The Need for an early $\bar{\nu}$ run of NOνA

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Neutrino oscillations: Things to be done

Quantities to be measured are

- Sign of Δ_{31} or to determine which is the lightest mass eigenstate: m_1 (the state with the largest component of ν_e) or m_3 (the state with the least component of ν_e)?
- The octant of θ_{23}: Is $\theta_{23} < 45^\circ$ (Lower Octant or LO) or $\theta_{23} > 45^\circ$ (Higher Octant or HO)?
- Is there CP Violation in the leptonic sector? If yes, what is the value of δ_{CP}?

The first problem is also called the determination of hierarchy.

Typically the lightest mass eigenstate is assumed to be very light.

Then for positive Δ_{31} or normal hierarchy (NH) we have the mass pattern $m_3 > m_2 \gg m_1$.

If Δ_{31} is negative or for inverted hierarchy (IH), the mass pattern is $m_2 \geq m_1 \gg m_3$.

$\nu_\mu \to \nu_e$ Oscillations in Long Baseline Experiments

- In the $\nu_\mu \to \nu_e$ oscillations in the long baseline accelerator experiments, one can see the full interplay of the three flavour mixing effects.
- These are oscillations are **special** because here we actually **see** the flavour of neutrino change. In all the previous experiments (with the exception of OPERA) one only observed a deficit of a particular flavour.
- Observation of these oscillations will help in resolving all the three unknowns mentioned in the previous slide.
- Unfortunately, these oscillations depend on the small parameters θ_{13} and α, so the oscillation probabilities are small.
- T2K (and earlier MINOS) have looked for $\nu_\mu \to \nu_e$ oscillations. NOνA, which is about start its run, will also detect these.

$\nu_\mu \to \nu_e$ Oscillations in Long Baseline Experiments

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

[Cervera et al., hep-ph/0002108, M. Freund, hep-ph/0103300]

$\hat{\Delta} = \Delta_{31} L/4E$, $\hat{A} = A/\Delta_{31}$, $\alpha = \Delta_{21}/\Delta_{31}$

$\nu_\mu \to \nu_e$ Oscillations in Long Baseline Experiments

- $\sin 2\theta_{13} \approx 0.3$ and $\alpha \approx 0.03$. So α^2 term can be ignored.
- Δ_{31} +ve for NH and -ve for IH
- A +ve for ν and -ve for $\bar{\nu}$
- For ν, $\hat{A}$ +ve for NH and -ve for IH
- For $\bar{\nu}$, $\hat{A}$ -ve for NH and +ve for IH
- $P_{\mu e}$ SENSITIVE to hierarchy
- $P_{\mu e}$ dependent of θ_{13}, hierarchy, octant of θ_{23}, δ_{CP}

Degeneracies in hierarchy determination

- In this talk, I will concentrate on the determination of hierarchy, which is within the reach of the current and upcoming experiments.
- But this determination is subject to the following degeneracies:
  - The (hierarchy-δ_{CP}) degeneracy:$P_{\mu e}(\theta_{13}, \mathrm{NH}, \delta_{CP}) = P_{\mu e}(\theta_{13}, \mathrm{IH}, \delta_{CP}{}')$
  - The (hierarchy-θ_{13}) degeneracy: $P_{\mu e}(\mathrm{NH}, \theta_{13}, \delta_{CP}) = P_{\mu e}(\mathrm{IH}, \theta_{13}{}', \delta_{CP})$
  - The (hierarchy-octant) degeneracy: $P_{\mu e}(\mathrm{NH}, \theta_{23}, \theta_{13}, \delta_{CP}) = P_{\mu e}(\mathrm{IH}, 90^\circ - \theta_{23}, \theta_{13}, \delta_{CP}{}')$

  [Barger et al., arXiv: hep-ph/0112119]
- Because of the first degeneracy, NOνA can determine the hierarchy for only half the values of δ_{CP}.

