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Getting the best out of T2K and NOvA

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We explore the combined physics potential of T2K and NOνA in light of the moderately large measured value of θ_{13}. For $\sin^2 2\theta_{13} = 0.1$, which is close to the best fit value, a 90% C.L. evidence for the hierarchy can be obtained only for the combinations (Normal hierarchy, $-170^\circ \leq \delta_{CP} \leq 0^\circ$) and (Inverted hierarchy, $0^\circ \leq \delta_{CP} \leq 170^\circ$), with the currently planned runs of NOνA and T2K. However, the hierarchy can essentially be determined for any value of δ_{CP}, if the statistics of NOνA are increased by 50% and those of T2K are doubled. Such an increase will also give an allowed region of δ_{CP} around its true value, except for the CP conserving cases $\delta_{CP} = 0$ or $\pm 180^\circ$.

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1. Introduction

The global fits to data from the accelerator experiments T2K [1] and MINOS [2] and the reactor experiments DChooz [3], Daya Bay [4] and RENO [5] have determined θ_{13} to be non-zero at 5σ level, with the best fit very close to $\sin^2 2\theta_{13} \simeq 0.1$ [6, 7]. In light of these current and expected near future measurements, the next goals of neutrino oscillation experiments are the determination of neutrino mass hierarchy, detection of CP violation in the leptonic sector and measurement of δ_{CP}. These goals can be achieved by high statistics accelerator experiments measuring $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities. In this paper, we study the combined ability of T2K and NOνA to achieve the above goals. For a detailed treatment of this same work, see [8].

2. Simulation Details

We use the software GLoBES [9, 10] for simulating the data of T2K and NOνA [11, 12, 13, 14, 15, 16, 17, 18, 19]. The basic properties of NOνA are taken from Ref. [14] and of T2K are taken from Ref. [11]. The efficiencies for each of the experiments are taken from GLoBES [9, 10].

We show the sensitivity of the experiments to hierarchy using the hierarchy exclusion plots. These are plotted in the plane of true values of $\sin^2 2\theta_{13}$-δ_{CP}. The contours in these plots define the line $\chi^2 = 2.71$. In computing this χ^2, we have marginalized over the neutrino oscillation parameter ranges. For all sets of parameter values to the right of the contour, the wrong hierarchy can be ruled out at 90% C.L. Throughout this paper, the phrase "hierarchy determination" implies 90% C.L. evidence for hierarchy.

3. Hierarchy determination with $P_{\mu e}$

In the presence of matter, the $\nu_\mu \to \nu_e$ oscillation probability, expanded perturbatively in the small mass-squared difference, Δ_{21} is given by [20, 21, 22]

$$\begin{aligned} P(\nu_\mu \to \nu_e) = P_{\mu e} &= \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2\hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2} \\ &+ \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\hat{\Delta}+\delta_{CP}) \frac{\sin\hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin\hat{\Delta}(1-\hat{A})}{1-\hat{A}} \\ &+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \frac{\sin^2\hat{\Delta}\hat{A}}{\hat{A}^2} \end{aligned} \tag{3.1}$$

where $\hat{\Delta} = \Delta_{31}L/4E$, $\hat{A} = A/\Delta_{31}$, $\alpha = \Delta_{21}/\Delta_{31}$. A is the Wolfenstein matter term [23] and is given by $A(\mathrm{eV}^2) = 0.76 \times 10^{-4}\rho$ (gm/cc)E(GeV). For NH, Δ_{31} is positive and for IH, Δ_{31} is negative. The matter term A is positive for neutrinos and is negative for anti-neutrinos. Hence, in neutrino oscillation probability, $\hat{A}$ is positive for NH and is negative for IH. For anti-neutrinos, $\hat{A}$ is negative for NH and positive for IH and the sign of δ_{CP} is reversed.

