Search for Diffuse High Energy Neutrinos with IceCube

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***Abstract*. We performed a search for diffuse high energy neutrinos using data obtained with the IceCube 22 string detector during a period 2007-2008. In this analysis we used an E^{-2} spectrum as a typical flux resulting from cosmic ray shock acceleration. Using a likelihood track reconstruction, approximately 5700 track-like neutrinos are extracted from 275.7 days data at an estimated 95% purity level. The expected sensitivities obtained are in a range of $2.2\times10^{-8} \sim 2.6\times10^{-8}$ E^{-2} GeV cm^{-2} s^{-1} sr^{-1} with four different energy estimators. The analysis method and results are presented along with discussions of systematics.**

***Keywords*: IceCube neutrino diffuse**

I. INTRODUCTION AND DETECTION PRINCIPLE

The IceCube neutrino observatory is the world's largest neutrino telescope under construction at the geographic South Pole. During 2007, it collected data with 1320 digital optical modules(DOM) attached to 22 strings (with 60 optical modules per string). They are deployed in clear glacial ice at depths between 1450 to 2450 meters beneath the surface, where the photon scattering and absorption are known by preceding *in situ* measurements [1]. When a neutrino interacts inside or close to the IceCube detector, DOMs capture Cherenkov photons from secondary charged particles with 10 inch photomultiplier tubes and generate digital waveforms. In most cases, we require at least 8 DOMs to be triggered within a 10 micro second time window. Once the trigger condition is satisfied, all digital waveforms are collected and then processed by online filtering programs to filter out background events. In this analysis we used 275.7 days livetime of data and obtained 5718 candidate neutrino induced events after the final event selection. The event selection process is described in Section II.

The event sample after the selection process mainly consists of atmospheric neutrinos. To separate extraterrestrial high-energy neutrinos from atmospheric neutrinos, one can apply two types of analysis techniques. The first is a point source analysis that uses the direction of the neutrinos to survey high-density event spots (hotspots). The second, called a diffuse analysis, examines the energy spectrum itself and compares it to various physics models. Since the diffuse analysis does not require multiple events from an astrophysical source, it is possible to take into account faint sources that are not significant by themselves in a point source analysis. However, in general, a diffuse analysis requires a better detector simulation. While a point source analysis uses data to search for a hotspot, the diffuse analysis has to rely on simulated parameter distributions under an assumption of a physics model to test observed distributions in the data.

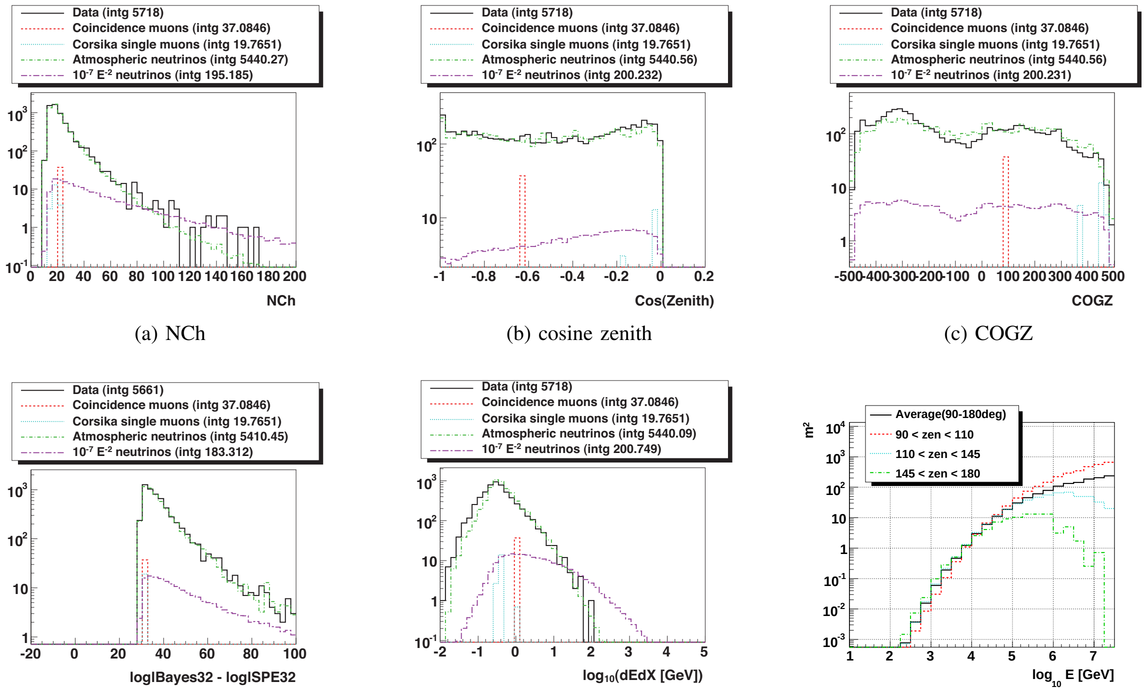
In this analysis we assumed a $\Phi \propto \mathrm{E}^{-2}$ energy spectrum for neutrinos from astrophysical sources resulting from shock acceleration processes [2]. Since the atmospheric neutrino flux has a much softer energy spectrum [3][4][5], the signal neutrinos may form a high-energy tail in an energy-related observable over atmospheric neutrinos. The search for an extraterrestrial neutrino component uses the number of events above an energy estimator cut after subtracting a calculated contribution from atmospheric neutrinos. The cut was optimized to produce the best limit setting sensitivity [6]. Results and possible sources of systematics errors are discussed in Section IV.

