Possible extragalactic astrophysical counterparts of IceCube neutrino events

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Abstract. Sources of the IceCube observed neutrino events within energy range 30TeV-2PeV, is now an open question in astronomy and astrophysics. The dominant shower-type neutrino events have large errors in measuring their directions, hence it is difficult to identify their astrophysical sources. These neutrinos can have counterparts in non-thermal X-rays and gamma rays. So a cross-correlation study of IceCube neutrino events with extragalactic candidate sources using X-ray and gamma-ray selected source catalogs such as Swift-BAT, 3LAC and TeV-Cat, will help in identifying sources of the neutrino events. In order to search for the most possible candidates we apply cuts on X-ray and gamma-ray fluxes of the sources in those catalogs, and then we study the statistical significance of correlation by using invariant statistics and Monte Carlo simulations for different classes of sources.

1. Introduction

IceCube Neutrino Observatory, the world's largest neutrino detector, has detected 54 neutrino events within 1347 days with energy between 20 TeV and 2.3 PeV [1, 2]. Shower events, most likely due to ν_e or ν_τ charge current νN interactions and also due to neutral current νN interactions of all flavors, dominate the event list (39 including 3 events with 1–2 PeV energy) while track events, most likely due to ν_μ charge current interactions, constitute the rest. Among a total of 54 events about 21 could be due to atmospheric neutrino ($9.0^{+8.0}_{-2.2}$) and muon (12.6 ± 5.1) backgrounds. A background-only origin of all 54 events has been rejected at a 6.5-σ level [2]. Therefore a cosmic origin of a number of neutrino events is robust. The track events have on average $\sim 1^\circ$ angular resolution, but the dominant, shower events have much poorer angular resolution, $\sim 15^\circ$ on average [2]. Searching for sources of these events is now one of the major challenges in astrophysics. Pinpointing the astrophysical sources of these neutrinos is difficult, due to a large uncertainty in their arrival directions.

High energy cosmic rays (CRs) can interact with low energy photons and/or low energy protons to produce neutrinos and high energy gamma rays inside the source or while propagating to the Earth. So a multi-messenger study of neutrinos, Cosmic Rays (CRs) and gamma rays can identify the possible astrophysical sources. In our first attempt to search for sources we tried to see a correlation with Ultra-High Energy (UHE) CRs with the earlier 37 cosmic neutrino events detected by IceCube [3].

Here we study correlation of IceCube neutrino events with TeVCat [4], *Swift*-BAT 70 month X-ray source catalog [5] and 3LAC source catalog [6]. To do specific correlation study we use

different cuts on the observed energy flux of these sources, and also different sets of source types, and showed the results of this study.

