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All-flavor Multi-Channel Analysis of the Astrophysical Neutrino Spectrum with IceCube

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The spectral shape and flavor composition of the high-energy astrophysical neutrino flux can contain important information about the sources and processes which produce it. The IceCube Neutrino Observatory has previously demonstrated the ability to observe neutrinos of all flavors by selecting events which interact within the detector volume. Sensitivity to charged current muon neutrino interactions in or close to the detector has also been shown by selecting muon track events whose directions indicate passage through the Earth. We present an updated analysis of starting events using 6 years of IceCube data taken from 2010–2016 focusing on energies from the PeV region down to 1 TeV, far below the threshold of the original data sample used in the initial discovery of the astrophysical flux. Astrophysical neutrinos remain the dominant component in the southern sky down to 10 TeV. We then also perform a unified analysis of the flavor and spectrum implications of this sample when combined with the recently published data on ν_μ induced muon tracks as well as recent work to identify candidate ν_τ events.

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1. Introduction

Neutrinos have the potential to provide important information for understanding the mechanisms of energetic astrophysical objects and their relationship to cosmic rays. With the successful observation of a diffuse flux of astrophysical neutrinos, both in the form of events starting within a fiducial volume of a detector [2, 5] and events with Earth-crossing directions [3], a major goal is now to determine the properties of this flux in the greatest possible detail. This can be pursued both by extending the selection of neutrino candidate events to capture as many astrophysical neutrinos as possible, including substantial numbers of atmospheric neutrinos to ensure that backgrounds are well understood, and by combining different selection techniques into more thoroughly integrated analyses of the total spectrum. Here, we discuss both improvement of the selection of starting events in the IceCube detector and a new iteration of a global analysis of the neutrino flux utilizing the latest high statistics datasets and event observables.

2. Starting Event Selection

Identifying of neutrino candidate events in IceCube by utilizing a division of the detector into an internal fiducial volume and a surrounding veto layer has proven highly successful in obtaining a high purity sample of neutrinos. Additionally, a large fraction of these neutrinos are expected to be of astrophysical origin. Because the development of this technique was spurred by the observation of events in the PeV range of energy [1], the initial focus was on these high energies. Lower energies, where backgrounds produced by cosmic ray air showers pose a greater challenge, were left unexplored. Subsequently, the veto technique has been extended, using additional event reconstruction information and dynamic scaling of the boundary between the fiducial and veto volumes. This lowers the selection threshold to events depositing around 1 TeV of energy [5], but thus far this enhanced technique has been applied to only two years of IceCube data. This new version of the selection further optimizes this technique to maximize efficiency. A splitting algorithm, using a form of agglomerative hierarchical clustering, is applied to each recorded event to attempt to separate unrelated, coincident events in the detector, with a success rate of about 75%. The 'outer layer' veto criterion as in [1] is then applied, rejecting all events which are observed to have more than three detected photons in the veto region. The splitting reduces the fraction of events falsely vetoed due to coincident events and makes this selection a superset of the selection of [1] for events which yield at least 6000 photoelectrons detected.

To provide efficient background rejection for lower energy events, following the technique of [5], a more sensitive veto for incoming particle tracks is then applied, relying on the reconstruction of the location of the interaction vertex (or a major energy deposition within the event) followed by a search over downward directions for detected photons whose timing is consistent with an incoming particle. Any event with more than two such veto photons is discarded. This same veto method is also applied in reverse to detect tracks directed outward and upward from the reconstructed event vertex, as such a track is a strong indication that the event is a charged-current ν_μ interaction. Events with at least 10 photoelectrons consistent with an upward track are immediately preserved. Finally, events which produce lower observed numbers of photons are subjected to a volume cut, more stringent with decreasing energy, increasing the amount of veto path length which

