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Search for Astrophysical Tau Neutrinos with IceCube

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High-energy (TeV-PeV) cosmic neutrinos are expected to be produced in extremely energetic astrophysical sources such as active galactic nuclei. The IceCube Neutrino Observatory at the South Pole has recently detected a diffuse astrophysical neutrino flux. While the flux is consistent with all flavors of neutrinos being present, identification of tau neutrinos within the flux is yet to occur. Although tau neutrino production is thought to be low at the source, an equal fraction of neutrinos are expected at Earth due to averaged neutrino oscillations over astronomical distances. Above a few hundred TeV, tau neutrinos become resolvable in IceCube with negligible background from cosmic-ray induced atmospheric neutrinos. Identification of tau neutrinos among the observed flux is crucial to precise measurement of its flavor content, which could serve to test fundamental neutrino properties over extremely long baselines, and possibly shed light on new physics beyond the Standard Model. We present the analysis method and results from a recent search for astrophysical tau neutrinos in three years of IceCube data.

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1. Introduction

The IceCube Neutrino Observatory has detected a diffuse astrophysical neutrino flux at $>$ 6σ significance over the atmospheric background [1, 2, 3]. To date, no neutrino point sources have been identified to have contributed substantially to the observed flux. Assuming a neutrino flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$, based on pion production at the source, equal fraction of neutrinos are expected at Earth due to standard neutrino oscillations over astronomical distances. Other scenarios of neutrino flavor ratios at the source ranging from $1 : 0 : 0$ and $0 : 1 : 0$ also all predict appreciable numbers of tau neutrinos at Earth. Analyses combining various event samples and performing global maximum likelihood fits found the neutrino flavor ratio to be consistent with $1 : 1 : 1$, but with large uncertainties [4, 5]. The largest uncertainty resides in the degeneracy of ν_e and ν_τ events in IceCube. Identification of ν_τ will help break this degeneracy. A multitude of new physics models predict significant deviation from equal mixing of astrophysical neutrinos [6, 7]. A precise measurement of the astrophysical neutrino flavor contents can help decode the neutrino production mechanisms at source, test standard neutrino oscillations over extremely long baselines, and constrain new physics models beyond the Standard Model.

IceCube is a cubic kilometer neutrino observatory located at the geographic South Pole. It was built to detect TeV-PeV astrophysical neutrinos. The construction of IceCube started in 2004 and completed in December 2010. The IceCube detector consists of 86 cables, called *strings*, deployed at depths between 1450 m and 2450 m. Each string is instrumented with 60 digital optical modules (DOMs). This array of 5160 DOMs encompasses $\sim$1 gigaton volume in ultra transparent glacial ice, making it the world's largest neutrino detector to date. The inter-string distance is $\sim$125 m, and the vertical distance between two DOM is $\sim$17 m. At the bottom center of IceCube, there is a denser sub-array called DeepCore with an inter-string distance of $\sim$60-70 m, and an inter-DOM distance of $\sim$7 m. DeepCore lowers the detection energy threshold of IceCube to $\sim$10 GeV, enabling neutrino oscillation physics with atmospheric neutrinos and new physics such as dark matter searches at these energies. The basic building blocks of IceCube are DOMs, which each include a 10 inch PMT which is housed in a high-pressure glass vessel that can withstand pressures up to 10,000 psi. Each DOM also has processing and digitization electronics. IceCube waveform digitization occurs in ice. There are two types of waveform digitizers: one called the Analog Transient Waveform Digitizer (ATWD) and the other called the fast Analog to Digital Converter (fADC). An ATWD has three channels with gains of (16, 2, 0.25) times the nominal gain of 10^7. During digitization, the highest gain channel is initiated first to capture the best details of the signal waveforms. The lower gain channel will be initiated if the higher gain channels are saturated. The ATWD digitizes at 3.3 ns per sample for 128 samples in one waveform (422.4 ns) [8].

