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Atmospheric neutrino results from IceCube-DeepCore and plans for PINGU

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Abstract. The IceCube neutrino observatory at the South Pole is the largest operating neutrino detector in the world and spans a wide range of science topics, from astronomy at the PeV-scale to particle physics at the GeV-scale. We present results from the search for a light, $\mathcal{O}(1)\,\mathrm{eV}^2$, sterile neutrino using the large IceCube array and, separately, using the lower energy extension DeepCore sub-array. Additionally, we review the atmospheric neutrino results and expected sensitivities related to oscillation physics (ν_μ disappearance and ν_τ appearance) as well as new limits on non-standard interactions. Continuing the success of the IceCube-DeepCore physics program, a proposed next generation in-fill detector with increased sensitivity to neutrinos of $\mathcal{O}(1)$ GeV will be covered.

1. Introduction

The IceCube Neutrino Observatory at the South Pole is the world's largest and most sensitive high energy neutrino telescope. The in-ice detector is composed of 5160 Digital Optical Modules, which house photomultiplier tubes and digitizing electronics designed to detect the Cherenkov photons from relativistic charged particles generated in neutrino-nucleon interactions. The detector instruments a cubic kilometer of ice and detects neutrinos of all flavors; classifying charged current ν_μ with an identifiable outgoing μ as 'tracks' and most other events with an isotropic photon emission profile as 'cascades' (charged current ν_e, charged current $\nu_\tau <\approx 2$ PeV, and all flavors of neutral current interactions). The details on the continued detection of astrophysical neutrinos with energies $> 100\,\mathrm{TeV}$ and the impact on neutrino astronomy are covered separately in [1].

Beyond the high energy neutrino capabilities, the addition of the DeepCore low energy extension created a unique opportunity to use atmospheric neutrinos to study neutrino oscillation. By deploying in the most clear ice, with a tighter instrumentation spacing, and more efficient PMTs than the rest of the IceCube detector, DeepCore can collect and reconstruct neutrino events down to $\approx 10\,\mathrm{GeV}$. Being located at the center of the IceCube array allows DeepCore to use the surrounding volume as an active veto volume to identify and reject penetrating atmospheric muon background, see Fig. 1.

2. Sterile Neutrinos

While we all know about the success of the Standard Model, the revelation of a non-zero neutrino mass portends new physics beyond this hallowed paradigm. In keeping with its exotic existence, the neutrino contributes fascination in part due to experimental anomalies

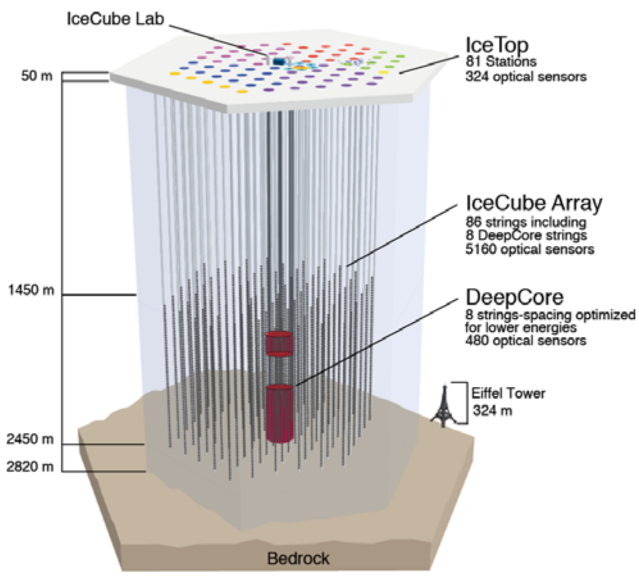

Figure 1: Layout of the IceCube detector, including the surface array (IceTop) and low energy extension (DeepCore).

that have been interpreted as coming from at least one additional sterile neutrino with a Δm^2_{41} of $\mathcal{O}(1)\,\mathrm{eV}^2$. While most of the current and previous experiments with results either supporting or constraining a sterile neutrino have come from accelerator or reactor experiments[2], the use of atmospheric neutrinos in conjunction with the huge size of IceCube contributes to the world's most sensitive search for eV-scale sterile neutrinos, in terms of mixing angles (θ_{24}) rejected at peak sensitivity.

