Resolving θ_{23} Octant in Current & Future Oscillation Facilities

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Present Understanding of the 2-3 Mixing Angle

Information on θ_{23} comes from: a) atmospheric neutrinos and b) accelerator neutrinos

In two-flavor scenario: $$P_{\mu\mu} = 1 - \sin^2 2\theta_{\rm eff} \sin^2\left(\frac{\Delta m^2_{\rm eff} L}{4E}\right)$$

For accelerator neutrinos: relate effective 2-flavor parameters with 3-flavor parameters:

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

$$\sin^2 2\theta_{\rm eff} = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)$$ where $$\frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2\theta_{23}$$

Nunokawa etal, hep-ph/0503283; A. de Gouvea etal, hep-ph/0503079

Combining bean and atmospheric data in MINOS, we have:

MINOS Collaboration: arXiv:1304.6335v2 [hep-ex]

$$\sin^2 2\theta_{\rm eff} = 0.95^{+0.035}_{-0.036}\ (10.71 \times 10^{21}\ \text{p.o.t})$$

$$\sin^2 2\bar{\theta}_{\rm eff} = 0.97^{+0.03}_{-0.08}\ (3.36 \times 10^{21}\ \text{p.o.t})$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\rm eff} = 1$ (≥ 0.94 (90% C.L.))

Talk by Y. Itow in Neutrino 2012 conference, Kyoto, Japan

Bounds on θ_{23} from the global fits

	Forero etal	Fogli etal	Gonzalez-Garcia etal
$\sin^2\theta_{23}$ (NH)	$0.427^{+0.034}_{-0.027} \oplus 0.613^{+0.022}_{-0.040}$	$0.386^{+0.024}_{-0.021}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$
3σ range	$0.36 \to 0.68$	$0.331 \to 0.637$	$0.34 \to 0.67$
$\sin^2\theta_{23}$ (IH)	$0.600^{+0.026}_{-0.031}$	$0.392^{+0.039}_{-0.022}$	**Relative 1σ precision of 11%**
3σ range	$0.37 \to 0.67$	$0.335 \to 0.663$	

All the three global fits indicate for non-maximal 2-3 mixing!

In ν_μ survival probability, the dominant term is mainly sensitive to $\sin^2 2\theta_{23}$!

If $\sin^2 2\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for θ_{23}:

one in lower octant (LO: θ_{23} < 45 degree), other in higher octant (HO: θ_{23} > 45 degree)

In other words, if ($0.5 - \sin^2\theta_{23}$) is +ve (-ve) then θ_{23} belongs to LO (HO)

This is known as the octant ambiguity of θ_{23} !

Fogli and Lisi, hep-ph/9604415

ν_μ to ν_e oscillation data can break this degeneracy!

The preferred value would depend on the choice of the neutrino mass hierarchy!

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel

$$P_{\mu e} = \beta_1 \sin^2\theta_{23} + \beta_2 \cos(\hat{\Delta} + \delta_{\rm CP}) + \beta_3 \cos^2\theta_{23}$$ (upto second order in $\alpha = \Delta_{21}/\Delta_{31}$ and $\sin 2\theta_{13}$)

$$\beta_1 = \sin^2 2\theta_{13} \frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2}, \quad \beta_3 = \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \frac{\sin^2 \hat{\Delta}\hat{A}}{\hat{A}^2}$$

$$\beta_2 = \alpha \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \frac{\sin \hat{\Delta}(1-\hat{A})}{1-\hat{A}}$$

$$A({\rm eV}^2) = 0.76 \times 10^{-4} \rho\ ({\rm g/cc}) E({\rm GeV}) \qquad \hat{\Delta} = \Delta_{31} L/4E,\ \hat{A} = A/\Delta_{31}$$

Cervera etal, hep-ph/0002108; Freund etal, hep-ph/0105071

We demand that: $P_{\mu e}({\rm LO}, \delta_{\rm CP}^{\rm LO}) = P_{\mu e}({\rm HO}, \delta_{\rm CP}^{\rm HO})$

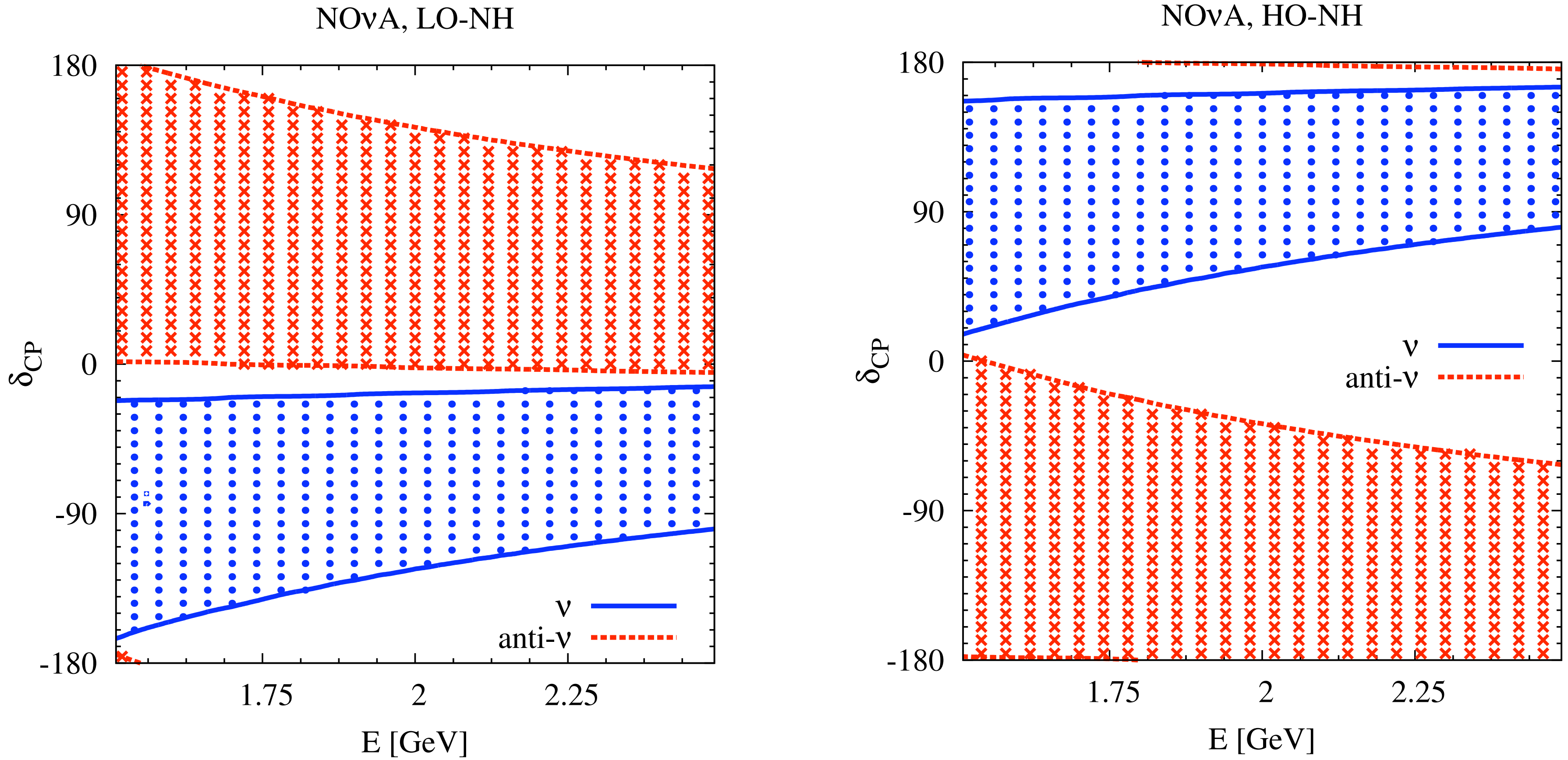
Above condition gives us: $\cos(\hat{\Delta} + \delta_{\rm CP}^{\rm LO}) - \cos(\hat{\Delta} + \delta_{\rm CP}^{\rm HO}) = \frac{\beta_1 - \beta_3}{\beta_2}(\sin^2\theta_{23}^{\rm HO} - \sin^2\theta_{23}^{\rm LO})$

