Mass Hierarchy determination with current/upcoming Neutrino Experiments

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Present Status of Oscillation Parameters

Known Parameters

Parameters	Best Fit	3σ range
Δ_{21}	$7.58 \times 10^{-5}\text{eV}^2$	$(6.99 - 8.18) \times 10^{-5}\text{eV}^2$
$\sin^2\theta_{12}$	0.312	(0.265 – 0.364)
$\sin^2 2\theta_{13}$	0.1	(0.02 – 0.19)
$\sin^2\theta_{23}$	0.42	(0.34 – 0.64)
$\lvert\Delta_{31}\rvert$	$2.35 \times 10^{-3}\text{eV}^2$	$(2.06 - 2.67) \times 10^{-3}\text{eV}^2$

[G.L.Fogli, et.al, arXiv:hep-ph/1106.6028v1] (with new Reactor Neutrino Fluxes)

- Recent T2K results : $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for normal (inverted) hierarchy at 90% C.L. for $\delta_{CP} = 0$
- Recent MINOS results : $0.0(0.0) < \sin^2 2\theta_{13} < 0.12(0.19)$ for normal (inverted) hierarchy at 90% C.L. for $\delta_{CP} = 0$
- CHOOZ upper bound : $\sin^2 2\theta_{13} < 0.19$ at 90% C.L.

Present Status of Oscillation Parameters

Unknown Parameters

CPV phase

Absolutely no knowledge about the value of CP-violating phase δ_{CP}

Mass Hierarchy

The sign of Δ_{31} is not known i.e. $m_1 < m_2 \ll m_3$ (Normal Hierarchy) or $m_3 \ll m_1 < m_2$ (Inverted Hierarchy)

Predictions with upcoming Reactor Neutrino Experiments

The Reactor Neutrino Experiments will be able to measure a non-zero θ_{13} at 90% CL if

- Daya Bay : $\sin^2 2\theta_{13} > 0.0066$
- RENO : $\sin^2 2\theta_{13} > 0.018$
- Double CHOOZ : $\sin^2 2\theta_{13} > 0.033$

[Huber et. al. arXiv:hep-ph /0907.1896v1]

The precision of these measurements will be $\boxed{\sigma\left(\sin^2 2\theta_{13}\right) = \pm 0.01}$

$P\left(\nu_\mu \rightarrow \nu_e\right)$: Matter effects and Degeneracies

$P\left(\nu_\mu \rightarrow \nu_e\right)$

$$\sin^2 2\theta_{13} \sin^2\theta_{23} \left[\frac{\sin^2\hat{\Delta}\left(1-\hat{A}\right)}{\left(1-\hat{A}\right)^2}\right]$$

$$+\alpha \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\hat{\Delta} \left[\frac{\sin\hat{\Delta}\hat{A}}{\hat{A}}\right]\left[\frac{\sin\hat{\Delta}\left(1-\hat{A}\right)}{1-\hat{A}}\right]$$

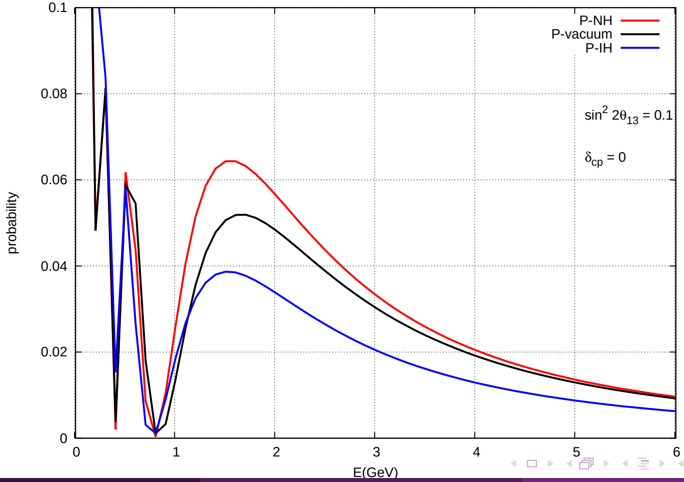
$$+\alpha \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\hat{\Delta} \left[\frac{\sin\hat{\Delta}\hat{A}}{\hat{A}}\right]\left[\frac{\sin\hat{\Delta}\left(1-\hat{A}\right)}{1-\hat{A}}\right]$$

$$+\alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{13} \cos^2\theta_{23} \left[\frac{\sin^2\hat{\Delta}\hat{A}}{\hat{A}^2}\right]$$

