

Methods for Detection of Astrophysical Tau Neutrinos in IceCube

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The IceCube Neutrino Observatory has reported the discovery of a diffuse flux of TeV-PeV astrophysical neutrinos at 5.7σ significance from an all-flavor search. Neutrinos are expected to be produced in hadronic interaction processes at the sources of high-energy cosmic rays. Possible astrophysical sources include the gamma-ray bursts (GRBs), microquasars, supernovae, and active galactic nuclei (AGNs). The expectation for the neutrino flavor ratio at the source is 1: 2: 0 ($\nu_e : \nu_\mu : \nu_\tau$). The flavor ratio of astrophysical neutrinos measured by ground-based detectors is modified due to neutrino oscillations averaged over astronomical distances. In particular, tau neutrinos should appear in the astrophysical neutrino flux and be detectable at Earth. Thus, tau neutrino searches are crucial to better determine the flavor composition. Methods to identify high-energy tau neutrino interactions in IceCube, a cubic-kilometer neutrino detector deployed in the glacial ice at the geographical South Pole, are described. An algorithm is presented for detecting a double pulse signature in the IceCube sensor signal, which can be an indication of the tau neutrino interaction and subsequent decay of the tau lepton inside the detector. Recent results for astrophysical tau neutrinos with three years of IceCube data is shown. Future prospects for tau neutrino detection in IceCube are discussed.

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1. Introduction

Recently, the IceCube collaboration announced the discovery of a high-energy diffuse flux of astrophysical neutrinos [1, 2]. The flavor composition of the detected flux is consistent with equal fractions of all neutrino flavors [3, 4]. The identification of a high-energy tau neutrino would be an additional evidence confirming this result. The source of this flux is as yet unknown. Candidate neutrino sources include active galactic nuclei, gamma-ray bursts, microquasars, and supernova remnants [5, 6]. Tau neutrinos are not produced in standard cosmic-ray atmospheric interactions and are expected at negligible levels in the prompt atmospheric neutrino flux [7]. In addition, oscillations of atmospheric ν_e and ν_μ into ν_τ are very limited at TeV and PeV energies and a travel distance comparable to the Earth diameter. In contrast, high energy ν_e and ν_μ neutrinos of astrophysical origin can oscillate over cosmic distances to produce a measurable number of ν_τ s at the detector. Assuming standard 3-flavor oscillations and $1 : 2 : 0$ ($\nu_e : \nu_\mu : \nu_\tau$) flux at the source, it is expected that flavor ratio at the detector will be close to $1 : 1 : 1$ [8]. Therefore, the identification of astrophysical ν_τ would be an independent confirmation of observed TeV-PeV energy astrophysical neutrino flux and it would be an important contribution to a measurement of the flavor composition.

2. IceCube Detector

IceCube is the world's largest neutrino detector, located near the geographic South Pole, instrumenting more than a cubic-kilometer of glacial ice. The detector consists of 86 cables ("strings"), each instrumented with 60 Digital Optical Modules (DOMs) deployed between depths of 1450 m and 2450 m. [9] The DOM consists of a 10-inch photomultiplier tube (PMT), calibration light sources, and digitizing electronics. [10]. The digitized PMT signal is called a waveform.

3. Detection Principle

Neutrinos are detected in IceCube by observing the Cherenkov light produced by charged particles created when neutrinos interact in the ice. The neutrino interaction events can be generally classified into three different groups, based on the characteristic patterns of the Cherenkov light that provides information about the energy, direction, and flavor of the parent neutrino.

- Track-like events (see Fig. 1, left panel) have a good angular resolution (typically $< 1^\circ$) but limited energy resolution when not fully contained in the detector volume. These events are produced mainly from the ν_μ CC interactions.
- Cascade-like events (see Fig. 1, middle panel) have a good energy resolution ($\sim 10\%$ at high energies) but limited angular resolution (typically $> 10^\circ$). They are described by a distinct spherical topology in the detector volume. This pattern results from ν_e, ν_μ, ν_τ NC and ν_e, ν_τ CC interactions.
- Composite events (see Fig. 1, right panel) are a mixture of track-like and cascade-like events or multiple cascade events. This pattern has been produced by ν_μ CC interactions and is expected for ν_τ CC interactions (not yet observed).

