# Search for sub-TeV gamma rays in coincidence with gamma ray bursts

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We report on a study of sub-TeV (10 GeV$<E_\gamma<$1 TeV) gamma-ray-induced muon secondaries in coincidence with BATSE gamma ray bursts (GRBs). Each TeV gamma ray striking the atmosphere produces $\approx$0.2 muons whose identity and angle can be measured by the Project GRAND array. Eight GRB candidates were studied; seven were selected based upon the optimum product of (detected BATSE fluence) $\times$ (GRAND's acceptance). One candidate was added because it was reported as a possible detection by the Milagrito Collaboration. Seven candidates show a positive, though not statistically significant, muon excess. The only significant possible coincidence shows an excess of 466$\pm$171 muons during the BATSE T90 time interval for GRB 971110. The chance probability of such an excess in GRAND's background at the time of this event is $3\times10^{-3}$. The chance probability of observing such an excess in one of the eight bursts studied here is 0.025. If this event is real, the implied fluence of energetic ($>$10 GeV) gamma rays necessary to account for the observed muon excess would require that most of the GRB fluence arrived in the form of energetic gamma rays.

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## I. INTRODUCTION

The mystery of the astrophysical origin for gamma ray bursts (GRBs) has been with us for some time. As of yet there is no consensus explanation for them. Nevertheless, a likely scenario is a burst environment involving collisions of an ultrarelativistic $e^+-e^-$ plasma fireball [1–3]. These fireballs may produce low-energy gamma rays either by "internal" collisions of multiple shocks [4,5], or by "external" collisions of a single shock with ambient clumps of interstellar material [6].

In either of these possible paradigms, however, it seems likely that energetic ($\sim$TeV) gamma rays and/or neutrinos might also be produced along with the low-energy GRB. For example, inverse Compton scattering of ambient photons with relativistic electrons could produce high-energy gamma rays [7]. Alternatively, baryons would be accelerated along with the pair plasma to very high energies [8,9,10]. Synchrotron emission from energetic protons [9], or hadroproduction of pions in the burst environment [10] and subsequent $\pi^0$ gamma ray decay might also yield a spectrum of energetic gamma rays.

Thus, it is plausible that energetic gamma rays could be emitted in coincidence with a lower-energy GRB. These energetic gamma rays would, however, be attenuated by the infrared background. Hence, their detection will require that the source be nearby and/or that their flux constitute a significant fraction of the energetic output of the source. Nevertheless, such energetic gamma rays, if detected, could provide valuable clues as to the baryon loading, Lorentz factor, and ambient magnetic field of the relativistic fireball. They might also provide a means to distinguish between an internal versus external shock origin for the bursts. This paper, therefore, reports on an independent search for the possible coincidence of high-energy gamma rays with GRBs.

There presently exists at least some evidence for a possible association of energetic gamma rays with low-energy GRBs in previous literature. The Energetic Gamma Ray Experiment Telescope (EGRET) detected seven GRBs which emitted high energy photons in the $\sim$100 MeV to 18 GeV range [11–13]. There have also been some results from the Tibet air shower array suggestive of gamma rays beyond the TeV range [14,15], although these results were not claimed as a firm detection. There has also been reported evidence for TeV emission in one burst out of 54 BATSE GRBs in the field of view of the Milagrito detector [16]. The chance probability for that event (out of 54 trials) was found to be $1.5\times10^{-3}$. During the present study, this Milagrito event was also within the field of view of GRAND, but at a relatively low elevation.

In this paper we report a marginal (2.7$\sigma$) detection of energetic ($E_\gamma>$10 GeV) gamma rays in time and angular coincidence with BATSE GRB (971110). The chance probability of such an excess from this burst is $3\times10^{-3}$. The chance probability of such an excess from our sample of eight bursts is 0.025. The constraint that this detection might place on the spectrum of energetic photons from the burst environment is discussed. The analysis of GRAND's data for the GRB reported as a possible detection by Milagrito finds an insignificant excess of muons (1.2$\sigma$, including statistical and systematic errors).