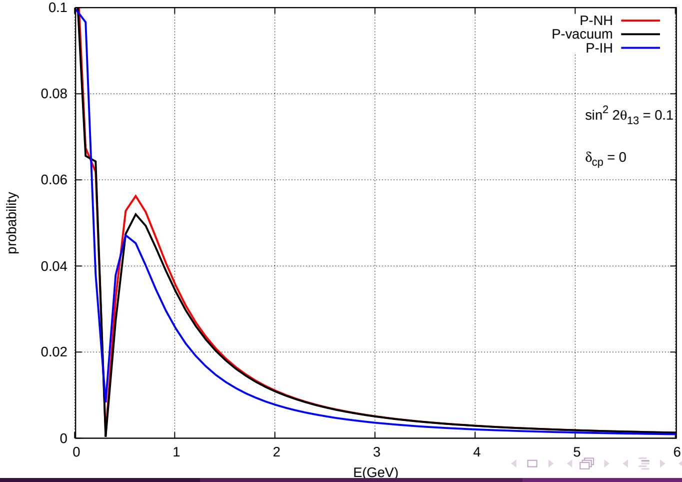
- $\hat{\Delta} = \frac{\Delta_{31} L}{4E}$; $\hat{A} = \frac{A}{\Delta_{31}}$; $\alpha = \frac{\Delta_{21}}{\Delta_{31}}$

Matter Effects : $P(\nu_\mu \to \nu_e)$

Matter Effects in $P(\nu_\mu \to \nu_e)$ for NOνA

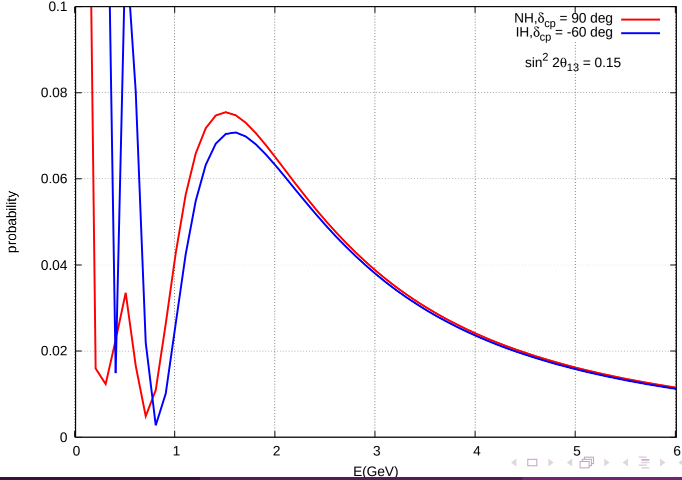


Matter Effects in $P(\nu_\mu \to \nu_e)$ for T2K



Degeneracies : $P(\nu_\mu \to \nu_e)$

Hierarchy - δ_{CP} degeneracy in $P(\nu_\mu \to \nu_e)$ for NOνA



Degeneracies : $P\left(\nu_\mu \rightarrow \nu_e\right)$

Possible to resolve this with data from two different Long Baseline experiments, such as T2K and NOνA.

NuMI Off-Axis ν_e Appearance Experiment

- Beam : NuMI beam source at Fermilab, 0.7 MW
- Detector : TASD, 15 kton
- Baseline : 812 km
- Signal : $\nu_e/\bar{\nu}_e$ appearance signal
- Exposure : 6.0×10^{20} POT/yr for both running modes (assuming $\sim$ 70 GeV protons)

Tokai 2 Kamioka

- Beam : J-PARC accelerator, 0.77 MW
- Detector : Super Kamiokande Water Cerenkov, 22.5 kton
- Baseline : 295 km
- Signal : $\nu_e/\bar{\nu}_e$ appearance signal
- Exposure : 10×10^{20} POT/yr for both running modes (assuming $\sim$ 50 GeV protons)

Simulation Details

- We use the software GLoBES for our analysis. [Huber et. al. arXiv:hep-ph /0407333v1]
- The runtime for NOνA is 6 years of ν running and 3 years of $\bar{\nu}$ running for all the plots shown.
- The runtime for T2K is 3 years of ν running and 4 years of $\bar{\nu}$ running for all the plots shown.
- Signal : Only electron appearance events considered as signal.
- Backgrounds : mis-identified muons, NC events, events due to beam-ν_e and beam-$\bar{\nu}_e$ contamination.

