Astroparticle Physics with the MINOS Far Detector

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Abstract. The MINOS Far Detector is sensitive to primary cosmic rays with energies around 10 TeV. A search for a cosmic ray point source with four and a half years of data produced no likely candidates.

Gamma Ray Bursts (GRBs) are expected to produce a brief, high intensity burst of neutrinos, and hundreds of GRBs have been cataloged by the Swift BAT. The MINOS Far Detector has observed atmospheric neutrinos since 2003, and a search for a coincidence with a GRB was performed with these data.

II. SEARCH FOR AN ASTROPHYSICAL COSMIC RAY SOURCE

Before an individual source can be examined, an all-sky survey must be performed. Though signals have been reported in only a very few locations on the sky, the analysis must not be biased by an a priori assumption of a source.

A. Statistics

An excess of muons in the context of this discussion is defined as a signal above background greater than the expected random fluctuation of the actual cosmic ray background. The data set is sufficiently large such that Gaussian statistics apply. The significance of an observed number of muons over background is given in terms of a Gaussian deviation:

\[ D_\sigma = \frac{N_{\text{obs}} - N_{\text{back}}}{\sqrt{N_{\text{back}}}} \]

where \( N_{\text{obs}} \) is the number of observed muons and \( N_{\text{back}} \) is the number of background muons.

In Gaussian statistics, a confidence limit of three from the expectation is a measure of how likely it is that a given signal could be caused by a random statistical background fluctuation. A 3σ deviation corresponds to a 0.27% likelihood that it is a background fluctuation mimicking a signal. A survey over multiple bins increases the trials factor for the search. For 32,000 bins, the actual probability that constitutes a 3σ likelihood is 0.000068%. Therefore, to get a true 3σ detection, a deviation \( D_\sigma = 5.2 \sigma \) must be found.

Especially important to the search for a sensitive signal is the signal-to-noise ratio. An unbinned search is the most sensitive to the detection of a source [7], but impractical for an all sky survey with an instrument of limited angular resolution. It has been shown that a binned survey is only 10% less sensitive if the bin size properly represents the angular resolution of the instrument [7]. To determine the proper bin size, a simple Monte Carlo simulation is needed.
Carlo was written to simulate a point source [8]. The maximum signal to noise ratio was found with a bin radius of 0.45°, which corresponds to a square bin 1° on a side.

B. The Data

The data for the cosmic ray point source search were accumulated from 1 August, 2003 until 31 December, 2007, numbering $6.7994 \times 10^6$ triggers. A number of data quality cuts were performed to ensure that instrumental noise and detector instabilities were removed from the data sample [8], and pointing cuts were performed to ensure that the muon track reliably pointed back to the sky [8]. An additional cut required zenith angle to be less than 76° because that was the limit of the rock map. After all cuts were applied, 61.26% of the data remained.

C. The Search

Simulated data was used to create a background grid in celestial coordinates of equal solid angle, $\alpha$ and $\sin(\delta)$ [8]. A problem arises when a source is divided into two bins. This occurs if the signal location falls along the line between adjacent cones. Four interdependent analyses were performed, with each one shifting the binning of the data histogram slightly such that if a source were divided amongst bins in one grid, it would not be in the next. The first analysis, Survey 1, used the same binning as the background, while Survey 2, used bins shifted in $\alpha$ by half a bin width (0.5°), keeping $\delta$ the same. Survey 3 used bins shifted $\delta$ by a half bin width with $\alpha$ the same, while Survey 4 shifted both a half of a bin width.

In the absence of a source, the subtraction of the smooth, simulated background from the data will give a value of zero in most cases, with the expected random fluctuations surrounding the mean. A table of fit parameters and histogram statistics is shown in table I for each of the four surveys. The mean is as expected, very nearly zero, while the width is one.

