Three Flavor Effects in Current and Future Oscillation Facilities

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The Standard Model: Massless Neutrinos

The Standard Model is a gauge theory & it unifies strong, weak & electromagnetic forces!

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

3-fold repetition of the same representation!

- 3 *active* neutrinos: ν_e , ν_μ , ν_τ
- Neutral elementary particles of Spin ½
- Only couple to *weak force* (& gravity)
- Only *left handed* neutrinos
- There are no right-handed neutrinos
- *No* Dirac Mass term: $m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

Neutrinos are massless in the Basic SM!

- ❑ Over the past decade, marvelous data from world class neutrino experiments firmly established that they change flavor after propagating a finite distance!

- ❑ Neutrino flavor change (oscillation) demands non-zero mass and mixing!

Non-zero ν mass: first experimental proof for physics beyond the Standard Model!

!! An extension of the Standard Model is necessary !!

Neutrino Physics: An Exercise in Patience

The three most fundamental questions were formulated in the past century…

1. How tiny is the neutrino mass? (Pauli, Fermi, '30s)

Recent Planck satellite data set an upper limit of 0.23 eV for the sum of neutrino masses!

Planck Collaboration, arXiv:1303.5076 [astro-ph.CO]

2. Can a neutrino turn into its own antiparticle? (Majorana, '30s)

Hunt for ν-less Double-β decay (Z,A → Z+2, A) is still on, demands lepton number violation!

Nice Review by Avignone, Elliott, Engel, Rev.Mod.Phys. 80 (2008) 481-516

3. Do different ν flavors 'oscillate' into one another? (Pontecorvo, Maki-Nakagawa-Sakata, '60s)

B. Pontecorvo, Sov. Phys. JETP 26, 984 (1968) [Zh. Eksp. Teor. Fiz. 53, 1717 (1967)]

The last question has been positively answered only in recent years. It is now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**!

With the recent measurement of the **last unknown mixing angle θ_{13}**, a clear first order picture of the 3-flavor lepton mixing matrix has emerged, signifies a major breakthrough in ν physics!

The year 2013 marks the **100th anniversary** of the birth of Pontecorvo, a great tribute to him!

Neutrino Oscillations in 3 Flavors

ν oscillation is a quantum mechanical phenomenon like electrons in the double slit experiment!
It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

Flavor States: ν_e, ν_μ, ν_τ (produced in weak interactions)
Mass States: ν_1, ν_2, ν_3 (propagate from source to detector)

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle \quad (\alpha = e, \mu, \tau)$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric sector — connection between solar and atmospheric — solar sector

$c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

U is a 3×3 unitary matrix containing θ_{23}, θ_{13}, θ_{12} and one CP violating (Dirac) phase δ_{CP}

3 mixing angles simply related to flavor components of 3 mass eigenstates

$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2}; \quad \tan^2\theta_{23} \equiv \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2}; \quad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

Over a distance L, changes in the relative phases of the mass states may induce flavor change!

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j}\mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

2 independent mass splittings Δm^2_{21} and Δm^2_{32}, for anti-neutrinos replace U by U^*

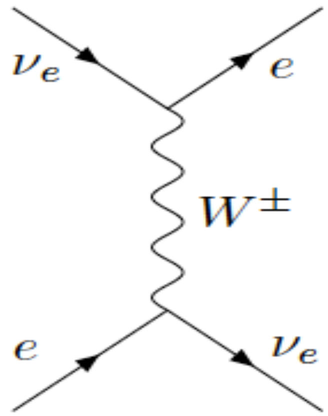
Neutrino Oscillations in Matter

Neutrino propagation through matter can modify the oscillations significantly!

There is coherent forward elastic scattering of neutrinos with matter particles!

Can be compared with the visible light travelling through glass!

Charged current interaction of ν_e with electrons creates an extra potential for ν_e!



Wolfenstein matter term: $A = \pm 2\sqrt{2} G_F N_e E$ or $A(\mathrm{eV}^2) = 0.76 \times 10^{-4} \rho\ (\mathrm{g/cc}) E(\mathrm{GeV})$

N_e = electron number density , + (-) for neutrinos (anti-neutrinos) , ρ = matter density in Earth

Matter term changes sign when we switch from neutrino mode to anti-neutrino mode!

$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$ → ***even if $\delta_{CP} = 0$, causes fake CP asymmetry!***

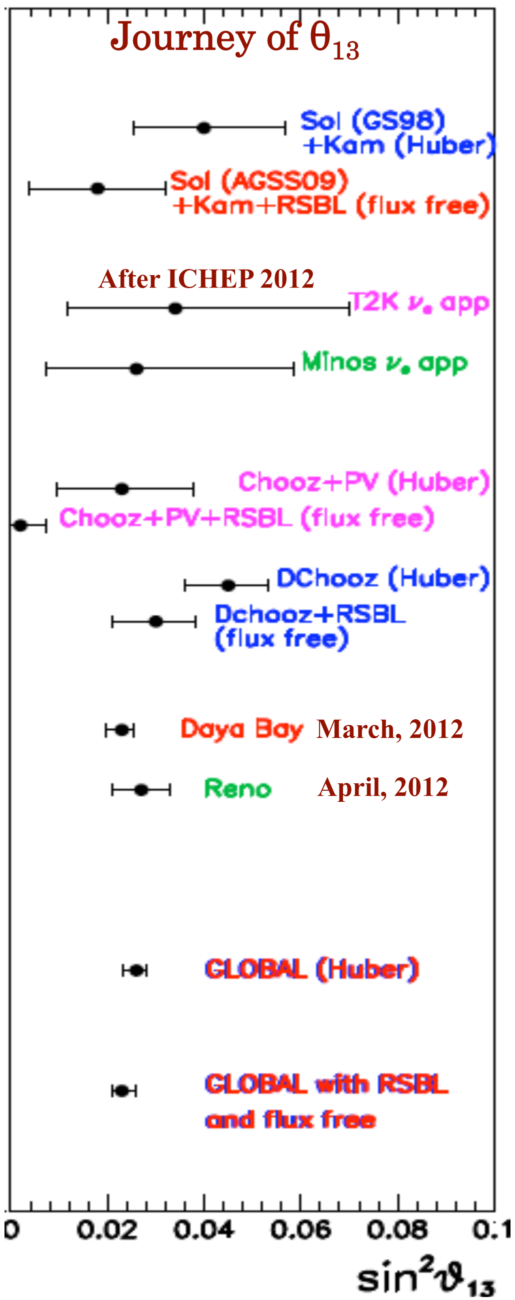
Matter term modifies oscillation probability differently depending on the sign of Δm^2

$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – the MSW effect***

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

→ ***Resonance occurs for neutrinos (anti-neutrinos) if Δm^2 is positive (negative)***

θ_{13} Revolution and Present Status of Neutrino Parameters



	bfp $\pm 1\sigma$	3σ range	Relative 1σ Precision
$\sin^2\theta_{12}$	0.30 ± 0.013	$0.27 \to 0.34$	(3.9%)
$\theta_{12}/^\circ$	33.3 ± 0.8	$31 \to 36$	
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.34 \to 0.67$	(11%)
$\theta_{23}/^\circ$	$40.0^{+2.1}_{-1.5} \oplus 50.4^{+1.2}_{-1.3}$	$36 \to 55$	
$\sin^2\theta_{13}$	0.023 ± 0.0023	$0.016 \to 0.030$	(10%)
$\theta_{13}/^\circ$	$8.6^{+0.44}_{-0.46}$	$7.2 \to 9.5$	
$\delta_{CP}/^\circ$	300^{+66}_{-138}	$0 \to 360$	(Not Known)
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.50 ± 0.185	$7.00 \to 8.09$	(2.4%)
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$2.47^{+0.069}_{-0.067}$	$2.27 \to 2.69$	(2.8%)
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.43^{+0.042}_{-0.065}$	$-2.65 \to -2.24$	

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, JHEP 1212 (2012) 123

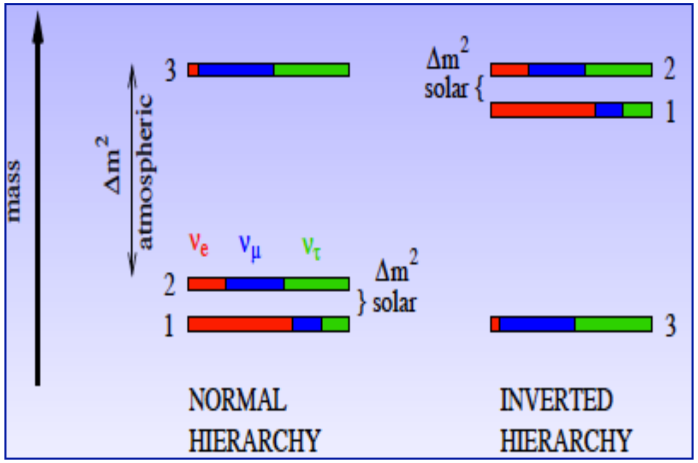
θ_{13} has been determined to be reasonably large, not too far from its previous upper bound!

