RECENT RESULTS FROM THE ICECUBE NEUTRINO TELESCOPE*

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The IceCube neutrino telescope detects neutrinos in the energy range from $\mathcal{O}(10\ \mathrm{GeV})$ up to the PeV scale. One of its primary goals is the detection of high-energy neutrinos connected with cosmic-ray acceleration and propagation. In this contribution, we introduce strategies to search for these neutrinos and highlight recent results in connection with these topics. The search for localized, point-like neutrino sources was performed on three years of data from partial configurations of the detector. The search for extremely high energy (EHE) neutrinos with two years of IceCube data includes the first year of data from the complete IceCube configuration. The results of both searches are compatible with the background expectation but the latter observes two interesting events with a p-value of 2.2σ.

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1. Introduction

The interaction of accelerated hadrons with matter or photon fields in or near their sources leads to the production of high-energy neutrinos. The detection of a flux of high-energy cosmic-rays and its measured properties are generally expected to point to the existence of still unidentified astrophysical accelerators. The IceCube neutrino telescope has the potential to contribute significantly to the study of potential acceleration sites by searching for the neutrinos associated with cosmic-ray production, see *e.g.* [1].

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Protons of energies above approximately 6×10^{19} eV, are attenuated by interactions with the cosmic microwave background (the GZK effect) if the sources are located at distances larger than 50 Mpc. A yet undetected cosmogenic neutrino flux is potentially produced in these interactions [2]. IceCube is sensitive to this flux whose strength depends on astrophysical parameters such as the cosmic-ray composition, the evolution of cosmic-ray sources with redshift, and the energy spectra of the sources.

2. The IceCube neutrino telescope

The IceCube neutrino telescope [3] consists of 5.160 digital optical modules (DOMs) placed at depths from 1.5 to 2.5 km along 86 vertically deployed cables (strings) in the Antarctic ice and a surface array called IceTop. Each optical module contains a 25 cm photomultiplier tube and an on-board signal digitization system. The detector was built in several stages, adding a new section to the three-dimensional grid of modules each year from 2004/2005 until 2010/2011. The instrumented volume of the complete configuration is roughly 1 km^3.

Neutrinos which undergo neutral current (NC) or charged current (CC) interactions in the Antarctic ice or the bedrock below the detector produce a hadronic cascade at the vertex and in the CC case a lepton of the same flavor as the neutrino. Events with an outgoing muon are excellent for searches based on directionality since muon tracks can be well reconstructed using the arrival times of Cherenkov photons in the three-dimensional grid of the IceCube sensors. The kinematic angle between the outgoing muon and the incoming neutrino is below 1° at energies above ~ 1 TeV.

3. Search strategies

On-line event filtering based on hit patterns and fast reconstructions is used to select quality events for satellite transfer. The selected data are primarily composed of events induced by muons produced in cosmic-ray interactions in the atmosphere above the detector. Atmospheric muons enter the detector from above, have a uniform distribution in right ascension and a softer energy spectrum than many assumed signal spectra. The vertices of these events are not contained in the instrumented volume and they can thus be vetoed if the outer areas of the neutrino telescope are used as veto layers [4]. Finally, they are accompanied by an air shower which can be used at high energies to veto the events with the surface array IceTop.

A several orders of magnitude lower contribution are atmospheric neutrinos. They are likewise uniform in right ascension and have a softer spectrum than assumed for the signal. Only atmospheric neutrinos from above are accompanied by a detectable air shower which can be used for vetoing. Atmospheric neutrinos from the Northern hemisphere are an irreducible background in many but not all IceCube searches. Most searches are, therefore, performed as statistical tests on a reduced number of background events. Cut-and-count approaches are used only at the highest energies or in searches for rare event signatures.

The potential neutrino signal from cosmic-ray accelerators follows the spatial distribution of the sources. This implies that a signal can be identified as a clustering of events over the uniform background as attempted in the analysis presented in the next section. Alternatively, it is possible to integrate the signal from all possible accelerators by studying the energy spectrum of all events from a large region of the sky. Cosmogenic neutrinos are characterized by very high energies. It is then possible to remove almost all of the background as in the analysis presented in Section 4.2.