In the absence of a statistically significant signal, limits on the the cosmic ray flux can be set for a source existing in an individual region of the sky [8]. The 95% confidence flux limits can be seen in figure II-C.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Mean</th>
<th>$\sigma$</th>
<th>$\chi^2$/ndf</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (centered)</td>
<td>0.048±0.0049</td>
<td>1.008±0.0033</td>
<td>75/78</td>
</tr>
<tr>
<td>2 ((\alpha) shifted)</td>
<td>0.046±0.0049</td>
<td>1.01±0.0033</td>
<td>75/78</td>
</tr>
<tr>
<td>3 ((\delta) shifted)</td>
<td>0.33±0.0059</td>
<td>1.2±0.004</td>
<td>99/93</td>
</tr>
<tr>
<td>4 ((\alpha, \delta) shift)</td>
<td>0.34±0.0060</td>
<td>1.2±0.004</td>
<td>113/89</td>
</tr>
</tbody>
</table>

III. Search for Gamma Ray Burst Particle Signature

A gamma ray burst is a catastrophic event that briefly floods the sky with highly energetic photons. The gamma ray sky is relatively quiet, so GRBs outshine all other gamma ray sources combined, including the sun. The relativistic fireball that expands rapidly outward from the central engine of the GRB creates an enormous shock wave when it encounters the ISM, which accelerates protons to $10^{15}$ eV. This leads to pion production when these protons interact with the $10^6$ eV photons carrying the bulk of the fireball energy [9], which decay to produce neutrinos. Neutrinos have become a golden channel to investigate GRBs because they are transparent to magnetic fields, the GRB shock wave and all other light matter. Many searches have been carried out, with no signal yet reported [4], [5], [6].

A. The Data

The Swift Gamma Ray observatory [10] has been observing GRBs and making rapid afterglow measurements since December 2004. The collaboration’s first data catalog was published in July, 2007 and contained spectral data and positions for 237 GRB [10]. These GRB were distributed
uniformly, consistent with extra-galactic origin. and this distribution can be seen in Fig. 2. GRBs are divided into two groups, long ($T_{90}$, the time to 90\% fluence, greater than 2 s) and short, with distinctly different physical processes describing each group. This difference is indicated on the GRB skymap with the long GRBs represented by black circles, and the short GRBs represented by red circles.

The beginning muon data set for this analysis are the 37.485 million events collected from 1 August, 2003 through 31 December 2007, after pointing cuts were applied [8]. Downward going (cosmic ray induced) events outnumber upward going (neutrino induced) events by a factor of $10^5$, and a timing error could have the result that the vertex and end point of a track are swapped, so a cosmic ray muon could be reconstructed as a neutrino candidate event. Only a detector with good timing resolution can separate upward going from downward going events. The direction of the track (upward or downward) was determined by plotting the time difference $\Delta T$ (ns) of each hit along the track as a function of its distance $\Delta S$ (m) from the first hit. If the $y$ positions of the hits increase along the length of the track, $\Delta S$ is positive; for $y$ decreasing along the track, $\Delta S$ is negative. Upward-going events have a positive slope for the straight line fit to the $\Delta T/\Delta S$ distribution. To ensure that only events with good timing information are selected, three additional cuts are applied [11]. After these additional cuts 34.99 million events remained, about half of the total number of triggers.

B. Search for GRB and Neutrino Coincidence

The reported Swift position error is less than 7.0′ (1.75°), and most often 2.0′ (0.5°) which is nearly an order of magnitude improvement over previous instruments. The pointing resolution for muons in the Far Detector is 0.6°, but the kinematics of the interaction between neutrinos and nucleons reduces the resolution of the measurement. The rms angle between a neutrino and the muon it produces is 3.7° [5]. From these considerations, a 5° half angle cone was chosen as the angular separation to be considered spatially coincident.

The most often compared theory of neutrinos produced by GRBs is that they are produced in the skywave of the expanding fireball at the same time as the gamma rays, and that the shock wave is transparent to both the gamma rays and neutrinos [9]. Thus, neutrinos and gamma rays should arrive at the same time (unlike supernovae, where a burst of neutrinos precedes the outburst of photons). The longest duration GRB in the Swift catalog, GRB060929, had $T_{90} = 554$ s, while the shortest, GRB050925, had $T_{90} = 0.07$ s. There were 15 GRB that did not have $T_{90}$ information for various reasons including instrumental failures or incomplete data. Rather than excluding these events from the search, it was assumed that they were simply short GRBs and assigned $\langle T_{90} \rangle = 2$ s. This is valid because the gamma ray sky is so quiet, so little is known about gamma ray progenitors, and if some of the information is lost, it is not possible to recover $T_{90}$ since it is integrated over time from the start of the burst.

