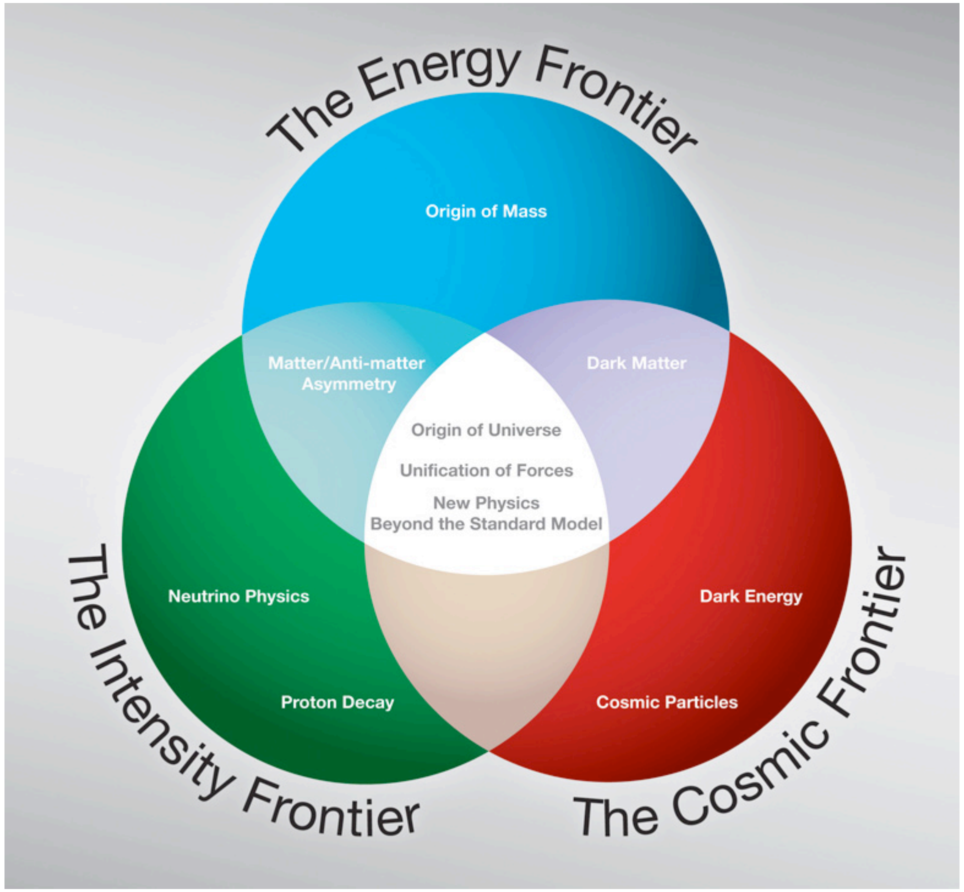
Neutrino Oscillation Experiments: Latest Results & Future Roadmap

Sanjib Kumar Agarwalla

sanjib@iopb.res.in

Institute of Physics, Bhubaneswar, India

Big News: Discovery of θ_{13}



WHEPP 2013 is very crucial & memorable

Exciting results from all the three frontiers

The Energy Frontier:
Discovery of Higgs at LHC

The Intensity Frontier:
Discovery of θ_{13}

The Cosmic Frontier:
High Precision Planck measurements

Discovery of moderately large value of θ_{13} has crucial consequences for future theoretical and experimental efforts

Non-zero θ_{13} is the gateway to discover leptonic CP violation & to measure δ_{CP}

Neutrino Physics: An Exercise in Patience

Three most fundamental questions were being asked in the past century…

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

Planck + BAO + WMAP polarization data: upper limit of 0.23 eV for the sum of ν 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)]

Last question positively answered only in recent years. Now an established fact that **neutrinos are massive** and leptonic flavors are not **symmetries of Nature**!

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

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

Neutrino Oscillations in 3 Flavors

It happens because flavor (weak) eigenstates do not coincide with mass eigenstates

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by
Atoms. ν and ν beam

θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by
Reactor and solar ν

Three mixing angles: θ_{23} , θ_{13} , θ_{12} and one CP violating (Dirac) phase δ_{CP}

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

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

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

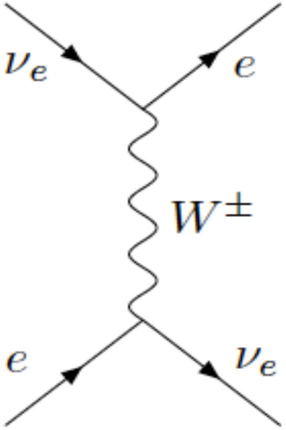
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij}$$

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

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

2 independent mass splittings Δm^2_{21} and Δm^2_{32} , for anti-neutrinos replace δ_{CP} by $-\delta_{CP}$

Neutrino Oscillations in Matter



Neutrino propagation through matter modify the oscillations significantly

Coherent forward elastic scattering of neutrinos with matter particles

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

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

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***

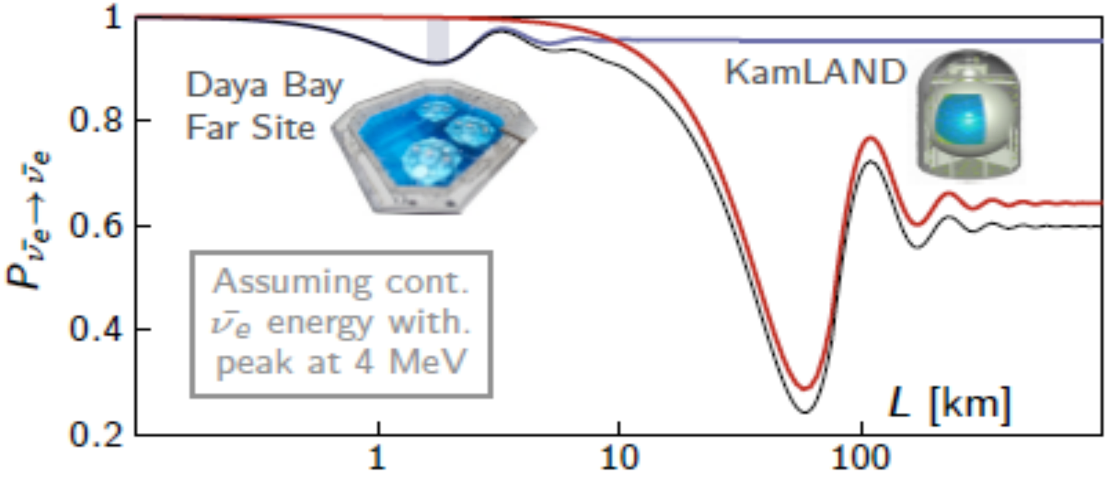
Matter term modifies oscillation probability differently depending on the sign of Δm^2

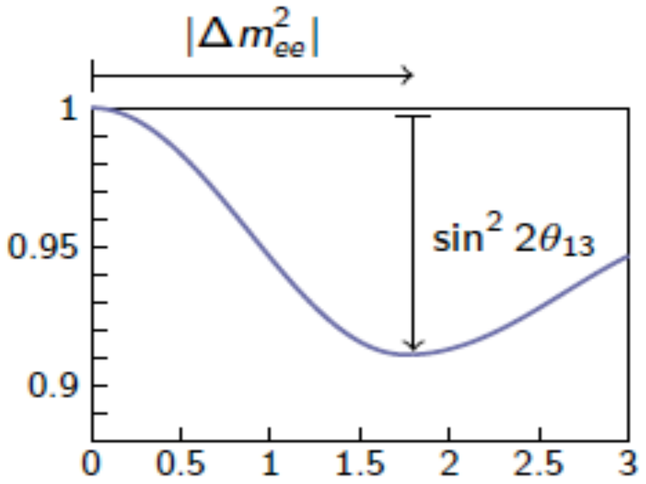
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – Matter effect***

	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)***

Short Baseline Reactor Neutrino Oscillation





θ_{13} measured by seeing the deficit of reactor anti-neutrinos at ~ 2 km

θ_{13} governs overall size of electron anti-neutrino deficit

Effective mass-squared difference $|\Delta m^2_{ee}|$ determines deficit dependence on L/E

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \underbrace{\sin^2 2\theta_{13}\sin^2\left(\Delta m^2_{ee}\frac{L}{4E}\right)}_{\text{Short Baseline}} - \underbrace{\sin^2 2\theta_{12}\cos^4 2\theta_{13}\sin^2\left(\Delta m^2_{21}\frac{L}{4E}\right)}_{\text{Long Baseline}}$$

$$\sin^2(\Delta m^2_{ee}\tfrac{L}{4E}) \equiv \cos^2\theta_{12}\sin^2(\Delta m^2_{31}\tfrac{L}{4E}) + \sin^2\theta_{12}\sin^2(\Delta m^2_{32}\tfrac{L}{4E})$$

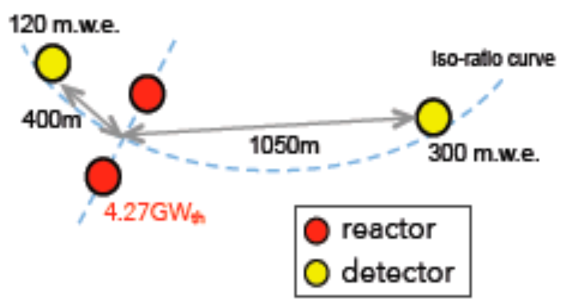
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21\times 10^{-5}\text{eV}^2$$

+: Normal Hierarchy
−: Inverted Hierarchy

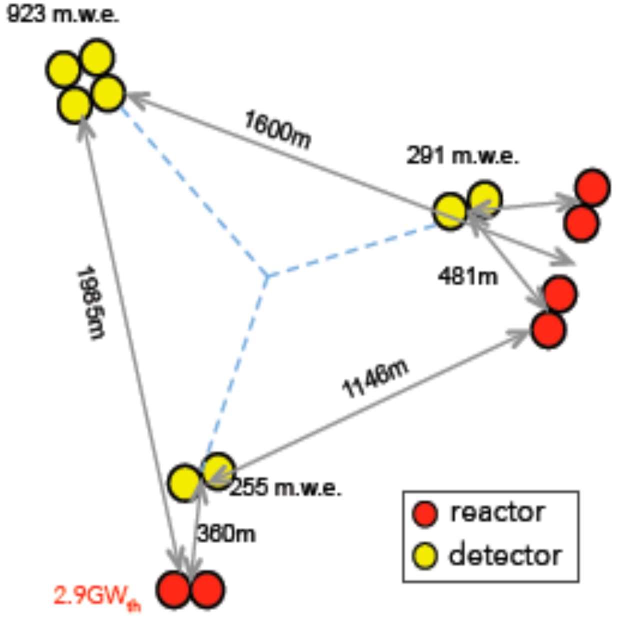
Hierarchy discrimination requires ~ 2% precision on both Δm^2_{ee} and $\Delta m^2_{\mu\mu}$

Currently Running Reactor θ_{13} Experiments

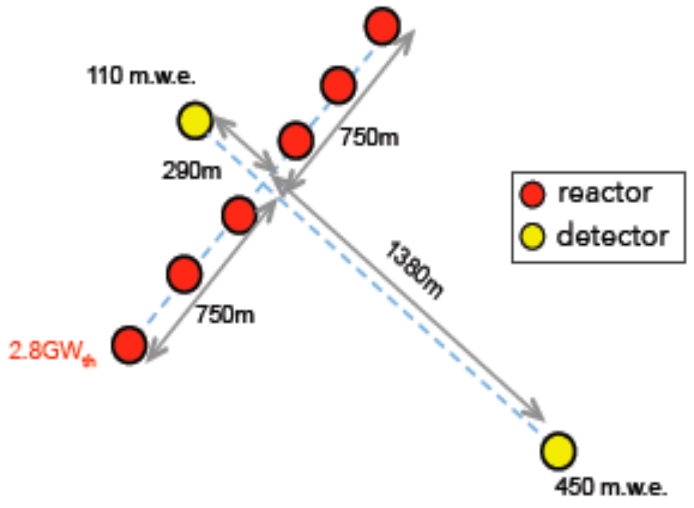
Double Chooz (France)



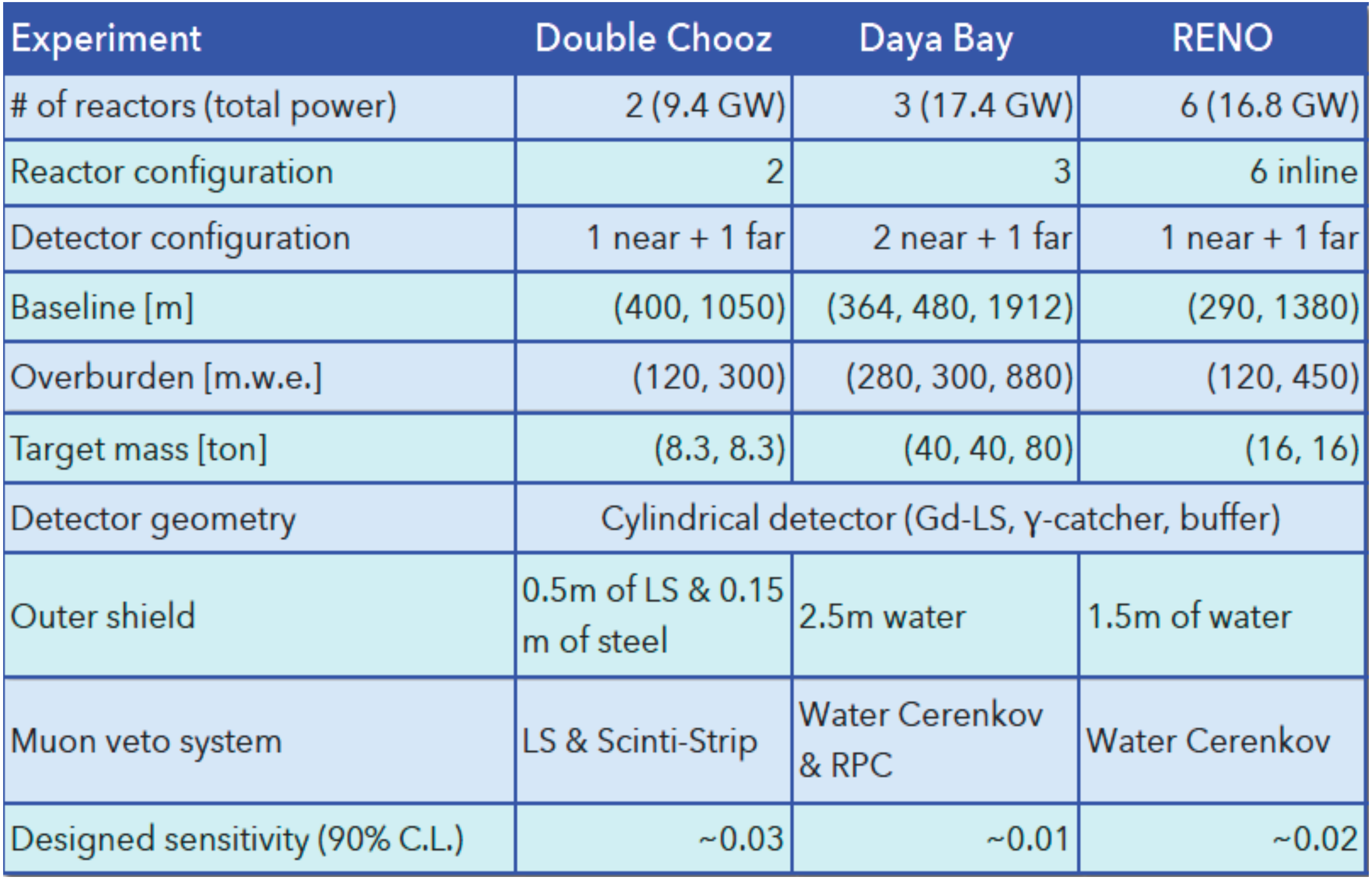
Daya Bay (China)



RENO (Korea)



Key Features of three Reactor Experiments

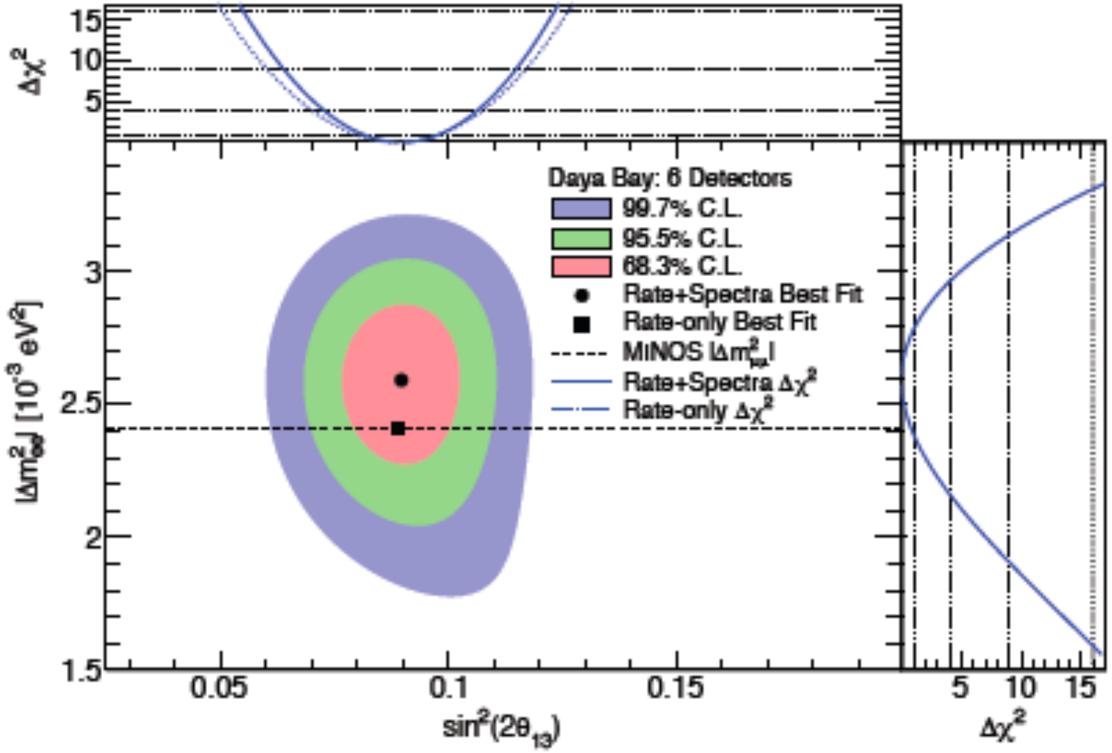


Experiment	Double Chooz	Daya Bay	RENO
# of reactors (total power)	2 (9.4 GW)	3 (17.4 GW)	6 (16.8 GW)
Reactor configuration	2	3	6 inline
Detector configuration	1 near + 1 far	2 near + 1 far	1 near + 1 far
Baseline [m]	(400, 1050)	(364, 480, 1912)	(290, 1380)
Overburden [m.w.e.]	(120, 300)	(280, 300, 880)	(120, 450)
Target mass [ton]	(8.3, 8.3)	(40, 40, 80)	(16, 16)
Detector geometry	Cylindrical detector (Gd-LS, γ-catcher, buffer)		
Outer shield	0.5m of LS & 0.15 m of steel	2.5m water	1.5m of water
Muon veto system	LS & Scinti-Strip	Water Cerenkov & RPC	Water Cerenkov
Designed sensitivity (90% C.L.)	~0.03	~0.01	~0.02

Daya Bay Strategy: Go strong, big and deep!