One search in IceCube for a light sterile neutrino is somewhat different than many other high-profile measurements relying on neutrino oscillation, because of the energy scale where a sterile signal may exist. An ensuing deficit of active neutrinos can manifest at TeV energies and is therefore unique to neutrino telescopes, which by their nature are sensitive to TeV-PeV neutrinos.

As neutrinos pass through the Earth, they can undergo matter induced interactions that alter their respective oscillation probabilities. For atmospheric neutrinos at the GeV-scale these are often minor perturbations, but there are specific energies and matter profiles, i.e. baselines, which can produce resonant enhancements. For a sterile neutrino with a mass squared splitting of $0.1\,\mathrm{eV}^2$ to $1\,\mathrm{eV}^2$, the Earth's matter density profile results in a pronounced resonant oscillation feature at TeV neutrino energies that is wholly absent in the conventional 3-flavor only model. For the IceCube search, this means that a characteristic deficit will be seen from oscillation into a sterile state that impacts $\nu_\mu \to \nu_\mu$ or $\bar{\nu}_\mu \to \bar{\nu}_\mu$, see Fig. 2.

Whether the new sterile is the lightest mass eigenstate "1+3" or heaviest "3+1" affects the sensitivity for IceCube, because the matter induced enhancement contributes for either ν or $\bar{\nu}$, but not both simultaneously. IceCube has no neutrino sign-selection at GeV or TeV energies, but thankfully there is an innate difference in both the atmospheric flux and cross-section of $\nu/\bar{\nu}$ that can be used to disentangle the existence of a new oscillation feature even though the deficit must be extracted from a combination of $\nu_\mu + \bar{\nu}_\mu$. The recent IceCube results are for a "3+1" model, which is a conservative choice because it puts the impact of a new sterile state in the $\bar{\nu}$ channel which has the lower flux and cross-section. The results of the search are shown in Fig. 3a where a more comprehensive description can be found in [3, 4], and the references therein.

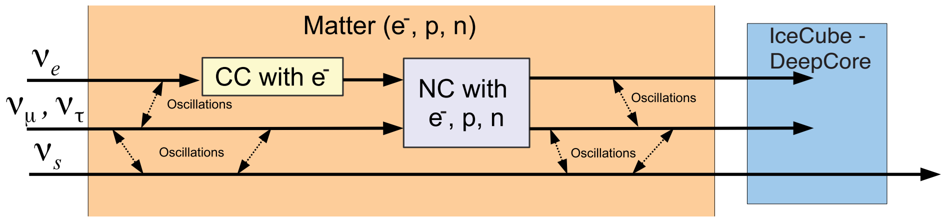

Figure 2: Cartoon of sterile neutrino oscillation and the contribution from matter interactions. Depending on the neutrino energy, matter density profile, and baseline there can be large resonant enhancements of the sterile induced disappearance signature for $\nu_\mu/\bar{\nu}_\mu$.

