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Neutrino mass hierarchy and octant determination with atmospheric neutrinos

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The recent discovery by the Daya Bay and RENO experiments that θ_{13} is nonzero and relatively large, significantly impacts existing experiments and the planning of future facilities. In many scenarios the nonzero value of θ_{13} implies that θ_{23} is likely to be different from $\pi/4$. Additionally, large detectors will be sensitive to matter effects on the oscillations of atmospheric neutrinos, making it possible to determine the neutrino mass hierarchy and the octant of θ_{23}. We show that a 50 kT magnetized liquid argon neutrino detector can ascertain the mass hierarchy with a significance larger than 4σ with moderate exposure times, and the octant at the level of $2-3\sigma$ with greater exposure.

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Introduction: Neutrino oscillations in the standard three flavor framework are parametrized by *a*) two mass-squared differences $\Delta m^2_{j1} = m^2_j - m^2_1$, $j = 2, 3$, *b*) three mixing angles θ_{ij} and *c*) one CP phase δ_{CP}. Over the past year, the T2K [1], MINOS [2] and Double Chooz [3] experiments have provided evidence that the mixing angle θ_{13} is nonzero and not significantly smaller than the upper bound set by the Chooz [4] experiment. Recently, the Daya Bay and RENO experiments have provided clinching evidence that $\theta_{13} \neq 0$ at more than 5σ: $\sin^2 2\theta_{13} = 0.089 \pm 0.011(stat) \pm 0.005(syst)$ [5], and $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)$ [6], respectively.

These results open new windows of opportunity for present day or near future neutrino experiments. If θ_{13} were tiny, an elaborate and expensive program would have been needed to measure the undetermined neutrino parameters. Its moderately large value allows for measurable matter effects [7] in both beam and atmospheric neutrino experiments. This will yield better than anticipated precision in measurements of neutrino parameters, and impacts the planning of future neutrino facilities. Specifically, it allows for a credible case to be made for building advanced technology, large mass atmospheric neutrino detectors. The resolution of important outstanding questions, such as the *mass hierarchy* (*i.e.*, whether $m_3 > m_1$ or $m_3 < m_1$) and the *octant of* θ_{23} (*i.e.*, whether θ_{23} is larger or smaller than $\pi/4$), may come within the purview of such detectors.

The mass hierarchy plays a crucial role in the formulation of any theoretical effort designed to carry us beyond the Standard Model (SM) because models with a *normal* hierarchy (NH) are significantly and qualitatively different from those with an *inverted* hierarchy (IH), see, *e.g.*, [8]. It plays the role of a discriminator capable of eliminating entire classes of models and consequently sharpening the focus of our search for new physics. A relatively large value of θ_{13} suggests that θ_{23} is unlikely to be maximal if the breaking of a $\mu - \tau$ exchange symmetry [9] in the lepton sector causes θ_{13} to be nonzero. A nonzero value of θ_{13} also opens the door to measurements of CP violation in the neutrino sector.

Atmospheric neutrino detectors have been very important as discovery tools in the past. While they may not match the precision to pin down the energy and direction of an event characteristic of long baseline experiments, they have some strong compensating advantages. Atmospheric neutrinos offer a broad range in baselines ($L \sim 20$ km to 12500 km) and energy E (100 MeV to 10 TeV) that can be tapped into by such an experiment. An important consequence of this is the resolution or alleviation of degeneracies endemic to long baseline beam experiments [10]. Large-mass Liquid Argon Time Projection Chambers (LAr-TPCs) are based on one of the most promising technologies for charged particle detection. They have unprecedented capabilities for the detection of neutrino interactions, rare events and dark matter due to precise and sensitive spatial and calorimetric resolution. The ICARUS [11] and ArgoNeuT [12] detectors have provided excellent examples of the capabilities of liquid argon as a neutrino interaction detector medium.

In this Letter we study how well the hierarchy and octant may be determined by a liquid argon detector using atmospheric neutrinos in light of the recently reported nonzero value of θ_{13}.

