Hierarchy and Octant Determination Potential of LBNE and LBNO

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July 18, 2013

Neutrino Oscillation measurements

- From KamLAND: $\Delta_{21} = 7.5 \times 10^{-5}$ eV^2.
- From MINOS: $\Delta m^2_{eff} = \pm 2.4 \times 10^{-3}$ eV^2.
- From Solar neutrino data: $\sin^2\theta_{12} = 0.3$.

Δm^2_{eff} is related to Δ_{31} through the formula

$$\Delta m^2_{\rm eff} = \Delta m^2_{31} - \Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}).$$

Two exciting results from the past year

- From Daya Bay and RENO: $\sin^2 2\theta_{13} = 0.089 \pm 0.011$ confirming the earlier result of T2K, MINOS and DoubleCHOOZ that $\theta_{13} \neq 0$.
  Good for future measurements such as hierarchy and CP violation.
- From MINOS: $\sin^2\theta_{23} = 0.94\pm$, indicating that θ_{23} is not maximal.
  Leading to two degenerate solutions $\sin^2\theta_{23} = 0.41$ in lower octant (LO) and $\sin^2\theta_{23} = 0.59$ in higher octant (HO).

Hierarchy Determination at upcoming experiments

Long baseline experiments, such as NOνA and T2K, aim to determine hierarchy and octant through measuring $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations.

$\nu_\mu \to \nu_e$ oscillation probability, expanded perturbatively in $\alpha = \Delta_{21}/\Delta_{31}$:

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

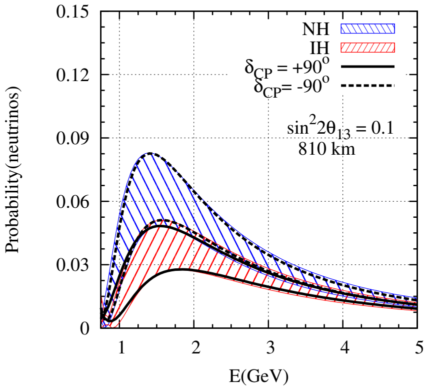
where $\hat{\Delta} = \Delta_{31} L/4E$ and $\hat{A} = A/\Delta_{31}$.

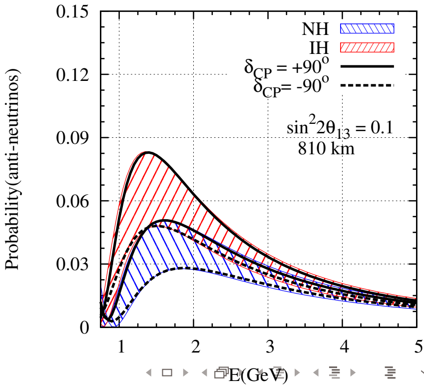
Wolfenstein matter term: $A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho(\mathrm{gm/cc}) E(\mathrm{GeV})$.

$\hat{A}$ changes sign if the hierarchy is changed. So $P_{\mu e}$ is sensitive to hierarchy. But, $P_{\mu e}$ also depends on δ_{CP}, of which we know nothing. Thus we are led to hierarchy-δ_{CP} degeneracy.

$P_{\mu e}$(as a band in δ_{CP}) vs. Energy for NOνA

Left panel: Neutrinos & Right panel: Anti-neutrinos





Partial resolution of hierarchy-δ_{CP} degeneracy

Matter term increases $P_{\mu e}$ for NH and decreases it for IH. Its effect on $P_{\bar{\mu}\bar{e}}$ is the opposite.

Hierarchy-δ_{CP} arises because the change due to matter term can be cancelled by taking a wrong value of δ_{CP}.

Have to do a careful study of δ_{CP} dependence of $P_{\mu e}$ and $P_{\bar{\mu}\bar{e}}$ to resolve this.

In $P_{\mu e}$ plots, the lines for $\delta_{CP} = \pm 90^\circ$ are emphasized. The line for $\delta_{CP} = -90^\circ (+90^\circ)$ is close to the top (bottom) for neutrinos and vice-verse for anti-neutrinos.

The lines for $\delta_{CP} = 0$ and180° are somewhere in the middle.

Favourable and Unfavourable Half-planes

$P_{\mu e}$ values for NH and δ_{CP} in lower half plane $(-180^\circ \leq \delta_{CP} \leq 0)$ are well above the values of $P_{\mu e}$ for IH and any δ_{CP}. Similarly $P_{\mu e}$ values for IH and δ_{CP} in upper half plane $(0 \leq \delta_{CP} \leq 180^\circ)$ are well below the values of $P_{\mu e}$ for NH and any δ_{CP}.