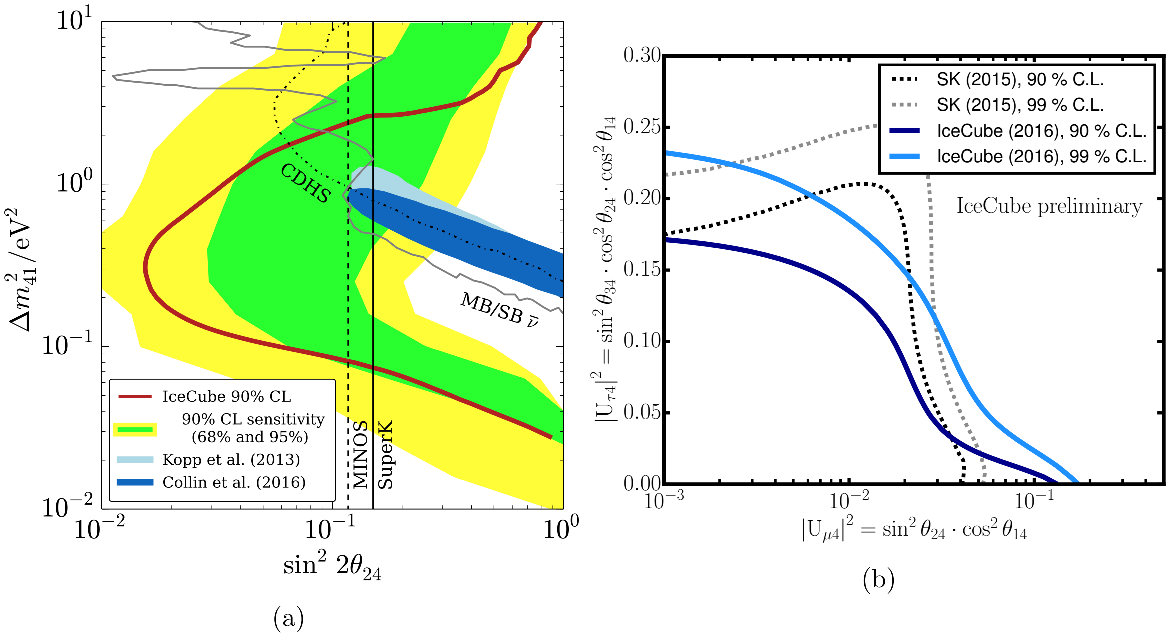

Figure 3: Results from two separate sterile neutrino searches using IceCube and relevant global fits[5, 6] and experimental limits[7, 8, 9, 10]. (a) is the search for a 'light' sterile neutrino with a resonant ν_μ oscillation feature which manifests at TeV energies. The lines represent the 90% CL exclusions, and the grey/blue region are the 99% CL allowed regions from global fits. (b) is an analysis of GeV spectral features using the DeepCore sub-array with the relevant limits from Super-Kamoikande[10].

2.1. Sterile Neutrinos in IceCube-DeepCore

Commensurate with a pronounced resonant oscillation feature at TeV energies from a light sterile neutrino, there are spectral energy features at GeV energies that also arise from an expansion of the 3×3 PMNS mixing matrix to 4×4. The added sterile state modifies the vacuum oscillation probability and the effective matter potential. The former introduces 'rapid oscillations' which are too fast in energy to be resolved, given the resolution of IceCube-DeepCore. Depending on the new sterile mixing parameters, the modified matter potential can introduce a change in the probability amplitude, shift in the probability frequency, or some combination of the two. For $\nu_\mu \to \nu_\mu$ using atmospheric neutrinos, IceCube-DeepCore is particularly sensitive to the mixing elements $|U_{\tau 4}|^2$ and $|U_{\mu 4}|^2$.

Because the matter potential induces changes to the oscillation probability, there is a direct correlation between the amount of matter traversed by the neutrino and the change in the

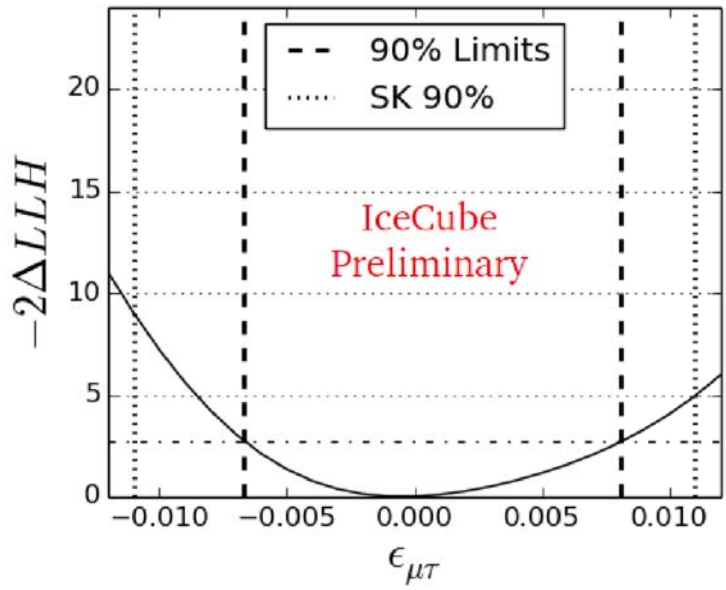

Figure 4: IceCube/DeepCore result (dash line) from the NSI analysis of $\epsilon_{\mu\tau}$ compared to Super-Kamiokande (dot line)[13]. The improvement for IceCube is due in part to a larger statistical sample as well as enhanced sensitivity to higher energy neutrino events.