## II. PROJECT GRAND

GRAND is located just north of the University of Notre Dame campus, approximately 150 km east of Chicago and 220 m above sea level at 86.2° W and 41.7° N. It detects cosmic ray secondaries at ground level by means of 64 tracking stations of proportional wire chambers (PWCs) [17]. Each station has four PWC detectors; each detector contains an x-plane (x=eastward) and a y-plane (y=northward) oriented horizontally and stacked vertically (z) [18,19]. The planes have an active area of 1.29 m$^2$ comprised of 80 detection cells (each 14 mm$\times$19 mm$\times$1.1 m). Each secondary muon is measured to 0.26° absolute precision (average value in each of two orthogonal planes) [20]. At present, GRAND's total detector area is 83 $m^2$; earlier data had smaller areas. A 51 mm thick steel plate inserted between the third and fourth PWCs allows muon tracks to be distinguished from electrons; 96% of muon tracks are correctly identified as muon tracks. Since, for single tracks, only 1/4 are electrons and 4% of these electrons are misidentified as muons, the muon sample has only 1% contamination from electrons. The data presented here are from single-track triggers which ignore time coincidences between stations; only muon candidates are selected.

GRAND utilizes the fact that gamma rays have a detectable signal of muons from gamma-hadro production in the atmosphere. The pions thus produced subsequently decay to muons which can reach detection level making it possible to study coincidences between GRBs and gamma ray showers in the $E_\gamma \geqslant 10$ GeV energy region. This energy threshold (10 GeV) depends slightly upon the spectral index of the gamma ray spectrum (see Fig. 6 in Ref. [21]) and is not a sharp threshold. It has been estimated [22] that the GRB rate for a threshold energy larger than 200 GeV is $\sim$10 GRBs per year; for the $\sim$10 GeV threshold energy of GRAND, this rate should be even greater.

Since the study reported here is similar to and includes the event reported by the Milagrito Collaboration, we note the differences between GRAND and Milagrito. Whereas GRAND detects secondary air-shower muons with PWCs, Milagrito detects secondary air shower charged particles by Cherenkov light as the shower particles traverse a light tight water reservoir. The main differences between the two detectors are that Milagrito has a larger active detection area, a somewhat better angular resolution in the single-track mode of interest here ($\sim 1°$ for Milagrito vs $\sim 5°$ for GRAND), and a higher detection threshold ($\sim$1 TeV for Milagrito vs $\sim$10 GeV for GRAND). The lower detection threshold for GRAND implies that it is sensitive to a lower energy part of the primary gamma ray spectrum which is not as likely to have been extinguished by internal [10] or intergalactic absorption [23,24]. Thus, even though no individual detection was overwhelmingly significant, the fact that a slightly positive signal-to-background ratio was deduced for all but one of the eight candidate bursts investigated might suggest that $\geqslant$10 GeV emission in association with low-energy GRBs is not altogether uncommon.

GRAND is a unique detector facility which measures the angles of single tracks and identifies which are muons. Inferring the implied gamma ray flux from the detected muons, however, requires confidence in the ability to simulate the muon production from gamma hadroproduction and muon propagation in the atmosphere. Recently, we have made a detailed analysis [21,25] of the spatial and energy distribution of muons in $\gamma$-induced air showers. These simulations are based upon the FLUKA Monte Carlo (MC) code. Unlike most MC codes used in cosmic ray research, this simulation is not specialized for this particular field but is a multipurpose particle transport code which has been tested in many diverse applications such as proton and electron accelerator shielding, calorimetry, medical physics, etc. It has therefore been verified against a large amount of nuclear experimental data and indirectly validated by comparisons with shower measurements obtained both at accelerators and in cosmic ray experiments. Of particular relevance to the present study is the fact that this code has been shown [26] to accurately predict hadron-generated muon spectra at different heights in the atmosphere. Hence, we expect its application here to photon-generated muon spectra be good to the $\sim$ few percent statistical accuracy of the simulations.

The MC simulation of [25] shows that a 1 TeV gamma ray normally incident upon the earth's atmosphere produces an average of 0.23 muons which reach GRAND. GRAND thus paradoxically uses muons as a *signal* for gamma ray primaries. In the energy region $\geqslant$10 GeV, the muon statistics are quite high; the current all-sky rate for recording identified muons is about 2400 Hz or 8.6 million muons per hour.

