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PINGU: The Precision IceCube Next Generation Upgrade

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The PINGU experiment, a planned low energy infill extension of the IceCube observatory, aims to provide a megaton-scale neutrino detector sensitive to $O(10)$ GeV neutrinos. While the prime motivation stems from its ability to determine the neutrino mass hierarchy, such a detector would also have an unprecedented sensitivity to neutrinos from galactic Supernovae and low-mass WIMP annihilation. The performance of PINGU is discussed in terms of effective volume, energy and directional resolution, as well as the sensitivity for the determination of the neutrino mass hierarchy. Finally, we summarize the project status.

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1. Introduction

Open ice/water Cherenkov neutrino detectors utilize transparent Antarctic ice or ocean/lake water to cost-effectively obtain large amounts of target material [1, 2, 3, 4]. The concept has already been successfully applied in the exploration of the high energy neutrino sky, with IceCube providing the first evidence of a high energy astrophysical neutrino flux [3, 5]. By increasing the density of instrumentation in the ice, the energy threshold of the neutrino detector can be lowered while still providing unprecedented large volumes. A successful example is DeepCore, which was installed as an infill array at the center of IceCube in the exceptionally clear ice between 2100 and 2450 m below the surface. By lowering the energy threshold to $\sim$20 GeV the detector became sensitivity to neutrino oscillations, constraining Δm^2_{23} and θ_{23} [6].

The sensitivity of megaton-sized atmospheric neutrino detectors to the neutrino mass hierarchy (NMH) was pointed out in [7]. The requirement for the measurement is an energy threshold below 10 GeV, as well as an effective target mass of several megatons to obtain sufficient statistics of atmospheric neutrinos. The proposed PINGU detector is designed to enable the NMH measurement, as well as improve the sensitivity to neutrino mixing parameters, low energy WIMPs and galactic Supernovae. In this contribution, we focus on the NMH measurement.

The sensor technology and deployment strategy of PINGU builds on the experience gained with IceCube. One detector configuration that has been simulated in detail consists of 40 strings (instrumented cables), each carrying 60 light sensors (PINGU Digital Optical Modules), arranged as an even denser infill at the center of DeepCore (see Fig. 1). In the following, we discuss the performance of this particular detector and its sensitivity to the NMH. The project status is summarized in the last section.

2. Event Reconstruction and Effective Volumes

Because of the low energies involved, events relevant for PINGU are mostly contained inside the geometrical bounds of the detector. Depending on the neutrino flavor, they will have a somewhat different topology: while ν_e and the majority of ν_τ will appear as isolated particle showers (called cascades), generating light in a fuzzy Cherenkov cone, charged current (CC) ν_μ events will have an additional muon track. Since the emerging muon travels faster than the speed of light in ice, photons produced by the track can arrive earlier than the light from the initial vertex, and hence can be used to discriminate the two event topology. At low energies (E$\lesssim$ 5 GeV), separation becomes generally difficult due to the short muon track. Simulated events are reconstructed using a log-likelihood method adapted from IceCube that incorporates the different event types (cascade-like, track-like), as well as light propagation effects in the ice. Energy and angular resolution for CC ν_μ events are shown in Fig. 2. Similar energy and angular resolution are found for CC ν_e events, while somewhat worse resolution are obtained for ν_τ, as well as NC events due to the generally smaller visible energy.

To be included in the final analysis sample, simulated events are required to satisfy veto, containment (75 m radial distance from the detector central axis) and directional criteria ($\theta_{\rm rec} > 90^\circ$, all events are upward going). The resulting effective volume after all cuts is shown in Fig. 3.

