

Atmospheric neutrinos: Status and prospects*

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Abstract

Atmospheric neutrinos are produced in the showers created by the interaction of cosmic rays in the Earth's atmosphere. Neutrino oscillations were discovered in 1998 by Super-Kamiokande using atmospheric neutrinos, and since then they have been continuously used as a tool to measure neutrino oscillations. Status of current measurements of active neutrino oscillations, as well as prospects of future experiments using atmospheric neutrinos are discussed here.

INTRODUCTION

This year, 2015, the Nobel prize was awarded to the discovery of neutrino oscillations [1]. The prize was split between T. Kajita (Super-Kamiokande) and A. B. McDonald (SNO) for discovering neutrino oscillations in the atmospheric neutrino flux in 1998 [2] and the solar neutrino flux in 2002 [3], respectively. Since these two detections, neutrino oscillations have also been measured using neutrinos produced in nuclear reactors and particle accelerators. All these observations provide a consistent picture and most of the parameters describing the 3-flavour standard neutrino oscillation have been measured with varying precision (see [4] and references therein). The remaining open questions in the standard neutrino framework are the value of CP violating phase (δ_{CP}), the neutrino mass hierarchy (the sign of Δm_{32}^2) and the octant of the mixing angle θ_{23} .

The atmospheric neutrino flux is produced from decays of π and K mesons produced by cosmic ray interactions in the Earth's atmosphere and the subsequent shower development [4]. The ν flux produced this way is roughly isotropic, with twice as many $\nu_\mu + \bar{\nu}_\mu$ than $\nu_e + \bar{\nu}_e$ and a similar content of neutrinos and anti-neutrinos. This is a particularly good description at lower energies where π decay dominates ($\pi^+ \rightarrow \mu^+ + \nu_\mu$ with a $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$ following, and their conjugate processes), nevertheless a full treatment of shower development and meson decays has been performed by several groups [5–7] with typical uncertainties on the overall flux of 10-30% below 100 GeV, and better than 10% precision on relative composition of neutrinos and anti-neutrinos or electron and muon neutrinos.

While it is possible to utilize this relatively well understood flux to probe neutrino oscillations and answer these currently open questions, the current generation of detectors is only able to provide hints as to their values. Future proposed detectors [8–12] have a good potential to measure the neutrino mass hierarchy and octant of θ_{23} . While a significantly

improved detector would be required to envisage measuring δ_{CP} directly with atmospheric neutrinos [13], the determination of the mass hierarchy using atmospheric oscillations could help disentangling the δ_{CP} and the neutrino mass hierarchy effects which are degenerate in $\text{NO}\nu\text{A}$ for in some cases [14].

NEUTRINO OSCILLATIONS

There is currently overwhelming experimental evidence for neutrino oscillation [4]. Theoretically that is described by a difference in the mass (ν_1, ν_2, ν_3) and flavor (ν_e, ν_μ, ν_τ) eigenstates of neutrinos, which will produce changes in the flavor composition of a neutrino flux depending on the energy of the neutrinos (E) and their propagation distance (L). That phenomena is described in vacuum by Eq. (1) and has an oscillation period that depends also on the difference of the mass squared between mass eigenstates ($\Delta m_{jk}^2 = m_j^2 - m_k^2$) and an amplitude that depends on the mixing matrix U . The standard decomposition of U , assuming three neutrino flavors, is shown in Eq. (2) where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$, with θ_{ij} mixing angles and δ_{CP} is the CP violating phase.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{j>k} \text{Re}(U_{\beta j} U_{\alpha j}^* U_{\beta k}^* U_{\alpha k}) \sin^2 \left(\frac{\Delta m_{jk}^2 L}{4E} \right) + 2 \sum_{j>k} \text{Im}(U_{\beta j} U_{\alpha j}^* U_{\beta k}^* U_{\alpha k}) \sin \left(\frac{\Delta m_{jk}^2 L}{2E} \right) \quad (1)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

As mentioned previously, the value of δ_{CP} and the sign of Δm_{32}^2 (mass hierarchy) have not yet been measured. The two possible cases for the neutrino mass hierarchy are the third mass eigenstate is the heaviest (positive Δm_{32}^2) which is referred to as ‘‘normal hierarchy’’ (NH), or it is the lightest (negative Δm_{32}^2) which is referred to as ‘‘inverted hierarchy’’ (IH).

