PROCEEDINGS OF SCIENCE

PINGU

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Neutrino oscillations have been measured since 1998 [1] with increasing precision. All three-flavour neutrino mixing parameters have been measured with the exception of the CP-violating phase and the ordering of the mass eigenstates. The measure of a relatively high value for the mixing angle θ_{13} creates the possibility for probing the ordering of the mass states through the measurement of atmospheric neutrino oscillation with very large volume detectors. A leading proposal to perform this measurement is the future low-energy extension to the IceCube-DeepCore detector, called PINGU (the Precision IceCube Next Generation Upgrade): by increasing the photocathode density in the DeepCore region it is possible to lower the energy threshold in the fiducial volume to the region affected by the MSW effect [2, 3], which then allows us to measure the ordering. Here we discuss the design of the PINGU detector, it's sensitivity to the mass ordering (approximately 3σ in 3.5 years) and measurements of ν_μ disappearance and ν_τ appearance.

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1. Introduction

Neutrino oscillations have been discovered by the Super-Kamiokande detector in 1998 [1] through the measurement of atmospheric neutrinos and since then have also been observed from neutrinos produced at other sources, such as particle accelerators, reactors, and the sun. The parameters describing the 3-flavor neutrino mixing matrix [4] with the exception of the CP-violating phase (δ_{CP}) and the mass ordering (the sign of Δm^2_{23}) are determined from the combination of these measurements [5]. For the latter, the case where the third mass eigenstate is heaviest (positive Δm^2_{23}) is referred to as “normal”, while when it is the lightest (negative Δm^2_{23}) it is referred to as “inverted”. A recent measurement [6] of a relatively large non-zero mixing angle between the first and third mass eigenstates (θ_{13}) has made it possible to consider determining the mass hierarchy using atmospheric neutrinos with very large detectors such as the proposed Precision IceCube Next Generation Upgrade (PINGU). Such a detector will also contribute to indirect dark matter searches, precision measurement of ν_μ disappearance and ν_τ appearance, supernova neutrino detection, and provides potential for first measurements of Earth neutrino tomography, all discussed in detail in [7].

2. The PINGU detector

The IceCube Neutrino Observatory [8] is the world’s largest neutrino detector instrumenting about 1 km^3 of the deep glacier near the South Pole Station, Antarctic, as shown in Fig. 1. The observatory was designed to detect interactions of high-energy neutrinos, where it was expected there would be a neutrino flux of astrophysical origin, and successfully provided first evidence for such flux recently [9]. In 2008, the original detector design was augmented by creating a region of the detector with a higher density of optical sensor in the deep, clearest, ice, therefore increasing the photocathode coverage in that volume. Such volume with increased photocathode density, called DeepCore [10], was added with the objective to lower the energy threshold of the IceCube detector to make competitive measurements of neutrino oscillations [11] and world-leading indirect dark matter searches [12].

With the goal of further lowering the energy threshold of the IceCube Neutrino Observatory, PINGU [7] was designed, further increasing the density of optical modules in the DeepCore region, see Fig. 2, where with the additional strings the horizontal string spacing is reduced to about 20 m (in comparison to 40-70 m for DeepCore) and the vertical spacing was reduced in the new strings to about 5 m (in comparison to 7 m for the surrounding DeepCore detector). This increased density effectively will lower the energy threshold of DeepCore from around 10 GeV to a few GeV. Furthermore, since PINGU will be located at the center of IceCube, we will be able to use the existing IceCube strings to provide an excellent active veto to reject atmospheric muons, as is currently done for the DeepCore analysis mentioned above. We have and continue to optimize the PINGU detector for its key parameters to achieve the highest sensitivity to the potential oscillation physics, including a measurement of the mass hierarchy, assuming the atmospheric neutrino signal-to-background levels achieved are comparable to those in DeepCore.

