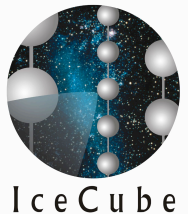

A Search for Astrophysical Tau Neutrinos in Three Years of IceCube Data

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For the IceCube Collaboration

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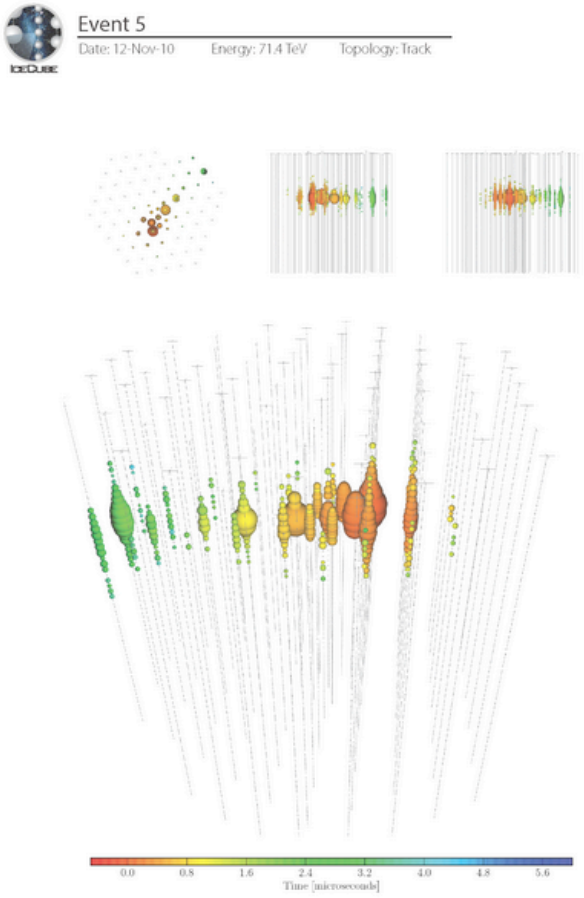
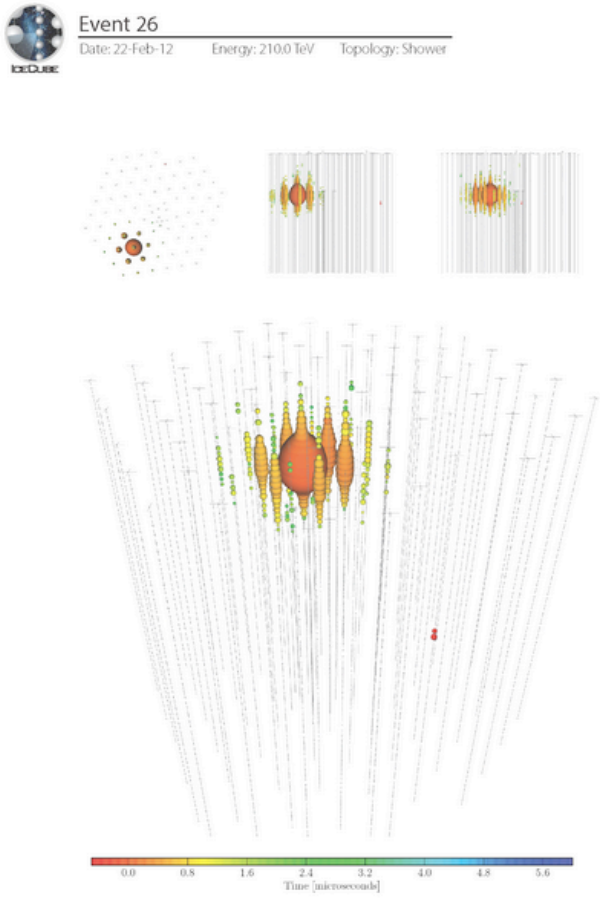
The Hague

