Latest results on atmospheric neutrino oscillations from IceCube/DeepCore

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Abstract. The IceCube Neutrino Observatory, located at the South Pole, is the world’s largest neutrino detector. DeepCore, the low energy extension for IceCube, with a threshold of about ten GeV is well suited to study neutrino oscillations using neutrinos produced in the Earth’s atmosphere and traveling distances as large as the Earth’s diameter before being detected. Using these neutrinos DeepCore makes measurements of the neutrino oscillation parameters $\theta_{23}$ and $|\Delta m^2_{32}|$ with precisions approaching that of dedicated experiments, and based on preliminary studies these results can still be further improved. These new studies as well as the current results obtained in DeepCore are discussed here.

1. Introduction

Neutrino oscillations were discovered by Super-Kamiokande in 1998 [1] through the measurement of atmospheric neutrinos, and SNO in 2002 [2] through the measurement of solar neutrinos. Since then neutrino oscillation has also been observed in various experiments using other neutrino sources, such as particle accelerators, and reactors. The parameters describing the standard 3-flavor neutrino oscillation have been measured with varying precision by these experiments (see [3] and references therein) with the exception of the CP-violating phase ($\delta_{CP}$) and the mass ordering (the sign of $\Delta m^2_{23}$). The amplitude of the neutrino oscillation is determined by the elements of the mixing matrix, described by the mixing angles ($\theta_{12}$, $\theta_{13}$, and $\theta_{23}$) and $\delta_{CP}$, while its oscillation period in vacuum depends on $|\Delta m^2_{32}|L/E$ and $|\Delta m^2_{21}|L/E$, where $E$ is the neutrino energy and $L$ is the distance between its production and interaction points.

Atmospheric neutrinos are particularly interesting for studying neutrino oscillations because they are produced with energies spanning many orders of magnitude and are available at varying values of $L$ (up to the Earth’s diameter of about 12700 km). For neutrinos travelling through the Earth’s core, the first maximum $\nu_\mu$ disappearance happens around 25 GeV, which makes its measurement possible for large-volume neutrino detectors. In particular, the IceCube/DeepCore energy threshold of around ten GeV allows it to map this first maximum of $\nu_\mu$ disappearance [4] as a function of $L$ and $E$ and therefore measure $|\Delta m^2_{32}|$ and $\theta_{23}$.

2. The IceCube/DeepCore detector

The IceCube Neutrino Observatory [5] is the world’s largest neutrino detector, with a total volume of about 1 km$^3$ in the deep glacier near the South Pole Station, Antarctica, and is

1 http://icecube.wisc.edu/collaboration/collaborators
instrumented with 5160 digital optical modules (DOMs), as shown in Fig. 1. The observatory was designed to detect high-energy neutrinos and look for an extraterrestrial component to the observed neutrino flux, for which it successfully provided first evidence recently [6]. In 2008, the original detector design was augmented by creating a region in the bottom center of the detector with a higher density of optical sensors in the deep, clearest ice, therefore increasing the photocathode coverage in that volume. This volume with increased photocathode density, called DeepCore [7], was added with the objective of lowering the energy threshold of the IceCube detector from hundreds to about ten GeV and thus make it possible to perform competitive measurements of neutrino oscillations and dark matter searches.

Figure 1. Diagram of the IceCube Neutrino Observatory at its completion, December 2010, with the DeepCore denser array indicated.

2.1. Background rejection
The main background in IceCube/DeepCore to observing $\nu$ oscillations consists of the atmospheric $\mu$ co-produced in the cosmic ray showers. In DeepCore analyses, this background is rejected by looking in the surrounding IceCube strings for signals indicating that the event could have in fact originated outside DeepCore and propagated into its volume. In addition to rejecting atmospheric $\mu$ events, some of these algorithms are also used to extract a sample used to estimate the shape of the distribution of this background in the final sample. Besides these veto criteria, atmospheric $\mu$ are down-going and signal $\nu$ are up-going, therefore restricting the final sample only to events reconstructed as up-going further reduces the atmospheric $\mu$ background.

