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Neutrino oscillations and PMNS unitarity with IceCube-DeepCore and the IceCube Upgrade

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The 3ν paradigm can be tested with precision measurements of the unitarity of the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) neutrino mixing matrix. However, such tests are hampered by the low precision of ν_τ oscillation measurements, and new measurements are required. A recent world-leading measurement of ν_τ appearance by the DeepCore sub-array of the IceCube neutrino observatory is presented, as well as the future prospects from the upcoming IceCube Upgrade.

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1. PMNS unitarity and ν_τ

The observation of neutrino oscillations, where a neutrino produced as one flavor may be detected some time later as another, implies mixing between the neutrino flavor and mass states, as well as non-zero masses for at least two of the neutrino mass states. For the three known neutrino flavor states (electron, μ and τ), this mixing is characterised by the Pontecorvo–Maki–Nakagawa –Sakata (PMNS) 3×3 matrix [1, 2]. The PMNS matrix is expected to be unitary, meaning that it completely describes the mixing between states, and any deviation from unitarity could indicate the presence of Beyond Standard Model (BSM) physics, including additional 'sterile' neutrinos states. Measurements of PMNS matrix unitarity therefore provide a powerful and model-independent test of the 3ν paradigm.

Testing the unitarity of the PMNS matrix requires measurements of all 9 matrix elements, ideally via measurements of all possible neutrino oscillation channels (e.g. $\nu_e \rightarrow \nu_e$, $\nu_e \rightarrow \nu_\mu$, etc). However, the vast majority of global neutrino oscillation measurements are derived from the appearance or disappearance of electron or μ neutrinos, whilst the τ sector remains relatively unexplored [3].

This lack of experimental data constraining the τ sector of the PMNS matrix significantly reduces the precision with which its unitarity can be tested, and is a consequence of the large τ lepton mass, which forbids ν_τ production via pion or kaon decays and suppresses the charged current (CC) ν_τ cross section below $\sim$1 TeV. Worse still, the short lifetime of the τ produced in CC interactions causes it to decay after travelling only microscopic distances in a detector, hampering identification of ν_τ events.

To date, three experiments have been able to measure ν_τ oscillations via the $\nu_\mu \rightarrow \nu_\tau$ channel (ν_τ appearance), albeit with precision significantly below that achieved in ν_e and ν_μ measurements. The OPERA experiment observed 10 ν_τ candidates appearing in the CNGS ν_μ beam [4], identified via the τ lepton decay topology utilising an emulsion cloud chamber detector to achieve sub-mm spatial precision. Separately, the Super-Kamiokande [5] and IceCube [6] collaborations have exploited the large naturally occurring flux of neutrinos produced by cosmic ray interactions with the Earth's atmosphere. Atmospheric ν_μ with $\sim$25 GeV crossing the Earth's diameter maximally oscillate to ν_τ, and at these energies the suppression to the CC ν_τ cross section is $\mathcal{O}(50\%)$ relative to the $\nu_{e,\mu}$ cross sections [7], resulting in significant numbers of ν_τ appearance events being observed in these massive underground detectors. The ν_τ are not individually identified, but the appearance of many ν_τ is observed statistically.

2. ν_τ appearance in IceCube-DeepCore

The IceCube neutrino observatory [8] consists of 5160 Digital Optical Modules (DOMs) instrumenting a cubic-km of glacial ice deep below the geographic South Pole, with each DOM containing a single photomultiplier tube (PMT). Via the Cherenkov light produced by the charged secondaries of ν-ice interactions, this vast 1 Gton instrument observes huge rates of neutrinos of atmospheric and astrophysical origin. The 10 Mton DeepCore [9] sub-array in the deepest, clearest ice is instrumented more densely, lowering the detection threshold to $\sim$5 GeV and providing sensitivity to ν_τ appearance.

Neutrino oscillations are measured in DeepCore by reconstructing the energy and zenith angle (a proxy for neutrino travel distance) of the detected neutrinos, and comparing the flavor composition to the expected atmospheric neutrino flux. The flavor composition cannot be fully reconstructed, but crucially ν_μ CC interactions can be identified due to the elongated track-like topology of the deposited light produced by the long-lived μ produced, in contrast to the more spherical cascade-like topology observed for all other neutrino interactions.

The ν_τ appearance measurement is performed by fitting Monte Carlo (MC) simulation to detector data, scaling the ν_τ contribution. This scaling is known as the ν_τ normalisation, N_{ν_τ}, with a value of 1 expected for a unitary PMNS matrix. Nuisance parameters representing the uncertainty in neutrino oscillation parameters, atmospheric neutrino flux, neutrino interaction cross sections, optical sensor efficiency, ice properties and atmospheric muon background are included.