Because the GRB and muon data are so well known in space and the window of time around each GRB is relatively small, the background on the search is minimal. The average muon rate after timing cuts were applied is 0.27 Hz. Considering that the average GRB $T_{90}$ is 70 s, 10 s before and after $T_{90}$ are added to the time search window, and that a 5° half angle cone search window is used, 0.037 events would be expected in each search window. A background map was constructed from the known contribution of atmospheric neutrinos and cosmic ray muons using Monte Carlo [8].
These background events were put in a histogram with square bins equivalent to the solid angle of a 5° half angle cone, scaled by the 90 s mean time window. Neutrinos interact in the rock above the detector and generate muons just as often as they do below the detector. Ordinarily, the signal from these downward going neutrinos is obscured by the much higher cosmic ray induced muon flux, so neutrino analyses are restricted to upward going or contained vertex events. Using only upward going events restricts the searchable sky by half, and contained vertex events are lower energy, so their pointing is worse than 3.7°.

All 34.99 million muons that pass the cuts were used in the analysis, which is a departure from all previous analyses, which only used events positively identified as neutrino induced. This is not necessary because backgrounds are quantified and low, much less than one event for every search window. This allowed for the first search for a GRB neutrino coincidence in the energy range $10^{5}$ GeV < $E_{\nu}$ < $10^{5}$ GeV in the northern sky. MACRO [4] used only upward going muons and so was insensitive to the northern sky, Super-K [5] used only neutrino candidates, (upward going events had the highest $\langle E \rangle$, 100 GeV), and AMANDA/IceCube [6] has a threshold energy of $10^{5}$ GeV. It is in this small region of space that the MINOS explored for the first time.

To perform the search, a time window of $T_{90} \pm 10$ s was drawn around the trigger time for each burst. For muons within this window, the angular separation from the GRB trigger location was calculated. If it was found to be within the 5° half angle cone, it was considered coincident. A list of GRBs with coincident muons observations can be seen in Table III-B. Also listed are the expected background and probability of such a coincidence occurring by chance.

### TABLE II

<table>
<thead>
<tr>
<th>GRB</th>
<th>$T_{90}$</th>
<th>$N_{B}$</th>
<th>$N_{C}$</th>
<th>$P(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>041220</td>
<td>(291.3°, 60.6°)</td>
<td>5.6</td>
<td>2</td>
<td>0.04</td>
</tr>
<tr>
<td>050713A</td>
<td>(320.0°, 77.0°)</td>
<td>124.7</td>
<td>3</td>
<td>0.81</td>
</tr>
<tr>
<td>050716</td>
<td>(388.6°, 38.6°)</td>
<td>69.1</td>
<td>2</td>
<td>0.11</td>
</tr>
<tr>
<td>060428B</td>
<td>(255.4°, 62.0°)</td>
<td>57.9</td>
<td>2</td>
<td>0.12</td>
</tr>
<tr>
<td>060507</td>
<td>(89.9°, 76.2°)</td>
<td>183.3</td>
<td>3</td>
<td>1.66</td>
</tr>
<tr>
<td>061126</td>
<td>(86.6°, 64.2°)</td>
<td>70.8</td>
<td>2</td>
<td>1.66</td>
</tr>
<tr>
<td>070616</td>
<td>(321.1°, 36.9°)</td>
<td>402.4</td>
<td>3</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### IV. CONCLUSIONS

A search for a point source of cosmic rays was performed with 4.12 live-years of muon data with the MINOS Far Detector. No statistically significant excesses were seen, so 95% flux limits were placed on a 1 deg$^2$ grid on the northern sky. The minimum flux limit was $7.8 \times 10^{-14}$ cm$^{2}$ s$^{-1}$, comparable to MACRO [3]. A search for correlation between GRB triggers and neutrinos was performed, with no significant coincidences detected.

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### REFERENCES