Detection of multi-γ-ray events with the Fermi-LAT

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We describe changes in LAT reconstruction algorithms which will allow us to detect multiple γ rays in a single readout

One of the striking improvements in performance of the Fermi-LAT over previous gamma-ray missions is its "shutter speed". When viewed as a camera, the LAT has a shutter speed approximately equal to its trigger window width (700 ns) and a frame advance time set by the readout dead time (26.5 μs).
The combination of speed and large effective area suggests the possibility of recording simultaneous photons. It has been indeed suggested that some astrophysical sources could produce coherent high-energy gamma rays. In addition, extraordinarily bright, short bursts from, for example, the evaporation of black holes could result in such multi-photon events. However, searches for such exotic events are not possible with the current reconstruction algorithms. More specifically, the lack of calorimeter clustering and a background rejection tuned on single-photon events kills almost completely any sensitivity the LAT might have to see such events. We are addressing both of these deficiencies with the re-design of the LAT reconstruction software currently underway. The new calorimeter clustering algorithm 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.

1) Motivation

Finding multiple simultaneous γ rays from an astrophysical source would be a significant discovery. Potential sources are exotic:
•Evaporating Primordial Black Holes [1-3];
•Bose-Einstein effect -> coherent emission [4];
•Terrestrial γ-ray Flashes (TGFs)[5]
•New Physics.
The LAT is the only instrument which can search in the MeV – GeV range[6].

3) Pass8 Reconstruction[7]

The "Pass8" iteration of the event reconstruction addresses several issues required for the analysis of multi-γ-ray events:
•Calorimeter clustering – in previous iterations no attempt was made to separate energy deposits in the calorimeter into clusters;
•Tree-Based tracking – the new tracking algorithm inherently associates nearby tracks into "Trees", to better reflect the shower-like nature of the events in the tracker;
•Use of trigger information – the new algorithms now use trigger information as part of the ground reconstruction, reducing the contamination for out-of-time signals and helping to identify cases where multiple γ rays arrived within the 700 ns trigger window

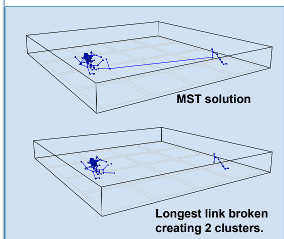


Fig 5) CAL cluster-finding. With Pass8 we make separate clusters by "breaking" any links above a certain length in the minimum spanning tree (MST).

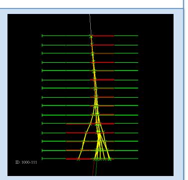


Fig 6) Tree structure found by new tracking algorithm keeps track of relationship between main track and other tracks in the shower. Enables matching TKR-CAL signals, a key to reducing physics backgrounds.

Should multiple γ rays arrive at the LAT during the peak of the shaping time we still have the challenge of disentangling the signal and reconstructing each γ ray. Our ability to do this depends on how well we can separate the CAL clusters. Below 1 GeV multiple scattering in the TKR and decreased signal-to-noise cause the clusters to be less well defined. This requires increasing the maximum link length with decreasing energy (see Fig. 7).

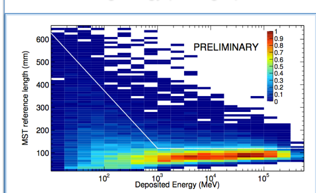


Fig 7) MST threshold for breaking links as a function of deposited energy (white line), compared with the reference cluster length (average +2σ of MST lengths) of simulated γ-rays. The color scale shows the relative number of events which have a given reference length.

2) Analysis issues

Instrument Timing

The LAT has three characteristic time constants:
Trigger window (700ns)
Shaper peaking time (3-10 μs)
Readout deadtime (26.5 μs)

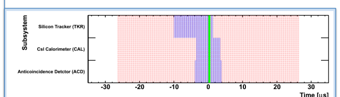


Fig 1) Time windows during which the LAT subsystems are insensitive to additional signals because of event readout (red), sensitive only to shaped signals (blue) and sensitive to both shaped signal and trigger signals (green)

Extremely High Fluxes of Soft γ rays

We can also identify events where the LAT was hit by dozens (or more) of 1-100MeV γ rays during the shaper window:

- For such low-energy events converted $e^{\pm}$ from will not travel far in the LAT– high ratio of TKR hits to CAL energy
- High flux < 30MeV will trigger Fermi-GBM[8]

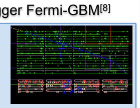


Fig 2) A single trigger from a TGF[5] with > 50 soft (1-50MeV) γ rays. The green dots and lines are TKR hits, the white and red boxes are CAL energy deposits.

Veto From Low Energy Flux

E.g., for E^{-2} source spectra:
2 γ rays at 1GeV during 1 trigger ->
20 γ rays at 100 MeV -> very messy event
2000 γ rays 1 MeV-> lot of noise in TKR
20000 γ rays at 100 keV – saturate ACD
Any of these would lead us to reject the event.
To avoid veto we need either very hard ($E^{-1.3}$) sources or coherent emission in LAT band.