Latest Results from Daya Bay

Rate + Spectra Oscillation Results [arXiv:1310.6732]



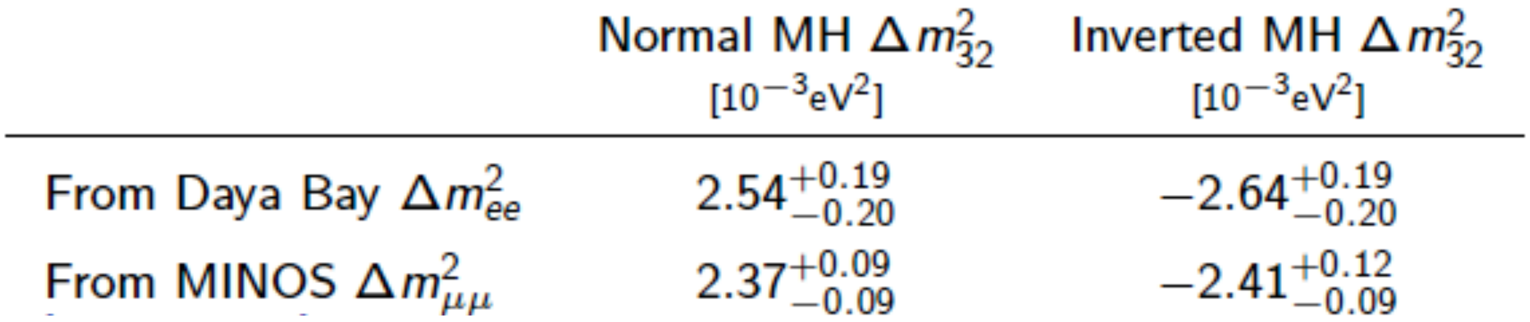
$\sin^2 2\theta_{13} = 0.090^{+0.008}_{-0.009}$

$|\Delta m^2_{ee}| = 2.59^{+0.19}_{-0.20} \times 10^{-3}\ \mathrm{eV}^2$

(world's first measurement in this channel)

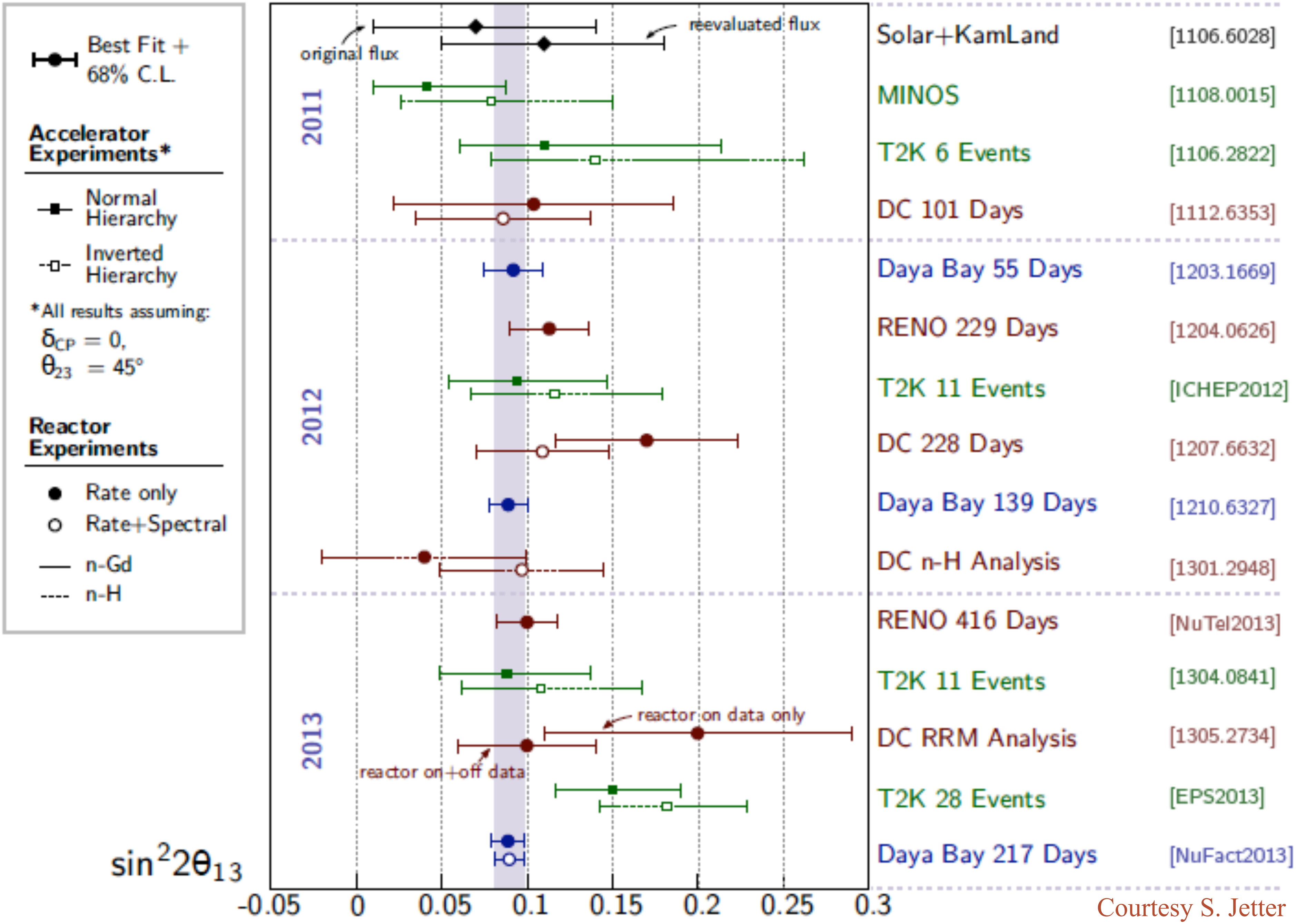
$\chi^2/N_{DoF} = 162.7/153$

Strong confirmation of oscillation-interpretation of observed $\bar{\nu_e}$ deficit



	Normal MH Δm^2_{32} $[10^{-3}\mathrm{eV}^2]$	Inverted MH Δm^2_{32} $[10^{-3}\mathrm{eV}^2]$
From Daya Bay Δm^2_{ee}	$2.54^{+0.19}_{-0.20}$	$-2.64^{+0.19}_{-0.20}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.12}_{-0.09}$

The θ_{13} Revolution



Courtesy S. Jetter

Present Understanding of the 2-3 Mixing Angle

Information on θ_{23} comes from: a) atmospheric neutrinos and b) accelerator neutrinos

In two-flavor scenario: $$P_{\mu\mu} = 1 - \sin^2 2\theta_{\rm eff} \sin^2\left(\frac{\Delta m^2_{\rm eff} L}{4E}\right)$$

For accelerator neutrinos: relate effective 2-flavor parameters with 3-flavor parameters:

$$\boxed{\Delta m^2_{\rm eff} = \Delta m^2_{31} - \Delta m^2_{21}(\cos^2\theta_{12} - \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23})}$$

$$\boxed{\sin^2 2\theta_{\rm eff} = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)}$$ where $$\boxed{\frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} = \tan^2\theta_{23}}$$

Nunokawa etal, hep-ph/0503283; A. de Gouvea etal, hep-ph/0503079

Combining beam and atmospheric data in MINOS, we have:

MINOS Collaboration: arXiv:1304.6335v2 [hep-ex]

$$\boxed{\sin^2 2\theta_{\rm eff} = 0.95^{+0.035}_{-0.036}\ (10.71 \times 10^{21}\ \text{p.o.t})}$$ $$\boxed{\sin^2 2\bar{\theta}_{\rm eff} = 0.97^{+0.03}_{-0.08}\ (3.36 \times 10^{21}\ \text{p.o.t})}$$

Atmospheric data, dominated by Super-Kamiokande, still prefers maximal value of $\sin^2 2\theta_{\rm eff} = 1$ (≥ 0.94 (90% C.L.))

Talk by Y. Itow in Neutrino 2012 conference, Kyoto, Japan

Bounds on θ_{23} from the global fits

In ν_μ survival probability, the dominant term mainly sensitive to $\sin^2 2\theta_{23}$!

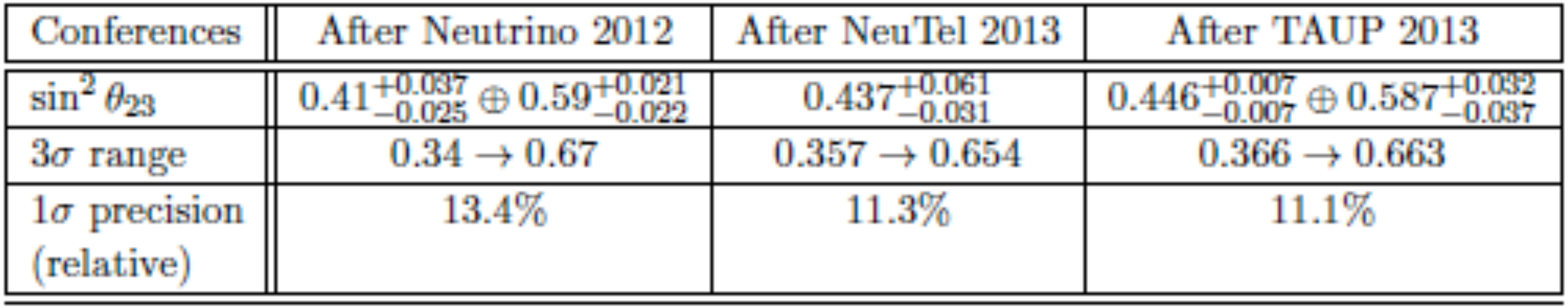
If $\sin^2 2\theta_{23}$ differs from 1 (as indicated by recent data), we get two solutions for θ_{23}:

one in lower octant (LO: $\theta_{23} < 45$ degree), other in higher octant (HO: $\theta_{23} > 45$ degree)

In other words, if $(0.5 - \sin^2\theta_{23})$ is +ve (-ve) then θ_{23} belongs to LO (HO)

This is known as the octant ambiguity of θ_{23} !

Fogli and Lisi, hep-ph/9604415



Conferences	After Neutrino 2012	After NeuTel 2013	After TAUP 2013
$\sin^2\theta_{23}$	$0.41^{+0.037}_{-0.025} \oplus 0.59^{+0.021}_{-0.022}$	$0.437^{+0.061}_{-0.031}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$
3σ range	$0.34 \to 0.67$	$0.357 \to 0.654$	$0.366 \to 0.663$
1σ precision (relative)	13.4%	11.3%	11.1%

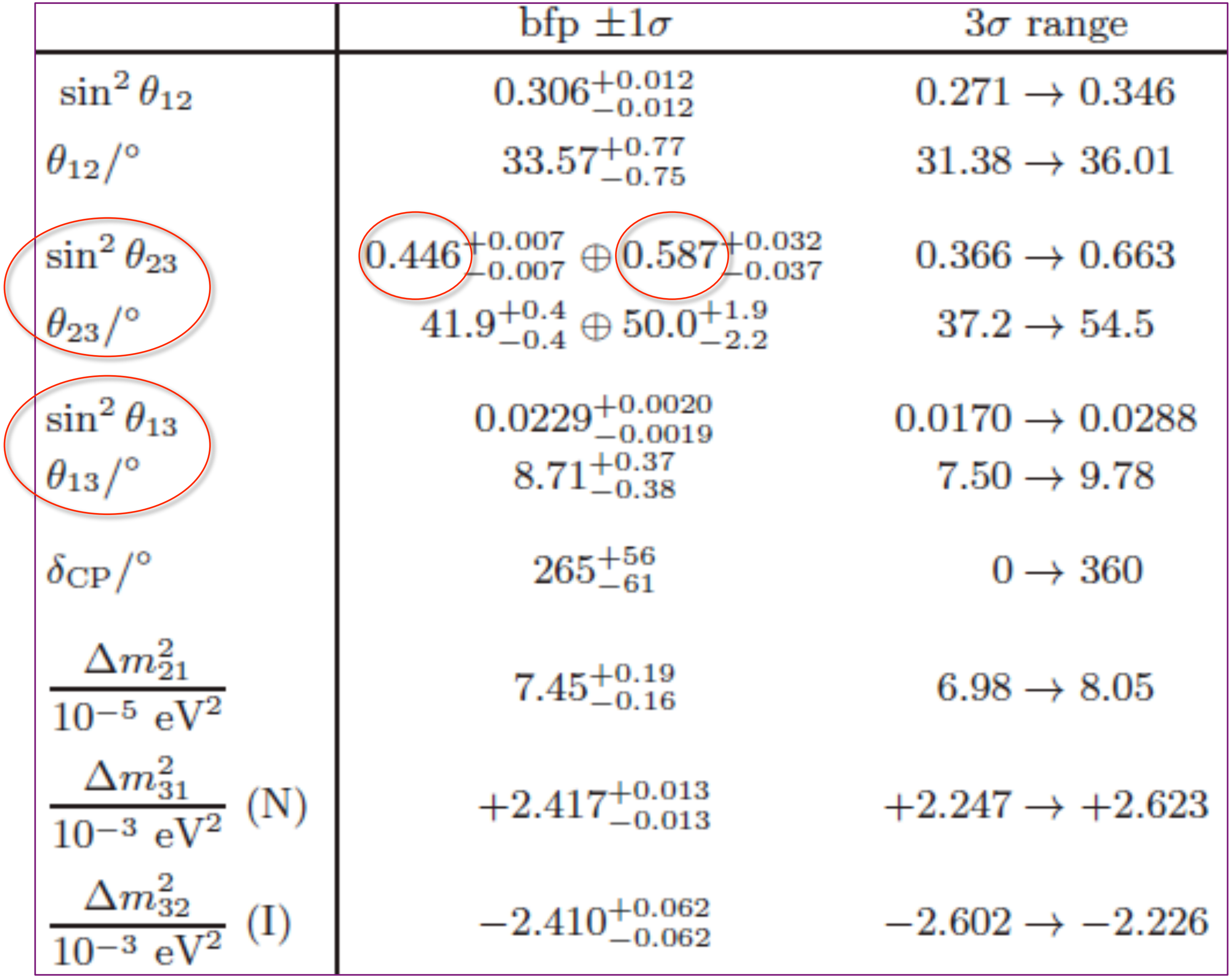
Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

Global fit disfavors maximal 2-3 mixing at 1.4σ confidence level (mostly driven by MINOS)

ν_μ to ν_e oscillation data can break this degeneracy!

The preferred value would depend on the choice of the neutrino mass hierarchy!

Present Status of Neutrino Parameters

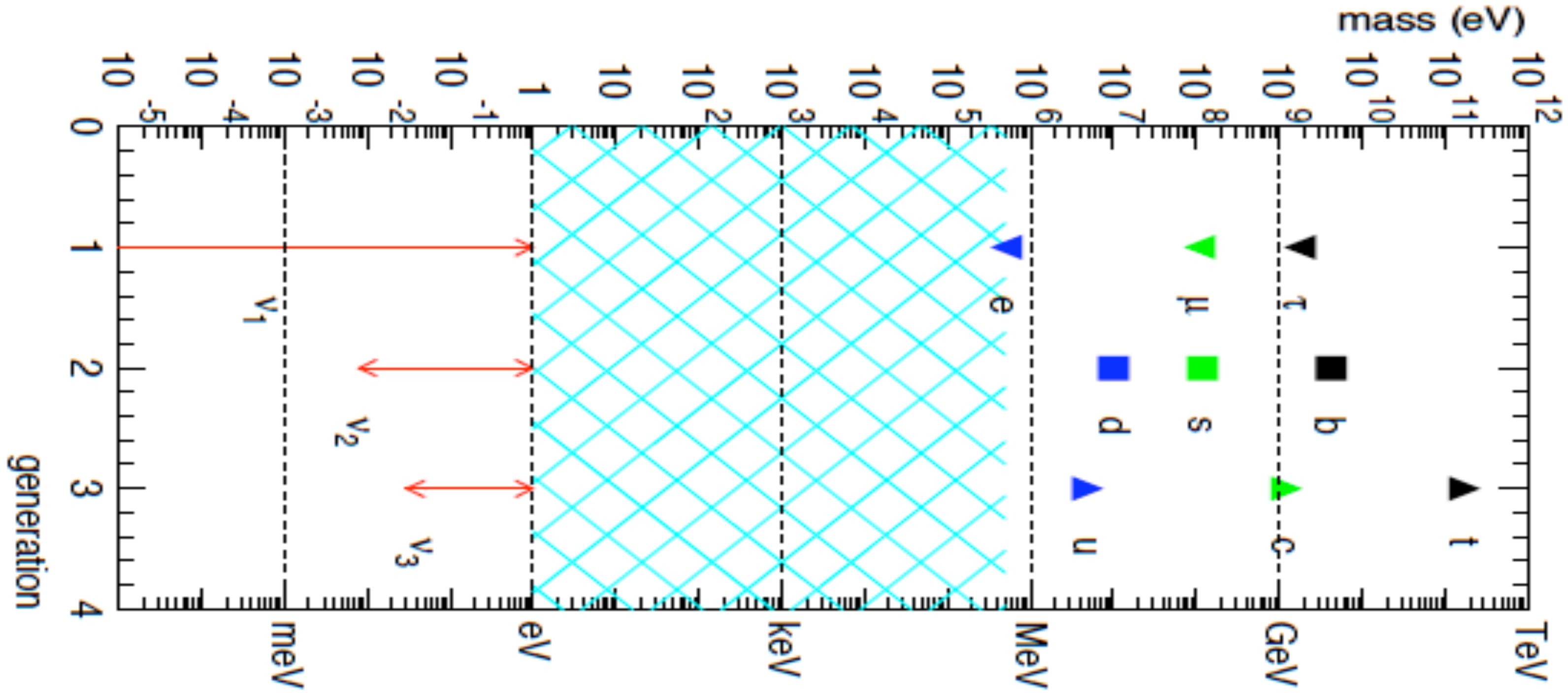


	bfp ±1σ	3σ range	Relative 1σ Precision
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.346$	4%
$\theta_{12}/^\circ$	$33.57^{+0.77}_{-0.75}$	$31.38 \to 36.01$	
$\sin^2\theta_{23}$	$0.446^{+0.007}_{-0.007} \oplus 0.587^{+0.032}_{-0.037}$	$0.366 \to 0.663$	11%
$\theta_{23}/^\circ$	$41.9^{+0.4}_{-0.4} \oplus 50.0^{+1.9}_{-2.2}$	$37.2 \to 54.5$	
$\sin^2\theta_{13}$	$0.0229^{+0.0020}_{-0.0019}$	$0.0170 \to 0.0288$	8.7%
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$	
$\delta_{\mathrm{CP}}/^\circ$	265^{+56}_{-61}	$0 \to 360$	(Not Known)
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	2.4%
$\dfrac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$	2.5%
$\dfrac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	