In order to study neutrino oscillations using atmospheric neutrinos it is essential to reconstruct both the energy and direction of the neutrinos (the zenith direction is needed to calculate L) to be able to map the oscillation as a function of L and E ; the neutrinos are produced with energies spanning many orders of magnitude and are available at varying

values of L (from about 10 km to 13 Mm). For neutrinos travelling through the Earth's core the first maximum ν_μ disappearance happens around 25 GeV.

One notable correction that needs to be taken into account to calculate the oscillation probabilities for atmospheric neutrinos is the fact that neutrinos are propagating through matter and not in vacuum [4, 15, 16]. This impacts the neutrino oscillation because ν_e and $\bar{\nu}_e$ interact with the electrons in the medium differently than the other neutrino and anti-neutrino flavors, given only ν_e and $\bar{\nu}_e$ can scatter off an electron with a W^\pm boson as mediator. For neutrinos propagating through the Earth, this creates the resonance condition shown in Eq. (3) where N_e is the electron density. The \pm in Eq. (3) depends if ν (+) or $\bar{\nu}$ (-) are propagating through matter, and therefore the resonance condition can only happen in the NH for ν and in the IH for $\bar{\nu}$, as those are the only cases where E is positive in Eq. (3). In the mantle, such condition happens for $E \sim 7$ GeV and while trajectories crossing only the mantle are not long enough to have the maximal resonant effect, it is close enough to significantly affect the oscillation probabilities. In core-crossing trajectories the formulations are more complicated [4] but also result in resonance conditions for ν in the NH case or $\bar{\nu}$ in the IH case, which will impact the oscillation probabilities. The effect of oscillation in vacuum and matter, in the presence of resonances, as a function of E and L is shown in Fig. 1. It is through the measure of these resonances that future experiments plan to determine the neutrino mass hierarchy using atmospheric neutrinos.

$$E = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{\pm N_e 2\sqrt{2}G_F}, + \text{ for } \nu \text{ and } - \text{ for } \bar{\nu} \quad (3)$$

CURRENT RESULTS

Of all detectors currently capable of studying the atmospheric neutrino flux, Super-Kamiokande [18] is certainly the one that has been in operation for the longest time and that has produced the most varied results in oscillations using the atmospheric neutrino flux. Since the discovery of neutrino oscillations by Super-Kamiokande [2], it has continued to collect data and improve the precision of the key parameters (θ_{23} and $|\Delta m_{32}^2|$) describing the neutrino oscillation of the atmospheric neutrino flux, as shown in Fig. 2.

The IceCube Neutrino Observatory, using its denser sub-array DeepCore [23], has also started to perform precise measurements of θ_{23} and $|\Delta m_{32}^2|$, which are also shown in Fig. 2.

