Getting the best out of T2K and NOνA

(arXiv: hep-ph/1201.6485v2)

Suprabh Prakash

Department of Physics
Indian Institute of Technology Bombay
Mumbai, India

July 5, 2012

$P_{\mu e}$: algebraic expression

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

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

where

- $\hat{\Delta} = \Delta_{31} L/4E$
- $\hat{A} = A/\Delta_{31}$

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

Results from Reactor Neutrino Experiments

Updated results from Reactor Neutrino Experiments (reported at Neutrino 2012):

- Daya Bay: $\boxed{\sin^2 2\theta_{13} = 0.089 \pm 0.011(stat) \pm 0.005(syst)}$, 7.7σ for non-zero θ_{13}
- RENO: $\boxed{\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat) \pm 0.019(syst)}$, 4.9σ for non-zero θ_{13}
- Double CHOOZ: $\boxed{\sin^2 2\theta_{13} = 0.109 \pm 0.030(stat) \pm 0.025(syst)}$, 3.1σ for non-zero θ_{13}

Global $\sin^2 2\theta_{13}$ best-fit: $\boxed{0.095}$ [Fogli et.al, arXiv:hep-ph/1205.5254v3]

Best final precision on $\sin^2 2\theta_{13}$: $\boxed{\text{Daya Bay: } \sim 5\%}$

$P_{\mu e}$: degeneracies

$P_{\mu e}$ depends on all oscillation parameters. A measurement of $P_{\mu e}$ therefore, has a number of degenerate solutions.

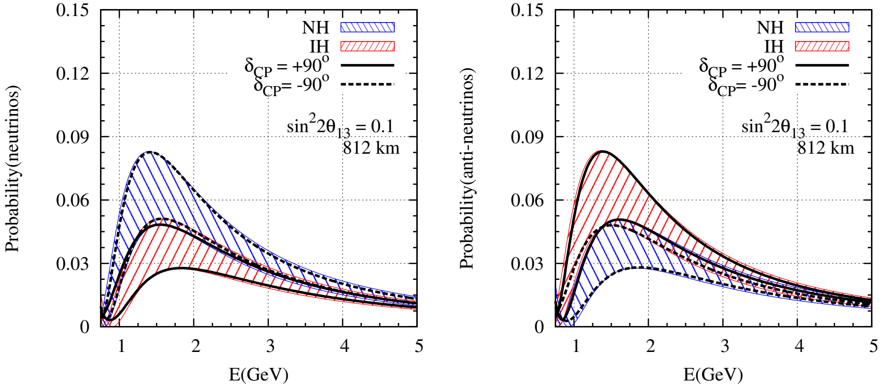
- We assume $\theta_{23} = 45^\circ$ so degeneracies involving θ_{23} are not relevant
- Because of precise measurement of $\sin^2 2\theta_{13}$ by reactor neutrino experiments, degeneracies involving θ_{13} are also not relevant
- We care about the hierarchy-δ_{CP} degeneracy only

Details of LBL Superbeam experiments considered

Characteristic	NOνA	T2K
Baseline	810 km	295 km
Location	Fermilab-Ash River	J-PARC-Kamioka
Beam	NuMI beam 0.8° off - axis	JHF beam 2.5° off - axis
Beam power	0.7 MW	0.75 MW
Beam peaks at	2 GeV	0.6 GeV
$P_{\mu e}$ 1st Osc. Maximum	1.5 GeV	0.55 GeV
Detector	TASD, 15 kton (now 14 kton)	Water Čerenkov, 22.5 kton
Runtime	3 in ν+3 in $\bar{\nu}$	5 in ν

$P_{\mu e}$: hierarchy and δ_{CP} effects

$P_{\mu e}$(as a band in δ_{CP}) vs. Energy.
For neutrinos(left panel) and anti-neutrinos(right panel).



