A study of the neutrino mass hierarchy with PINGU using an oscillation parameter fit

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Abstract: The determination of the neutrino mass hierarchy is among the most fundamental questions in particle physics. The recent measurement of a large mixing angle between the first and the third neutrino mass eigenstate and the first observation of atmospheric neutrino oscillations at tens of GeV with neutrino telescopes opens the intriguing new possibility to exploit matter effects in neutrino oscillations for its determination. A further extension of IceCube/DeepCore called PINGU (Precision IceCube Next Generation Upgrade) has been recently envisioned with the ultimate goal to measure this mass hierarchy. PINGU would consist of additional IceCube-like strings of optical sensors deployed in the deepest clearest ice in the center of IceCube. More densely deployed instrumentation would provide a threshold substantially below 10 GeV and enhance the sensitivity to the mass hierarchy signal in atmospheric neutrinos. Here we discuss an estimate of the PINGU sensitivity to the mass hierarchy using an approximation with an Asimov dataset and an oscillation parameter fit.

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1 Introduction

The neutrino field has progressed through a remarkable evolution since the first evidence of oscillations in 1998 [1]. In the past 15 years nearly all mixing parameters have been measured, with the θ_{13} angle most recently. What remains are two challenging key elements: the neutrino mass hierarchy (see section 2) and the CP-phase. Given a large value for θ_{13}, attention has been drawn to the potential of using the large natural flux of atmospheric neutrinos to resolve the ordering of neutrino masses, whether the hierarchy is normal or inverted [8, 9].

Neutrino telescopes are relatively new participants in the measurement of neutrino oscillation parameters [2, 3, 4, 5]. The enormous volume of these instruments make them ideal to exploit the statistics from atmospheric neutrinos. IceCube is currently the largest active neutrino telescope instrumenting a cubic-kilometer of ice at the geographic South Pole between depths of 1450 m and 2450 m with optical sensors deployed along vertical strings [7]. Neutrino identification with IceCube relies on the optical detection of Cherenkov radiation emitted by secondary particles produced in neutrino interactions in the surrounding ice or the nearby bedrock. An extension to IceCube, the DeepCore subarray, includes 8 densely instrumented strings optimized for low energies operating in conjunction with the 12 adjacent standard IceCube strings. Depending on the details of the analysis strategy, the energy threshold of DeepCore ranges from slightly below 10 GeV to 20 GeV.

With the first neutrino oscillation parameter measurements from DeepCore and ANTARES [2, 3, 4, 5], the "low-energy" particle physics potential of neutrino telescopes became evident. Estimates of the full potential of DeepCore, extrapolated from its current performance, show the detector may become competitive with current leading experiments in the field [6]. It is also evident that the DeepCore energy threshold near 10 GeV is not constrained by the detector medium. A further infill of the deep clear ice within the DeepCore volume, called the Precision IceCube Next Generation Upgrade (PINGU), would result in a further reduction of the energy threshold to a few GeV, thereby covering a region with high sensitivity for the measurement of the mass hierarchy with atmospheric neutrinos [9]. The herein proposed detector is currently being optimized to provide a first definitive measurement of this key quantity within the coming decade. The deployment of PINGU to the Antarctic ice is expected to be possible in two subsequent Antarctic summer seasons assuming 20 strings (see section 3), larger configurations would require (at least) 3 seasons.

2 Physics of Neutrino Mass Hierarchy

Neutrino oscillations occur because the neutrino mass eigenstates ν_1, ν_2, and ν_3 differ from the neutrino flavor eigenstates ν_e, ν_μ, and ν_τ. They can be parametrized by two mass differences $\delta m^2_{\text{solar}} = m_2^2 - m_1^2$ and $\Delta m^2_{\text{atm}} = m_3^2 - 1/2(m_2^2 + m_1^2)$, 3 mixing angles θ_{12}, θ_{23} and θ_{13} and a CP violating phase δ. While the mixing angles have been measured with good precision and the sign of δm^2_{solar} has been measured through matter effects in the neutrino oscillations in the sun [13], the sign of Δm^2_{atm} is unknown and δ is unbounded between 0 and 2π.

