for background rejection.

The third major improvement comes from utilizing the fast ACD signals provided to the LAT hardware trigger to mitigate the impact of ghost signals in the slower ACD pulse-height measurements. This improvement is especially important at low energies, where calorimeter backsplash is minimal and a small deposition of energy in the ACD can lead to the rejection of an event. In this regime the use of trigger

\(^2\)This loss was quantified and accounted for (but not recovered) in the generation of the post-launch IRFs, both in the Pass-6 and Pass-7 flavors.
information in the background rejection removes out-of-time signals from the ACD and provides a significant increase in effective area.

3. Event selection

As the event reconstruction is nearing completion, the LAT Collaboration is now focusing on the next step of the event-level analysis, namely that responsible for the final determination of the high-level event properties, such as particle type, energy and direction.

Similarly to what we did for the previous passes, we use Classification Trees (CTs) to select candidate gamma-rays on the basis of the reconstruction outputs. The particle identification CTs are trained using variables from all the three LAT subsystems. One noticeable difference is the use of the TMVA multivariate analysis framework [Hoecker et al. 2007]. Compared to the technology used in the current event classification, TMVA is capable of handling much larger data sets and allows for an overall faster development cycle. The CT performance is evaluated from the combination of background rate and gamma-ray acceptance that can be achieved for a given cut on the output signal probability. We note here that a differential background rate equal or slightly lower than the Extragalactic Gamma-ray Background (EGB) rate is desirable for point-source analysis.

We have studied several candidate Pass-8 event classes defined by event selections that allow varying levels of background contamination relative to the EGB. Each event class is composed of the following cuts: a selection on events with a reconstructed track that deposits at least 5 MeV in the calorimeter, an ACD pre-selection on events for which the reconstructed track points to an activated section of the ACD, and an energy-dependent cut on CT variables for the particle type and the quality of the angular reconstruction. As shown in Figure 1 at high energy we find a ∼ 25% increase in acceptance relative to the Pass-7 source event class while at low energies (below ∼ 300 MeV) the increase in acceptance can be as high as a factor three.

4. Extended Event Classes

In the current photon analysis, events with no track in the tracker or depositing less than 5 MeV in the calorimeter are simply discarded—though some of them are used in non-standard analyses such as the LAT Low-Energy technique (LLE) described in Pelassa et al. [2010]. One of the areas of improvement which is being investigated in the context of Pass 8 is the development of extended photon classes, e.g. tracker-only and calorimeter-only events. Although these events have worse energy resolution and/or PSF with respect to those in the standard photon classes, they can provide a very significant increase of effective area in some regions of the LAT phase space that might be exploited in specific science analyses.

4.1. Tracker-only Events

Below ∼ 100 MeV many of the $e^+$ and $e^-$ range out in the tracker and deposit no energy in the calorimeter. Since seeing calorimeter signals that are correlated with tracks is a powerful discriminator for well-reconstructed events and helps in rejecting particle backgrounds that would otherwise be difficult to identify, in the current event selection we do require a minimum (5 MeV) energy deposit in the calorimeter. However, the success of the LLE analysis for bright transients has made it clear that tracker-only events carry useful information that can be used in science analysis.

As the entire event selection process is now being reassessed in the context of Pass 8, tracker-only events provide the potential for a substantial increase in the effective area below 100 MeV, opening a region of the LAT phase space which is extremely interesting for many science analyses.

4.2. Calorimeter-only Events

While almost a half of the events above ∼ 50 GeV have no usable tracker information (either because

\[3\text{Technically, a significant fraction of these events would be discarded by the onboard filter, if this was not disengaged for events depositing more than 20 GeV in the calorimeter. At these energies the shower leakage is such that the 20 GeV (of deposited energy) high-pass threshold translates into a smooth effective threshold of } \sim 50 \text{ GeV, when measured in reconstructed energy.} \]
they convert in the calorimeter or due to mistracking), at these energies the LAT calorimeter provides a directional capability at the level of a few degrees or better.

