

PINGU Sensitivity to the Neutrino Mass Hierarchy[☆]

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Abstract

The neutrino mass hierarchy is one of the few remaining unknown parameters in the neutrino sector and hence a primary focus of the experimental community. The Precision IceCube Next Generation Upgrade (PINGU) experiment, to be co-located with the IceCube DeepCore detector in the deep Antarctic glacier, is being designed to provide a first definitive measurement of the mass hierarchy. We have conducted feasibility studies for the detector design that demonstrate a statistically-limited sensitivity to the hierarchy of 2.1σ to 3.4σ per year is possible, depending on the detector geometry (20 to 40 strings) and analysis efficiencies. First studies of the effects of systematic and theoretical uncertainties show limited impact on the overall sensitivity to the hierarchy. Assuming deployment of the first array elements in the 2016/17 austral summer season a 3σ measurement of the hierarchy is anticipated with PINGU in 2020.

The mixing angles and mass-squared differences that describe oscillations in the neutrino sector have been measured with high precision through the efforts of a variety of experiments worldwide [1]. We plan to submit a proposal to build the Precision IceCube Next Generation Upgrade (PINGU) experiment to measure one of the few remaining unknowns in the neutrino sector, the neutrino mass hierarchy (NMH). PINGU will leverage the demonstrated ability of IceCube's DeepCore in-fill array to measure atmospheric neutrino oscillation parameters [2] via deployment of a further increase in the photon detector density in the DeepCore region. This will enable us to isolate and reconstruct a high-statistics sample of 5–20 GeV atmospheric muon neutrinos that undergo matter effects over a wide range of baselines, providing sensitivity to the NMH [3, 4, 5]. Based on our preliminary estimates, we expect that we could determine the hierarchy with a statistical significance of 3σ with 1–2 years of data, and a significance of 5σ using 2–4 additional years of data.

The PINGU design and construction follows closely that of IceCube, with similar hot-water drilling techniques, down-hole cables, deployment strategy, Digital Optical Module (DOM) hardware, and online and offline software. We are evaluating the NMH sensitivity of three distinct detector geometries with either 20 or 40 strings of DOMs, and 60 to 100 DOMs per string, chosen to bracket the range of geometries deployable in either a two- or three-year period and consistent with drilling and deployment constraints. Using well-established metrics from IceCube experience, the cost to construct and deploy PINGU is estimated to be between \$8M–12M in startup costs associated with setting up DOM assembly and refurbishing the hot water drill used for IceCube construction, presuming the existing drill equipment remains available for use by PINGU, plus roughly \$1.25M per string related to the detector hardware and deployment. We anticipate that some of this funding, as well as logistical support, would come from US funding sources, but that a considerable portion would be provided by international partners. First deployments could start as early as the 2016/17 South Pole summer season, and be completed in 2–3 seasons depending on geometry. This would permit a determination of the hierarchy with 3σ significance by 2020.

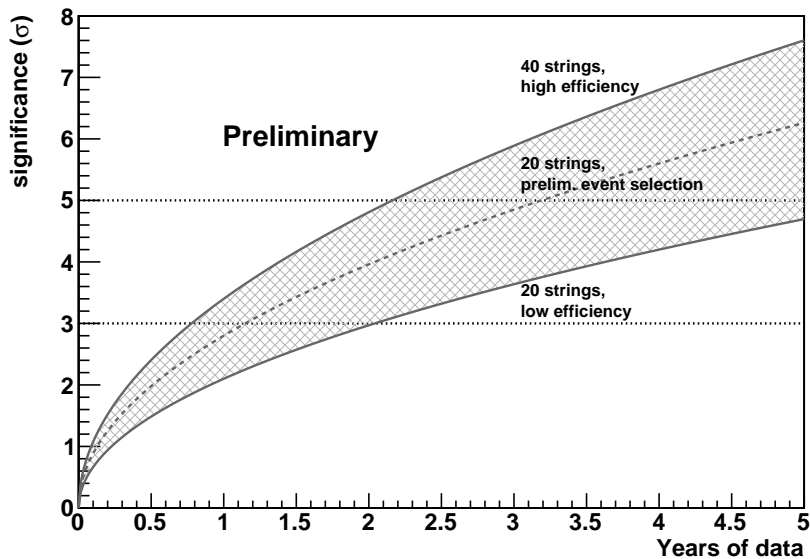
Detailed studies of the performance of PINGU and the significance with which it would determine the NMH are ongoing. These studies address detector energy and angular resolution, background rejection, systematic uncertainties, and the impact of degeneracies with physics parameters other than the NMH. At present, three independent estimates of the PINGU sensitivity to the NMH have been developed using different statistical techniques and assumptions regarding detector performance and including different combinations of physics degeneracies and detector systematics. Each study was designed to evaluate the impact of a particular factor or group of factors which may impact PINGU’s sensitivity, as discussed below. While we continue to work to include the full details in a single complete study, these targeted investigations give us confidence that there are no fundamental problems that could prevent a measurement of the NMH with PINGU within a few years. Since this work is still in progress, we present a range of estimated sensitivity (see figure), presenting both the different geometries under study as well as a range of predicted performance of background rejection and flavor identification algorithms.

