Identification of Extremely-high energy starting neutrino events with the IceCube observatory

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Abstract. The IceCube neutrino observatory is capable of detecting Extremely High Energy (EHE) neutrinos with energies beyond $10^8$ GeV originated in the highest energy cosmic rays. The high energy muon bundles associated with cosmic ray air showers constitute a major background and a reliable rejection mechanism must be developed. A possible approach is to identify events induced by neutrinos inside the detector instrumentation volume. The initial simulation study is briefly reported.

1. Introduction
Extremely high energy (EHE) neutrinos are expected to play a key role in understanding the origin of EHE cosmic rays (EHECRs), because energetic neutrinos can be produced by collisions of EHECRs and the cosmic microwave background photons, a process known as GZK mechanism [1]. In the initial stage, IceCube neutrino observatory [2] has performed the search for these EHE neutrinos by looking for extremely luminous events as the signal [3, 4]. Rejection and estimation of atmospheric muon background events is central to the analysis. However, the simulation of atmospheric muon events is associated with rather incomplete knowledges of the hadronic interactions in the relevant energy range, which leads to a hard-to-reduce uncertainty in muon background identification and rejection. One way to reduce this uncertainty is by selecting the neutrino events which are induced inside the detector instrumented volume, which in principle minimizes the dependence on our knowledge about the atmospheric muon bundles.

We report here the initial study of starting\textsuperscript{1} EHE neutrino event identification with full IceCube using Monte Carlo simulation. The MC sample studied consists of isotropic muons and starting $\nu_{\mu}$ events with energies from $10^5$ GeV to $10^{11}$ GeV, following $E^{-1}$ spectrum.

2. The methods to identify neutrino-induced events
We can expect that the location of $\nu_{\mu}$-N interaction is close to the center of the IceCube detector, so are the positions of the IceCube digital optical modules (DOMs) which first records the Cherenkov photons from the neutrino induced charged lepton or hadron secondaries in the event, while the earliest hits in atmospheric muon events are always found in the outer layer in-ice detectors. Fig. 1 shows the distribution of the first hit DOM locations of the simulated events in cylindrical coordinates where $z$ is depth and $\rho$ the distance from the central axis of the array. Only the DOMs recording more than 5 photo-electrons contribute in the plot to reduce

\textsuperscript{1} Starting neutrino events are defined as the ones with the neutrino interaction vertex point within sphere of 400 m radius from the array center.
Figure 1. Distribution of the first hit DOM from cylindrical coordinates. Blue dots are muon events and red dots are starting muon-neutrino events.

Figure 2. Examples of the lateral distribution for a muon event (left) and a starting muon-neutrino event (middle). Green dots are DOMs below a threshold (0.3 photo-electron). Color histogram shows distribution of DOMs with signal. Black solid line is derived by fitting the distribution. The right triangles are shaded in black and red. Distribution of the triangle area ratio obtained by the lateral distribution is plotted in the right panel for though going muon events (blue) and the starting $\nu_\mu$ events (red). The triangle ratio cut is fixed at 0.85 (black dotted line).

The chance of mistaking the earliest hit from noise as signal. This threshold was determined by the real data generated from nitrogen laser deployed in the deep ice together with the DOMs [5]. One can see that $\mu$ and starting $\nu_\mu$ events are clearly separated.

Another approach is based on the fact that, unlike muon which emits Cherenkov photons throughout its track, trajectories of neutrinos are invisible to the optical sensors and thus a starting neutrino induced event leaves sizable number of DOMs without photon signal near the neutrino trajectories. This can be observed in the characteristic lateral distributions. Shown on the left and middle in Fig. 2 is the number of photo electrons recorded in each DOM as a function of lateral distance (LD) of the DOMs from the MC-truth trajectories of the through-going $\mu$ and $\nu_\mu$, respectively. The green band at the bottom of each distribution represents those DOMs recording less than 0.3 photo-electron. To describe the difference, we define the two right triangles shaded in black and red shown in the left panel of Fig. 2. One has the right apex at zero LD, and the other at the LD of the closest LD DOMs with no photon signal recorded. Taking the ratio of the areas of these triangles event-by-event, it is observed that neutrino induced events are more likely to give this ratio close to unity because DOMs without photon hit exist at smaller lateral distances. The area ratio distributions are shown in the right panel of Fig. 2. The plot indicates that this method identifies approximately 70% of the starting neutrino events with the area ration cut of 0.85, while rejecting 99.95% of muon events.

3. Discussion

The first hit DOM method shows high efficiency but it relies on a single DOM information and requires state-of-the-art level of understanding of the detector response. The lateral distribution method can be more reliable, but a high accuracy of the track trajectory reconstruction is necessary. Note that the present study uses the simulation truth trajectories. We also found that irreducible background to this approach is a muon decay event which very rarely occurs in EHE range. A combination of the two methods described here might provide a more reliable way to identify neutrino induced events with less dependence on detailed detector response.

References

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