Implications of Recent Measurements in Neutrino Sector & Future Directions

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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: $m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$

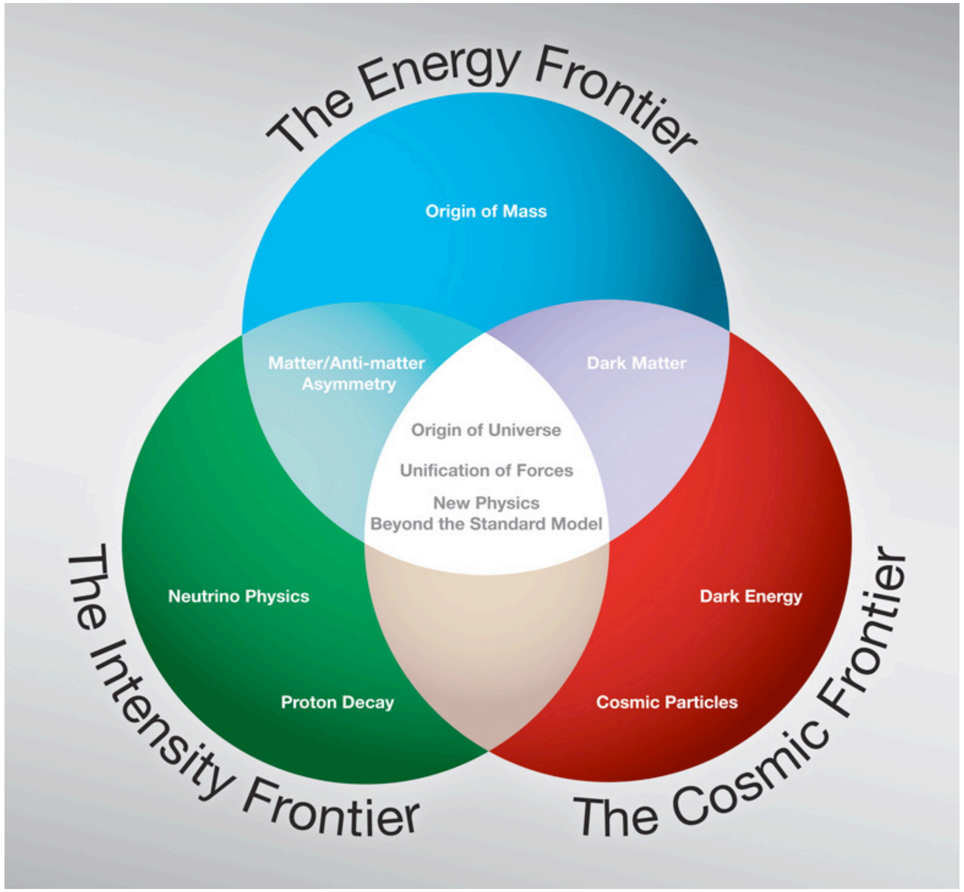
Neutrinos are massless in the Basic SM

- ❑ 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 !!

Big News in Neutrino Sector: Discovery of θ_{13}



We are going through an exciting phase

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

BICEP2 detected B-mode polarization
Smoking gun evidence for Inflation

Intensity Frontier: Neutrino properties: A window to our Universe and New Physics

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 $\boldsymbol{\theta_{13}}$, 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 60^{th} anniversary since ν detector of Reines & Cowan was turned on

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}

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

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!

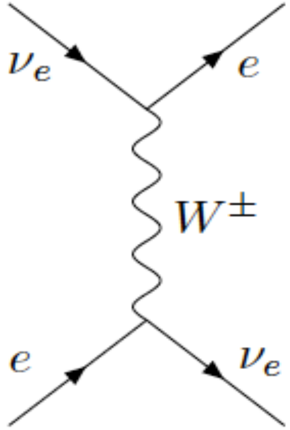
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j}]\sin 2\Delta_{ij},$$

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

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

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: $A = \pm 2\sqrt{2} G_F N_e E$ 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***

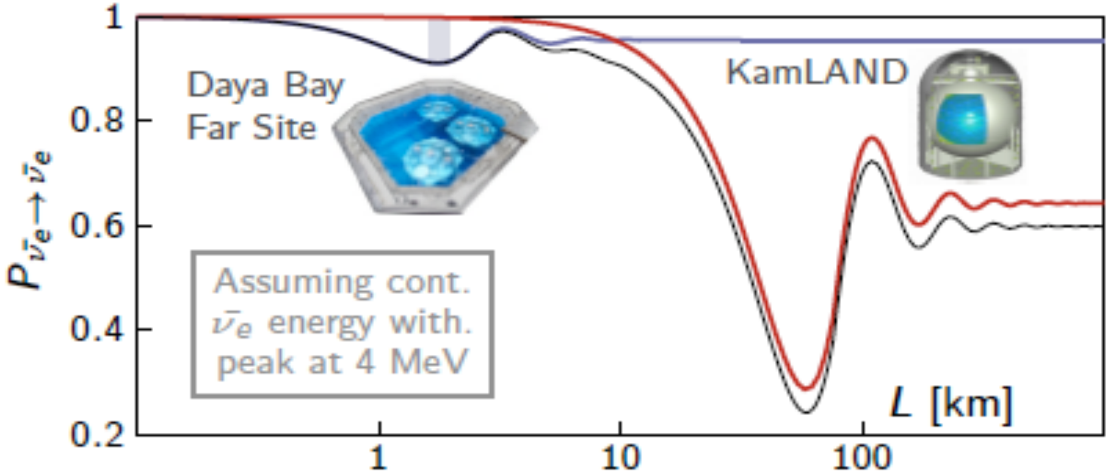
Matter term modifies oscillation probability differently depending on the sign of Δm^2

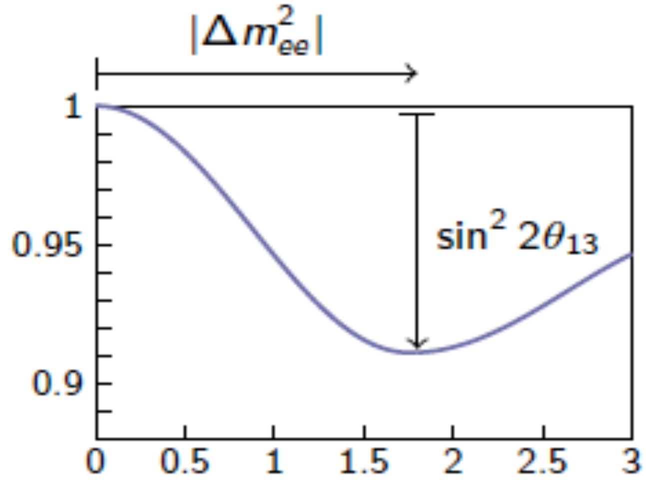
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – Matter effect***

	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

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

Short Baseline — Long Baseline

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

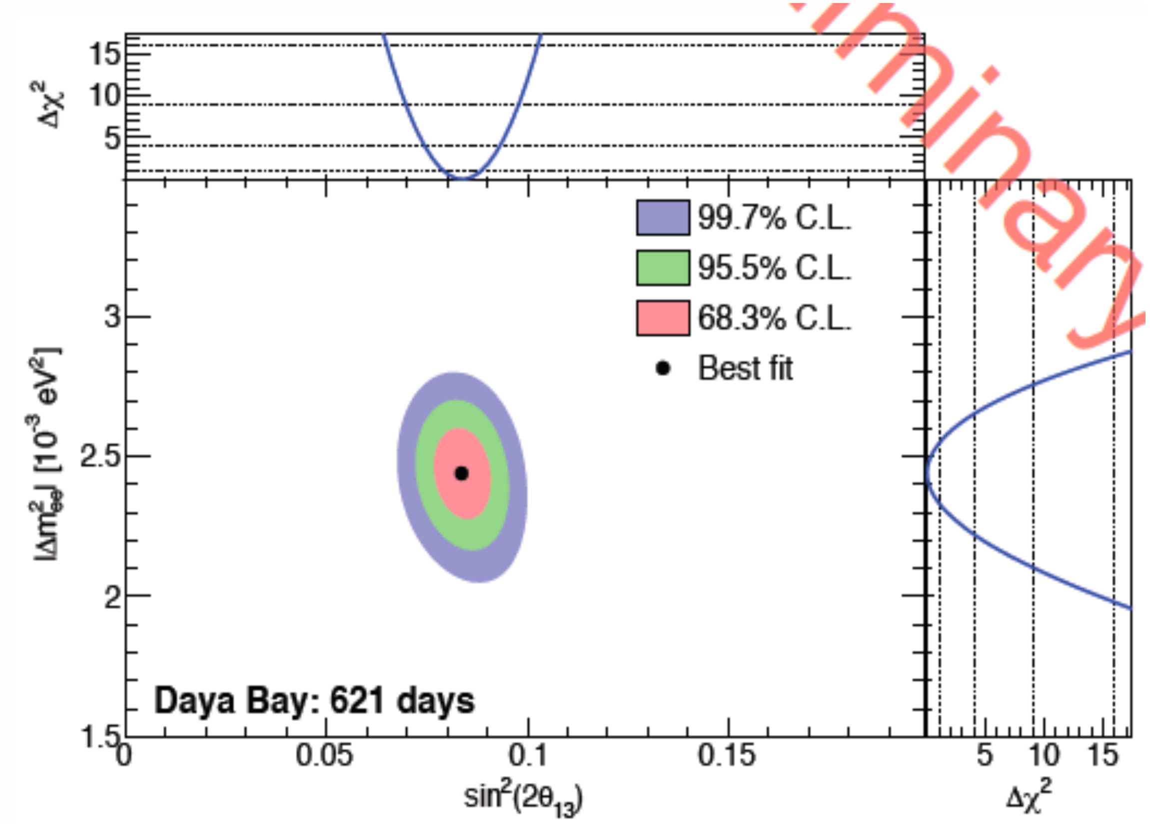
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$$

