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Nuclear Physics B Proceedings Supplement 00 (2012) 1–6

Nuclear Physics B Proceedings Supplement

Ultra-high energy neutrinos with IceCube

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Abstract

We report on a search for ultra-high energy neutrinos with energy greater than 10^6 GeV using the data taken with the IceCube detector at the South Pole. The data was collected between June 2010 and May 2011 when 90% of the IceCube detector was in operation and from May 2011 to May 2012 which corresponds to the first physics run with the fully completed IceCube detector. Two signal neutrino candidate events are observed in the sample of 670.1 days of livetime over expected background rates of 0.06 events. These events are consistent with the cascade-like events induced by ν_e charged current or $\nu_{e,\mu,\tau}$ neutral current interaction within the IceCube detector volume. Preliminary p-values for a background-only hypothesis are 1.6x10^{-3} (2.9 σ) without a prompt atmospheric neutrino contribution and 1.5x10^{-2} (2.2 σ) with a default perturbative QCD-based prompt neutrino contribution.

Keywords: Astrophysical neutrinos, Ultra-high energy cosmic-rays, the GZK effect

1. Introduction

Neutrinos are important probes for exploring the high energy universe. Because of their unique nature, neutrinos are undeflected in the galactic or extra-galactic magnetic fields and unabsorbed in the photon-filled universe, and thus they may be the missing link between TeV gamma-rays and EeV cosmic-rays. Photons, which are the conventional messengers from the universe, are highly attenuated by cosmic microwave background in this energy range. Therefore, cosmic neutrinos at PeV energies or higher are of particular importance for the complete survey of the ultra-high energy universe.

Cosmic neutrinos are expected to be produced by interactions of high energy hadronic beams from cosmic accelerators with surrounding photons and/or matter. However, the neutrino flux produced in each source is highly uncertain. A way of detecting neutrinos from possible weak sources is the diffuse neutrino search. This is because superposition of fluxes from all the weak astrophysical neutrino sources could compose a detectable signal. Still, the expected astrophysical neutrino flux is so small that a huge target is required in order for neutrinos to interact and produce secondary charged particles that can be detected through their Cherenkov emissions. With IceCube [1], the first cubic-kilometer scale neutrino detector is realized.

IceCube construction started in 2005 and was completed in December 2010. IceCube had been in operation with the partial detector configurations since 2005 until the beginning of the full configuration run. IceCube uses 2,800 m thick glacial ice as a Cherenkov medium. Cherenkov photons emitted from relativistic charged particles are detected by an array of Digital Optical Modules (DOMs) that amplify and digitally sample the high-speed pulses [3] from the enclosed photomultiplier tube (PMT) [2]. The cable assemblies, often called strings, were lowered into holes drilled to a depth of 2450 m. The DOMs occupy the bottom 1000 m at intervals of 17 m where the glacial ice is transparent. In addition to the large scale array of optical sensors, the inner dense array called DeepCore was also deployed. Additional DOMs frozen into tanks located at the surface near the top of each hole constitute an air shower array called IceTop. IceTop provides us with the capability to study the atmospheric muon background reliably. The strings and tanks are arranged in a hexagonal lattice pattern with a spacing of approximately 125 m. The array comprises 5160 DOMs on 86 strings of which 8 strings corresponds to DeepCore, and 324 modules in the surface array. The DeepCore array was excluded in the current analysis. From June 2010 to May 2011, 79 out of 86 strings were in operation. This run was followed by the initial year of data taken with the IceCube full 86 string configuration that continued until May 2012. In this paper, results from the diffuse ultra-high energy (UHE) neutrino searches at PeV energies and higher with the 79 and full 86 string configurations of IceCube with data taken between 2010 and 2012 in total of 670.1 days of effective livetime are presented.

2. Analysis

2.1. Signals and backgrounds

Possible sources of astronomical neutrinos at PeV energies and higher include potential accelerators of cosmic-rays above 3 x 10^{15} eV (the "knee" of the cosmic-ray spectra), such as AGNs or GRBs. These cosmic-ray source models and the resultant neutrino fluxes have large uncertainties. Still, many models predict signal neutrino spectra which follow a power-law. The spectral slope of the fluxes is predicted to be harder for cosmic neutrinos than that of background atmospheric muons and neutrinos.

