



## EHE Neutrino Search with the IceCube 9 String Array

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**Abstract:** The performance of the partially ( $\sim 10\%$ ) constructed IceCube neutrino detector on the search for extremely high energy (EHE) neutrino in data taken in 2006 is presented. Background event numbers are estimated based on an empirical model which reasonably describes a part of the same experimental sample. Following this background estimate an upper limit of the neutrino fluxes at 90% C.L. would be placed at  $E^2 \phi_{\nu_e + \nu_\mu + \nu_\tau} \simeq 1.6 \times 10^{-6} \text{ GeV/cm}^2 \text{ sec sr}$  for neutrinos with an energy of  $10^8 \text{ GeV}$  in the absence of signals in the 2006 sample. The corresponding neutrino effective area is also presented.

### Introduction

Extremely high energy (EHE) neutrinos are expected to fill a key role in connecting the observed EHE cosmic-rays to their birthplaces, which may shed light on the long standing puzzles of the origin of EHE cosmic-rays. Because of their low intensity, the detection of EHE neutrino requires a huge effective detection volume. The IceCube neutrino observatory [1], located at the geographic South Pole, will consist of a  $\text{km}^3$  fiducial volume of clean glacier ice as a Cherenkov radiator and an array of photon detectors. The initial IceCube 9 string array (IC-9) was deployed by February 2006. Each string was positioned with a spacing of approximately 125 m and with 60 optical sensors attached to it at intervals of  $\sim 17 \text{ m}$ . The IC-9 detector was operational from June through November of 2006. The high energy events sample used in this analysis is a part of the full dataset taken with IC-9 satisfying the condition that a minimum of 80 out of 540 IC-9 optical sensors (DOMs) record Cherenkov pulses within  $2 \mu\text{sec}$ . The effective livetime corresponding to this dataset is 124 days after rejecting events taken during times of unstable operation.

We report here for the first time on the expected sensitivity of this IC-9 detector configuration for neutrinos with energies  $10^7 \text{ GeV}$  and above.

### EHE events in IceCube

At extremely high energies, neutrinos are mainly detected by secondary muons and taus generated during propagation of EHE neutrino in the Earth [2]. The propagation of particles has been simulated in detail by the JULIeT package [3]. Particles are seen in the detector as series of energetic cascades from radiative energy loss processes rather than bare tracks. These radiative energy losses are proportional to the energies of muons and taus and so is the Cherenkov light deposit in the IceCube detector. Figure 1 shows distributions of the total number of photoelectrons (NPE) detected by the 540 DOMs as function of muon and tau energies from the full IceCube Monte Carlo simulation. The trigger condition of 80 or more recorded DOM signals has been applied. A clear correlation between NPE and the energy of particles measured at 880 m from the IceCube center is observed. The IC-9 DOM response to a large NPE signal is limited mainly due to its readout configuration and PMT performance. Taking fully into account these effects in the simulation, the visible departure from linearity stems from the saturation of the detector during signal capture. Particles traversing far away from the detector leave low NPE signals regardless of their energy. From these observation, we use NPE as a robust estimator of the particle energy - together with the zenith angle - as main selection criterion.

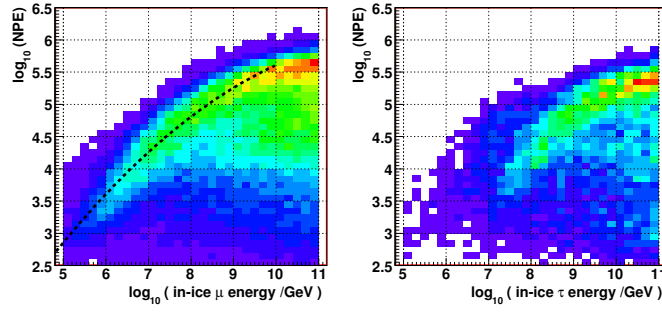


Figure 1: Event from the Monte Carlo simulation of the IC-9 detector in a plane of NPE and charged lepton energy measured at 880 meters from the IceCube center. Events passing within 880 m of the center of IceCube are considered in the plots and more distant events do not contribute to the data sample. The distribution in the left plot is for muons. The plot for taus on the right illustrates the suppression of energy loss compared to that of muons and the contributions from tau-decays. The charged lepton energy distribution is assumed to follow  $E^{-1}$  in these plots for illustrative purposes.

### Background modeling

EHE neutrino induced muons and taus enter mostly from near or above the horizon with down-going geometry because of the increase of neutrino cross section with energy. Therefore, atmospheric muon bundles, penetrating the detector from above, constitute a major background. However, the estimation of the atmospheric muon event rate in the relevant energy range is highly uncertain, as it involves poorly characterized hadronic interactions and a knowledge on the primary cosmic ray composition at energies where there is no direct measurement available. In the present analysis, we fit a part of the experimental IC-9 high energy event sample by an empirical formula to build the atmospheric muon background model. The model is then extrapolated to higher energies to estimate background intensity in the signal region.

