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Atmospheric neutrino oscillations in IceCube-DeepCore

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The IceCube Neutrino Observatory probes a breadth of particle physics through the DeepCore low-energy extension. DeepCore provides access to an abundance of earth-crossing neutrinos over much of the atmospheric cosmic-ray spectrum, from 5-100 GeV. Over such baselines, and having overcome the kinematic threshold for ν_τ charged current interactions, DeepCore provides unique multi-channel sensitivity to atmospheric oscillations (including ν_τ-appearance) with unprecedented statistical power. As a result, oscillations measurements from DeepCore are complementary to and competitive with those of long-baseline beam experiments. Here, recent and upcoming results from the current generation of IceCube oscillations analyses are summarised, including work on an 8+ year dataset which represents a milestone in high-statistics atmospheric mixing measurements.

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Atmospheric neutrinos in IceCube

The Standard Model (SM) of particle physics provides an incomplete picture of the universe; indirect evidence of new physics has been observed and the mechanism behind neutrino mass generation remains unexplained. Neutrino flavour oscillations provide an array of tests for new physics, thus far characterised through measurements of the PMNS matrix and its extension through non-standard interaction (NSI). IceCube DeepCore has complementarity with long-baseline (LBL) experiments as it probes the same physics but with different systematic uncertainties and at a much higher energy scale (in the DIS regime). The ν_τ PMNS matrix elements remain the least constrained experimentally [1], however the kinematic suppression of the ν_τ charged current (CC) cross section due to m_τ is in part overcome at the relatively high energy threshold of DeepCore [2]. This fact, combined with the statistical power of an atmospheric source in a uniquely large detector, makes DeepCore a world-leading probe of PMNS unitarity [3].

The IceCube Neutrino Observatory is a giga-tonne Cherenkov detector embedded within the glacial ice sheet of Antarctica. It consists of an array of ~5,000 PMTs at depths of ~1.5 km beneath the geographic South Pole designed to study PeV-scale astrophysical neutrinos. DeepCore is a 10 mega-tonne subarray at the bottom-centre of IceCube with five times the instrumentation density and a detection threshold of 5 GeV. DeepCore allows the study of the naturally occurring atmospheric neutrino flux originating from cosmic ray air showers all over the surface of the earth. This is an abundant source, dominated by $\nu_\mu/\bar{\nu}_\mu$, with a broad energy spectrum much higher than long-baseline beam experiments. Above $\mathcal{O}$(TeV) the flux begins to be absorbed in the earth while below 100 GeV oscillation baselines are comparable to the diameter of the earth.

The earth-crossing flux undergoes flavour oscillations such that the neutrinos will have an energy and direction dependant transition probability and, therefore, flavour rate. The neutrinos arriving in the detector interact with the nuclei in the ice whereby superluminal secondary products produce Cherenkov radiation in a forward-facing cone. The propagation of this visible light is dependent mainly upon the depth dependent scattering, absorption, and bulk flow crystal alignment of the glacial medium [4]. For oscillations studies, the muons produced in ν_μ CC interactions are below the energy limit dominated by stochastic losses and follow straight trajectories through the ice emitting a cylinder of Cherenkov photons reconstructed as *tracks*. Due to the difference in size between hadronic and electromagnetic showers in ice being smaller than the PMT spacing in the existing arrays, all other interaction types ($\nu_{e,\tau}$ CC or $\nu_{e,\mu,\tau}$ neutral current) form indistinguishable spherical distributions reconstructed as *cascades*.

Oscillations analyses in DeepCore

While DeepCore is optimised to probe the same primary transition maximum as LBL experiments, it does so over a continuum of oscillation baselines and in multiple channels. Oscillation measurements are performed as binned analyses, fitting templates in energy (E), zenith angle (θ_Z, a proxy for length of baseline, L), and particle identification (PID as a proxy for flavour) axes. Transition probabilities are observed as distortions in this 3D-space used to extract physics parameters through a detailed fit to a Monte Carlo (MC) simulation including nuisance parameters.

The latest DeepCore dataset represents a milestone for oscillations analyses at IceCube, being the first to benefit from: a detector-wide in-situ calibration of the individual optical sensors [5] and a charge independent analysis strategy; new event selection and machine learning based classifiers (>99% neutrino purity), as well as new reconstruction techniques and PID algorithms [6, 7]; an overhauled approach to systematic uncertainties, from new DIS cross section uncertainties in the numerical approach to flux modelling [8] to 6D-fits of discrete MC sets representing the systematic uncertainties used to reweight MC events continuously. The current generation of analyses has access to more than 8 years of data and the projected sensitivities for the standard mixing paradigm, summarised in Figures 1 & 2, showing ν_μ-disappearance results competitive with LBL experiments and an improvement on the world-leading result for ν_τ-appearance by a factor of two respectively.