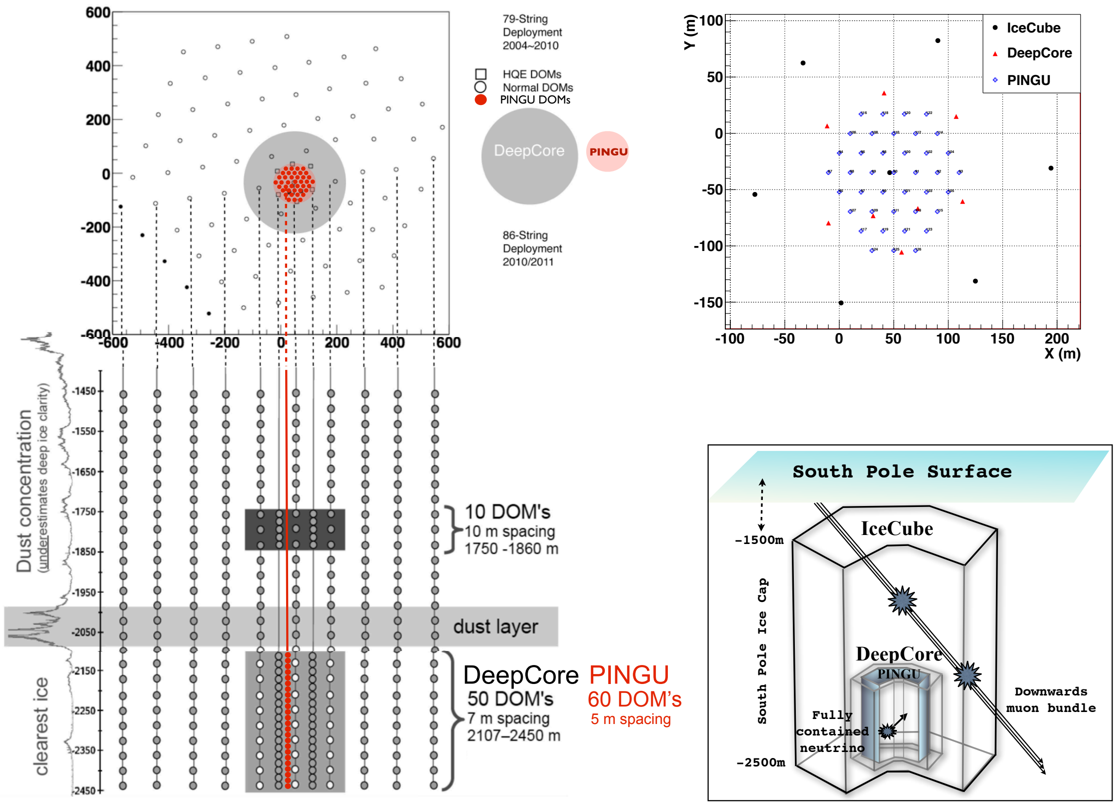

Figure 1: The left figure shows overhead and side views of the baseline 40-string PINGU detector. It also shows the surrounding IceCube and DeepCore strings, and vertical spacings for DeepCore and PINGU modules. In the interest of clarity, the side view only shows some of the strings. The leftmost curve along the side of the figure delineates the dust concentration in the ice, showing that PINGU will be located in the clearest ice. The top right figure shows an enlarged top view of the baseline 40-string geometry. The bottom right figure provides a sketch of a contained ν_μ CC event (signal) and a throughgoing muon bundle from a cosmic-ray air shower (one type of background, rarely coincident with neutrinos).

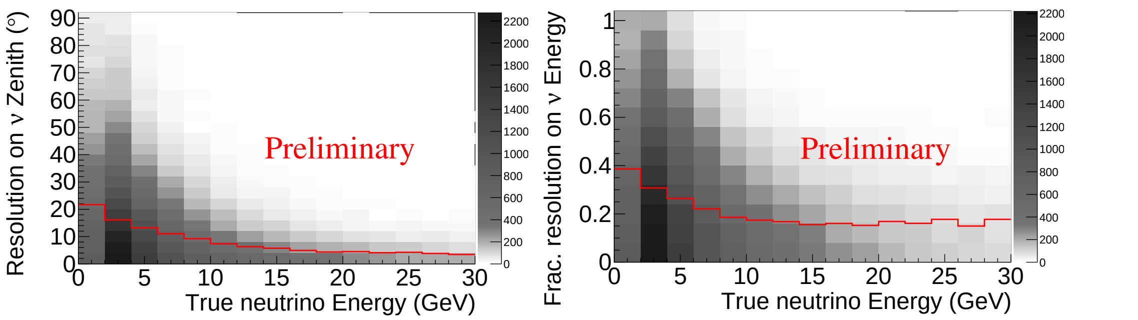

Figure 2: Zenith angle and fractional energy resolutions for ν_μ events with reconstructed vertices within the PINGU fiducial volume. The red line indicates the median value in each energy bin. The grey scale indicates number of simulated events in each bin.

