Abstract: We present a follow-up search on the previous detection of two PeV neutrino events with the IceCube detector during an observation period from May 2010 to May 2012. Selecting for high energy neutrino events with vertices well contained in the detector volume, our analysis has improved sensitivity and extended energy coverage down to approximately 50 TeV. We observed 26 new events in addition to the two events already observed earlier. The combined preliminary significance from both searches represents an excess at the $4\sigma$ level above expected backgrounds from atmospheric muons and neutrinos. The entire sample of 28 events includes the highest energy neutrinos ever observed, and has properties consistent in flavor, arrival direction, and energy with generic expectations for neutrinos of extraterrestrial origin.

Keywords: IceCube, extraterrestrial high-energy neutrinos.

1 Introduction

Observation of high-energy neutrinos provides insight into the problem of the origin and acceleration mechanism of high-energy cosmic rays. Cosmic-ray protons and nuclei produce neutrinos in interactions with gas and photons present in the environment of sources and in the interstellar space through decay of charged pions and kaons. These neutrinos have energies proportional to the cosmic rays that produced them and point back to their sources since they are neither affected by magnetic fields nor absorbed by matter opaque for radiation. Large-volume Cherenkov detectors like IceCube [1] can detect these neutrinos through production of secondary leptons and hadronic showers when they interact with the detector material.

Here we present a follow-up analysis to a recent IceCube search for neutrinos of EeV energies [2], which found two neutrino events with energies around 1 PeV, just above its total charge threshold. Their topologies were consistent with either a neutral-current interaction or a charged-current interaction of $\nu_e$ or $\nu_\tau$. By selecting for events with vertices well contained in the detector volume, our analysis has a lower energy threshold (starting at about 50 TeV), a higher sensitivity at energies up to 10 PeV and is sensitive to all neutrino flavors from all directions. The goal of this analysis is to characterize the flux responsible for these events.

Both analyses share the same data-taking period, starting in May 2010 using 79 strings and continuing with the completed detector (86 strings) from May 2011 to May 2012 for a total livetime of 662 days.

2 Event Selection

Backgrounds for cosmic neutrino searches arise entirely from interactions of cosmic rays in the Earth’s atmosphere. These produce secondary muons that penetrate into underground neutrino detectors from above as well as atmospheric neutrinos that reach the detector from all directions due to the low neutrino cross-section which allows them to penetrate the Earth from the opposite hemisphere.

Neutrino candidates were selected by finding events that originated within the detector interior. Included were those events that produced their first light within the fiducial volume (Fig. 1) and were of sufficiently high energy such that an entering muon track would have been reliably veto entering muons. This event selection rejects 99.999% of the muon background above 6000 p.e. (Fig. 2) while retaining approximately 98% of all neutrino events interacting within the fiducial volume at
energies above a few hundred TeV. This selection is largely independent of neutrino flavor, event topology, or arrival direction. It also removes 70% of atmospheric neutrinos in the Southern Hemisphere, where atmospheric neutrinos are usually accompanied into the detector by muons produced in the same parent air shower. To prevent confirmation bias, we conducted a blind analysis designed on a subsample of 10% of the full dataset.

3 Event Reconstruction

Neutrino interactions in IceCube have two primary topologies: showers and muon tracks. Secondary muon tracks are created primarily in $\nu_\mu$ charged-current interactions and have a typical range that is on the order of kilometers, larger than the dimensions of the detector. Showers are created by the secondary leptons produced in $\nu_e$ and $\nu_\tau$ charged-current interactions and in the neutral current interactions of neutrinos of all flavors. At the relevant energies, showers have a length of roughly 10 meters in ice and are, to a good approximation, point sources of light.

Using the timing patterns of photon arrival times in individual PMTs allows for reconstruction of shower and track directions and deposited energies. The main systematic uncertainties arise from uncertainties in modeling of photon propagation in the natural ice [3] and from uncertainties on the absolute energy scale. Overall, we estimate an uncertainty of better than 15% on the reconstruction of deposited energy. The typical median angular resolution for showers is $10^\circ$-$15^\circ$, whereas it is much better for tracks due to their extension (around 1° or better, depending on their energy and length).

4 Atmospheric Muon and Neutrino Background

Remaining atmospheric muon background in the analysis comes from tracks that produce too little light at the edge of the detector to be vetoed and instead emit their first detected photons in the interior volume, mimicking a starting neutrino. These events usually produce an observable muon track in the detector like that from a $\nu_\mu$ charged-current event.

The veto passing rate for throughgoing muons was evaluated from data by tagging entering events using the outer layer of IceCube. The rate of these known background events that pass the veto one layer of PMTs deeper can be used to estimate the veto efficiency of the original veto (without an outer tagging region) by correcting for the differences in fiducial volume. The resulting predicted veto passing rate agrees well with data at low energies where we expect the event rate to be background dominated (Fig. 2). In our signal region above 6000 p.e., we observed twenty-one were shower-like.

Figure 2: Distribution of deposited PMT charge ($Q_{\text{cl}}$) for events in IceCube. Muons at higher total charges are less likely to pass the veto layer undetected, causing the muon background (red, estimated from data) to fall faster than the overall cosmic ray spectrum (uppermost line). The data events in the unshaded region, at $Q_{\text{cl}} > 6000$, are the events reported in this work. The atmospheric neutrino flux (blue) and best-fit atmospheric spectrum have been determined using Monte Carlo simulations. The hatched region shows uncertainties on the atmospheric neutrino background including a potential component from charmed meson decays (the best-fit charm component included in the blue region is zero) and uncertainties on the normalization of the conventional atmospheric neutrino spectrum. For scale, two specific charm levels are also shown: a benchmark theoretical model (green line) and the experimental 90% CL upper bound (magenta line).

