Neutrino oscillation experiments: Future Prospects

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Neutrino Oscillations

- Standard three-flavour oscillation framework:

$$\mathbf{U} = \mathbf{U_{23}} \times \mathbf{U_{13,\delta}} \times \mathbf{U_{12}}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric + LBL **Reactor + LBL** **Solar + reactor**

Δm^2_{31} Δm^2_{21}

- Three mixing angles, two independent mass-squared differences, one CP-violating phase

Known measurements

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

1409.5439: Gonzalez-Garcia, Maltoni, Schwetz

See also:
1405.7540: Forero, Tortola, Valle
1312.2878: Capozzi et al.

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LO or HO?

δ_{CP}=?

NH or IH?

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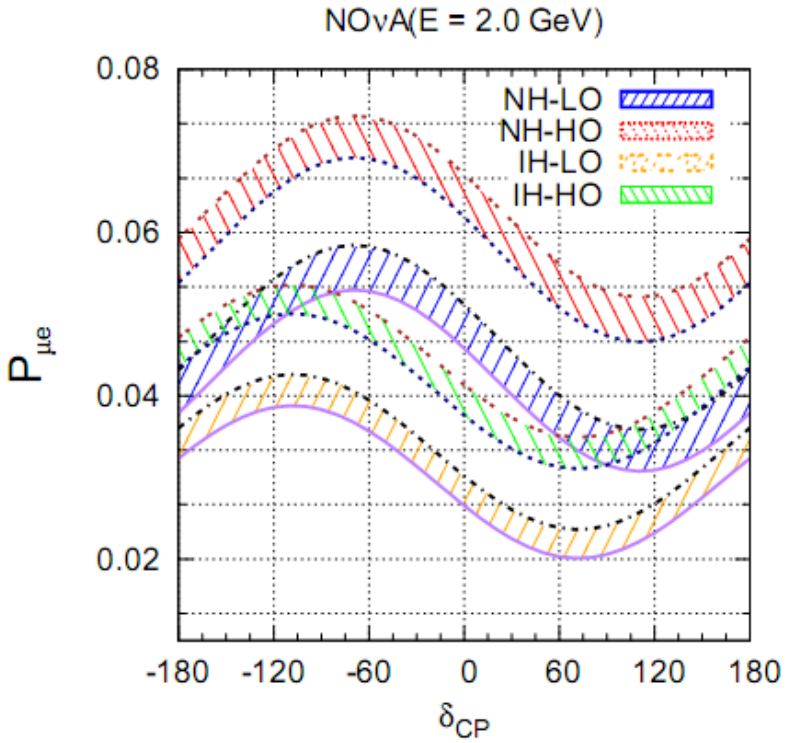
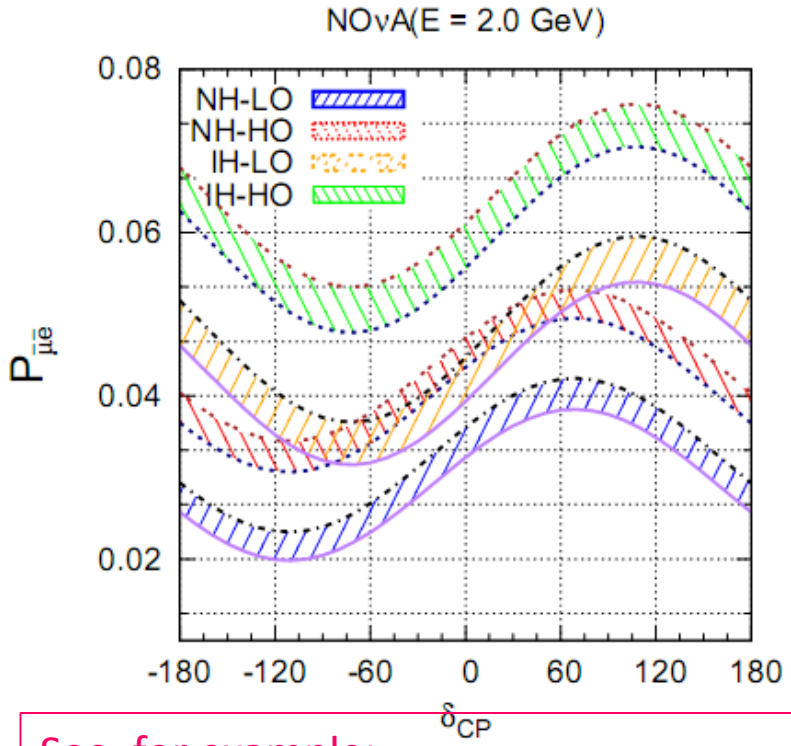
Why do we not know what we don't know?