The favourable and unfavourable half planes for a particular hierarchy can be defined from Eq. (3.1), where the δ_{CP} dependence occurs purely in the form $\cos(\hat{\Delta}+\delta_{CP})$. If NH is the true hierarchy, $\hat{\Delta} \approx 90°$ around the probability maximum. Then, the δ_{CP} dependent term increases $P_{\mu e}$ if δ_{CP} is in the lower half plane (LHP) and decreases it if δ_{CP} is in the upper half plane (UHP).

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Hence a cleaner separation from $P_{\mu e}(IH, \delta_{CP})$ can be obtained only if δ_{CP} is in the LHP. If IH is the true hierarchy, $\hat{\Delta} \approx -90^\circ$. Then $P_{\mu e}$ is reduced, and moved away from $P_{\mu e}(NH, \delta_{CP})$ if δ_{CP} is in the UHP. Thus UHP forms the favourable half plane for IH, whereas LHP is the favourable half plane for NH. Even if we use the anti-neutrino oscillation probabilities, the same considerations will hold. Therefore, the same relation between hierarchy and half-plane holds for both neutrino and anti-neutrino data.

3.1 Hierarchy discrimination ability of NOνA

We plot the hierarchy discrimination ability of NOνA with nominal and increased statistics in Fig. 1. We see that, for $\sin^2 2\theta_{13} = 0.1$ and with nominal design, the hierarchy can be determined at 90 % C.L. for the following two combinations: (NH, $-170^\circ \leq \delta_{CP} \leq -10^\circ$) or (IH, $10^\circ \leq \delta_{CP} \leq 170^\circ$). The statistics for the experiment are not quite enough to determine the hierarchy for the whole favourable half plane for this value of θ_{13}. If $\sin^2 2\theta_{13} = 0.12$, then the hierarchy can be determined for the whole favoured half plane. It was shown in Ref. [24] that NOνA can determine the hierarchy for 45 % of the δ_{CP} range for $\sin^2 2\theta_{13} = 0.1$.

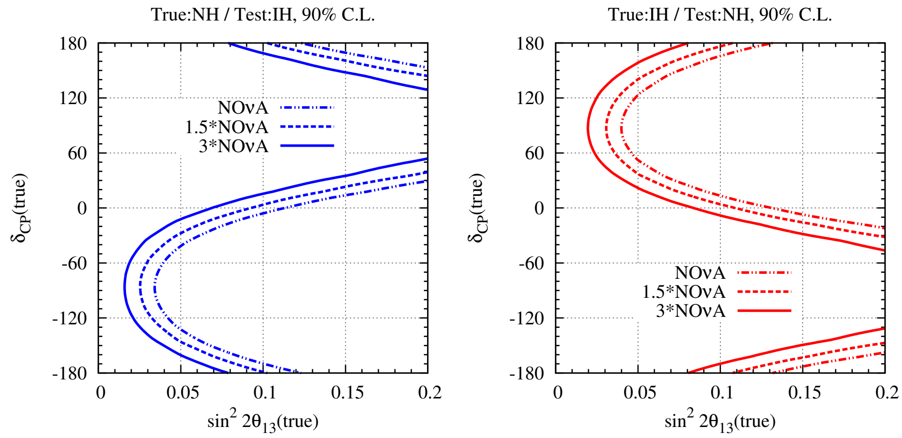

Figure 1: (colour online) Hierarchy exclusion plots for NOνA with boosted statistics for 3ν+$3\bar{\nu}$ running when NH is true (left panel) and when IH is true (right panel).

For smaller values of $\sin^2 2\theta_{13}$, one needs larger statistics to determine the hierarchy for the whole favourable half plane. With 1.5 times the presently projected statistics of NOνA , one can determine the hierarchy for the whole of the respective favourable half planes, for both NH and IH, for $\sin^2 2\theta_{13} = 0.1$. Similar conclusions were obtained earlier in Ref. [25]. If δ_{CP} happens to be in the unfavourable half plane, even tripling of statistics leads to hierarchy determination only for a very small range of δ_{CP}.