In the energy region above 1 PeV, in addition to neutrinos directly propagating from each source, there are highly expected secondary produced neutrinos in the propagation of the cosmic-rays. These "cosmogenic" neutrinos are produced in interactions of the highest energy cosmic-rays with the cosmic-microwave background (CMB) and higher energy (infra-red, optical, and ultra violet) background [8, 9]. They may provide us a direct evidence of the highest energy cosmic-ray sources. This is because the spectral shapes and flux levels are sensitive to the redshift dependence of the cosmic-ray source distributions and cosmic-ray primary compositions [10]. The undeflected and unabsorbed nature of the neutrino propagation also give us an insight into their origin. The cosmic-ray fluxes and the CMB density are well measured, and thus secondary neutrinos are guaranteed to exist due to well known photo-pion production mechanisms. The cosmogenic neutrinos are distributed in a higher energy region than possible background events. This makes the cosmogenic neutrino signal events less uncertain to be distinguished from background.

Most background events are induced by particles generated in the interaction of cosmic-rays in the atmosphere. These atmospheric interactions produce two types of background particles. One of these is muons with energies high enough to reach to at least the depth of 1.5 km in ice before losing all of their energy [11], and the other is atmospheric neutrinos. There is a great advantage in searches for neutrinos at PeV energies and higher also from the perspective of background reduction. Since the conventional atmospheric neutrino and muon spectra are proportional to $E^{-3.7}$ or steeper, a very small number of background events is expected in the energy region.

In addition to those energy dependence, the atmospheric muon distribution has a strong zenith angle dependence. Because of the difference in the propagation distance, atmospheric muons peaks at vertical downward-going direction and sharply decrease to the horizontal direction. Atmospheric neutrinos have a weaker zenith angle dependence due to the interaction probability of neutrinos in the Earth. Because the neutrino-nucleon cross-section increases with energy, the Earth is transparent to neutrinos from all directions only up to PeV energies. At higher energies, the neutrino mean free paths become significantly smaller than the Earth radius. At PeV energies and above, a neutrino distribution has a peak near the horizon.

When we refer to the atmospheric neutrinos, we assume the conventional atmospheric neutrinos unless explicitly written. The conventional atmospheric neutrinos come from decays of cosmic-ray induced pion and kaons in the atmosphere. At PeV energies and above, neutrinos from decays of charmed mesons are expected to dominate over the conventional atmospheric neutrinos, however. This contribution is called prompt atmospheric neutrinos. The energy at which prompt neutrinos begin to dominate is expected to be around $3\text{x}10^5$ GeV depending on models. The prompt atmospheric neutrino spectrum has a slope index of approximately -2.7, harder than that of conventional atmospheric neutrinos. The prompt atmospheric neutrino models involve highly uncertain charm meson production cross-section. While the perturbative-QCD calculations [4] predict prompt neutrinos with theoretical uncertainty of a factor of two, non-perturbative part of QCD in the charm production involves a larger uncertainty. We have not observed clear evidence for prompt contributions in the atmospheric neutrinos so far [1].

2.2. Event selections

Above PeV energies, the primary variable to discriminate signal from background is the energy of the particles. Because the amount of energy deposited by the neutrino-induced charged particles in the detector and observed as Cherenkov photons is highly correlated

