Getting the best out of T2K and NOνA

Suprabh Prakash

Department of Physics
Indian Institute of Technology Bombay
Mumbai, India

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This talk is based on the following works:

- SP, S. K. Raut, S. U. Sankar, *Getting the best out of T2K and NOνA* , Phys. Rev. D 86, 033012 (2012) arXiv:1201.6485
- S. K. Agarwalla, SP, S. K. Raut, S. U. Sankar, *Potential of optimized NOνA for large θ_{13} and combined performance with a LArTPC and T2K*, arXiv:1208.3644

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]

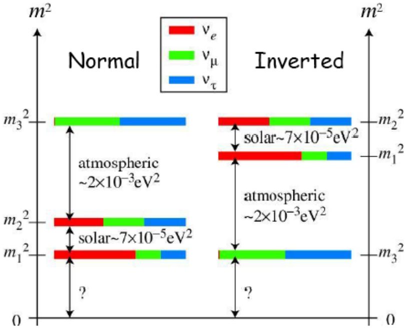
Best final precision on $\sin^2 2\theta_{13}$: $\boxed{\text{Daya Bay: } \sim 5\%}$

Defining the problem

$\boxed{\text{Mass hierarchy}}$

We do not know whether the hierarchy is

- Normal: $\boxed{m_1 < m_2 \ll m_3}$ or
- Inverted: $\boxed{m_3 \ll m_1 < m_2}$?



$\boxed{\text{Leptonic CP violation}}$

Whether CP is violated in the leptonic sector?

i.e. $\boxed{\text{is } P(\alpha \to \beta) \neq P(\bar{\alpha} \to \bar{\beta}) \text{ ?}}$

$P_{\mu e}$: algebraic expression

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

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

where

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

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

$P_{\mu e}$: degeneracies

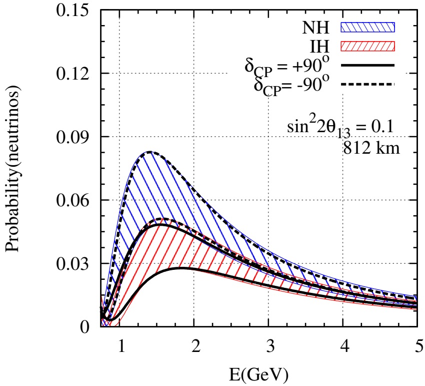
$P_{\mu e}$ depends on θ_{13}, hierarchy and δ_{CP} in addition to other well determined parameters. A measurement of $P_{\mu e}$ therefore, has a number of degenerate solutions.

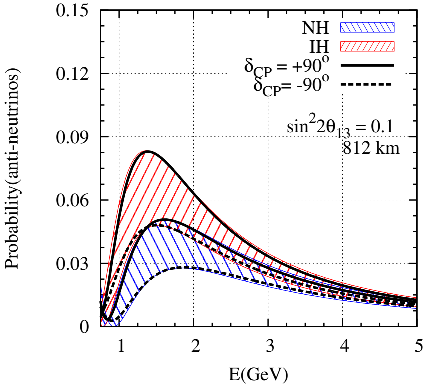
- We assume $\theta_{23} = 45^\circ$ so degeneracies involving θ_{23} have not been considered
- Because of precise measurement of $\sin^2 2\theta_{13}$ by reactor neutrino experiments, degeneracies involving θ_{13} are irrelevant now
- We care about the hierarchy-δ_{CP} degeneracy only

$P_{\mu e}$: 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, $\delta_{CP} = -90°$) is *farthest* from IH δ_{CP} band
- (IH, $\delta_{CP} = 90°$) is *farthest* from NH δ_{CP} band
- (NH, $\delta_{CP} \sim 90°$) is *closest* to IH δ_{CP} band
- (IH, $\delta_{CP} \sim -90°$) is *closest* to NH δ_{CP} band

Therefore,

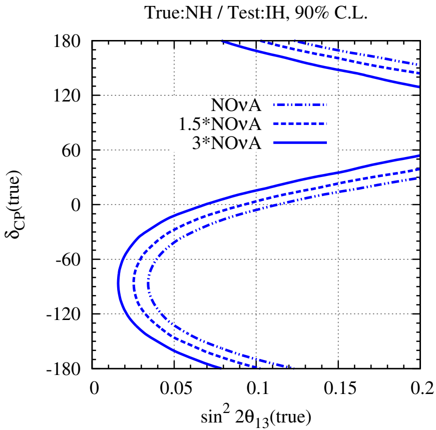
- lower half plane (LHP) of $(-180° \leq \delta_{CP} \leq 0)$ forms the *favourable* plane for NH
- upper half plane (UHP) of $(0 \leq \delta_{CP} \leq 180°)$ forms the *favourable* plane for IH

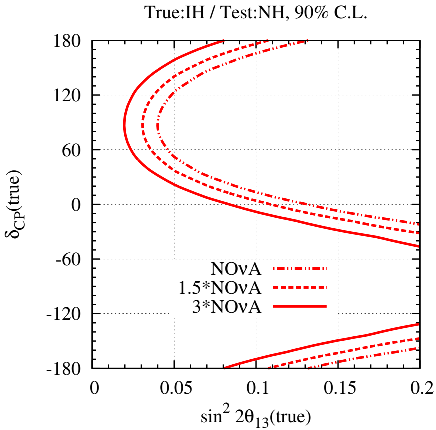
Details of LBL Superbeam experiments considered