- Parameter degeneracies:

  $P(NH, \delta_{CP}) = P(IH, \delta_{CP}')$; $P(\theta_{23}) = P(90\text{-}\theta_{23})$





See, for example:
1504.06283: Ghosh, Ghoshal, Goswami, Nath, SR
1406.2551: Coloma, Minakata, Parke

Parameter degeneracies

- Certain combinations of hierarchy and δ_{CP} suffer from degeneracies

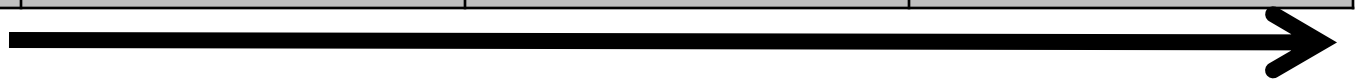
	NH	IH
Upper half-plane (UHP): $\delta_{CP} = (0, 180^o)$	Degeneracy (Unfavourable)	No degeneracy (Favourable)
Lower half-plane (LHP): $\delta_{CP} = (-180^o, 0)$	No degeneracy (Favourable)	Degeneracy (Unfavourable)

- For octant determination, the favourable and unfavourable combinations are different for neutrinos and antineutrinos

1301.2574: Agarwalla, Prakash, UmaSankar

A chronology of experiments

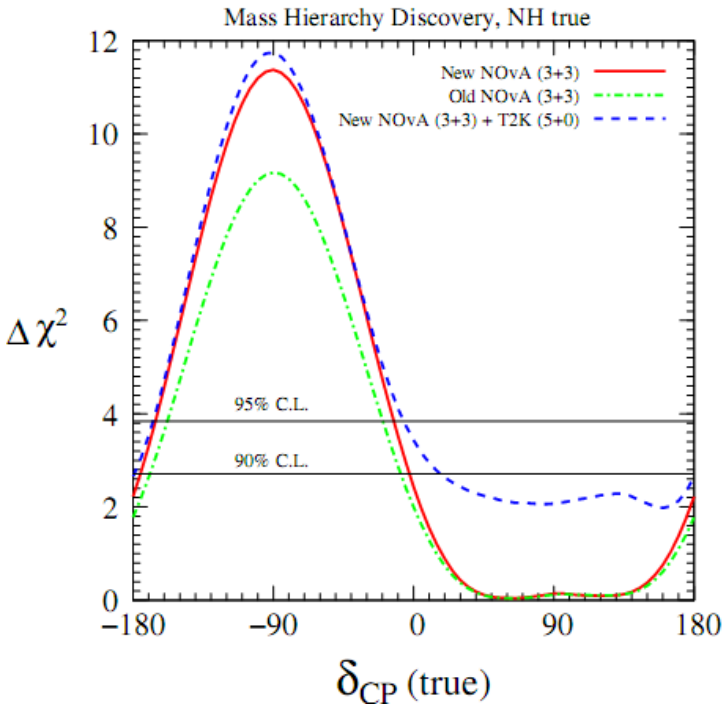
	Current expts	Upcoming (near future) expts	Future expts
Beam-based	T2K, NOvA, MINOS+		DUNE/LBNF/LBNE, T2HK, ESSnuSB
Atmospheric	SK, MINOS+	ICAL@INO	HK, PINGU
Reactor	D-Chooz, DayaBay, RENO	JUNO, RENO50	
Extra-terrestrial	Antares, IceCube		KM3NET



time

Far future:
Neutrino factory?
Beta-beam?

Current experiments



A1: Current expts: Hierarchy

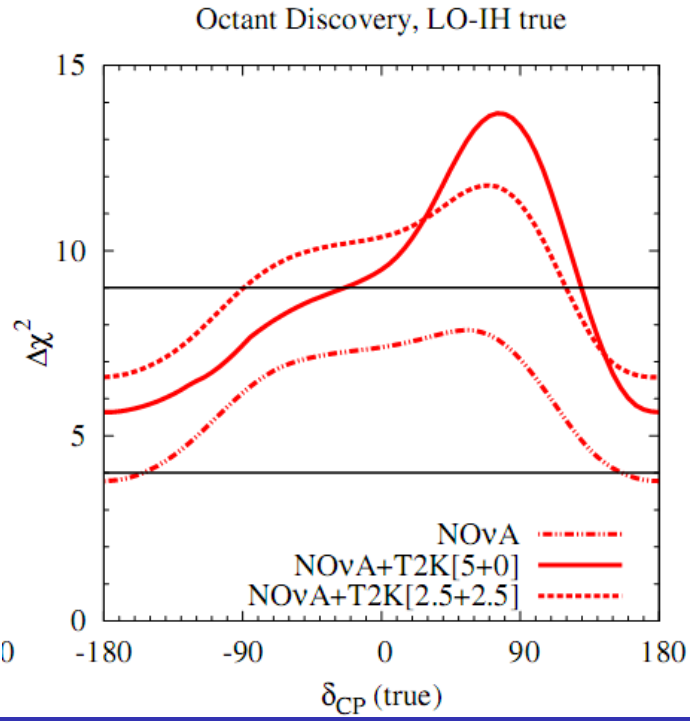
Hierarchy: For favourable combinations of parameters, NOvA and T2K can determine the hierarchy very well