Simulation Details

- Marginalisation done.
- Priors in θ_{13}, θ_{23} and Δ_{31} have been added. $\sigma\left(\sin^2 2\theta_{13}\right) = 0.01$, $\sigma\left(\sin^2 2\theta_{23}\right) = 0.02$ and $\sigma\left(\Delta_{31}\right) = 0.03 \times \left(\Delta_{31}\right)$

Including Reactor Neutrino Experiments

A prior of $\sigma\left(\sin^2 2\theta_{13}\right) = 0.01$ effectively takes into account the data due to Reactor Neutrinos Experiments

Simulation Details

We have taken care in defining Δ_{31}^{NH} and Δ_{31}^{IH} in terms of the measured quantity Δ_{atmos}.

$$\Delta_{31} = \Delta_{atmos} + \left(\cos^2\theta_{12} - \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\right)\Delta_{21}$$

- $\Delta_{atmos} = \pm 2.4 \times 10^{-3}\mathrm{eV}^2$; + : NH, - : IH

[Nunokawa et.al. arXiv:hep-ph/0503283v1]

Hierarchy Exclusion plots

- These plots show the ability of a given experiment to exclude the wrong hierarchy from the right one.
- Marginalization done over θ_{13}, θ_{23} and Δ_{31} in the 3σ range.
- Marginalization over the entire δ_{CP} range unless mentioned.

Simulation Details

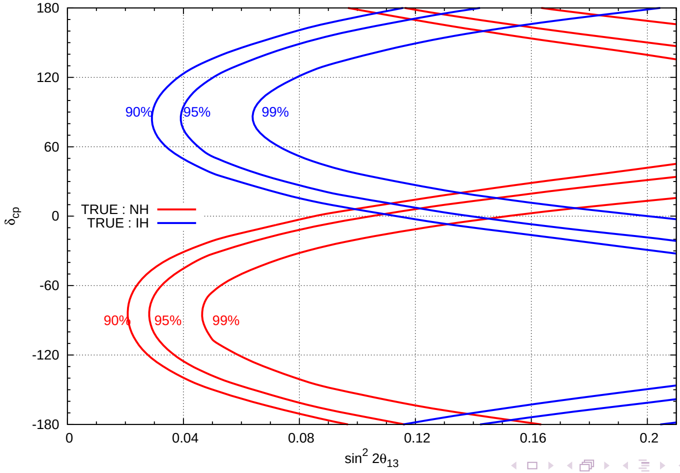
- True and Test $\sin^2 2\theta_{13}$ range taken to be 0.03 (T2K lower limit) to 0.22 ($\sim$ CHOOZ upper limit)
- The axes represent the TRUE parameters

Error Plots

- Plots show the error in $\sin^2 2\theta_{13}$ and δ_{CP} measurements.
- For 2 true points : $\left(\sin^2 2\theta_{13}, \delta_{CP}\right)$ = (0.05,-90°) and (0.15,90°)
- Marginalization done over θ_{23} and Δ_{31} in the 3σ range.
- Test $\sin^2 2\theta_{13}$ range taken to be 0.03 (T2K lower limit) to 0.22 ($\sim$ CHOOZ upper limit)
- The axes represent the TEST parameters

NOνA's limitations in hierarchy determination

Hierarchy Exclusion Plots for NOνA



NOνA's limitations in hierarchy determination

It can be seen from this plot that NOνA performs very well only for a particular range of δ_{CP} depending on the true mass hierarchy.