II. EVENT SELECTION

Cosmic ray interactions in the atmosphere create pions, kaons and charmed hadrons which can later decay into muons and neutrinos. The primary background before the event selection is atmospheric muons traveling downward through the ice. Their intensity strongly depends on the zenith angle of the muon: it decreases as the zenith angle increases because a higher zenith angle results in a longer path length from the surface of the Earth to the IceCube detector. The largest zenith angle of atmospheric muons is around 85 degrees and their path length inside the Earth is over 20 km. The first filter is thus designed to select only upward going events. For estimation of the zenith angle, we used a log likelihood reconstruction. In this analysis, the minimum zenith threshold is 90 degrees.

After the zenith angle filter is applied, the remaining data still contains many orders of magnitude more mis-reconstructed background than neutrino-induced events. They are downward going muons, but reconstructed as upward because of poor event quality (low number of triggered DOM, grazing an edge of detector, etc) or two muons that passed through the detector within a trigger time window (coincidence muons) and mis-reconstructed as a single upward going muon [1]. These mis-reconstructed events are effectively rejected by checking fit quality parameters [7]:

[1]This difficulty is mainly caused by scattering of photons in ice. The effective scattering length of Cherenkov photons in IceCube is around 30 m [1].



(a) NCh (b) cosine zenith (c) COGZ

(d) log likelihood ratio (e) log10(dEdX) (f) Effective Area

Fig. 1. (a - d) : Comparison of simulations and data for basic parameters after the purification process. COGZ(c) is the z-position of the center of charge-gravity of an event in the IceCube coordinate system. (d) : An alternative energy estimator. See Sec. III. (f) : Effective area of $\nu_\mu + \overline{\nu_\mu}$ after the event selection, in several zenith angle ranges.

- Number of direct hits (NDir) : number of hits which are assumed to result mostly from unscattered Cherenkov photons
- Projected length of direct hits (LDir) : Largest distance of a pair of projections from direct hit positions to a reconstructed track
- Reduced log likelihood : log likelihood result of a reconstructed track divided by number of degrees of freedom
- log likelihood ratio : difference of log likelihood parameters between a fit and a Bayesian fit which is forced to reconstruct as downward going
- smoothness of hits : a parameter for how hits are generated smoothly along a reconstructed track
- log likelihood ratio between single muon fit and Bayesian weighted double muon fit : similar parameter as log likelihood ratio, but uses two Bayesian fits as a hypothesis of coincidence muons

The "direct hits" are defined by the arrival times of photons at each DOM and a reconstruction. Once a reconstruction is determined, at each DOM, we obtain a minimum path and earliest possible arrival times of photons (geometrical hit times) from the Cherenkov light emission point. Some photons may take a longer path because of scattering, which result in a time delay from the geometrical hit time. In this analysis, we chose a time window of [-15ns, 75ns] from the geometrical hit time to accept a hit as a direct hit.

