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# A Search for Astrophysical Tau Neutrinos in Three Years of IceCube Data

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The IceCube Neutrino Observatory has reported a diffuse flux of TeV-PeV astrophysical neutrinos in three years of data. The observation of tau neutrinos in the astrophysical neutrino signal is of great interest in determining the nature of astrophysical neutrino oscillations. Tau neutrinos become distinguishable from other flavors in IceCube at energies above a few hundred TeV, when the particle shower from the initial charged current interaction can be separated from the cascade from the tau decay: the two cascades are called a "double bang" signature. An analysis is presented which uses the digitized signal from individual IceCube sensors to resolve the two showers, in order to be sensitive to taus at as low an energy as possible. This is the first IceCube search to be more sensitive to tau neutrinos than to any other flavor. No candidate events were observed in three years of completed IceCube data. The resulting limit and prospects for future high energy tau neutrino searches, including a search for higher energy double bangs, will be discussed.

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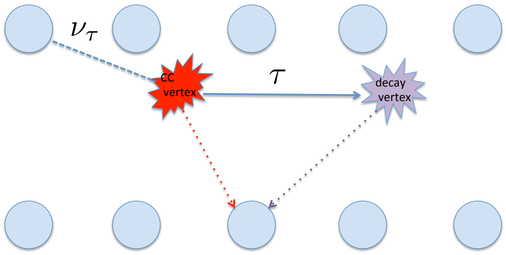

**Figure 1:** $\nu_\tau$ double bang event topology

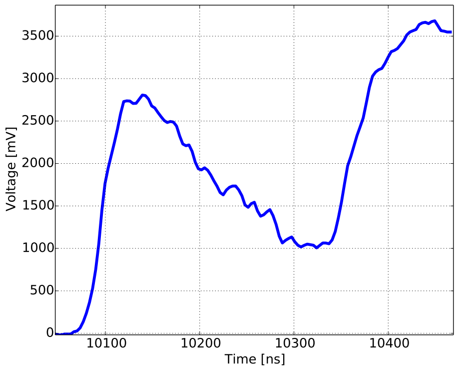

**Figure 2:** Simulated double pulse waveform from a $\nu_\tau$ CC interaction.

## 1. Introduction

The IceCube Neutrino Observatory recently announced a significant detection of diffuse high energy astrophysical neutrinos [1]. The flavor composition of the flux detected by IceCube is consistent with equal fractions of all neutrino flavors [2]. Of particular interest is the identification of tau neutrinos, which are only expected to be produced in negligible amounts in astrophysical accelerators, but should appear in the flux detected by IceCube due to neutrino flavor change. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole between depths of 1450 m and 2450 m [3]. Detector construction started in 2005 and finished in 2010. The reconstruction of neutrino properties relies on the optical detection of Cherenkov radiation emitted by secondary particles produced in neutrino interactions in the surrounding ice or the nearby bedrock. The basic IceCube sensor is the Digital Optical Module (DOM), which contains a photomultiplier tube (PMT) and electronics which digitize the PMT waveform.

Events in IceCube generally have one of two overall topologies: “track” events from $\nu_\mu$ charged current (CC) interactions, as well as from muons produced in cosmic ray induced air showers; and “cascade” events from $\nu_e$ CC interactions and neutral current (NC) interactions of all flavors. At energies below about 1 PeV, $\nu_\tau$ CC interactions will appear as a single cascade. At energies above about 1 PeV, the tau lepton decay length becomes large enough that IceCube can resolve the first $\nu_\tau$ CC interaction cascade from the second tau lepton decay cascade. This double cascade signature is called a double bang [4] and is shown in Figure 1. The first tau neutrino search in IceCube used the partially constructed detector (22 strings) and searched for partially contained double bangs [5]. This search was in fact more sensitive to $\nu_e$ and $\nu_\mu$ than to $\nu_\tau$. Here we present the result of a search for closely separated $\nu_\tau$ double bangs in the complete IceCube detector using individual DOM waveforms. This is the first $\nu_\tau$ search in IceCube to be more sensitive to tau neutrinos than to other neutrino flavors. We also discuss a search for well-separated contained double bangs in IceCube.

## 2. Double Pulse Event Search

This search for $\nu_\tau$ in IceCube looks for double bangs which are close enough together that the two cascades are not well resolved, but appear as a double pulse in a single IceCube DOM waveform. A simulated double pulse from a $\nu_\tau$ CC interaction in IceCube is shown in Figure 2. This search uses 914.1 days of data from the fully constructed IceCube detector between May 13, 2011 and May 6, 2014. The criteria for data selection are that all IceCube strings were collecting data, and no *in situ* calibration light sources were in use. The waveforms used are from the Analog Transient Waveform Digitizer (ATWD) which digitizes at 3.3 ns per sample for 128 samples [7]. Event selection criteria were developed using simulation and 10% of the data; the remaining 90% of data were kept blind until analysis cuts were finalized.