1208.3644: Agarwalla, Prakash, SR, UmaSankar

A2: Current expts: Octant

Octant: Depending on the true parameters, NOvA + T2K may determine the octant

1301.2574: Agarwalla, Prakash, UmaSankar



Current experiments

A3: Current expts: CP

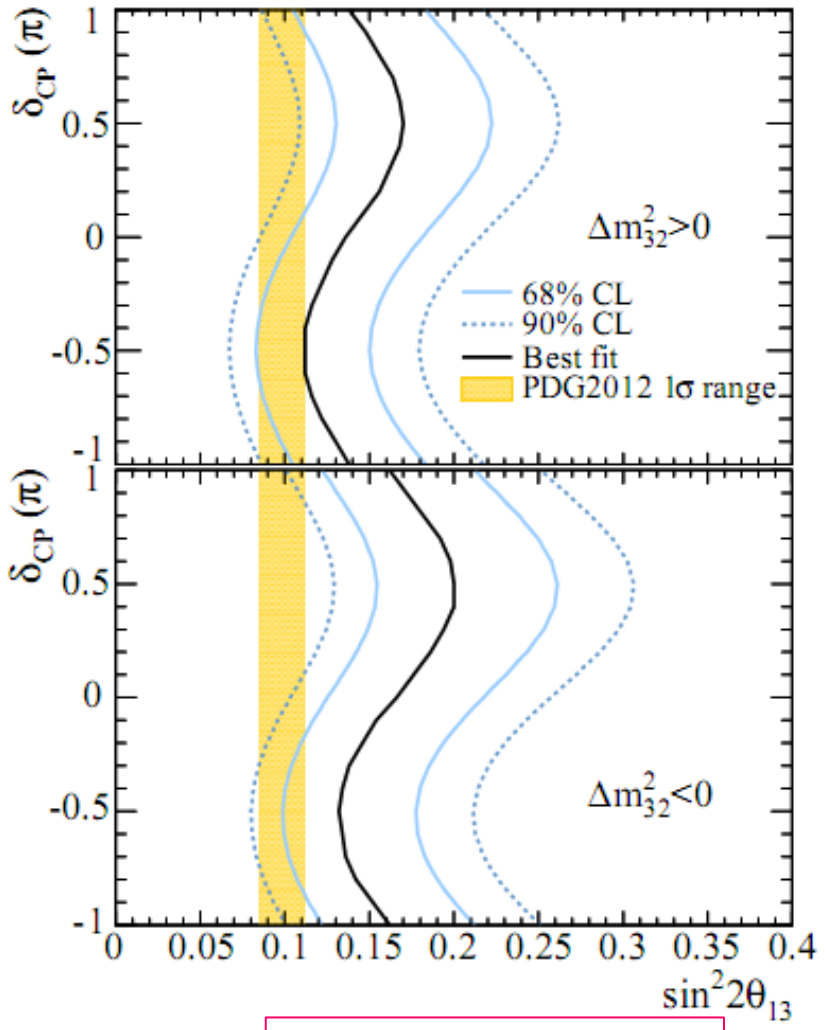
δ_{CP} : Does the existing T2K data already give a hint for δ_{CP} = -90?

Can we use this hint to draw conclusions about the hierarchy and octant?

	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	0.179	0.078	0.257
$\sin^2\theta_{23} > 0.5$	0.505	0.238	0.743
Sum	0.684	0.316	1.0

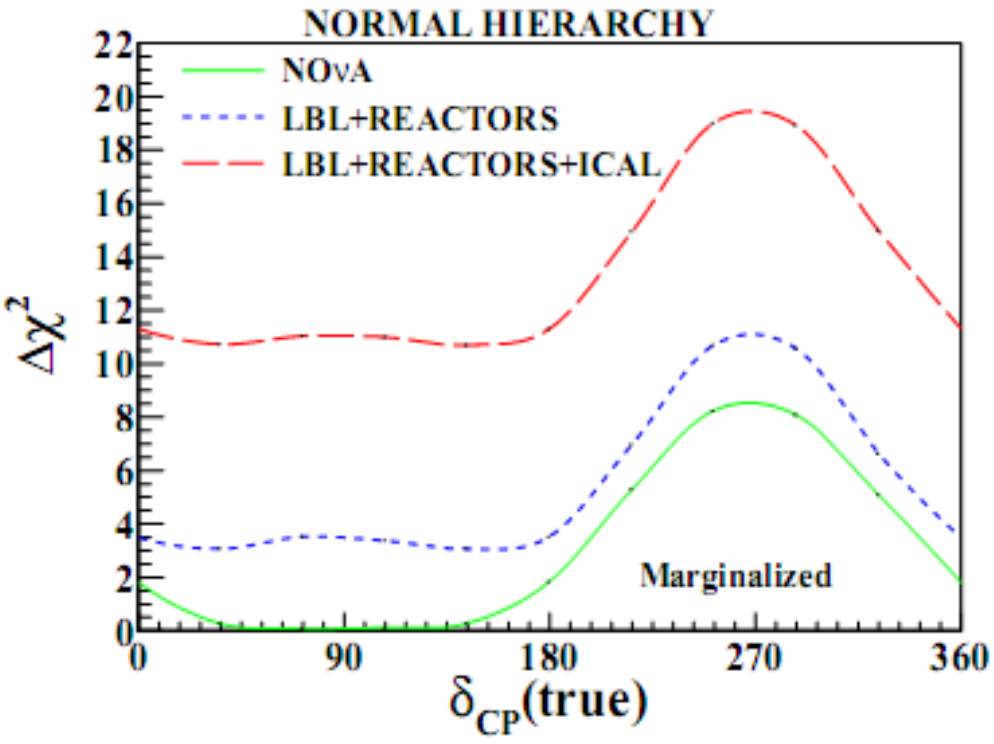
1502.01550: Abe et al.