+: Normal Hierarchy
−: Inverted Hierarchy

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

Latest Oscillation Results from Daya Bay

Rate + Shape Oscillation Results [Announced in Neutrino 2014]



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

6% precision in $\sin^2 2\theta_{13}$ achieved

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

	Normal MH Δm^2_{32} [10^{-3}eV^2]	Inverted MH Δm^2_{32} [10^{-3}eV^2]
From Daya Bay Δm^2_{ee}	$2.39^{+0.10}_{-0.11}$	$-2.49^{+0.10}_{-0.11}$
From MINOS $\Delta m^2_{\mu\mu}$	$2.37^{+0.09}_{-0.09}$	$-2.41^{+0.11}_{-0.09}$

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:

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

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

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]

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

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

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: θ_{23} < 45 degree), other in higher octant (HO: θ_{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	$0.34 \rightarrow 0.67$	$0.357 \rightarrow 0.654$	$0.366 \rightarrow 0.663$
1σ precision (relative)	13.4%	11.3%	11.1%

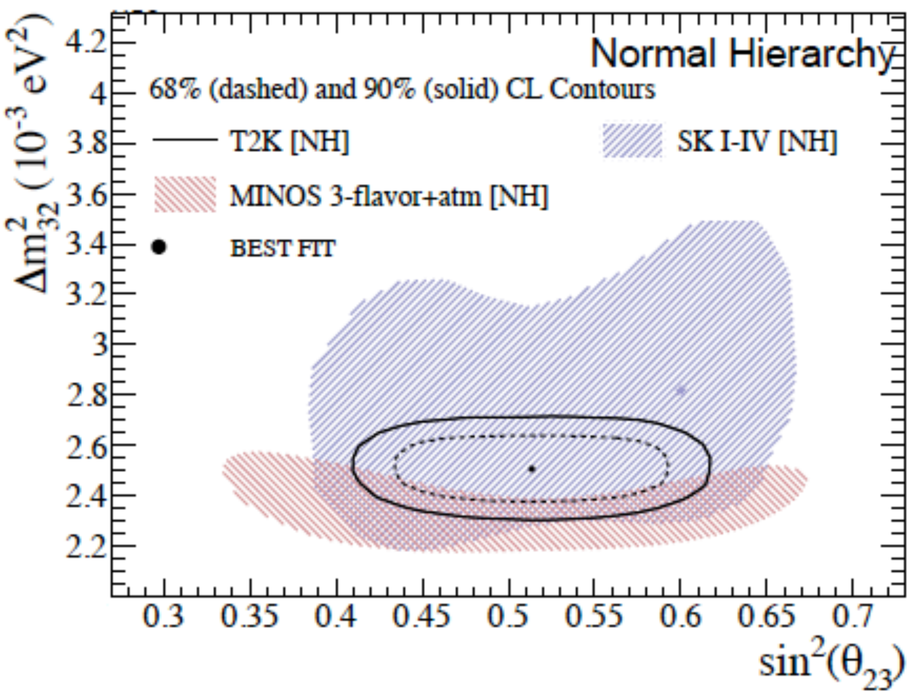
Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org

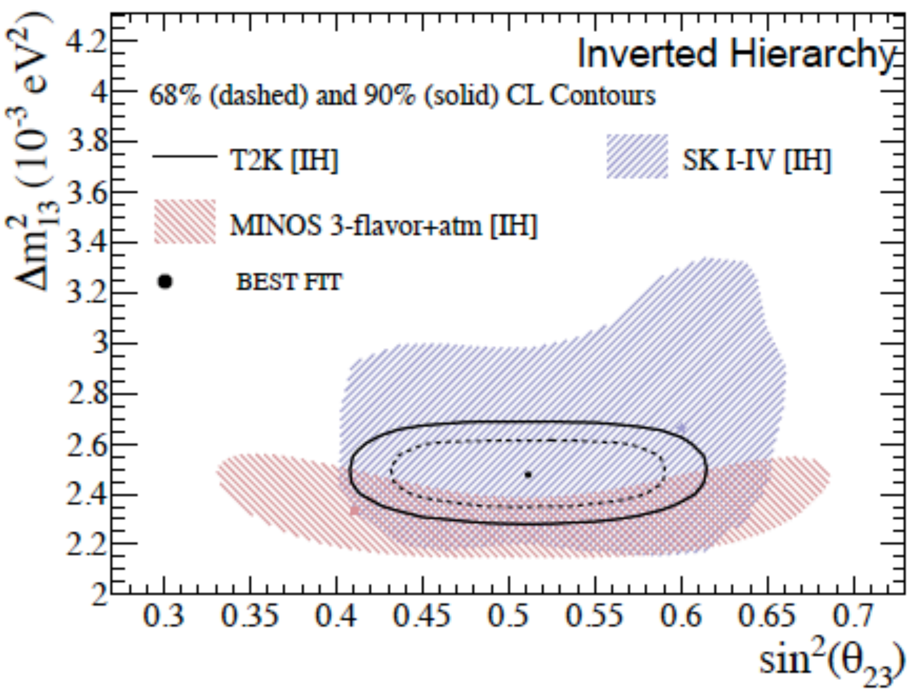
Global fit disfavors maximal 2-3 mixing at 1.4σ confidence level (mostly driven by MINOS)

ν_μ to ν_e oscillation data can break this degeneracy

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

New Measurements of Atmospheric Parameters





		Best-fit ± FC 68% CL (Δm^2 units 10^{-3} eV^2/c^4)
NH	$\sin^2\theta_{23}$	$0.514^{+0.055}_{-0.056}$
	Δm^2_{32}	2.51 ± 0.10
IH	$\sin^2\theta_{23}$	0.511 ± 0.055
	Δm^2_{13}	2.48 ± 0.10

Already mixing angle is better constrained by T2K in comparison to SK and MINOS

Talk by C. Walter in Neutrino 2014

Present Status of Neutrino Oscillation Parameters

	bfp $\pm 1\sigma$	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%
$\theta_{13}/^\circ$	$8.71^{+0.37}_{-0.38}$	$7.50 \to 9.78$	
$\delta_{CP}/^\circ$	265^{+56}_{-61}	$0 \to 360$	(Not Known)
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.45^{+0.19}_{-0.16}$	$6.98 \to 8.05$	2.4%
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N)	$+2.417^{+0.013}_{-0.013}$	$+2.247 \to +2.623$	2.5%
$\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I)	$-2.410^{+0.062}_{-0.062}$	$-2.602 \to -2.226$	