This study used an event sample with  $10^4 \leq \text{NPE} \leq 10^5$  in which the bias in the high energy event dataset from the filter requirement of 80 DOMs is minimal. Events are dominated by atmospheric muons over possible cosmic neutrino events by more than 2 orders of magnitude as shown in Ref. [4]. The empirical model is based on the Elbert formula [5] that describes the number of muons with energies greater than a energy threshold initiated in a cosmic ray air shower cascade. The energy weighed integration of the formula relates the total energy carried by a muon bundle to the primary cosmic ray energy. The relation associates muon bundle event rate to given primary

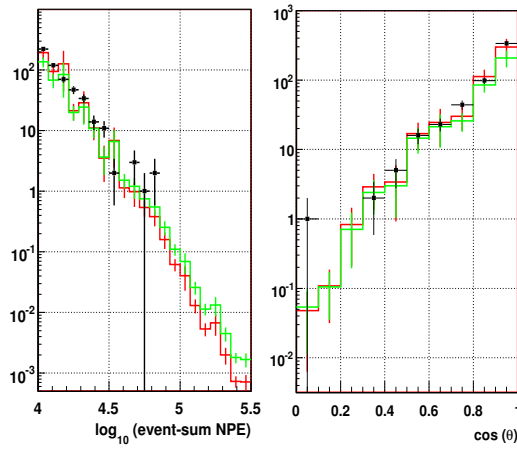


Figure 2: Event distributions of data as a function of NPE (left) and zenith angle  $\theta$  (right). Black dots with error bars denote the IC-9 high energy event sample in  $4.0 \leq \log_{10} \text{NPE} \leq 5.0$ . Red and green histograms are from the Monte Carlo simulation of the empirical atmospheric muon bundle model with two sets of parameters that gives similarly good agreement with experimental data.

cosmic-ray flux which was taken from the compilation in Ref. [6]. In other words, the background muon event rate is governed by the intensity of the cosmic ray flux and depends on the fraction of energy that goes to a muon bundle in an air shower. The two parameters of the model, the coefficient to determine multiplicity of muons in a bundle and the lowest energy of muons in a bundle to leave detectable signal in the IceCube detectors,

are estimated by comparing model simulation and experimental sample in the plane of NPE and reconstructed zenith angle for NPE below  $10^5$ . The comparison of the model and experimental data is shown in Fig. 2. The black dots show a mid-NPE subsample of the data. Colored lines indicate the model simulation with two sets of parameters that give similar goodness in fits in terms of  $\chi^2/d.o.f$  with respect to the experimental sample but with extreme cases of the low muon multiplicity coefficient (green line) and the low threshold energy coefficient (red line) in a bundle. Obviously, the models represent the experimental NPE and declination dependence well.

## Results

Event distributions for signal and muon-bundle induced background are shown in Fig. 3. For the signal we chose a GZK cosmogenic neutrino model [7] as calculated in Ref. [8]. The plots show that the atmospheric muon bundle model has a steeper distribution in NPE compared with that of the signal GZK model. The number of muons and taus originating from the propagation of the signal neutrino in the earth exceeds that of atmospheric muon bundles at directions near the horizon as well as at the higher NPE. These observations suggest that the background can be rejected by excluding events with low NPE values and vertical reconstructed directions. The signal domain is defined by the following conditions:

$$\log_{10}\text{NPE} \geq \log_{10}\text{NPE}_{\text{low}}, \quad (1)$$

and if  $\cos \theta \geq 0.1$ ,

$$\log_{10}\text{NPE} \geq 4.7 + \frac{1.1}{0.9}(\cos \theta - 0.1). \quad (2)$$

Summarized in Table 1 are the expected numbers of signal and background events above cut levels defined with different values of  $\log_{10} \text{NPE}_{\text{low}}$ .

The resulting sensitivity to the all flavor EHE neutrinos is calculated independent of the neutrino flux models with the quasi-differential method based on the flux per energy decade. A similar approach is found in Ref. [9]. The first year IC-9 sensitivity curves at 90% confidence level are shown in the left plot of Fig. 4 for the four cut levels in Table 1 with an assumption of negligible background. It is also shown that this EHE neutrino

Table 1: Preliminary numbers of expected IceCube EHE events of muons and taus produced from the GZK model [8] and from the background atmospheric muon model prediction. The predictions are normalized to a livetime of 124 days and presented for different  $\log_{10} \text{NPE}_{\text{low}}$  values in Eqs. (1) and (2). GZK  $\mu + \tau$  indicates the number of events with muons and taus induced by the GZK neutrino outside the IceCube detector volume defined by a sphere of 880 m radius. GZK  $\nu_e + \mu + \tau$  indicates contributions from charged particles created inside the sphere.