See also:
1409.5046: Ghosh, Goswami, SR



1311.4750: Abe et al.

Upcoming experiments



B1: Upcoming expts: Hierarchy

NOvA + T2K + reactors + ICAL can improve the hierarchy sensitivity even for unfavourable combinations of parameters

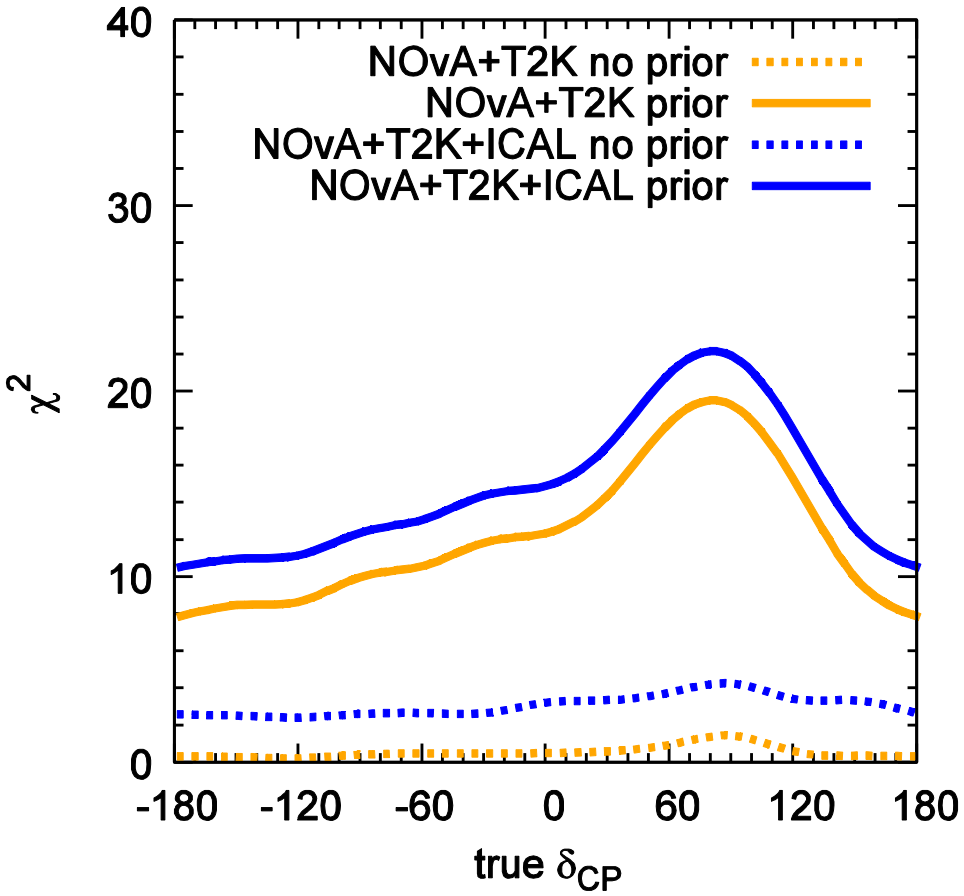
1212.1305: Choubey, Ghosh, Thakore

See also:
1203.3388: Blennow, Schwetz

Reactor experiments like JUNO are also sensitive to the hierarchy through spectral effects