Based on the data available after TAUP 2013 conference

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

The Two Fundamental Questions



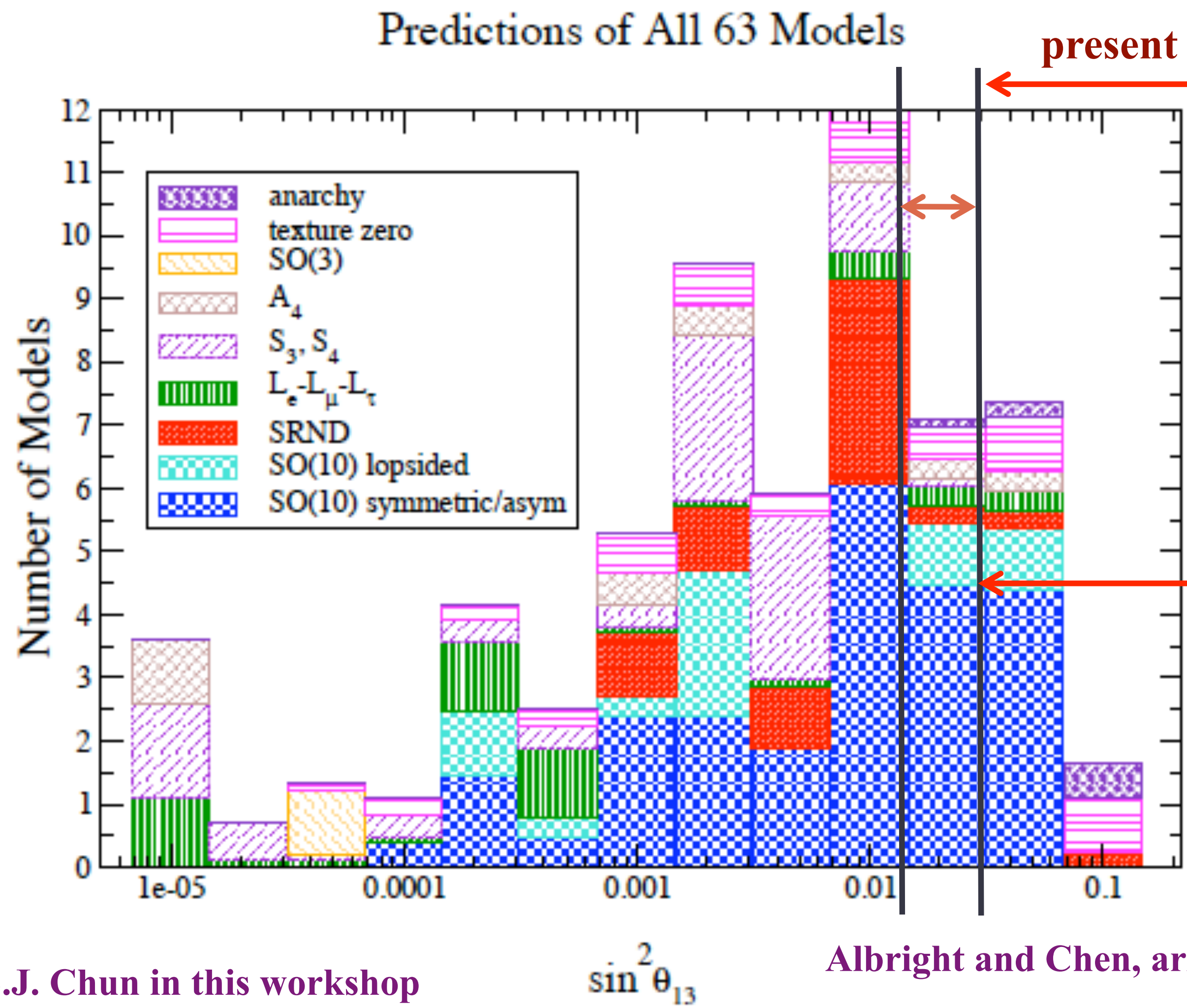
Why are neutrinos so light? The origin of Neutrino Mass!

	Neutrinos (PMNS)	Quarks (CKM)
θ_{12}	35°	13°
θ_{32}	43°	2°
θ_{13}	9°	0.2°
δ	unknown	68°

Why are lepton mixings so different from quark mixings?

The Flavor Puzzle!

Latest Results on θ_{13} : What happened to Mass models?



present 3σ range

only 7 models survived

See the talk by E.J. Chun in this workshop

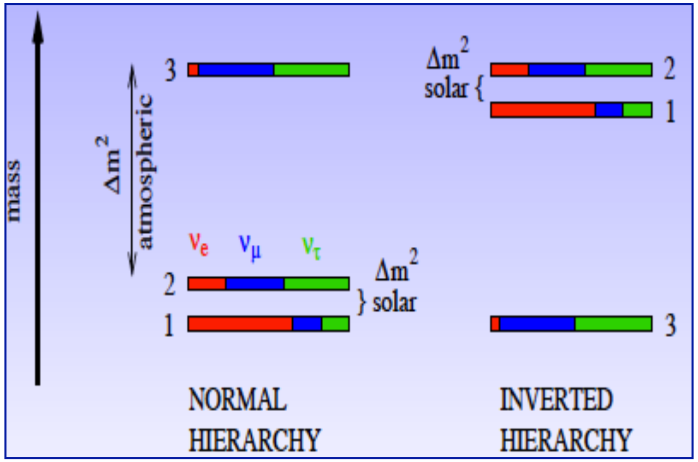
Albright and Chen, arXiv:hep-ph/0608137

Survey of 63 ν mass models in June 2006 by Carl H. Albright and Mu-Chun Chen!

Future high precision measurements of mixing angles, new information on neutrino mass ordering and CP phase will severely constrain these presently allowed models!

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 ($\theta_{23} > 45°$)?

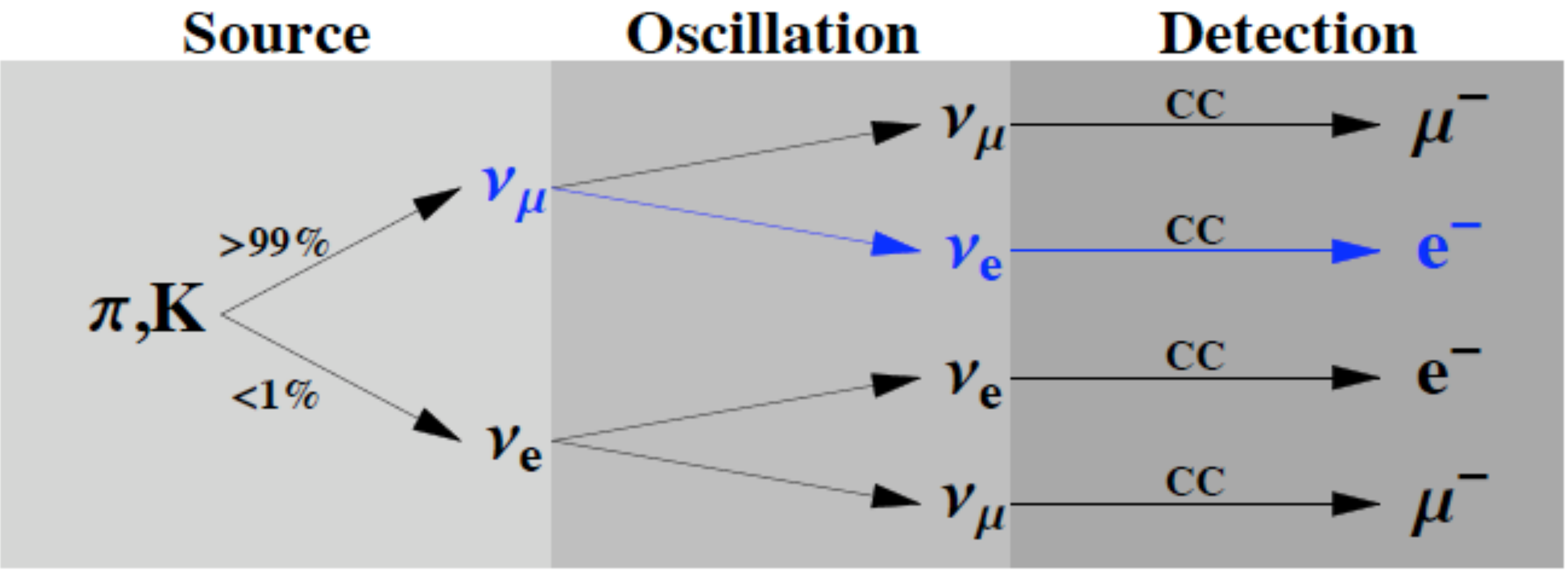
Measure θ_{23} precisely, Establish deviation from maximality at higher C.L. Then look for Octant

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 current knowledge of θ_{13}, resolving these unknowns fall within our reach!
Sub-leading 3 flavor effects are extremely crucial in current & future oscillation expts!

Superbeams



Traditional approach: Neutrino beam from pion decay

Current Generation Experiments: **Detailed discussion by S. Prakash, S. Raut in WGV**

Tokai to Kamioka (T2K) : 295 km (2.5° off-axis, 1st Osc. Max = 0.6 GeV)

J-PARC Beam: 0.75 MW, Total 7.8 × 10^{21} protons on target, 5 years ν run

Detector: Super-Kamiokande (22.5 kton fiducial volume)

FNAL to Ash River (NOνA) : 810 km (0.8° off-axis, 1st Osc. Max = 1.7 GeV)

NuMI Beam: 0.7 MW, Total 3.6 × 10^{21} protons on target, 3 yrs ν + 3 yrs anti-ν

Detector: 14 kton Totally Active Scintillator Detector (TASD)

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

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

$$
\begin{aligned}
P_{\mu e} \quad \simeq \quad & \boxed{\underbrace{\sin^2 2\theta_{13}}_{0.09}}\,\boxed{\sin^2\theta_{23}}\,\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \Rightarrow \theta_{13}\text{ Driven} \\
- \; & \boxed{\underbrace{\alpha \, \sin 2\theta_{13}}_{0.009}}\,\xi \, \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \Rightarrow \text{CP odd} \\
+ \; & \alpha \, \sin 2\theta_{13}\, \xi \, \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \Rightarrow \text{CP even} \\
+ \; & \boxed{\underbrace{\alpha^2}_{0.0009}}\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}; \Rightarrow \text{Solar Term}
\end{aligned}
$$

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 $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

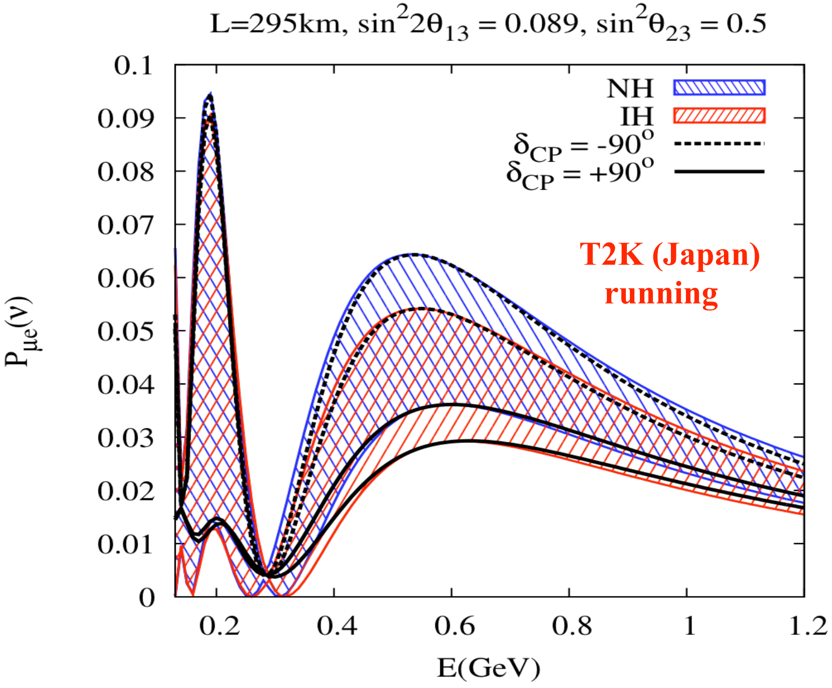
changes sign with sgn(Δm^2_{31})
key to resolve hierarchy!

changes sign with polarity
causes fake CP asymmetry!

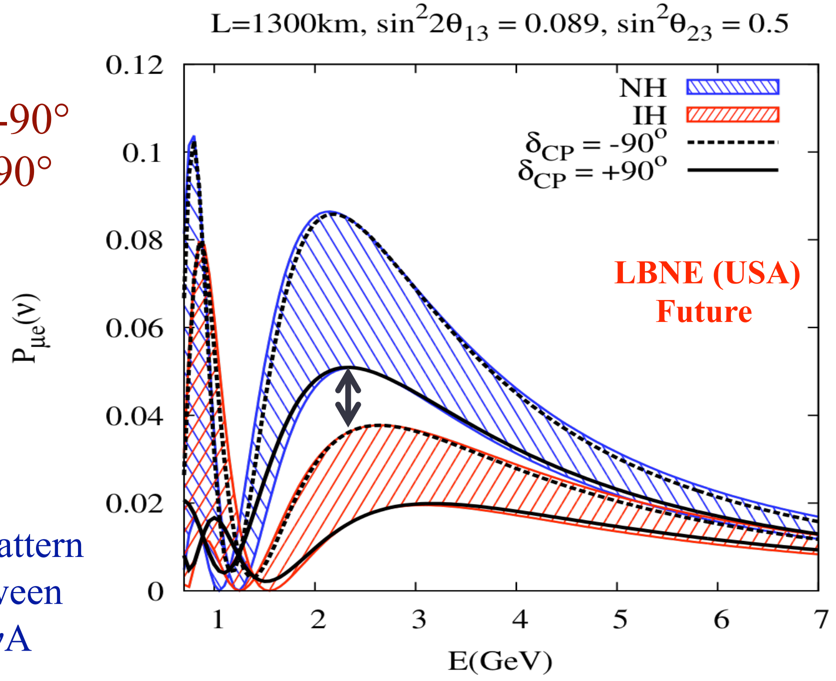
Cervera etal., hep-ph/0002108
Freund etal., hep-ph/0105071
See also, Agarwalla etal., arXiv:1302.6773 [hep-ph]

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

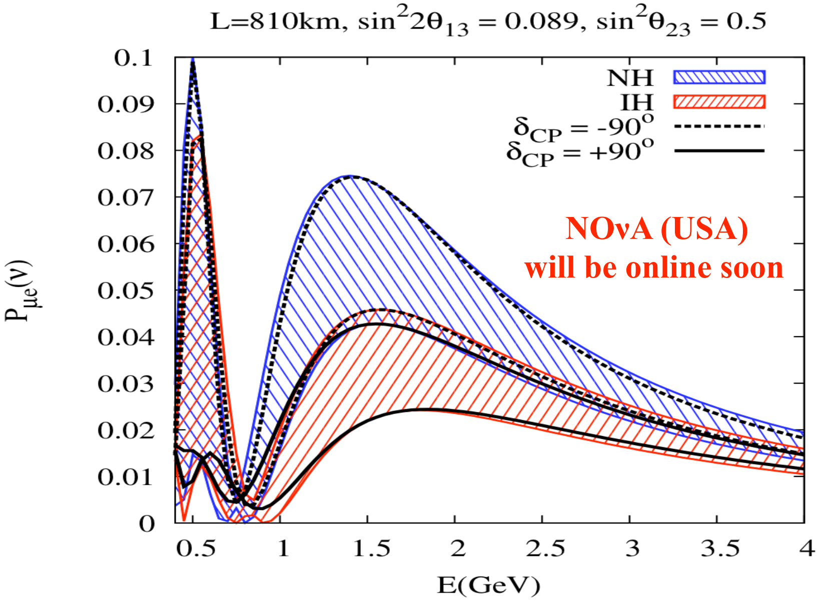
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel


L=295km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

For ν:
Max: NH, -90°
Min: IH, 90°


L=1300km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

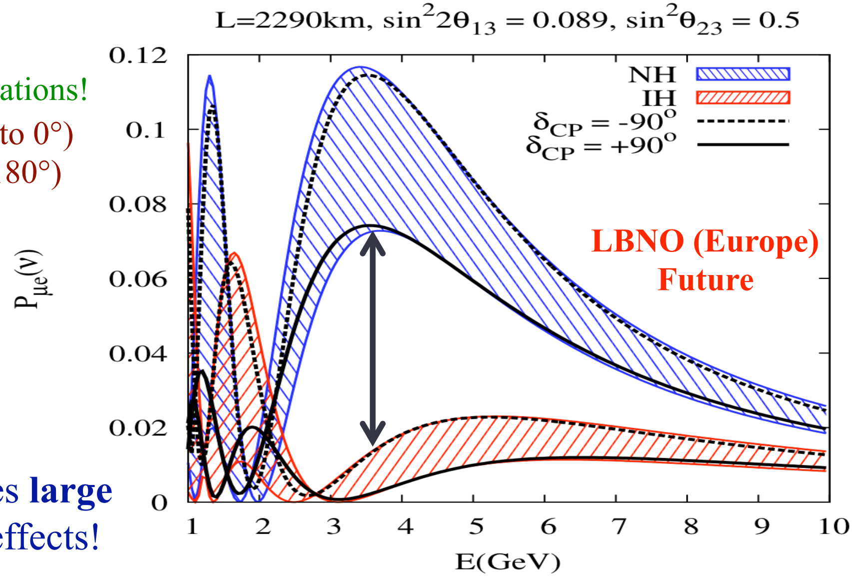
Degeneracy pattern
different between
T2K & NOνA


L=810km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

Favorable combinations!

