

## PAPER

## Starting track events in IceCube

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## Starting track events in IceCube

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**ABSTRACT:** The IceCube Neutrino Observatory is a cubic kilometer-sized detector designed to detect neutrinos of astrophysical origin. We summarize an ongoing dataset that will identify starting track neutrino events above 1 TeV over the entire sky. We discuss a method using a boosted decision tree (BDT) to classify and reduce the cosmic ray muon rates from billions per year to  $\sim 1$  per year while selecting  $\sim 1000$  starting track events per year. Muon tagging with the BDT also improves our sensitivity to astrophysical neutrinos from the southern sky, since it removes atmospheric neutrinos accompanied by muons from parent cosmic ray showers. Next, we introduce a Random Forest to reconstruct the energy of astrophysical neutrino candidates interacting inside the detector volume, with an energy resolution of 25% made possible by identification of the hadronic and muonic components of the neutrino interaction. Finally, the outgoing muon track is used to reconstruct the direction of the astrophysical neutrino candidates with an estimated median angular resolution of  $1.6^\circ$  at 1 TeV improving to  $0.5^\circ$  at 1 PeV. This dataset will eventually be used to measure the astrophysical diffuse flux, so we summarize the impact of systematic uncertainties on such a measurement.

**KEYWORDS:** Analysis and statistical methods; Neutrino detectors; Particle identification methods

<sup>1</sup>Full author list and acknowledgments are available at [icecube.wisc.edu](https://icecube.wisc.edu).

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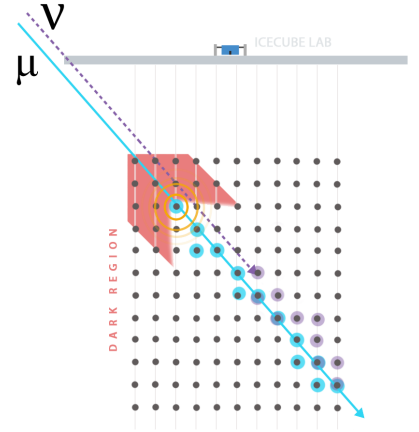
## 1 Introduction

IceCube discovered the astrophysical neutrino flux [1] and has searched for the sources of this flux primarily using tracks from the northern sky [2, 3] and “starting events” interacting inside the detector volume [4–6]. In recent publications [6] starting tracks have shown large advantages, but were statistically limited in the southern sky due to the overwhelming atmospheric muon background. Today, we describe a new dataset focusing on starting track events with significantly increased event rates. The eventual goal of this dataset is to be used in a measurement of the astrophysical diffuse flux. Here we describe the event topology and classification (section 2), energy and directional reconstruction (section 3), and sources of systematic uncertainties (section 4).

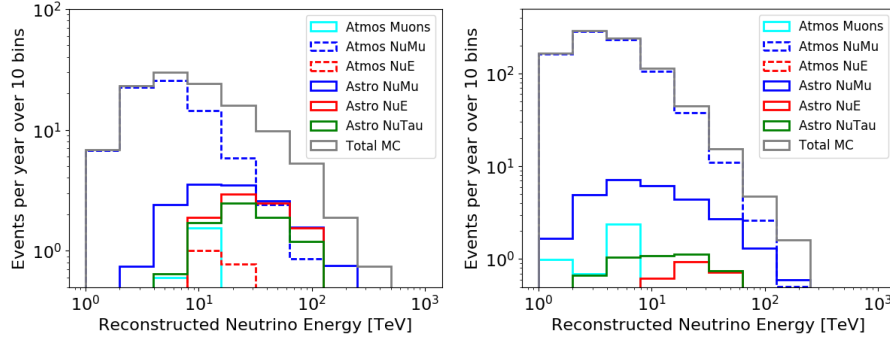
## 2 Event selection

Figure 1 shows how the reconstructed track (in blue) and vertex (in orange) are used to point backwards along the track and localize the dark region, defined as the region where no light should be detected if the event is a starting track event. For an atmospheric muon event, there is a large amount of light deposited in this dark region and the event can be removed. This cut is capable of reducing the  $\sim 3$  kHz atmospheric muon rate to  $\sim 30$  mHz with negligible effect on the astrophysical neutrino rate. In addition, this veto is also capable of selecting for and removing atmospheric neutrino events with muons from the same cosmic ray shower.

We then use a Boosted Decision Tree (BDT) to select for and remove the remaining atmospheric muons. The BDT is trained using information from 12 variables, such as the fraction of energy



**Figure 1.** The reconstructed muon track and vertex are used to define the dark region. Events with a large amount of light observed in the dark region are removed.



