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Status of atmospheric neutrino oscillation measurements in IceCube and PINGU*

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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 θ_{23} and $|\Delta m^2_{32}|$ with precisions approaching that of dedicated experiments. PINGU, a proposed low energy extension to IceCube, would further reduce the detector's energy threshold to a few GeV to allow the measurement of the neutrino mass hierarchy at the 3 σ level with 3-5 years of data, in addition to significant improvements to the determination of the parameters already being studied by DeepCore. Current results from DeepCore and PINGU sensitivity to θ_{23}, $|\Delta m^2_{32}|$ and the neutrino mass hierarchy are discussed here.

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 (δ_{CP}) and the mass hierarchy. For the latter, the case where the third mass eigenstate is heaviest (positive Δm^2_{32}) is referred to as "normal" (NH), while when it is the lightest (negative Δm^2_{32}) it is referred to as "inverted" (IH). The amplitude of the neutrino flavor oscillation is determined by the elements of the mixing matrix, which is described by the mixing angles (θ_{12}, θ_{13}, and θ_{23}) and δ_{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 it traveled 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 ν_μ 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 ν_μ disappearance [4] as a function of L and E and therefore measure the parameters

$|\Delta m^2_{32}|$ and θ_{23}.

A recent measurement [5] of a relatively large mixing angle between the first and third mass eigenstates (θ_{13}) has made it possible to determine the neutrino mass hierarchy using atmospheric neutrinos with megaton-scale detectors such as the proposed Precision IceCube Next Generation Upgrade (PINGU). This is possible due to matter effects [6, 7], that depend on the sign of Δm^2_{32}, affecting neutrinos propagating through the Earth's core and mantle which produce a resonant effect changing the event rates in the detector as a function of L and E around 5-15 GeV [8, 9]. PINGU will also contribute to improving the precision measurement of ν_μ disappearance among several other topics discussed in detail in [10].

THE ICECUBE/DEEPCORE AND PINGU DETECTORS

The IceCube Neutrino Observatory [11] 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 instrumented with 5160 digital optical modules (DOMs). 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 [12].

The original detector design was augmented by creating a region close to the 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 [13], 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.

With the goal of further lowering the energy threshold of the IceCube Neutrino Observatory, PINGU [10] is being proposed. It achieves that goal by further increasing the density of optical modules in the DeepCore region, as shown in Fig. 1. This increased photocathode density will effectively lower the energy threshold of the detector by an order of magnitude.

Background rejection

The main background in IceCube/DeepCore to observing ν oscillations consists of the atmospheric μ 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 μ events, some of these algorithms are also used to

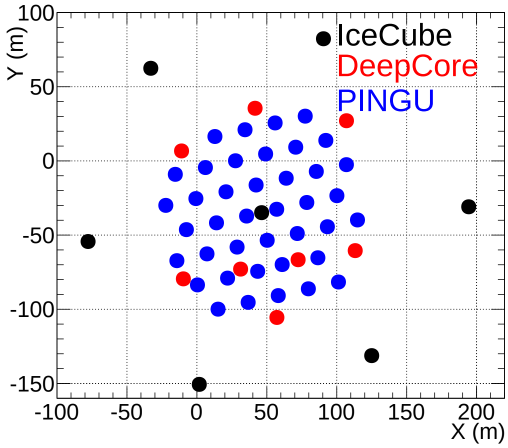

Figure 1: A top view of the proposed PINGU detector geometry used for the studies presented in this proceeding. The location of existing IceCube strings are shown in black, DeepCore in red and PINGU in blue.

extract a sample used to estimate the shape of the distribution of this background in the final sample. Besides these veto criteria, atmospheric μ are down-going and signal ν are up-going, therefore restricting the final sample only to events reconstructed as up-going further reduces the atmospheric μ 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.

In PINGU, while we have not performed extensive atmospheric μ background and dedicated detector self-triggering simulations, we expect to be able to reject these two backgrounds using the same techniques that are already successfully in use in DeepCore, and given the low rates of these backgrounds in the DeepCore they are currently neglected in PINGU analyses.

Reconstruction of events

The signal for the 3-flavor ν oscillation analysis are neutrinos with energy less than about 50 GeV. Given the detector threshold for both DeepCore and PINGU, most of the interactions are produced via deep inelastic scattering (DIS) which produce for ν charged current (CC) interactions a lepton of the same flavor as the neutrino and a hadronic shower, which are to a good approximation collinear.