Although this is much less precise than the typical tracker PSF, calorimeter-only events constitute a very promising event class for those analyses where the pointing accuracy is not critical. Preliminary simulations show that they might provide as much as $\sim 30\%$ increase in the high-energy acceptance, with an even larger enhancement of the effective area at large off-axis angles. The rejection of particle backgrounds in the absence of usable tracker information must still be studied in detail and constitutes one of the main challenges connected with the use of calorimeter-only events.

4.3. Compton Events

Although the LAT was not designed as a Compton scattering telescope, it does in fact have significant acceptance to record Compton interactions—around $\sim 200$ cm$^2$ sr at 5 MeV, with a peak value of $\sim 2000$ cm$^2$ sr around 20 MeV. Since the tungsten converters significantly degrade both the spatial and energy resolution for Compton interactions, extracting useful information out of them involves selecting the events that are less affected by multiple scattering—such as front-converting events, or events which convert after the final tungsten layer and leave signals in the last three tracker layers. The significant analyzing power of the Compton events for measuring polarization makes this event class particularly interesting.

5. New Analysis Techniques

Pass 8 will extend the scientific reach of the LAT in areas that are simply not accessible in the current event-level analysis. The new event reconstruction and selection are being designed with these scientific targets in mind and therefore in this section we provide a few illustrative examples.

5.1. Multi-photon Events

One of the most striking aspects of the LAT capability compared to prior missions is its high shutter speed. When viewed as a camera, the LAT has a shutter speed approximately equal to its trigger window width or $\sim 600$ ns and a frame advance time set by the readout dead time or $\sim 26.5$ $\mu$s. When this is considered in combination with its large effective area the possibility of recording simultaneous photons becomes tantalizing. It was suggested long before launch that some astrophysical sources could produce coherent bunches of high-energy gamma rays. In addition, extraordinary bright, short bright bursts from, for example, black-hole evaporation could also result in multi-photon events. However, searches for such exotic events are not possible with the current reconstruction algorithms. The lack of calorimeter clustering along with a background rejection tuned on single-photon events almost completely kills any efficiency the LAT might have to see such events. With the re-write of the LAT event-level analysis currently underway, both of these deficiencies are being addressed. The new calorimeter clustering algorithm for the first time recognizes and separates distinct energy depositions within it and this, coupled with the new tracker pattern recognition, will enable a search for multi-photon events. The Monte Carlo generator has been re-worked to allow for the generation of such events as well. This allows testing of the new reconstruction and will guide the design of analysis cuts to select potential candidates.

5.2. Polarization measurements

The idea of using the azimuthal distribution of the electron-positron opening plane to perform gamma-ray polarimetry in the pair-production regime dates back more than 60 years [Yang 1950] and has been extensively studied theoretically. The main limiting factor is that even fully polarized radiation only gives an overall 10–20% modulation. In addition to that, in a typical pair-conversion telescope this modulation is strongly suppressed (exponentially with the converter thickness) due to multiple Coulomb scattering.

Fermi, thanks to its good hit resolution and large effective area has a much larger sensitivity to polarimetry than any of its predecessors. The LAT polarimetric capabilities are, for the first time, being investigated in detail in the context of Pass 8—particularly in conjunction with the possibility of using gamma-ray conversions in the silicon detectors in order to limit the effect of the multiple scattering. Preliminary studies indicate that we might be able to provide meaningful information on the linear polarization for the strongest gamma-ray sources.

