PROCEEDINGS OF SCIENCE

Atmospheric Neutrino Oscillations with 8 years of data from IceCube DeepCore

Kayla Leonard DeHolton* on behalf of the IceCube Collaboration

Department of Physics and Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin - Madison, Madison, WI 53706, USA

E-mail: kayla.leonard@icecube.wisc.edu

The DeepCore detector is a densely instrumented sub-array of the IceCube Neutrino Observatory designed to observe atmospheric neutrino interactions above 5 GeV via Cherenkov radiation in the Antarctic ice. At these energies, Earth-crossing muon neutrinos have a high chance of oscillating to tau neutrinos. These oscillations have been previously observed in DeepCore through both muon neutrino disappearance and tau neutrino appearance. While DeepCore is able to measure oscillations with a precision comparable to accelerator-based experiments, it also complements accelerator measurements because it probes longer distance scales and higher energies, peaking above the tau lepton production threshold. Here we discuss the IceCube Collaboration's latest analyses of the atmospheric neutrino oscillation parameters using 8 years of data. These analyses benefit from more data compared to previous publications, as well as significant improvements in background rejection, reconstruction techniques, modeling of systematic uncertainties, and particle identification.

The 22nd International Workshop on Neutrinos from Accelerators (NuFact2021)
6–11 Sep 2021
Cagliari, Italy

*Speaker

PoS(NuFact2021)062

1. Introduction

The IceCube Neutrino Observatory is a kilometer-scale detector located at the South Pole comprising 5,160 digital optical modules (DOMs) that observe Cherenkov radiation from neutrino interactions [1]. Within IceCube is a sub-array known as DeepCore, which features denser spacing and allows for a lower energy detection threshold compared to the rest of IceCube [2]. As indicated in Figure 1, DeepCore is located in the bottom center portion of IceCube; the ice at these lowest depths offers the best optical properties and optimal detection efficiency. DeepCore measures atmospheric neutrino interactions down to primary neutrino energies of a few GeV, allowing for studies of atmospheric neutrino oscillations.

The atmospheric neutrino flux consists primarily of the muon and electron flavors. For neutrinos traveling across the diameter of the Earth, a large fraction of the muon neutrinos oscillate to tau neutrinos, with the oscillation maximum for these Earth-crossing neutrinos occurring at an energy of about 25 GeV. Assuming the three standard neutrino flavors, the oscillations are described by the PMNS mixing matrix. For the atmospheric oscillations measured by IceCube, the parameters of interest are the mixing angle $\sin^2(\theta_{23})$ and the mass splitting Δm^2_{32} (assuming the normal mass ordering).

Atmospheric oscillations were first discovered in 1998 by Super-Kamiokande [3], and the parameters $\sin^2(\theta_{23})$ and Δm^2_{32} have since been constrained by both atmospheric and accelerator experiments. The atmospheric neutrino oscillation parameters have previously been measured with IceCube DeepCore using three years of data [4, 5]. Since then, there have been significant improvements in background rejection techniques, reconstruction and particle identification, and modeling of systematic uncertainties. These recent improvements, along with additional years of data, allow for a measurement of the oscillation parameters with precision comparable to that of dedicated accelerator experiments.

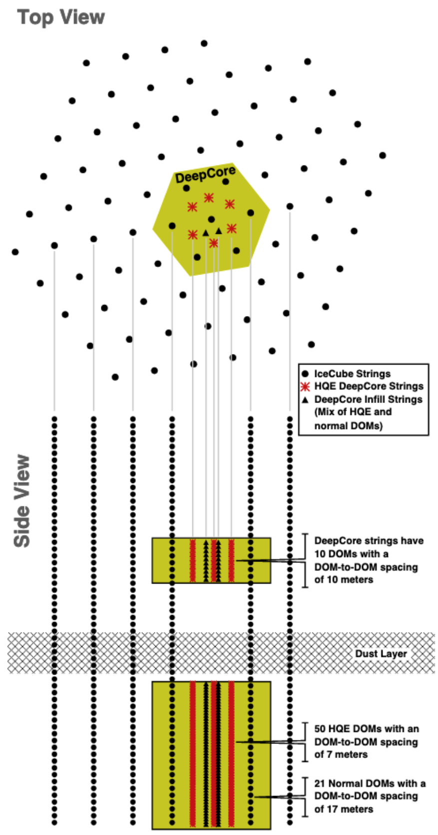

Figure 1: The DeepCore sub-array within IceCube. DeepCore is located in the bottom center portion of the detector. The spacing between modules is more dense than the rest of IceCube, and so DeepCore is able to detect lower energy events, down to a few GeV. [2]

2. Event Selection & Background Rejection

When looking for atmospheric neutrinos in DeepCore, the main backgrounds present are atmospheric muons and random noise hits. At trigger level, these backgrounds exceed the neutrino rate by approximately 3 orders of magnitude. Several levels of selection are applied to suppress backgrounds and create a neutrino-dominated sample (see Figure 2).