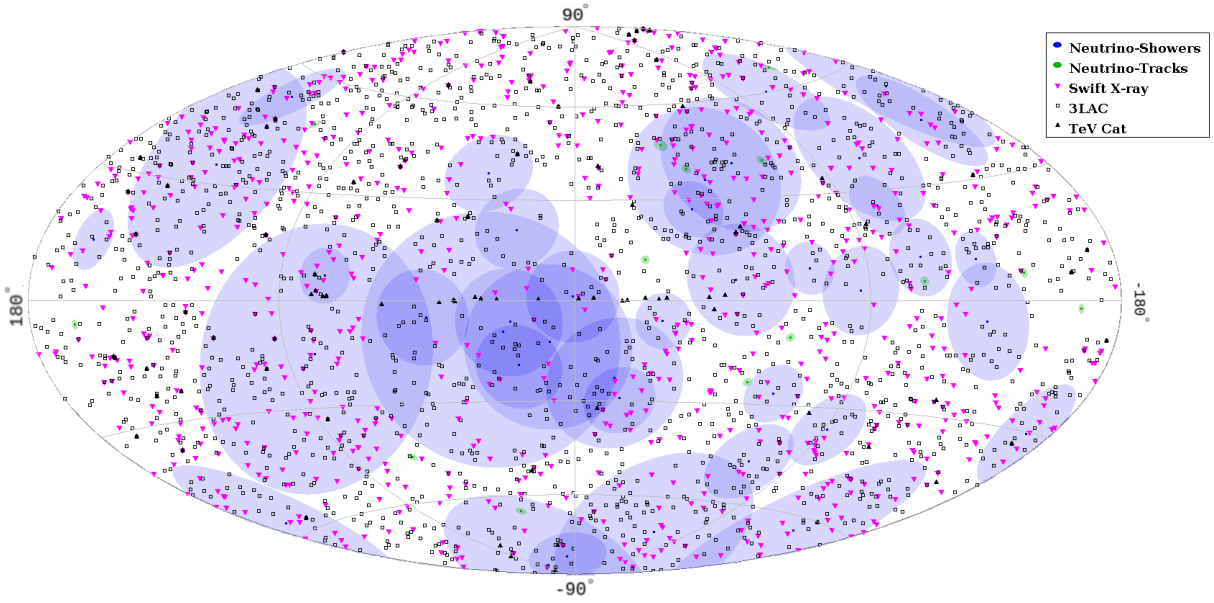

Figure 1. Sky map of the 52 IceCube cosmic neutrino events with error circles, and sources from different catalogs in Galactic coordinate system.

2. IceCube neutrino events and Source catalogs

For our analysis we have considered all 52 IceCube detected neutrino events. Two track events (event numbers 28 and 32) are coincident hits in the IceTop surface array and are almost certainly a pair of atmospheric muon background events [1]. Therefore we excluded them from our analysis. Fig. 1 shows the sky map of these 52 events in Galactic coordinates, with reported angular errors.

We have used 3 different source catalogs to do the correlation study. *Swift*-BAT 70 month X-ray source catalog [5], *Fermi* Third Catalog of Active Galactic Nuclei (3LAC) [6], TeVCat [4]. The sky map in Fig. 1 shows the extragalactic sources from these catalogs.

The *Swift*-BAT 70 month X-ray source catalog includes 1210 objects, from which only 785 are extragalactic sources, shown in Fig. 1. In our previous study [3] we found 18 sources from this catalog that are correlated simultaneously with UHECRs and IceCube neutrino events. The Pierre Auger observatory Collaboration has also found an anisotropy at $\sim 98.6\%$ CL in UHECRs with energy ≥ 58 EeV and within $\sim 18^\circ$ circles around the AGNs in the *Swift*-BAT catalog at a distance ≤ 130 Mpc [7] . These 18 sources mostly have an X-ray energy flux $\geq 10^{-11}$ erg cm^{-2} sec^{-1}. So, in the present analysis we use all the sources from this catalog which have a flux $\geq 10^{-11}$ erg cm^{-2} sec^{-1}. This condition decreased the number of sources to 687.

The TeVCat contains sources that are detected with very high energy (VHE) gamma rays with energy ≥ 50 GeV. It includes 161 sources, out of which 22 are unidentified sources. This is the highest energy source catalog, particularly interesting for ν production. Sky map in Fig 1 contains TeVCat extragalactic sources.

The *Third Catalog of Active Galactic Nuclei (AGNs)* detected by Fermi LAT (3LAC) [6] is a subset of the *Fermi* LAT *Third Source Catalog (3FGL)* [8]. The 3FGL catalog includes 3033 sources detected above a 4σ significance (test statistic > 25) on the whole sky, during the

first 4 years of the Fermi mission (2008-2012). The original 3LAC sample includes 1591 AGNs from 3FGL, though 28 are duplicate associations. An additional cut had also been performed to exclude the Galactic plane region ($|b| \leq 10^\circ$) where the incompleteness of the counterpart catalogs significantly hinders AGN association. However, in this paper, we chose to study what we call the "extended 3LAC" sample of 1773 sources, that includes sources of the Galactic plane, and that could be associated to several neutrino events. In the extended 3LAC sample, 491 sources are flat spectrum radio quasars (FSRQs), 662 are BL Lacs, 585 are blazars of unknown type (BCU), and 35 are non-blazar AGNs.