These secondary muons are primarily the result of interactions of primary cosmic rays with the atmosphere producing pions, which then decay to muons. The pions are produced at small angles relative to the primary cosmic rays; the noninteracting pions decay to muons which emerge at small angles relative to the pion; the muons are then deflected in the earth's magnetic field and scattered in the atmosphere resulting in an effective net angular resolution of about $\pm 5°$ (for the primary cosmic ray in each of the two orthogonal directions; this resolution depends slightly upon the primary energy spectrum or spectral index). The muon threshold detection energy is 0.1 GeV for vertical tracks to penetrate the 50 mm steel plate; however, these muons must have been born with at least several GeV of energy to penetrate the atmosphere in order to reach the detectors.

The precise response to primary gamma rays is described with a Monte Carlo calculation (see Fig. 6 of [27]); the result depends upon the assumed spectral index. The primary gamma-ray spectrum is assumed to be of the form $E_\gamma^\beta$ with a spectral index $\beta = -2.41$ (the average of the spectral indices reported in the third EGRET catalogue [28]). This spectrum of primary gamma rays is then multiplied by the number of muons per gamma ray which reach detection level [25,27]. This determines the number of detectable muons as a function of the primary gamma-ray energy. Qualitatively, each primary gamma ray produces a number of muons. This number at first increases sharply for gamma-ray primary energies from 1.5 to 10 GeV and then falls slowly for energies above 10 GeV. For a softer spectral index, the muon response peaks at a slightly lower primary gamma-ray energy and then falls off more rapidly above 10 GeV. For convenience, we characterize this response shape as having a threshold of $\sim$10 GeV for the primary gamma-ray spectral indices of interest.

GRAND's ability to correlate short bursts of muons with an identifiable source of primary radiation has been shown in a detection which was in time coincidence with a solar flare on 15 April 2001. The statistical significance of this observation was at the level of $6\sigma$ for a ground level event of 0.6 h duration [29].

## III. DATA ANALYSIS

To analyze GRB coincidences the complete GRB table, the flux table, and the duration table were downloaded from

TABLE I. Summary of events analyzed.

| GRB | Trig | T90 | RA | Dec | $\delta\theta$ | Elev | $LogLk$ | $N_{on}$ | $\lambda N_{off}$ | $N_{\mu}\pm\sigma_{Tot}$ | $\sigma_{Stat}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 971110 | 6472 | 195.2 | 242 | 50 | 0.6 | 81 | 5.18 | 18286 | 17820 | 466±171 | 141 |
| 990123 | 7343 | 62.5 | 229 | 42 | 0.4 | 56 | 5.13 | 1079 | 1076 | 3±36 | 30 |
| 940526 | 2994 | 48.6 | 132 | 34 | 1.7 | 66 | 4.68 | 498 | 478 | 20±28 | 23 |
| 980420 | 6694 | 39.9 | 293 | 27 | 0.6 | 68 | 4.02 | 1456 | 1417 | 39±47 | 39 |
| 960428 | 5450 | 172.2 | 304 | 35 | 1.0 | 70 | 3.83 | 3990 | 3933 | 57±78 | 64 |
| 980105 | 6560 | 36.8 | 37 | 52 | 1.4 | 79 | 3.46 | 2214 | 2229 | −15±61 | 50 |
| 980301 | 6619 | 36.0 | 148 | 35 | 1.3 | 76 | 3.17 | 2053 | 2015 | 38±56 | 46 |
| 970417a | 6188 | 7.9 | 290 | 54 | 1.6 | 62 | 2.08 | 186 | 166 | 20±17 | 14 |

Note: T90 is in seconds. Angles RA, Dec, $\delta\theta$, and Elev are in degrees.

the BATSE archive [30]. Two of the candidate GRBs are listed in the BATSE 4b catalogue, the other more recent events are in the BATSE archives. Table I lists some of the BATSE data including: the date of the trigger (GRB), the trigger number (Trig); the time duration for 90% of the burst's counts to occur (T90) in seconds, the right ascension (RA), declination (Dec), and the BATSE angular error ($\delta\theta$), all in degrees. Next to these BATSE entries are the calculated angular elevation (in degrees) above GRAND's horizon (denoted Elev) and our selection criterion ($LogLk$) described below. The last three columns of Table I summarize the muon secondaries observed by GRAND within a $\pm 5°$ square angular window centered on the burst location during the BATSE T90 time interval.

