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IceCube/DeepCore and IceCube/PINGU: Prospects for Few-GeV Scale ν Physics in the Ice

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Abstract

IceCube and its low energy extension, DeepCore, have been fully deployed at the South Pole and taking data since early 2010. With a neutrino energy threshold of about 10 GeV, DeepCore endows IceCube with access to a rich variety of atmospheric neutrino oscillation physics and enhanced sensitivity for indirect searches for WIMP dark matter. A new in-fill array, dubbed PINGU, is under consideration as a way to further lower the neutrino energy threshold to a regime with the potential to measure the type of the neutrino hierarchy. We describe early results from DeepCore and simulation studies of the sensitivity of PINGU to the hierarchy.

Keywords: neutrino, mixing, hierarchy

1. Neutrino Oscillations and the Neutrino Hierarchy

Evidence for neutrino oscillation has come from many different experiments, in particular those which study neutrinos produced in reactors, the sun and the atmosphere [1]. The combination of the results from these experiments has led to the development of a model in which neutrino oscillation is described using the 3×3 "PMNS" matrix [2] representing the probabilities of a neutrino of a certain mass eigenstate to be found in a particular flavor eigenstate. Experiments measure elements of the PMNS matrix by searching for the appearance or disappearance of particular neutrino flavors.

There are numerous fundamental parameters needed to fully describe neutrinos and their interactions. The various neutrino mixing parameters and mass-squared differences are currently being studied by many experiments, and many of the mixing parameters are being measured with high precision. Key parameters that have not yet been measured include the ordering of the neutrino masses, whether CP is violated in the weak sector, whether neutrinos are Dirac or Majorana particles, and the value of individual neutrino masses [1].

The unknown neutrino mass ordering–whether the neutrino mass eigenstate labeled ν_3 is heavier or lighter than the other two eigenstates–is known as the "neutrino hierarchy" problem. If ν_3 is heavier, the hierarchy is denoted "normal," otherwise it is denoted "inverted." As described in §4, depending on the neutrino energy and its trajectory through the earth, there can be enhancements of the oscillation probability affecting neutrinos or anti-neutrinos, depending on whether the hierarchy is normal or inverted [4, 5].

To exploit this opportunity, one needs a detector with an energy threshold of a few GeV capable of neutrino flavor identification and directional reconstruction in the same energy regime, with a sufficiently large fiducial volume to acquire adequate atmospheric neutrino statistics. The PINGU detector, described in §3, may be able to rise to this challenge.

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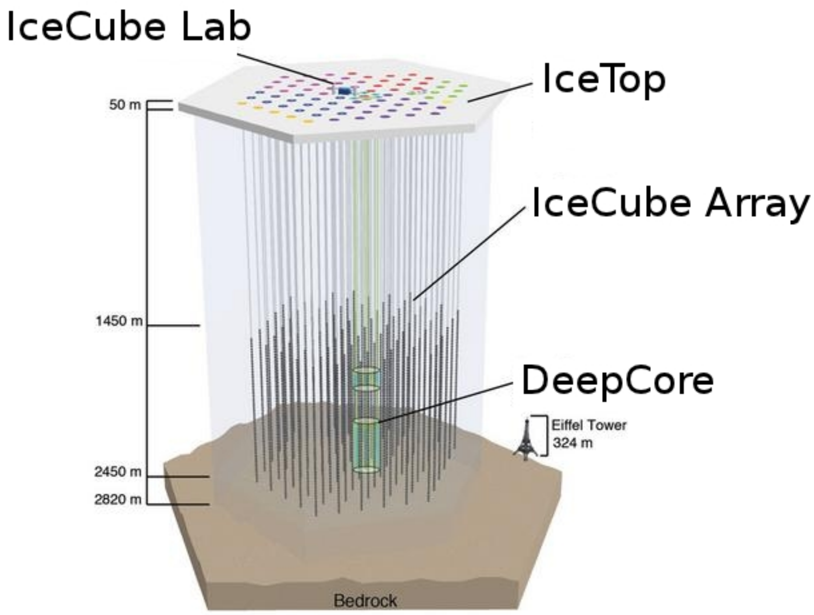


Figure 1: A sketch of the IceCube and DeepCore strings, and IceTop tanks, as currently deployed at the South Pole.