The measurement of the neutrino mass hierarchy with PINGU, i.e. the determination of the sign of Δm^2_{atm}, relies on the modification of vacuum oscillations due to interactions with matter in the Earth described by the MSW effect

[10, 11]. The size of these matter effects depends on the realized mass hierarchy, where the most relevant channel for atmospheric neutrinos in PINGU is muon neutrino disappearance.

3 PINGU simulation and reconstruction

The design of PINGU takes advantage of the elements learned from the construction and operation of IceCube and DeepCore. This includes the simulation of PINGU events which is based on the IceCube simulation software. Neutrino events are generated using the GENIE simulation package [14]. Particles generated at the vertex of charged current and neutral current interactions, and the subsequent hadronic and electromagnetic showers, are propagated by a full GEANT4 simulation [15, 16]. Each of the resultant Cherenkov photons from any charged secondary particles are then directly propagated within the detector volume. The detector geometry that will be selected for PINGU is that which achieves the optimal sensitivity to the mass hierarchy measurement.

Geometries under consideration, and subsequently simulated as outlined above, include an additional 20 – 40 detector strings, each holding 60 to 120 light detectors called Digital Optical Modules (DOMs), deployed within the DeepCore volume (see Fig. 1 for examples). The effective neutrino volume obtained from the simulation of PINGU events for the geometry shown in Fig. 1 (top) is shown in Fig. 2, demonstrating that a detector of several megatons is potentially achievable for low energy neutrinos of a few GeV. We

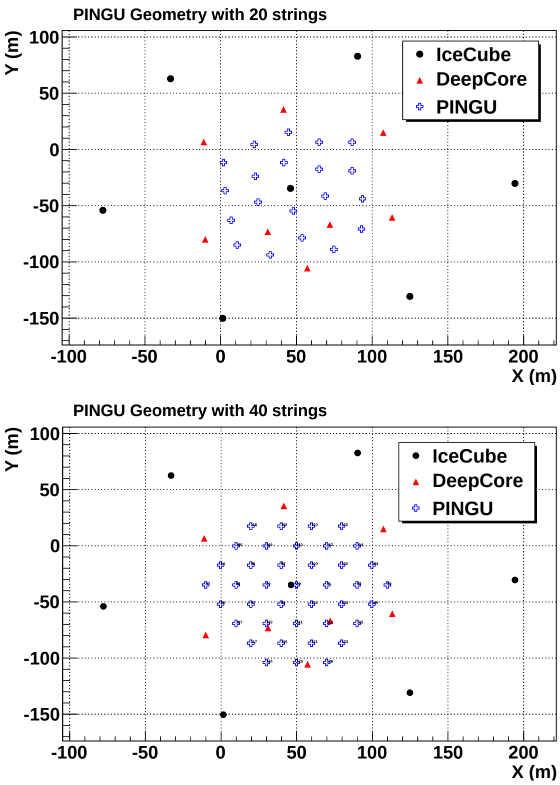

Figure 1: Overhead view of two geometry layouts currently under study for PINGU with 20 and 40 additional detector strings, respectively.

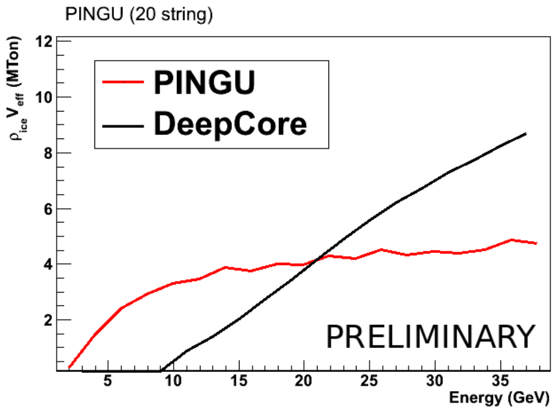

Figure 2: Effective volume for PINGU in the baseline configuration (20 strings) in comparison with DeepCore. For rejection of the atmospheric muon background, a fiducial volume defined by a cylinder with radius of 75 m and a height of 332 m is assumed. A threshold a threshold of 20 DOMs hit per event was assumed to take into account reconstruction inefficiencies.

also include detailed numerical simulations to calculate the oscillation probability of each atmospheric neutrino traversing the Earth, taking into account 3 flavor effects, where the matter density profile is parametrized according to the Preliminary Reference Earth Model (PREM) [12].

