Probing Beyond Standard Model Physics via Oscillations with IceCube DeepCore

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Abstract. For many years IceCube DeepCore has measured atmospheric neutrino interactions in the optically clear, deep ice at the South Pole. Analysing only three years of data has yielded the most precise measurements of the atmospheric neutrino oscillation parameters above 5 GeV. Measuring oscillations at these high energies, well above the tau-production threshold, and over extremely long baselines, provides strong constraints on new, Beyond Standard Model physics in a region of phase space uniquely accessed with atmospheric neutrinos. Here we report on the most recent searches for non-standard atmospheric neutrino oscillations with IceCube DeepCore.

1. Introduction
Neutrino oscillation is by now a well-established phenomenon [1, 2] that occurs because the flavour eigenstates in which neutrinos are produced and detected (νe, νμ and ντ) are superpositions of different, non-zero mass eigenstates (ν1, ν2 and ν3). In the standard paradigm, the flavour and mass states are connected via the 3 × 3 unitary PMNS mixing matrix that is parameterised by three mixing angles and a single CP-violating phase. Measuring these fundamental parameters, in addition to the mass differences, with high precision is the goal of many neutrino experiments today. With these parameters, we can describe neutrino oscillations as a function of neutrino energy, E, and the distance they travel, L [3].

IceCube DeepCore measures atmospheric neutrino oscillations. These neutrinos travel from their production point to the IceCube DeepCore detector over baselines O(20 km) for neutrinos produced above the South Pole, up to nearly 13,000 km for neutrinos that cross the Earth diametrically. To first order, we observe the oscillation of atmospheric νμ, which is driven by the mixing angle θ23 and mass difference Δm23. IceCube DeepCore has been successful in measuring standard atmospheric νμ oscillations with high precision at significantly higher energy and over longer baselines (through matter) than other contemporary oscillation experiments [4]. With access to this unique region of phase space in L/E, we can also search for anomalies that are inconsistent with the standard picture of three oscillating neutrinos, and thereby explore many Beyond Standard Model (BSM) theories. Here we review several recent searches for BSM oscillations using data from the IceCube DeepCore experiment.

2. The IceCube DeepCore Detector
The IceCube Neutrino Observatory, located at the geographic South Pole, consists of three components: IceTop, used for the study of cosmic rays; IceCube, the primary, in-ice array for high-energy neutrino detection; and DeepCore, a densely instrumented in-ice, sub-array for
lower-energy neutrino interactions. The results presented herein use only the in-ice arrays, IceCube and DeepCore. The basic detection unit of the arrays are Digital Optical Modules (DOMs) that consist of a single 10" photomultiplier tube (PMT) encased within a glass pressure sphere along with electronics for signal readout, module control and calibration. These DOMs are used to detect Cherenkov radiation that is produced when a neutrino interacts in the ice and creates a shower of relativistic, charged particles. Over 5,000 DOMs were deployed deep into the glacial ice, instrumenting a total volume of 1 km$^3$. Together, IceCube and DeepCore can resolve neutrino interactions over a broad energy range, from $\sim 5$ GeV up to several PeV [5].

3. Neutrino oscillations in IceCube DeepCore
The spatial and temporal distribution of observed light across DOMs is used to infer interacting particle type, energy and direction. Data are first filtered to remove atmospheric $\mu$ and detector noise, until a sample with high atmospheric neutrino purity is obtained. Events are then further divided into different classes to enhance the distinction between interacting neutrino flavours. Elongated light depositions are called tracks, and are mostly induced by $\nu_\mu$ charged current (CC) interactions. More spherical emission patterns are called cascades, and are indicative of $\nu_e$, $\nu_\tau$ CC and neutral current (NC) interactions from all flavours. For both event classes, the zenith direction of the incoming neutrino is reconstructed as a proxy for distance neutrinos have travelled from their production point in the atmosphere to the IceCube DeepCore detector.