The lepton produced by the ν interaction will either produce a track in the detector if there is a μ in the final state, or a shower otherwise. Given the detector granularity, the lepton induced showers and the hadronic showers produced by the DIS interactions will have a similar topology, while a μ track can be distinguished more easily from the showers. Because of that, the general hypothesis used for reconstructing events is of DIS ν_μ CC interactions. Using this hypothesis, the other interactions (with the exception of ν_τ CC interactions with a μ produced by the τ decay) will resemble a ν_μ CC interaction with a low energy μ produced, and given the similarities in the different shower topologies they are still reconstructed reasonably well. Additionally, looking for a μ in the final state is also used to either select mainly ν_μ CC events for ν_μ disappearance analyses, as shown in Fig. 2, or to classify events between tracks and cascades for the neutrino mass hierarchy analysis.

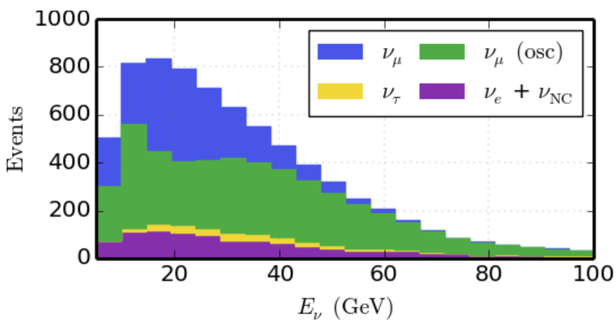

Figure 2: Composition of sample used for the ν_μ disappearance analysis [4] as a function of true neutrino energy. The blue shaded area shows the expected size of the oscillation effect reducing the event rate, while the purple and yellow region show the contamination of the sample by events that are not ν_μ CC (green).

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 [14]. 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.

A new reconstruction method has 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 [15]. 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. This new reconstruction is currently being tested in DeepCore with the goal of creating the next generation of oscillation analysis and is also the main reconstruction used in PINGU.

Neutrino mass hierarchy signature in PINGU

For neutrino energies around 5-15 GeV, the MSW effect changes the survival probabilities for neutrinos and anti-neutrinos differently, depending on the ordering of the mass states. The difference between the cross-section of neutrinos and anti-neutrinos makes it possible to use atmospheric neutrinos to measure the neutrino mass hierarchy without an explicit discrimination between ν and $\bar{\nu}$ as proposed by [8, 9]. This is possible by comparing the observed rate of neutrinos as a function of E and L (measured by reconstructing the neutrino direction) with the expected distributions from the NH and IH hypothesis. The expected difference between these two cases, shown in Fig. 3, while small, creates a pattern that is measurable and helps reduce the effects of various systematics.

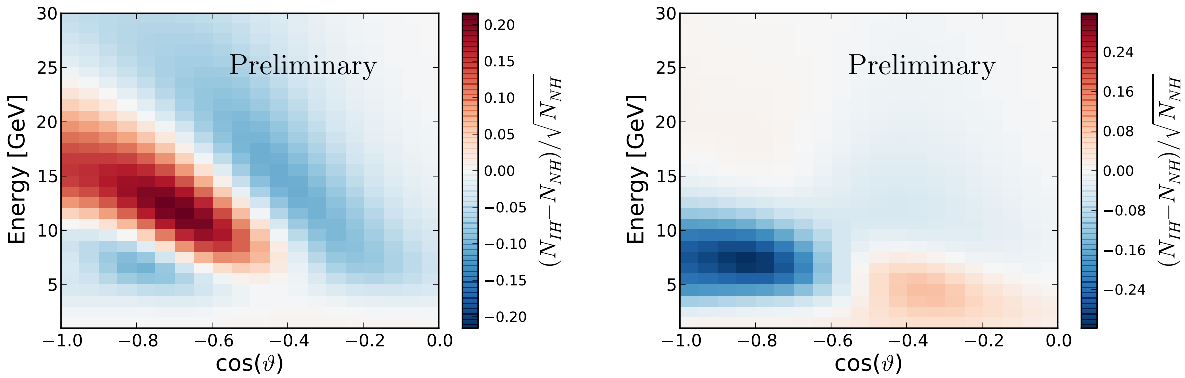

Figure 3: Distinguishability metric for track-like (left) and cascade-like (right) events for the neutrino mass hierarchy as defined in [9] for one year of simulated PINGU data.