The log likelihood ratio gives a comparison between two fits, a standard likelihood fit and a fit with a zenith-dependent weight which follows a zenith distribution of atmospheric muons. A reliable good quality fit should have a large ratio, while mis-reconstructed atmospheric muons have relatively smaller ratios.

With these quality parameters, we defined a set of cut parameters to purify neutrino-induced events using Monte-Carlo simulation. For atmospheric muons, we generated 10 days of single unweighted CORSIKA muons, 5×10^5 events of energy weighted CORSIKA muons[2], and 7.4 days of unweighted CORSIKA coincidence muons. For atmospheric neutrinos, 2.6×10^7 ν_μ events were generated with an E^{-1} spectrum and re-weighted with a conventional atmospheric neutrino flux [3] plus a prompt neutrino model [4][5]. The optimal cut is chosen to retain as many high energy neutrinos as possible while keeping purity of neutrinos above 95 %.

The optimized cut parameter is then applied to data and compared with Monte-Carlo predictions. In order not to bias the analysis, the highest energy tails of both data and simulation were kept hidden from the analyzer during this final optimization process of cuts. The number of DOMs that has at least one hit (NCh) is used to determine the open window: we compared events which NCh less than 80. Small discrepancies

[2]The power law index of the primary particle is changed to be harder by +1. The effective livetime varies in each primary energy bin, for example, 10 TeV weighted muons correspond to one year of effective livetime. The effective livetime also depends on zenith, e.g. a value of a year for muons around 70 degree.

between data and simulation around the threshold of some quality parameters were observed, mainly because of insufficient statistics of background coincident muon simulation. These events are removed by tightening the cut parameters moderately.

Figs. 1 shows the comparison of data and simulation after the final event selection. The Monte Carlo simulation reproduces data well in most event variables, but discrepancies are still present in some depth dependent variables like COGZ, the z (vertical, or depth) coordinate of the center-of-gravity of the charge in the event (z = 0 in the center of the detector). This systematics is discussed in Sec. IV. The neutrino effective area of ν_μ + $\overline{\nu_\mu}$ after optimal quality cuts for 275.7 days of livetime of IceCube 22 strings is shown in Fig. 1f.

III. Energy estimators and sensitivity

Unlike the previous detector AMANDA, the IceCube detector retains the original waveform by digitizing analog waveforms inside the DOM. This technology allows us to use charge information as an energy estimator. Recently, new techniques for energy reconstruction were developed using the charge information as well as the hit times. In this section, we compare the sensitivity of following energy estimators.

- NCh : number of triggered DOMs. It is simple, but has a relatively strong connection with the track geometry and the ice layers where the muon passed through.
- NPe : Total charge collected by all triggered DOMs of an event. Basically it is similar to NCh, but has a larger and smoother dynamic range than NCh.
- dEdx : A table based energy reconstruction. Using a table generated by a photon propagation program (Photonics [8]), it estimates the energy deposit along a reconstructed track. The reconstruction takes into account the ice properties as a function of depth. [9]
- MuE : a simple energy reconstruction. Similar to dEdx, but uses an homogeneous ice model instead of layered ice photonics tables. [10]

To obtain sensitivities, we assumed no extra-terrestrial signal over a given energy threshold, then calculated the expected upper limit using the Feldman-Cousins method [11]. The Model Rejection Factor [6] is then optimized to have the best sensitivity for E^{-2} test signal flux. Table I shows sensitivities at corresponding energy estimator thresholds. The average number of background neutrinos and $\Phi = 10^{-7}E^{-2}$ signal neutrinos above the threshold are also predicted.

