PROCEEDINGS OF SCIENCE

Search for Muon Excess from GRB 221009A in Data from the GRAPES-3 Muon Telescope

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GRB 221009A was the most energetic gamma-ray burst (GRB) ever recorded, with photon energies exceeding 10 TeV. Ground-based detectors such as LHAASO and Carpet-2 reported delayed ultra-high-energy photon events, and the Yangbajing muon telescope observed a coincident enhancement in ground-level muons, raising interest in secondary particle production in the atmosphere.

In this study, we analyzed 1-minute muon counting data from the GRAPES-3 muon telescope in Ooty, India, which was located at a zenith angle of about 11° with respect to the GRB direction at the time of the burst on October 9, 2022. Data from all 16 detector modules were summed and divided into nine angular sectors to search for directional excesses. After applying pressure correction, we found no statistically significant deviation in any direction.

This null result provides an independent constraint on GRB-induced atmospheric muon production and highlights the importance of high-precision, multi-directional observations for evaluating such rare transients. Future studies will benefit from detailed simulations of detector responses to high-energy atmospheric cascades.

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1. Introduction

Gamma-ray bursts (GRBs) are the most energetic phenomena in the Universe, characterized by an intense emission of high-energy photons over a short duration. They are broadly classified into two categories: short GRBs (lasting less than ~0.3 seconds), typically attributed to the merger of compact binary systems such as neutron stars; and long GRBs (lasting tens of seconds or more), which are widely believed to result from the collapse of rapidly rotating massive stars into black holes.

Among these events, GRB221009A, detected on October 9, 2022, at 13:17 UTC, stands out as the brightest and most energetic GRB ever recorded. Its extreme luminosity saturated the Fermi Gamma-ray Burst Monitor (Fermi-GBM) and significantly impacted Earths ionosphere. Moreover, delayed arrival of ultra-high-energy photonsranging from 10 TeV to several hundred TeVwas reported by multiple instruments including LHAASO [1], Carpet-2 [2], and Fermi-LAT [3].

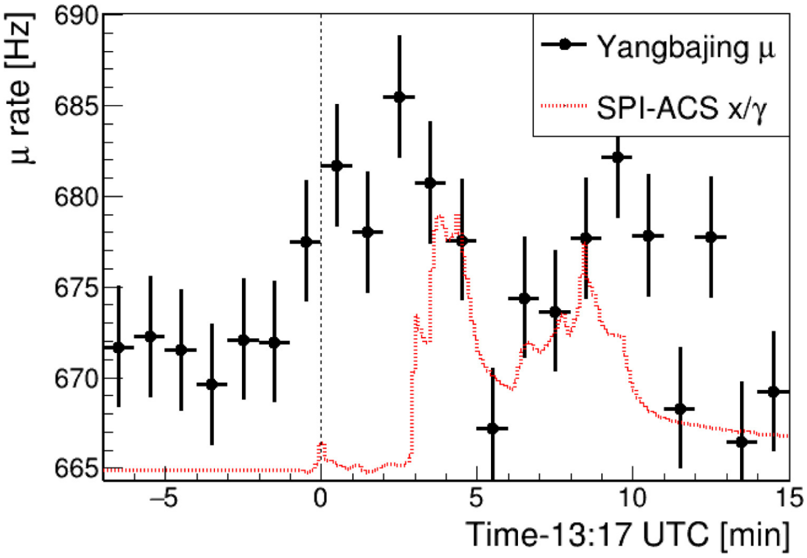

Figure 1: Muon counting rate at the Yangbajing telescope (black markers) around the GRB221009A trigger time (13:17 UTC), showing a sharp spike in temporal coincidence with the GRB onset. The red curve represents SPI-ACS x/γ-ray flux profile.
Source: Adapted from Fig. 3 of Nozzoli et al., *Astroparticle Physics*, Volume 165, February 2025, 103062.

A particularly intriguing report came from the Yangbajing muon telescope in Tibet [4], where a spike in the ground-level muon counting rate was observed in temporal coincidence with the onset of GRB221009A (see Figure 6). This raised the possibility that secondary particles generated in the atmosphere by the GRB might be detectable at the ground level.

