NEUTRINO MASS HIERARCHY AT LARGE DETECTORS

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In this talk we discuss the future prospects to determine the neutrino mass hierarchy with current and future Megaton-scale Čerenkov detectors with low energy threshold. We present the sensitivities of the DeepCore and PINGU detectors by exploting the θ_{13}-driven matter effects taking place along the propagation of atmospheric neutrinos deep through the Earth. If good angular and energy resolutions are realized, a determination of the mass ordering at the 5σ confidence level after one year in PINGU could be possible. Finally, we also study the sensitivity of these detectors to fluctuations on the normalization of the Earth's density.

1 Introduction

Recent measurements of the θ_{13} neutrino mixing angle from the Daya Bay [1], RENO [2] and Double Chooz [3] reactor experiments, in addition to the long-baseline T2K experiment [4], indicate that $\theta_{13} \sim 9^\circ$ [5,6,7]. This non-zero value of θ_{13} drives resonant matter effects in the propagation through the Earth of atmospheric neutrinos with GeV energies [8,9,10,11,12,13,14,15,16,17,18,19,20,21] and it is well known that these effects are very sensitive to the neutrino mass hierarchy [14,16,18,19], whether it is normal (NH) or inverted (IH).

A Megaton-scale neutrino telescope with low energy threshold ($\sim$ 10 GeV), such as the DeepCore extension of the Icecube detector, is currently taking data [22,23,24] and further natural extensions of this to reach even lower energies are being planned, such as the Precision IceCube Next Generation Upgrade (PINGU) [25] and within the context of the KM3NeT project, the Oscillations Research using Cosmics in the Abyss (ORCA) [26]. Although lowering the energy threshold to just a few GeV and achieving good energy and angular resolutions are very challenging tasks, if successful, the enormous amount of neutrino events that could be detected would offer a great opportunity for detailed oscillation studies. In the last year, this possibility (driven by the large value of θ_{13}) has boosted the interest on this issue and a number of works have analyzed the sensitivity of PINGU and ORCA to determine the neutrino mass hierarhy [27,28,29,30].

In this talk we summarize the main results obtained in Ref. [28] concerning the mass hierarchy determination and we briefly discuss the sensitivity of these huge Čerenkov detectors to fluctuations on the Earth's matter density by means of neutrino oscillation tomography.

2 Oscillations of atmospheric neutrinos in the Earth

Atmospheric neutrinos are produced after the hadronic showers from the interactions of cosmic rays with the nuclei of the Earth's atmosphere. Below $\sim$ 100 GeV, the neutrino flux is dominated by the pion decay chain, whereas above these energies, kaon decays dominate neutrino production. In this talk, we focus on the few GeV energy region where resonant matter effects could strongly modify the oscillation probabilities, for neutrinos in the case of NH and for antineutrinos if IH. To obtain our results we use the atmospheric neutrino fluxes from Ref. [31].

For neutrino energies in the range of a few GeV, the transition probabilities $\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$) and $\nu_e \to \nu_{\mu(\tau)}$ ($\bar{\nu}_e \to \bar{\nu}_{\mu(\tau)}$) of atmospheric neutrinos in their propagation through the Earth are relevant if genuine 3-flavor neutrino mixing takes place, i.e., for non-zero values of θ_{13} [8,9,10,11,12,13,14,15,16,17,18,19,20,21]. Moreover, in this energy range and for these baselines ($L >$ 1000 km), CP-violation effects are very small and can be safely neglected. Likewise, effects due to the 1-2 sector are also subdominant and, as a first approximation, can also be neglected. In this context, the calculation of the transition probabilities effectively reduces to a 2-neutrino problem, with Δm^2_{31} and θ_{13} playing the role of the relevant 2-neutrino oscillation parameters. There are analytical solutions for the transition probabilities for neutrinos crossing the Earth, and they reduce to the case of neutrino propagation in a medium of constant density for trajectories such that $\cos\theta > -0.83$, where θ is the zenith angle, i.e., for neutrinos which propagate only in the mantle. In this case, the resonant behavior, when maximal mixing in matter occurs, happens for the case of NH (IH) in the neutrino (antineutrino) channel at the resonant energy,