The PINGU simulated events are processed through a series of IceCube-DeepCore tools that include quality measures for event selection and reconstruction. IceCube has produced algorithms specifically designed to reconstruct lower energy events ($<$ 100 GeV) in the ice. Some are relatively fast independent reconstructions of energy (Monopod) and muon direction (SANTA), and one is a more sophisticated reconstruction that simultaneously reconstructs an 8-dimensional likelihood (HybridReco) which describes a cascade at the interaction vertex and the outgoing muon (if present). SANTA [5] is an algorithm originally developed by the ANTARES collaboration [17] that identifies the hits from the muon which have not been delayed due to scattering. Monopod reconstructs the maximum likelihood value of the energy from the light emitted by the hadronic and electromagnetic cascade produced at the neutrino interaction vertex. HybridReco performs a simultaneous fit for the 8 parameters of interest for an event (x, y, z, t, E of the cascade, muon track length, zenith and azimuth) and therefore involves a more sophisticated minimization. The preliminary performance of the Monopod and SANTA algorithms are shown in Figs. 3 and 4 for the 40 string PINGU geometry simulated events.

4 PINGU and the neutrino mass hierarchy

In order to ensure that statistical statements are robust, several approaches for determining the mass hierarchy with PINGU are pursued. Here, we elaborate on a study that uses a fit of neutrino oscillation parameters treating $\Delta m^2_{\rm atm}$ as a signed parameter. The aim of the analysis is to completely constrain the allowed parameter space to $\Delta m^2_{\rm atm} > 0$ (normal hierarchy) or $\Delta m^2 < 0$ (inverted hierarchy) and in this way to rule out the other hierarchy. Due to the parameter scan,

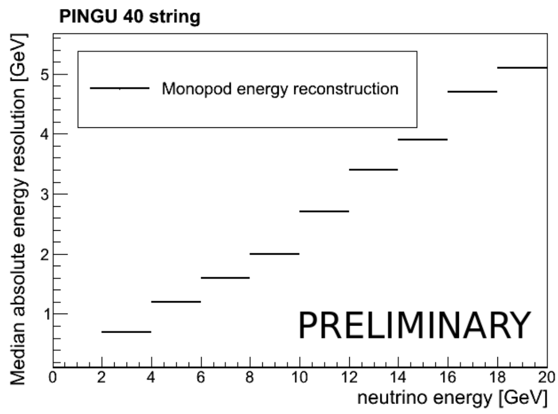

Figure 3: Median neutrino energy resolution as a function of true energy for the 40 string configuration.

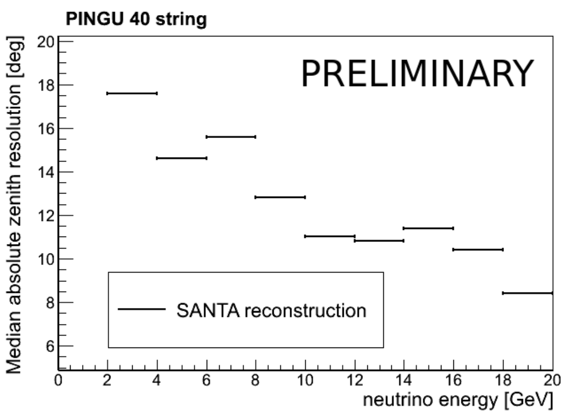

Figure 4: Median neutrino zenith resolution as a function of true energy.

the physics result is independent of the conventions used for the definition of the oscillation parameters.