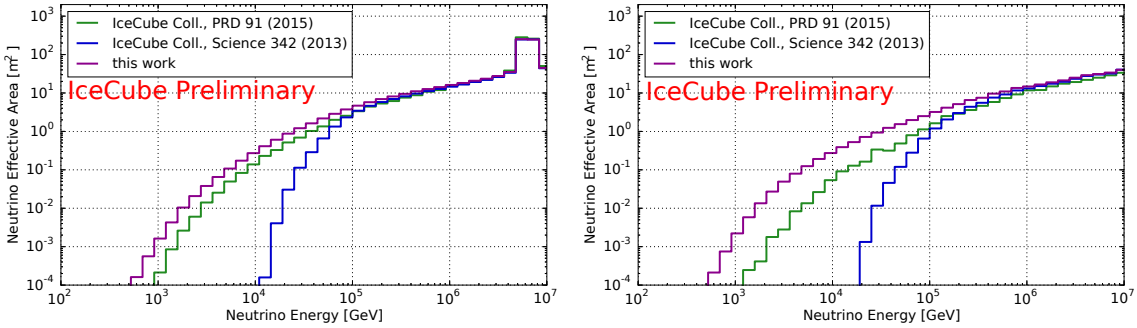


Figure 1: Effective area of the starting event selection for ν_e (left panel) and ν_μ (right panel) is shown in purple, compared to the effective areas from [1] in blue and [5] in green. All effective areas are averaged over neutrinos and antineutrinos. The effective area for ν_τ is quite similar to that for ν_e except for the lack of the resonance feature at several PeV.

a background muon would have to traverse unseen. An important change with respect to [5] is that to avoid discrimination against starting charged-current ν_μ interactions that produce more clearly track-like events, a broader selection using data from IceCube's first-level 'online' filters gives a considerable increase in the efficiency with which these events are selected. Fig. 1 shows the resulting effective area for this selection compared to the previous veto-based selections. This selection delivers higher efficiency for all event topologies, particularly a factor ~ 2 for ν_μ at around 100 TeV to a factor of ~ 8 at around 10 TeV. Further, it is intended that this selection will be applied to the same six years of IceCube data as in [4], three times the data-taking period covered by [5], and it is anticipated that this will continue to be extended in future as new data become available.

As this selection collects events of both track-like and cascade-like topologies, it is useful to distinguish between the two. Events with 10 photoelectrons of out-going light attributable to an up-going track are naturally classified as track-like. Otherwise, each event is reconstructed using both track and cascade hypotheses, and the average distance of the modules which observed light to the best fit particles is computed. This provides a useful observable because true track events tend to have light at large distances from the best fit cascade hypothesis. Finally, an unfolding of the probable energy depositions within each event is performed, using both a single, point-like deposition hypothesis, representing a cascade, and a hypothesis of a linear collection of depositions, representing a muon. For bright events with more than 6000 photoelectrons detected, if the linear unfolding has non-negligible depositions located more than 500 meters apart, the event is considered track-like. Likewise, bright events for which the observed charge associated with the linear unfolding is larger than the observed charge associated with the single point unfolding are classified as tracks; other bright events are classified as cascades. For dimmer events, if at least 1.5 photoelectrons of out-going charge are detected the event is classified as track-like, and otherwise it is considered cascade-like. Based on Monte-Carlo simulations, more than 98% of truly cascade-like events are correctly classified as such. Figure 2 shows the success rate for classification of true ν_μ charged-current events, which is above 80% when averaged over energy and position for an astrophysical spectrum $\propto E^{-2.5}$. Misclassified ν_μ charged-current events are expected to make up 30% of the cascade-like category from a conventional atmospheric spectrum, but only 5% from a spectrum $\propto E^{-2.5}$.

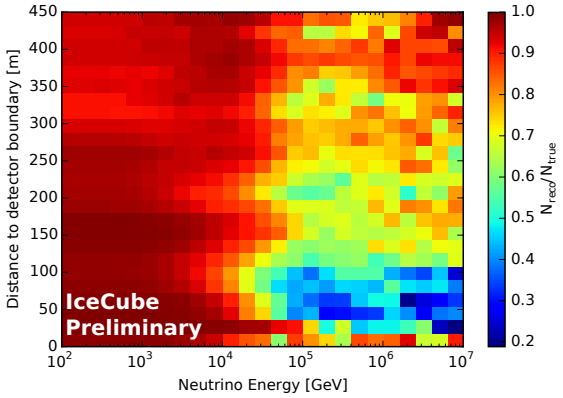


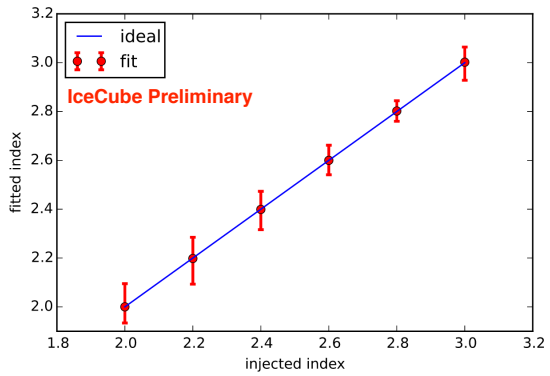
Figure 2: Probability that starting ν_μ charged-current events are correctly classified as track-like. Since the selection requires lower energy events to start deeper inside the detector, these are more likely to be correctly classified due to having an observation of the out-going track.