For L=810 km & E=2 GeV, we get for NH and neutrino: $\cos(\hat{\Delta} + \delta_{\rm CP}^{\rm LO}) - \cos(\hat{\Delta} + \delta_{\rm CP}^{\rm HO}) = 1.7$

$P_{\mu e}({\rm LO}, -116^\circ \le \delta_{\rm CP} \le -26^\circ)$ is degenerate with $P_{\mu e}({\rm HO}, 64^\circ \le \delta_{\rm CP} \le 161^\circ)$

Agarwalla, Prakash, Uma Sankar, arXiv:1301.2574

Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



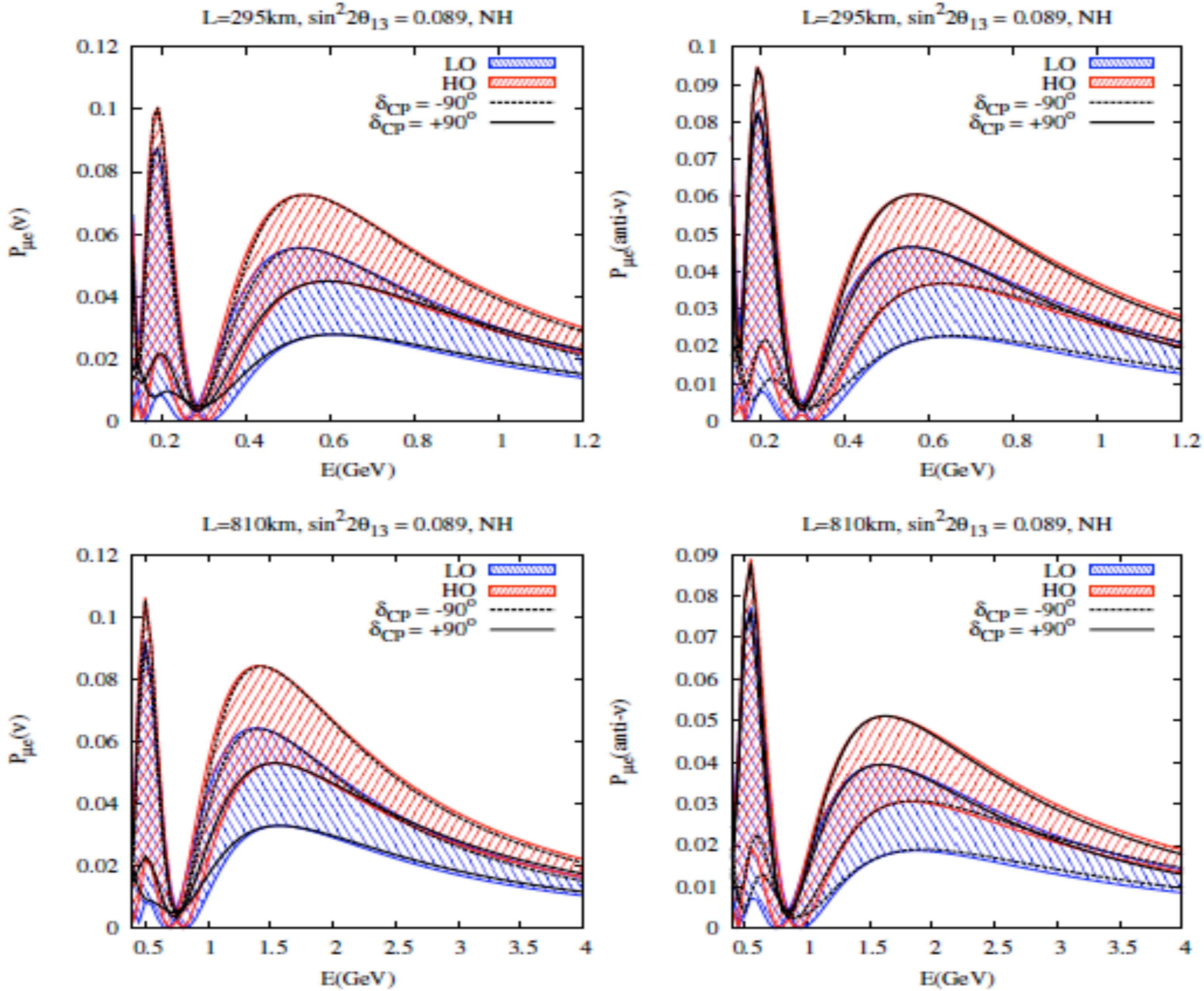
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

Octant – δ_{CP} degeneracy in $P_{\mu e}$ as a function of neutrino energy

At 2 GeV, $P_{\mu e}(\mathrm{LO}, -116^\circ \leq \delta_{CP} \leq -26^\circ)$ is degenerate with $P_{\mu e}(\mathrm{HO}, 64^\circ \leq \delta_{CP} \leq 161^\circ)$

As an example, $P_{\mu e}(\mathrm{LO}, \delta_{CP} = -90^\circ)$ is degenerate with $P_{\mu e}(\mathrm{HO}, \delta_{CP} \approx 66^\circ)$