$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\,\cos 2\theta_{13}}{2\sqrt{2}\,G_F\,n_e} \simeq 7\,{\rm GeV}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times10^{-3}\,{\rm eV}^2}\right)\cos 2\theta_{13}\,, \tag{1}$$

where n_e and ρ are the electron and total density of the Earth (assuming they are constant). The baseline at which both, the condition for the resonance and the condition for the first oscillation maximum are satisfied, is [14]

$$L_{\rm max} = \frac{\pi}{\sqrt{2}\,G_F\,n_e\,\tan 2\theta_{13}} \simeq 1.1\cdot10^4\,{\rm km}\left(\frac{4.5\,{\rm g/cm^3}}{\rho}\right)\left(\frac{1/3}{\tan 2\theta_{13}}\right)\,. \tag{2}$$

In the case of propagation through the core of the Earth ($\cos\theta < -0.83$), non-trivial resonant effects show up at slightly lower energies, but still in the few GeV range.

Hence, these resonant energies and baselines are obtained for GeV atmospheric neutrinos traversing deeply the Earth, which are suitable to be studied with neutrino telescopes with a low energy threshold. Neutrino telescopes are Čerenkov detectors, so they have no charge-identification capabilities and therefore cannot distinguish neutrinos from antineutrinos. But it turns out that in the limit where the 1-2 sector is neglected, the probabilities for neutrinos and NH are equal to those for antineutrinos and IH. Nevertheless, the fact that neutrino and antineutrino cross sections and atmospheric fluxes are different could allow us to distinguish NH from IH. All in all, as the resonances take place for NH for neutrinos and IH for antineutrinos and both types of events are summed up, the θ_{13}-driven matter effects would consequently be smeared and the sensitivity to them reduced as compared to the case when measurements of the neutrino-induced and antineutrino-induced rates can be performed separately (with magnetized detectors). However, the size of these detectors compensates for this loss of sensitivity.

3 Set-up and analysis

The IceCube/DeepCore detector [22] is a densely instrumented region (with six extra strings) located at the bottom center of the IceCube detector at a depth of between 2100 m and 2450 m. Moreover, the larger amount of photosensors in the additional strings, separated by 7 m instead of 17 m for IceCube, and the higher quantum efficiency, lead to a significant gain in sensitivity of up to a factor of 6, especially for low energy neutrinos. The rest of the IceCube detector could be used as an active veto for downgoing atmospheric muons, allowing the study also of downgoing atmospheric neutrinos. Unfortunately, neutrino telescopes have a poor angular resolution for