[Suprabh Prakash, Sushant Raut, S. Uma Sankar, arXiv: 1201.6485v3]

Residual degeneracies in NOνA ν data

We limit ourselves to favorable hierarchy-δ_{CP} combinations for which NOνA is capable of determining the hierarchy with a $(3\nu + 3\bar{\nu})$ run.
These are (NH, LHP $-180^\circ \leq \delta_{CP} \leq 0$) and (IH, UHP $0 \leq \delta_{CP} 180^\circ$).
We ask, "What can we learn from the first 3 years data of NOνA?"
We consider two possibilities.

- 3 year of ν run
- 1.5 year ν run + 1.5 year $\bar{\nu}$ run

WHY?

- Originally first 3 year ν run was considered to discover non-zero θ_{13}, in case it was small.
- But now θ_{13} is established to be non-zero at high confidence level and is measured to be moderately large ($\simeq 8^\circ$).
- So must consider which run combination has best chance to give an early hint of hierarchy.

[Suprabh Prakash, Ushak Rahaman, S. Uma Sankar, arXiv:1306.4125]

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Residual degeneracies in NOνA ν data

Pure neutrino data it is subject to some residual degeneracies.

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

- Because we decided to limit ourselves to favorable half-planes of δ_{CP}, the second term does not affect degeneracies too much.
- If the precision in θ_{13} is not very good, then hierarchy-θ_{13} degeneracy limits the hierarchy determination ability.

Residual degeneracies in NOνA ν data

- For example, let us assume NH is the true hierarchy. The combination $P_{\mu e}$(NH, θ_{13}) can be faked by $P_{\mu e}$(IH, $\theta_{13}{}' > \theta_{13}$).
- But $P_{\bar{\mu}\bar{e}}$(NH, θ_{13}) will be much lower than $P_{\bar{\mu}\bar{e}}$(IH, $\theta_{13}{}' > \theta_{13}$)).
- In other words, the fake hierarchy solutions, due to hierarchy-θ_{13} degeneracy, occur at different values of $\theta_{13}{}'$ for ν and $\bar{\nu}$.
- Thus, a combination of ν and $\bar{\nu}$ data is less susceptible to this degeneracy than pure ν data, if the precision on θ_{13} is about 10%.
- We verified this by simulations.

Simulations

NOνA Experiment

[Ayres et al., NOνA, Tech. Rep. (2007), Fermilab-Design-2007-01]

- 14 kiloton TASD
- 810 km away from Fermilab
- Detector locaton: 0.8° off axis from the NuMI beam
- ν flux peaks sharply at 2 GeV, oscillation maximum energy 1.5 GeV
- Equal ν and $\bar{\nu}$ run of 3 years each
- NuMI beam power 700 kW, corresponding to 6×10^{20} protons on target per year
- We have used retuned signal acceptance and background factor
  [R. Patterson, Talk at *Neutrino 2012*, Kyoto]
  [Sanjib Agarwalla, Suprabh Prakash, Sushant Raut, S. Uma Sankar, arXiv: 1208.3644]

Numerical Simulations

- $\sin^2\theta_{12} = 0.30$, $\Delta_{21} = 7.5 \times 10^{-5}\ eV^2 \longrightarrow$ kept fixed
- $\sin^2 2\theta_{13} = 0.089$, $\sigma(\sin^2 2\theta_{13}) = 10\%$, in preliminary calculations, 5% in later calculations, marginalization done over 2σ range.
- $\Delta m^2_{eff} = \pm 2.4 \times 10^{-3}\ eV^2$, positive (negative) for NH (IH)
- $\Delta m^2_{eff} = \sin^2\theta_{12}\Delta_{31} + \cos^2\theta_{12}\Delta_{32} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\cot\theta_{23}\Delta_{21}$, $\Delta_{31} \simeq \Delta_{32}$ [Nunokawa et al., arXiv: hep-ph/0503283]
- $\sigma(\Delta m^2_{eff}) = 3\%$ [Itow et al., arXiv: hep-ex/0106019], marginalization over $2\ \sigma$ range
- For maximal mixing, $\sin^2\theta_{23} = 0.5$
- For non-maximal mixing, $\sin^2\theta_{23} = 0.41$ for θ_{23} in lower octant and $\sin^2\theta_{23} = 0.59$ for θ_{23} in higher octant
- Marginalization range of $\sin^2\theta_{23}$ is [0.35, 0.65]- $3\ \sigma$ range of global fit
- Marginalization of δ_{CP} is full range- $[-180°, 180°]$