Favourable and unfavourable δ_{CP} planes for NOνA

Notice:

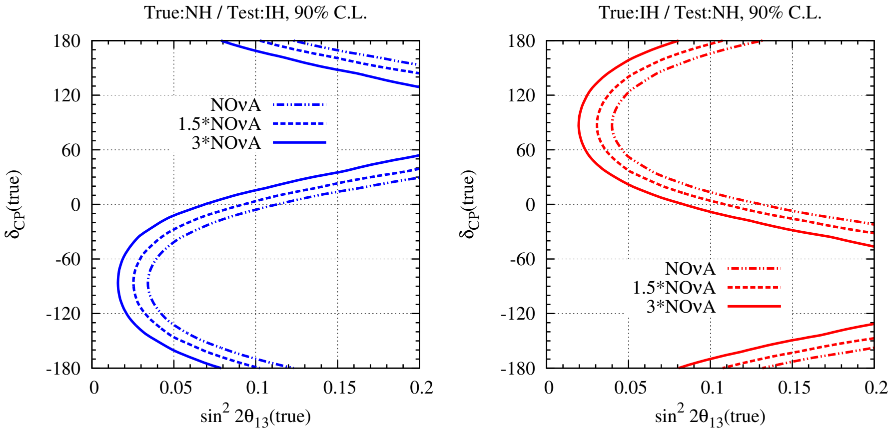
- (NH,$\delta_{CP} = -90^\circ$) is farthest from IH δ_{CP} band and (IH,$\delta_{CP} = 90^\circ$) is farthest from NH δ_{CP} band.
- (NH,$\delta_{CP} \sim 90^\circ$) is closest to IH δ_{CP} band and (IH,$\delta_{CP} \sim -90^\circ$) is closest to NH δ_{CP} band.

Therefore,

- lower half plane (LHP) of δ_{CP} forms the favourable plane for NH
- upper half plane (UHP) of δ_{CP} forms the favourable plane for IH

Hierarchy exclusion ability of NOνA

NOνA with various design statistics



For $\sin^2 2\theta_{13} = 0.1$, 1.5*NO$\nu$A can determine the hierarchy for entire favourable half plane, for both NH and IH.

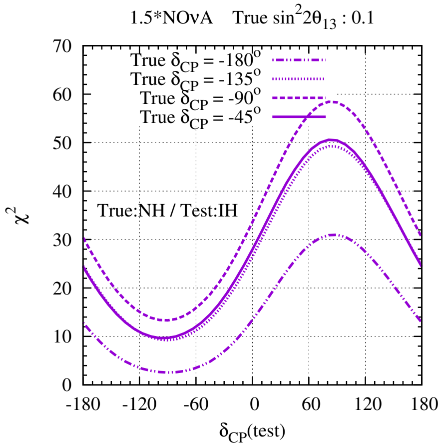
Breaking hierarchy-δ_{CP} degeneracy: Combining data from two LBL experiments

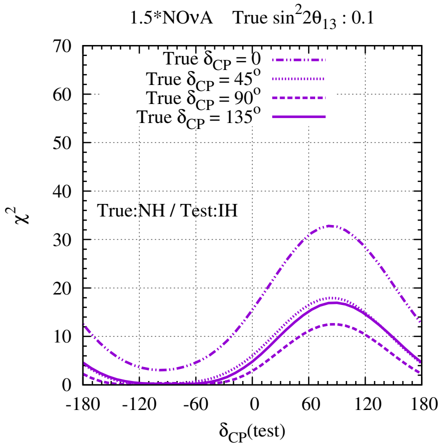
- Given a $P_{\mu e}$ measurement, two degenerate solutions: (correct hierarchy, correct δ_{CP}) and (wrong hierarchy, wrong δ_{CP})
- For a given experiment, [sin(correct δ_{CP}) $-$ sin(wrong δ_{CP})] is proportional to the matter term A for that experiment [O. Mena and S. Parke, arXiv:hep-ph/0408070]
- For T2K, this difference is small and is about 0.7 for $\sin^2 2\theta_{13} = 0.1$
- For NOνA it is three times larger.

A combined analysis of data from T2K and NOνA will pick out the correct hierarchy and a range of δ_{CP} around the correct value, provided the statistics from each experiment are large enough. We find that 1.5*NOνA +2*T2K is required for the present best-fit of $\sin^2 2\theta_{13}$

How does combining data help?