Neutrino Signals in IceCube

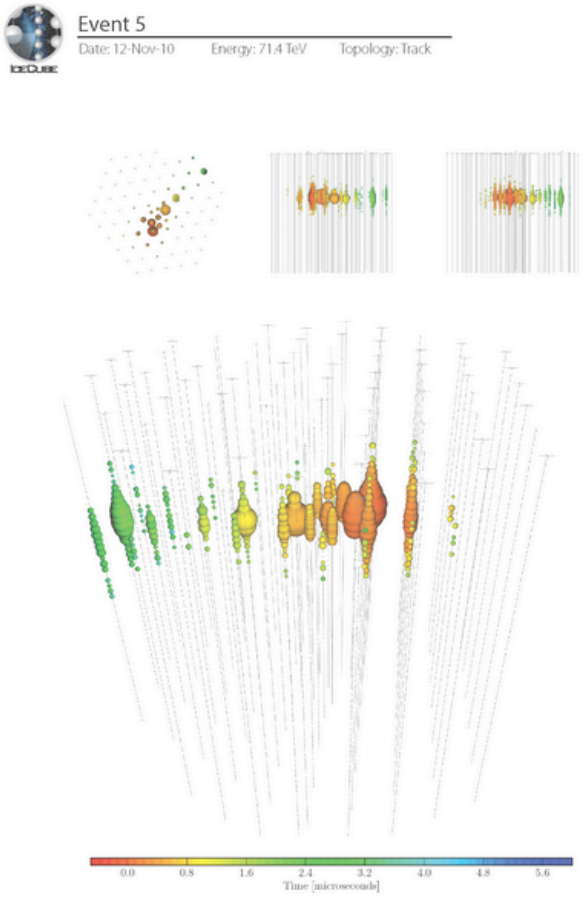


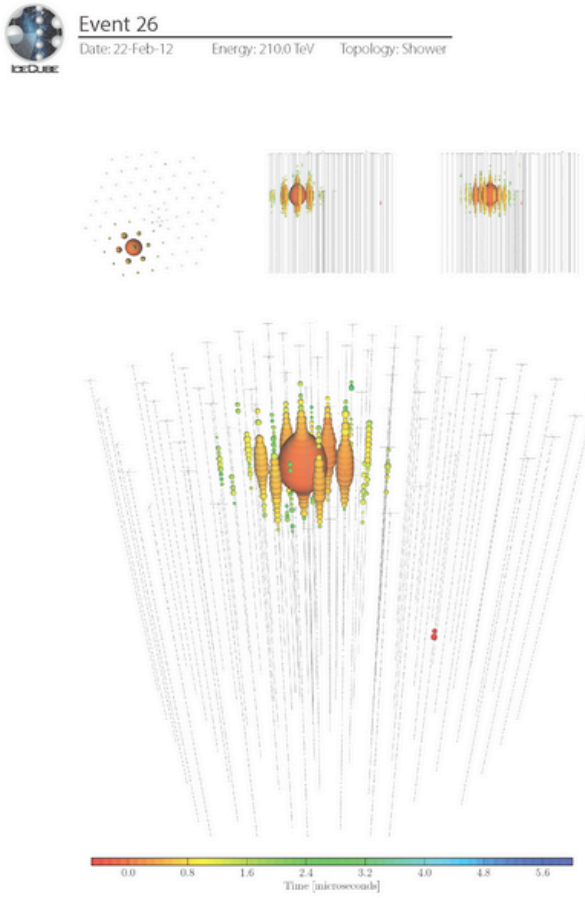


Tracks: ν_μ CC interactions

Cascades: NC and ν_e CC

Neutrino Signals in IceCube