Although gamma rays are electrically neutral and do not produce muons directly, they can initiate particle showers upon interacting with atomic nuclei in the upper atmosphere. In such interactions, high-energy gamma rays may generate pions (π^+, π^-) via photonuclear reactions. These pions rapidly decay into muons and neutrinos:

$$\pi^+ \to \mu^+ + \nu_\mu, \qquad \pi^- \to \mu^- + \bar{\nu}_\mu$$

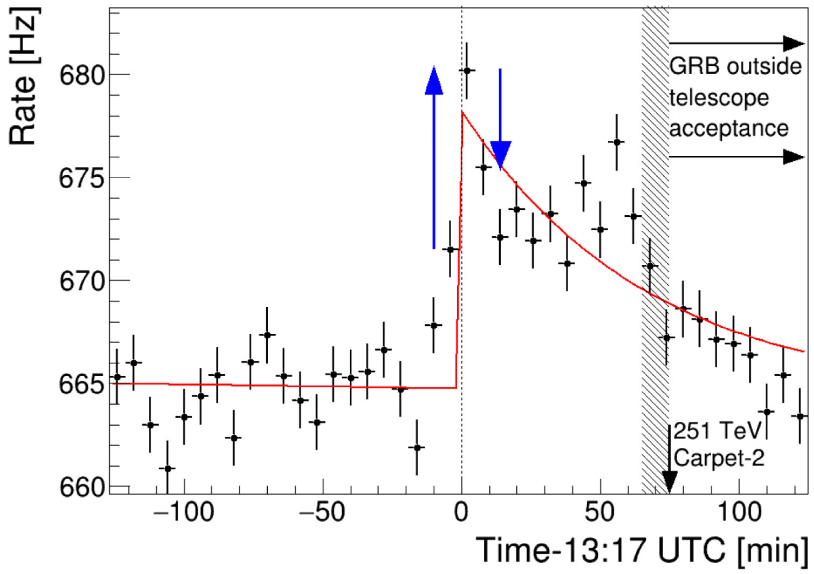

Figure 2: Extended muon excess observed by the Yangbajing telescope, modeled with an exponential decay following the initial spike. The GRB trigger occurs at t = 0. Hatched region marks the period outside the telescope's field of view.
Source: Adapted from Fig. 4 of Nozzoli et al., *Astroparticle Physics*, Volume 165, February 2025, 103062.

If the original gamma ray is sufficiently energetic (typically ≥10 GeV), the resulting muons may possess enough momentum to penetrate the atmosphere and be detected at ground level. Thus, ground-based muon telescopes can serve as indirect probes of astrophysical gamma-ray events, complementing photon-based observations.

In this context, we aim to investigate whether any such muon enhancement was detectable using the GRAPES-3 muon telescope, located in Ooty, India. GRAPES-3 is a high-statistics ground-based detector with a wide field of view and was ideally situated at a zenith angle of approximately 11° with respect to the GRB direction at the time of the event. By analyzing high time-resolution vertical muon data from October 2022, we search for transient enhancements possibly associated with the GRB.

2. Detector Description

The GRAPES-3 experiment is located in Ooty, India (11.4°N, 76.7°E, 2200 m altitude) and consists of a large-area air shower array and a high-resolution tracking muon telescope [5].The muon telescope consists of 16 detector modules, each of area 35 m^2. Each module contains four layers of 58 proportional counters (PRCs), each 600 cm in length and 10×10 cm^2 in cross-section, embedded in concrete. The concrete shielding imposes an energy threshold of approximately 1 GeV for vertical muons.

Muon arrival directions are reconstructed based on hits in the top and bottom PRC layers (see Figure 4). A 13×13 grid of discrete angular bins is formed by pairing a central PRC with ±6 neighbors in both horizontal projections, allowing 169 distinct arrival directions to be recorded every 10 seconds.

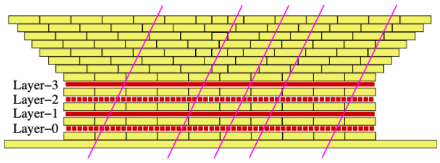

Figure 3: Schematic of the 4-layer GRAPES-3 muon telescope module. Each layer contains 58 PRCs. Four layers are embedded in concrete, with inclined muon tracks passing through.

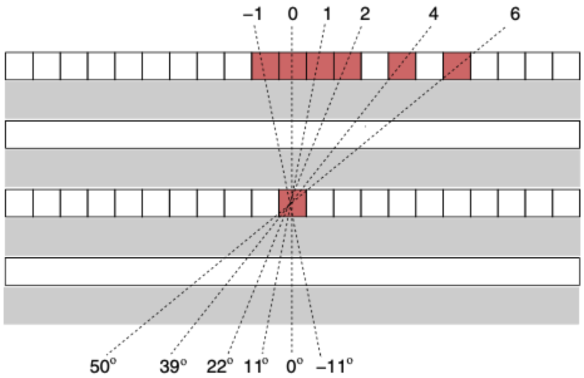

Figure 4: Schematic of angular reconstruction. A hit in a lower layer and one of 13 PRCs in the upper layer defines a discrete arrival angle.