5.3. Event-by-event Errors

The image of sources produced by the LAT is strongly energy-dependent: the PSF improves roughly as $E^{-0.8}$ in the multiple-scattering regime (i.e., below $\sim 10$ GeV). There are other factors influencing the image resolution, namely the conversion point in the tracker (the layout of the tungsten radiators is such that there is approximately a factor of two difference in angular resolution between front- and back-converting events) and the off-axis angle.
The IRFs do capture to some extent all these effects, but they are really averages of all the various event types which can occur within broad categories. On the other hand the reconstruction, in addition to providing the direction of the incoming gamma-rays, also calculates the errors in the form of an event-by-event covariance matrix deduced from the hit composition and the material crossed by the initial electron and positron tracks. For example, if a trajectory is missing an early hit due to the track passing through a gap between silicon sensors, the associated PSF is degraded by up to a factor of two. In addition, the current IRF formalism assumes the error for each event is circular on the sky, an assumption which becomes increasing inaccurate far off axis where the real photon error is highly elliptical.

In order to exploit the full potential of the LAT in terms of pointing resolution, Pass 8 will make the full event-by-event covariant information available in a form that can be readily used for science analysis. While an event-by-event analysis of the entire sky is unlikely to be feasible due to computational limitations, we anticipate that event by event errors might be key to specific analyses, such as the search for pair-halo effect in AGNs. More generally, they will be beneficial for source localization (especially for short transients) and for studying extended sources.

6. Conclusions

Pass 8 will come close to realizing the full scientific potential of the Fermi Large Area Telescope. It incorporates the knowledge gained from the prime phase of the mission and completes the analysis that was time-limited prior to launch. 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. We anticipate Pass 8 will be ready to be tested on real science analyses around the end of 2013.

We anticipate that many of the performance improvements will be beneficial to all science analyses: larger acceptance, better high-energy PSF, lower backgrounds and better control over the systematic uncertainties.

The new event reconstruction will allow us to extend the energy reach of the LAT both below 100 MeV (which is of interest for many scientific targets) and above 1 TeV (diffuse gamma and cosmic-ray electron spectra). The extended event classes will provide significant enhancements in the acceptance for specific analyses. Finally, Pass 8 will allow for new science topics which are precluded by the current event-level analysis, such as the search for multi-photon events and γ-ray polarization measurements.

Acknowledgments

The Fermi-LAT Collaboration acknowledges generous ongoing support from a number of agencies and institutes that have supported both the development and the operation of the LAT as well as scientific data analysis. These include the National Aeronautics and Space Administration and the Department of Energy in the United States, the Commissariat à l’Energie Atomique and the Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules in France, the Agenzia Spaziale Italiana and the Istituto Nazionale di Fisica Nucleare in Italy, the Ministry of Education, Culture, Sports, Science and Technology (MEXT), High Energy Accelerator Research Organization (KEK) and Japan Aerospace Exploration Agency (JAXA) in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the Swedish National Space Board in Sweden.

Additional support for science analysis during the operations phase is gratefully acknowledged from the Istituto Nazionale di Astrofisica in Italy and the Centre National d’Études Spatiales in France.

References

M. Ackermann, M. Ajello, A. Albert, A. Allafort, W. B. Atwood, M. Axelsson, L. Baldini, J. Ballet, G. Barbiellini, D. Bastieri, et al., The Astrophysical Journal Supplement 203, 4 (2012), 1206.1896.
W. B. Atwood, A. Abdo, M. Ackermann, W. Atwood, B. Anderson, M. Axelsson, L. Baldini, J. Ballet, D. L. Band, G. Barbiellini, et al., The Astrophysical Journal 697, 1071 (2009), 0902.1089.
L. Rochester, T. Usher, R. P. Johnson, and B. Atwood, ArXiv e-prints (2010), 1001.5005.
P. Bruel, Journal of Physics Conference Series 404, 012033 (2012), 1210.2558.
A. Hoecker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, and H. Voss, PoS ACAT, 040 (2007), physics/0703039.
V. Pelassa, R. Preece, F. Piron, N. Omodei, S. Guiriec, f. t. Fermi LAT, and GBM collaborations, ArXiv e-prints (2010), 1002.2617.
C. N. Yang, Physical Review 77, 722 (1950).