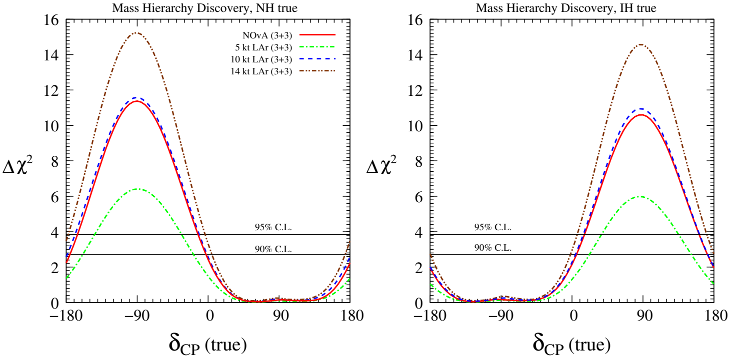
The same clear separation is there in $P_{\bar{\mu}\bar{e}}$ values also.

If nature chooses one of the two favourable combinations (NH with δ_{CP} in LHP or IH with δ_{CP} in UHP) then NOνA , by itself, can determine the hierarchy at 2σ to 3σ depending on δ_{CP}.

For unfavourable combinations, NH with δ_{CP} in UHP and IH with δ_{CP} in LHP, NOνA has NO sensitivity to hierarchy. This occurs because the data gives two degenerate solutions: One with correct hierarchy and correct δ_{CP} and one with wrong hierarchy and wrong δ_{CP}.

S. Prakash, S. Raut and SUS, Phys. Rev. D86 (2012) 033012.

Hierarchy sensitivity of NOνA



From: S. Agarwalla, S. Prakash, S. Raut and SUS, JHEP 1212 (2012) 075.

Does addition of T2K data help?

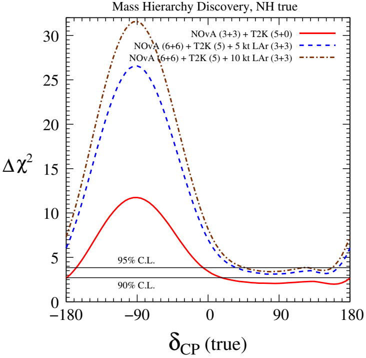
T2K has a shorter baseline and smaller energy compared to NOνA with only one third the matter effect.

Since the matter effects at T2K are small, can it determine the half plane of δ_{CP} independent of hierarchy?

NO. Now matter how small the matter effect, in the unfavourable regions, we get degenerate fake hierarchy solutions.

But T2K data will help a little bit. The degenerate solutions with wrong hierarchy, occur at different values of δ_{CP} for NOνA and for T2K. So the combined data has some moderate hierarchy sensitivity.
(O. Mena and S. J. Parke, hep-ph/040807, PRD70 (2004) 093011.)

Mass hierarchy sensitivity with NOνA and T2K

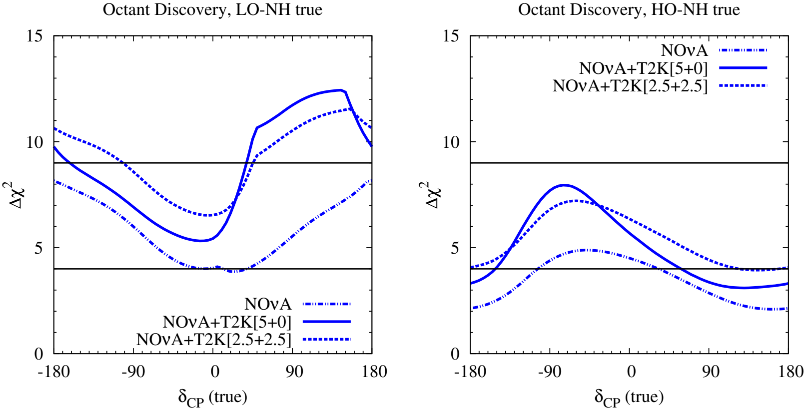


From: S. Agarwalla, S. Prakash, S. Raut and SUS, JHEP 1212 (2012) 075.
We have something close to 90% C. L. hierarchy discrimination for unfavourable combinations.

θ_{23}-octant resolution with NOνA and T2K

Octant discovery plots for reoptimized NOνA and T2K (modified)

Left panel: LO true & Right panel: HO true



From: S. Agarwalla, S. Prakash and SUS, arXiv:1301.2574 (in JHEP)

See also the poster by Suprabh Prakash

Need for future facilities

- Current experiments have less than 90% C.L. hierarchy sensitivity if the hierarchy-δ_{CP} combination is unfavourable.
- They have just about 95% C.L. for θ_{23} octant resolution.
- Their ability to rule out $\delta_{CP} \neq 0$ or 180° is also quite limited (can do so at 90% C.L.for a range of about $\pm 30^\circ$ around $\delta_{CP} = \pm 90^\circ$)
  S. Agarwalla, S. Prakash, S. Raut and SUS, JHEP 1212 (2012) 075.