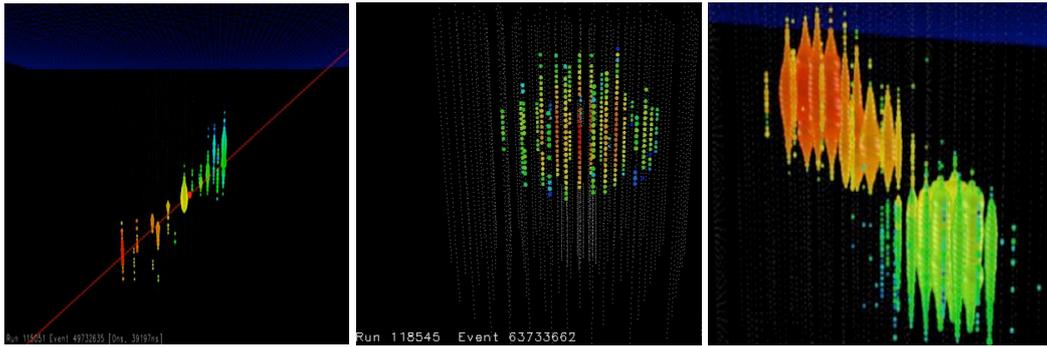


Figure 1: Neutrino interaction event topologies in IceCube: track-like event topology (left), cascade-like event topology (middle), and composite event topology (right). The size of the individual DOMs indicates the relative measured number of photoelectrons while the color represents the photon arrival times with red being early and blue late.

4. Methods to Identify High-Energy Tau Neutrino Interactions

Due to a large number of tau lepton decay modes and its long decay length at ultrahigh (TeV and PeV) energies, ν_τ interactions have a rich set of possible signatures in the IceCube detector. The tau decay length is about 50 m per PeV. Tau leptons with decay lengths less than 1 km can be fully contained in the detector volume. Therefore, we can classify ν_τ events into several categories based on the information about tau production and decay vertices:

- **Double Bang:** when ν_τ interaction occurs inside the detector (visible hadronic shower) and tau decays in the modes producing a second cascade ($\tau \rightarrow e\nu_e\nu_\tau$ and $\tau \rightarrow \text{hadrons } \nu_\tau$, total branching ratio (BR) $\approx 82\%$) inside the detector [8]. The tau lepton connecting the two showers will also emit Cherenkov light.
- **Double Pulse:** when two showers of a Double Bang event cannot be resolved as two separated cascades, there is an energy region where one or more DOMs near the showers will see double pulse waveforms.
- **Partially contained Double Bang:** two types of events contribute to this category:
 - tau lepton from ν_τ interaction is produced outside the detector and the initial hadronic shower is not visible but the tau enters the fiducial volume and decays to produce a shower (BR $\approx 82\%$).
 - tau lepton from ν_τ interaction is produced inside the detector and then decays undetectably outside the fiducial volume (no BR factor).
- **muonic tau decay:** a tau from the ν_τ interaction decays in the muonic tau decay channel (BR $\approx 18\%$). One can distinguish two types of events in this class:
 - tau lepton from ν_τ interaction is produced outside the detector but it decays in muonic channel inside the detector.

- tau from the ν_τ interaction is produced and decays in the muonic tau decay channel inside the detector.

5. Double Pulse Analysis

The goal of double pulse analysis is to use individual DOMs to detect double bangs which are not well resolved into separate cascades [11]. Such events may produce a double pulse waveform in the DOMs. An example of simulated double pulse waveform is shown in Fig. 2. The same signature can be mimic by several types of background events:

- high-energy atmospheric muons or muon bundles passing through the detector
- ν_μ CC interactions with succeeding energetic muons
- scattered photons from single cascade events from ν_e , ν_μ , ν_τ NC and ν_e CC interactions that arrive late.

The double pulse algorithm to determine rising and trailing edges has been developed based on the first derivatives of a waveform. This search uses 914.1 days of data from the completed IceCube detector between May 13, 2011 and May 6, 2014. Event selection criteria, carried out at three cut levels (see [11] for more information), were developed using simulation and 10% of the data. The initial event selection was based on the Extremely High Energy (EHE) filter to select only high energy ν_τ interactions where double pulses signature can be resolved. An additional charge cut on the number of observed photoelectrons ($\log_{10}(\text{QTot}) > 3.3$) was applied and waveforms were examined for double pulse characteristics (level 4). At the next level (level 5), track-like double pulse events, that are predominantly due to atmospheric muons, were removed using a cut on the reduced log likelihood ratio between a hypothesis of an infinite track and a hypothesis of a point-like cascade. This cut has eliminated most down-going energetic muons and muon bundles. To further reduce down going muons, the first hit in the event was required to be below the top 40 meters of the instrumented volume. At the end (level 6) a containment cut was applied to eliminate cosmic ray induced muons which pass near the edges of the detector and appear as cascade-like events. Figure 2 (left) summarizes the passing rate of signal and background events at each cut level. Table 1 shows predicted event rates from all sources at the final cut level. No candidate