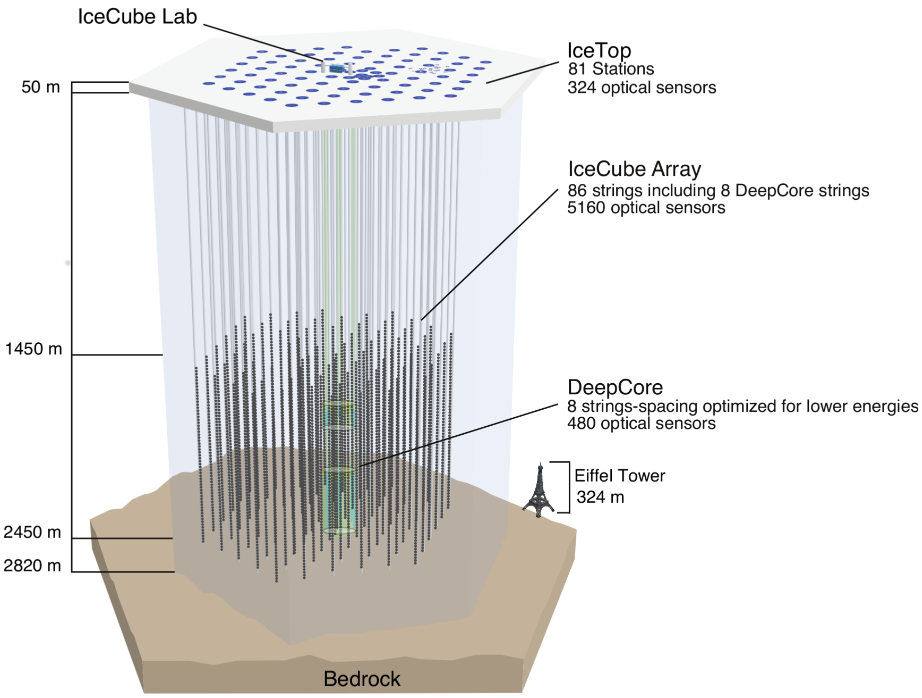

Figure 1: Diagram of the IceCube Neutrino Observatory at its completion, December 2010, with the DeepCore denser array indicated [8].

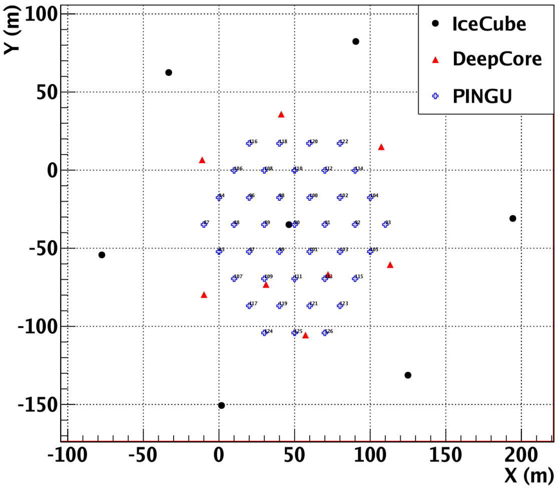

Figure 2: A top view of the proposed PINGU detector geometry [7] used for the studies presented in this proceeding. The location of existing IceCube strings are shown as circles, DeepCore as triangles and PINGU as crosses.

2.1 Detector response

The response of the PINGU detector is predicted using full IceCube Monte Carlo simulation, in particular a combination of the GENIE neutrino generator with GEANT4, to propagate the particles created from the neutrino interaction, and a custom-built GPGPU algorithm, called CLSim, to propagate photons in the detector. The events produced by the simulation are then analysed using tools developed for the DeepCore analysis, using an event reconstruction algorithm geared specifically for low-energy events that fits simultaneously eight parameters (interaction vertex and time, angle of incidence for the event, and energy of two outgoing particles) to obtain the highest likelihood for the given system to reproduce the charge and time distributions of the hits from the event. The key parameters for oscillation analysis: energy and zenith, which is related to the path length of the neutrino through the Earth, are shown in Fig. 3.