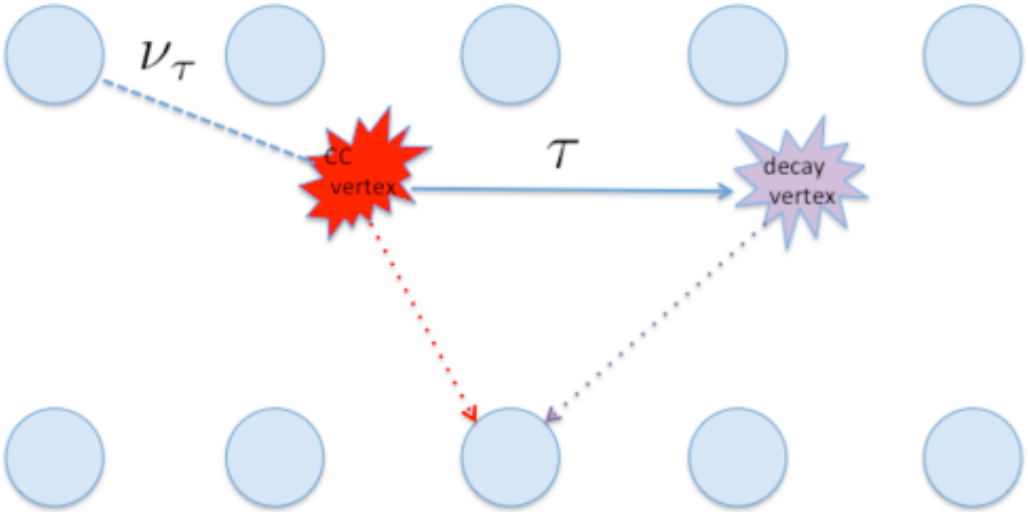
Tracks: ν_μ CC interactions

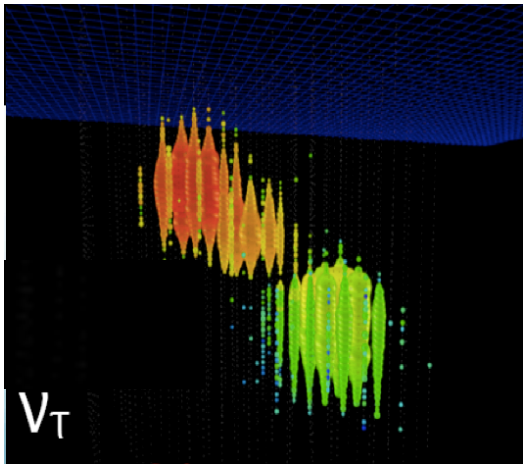
ν_τ CC interactions (17%)

Cascades: NC and ν_e CC

ν_τ CC (below ~PeV)