To reduce noise and increase statistics, these 169 directions are grouped into 9 broader angular sectors:

- Vertical (V): 3×3 central bins
- Cardinal directions (N, E, S, W): each 3×5 bins
- Diagonal directions (NE, NW, SE, SW): each 5×5 bins

Each of these sectors spans approximately 0.23 sr. The vertical cutoff rigidity is approximately 17 GV, varying from 14 to 32 GV across directions.

3. Methods

Based on the nine directional sectors defined above, we analyzed data from the GRAPES-3 muon telescope recorded on October 9, 2022, using 1-minute time resolution. Data from all detector modules were summed to increase the overall event statistics. The analysis was performed separately for each of the nine coarse directional sectors: vertical (V), four cardinal (N, E, S, W), and four diagonal (NE, NW, SE, SW) directions.

Muon rates were corrected for atmospheric pressure variations using the standard barometric correction factor calibrated for the GRAPES-3 site. After correction, the relative residual for each

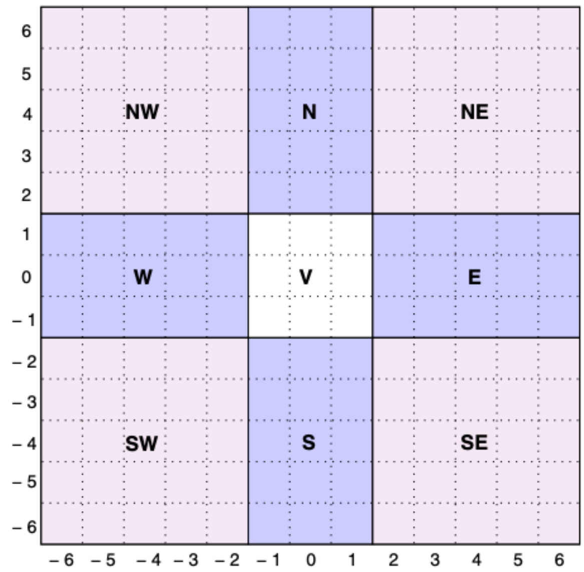

Fig. 3. A schematic of 169 muon directions that were subsequently combined into nine coarse directions. First, 3 × 3 vertical direction V, four 3 × 5 central (N,E,W,S), and four 5 × 5 outer directions (NE,SE,SW,NW).

Figure 5: Grouping of the 13×13 directional bins into 9 coarse angular sectors for improved statistics.

direction was computed as the deviation from the mean daily rate, using the full day of Indian Standard Time (IST) on October 9 as the reference baseline.

For the vertical direction (V), the mean muon rate was approximately 7800 Hz. All residuals presented in this study are expressed relative to these direction-specific daily means after pressure correction.

4. Results

We examined the residual muon rates in all nine directional sectors using 1-minute time bins over a 3.5-hour interval on October 9, 2022, centered on the GRB221009A trigger time (13:17 UTC). The residuals were calculated after correcting for atmospheric pressure and subtracting the mean value from the entire day in Indian Standard Time (IST).

Figure 6 shows the relative residuals in the vertical (V) direction around the GRB time in the vertical direction. No statistically significant increase was observed at or near the GRB trigger time. The residuals remained within ±0.004 (i.e., ±32 Hz for the V direction with a mean of 7800 Hz).

To assess long-term behavior, we analyzed 9-direction residuals over a 3.5-hour period from 11:30 to 15:00 UTC. Figure 7 displays the results for all directional channels across all directional channels. No extended excess, exponential decay, or coherent deviation was found in any direction.

While a short spike and exponential excess were reported by the Yangbajing muon telescope in Tibet in temporal coincidence with GRB221009A, no such enhancements were observed in GRAPES-3 data. The direction of the GRB was within 11° of zenith at Ooty, providing optimal conditions for potential detection.