2. IceCube/DeepCore

IceCube consists of 86 "strings" of 60 Digital Optical Modules (DOMs), each containing a photomultiplier tube (PMT) and buried in the ice at the South Pole, Antarctica. On the surface is an integrated array of tanks for detecting cosmic ray air showers. The horizontal distance between most of the buried IceCube strings is approximately 125 m while the DOMs on each string are separated by 17 m vertically. This geometry was supplemented by eight additional strings in the region shown in Fig. 1 which, in conjunction with the twelve strings surrounding them, make up the DeepCore detector. The horizontal distance between DeepCore strings ranges from 42 m to 72 m. The PMTs in six of the strings also have a higher quantum efficiency. These various factors make DeepCore sensitive to lower light levels and therefore lower energy neutrino interactions relative to IceCube alone [7].

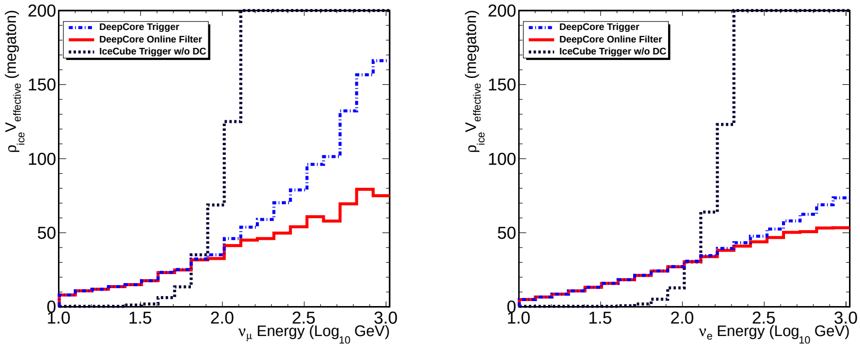
To benchmark the sensitivity of the IceCube detector for atmospheric neutrinos, the "effective volume" as a function of energy is calculated as

$$V_{\mathrm{eff}} = V_{\mathrm{gen}} N_{\mathrm{trig}} / N_{\mathrm{gen}}, \tag{1}$$

where V_{gen} is the volume in which the events were generated and N_{trig} and N_{gen} the number of events satisfying the trigger and the number generated, respectively. This calculation is carried out for electron and muon neutrinos for the simulated IceCube detector, with and without DeepCore (see Fig. 2).

From the figure one can see that while the large physical volume of the IceCube detector provides an excellent target for higher energy neutrino interactions, the addition of DeepCore increases IceCube's efficiency at neutrino energies below about 100 GeV.

DeepCore was fully deployed in May 2010, and several results have come from the analysis of the initial year of data collected. The first is the observation of atmospheric neutrino-induced showers, or "cascades." These cascades are produced by neutral current interactions of any neutrino flavour or charged current interactions of electron or tau type neutrinos. In the DeepCore detector, 1029 events were identified as potential cascade events. An estimated 59% of these events were true cascades, while the remaining 41% are attributed to background muon type neutrino CC interactions with muon tracks that were too short to reconstruct. This is the first detection of cascades by a high energy neutrino telescope, reaching an energy regime beyond that ever detected before (the average neutrino energy was about 180 GeV in the final sample) [8]. The analysis achieves roughly a 10^8 rejection of atmospheric muons from cosmic ray air showers by using the surrounding IceCube array as an active veto volume. The measured flux is



(a) Muon neutrino effective volumes.

(b) Electron neutrino effective volumes.

Figure 2: Effective volumes of the IceCube and DeepCore detectors under different event selection conditions. Dashed (black) lines indicate a hypothetical IceCube without DeepCore and events that pass the basic IceCube trigger condition of eight or more detected photons within 5μs. Dot-dash (blue) lines indicate events that pass the DeepCore trigger condition of three or more photons detected by DeepCore modules in 2.5μs. Solid (red) lines indicate events that pass both the DeepCore trigger condition and the DeepCore filter condition that rejects many events consistent with downward-going cosmic ray muon background, as described in Ref. [7].

consistent with current models of atmospheric neutrino flux and flavor composition [9].