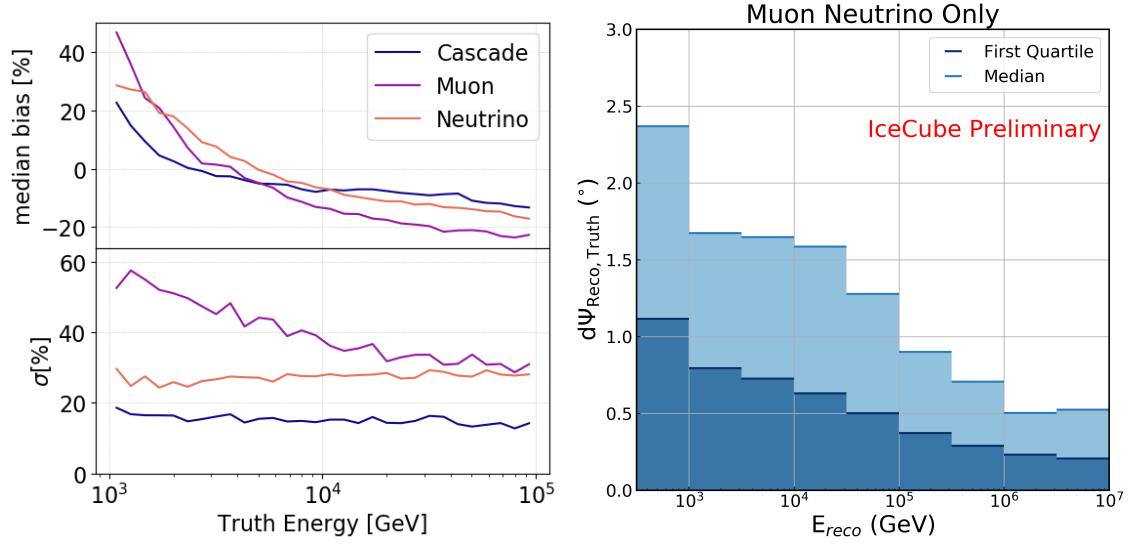
**Figure 2.** The expected astrophysical and atmospheric neutrino rates for the southern (left) and northern (right) sky. The atmospheric muons are reduced to  $\sim 0.3 \mu\text{Hz}$ .

deposited in the first 10 m of the track and the distance of the interaction vertex from the entry point in the detector. We then apply a cut on BDT score to reduce the atmospheric muons to  $\sim 0.3 \mu\text{Hz}$ . The final expected rates are shown in figure 2 for the southern and northern sky separately. We assume the single power law flux from ref. [7] (MESE) with spectral index of 2.46, normalization per flavor of 2.06 for astrophysical neutrinos, and the Gaisser H4a cosmic ray model [8] for atmospheric muons and neutrinos. The atmospheric neutrino flux was chosen for historical reasons. The self-veto effect is analytically computed for atmospheric neutrinos in the southern sky to account for the rejection of atmospheric neutrinos with accompanying muons [9]. For the southern sky, we expect  $\sim 30$  astrophysical neutrino events per year and  $\sim 90$  atmospheric neutrino events. For the northern sky, we expect  $\sim 40$  and  $\sim 900$  events per year respectively. Assuming a 10 year IceCube dataset is used, our final number of expected events is  $\sim 10000$ .

### 3 Energy and directional reconstruction

The neutrino energy reconstruction utilizes the Random Forest (RF) algorithm with similar inputs that were used in the IceCube inelasticity measurement [6]. The RF is trained to estimate the hadronic component of the event and the track component of the event separately. We then assume the sum of these components to be the total neutrino energy. Figure 3 shows the energy resolution and bias for each component over the energies of interest. The limiting factor for this event topology is the muon energy estimate due to the finite length of the track in the detector. The estimator uses the energy losses every 10 m along the entire track and the overall track length in the detector to estimate the total energy of the muon. However, the algorithm is limited below 10 TeV where minimum ionization and stochastic energy losses overlap in magnitude. Above 10 TeV, the muon energy resolution stabilizes at  $\sim 30\%$ . The cascade energy resolution improves as a function of energy from  $\sim 18\%$  at 1 TeV to  $\sim 13\%$  at 100 TeV. Overall, the neutrino energy resolution is  $\sim 25\%$  from 1 TeV to 100 TeV.

The directional reconstruction used for starting tracks is the SplineMPE algorithm [10]. This algorithm utilizes the maximum likelihood method with arrival times and amplitudes of Cherenkov photons used as parameters in the likelihood. Figure 3 shows the directional error quantiles as a function of the reconstructed neutrino energy for this particular dataset. At 1 TeV the median



**Figure 3.** Left: the energy bias and resolution for the cascade, muon, and neutrino of a starting track. The neutrino energy is the sum of the cascade and muon. Right: the angular resolution of a starting track event as a function of the reconstructed neutrino energy. The first quartile and median resolution are shown using simulated muon neutrinos.