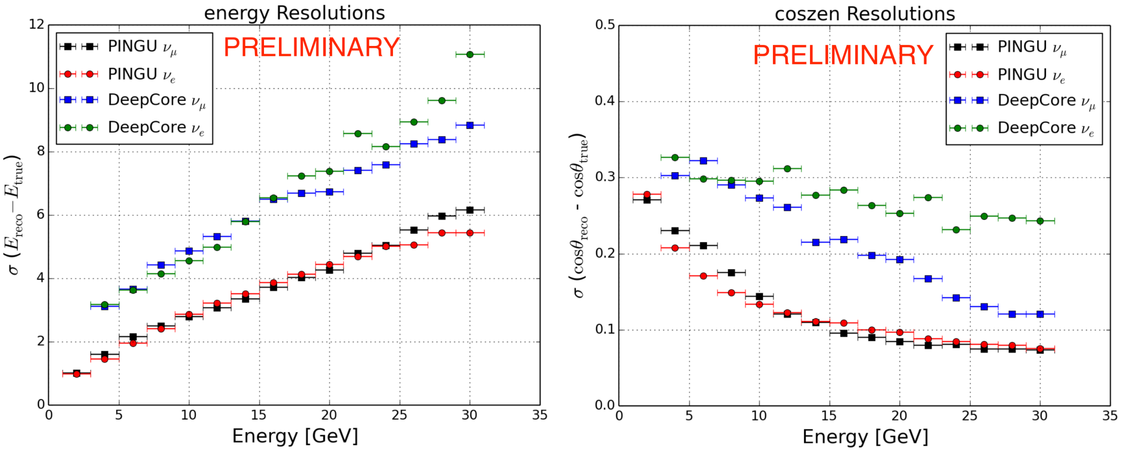

Figure 3: The PINGU detector energy (left) and zenith angle (right) resolution of charged current events separated by the event type (ν_μ or ν_e), as a function of the true neutrino energy compared to resolutions obtained using the same algorithm in the DeepCore array.

3. PINGU oscillation physics

3.1 Neutrino mass hierarchy

The main goal for PINGU is to provide a definitive measurement of the neutrino mass hierarchy using a statistically large sample of atmospheric neutrinos. For neutrino energies near and below 10 GeV, the MSW effect begins to impact the survival probabilities for neutrinos and antineutrinos differently, depending on the ordering of the mass states.The size of the effect depends on the size of θ_{13}, and the relatively large value for it measured recently provides enough differentiation between the hierarchies to allow its determination using atmospheric neutrinos as proposed by e.g. [13, 14], by comparing the observed rate of neutrinos as a function of energy and propagation path length (related to the zenith angle) with the expected distributions from the normal and inverted hierarchies. The difference between these two cases shown in Fig. 4, while small, creates a pattern that also helps in the identification of the hierarchy and reduces effects of various systematics.

From these distributions a full analysis is executed to compare the predicted oscillation template for a given hierarchy to a simulated measured dataset [7]. The result, shown in Fig. 5 for θ_{23}

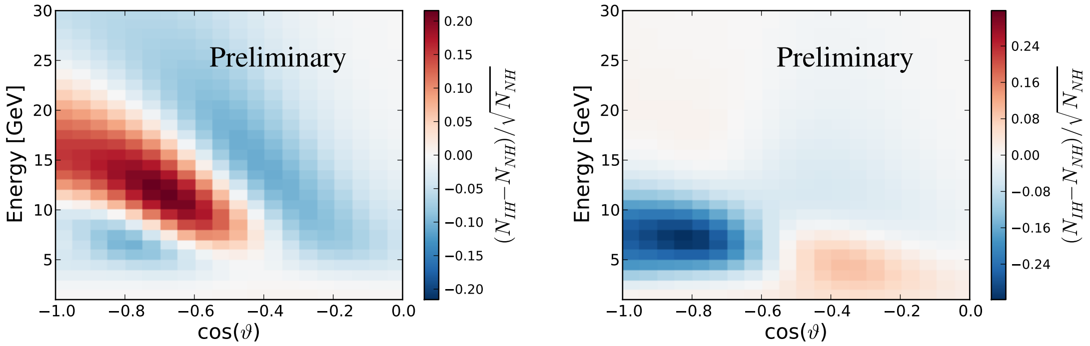

Figure 4: Distinguishability metric for track-like (left) and cascade-like (right) events for the neutrino mass hierarchy as defined in [14] for one year of simulated PINGU data with reconstruction and particle identification applied. Track-like events are composed mainly of ν_μ CC events while cascade-like events will be composed mainly of ν_e CC interactions, even though ν_τ CC and ν NC interactions typically will also be classified as cascade-like.

in the first octant, is the sensitivity to the mass hierarchy as a function of the full detector lifetime. As shown in the left plot, the sensitivity is statistically limited for the first 1.5 years of operation, but after that systematic errors start being a limiting factor to such measurement, as shown by the difference between the combined estimated significance and the $\sqrt{t}$ line. The primary systematic uncertainties that contribute to this measurement are shown in the right side of Fig. 5 with the energy scale and cross section uncertainties providing the largest impact. A series of other uncertainties, such as systematics associated with the GENIE neutrino generator, are currently under evaluation and are anticipated to be subdominant. The final result is a determination of the mass hierarchy at 3σ with approximately 3.5 years of data of the completed PINGU detector if θ_{23} is in the first octant and at more than 5σ, in the same period, if θ_{23} is in the second octant, as shown in Fig. 6.

