

IceCube Search for Earth-traversing ultra-high energy Neutrinos

The IceCube Collaboration

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The search for ultra-high energy neutrinos is more than half a century old. While the hunt for these neutrinos has led to major leaps in neutrino physics, including the detection of astrophysical neutrinos, neutrinos at the EeV energy scale remain undetected. Proposed strategies for the future have mostly been focused on direct detection of the first neutrino interaction, or the decay shower of the resulting charged particle. Here we present an analysis that uses, for the first time, an indirect detection strategy for EeV neutrinos. We focus on tau neutrinos that have traversed Earth, and show that they reach the IceCube detector, unabsorbed, at energies greater than 100 TeV for most trajectories. This opens up the search for ultra-high energy neutrinos to the entire sky. We use ten years of IceCube data to perform an analysis that looks for secondary neutrinos in the northern sky, and highlight the promise such a strategy can have in the next generation of experiments when combined with direct detection techniques.

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1. Introduction

The IceCube Neutrino Observatory is a gigaton-scale unsegmented ice-Cherenkov detector located at the geographical South Pole. Since its completion in 2012, IceCube has measured an extraterrestrial high-energy diffuse neutrino flux, whose sources are yet largely unidentified. The observed astrophysical flux has been measured between $O(10\text{TeV})$ and $O(1\text{PeV})$ and is well-described by an unbroken power-law [1–3]. IceCube has also reported the first hints of astrophysical neutrino sources in 2017, with the observation of neutrinos from the blazar TXS 0506+056 [4, 5]. More recently, analyses with more years of data and updated tools and reconstructions revealed NGC 1068 as a possible neutrino source [6].

Despite its success, IceCube has not observed neutrinos produced by interactions of cosmic-rays with cosmic microwave background (CMB) light. This cosmogenic neutrino flux, also known as the GZK flux due to the expected associated cut-off in the cosmic-ray spectrum, is a major target of current and next-generation neutrino telescopes. Moreover, predictions of neutrino fluxes from certain populations such as FSRQs and high-luminosity AGN jets show peaks around an EeV in energy with little emission at TeV-PeV, suggesting some sources may only be resolved at the highest energies [7, 8]. Searches for ultra-high energy neutrinos have been performed by looking at through-going very-high energy events in IceCube [9] and by looking at Earth-skimming events in cosmic-ray detectors such as the Pierre Auger Observatory, and with radio detectors such as ANITA, ARA, and ARIANNA [10–20]. In this contribution, we present the application of a new method to detect GZK neutrinos, which was first introduced in [21], and estimate the sensitivity of a search carried out with currently available IceCube data.

This new method relies on observing secondary neutrinos produced as tau neutrinos with EeV energies traverse the Earth. Secondary tau neutrinos produced in the cascading down process accumulate at energies close to 1 PeV for most trajectories through Earth, where the current astrophysical measurements have been performed. This accumulation implies that the angular and energy distribution of the UHE component is different from that of astrophysical neutrinos. A schematic illustrating signatures from such neutrinos is shown in Fig. 1. In the following we will describe an analysis to search for these neutrinos, and provide preliminary sensitivities to some benchmark ultra-high energy neutrino models.

2. Analysis description

We use the event selection described in [22], which selected for northern-sky through-going muons and achieves plateauing efficiency above a few TeVs in energy. We use the LeptonInjector Monte Carlo [23] to generate through-going muons, which could be produced either by muon-neutrino charged-current interactions or by tau-neutrino interactions where the tau decays leptonically to a muon; the latter process happens in 18% of the tau decays. Given that LeptonInjector does not simulate neutrinos, but charged particles (or final states) that can be matched a posteriori to several physical processes, we can add the contribution of the tau-neutrino interactions to muon tracks via reweighting. The effective tau weight is given by,