χ^2 vs. δ_{CP}(test) plots for NOνA

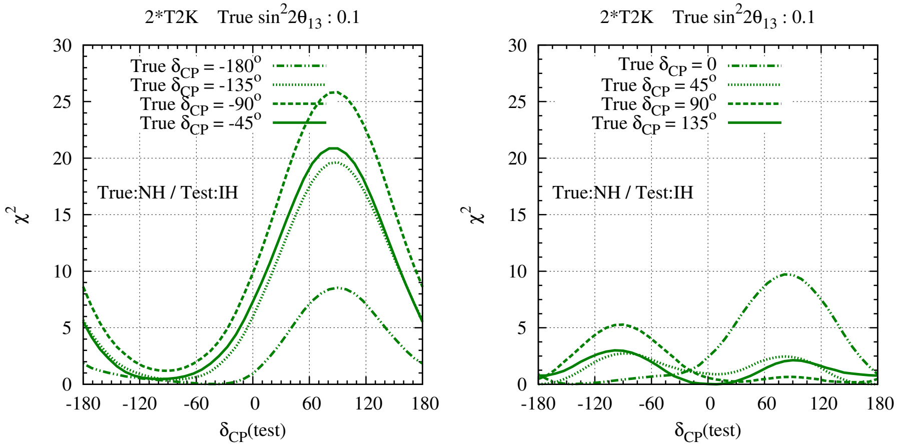




Irrespective of true δ_{CP}, χ^2_{min} always occurs around $-90°$. χ^2_{min} large for LHP, very small for UHP.

How does combining data help?

χ^2 vs. δ_{CP}(test) plots for T2K

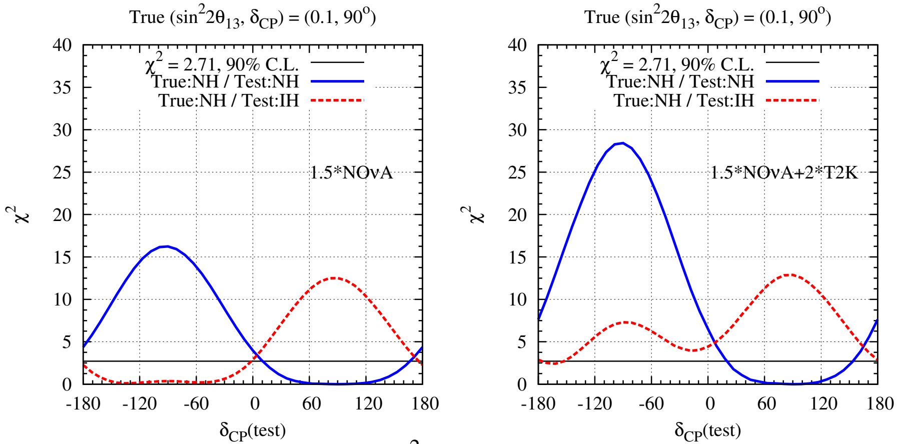


Left panel: χ^2_{min} occurs at -90° and is very small.

Right panel: χ^2 values are relatively large around -90°. χ^2_{min} occurs near CP conserving test δ_{CP} in the right half plane.

How does combining data help?

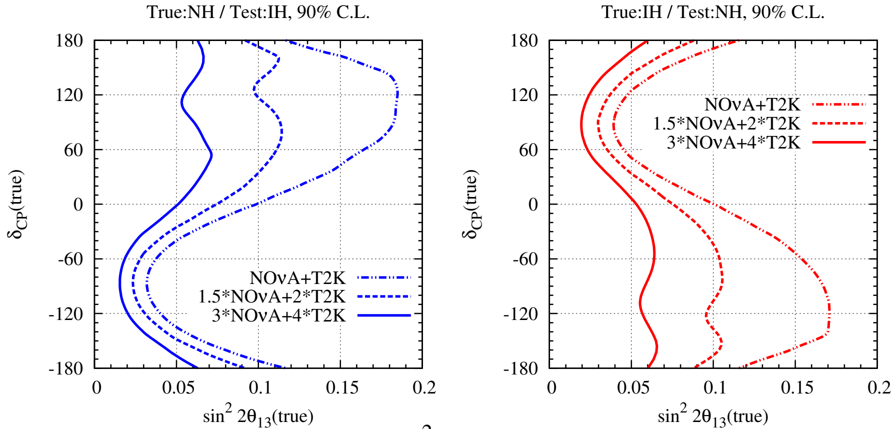
χ^2 vs. δ_{CP}(test) plots for 1.5*NOνA +2*T2K



