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PINGU and the Neutrino Mass Hierarchy

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Abstract

The nature of the neutrino mass hierarchy is one of the most interesting open questions in particle physics today, and thus has drawn a great deal of attention from the neutrino physics community. The measurement of a large mixing angle between the first and third neutrino mass eigenstates has made possible several methods of measuring this hierarchy. One of these methods is a proposed expansion of the IceCube/DeepCore detector called PINGU (Precision IceCube Next Generation Upgrade) which would use atmospheric neutrinos to make the determination. This extension is made up of additional strings of optical sensors (similar to those already deployed in the IceCube detector) which will be located in the ice at the centre of IceCube. The spacing between these sensors would be smaller than even the existing DeepCore detector (both vertically and horizontally) and this increased density would permit the lowering of the neutrino detection threshold to substantially below 10 GeV. The physical nature of the detector as well as the methods used to make this measurement are presented.

Keywords: neutrino, mass hierarchy

1. Introduction

The oscillation of neutrinos has been detected in a wide variety of sources such as reactors, the atmosphere and the Sun [1]. The combination of the results from these diverse experiments presents a consistent model for neutrino oscillations which is summarized by the PMNS matrix [2] in which the entries represent the probability that each mass eigenstate will be detected in that particular flavour eigenstate. Currently the differences in mass between the eigenstates is known, but the ordering is not. The two possibilities are the case in which the third mss eigenstate (ν_3) is the heaviest (the "normal" hierarchy) or that in which it is lightest (the "inverted" hierarchy). The distinction between these two situations is discernible using atmospheric neutrinos using an appropriate detector [3, 4].

The proposed PINGU detector adds optical sensors to the existing IceCube/DeepCore array in the South Pole ice, thereby building on the success of the original projects. The IceCube detector consists of 86 strings with 60 optical sensors deployed between depths of 1450 and 2450 m. The first 78 strings are installed at an average horizontal spacing of 125 m and an average vertical spacing of 17 m. These 4680 optical sensors were augmented with an additional 8 strings deployed in their centre with a horizontal spacing of 75m and a vertical spacing of 7 m. This first extension is called DeepCore, and lowered the energy threshold for neutrino detection from roughly 100 to 10 GeV [5]. The PINGU detector will further lower this threshold by adding another 40 strings with a 22 m average horizontal and 3 m vertical spacing. The energy and angular resolution of the low energy events will also be improved with the addition of the new strings.

The PINGU detector will follow the model of the DeepCore extension and be located at the centre of the

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IceCube strings. This allows the existing detector to be used as a veto for muons which enter the PINGU volume. These incoming events, which produce light outside of the PINGU strings, will be removed from the event sample using tools which have been used successfully in the DeepCore analyses [5].

2. PINGU Simulation and Reconstruction

All PINGU analyses to this point depend on the generation of a great deal of Monte Carlo simulation to characterize the response of the detector as well as to determine essential attributes such as the efficiency of the trigger and the ability to reconstruct incoming events. The generation of PINGU data builds on the simulation software used for the IceCube/DeepCore experiment, which uses a combination of the GENIE neutrino generator to produce the neutrinos, GEANT4 to propagate the interactions and a custom-built GPU code named CLSim to propagate the photons in the detector. In this manner the simulated PINGU detector has been used to perform a number of studies relating to both the inherent properties of the detector as well as the ability to make several physics measurements.

As previously described, the PINGU extension consists of 40 strings with 96 optical modules per string. These strings are spaced horizontally by an average of 22 m while the modules have a 3m vertical spacing along the string. A sketch of the detector is shown in Figure 1.