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

Table 1: Predicted event rates from all sources at the final cut level. Errors are statistical only. The assumed astrophysical flux is $E^2\Phi_\nu = 1.0 * 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$

events were observed in three years of IceCube data. An integrated astrophysical ν_τ flux upper limit of $5.1 * 10^{-8} \text{ GeV cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$ was derived assuming an astrophysical neutrino spectrum

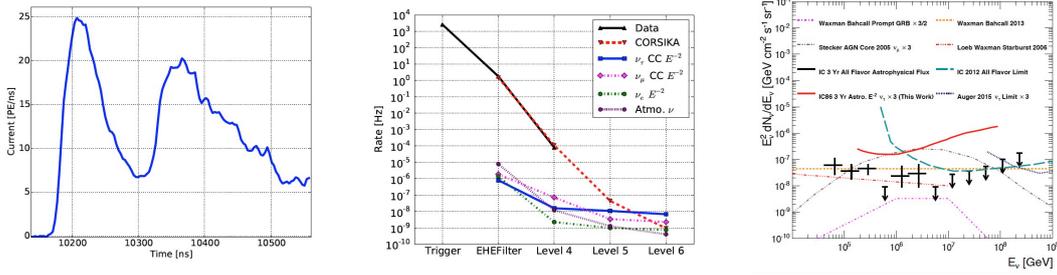


Figure 2: A simulated double pulse waveform obtained in one DOM from a ν_τ CC event (left). Passing rate for signal and backgrounds (middle). Neutrino flux upper limits and models as a function of the primary neutrino energy (right). The red curve is the differential upper limit derived from double pulse analysis (statistical and systematic errors are shown). The black error bars correspond to all flavor astrophysical neutrino flux observed by IceCube. [2].

with a spectral index of -2 . The differential upper limit on ν_τ flux in the energy region of 214 TeV to 72 PeV was also obtained (see Fig. 2 (right)).

6. Double Bang Analysis

The double bang analysis looks for well separated double bangs [12]. The event selection starts with the EHE filter to select only high energy ν_τ interactions. Fig. 3 presents the effective areas after the initial EHE cut for a few ν_τ double bang event samples with different minimum separations between the two cascades. The energy threshold for the ν_τ double bang identification

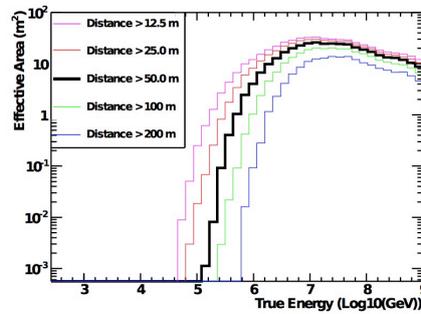


Figure 3: Effective areas after the initial EHE filter cut for ν_τ obtained by selecting contained double bang events with different minimum separations between the two cascades. No reconstruction errors are included.

increases with distance between the two cascades. At the next cut level (level 4), a stronger cut on the number of observed photoelectrons is applied (total charge deposited in the event > 3100 PE). Then a Boosted Decision Tree (BDT) is used to further suppress background (level 5). The BDT was trained using well contained simulated ν_τ double bang events, with a minimum separation between cascades of 50 m, as a signal and simulated cosmic ray muons as a background. At the next level (level 6), a detailed reconstruction based on the assumptions of double bang topology

was performed. To clean up the sample, several additional selection criteria were applied: The likelihood values obtained from the reconstruction cannot be too small, both cascades need to be reconstructed in or near the detector, the reconstructed separation between cascades cannot be smaller than 20 m, and the reconstructed energy asymmetry of cascades ($[E_1 - E_2]/[E_1 + E_2]$, where E_1 and E_2 are energies of the first and second cascade, respectively) has to be between -0.999 and 0.9. The preliminary event rates of the signal and different backgrounds at the final level are shown in Table 2. The biggest remaining background comes from atmospheric muons. Work

Data samples	Events in 1 year (final cut)
Double Bang	$(4.93 \pm 0.04) * 10^{-1}$
Atmospheric muons	(9.5 ± 1.8)
Astrophysical ν_e	$(8.2 \pm 0.3) * 10^{-1}$
Astrophysical ν_μ	$(8.9 \pm 0.2) * 10^{-1}$
Atmospheric ν_e	$(4.4 \pm 0.2) * 10^{-2}$
Atmospheric ν_μ	$(9.3 \pm 0.2) * 10^{-2}$

Table 2: Preliminary remaining event rates of signal and background contributions at the final level of double bang analysis.

is underway to further reduce this background.

7. Future Prospects

The proposed future extension, IceCube-Gen2 detector [13], will have a factor of 5 to 10 times better sensitivity to astrophysical tau neutrinos than the current IceCube detector. With these large data samples and improvements in the reconstruction and background rejection techniques, described searches can lead to the detection of astrophysical tau neutrinos.

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