Octant – δ_{CP} degeneracy in T2K and NOvA



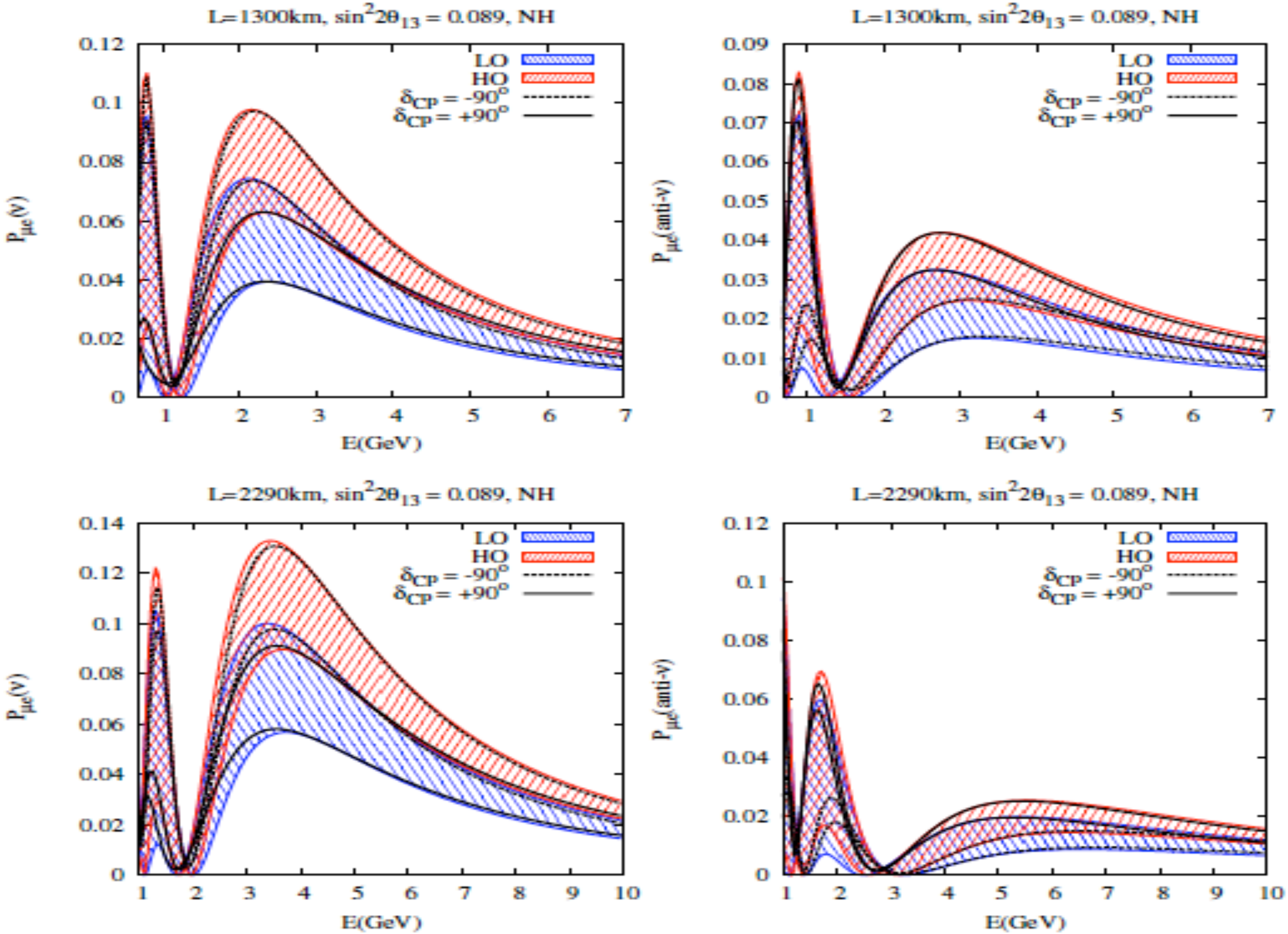
For neutrino: favorable combinations:
Max: HO, -90°
Min: LO, 90°

For anti-neutrino: favorable combinations:
Max: HO, 90°
Min: LO, -90°

Unfavorable CP values for neutrino are favorable for anti-neutrino and vice-versa!

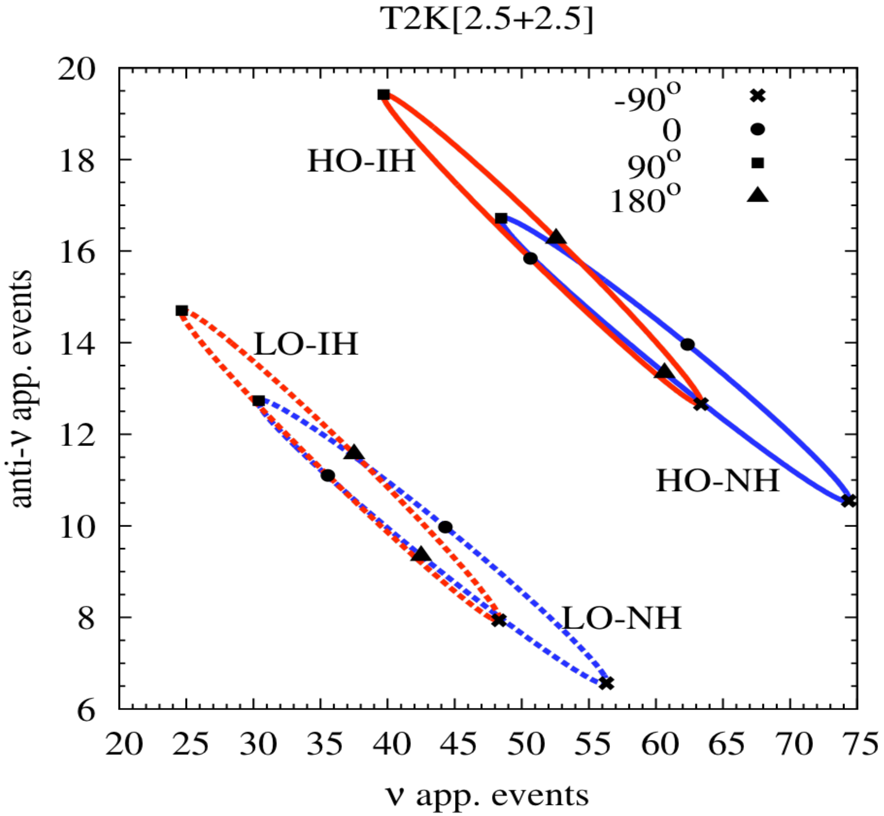
Agarwalla, Prakash, Uma Sankar, arXiv:1301.2574

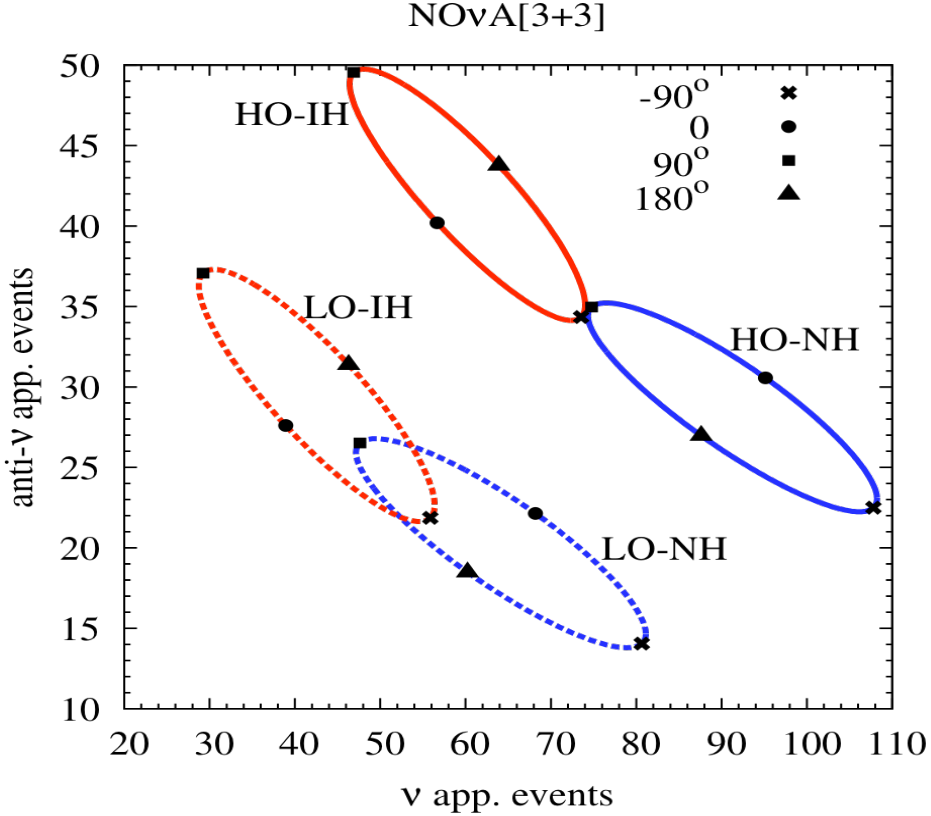
Octant – δ_{CP} degeneracy in LBNE and LBNO



Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

Bi-Event Plots for T2K and NOνA





Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]; see also the talk by T. Nakadaira in this workshop

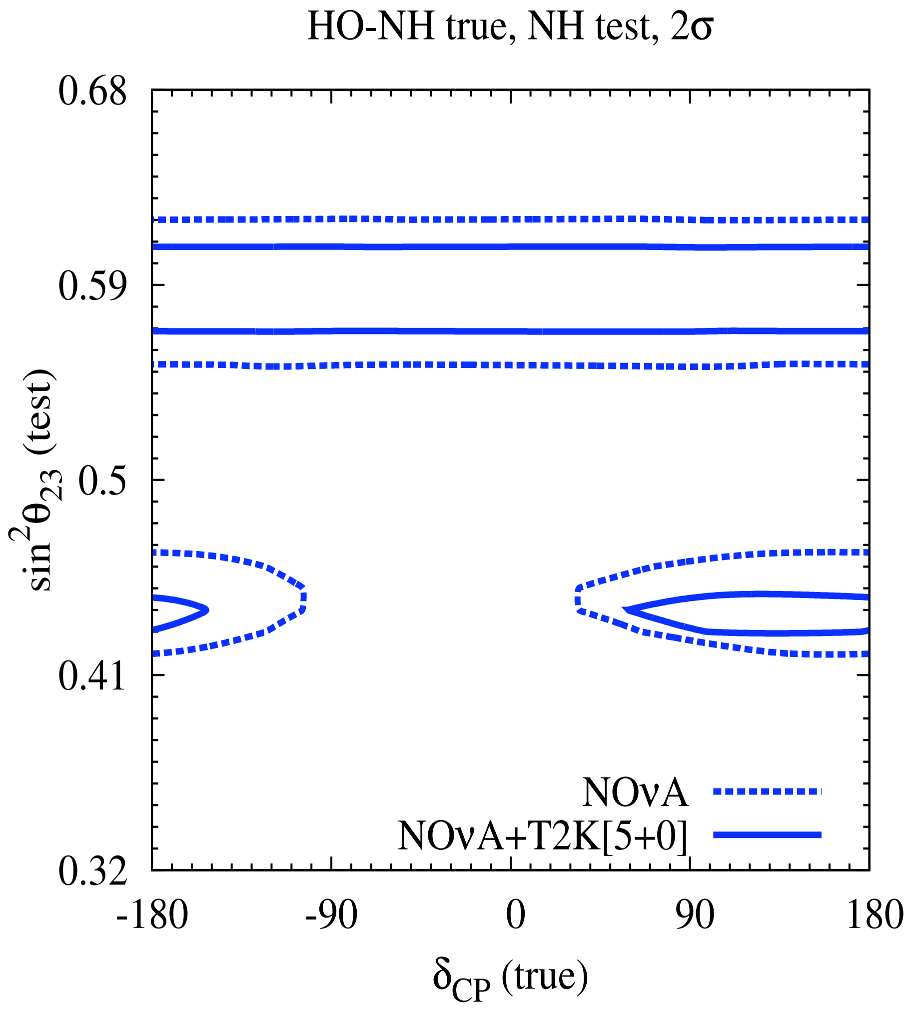
neutrino vs. anti-neutrino events for various octant-hierarchy combinations, ellipses due to varying δ_{CP}!

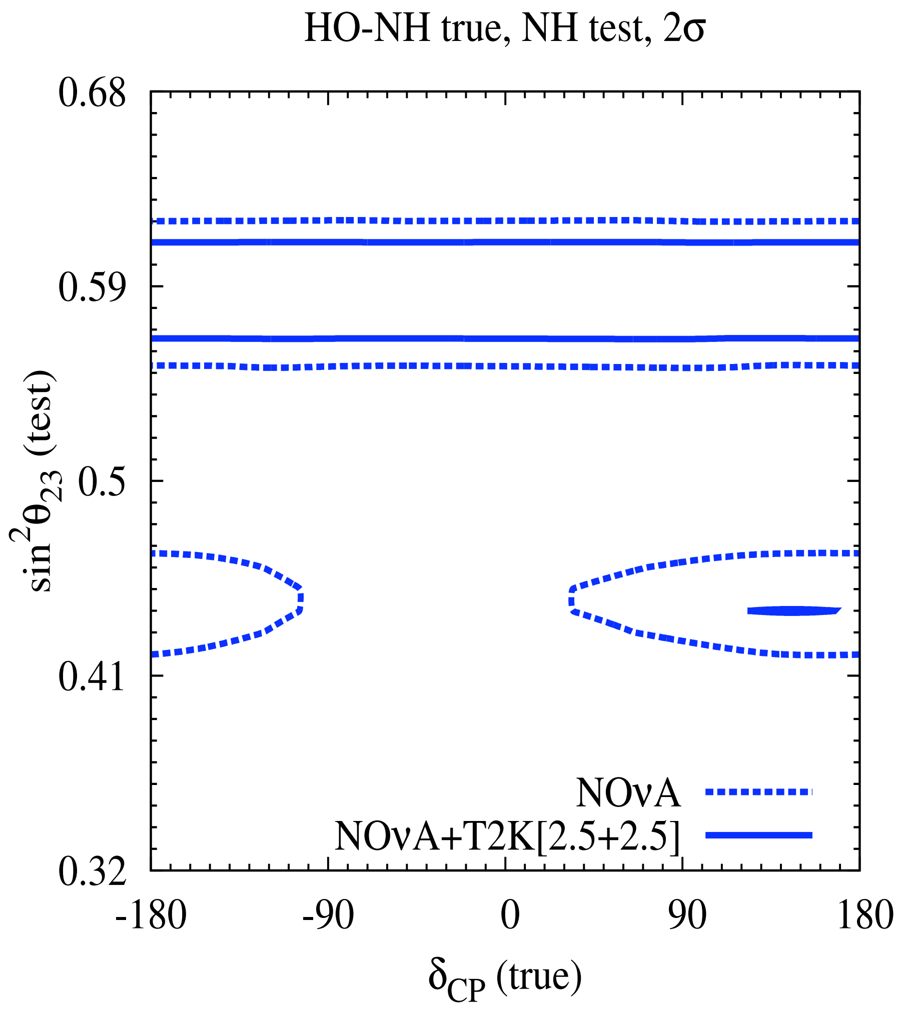
If δ_{CP} = -90° (90°), the asymmetry between ν and anti-ν events is largest for NH (IH)

For NOνA & T2K, the ellipses for the two hierarchies overlap whereas the ellipses of LO are well separated from those of HO, the same is true for T2K as well!