More than 10σ confirmation of non-zero θ_{13}! Relative 1σ precision of 10% achieved!

Indication of non-maximal 2-3 mixing angle (~ 2σ) by the MINOS accelerator experiment!

Fundamental Unknowns in Neutrino Sector

1. What is the hierarchy of the neutrino mass spectrum, normal or inverted?



- *The sign of* $\Delta m^2_{31} = m^2_3 - m^2_1$ *is not known!*
- *Currently do not know which neutrino is the heaviest?*
- *Only have a lower bound on the mass of the heaviest ν!*

$$\boxed{\sqrt{2.5 \cdot 10^{-3}\mathrm{eV}^2} \sim 0.05\ \mathrm{eV}}$$

2. What is the octant of the 2-3 mixing angle, lower ($\theta_{23} < 45°$) or higher ($\theta_{23} > 45°$)?

If $\sin^2 2\theta_{23}$ differs from 1 as indicated by the recent neutrino data, we get two solutions for θ_{23}: one < 45°, termed as lower octant (LO) and the other > 45°, known as higher octant (HO)

2. Is there CP violation in the leptonic sector, as in the quark sector?

Mixing can cause CP violation in the leptonic sector (if δ_{CP} differs from 0° and 180°)!
Need to measure the CP-odd asymmetries: $\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta; L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta; L)$ $(\alpha \neq \beta)$

With our current knowledge of θ_{13}, resolving these fundamental unknowns fall within our reach!
Sub-leading 3 flavor effects are extremely crucial in current and future long baseline experiments!

Three Flavor Effects in $\nu_\mu \rightarrow \nu_e$ oscillation probability

The appearance probability $(\nu_\mu \to \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (0.03) and $\sin 2\theta_{13}$ (0.3),

$$P_{\mu e} \simeq \underbrace{\sin^2 2\theta_{13}}_{0.09} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$ → θ_{13} Driven

$$- \underbrace{\alpha \sin 2\theta_{13}}_{0.009} \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$ → CP odd

$$+ \alpha \sin 2\theta_{13} \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$ → CP even

$$+ \underbrace{\alpha^2}_{0.0009} \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};$$ → Solar Term

$\sin^2\theta_{23}$ → Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2}G_F n_e E)/\Delta m^2_{31}$

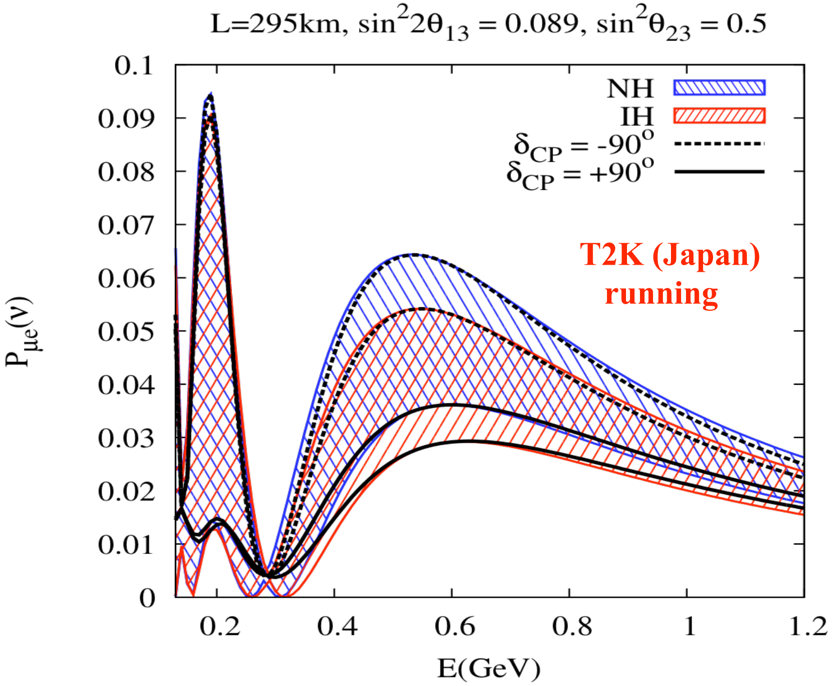
$\hat{A}$ → changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

$\hat{A}$ → changes sign with polarity causes fake CP asymmetry!

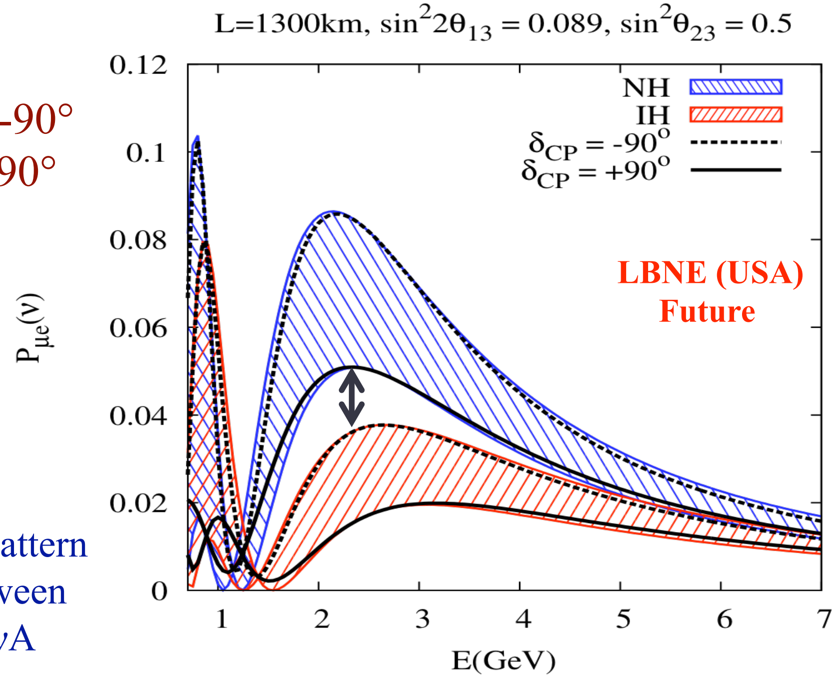
Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

This channel suffers from: (Hierarchy – δ_{CP}) & (Octant – δ_{CP}) degeneracy! How can we break them?

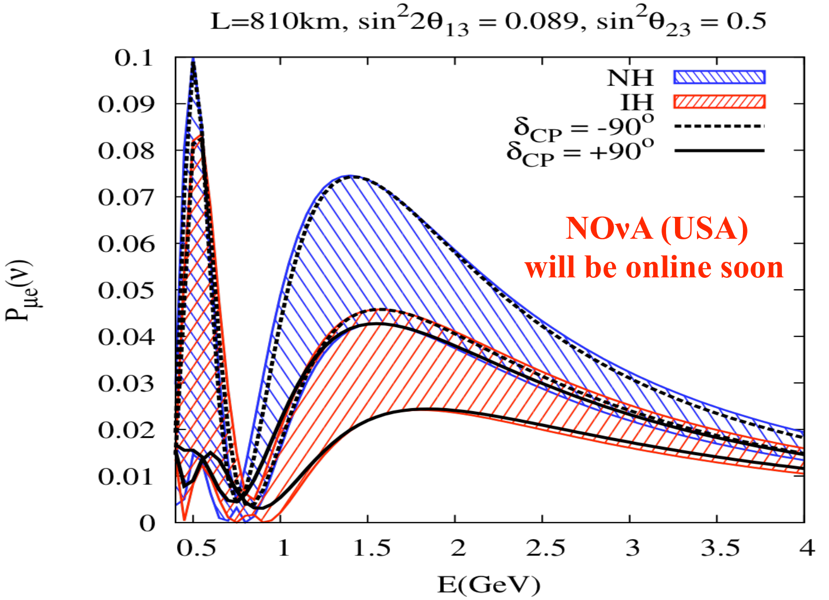
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