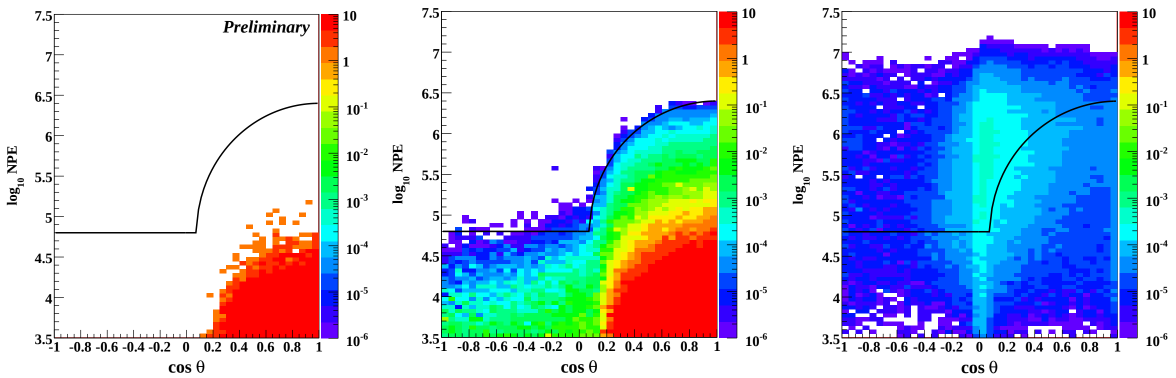

Figure 1: Event number distributions on the plane of NPE and reconstructed zenith angle in 498.4 hours are shown for the experimental 10% test sample from 2011-2012 (left panel), the total background (middle panel), and signal cosmogenic neutrino model [13] Monte Carlo simulations (right panel). The colors indicate event numbers per bin. The signal distributions are adding all three flavors of neutrinos. The background distributions include atmospheric muons from the CORSIKA package with SIBYLL high energy interaction model and conventional atmospheric neutrinos. The solid lines in each panel indicate the final selection criteria.

with their energy, the extremely-high energy neutrino signal stands out against the atmospheric muon and neutrino background due to the much higher light deposition [7]. The total number of photo-electrons (NPE) recorded in a time interval of 11 μs of an event is used as the main distinctive feature to separate signal from background after a lower level background reduction requesting the number of hit DOMs greater than 300.

Then as the second step, we reconstruct the direction of in-coming particles. Since the background atmospheric muons are concentrated in the direction of vertically downward-going while expected neutrino signals above PeV energies can only enter the IceCube detector from directions above slightly below the horizontal geometries, the final selection criterion was obtained as a reconstructed direction dependent NPE threshold value.

From May 31, 2010 to May 12, 2011, IceCube with 79 strings was in operation, and the first year IceCube full configuration with 86 strings took data from May 13, 2011 to May 15, 2012. The corresponding effective livetimes for 2010-2011 and 2011-2012 runs are 319.18 days and 350.91 days respectively excluding the period of detector calibration and unstable operation. Selection criteria are obtained by optimizing in each set of samples with different detector configurations using slightly different zenith angle reconstruction algorithms to minimize the model discovery factor [5, 6]. Presented here as an example is the selection criteria for the full string configuration run. The criteria for the 2010-2011 data sample is quite similar but with slightly different values. The final selection criteria for 2011-2012 sample are events with NPE exceeding the threshold values as:

$$\log_{10}\mathrm{NPE} \geq \begin{cases} 4.8 & \cos\theta \leq 0.075 \\ 4.8+1.6\sqrt{1-(\frac{\cos\theta-1.0}{0.925})^2} & \text{otherwise.} \end{cases} \quad (1)$$

In Fig. 1, the event number distributions of the Monte Carlo simulations and experimental data for 498.4 hours are shown. The period corresponds to the livetime of a 10% test sample for the IceCube 2011-2012 configuration for examinations of the Monte Carlo simulations and detector responses. Following the blind analysis strategy, the signal selection criteria is obtained fully based on the Monte Carlo simulations of background and signal events. The solid lines in Fig. 1 indicates the final criteria (Eq. 1) for the sample.

The effective neutrino area of the analysis averaged over the approximately two years period with the different IceCube detector configurations from June 2010 to May 2012 is shown in Fig. 2. The effective areas are given for each neutrino flavor, averaged over 4π solid angle. An equal flux of neutrinos and anti-neutrinos is assumed. The effective areas are approximately two times larger than for the 40 string configuration of data sampling period from 2008-2009 [5]. The sharp peaked structure for electron neutrino effective area corresponds to the Glashow resonance [12].