oscillation probability. This results in the up-going neutrinos which cross the Earth's inner/outer core having the highest sensitivity to a sterile neutrino. The results of the search are shown in Fig. 3b, for a 3+1 model, all CP-phases set to zero, and a fixed value of $\Delta m^2_{41} = 1\,\mathrm{eV}^2$. Unlike the search in the TeV region, the sterile search using IceCube-DeepCore is insensitive to Δm^2_{41}, provided the splitting is $> 0.3\,\mathrm{eV}^2$.

2.2. Non-Standard Interactions

Deviations from the conventional 3-flavor neutrino paradigm are not the sole providence of sterile neutrino phenomenology, but can also arise from interactions mediated by non-Standard Model particles, i.e. mediators other than the canonical Z^0 and $W^\pm$, as neutrinos traverse through matter. In the presence of these Non-Standard Interactions (NSI), the parameterization of neutrino oscillations by a 3×3 matrix is accompanied by an additional 3×3 matrix (ϵ)[11]. In this NSI-regime, there is a consistent suppression to both the ν_μ and $\bar{\nu}_\mu$ survival probability for energies $> 100\,\mathrm{GeV}$, as well as spectral energy features for $< 100\,\mathrm{GeV}$. In order to provide a very pure $\nu_\mu/\bar{\nu}_\mu$ event sample, the event selection from the 3-year ν_μ disappearance publication was used[12]. Prior to running the analysis on the data, an under-modeled background was discovered in the original event selection. While other results (ν_μ disappearance and DeepCore sterile search) now use a modified version of the selection used in [12], studies of the NSI analysis found no impact in the sensitivity or physics result, and as such the unmodified selection was used to determine $\epsilon_{\mu\tau}$.

Results for the NSI analysis are shown for the $\epsilon_{\mu\tau}$ parameter in Fig. 4 along with the Super-Kamiokande limits[13]. The result uses the full 3-flavor oscillation probability calculation, sets the non-dominant NSI terms to zero, and omits the CP-violating terms.