The approach presented here uses a binned analysis in $\cos(zenith)$ and $\log_{10}(energy)$ as variables with a χ^2 statistic using pulls for systematic uncertainties, a method used and described in [2]. The χ^2 between prediction and (pseudo-) data is calculated as a function of the considered oscillation parameters. The test statistics for the purpose of hierarchy measurement is defined by

$$\Delta\chi^2 = \min\{\chi^2|\Delta m^2 > 0\} - \min\{\chi^2|\Delta m^2 < 0\}.$$

If $\Delta\chi^2 > 0$, the inverted hierarchy is favored, while for $\Delta\chi^2 < 0$ the data favors the normal hierarchy. We evaluated the 40 string PINGU configuration with 60 DOMs on each string (see Fig.1 (bottom)) using the SANTA and Monopod reconstruction algorithms applied to all events. Hence, the detector resolution, including the tails of the distributions, is fully taken into account. Based on the reconstruction performance studies, the application of HybridReco is expected to improve the sensitivity towards neutrino mass hierarchy.

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 [18]. This pseudo-data set is defined by the average expected number of events obtained from Monte Carlo simulations to which the analysis is applied. The analysis of an Asimov data set is shown, for example, in Fig. 5, where the true oscillation parameters were set to $\Delta m^2_{\text{atm}} = -2.4 \cdot 10^{-3}$ eV^2 (inverted hierarchy), $\sin^2(\theta_{13}) = 0.024$ and $\sin^2(\theta_{23}) = 0.35$. The plot shows the distribution of the χ^2 of this Asimov data set as a function of the oscillation parameters. On the left side of Fig. 5, negative values for Δm^2_{atm} were considered (inverted hierarchy), while on the right positive values were assumed (normal hierarchy). The value of 12.1 for the test statistics $\Delta\chi^2$ for this Asimov data set results from the difference of the minimum χ^2 of these sub-figures. The denser geometry with 40 detector strings (see Fig. 1) was used, and the assumed livetime is one year. Backgrounds from downwards going air shower muons and from ν_e and ν_τ events are not taken into account. The appearance of ν_μ due to $\nu_e \to \nu_\mu$ is included.

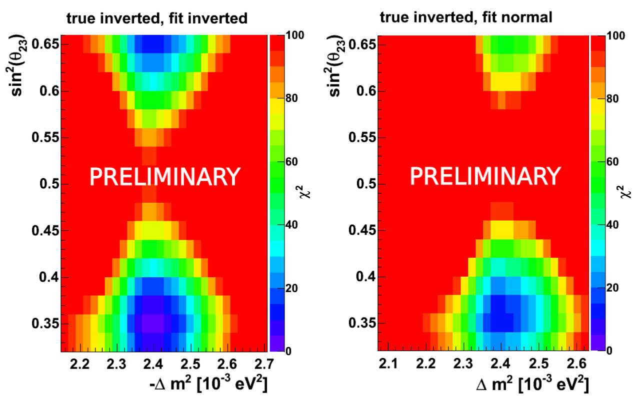

Figure 5: Example for the analysis of an Asimov data set: χ^2 as a function of Δm^2_{atm} and $\sin^2(\theta_{23})$. The true oscillation parameters were set to $\Delta m^2_{\text{atm}} = -2.4 \cdot 10^{-3}$ eV^2 (inverted hierarchy), $\sin^2(\theta_{13}) = 0.024$ and $\sin^2(\theta_{23}) = 0.35$.

We have tested the interpretation of the $\Delta\chi^2$ obtained in the Asimov approach as the median significance via a χ^2 distribution with 1 degree of freedom with a full ensemble simulation with a large number of pseudo-experiments. Here the event numbers in each bin were modified according to Poisson fluctuations around their expectation values. In cases where $\Delta\chi^2 > 0$, i.e. the inverted hierarchy is favored, the p-value p($\Delta\chi^2$) for rejecting a single parameter point (mass splitting, mixing angle) with the normal hierarchy is defined as the fraction of pseudo-experiments which favor normal hierarchy by more than $\Delta\chi^2$. The p-value for the rejection of the normal hierarchy hypothesis is then defined as the maximum p-value obtained for any true parameter point with the normal hierarchy. In the case where the normal hierarchy is favored, the p-value for the inverted hierarchy rejection is defined in an analogous way. The p-value as a function of $\Delta\chi^2$ obtained in this way is shown in Fig. 6 in comparison with the expectation from the Asimov approach given by a χ^2 distribution. Pseudo-experiments were generated for 7 different assumptions of the true oscillation parameters. Fig. 6 shows the maximum p-value of these, corresponding to the above defined p-value for the rejection of the hierarchy hypothesis. We find the χ^2 distribution (assumed for the Asimov approach) to deliver a higher p-value over most of the $\Delta\chi^2$ range, indicating that the Asimov approach provides a conservative estimate of the median sensitivity in most cases.