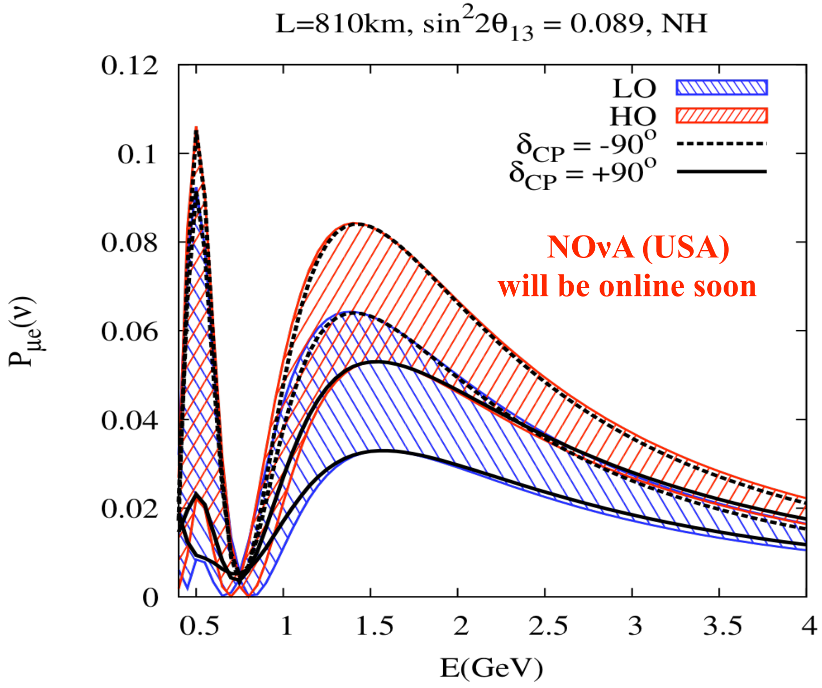
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

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


L=2290km, $\sin^2 2\theta_{13} = 0.089$, $\sin^2\theta_{23} = 0.5$

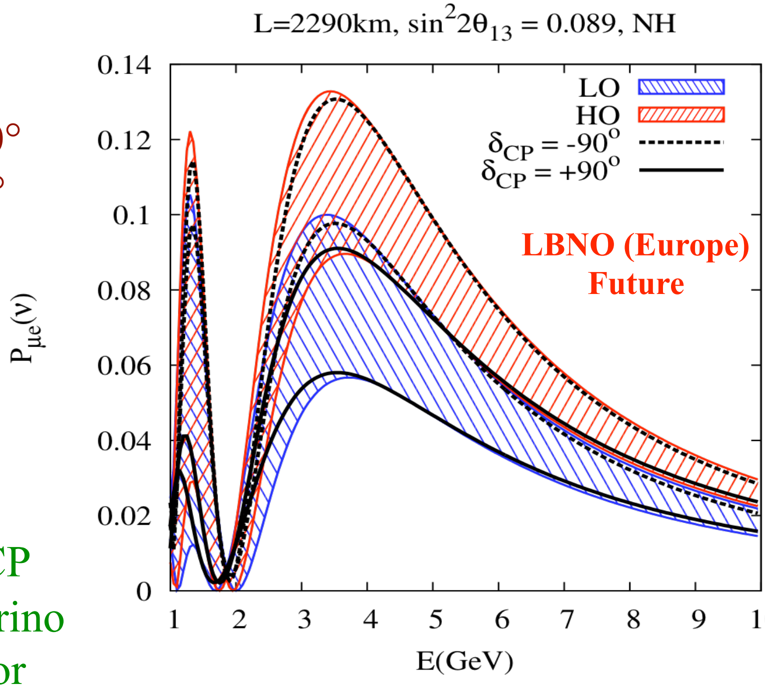
Agarwalla, Prakash, Raut, Sankar, 2012-2013

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



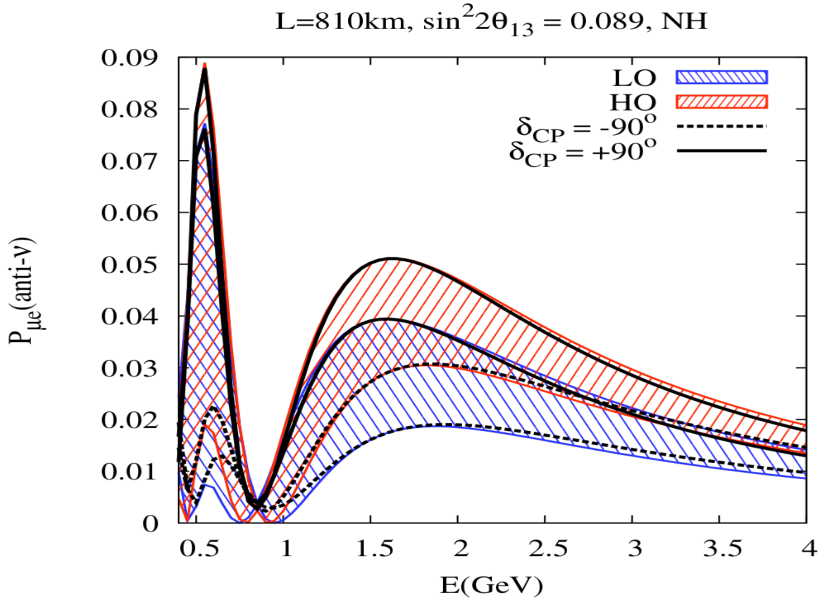
NOvA (USA)
will be online soon

For ν:
Max: HO, -90°
Min: LO, 90°

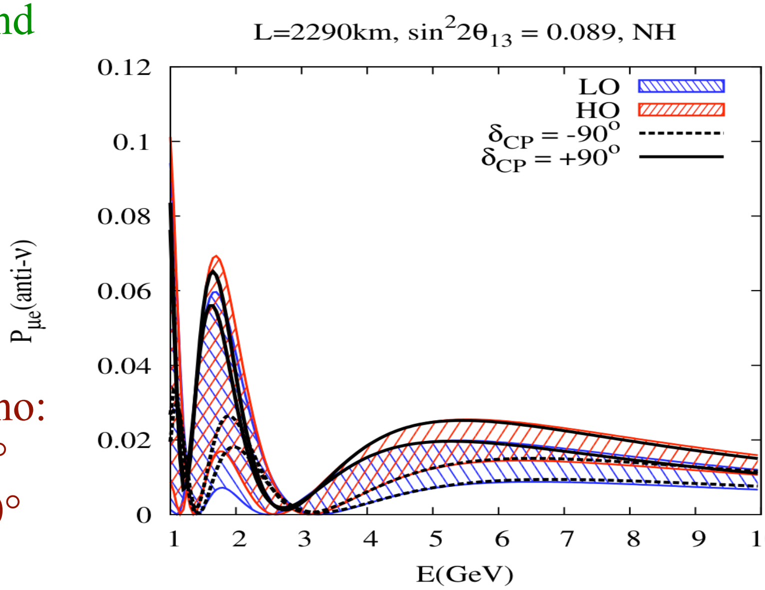


LBNO (Europe)
Future

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



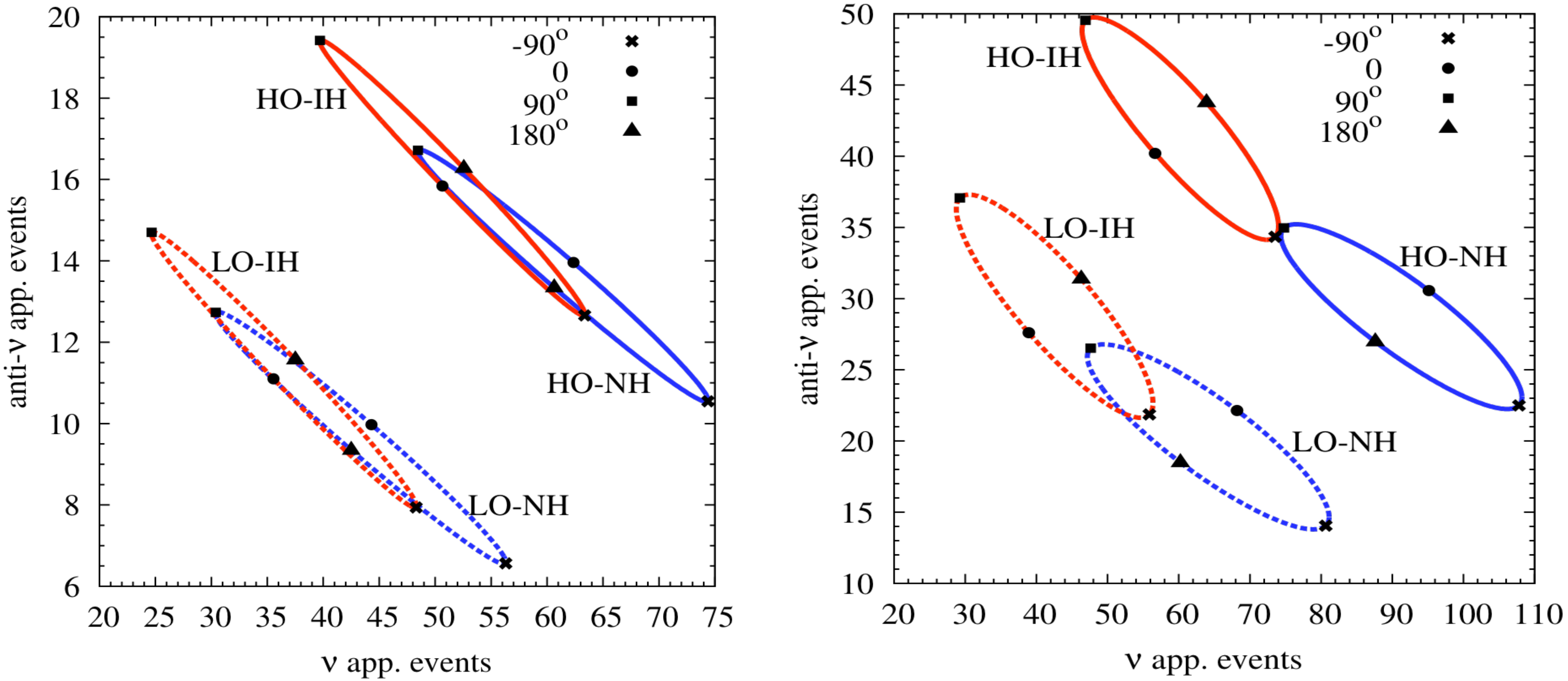
For anti-neutrino:
Max: HO, 90°
Min: LO, -90°



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]

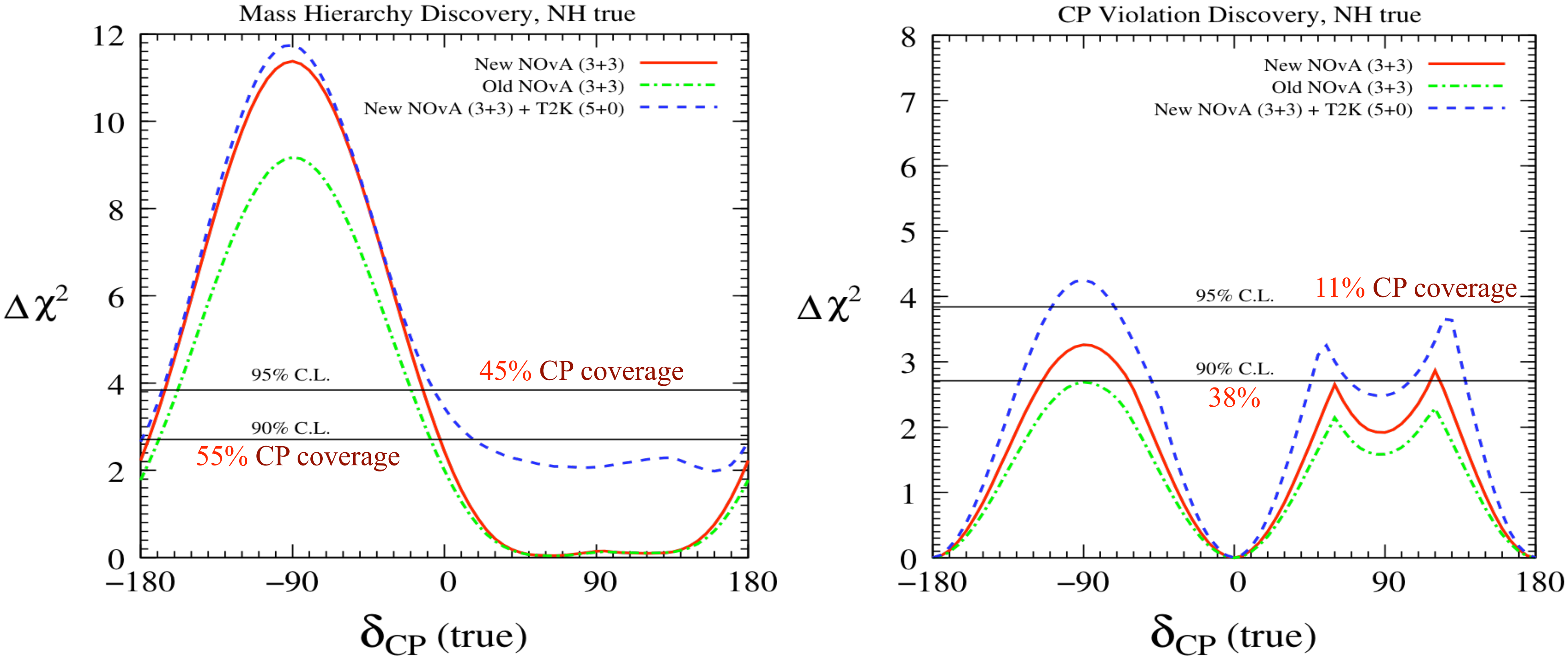
ν vs. anti-ν events for various octant-hierarchy combinations, ellipses due to varying δ_{CP}!

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



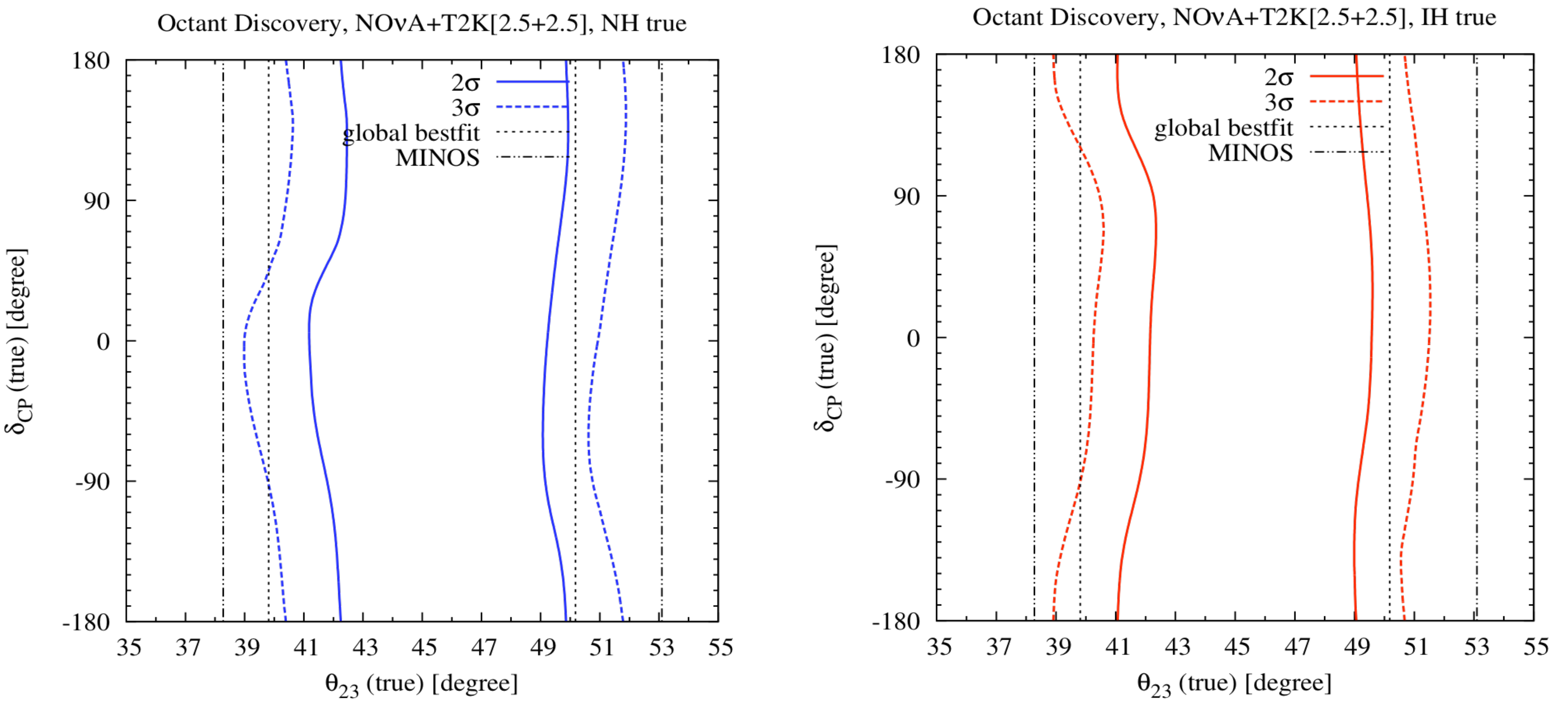
Agarwalla, Prakash, Raut, Sankar, JHEP 1212, 075 (2012)

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

Resolving Octant of θ_{23} with T2K and NOvA



Agarwalla, Prakash, Sankar, arXiv:1301.2574 [hep-ph]
See also, Chatterjee, Ghoshal, Goswami, Raut, arXiv:1302.1370 [hep-ph]

If $\theta_{23} < 41°$ or $\theta_{23} > 50°$, we can resolve the octant issue at 2σ irrespective of δ_{CP}

If $\theta_{23} < 39°$ or $\theta_{23} > 52°$, we can resolve the octant issue at 3σ irrespective of δ_{CP}

Important message: T2K must run in anti-neutrino mode in future!

Future Facilities for Long Baseline Neutrino Experiments

LBNE: FNAL to Homestake : 1300 km (1st Osc. Max = 2.52 GeV)

Beam: 120 GeV, 0.7 MW, 6 × 10^{20} POT/yr, 5 yrs ν + 5 yrs anti-ν

Detector: 10 kton LArTPC (Phase1), 35 kton LArTPC (Phase2)

LBNO: CERN to Phyasalmi : 2300 km (1st Osc. Max = 4.54 GeV)

Beam: 400 GeV, 0.77 MW, 1.5 × 10^{20} POT/yr, 5 yrs ν + 5 yrs anti-ν

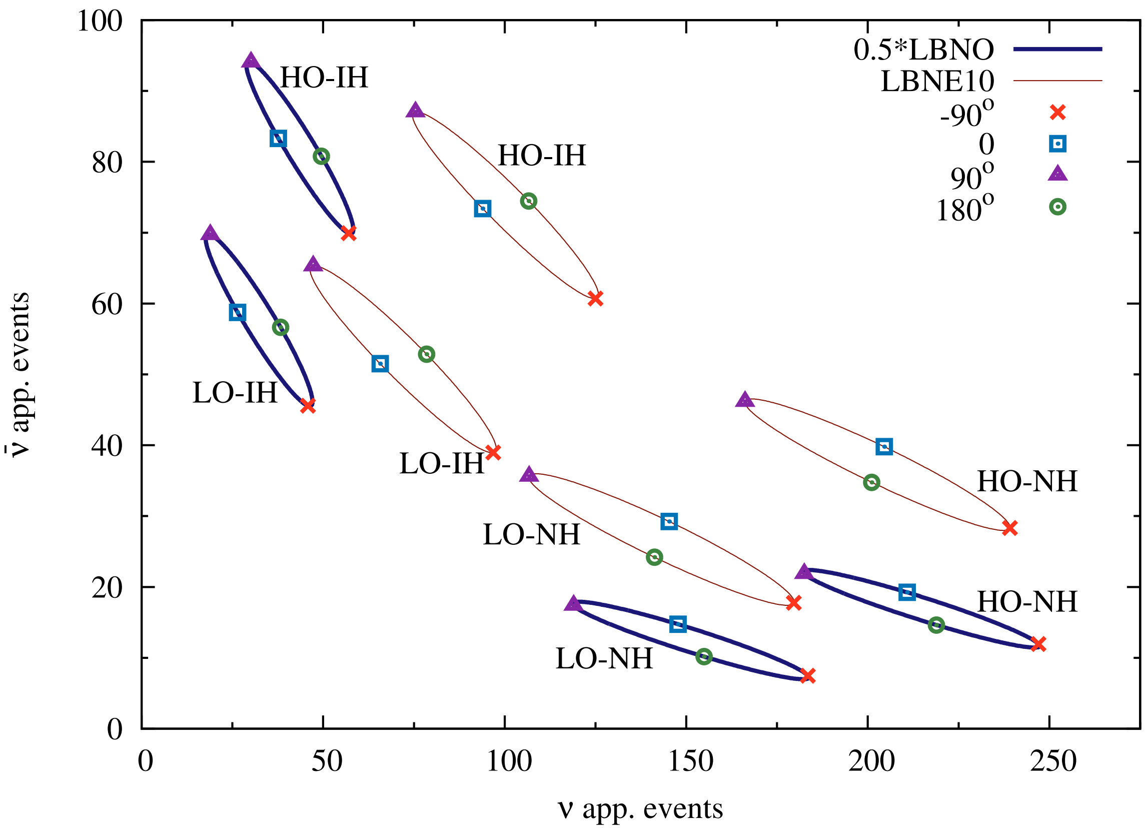
Detector: 20 kton LArTPC (Phase1), 100 kton LArTPC (Phase2)