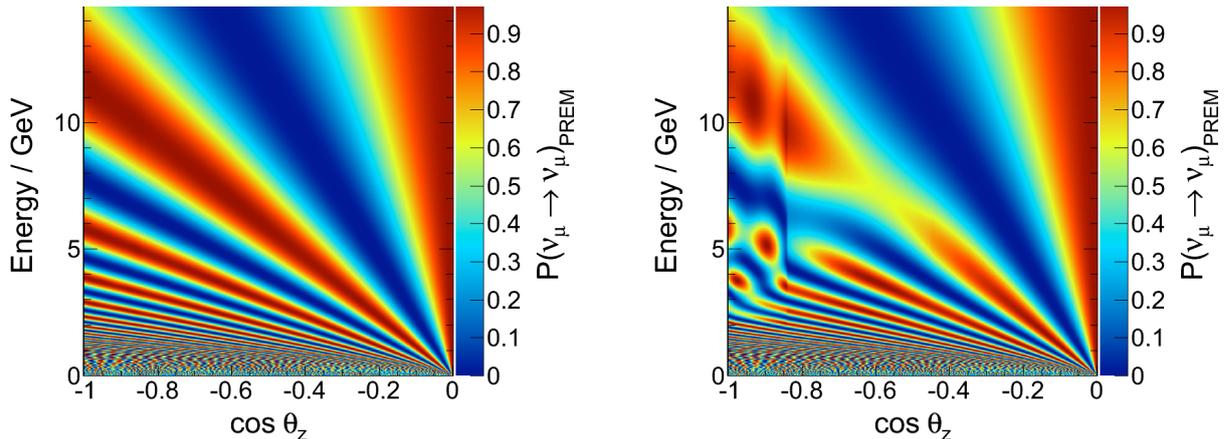


Figure 1: Oscillation probability for $\nu_\mu \rightarrow \nu_\mu$ as a function of the neutrino energy (E) and zenith angle ($\cos\theta_z \sim -L/2R$, with R being the Earth's radius). In the left is shown the ν_μ survival probability in the absence of matter induced resonances (IH for ν) while on the right is shown the same thing when resonances are accounted for (NH for ν). $\cos\theta_z \sim -0.84$ corresponds to the mantle-core transition which correspond to a large change in the medium electron density [17] and therefore produce the discontinuity seen in the right figure.

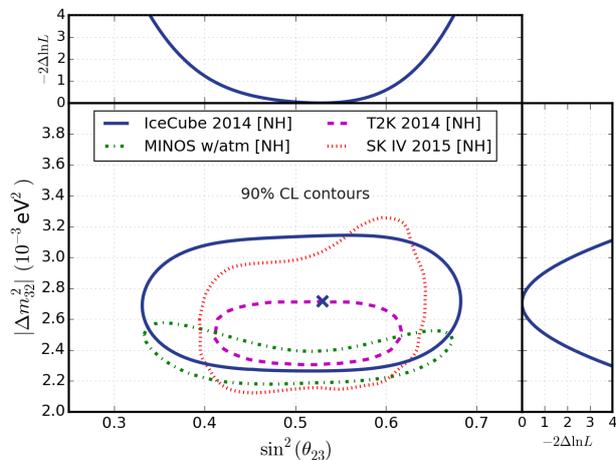


Figure 2: Current precision on the measure of θ_{23} and $|\Delta m_{32}^2|$, assuming NH is true. Of these results, Super-Kamiokande [19] (dotted line) and IceCube [20] (solid line) were produced using exclusively atmospheric neutrinos, MINOS [21] (dash-dotted line) uses both accelerator and atmospheric neutrinos, and T2K [22] (dashed line) uses exclusively accelerator neutrinos.

While currently the best limits to θ_{23} and $|\Delta m_{32}^2|$ were obtained by long baseline accelerator experiments, looking for oscillations at a specific L and E , it is worth noting that the atmospheric neutrino measurements were done using a wide range of L and E which allow for the check of the validity of the neutrino oscillation framework over a larger parameter space. Also, notably the L and E ranges probed by Super-Kamiokande and IceCube are different as each detector is more sensitive at different energy ranges.

Besides these two detectors, there are currently several other detectors capable of measuring the atmospheric neutrino flux. For example, MINOS uses their measurement of atmospheric neutrinos jointly with their accelerator neutrinos to produce their results on θ_{23} and $|\Delta m_{32}^2|$ [21], also shown in Fig. 2, and ANTARES is mostly sensitive to the atmospheric neutrino flux at higher energies and has obtained weaker constraints to those parameters [24].

Besides measuring θ_{23} and $|\Delta m_{32}^2|$, Super-Kamiokande has also looked for ν_τ appearance created from $\nu_\mu \rightarrow \nu_\tau$ oscillation to test the 3-flavor neutrino oscillation framework and observed it with a significance of 3.8σ [25]. Additional studies from Super-Kamiokande [26] also preliminarily provide $\sim 1 \sigma$ preference for NH, the second octant of θ_{23} and $\delta_{CP} \in [\pi, 2\pi]$. Going beyond the three neutrino flavors paradigm, Super-Kamiokande has also put constraints in the sterile neutrino phase space [27].

A more in-depth discussion of the results from Super-Kamiokande and IceCube are found in other contributions to this conference [26, 28].

FUTURE DETECTORS AND EXPECTED SENSITIVITIES

As discussed previously, the current experiments measuring the neutrino atmospheric flux are not likely to answer the remaining open questions in the standard neutrino oscillations framework, however several proposed experiments are able to determine at 3σ the neutrino mass hierarchy and have potential to determine the octant of θ_{23} .