3. Statistical method for Correlation study

To study correlation between cosmic neutrinos and sources from different catalogs separately, we map the Right Ascension and Declination (RA, Dec) of the event directions and sources into unit vectors on a sphere as

$$\hat{x} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)^T,$$

where $\phi = RA$ and $\theta = \pi/2 - Dec$. The scalar product of the neutrino and source vectors ($\hat{x}_{\rm neutrino} \cdot \hat{x}_{\rm source}$) therefore is independent of the coordinate system. The angle between the two vectors

$$\gamma = \cos^{-1}(\hat{x}_{\rm neutrino} \cdot \hat{x}_{\rm source}), \tag{1}$$

is an invariant measure of the angular correlation between the neutrino event and source directions [3, 9]. Following ref. [9] we use a statistic made from invariant γ for each neutrino direction $\hat{x}_i$ and source direction $\hat{x}_j$ pair as

$$\delta\chi_i^2 = \min_j(\gamma_{ij}^2/\delta\gamma_i^2), \tag{2}$$

which is minimized for all j. Here $\delta\gamma_i$ is the 1-σ angular resolution of the neutrino events. We use the exact resolutions reported by the IceCube collaboration for each event [1].

A value $\delta\chi_i^2 \leq 1$ is considered a "good match" between the i-th neutrino and a source directions. We exploit distributions of all $\delta\chi_i^2$ statistics to study angular correlation between IceCube neutrino events and sources in catalog. The distribution with observed data giving a number of "hits" or $N_{\rm hits}$ with $\delta\chi^2 \leq 1$ therefore forms a basis to claim correlation. Note that in case more than one source direction from the catalog are within the error circle of a neutrino event, the $\delta\chi^2$ value for UHECR closest to the neutrino direction is chosen in this method.

We estimate the significance of any correlation in data by comparing $N_{\rm hits}$ with corresponding number from null distributions. We construct null distributions by randomizing only the RA of the sources, keeping their Dec the same as their direction in the catalog. This *semi-isotropic null* is a quick-way to check significance. We perform 100,000 realizations of drawing random numbers to assign new RA and Dec values for each event to construct $\delta\chi^2$ distributions in the same way we did with real data.

We calculate statistical significance of correlation in real data or p-value (chance probability) using frequentists' approach. We count the number of times we get a random data set that gives equal or more hits than the $N_{\rm hits}$ in real data within $\delta\chi^2 \leq 1$ bin. Dividing this number with the total number of random data sets generated (100,000) gives us the p-value. We cross-check this p-value by calculating the Poisson probability of obtaining $N_{\rm hits}$ within the $\delta\chi^2 \leq 1$ bin, given the corresponding average hits expected from the null distribution. We found the $N_{\rm hits}$ distribution in $\delta\chi^2 \leq 1$ does not follow the Poisson distribution.

4. Results and Discussions

We used the 45 HBL (high-frequency peaked BL Lacs) sources listed in TeVCat for our first correlation study with the neutrino events. A similar correlation study was carried out in [10],

using HBL sources with the 3 year IceCube neutrino events. Our study showed a p-value 0.58 with frequentists method. There are 16 neutrino events that correlated within 1σ error reported by IceCube with different HBLs, which is almost the same as for the null distribution. The Poisson distribution p-value, defined as $\lambda^k e^{-\lambda}/k!$, where k and λ are the $N_{\rm hits}$=16 for real data and null distribution respectively, is 0.1 for $\delta\chi^2 \leq 1$. The total distribution is shown in Fig. 2, where the blue histograms represent the number of neutrino events correlated with the HBLs while the red line represents the number in the case of the null distribution for different $\delta\chi^2$.