Non-maximal $> 1.4\sigma$

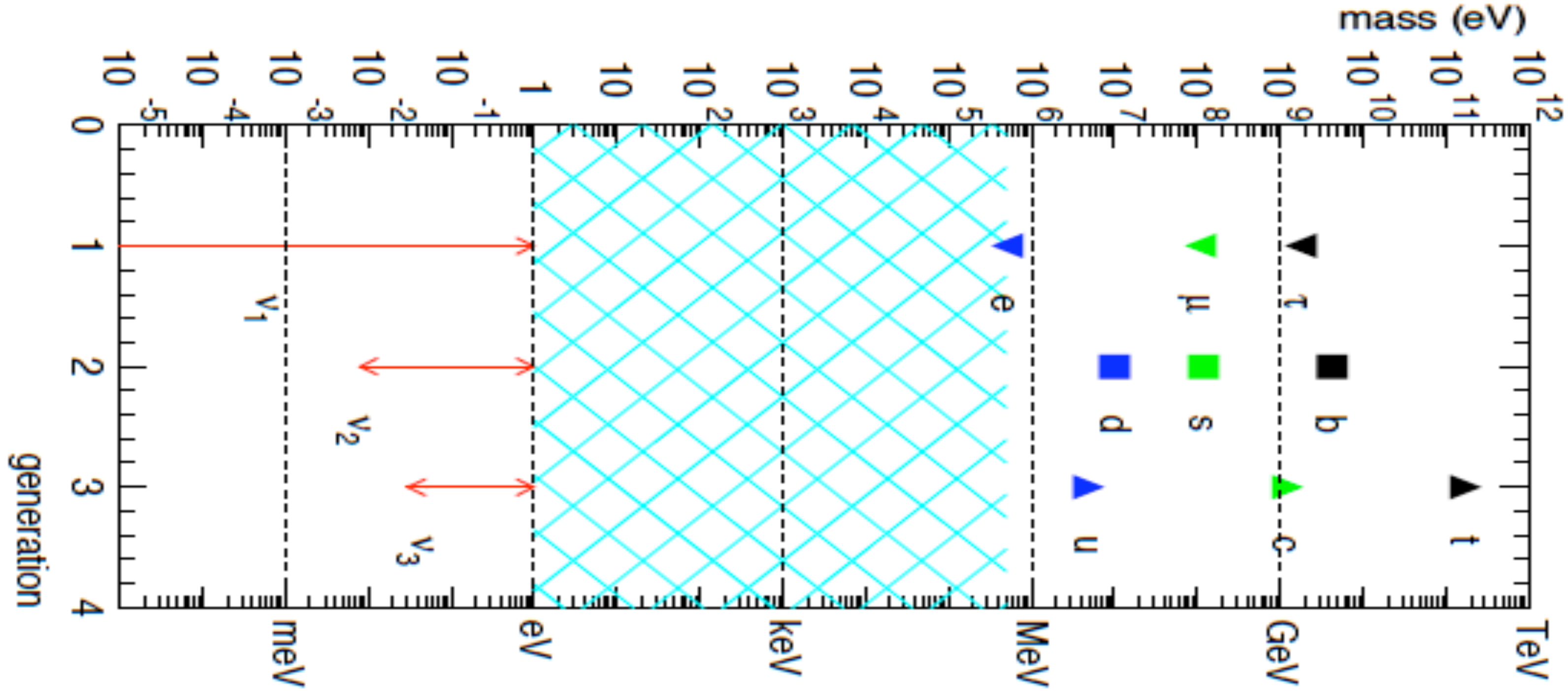
Non-zero $> 10\sigma$

$\sin\delta_{CP} < 0$ at 90% C.L.

See also the work by F. Capozzi etal D.V. Forero etal

Based on the data available after TAUP 2013 conference

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



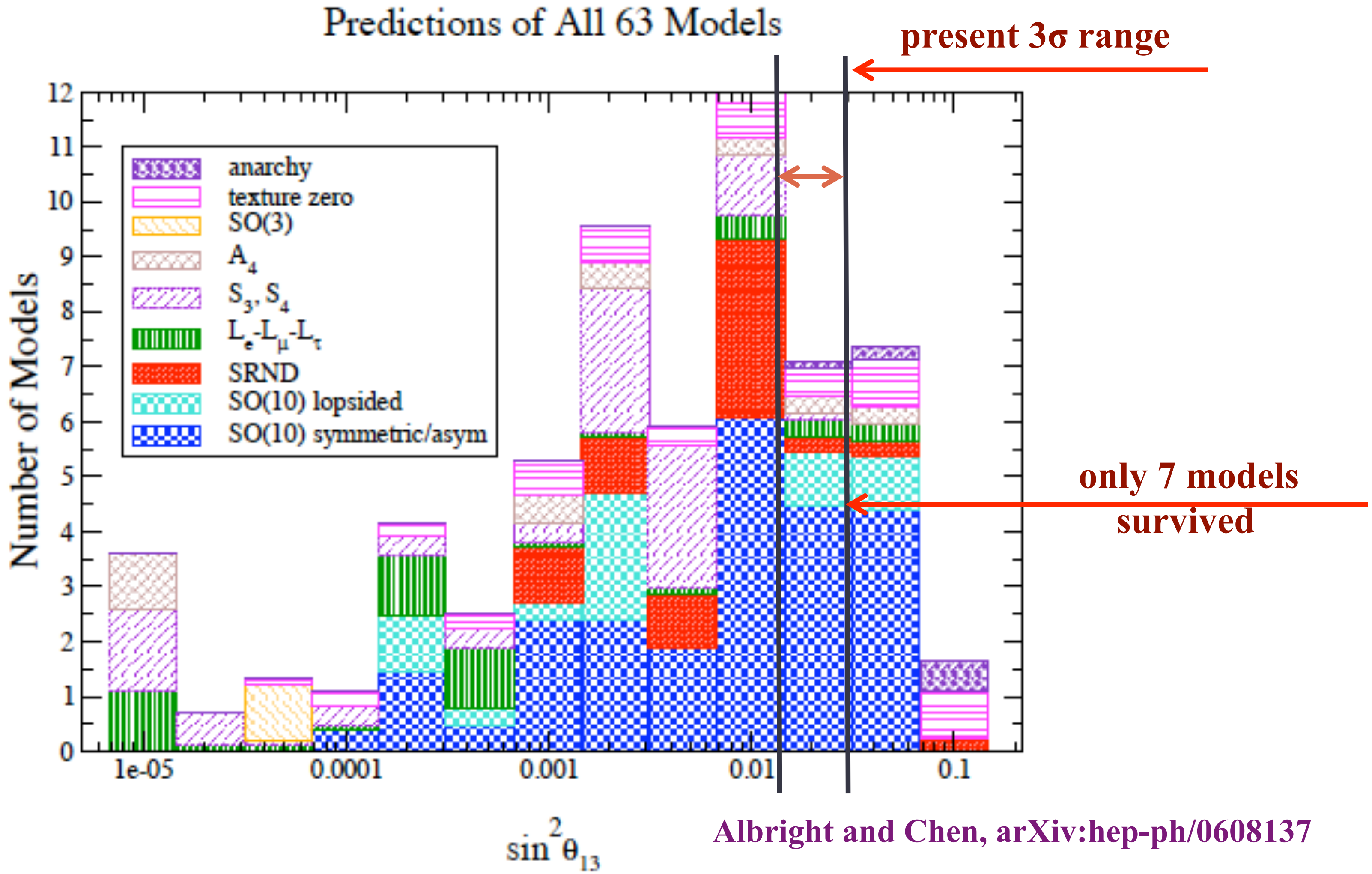
Why are neutrinos so light? **The origin of Neutrino Mass!**

	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?



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

Implications of Recent Measurement of θ_{13}

Simplest models that are ruled out!

- **Bimaximal mixing:** [Vissani (97), Barger, Pakvasa, Weiler, Whisnant (98)]

  It predicts: $\theta_{12} = 45°$, $\theta_{23} = 45°$, and $\theta_{13} = 0°$

predicted in flavor symmetry models with symmetry groups like A4, S4, A5

- **Tri-bimaximal mixing:** [Vissani (97), Harrison, Perkins, Scot (02)]

$$U_{\rm TBM} = R_{32}\left(\theta_{32} = \frac{\pi}{4}\right) R_{13}(\theta_{13} = 0)\, R\left(\theta_{21} = \tan^{-1}\left(\frac{1}{\sqrt{2}}\right)\right) = \frac{1}{\sqrt{6}}\begin{pmatrix} 2 & \sqrt{2} & 0 \\ -1 & \sqrt{2} & \sqrt{3} \\ 1 & -\sqrt{2} & \sqrt{3} \end{pmatrix}$$

- **Golden ratio:** [Datta, Ling, Ramond (03), Kajiyama, Raidal, Strumia (07)]

  It predicts: $\theta_{12} = 31.7°$, $\theta_{23} = 45°$, and $\theta_{13} = 0°$

Simplest models that are still alive!

- **Anarchy (ν mass matrix completely random):** [Hal, Murayama, Weiner (99), de Gouvea, Murayama (03, 12)]

  It predicts: large θ_{13}, okay with observed value of θ_{13}

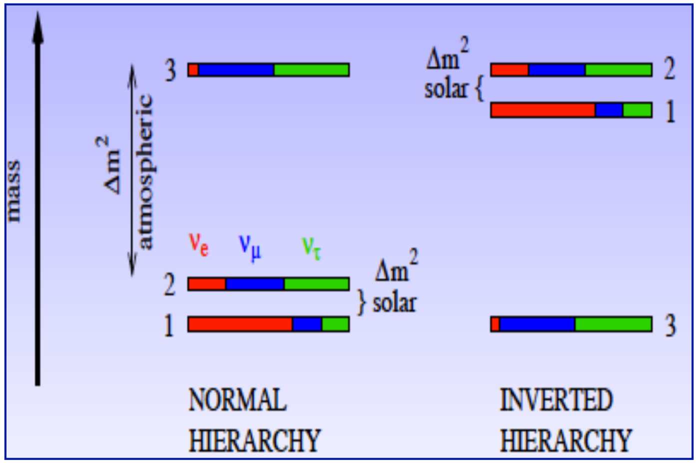
- **Quark-Lepton Complementarity:** [Minakata, Smirnov (94), Raidal (04)]

  Based on observation: θ_{12} (PMNS) + θ_{12} (CKM) = 45°

  It predicts: $\sin\theta_{13} \approx \sin\theta_C /\sqrt{2} \approx 0.16$ (close to the observed value, other relations needs to be tested!)

