IceCube : latest results on point and extended neutrino source searches

THE ICECUBE COLLABORATION[1]

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Abstract: We present a variety of searches for time-independent neutrino emissions from astrophysical sources with the IceCube detector. The analyses use data collected between April 2008 and May 2011 by the partially-completed IceCube detector, as well as the first year of data from the completed 86-string detector. An unbinned maximum likelihood method is used to distinguish astrophysical signals from atmospheric backgrounds, utilizing both spatial and energy information. The analyses include searches for individual point sources, spatially extended sources, and targeted searches using stacked source catalogs. These analyses are sensitive to TeV - PeV energy neutrinos in the northern sky and PeV - EeV neutrinos in the southern sky. Limits on extraterrestrial neutrino fluxes are compared to model predictions. The expected performance with multiple years of data from the full IceCube detector is discussed.

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1 Introduction

IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole [1] between depths of 1450 m and 2450 m. Detector construction started in 2005 and finished in 2010. Neutrino event reconstruction relies on the optical detection of Cherenkov radiation emitted by secondary particles produced in neutrino interactions in the surrounding ice or the nearby bedrock. During its construction, the IceCube telescope ran in various configurations. From April 2008 to May 2009, 40 strings were operational and collecting data. The array increased to 59 strings in May 2009 and 79 strings in May 2010. Construction was completed on 18th December 2010, and data-taking with the 86 string detector began the following May.

Astrophysical neutrinos are excellent candidates for studying acceleration mechanisms of Cosmic Rays (CRs). Produced in the same environmental conditions as CRs and Gamma Rays, their neutral charge allows them to propagate directly from the source to Earth, preserving directional information. Their detection will shed light on sources of CRs and the acceleration mechanisms in extreme environments (Supernova Remnant Shocks, Active Galactic Nuclei jets, Gamma Ray Bursts etc).

Finding neutrino point sources in the sky requires locating an excess of events from a particular direction over the background, which consists of atmospheric neutrinos and muons. In addition to the spatial distribution, signal events are likely to have a different energy spectrum that allows us to distinguish them from the background. In this paper we will focus on the search for steady neutrino sources while optimized searches for time dependent emission are reported elsewhere [2]. The analysis carried out is on data from three years of operation in partial levels of completion and the first year of the completed 86 string detector.

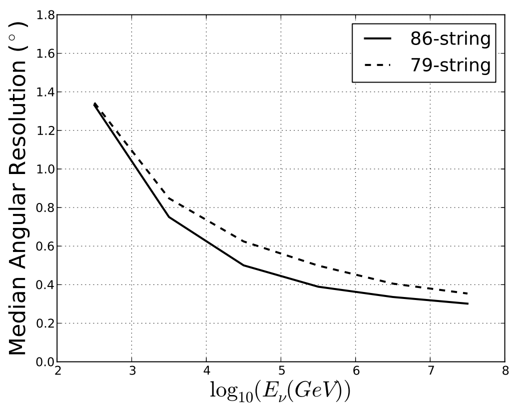

Figure 1: Median angular resolution (angle between reconstructed track and neutrino direction) as a function of neutrino energy for event samples from the 86-string (solid) and 79-string detectors (dashed). At 30 TeV, the 40 and 59 string event selections (not shown) give angular resolutions of $\sim 0.8^\circ$ and $\sim 0.75^\circ$, respectively [4].

2 Data Selection and Detector Performance

The event selection for data from the 40, 59 and 79 string configurations is described in detail in [3] and [4] respectively. In the analysis of data from these configurations of IceCube, no significant excess over background fluctuations have been found and upper limits have been published [4].

Event selection for data from the first year of the 86-string detector closely follows strategies used in previous analyses [4]. The data stream is first reduced from a trigger rate of $\sim$ 2500 Hz to 2 Hz by a combination of real-time filtering and subsequent offline, CPU-intensive processing. At these stages, the data is dominated by atmospheric muons from cosmic rays, either as direct down-going muons in the southern sky, or mis-reconstructed as up-going muons in the northern sky. These events are removed via quality cuts, first using simple reconstructions and event quality parameters, followed by advanced, likelihood-based muon reconstructions calculated offline.