ANALYSIS METHOD AND SYSTEMATICS

The current oscillation analysis in DeepCore aims at measuring θ_{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 χ^2 approximation. In those fits θ_{13} is allowed to vary in the region allowed by the global fit to data [3], while δ_{CP} is fixed to 0 and θ_{12} and Δm^2_{21} are fixed to their best fit value [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 ν and μ flux, neutrino interactions and detector related effects. Table I lists all the parameters considered.

Table I: Nuisance parameters used in DeepCore ν_μ disappearance analysis [4].

Nuisance parameters		Nominal value	Variation
Atmospheric flux	overall ν normalization	Honda 2015 [16]	Free
	atm. flux spectral index		$\pm 5\%$
	ν_e/ν_μ flux ratio		$\pm 20\%$
	overall μ normalization	from data	Free
Neutrino interactions	QE axial mass	GENIE [17]	from GENIE
	RES axial mass		
	DIS Bodek-Yang parameters		
Detector	DOM angular acceptance	flashers [15]	from range of models
	DOM overall efficiency	flashers and μ	$\pm 10\%$
	Bulk ice surrounding detector	flashers	compared 2 models
	Hadronic energy scaling	Geant4[18]	$\pm 5\%$

For PINGU analyses, the data is replaced either by an ensemble of pseudo-experiments or by an average experiment in the fitting procedure described above. The sensitivity to the neutrino mass hierarchy, in the case where an ensemble of pseudo-experiments is used, is estimated by computing the probability to reject the other hierarchy for the median experiment using the likelihood ratio between fitting each hierarchy; alternatively in the case where an average experiment is used, the sensitivity is estimated by computing the $\Delta\chi^2$ obtained with from fitting either hierarchy and assuming the value is distributed as a χ^2 with 1 degree of freedom [19]. In both cases the "wrong hierarchy" parameters tested are chosen to minimize the difference to the "true hierarchy" being tested. The sensitivity to $|\Delta m^2_{32}|$ and θ_{23} is estimated using the same procedure as for the average experiment, however it is compared to a χ^2 with 2 degrees of freedom.

The nuisance parameters considered in PINGU analysis are similar to those used for DeepCore for the atmospheric ν flux, neutrino interactions and ν oscillations. An additional uncertainty of 10% on the $\nu/\bar{\nu}$ ratio has been added and the range of variation allowed for the atmospheric ν flux parameters was re-evaluated based on [20]. The neutrino interaction uncertainties as well as a more detailed description of the atmospheric ν flux uncertainties have only been accounted for with the χ^2 method and were shown to have a small impact in the results. The detector uncertainties accounted for in DeepCore are are not currently considered in PINGU, however an energy scale uncertainty of 10% is used in PINGU as a proxy for the DOM efficiency uncertainty. $|\Delta m^2_{32}|$ and θ_{23} are free nuisance parameters for the neutrino mass hierarchy analyses and are found to be the parameters with the largest impact in its significance.

RESULTS

The latest published ν_μ disappearance analysis in DeepCore [4] was obtained using 3 years of data. The events selected with reconstructed energy between 6 and 56 GeV were used to measure $\sin^2\theta_{23} = 0.53^{+0.09}_{-0.12}$ and $|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} \times 10^{-3}\text{eV}^2$. The best fit point and 90% confidence regions as a function of these oscillation parameters are shown in Fig. 4.

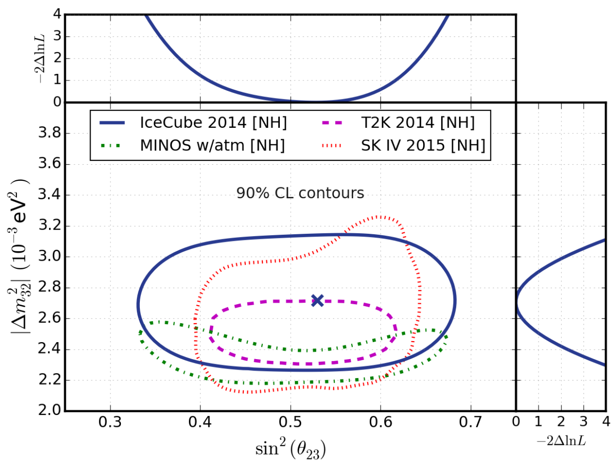

Figure 4: Latest DeepCore ν_μ disappearance results [4] (blue) compared with other experiments [21–23].