T2HK: J-PARC to Kamioka : 295 km (1st Osc. Max = 0.6 GeV)

Beam: 30 GeV, 1.66 MW, 5 × 10^{21} POT/yr, 1.5 yrs ν + 3.5 yrs ν

Detector: 560 kton Water Cherenkov (Hyper-Kamiokande)

Future Superbeam Expts with LAr Detector: LBNE & LBNO



LBNO with 10 kt LArTPC

(LO/HO)-IH ellipses well separated from (LO/HO)-NH ellipses

Excellent hierarchy discrimination capability with just neutrino data

For octant, balanced ν & anti-ν data must

LBNE with 10 kt LArTPC

For LO, hierarchy discovery is limited

Octant discovery: similar to 0.5*LBNO

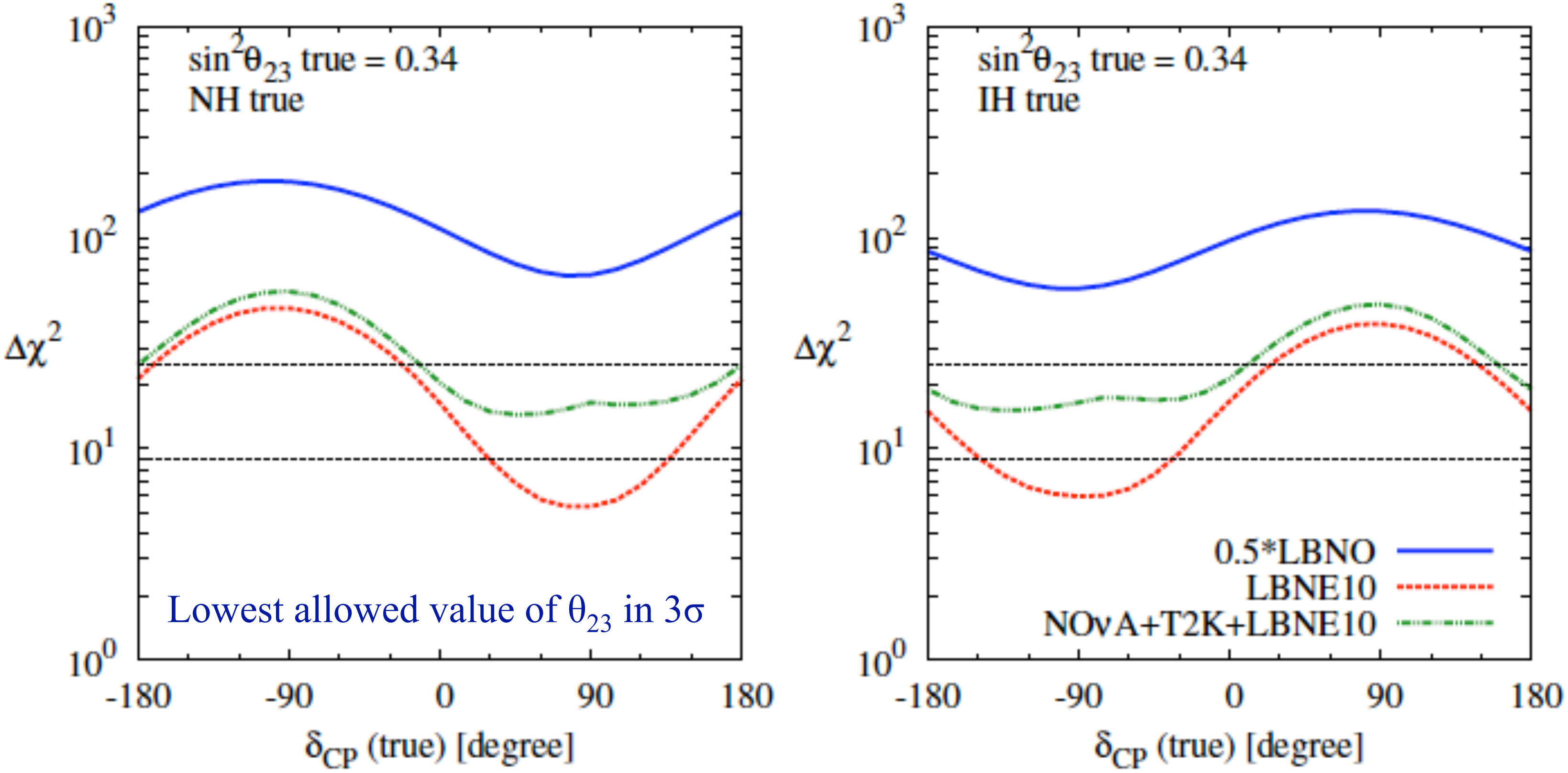
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

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



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

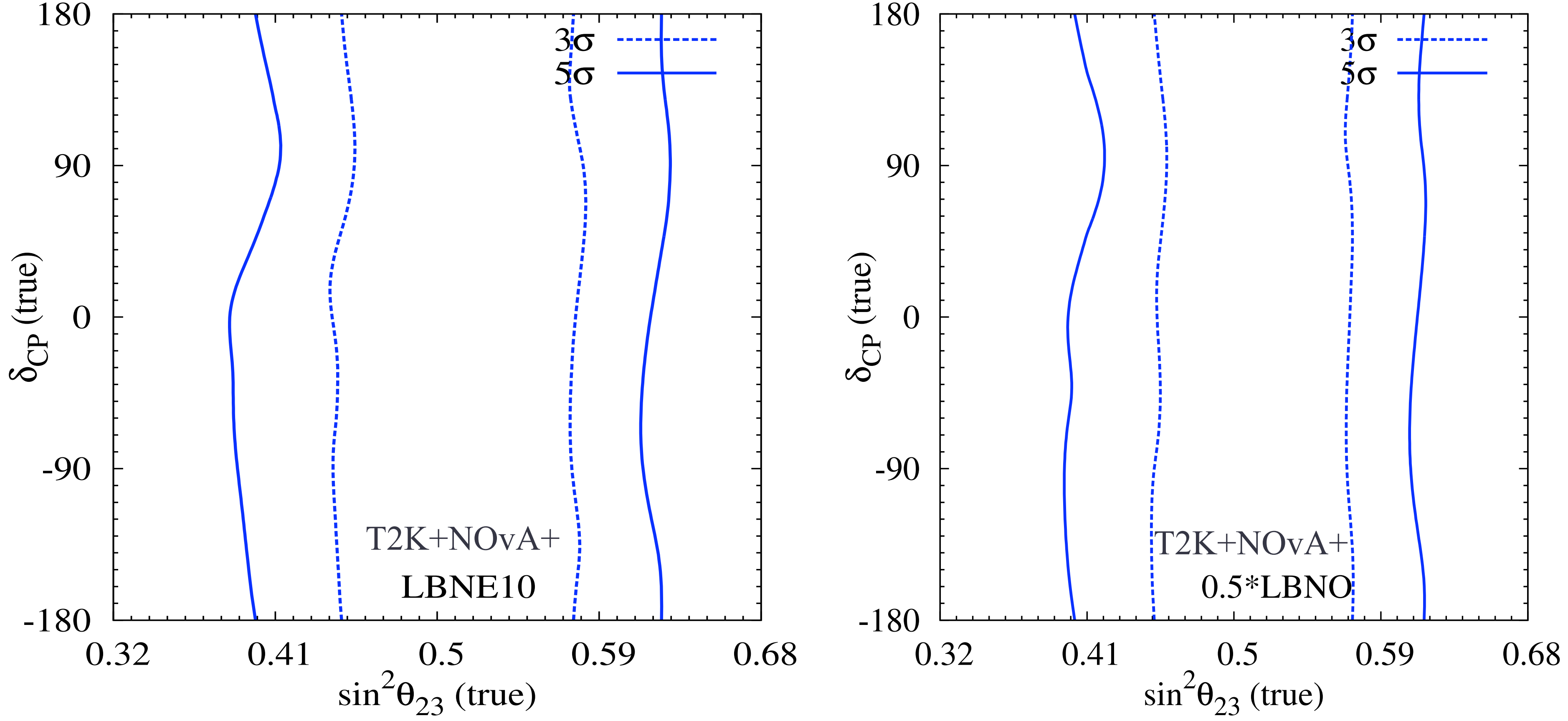
LBNO w/ 10 kt detector > 7σ hierarchy discovery potential for all θ_{23}-δ_{CP}-hierarchy combinations

LBNE w/ 10 kt detector + T2K + NOvA > 3σ hierarchy discovery potential for any parameter choice

Projected data from T2K and NOvA will play a crucial role in the first phases of LBNE and LBNO

Interesting synergy between off-axis and on-axis experiments

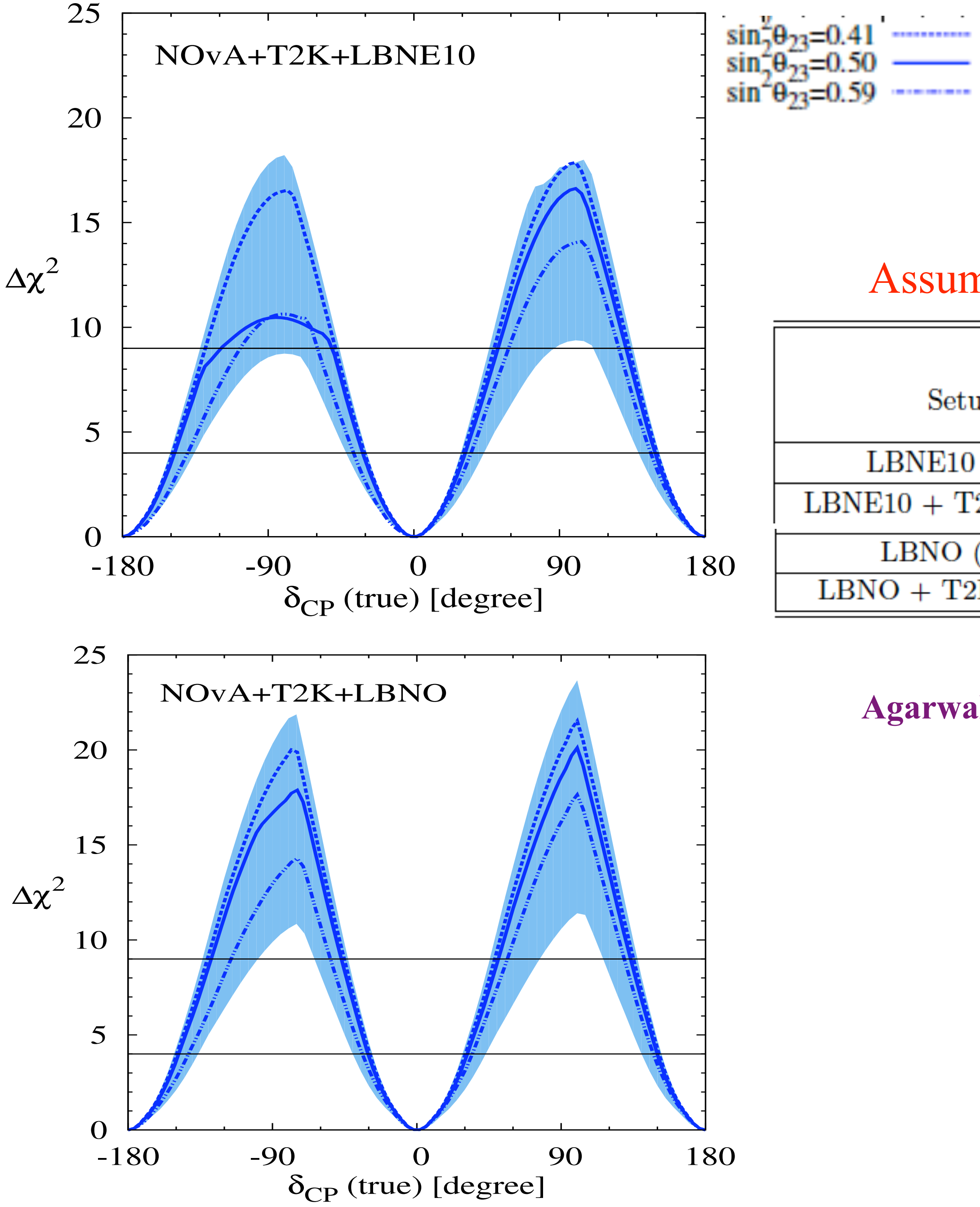
Octant Discovery with LBNE and LBNO



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

If $\sin^2\theta_{23} \leq 0.44$ or $\sin^2\theta_{23} \geq 0.58$, octant can be resolved at 3σ irrespective of δ_{CP}

CP violation Discovery with LBNE and LBNO



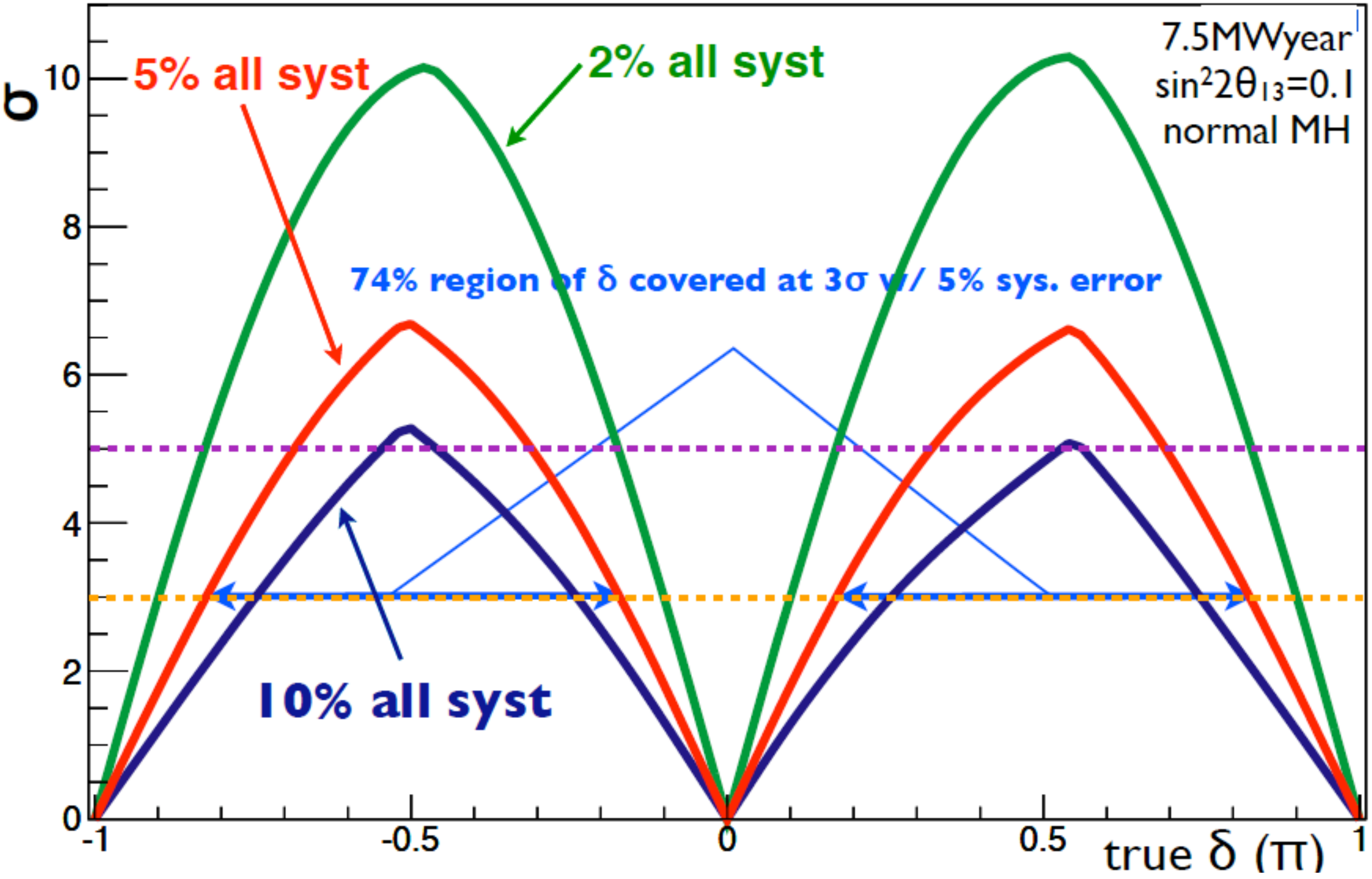
Assuming maximal mixing as true choice

Setups	Fraction of δ_{CP}(true)	
	2σ confidence level	3σ confidence level
LBNE10 (10 kt)	0.51	0.03
LBNE10 + T2K + NOνA	0.63	0.43
LBNO (20 kt)	0.51	0.23
LBNO + T2K + NOνA	0.69	0.46

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

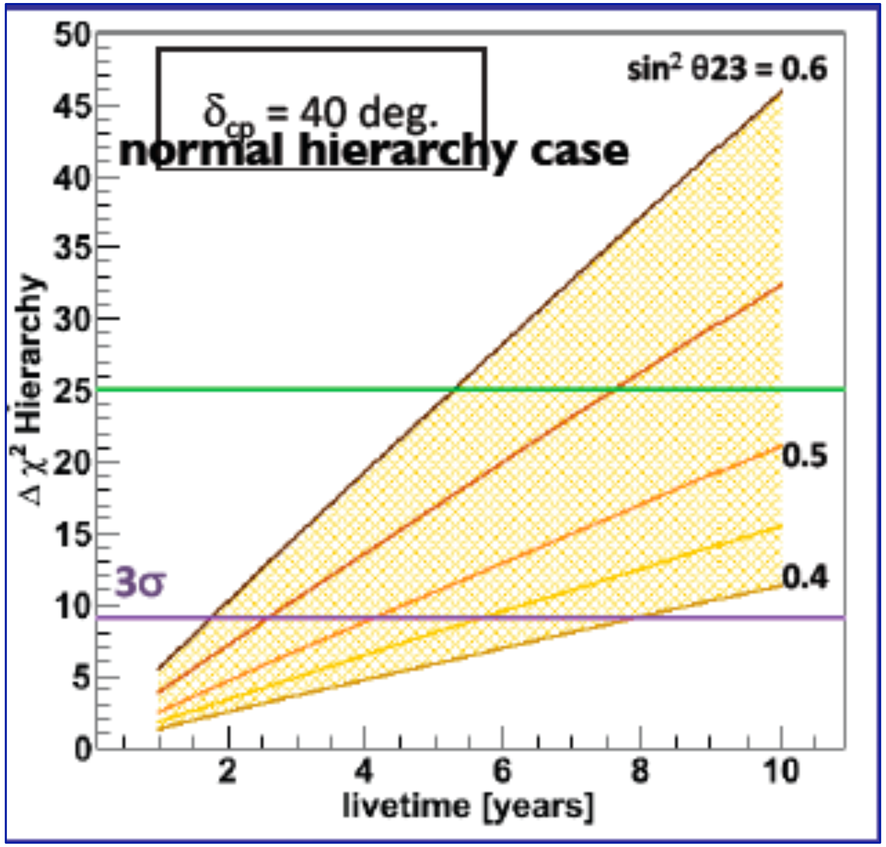
Detailed discussion by S. Raut in WGV

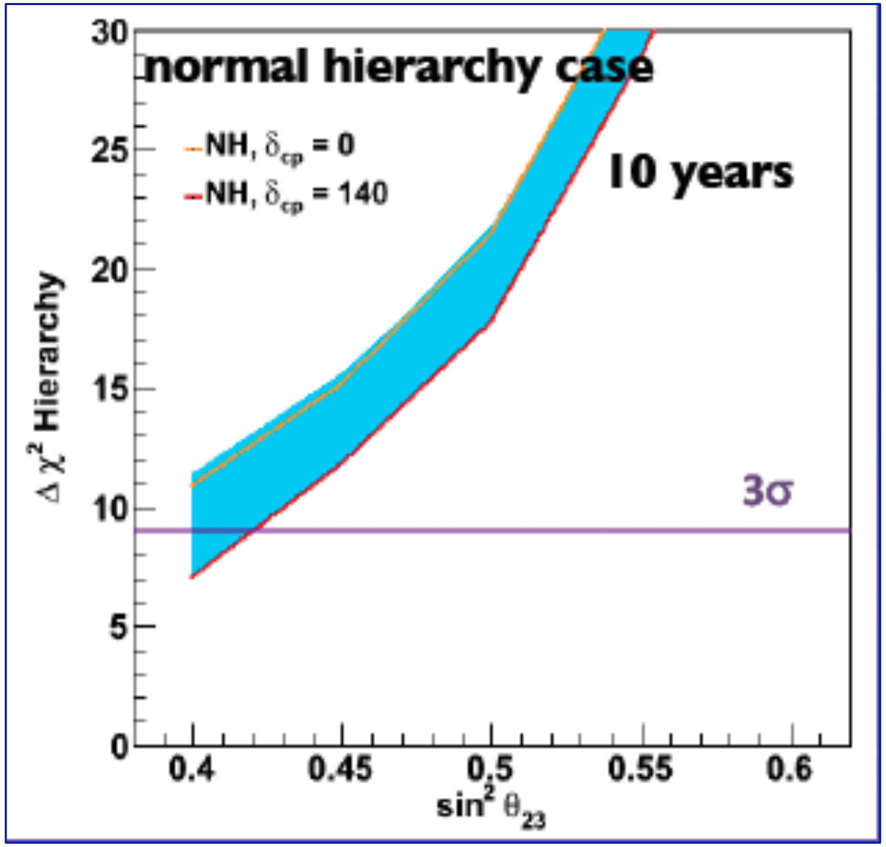
CPV Discovery in T2HK Setup (w/ Mass Hierarchy known)



