Selection of High Energy Tau Neutrinos in IceCube

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***Abstract*. Astrophysical neutrino sources are expected to produce electron and muon flavor neutrinos via charged pion decay. Over cosmological distances, standard neutrino oscillations will change the flavor content to include equal fluxes of all three flavors. Tau neutrinos with energies above a few PeV will produce characteristic signatures known as double-bangs and lollipops. In contrast to searches for cosmological electron and muon neutrinos, which must contend with backgrounds from atmospheric neutrinos, tau neutrinos are expected to be background-free. Thus far no searches for tau neutrino events with these characteristic signatures have been performed because their detection requires a kilometer-scale detector. In this talk, we will present current results from several methods for searching for high energy tau neutrinos in IceCube.**

***Keywords*: Tau neutrinos, Double-bangs, IceCube**

I. INTRODUCTION

One of the main research topics in neutrino telescopes such as ANTARES and IceCube is to search for neutrinos of astrophysical origin. Astrophysical particle accelerators like AGNs and GRBs may produce high energy neutrinos [1], [2]. As daughters of charged pion decay, the emerging neutrinos are expected to have the flavor flux ratio of 1:2:0 (ν_e:ν_μ:ν_τ). Due to neutrino oscillations, this neutrino flux is expected to be observed in the flavor ratio of approximately 1:1:1 on Earth. There are also models which predict different ratios of neutrino flux observed on the Earth but they all lead to non-zero flux of ν_τ [3], [4].

Here we discuss aspects of a search for high energy (greater than a few PeV) ν_τ's with the IceCube 22-string array ("IC-22"). High energy ν_τ's can leave very distinctive signatures in the IceCube detector owing to the very short life time and numerous decay channels of tau leptons. We denote these signatures "lollipops," "inverted lollipops" and "double-bangs" [5], [6]. Although high energy ν_τ's can traverse the Earth through the "regeneration" process [7], they typically emerge with energies too low to create any of the signatures under study here. The low energy (below PeV) ν_τ's can be detected in 4π in IceCube but are seen as "cascade-like" events, which is described elsewhere.

The lollipop and inverted lollipop topologies are characterized by having either the production or decay vertex of the tau lepton well outside the detector fiducial volume, respectively. In these topologies we expect to see a track due to the tau lepton and a single shower at the contained vertex. The double-bang topology as shown in Fig. 1 is characterized by having both production and decay vertices contained within the detector fiducial volume, and the tau track long enough to clearly separate the two showers from one another.

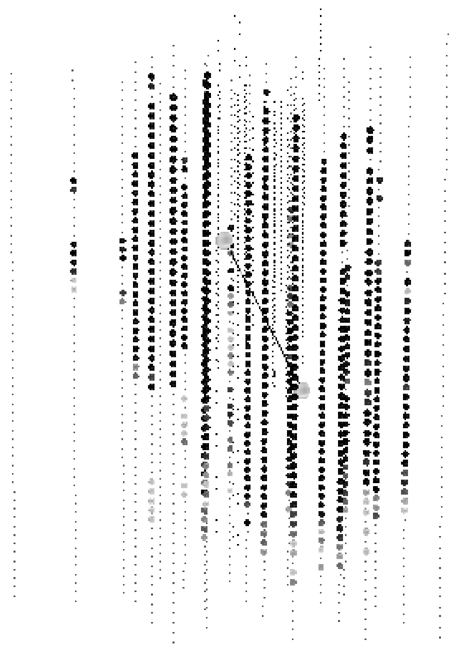

Fig. 1. A simulated double-bang event produced from a primary neutrino energy of 47 PeV that enters the IC-22 detector with 35^o zenith angle. The two showers are separated by a tau track of 332 m long. The colors (online version only) represent the relative hit times, with red for the earliest hits, blue for the latest hits, and other times in between according to the colors of the rainbow.

These astrophysical high energy ν_τ events are contaminated much less by atmospheric background from cosmic ray interactions compared to ν_μ and ν_e [8]. This is because the conventional atmospheric ν_τ flux is nearly zero, and the prompt ν_τ flux produced from charmed meson decay in the atmosphere is also expected to be very small [9], [10].