- For NH, this range is $\boxed{-120^\circ \text{ to } -60^\circ}$
- For IH, this range is $\boxed{60^\circ \text{ to } 120^\circ}$

Good performance in the above mentioned ranges can be understood by studying the beahviour of the term $\frac{\sin^2 \hat{\Delta}(1-\hat{A})}{(1-\hat{A})^2}$ corresponding to the two hierarchies for $\left(\frac{L}{E}\right)$ of NOνA.

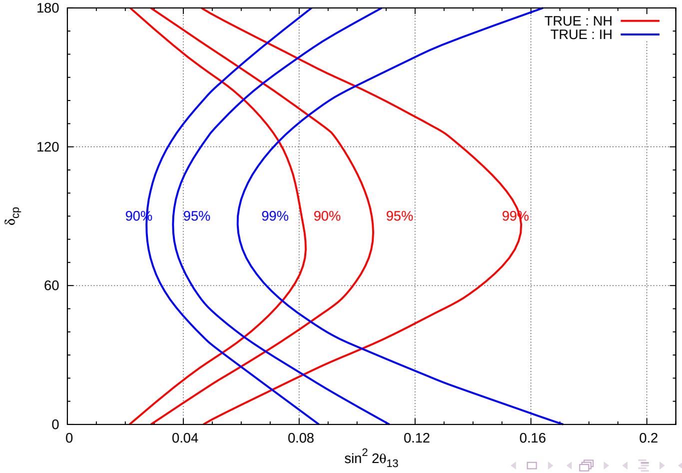
The reason for poor performance otherwise is because of hierarchy-δ_{CP} ambiguity (explained later).

What if δ_{CP}-half-plane is known?

- Let us assume for a moment that the half-plane of δ_{CP} is known.
- That is, when the true δ_{CP} is in the upper half plane(UHP) of $[0, 180]$, we marginalise over test δ_{CP} in UHP only. And when the true δ_{CP} is in the lower half plane(LHP) of $[-180, 0]$, we marginalise over test δ_{CP} in LHP only.
- The following hierarchy exclusion plots for NOνA show this half-plane marginalisation.

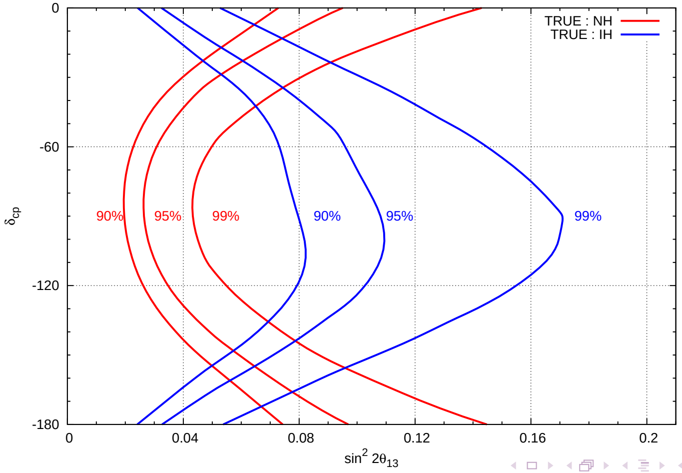
What if δ_{CP}-half-plane is known?

Hierarchy Exclusion Plots for NOνA : UHP



What if δ_{CP}-half-plane is known?

Hierarchy Exclusion Plots for NOνA : LHP



What if δ_{CP}-half-plane is known?

- For the case when NH is the true hierarchy, NOνA performs very well even in the unfavourable $[0^\circ, 180^\circ]$ UHP of δ_{CP}
- Similar improvements when IH is the true hierarchy, in the unfavourable $[-180^\circ, 0^\circ]$ LHP of δ_{CP}