Fundamental Unknowns in Neutrino Oscillation

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!*

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

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

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Analytical approximation of the neutrino oscillation matter effects at large θ_{13}

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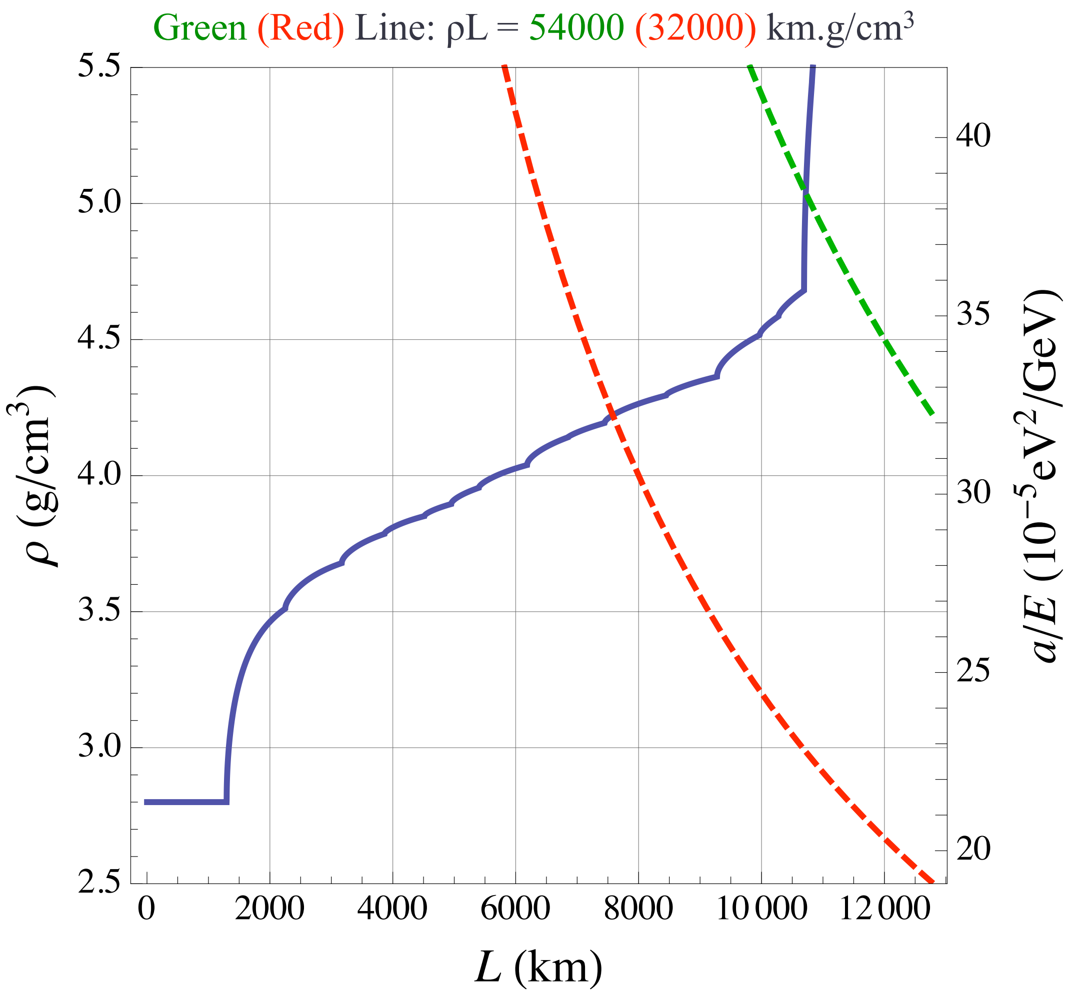
ABSTRACT: We argue that the neutrino oscillation probabilities in matter are best understood by allowing the mixing angles and mass-squared differences in the standard parametrization to 'run' with the matter effect parameter $a = 2\sqrt{2}G_F N_e E$, where N_e is the electron density in matter and E is the neutrino energy. We present simple analytical approximations to these 'running' parameters. We show that for the moderately large

JHEP04(2014)047

Matter Effect Parameter a

$$a = 2\sqrt{2}G_F N_e E \quad = 7.63\times10^{-5}(\text{eV}^2)\left(\frac{\rho}{\text{g/cm}^3}\right)\left(\frac{E}{\text{GeV}}\right)$$



Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

- Matter effects play an important role
- Mixing angles and and mass-squared differences run with the matter effect parameter 'a'
- We present simple analytical approximations to these running parameters using the Jacobi method
- We show that for large θ_{13}, the running of θ_{23} and δ_{CP} can be neglected, simplifying the probability expression
- We need to rotate only θ_{12} and θ_{13}

Our Approach

Use the expressions for the vacuum oscillation probabilities as it is, but make the following replacements:

$$\theta_{12} \to \theta'_{12}, \quad \theta_{13} \to \theta'_{13}, \quad \delta m^2_{jk} \to \lambda_j - \lambda_k$$

where

$$\tan 2\theta'_{12} = \frac{(\delta m^2_{21}/c^2_{13})\sin 2\theta_{12}}{(\delta m^2_{21}/c^2_{13})\cos 2\theta_{12} - a}, \qquad \tan 2\theta'_{13} = \frac{(\delta m^2_{31} - \delta m^2_{21} s^2_{12})\sin 2\theta_{13}}{(\delta m^2_{31} - \delta m^2_{21} s^2_{12})\cos 2\theta_{13} - a},$$

$$\lambda_1 = \lambda'_- \qquad \lambda'_\pm = \frac{(\delta m^2_{21} + a c^2_{13}) \pm \sqrt{(\delta m^2_{21} - a c^2_{13})^2 + 4 a c^2_{13} s^2_{12} \delta m^2_{21}}}{2}$$

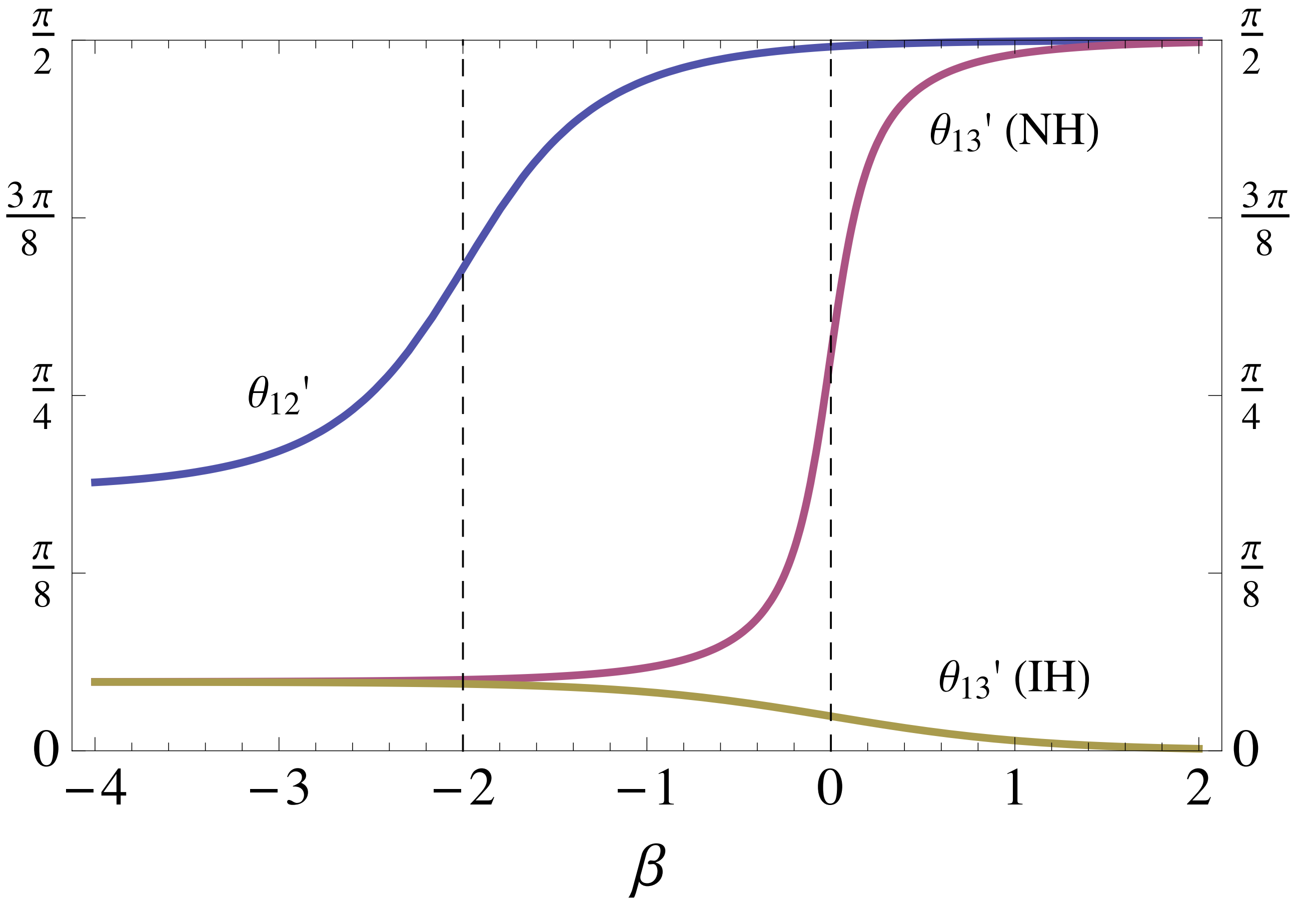
$$\lambda_2 = \lambda''_\mp$$

$$\lambda_3 = \lambda''_\pm \qquad \lambda''_\pm = \frac{\left[\lambda'_+ + (\delta m^2_{31} + a s^2_{13})\right] \pm \sqrt{\left[\lambda'_+ - (\delta m^2_{31} + a s^2_{13})\right]^2 + 4 a^2 s'^2_{12} c^2_{13} s^2_{13}}}{2}$$