For ν:
Max: NH, -90°
Min: IH, 90°

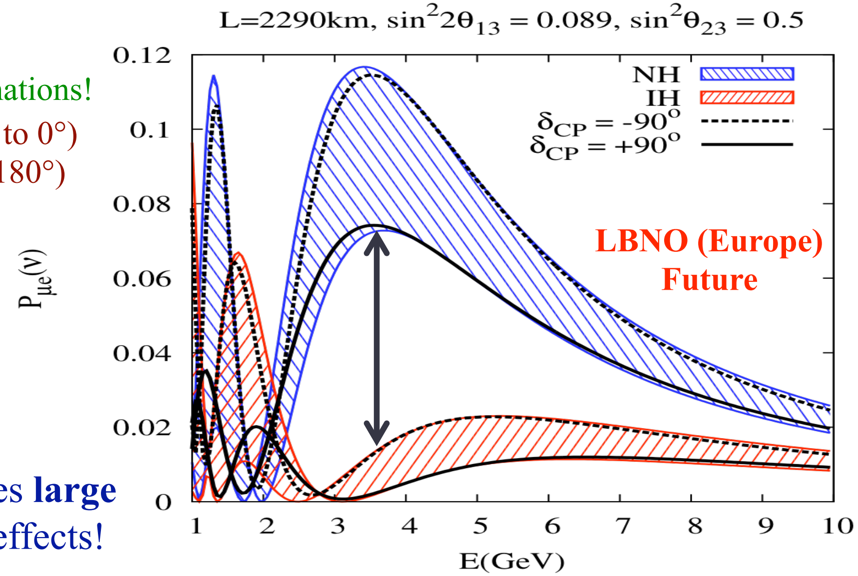


Degeneracy pattern different between T2K & NOνA



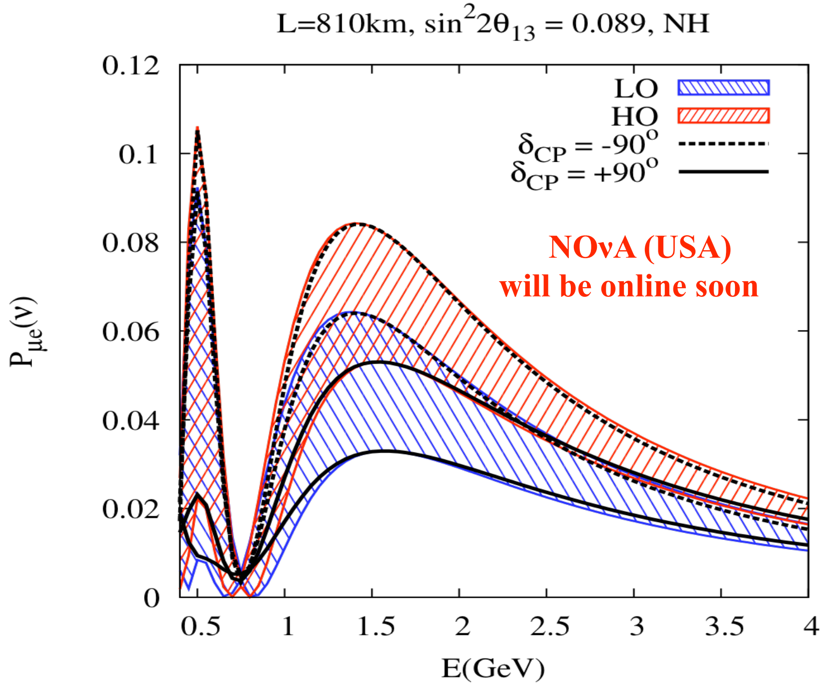
Favorable combinations!
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

Large θ_{13} causes **large** Earth matter effects!

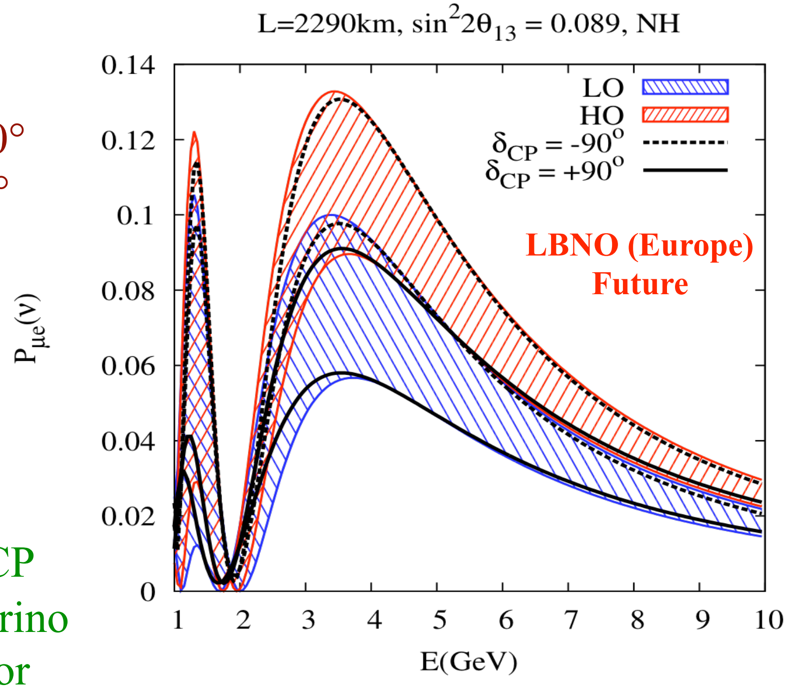


Agarwalla, Prakash, Raut, Sankar, 2012-2013

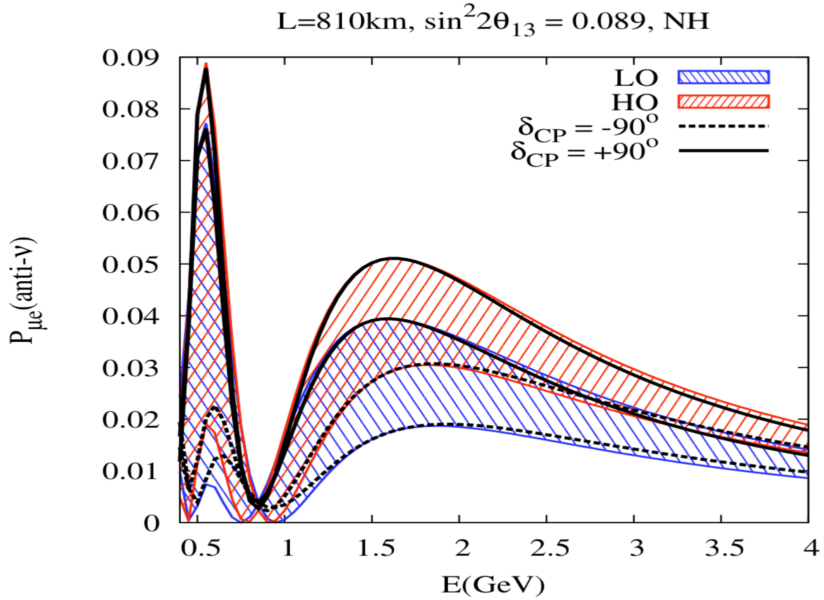
Octant – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