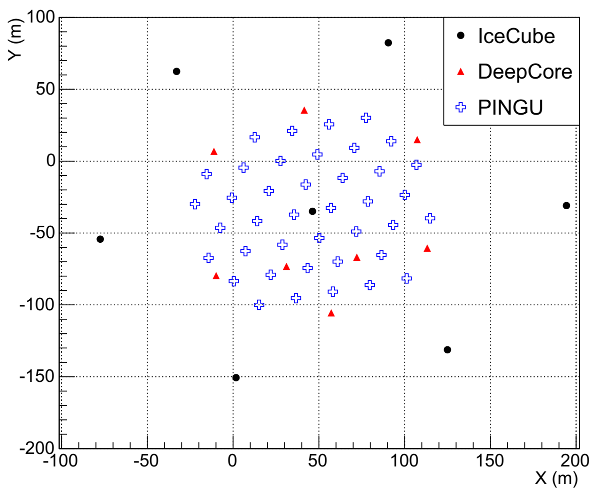


Figure 1: Geometry of the PINGU extension. The location of the strings in the ice are shown in a top view.

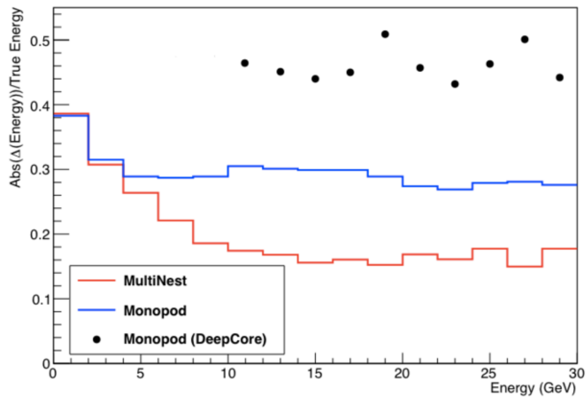


Figure 2: Energy resolution using several reconstruction methods, including the baseline MultiNest algorithm. The relative reconstructed energy difference is plotted with respect to the true neutrino energy.

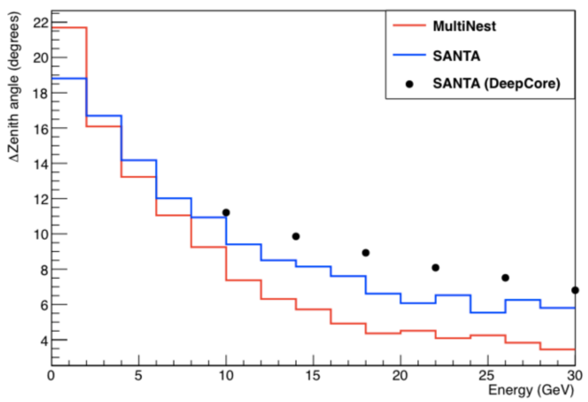
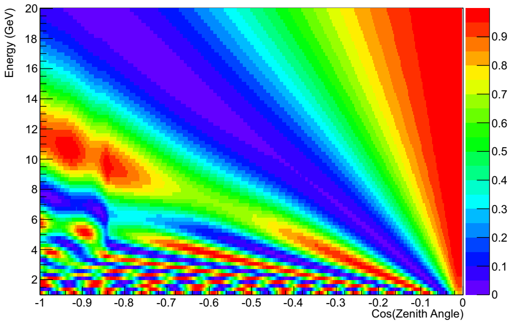
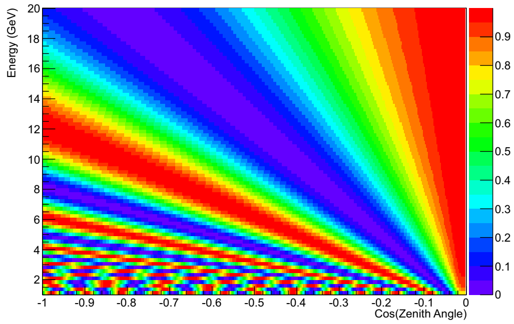


Figure 3: Energy resolution using several reconstruction methods, including the baseline MultiNest algorithm. The zenith angle reconstructed difference is plotted with respect to the true neutrino energy.