cut level	1	2	3	4
$\log_{10} \text{NPE}_{\text{low}}$	4.4	4.6	4.8	5.0
GZK $\mu + \tau$	0.033	0.027	0.020	0.011
GZK $\nu_e + \mu + \tau$	0.028	0.024	0.020	0.015
atmospheric $\mu$	0.003	$\leq 10^{-4}$	$\leq 10^{-4}$	$\leq 10^{-4}$

search is sensitive to the neutrinos with energies on the surface ranging between  $\sim 10^7$  and  $\sim 10^9$  GeV. Choosing cut level number 2, the 90% C.L. upper limit of EHE neutrino fluxes by the 2006 IC-9 observation would be placed at  $E^2 \phi_{\nu_e + \nu_\mu + \nu_\tau} \simeq 1.6 \times 10^{-6} \text{ GeV/cm}^2 \text{ sec sr}$  for neutrinos at an energy of  $10^8$  GeV; the corresponding neutrino effective area with our preferred cut level 2 is also shown on the right plot of Fig. 4.

## Discussion

The sensitivity estimate has been obtained with the assumption of negligible background based on the empirical model prediction. The systematic uncertainties in the background estimation must be further considered, however. Possible contributions from fluctuations in the hadronic interaction processes in the air shower cascades and fluctuations in the muon bundle spatial distribution at IceCube detector depths (1450-2450 m) are disregarded in the current study. The estimation of these effects must be performed before the cuts are finalized. We would like to also remark that estimations of the contribution from the prompt muon in the present background model are uncertain. While the IC-9 high energy sample below  $10^5$  NPE (corresponding roughly to  $E \leq 10^{7-8}$  GeV) shows no indication of a significant prompt muon contribution, a potential excess of events beyond the atmospheric muon bundle model could either be due to prompt muons, cosmic neutrinos or due to events of exotic physics origin.

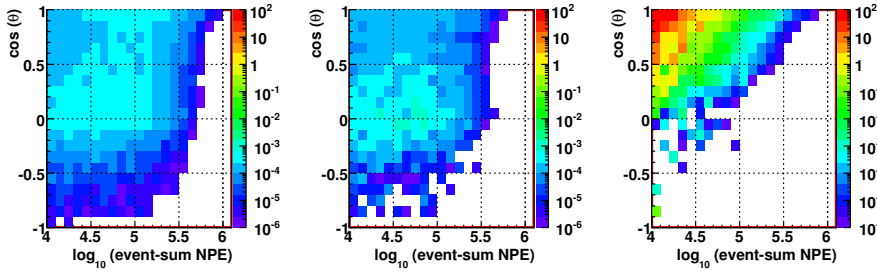


Figure 3: Event distribution in the plane of NPE and cosine of zenith angle obtained by Monte Carlo simulations. Plotted on the left and middle are those for GZK neutrino-induced muon and tau signals, respectively. The background atmospheric muon bundle model is shown on the right. Projections of the atmospheric muon bundle distribution is represented by green lines in Fig. 2.

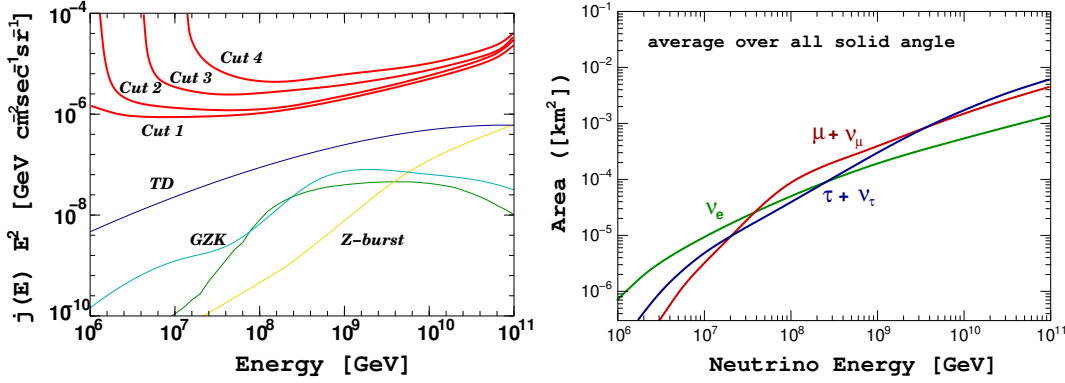


Figure 4: The 2006 IC-9 sensitivity curves at 90% C.L. on the EHE neutrino model fluxes is shown on the left. The fluxes of the three neutrino flavors  $\nu_e$ ,  $\nu_\mu$ ,  $\nu_\tau$  are summed up. GZK refers to the GZK model from Ref. [8] for the lower curve and Ref. [10] for the upper curve. The TD and Z-burst predictions are from Ref. [11] and Ref. [12], respectively. Plotted on the right is the corresponding neutrino effective area of three neutrino flavors for cut level 2.

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