Hyper-Kamiokande, Letter of Intent, arXiv:1109.3262 [hep-ex]

T2HK: Mass Hierarchy Discovery combining Atmospheric ν





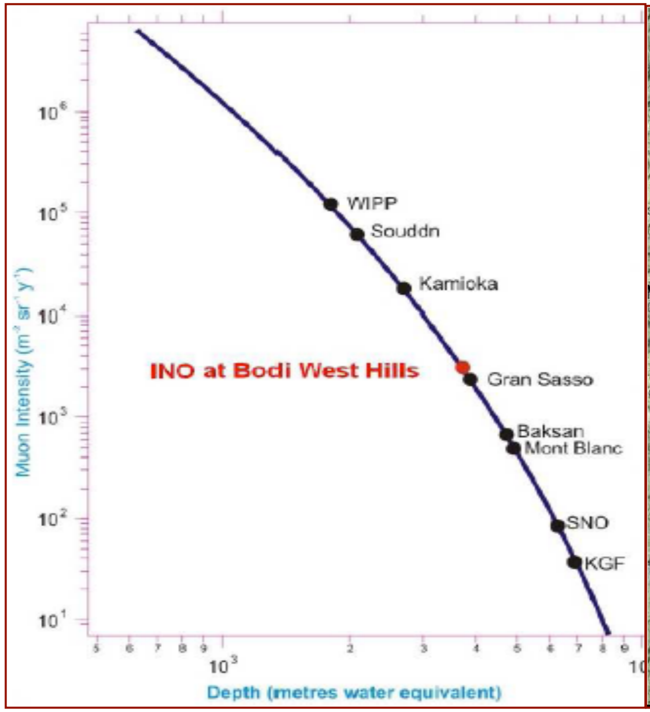
3σ hierarchy discrimination for $\sin^2\theta_{23} > 0.42$ in case of normal hierarchy

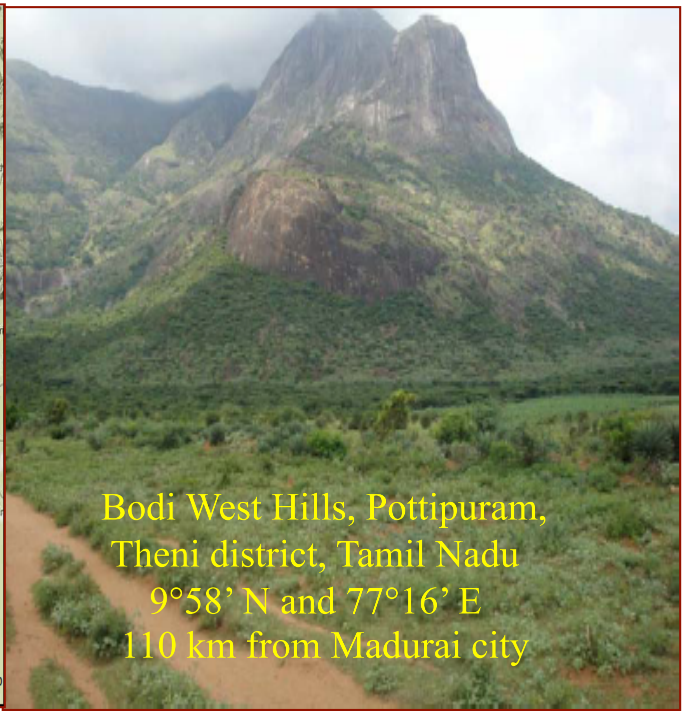
Hyper-Kamiokande, Letter of Intent, arXiv:1109.3262 [hep-ex]

India-Based Neutrino Observatory

- *A multi-institutional attempt to build a world-class underground facility to study fundamental issues in science with special emphasis on neutrinos*
- *With ~1 km all-round rock cover accessed through a 2 km long tunnel. A large and several smaller caverns to pursue many experimental programs*
- *Complementary to ongoing efforts worldwide to explore neutrino properties*
- *A mega-science project (~250 M$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology*
- ***INO project was discussed and approved by the Atomic Energy Commission on 17th August, 2013 at New Delhi***
- *Regarding Final approval: Clearance from the Cabinet expected soon*
- *International Community is welcome to participate in ICAL@INO as well as the INO facility is available to the entire community for setting up experiments like Neutrino-less Double Beta Decay, Direct Dark Matter searches*

Location of INO & Unique Features



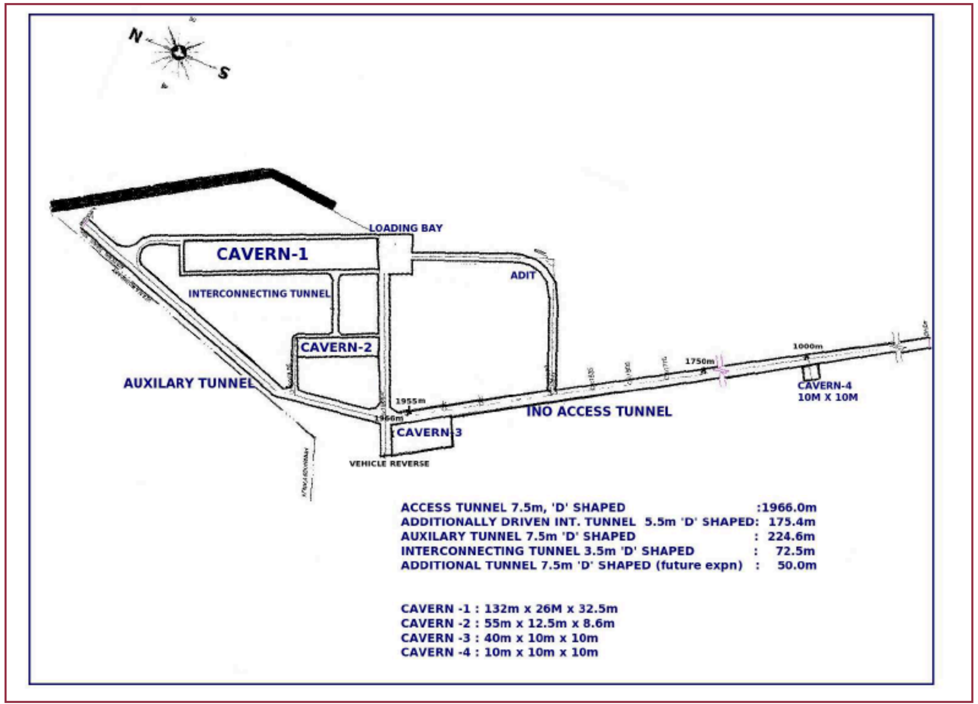


Bodi West Hills, Pottipuram,
Theni district, Tamil Nadu
9°58’ N and 77°16’ E
110 km from Madurai city

- ***Transport:*** *Flat terrain with good access from major roads*
- ***Geotechnical Issues:*** *Good rock quality, Cavern set in massive Charnockite rock under the 1589 m peak, Vertical cover approx. 1289 m, Tunnel length 1.91 km*
- ***Environmental Issues:*** *Portal set outside the Reserved Forest boundary, no disturbance. Surface facilities not on Forest Land. No clearing of forest*
- ***Weather :*** *Warm, low rainfall area, low humidity throughout the year*

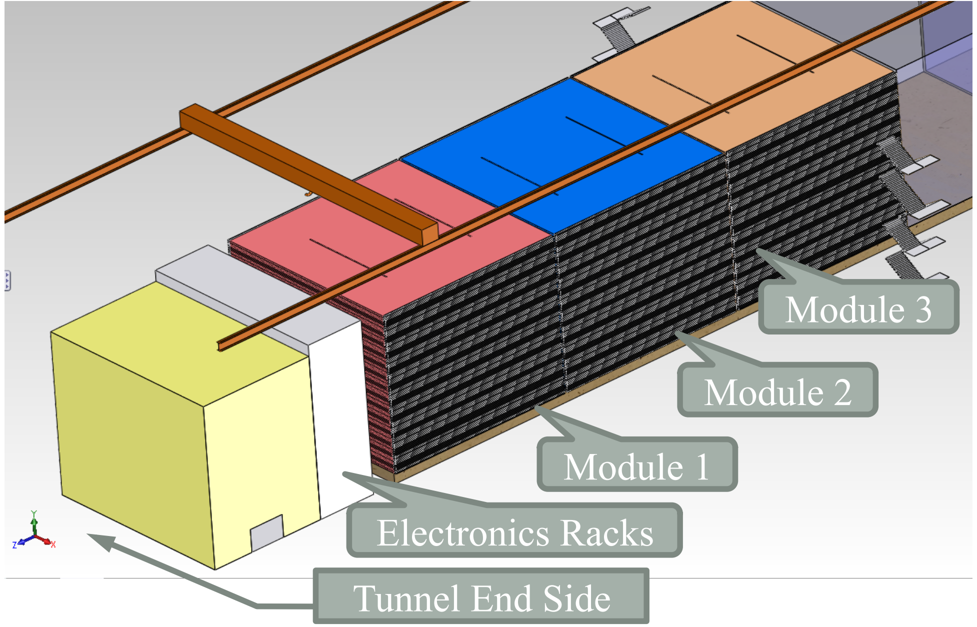
Approved projects under INO

- *Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu*
- *Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of neutrinos*
- *Construction of INO centre at Madurai: Inter-Institutional Centre for High Energy Physics (IICHEP)*
- *Human Resource Development (INO Graduate Training Program)*
- *Completely in-house Detector R&D with substantial INO-Industry interface*
- *Time Frame for 1st module: 2018*



ACCESS TUNNEL 7.5m, 'D' SHAPED :1966.0m
ADDITIONALLY DRIVEN INT. TUNNEL 5.5m 'D' SHAPED: 175.4m
AUXILARY TUNNEL 7.5m 'D' SHAPED : 224.6m
INTERCONNECTING TUNNEL 3.5m 'D' SHAPED : 72.5m
ADDITIONAL TUNNEL 7.5m 'D' SHAPED (future expn) : 50.0m

CAVERN -1 : 132m x 26M x 32.5m
CAVERN -2 : 55m x 12.5m x 8.6m
CAVERN -3 : 40m x 10m x 10m
CAVERN -4 : 10m x 10m x 10m



Physics Issues with ICAL-INO in Phase 1

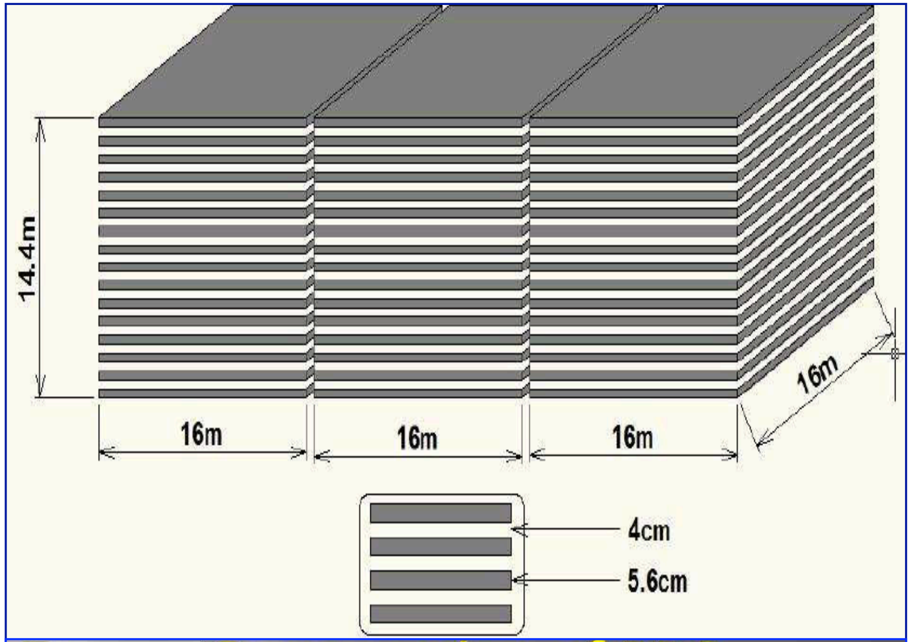
Study Atmospheric neutrinos w/ a wide range of Baselines & Energies

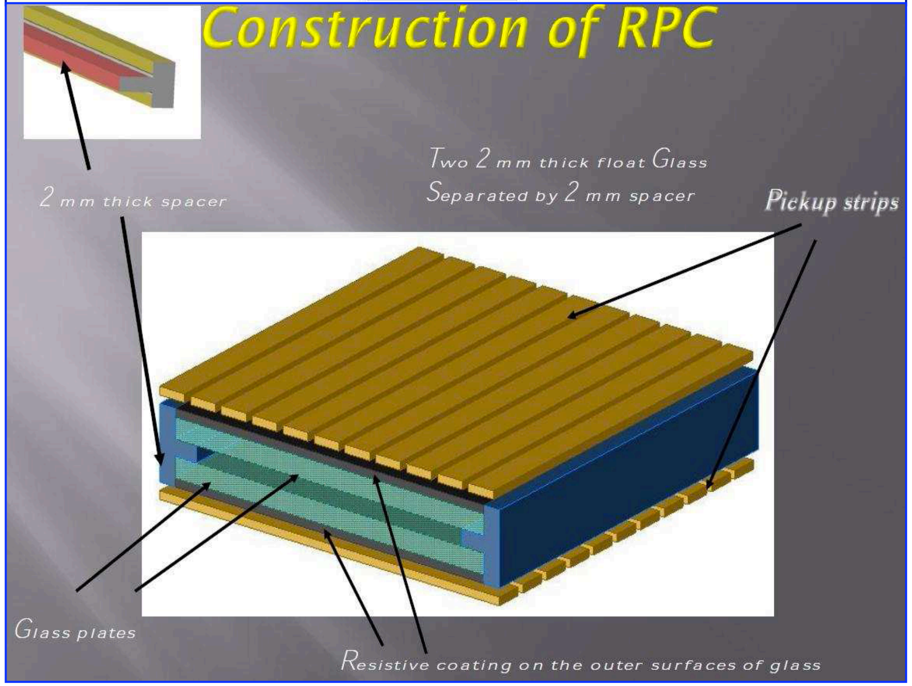
Recent discovery of large θ_{13} : A great news for ICAL-INO

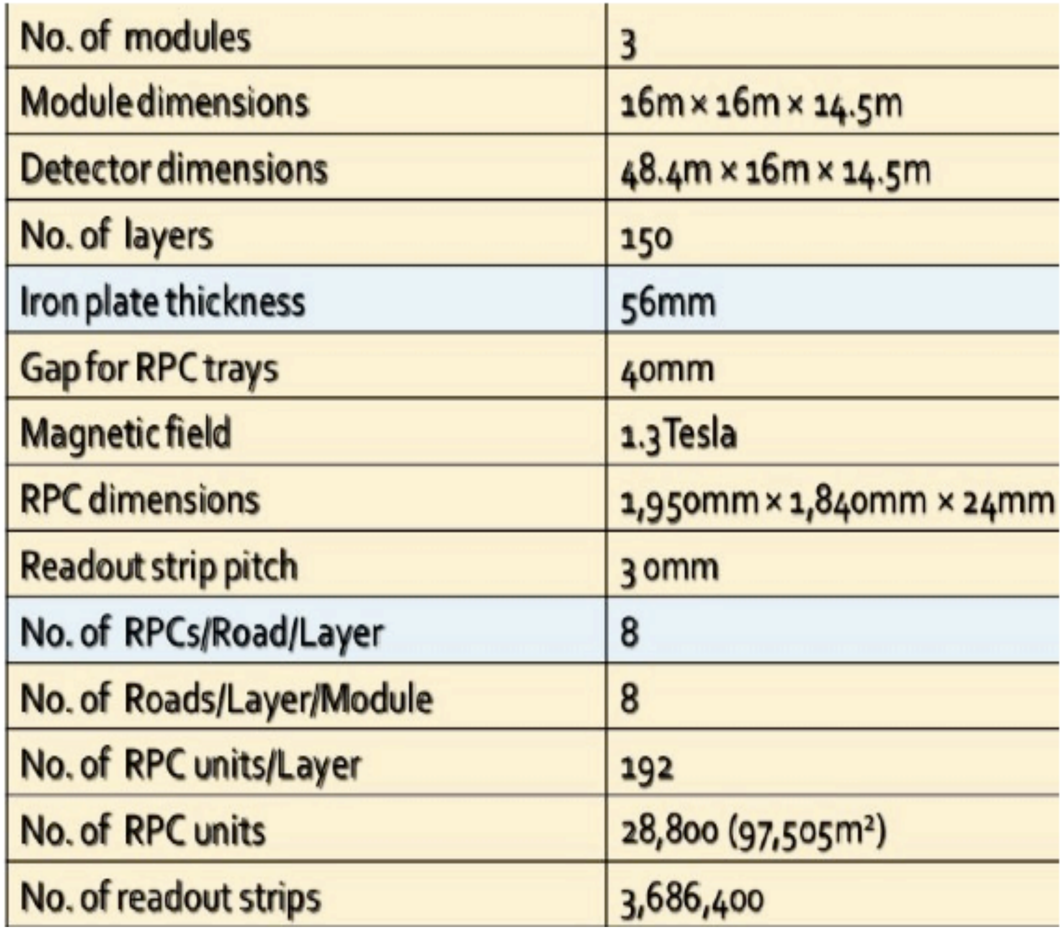
What do we want to achieve?