4. Neutrino point source search with IceCube

The goal of this analysis is to search for a directionally clustered excess of neutrino events in the sky. The spatial pattern of the signal was assumed to be point-like and its energy spectrum modeled by a power law. By considering all possible directions, we made full use of IceCube's All-Sky field of view.

4.1. Data samples, event selection and analysis method

The analysis was performed on three years of IceCube data, each obtained with a different, partial configuration of the detector. 376 days of quality data were taken with the first 40 strings of IceCube. In the next season, 348 days of data were collected with 59 strings. The latest data used in this analysis is from IceCube 79-strings, a close-to-final configuration of the detector and includes 316 days of quality data.

For each year, a subset of all transferred events were selected for the analysis. While the details of the event selection differ from year to year, the key features of the event selection are the same. In each year, we have selected a sample of up-going neutrino candidates in the Northern Sky using a combination of event characteristics which are sensitive to the quality of the reconstruction, the event topology and the muon energy. In addition, a sample of high-energy muons and muon bundles in the southern sky was selected, mostly relying on a declination-dependent energy cut. The effective area of the 79-string event selection is shown in figure 1.

A test of a composite signal and background hypothesis *versus* a pure background hypothesis was performed at each point of a $0.1^\circ \times 0.1^\circ$ grid across the sky. The test was realized as a maximum likelihood ratio test

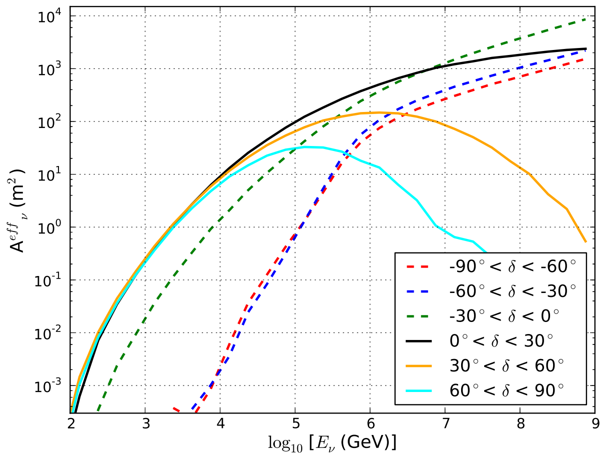

Fig. 1. Effective area of the IceCube 79-string event selection for point source searches in six different declination bands.

assuming a point-like signal shape and a power-law signal spectrum with variable spectral index γ [6]. While the background probability density functions (pdf) were modeled with randomized data, simulation was used to derive the signal pdfs. The test was applied to the three years of data simultaneously. The signal was assumed to have a constant strength and a constant spectral index over the whole period and the pdfs were derived for each data set separately to account for their different acceptance. The resulting sensitivity (see figure 2) of the search is about a factor ~ 3.5 better than the latest published IceCube sensitivity for neutrino point sources [5].

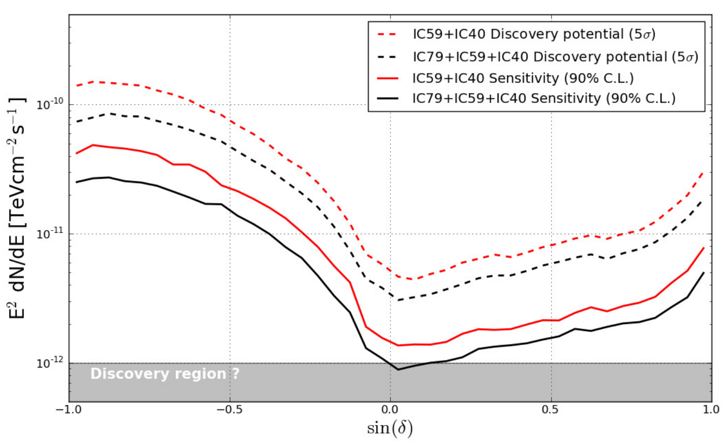

Fig. 2. Sensitivity and discovery potential for E^{-2} neutrino sources.