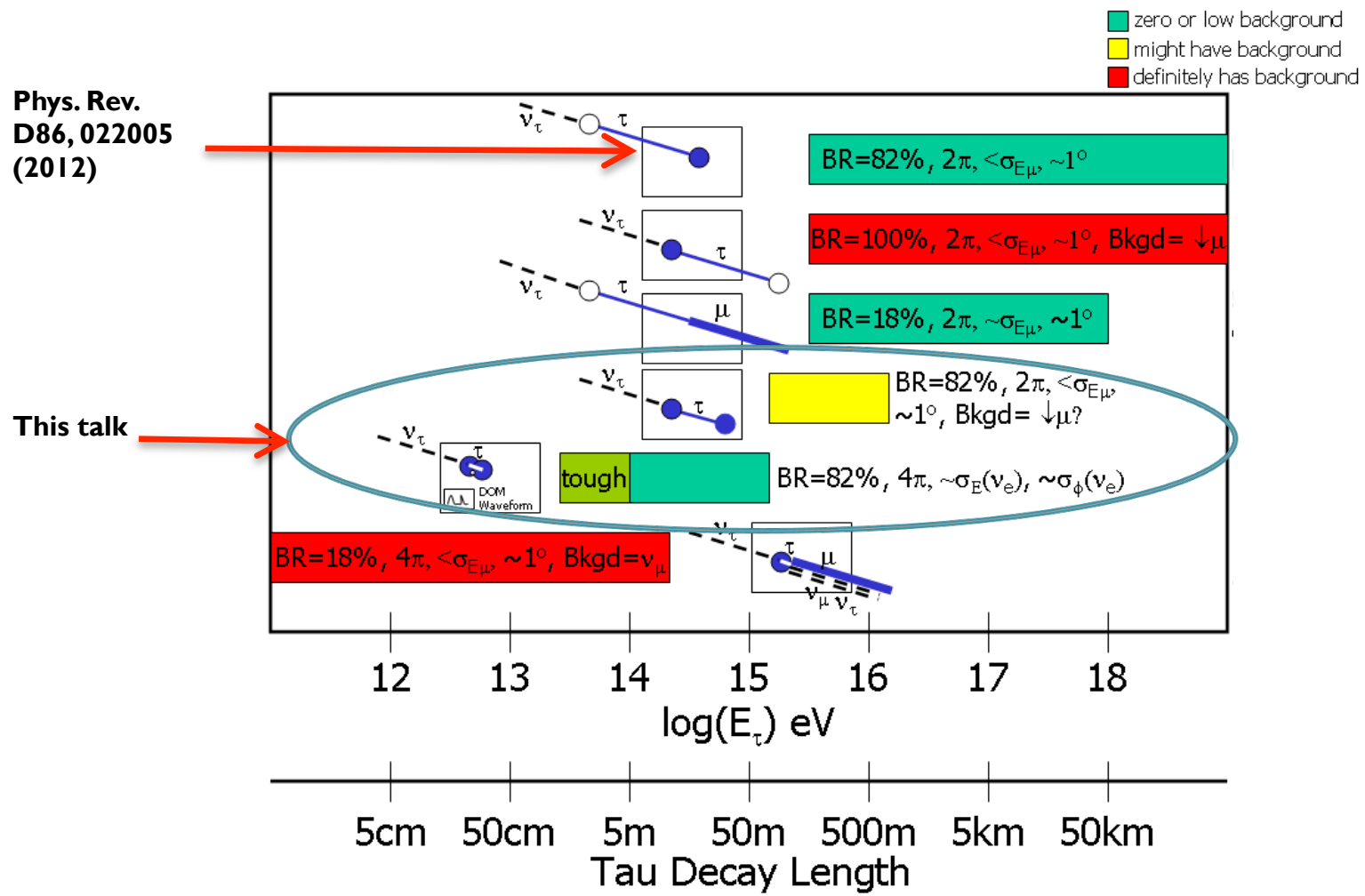
Tau Double Bang Signature



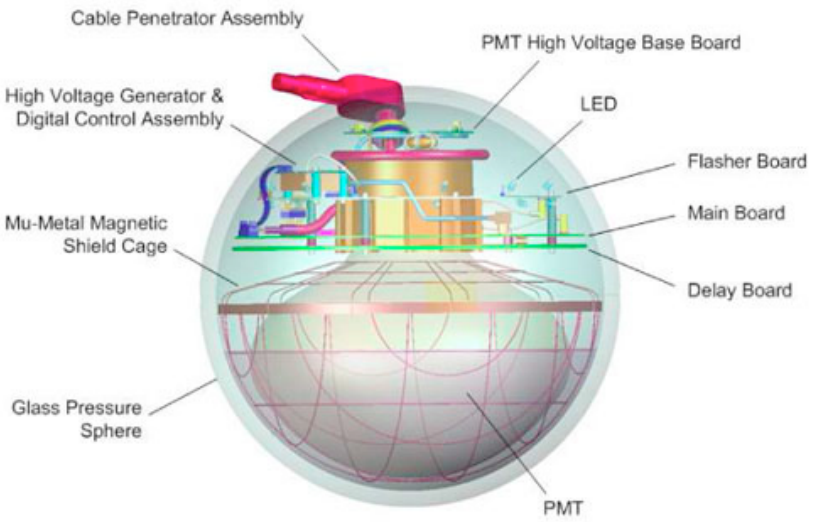


A tau neutrino of energy greater than ~100 TeV may produce a tau with sufficient decay length to produce two well separated cascades in IceCube