Neutrinos are difficult to detect, and they cannot be detected directly. In IceCube, neutrino interactions are detected via the Cherenkov radiation emitted by extremely relativistic secondary particles which are produced by neutrinos interacting with the ice nuclei. The identification of a neutrino interaction event relies on the precise reconstruction of the event based on the timing and charge information collected by the DOMs during an event readout. There are two major types of event topologies in IceCube. One is called *track*, made by cosmic-ray induced atmospheric muons or ν_μ-induced muons. These muons can penetrate long distances in the ice at speeds close to the light speed in vacuum, emitting Cherenkov light along their trajectory. The other is called *cascade*,

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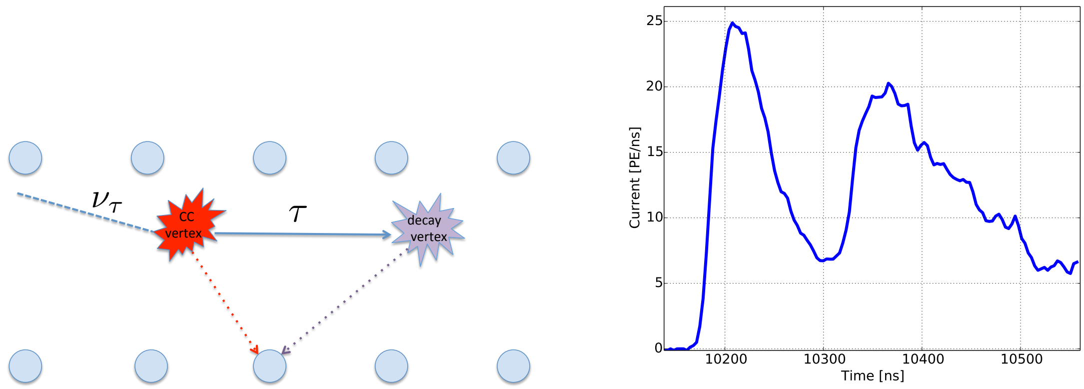

Figure 1: Left: A sketch of a tau neutrino undergoing CC interaction in IceCube. The figure is not drawn to scale. Right: A double pulse waveform from a simulated ν_τ CC event [11].

or *shower*. Cascade events have high levels of degeneracy. They can be made by charged current (CC) interactions of ν_e, low energy ν_τ, and neutral current (NC) interactions of all neutrino flavors. During these interactions, hadrons or electrons are produced at the interaction vertices, which subsequently interact with the ice and produce cascades of secondary particles. The energy resolution for cascade and track events above 100 TeV are $\sim$10% and a factor of 2, respectively. While at these energies, the angular resolution for cascades and tracks are 15° and $< 1^\circ$, respectively [9]. A third type of event topology called *double cascade*, or *double bang*, can be made by high energy ν_τ CC interactions [10]. These types of events have not been observed. A high energy ν_τ undergoing CC interaction in the ice produces a first cascade, and the outgoing τ lepton[1] decays subsequently into hadrons or electrons with a total branching ratio of $\sim$83%[2], producing a second cascade (left panel of Fig. 1). The separation between the two cascades scales as $(\frac{E_\tau}{1\,\mathrm{PeV}} \cdot 50\ \mathrm{m})$, with E_τ being the energy of the tau lepton. At energies below PeV, the double cascade signature is difficult to distinguish from a single cascade, due to the sparse spacing of DOMs. However, the double pulse process from the ν_τ CC interaction could manifest itself in the photon sensors as double pulse waveforms. The right panel of Fig. 1 shows one example of such double pulse waveforms.

2. A search for astrophysical tau neutrinos

2.1 Double pulse algorithm

The double pulse algorithm (DPA) is designed to identify bright waveforms with double peak signatures that are consistent with ν_τ CC interactions, while rejecting bumpy waveforms caused by late scattered photons from single energetic cascades (NC events of all flavor and ν_e CC events). Below 1 PeV, it is extremely difficult to separate double cascades from single cascades using event topologies. So it is of essential importance to bring the single cascade backgrounds under control at the waveform level. A double pulse waveform is defined by a rising edge, followed by a trailing

[1] IceCube cannot discriminate neutrino and anti-neutrinos, so τ^- and τ^+ will behave the same.

[2] The τ lepton decays muonically 17% of the time, producing an abruptly brightened track.