From the 2 Hz of remaining data (still dominated by the atmospheric muon background), 4.8 mHz of events are selected for the final analysis sample. In the northern sky the mis-reconstructed muon background can be mostly eradicated so that a nearly pure sample of up-going atmospheric neutrinos remains. The event selection in this region of the sky is done using a classification algorithm, Boosted Decision Trees (BDTs). We trained four BDTs to separate astrophysical neutrino signal from the atmospheric muon background. We separate the northern hemisphere into two zenith bands, and in each band we train two BDTs for different neutrino signal spectra. Each BDT is trained using 11 event variables for signal/background discrimination, with detector data describing the background distributions. Of these eleven variables, four control for reconstruction stability, five can be considered event quality variables, and two describe the event topology. Cuts on the BDT output scores are optimized to achieve the best discovery potential for both E^{-2} and $E^{-2.7}$ signal spectra. This event selection covers the entire northern hemisphere and extends 5° above the horizon, where the Earth and glacial ice still provide a shield from the cosmic ray background.

More than 5° above the horizon, we cannot isolate a pure neutrino sample. The data are dominated by high-energy atmospheric muon bundles, which closely mimic neutrinos. However, the background can be reduced via parameters that select neutrinos and reject muon bundles. One BDT is trained for the entire region, using data to describe the background and E^{-2} neutrino simulation for signal. Eleven variables are used in training the BDT. Five of these variables describe track quality, three describe event topology, and three exploit differences between single muons and bundles. These parameters rely on event topology and energy loss information. Large muon bundles consist of many low-energy muons that typically lose energy at a constant rate as they traverse the detector. Photons from these muons are detected within a wide time range. High-energy neutrino-induced muons instead have relatively stochastic energy loss profiles and narrower photon timing distributions. These properties are quantified by a likelihood technique and are used in the BDT. To obtain the final sample, a cut on BDT score is varied with zenith to select an equal event rate per solid angle. This technique avoids any hard energy threshold in the southern hemisphere, which previous analyses have used.

The final data sample for the 86-string detector has ~140,000 events, including ~70,000 atmospheric neutrino candidates in the northern hemisphere sample. The neutrino effective area for this selection is very similar to the 79-string analysis [4]. New to this event sample, a new muon reconstruction technique is used to improve the neutrino angular resolution. This likelihood-based reconstruction is similar to the reconstruction used in previous analyses [4], but uses more detailed information to describe the scattering and absorption of photons in the glacial ice. This leads to a 26% improvement in neutrino angular resolution at 30 TeV. The neutrino angular resolution for the 79 and 86 string event samples is shown in Figure 1. The expected sensitivity

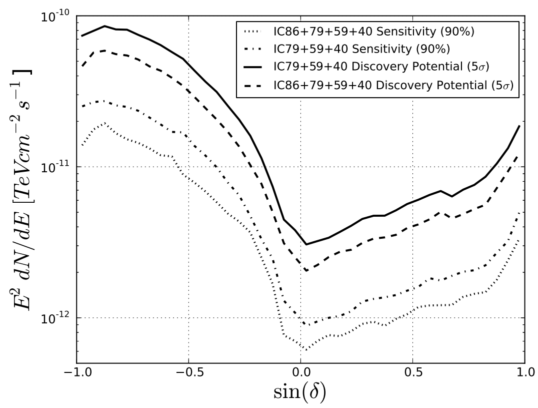

Figure 2: Flux required for 5σ discovery of a point source emitting an E^{-2} flux at different declinations, for three years (solid, dotted) and four years (dashed) of data. The 90% sensitivity for four years is shown as a dashed-dotted line.

and discovery potential combining this event sample with the previous three years of data is shown in Figure 2.