The primary oscillation effect observed in IceCube DeepCore data is the transition of $\nu_\mu \rightarrow \nu_\tau$, as shown in Fig. 1. The detector threshold is above the $\tau$-production threshold ($\approx 3.35$ GeV), and therefore is sensitive to both the $\nu_\mu$ disappearance and $\nu_\tau$ appearance. In practice, this is done by counting the number of track and cascade events reconstructed in the detector as a function of their energy and zenith angle. These measured event rates are compared to an expected number of events that is given by modelling of neutrino production in the atmosphere, interaction cross sections, detection efficiency and a set of neutrino oscillation parameters.

4. Recent Searches for BSM Physics
The key to IceCube DeepCore’s sensitivity to BSM effects through oscillations lies in the high neutrino energies and the long distances they travel through matter. Many BSM theories include new particles that modify the way neutrinos interact with matter. This ultimately leads to modifications of the oscillation pattern that are inconsistent with three oscillating neutrinos.
4.1. $\nu_\tau$ Appearance

A simultaneous measurement of both $\nu_\tau$ appearance and $\nu_\mu$ disappearance is a model-independent probe of new physics that tests the PMNS matrix unitarity [8]. Experimentally, this is seen as a deficit of track events, and an increase in cascade events that follows a characteristic pattern in $L/E$. The best fit normalisation for the $\nu_\tau$ CC + NC component of the data is shown in Fig. 2 (left) for 3 years of data. A value differing from 1.0 would indicate non-unitarity. However, we find the rates are consistent with a normalisation of 1.0 within the experimental uncertainties. The result from IceCube DeepCore is shown compared to the OPERA and Super-Kamiokande experiments, and all measurements are in agreement.

4.2. Sterile Neutrinos

Many BSM theories posit the existence of additional neutrino mass states. Any additional states must be mostly sterile with respect to the weak interaction, due to constraints from collider experiments [9]. If we consider a single eV-scale mass state, this could mix with the three weakly interacting neutrinos and be responsible for anomalous oscillations in various experiments [10, 11, 12, 13]. This would require an extended $4 \times 4$ mixing matrix with additional mixing angles and CP-violating phases. IceCube DeepCore has performed two independent searches for such an eV-scale sterile neutrino, where we are sensitive to the mass difference $\Delta m^2_{41}$, and the mixing angles $\theta_{24}$ and $\theta_{34}$. Because they are sterile, we cannot directly detect these neutrinos. However, their existence would still leave an imprint on the observed neutrino flux and flavour composition. At low energies, the presence of sterile neutrinos would distort the observed oscillation pattern especially for neutrinos crossing the Earth’s core. At high energies, $\mathcal{O}$(TeV), where no oscillations are nominally expected, the signal is a resonant disappearance of $\bar{\nu}_\mu$. No evidence for sterile neutrinos was found in either search. With the low-energy sample, we obtain limits on $|U_{\mu 4}|^2 = \sin^2 \theta_{24} < 0.11$ and $|U_{\tau 4}|^2 = \sin^2 \theta_{34} \cdot \cos^2 \theta_{24} < 0.15$ at 90\% C.L. for $\Delta m^2_{41} = 1\text{eV}^2$ with three years of data [14]. At high energy, the exclusion limits for $\Delta m^2_{41}$ and $\sin^2 2\theta_{24}$ at 90\% C.L. are shown in Fig. 2 (right) using only one year of data [15].

4.3. Non-standard Interactions

The existence of additional gauge bosons would also impact neutrino propagation through the Earth by altering the matter potential through Non-Standard Interactions (NSI) [16]. By
measuring the neutrino flavour composition from 5–100 GeV, we can search for indications of such a new boson. The signal can manifest itself as a distortion of the standard oscillation maximum for neutrinos that cross the core, or else as anomalous appearance or disappearance effects in regions of $L/E$ that are inconsistent with standard oscillations. No signs of NSI signatures are found in three years of IceCube DeepCore data. The limits for several real NSI couplings are shown in Fig. 3 compared to other experiments. The fit is also performed assuming that the couplings are real, allowing phases between 0–180°. Here again, no significant indications of NSI interactions are found.

5. Conclusion

IceCube DeepCore data can be used to search for anomalous oscillations indicative of BSM physics. With less than half of the available livetime, strong limits on new physics are set using both model-independent and -dependent approaches. Current efforts are focused on extending these studies to incorporate more data with improved calibrations and analysis techniques.

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