### A. Selection criterion

For each GRB, an approximate total acceptance factor, $A$, was calculated for the detector stations of GRAND:

$$A \simeq [(1-g\times\tan\theta_x)(1-g\times\tan\theta_y)\times\cos\theta]\times\cos^2\theta \quad (1)$$

where the geometrical factor $g\equiv d/L$, with $d$ the vertical spacing between the top and bottom plane (0.61 m), and $L$ the length of a single plane (1.1 m). The angles $\theta_x$ and $\theta_y$ are the angle of the track from vertical ($\theta$, the complement of Elev) projected onto the xz- and yz-planes, respectively. The quantity in square brackets is the geometrical acceptance of a detector station; this acceptance has been multiplied by $\cos^2\theta$ to account for the added absorption of a muon traversing an increased path length through the atmosphere for tracks inclined from the vertical.

As a rudimentary criterion to select which events to analyze, the relative likelihood $LogLk$ of GRAND to observe each GRB is taken as proportional to the (base 10) logarithm of the product of the total acceptance factor, Eq. (1), times the BATSE fluence in the highest of four energy bins (i.e. $E_{\gamma}\geqslant 300$ KeV). The GRBs with the 21 largest values for $LogLk>3$ from the BATSE archive were selected for further consideration. In addition, it was recognized that the Milagrito event was in the field of view of GRAND, and even though it did not satisfy the selection criterion, it was included in the analyses.

The entries in Table I are ordered with the highest value of $LogLk$ at the top. This $LogLk$ factor, however, did not take into account the fact that the array was under continuous construction during this time and had varying (usually increasing) numbers of operational detectors at a given time. The data for each GRB analyzed were checked to ensure no huts were turning on or off during the time of analysis for that GRB. Data for 11 of the top 21 GRBs by this $LogLk$ criterion were available on archived data tapes. Of the 11, one was found to have individual stations with large time dependent inefficiencies and was discarded. In addition, three of the candidate GRBs were before 1994 when the detector area was small and had errors in the clock's seconds bit. Since these three bursts had the shortest T90 times, they were most sensitive to the precise time. Furthermore, the BATSE angular errors were largest (two were comparable to the total width of our analysis window). Therefore, these three events were eliminated from the present analyses. [These three events were included in a previous preliminary analysis [31] with chance probabilities of $+1.6$, $-0.1$, and $-1.4\sigma$ (Stat).] The calculation of time from the data was checked to ensure that the times of the remaining GRBs are correct.

In a preceding preliminary analysis [31], we employed an angular window using fixed angles of right ascension (RA) and declination (Dec). However, the signal and background data in this analysis showed systematic variations due to: (1) The local angles $\theta_x$ and $\theta_y$ change with time during a burst, which means that event tracks are recorded with differing numbers of wire combinations leading to systematic fluctuations in the count rate. (2) The detector's solid angle increases as a fixed RA and Dec moves toward the vertical (or conversely). (3) There is dead time (tens of milliseconds) whenever: (a) the data input is stopped in order to write an event buffer to magnetic tape; or (b) a trigger is received for a concurrently running air-shower experiment. These systematic effects were accounted for in the current analysis method as follows:

First, the BATSE GRB locations in RA and Dec were transformed to a horizon coordinate system of elevation and azimuth and then projected onto the xz-plane ($\theta_x$) and the yz-plane ($\theta_y$). A window of $\pm 5°$ in $\Delta\theta_x$ and $\Delta\theta_y$ was centered on the location of the GRB.

As time progressed during the T90 burst interval, the local windows of $\theta_x$ and $\theta_y$ stay fixed thus removing problems (1) and (2) above. To correct for the dead time (3), the total event rate over the whole sky was employed as a high-statistics measure of the live time of each time bin; each bin's data were corrected for its corresponding live time. After this correction, the data inside the angular cuts were almost independent of the random dead times. These corrected numbers of muons inside the angular window were studied to obtain the (background + signal) within the T90 interval. The background was determined during a time interval of $\approx 20\times$T90 before the start of the BATSE trigger (except in the case of GRB 971110 it was $\approx 10\times$T90 as the longer interval of time was not available on the same data tape for this event).