1303.6733: Li, Cao, Wang, Zhan

Upcoming experiments



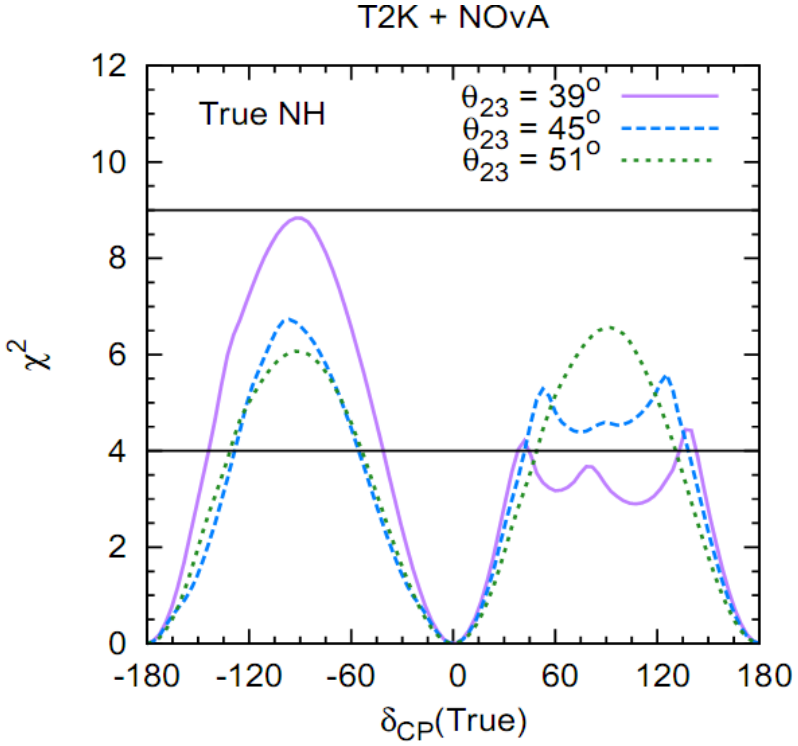
B2: Upcoming expts: Octant

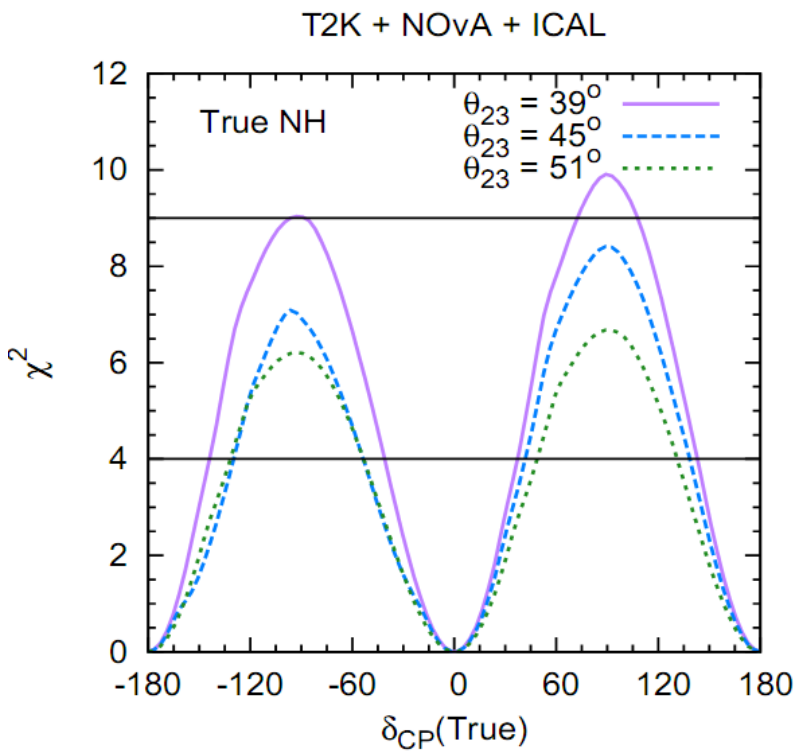
Adding information from reactors + ICAL can improve the octant sensitivity dramatically

Note the role of the reactors (represented by priors on θ_{13}): synergy between long-baseline and reactor experiments