The *Swift*-BAT 70 month X-ray source catalog includes 657 sources with observed energy flux more than 10^{-11}erg cm^{-2} sec^{-1}. The study of correlation with neutrino events showed a p-value 0.825 with 39 $N_{\rm hits}$ for the neutrino data and nearly 40 for the null distribution. The detail study of the correlation is shown in Fig. 3.

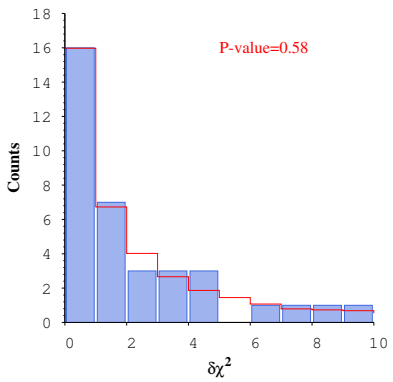

Figure 2. Correlation study of the 45 HBL sources from TeVCat with the IceCube neutrino events. The blue histogram shows the number of times the neutrino events are correlated with the HBLs within different $\delta\chi^2$, while the red line is for the null distribution.

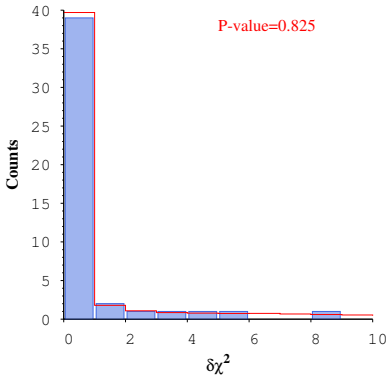

Figure 3. Correlation study of the *Swift* BAT X-ray catalog sources with energy flux more than 10^{-11}erg cm^{-2} sec^{-1} with the IceCube neutrino events. The blue bars shows the number of sources correlated with the neutrino events and the red line is for the null distribution of the sources.

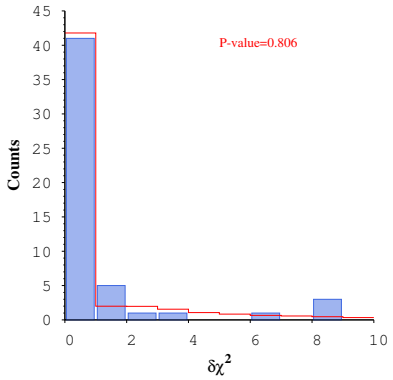

Figure 4. Correlation study of 1773 sources from the extended 3LAC source catalog with the IceCube neutrino events. The blue bars shows the number of sources correlated with the neutrino events and the red line is for the null distribution of the sources.

Our correlation study of all the 1773 sources in the extended 3LAC catalog gives a p-value 0.806 having 41 $N_{\rm hits}$ for the 52 neutrino events, as shown in Fig. 4. The distribution of the extended 3LAC sources according to their observed energy flux is shown in Fig. 5. It can be seen that most of the sources are populated in the region of energy flux 10^{-11}erg cm^{-2} sec^{-1}, and

the population decreases abruptly at higher flux. So, we took a set of sources with energy flux $\geq 10^{-11}$erg cm^{-2} sec^{-1}. It so decreased the number of sources in the set to 652. The correlation study of the neutrino events with these 652 sources show a p-value 0.763, having 39 $N_{\rm hits}$ in $\delta\chi^2 \leq 1$, shown in Fig. 6.