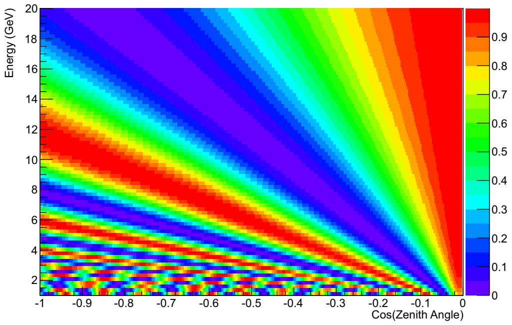
One of the primary uses of the simulated data has been to develop new reconstruction algorithms for use with the lower energy (and therefore lower light-producing) events in the PINGU data sets. The existing algorithms used are called Monopod (which reconstructs the energy) and SANTA (which reconstructs the zenith angle), and these have been tested on both the original IceCube detector as well as the setup augmented with the DeepCore strings. A new minimization routine called MultiNest [6] has been used in conjunction with the existing likelihood framework specifically on the data generated using the PINGU detector. This method builds on the likelihood calculation used in IceCube/DeepCore and improves it by fitting all parameters of the neutrino simultaneously using a sophisticated algorithm to find the values with the best likelihoods. While there are a total of eight parameters fit (the ver-



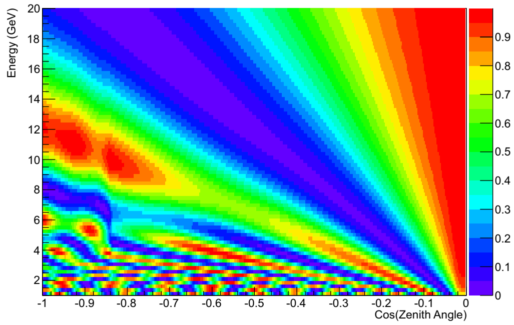
(a) Survival probability for muon neutrinos in the normal hierarchy



(b) Survival probability for muon neutrinos in the inverted hierarchy



(c) Survival probability for muon anti-neutrinos in the normal hierarchy



(d) Survival probability for muon anti-neutrinos in the inverted hierarchy

Figure 4: The survival probability for muon neutrinos following travel through the Earth, shown with respect to the true neutrino energy and zenith angle.

tex position (x,y,z) and time of the interaction, the angle for the azimuth and zenith and the energy of both the neutrino and the produced particle(s)) the analysis relies primarily on the neutrino energy and zenith angle. The resolutions of these important parameters from these studies are included in Figures 2 and 3.

As shown in Figure 2, the energy resolution achieved in DeepCore using the Monopod method (shown in the black circles) is improved when applied to the PINGU geometry (blue line). Further improvement in the resolution is achieved using the MultiNest algorithm, as shown in the red line. Using this method, the relative energy resolution is seen to be better than 0.2 at energies above 10 GeV. Similar results are seen in Figure 3 for the resolution on the zenith angle. In this figure, the zenith resolution is seen to improve with the increased energy, as expected, and to reach a plateau at roughly 5° above 20 GeV.

The reconstructions shown in Figures 2 and 3 as the MultiNest lines have been adopted as the baseline reconstructions for use in the PINGU analyses, including the determination of the neutrino mass hierarchy.

3. Determination of the Neutrino Mass Hierarchy with Atmospheric Neutrinos

The use of atmospheric neutrinos to determine the hierarchy relies upon the MSW effect as these neutrinos travel through the Earth [7, 8]. This is a modification to the vacuum oscillation probability, which predicts that muon-type neutrinos with an energy of roughly 10 GeV which travel through the Earth will experience an enhancement of the $\nu_\mu \rightarrow \nu_e$ transition, provided the hierarchy is normal. If the hierarchy is inverted (ν_3 is the lightest eigenstate) the enhanced transition will be in the anti-neutrinos, i.e. $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$.

The transition of neutrinos as they travel through the Earth is also affected by a parametric enhancement in these oscillations in which neutrinos which travel through the Earth's core have a modified probability of oscillation [9]. This effect is seen to be particularly prominent in enhancing the $\nu_\mu \rightarrow \nu_e$ transition for neutrinos traveling through the Earth's core. Since this effect also depends on the hierarchy, this adds to the differences which can be used to determine the hierarchy from the oscillation data.