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, 14 kton	Water Čerenkov, 22.5 kton
Runtime	3 in ν+3 in $\bar{\nu}$	5 in ν

Hierarchy exclusion ability of NOνA

NOνA with various design statistics

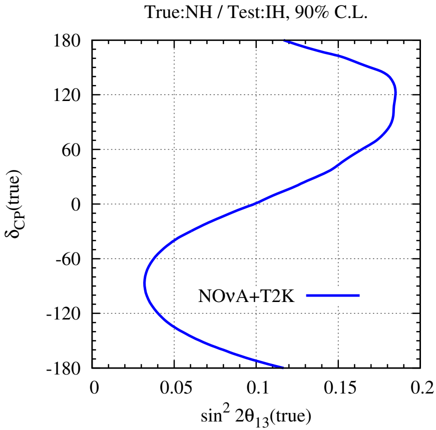


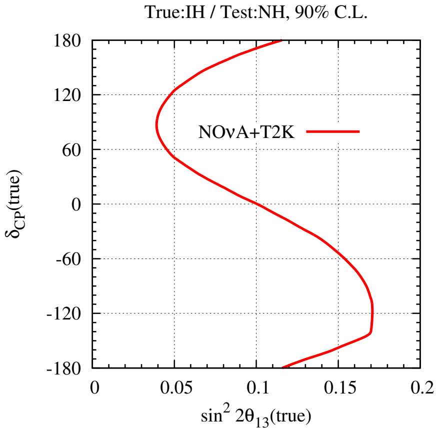


For $\sin^2 2\theta_{13} = 0.1$, 1.5*NO$\nu$A can determine the hierarchy for entire favourable half plane, for both NH and IH.

Hierarchy exclusion ability of NOνA + T2K

NOνA + T2K with nominal design statistics





Adding T2K data helps in the unfavourable plane

Resolving hierarchy-δ_{CP} degeneracy using two different LBL experiments

Event sample observed in the detector has to be analyzed assuming a true mass hierarchy. If the assumption is right, we get a right estimate of δ_{CP} ($\Delta\chi^2_{\text{min}}$ occuring at right δ_{CP}). If the assumption is wrong, we get a wrong estimate of δ_{CP} ($\Delta\chi^2_{\text{min}}$ occuring at wrong δ_{CP}).

- measurement has degenerate solutions: $(\text{hier}^{\text{right}}, {\delta_{CP}}^{\text{right}})$ and $(\text{hier}^{\text{wrong}}, {\delta_{CP}}^{\text{wrong}})$
- For a given experiment, $(\sin {\delta_{CP}}^{\text{right}} - \sin {\delta_{CP}}^{\text{wrong}}) \propto \text{A} \propto \text{E} \propto \text{L}$ for that experiment [O. Mena and S. Parke, arXiv:hep-ph/0408070]
- $\text{E}^{810\text{ km}}_{\text{peak flux}} \simeq 3 \cdot \text{E}^{295\text{ km}}_{\text{peak flux}}$
- $(\sin {\delta_{CP}}^{\text{right}} - \sin {\delta_{CP}}^{\text{wrong}}_{\text{NO}\nu\text{A}}) \simeq 3 \cdot (\sin {\delta_{CP}}^{\text{right}} - \sin {\delta_{CP}}^{\text{wrong}}_{\text{T2K}})$
- ${\delta_{CP}}^{\text{wrong}}$ predicted by two LBL experiments with different matter effects are different

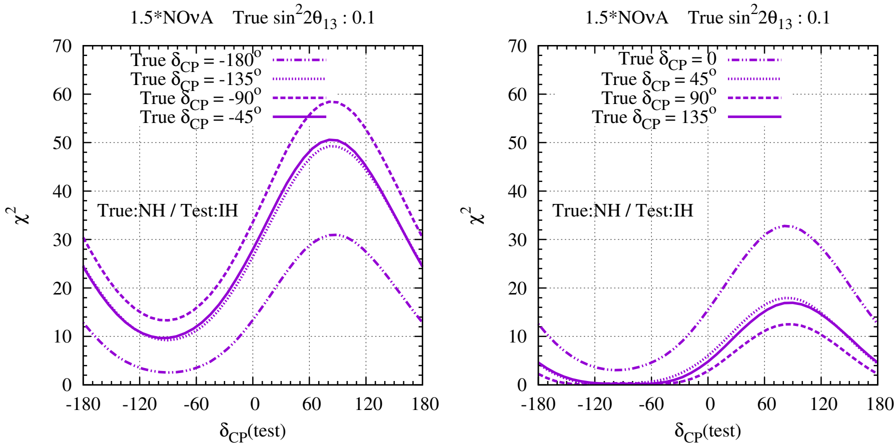
Resolving hierarchy-δ_{CP} degeneracy using two different LBL experiments

- $[\Delta\chi^2_{\rm min}]_{\rm NO\nu A}$ at (hier$^{\rm right}$, ${\delta_{CP}}^{\rm right}$) and (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}_{\rm NO\nu A}$)
- $[\Delta\chi^2_{\rm min}]_{\rm T2K}$ at (hier$^{\rm right}$, ${\delta_{CP}}^{\rm right}$) and (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}_{\rm T2K}$)
- $[\Delta\chi^2]_{\rm NO\nu A}$ not minimal at (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}_{\rm T2K}$)
- $[\Delta\chi^2]_{\rm T2K}$ not minimal at (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}_{\rm NO\nu A}$)
- $[\Delta\chi^2_{\rm min}]_{\rm NO\nu A+T2K}$ not at (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}_{\rm NO\nu A}$) or (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}_{\rm T2K}$)
  $\Longrightarrow$ wrong solutions excluded

Caveat: In order to have reasonable excluding sensitivity, $\Delta\chi^2_{\rm min}$ value at (hier$^{\rm wrong}$, ${\delta_{CP}}^{\rm wrong}$) should be much larger than $\Delta\chi^2_{\rm min}$ value at (hier$^{\rm right}$, ${\delta_{CP}}^{\rm right}$). Therefore, the experiments must have enough statistics.