II. SIGNATURE BASED SEARCH METHOD

In IC-22, the search for high energy ν_τ does not incorporate full event reconstruction [11], but instead relies on a simpler approach that exploits the unique signatures

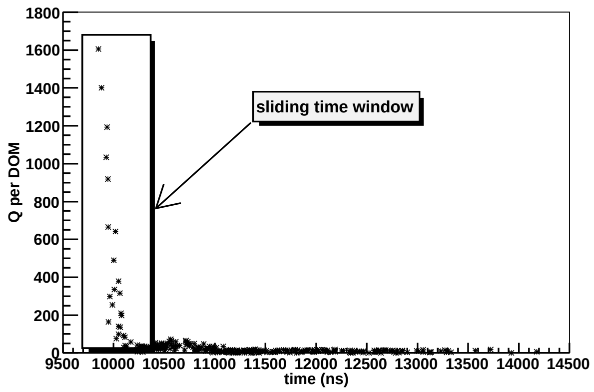

Fig. 2. Charge (number of photo-electrons) per DOM distribution as a function of light arrival time (ns) for a simulated inverted lollipop event produced from a primary neutrino energy of 64 PeV. The initial peak corresponds to a shower from ν_τ charged-current interaction, followed by a tau track.

of these events. An example of a simple criterion is given in Fig. 2 which shows the distribution of detected charge (proportional to the amount of Cherenkov light) per digital optical module (DOM) as a function of the time at which the light arrived, for a simulated inverted lollipop event.

As shown in the figure the inverted lollipop event produces a unique topology consisting of a shower followed by a track inside the detector compared to typical muons that produce simple track-like signatures with smooth light deposition along its track length. A set of simple variables based on the differences in the topologies can select (inverted-)lollipop and double-bang events while removing track-like muon backgrounds. One of the variables invented for this purpose is maximum "current ratio," $I_{\mathrm{R,max}}$. This variable is defined as a ratio of the two currents, I_{R}, themselves defined as the amount of charge per unit time, inside and outside a sliding time window, as shown in Fig. 2. When the sliding time window passes through the event's time-ordered hits, I_{R} is calculated, and its maximum value $I_{\mathrm{R,max}}$ is used as a cut variable. For signal events, $I_{\mathrm{R,max}}$ is expected to be greater than 1 but for simple track-like muon backgrounds it is expected to be closer to 1.

However, energetic muons can leave a big shower from bremsstrahlung during their passage through the fiducial volume so that these events could survive the $I_{\mathrm{R,max}}$ cut due to the similarity of the event topology. To remove these energetic muon events another variable called the "local current," I_{L}, is used. The I_{L} is defined as the current calculated in three equally-spaced time regions of an event's time-ordered hits. Of the first and last third, we choose the one with the largest IL as the selection criterion. We intentionally ignore the middle third to help reject energetic muons that have an accompanying bremsstrahlung somewhere in the middle of its track length. This variable showed good discrimination power between signal and background events.

III. Cuts and Efficiencies

So far the cuts have been developed in six distinct levels after application of a trigger and online filter. The trigger, denoted "SMT8," applies a simple majority condition of 8 hits within 5 μs to the data as it is acquired. The online filter is a logical OR of IceCube's cascade and Extremely High Energy (EHE) filters. The cascade filter is designed to select events which satisfy minimum condition of "cascade-like" events [12]. For the EHE filter, a minimum of 80 hits were required.

The level 0 and 1 (L0, L1) cuts are designed to remove track-like muon backgrounds. The L2 cuts are designed mainly to remove energetic muons accompanying bremsstrahlung in the middle of their passage. The L3 cuts are designed to remove downwards-going events, and the L4 cuts are designed to select events that look more "cascade-like" than "track-like" using different variables from those used in L0 and L1. The L5 cuts are designed to remove events which are not sufficiently contained inside the detector. Fig. 3 shows the relative efficiencies at each cut level for signal and background events.