- ***Reconfirm neutrino oscillations using neutrinos and anti-neutrinos separately***
- ***Improved precision of atmospheric oscillation parameters***
- ***Determine neutrino mass hierarchy using matter effects via charge discrimination***
- ***Measure the deviation of 2-3 mixing angle from its maximal value and its octant***
- ***Test bed for various new physics like NSI, CPT violation, long range forces***
- ***Detect Ultra High Energy Neutrinos, Cosmic Muons, Indirect searches of DM***

Specifications of the ICAL Detector







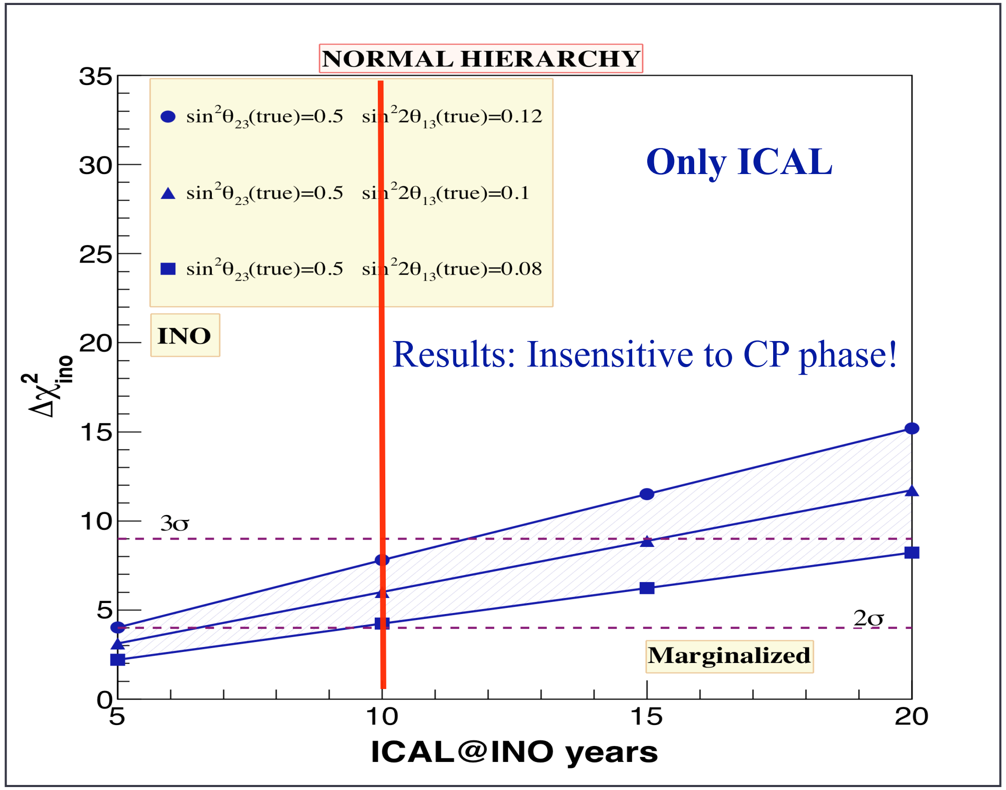
No. of modules	3
Module dimensions	16m × 16m × 14.5m
Detector dimensions	48.4m × 16m × 14.5m
No. of layers	150
Iron plate thickness	56mm
Gap for RPC trays	40mm
Magnetic field	1.3Tesla
RPC dimensions	1,950mm × 1,840mm × 24mm
Readout strip pitch	30mm
No. of RPCs/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
No. of RPC units	28,800 (97,505m²)
No. of readout strips	3,686,400

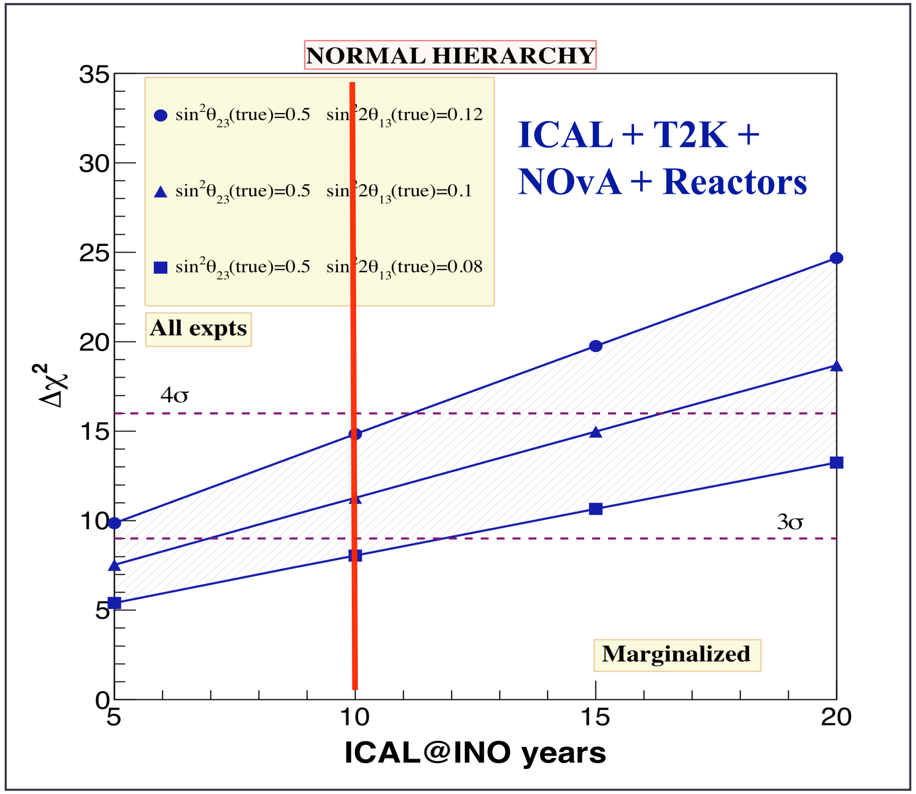
Rapid progress in all fronts

2011-2013: A productive phase for INO!

Several milestones achieved

Mass Ordering with ICAL-INO





All systematic uncertainties are included!

Ghosh, Thakore, Choubey, JHEP 1304 (2013) 009

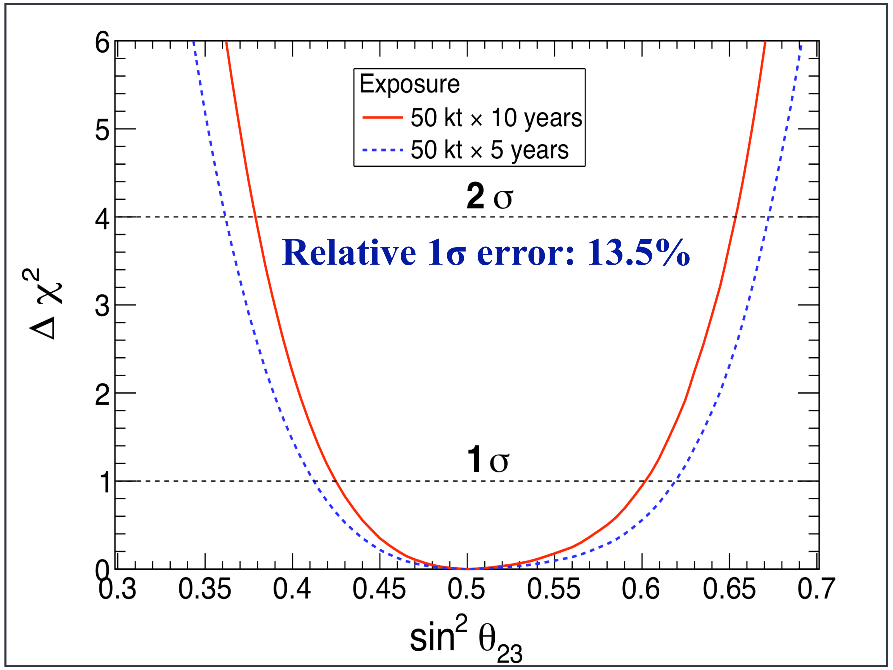
Events generated with NUANCE! Two Dimensional Muon analysis with ICAL resolutions!
E_μ = 20 energy bins in the range 1 GeV to 11 GeV, $\cos\theta_\mu$ = 80 angular bins in the range -1 to +1

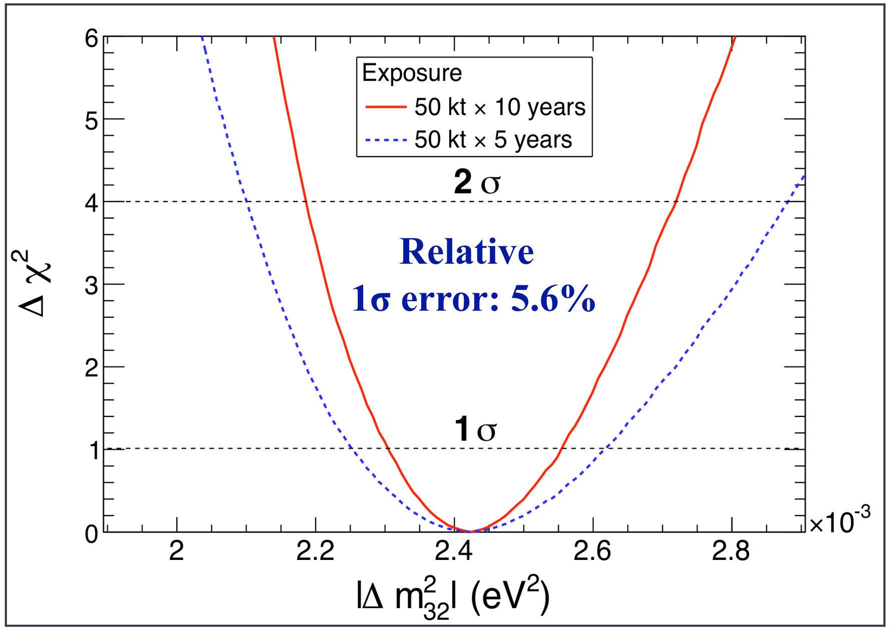
For $\sin^2 2\theta_{13} = 0.1$ & $\sin^2\theta_{23} = 0.5$, Only ICAL with 500 kt-years exposure: **2.5σ MH discovery**
ICAL + T2K + NOvA + Double Chooz + RENO + Daya Bay: **3.4σ MH discovery**

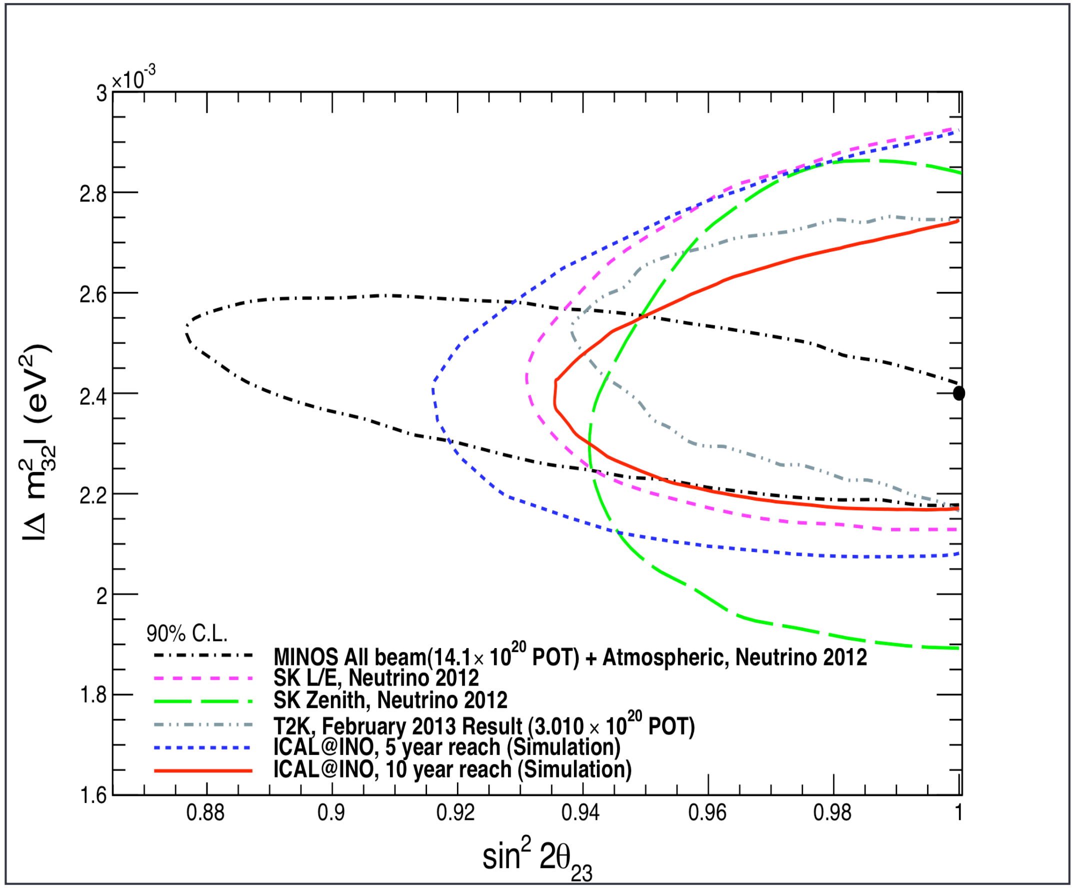
Information on MH from ICAL can increase CP violation reach for LBL experiments

Ghosh, Ghosal, Goswami, Raut, arXiv:1306.2500

Precision of Atmospheric Oscillation Parameters







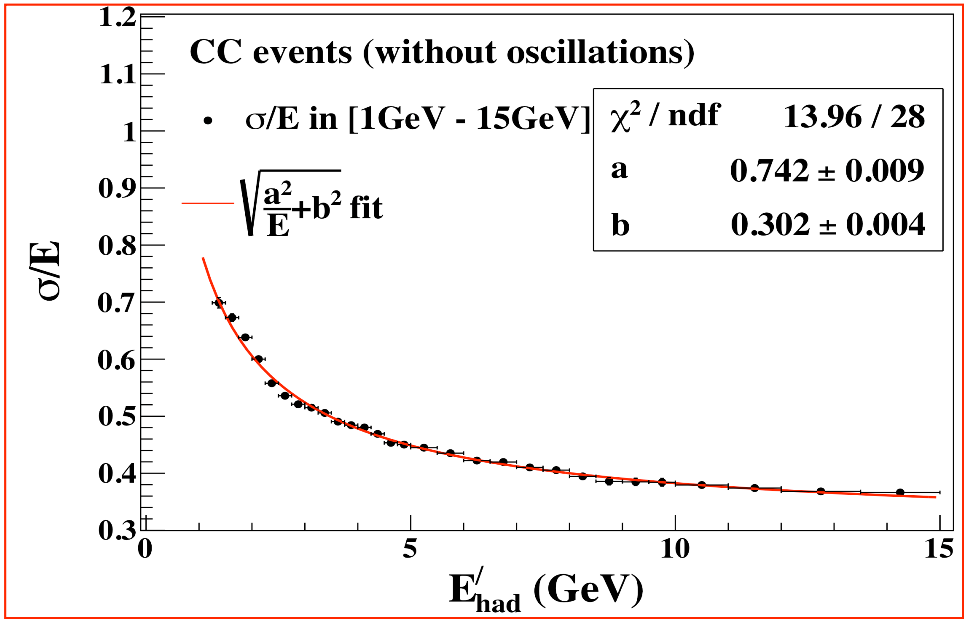
Thakore, Ghosh, Choubey, Dighe, JHEP 1305 (2013) 058

Two Dimensional Muon analysis w/ ICAL resolutions!

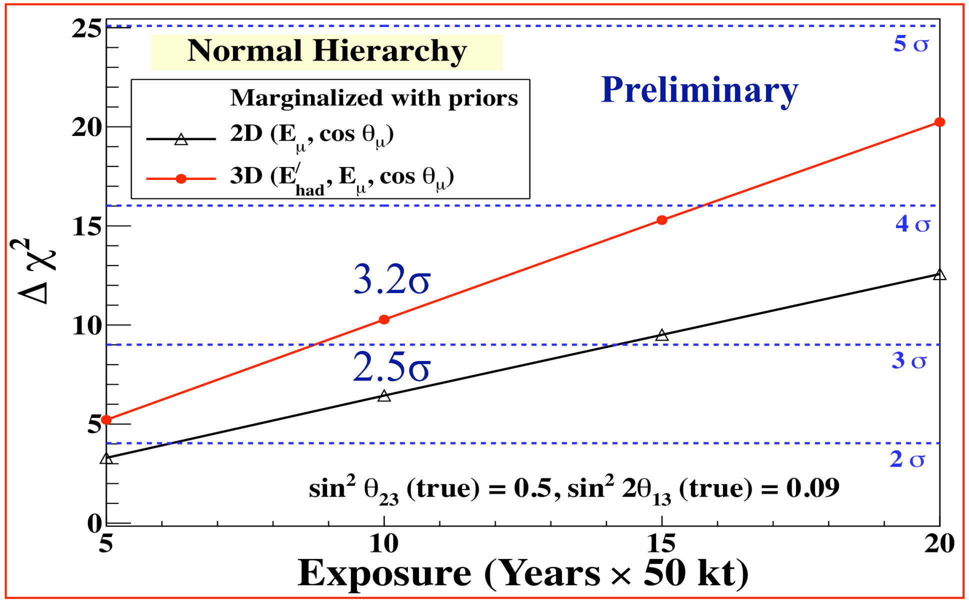
Precision complementary to LBL experiments!

Sensitivity comparable to SK with a similar exposure!