How does combining data from two LBL help?

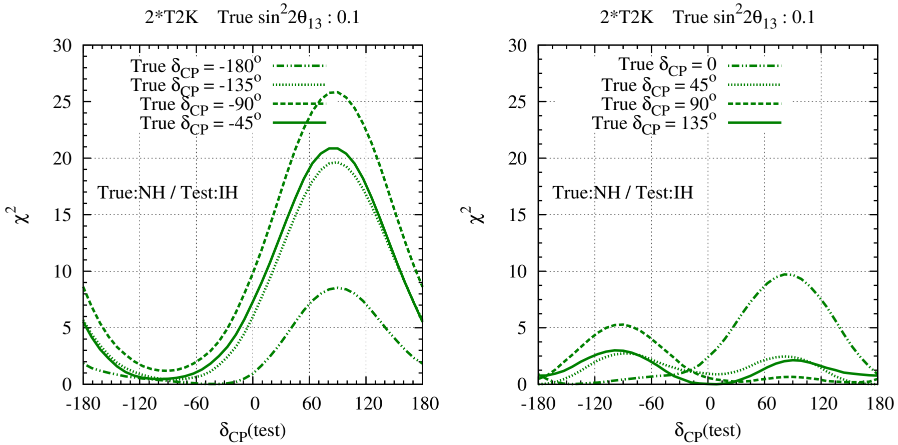
χ^2 vs. δ_{CP}(test) plots for NOνA



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 from two LBL help?

χ^2 vs. δ_{CP}(test) plots for T2K

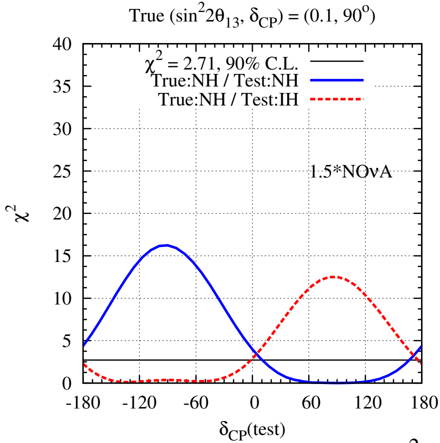


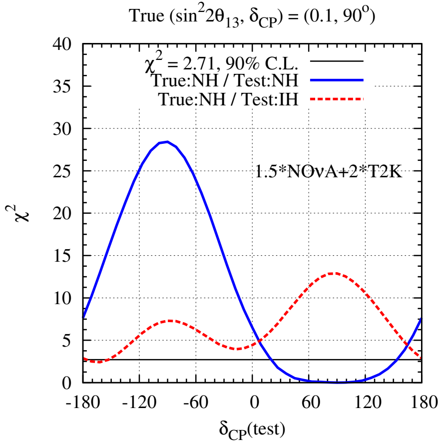
Left panel: χ^2_{min} occurs at $-90°$ and is very small.

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 from two LBL help?

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

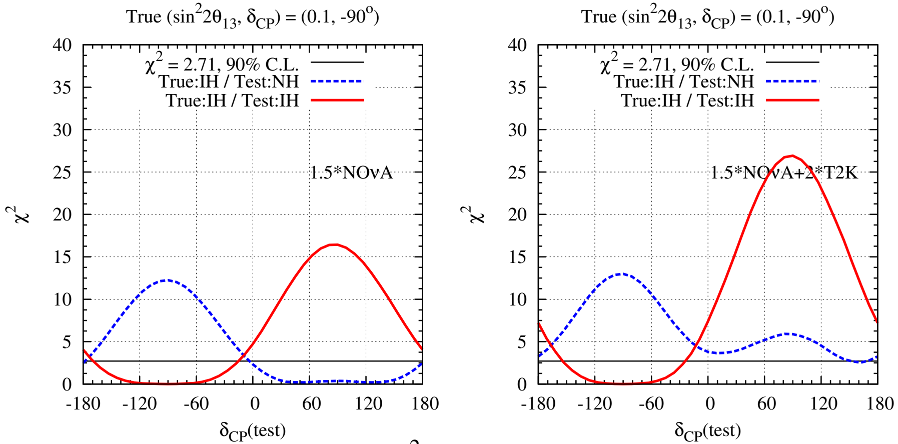




From the right panel, we see that χ^2 dips just below 2.71 when IH is the test hierarchy. Similar features are observed for other unfavourable δ_{CP} values also.

How does combining data from two LBL 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 NH is the test hierarchy. Similar features are observed for other unfavourable δ_{CP} values also.