From the right panel, we see that χ^2 dips just below 2.71 when IH is the test hierarchy. Similar features are observed for other unfavourable δ_{CP} values and also when IH is the true hierarchy.

Hierarchy exclusion with NOνA and T2K combined

Hierarchy exclusion plots for NOνA and T2K with various design statistics



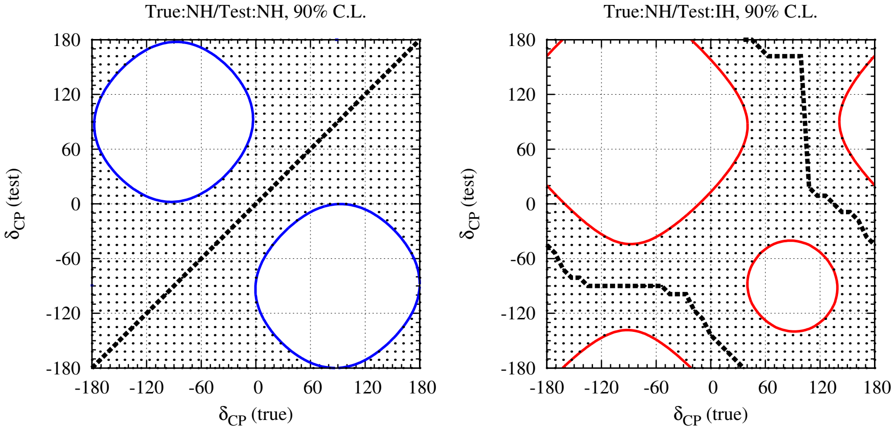
From these plots, we see that for $\sin^2 2\theta_{13} = 0.1$, 1.5*NO$\nu$A + 2*T2K is able to exclude wrong hierarchy for all δ_{CP} except some small regions in the unfavourable plane.

Hierarchy exclusion with NOνA and T2K combined

- It seems as if (1.5*NOνA +2*T2K) is insufficient to exclude wrong hierarchy for some δ_{CP} values in the unfavourable plane
- These are those δ_{CP} values for which χ^2 dips just below the cut-off for 90% C.L.
- With a small increase in statistics, hierarchy can be excluded at 90% C.L. for these troublesome regions also
- Thus, (1.5*NOνA +2*T2K) can essentially determine hierarchy for the entire δ_{CP} plane for both NH and IH for $\sin^2 2\theta_{13} \geq 0.1$

Can δ_{CP} be measured before hierarchy?

Allowed δ_{CP} plots for 1*T2K[3+3]

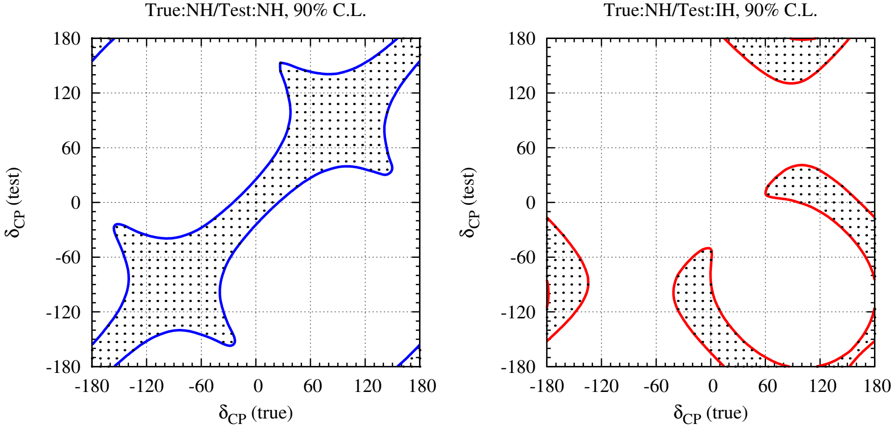


Left panel: allowed range of test δ_{CP} is around true δ_{CP}.