Hence there is a need to consider future facilities, which can make robust measurements of the above three quantities.

Hierarchy and octant of θ_{23} resolutions should be considered the first steps of these future facilities. CP non-conservation and measurement of δ_{CP} are more difficult measurements and can be considered at later stages.

Physics constraints on future facilities

- Matter effects at these facilities should be large enough so that $P_{\mu e}$ and $P_{\bar{\mu}\bar{e}}$ are well separated for NH and for IH, *even for θ_{23} in lower octant*.
- Since the matter effect is proportional to energy, the ν ($\bar{\nu}$) beam energy must be reasonably large.
- Since the oscillation probabilities depend on L/E, the baseline should be correspondingly larger.
- As the flux falls off at longer distances, there must be high intensity sources.
- The detectors should have very good particle identification so that the neutrino events can be kinematically reconstructed. This is needed to suppress the neutral current single π^0 background to the electron appearance events.

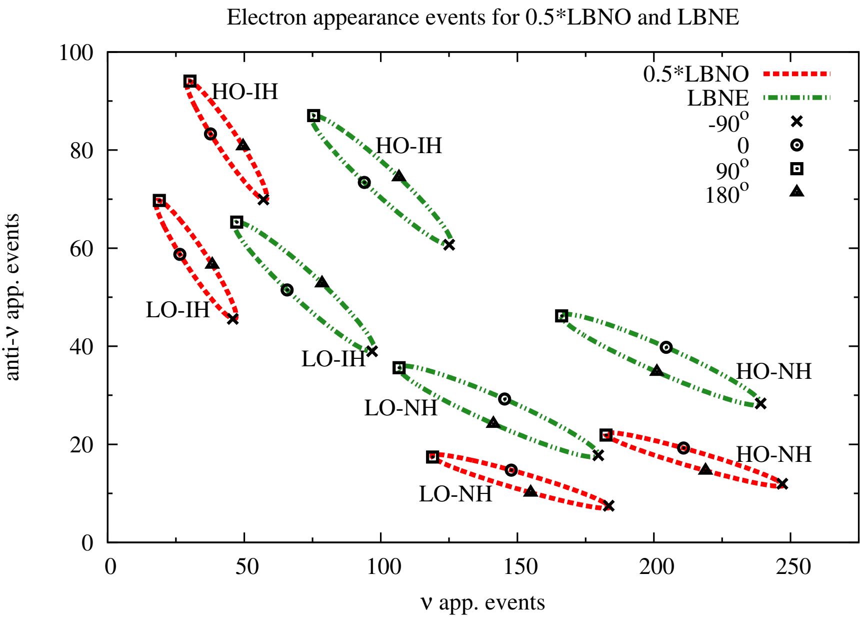
LBNE and LBNO

Characteristic	LBNE	LBNO
Baseline	1300 km	2300 km
Location	Fermilab-Homestake	CERN-Pyhasalmi
Proton energy	120 GeV	400 GeV
Beam	on - axis	wideband
Beam power	0.7 MW	0.75 MW
Protons of Target	6×10^{20} per year	1.5×10^{20} per year
Detector	LArTPC (10 kton)	LArTPC (20 kton)
Runtime	5 in ν + 5 in $\bar{\nu}$	5 in ν + 5 in $\bar{\nu}$

Simulation Details

- We have used best fit neutrino parameter values quoted in slide-1 and the detector properties quoted in slide-13.
- We have taken $\sigma(|\Delta m^2_{eff}|) = 4\%$, $\sigma(\sin^2 2\theta_{13}) = 5\%$ and $\sigma(\text{density}) = 5\%$.
- In computing $\Delta\chi^2$, we marginalized over the above parameters in their 2σ ranges and $\sin^2\theta_{23}$ in the range $0.36 - 0.67$ (3 σ range from the global best fits).
- We have computed the hierarchy and the octant determination capability of LBNE, LBNO and also 0.5*LBNO (a hypothetical case where the detector mass is the same as LBNE).