Another non-negligible background to analyses in DeepCore are events produced by the detector self-triggering due to the presence of noise in the DOMs. Such events are rejected by requiring a minimum number of photons in the event that are consistent with a Cherenkov wavefront propagating in the ice in which the detector is embedded and by requiring a minimal quality to the event reconstruction. After these rejection cuts, the main impact of detector noise in the analysis is through potential reconstruction biases and efficiency of the veto algorithms used to reject atmospheric $\mu$ events, which is accounted for in the simulation thanks to extensive work tuning the simulation to the observed noise in the detector.
2.2. Reconstruction of events

The signal for the 3-flavor $\nu$ oscillation analysis are low energy neutrons ($E_\nu < \sim 50$ GeV), and in particular $\nu_\mu$ events interacting through charged-current (CC) processes given the main observable effect is $\nu_\mu$ disappearance. Given the detector threshold of roughly ten GeV, most of the interactions are produced via deep inelastic scattering (DIS) which produce, for $\nu_\mu$ CC events, a hadronic shower and a $\mu$, which are to a good approximation collinear. That is the general hypothesis used for reconstructing the events.

Typically only a few tens of photons produced in these low energy neutrino interactions will be detected in DeepCore and some of those will have scattered multiple times before being detected. The latest results from DeepCore [4] relied on identifying unscattered photons and using them to reconstruct the direction of the event that produced them, following [8]. The identification of unscattered, or direct, photons is performed by requiring a specific pattern of their arrival time and location. In order for the directional reconstruction to perform well it is required for the event to have at least 5 unscattered photons identified, which reduces significantly the size of the available sample that can be used in the analysis as only 30% of the events have the required number of direct photons. After the direction of the event is reconstructed using only the unscattered photons, the energy and vertex of the neutrino are reconstructed using all the observed photons in the event, without allowing the reconstructed direction to change.

To measure $\nu_\mu$ disappearance, in addition to reconstructing the $\nu$ direction and energy for each event, it is useful to also distinguish $\nu_\mu$ CC events from the other interactions ($\nu_e$ CC, $\nu_\tau$ CC and neutral-current). This is done by looking for a $\mu$ in the final state as there are no $\mu$ produced by the other neutrino interactions, with the exception of a small fraction of $\nu_\tau$ CC interactions where a $\mu$ will be produced from the $\tau$ decay. Technically this is done by comparing the fit quality between the direction reconstruction mentioned above and a reconstruction assuming isotropic and instantaneous light emission from a single location in space. The classification stabilizes for energies above 30 GeV with 60% of the signal events being correctly classified while misidentifying 30% of the remaining background events. The total number of events for each flavor expected in the sample as a function of the true neutrino energy is shown in Fig. 2.

![Figure 2](image.png)

**Figure 2.** Composition of sample used for oscillation analysis as a function of true neutrino energy. The blue shaded area shows the $\nu_\mu$ event rate without oscillations, and the green region the rate with oscillations, while the purple and yellow region show the contamination of the sample by events that are not $\nu_\mu$ CC.

A new reconstruction method has been matured in the last few years to make possible the reconstruction of events that do not have a large number of unscattered photons. This new reconstruction estimates simultaneously the interaction vertex, the neutrino direction, and energy by maximizing the likelihood of the tested hypothesis to yield the observed light distribution in the detector, both in terms of its position, time, and charge. In order to estimate the expected light distribution, the optical properties of the South Pole ice are accounted for based on the in-situ measurements of its properties [9]. This new method achieves a precision comparable to the one described above, while at the same time being able to reconstruct nearly all neutrino events. The procedure to identify $\nu_\mu$ CC events described above is still effective and is also used with this reconstruction method. This new reconstruction is currently being tested in DeepCore with the goal of creating the next generation of oscillation analysis.
3. \( \nu_\mu \) disappearance analysis method and systematics

The current oscillation analysis in DeepCore aims at measuring \( \theta_{23} \) and \( |\Delta m^2_{32}| \). To extract those parameters, the simulation is fit to the data under both hierarchy assumptions and both results are reported. A likelihood ratio method is used both for the fitting and to estimate the uncertainty of the measurement using a \( \chi^2 \) approximation. In those fits \( \theta_{13} \) is allowed to vary in the region allowed by the global fit to data [3], while \( \delta_{CP} \) is fixed to 0 and \( \theta_{12} \) and \( \Delta m^2_{21} \) are fixed to their best fit values [3], as DeepCore is insensitive to these last parameters. Besides the neutrino oscillation parameters, the fitting procedure also minimizes over several nuisance parameters accounting for the current knowledge of the atmospheric \( \nu \) and \( \mu \) flux, neutrino interactions and detector related effects. Table 1 lists all the parameters considered.