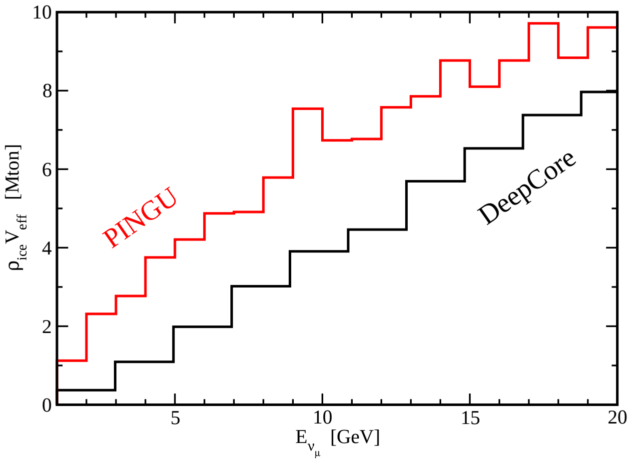


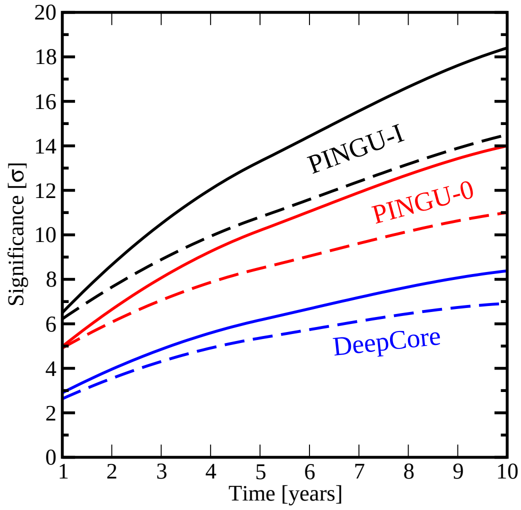
Figure 1: *Effective mass for DeepCore and PINGU for the energy range considered in this study (see text for details). In both cases, we add a post-trigger detection efficiency of* 50% *(not included in this plot).*

cascades, so we do not consider here the electron neutrino-induced event rates, where these resonant effects are expected to be larger, and focus on the muon neutrino-induced track event rates, using the effective mass for the 86-string configuration (IC86) at trigger (SMT3) and online filter level as shown in Fig. 1 [32]. Nevertheless, in a conservative approach, we only consider a single energy bin ($E_\nu = [10,\ 15]$ GeV).

On the other hand, PINGU is a recent proposal to further upgrade IceCube by adding 20 additional strings within the DeepCore volume so that the neutrino energy threshold can get lowered down to $\mathcal{O}(1)$ GeV. The effective mass considered in this talk is also shown in Fig. 1 and was obtained assuming a trigger setting of 3 digital optical modules hit in 2.5 μs that are in local coincidence, a containment criterium which is implemented by a cut on the z-position that matches the DeepCore fiducial volume (-500 m $< z < -157$ m) and a tight radius cut from string 36 ($r < 150$ m) which is the center of DeepCore/PINGU [32]. Here we consider two simplified scenarios: PINGU-0, with an energy threshold of 5 GeV and two 5 GeV energy bins ($E_\nu = [5,\ 10]$ GeV and $[10,\ 15]$ GeV); and PINGU-I, with four 2.5 GeV energy bins ($E_\nu = [5.0,\ 7.5]$ GeV, $[7.5,\ 10.0]$ GeV, $[10.0,\ 12.5]$ GeV and $[12.5,\ 15.0]$ GeV).

In all configurations we assume that the post-trigger efficiency of the detector, for all bins, is 50% and take angular bins in $\cos\theta$ of width 0.1 for $\cos\theta \in [-1, 0]$.

In order to perform the sensitivity analysis, the values of the oscillation parameters we use lie within the allowed ranges at 1σ confidence level (CL) obtained from global fits of the current neutrino data, except for the value of $\sin^2\theta_{23}$ [5,6,7], which we take to be $\sin^2\theta_{23} = 0.5$, as discussed in Ref. [28]. In our fits, we marginalize over $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{23}$, and the atmospheric mass square difference within their presently allowed $\pm 2\sigma$ ranges and impose a prior (Gaussian error at 1σ) of 5%, 2% and 4% on them, respectively. We keep θ_{12}, Δm^2_{21} and $\delta_{\rm CP}$ fixed both in data and in theory and no marginalization has been performed for these oscillation parameters since their effect on the results is negligible. In the case of the mass hierarchy sensitivity, we also marginalize over the Earth's matter density distribution, by allowing its normalization to vary freely within ± 10%. Finally, we also add a 20% fully correlated systematic error in the normalization of the number of events, which could be originated from errors on the normalization of the atmospheric neutrino flux, the cross section, the detector effective mass or the efficiency. We refer the reader to Ref. [28] for further details on the statistical analysis and the χ^2 definitions.