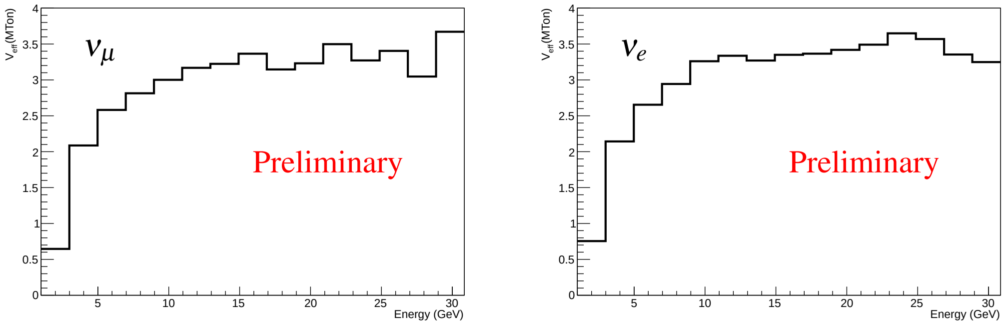

Figure 3: Effective volume for ν_μ (left) and ν_e (right) events after final selection cuts.

3. Neutrino Mass Hierarchy

3.1 Signature

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 [8], while the mass ordering is still unknown. PINGU will be capable of determining this mass ordering by virtue of its ability to collect a high-statistics sample of atmospheric neutrinos in the energy range above a few GeV. The ordering, or mass hierarchy, is denoted "normal" (NH) when ν_3 is the most massive of the three neutrino mass eigenstates and "inverted" (IH) if it is the least. This ordering can be described in terms of the sign of mass-squared difference measured by atmospheric neutrino oscillation experiments, $\Delta m^2_{\rm atm}$, where $\Delta m^2_{\rm atm} > 0$ corresponds to the normal hierarchy and $\Delta m^2_{\rm atm} < 0$ to the inverted.

Besides vacuum oscillations, there are two distinct physical effects that play a role as neutrinos propagate through the Earth. The first is the MSW effect [9, 10] that results in an enhancement of the oscillation probability for $\nu_\mu \to \nu_e$ (NH), or $\bar{\nu}_\mu \to \bar{\nu}_e$ (IH), and is strongly dependent on the density along the flight path. The second effect arises from the density transition at the Earth's mantle-core interface, where neutrinos can undergo "parametric enhancement" of their oscillation probability [11]. The aggregate effect of these phenomena on muon neutrinos, in both NH and IH scenarios, is shown in Fig. 4. The survival probabilities of antineutrinos in the NH are essentially identical to those of neutrinos in the IH, and vice versa. However, asymmetries in the cross sections and kinematics of ν and $\bar{\nu}$ interactions with nuclei, along with the higher atmospheric flux of neutrinos relative to antineutrinos, lead to different detected event rates depending on the hierarchy. Therefore a precision measurement of the survival probabilities in the energy range targeted by PINGU permits a determination of the NMH without explicit $\nu - \bar{\nu}$ discrimination [12].

The impact of MSW effect and parametric enhancement on atmospheric neutrinos, and thus the signal for determining the hierarchy, is illustrated in Fig. 5. The figure shows the difference between the number of detected neutrino events per year under each hierarchy, after applying the selection criteria and event reconstruction described above, scaled by the Poisson error on the number of NH events to obtain something analogous to a χ^2 term. The plots are binned as a function of the reconstructed neutrino energy, E_ν, and the cosine of the reconstructed zenith angle of the neutrino ($\cos\theta_\nu$). To illustrate the individual contributions to the NMH signal, ν_μ and