### B. Significance

The signal (Sig) calculated for a GRB is the difference between the total counts $N_{on}$ inside the T90 interval (corrected for dead time) and the background counts $N_{off}$ normalized to the live time of the T90 time interval and corrected for dead time. The statistical significance $Sig/\delta Sig$ (number of standard deviations above background) of each event was determined according to the likelihood ratio method of Li and Ma [32],

$$Sig/\delta Sig=\sqrt{2}\left\{N_{on}\ln\left[\frac{1+\lambda}{\lambda}\left(\frac{N_{on}}{N_{on}+N_{off}}\right)\right]+N_{off}\ln\left[(1+\lambda)\left(\frac{N_{off}}{N_{on}+N_{off}}\right)\right]\right\}^{1/2}, \quad (2)$$

where $\lambda$ is the ratio $\lambda\equiv t_{on}/t_{off}$. This method makes a best accounting of the true significance of an event when the background and event time intervals differ, i.e. $\lambda\neq 1$. For all of these events $\lambda\approx 0.05$ except for GRB 971110 for which $\lambda\approx 0.10$. The statistical errors from this analysis are listed in the last column of Table I.

The data for these GRBs were tested before, during, and after the signal region to see if any station's data had excessive noise or erratic time dependences which could erroneously mimic a GRB signal. These rates exhibited no pathological time structure.

The only possibly significant single observation among the eight GRBs in Table I corresponds to GRB 971110. The time distribution of the data before and after the BATSE event trigger are illustrated in Fig. 1. Here the data are plotted in a manner similar to the way in which the Milagrito [16] event was presented, i.e., with two different values for the time-bin resolution and for different durations before and after the GRB. In this figure negative background-subtracted events are also included giving added information on the fluctuations in the background. There are excess events in the T90 window (and possibly before and after as well). The muon excess in the T90 window is 3.3$\sigma$ above the $\sqrt{N}$ fluctuations expected from pure counting statistics. Nevertheless, it is also possible that the background fluctuates in excess of the expected $\sqrt{N}$ statistics. This could happen due to real variations in the muon arrival rate at a given angle or to variations in the detector response not already accounted for in our dead time correction. In either case, the additional

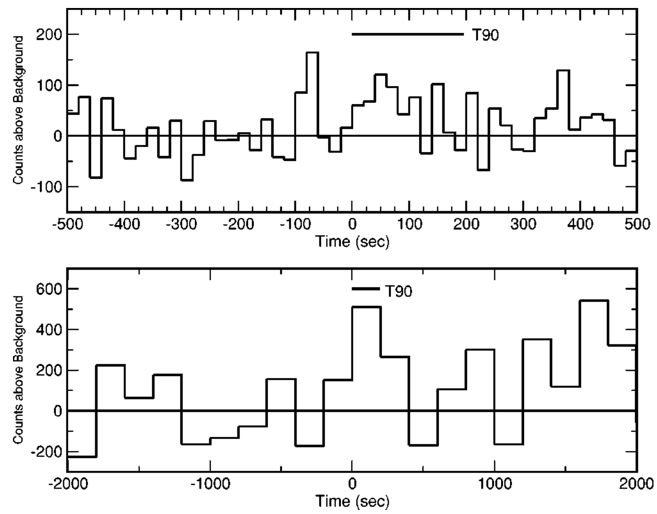


FIG. 1. Background-subtraced event rate in the Project GRAND array before and after the BATSE 6472 event trigger. The T90 interval for this burst is indicated by a horizontal line above each of the two histograms.

systematic error associated with such possible excess fluctuations can be deduced directly from the observed data rate as we now describe.

### C. Systematic error

As a check on systematic errors in the signal for GRB 971110, similar angular sections of the sky (which have the same absolute values of $\theta_x$ and $\theta_y$ and thus the same average counting rates) and the same time interval (T90) but at different, neighboring times were analyzed. These time intervals span $\pm 26$ h relative to the BATSE trigger for GRB 971110. The data on the tape were also analyzed for T90 intervals beginning at times before and after the GRB, and for different $\theta_x$ and $\theta_y$ locations in the sky but at the same elevation angle. This analysis was done in the same way as described in the preceding paragraphs.