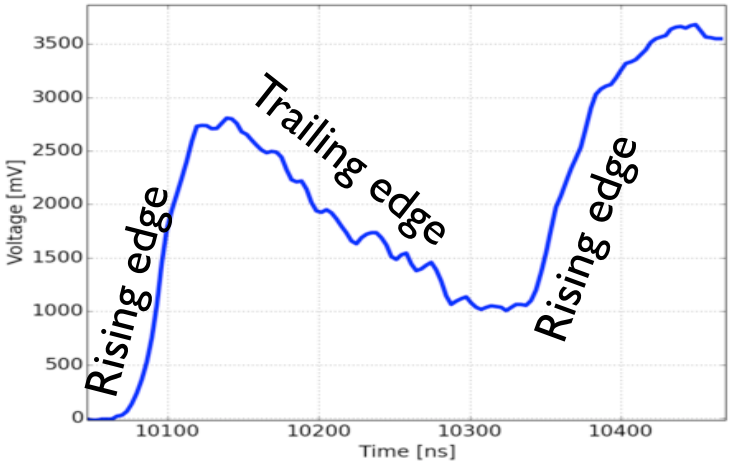
Tau Signatures in IceCube



The Double Pulse Signature



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



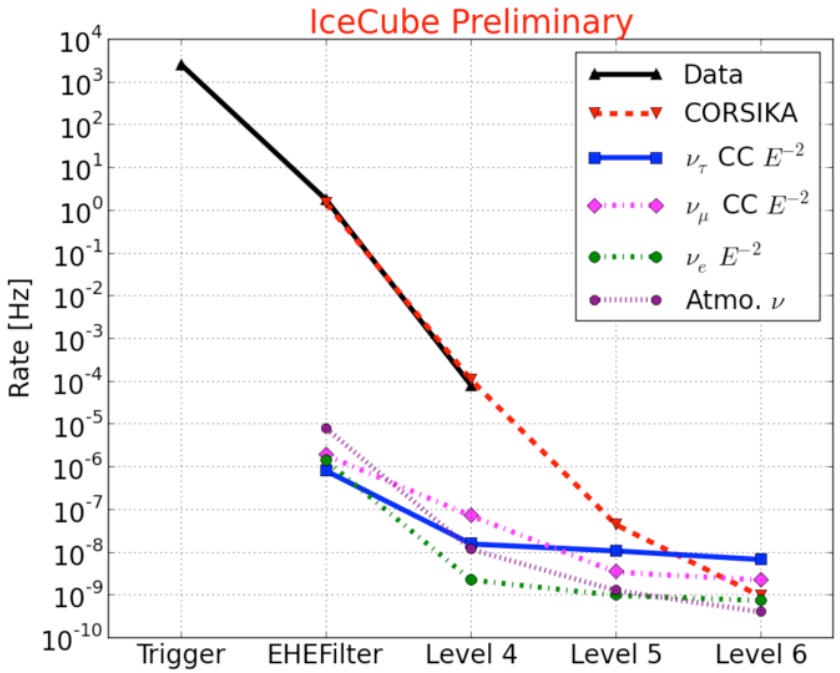
A double bang where the cascades are not well resolved may appear as a double pulse waveform

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



Data sample	Events in 914 days
Astrophysical ν_τ CC	(5.4 ± 0.1) •10^{-1}
Astrophysical ν_μ CC	(1.8 ± 0.1) •10^{-1}
Astrophysical ν_e	(6.0 ± 1.7) •10^{-2}
Atmospheric ν	(3.2 ± 1.4) •10^{-2}
Atmospheric muons	(7.2 ± 5.8) •10^{-2}

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

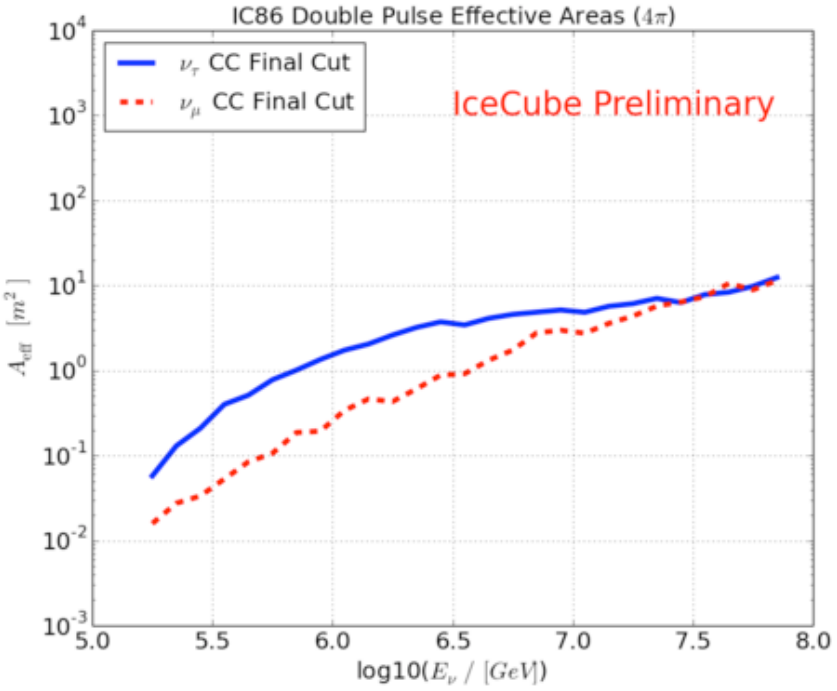
Astrophysical per flavor flux is
$E^2 \phi_\nu = 1.0 \times 10^{-8}$ GeV s^{-1} cm^{-2} sr^{-1}