NOνA upgrade

- We study the physics reach of the reoptimized NOνA (in conjunction with T2K) to determine the mass hierarchy and CP violation
- There is considerable enthusiasm in the NOνA and LBNE collaborations for an additional small liquid argon detector at the Ash River site
- We consider the possiblility of such a module

Reoptimized NOνA

- Previous optimization: done under the assumption $\sin^2 2\theta_{13} = 0$ with objective to have least background
- New optimization: for moderately large θ_{13} with relaxed cuts for event selection criteria which allow more signal and background [talk by R. Patterson in NuFACT 12]

The main differences between the old criteria and new criteria are:

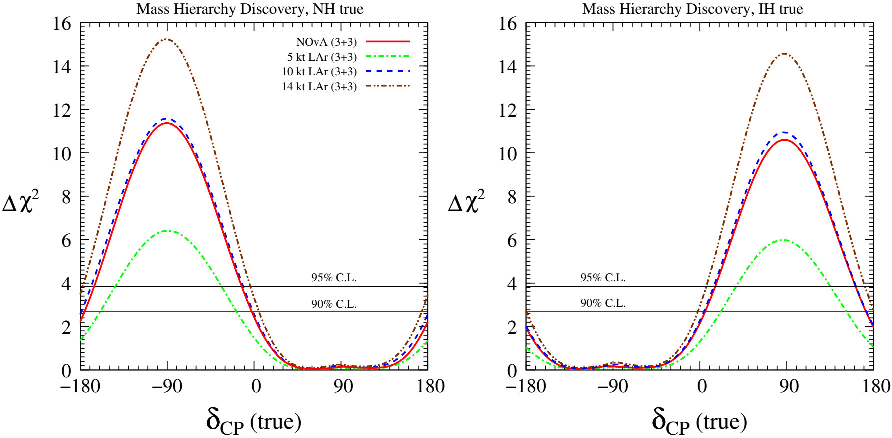
- The signal efficiencies for new NOνA are higher than that of old one by roughly a factor of 2 for neutrino events
- The background acceptance has also increased
- The NC spectrum shift to the measured energies is implemented through migration matrices. [LBNE Collaboration, T. Akiri et al. arXiv:1110.6249]
- We have taken care of the neutrino contamination in the anti-neutrino beam

Liquid Argon TPC

- A 10 kt liquid argon time projection chamber (LArTPC) constructed close to NOνA
- A signal efficiency of 80% for $e^{\pm}$ compared to 45% for TASD [LBNE Collaboration, T. Akiri et al. arXiv:1110.6249]
- The energy resolution and background rejection for the LArTPC and TASD are comparable
- Such a detector will come on line much later than NOνA
- In considering NOνA + LArTPC, we assume equal 6 years ν and $\bar{\nu}$ runs for NOνA and equal 3 years ν and $\bar{\nu}$ runs for LArTPC

Results: Mass hierarchy discrimination

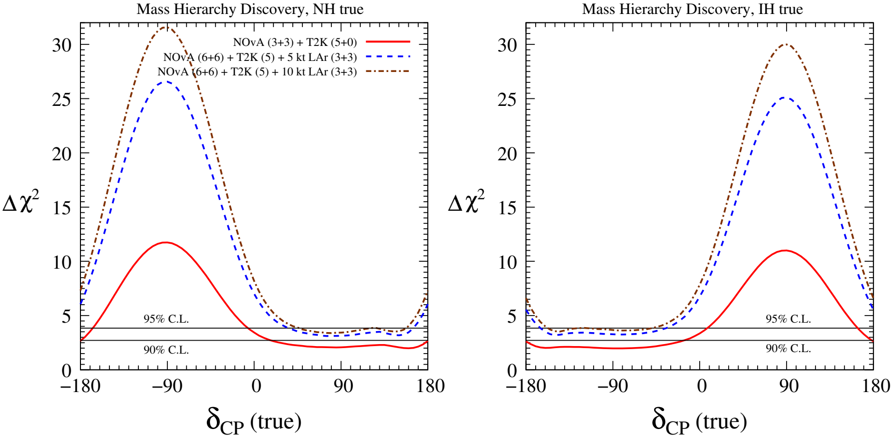
Hierarchy discovery for different LArTPC detector masses and new NOνA



A LArTPC of mass 10 kt can be as effective as NOνA. But none of the detectors are effective if the true value of δ_{CP} is in the unfavourable half-plane.

Results: Mass hierarchy discrimination

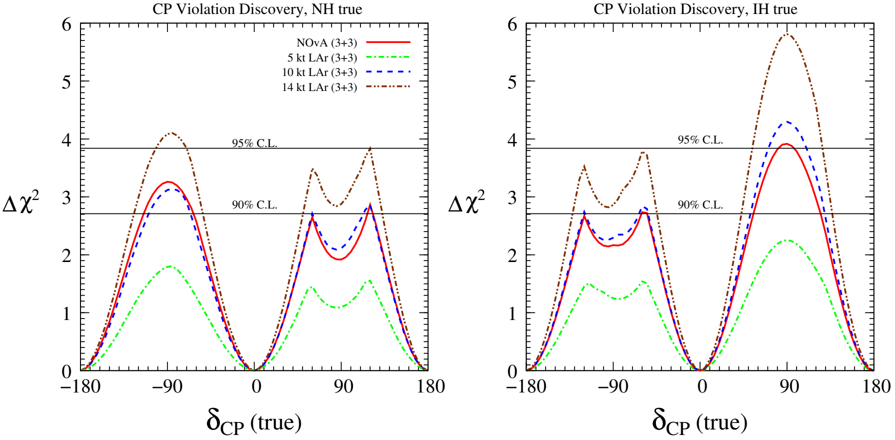
Combined performance of new NOνA, T2K and LArTPC