Experimental specifications: We consider a large liquid argon detector as discussed in [13–15], which can detect charged particles with good resolution over the energy range of MeV to multi GeV. Magnetization over a 50-100 kT volume has been proposed [16] and we assume it in what follows. We also assume the following detector resolutions over the GeV energy ranges relevant to our calculations [13, 18]:

$$\begin{aligned}\sigma_{E_e} &= \sigma_{E_\mu} = 0.01\,,\\ \sigma_{E_{had}} &= \sqrt{(0.15)^2/E_{had} + (0.03)^2}\,,\\ \sigma_{\theta_e} &= 0.03 \text{ radians} = 1.72^\circ,\\ \sigma_{\theta_\mu} &= \sigma_{\theta_{had}} = 0.04 \text{ radians} = 2.29^\circ\,,\end{aligned}$$

where E_{had} is the hadron energy in GeV, σ_E are the energy resolution widths in GeV and σ_θ are the angular resolution widths of electrons, muons and hadrons.

Since $E_\nu = E_{lep} + E_{had}$, the neutrino energy resolution width, for both ν_μ and ν_e, is

$$\sigma_{E_\nu} = \sqrt{(0.01)^2 + (0.15)^2/(yE_\nu) + (0.03)^2}\,, \qquad (1)$$

where we have used $E_{had} = yE_\nu$, y being the rapidity. In our computation, we take the average rapidity in the GeV energy region to be 0.45 for neutrinos and 0.3 for antineutrinos [17]. The angular resolution of the detector for neutrinos can be worked out to be $\sigma_{\theta_{\nu e}} = 2.8^\circ$, $\sigma_{\theta_{\nu\mu}} = 3.2^\circ$ [18]. Charged lepton detection and separation (e vs. μ) without charge identification is possible for $E_{lepton} >$ few MeV. The charge identification capability of the detector is incorporated as discussed in [19]. For electron events, we have conservatively assumed a 20% probability of charge identification in the energy range $1-5$ GeV, and none for events with energies higher than 5 GeV. The muon charge identification capability of a LAr-TPC is excellent for energies 1-10 GeV and we have assumed it to be 100%

The atmospheric fluxes are taken from the 3-dimensional calculation in [20]. The earth matter profile defined in [21] is used to take into account matter effects on the oscillation probabilities.

Hierarchy sensitivity: The hierarchy sensitivity from atmospheric neutrinos is computed with marginalization over the following test parameter ranges:

- θ_{23} from $38^\circ - 52^\circ$ $(\sin^2\theta_{23} = 0.38 - 0.62)$,
- $|\Delta m^2_{31}|$ from $(2.05 - 2.75) \times 10^{-3}$ eV^2,
- θ_{13} from $5.5^\circ - 11.0^\circ$ $(\sin^2 2\theta_{13} = 0.04 - 0.14)$,
- δ_{CP} from $0 - 2\pi$.

We take the true values to be $(|\Delta m^2_{31}|)_{tr} = 2.4 \times 10^{-3}$ eV^2, $(\delta_{CP})_{tr} = 0$, $(\sin^2\theta_{23})_{tr} = 0.4, 0.5$ and 0.6 which allows for both maximal and nonmaximal values, and $(\theta_{13})_{tr}$ over the 3σ range of recent measurements. The solar parameters Δm^2_{21} and θ_{12} are fixed at the values of 8×10^{-5} eV^2 and 34° respectively, since the effect of their variation within uncertainties is negligible. The true value of δ_{CP} is chosen to be zero throughout these calculations, since the principal contribution to both the hierarchy and the octant sensitivity is from the muon survival probability, which has a weak dependence on $(\delta_{CP})_{tr}$. So the sensitivity is largely unaffected by the value of this parameter [22]. We assume the true hierarchy to be normal and compute the ability of the detector to rule out the inverted hierarchy and vice-versa. Flux uncertainties and systematic errors are included using the method of pulls as described in [22]: flux normalization error 20%, flux tilt factor, zenith angle dependence uncertainty 5%, overall cross section uncertainty 10%, overall systematic uncertainty 5%. The number of bins is chosen to be 9 energy bins in the range $1-10$ GeV and 18 $\cos\theta_z$ bins in the range -1.0 to -0.1.