3.2 Hierarchy discrimination ability of NOνA and T2K

In this subsection, we explore how data from T2K can help in improving the sensitivity to hierarchy. We found that for $\sin^2 2\theta_{13} \leq 0.1$, hierarchy determination is not possible for any δ_{CP} in the unfavourable half-plane, if nominal design statistics of NOνA and T2K are assumed. Hence, we consider how hierarchy sensitivity improves with increasing statistics. We consider three scenarios:

- T2K will have a 5 year neutrino run with its design luminosity and NOνA will run according to its present plan.

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- T2K will have twice the above statistics and NOνA will have 1.5 times its designed statistics.
- T2K will have four times the above statistics and NOνA will have thrice its designed statistics.

The exclusion plots are given in Fig. 2. For all points to the right of the contours, the wrong hierarchy can be ruled out.

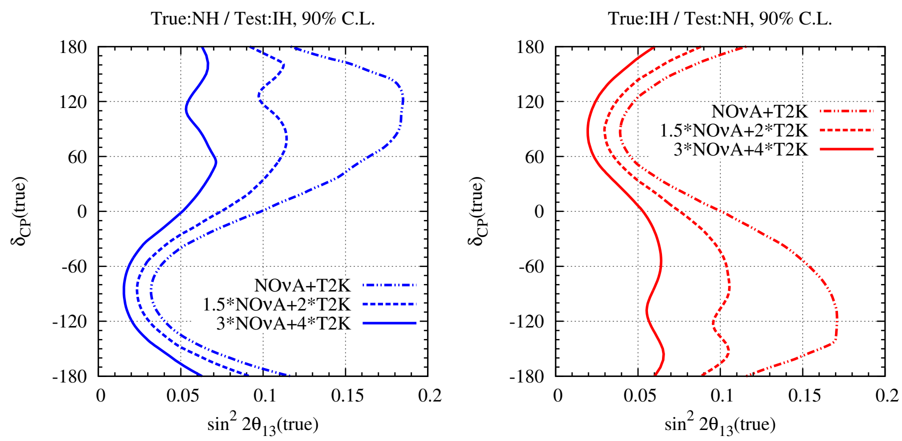

Figure 2: (colour online) Hierarchy exclusion plots for combined data from NOνA and T2K with various boosts in statistics when NH is true (left panel) and when IH is true (right panel).

In the left panel we assumed NH is the true hierarchy and in the right panel we assumed IH is the true hierarchy. We see that increasing the statistics from nominal values to 1.5*NOνA + 2*T2K dramatically improves the ability to rule out the wrong hierarchy, if δ_{CP}(true) is in the unfavourable half-plane. Further improvement occurs if the statistics are increased even more. In particular, if $\sin^2 2\theta_{13} = 0.1$ [6, 7], the hierarchy can be essentially established at 90% C.L., for any true value of δ_{CP}, with 1.5 times the designed statistics of NOνA and twice the designed statistics of T2K. This point was noted previously in Ref. [25].

4. Measuring δ_{CP} with $P_{\mu e}$

In the following, we present 'allowed δ_{CP}' graphs. In generating these, we have kept $\sin^2 2\theta_{13}$ fixed at 0.1. The graphs are plotted in the true δ_{CP}-test δ_{CP} plane. For every true value of δ_{CP}, we indicate the range in test δ_{CP} that can be excluded at 90% C.L. The plots have been shown for both true and wrong hierarchies. The dotted range, defined by $\chi^2 \leq 2.71$, shows the values of test δ_{CP} that are compatible with the data, generated with δ_{CP}(true) as input. For a given true value of δ_{CP}, the error in measuring δ_{CP} is indicated by the spread of the dotted range along that δ_{CP}(true) vertical line.