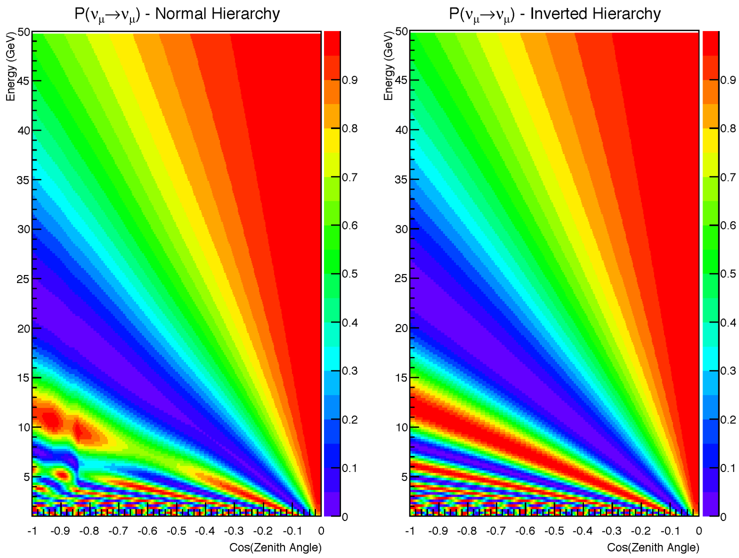

Figure 4: Muon neutrino survival probability after traveling through the earth, binned in both neutrino energy and cosine of the zenith angle. (A path directly through the center of the Earth corresponds to $\cos\theta = -1$.)

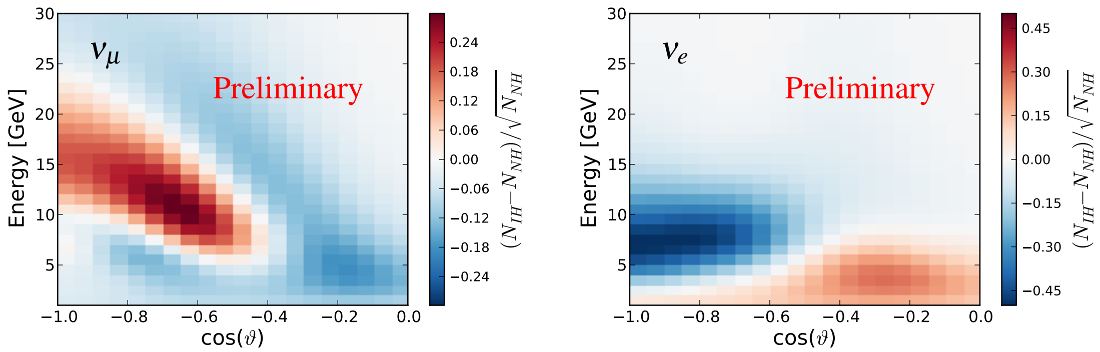

Figure 5: Distinguishability metric as defined in [7] for one year of simulated PINGU data. The sum of the absolute values of each bin in each plot gives an estimate of the number of σ separating the two hierarchies. The left figure shows track-like events from CC ν_μ interactions. The right figure shows ν_e CC events. For illustrative purposes we assume perfect particle ID in creating these figures.

ν_e are shown separately, i.e., assuming perfect flavor identification (ν_τ is contributing less to the signal). One finds regions in which the number of events expected for the NH is greater than that expected for the IH (blue regions) and vice-versa (red regions). Sensitivity to this pattern of the event number differences as a function of E_ν and $\cos\theta_\nu$ permits determination of the neutrino mass hierarchy. This "distinguishability" metric [7] is relevant for understanding the regions of interest in the energy-angle space from which useful information may be extracted, and can be used to calculate a rough approximation of the PINGU sensitivity to the NMH. More detailed simulations and analysis methods are then used to determine the sensitivity with improved accuracy, as discussed below.

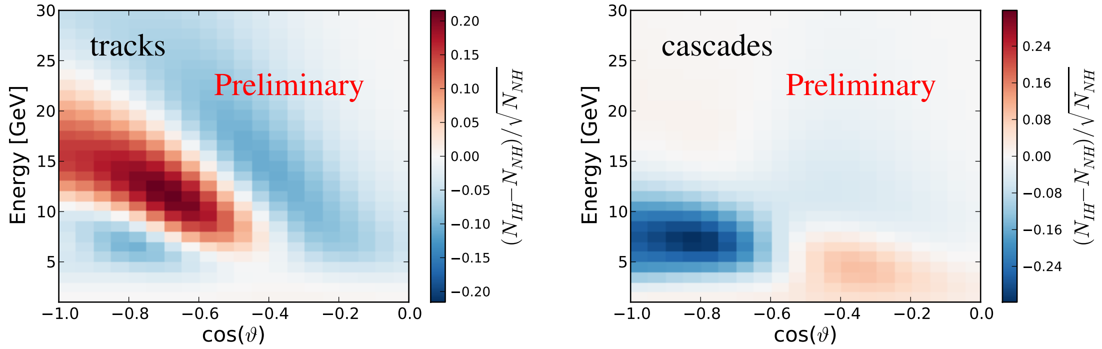

Figure 6: Distinguishability metric as defined in [7] for one year of simulated PINGU data with reconstruction and particle identification applied. The left panel shows track-like events (mostly due to CC ν_μ) while the right shows cascade-like events (mostly ν_e and ν_τ CC events, as well as NC events from any neutrino flavors).