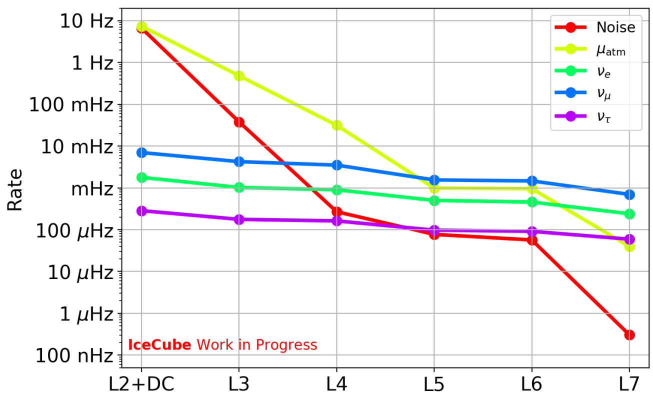

Figure 2: Several levels of selection are applied to eliminate the primary backgrounds of atmospheric muons and random noise. After starting with background rates about 3 orders of magnitude higher than the neutrino rate, we ultimately achieve a neutrino-dominated sample with background rates on the order of a few percent.

In the first three levels of background rejection, fast and simple cuts are applied to remove obvious backgrounds. For example, to eliminate atmospheric muon tracks passing through the detector, we look for light deposited in the upper and outer regions of the detector which we define as our veto region. Data cleaning methods are applied to remove noise hits from each event, and the remaining "cleaned" pulses are examined to determine if there are enough non-noise hits left and if their timing is consistent with a signal event. In Level 4, we apply two boosted decision trees (BDTs) to further target these backgrounds; one BDT is trained to eliminate muons and one to eliminate noise events. The input variables for these BDTs rely on timing and location of the hits in the detector to predict the type of event given the pattern of hits.

In Level 5, we aim to reduce the muon background below the neutrino rate. Most of the muons remaining at Level 5 don't look like typical muon tracks, otherwise they would have been identified and rejected earlier. At this point, we apply two types of cuts: "containment" cuts and "corridor" cuts. We are interested in neutrino events with interaction vertices contained within DeepCore. Although a full reconstruction has not yet been applied by Level 5, we use information about the earliest hits and the brightest strings to get estimates for the the radial position and depth of the original interaction vertex. We then require these vertex estimates to be contained within DeepCore. The corridor cuts target an additional class of background events consisting of muons which can sneak between the sparse corridors in the hexagonal grid of IceCube before reaching DeepCore. The DOMs along these corridors are examined to determine how many of them registered light; if there are more than 2 hit DOMs along the corridor, the event is rejected as likely background.

By Level 6, we have achieved a neutrino-dominated sample and it becomes computationally feasible to apply a more thorough and robust reconstruction algorithm: Retro Reco [1] . After reconstruction, at Level 7, we train a BDT to identify remaining muon background events based on reconstructed quantities, such as the position of the reconstructed interaction vertex for containment cuts. At this point we also tighten cuts made at previous levels to more stringent values to further reduce the backgrounds. In all, we suppress our muon and noise backgrounds by 5 and 7 orders of

[1] https://github.com/icecube/retro

magnitude respectively, while only losing about 1 order of magnitude in neutrino rate.

3. Analysis Techniques

Once we arrive at the final level of the event sample, we are interested in classifying our events to get information about the flavor composition, in order to perform a measurement of the flavor oscillations. The classification method, also known as particle identification (PID), uses a BDT to assign a score for an event being a muon neutrino charged current (ν_μ CC) interaction. This method is described in detail in [6]. The output scores, shown in Figure 3, are divided into three bins. This results in a mixed bin with approximately equal amounts of ν_μ CC and other events, as well as low-purity and high-purity ν_μ CC bins in which 72% and 97% of events respectively are ν_μ CC.

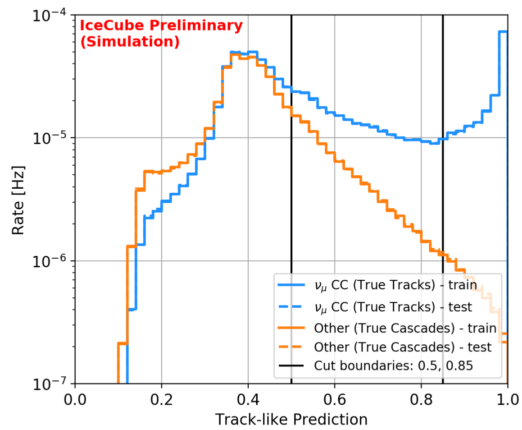

Figure 3: Distribution of output scores from the PID BDT. Cuts are placed at 0.5 and 0.85 to create 3 bins with varying ν_μ CC purity.