We also take into account the uncertainties of neutrino parameters in the form of appropriate priors with the following 1σ ranges: $\sigma(|\Delta m^2_{31}|) = 0.05|\Delta m^2_{31}|$, $\sigma(\sin^2 2\theta_{13}) = 0.01$, and $\sigma(\sin^2 2\theta_{23}) = 0.02\sin^2 2\theta_{23}$. The hierarchy sensitivity with priors ${\chi^2_{tot}}^{prior}$ is obtained from a combined minimization of $\chi^2_\mu + \chi^2_e + \chi^2_{prior}$.

Figure 1 depicts the hierarchy sensitivity for both NH and IH as a function of $(\theta_{13})_{tr}$ for $(\sin^2\theta_{23})_{tr} = 0.4$, 0.5 and 0.6. The Daya Bay and RENO best-fit points are indicated in the figures. In general, the hierarchy sensitivity from both muon and electron events improves with an increase in the true value of θ_{13} and θ_{23}. However, the sensitivity arising from muon events is considerably greater due to the statistical advantage enjoyed by muon events and the superior charge identification capability for muons as compared to electrons [22, 23]. For both hierarchy and octant calculation below, sensitivity strongly depends on matter effects, the detection of which relies on charge identification. Additionally, as also discussed in [19, 22, 23], the excellent angular resolution of LAr-TPC enables a full exploitation of the variations in the survival probability $P_{\mu\mu}$ (the main constituent of muon events) with baseline.

In Table I we list the χ^2 values for hierarchy sensitivity for $(\sin^2 2\theta_{13})_{tr} = 0.1$ and $(\sin^2\theta_{23})_{tr} = 0.5$. To highlight the role of the measurement uncertainty in θ_{13}, we provide χ^2 values for three cases: a) no prior, b) prior with $\sigma(\sin^2 2\theta_{13}) = 0.01$ (present uncertainty), and c) $\sigma(\sin^2 2\theta_{13}) = 0.005$ (expected uncertainty in the near future). As expected, prior knowledge of $\sin^2 2\theta_{13}$ has a dramatic effect on the ability to determine the hierarchy. However, an improvement in $\sigma(\sin^2 2\theta_{13})$ below the current value does not give a concomitant improvement in the sensitivity. We note that without priors, the hierarchy sensitivity is much greater for a true NH, since in this case the sensitivity arises from resonant matter effects in the muon events, while for a true IH the matter resonance occurs in the anti-muon events. The atmospheric ν_μ flux is about twice the $\bar{\nu}_\mu$ flux, leading to greater sensitivity for NH. The prior terms tend to move the test parameters at the χ^2_{min} closer to their true values. This causes a tension between $\chi^2_\mu + \chi^2_e$ and χ^2_{prior} resulting in an overall increase in the total χ^2. If the true hierarchy is inverted, then the test parameter values at the χ^2_{min} without priors are further removed from the true values as compared to NH. Also, the sensitivity for $\sin^2\theta_{23} = 0.5$ becomes superior to that for $\sin^2\theta_{23} = 0.6$, as can be seen from the right panel of Figure 1; we have checked that without the prior term the χ^2s for IH for different values of θ_{23} follow the same behaviour as that for NH. Clearly, the effect of