3. Starting Event Analysis

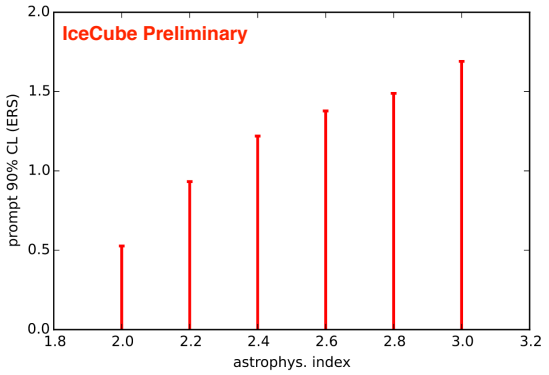
A new sample of starting neutrino events provides opportunities for studying the diffuse neutrino flux. These data will be analyzed using a binned, forward-folding maximum likelihood fit to a set of parameterized models, as in many previous analyses. Three observables are used in the likelihood fit. The reconstructed event energy gives access to spectral shape information. Reconstructed event direction (zenith angle in detector coordinates) carries information about atmospheric origin due to non-uniform production of atmospheric neutrinos from light meson decays ('conventional' atmospheric neutrinos) and the self-veto effect of muons produced in the same air showers. Last, the assessed event topology gives the analysis a degree of flavor sensitivity. In terms of the model which will be used to fit the data, four spectral components will be included: the conventional atmospheric neutrinos, 'prompt' atmospheric neutrinos (from short-lived particle decays), penetrating muons from cosmic ray air showers, and a diffuse, astrophysical flux of neutrinos.

The three atmospheric components are each allowed to vary in normalization. No prior is placed on the normalization of the conventional component as it is expected to be well constrained by the data, the prompt component is given a gaussian prior centered at zero with a width of 2.3 times the ERS model normalization [6] following the result obtained in [7], and the penetrating muons are given a prior centered at the rate estimated from a tagged sample of experimental background events with a width of 50% [2]. These priors are expected to have only weak influence on the final result. In addition, to treat systematic uncertainties arising from the primary cosmic ray flux and from the modeling of hadronic interactions in air showers, parameters will be included for variation in the effective cosmic ray spectral index and the relative production rates of kaons with respect to pions in air showers. Systematic treatment of uncertainties in the response of the detector itself will also be addressed, specifically the absolute optical efficiency of the detector, the optical properties of the ice surrounding the modules, and the scattering of the ice which was melted and refrozen during installation of the instrumentation.

For the purposes of this study, the astrophysical neutrinos are assumed to be isotropic and have equal contributions from all neutrino flavors. The base model to be tested will be a single



(a) 68% sensitivity to spectral index of a single astrophysical power law flux



(b) 90% sensitivity to a prompt atmospheric neutrino flux assuming the spectrum of ERS [6] relative to the normalization of that model

Figure 3: Median projected sensitivity of the starting event analysis to model parameters assuming 6 years of data. A variety of spectral indices are considered to ensure that the analysis performs well for any possible input.

power law with variable normalization and spectral index. Additionally, a set of more advanced astrophysical models will be tested, including an exponential spectral cutoff, a second power law component, and the combination of both of these additions. Finally, the flavor composition of the astrophysical flux will be tested by allowing the normalization associated with each neutrino flavor to float independently in the fit, although all three flavors will be assumed to have the same spectral shape. Fig. 3 shows the expected median sensitivity of this analysis for two of the parameters considered over a variety of possible true astrophysical fluxes with different spectral indices and normalizations chosen to be consistent with the observations of [2]. This analysis is expected to have good resolution of the spectral index of a single astrophysical power law component, but the sensitivity to a prompt atmospheric component is expected to be limited by the strength (and also uncertainty) of the astrophysical flux, particularly if that flux is relatively soft.