In order to measure the neutrino mass hierarchy with atmospheric neutrinos it is essential to distinguish if the resonances happen for ν or $\bar{\nu}$, as that changes for each hierarchy. In order to make this distinction, INO proposes to use a magnetized iron calorimeter and directly separate ν_μ and $\bar{\nu}_\mu$ achieving the measurement of the neutrino mass hierarchy at 3σ with 7-13 years of data [29]. All other experiments use a different approach to the problem, as suggested by [30, 31], in which the difference in the neutrino and anti-neutrino cross-section produces a slightly different $E \times \cos \theta_z$ pattern for neutrinos and anti-neutrinos, without relying in any capability for the detector to be able to individually distinguish between neutrino and anti-neutrino events. Using this technique PINGU [12] and ORCA [11] can reach 3σ sensitivity to the mass hierarchy for any value for θ_{23} with 3-5 years of data, while it would take Hyper-Kamiokande [9] and the far detector of DUNE [8] about 10 years

of full detector lifetime to reach such precision using atmospheric neutrinos. Note that DUNE will also be able to measure at 3σ the neutrino mass hierarchy using accelerator neutrinos with 6 years of lifetime with a 1.2 MW beam for all values of δ_{CP} [8]. Fig. 3 shows the neutrino mass hierarchy sensitivity as a function of time for the above mentioned atmospheric neutrino experiments.

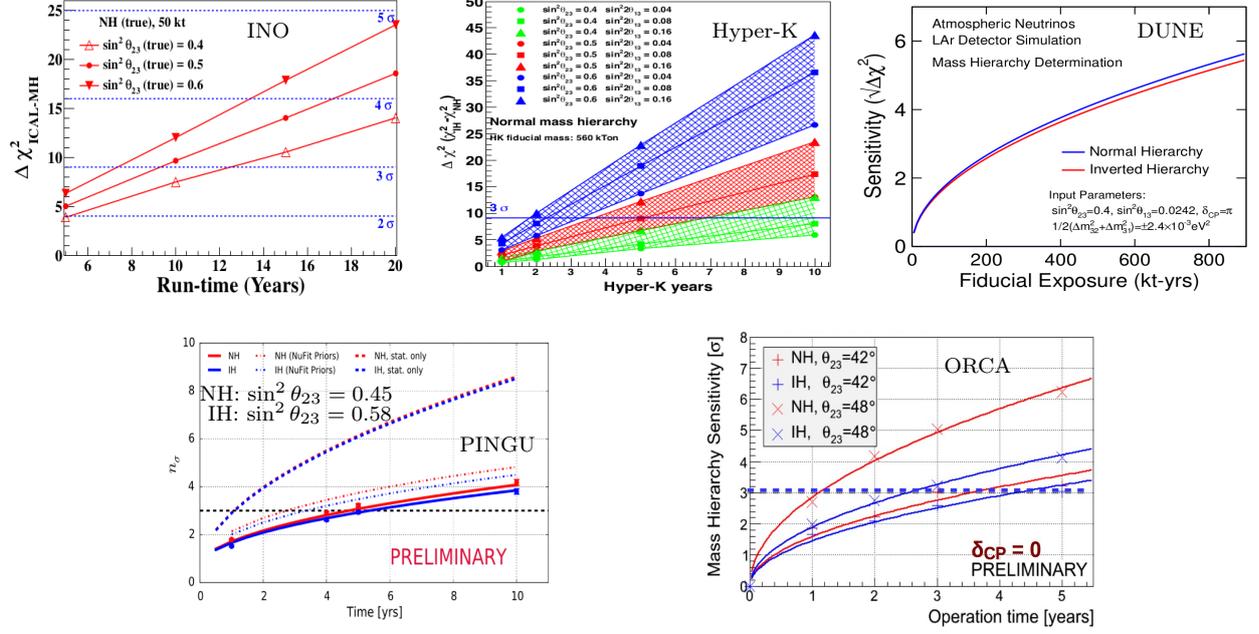


Figure 3: Sensitivity to the neutrino mass hierarchy for INO [29], Hyper-Kamiokande [9], DUNE [8] PINGU [28], and ORCA [11] as a function of time.