Right panel: allowed range of test δ_{CP} includes a large region of the wrong half-plane also. Best-fits, in general, are far away from true point.

Can δ_{CP} be measured before hierarchy?

Allowed δ_{CP} plots for 10*T2K[3+3]

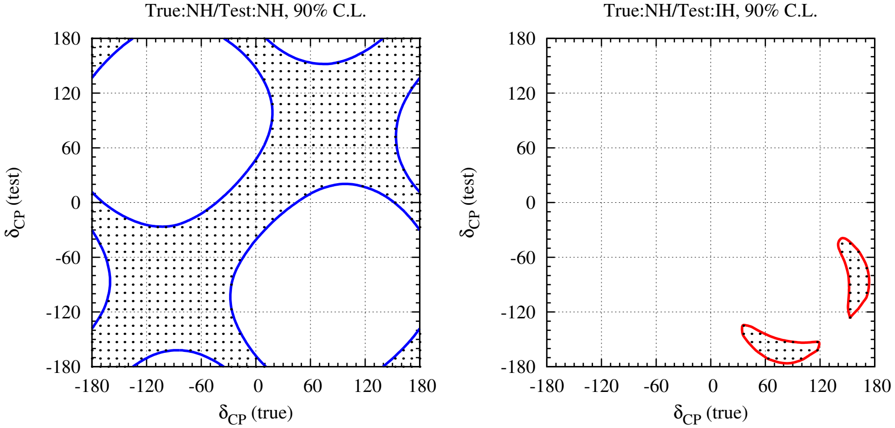


Not knowing hierarchy gives incorrect δ_{CP} solutions.

Right panel: For true δ_{CP} around CP conserving values, test δ_{CP} range around maximum CP violating values and vice versa.

δ_{CP} measurement with T2K and NOνA

Allowed δ_{CP} plots for 1.5*NOνA + 2*T2K[5+0]



1.5*NOνA + 2*T2K can measure δ_{CP} with an accuracy of $\pm 40^\circ$ for true $\delta_{CP} = 0$ and $\pm 60^\circ$ for true $\delta_{CP} = \pm 90^\circ$.

Summary

- Hierarchy - δ_{CP} degeneracy severely limits the ability of any single experiment to determine hierarchy as well as δ_{CP}.
- The observed moderately large value of θ_{13} is certainly a very good news for the upcoming NOνA.
- 1.5*NOνA by itself can resolve the hierarchy at 90% C.L. if δ_{CP} is in the favourable half-plane and $\sin^2 2\theta_{13} \geq 0.1$.
- When δ_{CP} is in the unfavourable half-plane, the data from NOνA and T2K beautifully complement each other to rule out the wrong hierarchy.
- 1.5*NOνA + 2*T2K can *essentially* resolve mass hierarchy at 90% C.L. for the entire δ_{CP} range.
- Without knowing the hierarchy, δ_{CP} cannot be measured.
- With 1.5*NOνA + 2*T2K, the correct half-plane of δ_{CP} can be determined at 90% C.L. for most values of δ_{CP}.


THANK
you !