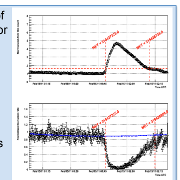


Fig 3) Increase in rate of anti-coincidence detector (ACD) hits during an X-class Solar Flare, coincident with a decrease in the rate of events classified as γ-rays. High numbers of ACD hits are not expected in γ-ray events and cause misclassifcation

Analysis Strategies

•Above about 1 GeV we can fully reconstruct and identify multiple-γ-rays in a single LAT trigger (700 ns)
•Below about 100 MeV we can estimate the total energy seen in the LAT and the total number of soft γ rays which converted in the tracker during the shaping time (10 μs)

Particle Backgrounds

•Recall: particle rates of up to 10 kHz in LAT
•Particles entering the back of the LAT, leaving tails of shower in the TKR
•CAL+TKR combined reconstruction
•Interactions outside the LAT scattering γ rays into the LAT field-of-view
•Physics interactions in the LAT causing γ-ray-like vertices
•Simultaneous γ rays from different sources
•Direction reconstruction!
•TeV atmospheric showers?
•Potential "calibration" source

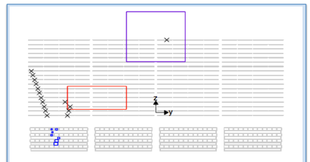


Fig 4) Typical physics background event for two γ-ray-event reconstruction. Likely a charged particle which entered the back of the CAL(blue boxes) and made two tracks in the TKR (black x's), one of which left energy in the ACD (red box). Note also the single tracker hit and smaller ACD signal (purple box) near the top of the LAT.

4) Performance Considerations

For coherent emission, the γ-ray separation distance at the LAT is set by the uncertainty principle and the angle (L/d) subtended by the coherence region

$$\Delta x = \frac{hc}{E}\frac{L}{d} = 2.4m\left(\frac{d}{Gpc}\right)\left(\frac{L}{a.u.}\right)^{-1}\left(\frac{E}{GeV}\right)^{-1}$$

Assuming Δx is similar to or larger than the LAT, for a given flux of coherent γ-ray pairs $F_c(E)$, and energy and incident angle (θ) dependent effective area A_{eff} and separation efficiency Q we will observe differential counts dN/dE:

$$\frac{dN_c(E)}{dE} = \frac{F_c(E)}{\pi(\Delta x)^2}\int A^2_{eff}(E,\theta_t)Q(E,\theta_t)dt$$

For high-flux but incoherent γ-ray sources the rate depend on the energy of both γ rays as well as the trigger width (w):

$$\frac{d^2N_2(E,E')}{dEdE'} = wF(E)F(E')\int A_{eff}(E,\theta_t)A_{eff}(E',\theta_t)Q(E,\theta_t)dt$$

Since we don't know *a priori* the nature of the emission we can consider a figure-of-merit for detecting and separating two γ rays:

$$\boxed{A^2_{eff}(E,\theta)Q(E,\theta)}$$

The separation efficiency is determined by the cross-sectional area of the CAL relative to the typical clustering length. The cross section of the CAL decreases at high incidence angles, while the clustering length increases at low energies (Fig 7.)

Furthermore, LAT A_{eff} decreases roughly linearly with cosθ for much of the LAT energy range, implying that much of our sensitivity to multi-γ-ray events will come near the LAT boresight.

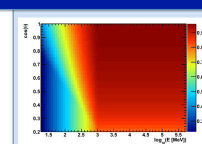
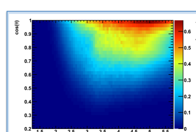
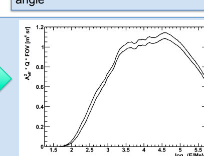


Fig 8) Separation Efficiency Q as a function of Energy and incidence angle



Integrate over FoV



θ-dep. at 1GeV

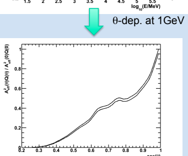


Fig 9) The figure-of-merit A_{eff}^2Q, shown on the color scale as a function of energy and incidence angle (top left), integrated over the field-of-view to show the energy dependence (top right) and the roughly quadratic θ-dependence shown at 1GeV.

Conclusions

The LAT can be sensitive to multi-γ-ray events in two ways:
•Very hard (> $E^{-1.3}$), or sharply peaked or coherent γ rays in the 1-100GeV range which are fully reconstructed
•Figure of merit is more biased towards LAT boresight than for single γ-ray events
•Some sensitivity in wider (300MeV – 300GeV) energy range
•Extreme fluxes of 1 – 100 MeV γ rays (e.g., TGFs, usually softer sources)
•May be able to extract energy flux, energy end point and count rate limits without reconstructing each γ ray

References & Acknowledgements

[1-3] Some recent papers about γ rays from PBH:
Ukwatta et.al. 2010arXiv1003.4515U
Lehoucq et.al. 2009A&A...502...37L
Cline & Otwinowski 2009arXiv0908.1352C
[4] E.g., Harwit, Protheroe & Biermann 1999ApJ...524L..91H
[5] "Observation of Terrestrial Gamma-ray Flashes with Fermi LAT" Poster at this session
[6] EGRET results: Fichtel et.al. 1994ApJ...434..557F
[7] "Pass 8: a comprehensive revision of the Fermi LAT event-level analysis" Poster at this session
[8] Fermi Gamma-ray Burst Monitor, the other instrument on the Fermi observatory. Meegan et.al. 2009ApJ...702..791M

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