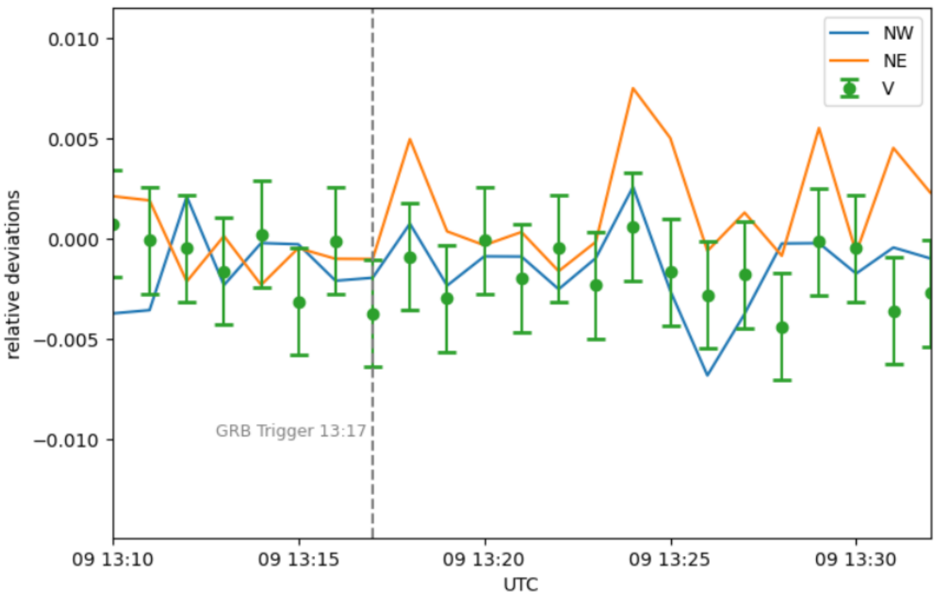

Figure 6: Relative muon rate deviations for the vertical (V) and two horizontal directions (NW and NE) over a 20-minute window centered on the GRB221009A trigger. The dashed vertical line marks 13:17 UTC. No significant excess is visible.

We conclude that the GRAPES-3 muon data do not show any evidence of GRB-induced ground-level muon enhancements for this event, within the statistical sensitivity and directional resolution of our instrument.

Discussion and Conclusion

Although GRB221009A was one of the most energetic gamma-ray bursts ever observed, and occurred near zenith over the GRAPES-3 muon telescope, no statistically significant excess in ground-level muon flux was detected in any of the nine directional sectors analyzed.

This result differs from the report by the Yangbajing muon telescope, which recorded a coincident spike and an exponentially decaying enhancement (Figure 7). However, it should be noted that GRAPES-3 has significant observational advantages, including a larger detection area and high statistical precision.

One factor that could affect sensitivity is the directional averaging inherent in the 9-sector grouping used in this analysis. If the signal were spatially narrow, such binning might reduce detectability. Investigating the directional resolution effects and optimizing angular binning will be important for future studies.

As noted by Nozzoli et al. (2025), the observation of delayed ultra-high-energy photons and possible ground-level muon enhancements may point to exotic physics mechanisms, including axion-like particles, sterile neutrinos, or violations of Lorentz invariance.

Although our null result does not support the presence of such an excess at GRAPES-3, it offers valuable constraints. Further progress will require detailed simulations that incorporate the specific

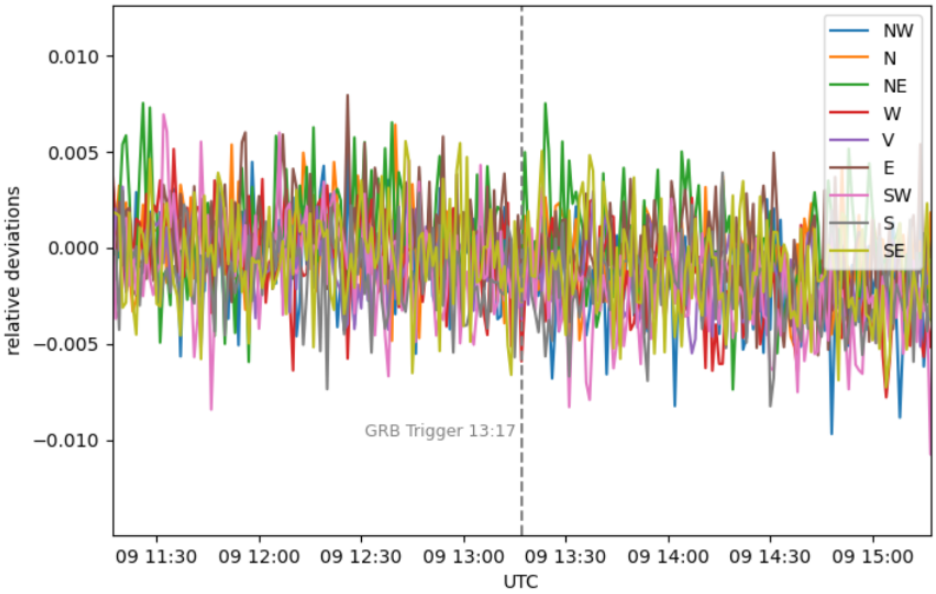

Figure 7: Directional muon rate deviations from GRAPES-3 across a 3.5-hour time window. Each trace represents one of the nine FOV directions. The dashed line indicates the GRB trigger time. The data are consistent with background fluctuations.

characteristics of each detector system, including geometry, threshold, and directional response, to enable robust cross-comparisons.

Future work should include comparative analyses across multiple detectors, detailed Monte Carlo simulations of photon-induced atmospheric cascades, and further theoretical studies to explore and evaluate such possibilities.

Acknowledgments

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