Lesson

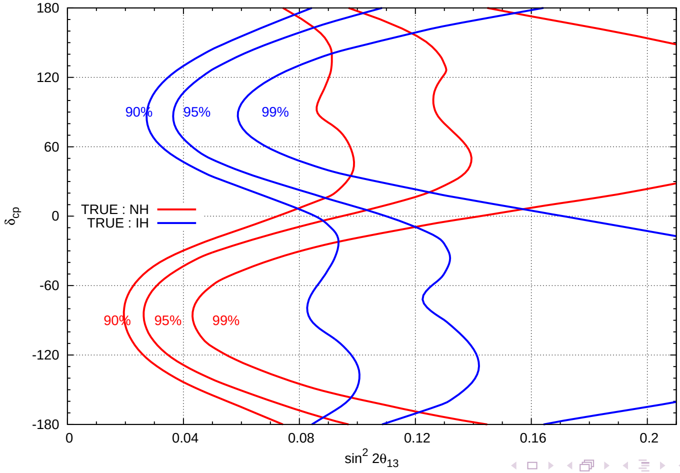
It is the lack of information about δ_{CP} which leads to poor sensitivities in the unfavourable half-planes of δ_{CP}.

How and Why does T2K data help?

We now explore the mass hierarchy potential of the combined data from NOνA and T2K.

How and Why does T2K data help?

Hierarchy Exclusion Plots with NOVA and T2K



How and Why does T2K data help?

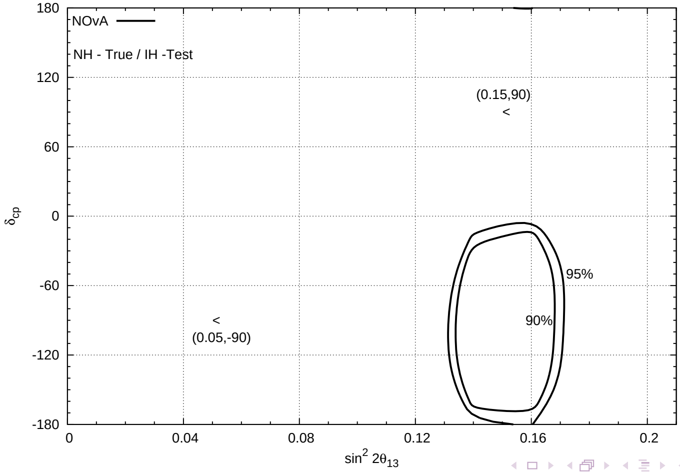
At 90% C.L., T2K data boosts significantly NOνA's ability for determining mass hierarchy

- For NH as the true hierarchy, in the UHP
- For IH, in the LHP

To understand this behavior let's look at the Error Plots due to individual runs of NOνA and T2K with NH as the true hierarchy and IH as the test hierarchy for the true points : $\sin^2 2\theta_{13} = 0.05$, $\delta_{CP} = -90^\circ$ and $\sin^2 2\theta_{13} = 0.15$, $\delta_{CP} = 90^\circ$

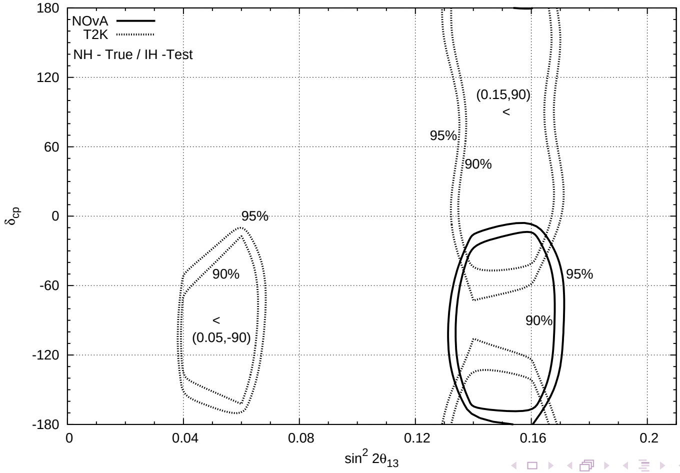
How and Why does T2K data help?

Error Plots in the $\theta_{13} - \delta_{CP}$ plane



How and Why does T2K data help?

Error Plots in the $\theta_{13} - \delta_{CP}$ plane



How and Why does T2K data help?