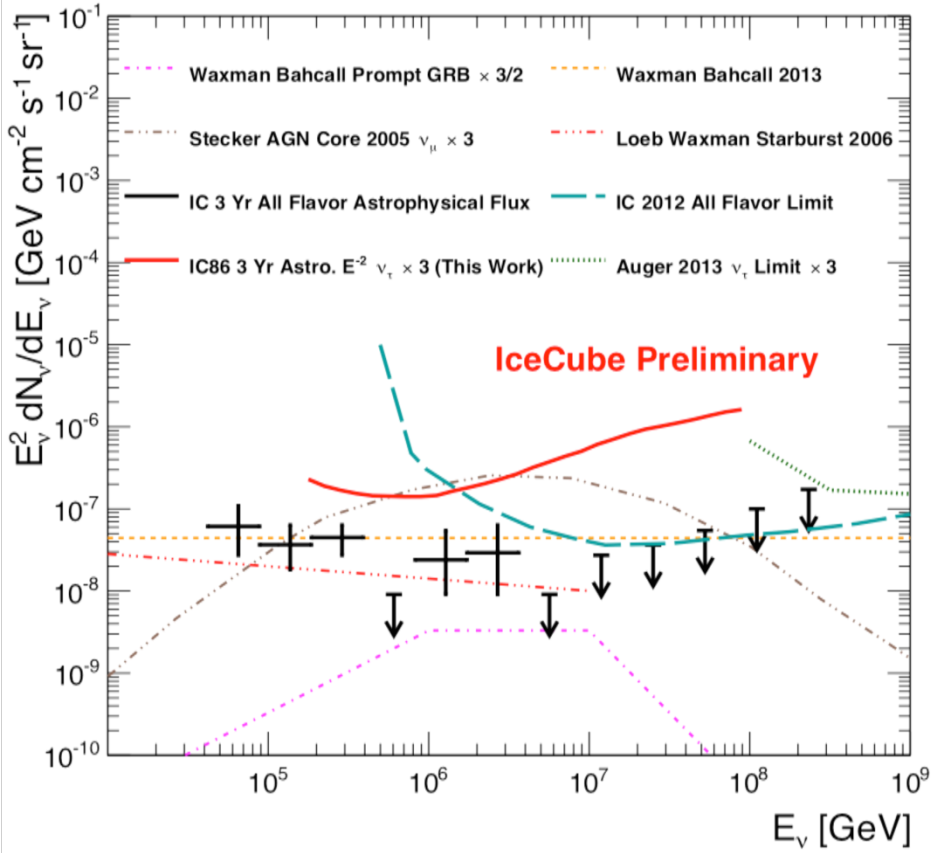
90% of signal events are between 0.21 and 72 PeV