Figure 2 shows the distribution of fluctuations above and below background for 1587 separate analyses (not including

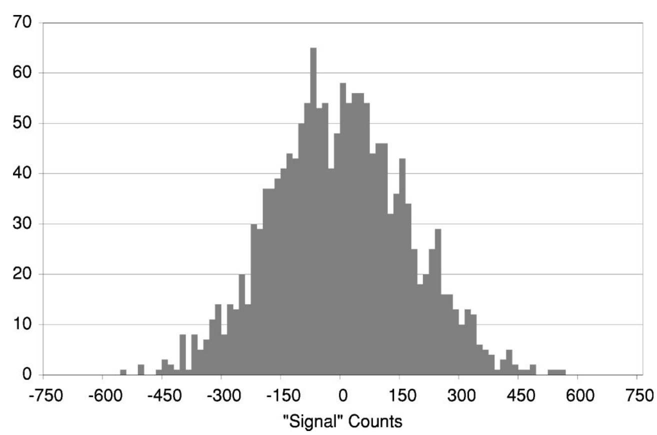


FIG. 2. Distribution of fluctuations above and below background for 1587 random T90 intervals observed by GRAND near the time of GRB 971110.

the time and angle of the GRB 97110 event). The resulting distribution is centered on zero, and is approximately Gaussian in shape. However, this distribution has a larger width than that calculated from the Poisson random statistics of the counts within the T90 and background intervals. The standard deviation width of this distribution is 171 counts, whereas the expected statistical deviation is only 141 counts based upon the background count rate. A total statistical plus systematic standard deviation is 171 counts for this distribution. Adopting this total error as the quadrature sum of the statistical and systematic errors, then 97 counts are ascribed as the additional systematic error in our analysis for GRB 971110. With this additional systematic error, the ratio of signal-to-noise becomes $Sig/\delta Sig = 2.72$.

The probability of a $+2.7\sigma$ fluctuation in a Gaussian white-noise distribution is $4.9\times 10^{-4}$. However, the histogram in Fig. 2 can be used to measure the probability of GRAND's detection being real without assuming a distribution which is Gaussian. In this histogram there are 10 random fluctuations either $\geqslant +466$ or $\leqslant -466$. This corresponds to a probability of $3\times 10^{-3}$ for a background fluctuation to produce a $\geqslant +466$ signal. For one event out of the 8 analyzed to exhibit this much deviation would correspond to a random probability of 0.025. Thus, the statistics of this event are interesting but not compelling.

The total statistical plus systematic error derived above is consistent with a white-noise fluctuation that would scale with the statistical error. In this case, it is reasonable to take the ratio of total to statistical error as a constant independent of the particular T90 interval in question. This constant factor ($\sim 1.2$) can then be used to roughly estimate the systematic error for the remaining events. These remaining events (except one) indicate positive (though not significant) deviations.

## IV. DISCUSSION

Accepting for the moment the proposition that the muon excess associated with GRB 971110 may be real, it is worthwhile to consider some of the implications of this event. First, we wish to consider the possibility of whether these events could be explained by a naive extension of the low-energy burst spectrum. Indeed, it is known from EGRET detections [11] that it is possible for the spectrum of the low-energy burst detected by BATSE to extend up to $\sim 10$ GeV with no change in the spectral index. On the other hand, such an extension is not guaranteed. For example, no sub-MeV photons were observed at the time that EGRET observed an 18 GeV gamma ray.