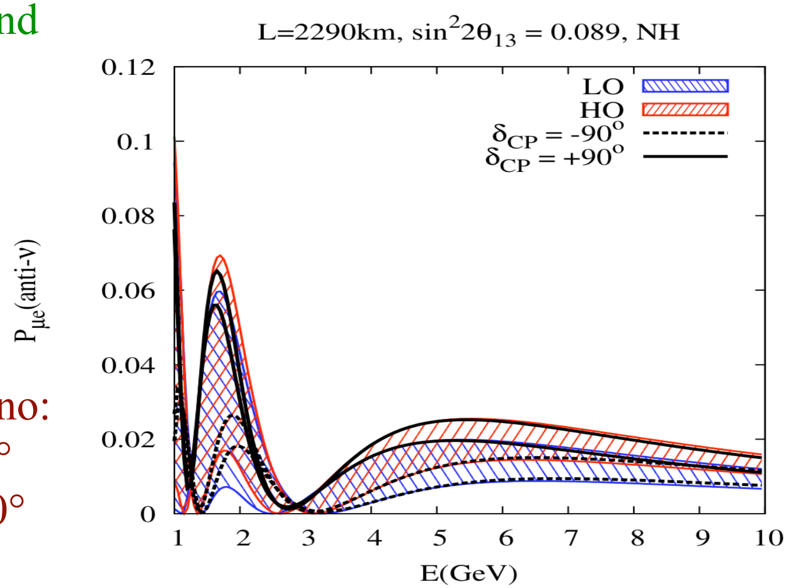
For ν:
Max: HO, -90°
Min: LO, 90°



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



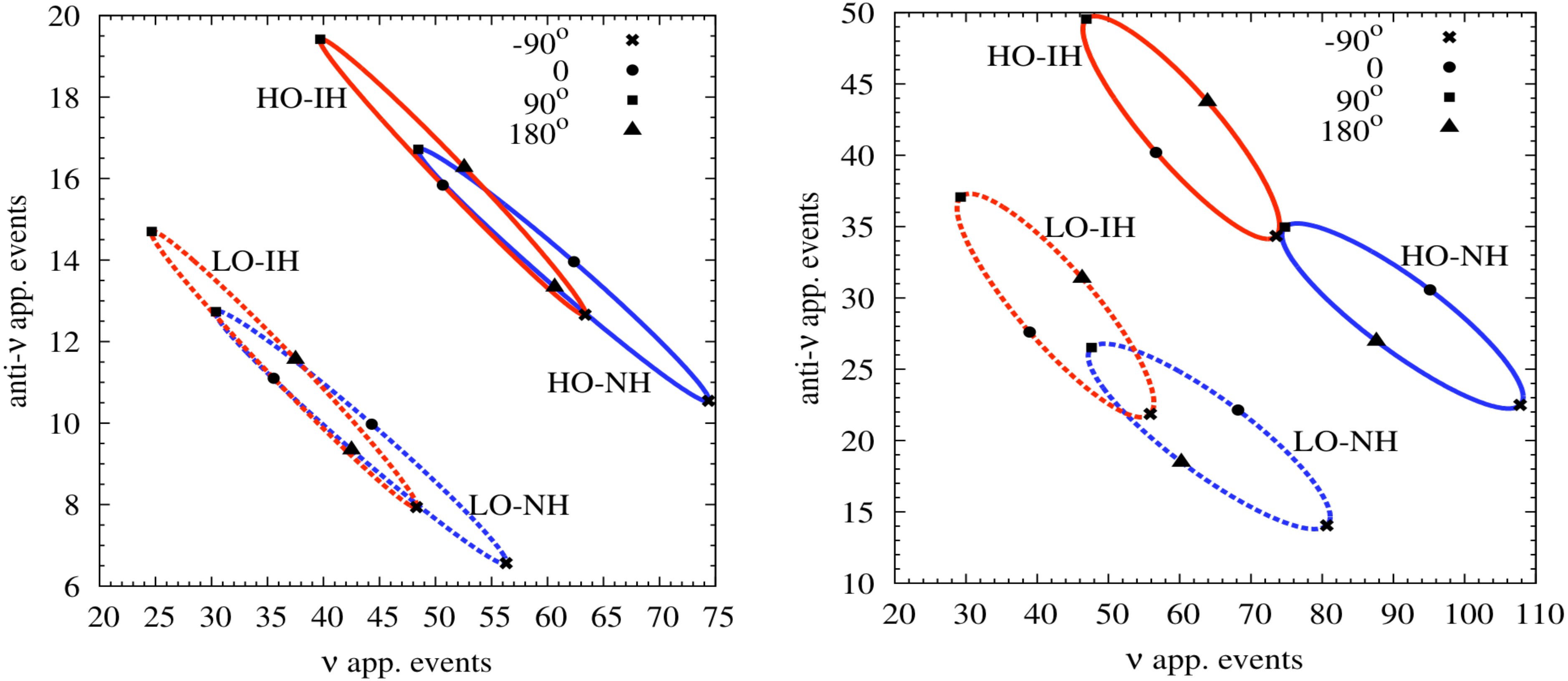
For anti-neutrino:
Max: HO, 90°
Min: LO, -90°



Agarwalla, Prakash, Sankar, 2013

Bi-Event Plots for T2K and NOνA

T2K[2.5+2.5] T2K & NOνA: both off-axis experiments NOνA[3+3]



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

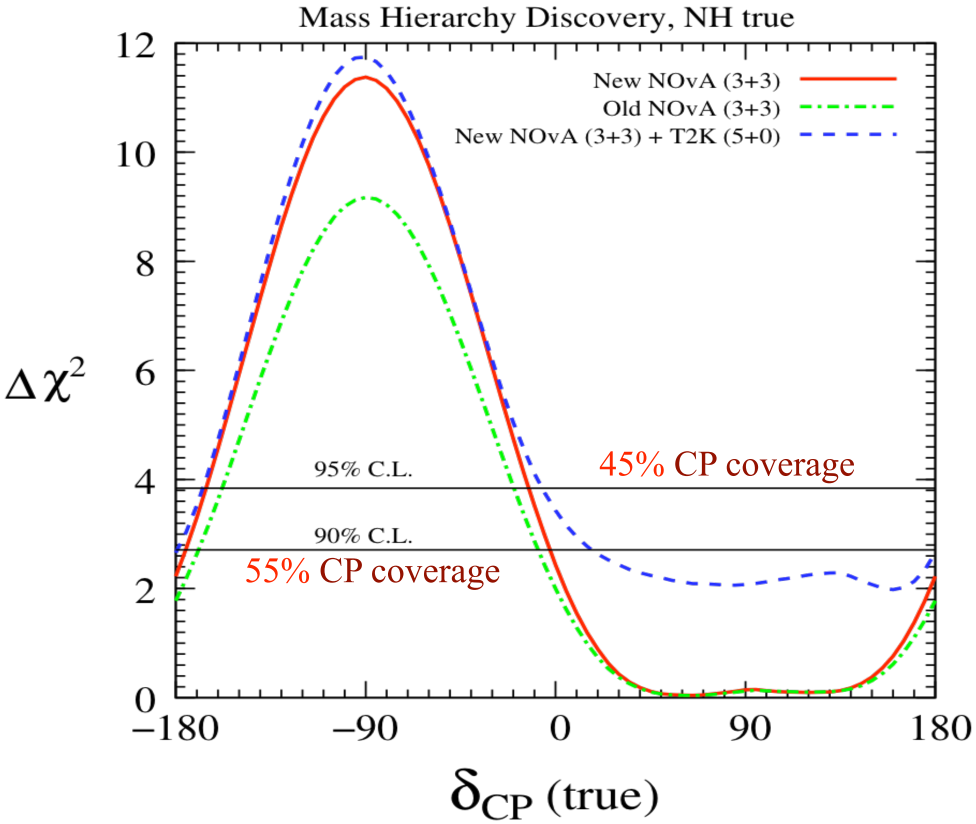
ν vs. anti-ν events for various octant-hierarchy combinations, ellipses due to varying δ_{CP}!

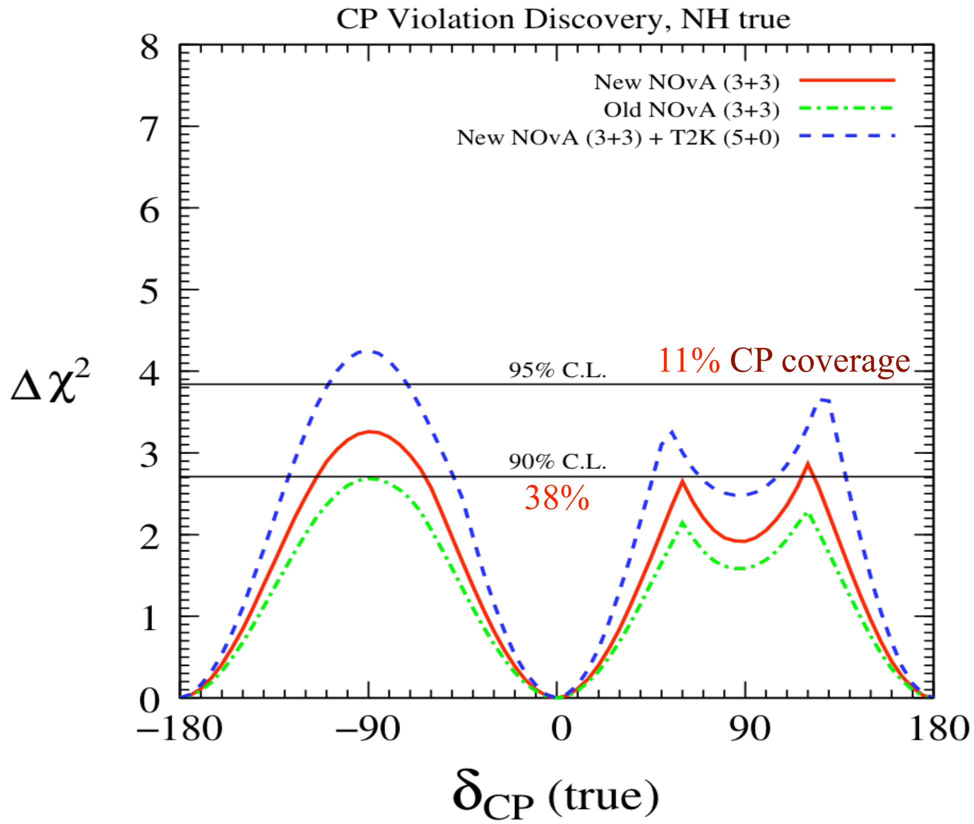
If δ_{CP} = -90° (90°), the asymmetry between ν and anti-ν events is largest for NH (IH)

Hierarchy discovery: data from two experiments with widely different baselines mandatory!