With the addition of a 10 kt LArTPC, close to 95% C.L. hierarchy discrimination becomes possible for all the values of δ_{CP}

Results: CP violation discovery

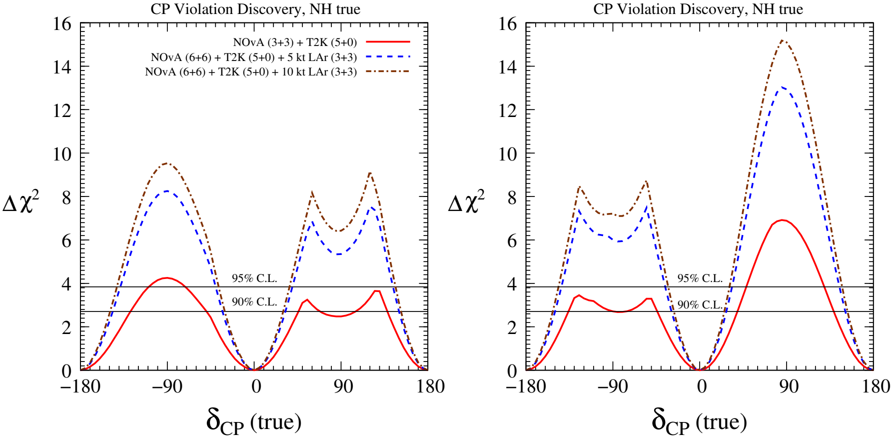
CP violation discovery for different LArTPC detector masses and new NOνA



Performance of a 10 kt LArTPC detector is closest to the performance of the new NOνA

Results: CP violation discovery

Combined performance of new NOνA, T2K and LArTPC



Addition of the LArTPC leads to an significant increment in the range of true δ_{CP} for which CP conservation can be ruled out at 95% C.L.

Fraction of δ_{CP} values for which mass hierarchy can be determined/CP violation can be detected

Setups	Fraction of δ_{CP}(true)			
	MH		**CPV**	
	NH true	IH true	NH true	IH true
NOνA (3+3)	0.48 (0.43)	0.46 (0.41)	0.16 (0)	0.21(0.04)
NOνA (3+3) + T2K (5+0)	0.55 (0.45)	0.54 (0.43)	0.38 (0.11)	0.49 (0.23)
NOνA (6+6) + T2K (5+0) + 5 kt LArTPC (3+3)	1 (0.64)	1 (0.64)	0.64 (0.56)	0.68 (0.61)
NOνA (6+6) + T2K (5+0) + 10 kt LArTPC (3+3)	1 (0.71)	1 (0.73)	0.67 (0.60)	0.71 (0.64)

Summary

- A 10 kt LArTPC is found to be equivalent to new NOνA in its ability to exclude the wrong hierarchy and CP violation discovery
- For increased exposure for NOνA, the combination of data from NOνA, LArTPC and T2K (nominal) can determine hierarchy at almost 2σ level for all the values of δ_{CP}
- NOνA by itself can discover CP violation only for a small fraction of the favourable half-plane, and only at 90% C.L.
- Addition of data from T2K causes a remarkable increase in the range of δ_{CP} for which CP violation can be established
- With the combination of additional data from the LArTPC detector with boosted NOνA and nominal T2K, CP violation can be discovered at 95% confidence level for around 60% of the entire δ_{CP} range


THANK
you !

Flavor Oscillations and Neutrino Parameters

- n flavor eigenstates $|\nu_\alpha\rangle$; connected to n mass eigenstates $|\nu_i\rangle$ through unitary PMNS mixing matrix U.
$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$
- $U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$
- $U = U^{23}\left(\theta_{23}\right) \times U^{13}\left(\theta_{13}, \delta\right) \times U^{12}\left(\theta_{12}\right) \times U^{Maj}$
- $\mathcal{P}\left(\alpha \to \beta\right) =$
$\delta_{\alpha\beta} - 4\Re \sum_{j>i} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin^2 \frac{\Delta_{ji} L}{4E} + 2\Im \sum_{j>i} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \sin \frac{\Delta_{ji} L}{2E}$
- $\Delta_{ji} = m_j^2 - m_i^2$

Flavor Oscillations and Neutrino Parameters

Neutrino Parameters

Sensitivity to 6 neutrino parameters. Three mixing angles θ_{12}, θ_{13}, θ_{23}, the CP-violating phase δ_{CP} and two mass squared differences Δ_{32} and Δ_{21}.

Known Parameters

Atmospheric and Accelerator :
$|\Delta_{32}| = 2.5 \times 10^{-3} eV^2$ and $\theta_{23} \approx 45^\circ$
Solar and Reactor :
$\Delta_{21} \approx 8 \times 10^{-5} eV^2$ and $\theta_{12} \approx 32^\circ$

Unknown Parameters

- sign of Δ_{32} + : Normal Hierarchy
  - : Inverted Hierarchy
- lower bound on θ_{13}
- no information on δ_{CP}

Oscillation Parameters: Latest best-fits

Neutrino Oscillation Parameters:

Parameters	Best Fit	3σ range
$\Delta_{21}/10^{-5}\text{eV}^2$(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
$\Delta_{31}/10^{-3}\text{eV}^2$(NH)	2.43	2.19-2.62
$\Delta_{31}/10^{-3}\text{eV}^2$(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 $\Delta_{\mu\mu}$.