Below 5 PeV, the effective area of electron neutrinos exceeds that of muon or tau neutrinos. This reflects the fact that muon and tau tracks from muon/tau neutrinos partially deposit their energies into the detector volume while the electromagnetic (EM) cascades from electron neutrinos deposit 100% of their energy. While tracks have a longer propagation length, they do not satisfy the

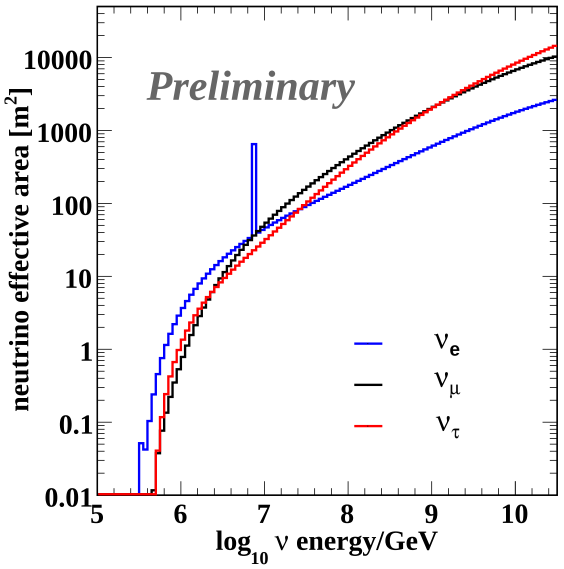

Figure 2: The IceCube neutrino effective area averaged over 670.1 days with different string configurations. Exposure of the sample used in this analysis is obtained by multiplying the effective area with the 670.1 days of livetime and 4π solid angle. The sharp peaked structure at 6.3 PeV for electron neutrino is due to the Glashow resonance [12].

selection criteria (Eq. 1) in the energy region, in contrast to the EM cascades induced within detector.

The quasi-differential model-independent IceCube sensitivity on neutrino fluxes using two years of IceCube data is shown in Fig. 3. The sensitivity is calculated as in [20] requiring 2.44 events in a bin size of one energy decade. The 2.44 is the Feldman-Cousins up-fluctuation 90% CL limit event number for null expected events. The IceCube sensitivity to the neutrino fluxes in the region between 1 PeV to 100 EeV from previous study [5] is approximately a factor of four improved. The factor of four improvement from previous IceCube results is due to approximately a factor of two longer livetime and a factor of two gain in the effective area, while we are able to keep the similar background event rates with the improved reconstruction algorithms and Monte Carlo simulations.

3. Results

After unblinding of the full data sample with 670.1 days of effective livetime, we observe two signal candidate neutrino events that pass all the selection criteria. One event is from August 8th, 2011 with the NPE value of 7.0×10^4 p.e. and 312 DOMs recorded photon