To explore the possibility that the observed muon excess could be explained by a straightforward extension of the BATSE spectrum, the GRB 971110 spectrum was fit using the standard BATSE empirical spectral model [33,34]:

$$\frac{d^3N}{dEdAdt} = B\left(\frac{E}{100\ \text{keV}}\right)^{\alpha} \exp\left(-\frac{E(2+\alpha)}{E_{peak}}\right) \quad (3)$$

for low energy, $E<(\alpha-\beta)E_{peak}/(2+\alpha)$, and

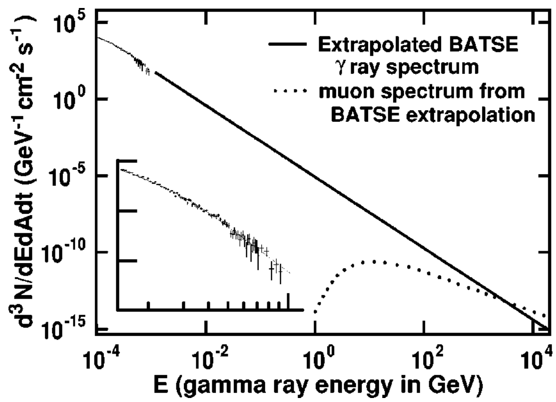


FIG. 3. Extrapolation of the best-fit energy spectrum for BATSE GRB 971110. A portion of the BATSE data are shown in the inset. Multiplying the extrapolated BATSE gamma ray spectrum by the gamma to muon conversion efficiency (as calculated by FLUKA [25]) gives the spectrum of muons which would be observed by GRAND.

$$= B\left\{\frac{(\alpha-\beta)E_{peak}}{[100\ \text{KeV}(2+\alpha)]}\right\}^{\alpha-\beta}\left(\frac{E}{100\ \text{keV}}\right)^{\beta}\exp(\beta-\alpha) \quad (4)$$

for $E\geqslant(\alpha-\beta)E_{peak}/(2+\alpha)$. The best-fit parameters for this burst are $\alpha=-1.02\pm 0.04$, $\beta=-2.33\pm 0.11$, $B=0.0095\pm 0.0003$, and $E_{peak}=303\pm 17$ KeV, with a reduced $\chi^2$ of 0.93.

The solid line in Fig. 3 shows the optimum fit to the BATSE spectrum extended to the energy range of GRAND. Note that this naive extension is probably an overestimate, since absorption due to pair production from interactions of gamma rays with the intergalactic infrared background is expected to become significant above $\sim 200$ GeV [23,24].

This extended spectrum was folded with the known efficiency, $\epsilon_\mu$, of high-energy photon to muon conversion in the atmosphere (in the region of GRAND $\epsilon_\mu \approx 0.23E_{TeV}^{1.17}$ [25]) to yield the spectrum of muons at GRAND expected from this extrapolation of the BATSE spectrum (dotted curve in Fig. 3). The broad peak of the muon spectrum at around 10 GeV illustrates the peak (threshold) sensitivity of GRAND for this particular gamma ray spectrum. Integrating this muon spectrum over the primary gamma ray energy, $E_\gamma$, yields the number of muons per area per time based upon this extrapolation. Multiplying this result by the effective muon detection area of GRAND at the time of this burst and by its T90 time interval yields $0.3\pm 0.6$ muons—well below the observed $466\pm 171$ excess muons detected for this event. Even if all of the fit variables are adjusted to their respective upper $1\sigma$ limits, only four muons would be expected.

Clearly, a simple, naive (very long) extrapolation from the BATSE spectrum is inconsistent with the observed muon excess at GRAND. In a related paper [7] the specific constraints which these data place upon possible mechanisms for energetic gamma ray emission such as energetic proton-synchrotron emission [9], inverse-Compton scattering from relativistic electrons, or hadronic production of pions in the burst [10] are discussed.

## V. CONCLUSION

We have completed a search for evidence for energetic sub-TeV gamma rays in coincidence with low-energy gamma ray bursts. No convincing evidence is found, though there is a possible $2.7\sigma$ detection associated with the best candidate burst. There is an insignificant, $1.2\sigma$, muon excess observed in association with the Milagrito event (GRB 970417a), as well as a slight positive excess for all (but one) of the remaining events investigated.

Based upon an analysis of the most significant event, we conclude that if the detected muon excess is real, then probably a new sub-TeV component to the gamma ray spectrum is required. A determination of the magnitude of this component, however, will require knowledge of the source spectrum as well as the effects of photon absorption both in the burst environment and enroute. Studies along this line are discussed in a separate paper [7]. Preliminary indication is that, if the coincidence with GRB 971110 is real, then most of the GRB energy arrived in the form of energetic gamma rays.

