Very-high-energy GRB events in novel Fermi-LAT photon data and their emission mechanism

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Overview

Too high energy for synchrotron

Few photons above tens of GeV

~40-70% increase in statistics

4 events with >50 GeV coincident with GRBs

Standard data

Novel data

Fermi-LAT

Gravitational Waves

NASA

Fermi
-LAT
Fermi Large Area Telescope

- Energy range: from ~20 MeV to > 300 GeV
- Effective area: >0.8 m² for normal incidence
- Field of view: 2.4 sr for 1 GeV

Tracker (TKR)

Anti-Coincidence Detector (ACD)

Calorimeter (CAL)

Sensitivity is limited by signal statistics above 10 GeV

[Atwood+ 09]
GRB photons with energy > tens of GeV

- Afterglow of gamma-ray bursts is usually explained by synchrotron emission from external shocks

- Photons whose energy is challenging for synchrotron scenario have been detected
  - LAT: 130427A, etc.

- Possibly requires another component such as inverse Compton

- MAGIC detected emission above 300 GeV from 190114C

- Improving LAT sensitivity above tens of GeV is important

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; Razmik Mirzoyan on behalf of the MAGIC Collaboration on 15 Jan 2019; 01:03 UT
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Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst
Referred to by ATel #: 12395, 12475
CalOnly classes

Standard event

- TKR ~1.5X₀
- CAL ~8.6X₀
- TKR TOT (ave, num, sat): (91.2, 78, 12)
- TKR total hits: 417
- TkrNumHits: 181
- TkrNumTracks: 2.0

CalOnly event

- No usable TKR information

Make CalOnly events with energy >20 GeV usable for analysis

Arrival direction is determined by a few degrees

Improve in statistics

Unpublished

No usable TKR information
Background rejection

Event data

Boosted Decision Trees

- Veto of ACD
  - ACD hit count, correlation with shower axis, etc.
- Shower profile in TKR and CAL
  - Transversal RMS, longitudinal maximum, etc.

Gamma-ray-like

Cosmic-ray-like

Optimize for CalOnly events

- Find best combination of separators
- Tune configuration
- Introduce new separators

Larger statistics

Less contamination
Performance evaluated with MC

6.3.2 Acceptance

The acceptance is the effective area integrated over the FoV. It yields the signal statistics we can get from a certain source during a long observation. It depends on $E$ and $\theta$. The dependence on only $E$ is plotted in Fig. 6.7. The peak locates around 100 GeV. At the peak, the acceptance of the CalOnly R100 and R003 corresponds to $\sim 70\%$ and $\sim 40\%$ of the standard SOURCE class, respectively. These fractions of photons are recovered for analysis on top of the conventional data. This is a significant improvement because, at 50 - 100 GeV, the LAT sensitivity is limited by statistics for most of the sources, hence the gain in acceptance leads to a gain in sensitivity.

The dependence on $E$ and $\theta$ are plotted in Fig. 6.8. The acceptance is basically larger at smaller off-axis angles because most of the MVA separators work better. Exceptionally, the acceptance is suppressed for small $\theta$ in the energy range below 60 GeV because the deposited energy does not reach the threshold 20 GeV if a fraction of the energy leaks from the CAL. The acceptance for $\cos \theta < 0.2$ is almost zero, and hence I introduced one of the precuts, $\cos \theta \geq 0.2$ (cf. Table 6.1) for simplicity.

6.3.3 Point spread functions

The PSFs strongly depend on $E$ and $\theta$ as plotted in Fig. 6.9. They are better for larger $\theta$ because the CAL is geometrically thicker, and thus the tracks become longer. The $\theta$-integrated PSFs distribute from two to four degrees as plotted in Fig. 6.10. These are more than one order of magnitude.

~50\% increase in statistics from ~50 to ~300 GeV

~30 times worse PSF
Data for 8.3 years
Galactic disk and bright point sources are apparently seen
GRB photon search

Sample: 24 GRBs coincident with >10 GeV standard event (up to 2016)

Data selection
Time: $T_0 - 100$ s $-$ $T_0 + 10$ ks
RoI: PSF68% + (GRB localization error)

Boosted Decision Trees

Focused in this contribution

4 events found to be coincident with one of GRB 090926A, 150902A and 160509A
Background estimation

✦ ON/OFF analysis

ON (GRB) data

OFF (high-galactic-latitude) data

\[ N_{BKG} = \frac{N_{OFF}}{\mathcal{E}_{ON} / \mathcal{E}_{OFF}} \]

Estimated background in ON

Observed background in OFF

Exposure of ON

Exposure of OFF

Fake detection probability \( p_{BKG} \)

Dependence on energy, off-axis angle and zenith angle is taken into account
CalOnly event correlated to GRB 090926A

- No ACD signal on shower axis
- Small spatial dispersion
- Event class: CalOnly_R003
- Observed energy (GRB-frame energy): 50 GeV (157 GeV)
- Arrival time: $T_0 + 424$ s
- Angular sep. (cf. PSF68%): 0.8° ($1.7^\circ$)
- BKG prob.: $\sim 0.02\%$

✦ Side-entering event ($\theta=62^\circ$)
  - Good PSF
  - Robust energy reconstruction

Unpublished
CalOnly events around GRB 090926A for 8.3 yr

Event at $T_0+424$ s

Gamma-likeness from BDT

(Angular distance from GRB [deg])^2

- Temporally coincident
- CalOnly_R100
- CalOnly_R030
- CalOnly_R010
- CalOnly_R003
Discussion

✦ 50 GeV event arrived at $T_0 + 424$ s
  ▸ Much later than end of prompt phase $T_{95} = T_0 + 15.9$ s (*Fermi*-GBM)

✦ Jet is expected to be decelerated by external matter
  ▸ Lorentz factor of shocked fluid $\Gamma \lesssim 800$ at $T_0 + 424$ s
    
    $$\Gamma(t_{obs}) \sim 55 \left( \frac{E}{10^{53} \text{erg}} \right)^{1/8} \left( \frac{n_1}{\text{cm}^3} \right)^{-1/8} \left( \frac{t_{obs}}{1000 \text{s}} \right)^{-3/8}$$
    
    – based on classic external shock model (adiabatic evolution)
    – uniform ambient matter is assumed

  ▸ Synchrotron limit: $50 \text{ MeV} \times \Gamma/(1+z) \lesssim 13 \text{ GeV}$
    • CalOnly event energy is $\sim 4$ times higher than this

  ▸ Another component is suggested
    • inverse-Compton scattering?

✦ Alternative possibility:
  ▸ Energy injection from central engine to external shock lasted until $\sim 400$ s
Afterglow of gamma-ray bursts (GRBs) was usually explained as synchrotron radiation from external shock

Gamma rays with energy above tens of GeV have been observed
  ✦ may be too high for synchrotron scenario

Improving *Fermi*-LAT sensitivity above tens of GeV is important
  ✦ observe more GRBs
  ✦ cover both prompt and afterglow

We have developed novel data classes to increase statistics
  ✦ Sensitivity is limited by signal statistics for \( \gtrsim 10 \) GeV

In novel classes, four events are found to be spatially and temporarily correlated with LAT GRBs
  ✦ One of them was coincident with GRB 090926A (\( z \approx 2.1 \))
    • \( E_{\text{obs}} = 50 \text{ GeV}, t_{\text{obs}} = T_0 + 424 \text{ s}, p_{\text{bkb}} \sim 0.02\% \)
      – difficult for synchrotron from decelerated jet

Usability for scientific studies is demonstrated