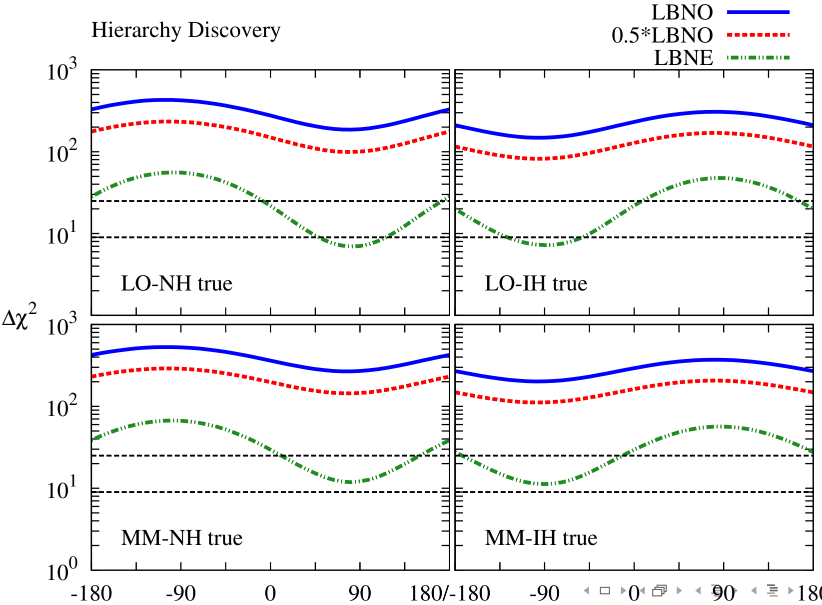
The full details are given in
S. Agarwalla, S. Prakash and SUS, arXiv:1304.3251


Electron appearance events for 0.5*LBNO and LBNE
0.5*LBNO
LBNE
-90°
0
90°
180°
HO-IH
HO-IH
LO-IH
LO-IH
LO-NH
LO-NH
HO-NH
HO-NH
anti-ν app. events
ν app. events
0
20
40
60
80
100
0
50
100
150
200
250

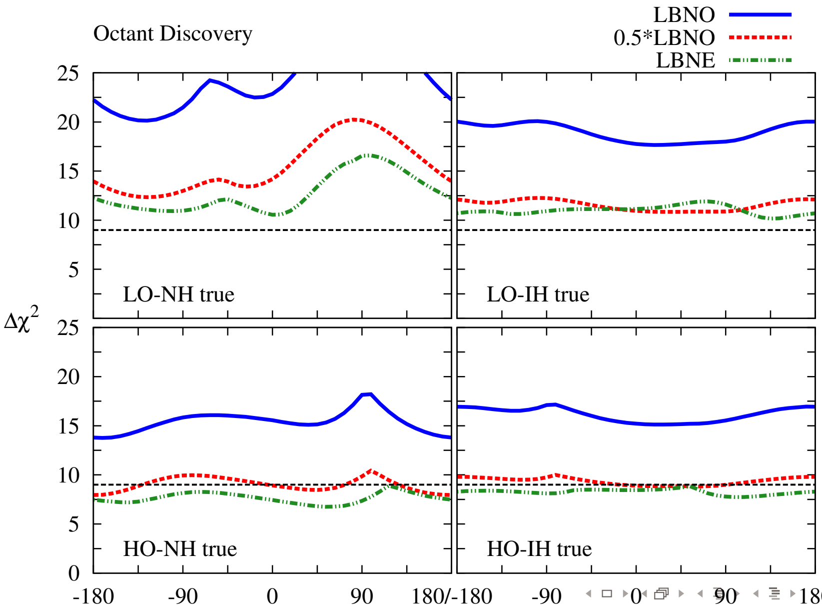
Physics from event contour plots

- We plot the ν_e appearance events vs $\bar{\nu}_e$ appearance events for LBNE and 0.5*LBNO. Varying δ_{CP} in its full range leads to the ellipses.
- The ability of an experiment to distinguish hierarchy/octant depends on the separation between the ellipses for different hierarchies and different octants.
- 0.5*LBNO has excellent hierarchy determination capability, just from its neutrino run. This is because it is close to being the bimagic baseline.
  S. Raut, R. S. Singh and SUS, Phys. Lett. B696 (2011) 227 and
  A. Dighe, S. Goswami and S. Ray, Phys. Rev. Lett. 105 (2010) 261802.
- Anti-neutrino run is required to obtain octant discrimination.
- If the true octant is LO, then the hierarchy discrimination of LBNE is limited, especially for the most unfavourable values of δ_{CP}.

Hierarchy sensitivity of LBNE and LBNO



Octant sensitivity of LBNE and LBNO



Summary

- LBNE and LBNO are two planned future very long baseline facilities to explore the next stage of neutrino oscillation measurements.
- Physics goals are hierarchy determination (should NOνA find the hierarchy-δ_{CP} combination to be unfavourable), θ_{23} octant determination and search for CP violation.
- LBNO has excellent hierarchy determination capability for all octant-hierarchy combinations, whereas that LBNE, as currently planned, is limited if the true octant is LO and δ_{CP} is most unfavourable.
- Octant determination capabilities of both experiments are similar.

Thank You