Double Pulse Search Results

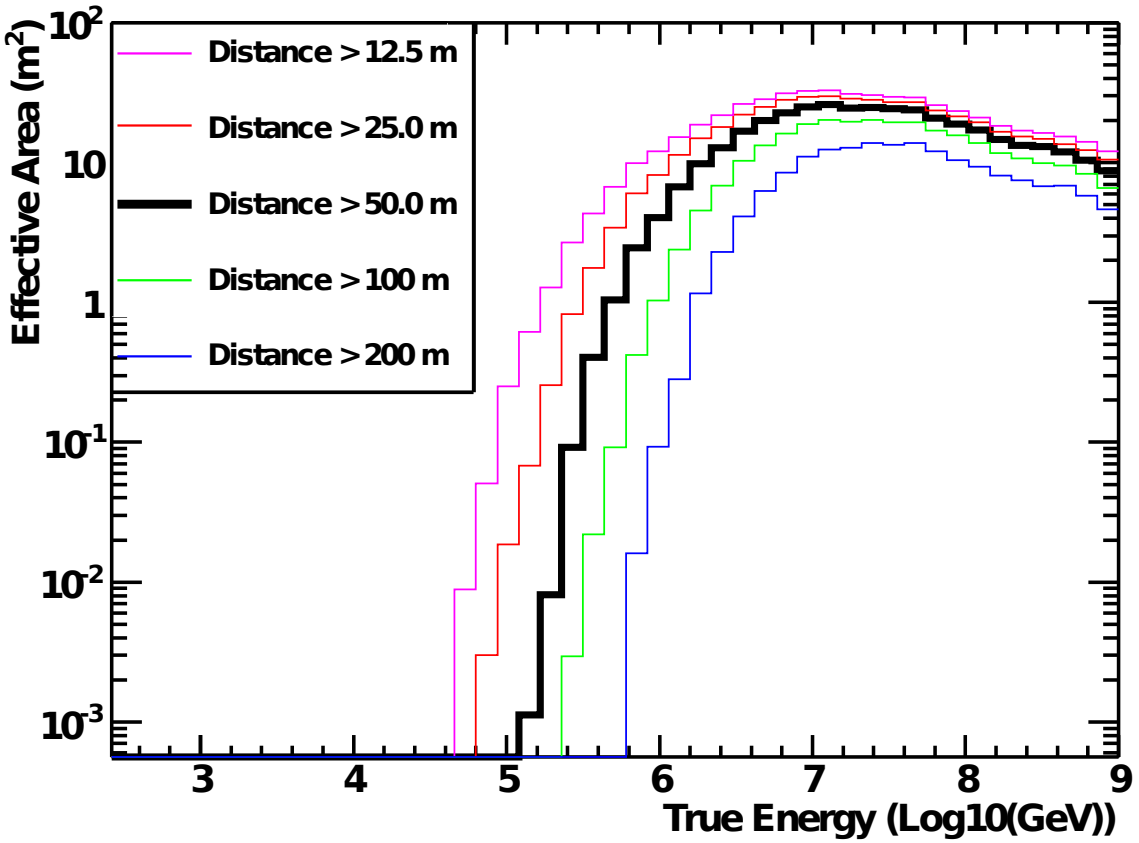
No candidate events found in 914 days of data

ν_τ flux limit is 5.1×10^{-8} GeV s^{-1} cm^{-2} sr^{-1} between 0.21 and 72 PeV





Double Bang Search



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

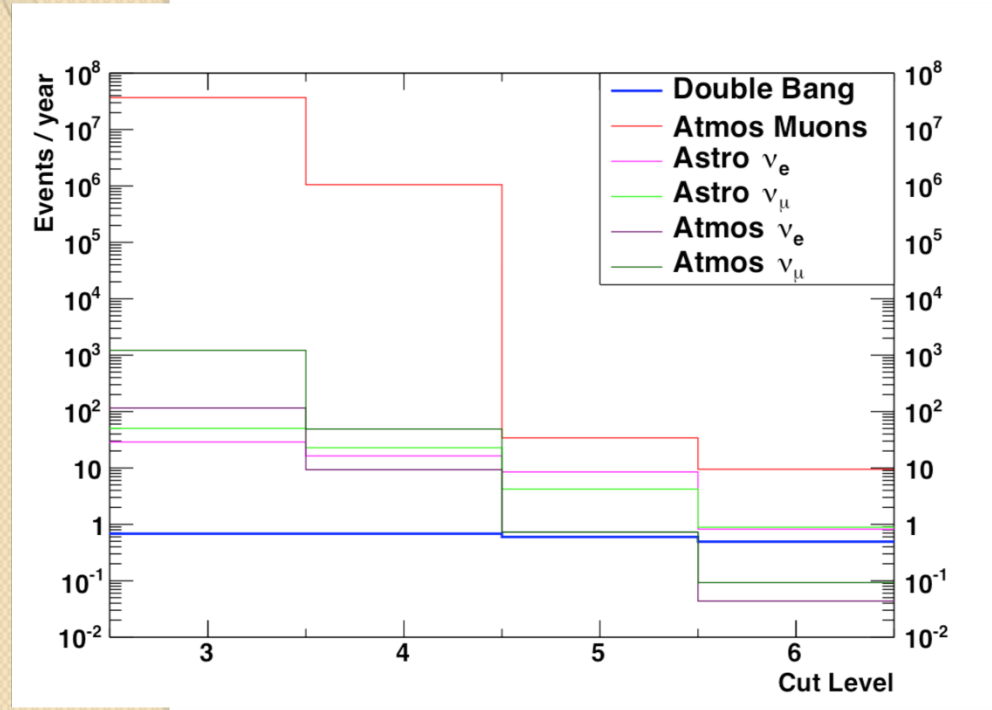
- Level 4: Charge cut of 3100 PE per event
- Level 5: BDT trained on simulated contained ν_τ CC events with at least 50 m tau decay length
  - Total charge
  - Duration of event in detector
  - Average depth of 1st 5 hit DOMs
  - Number of peaks in distribution of collected charge as a function of time
  - 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