upper (lower) sign is for the normal (inverted) hierarchy

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

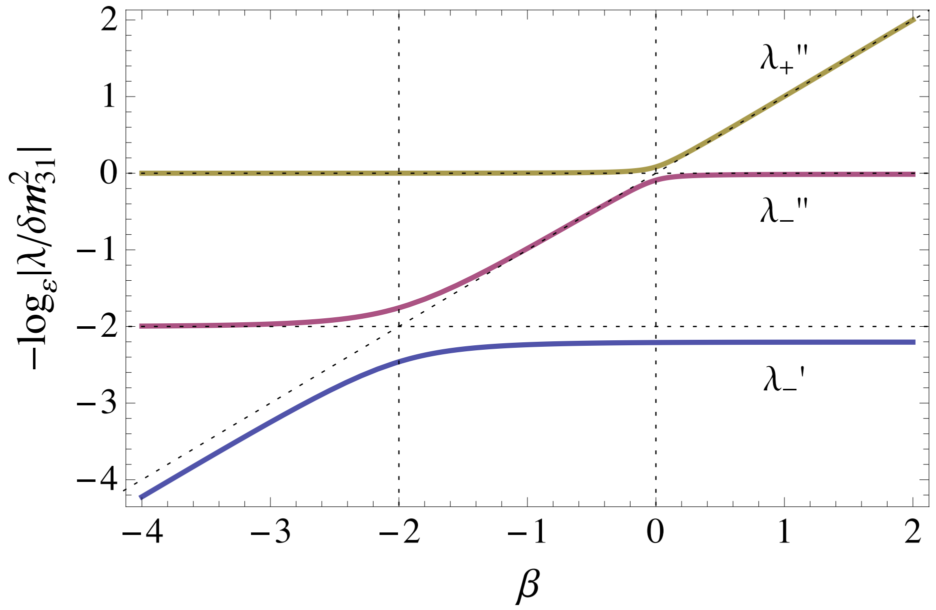
a-dependence of effective mixing angles



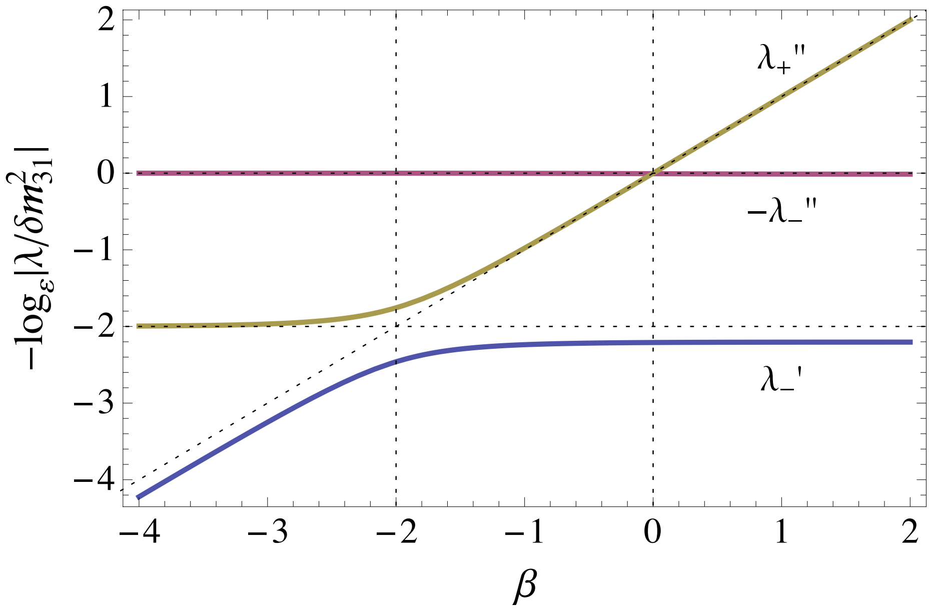
$$\frac{a}{|\delta m_{31}^2|} = \varepsilon^{-\beta}, \qquad \varepsilon = \sqrt{\frac{\delta m_{21}^2}{|\delta m_{31}^2|}} \approx 0.17$$

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

a-dependence of effective mass-squared differences



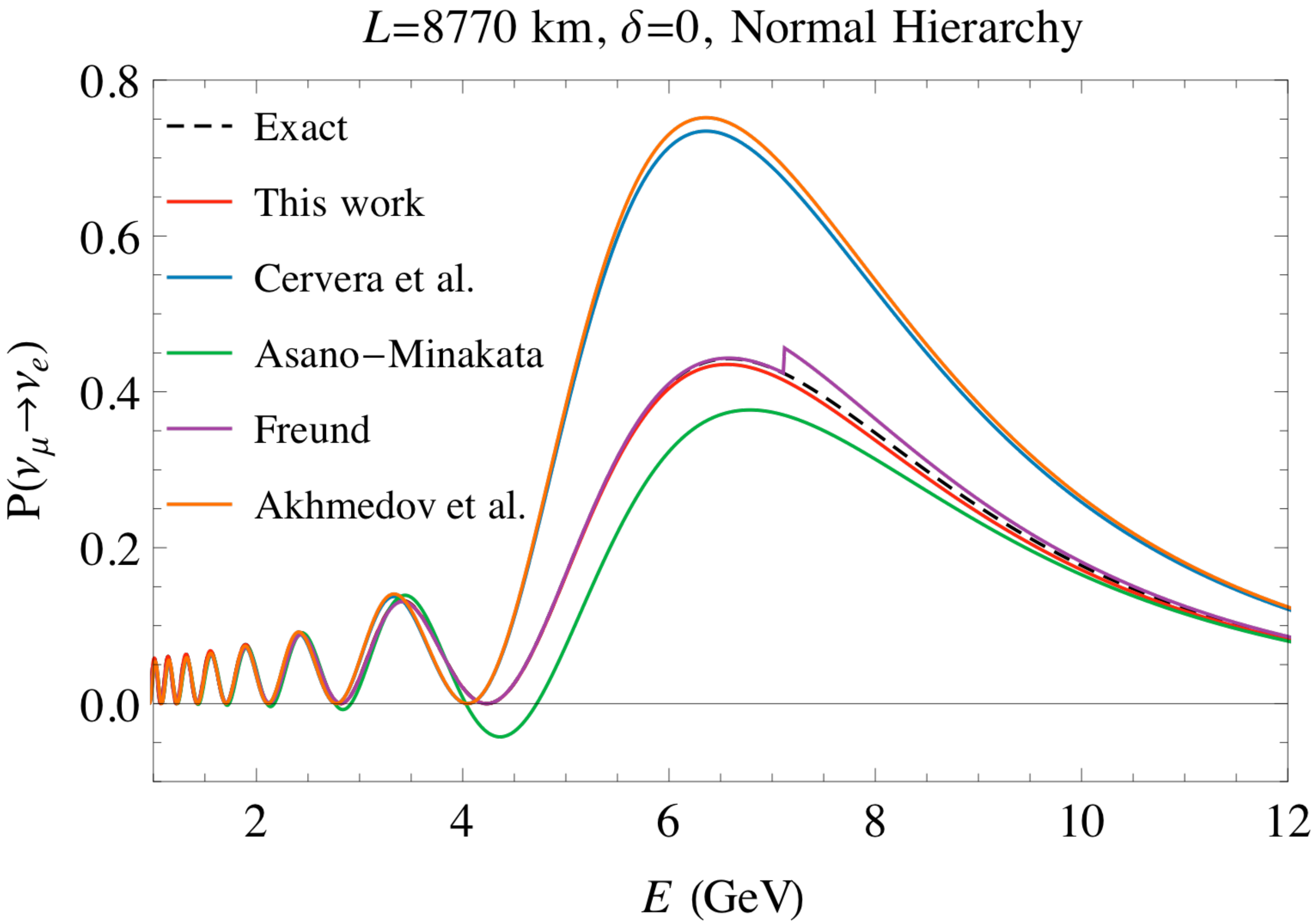
Normal Hierarchy



Inverted Hierarchy

Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)