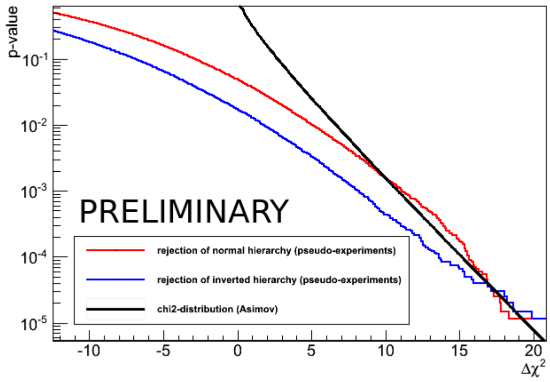

Figure 6: The p-value as a function of $\Delta\chi^2$ from pseudo-experiments for normal hierarchy (red) and inverted hierarchy (blue) in comparison to the cumulative χ^2 distribution with 1 degree of freedom (black). Pseudo-experiments were performed for 7 different values of the true oscillation parameters, the curves show the highest p-value obtained for any of these.

The results of the different approaches to calculate PINGU's sensitivity are summarized in Fig. 7, see also [20]. The upper curve represents the results of the approach discussed here, the lower curve represents the result from a second approach based on the use of likelihood ratios. Similar to [19], patterns are defined as the expectation of the number of events in each bin of cos(zenith) and $\log_{10}$(energy) for normal and inverted hierarchy and the likelihood of the (pseudo-) data is calculated for these patterns. Various patterns are considered corresponding to different assumptions of the true $\Delta m^2_{\mathrm{atm}}$. The likelihood ratio between the normal and inverted hierarchy patterns is used as the test statistics. The distribution of the likelihood ratio is obtained from pseudo-experiments. The expected significance according to this study is smaller, since a 20-string configuration and a smaller signal efficiency were asumed here.

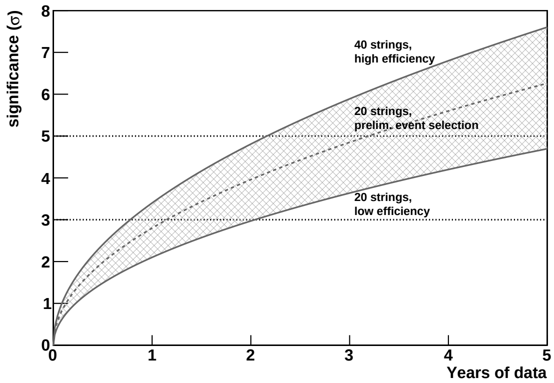

Figure 7: Expected significance for the neutrino mass hierarchy by PINGU as a function of time [20].

5 Further physics topics for PINGU

Beyond the measurement of the neutrino mass hierarchy, PINGU has a rich physics potential. In the field of neutrino flavor physics, this includes precision measurements of mixing parameters which could aid in solving the question of whether θ_{23} is non-maximal, i.e. $\theta_{23} \neq 45°$, and if so what is the octant. PINGU's potential, however, is not restricted to neutrino flavor physics. The Earth core composition influences neutrino oscillation patterns for neutrinos traversing the Earth. Utilizing the arguments made in the oscillation analysis, PINGU may provide constraints on the composition of the Earth core which would be relevant for the geophysics community. Further, this new detector array would extend IceCube's and DeepCore's dark matter searches to WIMP masses below 20 GeV with significantly improved sensitivity; a region where hints of a possible dark matter signal have been reported by DAMA, CoGeNT, CRESST and most recently by the CDMS-Si data. Finally, PINGU also has improved sensitivity in the detection of low-energy supernova neutrinos. While not sufficient to detect supernovae from distant galaxies, it will improve the measurement of any supernova in our galaxy, provide some informaton on the neutrino energy spectrum and track the time-dependence of the average neutrino energy [21].

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