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[1] B. Paczyński, Astrophys. J. Lett. **308**, L43 (1986).
[2] J. Goodman, Astrophys. J. Lett. **308**, L47 (1986).
[3] R. Sari, T. Piran, and R. Narayan, Astrophys. J. Lett. **497**, L17 (1998).
[4] B. Paczyński and G. Xu, Astrophys. J. **427**, 708 (1994).
[5] M. Rees and P. Mészáros, Mon. Not. R. Astron. Soc. **258**, P41 (1992).
[6] P. Mészáros and M. Rees, Mon. Not. R. Astron. Soc. **269**, L41 (1994).
[7] P.C. Fragile *et al.* (unpublished).
[8] E. Waxman, Phys. Rev. Lett. **75**, 386 (1995).
[9] T. Totani, Astrophys. J. Lett. **502**, L13 (1998); **509**, L81 (1998).
[10] E. Waxman and J. Bahcall, Phys. Rev. Lett. **78**, 2292 (1997).
[11] E.J. Schneid *et al.*, Astron. Astrophys. **255**, L13 (1992).
[12] K. Hurley, Nature (London) **372**, 652 (1994).
[13] J.R. Catelli, B.L. Dingus, and E.J. Schneid, in Gamma Ray Bursts, edited by C.A. Meegan, AIP Conf. Proc. No. 428 (AIP, New York, 1997).
[14] M. Amenomori *et al.*, Astron. Astrophys. **311**, 919 (1996).
[15] L. Padilla *et al.*, Astron. Astrophys. **337**, 43 (1998).
[16] Milagrito Collaboration, R. Atkins *et al.*, Astrophys. J. Lett. **553**, L119 (2000); R. Atkins *et al.* (unpublished); I.R. Leonor *et al.*, in *Proceedings of the 26th International Cosmic Ray Conference*, Salt Lake City, 1999, edited by D. Kieda, M. Salamon, and B. Dingus (International Union of Pure and Applied Physics, Salt Lake City, 1999), Vol. 4, p. 12.
[17] J. Gress *et al.*, in *Proceedings of the 21st International Cosmic Ray Conference*, Adelaide, 1990, edited by R.J. Protheroe (International Union of Pure and Applied Physics, Adelaide, 1990), Vol. 10, p. 335.
[18] J. Linsley *et al.*, J. Phys. G **13**, L163 (1987).
[19] J. Poirier *et al.*, Nucl. Phys. **B14A**, 143 (1990).
[20] J. Gress *et al.*, Nucl. Instrum. Methods Phys. Res. A **302**, 368 (1991).
[21] J. Poirier, S. Roesler, and A. Fassò, Astropart. Phys. **17**, 441 (2002).
[22] K. Mannheim, D. Hartmann, and B. Funk, Astrophys. J. **467**, 532 (1996).
[23] M.H. Salamon and F.W. Stecker, Astrophys. J. **493**, 547 (1998).
[24] T. Totani, Astrophys. J. Lett. **536**, L23 (2000).
[25] A. Fassò and J. Poirier, Phys. Rev. D **63**, 036002 (2001).
[26] S. Roesler, W. Heinrivh, and H. Schraube, Radiat. Res. **149**, 87 (1998); G. Battistioni *et al.*, Astropart. Phys. **9**, 277 (1998); **12**, 315 (2000).
[27] J. Poirier, S. Roesler, and A. Fassò, Astropart. Phys. **17**, 441 (2002).
[28] R.C. Hartman *et al.*, Astrophys. J., Suppl. Ser. **123**, 79 (1999).
[29] J. Poirier and C. D'Andrea, J. Geophys. Res., [Space Phys.] (to be published).
[30] http://www.batse.msfc.nasa.gov/batse/
[31] T.F. Lin *et al.*, in *Proceedings of the 26th International Cosmic Ray Conference*, Salt Lake City, 1999 [16], Vol. 4, p. 24.
[32] T.-P. Li and Y.-Q. Ma, Astrophys. J. **272**, 317 (1983).
[33] D. Band *et al.*, Astrophys. J. **413**, 281 (1993).
[34] E.E. Fenimore and E. Ramirez-Ruiz, astro-ph/0004176; D.E. Reichart *et al.*, Astrophys. J. **552**, 57 (2001).