3.2 Analysis

The analysis is performed on atmospheric neutrinos with fluxes as predicted by [13], which are tracked through the Earth using a full three-flavor formalism including matter effects based on the standard PREM model of the Earth [14]. The simulated neutrino events are all reconstructed without regard to neutrino flavor and employ a basic algorithm for particle identification (PID) to separate track-like events produced by ν_μ CC interactions from cascade-like events produced by ν_e CC, ν_τ CC, and all-flavor NC interactions. In Fig. 6 we show the distinguishability metric evaluated for the track and cascade channel, where the energy-dependent PID efficiency is parametrized using a full simulation and reconstruction of simulated data.

Three independent analyses were employed in studying PINGU's sensitivity to the NMH. The most detailed method uses a library of simulated events to generate the distribution of E_ν and $\cos\theta_\nu$ expected from different possible combinations of true oscillation parameters, generates ensembles of pseudo-experiments for these scenarios and uses a likelihood ratio method to determine the degree to which one hierarchy is favored. The second analysis likewise starts with the same library of simulated events, but uses the so-called "Asimov" approximation instead of generating ensembles of pseudo-experiments for every possible combination of oscillation parameters [15]. This technique essentially assumes that statistical fluctuations in the experimental data are as likely to reinforce as to obscure the signature of the correct hierarchy, such that only the single most probable set of data for any given set of parameters needs to be analyzed. A χ^2 statistic can then be calculated between the assumed true distribution and every alternate set of observables. Systematic uncertainties are incorporated as nuisance parameters to be fit simultaneously, and the significance of the hierarchy is determined from the $\Delta\chi^2$ between the best fits in the subspaces corresponding to normal and inverted hierarchies.

The third analysis, from which the results presented here were derived, uses the simulated events to build a parametrized model of the detector response. This includes effective volumes, analysis selection efficiency, reconstruction resolutions and biases, and the particle identification efficiency, similar to the procedure used in [16, 12, 7]. At the heart of the method lies the Fisher information matrix, consisting of the partial derivatives of the event counts in each bin with respect to all parameters under study (calculated numerically) for the true parameters, weighted by the statistical errors:

$$F_{kl} = \sum_i \frac{1}{\sigma_{n_i}^2} \frac{\partial n_i}{\partial p_k} \frac{\partial n_i}{\partial p_l}. \tag{3.1}$$

Here p_k, p_l denote the parameters with index k and l, while n_i is the expected number of events in bin i and $\sigma_{n_i} = \sqrt{n_i}$ the corresponding uncertainty. Inverting the Fisher matrix yields the full covariance matrix between the parameters of interest, while the statistical uncertainty of parameter i is given by $1/\sqrt{F_{ii}}$. Since all parameters must be continuous to be incorporated, the mass hierarchy is represented by a parameter h, linearly incorporating the observed event counts in each bin according to $n_i^{obs} = hn_i^{true} + (1-h)n_i^{alt}$. The significance of the NMH measurement is given by $1/\sigma_h$, where σ_h follows from the inverted Fisher matrix.

The advantages of this method are the simplicity and small computational demands with which one can include a large number of systematic errors through nuisance parameters. Another advantage arises from the fact that the analysis is not limited by the size of the available Monte Carlo event library. Although the event library corresponds to approximately 5 years of actual data, there is evidence that statistical noise in the expected distributions causes a systematic upward bias [17] in the significances predicted by the first two analyses described above, that is not present in the parametric Fisher information matrix method.

The derivatives for the other parameters are obtained numerically and, in the range of interest, the linear approximation of the parameter dependence is sufficiently accurate (as previously shown in [18]). Only the CP-violating phase, δ_{CP}, can not be incorporated reliably in this approach, due to the lack of external constraints on its value, but PINGU is expected to have low sensitivity to this parameter [7], which we have verified using the LLR analysis. Since the dependence of the hierarchy measurement on δ_{CP} is small, we fix $\delta_{\text{CP}} = 0$. Strong covariance of another parameter with the hierarchy parameter would indicate that there is a potentially important systematic which might affect our ability to measure the hierarchy.