### Table 1. List of nuisance parameters used in the latest DeepCore \( \nu_\mu \) disappearance analysis.

| Nuisance parameters                        | Nominal value       | Variation               |
|-------------------------------------------|---------------------|-------------------------|
| Atmospheric flux                          | overall \( \nu \) normalization | Honda 2015 [10]         | Free                     |
|                                           | atm. flux spectral index |                         | \( \pm 5\% \)            |
|                                           | \( \nu_e/\nu_\mu \) flux ratio |                         | \( \pm 20\% \)          |
|                                           | overall \( \mu \) normalization | from data               | Free                     |
| Neutrino interactions                     | QE axial mass       | GENIE [11]              | from GENIE               |
|                                           | RES axial mass      |                         |                         |
|                                           | DIS Bodek-Yang parameters |                        |                         |
| Detector                                  | DOM angular acceptance | flashers [9]            | from range of models     |
|                                           | DOM overall efficiency | flashers and \( \mu \) | \( \pm 10\% \)           |
|                                           | Bulk ice surrounding detector | flashers         | compared 2 models        |
|                                           | Hadronic energy scaling | Geant4[12]             | \( \pm 5\% \)           |

4. Results

The latest published \( \nu_\mu \) disappearance analysis [4] was obtained using 3 years of full detector lifetime. The up-going events selected with reconstructed energy between 6 and 56 GeV were used to measure \( \sin^2 \theta_{23} = 0.53^{+0.09}_{-0.13} \) and \( |\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\text{eV}^2 \). Since then the sample was augmented with an additional year of detector data, taken during detector construction and processed using similar techniques as the 3 year sample, yielding \( \sin^2 \theta_{23} = 0.54^{+0.08}_{-0.13} \) and \( |\Delta m^2_{32}| = 2.80^{+0.36}_{-0.20} \times 10^{-3}\text{eV}^2 \). The best fit point and 90\% confidence regions as a function of the atmospheric oscillation parameters for these two measurements are shown in Fig. 3.

**Figure 3.** Latest DeepCore results for the 3 years [4] (cyan) and 4 years (blue) analysis compared with other experiments [13, 14, 15].
4.1. Prospects of new analysis using DeepCore
As discussed previously, the new reconstruction techniques recently developed would allow an increase of about 5 times in the number of events used to measure the atmospheric neutrino oscillation parameters. In conjunction with that, improvements in the event selection would make a full-sky analysis possible, accessing a region where no effect is expected that can be used for constraining the systematic uncertainties. The expected improvement in sensitivity is shown in Fig. 4.

Figure 4. Comparison of latest DeepCore results for the 3 years [4] analysis (cyan) and projected sensitivity expected based on the reanalysis of the same data with new selections and reconstructions (orange), obtained from a MC data challenge with injected oscillation parameters shown by the orange cross.

5. Conclusions
Since being used for the discovery of neutrino oscillations, atmospheric neutrinos are still a valuable tool to study this phenomena; recent results obtained with DeepCore have started to approach the sensitivities obtained by dedicated experiments, and preliminary studies indicate that the full potential of the detector has not yet been reached.

Besides improvements in reconstruction techniques and event selection, an extension to the detector could greatly enhance the capabilities of the detector to measure neutrino oscillations. This proposed extension is PINGU, which would further lower the energy threshold of the detector and make it possible to determine the mass hierarchy [16] and make meaningful improvements on the determination of the atmospheric oscillation parameters. This project is further discussed in another contribution to the proceedings of this conference.

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