Enhanced Starting Track Event Selection for Astrophysical Neutrinos in IceCube

To cite this article: Kyle Jero and IceCube Collaboration 2017 J. Phys.: Conf. Ser. 888 012107

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Enhanced Starting Track Event Selection for Astrophysical Neutrinos in IceCube

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Abstract. IceCube’s measurements of the astrophysical neutrino flux have applied veto techniques to suppress atmospheric neutrinos and muons. All the vetos thus far have used the outer regions of the detector to identify and reject penetrating muon tracks, leaving the inner parts of the detector available to observe the astrophysical neutrino flux. Here we discuss a method that is optimized for muon neutrinos which have a charged-current interaction with a contained vertex. This analysis exploits the high quality directional information of muons to determine a veto on an event by event basis. The final sample will contain astrophysical neutrinos with good purity starting around 10 TeV.

1. Introduction
For any neutrino search in IceCube, the first thing that must be done is to suppress the down-going muon background. One option is to use the Earth, which is opaque to muons, as a shield by looking for events which pass upwards in the detector. For IceCube, track-like muon events provide the pointing resolution necessary to attain such a sample. Event samples based on shielding from the Earth are sensitive to the astrophysical flux starting around 100 TeV, where the astrophysical neutrinos are more prevalent than their atmospheric counterpart [1][2]. The other option is to utilize the atmospheric self-veto [3]. When muon neutrinos are produced in air showers, a muon is also be produced; in the case of a two-body decay, the neutrino and muon energy are linked. This makes it possible to define when a muon will accompany the neutrino at the detector depth. For electron neutrinos there is a weaker link than for muon neutrinos. However, this is offset by the smaller rate of atmospheric cascade background [4]. Astrophysical neutrinos are not accompanied by partner muons. Thus, a clear signature of an astrophysical neutrino is an event which starts inside the detector and has enough energy that a similar atmospheric neutrino would be accompanied by a muon. An event selection was designed to search for starting events with a threshold around 1 TeV and is referred to hereafter as the scaling veto analysis [5]. For this a veto which increased in thickness from the edge of the detector as the neutrino energy decreased was employed. For interactions which leave a cascade signature, this veto technique is appropriate since they lack information about their direction of origin. However, for charged-current (CC) muon neutrino interactions where a neutrino passed through the detector before the conversion to a muon, the passage can be inferred by the high quality direction and position properties of track events in IceCube [6]. We describe an event selection to identify starting tracks by employing a new veto technique.
2. Veto Method
A starting track can be identified when there is no light received by Digital Optical Modules (DOMs) before the neutrino interaction and a collection of DOMs which receive light in a track pattern after the neutrino interaction. This topology is different from that of a through-going track where light is received all along the track. The veto method developed takes a reconstructed track and identifies the most likely position of earliest emission along it, based on the predicted photon signal accounting for the light propagation in ice [7]. From the inferred point the DOMs are split into two groups. Those DOMs which observed light from the event after the inferred split point and those which did not observe light before the inferred split point. This concept is illustrated in Figure 1. The DOMs which observed light are used to normalize the photon signal. This normalized signal is then used as the expectation for the Poisson probability of observing no light on each DOM before the earliest light emission point. The product of the probabilities represents the probability of the event being through-going given the absent light. For starting events this value is small while for incoming events the probability is often close to 1, or consistent with the hypothesis of a through-going track. Various reconstructions which assume a track hypothesis are available at IceCube’s base level of processing and all of them are tested with this method. To be conservative, all the tested track reconstructions must have a probability smaller than 1% to remain in the selection. Even after this, the event selection is dominated by background, mainly from mis-reconstructed events. In order to overcome the background, more reconstructions are applied to the event to identify the correct track. Any additional reconstruction is tested with the described veto method.

3. Results From Simulation Study
In the down-going region where the self-veto effect becomes important, this event selection will identify new events. However, because the events found are starting tracks there will be overlap between this and other event selections. IceCube has unblinded two years of data from a through-going muon analysis [2] and a scaling veto analysis [5]. Using simulation for this selection, comparison can be made to both. Given that the overlap with the scaling veto analysis is larger, it’s astrophysical flux normalization of $2.06 \times 10^{-18} \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1}$ and index 2.46 are used for the simulation prediction. In Figure 2 the number of events per year above a given energy in the region below -30 degrees declination can be seen. As was mentioned in the introduction, the atmospheric contribution is greatly reduced but not completely removed. Atmospheric neutrinos dominate below 8 TeV, and astrophysical neutrinos dominate.

![Figure 1](image1.png)

**Figure 1:** The earliest hit defines the separating line between the observed event and the missed DOMs. The information in the observed region is used to infer how likely the event was to be a through-going event.

![Figure 2](image2.png)

**Figure 2:** Comparison of the cumulative number of atmospheric and astrophysical events found above a given energy and below -30 degrees declination in simulation from this selection. The text on the grey histogram is the bin values.
above. If the assumed flux correctly describes the true astrophysical flux, approximately eight new events can be expected from this selection in two years. These eight tracks would be a 45% increase in astrophysical tracks. This increase would be helpful in further constraining the astrophysical flavor ratio reported by IceCube [9]. In addition, these events will be interesting to examine for a neutrino source because many of the events will be very pure by virtue of the self-veto. In Figure 3, contours of the astrophysical to conventional atmospheric flux ratios can be seen from 1:10 to 1000:1. Above 1:1 the astrophysical flux dominates and the respective events from the two analyses are added as well as the events found in simulation by this analysis. In the cascades, there is a slight enhancement from the self-veto with the majority of the observed neutrinos. For tracks, the self-veto has a stark effect in the southern hemisphere. Moving from 10:1 to 100:1, the contour moves up very little in energy. Beyond this, the contour ceases to move at all. This is because events of this energy will always have a partner muon at depth and the veto becomes guaranteed. Even though the southern hemisphere is where the most pure events stand to be found, it is not where most tracks have been found to date. By properly searching for these events, this event selection has the potential to find four new astrophysically interesting events per year in the southern hemisphere. This alone is not new, since there are also many cascades which originate from the southern hemisphere and are astrophysically interesting. However, it is important to remember that cascades have a pointing resolution of >15 degrees compared to the 0.5 degree resolution of tracks. This makes these new events powerful in the search for a neutrino point source where they can improve point source searches in the southern hemisphere and provide high-purity candidates to future real time detection efforts.

4. Conclusions and Outlook
A new veto-based event selection has been developed. This selection relies on a new style of veto which uses the good pointing of tracks in IceCube to infer when a track is starting versus incoming. Because the events are starting, the atmospheric neutrinos and muons are removed. The expectation from simulation, assuming a reasonable astrophysical flux from a similar measurement, predicts four new events per year.

5. References