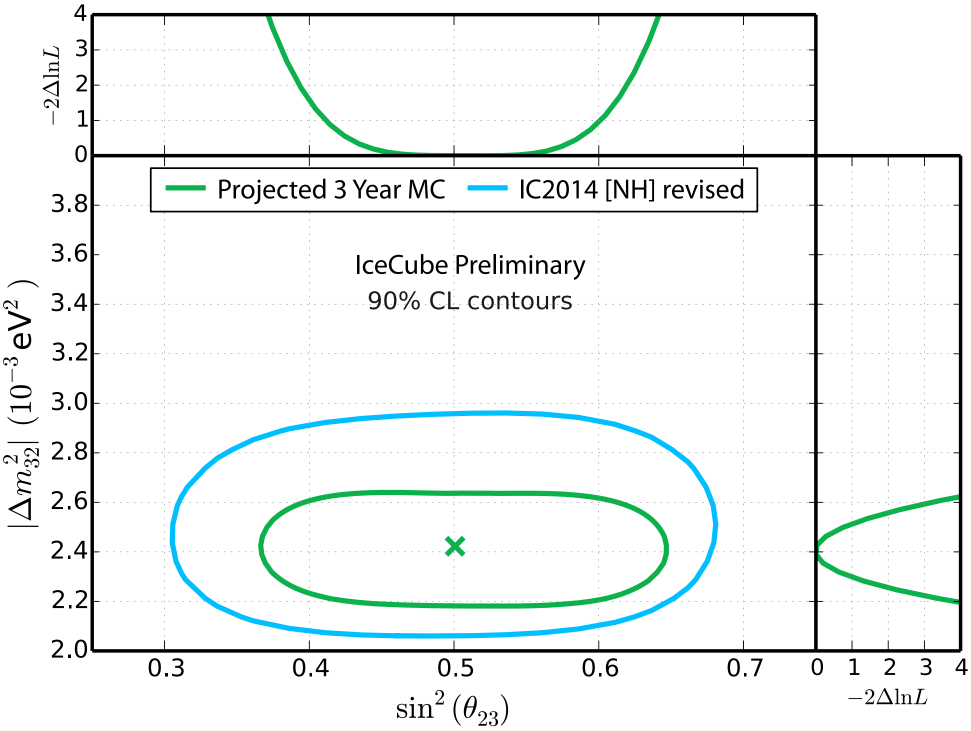

Figure 5: Contour of Δm^2_{32} and $\sin^2\theta_{23}$ for the 3-year result using the revised high purity track-like event selection with accompanying improvements in Monte Carlo simulation. Also shown is the projected 3-year sensitivity using a different event selection with higher statistics of track-like events ($\times 4$) as well as cascade-like ($\times 10$). A separate event selection with roughly a further $\times 2$ increase in both cascade- and track-like statistics yields a similar sensitivity as the illustrated 3-year projection.

3. Atmospheric Neutrino Oscillation In IceCube-DeepCore

The history of neutrino oscillation has been strongly coupled with using the natural flux of atmospheric neutrinos. That tradition is continued with DeepCore, which is deployed in the deepest and clearest ice, with higher quantum efficiency PMTs, and a decreased instrumentation spacing compared to the larger IceCube array. Being located at the center of the IceCube array allows DeepCore to use the surrounding volume as a veto to identify and reject penetrating muon background.

By using atmospheric neutrinos, IceCube-DeepCore can probe a multitude of baselines from 10 km to 12700 km. For measurements of the atmospheric oscillations parameters θ_{23} and Δm^2_{32}, the effect is most apparent for up-going neutrinos, i.e. those with baselines near the Earth's diameter. While the horizontal and down-going neutrinos have baselines that push their oscillation minima/maxima below the energy threshold of DeepCore analyses, the down-going region is useful as a constraint for systematic uncertainties such as the atmospheric muon contamination.

The IceCube-DeepCore ν_μ disappearance result of the oscillation parameters θ_{23} and Δm^2_{32} is from an analysis centered on a high-purity event selection and a directional reconstruction based on minimally scattered photons [12]. The analysis uses 3-years (953 days) of data from 2011 to 2013, with a median zenith angle resolution of $12°(5°)$ at $E_\nu = 10\,\mathrm{GeV}(40\,\mathrm{GeV})$ and energy resolution of 30%(20%) at $E_\nu = 8\,\mathrm{GeV}(15\,\mathrm{GeV})$. In the process of using the aforementioned high-purity event selection in the separate DeepCore-based sterile neutrino search, a new cut

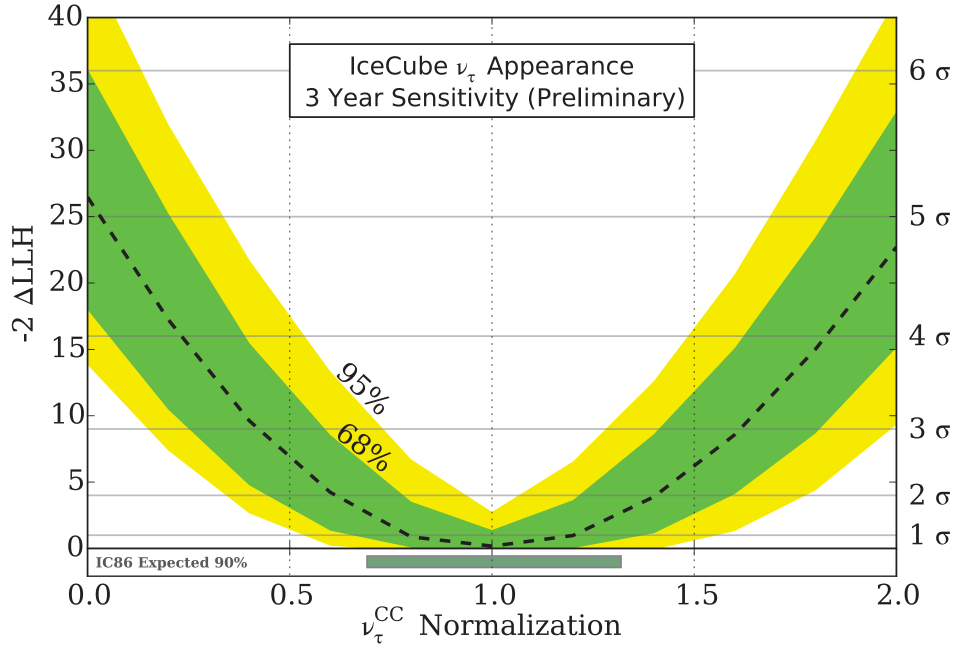

Figure 6: Sensitivity for the ν_τ appearance analysis in DeepCore using the high-statistics event selection for a true $N_{\nu_\tau CC}= 1$.