The results of two independent DeepCore ν_τ appearance measurements [6] are shown Figure 1. Three years of DeepCore data were used, achieving world-leading precision. The lead analysis observed a total of 1804$\pm$9 CC events at the best fit point, an order of magnitude more than any previous measurement, corresponding to a ν_τ normalisation of $0.73^{+0.30}_{-0.24}$, consistent with the expectation for a unitary PMNS matrix within 1σ. The second analysis obtains a consistent result. The DeepCore results indicate a lower ν_τ normalisation than measured by OPERA and Super-Kamiokande, though the tension is mild given the large uncertainties. A new measurement using 8 years of DeepCore data is currently underway.

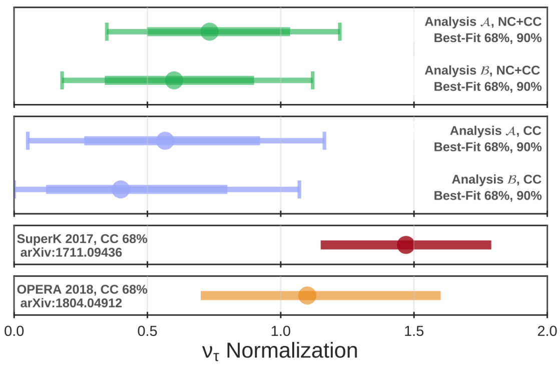

Figure 1: Measured ν_τ normalisation, including 1σ and 90% uncertainty, in two DeepCore analyses using 3 years of data [6]. The results of the Super-Kamiokande [5] and OPERA [4] experiments are shown for comparison.

The ν_τ normalisation can also be interpreted as a deviation of the ν_τ CC cross section relative to the theoretical prediction. This cross section is poorly known experimentally, although shares many theoretical similarities with the much more precisely measured ν_μ CC cross section.

3. The IceCube Upgrade

The IceCube Upgrade, to be deployed in 2022-23, will feature $\sim$700 new and enhanced multi-PMT optical sensors in a dense configuration within the already dense DeepCore array, as well as a suite of new calibration devices, and will be utilised to perform precision neutrino oscillation measurements. The increased light observed from neutrino interactions in the new detector is

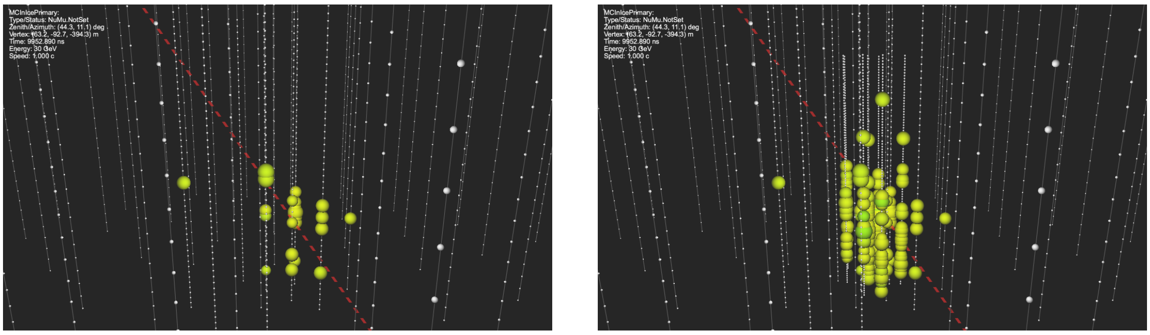

Figure 2: Event displays showing the same 30 GeV ν_μ CC interaction in the DeepCore (left) and IceCube Upgrade (right) sub-arrays. The white spheres represent optical sensors, whilst the colored spheres indicate photon hits on the sensors. The red line shows the path of the neutrino.

shown in Figure 2, along with the existing DeepCore array. This will significantly increase the rate of detected neutrinos in the DeepCore energy range, as well as lowering the detection threshold to provide high statistics measurements of ~1 GeV neutrinos, probing the second neutrino oscillation maximum and potentially providing sensitivity to the neutrino mass ordering via matter effects.

The performance of reconstructions of the neutrino energy and direction will be significantly enhanced in this new detector, with a factor 3 improvement in cascade zenith angle resolution at ~25 GeV expected, shown in Figure 3. The ability to identify ν_μ CC track-like events will also be improved.

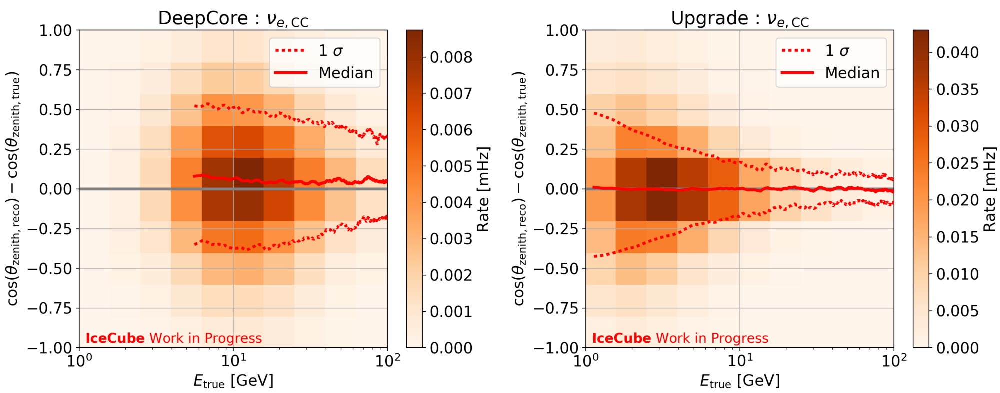

Figure 3: Histogram of the zenith angle reconstruction error for ν_e CC (cascade-like) events in DeepCore (left) and the IceCube Upgrade (right), shown as a function of neutrino energy. The solid red line indicates the median performance, whilst the dotted red lines show the region enclosing the central 68% of events.