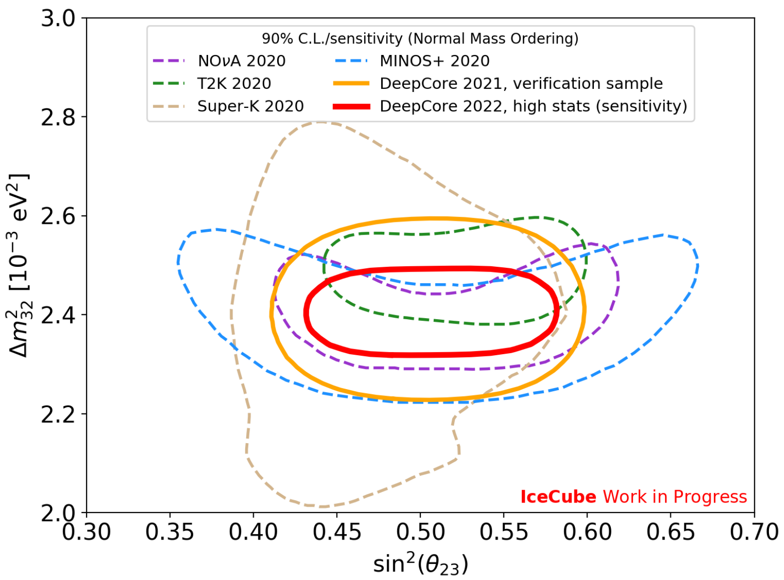

Figure 1: Standard mixing ν_μ-disappearance sensitivity with 8.3 years of DeepCore data: contours for atmospheric mixing angle, $\sin^2(\theta_{23})$, and mass splitting, Δm^2_{32}, where the *high stats* sensitivity projection represents 200k *track* and *cascade* events with full 8D reconstruction (assuming *verification* best-fit point) and *verification*, using 20k *track*-only events selected using low-scattered light criteria, is the latest constraint from DeepCore compared to results from NOνA [9], MINOS+ [10], Super-K [11], and T2K [12].

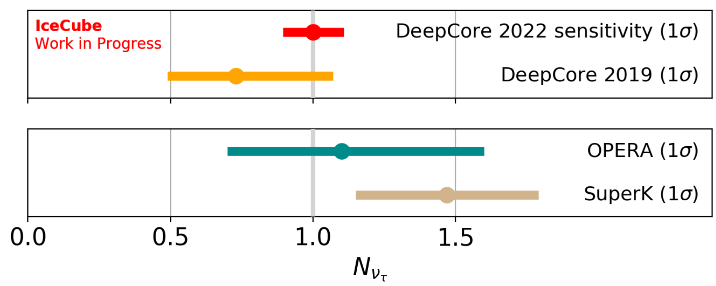

Figure 2: Standard mixing ν_τ-appearance sensitivity with 8.3 years of DeepCore data: ν_τ-normalisation precision assuming $N_{\nu_\tau} = 1$ compared with the previous world-best from DeepCore with 3 years of data [3] and results from Super-K [13] and OPERA [14].

Coherent forward scattering of neutrinos in matter may be enhanced by a beyond SM heavy mediator. Such effects are parameterised by an NSI matrix used to modify the existing model for flavour mixing. In an experimental first, a 3-year DeepCore O(GeV) all-flavour analysis provided sensitivity to all NSI matrix elements simultaneously, lepton flavour universality violating and flavour changing alike, with competitive or leading limits upon each [15]. These efforts are complementary to O(TeV) *track* analyses from IceCube which have a strong sensitivity to flavour-changing NSI element, $\epsilon_{\mu\tau}$ [16]. An 8-year analysis is underway for DeepCore's all-flavour NSI.

The first-ever search for unstable sterile neutrinos performed at IceCube aimed to resolve tensions in global fits to eV-sterile neutrinos with short-baseline (SBL) experimental anomalies [17]. Such tensions may relax if an unstable fourth state decays over LBLs, dampening oscillations observed. Fits to this 3+1+decay model using 8 years of data found no preference over the standard 3ν paradigm despite weak preference over a 3+1 scenario [18]; tensions with SBL data remain.