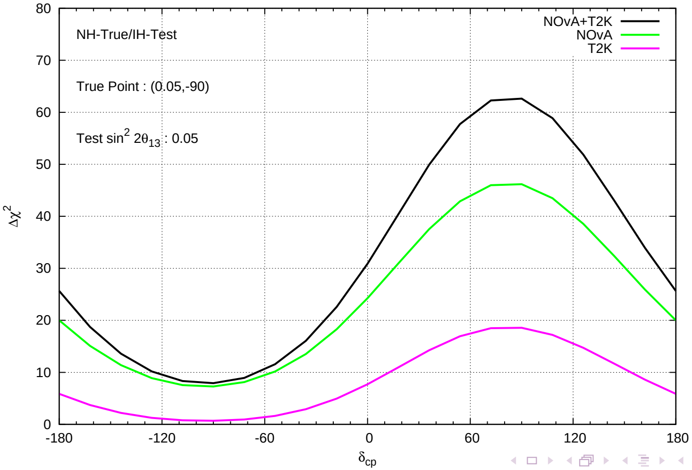
- For the favourable LHP, NOνA gives better results that T2K and hence performs very well by itself [true point : (0.05,-90°)].
- For the unfavourable UHP, NOνA gives wrong results [true point : (0.15,90°) outside 90% and 95% contours].
- The reason is that for True(NH,90°), Test(IH,-90°) gives the degenerate solution. This is the opposite sign δ_{CP} faking matter effects.
- Since for the T2K baseline, matter effects are much less pronounced, this effect does not happen and it gives the correct solution.

T2K does this :

T2K data provides the necessary additional χ^2 to move away form the wrong hierarchy - wrong δ_{CP} point. The following graphs show these effects.

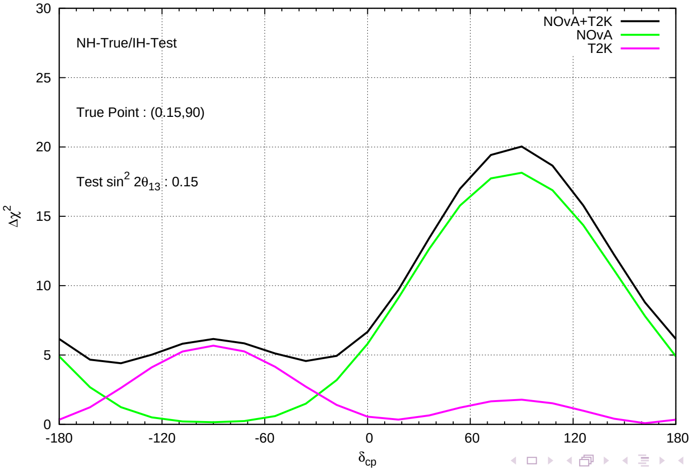
How and Why does T2K data help?

$\Delta\chi^2$ when true point is in favourable half-plane for NH



How and Why does T2K data help?

$\Delta\chi^2$ when true point is in unfavourable half-plane for NH

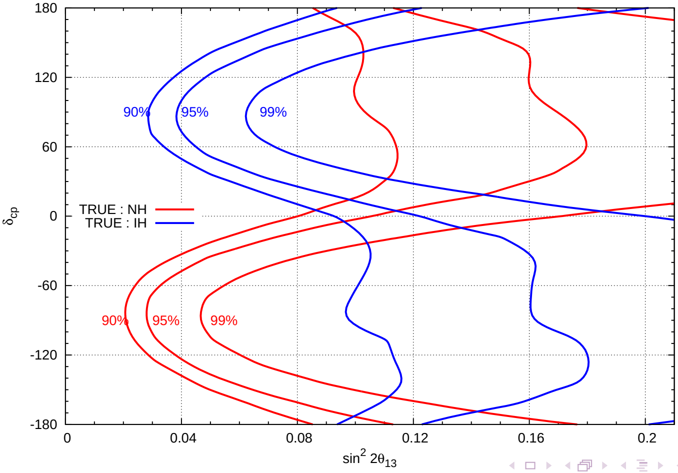


Results with NOνA and T2K combined

We now include systematics uncertainties while doing minimization. These uncertainties have been taken to be 5% on both, signal and backgrounds.