Upcoming experiments

B3: Upcoming expts: CP



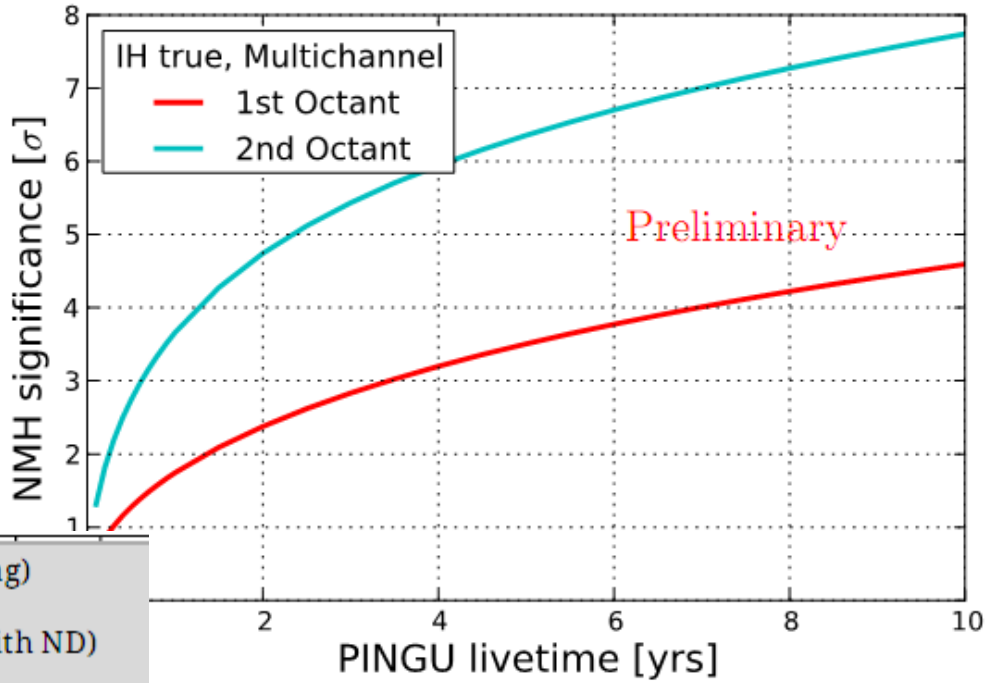


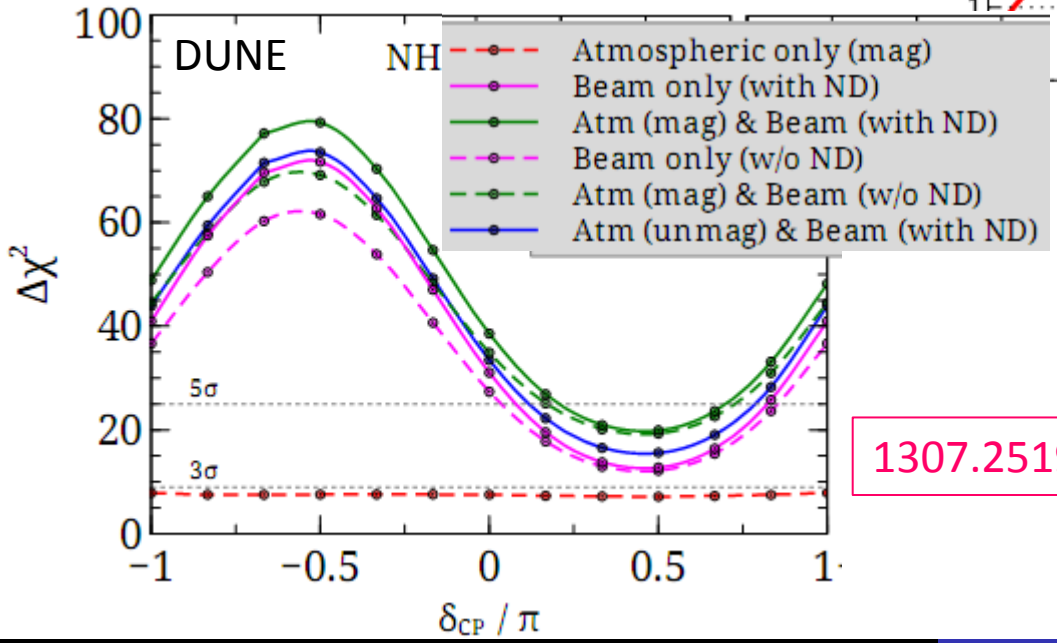
ICAL does not have any intrinsic CP sensitivity, but it is sensitive to the hierarchy. Thus, it helps the discovery of CP violation indirectly, by breaking the hierarchy- δ_{CP} degeneracy. 1306.2500: Ghosh, Ghoshal, Goswami, SR

Future experiments

C1: Future expts: Hierarchy

1401.2046: Aartsen et al.