Outlook

Oscillations physics at IceCube has much to offer in the near future. In addition to the 8-year all-flavour NSI and further tests for the existence of sterile neutrinos, its beyond SM reach extends to neutrino decoherence [19]. Hypothesised quantum gravitational effects upon the path length of neutrinos in flight, which aggregate over LBLs to produce measurable effects both at atmospheric mixing energies and above, could be a source of decoherence if observed. There are 8-year mutually complementary analyses of O(GeV) atmospheric and O(TeV) astrophysical neutrinos underway.

The *high stats* standard mixing described here, which will improve the global statistics for ν_τ detection even further, could open the door to direct constraints upon PMNS matrix elements. If DeepCore alone does not reach this goal, the IceCube Upgrade, a future infill to the DeepCore volume, is set to provide an even greater leap in statistical power and may yet do so. With a 1 GeV threshold and a corresponding improvement in reconstruction performance and neutrino rate [20] (as well as unprecedented calibration capabilities set to constrain leading detector-based systematic uncertainties), world-leading oscillation sensitivities from joint fits of combined DeepCore & Upgrade data and the 10+ years of existing DeepCore data are expected to follow as a result.

References

[1] Stephen Parke and Mark Ross-Lonergan. "Unitarity and the three flavor neutrino mixing matrix". *Physical Review D* 93.11 (2016), p. 113009.

[2] S Kretzer and MH Reno. "Tau neutrino deep inelastic charged current interactions". *Physical Review D* 66.11 (2002), p. 113007.

[3] MG Aartsen et al. "Measurement of atmospheric tau neutrino appearance with IceCube DeepCore". *Physical Review D* 99.3 (2019), p. 032007.

[4] Martin Rongen and Dmitry Chirkin. "A novel microstructure-based model to explain the icecube ice anisotropy". *arXiv preprint arXiv:2107.08692* (2021).

[5] MG Aartsen et al. "In-situ calibration of the single-photoelectron charge response of the IceCube photomultiplier tubes". *Journal of Instrumentation* 15.06 (2020), P06032.

[6] Philipp Eller et al. "A flexible event reconstruction based on machine learning and likelihood principles". *arXiv preprint arXiv:2208.10166* (2022).

[7] R Abbasi et al. "Graph Neural Networks for Low-Energy Event Classification & Reconstruction in IceCube". *arXiv preprint arXiv:2209.03042* (2022).

[8] Anatoli Fedynitch et al. "Hadronic interaction model Sibyll-2.3c and inclusive lepton fluxes". *Physical Review D* 100.10 (2019), p. 103018.

[9] MA Acero et al. "An Improved Measurement of Neutrino Oscillation Parameters by the NOvA Experiment (2021)". *arXiv preprint arXiv:2108.08219* (2021).

[10] MINOS+ Collaboration et al. "Precision constraints for three-flavor neutrino oscillations from the full MINOS+ and MINOS data set". *arXiv preprint arXiv:2006.15208* (2020).

[11] Volodymyr Takhistov. "Atmospheric Neutrino Oscillations with Super-Kamiokande". *(IH-CEP 2020 slides)* (2020).

[12] Patrick Dunne. "Latest Neutrino Oscillation Results from T2K". *(Neutrino 2020 slides)* (2020).

[13] Z Li et al. "Measurement of the tau neutrino cross section in atmospheric neutrino oscillations with Super-Kamiokande". *Physical Review D* 98.5 (2018), p. 052006.

[14] N Agafonova et al. "Final Results of the OPERA Experiment on ν_τ Appearance in the CNGS Neutrino Beam". *Physical review letters* 120.21 (2018), p. 211801.

[15] R Abbasi et al. "All-flavor constraints on nonstandard neutrino interactions and generalized matter potential with three years of IceCube DeepCore data". *Physical Review D* 104.7 (2021), p. 072006.

[16] R Abbasi et al. "Strong constraints on neutrino nonstandard interactions from TeV-scale ν_μ disappearance at IceCube". *arXiv preprint arXiv:2201.03566* (2022).

[17] R Abbasi et al. "First Search for Unstable Sterile Neutrinos with the IceCube Neutrino Observatory". *arXiv preprint arXiv:2204.00612* (2022).

[18] MG Aartsen et al. "eV-scale sterile neutrino search using eight years of atmospheric muon neutrino data from the IceCube neutrino observatory". *Physical review letters* 125.14 (2020), p. 141801.

[19] Thomas Stuttard and Mikkel Jensen. "Neutrino decoherence from quantum gravitational stochastic perturbations". *Physical Review D* 102.11 (2020), p. 115003.

[20] Aya Ishihara. "The IceCube Upgrade – Design and Science Goals". *arXiv preprint arXiv:1908.09441* (2019).