Data collected from the combined IceCube and DeepCore detectors has been analyzed to look for atmospheric ν_μ oscillations [10]. These oscillations, though expected, until now have not been observed at energies as high as in this data set. The analysis benefits from a dip in the ν_μ survival probability to $P(\nu_\mu \rightarrow \nu_\mu) = 0$ at about $E_\nu = 25$ GeV for baselines equal to the earth's diameter. The combined IceCube DeepCore detector rules out the "no oscillation hypothesis" for ν_μ at these energies at 5.6 σ.

These data are also being used to search for ν_τ appearance at about $E_\nu = 25$ GeV, where it is expected that the muon neutrinos are oscillating primarily into tau neutrinos, as indicated by previous measurements [11]. Preliminary studies have shown that there is enough statistical power in this measurement to allow the hypothesis in which there is no tau neutrino appearance to be ruled out with high significance.

DeepCore is also being used to search for WIMP dark matter that annihilates in the solar core, leading to an excess high-energy neutrino flux from the sun. Sensitivity to neutralino masses as low as 50 GeV is expected [12].

3. IceCube/PINGU

To further drive down the energy threshold of the detector, another stepwise increase in module density is being considered for deployment within the DeepCore fiducial volume. This upgrade is called the Precision IceCube Next-Generation Upgrade, or PINGU. PINGU will consist of about 20 new strings with a smaller horizontal distance between strings and a smaller vertical distance between DOMs on the strings relative to DeepCore. This will serve to further lower the energy threshold from roughly 10 GeV for DeepCore down to a few GeV.

To quantify the improvement in sensitivity afforded by the new detector geometry, effective volume plots similar to those produced for DeepCore are used. The plots shown in Fig. 3 show that the target mass below 10 GeV is dramatically improved with the addition of the PINGU strings.

PINGU will also benefit from a likely redesign of the calibration hardware installed with the DOMs. The calibration sources will likely still be LEDs mounted in the DOMs, as for IceCube and DeepCore, but efforts are underway to improve the accuracy of the pointing and opening angle, and to provide a very fast (order of 2 ns) rise time pulse. With these enhancements, we can exert better control over absolute light yield, improving calibrations of DOM sensitivity and optical properties of the ice, as well as allowing for more accurate timing calibration, throughout the PINGU detector volume.

4. PINGU Physics

The increased sensitivity of the PINGU detector to events at low energies will enhance the sensitivity of on-

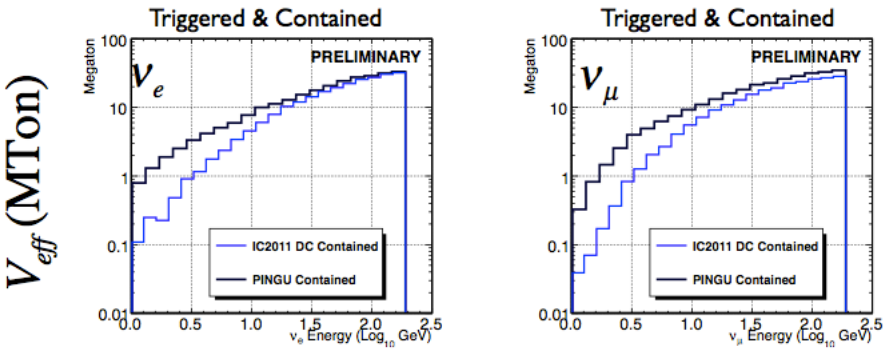
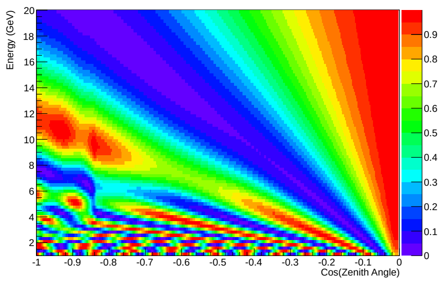
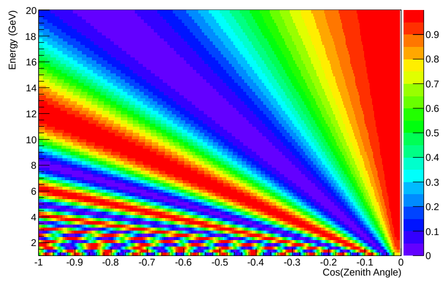