IV. Results and discussion

Table I also lists the number of data events above the optimized energy thresholds for the four energy estimators. We observed a statistically significant excess of data over the atmospheric neutrino prediction (including prompt atmospheric neutrinos) for all energy estimators except for dEdx. However, disagreements between data and simulation in depth dependences (for example, in COGZ in Fig. 1c) point to unresolved systematics in our simulation. In this section we discuss the effect of the COGZ problem to this analysis.

The depth dependences in the optical properties of the glacial ice, reflecting changes in dust concentration due to climate variations when the ice was formed [1], are taken into account in the detector simulation. However, as Fig. 1c shows, these dependences are not fully reproduced by the simulation. In this analysis, the discrepancy is most severe in the deep part of the detector, for COGZ $<$ -250 m, which is also where most of the highest-energy events lie. The event excess we observed thus could be due to systematics rather than a signal flux.

To test the hypothesis that the excess is due to inaccuracies in our simulation of depth dependences, we repeated the analysis on data from the shallow (COGZ $>$ 0 m) part of the detector and from the deep (COGZ $<$ 0 m) part separately. Fig. 1 shows the COGZ distribution as a function of cosine zenith for the data, atmospheric neutrino simulation, and a subtraction of the simulation from data. To eliminate any bias from hard components like prompt neutrinos or extra-terrestrial neutrinos, we set an additional energy cut NCh $<$ 50 to plot Fig. 1. Fig. 2c indicates that the systematic problems are not specific to the highest energy events. Using events with COGZ $>$ 0 m and cosine zenith less than -0.2, the data and simulation agrees relatively well. We performed the same procedures on the full dataset and no data excess is observed in any of the energy estimators. This result could be compared with the AMANDA diffuse analysis [12] because the majority of hits are recorded by DOMs at depths where AMANDA is deployed. Considering the sensitivities listed in Table II, this result is consistent with the current upper limit for diffuse muon neutrinos $7.4\times10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$. On the other hand, at COGZ $<$ 0 m with the same zenith cut, we observed an event excess with three energy estimators. Since the sensitivities of the lower COGZ sample are worse than the upper COGZ events, the event excess we observed with the full data set is highly likely due to systematics. Table II summarizes all numbers obtained from the two subsets.

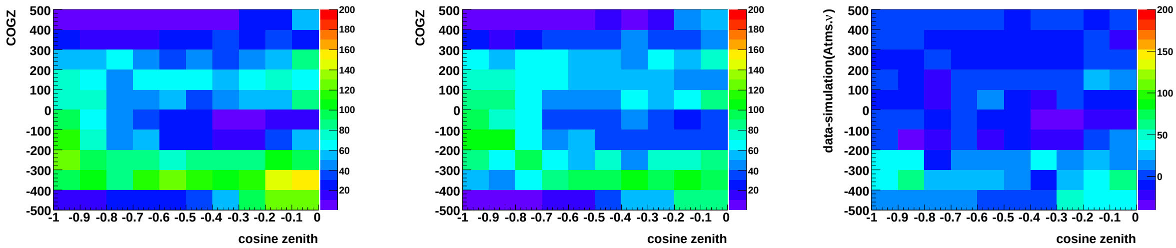
Some of the systematics issues will be resolved with ongoing calibration studies. Our description of the optical ice properties has larger uncertainties in the deep ice, where we so far have relied on extrapolations of the AMANDA measurements in the shallower ice [1], using measurements of dust concentration in Antarctic ice cores for the extrapolation. The ice core data indicate a strong improvement in ice clarity below AMANDA depths, with an estimated increase in average scattering and absorption lengths of up to 40% at depths greater than 2100 m. With such different ice properties in the two parts of the detector, we are investigating our possibly increased sensitivity to systematic error sources that are present at AMANDA depths but become more significant in the deeper, clearer ice. We are also

TABLE I
SENSITIVITIES OF ICECUBE 22 STRINGS 275.7 DAYS WITH VARIOUS ENERGY ESTIMATORS. NO SYSTEMATICS ERROR INCLUDED.

