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

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34th International Cosmic Ray Conference, 2015
The Hague
Neutrino Signals in IceCube

Tracks: $\nu_{\mu}$ CC interactions

Cascades: NC and $\nu_{e}$ CC

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Neutrino Signals in IceCube

Tracks: $\nu_\mu$ CC interactions
$\nu_\tau$ CC interactions (17%)

Cascades: NC and $\nu_e$ CC
$\nu_\tau$ CC (below ~PeV)
A tau neutrino of energy greater than \( \sim 100 \text{ TeV} \) may produce a tau with sufficient decay length to produce two well separated cascades in IceCube.
Tau Signatures in IceCube


This talk

BR=82%, 2π, <σ_Eμ, ~1.0°
BR=100%, 2π, <σ_Eμ, ~1.0°, Bkgd=↓μ
BR=18%, 2π, <σ_Eμ, ~1.0°

BR=82%, 2π, <σ_Eμ, ~1.0°, Bkgd=↓μ
BR=82%, 4π, ~σ_E(v_e), ~σ_μ(v_e)
BR=18%, 4π, <σ_Eμ, ~1.0°, Bkgd=ν_μ

log(E_τ) eV

5cm 50cm 5m 50m 500m 5km 50km

Tau Decay Length

zero or low background
might have background
definitely has background
The Double Pulse Signature

The IceCube Digital Optical Module (DOM) digitizes the waveform of a 10” PMT

A double bang where the cascades are not well resolved may appear as a double pulse waveform

Rising and trailing edges identified using 1st time derivatives (D. Xu, D. Williams, P. Zarzhitsky ICRC 2013)
Event Selection

- Backgrounds are mainly double pulses due to stochastic losses from muons very close to DOMs
- Cuts are designed to remove low energy events, single cascades, and muons
  - Use IceCube Extremely High Energy (EHE) filter: require at least 1000 PE per event
  - Level 4: Increase charge cut to 2000 PE per event, and require at least one double pulse waveform
  - Level 5: Require event to reconstruct as more cascade-like than track-like
  - Level 6: Containment cut
Predicted event rates

\[ \text{Astrophysical } \nu_\tau \text{ CC } (5.4 \pm 0.1) \times 10^{-1} \]
\[ \text{Astrophysical } \nu_\mu \text{ CC } (1.8 \pm 0.1) \times 10^{-1} \]
\[ \text{Astrophysical } \nu_e \text{ (6.0 \pm 1.7) } \times 10^{-2} \]
\[ \text{Atmospheric } \nu \text{ (3.2 \pm 1.4) } \times 10^{-2} \]

First IceCube search to be more sensitive to tau neutrinos than to any other flavor

90% of signal events are between 0.21 and 72 PeV

\[ \text{Astrophysical per flavor flux } E^2 \phi_\nu = 1.0 \times 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \]
Double Pulse Search Results

No candidate events found in 914 days of data
\( \nu_\tau \) flux limit is \( 5.1 \times 10^{-8} \text{ GeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \) between 0.21 and 72 PeV

IceCube Preliminary

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A search for well separated double bangs
At least 50 m between cascades, corresponding to energies > 1PeV
Energy threshold increases with distance between cascades
Event Selection

- Level 4: Charge cut of 3100 PE per event
- Level 5: BDT trained on simulated contained $\nu_\tau$ CC events with at least 50 m tau decay length
  - Total charge
  - Duration of event in detector
  - Average depth of 1st 5 hit DOMs
  - Number of peaks in distribution of collected charge as a function of time
  - Movement of the center of gravity of the event as it develops in the detector
Event Selection

- Level 6: Likelihood reconstruction with double cascade hypothesis
  - Cascades at least 20 m apart
  - Cascades causally connected
  - Limit on energy asymmetry between cascades

\[-0.999 < \frac{E_1 - E_2}{E_1 + E_2} < 0.9\]
Double Bang Event Rates

Data sample | Events in 1 year
---|---
Astro. $\nu_\tau$ CC | $(4.93 \pm 0.01) \cdot 10^{-1}$
Atmo. muons | $(9.5 \pm 1.8)$
Astro. $\nu_e$ | $(8.2 \pm 1.3) \cdot 10^{-1}$
Astro. $\nu_\mu$ | $(8.9 \pm 0.2) \cdot 10^{-1}$
Atmo. $\nu_e$ | $(4.4 \pm 0.2) \cdot 10^{-2}$
Atmo. $\nu_\mu$ | $(9.3 \pm 0.2) \cdot 10^{-2}$

Still background dominated: further studies underway to reduce background in the double bang search
Conclusions

- Double pulse search in IceCube is more sensitive to PeV tau neutrinos than to any other flavor
- Fewer than one double pulse tau neutrino event expected in three years of IceCube data
- No double pulse tau candidate events observed
- Searches for well separated double bangs in progress
- Proposed IceCube-Gen2 detector will have a factor of 5 to 10 times more sensitivity to astrophysical tau neutrinos
Three events passed Level 5 of the double pulse search but failed containment cut: all consistent with atmospheric muons passing near the corner of the detector, double pulses are due to stochastic losses from the muon