The muon survival probabilities can be shown binned by both neutrino energy and the cosine of the zenith angle for all cases (neutrinos and anti-neutrinos in the normal and inverted hierarchies) and these oscillograms are shown in Figure 4.

The primary difference shown in Figure 4 is seen when comparing the two cases for the hierarchy, i.e. Figure 4a to 4b for the ν_μ probabilities and Figure 4c to 4d for the $\bar{\nu}_\mu$ probabilities. These comparisons allow the determination of the hierarchy in experiments which have the ability to distinguish between ν_μ and $\bar{\nu}_\mu$ interactions. Since the PINGU detector does not have this capability, the plots from each hierarchy are added (weighted appropriately for the ν and $\bar{\nu}$ flux) to provide the observed signal. The final method then involves comparing the addition of Figures 4a and 4c to the addition of Figures 4b and 4d. The difference in oscillation patterns between these summed plots are sufficient to permit the determination of the mass hierarchy using this data.

The addition of these plots can be used to illustrate the difference in signal between the two hierarchies using a method proposed in previous studies with atmospheric neutrinos [4]. In these plots, all neutrino types have been included (ν_e, ν_μ, and ν_τ) with separation only into qualities which are derived from the data. In this case, the neutrinos have been divided into "tracks", charged current muon-type neutrino events which produce long muon track in the detector, and "cascades", all other interactions which primarily produce showers of short-lived hadronic particles.

Both of Figures 5 and 6 show that there is sufficient difference in the oscillation patterns between the hierarchies to allow for the distinction of the hierarchy using atmospheric neutrinos. In these plots the reconstruction resolution has been included using a parameterization method, in which the energy-dependent resolution (for both energy and zenith angle) is determined using a sample of simulated neutrinos and then applied to the full set [10]. It should also be noted that the differentiation between "track" and "cascade" events is assumed to be perfect in Figures 5 and 6. The true distinction between these events is currently being quantified, but looks to be very reliable, particularly at energies above 10 GeV.

The sum of the absolute value of the bin content in Figures 5 and 6 provides an estimate of the number of σ separation between the two hierarchies. A more thorough determination of the separation between hierarchies involves a more detailed method which will be described in detail.

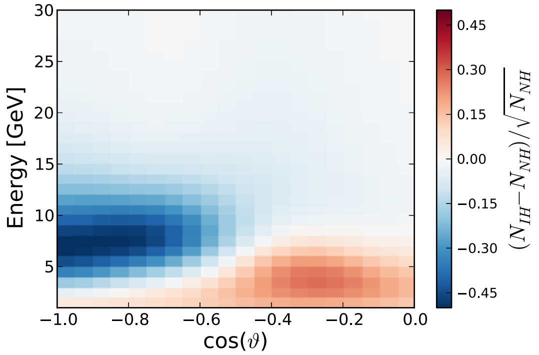


Figure 5: Distinguishability metric of the two hierarchies using cascade-type events in the PINGU detector. The metric is defined as the difference in the number of annual counts in the inverted hierarchy and the normal hierarchy (N_{IH} - N_{NH}) scaled by the square root of the number of counts in the normal hierarchy.

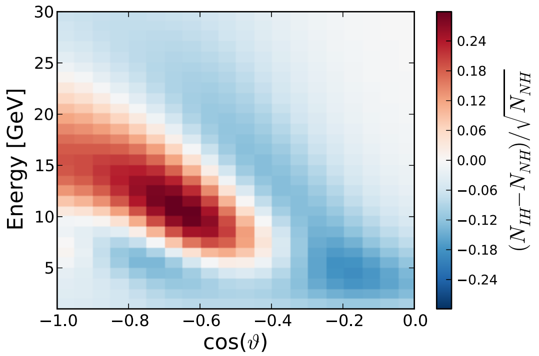


Figure 6: Distinguishability metric of the two hierarchies using track-type events in the PINGU detector. The metric is defined as the difference in the number of annual counts in the inverted hierarchy and the normal hierarchy (N_{IH} - N_{NH}) scaled by the square root of the number of counts in the normal hierarchy.