4. Global Flavor Analysis

Beyond analyzing the more complete dataset of starting events, it is desirable to unify the analysis of all types of neutrino data observed by IceCube. This type of analysis has been performed previously [8]; the purpose of this new iteration is to use newer datasets and observables which have become available. Particularly complementary to the starting event sample is the high statistics sample of muons from Earth crossing neutrinos analyzed previously [3], and continues to be extended to newer data [10]. While the starting event selection is most sensitive to the astrophysical neutrino flux in the southern portion of the sky, as this is the angular region in which atmospheric neutrinos are most strongly self-vetoed, the Earth-crossing neutrinos are most sensitive to high energy events near the horizon. Consisting almost entirely of ν_μ charged-current events, the Earth-crossing sample has essentially no flavor sensitivity on its own, but provides a strong constraint on the ν_μ portion of the astrophysical flux. The starting event sample constrains the combined flux of ν_e and ν_τ in addition to contributing to the ν_μ measurement. In fact, it is

possible to do better than treating ν_e and ν_τ as equivalent cascade-like events by using specialized reconstruction for double cascade events resulting from ν_τ charged-current interactions as detailed in [9]. Some care must be taken when combining these three datasets to avoid double counting events. Since the ν_τ component is the least well constrained, the τ observables only function well for high energy events, and the starting event and ν_τ analysis samples are nearly equivalent at the energies where they overlap, the ν_τ optimized sample is given the highest priority. Events passing the ν_τ optimized selection are treated using its topology classification scheme: For events classified as single cascades and tracks, deposited energy and zenith angle are used as observables, while for those classified as double cascades, tau length and decay energy observables are used. It would be desirable to use the total deposited energy and direction observables for the double cascade events, but it appears that doing so would involve dividing the data into too many bins for the amount of simulated data currently available to provide precise model expectations in all bins. The remaining events of the new, high statistics starting event sample are then included using the same observables as in the analysis of that sample alone. Finally, the Earth-crossing muons are included in the fit, omitting those starting muon events which were already selected by the starting sample. Muon zenith angles and reconstructed muon energies are used for fitting, as in [3]. After de-duplication of the input data, events are classified by topology: Single cascade, double cascade, starting track, or through-going track, depending on either the topology classification of the source dataset, or by treating the entire dataset as a topology category in the case of the through-going muons remaining in the Earth-crossing dataset after the starting events are removed. The topology categories do not all map to single neutrino flavor, nor are the classifications always correct. These limitations are encompassed by the Monte Carlo simulated data, which include all neutrino flavors and interaction process relevant in the energy range of the analysis, and which are processed and classified in exactly the same manner as the observed experimental data. Furthermore, a new feature of this analysis is use of a consistent set of simulated data for fitting all observations, ensuring that systematic effects will be accounted for in a consistent manner. This is planned to coincide with a reprocessing of IceCube data over the time period to be used which will bring old data up to the same standard as the most recent data-taking periods, eliminating season to season variations from software changes, removing the need for complex treatment to fit these differences out.

The analysis fit will be performed using the same method as the starting event only analysis, and as such the same model parameters will be included. However, as the primary goal of this combined analysis is the flavor composition, all fits will be performed with the three flavor components of the astrophysical flux allowed to float to distinct normalizations. Additionally, allowing the fitted fraction of neutrinos to vary with respect to the fraction of anti-neutrinos has been explored using Monte-Carlo studies. While this analysis would have some ability to constrain such a parameter, due to resonant W^- production by high energy $\bar{\nu}_e$ interacting with electrons in the Earth (the Glashow resonance) and small changes to the absorption of the flux in the Earth due to the difference between neutrino and antineutrino cross sections, the sensitivity does not appear to be great enough to be useful at this time, and it seems preferable to continue with the assumption of a flux with equal parts neutrinos and antineutrinos and keep this degree of freedom out of the fit. Fig. 4 shows the projected sensitivity of this analysis using the three samples outlined above. Overall, the result is similar to the expectation for the ν_τ analysis of [9], but the inclusion of the Earth-crossing muons considerably reduces uncertainty on the ν_μ fraction. Fig. 5 shows the ability of this analysis