Simulations

Event number simulations and the $\Delta\chi^2$ calculations are done by using GLoBES [Huber et al., arXiv: hep-ph/0407333, Huber et al., arXiv: hep-ph/0701187]

Minimum $\Delta\chi^2$ is calculated by doing a marginalization over the above mentioned parameters.

Effect of Precision of $\sin^2 2\theta_{13}$

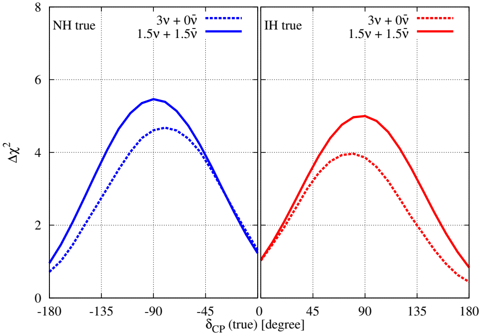
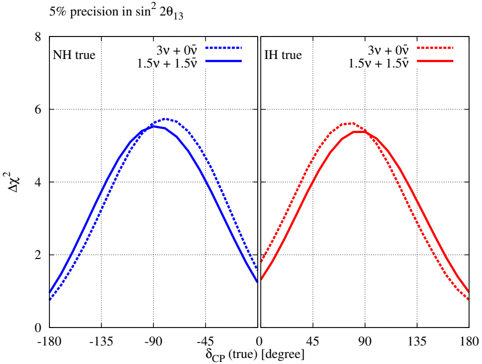


Figure: Hierarchy sensitivity assuming 10% uncertainty in $\sin^2 2\theta_{13}$ and maximal θ_{23}. In the left (right) panel, the true hierarchy is taken to be NH (IH).

Effect of Precision of $\sin^2 2\theta_{13}$

If the uncertainty in $\sin^2 2\theta_{13}$ is reduced to 5%, the hierarchy reach for 3ν becomes equal to that of $1.5\nu + 1.5\bar{\nu}$ run. The larger statistics of 3ν data makes this possible.



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Non-maximal θ_{23}

- Recently MINOS experiment measured $\sin^2 2\theta_{23}$ to be non-maximal. [R. Nichol, Talk at *Neutrino 2012* Kyoto, and P. Adamson *et al*, arXiv:1304:6335.]
- We need to worry about an additional degeneracy, ”hierarchy-octant” [Sanjib Agarwalla, Suprabh Prakash, S. Uma Sankar, arXiv: 1301.2574]
- Pure neutrino data is susceptible to this degeneracy whereas combination of ν and $\bar{\nu}$ data is not.

Non-maximal θ_{23}

- Suppose HO is the true octant and NH is the true hierarchy. Then the first term in $P_{\mu e}$ gets a double boost and $P_{\mu e}(\mathrm{NH}) > P_{\mu e}(\mathrm{IH})$ for all parameter values.
- Similarly $P_{\mu e}$ gets a double suppression if LO is the true octant and IH is the true hierarchy.
- For these two octant-hierarchy combinations, pure ν data has a very good hierarchy determination capability.
- But the other two combinations, LO-NH and HO-IH, are nearly degenerate because the boost due to hierarchy is nearly cancelled by the suppression due to octant or *vice-verse*.

