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Astrophysical neutrino source searches with IceCube starting track events

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Abstract: Muons and neutrinos created by cosmic rays interacting in the atmosphere create a significant background for IceCube astrophysical neutrinos in the Southern Sky. However, looking for neutrino events that start in the detector can reduce both the atmospheric muon and atmospheric neutrino background while retaining the astrophysical neutrino signal. The method presented here results in a higher astrophysical neutrino purity for IceCube events at declinations less than -25°. We specifically select for track events, which results in better directional reconstruction due to the long signature the muon leaves in the detector than for cascade events. Due to the improved signal-background ratio and good pointing resolution, we will discuss how this event selection will improve the IceCube sensitivity to southern neutrino sources. We will focus on its impact on searches for galactic plane point sources and diffuse galactic plane neutrino emission. This selection also allows IceCube to send out high astrophysical purity realtime alert events with neutrino energies in the tens of TeV to the multimessenger community.

Keywords: Data analysis; Neutrino detectors

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[1] Full author list and acknowledgments are available at https://icecube.wisc.edu/collaboration/authors/#collab=IceCube&date=2021-05-18&formatting=web&tag=VLVnT+2021.

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Contents

1 Introduction

IceCube and other neutrino telescopes seek out astrophysical neutrinos which lie among a background of neutrinos and muons generated in cosmic ray interactions in the atmosphere. The atmospheric muon background can be reduced by looking at events that traverse through the earth, leaving us with astrophysical and atmospheric neutrinos that can be distinguished using their energy and zenith [3]. The astrophysical neutrino flux becomes the dominant component above 100 TeV. However, many sources may not be able to produce neutrinos at energies in the hundreds of TeV, which can make it difficult to find the lower energy signals in the sea of atmospheric neutrinos.

We discuss another method that allows us to reject both the atmospheric muon and the atmospheric neutrino background by looking for track events which start inside of the detector volume [4]. With this method, we can create a high purity astrophysical neutrino sample that improves IceCube's sensitivity to neutrino sources in the southern sky.

2 Starting Track Event Selection

By rejecting events that deposit light on the outer layer of the detector, we can reject not only incoming atmospheric muons, but also atmospheric neutrino events. For atmospheric neutrinos of energies 1TeV or greater, the angular distance between the neutrinos and muons created in the meson decays becomes negligible [4]. For increasingly energetic atmospheric neutrinos, the probability that they enter into the detector with a muon from the same cosmic ray air shower increases [4]. If the atmospheric neutrino interacts in the detector volume but is also accompanied by a muon from the same shower, it would be rejected as a starting track due to light deposition from the incoming muon. The High Energy Starting Event (HESE) sample was used in the initial IceCube discovery of the diffuse astrophysical neutrino flux, which used a fixed veto volume to reject incoming events [7]. However, this event selection requires events to be high in energy and, in order to look at lower energy events, the fiducial volume needs to be restricted further [5]. For the event selection described here, we look for starting muon tracks which have a better angular resolution than cascade events which dominate the HESE selection. Further discussions of the advantages of this event selection, especially concerning measurements of the diffuse flux, can be found in [8].

To define an incoming event veto parameter, we start with the hypothesis that we have a through-going track with a given reconstructed direction. Assuming the initial track hypothesis, we find the DOMs which observed light in the expected time window from photon modeling to reconstruct the interaction vertex. The probability that DOMs behind the vertex missed light from an incoming muon traveling along the fit track (p_{miss}) is calculated. A low miss probability means the interaction vertex was likely inside the instrumented volume as it is unlikely that an incoming event could pass by the DOMs without depositing light. We also use a boosted decision tree (BDT) to arrive at the final level of our event selection. In table 1, we show the final level event rates for our expected livetime of ten years. The signal and background rates can be tuned using the BDT score for optimal sensitivity or purity.

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Table 1. Ten year event rates for astrophysical neutrinos assuming the flux from [5] and background atmospheric neutrinos and muons. The final BDT cut allows us to tune the muon background for optimal sensitivity. The background rates of the previous IceCube point source tracks analysis are shown in figure 3 of [6].

10 year event rates	Astrophysical $\nu_{\text{all flavor}}$	Atmospheric $\nu_{\text{all flavor}}$	Atmospheric μ
Northern Sky ($\theta \geq 80^\circ$)	378	8435	116
Southern Sky ($\theta < 80^\circ$)	328	845	98

3 Neutrino source searches

We use maximum likelihood estimation to search for statistically significant clusters of events. In figure 1 the sensitivity — flux where 90% of the test statistics are greater than the median background test statistic — is shown as a function of declination for the new starting track selection versus two previously published results. The starting tracks will be used to search across the whole sky and for more targeted searches looking at the brightest galactic and extra galactic gamma ray sources.

With this new event selection, we can improve the IceCube sensitivity in the Southern Sky especially for sources with softer fluxes and sources with energy cutoffs. In figure 2, we can see the sensitivity to Vela X modeled with a single power law flux with an exponential cutoff. The shape and normalization of the flux is generated from TeV gamma ray data and optimistically converted to the neutrino flux assuming 100% of the gamma ray flux is from meson decays which are created in proton-proton interactions. We can also study if our neutrinos correlate with galactic plane source classes by stacking the test statistics calculated at multiple source locations of the same source class. If we take the top 12 brightest supernova remnants, pulsar wind nebulae, and unidentified galactic plane TeV gamma ray sources, we find we are sensitive respectively to 151%, 36%, and 49% of the expected neutrino flux calculated using the optimistic gamma ray scenario described above.