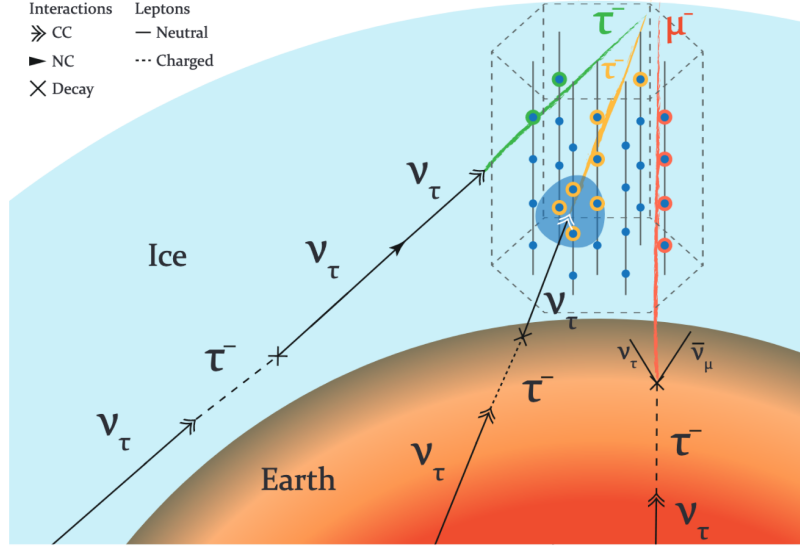


Figure 1: Schematic of neutrino propagation through Earth followed by an event signature in IceCube. EeV tau-neutrino secondaries can be detected in three possible ways, though this work focuses on the rightmost signature. Right: The tau decays before reaching the detector, producing a muon in $\sim 18\%$ of the cases, which subsequently enters the detector. Center: The interaction vertex is contained in the fiducial volume of the detector in this case, producing a cascade from the charged-current interaction, along with an outgoing tau track. Left: A throughgoing tau track, which is possible for taus at or above 10 PeV.

$$w_{\tau}(E_{sh}, E_{\mu}) = \int dE_{\tau} \frac{d^2\sigma}{dE_{sh}dE_{\tau}}(E_{sh}, E_{\tau}; E_{\nu} = E_{sh} + E_{\tau}) \frac{dN_{\mu}}{dE_{\mu}}(E_{\mu}; E_{\tau}) \beta_{\tau\mu} \quad (1)$$

where E_{sh} is the energy imparted to the hadronic shower in a charge-current interaction, E_{μ} is the muon energy, σ is the neutrino-nucleon cross-section, dN_{μ}/dE_{μ} is the energy distribution of muons from tau decay, and $\beta_{\tau\mu}$ is the branching fraction of taus to muons. In this way, specifically by re-weighting simulated muons with the above expression, we can incorporate the contributions of tau neutrinos to throughgoing tracks without the need to generate additional Monte Carlo sets.

In order to estimate sensitivities to UHE neutrinos, our analysis takes into account contributions from atmospheric neutrinos, astrophysical neutrinos described by an unbroken power-law, and an ultra-high energy component. The cosmogenic/UHE astrophysical neutrinos look like an additional contribution to the already measured astrophysical spectrum, but with a modified energy and zenith distribution. Both astrophysical and UHE contributions to track event selections are shown in Fig. 2 in true quantities. We ignore the contribution of atmospheric muons, since the event selection purity is greater than 99.9% [22]; we also neglect, for the results shown here, the contribution of neutrinos from charmed meson decays as those are sub-leading to the observed astrophysical component. This component will, however, be included in the final analysis. We construct a forward-folding likelihood problem in which we organize the Monte Carlo events in logarithmically spaced bins in reconstructed energy and linearly spaced bins in the cosine of the reconstructed zenith angle.

We then compare the expected distribution in energy and direction to an Asimov set which does not include a UHE component, by means of a modified Poisson likelihood that accounts for

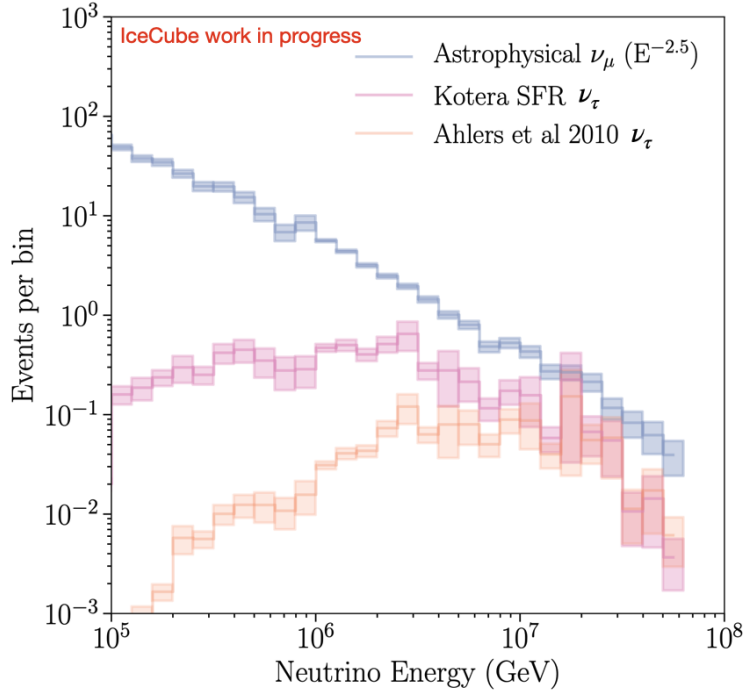


Figure 2: Expected number of muon events in the northern sky, binned in true neutrino energy. This assumes nine years of data and an unbroken power-law with a spectral index of 2.5 for the astrophysical muon-neutrino flux. The GZK contributions according to two models, labeled Kotera and Ahlers et al have comparable rates above a PeV in energy. The error bars encompass statistical monte carlo uncertainties.