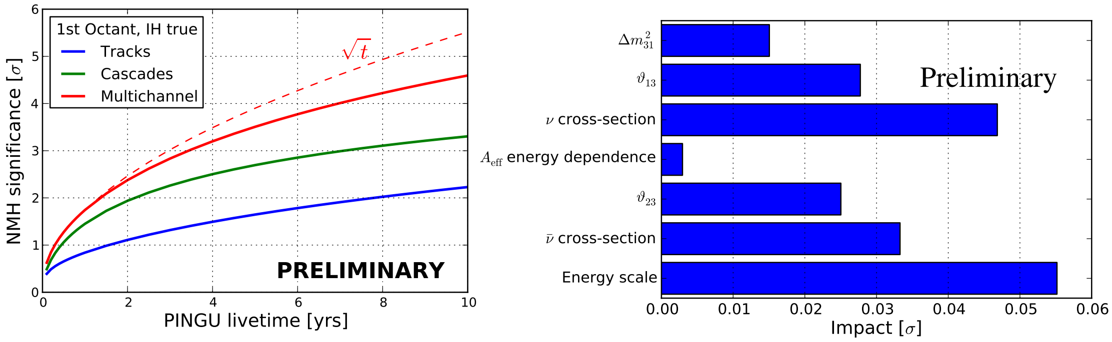

Figure 5: PINGU significance to the neutrino mass hierarchy (left panel) as a function of time for the first octant ($\theta_{23} = 38.7°$), using analysis in [7] and considering systematics in the right panel. The dashed line shows the expectation for a $\sqrt{t}$ dependence.

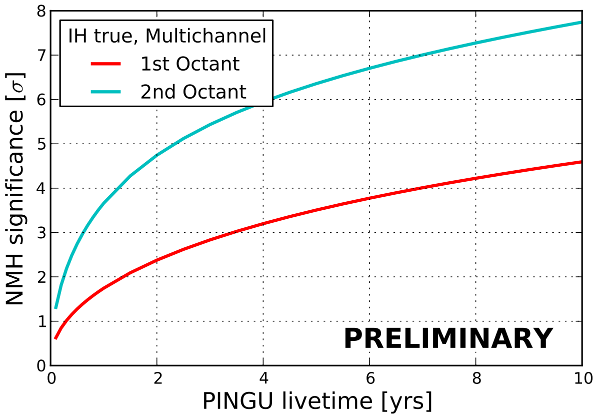

Figure 6: PINGU significance to the neutrino mass hierarchy as a function of time using analysis in [7]. Calculations done assuming true $\theta_{12} = 33.5°$, $\theta_{23} = 38.7°$ for first octant or $\theta_{23} = 51.3°$ for second octant, $\theta_{13} = 8.93°$, $\Delta m^2_{21} = 7.54 \cdot 10^{-5}$ eV^2/c^4, $\Delta m^2_{31} = -2.38 \cdot 10^{-5}$ eV^2/c^4 and $\delta_{CP} = 0$, values based on [5]. The dependence to the mass hierarchy significance of the true hierarchy is small, so even though this calculations were made for true “inverted” hierarchy results still apply if the true hierarchy is “normal”. The same set of systematics shown in Fig. 5 were considered.

3.2 ν_μ disappearance

Since DeepCore is already capable of measuring the atmospheric mixing parameters with results that are competitive to the currently leading experiments, and given that PINGU will have a lower the energy threshold and will also be able to reconstruct better the neutrino energy and direction, it comes naturally that PINGU should perform very well to measure the atmospheric mixing parameters, and will certainly improve in relation to what DeepCore currently can do.

With the lower energy threshold, PINGU will be able to map at least two ν_μ survival probability minima and one maximum, permitting analyzers to measure the values of the mixing angle θ_{23} and mass splitting Δm^2_{23}. By applying the mass hierarchy analysis described above and including the impact of the same systematic uncertainties one obtains preliminary sensitivities that are expected to be competitive with the world-leading experiments with approximately $0.38 < \sin^2\theta_{23} < 0.35$ and $2.38 \cdot 10^{-3}$ eV^2 $< |\Delta m^2_{23}| < 2.42 \cdot 10^{-3}$ eV^2 at 90% confidence level assuming an input of the current global best fit for the parameters [5].