4. Analysis methods in PINGU

The PINGU collaboration has chosen two separate methods to distinguish the neutrino mass hierarchies using the simulated data: the Fisher Analysis Matrix and the Log Likelihood Ratio (LLR) methods. The more traditional LLR method has been used from the start as it is well understood and can be implemented simply with the simulated data. This method has been shown to be slow when including systematics, however, and a more efficient method was desired to give a result while the speed of the LLR method was increased. The faster method is the Fisher Analysis Matrix method, which has been used commonly in other fields for analyses with numerous systematic parameters [11].

Both of these methods have been pursued by the collaboration with significant effort applied to ensuring that the results from both methods agree. This has been shown to be the case in several varying situations [10] so the distinguishability results from the Fisher method are shown in Figure 7.

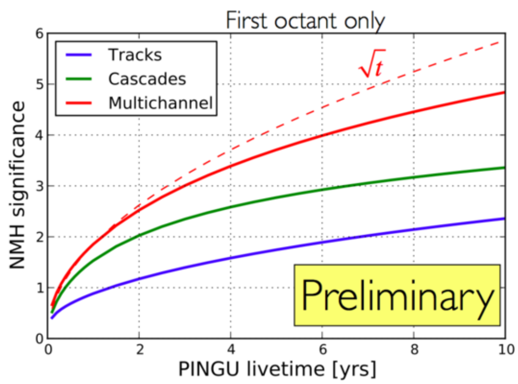


Figure 7: The significance of the measurement of the neutrino mass hierarchy using the PINGU detector evolving with time. In this determination, the inverted hierarchy and the location of the oscillations in the first octant have been assumed to be true.

As Figure 7 shows, the analysis of the track-type events alone provides a confidence in the determination of just under two sigma in five years, while the analysis of the cascade-type events provides just under three sigma. The combination of these signals gives roughly 3.7 sigma in five years, placing the PINGU analysis in a very competitive position when compared to other experiments also determining the hierarchy [12]. The results shown here are for the situation in which the true neutrino mass hierarchy is inverted and the θ_{23} value is in the first octant, the most conservative situation [10].

Use of the Fisher method has also allowed for calculation of the impact of various systematic effects which have been studied to this point. A chart of these impacts on the one year significance measurement is shown in Figure 8, in which the parameters with the most significant impact are shown with the scale of their effect.

The most significant impact is seen when including the energy scale (varied ±5%) and the neutrino cross-section (varied ±15%). These are shown to have an impact on the final significance of roughly 0.055 and 0.045 sigma, respectively. Further studies are currently underway to mitigate these effects to the extent this is possible.

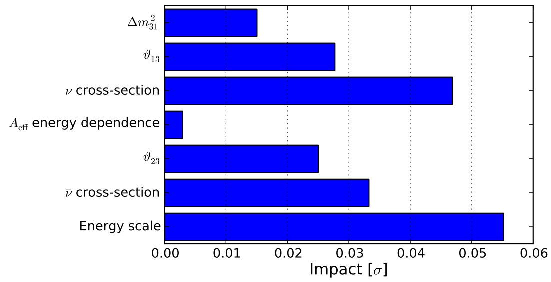


Figure 8: The scale of the impact on the neutrino mass hierarchy determination after one year of data collection due to the most significant systematic parameters. In each of these, the calculation involved turning off each parameter individually and observing the resulting increase in the significance.

5. Additional PINGU Physics

Although the PINGU detector has been discussed largely as an atmospheric neutrino detector which is used to determine the mass hierarchy, the large neutrino flux and increased low-energy sensitivity of this detector in relation to IceCube/DeepCore provides many options for other studies. Of particular note are the measurements of low-mass dark matter, the study of supernovae and the possibility of using neutrinos for tomography of the Earth itself [10].

6. Conclusion

The PINGU detector will continue the successful trend of neutrino physics started with IceCube by lowering the detection threshold for neutrinos and potentially providing a final determination of the neutrino mass hierarchy. In addition to this goal, there are many other physics topics which will be investigated.

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