was introduced in order to remove more atmospheric muon background events. Coupled with improvements in the atmospheric neutrino flux simulation, more accurate charge calibration, and improved modeling of the detector noise the updated result is shown in Fig. 5.

The use of a high-purity ν_μ event selection is beneficial in regards to being minimally sensitive to a range of systematic uncertainties (photon scattering, atmospheric muon background, etc.), but has a low efficiency. Additional analyses are in development with less-stringent selection criteria, i.e. added statistics and efficiency but lower purity, and alternative angular reconstructions based on likelihood fits using all the collected photons, not just those which were minimally scattered. The sensitivity for a 3-year data set for an analysis using an event selection with a factor of ≈ 4 more statistics than the high-purity selection is also shown in Fig. 5. Yet another event selection with an additional factor 2 increase in statistics, but more background contamination and impacts from systematic uncertainties, has been developed for the search for ν_τ appearance in DeepCore.

The appearance of ν_τ from ν_μ disappearance, $\nu_\mu \rightarrow \nu_\tau$, is an important experimental observable towards confirming the unitarity of the 3×3 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix. A difference in the number of 'appearing' ν_τ from the number of disappearing ν_μ would be a strong signature of new neutrino physics, e.g. non-unitarity of the neutrino mixing matrix, sterile neutrino(s), non-standard interactions, etc. The OPERA experiment has ruled out a $N_{\nu_\tau CC}= 0$ at 5σ significance[14], with Super-Kamiokande[15] similarly rejecting $N_{\nu_\tau CC}= 0$ at 4.6σ.

Some inherent difficulties in such an analysis are that the oscillated signal ν_τ's have a low cross-section, the τ lepton from a CC interaction is only a few mm long for baselines of $\mathcal{O}(100)$ km to $\mathcal{O}(10\,000)$ km and hard to identify, and the τ lepton decays quickly with at least one daughter neutrino that escapes with missing energy. The signal events of CC ν_τ are cascade-like, and unlike the track-like events from a CC ν_μ have a larger background and worse angular

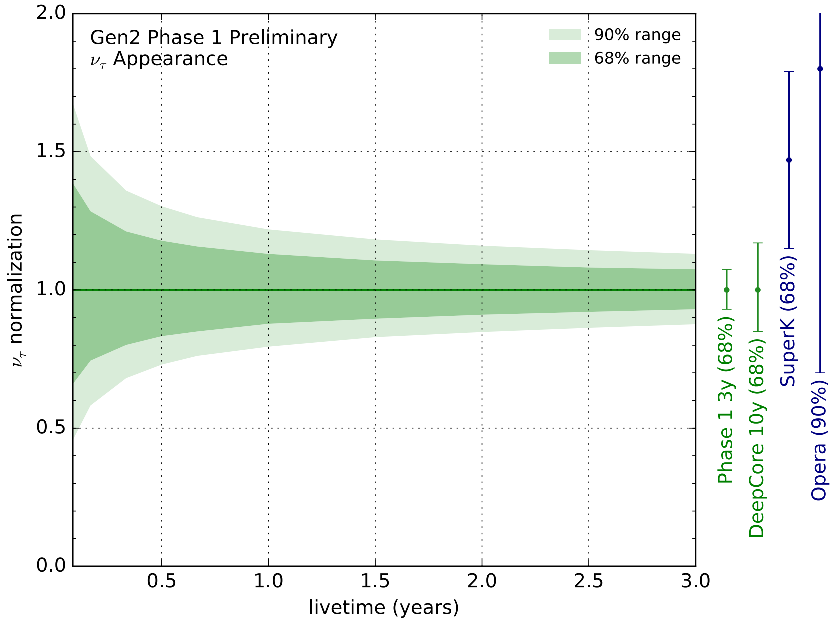

Figure 7: Sensitivity for the ν_τ appearance analysis for Phase-1 for a true $N_{\nu_\tau CC}= 1$. In the absence of a large Phase-1 simulation set of atmospheric muons for background estimation, a conservative choice was made to use the medium statistics – but lower background, event selection; the same used for the projections in Fig. 5.