Since resolved double pulses will only be produced in high energy $\nu_\tau$ interactions, this analysis selects events which pass the IceCube Extremely High Energy (EHE) filter, which requires that the event deposit at least 1000 photoelectrons (PE) in the detector. Further event selection criteria are denoted as Level 4 and higher.

At Level 4, an additional charge cut is applied, requiring events to deposit at least 2000 PE in the detector. Individual DOM waveforms are then examined for double pulse characteristics. An updated implementation of the double pulse algorithm (DPA) previously described in [6] is run on each individual DOM which records a charge of at least 430 PE. This algorithm searches for a rising edge in the waveform followed by a falling edge, which defines the first pulse, followed by another rising edge which defines the second pulse. The falling edge of the second pulse is often outside of the 422 ns ATWD window and is therefore not included in the algorithm. The DPA is optimized to reject small pulses from late light due to scattering. An event is defined as a double pulse event and passes Level 4 if at least one DOM in the event passes the DPA.

The Level 5 event selection is designed to reject track-like events which pass the DPA. Such events result from muons which undergo large stochastic energy losses within a few meters of a DOM. Each event is reconstructed using a maximum likelihood method based on the hypothesis of an infinite track and the hypothesis of a point-like cascade. These reconstructions only make use of the timing information for the earliest photon arriving at the DOMs. The log likelihood ratio between the two hypotheses $\log(L_{\text{cascade}}/L_{\text{track}})$ is required to be negative, indicating the event topology is more cascade-like than track-like. Additionally, the first hit in the event is required to be below the top 40 meters of the instrumented volume.

The final event selection at Level 6 requires events to pass a containment cut in order to eliminate muons interacting near the edge of the detector. An additional reconstruction algorithm is performed on all events which pass the preceding cuts, using full charge and time information, and the reconstructed vertex of the event is required to be within the detector boundary.

The expected number of events in 914 days at the final event selection level are shown in Table 1 for both signal and background. Event rate predictions for astrophysical neutrinos assume a flux of $E^2\Phi_\nu = 1.0 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ per flavor [8]. Backgrounds include muons and neutrinos from cosmic ray induced air showers and astrophysical neutrinos of other flavors. The atmospheric neutrino rate prediction takes into account both the $\pi/K$ decay neutrinos [11] and the charmed meson decay neutrinos [12]. A knee-corrected cosmic ray spectrum is used in predicting the $\pi/K$ production in the atmosphere [13]. We expect 0.54 signal events and 0.35 background

**Table 1:** Predicted event rates from all sources at final cut level for the double pulse event search. Errors are statistical only.

| Data samples | Events in 914.1 days (final cut) |
|---|---|
| Astrophysical $\nu_\tau$ CC | $(5.4 \pm 0.1) \cdot 10^{-1}$ |
| Astrophysical $\nu_\mu$ CC | $(1.8 \pm 0.1) \cdot 10^{-1}$ |
| Astrophysical $\nu_e$ | $(6.0 \pm 1.7) \cdot 10^{-2}$ |
| Atmospheric $\nu$ | $(3.2 \pm 1.4) \cdot 10^{-2}$ |
| Atmospheric muons | $(7.5 \pm 5.8) \cdot 10^{-2}$ |

events in 914 days. The largest background is from astrophysical $\nu_\mu$ CC interactions, which can produce a high energy muon that loses energy stochastically near a DOM and causes a double pulse waveform.

After unblinding the remaining 90% of the data sample, no events are found in 914 days. The integrated astrophysical $\nu_\tau$ flux upper limit between 214 TeV and 72 PeV is found to be $5.1 \times 10^{-8}$ GeV cm$^{-2}$ sr$^{-1}$ s$^{-1}$, which about 5 times higher than the per-flavor best fit to the IceCube astrophysical flux. A $\nu_\tau$ flux differential upper limit in the energy region of 214 TeV to 72 PeV is shown in Figure 3. The differential upper limit was extracted following the procedure that was employed in deriving quasi-differential upper limits from previous EHE cosmogenic neutrino searches in IceCube [14, 15, 10]. In this procedure, flux limits were computed for each energy decade with a sliding energy window of 0.1 decade, assuming that the neutrino event spectrum evolves as $1/E$ [16]. Since zero events were found, the 90% C.L. event count limit in each energy decade is 2.4 based on the Feldman-Cousins approach [17]. The energy threshold of this limit is 1000 times lower than previous dedicated tau neutrino searches by cosmic ray air shower detectors [18].