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

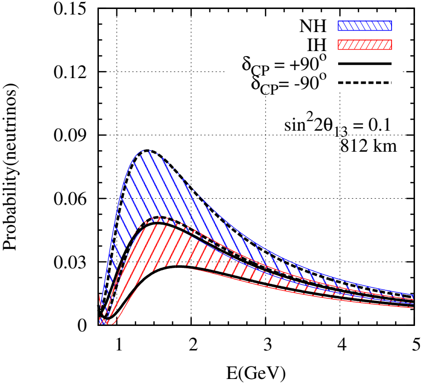
- $\Delta m^2_{\mu\mu} = \pm 2.4 \times 10^{-3}\text{eV}^2$; +: NH, -: IH

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

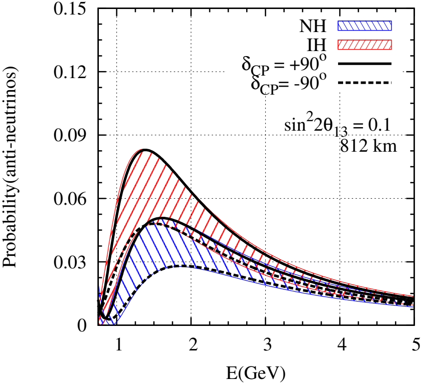
Mainly, 3 kinds of plots have been shown.

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

Back Up

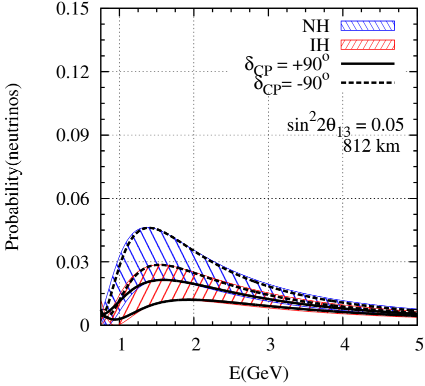


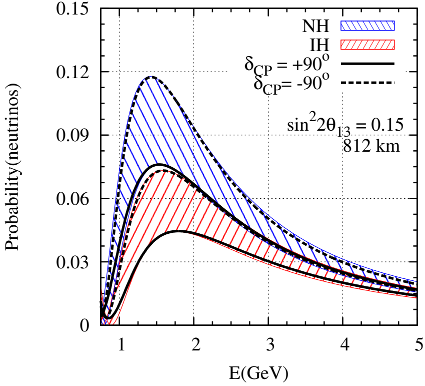
0.15
0.12
0.09
0.06
0.03
0
1
2
3
4
5
E(GeV)
Probability(neutrinos)
NH
IH
$\delta_{CP} = +90^o$
$\delta_{CP} = -90^o$
$\sin^2 2\theta_{13} = 0.1$
812 km



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

$P_{\mu e}$: θ_{13} effect





Oscillation Parameters: Known best fit values

Known Parameters

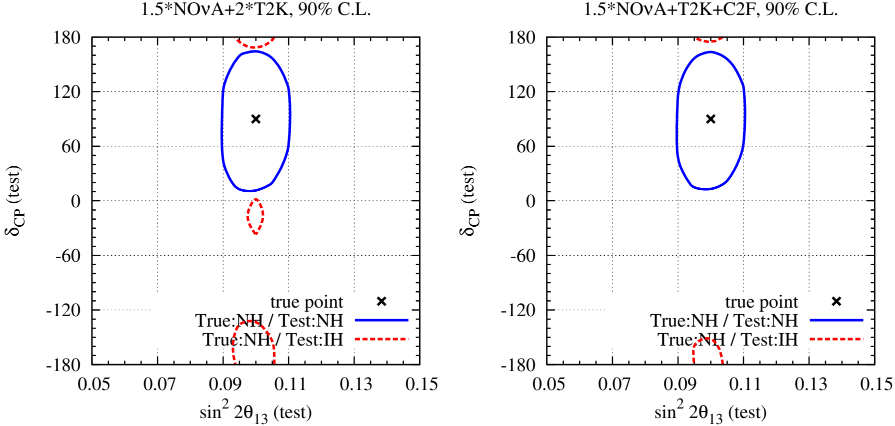
Parameters	Best Fit	3σ range
Δ_{21}	$7.58 \times 10^{-5}\mathrm{eV}^2$	$(6.99 - 8.18) \times 10^{-5}\mathrm{eV}^2$
$\sin^2\theta_{12}$	0.312	$(0.265 - 0.364)$
$\sin^2 2\theta_{13}$	0.1	$(0.02 - 0.19)$
$\sin^2\theta_{23}$	0.42	$(0.34 - 0.64)$
$\lvert\Delta_{31}\rvert$	$2.35 \times 10^{-3}\mathrm{eV}^2$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

[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 ?