The expected sensitivity of the IceCube Upgrade to ν_τ appearance is shown in the left panel of Figure 4, where a precision of 10% on the ν_τ normalisation is achieved after only a single year of data taking, more than 3× more precise than the current DeepCore result. In addition, the IceCube Upgrade will also be able to measure ν_μ disappearance with a precision comparable to current long-baseline accelerator neutrino experiments, at an order of magnitude higher energy. The IceCube Upgrade ν_μ disappearance sensitivity after 3 years is shown in the right panel of Figure 4.

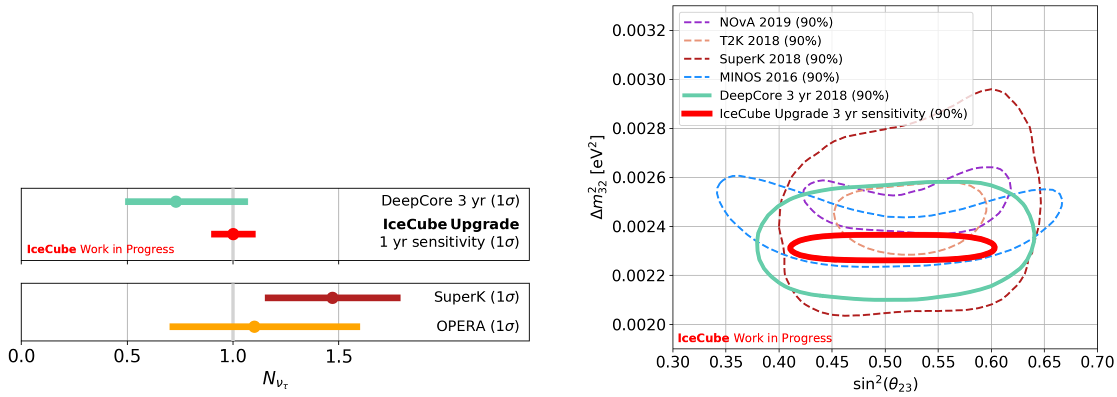

Figure 4: Sensitivity of the IceCube Upgrade to ν_τ appearance (left) ν_μ disappearance (right), assuming normal neutrino mass ordering and νFit 4.0 [10] oscillation parameters, with the exception that the atmospheric mixing angle and mass splitting measured in the 2018 DeepCore ν_μ disappearance measurement [11] are assumed in the right panel. References to external results can be found in [12].

4. Conclusions

Measuring the unitarity of the PMNS neutrino mixing matrix is a powerful test of the 3ν paradigm, and measurements of ν_τ oscillations are essential to achieve this goal. The DeepCore sub-array of the IceCube neutrino observatory has produced the world's most precise measurement of ν_τ appearance in 2019 using three years of data, and the under-construction IceCube Upgrade will provide better than 10% precision on the ν_τ normalisation during the next decade.

The IceCube Upgrade will also feature a broad particle physics program, providing world-leading sensitivity to a range of BSM physics, and pave the way for IceCube Gen2, an expansion of the entire IceCube array initiating a new era in astroparticle physics.

References

[1] B. Pontecorvo, *Sov. Phys. JETP* **6**, 429 (1957). [Zh. Eksp. Teor. Fiz.33,549(1957)].

[2] Z. Maki, M. Nakagawa, S. Sakata, *Progress of Theoretical Physics* **28**, 870 (1962).

[3] S. Parke, M. Ross-Lonergan, *Physical Review D* **93** (2016).

[4] N. Agafonova, *et al.*, *Phys. Rev. Lett.* **120**, 211801 (2018).

[5] Z. Li, *et al.*, *Physical Review D* **98** (2018).

[6] M. Aartsen, *et al.*, *Physical Review D* **99** (2019).

[7] S. Kretzer, M. H. Reno, *Phys. Rev. D* **66**, 113007 (2002).

[8] M. G. Aartsen, *et al.*, *JINST* **12**, P03012 (2017).

[9] R. Abbasi, *et al.*, *Astroparticle Physics* **35**, 615–624 (2012).

[10] I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, T. Schwetz, *Journal of High Energy Physics* **2019**, 106 (2019).

[11] M. Aartsen, *et al.*, *Physical Review Letters* **120** (2018).

[12] A. Ishihara, *et al.*, *PoS (ICRC2019) 928* (2019).