3.3 ν_τ appearance

Complementing the ν_μ disappearance measurement described above, PINGU will also have the capability to perform a statistical measurement of ν_τ appearance. Both Super-Kamiokande [15] and OPERA [16] have already looked for ν_τ appearance and confirmed it to about 4σ. While it is very likely from these results that ν_τ is indeed appearing from ν_μ oscillations, we still can learn more about neutrino oscillations by comparing the ν_τ appearance rate to the ν_μ disappearance rate; namely, we may examine if the ν_τ appearance rate is the value expected from the rate of ν_μ disappearance. If those rates are not compatible we would have a clear indication of new physics either from non-unitary of the lepton mixing matrix (indicating the presence of sterile neutrinos) or from non-standard interactions.

A preliminary analysis has been performed to look for ν_τ appearance using the same event selection criteria as for the neutrino mass hierarchy analysis to reject atmospheric muons [7], while selecting the events on the sample classified as "purer" cascade-like events. In that sample we expect roughly 1.7×10^3 ν_τ induced events per year in a background of 11.2×10^3 background events per year. Furthermore, the signal is concentrated around the up-going region, while the background is concentrated around the horizon, as shown in the left panel of Fig. 7. Even though there is still more background than signal in the up-going region, the measure of ν_τ appearance remains statistically significant, as shown in the right panel of Fig. 7. The analysis was performed assuming a similar set of systematic errors as for the neutrino mass hierarchy analysis and yields an expected 5σ exclusion of no ν_τ appearance hypothesis with 1 month of data and 10% precision on the ν_τ normalization after 6 months, as shown in Fig. 8.

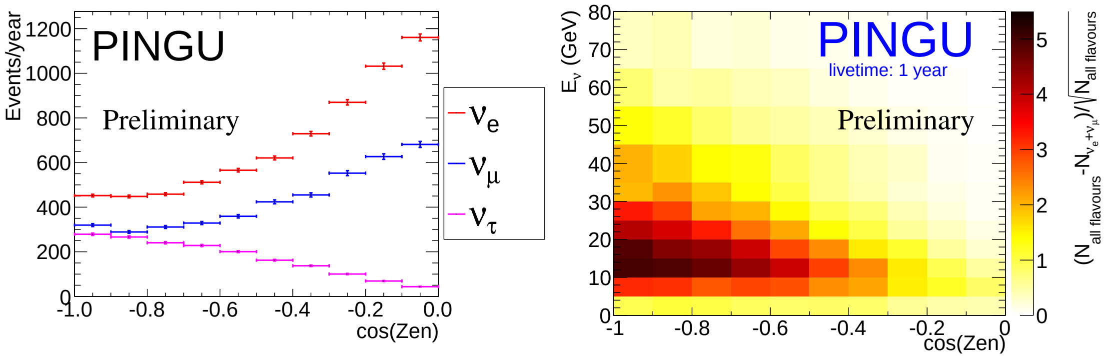

Figure 7: Left: Expected event rate for different path lengths through the Earth (described by zenith angle) in PINGU with a selection criteria designed for "purer" cascade events. Right: Distinguishability metric for ν_τ appearance on the "purer" cascade-like channel, for one year of simulated PINGU data with reconstruction and particle identification applied.

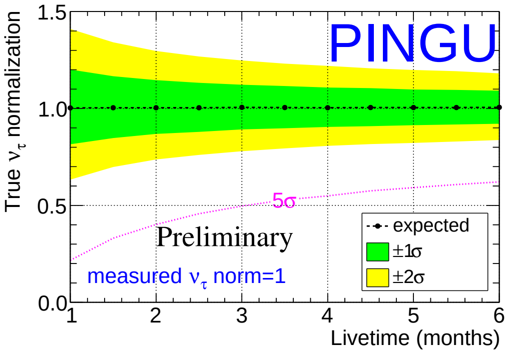

Figure 8: Normalization precision versus time for ν_τ appearance events with the PINGU detector.

4. Conclusions

PINGU builds on a successful particle physics program in the Antarctic established by the DeepCore array providing competitive measurements of atmospheric neutrino oscillations and world-leading indirect dark matter searches. It was designed to provide the first definitive measurement of the neutrino mass hierarchy using a statistically large sample of atmospheric neutrinos. PINGU will also be capable of significantly improving leading measurements of the atmospheric neutrino mixing parameters by measuring ν_μ disappearance and also will measure ν_τ appearance. Beyond this program of atmospheric neutrino measurements, PINGU would enhance sensitivity to low-mass WIMP indirect dark matter searches, to supernova neutrinos, and provides potential for first measurements of Earth neutrino tomography. In this way, PINGU is a vibrant and significant part of the planned upgrades to the IceCube facility at the South Pole.

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