From the preliminary studies we anticipate the sensitivity will be statistically limited for the first few years, and the projected time dependence is based on this assumption. All estimates are based on a full three-flavor treatment of neutrino oscillations including matter effects, and although to date we have not fully examined the influence of non-zero δ_{CP} or uncertainties in the true values of θ_{12} and Δm_{12}^2 , their impact is not expected to be large [4]. We have found that the ability to measure neutrino oscillations across a wide range of energies and baselines allows us to constrain our systematic uncertainties and resolve degeneracies between physics parameters quite accurately from the data itself. The matter effects we would exploit to measure the NMH produce distinctive signatures in the energy-angle space, and systematic uncertainties related to the detector do not reproduce these complicated patterns. We note that an additional study using a simplified detector model was conducted to assess the relative importance of physics degeneracies, reaching conclusions similar to [4, 5], and suggesting that a sensitivity of 5σ could be reached before systematic effects limit further increases in sensitivity.

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Event quality and selection are key elements in these studies. The simulations of the angular and energy resolution of the three detector geometries have been conducted using established, computationally fast, DeepCore algorithms optimized for the PINGU geometry. These algorithms yield a median neutrino energy resolution of about $(0.7 \text{ GeV} + 0.2 \times E_\nu)$, and a median neutrino angular resolution improving from 15° to 8° as E_ν increases from 5 to 20 GeV. More computationally intensive algorithms yield better resolutions at higher efficiency, but we use the fast algorithms in the studies presented here of PINGU’s NMH sensitivity, partly to be conservative and partly to reduce turnaround time while studying the systematic uncertainties. We assume that we will be able to reduce the atmospheric muon background rate to a low level without substantial loss of signal efficiency based on our experience with DeepCore [2, 6] and on the knowledge that PINGU will benefit from the enhanced active vetoing provided by the outermost DeepCore strings. Studies of atmospheric muon rejection are underway to confirm this assumption. After reducing the atmospheric muon background, we expect that neutrino events other than ν_μ CC will dominate as the remaining background. The three estimates discussed below use different methods to estimate the effect of this background.

The first analysis models a 40 string detector, and makes aggressive assumptions regarding signal efficiency. Our



Estimated significance for determining the neutrino mass hierarchy with PINGU. The top of the range is based on a 40 string detector with a high assumed signal efficiency in the final analysis; the bottom uses a 20 string detector and assumed a lower signal efficiency.

more computationally expensive event reconstructions indicate that approximately 85% of neutrino-induced shower events reconstruct with a track length $L_\mu < 15$ m; rejecting events reconstructing with shorter L_μ corresponds to imposing a muon energy threshold of ~ 3 GeV and a neutrino energy threshold of $E_\nu \sim 6$ GeV, which is comparable to the threshold for successful event reconstruction with the faster algorithms used in this study. In this first analysis, we therefore assume that this efficiency of successful event reconstruction will be comparable to the final efficiency of the eventual PINGU analysis.