When examining the same sets of external nuisance parameters and after accounting for the bias due to limited Monte Carlo statistics, we have found that the results from the Fisher information matrix agrees well with the Asimov Monte Carlo simulation approach. We are therefore confident that the parametric approximations used in this analysis are reliable, and use it to incorporate a wider variety of systematics and determine the sensitivity of PINGU to the hierarchy for longer exposures than can be estimated using Monte Carlo-based methods.

3.3 Systematics and Results

The neutrino oscillation pattern appearing in the PINGU detector arises from the wide range of atmospheric neutrino energies and baselines to which PINGU is sensitive. PINGU has sufficient energy and angular resolutions to determine the NMH, and it is shown in the following that detector-related systematics are not expected to impact the oscillation pattern in such a way as to induce a hierarchy misidentification. We categorize as a second broad class of systematics those arising from uncertainties in externally measured values of neutrino fluxes and oscillation parameters. In the following we describe and quantify each of these systematics, and indicate possible ways to better constrain them to reduce their impact on the final significance.

The external systematics studied include uncertainties in the atmospheric neutrino flux and spectral index, Δm^2_{12}, $\sin^2(\theta_{12})$, Δm^2_{23}, and $\sin^2(\theta_{23})$. Relevant detector-related systematics studied so far include uncertainties in the absolute energy scale (*i.e.*, energy calibration), a scale factor and energy-dependent shift in the effective volume, as well as uncertainties in the neutrino interaction cross sections (both for neutrinos and anti-neutrinos). Some detector uncertainty parameters are degenerate with each other, such as the scale factors applied to the atmospheric neutrino flux, effective volume and cross-sections, and therefore we only include one of these uncertainties. On the other hand, the flux and cross-section are different for neutrinos and anti-neutrinos. Since the signal depends on the difference between neutrinos and anti-neutrino events, one needs to treat these two systematics separately. Although MINERvA [19] results will likely reduce the uncertainties on the relevant cross-sections substantially by the time of the PINGU data analysis, we have added a conservative Gaussian uncertainty of 15% on possible scale factors for neutrino and anti-neutrino cross-sections. The cross-section, the effective volume, or the flux can show an energy dependence that is not properly modeled; we include this possibility by adding an extra linear energy dependence of the effective volume, such that $V^{\rm sys}_{\rm eff}(E_\nu) = V_{\rm eff}(E_\nu)(1+\varepsilon E_\nu)$, where ε is a nuisance parameter determined by the data. The list of systematic uncertainties investigated so far is extensive but not complete. For instance, the impact of uncertainties in the optical ice properties still needs to be studied although calibration devices to be deployed as part of PINGU will reduce them considerably compared to their present values.

The effect of the systematic uncertainties on the event rates is parametrized, providing one linear (nuisance) parameter for each source. The Fisher information matrix is then evaluated including the systematic uncertainties, leading to a significance of 1.75σ with the first year of data. Figure 7 illustrates the "impact" of the individual sources of uncertainty, defined as the increase in significance seen when a particular uncertainty is disabled in the analysis. The figure also indicates that the combined effect of individual detector-specific uncertainties studied so far is moderate and generally dominated by the combined physics-related uncertainties. Our studies indicate that the measurement is limited by systematics and that the significance will grow slightly more slowly than $\sqrt{t}$ on the time scale of a few years. The resulting significance as a function of the amount of data taken by the full detector is summarized in Fig. 8, assuming θ_{23} is in the first octant. If instead θ_{23} is in the second octant, the significance with which one can determine the NMH would be nearly a factor two larger.

There are a number of future improvements that we believe will further increase the significance. Two promising ones are better particle ID and the use of the reconstructed inelasticity of the neutrino event, which is a weak $\nu/\bar{\nu}$ discriminator. More sophisticated particle ID will enable better exploitation of the distinct patterns of ν_μ events relative to those of $\nu_{\rm e}$ and ν_τ. The use of the inelasticity would help us distinguish neutrinos from antineutrinos on a statistical basis and could provide a 20-50% increase in significance [20, 21]. Other lines of investigation include geometry optimization, improved event selection efficiency and more accurate event reconstruction.