Accuracy of Our Method and Comparison with Existing Literature



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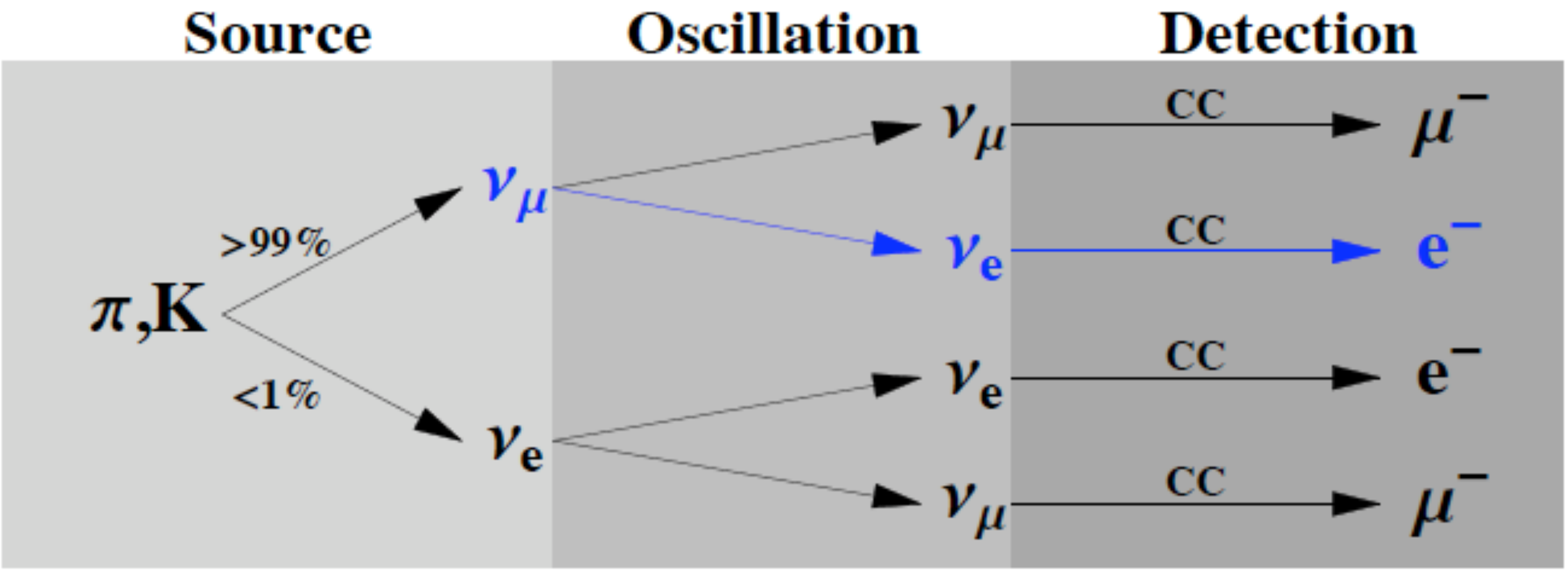
Other analytical expressions suffer in accuracy due to their reliance on expansion in θ_{13}, or in simplicity when higher order terms in θ_{13} included

Our method gives accurate probability for all channels, baselines and energies

Superbeams



Traditional approach: Neutrino beam from pion decay

Current Generation Experiments:

Tokai to Kamioka (T2K) : 295 km (2.5^{o} 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 (NOvA) : 810 km (0.8^{o} 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 $(\nu_\mu \to \nu_e)$ 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),

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

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

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

$\sin^2 2\theta_{13}$: 0.09; $\alpha \sin 2\theta_{13}$: 0.009; α^2: 0.0009

$\sin^2\theta_{23}$ → 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 $\hat{A} \equiv \pm(2\sqrt{2}G_F n_e E)/\Delta m^2_{31}$

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?

Physics Potential of T2K & NOνA in light of large θ_{13}

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Potential of optimized NOνA for large θ_{13} & combined performance with a LArTPC & T2K

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ABSTRACT: NOνA experiment has reoptimized its event selection criteria in light of the recently measured moderately large value of θ_{13}. We study the improvement in the sensitivity to the neutrino mass hierarchy and to leptonic CP violation due to these new features. For favourable values of δ_{CP}, NOνA sensitivity to mass hierarchy and leptonic CP violation is

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Resolving the octant of θ_{23} with T2K and NOνA

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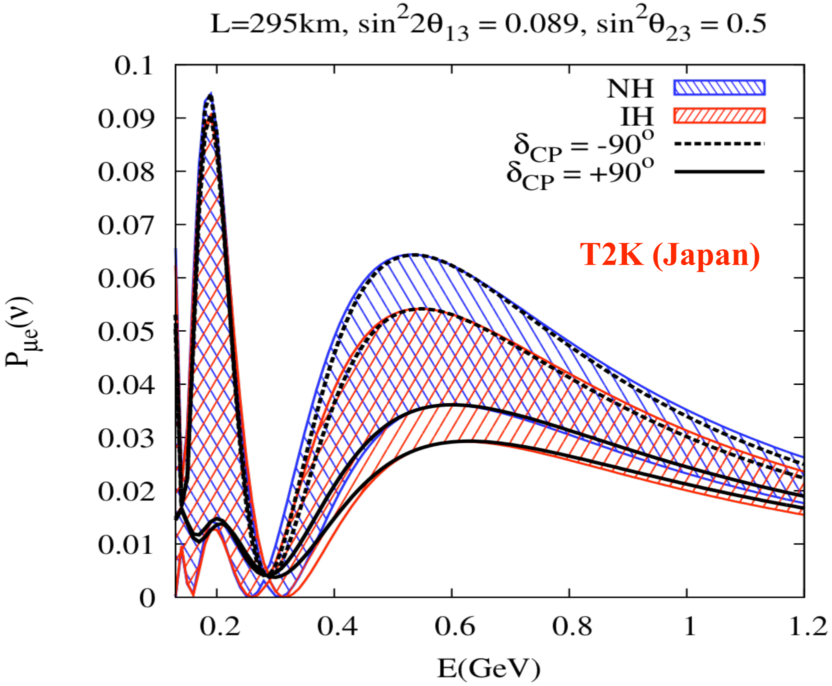
ABSTRACT: Preliminary results of MINOS experiment indicate that θ_{23} is not maximal. Global fits to world neutrino data suggest two nearly degenerate solutions for θ_{23}: one in the lower octant (LO: $\theta_{23} < 45°$) and the other in the higher octant (HO: $\theta_{23} > 45°$). $\nu_\mu \to \nu_e$ oscillations in superbeam experiments are sensitive to the octant and are capable of resolving this degeneracy. We study the prospects of this resolution by the current T2K and upcoming NOνA experiments. Because of the hierarchy-δ_{CP} degeneracy and the octant-δ_{CP} degeneracy, the impact of hierarchy on octant resolution has to be taken into account.

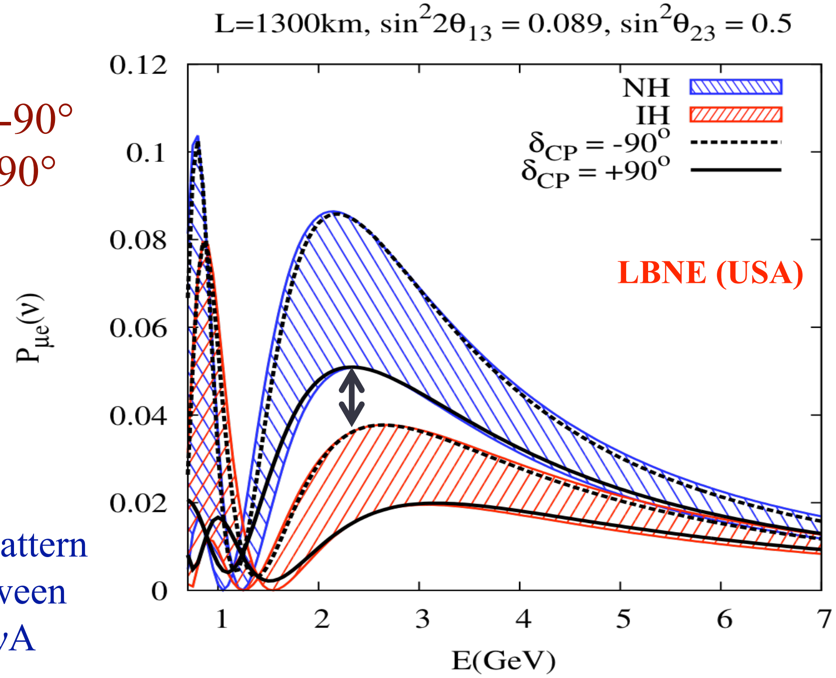
JHEP07(2013)131

Combined data from T2K and NOνA are expected to provide
the first hint for neutrino mass hierarchy, leptonic CP violation, and octant of θ_{23}

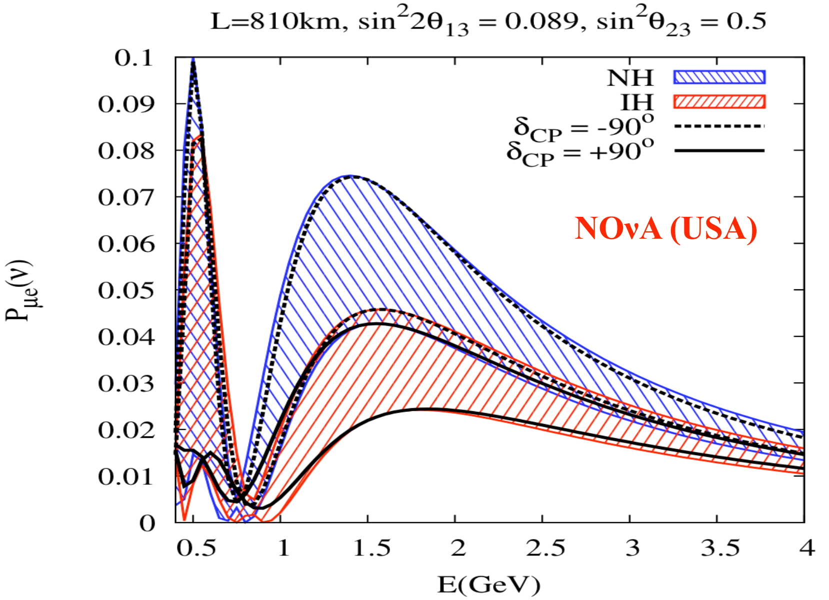
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