Octant discovery: balanced neutrino & anti-neutrino runs needed in each experiment!

Allowed regions in test $\sin^2\theta_{23}$ - true δ_{CP} plane





Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

Balanced neutrino & anti-neutrino runs from T2K are mandatory
if HO turns out to be the right octant!

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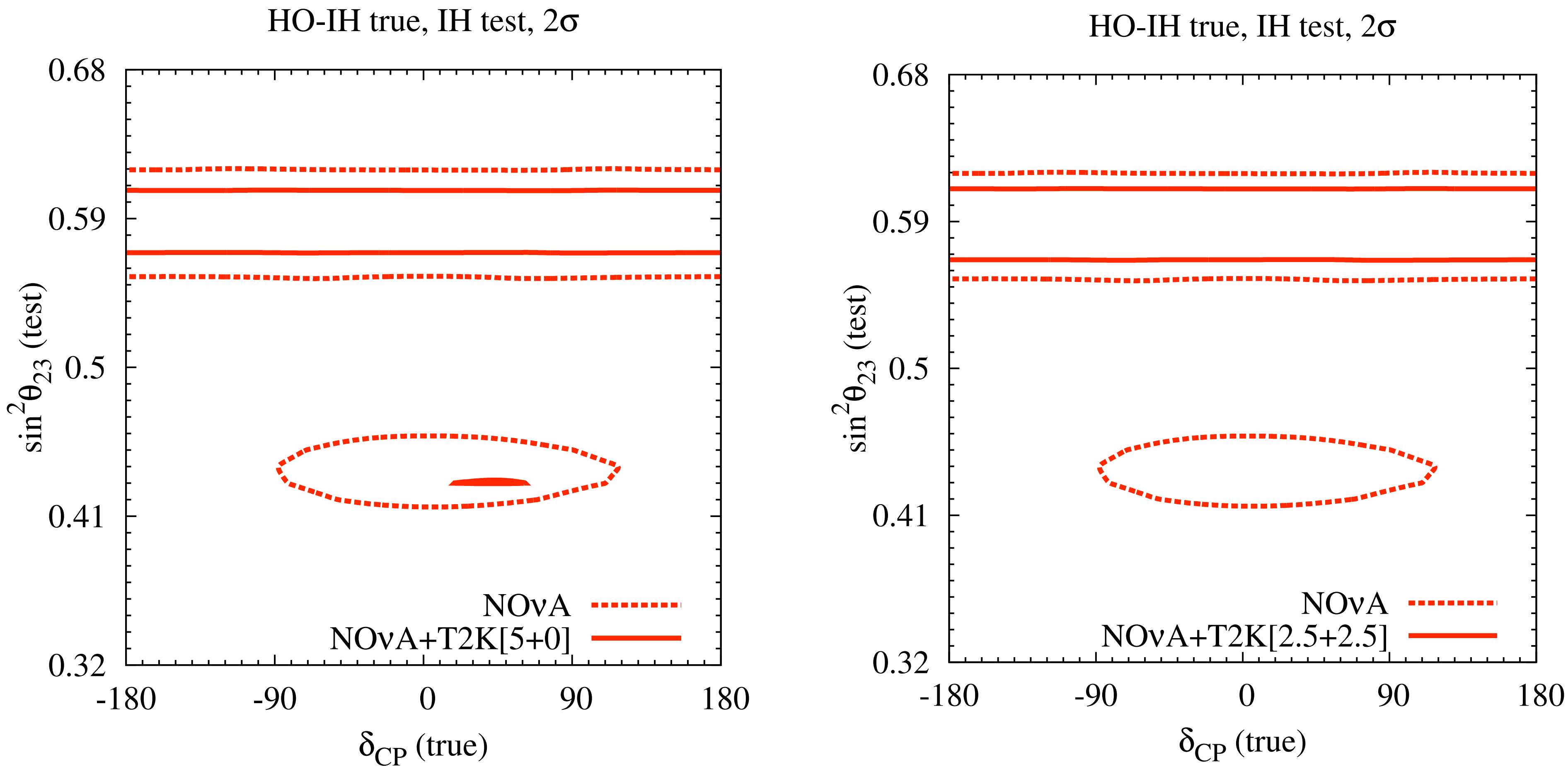
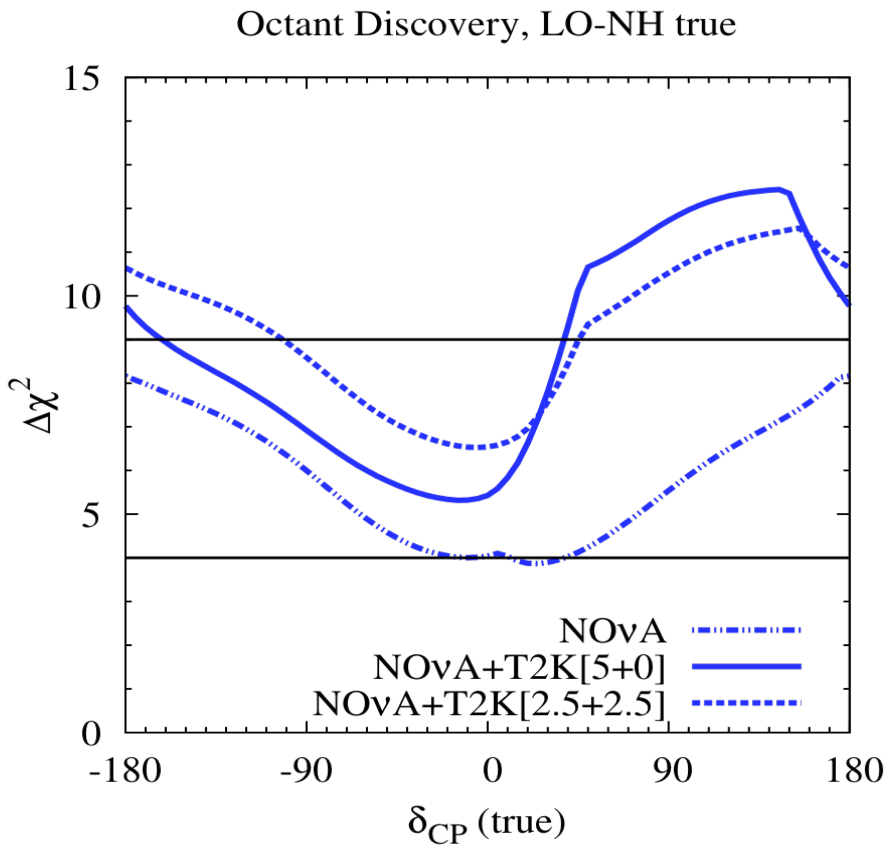
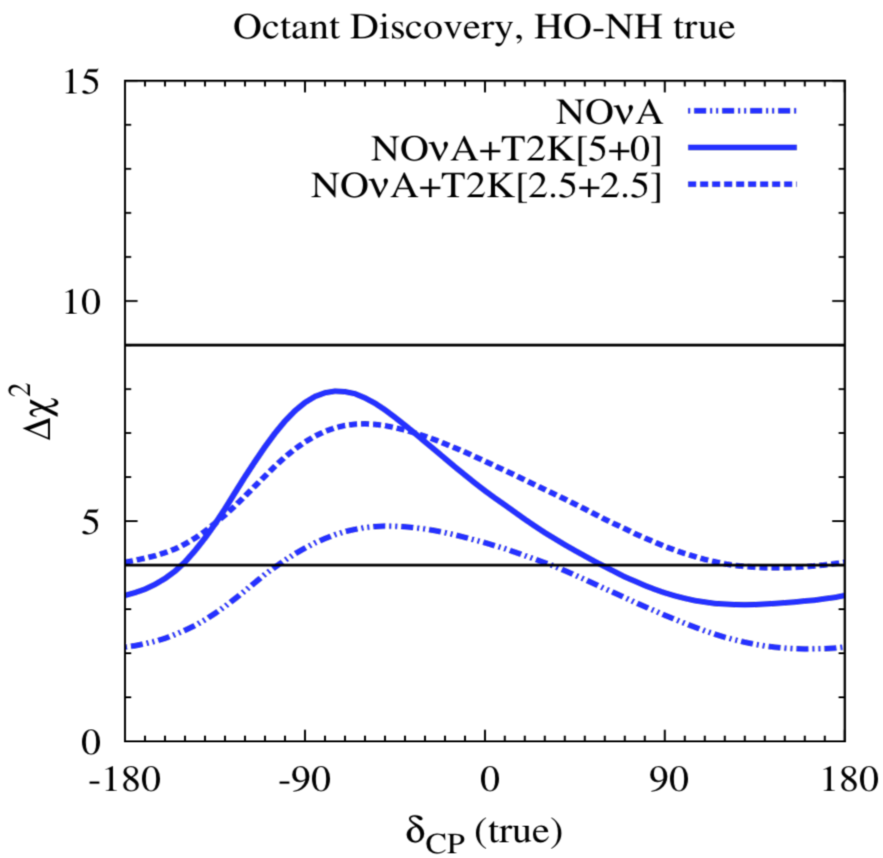


Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

Balanced neutrino & anti-neutrino runs from T2K are mandatory if HO turns out to be the right octant!

Resolving Octant of θ_{23} with T2K and NOvA



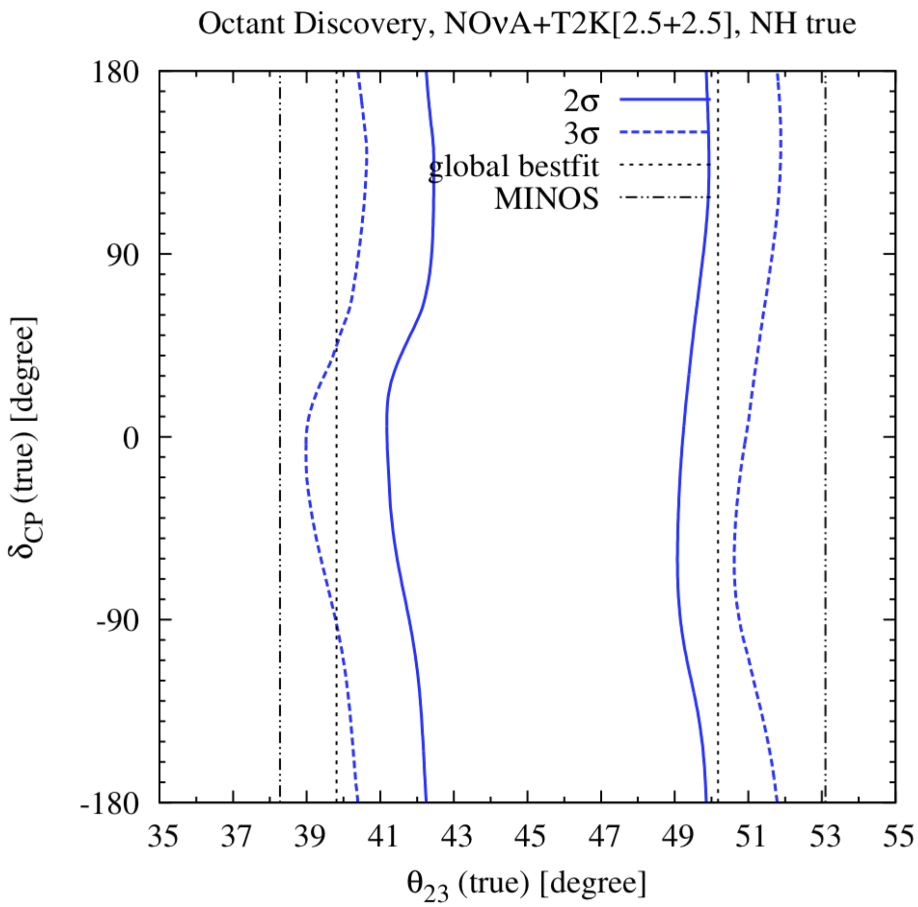


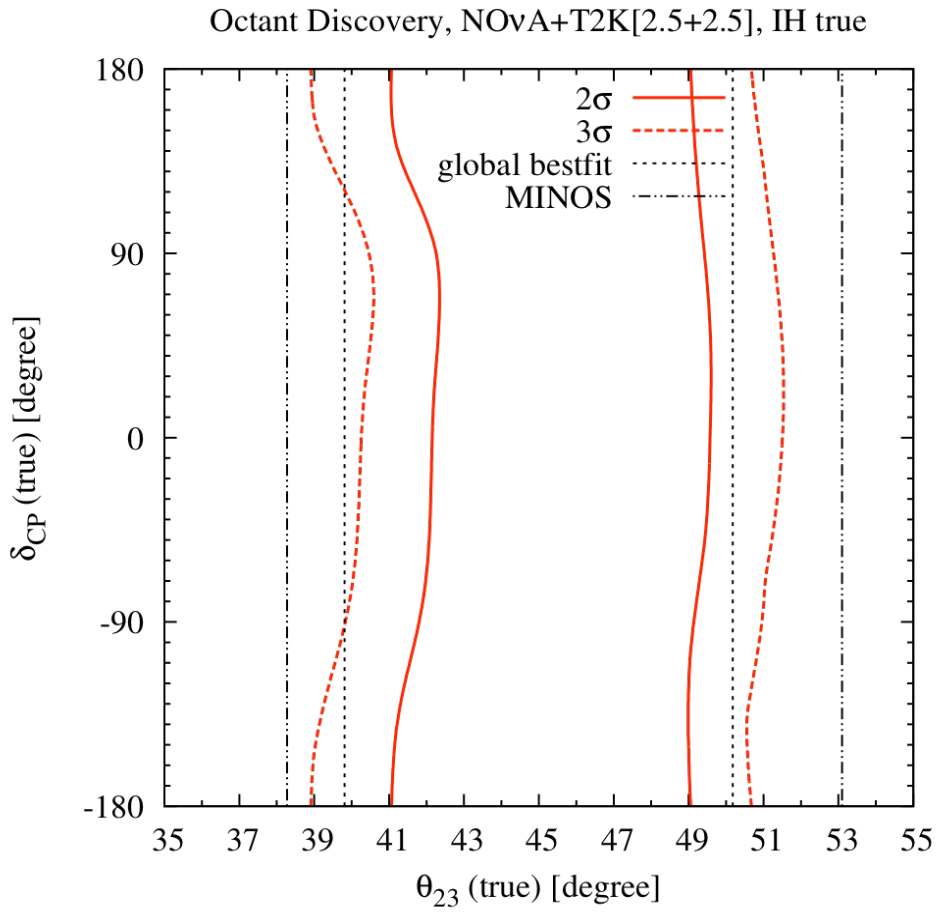
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

A 2σ resolution of the octant, for all combinations of neutrino parameters, becomes possible if we add the balanced neutrino and anti-neutrino runs from T2K (2.5 years ν + 2.5 years anti-ν) and NOνA (3 years ν + 3 years of anti-ν)

Important message: T2K must run in anti-neutrino mode in future!