3 Method

This analysis uses an unbinned maximum likelihood ratio test [5]. The significance of an excess of neutrinos above the background for a given direction can be calculated using this method. Both the reconstructed direction of the event and the reconstructed visible muon energy are used in order to discriminate between signal and background [3]. This method has been demonstrated to provide superior sensitivity over simple directional clustering based methods, as the signal events have a harder energy spectrum compared to the atmospheric neutrino and muon backgrounds. For each direction in the sky, the likelihood function is maximized with respect to the number of signal events n_s and the index of the power law neutrino spectrum, γ. The ratio of the likelihoods between the best fit hypothesis and the null hypothesis ($n_s = 0$) forms the test statistic. To evaluate the background test statistic distribution, the analysis is performed repeatedly on scrambled data sets, wherein the right ascensions of the events are randomized but all other event properties are fixed. Uniform exposure in right ascension is ensured by the daily rotation of the detector with respect to the sky. Events close to the polar regions of the sky (declination $< -85°$ or $> 85°$) are excluded from the analysis as scrambling in right ascension does not work in these regions. The power of the method is expressed in terms of the flux required to produce a 5σ discovery. Three different searches are performed:

3.1 All Sky Scan

The maximum likelihood is evaluated for each direction in the sky on a grid of $0.1° \times 0.1°$, much finer than the angular resolution of the detector. The significance of any point on the grid is determined by the fraction of scrambled data sets containing at least one grid point with a likelihood ratio higher than the one observed in the data, and serves as the post-trial p-value for the all sky search. The search presented here is carried out with four years of data, including three years from partial detector configurations and one year of data from the full 86 string configuration.

3.2 *A Priori* Source list

Since the power of the all sky search is limited by the large number of effective trials, the second search is a scan over a restricted *a priori* selected set of 44 sources of interest (based on gamma ray observations and astrophysical modeling predicting neutrino emission [3]). The post-trial p-value is calculated by performing the same analysis on scrambled data sets. This search is carried out with data from the 40, 59 and 79 string configurations only.

3.3 Stacked Searches

The stacking method and its advantages are described in detail in [3] where it is explained how the signal and background are integrated over a set of sources using a uniform weighting for all stacked sources or a weighting scheme based on theoretical predictions. The fractional flux required for discovery for stacked sources scales inversely with the number of sources. The catalogs to stack are selected according to theoretical models or observational parameters connecting photon to neutrino emission. The stacking searches presented here are performed on a combination of the 40, 59 and 79 string samples only, with the exception of one catalog. We perform:

1. A stacking of 6 sources reported by Milagro with supernova remnant (SNR) associations, found *a posteriori* to have an excess in a stacking of 17 sources reported by Milagro carried out on data from the 40 string configuration [3], motivated by [6]. This search is hence confined to data from just the 59 and 79 string configurations to avoid bias.

2. A stacking search for 127 local ($z < 0.03$) starburst galaxies [7]. Relative source luminosities are assumed to be proportional to their Far InfraRed (FIR) fluxes (60 μm), due to models suggesting correlation between Radio, FIR and neutrino fluxes [7].

3. A stacking search for 5 nearby clusters of galaxies (GCs), consisting of Virgo, Centaurus, Perseus, Coma and Ophiuchus. Four different flux models are provided in [8] and described in detail in [3], differing in their assumption as to how the CRs are distributed within the cluster. Due to the very different extension of the sources as predicted by the different models [3], four different searches are carried out for this catalog. Relative source luminosities are taken from the norm of the predicted flux for each source, for each model.

4. A stacking search of 4 Supernova Remnants (SNRs) with Molecular Cloud associations detected in GeV and TeV photons by MAGIC, AGILE, Fermi, Veritas, HESS and HEGRA. Integrated Gamma Ray Fluxes above 1 TeV in Crab units are taken to be the relative source luminosities. Two of these sources, IC443 and W44 have been observed by the Fermi LAT to emit GeV photons that follow a typical neutral pion decay spectrum.[9].