Oscillation Parameters: Latest best-fits

Neutrino Oscillation Parameters:

Parameters	Best Fit	3σ range
$\Delta_{21}/10^{-5}\mathrm{eV}^2$(NH or IH)	7.54	6.99-8.18
$\sin^2\theta_{12}$(NH or IH)	3.07	2.59-3.59
$\sin^2 2\theta_{13}$(NH)	0.094	0.066-0.121
$\sin^2 2\theta_{13}$(IH)	0.095	0.067-0.122
$\sin^2\theta_{23}$(NH)	0.386	0.331-0.637
$\sin^2\theta_{23}$(IH)	0.392	0.335-0.663
$\Delta_{31}/10^{-3}\mathrm{eV}^2$(NH)	2.43	2.19-2.62
$\Delta_{31}/10^{-3}\mathrm{eV}^2$(IH)	2.42	2.17-2.61
δ/π(NH)	1.08	...
δ/π(IH)	1.09	...

[Fogli et.al, arXiv:hep-ph/1205.5254v3]

Experiments considered

In this analysis we simulate data from the following experiments.

- NOνA
- T2K
- C2F

The details of these experiments are in the following table.

Experiment Details

Characteristic	NOνA	T2K	C2F
Baseline	812 km	295 km	130 km
Location	Fermilab - Ash River	J-PARC - Kamioka	CERN - Fréjus
Beam	NuMI beam 0.8° off - axis	JHF beam 2.5° off - axis	SPL super-beam
Beam power	0.7 MW	0.75 MW	0.75 MW
Beam peaks at	2 GeV	0.6 GeV	0.35 GeV
$P_{\mu e}$ 1st Osc. Maximum	1.5 GeV	0.55 GeV	0.25 GeV
Detector	TASD, 15 kton	Water Čerenkov, 22.5 kton	Water Čerenkov, 22.5 kton
Runtime	3 in ν+3 in $\bar{\nu}$	5 in ν	3 in ν+3 in $\bar{\nu}$

Calculating χ^2

- We use the software GLoBES for our analysis. [Huber et. al. arXiv:hep-ph /0407333v1]
- We calculated statistical χ^2 including the systematical errors and priors.
- Solar parameters, Δ_{21} and θ_{12}, were kept fixed at their best fit values.
- χ^2 marginalised over Δ_{31}, $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$ and δ_{CP}
- Priors in $\sin^2 2\theta_{13}$, $\sin^2\theta_{23}$ and $|\Delta_{31}|$ have been added. $\sigma\left(\sin^2 2\theta_{13}\right) = 0.005$, $\sigma\left(\sin^2 2\theta_{23}\right) = 0.02$ and $\sigma(|\Delta_{31}|) = 0.03 \times |\Delta_{31}|$

Including Reactor Neutrino Experiments

A prior of $\sigma\left(\sin^2 2\theta_{13}\right) = 0.005$ effectively takes into account the data due to Reactor Neutrinos Experiments

Calculating χ^2

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

$$\boxed{\Delta m^2_{\mu\mu} = \Delta_{31} - \left(\cos^2\theta_{12} - \cos\delta\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\right)\Delta_{21}}$$

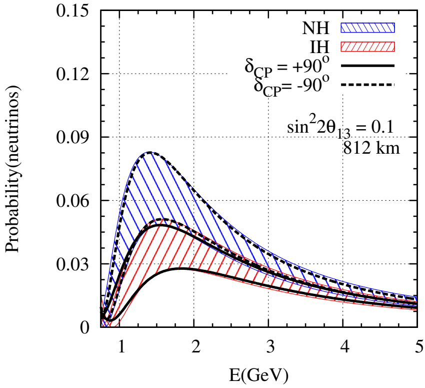
- $\Delta m^2_{\mu\mu} = \pm 2.4 \times 10^{-3}\text{eV}^2$; +: NH, -: IH

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

Mainly, 3 kinds of plots have been shown.