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

Mass Hierarchy & CP Violation Discovery with T2K and NOvA





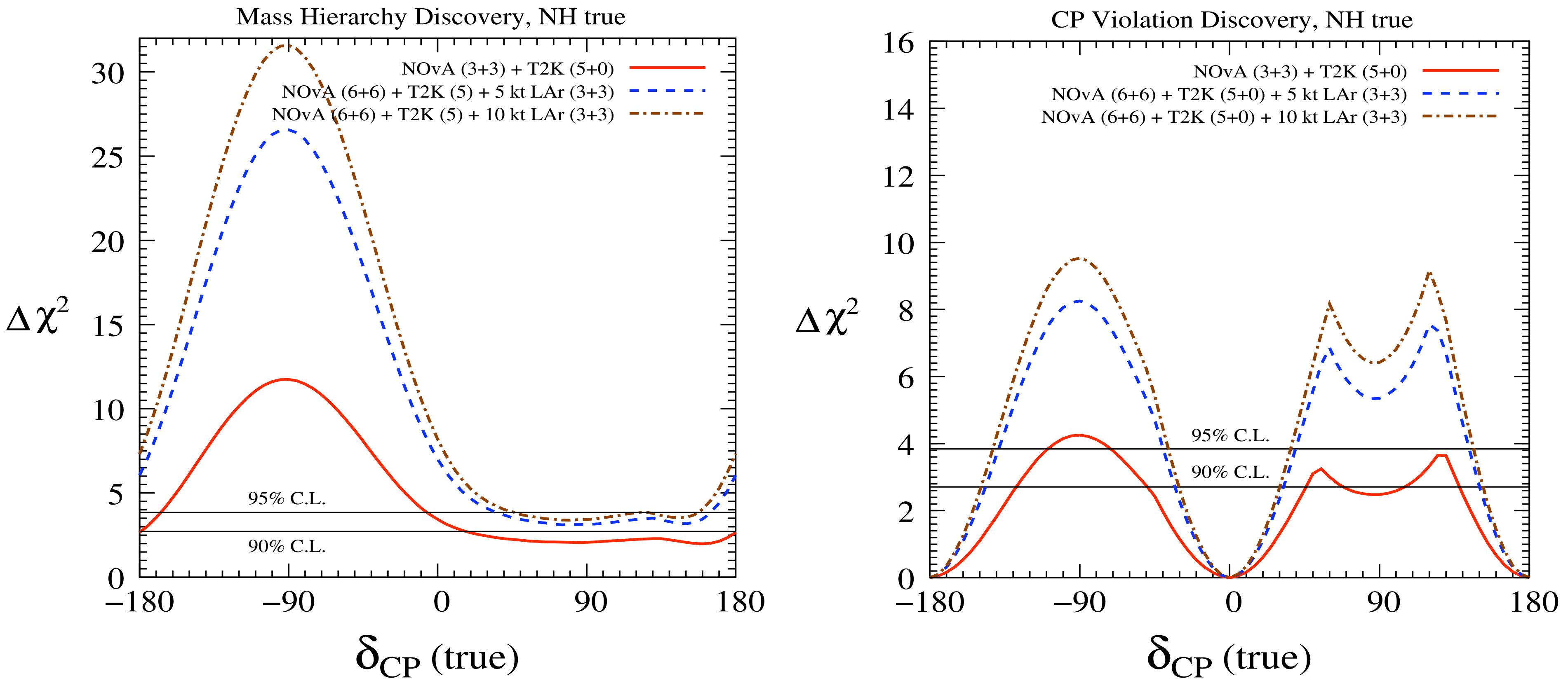
Agarwalla, Prakash, Raut, Sankar, JHEP 1212, 075 (2012)

For large θ_{13}, NOνA has reoptimized its event selection criteria. Relaxing the cuts, they now allow more events in both signal and background. Additional NC backgrounds are reconstructed at lower energies and can be managed by a kinematical cut!

Adding data from T2K and NOνA is useful to kill the intrinsic degeneracies!

CP asymmetry $\propto 1/\sin 2\theta_{13}$, large θ_{13} increases statistics but reduces asymmetry, Systematics are important!

Add a small LArTPC in the NOνA Beam Line



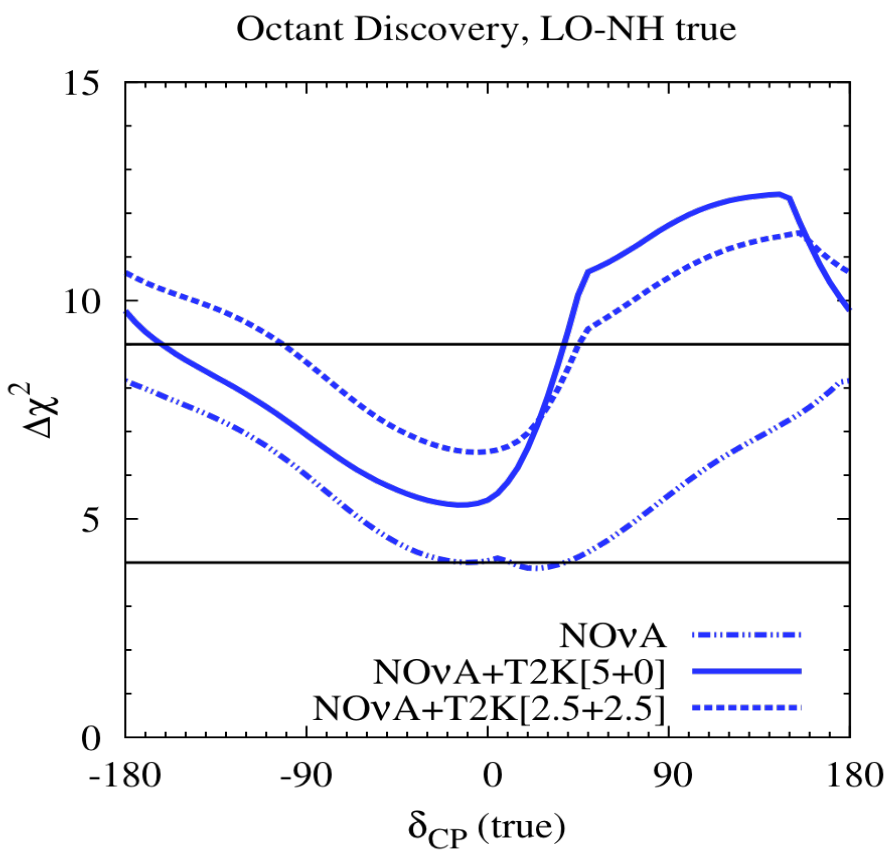
Agarwalla, Prakash, Raut, Sankar, JHEP 1212, 075 (2012)

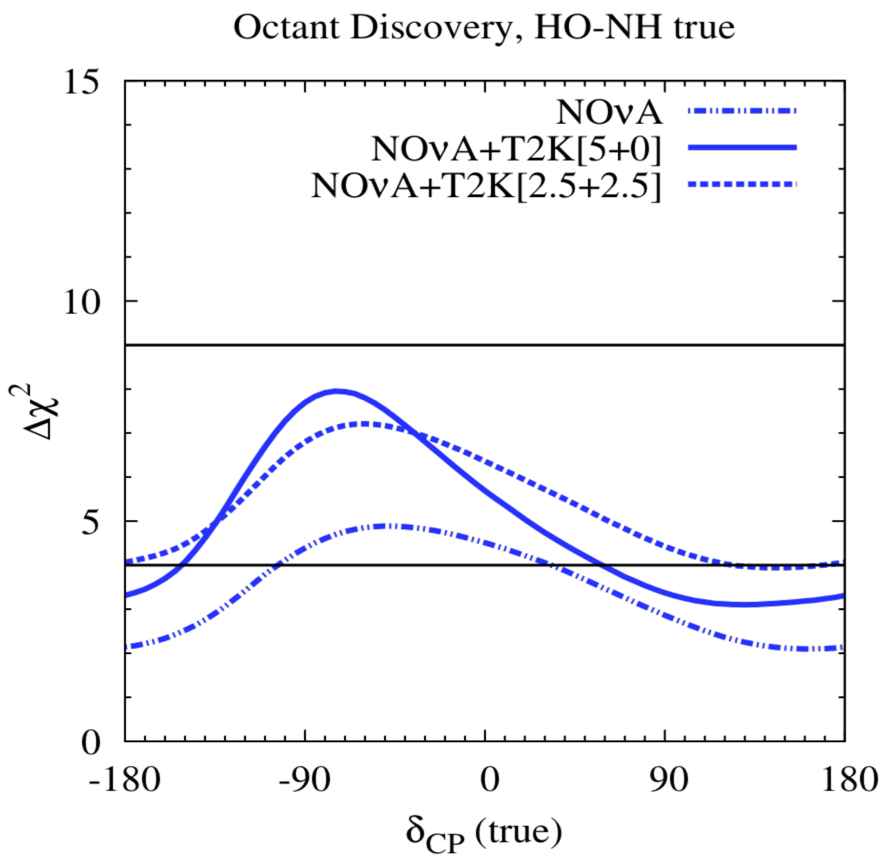
Add a small LArTPC (5 to 10 kton) in the NOνA Beam Line taking data simultaneously!