Octant discovery in θ_{23} (true) – δ_{CP} (true) plane with T2K & NOνA





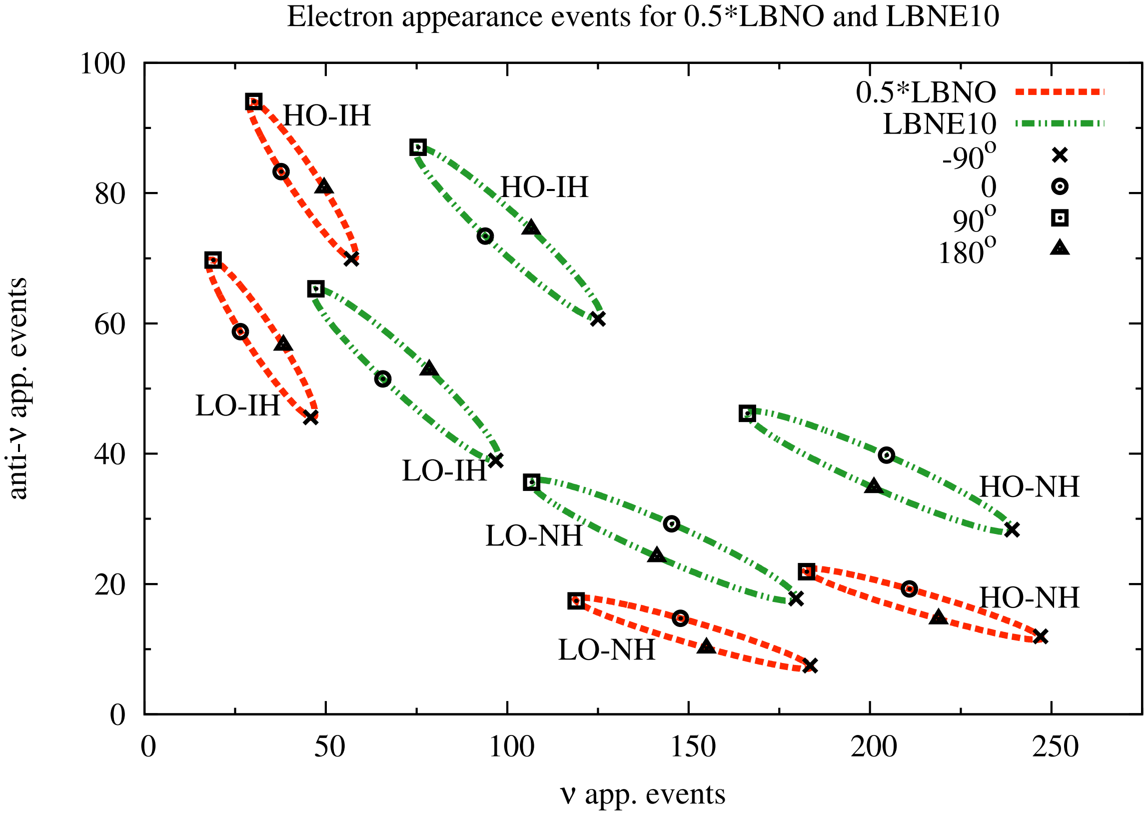
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

With Normal Hierarchy

If $\theta_{23} < 41°$ or $\theta_{23} > 50°$, we can resolve the octant issue at 2σ irrespective δ_{CP}

If $\theta_{23} < 39°$ or $\theta_{23} > 52°$, we can resolve the octant issue at 3σ irrespective δ_{CP}

Future Superbeam Expts with LAr Detector: LBNE & LBNO



<u>LBNO</u>: CERN-Pyhasalmi (2290 km)
750 kW beam power, 20 kt LArTPC

<u>0.5*LBNO</u>: reduce detector size to 10 kt

For octant, balanced ν & anti-ν data must!

<u>LBNE10</u>: FNAL-Homestake (1300 km)
708 kW beam power, 10 kt LArTPC

For LBNE10, in case of LO, hierarchy discovery is very limited!

Octant determination in LBNE10 is similar to 0.5*LBNO!

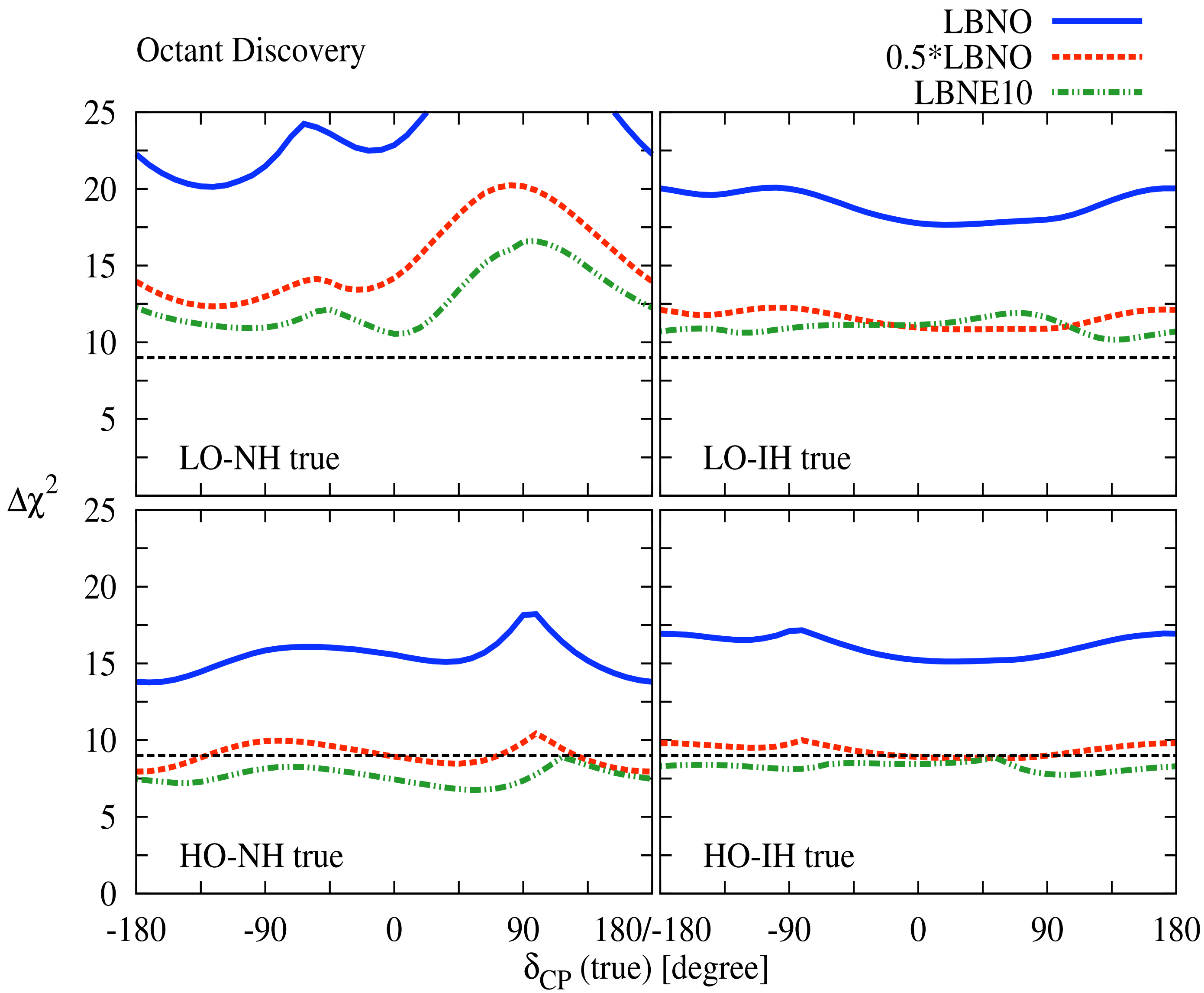
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