For ν:
Max: NH, -90°
Min: IH, 90°

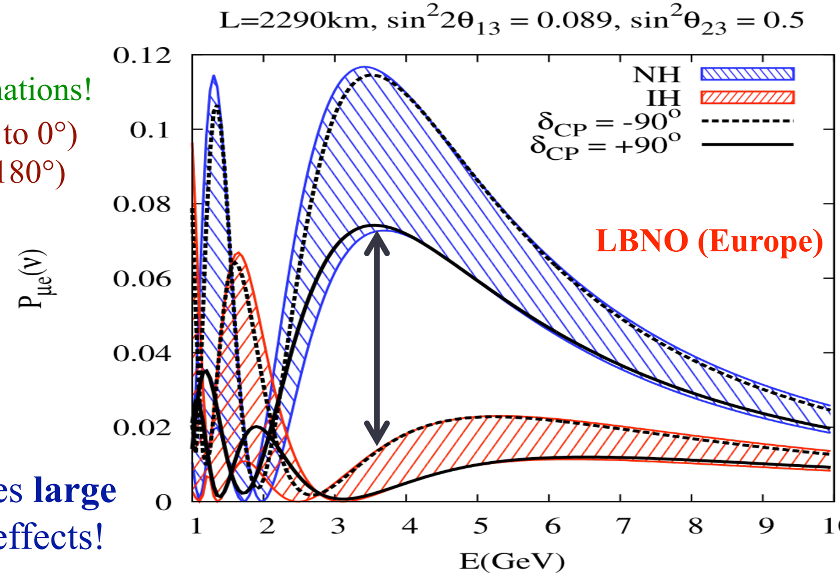


Degeneracy pattern different between T2K & NOvA



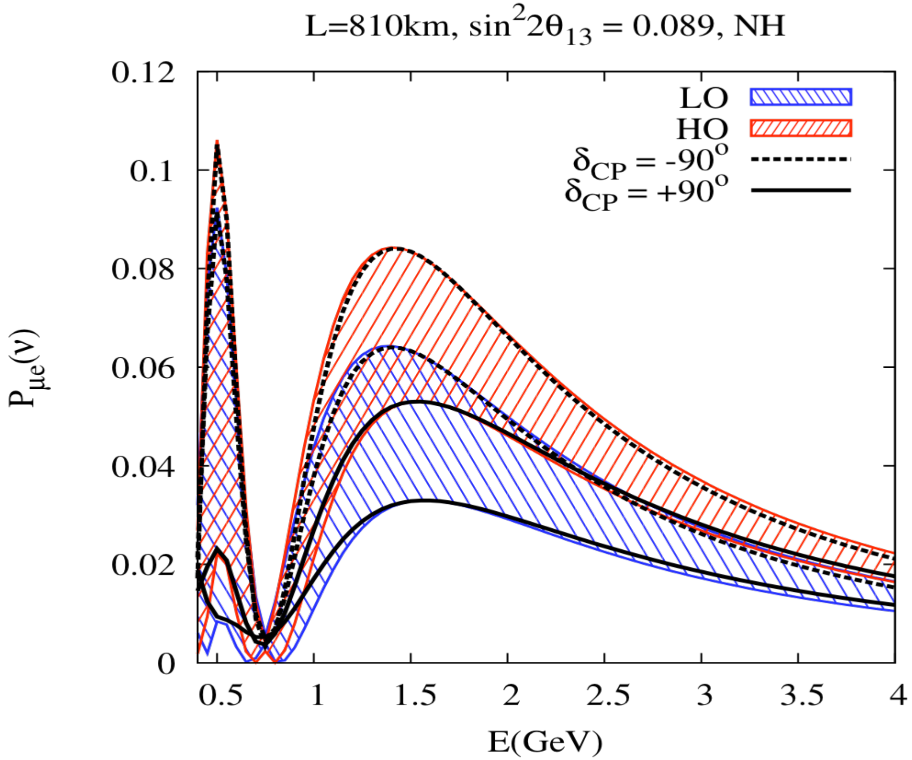
Favorable combinations!
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

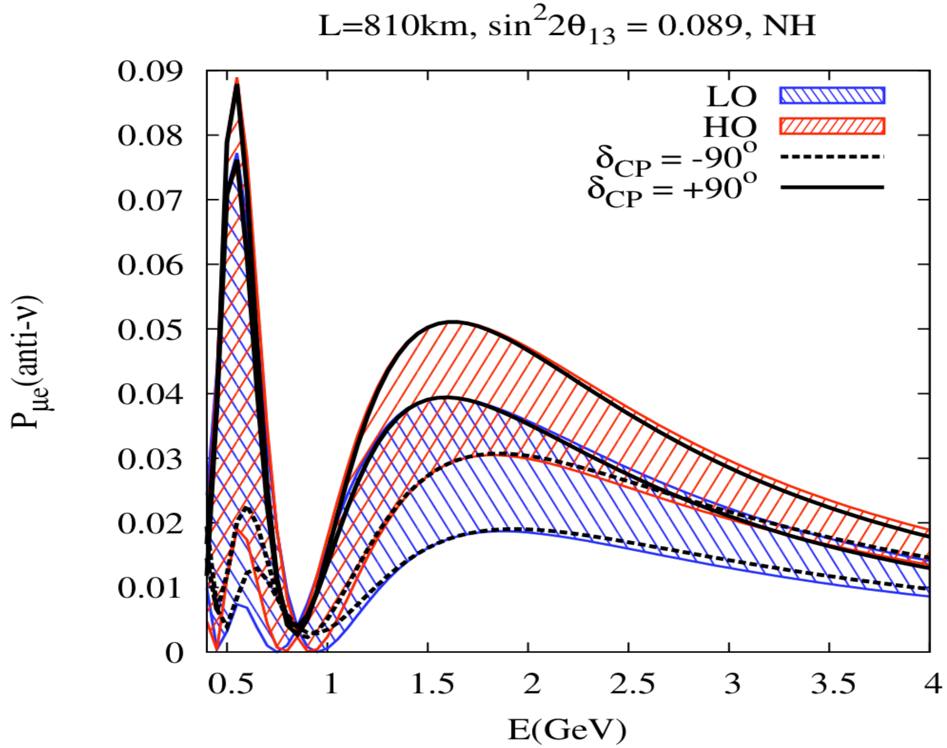
Large θ_{13} causes **large** Earth matter effects!



Agarwalla, Prakash, Raut, Sankar, 2012-2013

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





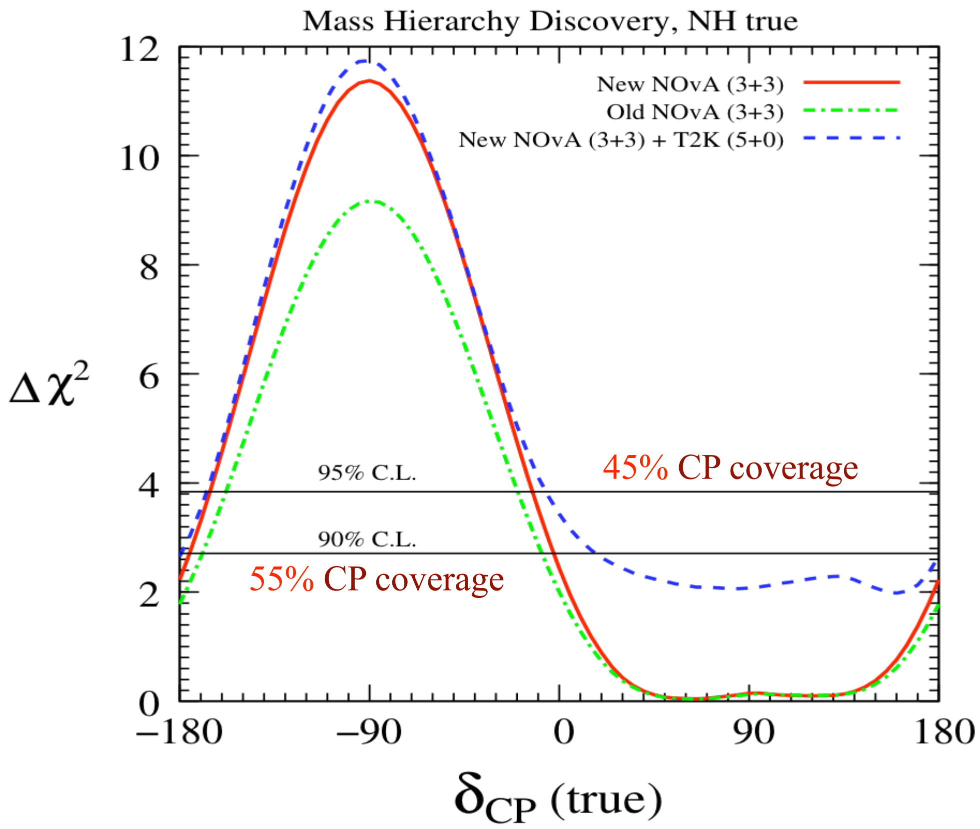
For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