If the statistics are increased to 1.5*NOνA + 2*T2K, as seen in Fig. 3 then most of the wrong hierarchy allowed region is ruled out as already noted in section 3. For the true hierarchy, the allowed region is centered around true δ_{CP} and is mostly in the correct half-plane. For the CP conserving case $\delta_{CP} = 0$ ($\delta_{CP} = \pm 180^\circ$), there is a small additional allowed region around $\delta_{CP} = \pm 180^\circ$ ($\delta_{CP} = 0$) but for which χ^2 is higher. If we limit our attention to the regions around χ^2_{min},

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then 1.5*NOνA + 2*T2K can measure δ_{CP} with an accuracy of $\pm 40^\circ$ for true $\delta_{CP} = 0$ and $\pm 60^\circ$ for true $\delta_{CP} = \pm 90^\circ$.

Thus we are led to the following important conclusion: 1.5*NOνA + 2*T2K can essentially determine the hierarchy and also give an allowed region of δ_{CP} centered around its true value. Doubling of statistics will not lead to too much improvement in the allowed range of δ_{CP}. Further strategies are needed to measure δ_{CP} to a good accuracy.

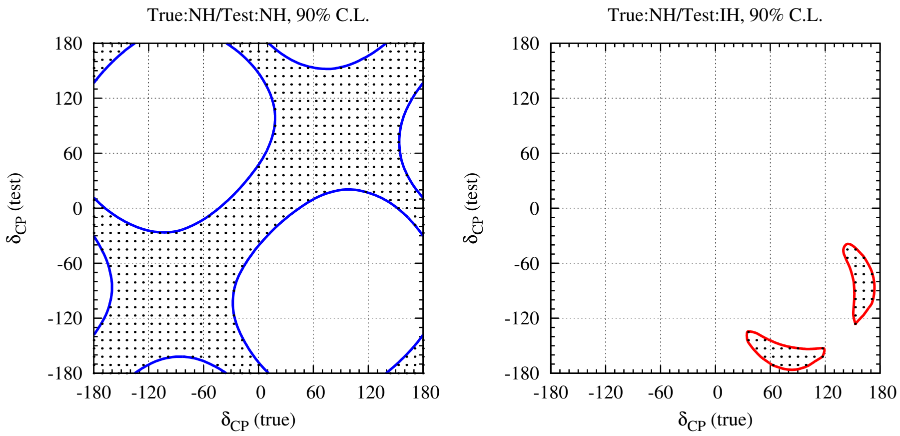

Figure 3: (colour online) Allowed δ_{CP} plots for 1.5*NOνA + 2*T2K. Here NH is true. True and test $\sin^2 2\theta_{13} = 0.1$. Test hierarchy is normal (left panel) and inverted (right panel).

References

[1] **T2K** Collaboration, K. Abe et al., *Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam*, *Phys. Rev. Lett.* **107** (2011) 041801, [1106.2822].

[2] **MINOS Collaboration** Collaboration, P. Adamson et al., *Improved search for muon-neutrino to electron-neutrino oscillations in MINOS*, *Phys. Rev. Lett.* **107** (2011) 181802, [1108.0015].

[3] **Double Chooz** Collaboration, Y. Abe et al., *Indication for the disappearance of reactor electron antineutrinos in the Double Chooz experiment*, *Phys. Rev. Lett.* **108** (2012) 131801, [1112.6353].

[4] **Daya-Bay Collaboration** Collaboration, F. An et al., *Observation of electron-antineutrino disappearance at Daya Bay*, *Phys.Rev.Lett.* **108** (2012) 171803, [1203.1669].

[5] **RENO collaboration** Collaboration, J. Ahn et al., *Observation of Reactor Electron Antineutrino Disappearance in the RENO Experiment*, *Phys. Rev. Lett.* **108** (2012) 191802, [1204.0626].

[6] P. Machado, H. Minakata, H. Nunokawa, and R. Funchal, *Combining Accelerator and Reactor Measurements of theta_13: The First Result*, 1111.3330.