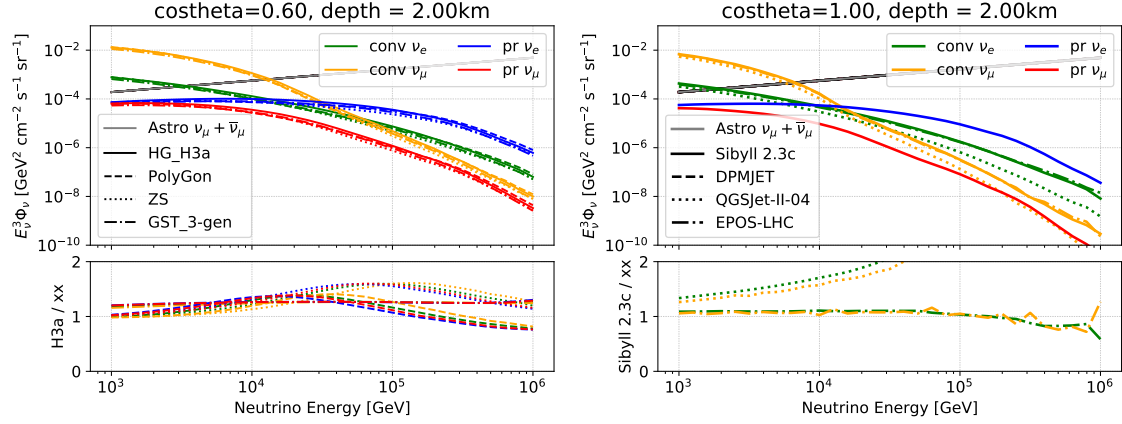
directional error is  $1.6^{\circ}$  improving to  $0.5^{\circ}$  at 1 PeV. The angular resolution is worse than the  $1^{\circ}$  to  $0.25^{\circ}$  quoted in other published IceCube analyses (e.g. [2]) because of the shorter track lengths expected in a starting tracks dataset. Improvements to the angular resolution are possible with the usage of an algorithm that takes advantage of both the cascade and muon information simultaneously but is beyond the scope of this work.

#### 4 Systematic uncertainties

A measurement of the diffuse flux relies on the forward folding binned likelihood technique using simulated data, therefore the simulation needs to be well understood. The detector systematic uncertainties are modeled to account for the normalization and angle-dependence of the efficiency of the optical modules. The normalization is varied by  $\pm 10\%$  and the angular efficiency is modeled using two dimensionless parameters which modify zenith dependence of the module response. Additional systematic uncertainties due to the bulk ice absorption and scattering coefficients are also necessary but are expected to be sub-dominant [11].

The various neutrino fluxes shown in figure 4 are computed using MCEq [12] with different cosmic ray (CR) [8, 13, 14] and hadronic interaction (HI) [15–17] models. The ratio plot shows the differences in the neutrino flux with respect to Gaisser H4a with Sibyll 2.3c model. The green and orange lines are the conventional electron and muon neutrinos fluxes respectively, while the blue and red lines are the prompt electron and muon neutrinos fluxes. These shape differences are what we define as our theoretical CR and HI systematics. We expect theoretical systematics to play a dominant role in a measurement of the astrophysical diffuse flux given the large shape differences seen between choice of models. We do want to note that the precise calculation of these various fluxes is an improvement in the treatment of atmospheric neutrino flux uncertainties with respect

to recent IceCube publications [4, 5] where these uncertainties were modeled as corrections to the expected atmospheric flux as a single  $\Delta\gamma_{\text{CR}}$  or  $\pi/K$  ratio component.



**Figure 4.** The atmospheric electron and muon neutrino flux for various cosmic ray (left) and hadronic interaction (right) models. The ratios are with respect to Gaisser H3a with Sibyll 2.3c.

## 5 Conclusion and outlook

A new dataset focusing on starting events in IceCube was shown. Using a BDT for event selection and improved reconstruction of the energies and arrival directions of astrophysical neutrino events, we expect to produce a sample of  $\sim 10\,000$  neutrino candidates using 10 years of IceCube data. While the energy resolution of 25% and angular resolution of  $1.6^\circ$  (1 TeV) to  $0.5^\circ$  (1 PeV) are comparable to previous diffuse analyses. The event selection will substantially increase the event statistics in the next measurement of the diffuse astrophysical neutrino flux.

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