Mass Hierarchy: 100% CP coverage @ 90% C.L. & 64% CP coverage @ 95% C.L. w/ 5 kt LArTPC

CP Violation: 64% CP coverage @ 90% C.L. & 56% CP coverage @ 95% C.L. w/ 5 kt LArTPC

Resolving Octant of θ_{23} with T2K and NOνA



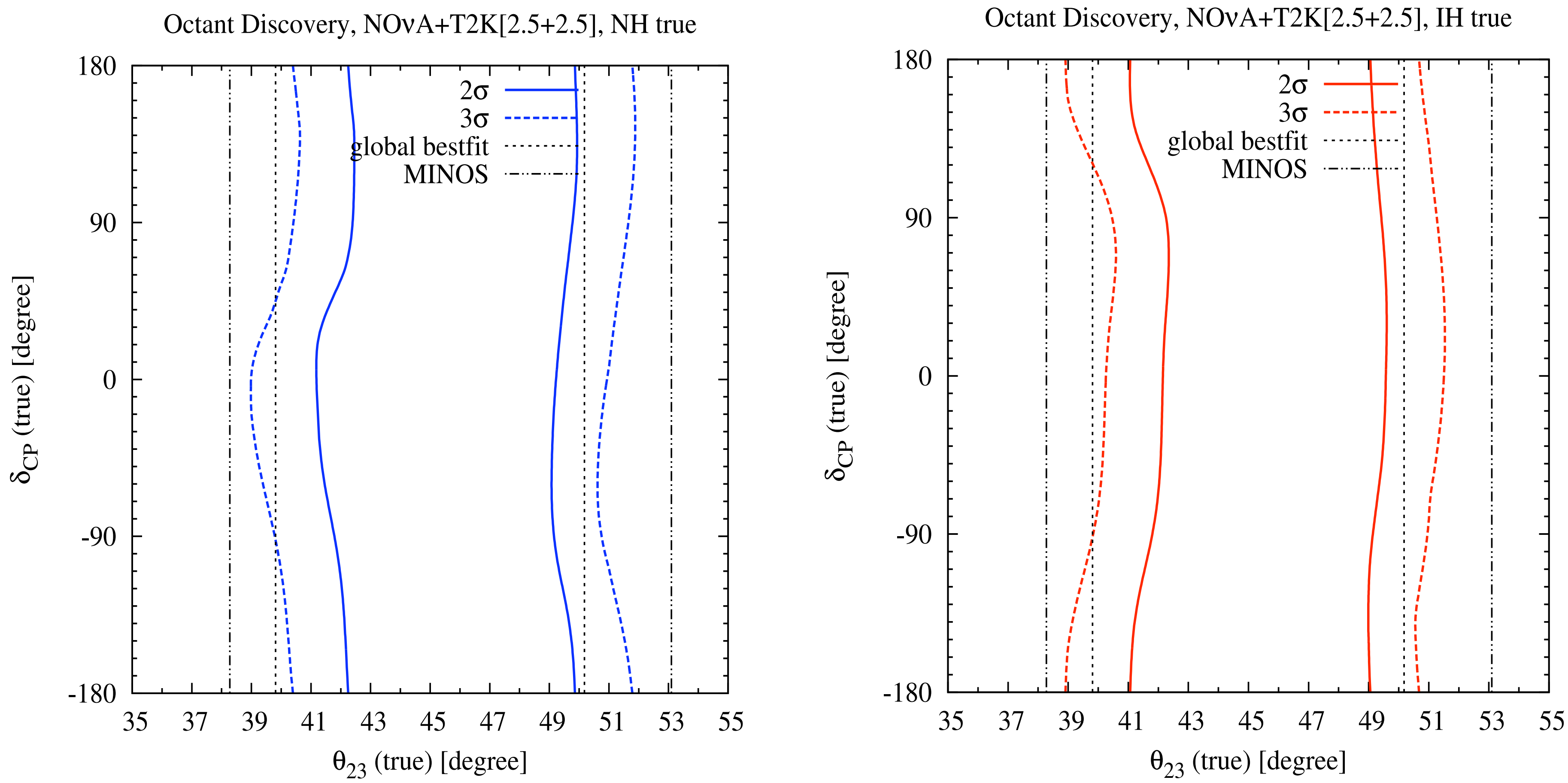


Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

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 & NOvA



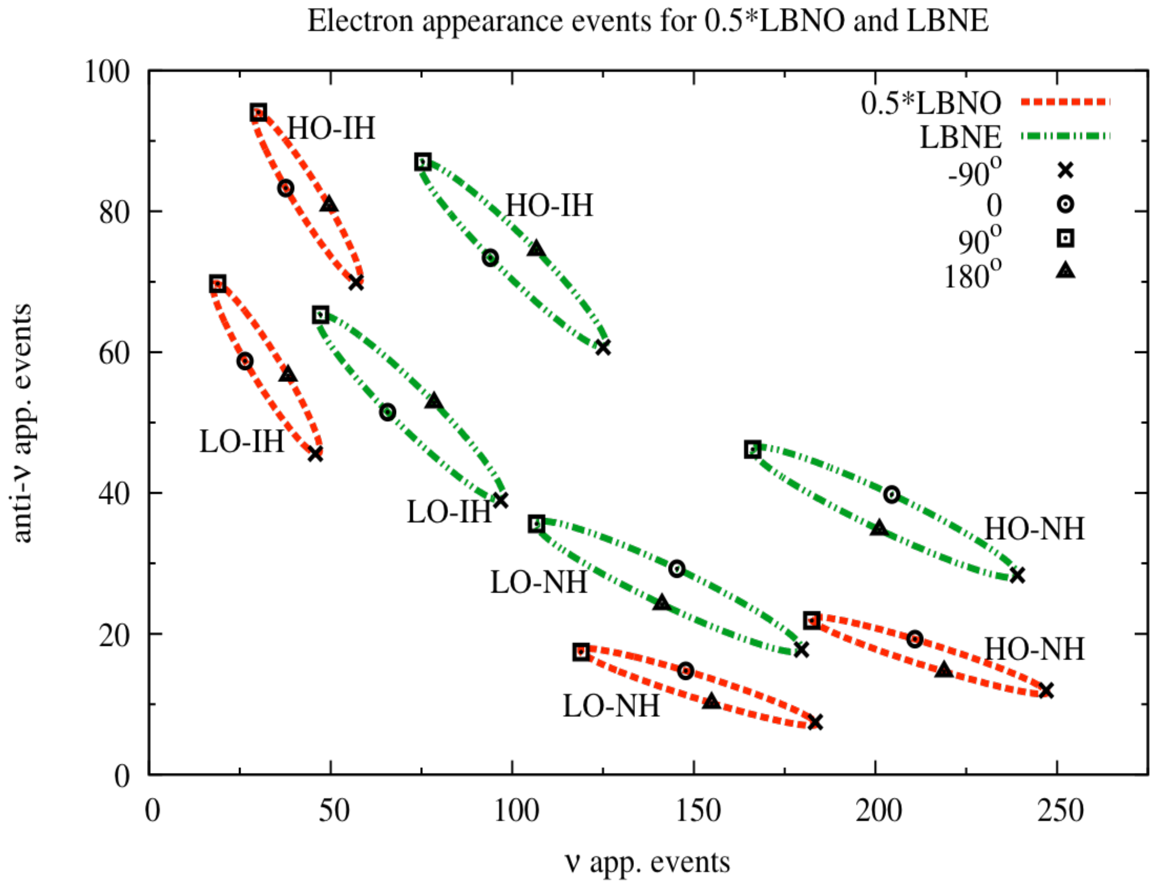
Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]

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



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

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

0.5*LBNO: 2 (LO/HO)-IH ellipses well separated from 2 (LO/HO)-NH ellipses! Excellent hierarchy discrimination capability with just neutrino data!