## 3. Double Bang Event Search

Double bang events have a larger separation between the two cascades than double pulse events, and thus occur at a higher primary neutrino energy. The event selection requires events to pass the EHE filter, denoted Level 3. Figure 4 shows the effective areas after the EHE filter cut for $\nu_\tau$ obtained by selecting contained double bang events with different minimum separations between the two cascades. It can be seen that the energy threshold for the identification of $\nu_\tau$ via this signature increases with distance between the two cascades. At Level 4, an additional charge cut is applied, requiring at least 3100 PE total charge deposited in the event. At Level 5, a Boosted Decision Tree (BDT) is used for further background rejection. This BDT is trained using simulated $\nu_\tau$ CC events (with a minimum separation of 50 m and with the two cascades contained within the detector volume) as signal, and simulated cosmic ray muons as background. Six variables are used in the BDT:

- Total charge
- Duration of the event in the detector
- Average height of the first 5 hit DOMs

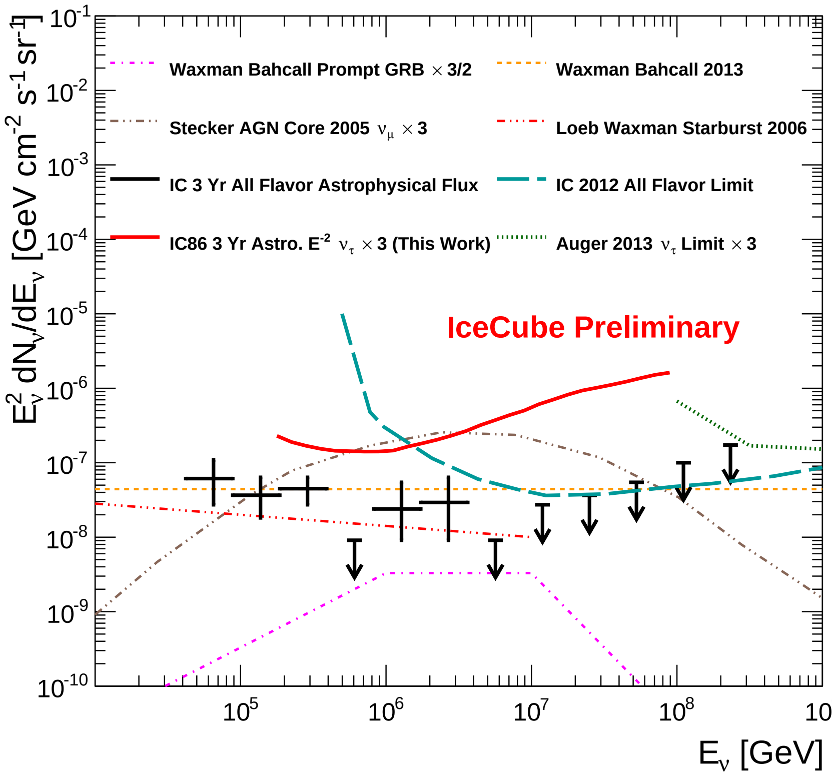

**Figure 3:** Neutrino flux upper limits and models as a function of the primary neutrino energy. The thick red curve is the $\nu_\tau$ differential upper limit derived from this analysis. The black crosses depict the all flavor astrophysical neutrino flux observed by IceCube [1]. The thick dashed line is the differential upper limit derived from a search for extremely high energy events which has found the first two PeV cascade events in IceCube [9, 10]. The thick dotted line is the Auger differential upper limit from $\nu_\tau$ induced air showers [18]. The thin dash line (orange) is the Waxman-Bahcall upper bound which uses the UHECR flux to set a bound on astrophysical neutrino production [19]. The dash-dotted line (magenta) is prompt neutrino flux predicted from GRBs; prompt in this context means in time with the gamma rays [20]. The dash-dot-dot line (grey) is neutrino flux predicted from the cores of active galaxies [21]. The thin dotted line (red) is neutrino flux predicted from starburst galaxies, which are rich in supernovae [22].

- Number of peaks in the distribution of collected charge as a function of time
- Maximum fraction of the total charge collected in a 100 ns timebin
- A variable based on the movement of the center of gravity of the event during the development of the event in the detector

For every event a BDT score is calculated based on these variables ranging from -1 (background-like) to +1 (signal-like) and only events with a sufficiently high score are retained.