4.2. Results

The results of this search are presented as a significance map. For each point of the $0.1° \times 0.1°$ grid, we calculated the local p-value of the best fit composite signal and background hypothesis. The most significant deviation in the northern sky is observed at 34.25° r.a. and 2.75° dec with a pre-trial p-value of 1.96×10^{-5} resulting in a trial-corrected p-value of 57%. In the Southern sky, the largest fluctuation is observed at 219.25° r.a. and −38.75° dec. and has a pre-trial p-value of 8.97×10^{-5} and post-trial p-value of 98%. The results are, therefore, compatible with the background-only hypothesis. More optimistic models predict event rates $\mathcal{O}(1)$ per year in IceCube from cosmogenic neutrinos. These events are characterized by their extraordinarily high energies and the atmospheric muon and neutrino background can be suppressed efficiently by using this property.

4.3. Data samples and event selection

The most sensitive search to date for these events with IceCube data was performed using the 79-string configuration and the first year of data from the complete 86-string detector. The properties of the signal events allow for a comparably simple event selection based on the reconstructed direction of the detected particles and the amount of light detected by IceCube's optical modules (number of photo electrons or NPE) as an energy proxy.

The event selection was optimized on background simulation which has been cross-checked against 10% of the experimental data. The rest of the data have been kept blind in the development of the analysis. The expected background of atmospheric muons and neutrinos in the remaining 670 days of data are 0.057 events. This number increases to 0.19 events when prompt atmospheric neutrinos from production of charmed mesons [7] are included.

4.4. Results

Two high-energy events were observed in the data sample. These neutrino candidates are cascade-like events as are expected from NC neutrino interactions or electron or tau neutrino CC interactions. Their energies have been reconstructed to 1.1 and 1.3 PeV, with an uncertainty of $\sim 35\%$ accounting for the uncertainty in the absolute sensitivity of IceCube's optical modules and the parametrization of the ice properties. The significance of the observation of these two events is $2.2\,\sigma$ ($2.9\,\sigma$ if prompt atmospheric neutrinos are excluded) with respect to the background-only hypothesis without inclusion of systematic uncertainties. The brightness of the two events measured by the number of detected photo electrons is shown in figure 3 along with the expected background distribution.

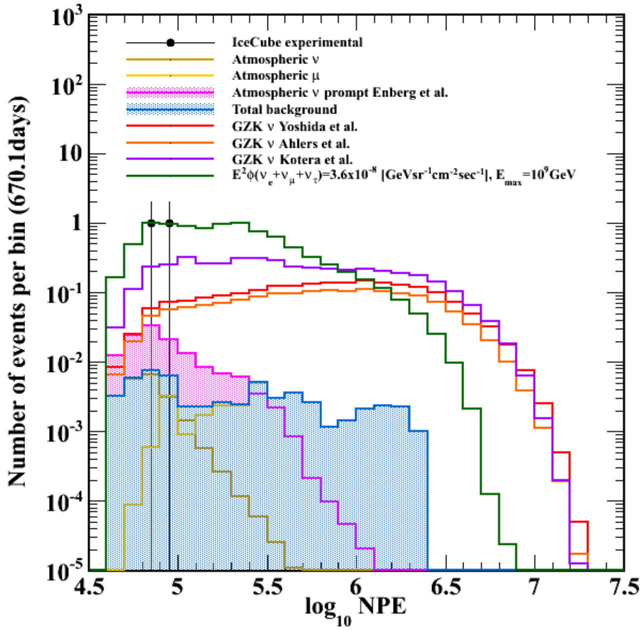

Fig. 3. Brightness measured as number of detected photo electrons (NPE) for the two detected EHE events, including the expected background distribution and several signal models.

5. Conclusions

The completed IceCube neutrino telescope is entering an exciting phase. Searches for neutrinos produced at cosmic-ray sources can now be applied to three years of filtered data from partial IceCube configurations. The interpretation of the upper limits from the search for single, strong point-like sources in these data is on-going. Several analyses to explore more specific source scenarios are likewise under way and will further exploit the potential of the existing data. The selection of neutrino candidate events from the two first years of data from the complete detector is under preparation and will, once more, significantly increase the sensitivity of these searches.

At higher energies two very bright neutrino candidates have been detected in the search for a cosmogenic neutrino flux. The energies of these events are close to the threshold of the event selection and follow-up analyses with a lower energy threshold will be performed to establish whether these events could potentially form part of a larger population of events.

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