5. A stacking of Black Hole Candidates within the GZK radius of 100 Mpc. A strong mass cut, motivated by [10] is applied on the catalog published in [11] to remove all but the most powerful emitters and the relative source luminosities are taken to be proportional to the Near InfraRed (NIR) flux (2 μm) for the final 233 sources due to the high correlation shown between the NIR flux and the M/D^2.

4 Systematics

The background in the above searches is estimated from randomized data. Hence the p-values are unaffected by uncertainties in the theoretical estimate of atmospheric muon and neutrino fluxes which are influenced by hadronic models of shower development in the atmosphere and the CR composition. They are also unaffected by uncertainties in prompt neutrino fluxes and in the detector simulation.

However, the upper limits are affected by the systematic errors on the simulation of the detector response to the flux of neutrinos. The detector efficiency and effective area are estimated from these simulations. Since the angular resolution is also affected by these systematic uncertainties, we propagate each of the detector simulations through the likelihood search and calculate the sensitivity of the search to a discrete set of simulated signal responses within the allowed range of uncertainties.

The two most relevant uncertainties concern the absolute efficiency of the optical modules and the uncertainties in modeling of the optical properties of the ice. Uncertainties in the relative sensitivity of the individual DOMs with respect to the detector average have been observed to have negligible impact. As a conservative estimate, we allow for a $\pm10\%$ uncertainty on both the absolute sensitivity of the optical modules, and in the absorption and scattering of the ice model, parameterized as in [12].

By summing in quadrature all the different contribution the expected uncertainty in the IC-79 sensitivity is about 18%. This is compatible with the 16% estimated for the IC-40 configuration [3].

The presented upper limits are for a pure muon neutrino signal, assuming contribution from no other flavors. With large mixing angles such as $\Theta_{23} \sim 45^\circ$ and baselines of astrophysical scale, typical source flavor ratios of $\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 will translate to a 1:1:1 flavor ratio at Earth. Since the taus produced decay into muons with a branching ratio of about 17%, ν_τ can contribute to a possible signal flux in this analysis. In [3], this contribution has been estimated to be 10 - 16% of the ν_μ contribution.

5 Results

All observations are compatible with the background-only hypothesis. In the all sky scan with four years of data, the most significant deviation in the northern sky has a pre-trial p-value of 9.15×10^{-6} and is located at 11.45° r.a. and 31.35° dec. while in the southern sky it is at 296.95° r.a. and -75.75° dec. and has a pre-trial p-value of 1.10×10^{-6}. The post-trial probabilities (the fraction of scrambled sky maps with at least one spot with an equal or higher significance for each region of the sky) corresponds to 38% and 9% respectively and are well compatible with the background hypothesis.

The *a priori* sources list search with three years of data found HESS J0632+057 as the most significant source in the northern sky with a probability of 5.8% while for the southern sky it was PKS 1454-354 with 23%. Their post-trial probabilities were 65% and 70% respectively and are also compatible with the background hypothesis. Table 1 lists a few of the most interesting sources from an astrophysical point of view and also the sources that produced the strongest deviations. Fig 3 shows upper limits for the Crab Nebula. Similar illustrations of flux limits for other interesting sources can be found in [4].

None of the stacking searches found a significant excess, with the smallest p-value (i.e. highest significance) found for the Milagro 6 catalog with a probability of 20.4%. Fig 4 shows the 90% C.L upper limits for some of the flux models motivating the stacking searches. The 90% C.L. upper limit on $\Phi^{90\%}_{\nu_\mu+\bar{\nu_\mu}}$ was found to be 1.84 times the total flux predicted by the model of Halzen et al [6] for Milagro