The PINGU sensitivity to the neutrino mass hierarchy depends strongly on the value of θ_{23} as shown in the left of Fig. 5. Assuming the best fit values for θ_{23} and Δm^2_{32} quoted by the global fit [24], a 3 σ determination of the neutrino mass hierarchy is expected with 5 years of data as shown in the right of Fig. 5. Using current information provided by global fits [24] the time to reach 3 σ is reduced to about 3 years. This is a somewhat pessimistic scenario as the global best fits for $\sin^2\theta_{23}$ are close to the minimal sensitivities expected as a function of θ_{23}. PINGU's capability to measure θ_{23} and $|\Delta m^2_{32}|$ is shown in Fig. 6.

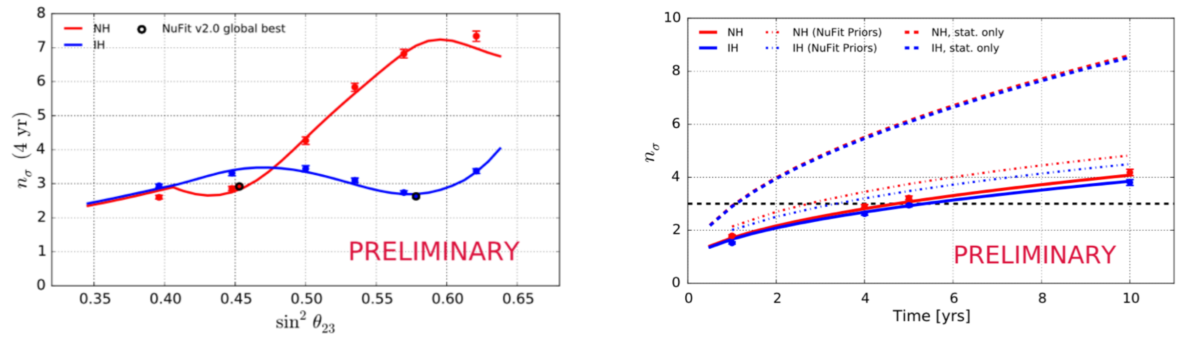

Figure 5: PINGU sensitivity to the neutrino mass hierarchy using ensembles of pseudo-experiments (points) and average experiments (lines) as a function of $\sin^2\theta_{23}$ for 4 years on the left, and as a function of time for θ_{23} from [24] on the right. On the right figure, in addition to the base analysis where all systematics are accounted and no external information is used to constrain θ_{23} and $|\Delta m^2_{32}|$ (solid lines and points) the cases where we use current knowledge on oscillation parameters from [24] (dotted lines) or assume statistical only errors (dashed lines) are also shown.

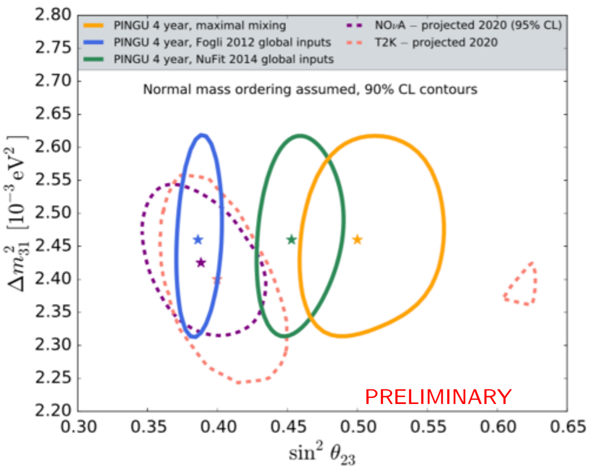

Figure 6: PINGU sensitivity to θ_{23} and $|\Delta m^2_{32}|$ assuming NH for different assumed true parameters [24, 25] (solid lines) compared to projected T2K [26] and NOνA [27] results.

CONCLUSIONS

Despite being used for almost 20 years since the discovery of neutrino oscillations, atmospheric neutrinos are still a valuable tool to study this phenomenon; recent results obtained with DeepCore have started to approach the sensitivities obtained by dedicated experiments, and the proposed low-energy extension to IceCube, PINGU, will have capability of measuring at 3 σ the neutrino mass hierarchy with 3-5 years of data in addition to significantly improving the measurement of θ_{23} and $|\Delta m^2_{32}|$.

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