We estimate an atmospheric neutrino background of $4.6^{+3.7}_{-3.0}$ events in our livetime of 662 days. These events would be concentrated near the energy threshold of the analysis due to the steeply falling atmospheric neutrino spectrum. Uncertainties are dominated by a potential component from charmed meson decays, chemical composition of cosmic rays, hadronic interaction models and the detector energy scale.

5 Results

In the two-year dataset, 28 events with deposited energies between 30 and 1200 TeV were observed (Fig. 3) on an expected background of $10.6^{+5.0}_{-3.6}$ events from atmospheric muons and neutrinos. The two highest-energy of these are the previously reported PeV events [2]. Seven events contained clearly identifiable muon tracks, while the remaining twenty-one were shower-like.

The significance of the excess over atmospheric backgrounds was evaluated based on both the total rate and properties of the observed events. From each event, the total deposited PMT charge, arrival angle, and reconstructed en-
neutrinos of 1-2 events above 100 TeV. Raising the normalization of this flux both violates previous limits and, due to $\nu_\mu$ bias in $\pi$ and $K$ decay, predicts too many muon tracks in our data (2/3 tracks vs. 1/4 observed, including muon backgrounds).

Another possibility is that the high energy events result from charmed meson production in air showers [7, 9]. These produce higher energy events with no bias toward muon neutrinos, matching our observed muon track fraction reasonably well. However, our event rates are substantially higher than even optimistic models [9] and the energy spectrum even from charm production is too soft to explain the data. More importantly, increasing charm production to the level required to explain our observations violates existing experimental bounds [5]. The additional events added by an increased flux from charm would originate predominantly from the northern rather than the southern sky, whereas the majority of our events are contained in the southern sky where atmospheric neutrinos produced by any mechanism are suppressed by detection of their accompanying air showers.

By comparison, a neutrino flux produced in extraterrestrial sources would, like our data, be heavily biased toward showers because neutrino oscillations over astronomical baselines tend to equalize neutrino flavors [10, 11]. The observed zenith distribution is also typical of such a flux: as a result of absorption in the Earth above tens of TeV energy, most events (approximately 60%, depending on the energy spectrum) from even an isotropic high-energy extraterrestrial population would be expected to appear in the Southern Hemisphere. Although the zenith distribution is well explained (Fig. 4) by an isotropic flux, a slight southern excess remains, which could be explained either as a statistical fluctuation or by a source population that is either relatively small or unevenly distributed through the sky.

This discussion can be quantified by an a posteriori fit to the energy and zenith distributions of the events above 60 TeV as a combination of the conventional atmospheric background, a possible prompt component, and an isotropic equal-flavor extraterrestrial power-law flux. The best-fit energy spectrum of the extraterrestrial component is similar ($E^{-2.2}$) to the $E^{-2}$ spectrum generically expected from a primary cosmic ray accelerator. For such a generic $E^{-2}$ spectrum we obtain a best-fit normalization of $E^2\Phi(E) = (3.6 \pm 1.2) \times 10^{-8}$ GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$ (shown in Fig. 4) and a cutoff energy of 1.6$^{+1.5}_{-0.4}$ PeV. The cutoff fitted here is a hard energy cutoff, but due to low statistics its shape cannot be constrained by our fit. A flux at this level is compatible with previous IceCube observations [2, 5].

In order to test for spatial clustering of the events, a significance against the hypothesis that all events in this sample are uniformly distributed in right ascension was calculated. This test (performed once on the full sample and again on the subset of shower-like events) did not yield a significant result. Several other tests (among them a galactic plane correlation study and multiple time clustering tests) did not yield significant results, either. A future larger dataset containing more well-resolved events than in our sample may allow identification of potential galactic or extragalactic sources.

7 Conclusion

An analysis of two years of IceCube data from 2010 to 2012 has revealed 28 events with deposited energies between 30
Figure 4: Distribution of the deposited energies (left) and declination angles (right) of the observed events compared to model predictions. Zenith angle entries for data are the best-fit zenith position for each of the 28 events. For some of them the angular uncertainty can lead to zenith widths wider than the shown bin width. Energies plotted are in-detector visible energies, which are lower limits on the neutrino energy. The estimated distribution of the background from atmospheric muons is shown in red. Due to lack of statistics from data far above our cut threshold, the shape of the distributions from muons in this figure has been determined using Monte Carlo simulations with total rate normalized to the estimate obtained from our in-data control sample. Combined statistical and systematic uncertainties on the sum of backgrounds are indicated with a hatched area. Two specific charm levels are shown, one at a benchmark theoretical model [7] (green line) and one at the current experimental 90% CL upper bound [5] (magenta line). The gray line shows the best-fit $E^{-2}$ astrophysical spectrum with all-flavor normalization (1:1:1) of $E^2\Phi_\nu(E) = 3.6 \times 10^{-8} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ and a cutoff energy of 2 PeV.

and 1200 TeV, including the most energetic neutrinos ever observed. The set of events does not seem to be compatible with expectations for terrestrial processes, deviating at a preliminary significance of 4.1σ from standard assumptions. It contains a mixture of neutrino flavors with events originating primarily from the Southern Hemisphere where high energy neutrinos are not absorbed by the Earth. The events are compatible with a flux proportional to $E^{-2}$, a spectrum expected for neutrinos associated with primary cosmic ray acceleration. The sample is thus consistent with generic expectations for a neutrino population with origins outside the solar system. We did not observe significant spatial clustering of the events, although this study is currently limited by low statistics and poor angular resolution for the majority of the observed events. Future observations with IceCube will provide improved measurements of the energy spectrum and origins of this flux, providing insight into the underlying processes responsible for these events.

References