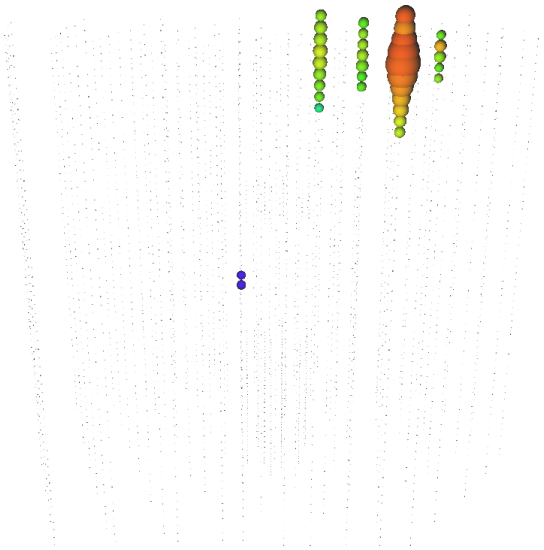
Data sample	Events in 1 year
Astro. ν_τ CC	$(4.93 \pm 0.01) \cdot 10^{-1}$
Atmo. muons	(9.5 ± 1.8)
Astro. ν_e	$(8.2 \pm 1.3) \cdot 10^{-1}$
Astro. ν_μ	$(8.9 \pm 0.2) \cdot 10^{-1}$
Atmo. ν_e	$(4.4 \pm 0.2) \cdot 10^{-2}$
Atmo. ν_μ	$(9.3 \pm 0.2) \cdot 10^{-2}$

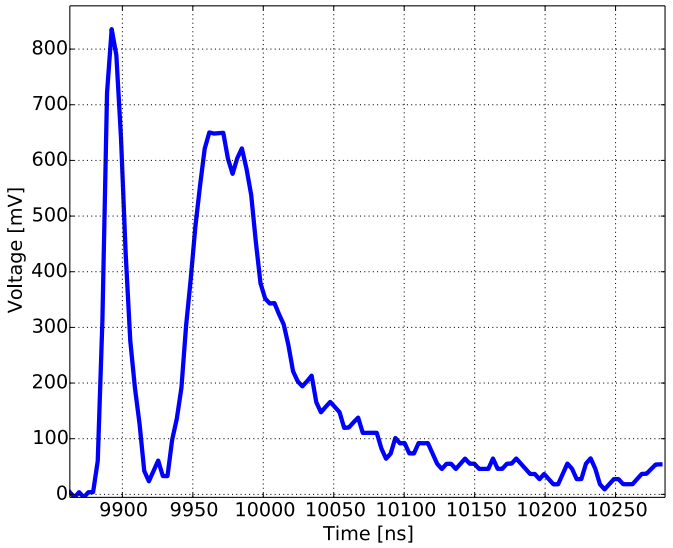
Still background dominated: further studies underway to reduce background in the double bang search

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

Backup: Level 5 Double Pulse Events





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