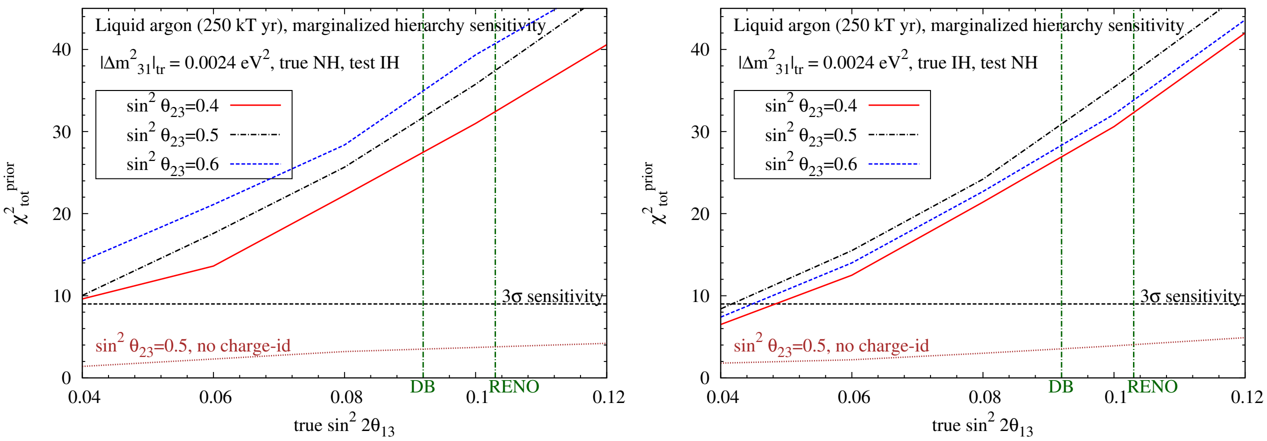

FIG. 1: *Marginalized hierarchy sensitivity including priors in a liquid argon detector with 250 kT yr exposure as a function of* $(\sin^2 2\theta_{13})_{tr}$ *for* $(\sin^2\theta_{23})_{tr} = 0.4, 0.5, 0.6$. *The vertical lines represent the Daya Bay and RENO best-fit values. The left panel is for a true normal hierarchy (NH) and the right panel is for a true inverted hierarchy (IH). Sensitivities for the non-magnetized version of the detector for* $\sin^2\theta_{23} = 0.5$ *are also shown.*

$\sigma(\sin^2 2\theta_{13})$	χ^2_{NH}	χ^2_{IH}
No Prior	25.6	11.7
0.01	35.8	35.4
0.005	36.1	37.2

TABLE I: Values of marginalized hierarchy sensitivity (${\chi^2_{tot}}^{prior}$) for various values of $\sigma(\sin^2 2\theta_{13})$ with 250 kT yr exposure for $(\sin^2 2\theta_{13})_{tr} = 0.1$ and $(\sin^2\theta_{23})_{tr} = 0.5$. The second column is for a true normal hierarchy and the third column is for a true inverted hierarchy.

priors is more significant for IH.

For comparison we also present the sensitivity for a non-magnetized version of the detector in Figure 1 for $\sin^2\theta_{23} = 0.5$. Note the crucial role played by the charge identification capability of a magnetized detector in discerning the mass hierarchy.

In summary, it is evident that if the value of θ_{13} lies within the 1σ range preferred by Daya Bay/RENO, then with a 50 kT detector running for 5 years, a $\sim 6\sigma$ hierarchy determination is possible for both hierarchies for $\sin^2 2\theta_{13} = 0.1$ and $(\sin^2\theta_{23})_{tr} = 0.5$ (*cf* Table I). Hence, even a reduced exposure of 100 kT-yr may give a 4σ hierarchy discrimination irrespective of whether the hierarchy is normal or inverted.

Octant sensitivity: For this analysis, we adopt the viewpoint that once the hierarchy is determined with 250 kT yr exposure, the octant may be tackled with additional exposure and a priori knowledge of the hierarchy. We assume a total exposure of 500 kT yr and consider the octant discrimination separately for NH and IH. As with hierarchy discrimination, we include priors and perform a combined minimization of $\chi^2_\mu + \chi^2_e + \chi^2_{prior}$. The principal contribution to the octant sensitivity is again from muon events due to the $\sin^4\theta_{23}$ term in the survival probability [24].