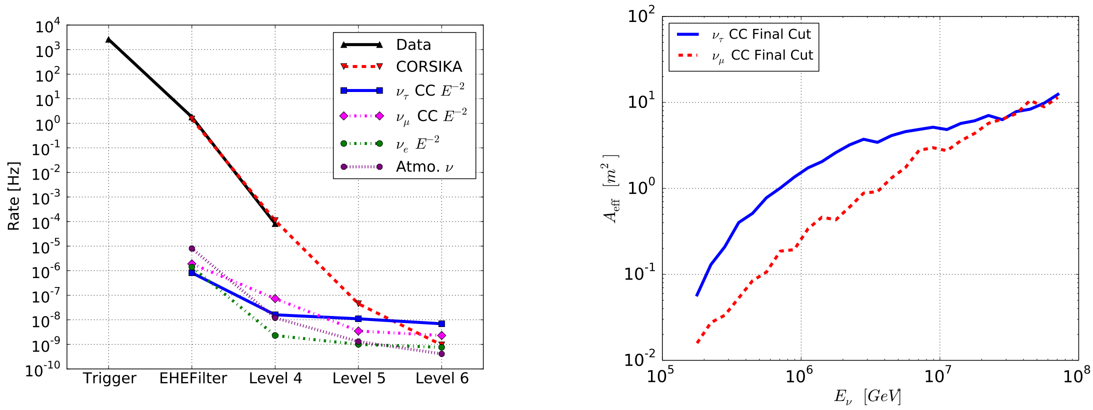

Figure 2: Left: Event passing rates at various cut levels. Right: Effective areas for ν_τ CC and ν_μ CC events at final cut level [11].

edge and then followed by a second rising edge. A second trailing edge is not required as it usually runs outside of the ATWD time window. The DPA uses 7 configurable parameters based on the first derivatives of an ATWD waveform to characterize the rising and trailing edges [11, 12]. The flow of the DPA is summarized as follows. Since the ν_τ CC events that could produce resolvable double pulse waveforms are usually close to a DOM, the waveforms are bright. Therefore, in order to increase computational efficiency, the DPA is only run on waveforms with an integrated charge greater than 432 photoelectrons (PE). A sliding time window with bin size of 3.3 ns is employed to determine the beginning of a waveform. The first rising edge is considered starting if there is a monotonic increase in 6 bins, a duration of 3.3×6=19.2 ns. Once the starting of the first rising edge is identified, the waveform is divided into segments with 4 ATWD bins (3.3×4=13.2 ns), and the first derivatives are computed in each segment. The time segments of the first derivatives above/below zero, which represent duration of rising/trailing edges, are set to be at least 2, 2, 3 for the first rising, the first trailing and the second rising edges, respectively. The integrals of the continuous positive and negative first derivative values, which are representations of steepness of the rising and trailing edges, are set to be at least 23 PE, 39 PE and 42 PE for the first rising, the first trailing and the second rising edges, respectively. The DPA parameters were optimized using a variety of IceCube event waveforms including neutrino Monte Carlos of all flavors, simulated atmospheric muons, and *in situ* calibration lasers.

2.2 Event selection and results

Event selections were developed based on Monte Carlo samples of neutrinos, atmospheric muons and 10% of data (called the *burn sample*). To avoid introducing artificial bias, the remaining 90% of data were kept blind until the selection methods were well tested and finalized. Data samples analyzed were collected between May 13, 2011 and May 6, 2014. Exclusions of the 10% burn sample, data collection with only partial detector operation or calibration runs when light sources were in use, resulted in a total of 914.1 days of livetime.

The event selection began with the IceCube Extremely High Energy (EHE) filter, which re-

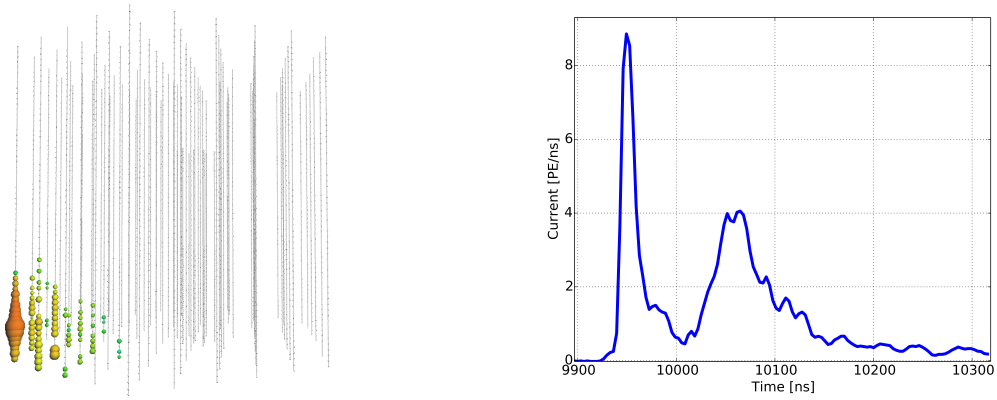

Figure 3: Left: A corner clipper event with double pulse waveforms at Level 5. Right: The corresponding double pulse waveform, which was from the brightest hit DOM of this event [11].