reconstruction resolution, making them more difficult to identify as up-going. The oscillated ν_τ can be distinguished from the background of cascade-like neutrinos (CC ν_e, CC ν_μ with short muons, and NC events of all flavor) by the characteristic angular distribution and energy spectrum, arising from their appearance via flavor oscillation at specific length/energy. Thus, the experimental signature is a statistical excess in contrast to unique identification of individual CC ν_τ interactions. Any absence of CC ν_τ interactions should also be accompanied by an absence of the NC ν_τ events as well, but in Fig. 6 we only show the sensitivity to the CC interactions in order to match the conventions of the other global results in terms of the ν_τ normalization ($N_{\nu_\tau CC}$) – where $N_{\nu_\tau CC}= 1$ agrees with the 3 flavor oscillation and $N_{\nu_\tau CC}\neq 1$ constitutes new physics. The sensitivity shown in Fig. 6 uses yet a different event selection than the two used for the ν_μ disappearance analyses shown in Fig. 5, and is specially optimized for the detection of very low energy events necessary for such a search, but includes higher background rates

4. PINGU and Phase-1 of IceCube-Gen2

The proposed PINGU detector is an in-fill to the DeepCore region designed to further lower the IceCube energy threshold, preserve a large fiducial mass, and use the outer IceCube layers as an active veto against cosmic ray muon background[16]. It is part of a wider effort, IceCube-Gen2, to extend the capabilities of IceCube at lower energies to enhance neutrino-based particle physics, and at higher energies to capitalize on the nascent field of neutrino astronomy. For the high energy IceCube-Gen2 counterpart see [1]. For PINGU, the increased density of Digital Optical Modules will enhance the on-going neutrino oscillation searches (notably ν_τ appearance), improve the low-mass region of indirect dark matter searches, and provides a complement to resolving the neutrino mass hierarchy (inverted or normal) using atmospheric neutrinos.

As the initial deployment of IceCube-Gen2, a phased approached is being examined for PINGU which will introduce 7 new vertical strings with multi-PMT digital optical modules (mDOMs). The Phase-1 strings are envisioned to have roughly 125 mDOMs, each with 24 independent 3" PMTs distributed nearly uniformly within a spherical pressure vessel to provide 4π coverage, similar to the KM3NeT design[17]. The strings will feature new calibration devices to better measure the optical properties of the ice, enhancing IceCube's already strong contribution to multimessenger astrophysics via improved reconstruction of the direction of high energy cascade events. The new calibration devices, degassing of the water used for the hot water drilling, and an improved ability to use down-going atmospheric muons as in-situ calibration sources because of the 4π mDOM coverage will improve not just PINGU measurements, but potentially all IceCube measurements with significant systematic uncertainties due to the ice optical properties.

A preliminary sensitivity of a measurement of ν_τ appearance ($N_{\nu_\tau CC}$) in Phase-1 is shown in Fig. 7. Because a few systematic uncertainties (specifically the contribution from atmospheric muons) have not yet been fully examined, we currently use a lower statistics event selection than what is used in Fig. 6. Even with the conservative analysis choice and excluding the contribution of the previous years of DeepCore data, the addition of Phase-1 strings improves the worldwide precision by a factor of two with less than two years' livetime, and reaches roughly 10% precision on this key measurement with about five years of livetime. Beyond the world-best precision measurement of $N_{\nu_\tau CC}$, neutrino oscillation measurements by IceCube-DeepCore and Phase-1 will complement accelerator and reactor neutrino experiments due in no small part to the different set of systematic uncertainties. As the neutrino oscillation field steps towards hopefully measuring the weak impact of a CP-violating phase (δ_{CP}), the robustness of global neutrino oscillation fits can be greatly enhanced by having orthogonal data sets.

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