Non-maximal θ_{23}

- This degeneracy in $P_{\mu e}$ is resolved by $P_{\bar{\mu}\bar{e}}$.
- For anti-neutrinos, both LO and NH suppress $P_{\bar{\mu}\bar{e}}$ and both HO and IH boost $P_{\bar{\mu}\bar{e}}$.
- NO octant-hierarchy degeneracy in a combination ν and $\bar{\nu}$ data

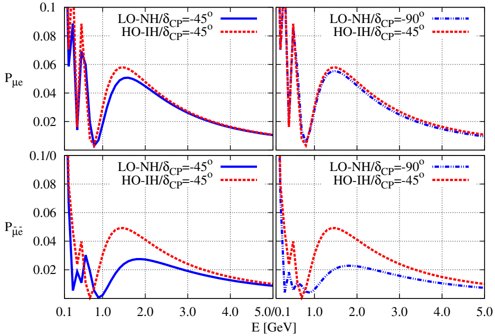

Figure: Illustration of degenerate $P_{\mu e}$ and non-degenerate $P_{\bar{\mu}\bar{e}}$ for the following two cases. Left: (LO-NH, $\delta_{CP} = -45°$) and (HO-IH, $\delta_{CP}' = -45°$), Right: (LO-NH, $\delta_{CP} = -90°$) and (HO-IH, $\delta_{CP}' = -45°$).

Non-maximal θ_{23}

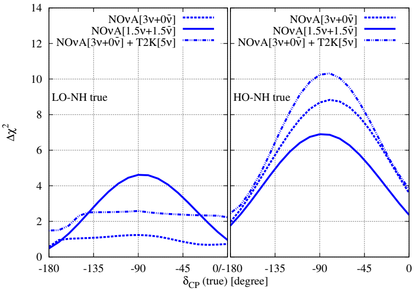

Figure: Hierarchy sensitivity assuming 5% uncertainty in $\sin^2 2\theta_{13}$ for NH and LHP. In the left (right) panel, the true $\sin^2 \theta_{23}$ is taken to be 0.41 (0.59).

[Suprabh Prakash, Ushak Rahaman, S. Uma Sankar, arXiv: 1306.4125]

Non-maximal θ_{23}

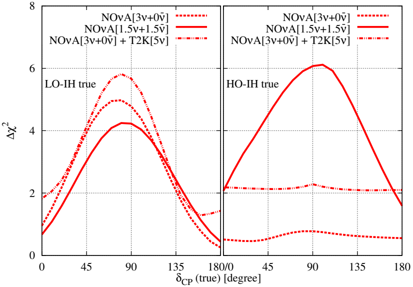

Figure: Hierarchy sensitivity assuming 5% uncertainty in $\sin^2 2\theta_{13}$ for IH and UHP. In the left (right) panel, the true $\sin^2 \theta_{23}$ is taken to be 0.41 (0.59).

[Suprabh Prakash, Ushak Rahaman, S. Uma Sankar, arXiv: 1306.4125] (Accepted for publication in JHEP)

Non-maximal θ_{23}

- HO-NH combination has a 2σ hierarchy discrimination for 80% (70%) of the favorable half plane for 3ν ($1.5\nu + 1.5\bar{\nu}$)
- LO-IH combination has a 2σ hierarchy discrimination for 40% (20%) of the favorable half plane for 3ν ($1.5\nu + 1.5\bar{\nu}$)
- For HO-NH and LO-IH$1.5\nu + 1.5\bar{\nu}$ is slightly worse than 3ν.
- For LO-NH and HO-IH, $1.5\nu + 1.5\bar{\nu}$ has a far better sensitivity to hierarchy than 3ν

Conclusion

- $1.5\nu + 1.5\bar{\nu}$ run has a better hierarchy sensitivity than 3ν run, if $\sigma(\sin^2 2\theta_{13}) = 10\%$.
- If $\sigma(\sin^2 2\theta_{13})$ is reduced to 5%, the hierarchy sensitivities of $1.5\nu + 1.5\bar{\nu}$ run and 3ν run are comparable if θ_{23} is maximal.
- For non-maximal θ_{23}, $1.5\nu + 1.5\bar{\nu}$ run good hierarchy sensitivity for all possible hierarchy-octant combinations, where as 3ν has no sensitivity at all for LO-NH and HO-IH
- For these two combinations, addition of T2K data does not help much.
- It is imperative for NOνA to plan on early $\bar{\nu}$ run to get a quick hint of hierarchy for all combinations of octant and hierarchy.


THANK
YOU !