quires an event has at least 1000 PE. Event rates after this filter are $\sim$ 1 Hz. The subsequent event selection process took three stages, named Level 4, Level 5 and Level 6. At Level 4: an additional event-wise charge cut was placed at >2000 PE. Then the DPA was applied and events with at least one waveform passing were kept. At the Level 5 stage, the dominant backgrounds are energetic atmospheric muons which lose energy stochastically with two coincident energy losses making double pulse waveforms. High energy ν_μ CC events could also make double pulse waveforms with the first pulse coming from the CC vertex, and the second pulse from the coincident stochastic loss of the outgoing energetic muon. A reduced likelihood ratio cut of $\mathrm{L_R} = (\mathrm{L_{cascade}}/\mathrm{L_{track}}) < 0$ was employed to separate the cascade-like ν_τ CC events from the track-like atmospheric muon and ν_μ CC double pulse events. $\mathrm{L_{track}}$ and $\mathrm{L_{cascade}}$ are likelihood values based on an infinite track and a point-like cascade hypothesis, respectively. The first hit in an event was also required to be at least 40 m below the top layer of the detector to further veto downgoing atmospheric muons. At this level, the dominant background is still atmospheric muons, with a total of 3.5$\pm$3.4 expected in 914.1 days. At the Level 6 stage: events surviving up to this stage are cascade-like and with at least one double pulse waveforms. Particularly, the surviving cascade-like atmospheric muons are the ones starting outside and clipping the corners of the detector (called *corner clippers*). To eliminate these corner clippers, a geometrical containment cut was cast which required the reconstructed starting vetex of an event to be within the detector's instrumented volume and some distance away from the edge surface of the detector. The containment cut reduced the atmospheric muon background significantly, yielding a total of 0.54 signal ν_τ double pulse events and 0.35 total background double pulse events in 914.1 days. The expected event rates are summarized in Table 1.

Zero events were found upon unblinding the remaining 90% data, consistent with expectation. Based on these zero findings, for the first time, a differential upper limit on the astrophysical tau neutrino flux is set near the PeV energy region, as shown in Fig. 4. The energy range encompassing the middle 90% of signal events is from 214 TeV to 72 PeV. At Level 5, three corner clipper events were found, each of which has only one double pulse waveform. This finding matches the Monte Carlo prediction of 3.5$\pm$3.4 in 914.1 days, indicating robustness of the analysis methods.

Table 1: Predicted event rates from all sources at final geometrical containment cut. The astrophysical ν_τ CC double pulse events dominate at final cut, with the leading background being astrophysical ν_μ CC double pulse events. Errors are statistical only.

Data samples	Events in 914.1 days
Astrophysical ν_τ CC	$(5.4 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_μ CC	$(1.8 \pm 0.1) \cdot 10^{-1}$
Astrophysical ν_e CC	$(6.0 \pm 1.7) \cdot 10^{-2}$
Atmospheric ν	$(3.2 \pm 1.4) \cdot 10^{-2}$
Atmospheric muons	$(7.5 \pm 5.8) \cdot 10^{-2}$

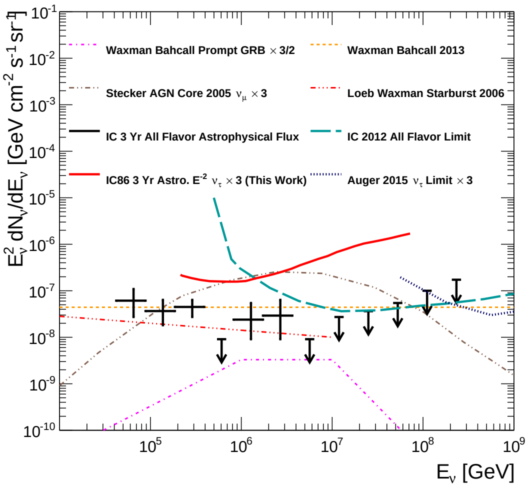

Figure 4: Differential upper limit on astrophysical ν_τ flux at 90% C.L (red solid line) [11].

3. Conclusion and outlook

Searching for astrophysical tau neutrinos in the IceCube waveforms is shown to be robust, with Monte Carlo predictions matching experimental results. Zero events were found at the final cut, consistent with expectation of 0.5 signal events in three years of IceCube data. More sophisticated methods including machine learning algorithms are under development to identify more ambiguous ν_τ double pulse waveforms from the enormous number of waveforms. Analyses to search for resolvable double bang event topologies via precise reconstructions of event vertices are well under way. With a suite of promising techniques, and continuous accumulation of data, IceCube is getting closer than ever to discover astrophysical tau neutrinos.

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