In Figure 2, we plot the χ^2_{min} values indicating the ability of the experiment to rule out the wrong octant for two values of θ_{13} close to the Daya Bay and RENO best fits. In the left panel the hierarchy is assumed to be normal and for the right panel it is inverted.

We see that a 2σ discrimination is possible for $|\theta_{23} - \pi/4| > 3.5^\circ$ for values of θ_{13} close to the present best-fit, if the hierarchy is normal. That is, the octant discrimination is possible only if the value of $\sin^2 2\theta_{23}$ is less than 0.985. For larger values of θ_{23}, octant discrimination is difficult. For smaller values of $\sin^2 2\theta_{23}$, the value of χ^2_{min} increases rapidly and a 3σ octant discrimination is possible for $|\theta_{23} - \pi/4| > 5^\circ$ or $\sin^2 2\theta_{23} < 0.97$ for a normal hierarchy. If the hierarchy is inverted, octant sensitivity is worse, and only a 2σ discrimination is possible for $|\theta_{23} - \pi/4| > 4^\circ$ or $\sin^2 2\theta_{23} < 0.98$.

Conclusions: The nature of the neutrino mass hierarchy and the octant of θ_{23} are vital to our efforts to build theories beyond the SM. With regard to these two issues, we have explored the implications of the recent Daya Bay and RENO results on θ_{13} for the planning of future experiments. In particular, we have demonstrated the exceptional capability of a large mass magnetized LAr-TPC to determine the hierarchy to high significance with moderate exposure times. The detector is also sensitive to the octant of θ_{23} although with a lower significance. Our results highlight the superior capability of a magnetized detector as compared to one without magnetization.

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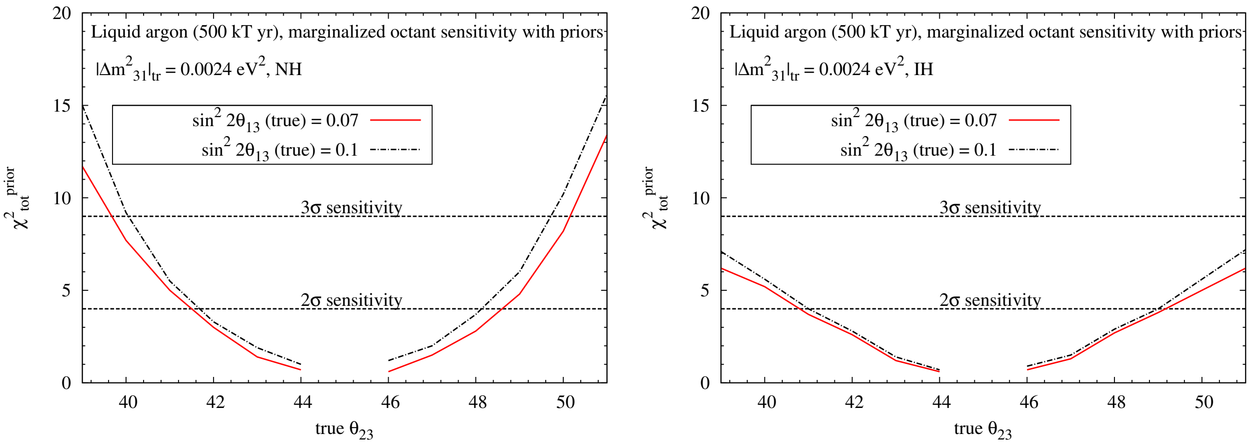

FIG. 2: *Marginalized octant sensitivity including priors in a liquid argon detector with 500 kT yr exposure as a function of true* θ_{23} *for* $(\sin^2 2\theta_{13})_{tr} = 0.07$ *and* 0.1. *The left panel is for NH and the right panel is for IH.*

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