Just as neutrinos are created in the atmosphere from cosmic ray air showers, the same cosmic ray interactions are expected to occur in the galactic plane medium creating a gamma ray and neutrino flux across the galactic plane. Using gamma ray and cosmic ray data, two models have been created for the neutrino flux that we refer to here as the Fermi π^0 model [13] and the KRA$_\gamma$ model [9]. In table 2 we show that our starting track selection results in the lowest sensitivities

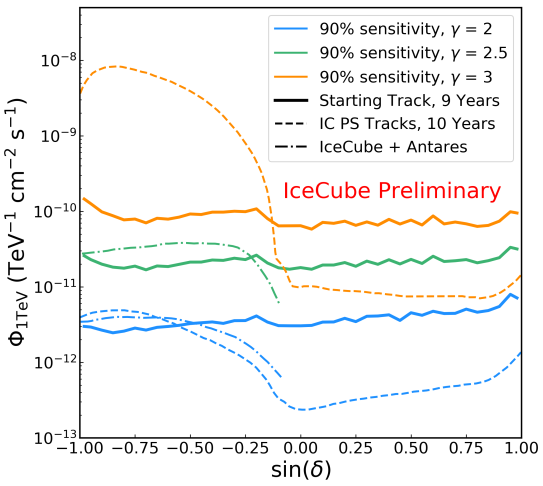

Figure 1. The starting track sensitivity is shown in the solid line compared to the sensitivities reported for the ten year IceCube point source search with tracks [1] and the IceCube and Antares combined point source search [2] for various source power law indices.

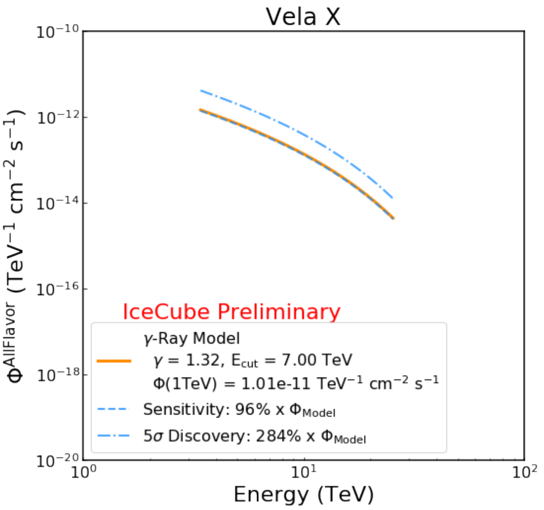

Figure 2. The starting track sensitivity to Vela X is shown. The energy range represents the range where 90% of injected simulation events lie. The sensitivity and discovery are reported as percentages of the flux derived from gamma ray data.

Table 2. A comparison of the Starting Track sensitivity for nine years of data to previously published sensitivities for the diffuse galactic plane neutrino models. We model the Fermi π^0 model energy spectrum with a power law assuming $\gamma = 2.5$ and the KRA$_\gamma$ model energy spectrum using the spectrum given in the model paper [9].

	Ferm π^0 ($\gamma = 2.5$) (x 10^{-11} TeV cm^{-2} s^{-1})	KRA$_\gamma$ with 5 PeV Cutoff (x KRA$_\gamma$ Flux) [9]
9 Years IceCube Starting Tracks	1.92	30.9%
IceCube Cascades [10]	2.5	58%
IceCube Through-going Tracks [11]	2.97	–
Joint ANTARES and IceCube [12]	–	81%

to these models. This improvement is likely due to the expected energy spectrum shape and the location of the center of the galaxy in the southern sky.

Due to the purity of this event selection at the final level, it is ideal for a realtime neutrino alert stream. The suppression of atmospheric neutrinos in the southern sky allows us to send out neutrino alerts with a high “signalness” with energies in the tens of TeV as illustrated in figure 3. For this alert stream, we expect 3.2 astrophysical neutrinos per year with a signalness greater than 50% assuming a single power law with $\gamma = 2.46$ from [5].

4 Conclusion

By selecting for starting events, we are able to better reject atmospheric neutrino events from the southern sky. This allows us to improve the IceCube sensitivity to neutrino sources in the southern

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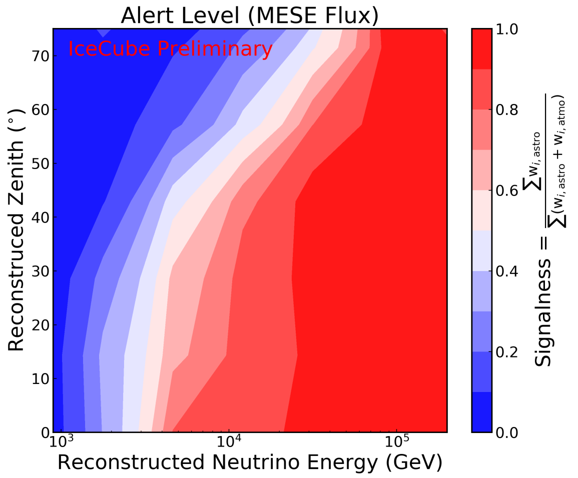

Figure 3. The signalness–ratio of expected signal to all expected events for a given declination and energy–for the starting track realtime alert stream. The astrophysical neutrino flux from [5] is assumed.

sky. It also gives IceCube an avenue to send out neutrino alerts with high signalness in the tens of TeV energy range. Alerts in this energy may help the multimessenger astronomy community identify transient neutrino sources which cannot accelerate cosmic rays to the energies needed to produce neutrinos with energies in the hundreds of TeV. Looking for starting tracks in other neutrino telescopes would increase the rate of these lower-energy, high-signalness alerts; however, the modular or less dense designs of the upcoming neutrino telescopes may impact the feasibility of distinguishing starting tracks from incoming muons.

Acknowledgments

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