Spatially Coincident Fermi-LAT $\gamma$ Ray Sources to IceCube $\nu_\mu$ Events

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Abstract

IceCube has detected several very high energy muon neutrino events, of a several hundred TeV to a few PeV, beginning inside the detector. These events are unlikely to have originated in the atmosphere, and are suspected to come from astrophysical sources, the likes of which can also be observed in gamma rays by the Fermi Space Telescope. In this paper, I explore the gamma-ray sky around 16 of the aforementioned high-energy neutrino events to search for spatially coincident gamma ray point sources.

I. INTRODUCTION

I. Neutrino and Multi-Messanger Astronomy

One of the most sought-after unsolved problems in astronomy is the origin of cosmic rays. Cosmic rays were discovered in 1912 by Austrian physicist Victor Hess. While riding in a balloon during a solar eclipse, Hess detected rising radiation levels at rising altitudes, concluding that there must be a fairly constant source of radiation other than the Sun bombarding the Earth. Cosmic rays consist mainly of charged particles and light ions, which enter the atmosphere from all directions.

Charged particles do not "point back" to their sources. Charged particles can be accelerated and change direction along galactic and extragalactic magnetic fields, making it impossible to directly trace their paths from their cosmic source to Earth. During the interaction of these charged particles with nearby radiation fields or ambient matter, charged and neutral pions can be produced, which in turn decay into neutrinos and gamma rays. Neutrinos, being only weakly interacting, can pass from their sources through space and straight through Earth without being absorbed or scattered. Neutrinos can thus too be observed effectively from all directions, no matter the placement of the detector on Earth. Space-based gamma ray telescopes also serve this purpose and are able to sweep large swaths of sky in a reasonable amount of time. Using a multi-messanger approach and data from both neutrino and gamma ray observatories, sources of cosmic rays could be detected.

II. IceCube Neutrino Observatory

The IceCube Neutrino Observatory is located at the South Pole. The facility is a cubic kilometer of Antarctic ice extending down to almost 2,500 meters below the surface. Drilled into the ice are 5,160 Photomultiplier Tubes (PMTs) attached to 86 vertical strings. These are arranged hexagonally with a separation of 125 meters between the strings. The PMTs detect Cherenkov radiation via the charged leptons produced following the interaction of a neutrino with molecules in the ice. IceCube is capable of detecting electron, muon, and tau neutrinos at energies of about 100 GeV to several PeV.

The total number of neutrino candidates for three years’ worth of data is 398,804 for the 40-, 59-, and 79-string configurations of the detector[1]. The vast majority of these events originated in the atmosphere and are not astrophysical. For the purposes of this study, I was only interested in 16 muon events which started inside the detector. Selecting for only upgoing events, which enter the detector from below the horizon (thus passing through Earth,) allows for the elimination of background muons which come from Earth’s atmosphere. Only looking at muon events allows for a much better angular error, approximately 1° versus approximately 20° for cascades from other flavors. Neutrino charged-current interaction produces the neutrino’s partner lepton. The high energy of the muon allows it to travel in a long track, as opposed to the electron, which quickly produces a shower, making it much more difficult to reconstruct the direction of the event. It is thus far unknown if IceCube as seen tau neutrinos, which have a very
short lifetime and thus produce showers nearly indistinguishable from electron neutrino events.

III. Fermi-LAT \( \gamma \) Ray Observatory

The Fermi Gamma Ray Observatory is a space-based gamma ray telescope sensitive to photon energies up to 1 TeV, and is most sensitive between 1-300 GeV. The main instrument, the Large Area Telescope (LAT,) is capable of sweeping 20% of the sky at a given moment, and can cover the entire sky in approximately three hours. The space-based nature of the telescope gives it a few distinct advantages over ground-based gamma ray observatories. As previously stated, Fermi-LAT is able to look at the entire sky, whereas a ground-based observatory is restricted to its own hemisphere and must dedicate most of its time to one patch of sky. In addition, ground-based telescopes must be impractically large to observe low-energy gamma rays, which are typically absorbed by the Earth’s atmosphere.

LAT consists of an anticoincidence detector, tracker, calorimeter, and data acquisition system. A gamma ray enters the anticoincidence detector, which rejects stray cosmic rays and gamma rays originating in Earth’s atmosphere. If a signal is not produced, it passes to one of 16 tungsten sheets, where it is converted to an electron-positron pair. The tracker consists of silicon strips which measure the path of the pair. Finally, the particles enter the calorimeter, which measures their energy.