4. Project Status and Outlook

The IceCube-PINGU collaboration consists of the IceCube collaborators, with several new and associated groups focusing on the low-energy infill extension. A Letter of Intent has been

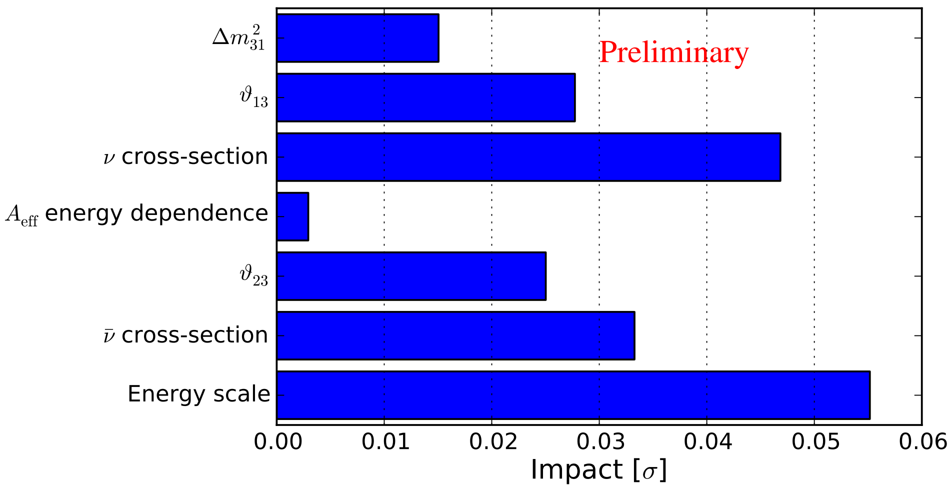

Figure 7: Summary of the systematic errors, their assumed variations, and their impacts on the estimated one-year significance of the mass hierarchy measurement. See text for details.

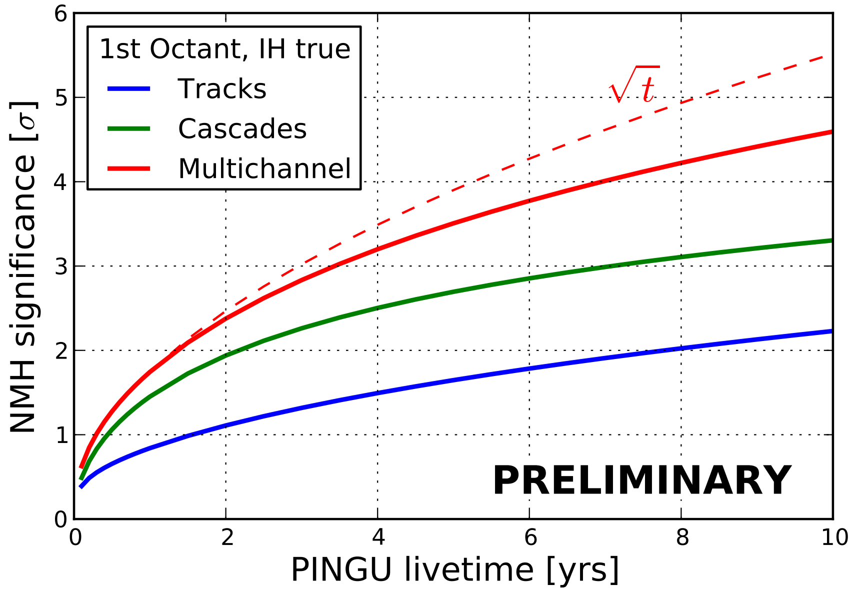

Figure 8: Significance of the neutrino mass hierarchy determination as a function of time, using the Fisher/Asimov approach and a full complement of systematics (see text for details). Note the red dashed line shows the expectation for a $\sqrt{t}$ dependence.

submitted in December 2013, containing a NMH sensitivity study for the 40-string geometry, as well as covering a range of other science opportunities for PINGU. Photodetectors, communication and ice drilling technology are based on existing IceCube technology, with a high degree of present readiness. Assuming that funding can be secured in 2014, installment of the detector at the South Pole could start in 2018 and be completed by 2020.

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