At this point, a binned analysis is performed using 12 logarithmic bins in reconstructed energies between 5 and 300 GeV, 10 uniform bins in reconstructed cos(θ_{zenith}) between -1.0 (upgoing) and 0.3 (slightly above the horizon), and 3 PID bins. Example event distributions are shown in Figure 4. These simulated templates are produced for various combinations of the nuisance parameters describing our systematic uncertainties and the physics parameters $\sin^2(\theta_{23})$ and Δm^2_{32}. The main systematic uncertainties are due to the atmospheric neutrino and muon fluxes, neutrino interaction cross sections, and detector uncertainties such as the ice properties and the PMT efficiency. This analysis is being performed in a blind way such that we do not currently have the true data template. Ultimately, a fit will be performed to determine what combination of physics and nuisance parameters most closely matches the data.

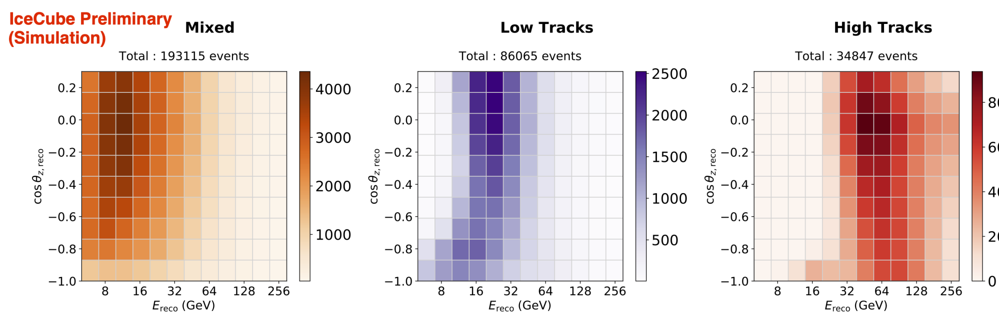

Figure 4: Simulated event distributions binned in reconstructed energy and cos(θ_{zenith}) for the 3 PID classifications.

4. Projected Sensitivity

We can estimate our sensitivity to the atmospheric neutrino oscillation parameters, $\sin^2(\theta_{23})$ and Δm^2_{32}, as shown in Figure 5. We find that with our 8-year data sample, we will be able to perform a measurement with precision comparable to dedicated accelerator experiments. Because IceCube DeepCore probes longer distances, higher energies, and different production and detection mechanisms than accelerator experiments, it is subject to very different systematic uncertainties, and therefore is well suited to provide a complementary measurement.

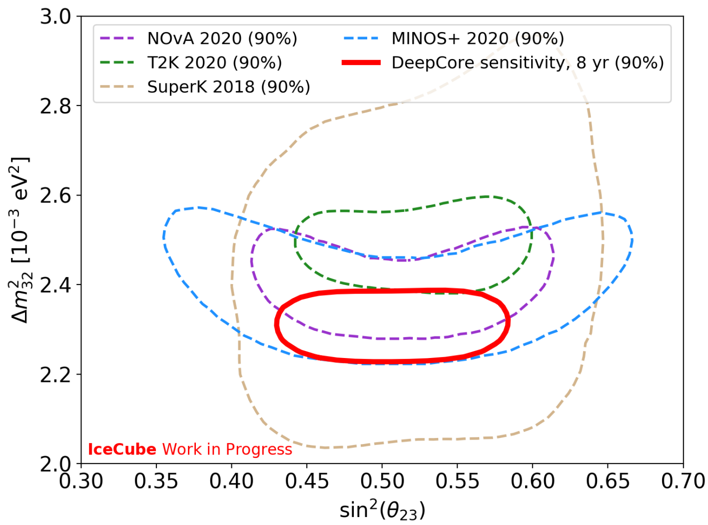

Figure 5: Estimated sensitivity of the 8-year DeepCore sample (red) to the atmospheric mixing parameters, as compared to recent accelerator and atmospheric results, shown in the dashed lines.

References

[1] IceCube collaboration, *The IceCube Neutrino Observatory: Instrumentation and Online Systems*, *Journal of Instrumentation* **12** (2017) P03012 [1612.05093].

[2] IceCube collaboration, *The Design and Performance of IceCube DeepCore*, *Astroparticle Physics* **35** (2012) 615 [1109.6096].

[3] Super-Kamiokande collaboration, *Evidence for Oscillation of Atmospheric Neutrinos*, *Phys. Rev. Lett.* **81** (1998) 1562 [hep-ex/9807003].

[4] IceCube collaboration, *Measurement of Atmospheric Tau Neutrino Appearance with IceCube DeepCore*, *Phys. Rev. D* **99** (2019) 032007 [1901.05366].

[5] IceCube collaboration, *Measurement of Atmospheric Neutrino Oscillations at 6-56 GeV with IceCube DeepCore*, *Phys. Rev. Lett.* **120** (2018) 071801 [1707.07081].

[6] K. Leonard DeHolton for the IceCube collaboration, *Low energy event classification in IceCube using boosted decision trees*, *Journal of Instrumentation* **16** (2021) C12007.