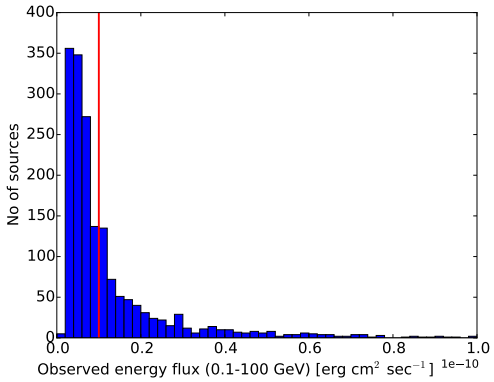

Figure 5. Distribution of energy flux of the extended 3LAC sources. The red vertical line indicate the energy flux 10^{-11}erg cm^{-2} sec^{-1}

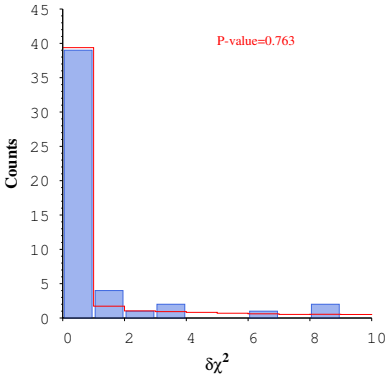

Figure 6. Correlation Study for sources from the extended 3LAC catalog with energy flux $\geq 10^{-11}$erg cm^{-2} sec^{-1}.

For further correlation studies we have used the 662 BL Lac source set from the extended 3LAC catalog. The correlation p-value for these sources is 0.764 as shown in Fig. 7. Similarly for the 491 FSRQ sources from the extended 3LAC catalog the p-value is 0.784, shown in Fig. 8. For BL Lac and FSRQ sources we found 39 and 38 $N_{\rm hits}$ respectively.

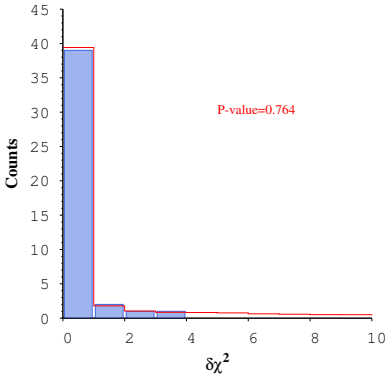

Figure 7. Correlation study of IceCube neutrino events with the BL LAC sources from the extended 3LAC catalog.

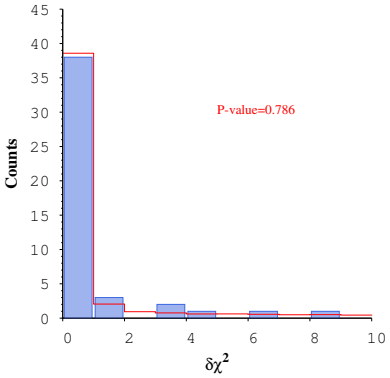

Figure 8. Correlation study of IceCube neutrino events with the FSRQ sources from the extended 3LAC catalog.

We have performed the correlation study of the IceCube neutrino events with different types of sources, as TeVCat HBL, 3LAC BL Lacs and FSRQs, but we have not found any statistically significant result for these sets. We have also taken subsets of the 3LAC catalog and the sources observed by the *Swift* during 70 months, by putting constraints on the observed energy flux, but the results remained similar. However these studies help us to discarding different types of astrophysical sources as the origin of the IceCube neutrino events.

5. Summary

The IceCube neutrino observatory has detected at least 54 neutrino events within the 30TeV–2PeV energy range. The Origin of these events is still a puzzle for both particle physics and astrophysics. In our project we have tried to find correlations of the arrival direction of these events with the positional direction of sources from the TeVCat, *Swift* and 3LAC catalogs. In order to test correlations we have used the minimum $\delta\chi^2$ invariant statistics, as in [3, 9]. Out of the 52 neutrino events, 16 were correlated with HBLs from TeVCat, but the statistical significance of this correlation is given by a $p-$value 0.58. Similarly we study correlations of neutrino events with the sources from the *Swift* and 3LAC catalogs, having observed an energy flux $\geq 10^{-11}\mathrm{erg\,cm^{-2}\,sec^{-1}}$. We also found a poor statistic significance. The FSRQs and BL Lacs from the 3LAC catalog also showed a low significant statistics in this correlation study.

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