Results with NOνA and T2K combined

Hierarchy Exclusion Plots with Systematics



Results with NOνA and T2K combined

Results (including Systematics) with present statistics

The combined setup of the LBL - NOνA and T2K and the Reactor Neutrino Experiments will be able to exclude the Wrong Hierarchy from the Right one @ 90%C.L. for all δ_{CP} provided $\boxed{\sin^2 2\theta_{13} > 0.115}$

Results with NOνA and T2K combined

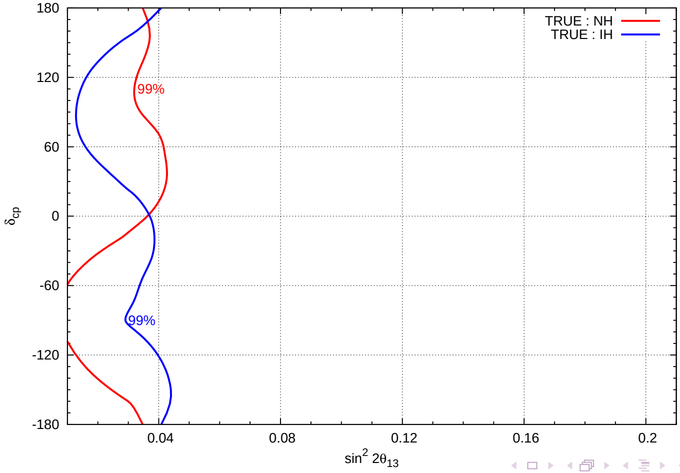
90% C.L. gives just indications.

What sensitivities can be achieved if the statistics of each of these 2 experiments are increased to 10 times the present statistics ?

That is equivalent to increasing Beam Power to 3 times and increasing Detector size to 3.33 times.

Results with NOνA and T2K combined

Hierarchy Exclusion Plots with Systematics



Results with NOνA and T2K combined

Results (including Systematics) with increased statistics

The combined setup will be able to exclude the Wrong Hierarchy from the Right one @ 99%C.L. for all δ_{CP} provided $\boxed{\sin^2 2\theta_{13} > 0.045}$


Thanks

Backup slides

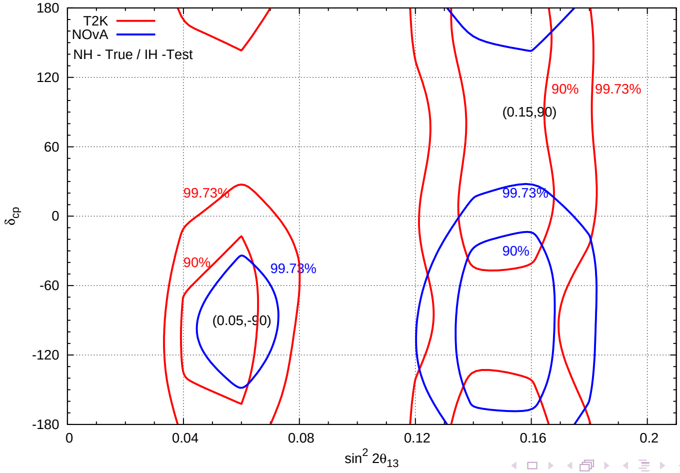
$$\sin^2 2\theta_{13} \sin^2 \theta_{23} \left[\frac{\sin^2 \hat{\Delta} \left(1 - \hat{A}\right)}{\left(1 - \hat{A}\right)^2} \right]$$

$$+\alpha \cos\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\hat{\Delta} \left[\frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \right] \left[\frac{\sin \hat{\Delta} \left(1 - \hat{A}\right)}{1 - \hat{A}} \right]$$

$$+\alpha \sin\delta \cos\theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin\hat{\Delta} \left[\frac{\sin \hat{\Delta}\hat{A}}{\hat{A}} \right] \left[\frac{\sin \hat{\Delta} \left(1 - \hat{A}\right)}{1 - \hat{A}} \right]$$

$$+\alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{13} \cos^2 \theta_{23} \left[\frac{\sin^2 \hat{\Delta}\hat{A}}{\hat{A}^2} \right]$$

Error Plots in the $\theta_{13} - \delta_{CP}$ plane



Backup slides

[Parke et.al. arXiv:hep-ph/0503283v1]

$$\Delta_{31}{}^{eff} = \sin^2\theta_{12}\Delta_{31} + \cos^2\theta_{12}\Delta_{32} + \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta_{21}$$