Estimator	MRF (sensitivity)	Energy Threshold	Mean Background	Mean Signal	Data observed
NCh	0.22 ($2.2 \times 10^{-8}E^{-2}$)	NCh $\geq$ 99	9.3	29.4	22
NPe	0.26 ($2.6 \times 10^{-8}E^{-2}$)	log10(NPe) $\geq$ 3.15	6.6	22.5	10
dEdx	0.25 ($2.5 \times 10^{-8}E^{-2}$)	log10(dEdx) $\geq$ 1.4	4.1	19.8	4
MuE	0.24 ($2.4 \times 10^{-8}E^{-2}$)	log10(MuE) $\geq$ 5.05	6.4	28.4	13

TABLE II
SENSITIVITIES OF ICECUBE 22 STRINGS 275.7 DAYS WITH ADDITIONAL COGZ CUT AND COSINE ZENITH CUT (COSθ < -0.2). NO SYSTEMATICS ERROR INCLUDED.

Estimator	COGZ cut	MRF (sensitivity)	Energy Threshold	Mean Background	Mean Signal	Data observed
NCh	COGZ>0	0.41 ($4.1 \times 10^{-8}E^{-2}$)	NCh $\geq$ 68	7.9	15.0	3
NPe	COGZ>0	0.54 ($5.4 \times 10^{-8}E^{-2}$)	log10(NPe) $\geq$ 2.85	8.0	11.3	5
dEdx	COGZ>0	0.50 ($5.0 \times 10^{-8}E^{-2}$)	log10(dEdx) $\geq$ 0.97	7.9	12.2	5
MuE	COGZ>0	0.50 ($5.0 \times 10^{-8}E^{-2}$)	log10(MuE) $\geq$ 4.65	9.9	13.2	7
NCh	COGZ<0	0.47 ($4.7 \times 10^{-8}E^{-2}$)	NCh $\geq$ 80	12.8	15.7	25
NPe	COGZ<0	0.64 ($6.4 \times 10^{-8}E^{-2}$)	log10(NPe) $\geq$ 3.15	2.4	6.4	4
dEdx	COGZ<0	0.58 ($5.8 \times 10^{-8}E^{-2}$)	log10(dEdx) $\geq$ 0.91	15.5	14.0	14
MuE	COGZ<0	0.62 ($6.2 \times 10^{-8}E^{-2}$)	log10(MuE) $\geq$ 5.00	2.9	7.1	6



(a) Data (b) Atmospheric ν (c) Data - Atmospheric ν

Fig. 2. (a,b) : Number of Low NCh events at final cut level in COGZ vs cosine zenith. Events contributing to the plot are limited to NCh < 50. (c): Subtraction of plots (a) and (b). The boxes checked with x represent negative values.

improving our photon propagation simulation to better reproduce the data in the clearest ice. This improved simulation will be tested with data from in-situ light sources (LED flashers, nitrogen lasers) and well-reconstructed downward going muons.

Among the four energy estimators, dEdx shows the most stable results. However, all the systematic problems must be understood before we proceed to claim a physics result. The IceCube 22 string configuration is the first detector which allows a detailed study of Monte-Carlo simulation and the detector in the deep ice with reasonable statistics. These results will be essential not only for this analysis, but also for upcoming analysis with the IceCube 40 string configuration.

V. CONCLUSION

Using 275.7 days of upward going muon events collected by the IceCube 22 string configuration, we performed a search for a diffuse flux of high energy extraterrestrial muon neutrinos. The expected sensitivities are around 2.5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} for an E^{-2} flux using four different energy estimators. We observed an excess of data over that expected from background above the best energy cut with some energy estimators. In order to test the geometric stability of this analysis, we performed the same analysis using two subsets of data divided by a threshold COGZ = 0 m. Having inconsistent results between these two subsets, the data excess we observed is highly likely dominated by systematics. With events at COGZ > 0 m, we observed no data excess with any of the energy estimators, which is consistent with the current upper limit on a diffuse flux of muon neutrinos obtained by the AMANDA diffuse analysis [12]. Many ongoing calibration studies will reveal the unknown systematics in the near future.

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