II. Potential \( \nu \) and \( \gamma \) Sources

Active Galactic Nuclei (AGN) are extremely bright regions present in typically distant galaxies, surrounding supermassive black holes. They are generally characterized by the long relativistic jets of radiation they produce. Two types of active galactic nuclei are quasars, AGN which are extremely distant and appear starlike, and blazars, which are extremely compact quasars whose jets face Earth head-on and contribute to most of the gamma ray point sources detected by Fermi. The subtypes of interest for this paper are Flat-Spectrum Radio Quasars (FSRQs,) and BL Lac Objects. BL Lac objects are lower in luminosity and lack the broad emission lines of FSRQs.

It is suspected that active galaxies could be a source of high-energy neutrinos. The process which should produce astrophysical neutrinos, charged pion decay (Equation 1, 2, 3,) ought to occur in the relativistic jets as a result of proton interaction or proton-photon interaction via synchrotron radiation or excess radiation from the accretion disk. These processes also produce gamma rays.

\[
pp \rightarrow p + n + \pi^+ \quad (1) \\
p\gamma \rightarrow n + \pi^+ \quad (2) \\
\pi^+ \rightarrow \nu_\mu + \mu^+ \quad (3)
\]

It is predicted that for AGN with optically thick accretion disks, photomeson interactions could regularly produce neutrinos on the order of a few hundred TeV[2]. The broad emission lines of FSRQs suggest the presence of an optically thick accretion disk with a UV-bright radiation field capable of initiating these processes. During an FSRQ flare, such as the one from 3C 279 in 1996, Atoyan and Dermer[2] predict that a detector such as IceCube would have an approximately 30% chance of detecting a muon neutrino from the object. Because BL Lac objects lack the broad emission lines and are less bright in gamma rays, Atoyan and Dermer[2] predict that a neutrino detector such as IceCube is far less likely to observe neutrinos, with a probability of approximately \(10^{-6}\) during a flare such as the 1997 one from Markarian 501.

III. METHODS

I. Counts, Model, and Residuals Maps

I used the Fermi Science Tools to analyze an area of sky with a region of interest (ROI) of 10°, with the neutrino position at the center. I looked at data from the entire 4-year Fermi data set, with an energy range of 100 MeV to 300 GeV. I then used a Binned analysis to produce 7° by 7° counts, model, and residuals maps. Counts maps are constructed from the photons observed by Fermi which pass all necessary anticoincidence and other cuts in the selected time and energy range. The model map is a best fit to that data using and XML file with the diffuse and point source emission models in the catalog. The residuals maps were produced using WebHera, using residual=sky-model/model. Each are essentially smooth, showing no evidence of new gamma-ray sources not included in the Fermi 3FGL catalog. On each plot, the neutrino position is
located at the center of the circle of radius one, representing the angular error. Of the 16 neutrino events, four had at least one gamma ray point source within the $1^\circ$ error radius. Neutrino event 12, seen in Figure 2, had two. The sources around neutrino events 12 and 19 are BL Lac Objects, the source around neutrino event 11 is a Flat-Spectrum Radio Quasar (FSRQ), and the source around neutrino event 17 was not classified. The data extracted for these maps is Pass 7 data, P7REP_SOURCE_V16. I observed no excess in the any of the residuals maps consistent with a new point source. An earlier analysis of eight different muon neutrino events saw one that was spatially coincident with a Fermi source[3].

![Counts Map](image1)

![Model Map](image2)

![Residuals Map](image3)

**Figure 1:** Neutrino Event 11—The FSRQ is well within the error radius.
(a) Counts Map

(b) Model Map

(c) Residuals Map

Figure 2: Neutrino Event 12-Two BL Lac Objects are seen well within the error radius.
Figure 3: Neutrino Event 17—This unclassified source is considerably dimmer than the others.
II. Light Curves of Sources

In order to see if the spatially coincident neutrinos were detected around any time of a flux increase in the sources, I created light curves. The light curves were constructed using Pass 8 data, P8R2_SOURCE_V6[4], which was released by the Fermi collaboration one day after the count, model, and residuals maps were completed. To generate the light curves, I performed an UNBINNED analysis using the Fermi Tools on an ROI of $10^\circ$ around the five sources seen within the neutrino error radius. I binned the data into 14 one-day bins, one week before the neutrino event, and one week after. Using the gtlike tool available from the Fermi Tools, I was able to see the Test Statistic (TS) value of each bin when generating integral flux values from the photon counts. I then rejected bins with a TS less than 4 in favor of upper limits.

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Figure 4: Neutrino Event 19-The BL Lac Object in the error radius is dim, similar to the source around neutrino event 17.
Aside from the source around neutrino event 11 and some bins of one of the sources around neutrino event 12, most of the sources had very low TS values. None of the sources showed any excess activity during the two-week period I looked at, and none of the neutrino events correspond to any of the highest-

activity days of their respective sources during this period. The FSRQ around neutrino event 11 was by far the strongest source.