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

LBNE: FNAL-Homestake (1300 km)
708 kW beam power, 10 kt LArTPC

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

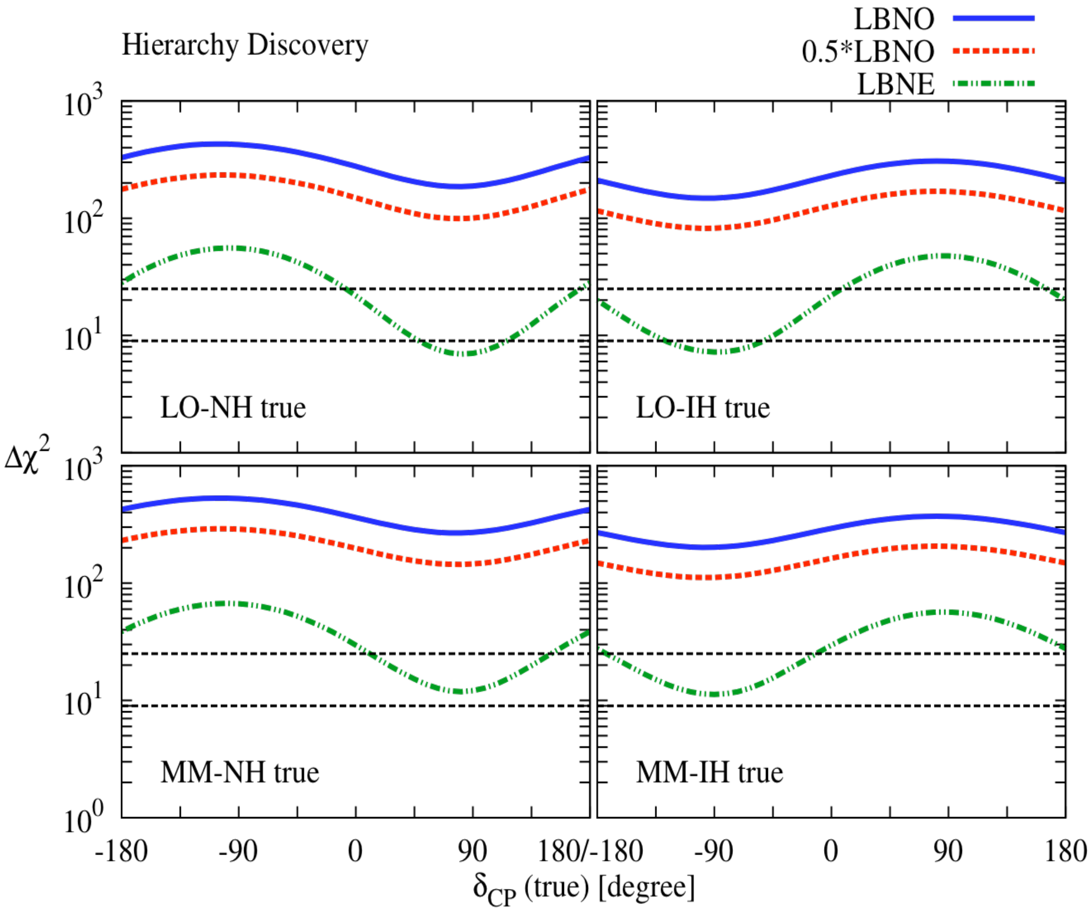
Octant determination in LBNE is similar to 0.5*LBNO!

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

Hierarchy Discovery with LBNE and LBNO



Mass hierarchy issue need to be resolved at high C.L. before we look for CPV discovery!

First phases of LBNE & LBNO: limited reach for CPV, only for 10-20% of the entire range, at 3σ C.L.!

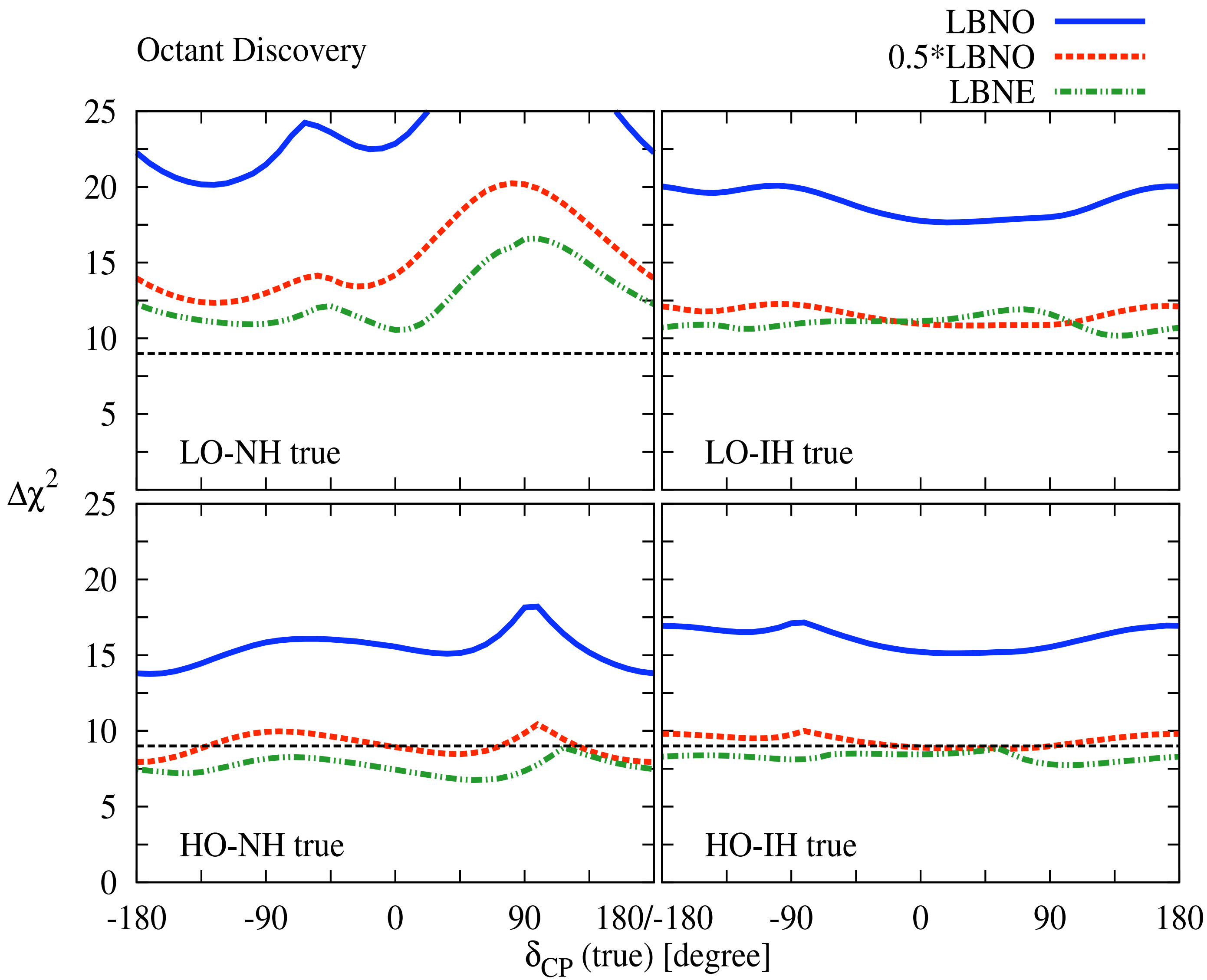
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

Even a 50% scaled down version of LBNO has a ~ 10σ hierarchy discovery potential for all octant-hierarchy combinations and for any δ_{CP}!

LBNE in its first phase will not provide a 5σ hierarchy discovery for about 50% of the δ_{CP} range!

If NOνA indicates unfavorable hierarchy-δ_{CP} choice, LBNE must increase their exposure in first phase!

