Neutrino Physics with the Precision IceCube Next Generation Upgrade (PINGU)

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The IceCube Neutrino Observatory at the geographic South Pole is the largest neutrino telescope on Earth. IceCube and its low energy extension, DeepCore, were fully assembled at the end of 2010. DeepCore lowered the IceCube neutrino energy threshold to about 10 GeV, allowing access to a rich variety of atmospheric neutrino oscillation physics, and further improving sensitivity to indirect searches for WIMP dark matter and other phenomena. The recent measurements of a relatively large θ_{13} mixing angle and the first observations of atmospheric neutrino oscillations in the tens of GeV region in DeepCore open the possibility to determine the Neutrino Mass Hierarchy (NMH) in the proposed new in-fill array called Precision IceCube Next Generation Upgrade (PINGU). PINGU would lower the neutrino energy threshold and significantly increase the sensitivity to the NMH. For every year of the PINGU detector operation, on the order of one hundred thousand atmospheric neutrinos will be collected. These high statistics will allow PINGU to distinguish between the normal and inverted NMH at 3σ significance with an estimated 3.5 years of data.

1 Introduction

In the past 15 years, the neutrino oscillations have been studied in many different experiments, using neutrinos from man-made neutrino sources (beams, reactors), from the Sun, and from the atmosphere [1]. Neutrino oscillations occur because the neutrino flavor eigenstates are different than neutrino mass eigenstates. This phenomenon can be described in the standard three-flavor mixing scheme (3 x 3 "PMNS" mixing matrix) [2]. Recently, the last unknown mixing angle θ_{13} was measured by reactor and accelerator experiments [3, 4, 5]. The moderately large value of $\theta_{13}(\simeq 9^\circ)$ opens a new epoch in the studies of CP violation and determination of the neutrino mass hierarchy [6]. The measurement of the NMH with PINGU relies on the fact that Earth has an average density close to that of MSW resonance for neutrinos in the few GeV energy range. Therefore, significant oscillation probability modifications will occur for atmospheric neutrinos passing through Earth. The character of those modifications strongly depends on the sign of the NMH. This effect can be studied in a detector with a neutrino energy threshold of a few GeV and a large fiducial volume to acquire sufficient statistics. In addition, flavor identification and directional reconstruction in the same energy regime is required. The NMH determination depends on oscillations of both the neutrinos and anti-neutrinos. The survival probability distribution for muon neutrinos and muon anti-neutrinos in Normal Hierarchy (NH) and Inverted Hierarchy (IH) are shown in Fig. 1.

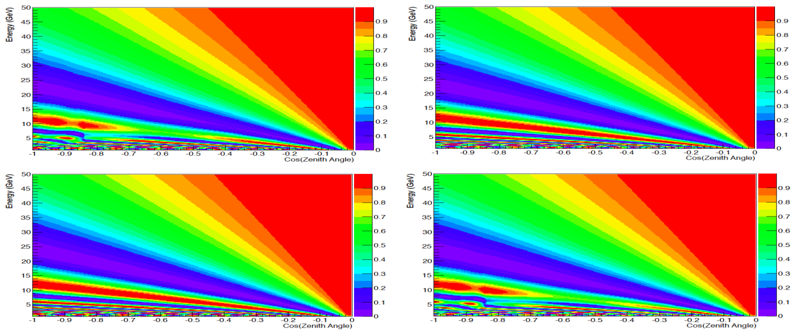

Figure 1: Survival probabilities for muon neutrinos passing through the Earth as a function of energy and zenith angle. A value of Cos(Zenith Angle) = -1 is a directly up going neutrino which is passing through the Earth's core. Muon neutrinos and NH (top left), muon neutrinos and IH (top right), muon anti-neutrinos and NH (bottom left), muon anti-neutrinos and IH (bottom right).

2 IceCube/DeepCore and proposed PINGU detector

IceCube consists of 86 cables ("strings"), each instrumented with 60 Digital Optical Modules (DOMs). The DOM consists of a 10 inch photomultiplier tube (PMT), calibration light sources and digitizing electronics. The DOMs are deployed at depths between 1450m and 2450m below the surface. The horizontal distance between most of the IceCube strings is 125 m and the vertical spacing between DOMs is 17 m. Eight strings near the center are more densely spaced with 42 - 72 m horizontal spacing and 7 m vertical spacing. Most DOMs on these eight strings contain PMTs with 35% higher quantum efficiency than standard IceCube DOMs. These eight densely instrumented strings in conjunction with the twelve IceCube strings surrounding them make up the DeepCore detector. IceCube also includes 81 surface stations, called IceTop. A sketch of IceCube and DeepCore strings, and IceTop stations is shown in Fig. 2. This

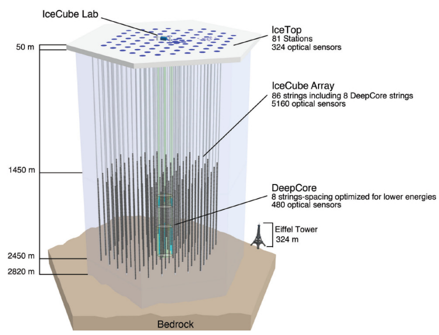

Figure 2: A sketch of IceCube and DeepCore strings, and IceTop stations.

configuration lowered the neutrino energy threshold to 10 GeV. The PINGU design follows closely that which was used for IceCube and DeepCore. PINGU will consist of 40 new strings with 20 m horizontal distance between strings and 5 m vertical distance between DOMs.