[7] G. Fogli, E. Lisi, A. Marrone, D. Montanino, A. Palazzo, et al., *Global analysis of neutrino masses, mixings and phases: entering the era of leptonic CP violation searches*, 1205.5254.

[8] S. Prakash, S. K. Raut, and S. U. Sankar, *Getting the Best Out of T2K and NOvA*, *Phys.Rev.* **D86** (2012) 033012, [arXiv:1201.6485].

[9] P. Huber, M. Lindner, and W. Winter, *Simulation of long-baseline neutrino oscillation experiments with GLoBES*, *Comput. Phys. Commun.* **167** (2005) 195, [hep-ph/0407333].

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[10] P. Huber, J. Kopp, M. Lindner, M. Rolinec, and W. Winter, *New features in the simulation of neutrino oscillation experiments with GLoBES 3.0*, *Comput. Phys. Commun.* **177** (2007) 432–438, [hep-ph/0701187].

[11] **T2K** Collaboration, Y. Itow et al., *The JHF-Kamioka neutrino project*, hep-ex/0106019.

[12] M. Ishitsuka, T. Kajita, H. Minakata, and H. Nunokawa, *Resolving Neutrino Mass Hierarchy and CP Degeneracy by Two Identical Detectors with Different Baselines*, *Phys. Rev.* **D72** (2005) 033003, [hep-ph/0504026].

[13] P. Huber, M. Lindner, and W. Winter, *Superbeams versus neutrino factories*, *Nucl.Phys.* **B645** (2002) 3–48, [hep-ph/0204352].

[14] **NOvA Collaboration** Collaboration, D. Ayres et al., *NOvA: Proposal to build a 30 kiloton off-axis detector to study nu(mu) —> nu(e) oscillations in the NuMI beamline*, hep-ex/0503053.

[15] **NOvA** Collaboration, T. Yang and S. Wojcicki, *Study of physics sensitivity of ν_mu disappearance in a totally active version of nova detector*, Off-Axis-Note-SIM-30.

[16] M. D. Messier, *Evidence for neutrino mass from observations of atmospheric neutrinos with Super-Kamiokande*, . Ph.D. Thesis (Advisor: James L. Stone), UMI-99-23965.

[17] E. Paschos and J. Yu, *Neutrino interactions in oscillation experiments*, *Phys.Rev.* **D65** (2002) 033002, [hep-ph/0107261].

[18] M. Fechner, *Détermination des performances attendues sur la recherche de l'oscillation $\nu\_\mu \to \nu\_e$ dans l'expérience T2K depuis l'étude des données recueillies dans l'expérience K2K*, . Presented on 9 May 2006.

[19] **T2K Collaboration** Collaboration, I. Kato, *Status of the T2K experiment*, *J.Phys.Conf.Ser.* **136** (2008) 022018.

[20] A. Cervera et al., *Golden measurements at a neutrino factory*, *Nucl. Phys.* **B579** (2000) 17–55, [hep-ph/0002108].

[21] E. K. Akhmedov, R. Johansson, M. Lindner, T. Ohlsson, and T. Schwetz, *Series expansions for three-flavor neutrino oscillation probabilities in matter*, *JHEP* **04** (2004) 078, [hep-ph/0402175].

[22] M. Freund, *Analytic approximations for three neutrino oscillation parameters and probabilities in matter*, *Phys. Rev.* **D64** (2001) 053003, [hep-ph/0103300].

[23] L. Wolfenstein, *Neutrino oscillations in matter*, *Phys. Rev.* **D17** (1978) 2369–2374.

[24] P. Huber, M. Lindner, T. Schwetz, and W. Winter, *First hint for CP violation in neutrino oscillations from upcoming superbeam and reactor experiments*, *JHEP* **11** (2009) 044, [0907.1896].

[25] **NOvA Collaboration** Collaboration, D. Ayres et al., *The NOvA Technical Design Report*, . FERMILAB-DESIGN-2007-01.

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