The analysis uses a binned χ^2 approach using “pull factors” to account for experimental and theoretical systematic uncertainties [7]. The simulated data sets used for the analysis are reconstructed using the fast algorithms discussed above, binned in the reconstructed energy and angle, with bin widths commensurate with the expected resolutions. Systematic uncertainties are incorporated into the analysis as nuisance parameters in the χ^2 sum and are simultaneously fit to the data with penalty terms according to the current estimated uncertainties. An approximation for the median sensitivity of the detector is provided by the analysis of a representative dataset, also known as the “Asimov” data set [8], under the assumption that the test statistic will be approximately χ^2 distributed despite the discrete nature of the measurement. We verified the accuracy of this procedure using ensembles of pseudo-experiments in which both the mass splitting and the values of the nuisance parameters responsible for the primary systematic uncertainties were fit, and found that the approximation was generally conservative. We have evaluated the impact of systematic uncertainties in our effective volume for neutrino events (30%) and in the spectral index of the atmospheric muon neutrino flux (± 0.05), as well as potential biases in our absolute energy scale calibration (10%) and directional reconstruction (10%), and errors in our estimated energy and angular resolutions (10%). Theoretical uncertainties in the values of θ_{23} and Δm_{atm}^2 are treated in the same manner. With these systematics included, we obtain a median expected significance of 3.4σ per year for the current world average values of the oscillation parameters (top curve in figure). Considering the full range of atmospheric mass splitting and mixing angle preferred by current world measurements, a significance of 2.8σ or better is expected from one year of data.

A second analysis models a less densely instrumented 20 string detector and uses a similar statistical analysis, although a likelihood ratio is calculated rather than a χ^2 . This analysis includes full event reconstruction and background rejection based on DeepCore analysis methods, modified for the denser PINGU geometry and using the outermost DeepCore strings to veto atmospheric muons in view of the smaller PINGU fiducial volume. Signal efficiencies of around 9% are obtained in the range from 5–15 GeV. While this event selection provides some rejection of NC and ν_e backgrounds, the residual backgrounds are accommodated in the statistical analysis. The ν_e flux normalization is treated as an additional nuisance parameter to accommodate uncertainties in the production rate in air showers. This analysis included the theoretical uncertainty on θ_{13} as well as the atmospheric mass splitting and mixing angle, but did not examine the impact of potential reconstruction biases or errors in detector resolution. This analysis found an expected significance of 2.8σ from one year of PINGU data (middle curve in figure) assuming the world average oscillation parameters (including non-zero δ_{CP}) in the inverted hierarchy scenario, and slightly higher for the normal hierarchy.

The third analysis used the more CPU-intensive approach of generating and fitting ensembles of pseudo-experiments using a likelihood ratio-based analysis. This analysis also considered the 20-string detector but assumed that a much lower signal efficiency, ranging from about 1% at 5 GeV to 30% at 15 GeV, would be achieved after rejection of backgrounds due to atmospheric muon and neutrino-induced cascades. To reduce processing time, detector resolution effects were modeled with a Gaussian smearing based on the resolutions given above instead of explicit reconstruction of each event. Even with the lower assumed efficiencies used in this analysis, we estimate that a 3σ measurement of the hierarchy would be possible with 2 years of data (bottom curve in figure). Given the shorter deployment schedule of the smaller detector, this measurement could also be completed by 2020. Due to the computational intensity of this approach only the primary physics systematic, which was found to be the value of Δm_{31}^2 , consistent with [4, 5], was explicitly included in this study. However, just as in the first analysis described above, we find that the expected significance of the measurement is essentially independent of the true value of Δm_{31}^2 when the full energy-angle range of the data is used to determine the NMH. Further work is underway to confirm that the other systematics (including the mixing angles and δ_{CP}) can be similarly handled without reducing the expected significance.

While we continue to work to optimize the PINGU geometry, to model more accurately the impact of background rejection and physics degeneracies on the final analysis, and to investigate further the impact of possible detector-related systematics, we believe that these studies demonstrate that all of the major potential issues are manageable

and that a measurement of the NMH would be possible with PINGU by 2020. We are currently preparing a detailed Letter of Intent discussing these studies and secondary PINGU physics topics, to be followed by a full proposal.

References

- [1] J. Beringer *et al.* (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
- [2] M. G. Aartsen *et al.* (IceCube Collaboration), arXiv:1305.3909v1, accepted by Phys. Rev. Lett. (2013).
- [3] O. Mena, I. Mocioiu and S. Razzaque, Phys. Rev. D 78, 093003 (2008).
- [4] E. Kh. Akhmedov, S. Razzaque and A. Yu. Smirnov, arXiv:1205.7071v2 (2012).
- [5] W. Winter, arXiv:1305.5539 (2013).
- [6] M. G. Aartsen *et al.* (IceCube Collaboration), Phys. Rev. Lett. 110, 151105 (2013).
- [7] G. L. Fogli, E. Lisi, A. Marrone, and A. Palazzo, arXiv:hep-ph/0506083v2 (2008).
- [8] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Euro. Phys. J. C 71:1554 (2010).