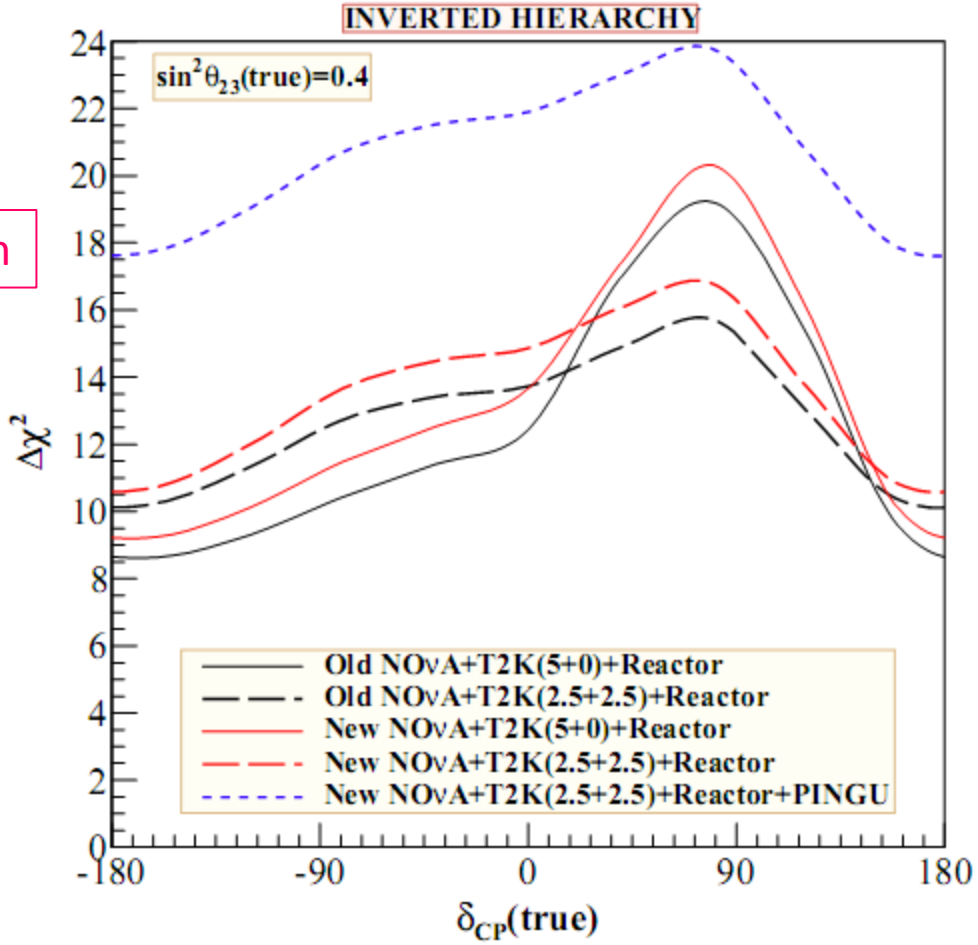


1307.2519: Barger et al.

Future experiments

C2: Future expts: Octant

1309.5760: Choubey, Ghosh



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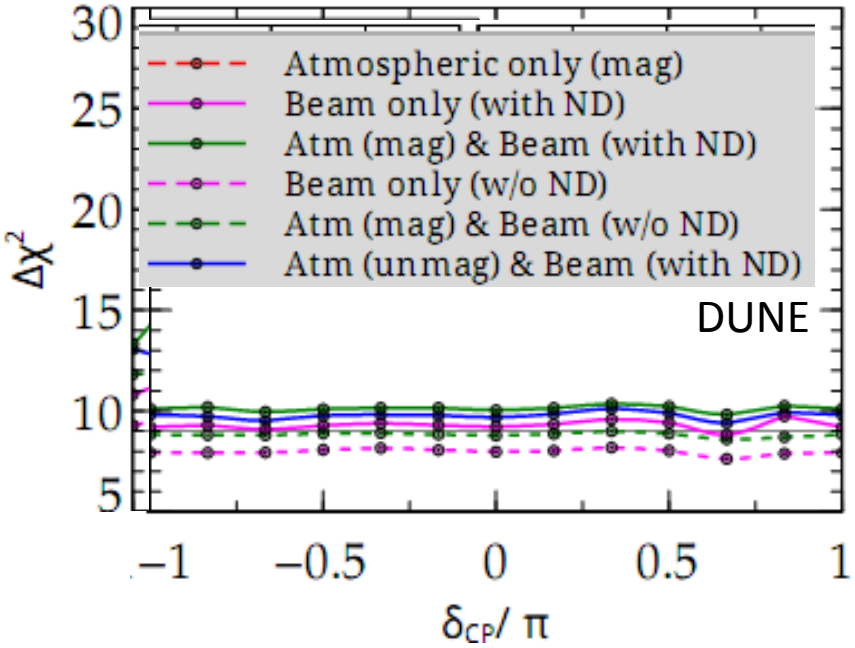
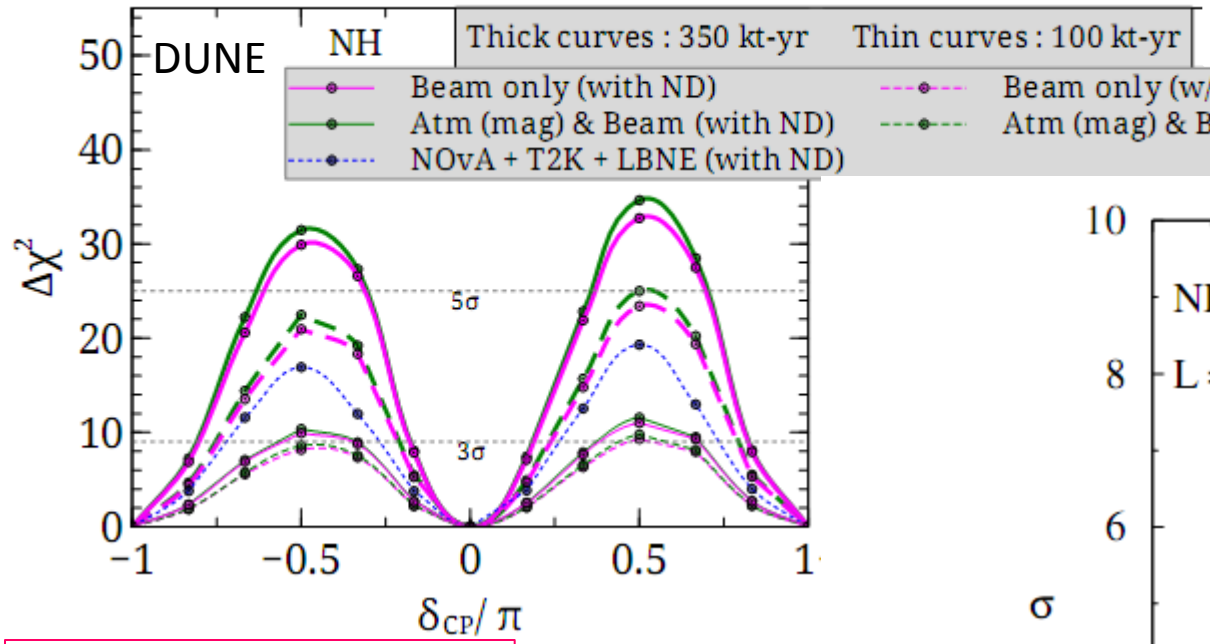