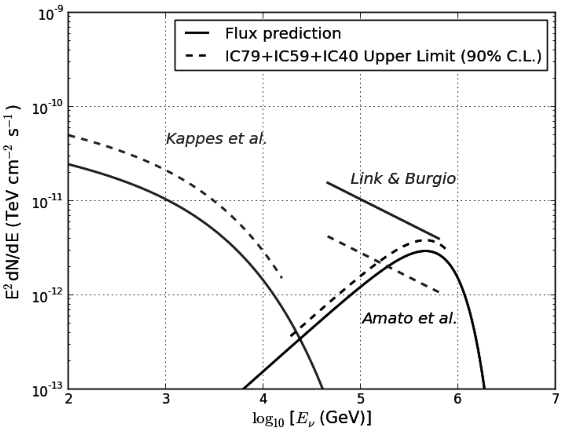

Figure 3: Predicted muon neutrino fluxes for several hadronic models about the Crab steady emission and upper limits based on 3 years of IceCube data. Solid lines indicates the flux prediction and the dashed lines the corresponding upper limit flux for a 90% C.L. for an energy range that contains 90% of the signal. Neutrino oscillations are accounted for.

Source	$\Phi^{90\%}_{\nu_\mu+\bar{\nu}_\mu}$	p-value	$\hat{n}_s$
PKS 1502 +106	2.40	0.076	8.4
HESS J0632+057	2.23	0.058	15.6
IC443	1.63	0.43	2.8
Mrk 421	3.45	0.18	3.7
Mrk 501	2.84	0.34	4.8
Cyg X-3	2.35	0.43	2.4

Table 1: A few sources from the *a priori* source list search and their pre-trial p-values calculated from 3 years of IceCube data. $\Phi^{90\%}_{\nu_\mu+\bar{\nu}_\mu}$ is the normalization for an E^{-2} flux in units of 10^{-12} TeV^{-1}cm^{-2}s^{-1} denoting the 90% C.L upper limit in the Neyman frequentist method and $\hat{n}_s$ is the fitted number of signal events in the likelihood maximization.

6. For the Galaxy Clusters A, B, Isobaric and Central AGN Models, this upper limit was found to be 2 – 6 times the total predicted flux, depending on the assumed model of CR density.

6 Conclusion

The search for point sources of neutrinos with four years of data from the IceCube Neutrino Observatory has found no evidence of point source neutrino emissions in both the northern and southern hemisphere. The post-trial probabilities of the most significant coordinate in each hemisphere are compatible with the background hypothesis. More specific searches such as the *a priori* source list search and the catalog stacking searches, carried out with 3 years of data from the 40, 59 and 79 string configurations also have not found any significant fluctuations. 90% C.L. upper limits on the muon neutrino fluxes were calculated and compared to predictions. The most optimistic predictions can be ruled out while other limits are a factor of 2-6 worse than the predictions.

The muon neutrino upper limits presented are a factor of 3.5 better than the previous published by IceCube [3], and are the strictest limits to date in the TeV-PeV energy range in the northern sky and the PeV-EeV energy range in the southern sky. Some of these have reached the level of 10^{-12} TeV cm^{-2} s^{-1} necessary to test current models of neutrino emission expected from galactic sources such as SNRs. With an additional four years of data from the full configuration of the detector, these limits are expected to further improve by a factor of ~ 2.

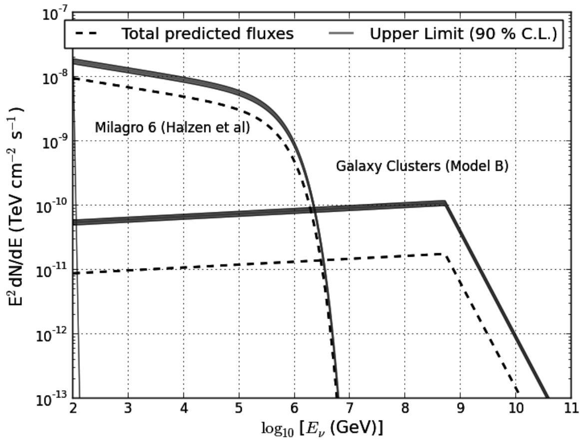

Figure 4: Upper limits (with bands denoting systematic uncertainties) for some of the models motivating the stacking searches. The fluxes are for muon neutrino fluxes at earth after oscillations.

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