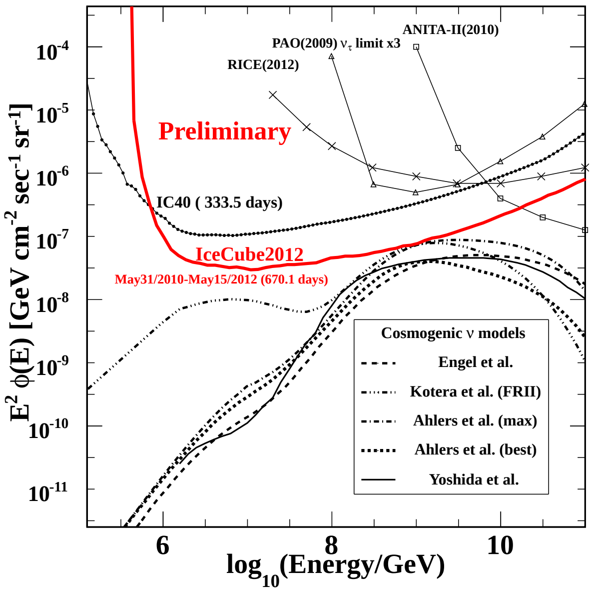

Figure 3: The IceCube differential sensitivity to all flavor neutrino flux by the 2010-2012 ultra-high energy neutrino analysis with an effective livetime of 670.1 days (red solid line). The systematic errors are not included. Several model predictions are shown for comparison: Engel et al. ($\Omega_\Lambda = 0.7$) [14], Kotera et al. (FRII) [15], Ahlers et al. (best and max) [16], Yoshida et al. ($(m, Z_{max}) = (4,4)$) [13]. Model fluxes are summed over all neutrino flavors, assuming standard neutrino oscillations. The model independent differential upper limits by other experiments are also shown for Auger (PAO) [17], RICE [18], ANITA [19], and the previous IceCube result (IC40) [5]. Limits from other experiments are converted to the all flavor limit assuming standard neutrino oscillation and a 90% quasi-differential limit per one energy decade when necessary.

signal. The other event is from Jan 3rd, 2012 with the NPE value of 9.6×10^4 p.e. and 354 DOMs recorded photon signal.

The expected background event rate of atmospheric muons and conventional atmospheric neutrinos is 0.057 events in the period. The background with prompt atmospheric neutrinos is 0.190 events assuming the standard prompt neutrino flux from Ref. [4]. Expected total background numbers and each background contribution are presented in Table 1. The preliminary p-value for the background only hypothesis is calculated to be 1.6×10^{-3} ($\sigma = 2.9$) and for the background with the nominal number of prompt atmospheric neutrinos [4] is 1.5×10^{-2} ($\sigma = 2.2$).

An event display of the event from August 2011 is shown in Fig. 4. Both events have a characteristic spherical photon distribution. These distributions are consistent with Cherenkov photons from particle cascades in-

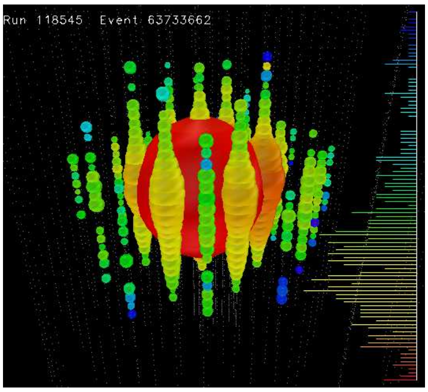

Figure 4: An event display of the one of the two observed events. Each spheres represent a DOM. Colors indicate the arrival timing of the photon (red = earliest, blue= latest). The size of the sphere indicates the measured photon in each DOM.

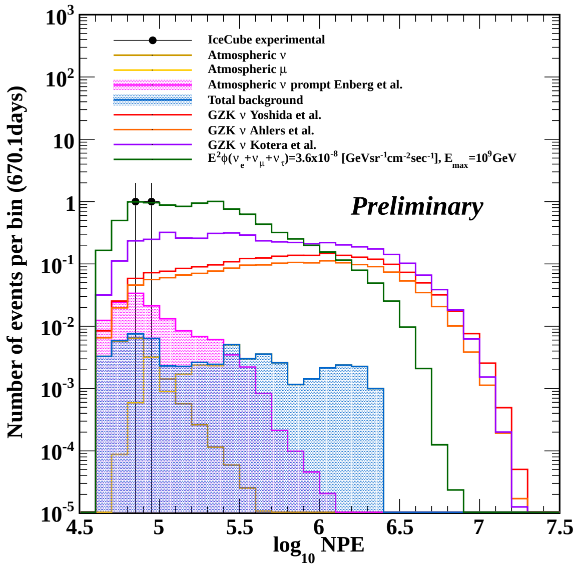

Figure 5: Event distributions from 2010-2012 sample passing the final selection criteria as function of $\log_{10}$NPE. Black marks indicate experimental data. Purple, red and orange solid lines indicate cosmogenic neutrino models with different assumed parameters. Green line indicates a power-law flux which follows E_ν^{-2} up to $E_\nu = 10^9$ GeV with the three flavor neutrino flux level of $E^2\phi_{\nu_e+\nu_\mu+\nu_\tau} = 3.6\text{x}10^8$ GeV $\text{sr}^{-1}\text{sec}^{-1}\text{cm}^{-2}$ corresponding to the obtained upper limit from the previous IceCube result in the similar energy range [5]. Filled magenta area is prompt atmospheric neutrino distribution and filled blue area is conventional atmospheric muon and neutrino background sum.