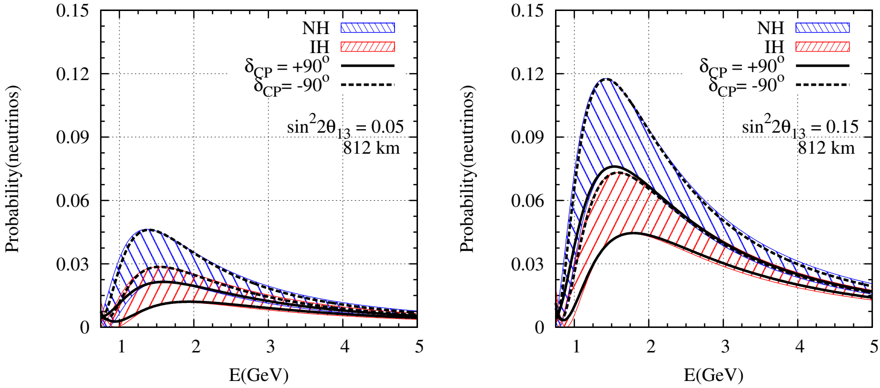
- Hierarchy exclusion plots
- Allowed $\sin^2 2\theta_{13}$-δ_{CP} plots
- Allowed $\delta_{CP}(test)$-$\delta_{CP}(true)$ plots

Back Up



Probability(neutrinos)
NH
IH
$\delta_{CP} = +90^o$
$\delta_{CP} = -90^o$
$\sin^2 2\theta_{13} = 0.1$
812 km
0.15
0.12
0.09
0.06
0.03
0
1
2
3
4
5
E(GeV)
Probability(anti-neutrinos)
NH
IH
$\delta_{CP} = +90^o$
$\delta_{CP} = -90^o$
$\sin^2 2\theta_{13} = 0.1$
812 km
0.15
0.12
0.09
0.06
0.03
0
1
2
3
4
5
E(GeV)

$P_{\mu e}$: θ_{13} effect



Oscillation Parameters: Known best fit values

Known Parameters

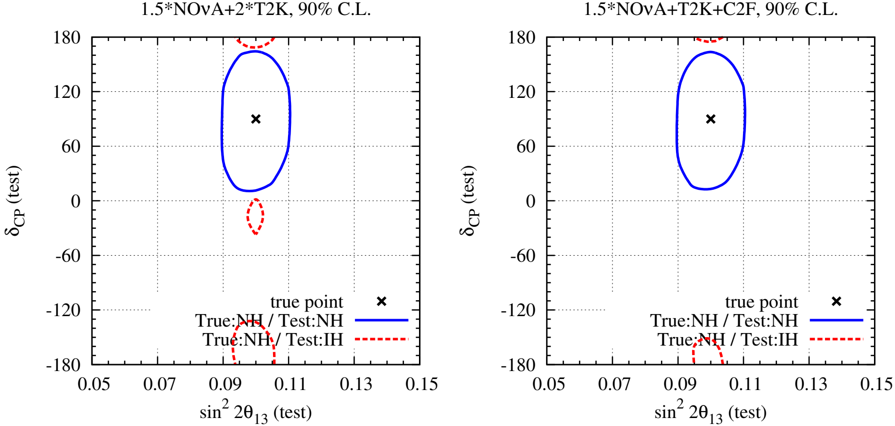
Parameters	Best Fit	3σ range
Δ_{21}	$7.58 \times 10^{-5} eV^2$	$(6.99 - 8.18) \times 10^{-5} eV^2$
$\sin^2\theta_{12}$	0.312	$(0.265 - 0.364)$
$\sin^2 2\theta_{13}$	0.1	$(0.02 - 0.19)$
$\sin^2\theta_{23}$	0.42	$(0.34 - 0.64)$
$\lvert\Delta_{31}\rvert$	$2.35 \times 10^{-3} eV^2$	$(2.06 - 2.67) \times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

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

- Recent T2K results: $\boxed{0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)}$ for normal (inverted) hierarchy at 90% C.L. for $\delta_{CP} = 0$
- Recent MINOS results: $\boxed{0.0(0.0) < \sin^2 2\theta_{13} < 0.12(0.19)}$ for normal (inverted) hierarchy at 90% C.L. for $\delta_{CP} = 0$
- Latest DChooz results: $\boxed{\sin^2 2\theta_{13} = 0.085 \pm 0.051}$ at 68 % C.L.

Will adding a shorter baseline help ?

Allowed $\sin^2 2\theta_{13}$-δ_{CP} plots



It can be seen that adding C2F provides only a marginal improvement, over and above T2K.