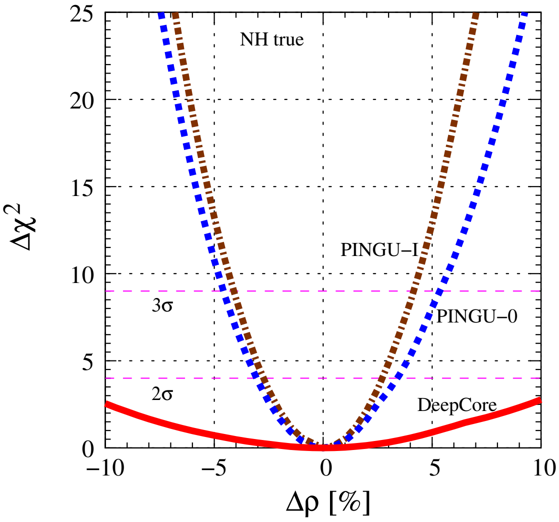


Figure 2: *Left panel: Sensitivity to the neutrino mass hierarchy for the three detector configurations discussed in this talk as a function of the exposure time. We show the results for NH (solid lines) and IH (dashed lines) as the true hierarchy. Right panel: Sensitivity, for the three detector configurations, to fluctuations on the overall normalization of the Earth's density for the case of NH as the true hierarchy.*

4 Results

In the left panel of Fig. 2 we show the results for the sensitivity to the neutrino mass hierarchy by using the number of muon-like events in the three possible neutrino configurations considered in this work. We can see that the prospects of measuring the neutrino mass hierarchy are very promising. For maximal θ_{23} mixing the ongoing DeepCore detector, with the signal efficiency and the energy reconstruction capabilities assumed here, could provide a measurement of the neutrino mass hierarchy at the 3σ CL (5σ CL) after slightly more than 1 year (less than 5 years) if nature has chosen NH and after less than 2 years (5 years) for IH. On the other hand, with PINGU-0 and PINGU-I, the mass hierarchy could be measured at $\sim 5\sigma$ CL and $> 6\sigma$ CL after 1 year for both NH and IH, respectively. In all cases, the results for the IH scenario are worse because in this case the resonant behavior occurs in the antineutrino channel, which is statistically suppressed due to the smaller antineutrino cross sections and initial fluxes.

On the other hand, in the right panel of Fig. 2 we show the results for the three detector configurations for the sensitivity to the Earth's matter density for NH as the true hierarchy and for 10 years of data taking. Here, in addition to the marginalizations discussed above, we also marginalize over the neutrino mass hierarchy. For the DeepCore configuration, fluctuations in the normalization of the Earth's density of $\Delta\rho \simeq \pm 10\%$ can be detected at the $\sim 1.6\sigma$ CL ($\sim 1\sigma$ CL) if NH (IH) is the true hierarchy. The results are significantly better for the PINGU-0 and PINGU-I configurations, due to the information contained in the lower energy bins. For NH (IH), PINGU-0, matter fluctuations of $\Delta\rho \simeq \pm 3\%$ ($\pm 9\%$) could be determined at the 2σ CL. PINGU-I could improve these numbers to $\Delta\rho \simeq \pm 2\%$ ($\pm 6\%$) for NH (IH).

Finally, let us note that, although we have included the marginalization over relevant parameters, have taken large energy bins and have added the impact of uncorrelated errors, a more accurate account of the resolutions (in particular the angular resolution) and the effect of uncorrelated errors would likely decrease the sensitivities significantly.

5 Conclusions

In this talk, we have discussed the sensitivities for the ongoing DeepCore and the proposed PINGU detectors to determine the neutrino mass hierarchy with muon-like atmospheric neutrino events in the GeV range by exploiting the θ_{13}–driven matter effects in the propagation of neutrinos through the Earth. The large statistics that could be accumulated by these detectors, thanks to the large value of θ_{13}, might make possible the determination of the neutrino mass hierarchy in short time scales.

Finally, we have also discussed the possibility to infer overall fluctuations in the Earth's matter density profile with these detectors. Although, in principle, geophysics can obtain more precise results, the results from atmospheric neutrino oscillation tomography would represent an independent and complementary assessment of the Earth's internal structure.

Acknowledgments

SPR is supported by the Spanish Grant FPA2011-23596 of the MINECO and by the Portuguese FCT through CERN/FP/123580/2011 and CFTP-FCT UNIT 777, which are partially funded through POCTI (FEDER).

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