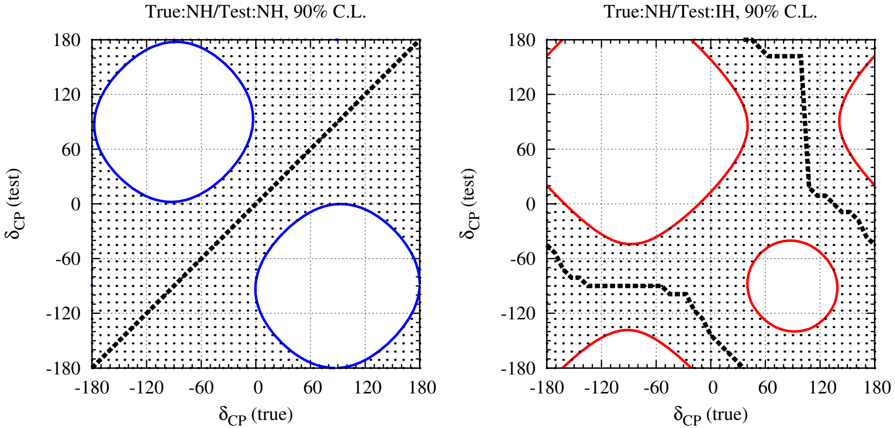
Allowed $\sin^2 2\theta_{13}$-δ_{CP} plots



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

Can δ_{CP} be measured before hierarchy?

Allowed δ_{CP} plots for 1*T2K[3+3]

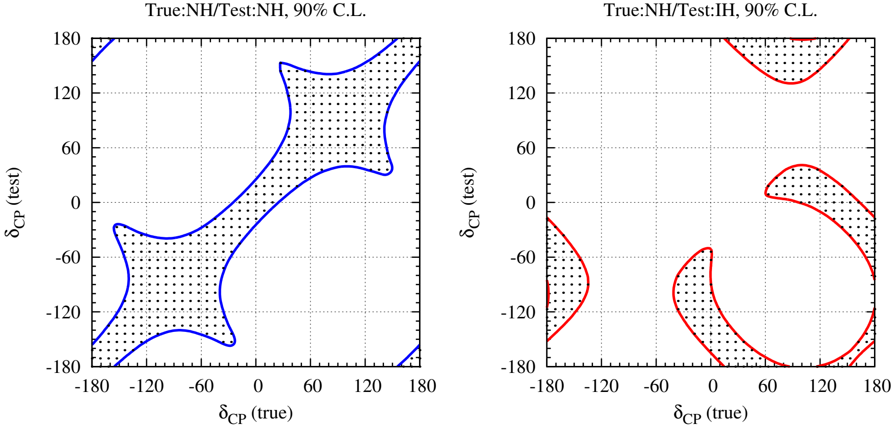


Left panel: allowed range of test δ_{CP} is around true δ_{CP}.

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?

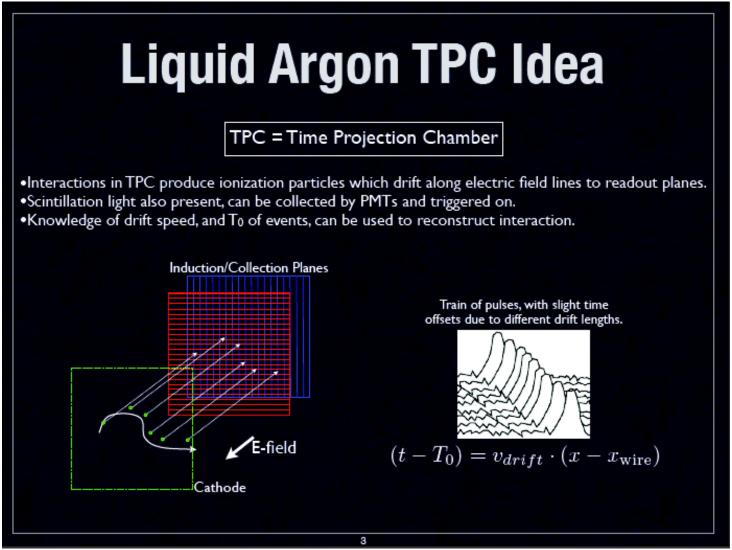
Allowed δ_{CP} plots for 10*T2K[3+3]



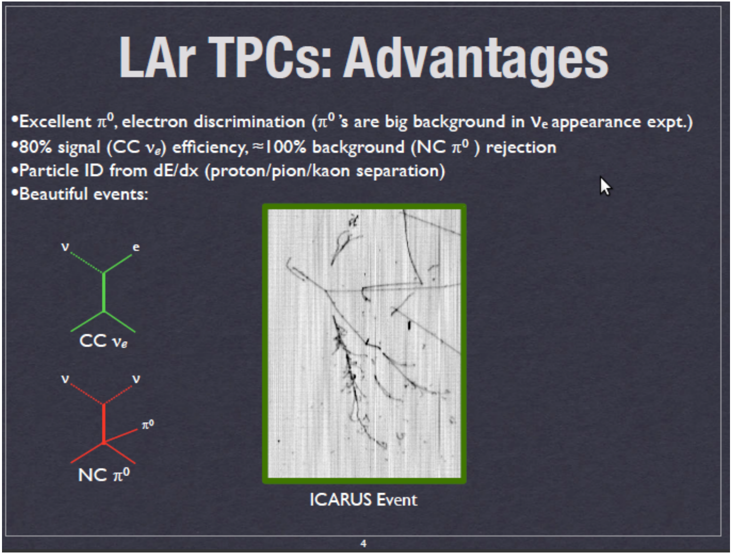
Not knowing hierarchy gives incorrect δ_{CP} solutions.