Figure 3: Effective volumes of the DeepCore and PINGU detectors.

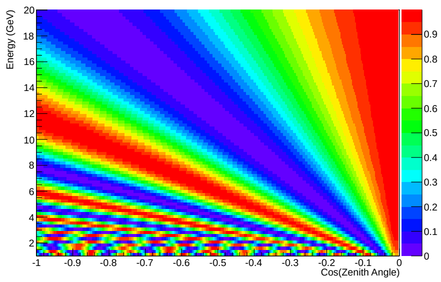
going DeepCore analyses and may also enable the determination of the neutrino hierarchy [6]. Atmospheric muon neutrinos with $E_\nu \sim 10$ GeV created in the northern hemisphere that pass through the earth's mantle will experience a resonant MSW enhancement of $\nu_\mu \to \nu_e$ oscillations if the hierarchy is normal; these oscillations are enhanced for $\bar{\nu_\mu}$ if the hierarchy is inverted. Furthermore, ν_μ with $E_\nu \sim 5$ GeV that pass through the the earth's core may also experience parametric enhancement of oscillations, the character of which will also depend on the type of the hierarchy. With an ideal detector, the MSW enhancement plays a larger role than parametric enhancement in determining PINGU's sensitivity to the type of the hierarchy. However, after the application of event selection criteria that are likely to have greater acceptance for upward-going neutrinos relative to more horizontal neutrinos, the two enhancements may have more or less equal impact on PINGU's sensitivity. It is worth noting that if PINGU is able to determine the type of the hierarchy, it will also have detected paramet-



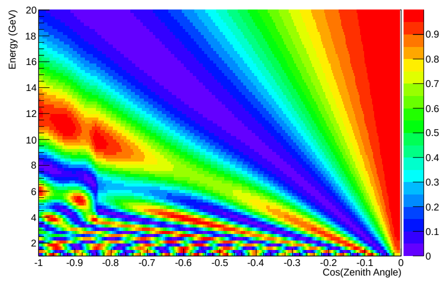
(a) Probability for muon neutrinos, normal hierarchy



(b) Probability for muon neutrinos, inverted hierarchy



(c) Probability for muon anti-neutrinos, normal hierarchy



(d) Probability for muon anti-neutrinos, inverted hierarchy

Figure 4: Probabilities for muon (anti-)neutrinos to be detected as muon (anti-)neutrinos after traversing the Earth. The complicated structure at energies below 15 GeV and zenith angle below -0.83 is due to the parametric resonances.

ric oscillations for the first time.

The effect of the resonances on the probability of the neutrino oscillating can be seen in Fig. 4, which were generated in the style of those shown in Ref. [6]. In these plots, the atmospheric ν_μ survival probability is shown as a function of ν_μ energy and zenith angle. The plots are made only for up-going neutrinos since downward-going neutrinos will not experience parametric oscillations. The ability to detect the hierarchy depends crucially on the oscillation of both the neutrinos and anti-neutrinos, the probabilities for which are shown in Fig. 4. PINGU has no ability to distinguish between neutrinos and anti-neutrinos, but since neutrinos in this energy regime have a cross section with matter roughly double that of anti-neutrinos, a potentially measurable effect remains. In our simulations we use neutrinos and anti-neutrinos.