Wide Band Beam ➔ Higher statistics ➔ cover several L/E values ➔ kill clone solutions

LAr Detector ➔ Excellent Detection efficiency at 1st & 2nd Osc. maxima, good background rejection!

High L ➔ High E ➔ High cross-section ➔ Less uncertainties in cross-section at high E

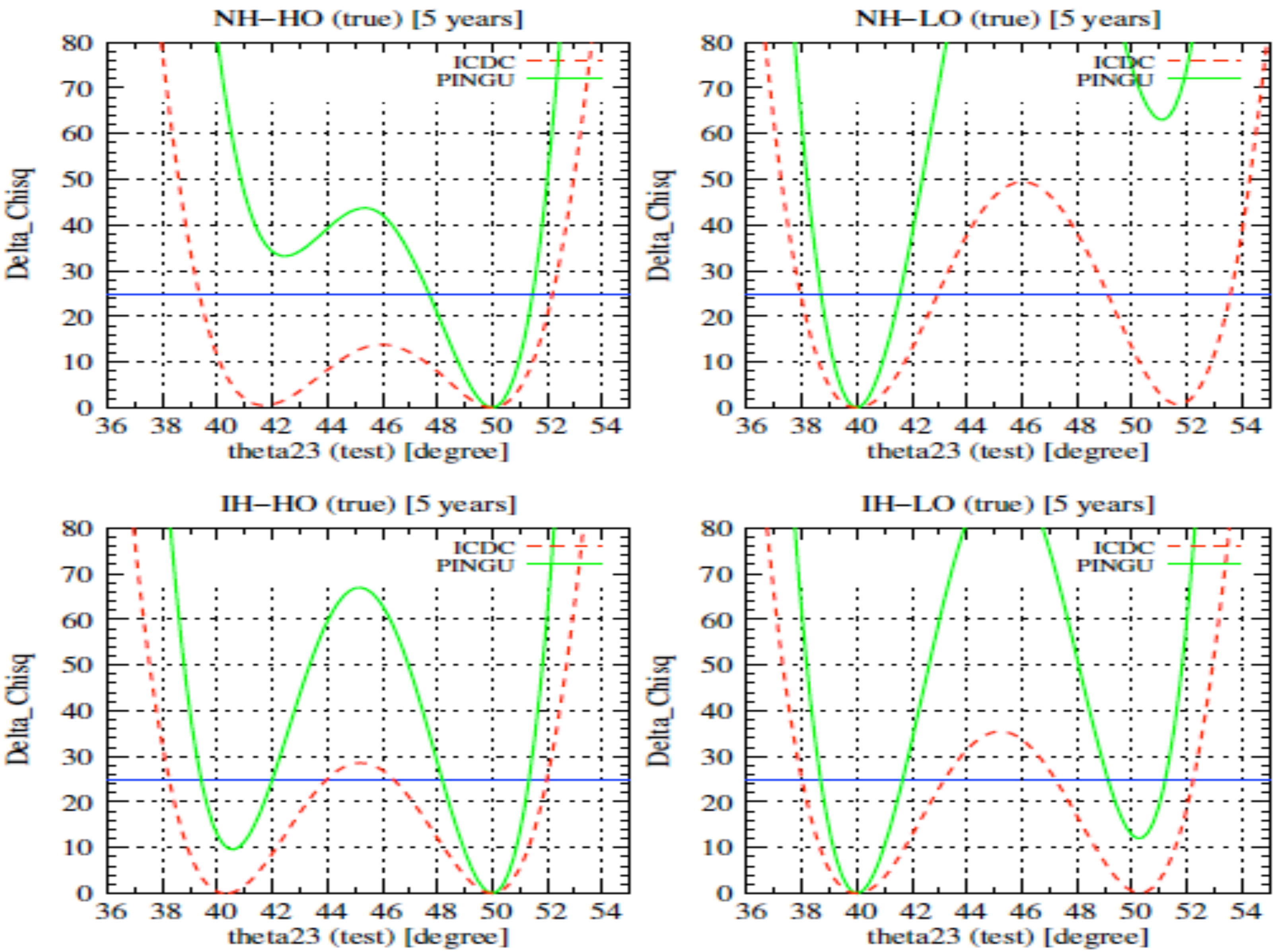
Octant Discovery with LBNE and LBNO



Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

For octant: in their first phases, 4σ discovery for LBNO and 3σ for LBNE10!

Octant Discovery with Atmospheric Neutrinos



Agarwalla, Mena, Palomares-Ruiz, work in progress
Attend the talks by S. Choubey and N.K. Mondal in this workshop

Concluding Remarks

Recent measurement of a moderately large value of θ_{13} signifies an important breakthrough in establishing the standard three flavor oscillation picture of neutrinos!

It has opened up exciting possibilities for current & future oscillation experiments!

T2K and NOνA are now poised to probe the impact of full 3 flavor effects to discover octant of θ_{23} (a first step towards CP violation discovery)!

Balanced ν and anti-ν runs from T2K & NOνA can establish the correct octant at 2σ for any combination of hierarchy and CP phase if $\sin^2\theta_{23} \leq 0.43$ or ≥ 0.58

In its first phase, LBNE10 can resolve the octant ambiguity of θ_{23} around 3σ C.L.

In its first phase, LBNO can decide the correct octant of θ_{23} around 4σ C.L.

Large value of θ_{13} allows us to explore Octant with atmospheric neutrinos! ICAL@INO experiment, IceCube Deepcore, PINGU will play a vital role!

THANK YOU FOR YOUR ATTENTION!