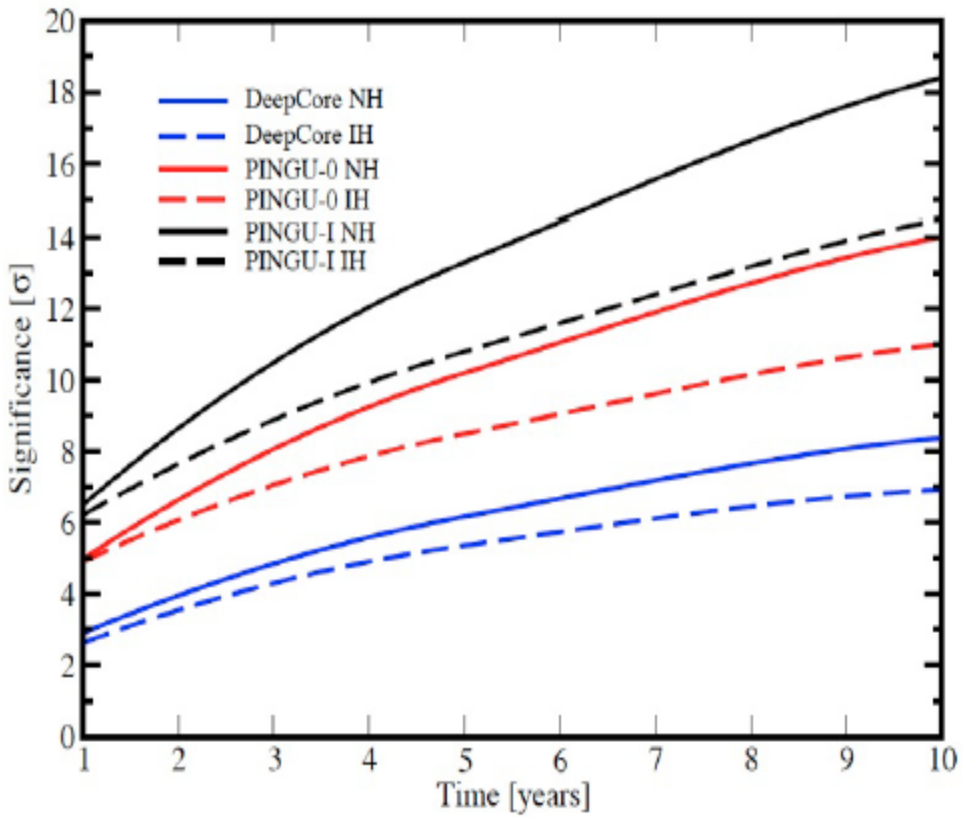
Octant Discovery with LBNE and LBNO



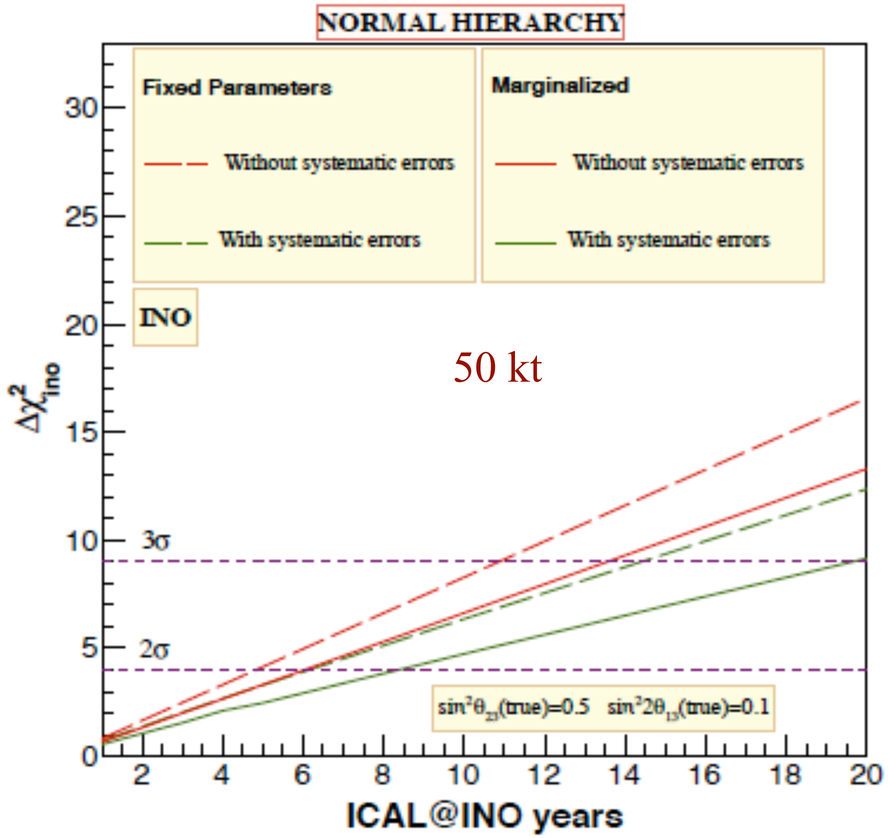
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

For octant: 4σ discovery for LBNO and 3σ for LBNE!

Mass Hierarchy Discovery with Atmospheric Neutrinos



Agarwalla, Li, Mena, Palomares-Ruiz, arXiv:1212.1305 [hep-ph]



Ghosh, Thakore, Choubey, arXiv:1212.1305 [hep-ph]

DeepCore: 1 energy bin
10-15 GeV

PINGU-0: 2 energy bins
5-10 and 10-15 GeV

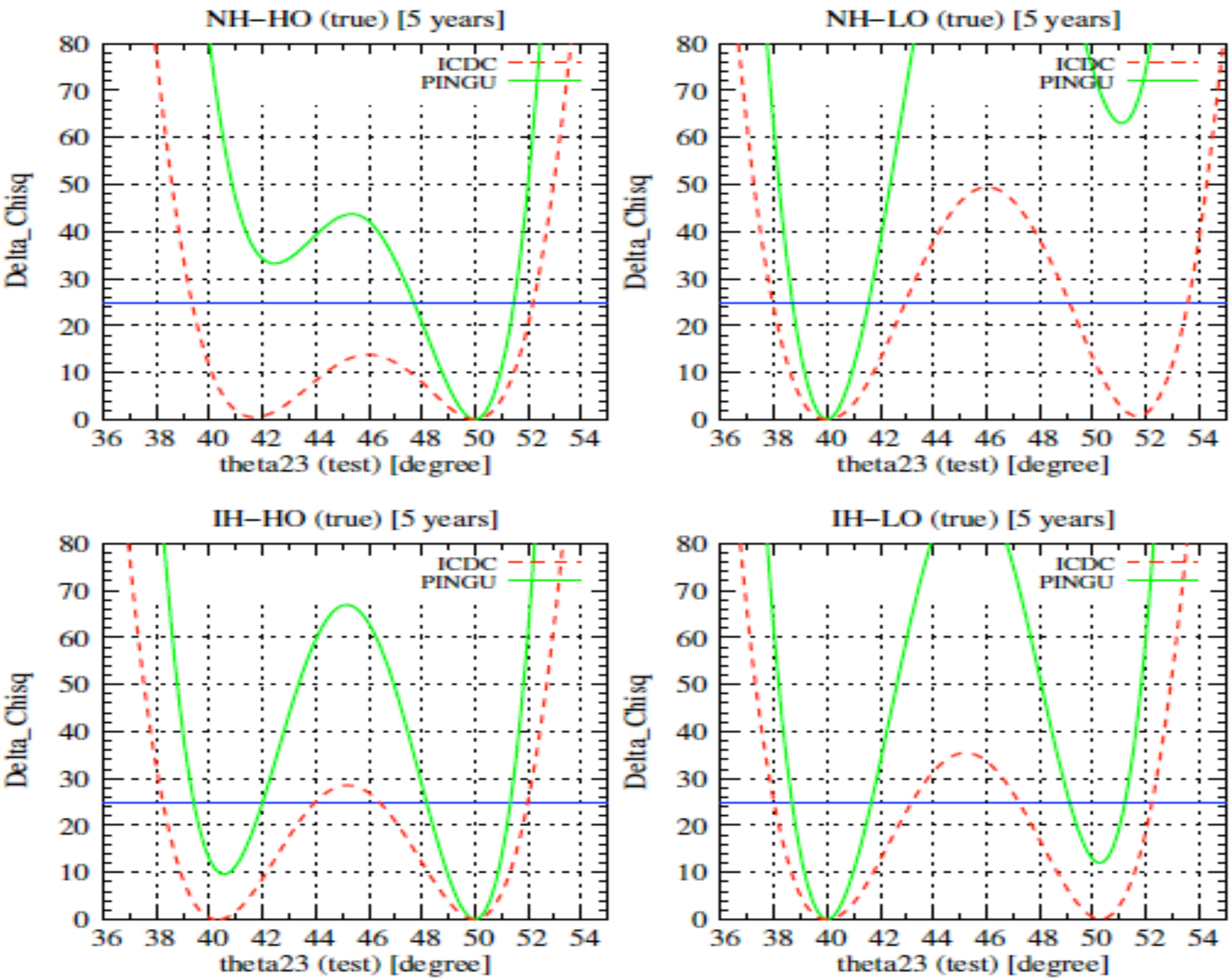
PINGU-I: 4 energy bins
5-7.5, 7.5-10,
10-12.5, 12.5-15 GeV

10 angular bins
$\Delta\cos\theta = 0.1$ for $\cos\theta = [-1,0]$

Muon energy range:
1 to 11 GeV with a bin-size of 1 GeV

Zenith angle range in $\cos\theta$:
-1 to 1 with a bin size of 0.1

Octant Discovery with Atmospheric Neutrinos



Agarwalla, Mena, Palomares-Ruiz, work in progress

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!

Current experiments (T2K and NOνA) are now poised to probe the impact of full 3 flavor effects to discover neutrino mass hierarchy, CP violation & octant of θ_{23}!

Neutrino and anti-neutrino data from T2K and NOνA should be synergistically combined to kill the parameter degeneracies! They can provide a near 2σ hint for mass hierarchy and octant discovery for favorable ranges of parameters!

Future facilities are must to cover the entire parameter space at unprecedented C.L.!

In their first phase, both LBNE & LBNO will have a very limited reach for CP violation discovery. Therefore, for them, the first step would be to focus on hierarchy and octant measurements!

Concluding Remarks (continued)

A 50% scaled down version of LBNO has a ~ 10σ hierarchy discovery potential for all octant-hierarchy combinations and for any δ_{CP} value!

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

LBNE10 suffers in this regard and will not provide a 5σ result for about 50% of the CP range. Moreover, it fails to provide even a 3σ hierarchy discovery for LO and the worst case combinations!

For octant, both the set-ups have reasonable sensitivities; about 4σ for LBNO and 3σ for LBNE!

If the data from NOνA indicates an unfavorable hierarchy – δ_{CP} combination, then LBNE must plan to increase their exposure in the first phase itself so as to have a hierarchy measurement at a high C.L.!

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

THANK YOU FOR YOUR ATTENTION!