Caveat: Octant sensitivity depends on the value of θ_{23} in nature

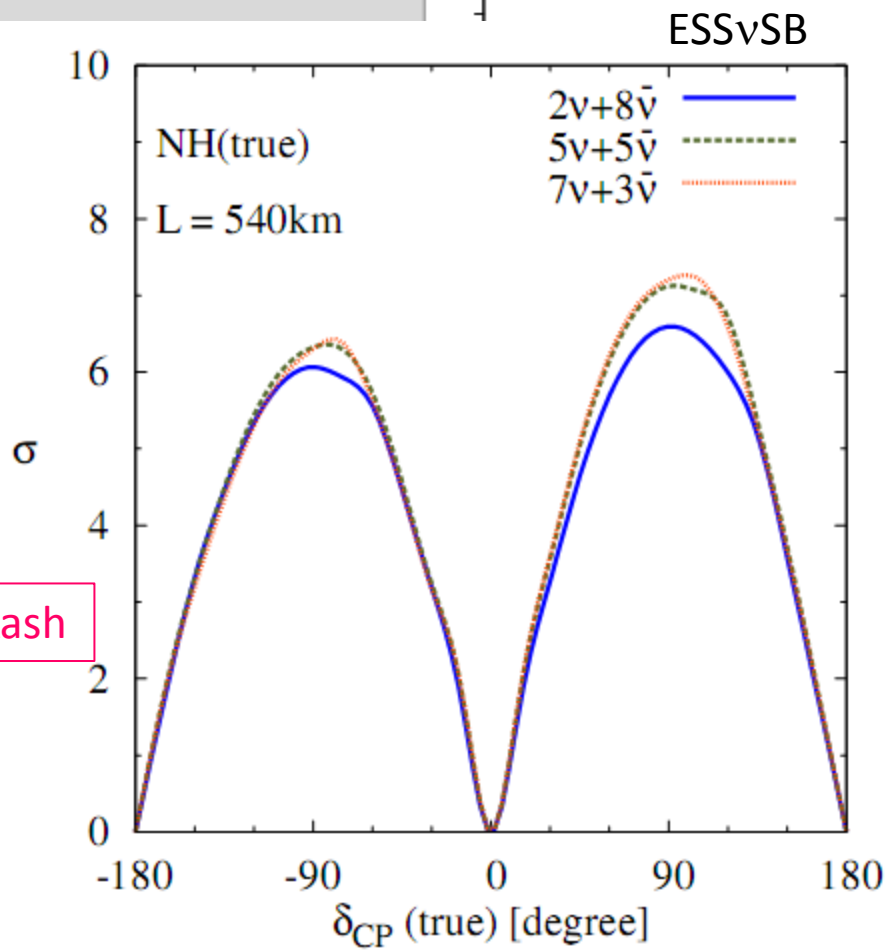
Future experiments

C3: Future expts: CP



1307.2519: Barger et al.

1406.2219: Agarwalla, Choubey, Prakash



Also: DAR experiments

Summary

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- If nature has chosen favourable combinations of the parameters, then the current experiments will be able to determine the hierarchy, octant and maybe the CP phase.
- If the combinations are unfavourable, the upcoming experiments like ICAL will conclusively determine the hierarchy, and possibly the octant (depending on θ_{23})
- The discovery of CP violation and a precise measurement of the phase may have to wait until the next generation of experiments like DUNE and ESSνSB.

Some questions for the future

- Is the standard three-flavour oscillation scenario enough? Steriles? NSIs?
- How precise is precise? Look to models for answers?
- Are we motivated enough to invest in new and technologically challenging facilities like neutrino factories and beta beams?
- Statistics: Frequentist vs Bayesian. How should we interpret our chi-squared?
- What other physics can we do with neutrino oscillations? Supernovae, UHE physics, tomography?