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

LArTPC


Liquid Argon TPC Idea
TPC = Time Projection Chamber
•Interactions in TPC produce ionization particles which drift along electric field lines to readout planes.
•Scintillation light also present, can be collected by PMTs and triggered on.
•Knowledge of drift speed, and T0 of events, can be used to reconstruct interaction.
Induction/Collection Planes
E-field
Cathode
Train of pulses, with slight time offsets due to different drift lengths.
$(t - T_0) = v_{drift} \cdot (x - x_{\mathrm{wire}})$
3

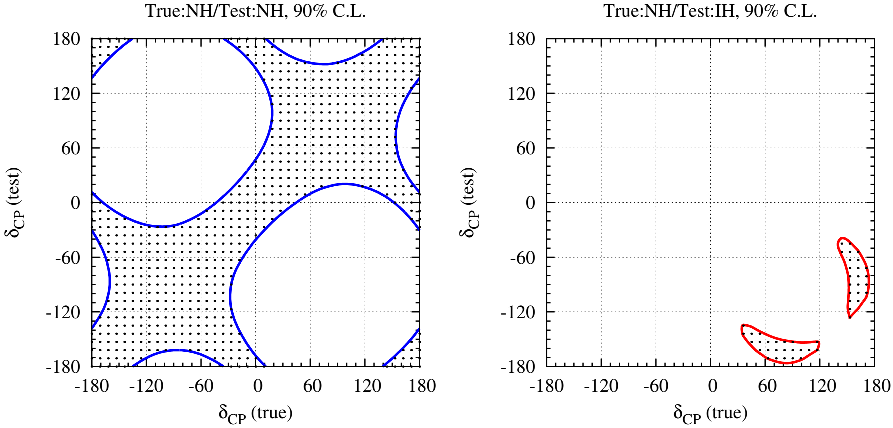
LArTPC



LAr TPCs: Advantages
•Excellent π^0, electron discrimination (π^0's are big background in ν_e appearance expt.)
•80% signal (CC ν_e) efficiency, ≈100% background (NC π^0) rejection
•Particle ID from dE/dx (proton/pion/kaon separation)
•Beautiful events:
ν
e
CC ν_e
ν
ν
π^0
NC π^0
ICARUS Event
4

δ_{CP} measurement with T2K and NOνA

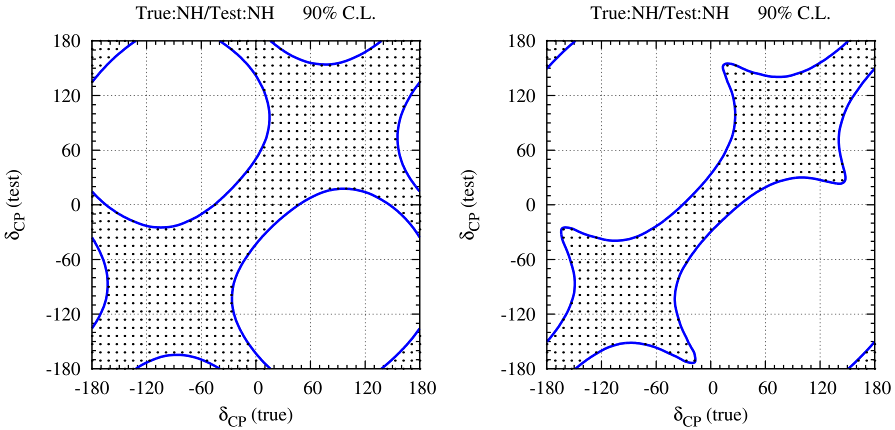
Allowed δ_{CP} plots for 1.5*NOνA + 2*T2K[5+0]



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 $\delta_{CP} = \pm 90^\circ$.

Results: δ_{CP} measurement

Allowed δ_{CP} plots for
new NOνA + T2K [Left] and new NOνA + T2K + LArTPC [Right]

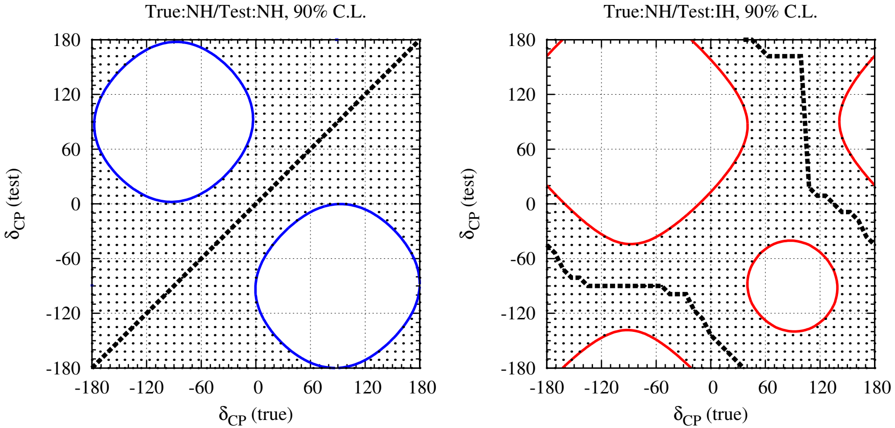


Can δ_{CP} be measured before hierarchy?

- Can a short LBL experiment such as T2K(295 km) or CERN-Frejus(130 km) measure the δ_{CP} phase independent of hierarchy with electron appearance channel?
- A short baseline has small matter effects and therefore is relatively free of hierarchy-δ_{CP} degeneracy. Therefore, it is expected that it can provide a clean δ_{CP} measurement.
- But it cannot!!

Can δ_{CP} be measured before hierarchy?

Allowed δ_{CP} plots for 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 CERN-Frejus(130 km)