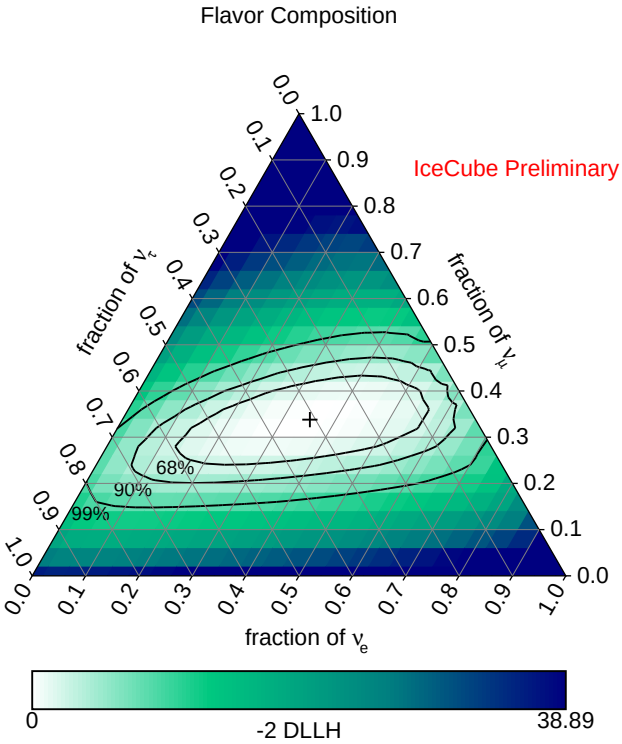


Figure 4: Median sensitivity of the global analysis to an astrophysical neutrino flux of $\Phi(E_\nu) = 1.5 \times 10^{-18}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,(E_\nu/100\mathrm{TeV})^{-2.3}$ per flavor. This plot shows the profile likelihood space for the flavor composition with the total flux normalization allowed to float freely. The sensitivity does not change substantially for other spectra which are statistically consistent with previous observations.

to constrain an exponential cutoff in the astrophysical spectrum under various scenarios. A cutoff can be constrained, except for soft spectra where it becomes impossible to distinguish due to the expected number of high energy events being very small whether the cutoff is present or not.

5. Future Extensions

Besides the three samples currently integrated into the combined fit, several other data sets are complete or nearing completion which can enhance the sensitivity of this analysis. The cascade selection of [11] uses different techniques to select starting events and demonstrated to have a large fraction of events which do not appear in the starting sample offers the opportunity to substantially increase the statistics for cascade events. In addition, the selection for cascade event which are not fully contained within the detector [12] will add events not included in either of the contained event selections. Similar gains may be possible for ν_τ candidate events; [13] represents a completely different paradigm for identifying double cascades, which is expected to have very different strengths and weaknesses, and is therefore likely to be a good complement to [9]. Finally, new veto-based techniques for selecting additional starting track events [14] may further enhance the number of astrophysical neutrinos which can be collected with highly down-going directions. As many of these data sets as possible are planned to be included to form a truly global analysis, along with

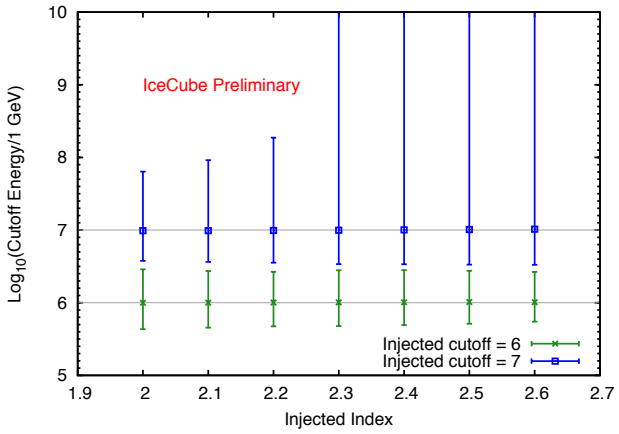


Figure 5: Median sensitivity of the global analysis to the energy of an exponential cutoff in the astrophysical neutrino spectrum. Error bars show 68% uncertainty intervals for the fitted cutoff. The extension of these intervals to energies far larger than any event expected to be observed in data for soft spectra indicates an inability to distinguish the injected cutoff from a case with no cutoff.

any other new selections and observables which may become available in the near future. Furthermore, this type of analysis will benefit from improved calibration which will become possible with IceCube-Gen2.

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