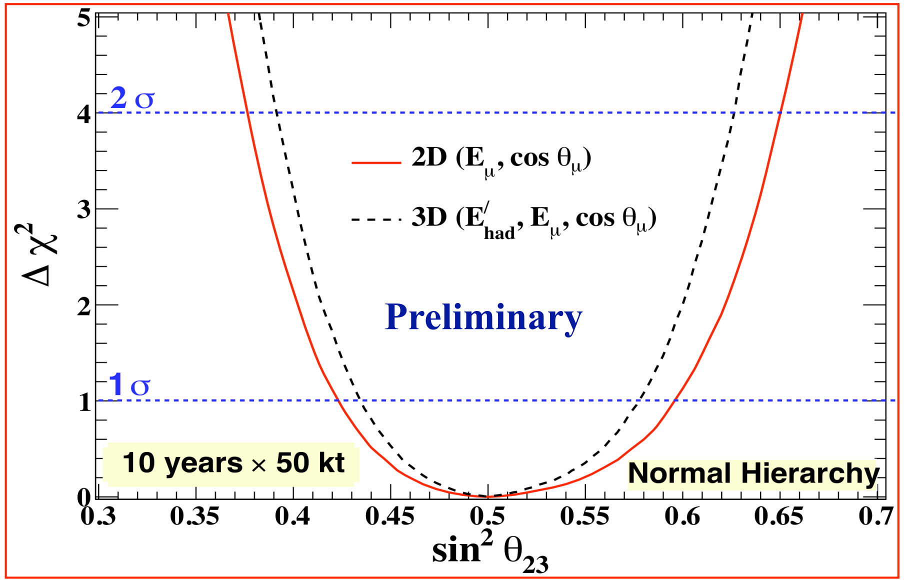
3D Analysis including information on Hadrons

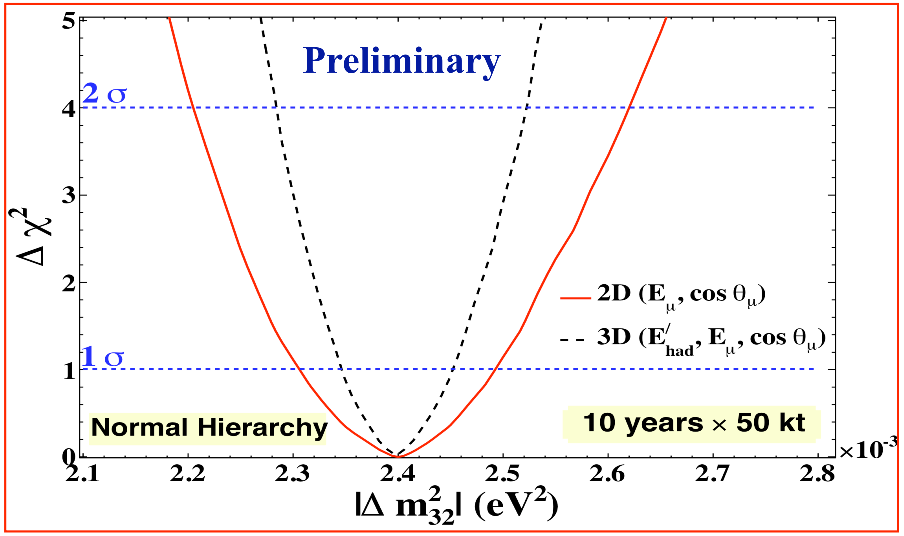


Devi, Ghosh, Kaur, Lakshmi etal., 2013 JINST 8 P11003



Devi, Thakore etal., in preparation





$E^{/}_{h} = E_\nu - E_\mu$ (from hadron hit calibration)

Significant improvement going from 2D to 3D

Concluding Remarks

Recent discovery 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

At present, we have:

$$|U|_{\mathrm{LEP}(3\sigma)} = \begin{pmatrix} 0.799 \to 0.844 & 0.515 \to 0.581 & 0.129 \to 0.173 \\ 0.212 \to 0.527 & 0.426 \to 0.707 & 0.598 \to 0.805 \\ 0.233 \to 0.538 & 0.450 \to 0.722 & 0.573 \to 0.787 \end{pmatrix}$$

Satisfactory progress in last 15 years but still very far from the 'dream' precision:

$$|V|_{\mathrm{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046} \end{pmatrix}$$

!! Let us work together and achieve it !!

Thank you!

The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

  $*$ Introduce ν_R AND impose L conservation $\Rightarrow$ Dirac $\nu \neq \nu^c$:

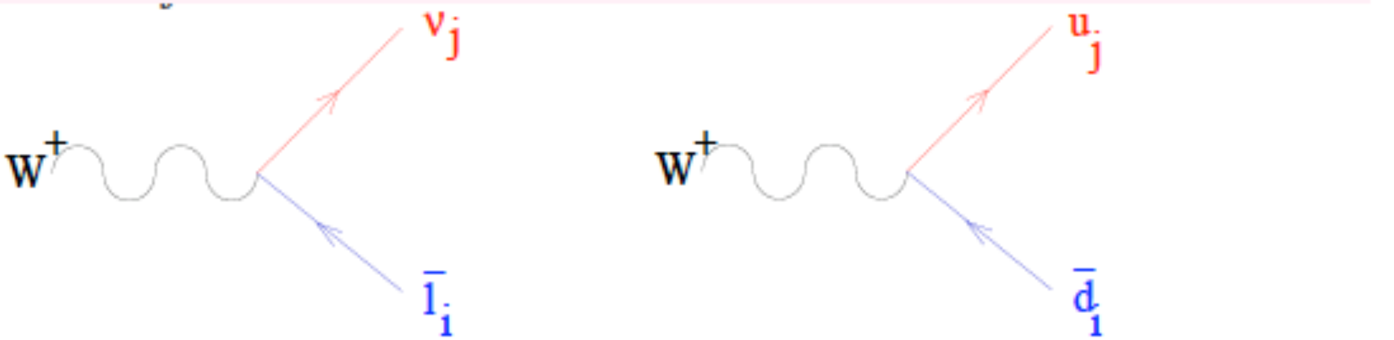
  $$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ NOT impose L conservation $\Rightarrow$ Majorana $\nu = \nu^c$

  $$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu_L} \nu_L^C + h.c.$$

- The charged current interactions of leptons are not diagonal (same as quarks)

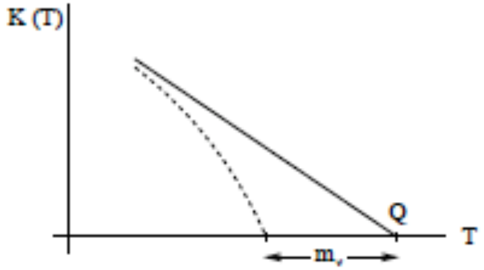
$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{\mathrm{LEP}}^{ij}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \;+\; U_{\mathrm{CKM}}^{ij}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \;+\; h.c.$$



Courtesy to Concha Gonzalez-Garcia

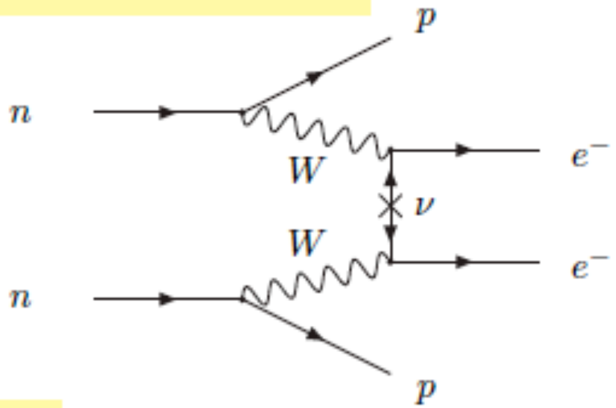
Neutrino Mass Scale

Single β decay : Dirac or Majorana ν mass modify spectrum endpoint



$$m^2_{\nu_e} = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

ν-less Double-β decay: $\Leftrightarrow$ Majorana $\nu's$ sensitive to Majorana phases



If m_ν only source of ΔL $(T^{0\nu}_{1/2})^{-1} \propto (m_{ee})^2$

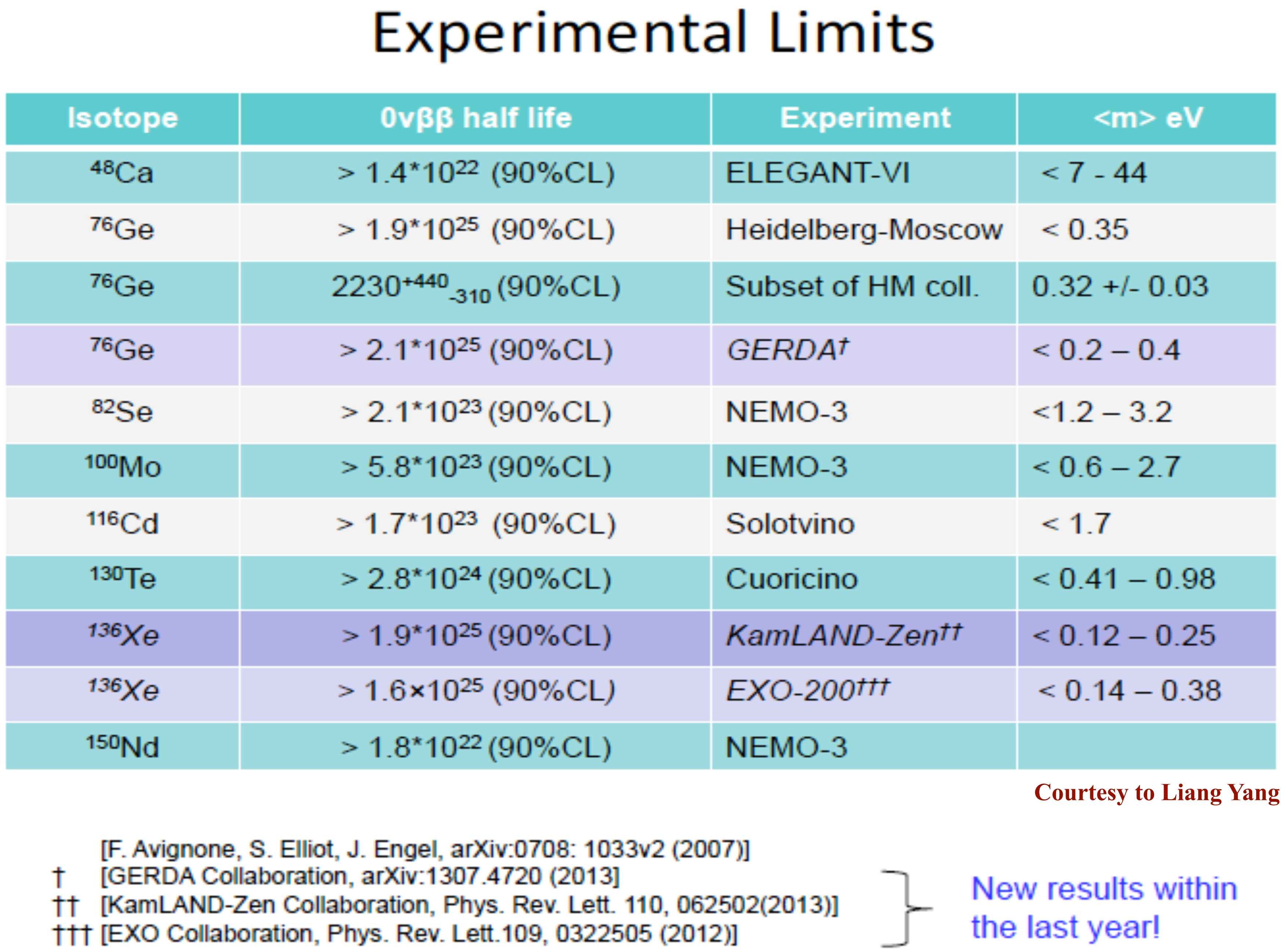
$$m_{ee} = \left|\sum U^2_{ej} m_j\right|$$

$$= \left|c_{13}^2 c_{12}^2 m_1 \, e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 \, e^{i\eta_2} + s_{13}^2 m_3 \, e^{-i\delta_{CP}}\right|$$

COSMO Neutrino mass (Dirac or Majorana)
modify the growth of structures

$$\sum m_i$$

Courtesy to Concha Gonzalez-Garcia



Experimental Limits

Isotope	$0\nu\beta\beta$ half life	Experiment	<m> eV
^{48}Ca	$> 1.4*10^{22}$ (90%CL)	ELEGANT-VI	< 7 - 44
^{76}Ge	$> 1.9*10^{25}$ (90%CL)	Heidelberg-Moscow	< 0.35
^{76}Ge	2230^{+440}_{-310} (90%CL)	Subset of HM coll.	0.32 +/- 0.03
^{76}Ge	$> 2.1*10^{25}$ (90%CL)	*GERDA*†	< 0.2 – 0.4
^{82}Se	$> 2.1*10^{23}$ (90%CL)	NEMO-3	<1.2 – 3.2
^{100}Mo	$> 5.8*10^{23}$ (90%CL)	NEMO-3	< 0.6 – 2.7
^{116}Cd	$> 1.7*10^{23}$ (90%CL)	Solotvino	< 1.7
^{130}Te	$> 2.8*10^{24}$ (90%CL)	Cuoricino	< 0.41 – 0.98
^{136}*Xe*	$> 1.9*10^{25}$ (90%CL)	*KamLAND-Zen*††	< 0.12 – 0.25
^{136}*Xe*	$> 1.6\times10^{25}$ (90%CL)	*EXO-200*†††	< 0.14 – 0.38
^{150}Nd	$> 1.8*10^{22}$ (90%CL)	NEMO-3	

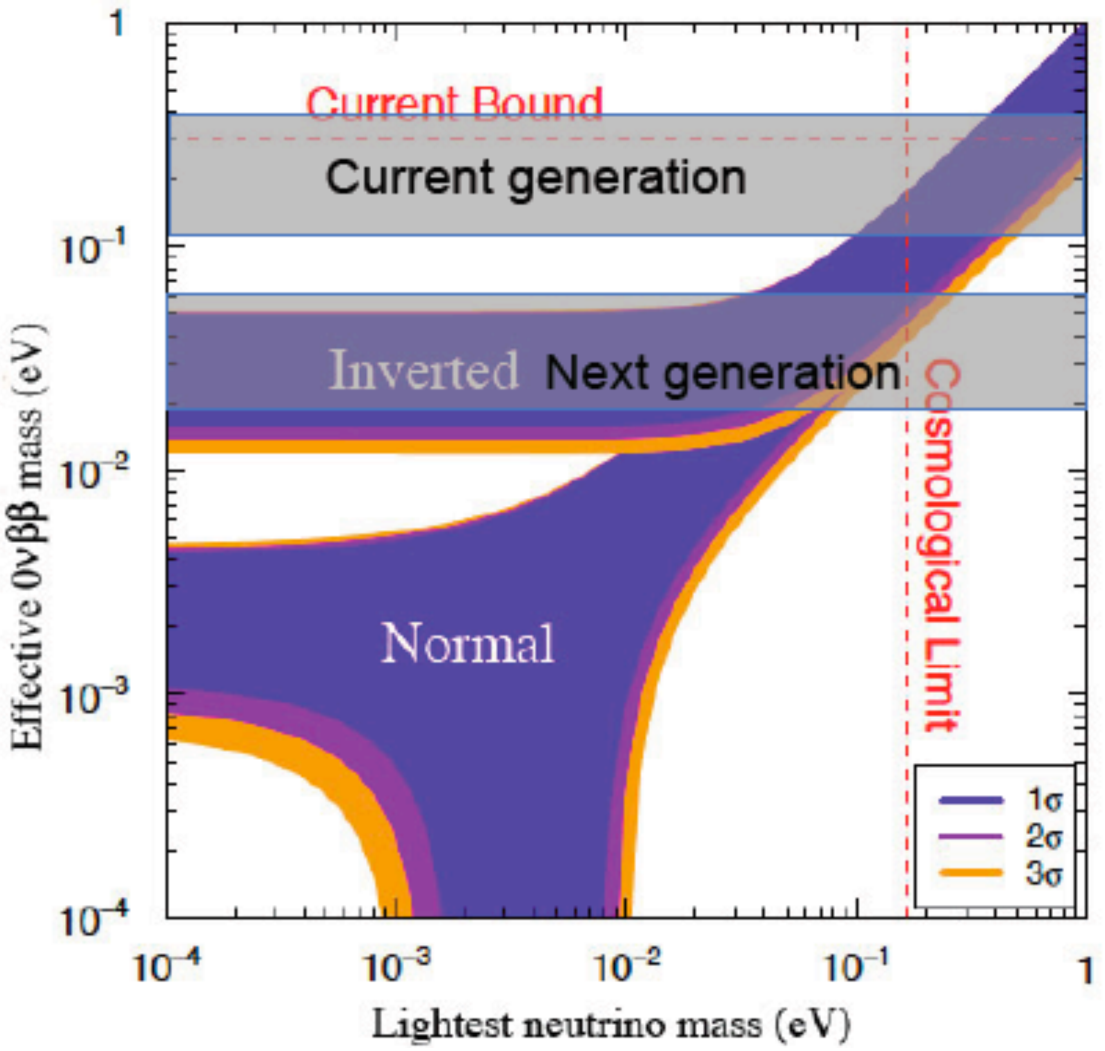
Courtesy to Liang Yang

[F. Avignone, S. Elliot, J. Engel, arXiv:0708: 1033v2 (2007)]
† [GERDA Collaboration, arXiv:1307.4720 (2013]
†† [KamLAND-Zen Collaboration, Phys. Rev. Lett. 110, 062502(2013)]
††† [EXO Collaboration, Phys. Rev. Lett.109, 0322505 (2012)]

New results within the last year!

Experimental Sensitivity to Neutrino Mass

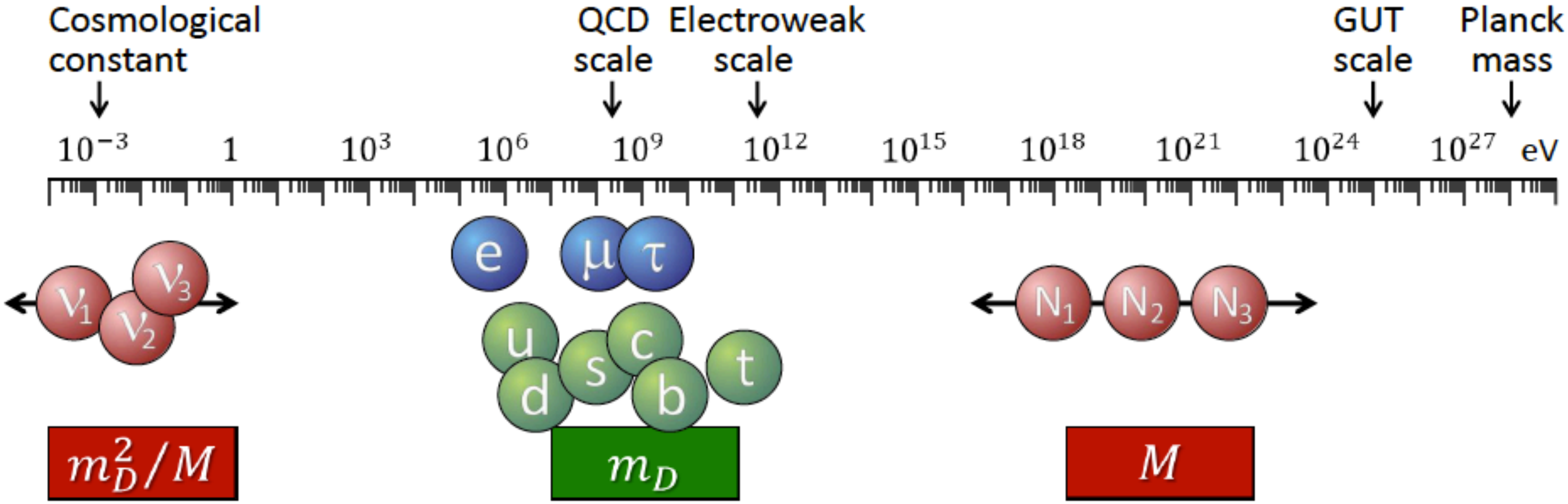
Isotope Mass	Background
10-100 kg	10-100cts/yr/ton
1-10 ton	0.1-1cts/yr/ton



arXiv:1203.5250v1

Courtesy to Liang Yang

Backup Slides (See-Saw & Neutrino Mass)



Mass matrix for one family of ordinary and heavy r.h. neutrinos

$$(\bar{\nu}_L, \bar{N}_R)\begin{pmatrix}0 & m_D\\ m_D & M\end{pmatrix}\begin{pmatrix}\nu_L\\ N_R\end{pmatrix}$$

Diagonalization

$$(\bar{\nu}_L, \bar{N}_R)\begin{pmatrix}m_D^2/M & 0\\ 0 & M\end{pmatrix}\begin{pmatrix}\nu_L\\ N_R\end{pmatrix}$$

One light and one heavy Majorana neutrino

Courtesy to George Raffelt