duced by neutrino interactions within the IceCube detector without outgoing muon or tau tracks. It is likely that these events are induced by either electron neutrinos of any interaction or neutral current interaction of muon or tau neutrinos. The preliminary total reconstructed energy deposits of these two cascade events are 1.1 and 1.3 PeV with the reconstruction uncertainties of ∼35% including statistical uncertainty and systematic uncertainties associated with the ice properties and the absolute DOM sensitivity. These energy deposits correspond to the incoming neutrino energy if each cascade is the result of a charged current interaction of an electron neutrino where 100% of the neutrino energy is deposited near the interaction vertex. Including the hypothesis of neutral current interaction of three flavors of neutrinos, the statistical error, and the systematic error, the 90% most probable neutrino energies of two events at the earth surface correspond to 780 TeV-5.6 PeV and 890 TeV-8.5 PeV, respectively, assuming that the surface neutrino flux follows an E^{-2} power law.

Background Contributions	Event Rates in 670 days
Atmospheric muons	0.036
Conventional atmospheric neutrinos	0.021
Total background	0.057
Total background with prompt ν [4]	0.190

Table 1: Preliminary number of background events in 670.1 days of effective livetime. Systematic uncertainties are not included. The magnitude of these uncertainties can be larger than the best-fit background expectation listed in the table.

Figure 5 shows event distributions from two years of data passing the final selection criteria as a function of $\log_{10}$NPE for experimental data, signal and background Monte Carlo simulations. Signal models include three cosmogenic neutrino models with different cosmic-ray source distributions or spectra. Among the three cosmogenic neutrino models, the distribution from Ref. [15], with an assumption that cosmic-ray spectra at sources extend to lower energy than the other models, shows a better agreement compared to the other models, which produce neutrinos from interaction of UV/optical photons. One of the signal models is an E^{-2} power-law neutrino flux which represent the contribution from direct neutrino production in cosmic-ray sources. The flux level corresponds to the upper limit obtained by the 2008-2009 IceCube data [5]. Table 2 presents the expected numbers of signal events from reference cosmogenic neutrino models and experimentally observed numbers after the final selection. The numbers are given for the full energy region and the region above 100 PeV. Most of the cosmogenic neutrinos are neutrinos with energies above 100 PeV. We would like to note that while

Cosmogenic ν Signal Models	Event Rates All	$E_\nu \geq$100 PeV
Yoshida et al. [13]	2.1	2.0
Kotera et al. (FRII) [15]	4.1	2.6
Ahlers et al. (maximal) [16]	3.2	3.0
Ahlers et al. (the best fit) [16]	1.6	1.5

IceCube Experimental	Event Rates All	$E_\nu \geq$ 100 PeV
May 31, 2010 - May 15, 2012	2	0

Table 2: Preliminary number of signal events from Monte Carlo simulations and experimentally observed events in 670.1 days of effective livetime at the final level of the analysis. Numbers are given for all the energy range and for the primary neutrino energy larger than 100 PeV. Errors are not included.

the cosmogenic neutrino models in the table predict 1.6~4.1 events in 670.1 days of an effective livetime, which is consistent as total rates with the experimental observation of two neutrino events, some of the models can be constrained with null observation of events above 100 PeV.

4. Summary

We presented the results of the analysis using the 2010-2012 data by the 79-string and 86-string IceCube detector to search for the ultra-high energy neutrinos with energies exceeding 10^6 GeV. The sensitivity of the analysis is improved by approximately a factor of four from the previous analysis [5]. Not including systematic uncertainties, the observation of 2 neutrino events corresponds to a 2.9 sigma excess above the event rates expected from atmospheric muons and conventional atmospheric neutrinos and 2.2 sigma excess with prompt atmospheric neutrinos. It is however possible that the significance of the excess may be reduced by the systematic uncertainties in the background estimate. The level of expected flux from the observation is consistent with the upper limit obtained by the previous UHE neutrino search [5], which is already below the Waxman-Bahcall limit [21].

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