To measure the efficacy of PINGU for determining the type of the hierarchy, we use the metric described in [6] and shown in Eq. 2,

$$\sum_{ij} \frac{\mathrm{N}^{\mathrm{IH}}_{ij} - \mathrm{N}^{\mathrm{NH}}_{ij}}{\sqrt{\mathrm{N}^{\mathrm{NH}}_{ij}}}, \qquad (2)$$

where $\mathrm{N}^{\mathrm{IH}}_{ij}$ is the number of ν_μ events in the ij^{th} bin in energy and angle produced under the assumption of an inverted hierarchy, and $\mathrm{N}^{\mathrm{NH}}_{ij}$ the same but for normal hierarchy. The result is scaled such that the summation may be interpreted as a number of sigma distinguishing normal from inverted hierarchy. In Fig. 5, we show the contents of the individual angular and energy bins that contribute to the summation. Here, the zenith angle used is obtained from the true direction of the outgoing muon (not the incoming neutrino) in order to account for the kinematic effects in the neutrino interaction. Additionally, the figures and values are calculated using one particular PINGU geometry. The geometry used for Fig. 5 has a horizontal spacing of 26 m between strings and a vertical spacing of 5 m between DOMs. Other configurations are being studied to determine, for a fixed number of DOMs, the optimum balance between improved angular and energy resolution due to higher module density and the higher event rates afforded by a larger and more sparsely instrumented detector.

Figure 6 shows the calculated metric obtained using Eq. 2 for a variety of angle and energy resolutions over a period of one year of data taking. To show the impact of the resolutions, a range in both angle and energy has been selected. The energy resolutions vary from 2 to 20 GeV, spanning the range of likely DeepCore performance. Similarly, the resolutions on the zenith angle vary from 2 to 20 degrees. In order to simulate the resolutions, a Gaussian smearing was applied to the simulated data. Although systematic effects are extremely important and not yet taken into consideration here, preliminary estimates of experimental resolution indicate that a determination of the neutrino hierarchy by PINGU may be in reach.

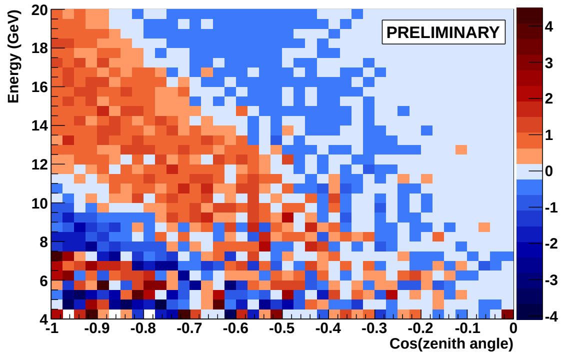


Figure 5: Normalized difference between normal and inverted hierarchies for bins of energy and angle (see Eq. 2), summed over neutrinos and anti-neutrinos and using one year of PINGU data.

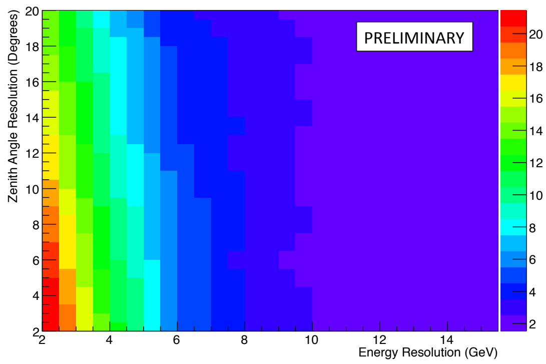


Figure 6: The hierarchy sensitivity metric for one year of PINGU data in units of σ (see text) summed over neutrinos and anti-neutrinos and calculated for a variety of angular and energy resolutions. We use Gaussian smearing to apply the resolutions and all values are calculated using the angle of the muon daughter.

5. Conclusion

The IceCube Collaboration has had great success lowering its energy threshold by adding more densely spaced modules. At neutrino energies still well in excess of any other previous measurement, DeepCore has already been used to detect cascades produced by ν_e and ν_τ atmospheric neutrino interactions and to study neutrino oscillations. Following in the successful steps of DeepCore, the PINGU detector would further lower the neutrino energy threshold and potentially permit a measurement of the type of the neutrino hierarchy, one of the most important unmeasured parameters in fundamental neutrino physics.

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