3 Neutrino Mass Hierarchy with PINGU

The proposed PINGU detector, described in Sec. 2, has no ability to distinguish between neutrinos and anti-neutrinos. However, atmospheric neutrinos in a few GeV energy region have an interaction cross section with matter almost two times larger than anti-neutrinos. Furthermore, the atmospheric neutrino flux is larger than the atmospheric anti-neutrino flux. Therefore, a potentially measurable effect, connected with significant oscillation probability modifications (see Fig. 1), remains. The distinguishability metric defined as follows [7]:

$$S_{tot} = \sqrt{\frac{(N_{i,j}^{IH} - N_{i,j}^{NH})^2}{N_{i,j}^{IH}}}$$

where $N_{i,j}$ is the number of muon neutrino events in the i and jth bin in neutrino energy and cosine of zenith angle, can be used to quantify the observable difference between the NH and IH. The distinguishability metrics for one year of simulated PINGU data after applying the selection criteria and event reconstruction described in [8] are shown in Fig. 3.

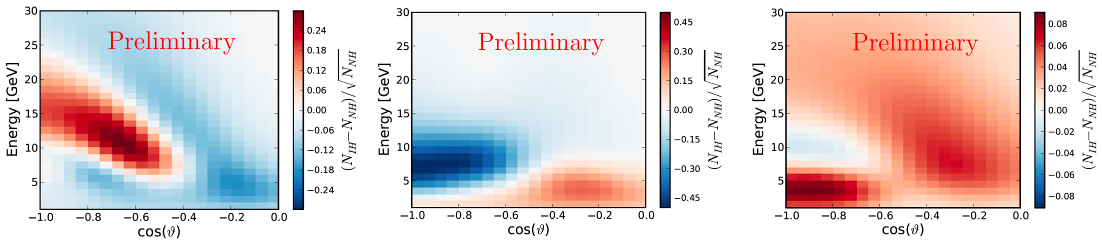

Figure 3: Distinguishability metrics for one year of simulated PINGU data: ν_μ CC (left), ν_e CC (middle), ν_τ CC events (right).

Three independent methods of determining the NMH significance in PINGU were developed: the log likelihood ratio method, the Asimov approach, and the Fisher information matrix method. Full details of these statistical methods are given in [8]. The first method is the most detailed, but it is too computationally intensive to incorporate the full range of systematics. Therefore, it was used mainly as a statistical error estimation benchmark to the other methods. The results from different methods were validated with each other and also agree well with external studies [9]. The main systematic error sources come from the energy calibration scale and physics-related uncertainties from limited knowledge of flux normalization and neutrino cross sections, and known precision of oscillation parameters. The systematic error studies connected with particle identification, cross section details, and ice model are not conducted. The significance of the neutrino mass hierarchy determination as a function of time, using the Fisher/Asimov approach including particle ID performance and a full complement of systematics (reconstruction errors are not included), under assumption of IH and θ_{23} in the first octant is shown in Fig. 4 (left). The influence of the change of the θ_{23} octant is shown in Fig 4(right).

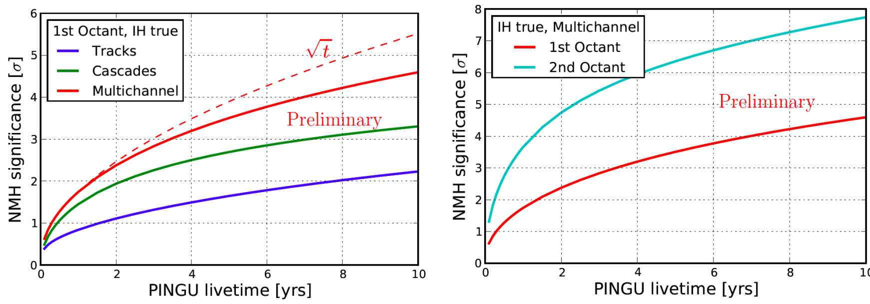

Figure 4: The significance of the neutrino mass hierarchy determination as a function of time for the IH and the first octant (left) and compared to the second octant (right) for multichannel case. The red dashed line (left) shows the expectation for a $\sqrt{t}$ dependence.

4 Conclusions

PINGU has the potential to answer one of the most important questions in the fundamental neutrino physics, namely what the sign of the Neutrino Mass Hierarchy is. We expect PINGU to be very competitive with the significance and timescale quoted for the other proposed experiments (INO, HyperK, LBNF/NOνA, JUNO) [10]. PINGU will be able to distinguish between the normal and inverted NMH at 3 σ level in 3.5 years. Beyond the measurement of the NMH, PINGU has a rich physics program. PINGU will have highly competitive sensitivity to ν_μ disappearance, θ_{23} octant and maximal mixing, and ν_τ appearance. Furthermore, PINGU will extend IceCube's and DeepCore's dark matter searches to WIMP masses below 20 GeV and improve sensitivity in the detection of low-energy supernova neutrinos.

Acknowledgments

The full IceCube/PINGU Collaboration author list and acknowledgments page can be found online here: https://icecube.wisc.edu/collaboration/authors/pingu

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