At Level 6, a detailed reconstruction of the events is performed assuming a double cascade topology. Several criteria are applied to remove events which are badly reconstructed as double bangs: the maximized likelihoods cannot be too small, causality is required between the two cas-

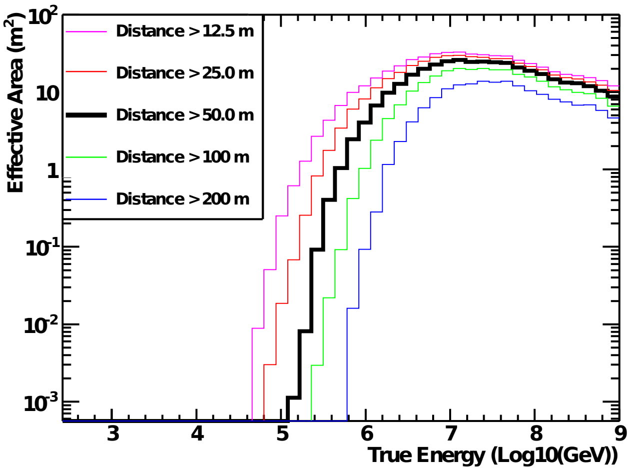

**Figure 4:** Effective areas after the EHE filter cut for $\nu_\tau$ obtained by selecting contained double bang events with different minimum separations between the two cascades. No reconstruction errors are included.

**Table 2:** Preliminary remaining event rates for signal and different backgrounds at Level 6 of the double bang search. The assumed fluxes of the signal and different background are the same as for the double dulse event search. Errors are statistical only.

| Data samples | Events in 1 year |
|---|---|
| Double Bang | $(4.93 \pm 0.04) \cdot 10^{-1}$ |
| Atmospheric muons | $(9.5 \pm 1.8)$ |
| Astrophysical $\nu_e$ | $(8.2 \pm 0.3) \cdot 10^{-1}$ |
| Astrophysical $\nu_\mu$ | $(8.9 \pm 0.2) \cdot 10^{-1}$ |
| Atmospheric $\nu_e$ | $(4.4 \pm 0.2) \cdot 10^{-2}$ |
| Atmospheric $\nu_\mu$ | $(9.3 \pm 0.2) \cdot 10^{-2}$ |

cades, both cascades need to be reconstructed in or near the detector and not too close together (minimum 20 m apart) and the energy asymmetry ($[\mathrm{E}_1 - \mathrm{E}_2] / [\mathrm{E}_1 + \mathrm{E}_2]$, with $\mathrm{E}_1$ and $\mathrm{E}_2$ the energies of the first and second cascade) has to be between -0.999 and 0.9. The median resolution (depending on the energy) of the reconstructed parameters of the remaining signal events at the end of this reconstruction chain is about 3-6% for the distance between the two cascades, 1-4° for the direction and 10-20% for the energy of each cascade.

The remaining event rates of the signal and different backgrounds are shown in Figure 5 and Table 2. The atmospheric neutrino background has been reduced to about an order of magnitude below the signal rate. The astrophysical fluxes of $\nu_e$ and $\nu_\mu$ are of the same order and slightly higher than the signal but the biggest remaining background is still the atmospheric muons. Work is underway to further reduce these backgrounds.

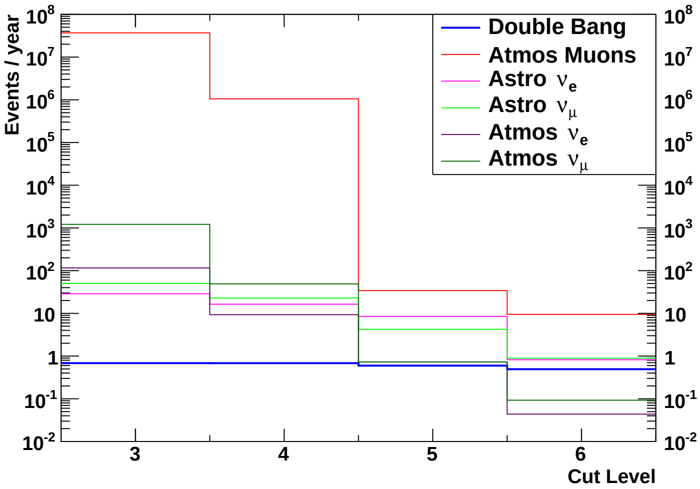

**Figure 5:** Preliminary remaining event rates for signal and different background at every cut level. The assumed fluxes of the signal and different background are the same as for the Double Pulse event search.

## 4. Conclusions

The double pulse search for $\nu_\tau$ in IceCube is more sensitive to tau neutrinos in the $O(100)$ TeV to $O(10)$ PeV energy range than to any other flavor. Given the astrophysical neutrino flux observed by IceCube, fewer than one double pulse tau neutrino event is expected in three years of IceCube data, and none are observed. Searches for well separated double bangs are in progress. Future extensions of IceCube such as the proposed IceCube-Gen2 detector [23] will have a factor of 5 to 10 times more sensitivity to astrophysical tau neutrinos than the current IceCube detector.

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