These experiments also have good sensitivity to θ_{23} and $|\Delta m_{32}^2|$ (see Fig. 4 for PINGU and INO) and could determine the octant of θ_{23} if it's not too close to maximal (see Fig. 5 for Hyper-Kamiokande and DUNE). Besides those results, they are also expected to provide improved limits on several of the results mentioned above from Super-Kamiokande, such as ν_τ appearance and sterile neutrino searches.

A more in-depth discussion about the capabilities of Hyper-Kamiokande, PINGU and INO to measure atmospheric neutrinos are found in other contributions to this conference [28, 32, 33].

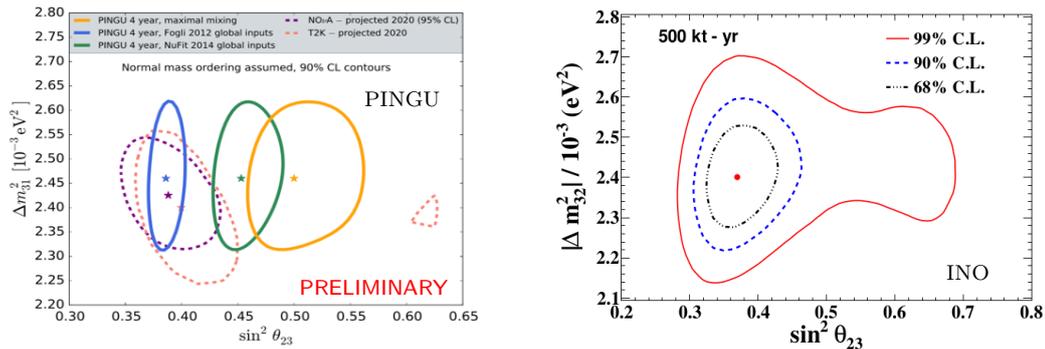


Figure 4: Sensitivity to θ_{23} and $|\Delta m^2|$ for PINGU [28] and INO [10] for 4 and 10 years of lifetime, respectively.

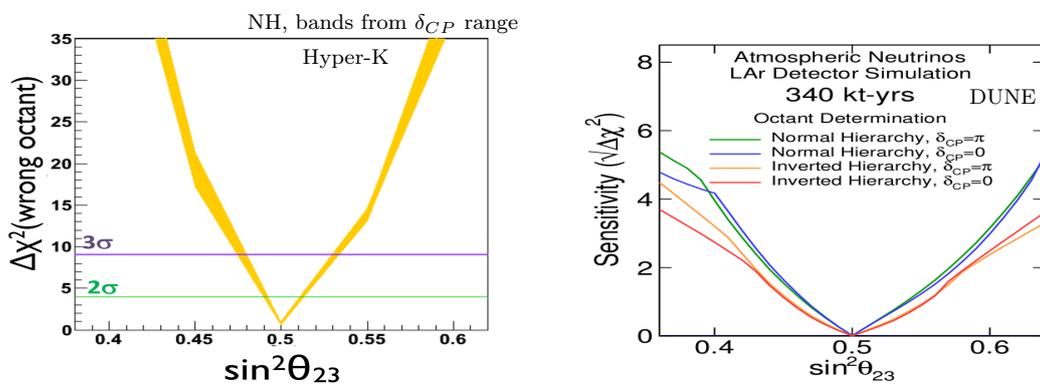


Figure 5: Sensitivity to the octant of θ_{23} , using exclusively atmospheric neutrinos, for Hyper-Kamiokande [32], and DUNE [8] as a function of the true value of θ_{23} for 10 years of lifetime, in both cases.

SUMMARY

Atmospheric neutrinos were fundamental to the discovery of neutrino oscillations. Since then they have continued to provide quality measurements of neutrino oscillations on a wide L and E ranges, in particular measurements of θ_{23} and $|\Delta m_{32}^2|$, searches for sterile neutrinos and ν_τ appearance searches.

The next generation of experiments is expected to further improve on these measurements, may determine the octant of θ_{23} , depending on the true value of that mixing angle, and will be able to measure the neutrino mass hierarchy at 3σ in as few as 3-5 years for some experiments.

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