Monte Carlo statistical uncertainty. The likelihood function is given by,

$$\mathcal{L}_{\text{Eff}}(\vec{\theta} | k) = \left(\frac{\mu}{\sigma^2}\right)^{\frac{\mu^2}{\sigma^2}+1} \Gamma\left(k + \frac{\mu^2}{\sigma^2} + 1\right) \left[k! \left(1 + \frac{\mu}{\sigma^2}\right)^{k + \frac{\mu^2}{\sigma^2} + 1} \Gamma\left(\frac{\mu^2}{\sigma^2} + 1\right) \right]^{-1}, \quad (2)$$

where $\vec{\theta}$ is the set of parameters describing the hypothesis being tested, k is the number of observed events in a bin, $\mu \equiv \sum_{i=1}^m w_i$ is the sum of the weights w_i of m Monte Carlo events in a given bin, and similarly $\sigma^2 \equiv \sum_{i=1}^m w_i^2$. For a detailed explanation and a complete derivation of this function, refer to [24]. The expected event distributions in terms of energy and reconstructed angle quantities are shown in Fig. 3 for nominal choices of the astrophysical flux parameters. Our likelihood problem depends on four variables: the normalization of the conventional atmospheric component, the astrophysical neutrino power-law normalization and spectral index, and the UHE neutrino model normalization. We use the same conventional atmospheric model described in [22, 25] and test several benchmark UHE neutrino models given in [26, 27].

3. Results and conclusions

We run a Markov Chain Monte Carlo (MCMC) in order to derive allowed regions of parameter space. In our analysis, we use uniform priors on the normalization of each of the components. The astrophysical power-law and the GZK components are given improper uniform priors from 0

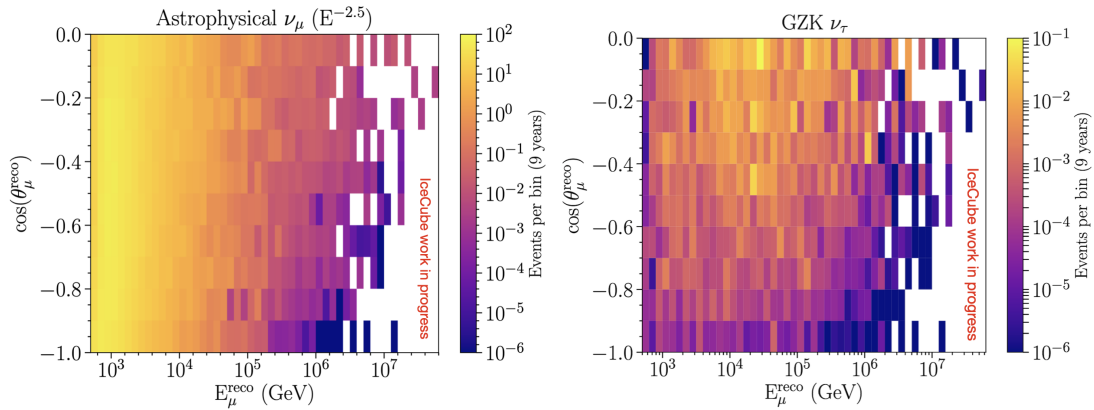


Figure 3: Expected number of events shown in reconstructed quantities for both energy and zenith angle. Left: Muon neutrino events Assuming an equal-flavor astrophysical flux with a spectral index of 2.5 and a normalization of $10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. Right: Muon events in the Northern Sky from GZK tau neutrinos assuming the flux given by [26].

to infinity, while the conventional component is priored by a Gaussian distribution as discussed in [22].

From the MCMC we obtain the model rejection factor, which is defined as the 90% C.R. (confidence region) upper limit of the chosen model normalization with respect to its nominal prediction. In other words, a rejection factor of 1 or less means the nominal prediction is constrained. We obtain a 90% C.R. UL of 4.11 for the Kotera SFR model and 7 for Ahlers et al. We note that this analysis can be improved by adding the secondary contributions of other neutrino flavors produced in tau decays, which have been shown to contribute equally to events at the detector. Further, the energy reconstruction used in this work provides poor separation of muons above 10 TeV, whereas recent work has shown significant improvement in muon energy resolution at high energies, as reported in [28]. As energy separation is crucial to the performance of this analysis, we expect a significant improvement to the sensitivity with updated energy reconstruction. Despite these limitations, the model rejection factors obtained in this work are promising as they are comparable with dedicated analysis upper limits from other experiments. Future work will improve the points noted above and include additional years of data taking.

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