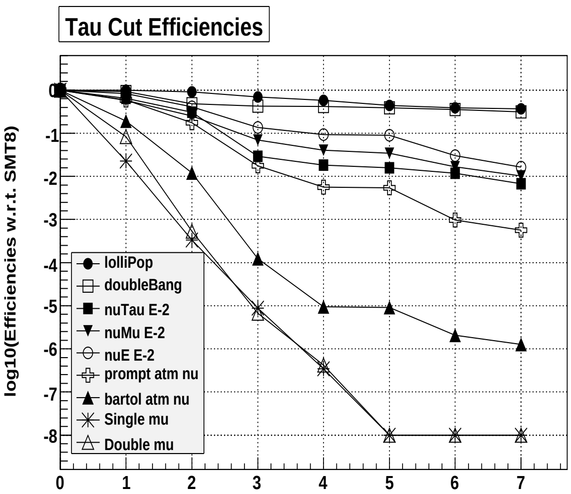

Fig. 3. High energy ν_τ selection cut efficiencies w.r.t. SMT8 for lollipop, double-bang, astrophysical ν_τ, ν_μ and ν_e, and atmospheric background events for IC-22. The numbers from 0 to 8 on the x-axis represent SMT8, the online filter, and L0, L1, L2, L3, L4 and L5 cuts, respectively.

As shown in Fig. 3, lollipop and double-bang events keep the highest efficiencies because they are specially selected from all generated ν_τ's so that they are well contained within the IC-22 detector ("golden events"). Next highest efficiency group is astrophysical neutrinos of all flavors. Note that, for the astrophysical ν_τ's, they are unbiased data samples including all generated ν_τ events unlike the "golden events". Atmospheric neutrino backgrounds, prompt and conventional, come next to astrophysical neutrinos. Atmospheric muon backgrounds, single and coincident, show the lowest efficiencies even though they run out of statistics from L3 cut which need statistical improvement in near future.

It is good that the cuts developed so far segregate well between astrophysical signal and atmospheric background events. Within astrophysical neutrinos, however, the cuts are almost equally sensitive to all flavors so that we lose the discrimination power for the specific flavor under study, ν_τ. This is due to the fact that the cuts are still quite general. To better distinguish astrophysical ν_τ from astrophysical ν_μ and ν_e, which can more easily mimic lollipop than double-bang signatures, the future direction this analysis will take is to focus exclusively on the double-bang topology.

IV. Double-bang search

Fig. 4 shows charge per DOM distribution as a function of DOM hit time for a simulated double-bang event produced from a primary neutrino energy of 50 PeV. As shown in the figure the double-bang event has two showers separated by a track (403 m long).

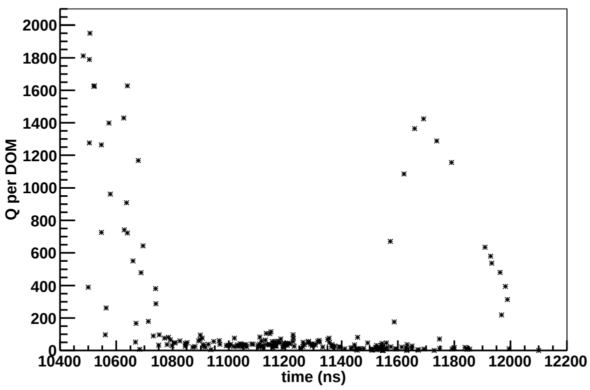

Fig. 4. Charge (number of photo-electrons) per DOM distribution as a function of DOM hit time (ns) for a simulated double-bang event. The first peak corresponds to a shower from ν_τ CC interaction and the second peak from the tau decay. Only hits arriving within 900 ns of residual time were used. (Residual time is the time difference between expected and actual photon arrival time.)

Using the local current variable described above, requiring a large $I_{\rm L}$ in both the first and last parts of the event, double-bang events can be selected. However, very energetic muons which produce two bremsstrahlungs in sequence could survive this cut. Further cuts are still being developed and evaluated.

V. Conclusion

Nature produces high energy neutrinos and they can be observed in all flavors. We try to detect especially high energy ν_τ's which can leave unique signatures inside the IceCube detector. So far our approach is rather simple but we will continue investigate the IceCube potential especially for double-bang type events.

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