Figure 5: Flux points are denoted by dots, upper limits are denoted by errors. The time of the neutrino event is denoted by the black line.
IV. DISCUSSION

I. Isotropic Neutrino Flux

In order to see how the flux of the gamma ray sources compared with the all-sky neutrino flux see by IceCube, I calculated the isotropic neutrino flux using the power law:

\[ E^2 F = A(E/E_0)^{-0.3} \]

where \( A = 1.5 \times 10^{-8} \) and \( E_0 = 100 \) TeV[5]. By integrating both sides of the equation with respect to the energy, I obtained a number in units \( \text{sr}^{-1} \text{s}^{-1} \text{cm}^{-2} \). By multiplying the result by \( 4\pi \) I was able to get rid of the steradians. The isotropic flux I obtained was \( 2.84 (96861517) \times 10^{-5} \text{s}^{-1} \text{cm}^{-2} \).

I then took ratios of the total gamma ray flux \( (F_\gamma) \) of each one-day bin for the five sources and the isotropic neutrino flux: \( F_\gamma/F_\nu \). The ratios were typically on the order of \( 10^{-3} \) or \( 10^{-2} \), suggesting that, in order to account for the IceCube neutrino flux, there should be at least 100 gamma ray point sources associated with IceCube events. This is assuming that the entire gamma ray flux is produced via processes which also produce neutrinos, which is most likely not the case, as gamma rays can also be produced via leptonic processes, meaning that the number of sources needed is likely higher. The purpose of this exercise is mostly to demonstrate that no one point source can account for the total IceCube neutrino flux. If such a source existed, IceCube would have detected it, and thus far, it sees no evidence for significant event clustering[6]. Again, I see no increase in gamma-ray flux of the sources correlated with the time of the neutrino events.

II. Probability of Random Coincidence

In order to determine if the probability of IceCube neutrinos being randomly spatially coincident with Fermi-LAT sources, I generated 16 random right ascensions for each of the neutrino positions, while keeping the declinations constant. I repeated this process 10,000 times, for a total of 625 random right ascensions per declination, each time searching the 3FGL catalog to see how many of the random positions (out of 16) were coincident a Fermi source within the radius of 1°. From the generated plot (Figure 6,) I calculated that approximately 96% of positions had one or more sources within the error radius of 1°. Four out of the original 16 neutrinos were coincident with a total of five sources.

Figure 6: Histogram of random neutrino position trials for the 16 muon events. The x-axis represents the number of random positions spatially coincident with 3FGL sources (out of 16) and the y-axis represents the number of trials out of 10,000 containing said number.
I also performed a similar analysis (Figure 7,) on the total 107,569 muon events from the 59-string configuration. This time, I generated 100 random right ascensions per declination, which I kept constant again. The vast majority of these events are not energetic enough to be astrophysical and likely originated in the atmosphere. For these positions, most contained no sources, unlike in the scrambled analysis of the 16 neutrino sources. This is due to a slight difference in the codes for the 16 neutrino events analysis and the total muon data analysis. For the total muon data, I took each position one at a time, thus looking at how often a single neutrino was closer to a 3FGL source than the error radius. The analysis for the 16 events looked at 16 randomized events per trial at once. I have not found an efficient way to replicate the analysis of the 16 events for the total muon data, and am hoping that, by making an energy cut to eliminate the lower-energy events, I will be able to achieve a better measurement.

![Figure 7: Histogram of random neutrino position trials for the total 59-string muon events. The x-axis again represents the number of sources, and the y-axis the number of trials containing the sources within the error radius (not constant, taken from the IceCube data set.)](image)

V. CONCLUSION

Because the probability of random spatial coincidence is so high, and because most of the sources were BL Lac Objects with extremely low test statistics, it is likely that most, if not all, of the spatially coincidences I observed were random. While neutrino event 11 came from an FSRQ with a better test statistic, it did not occur during a flare, which, if similar to the flare of 3C 279, would have put the gamma ray fluxes on the order of $10^{-6}$, or even during the most energetic day I observed. While it is predicted that energetic muon neutrinos could be observed even from quiescent FSRQs, it will be necessary to observe several more neutrino events coincident with the source to draw any significant conclusions. In the future, I would like to make an energy cut on the data from the 59-string configuration in order to rule out events that are likely not astrophysical, rerun the scrambled analysis in order to make it closer to the analysis of the 16 events, and strengthen the measurement of random coincidence. I also hope to pursue an analysis of the sources with the ground-based gamma ray observatory VERITAS, as well as perform another Fermi analysis on upcoming muon events.
VI. ACKNOWLEDGEMENTS

I would like to thank John Parsons, Mike Shaevitz, Nevis Labs, Columbia University, and the National Science Foundation for making this opportunity possible. Tremendous gratitude to Marcos Santander for his guidance, knowledge, and belief in the project. This research would not have been possible without him. Finally, special thanks to the rest of the REU students for making this summer so enjoyable.

REFERENCES