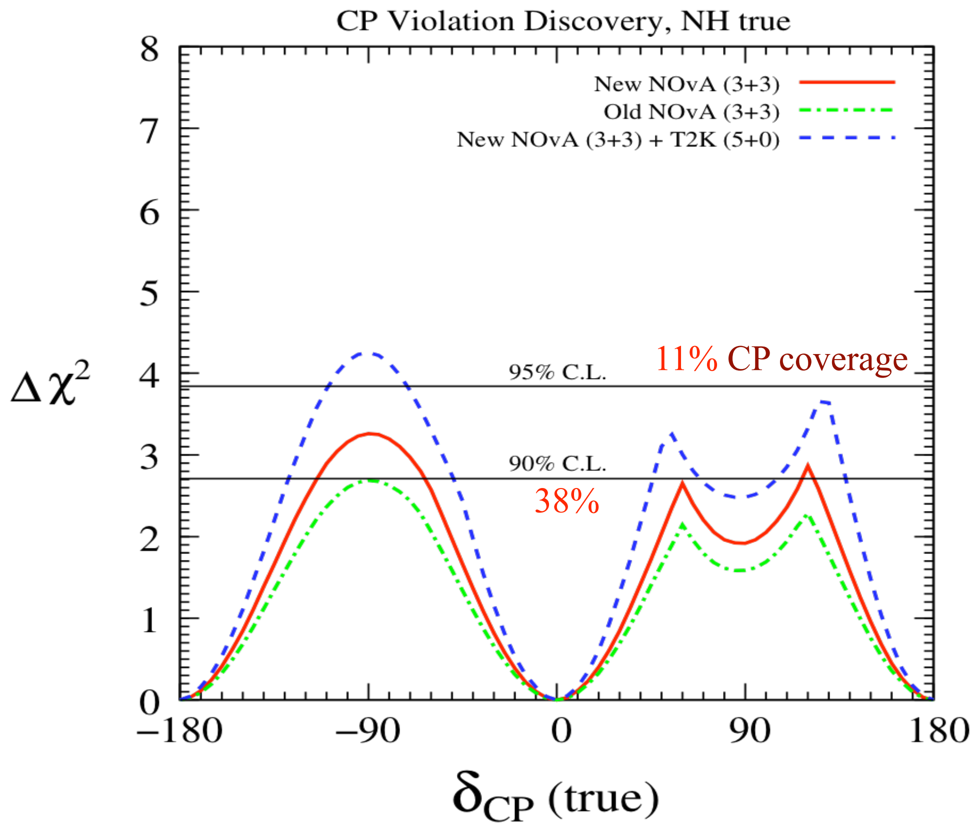
For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

Unfavorable CP values for neutrino are favorable for anti-neutrino & vice-versa

Agarwalla, Prakash, Sankar, arXiv: 1301.2574

Mass Hierarchy & CP Violation Discovery with T2K and NOvA



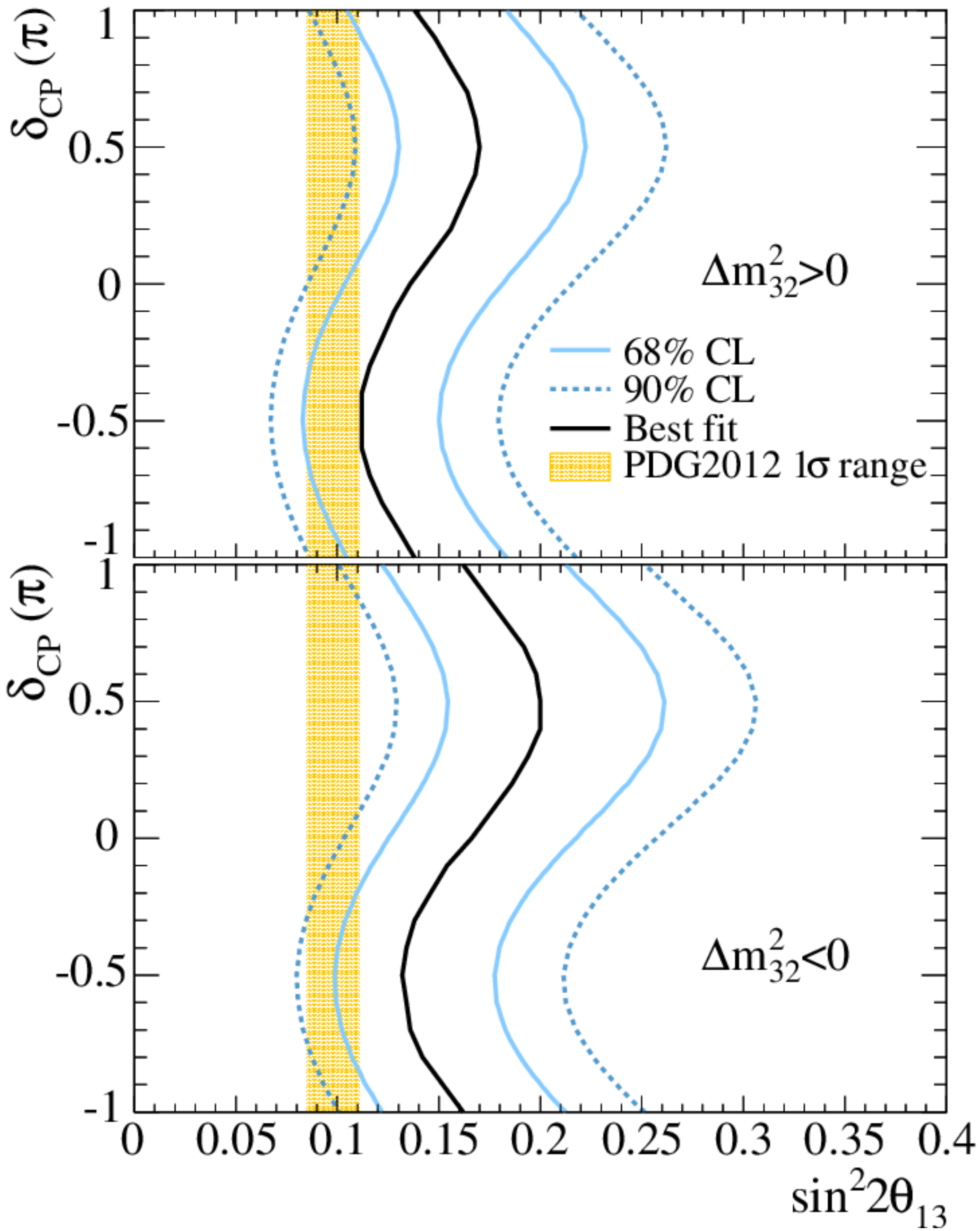


Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644
See also, Huber, Lindner, Schwetz, Winter, arXiv: 0907.1896;
Machado, Minakata, Nunokawa, Funchal, arXiv: 1307.3248;
Ghosh, Ghosal, Goswami, Raut, arXiv: 1401.7243

Adding data from T2K and NOvA 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

Important Synergy between Reactor and Accelerator data



First hint of δ_{CP} combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

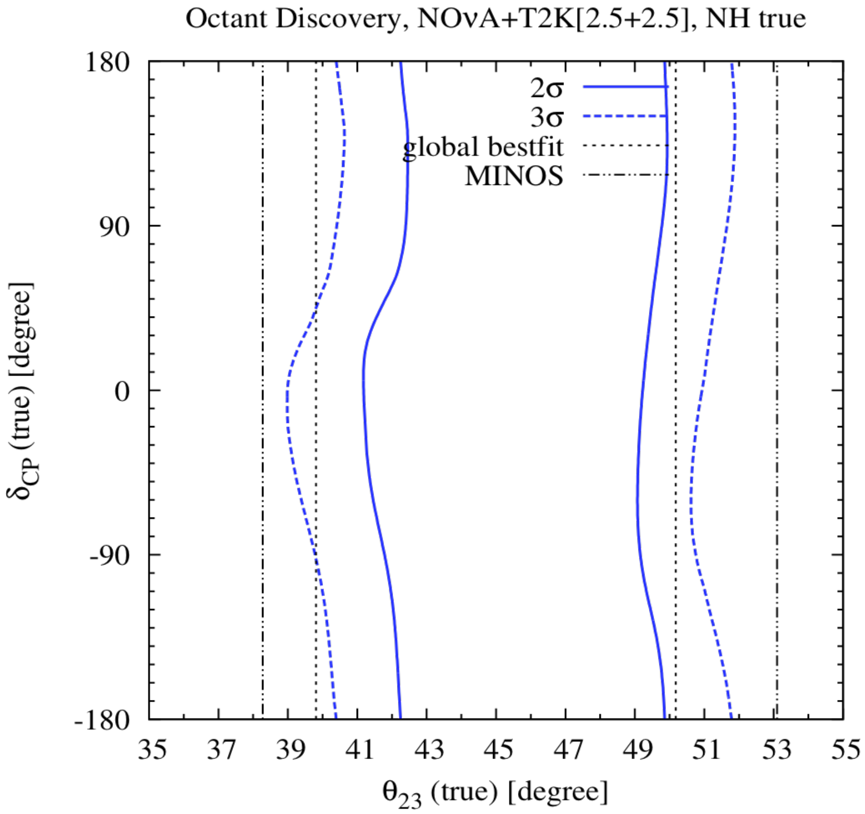
- ⋆ **Is Nature very kind to us?**
- ⋆ **Are we very lucky?**
- ⋆ **Is CP violated maximally?**

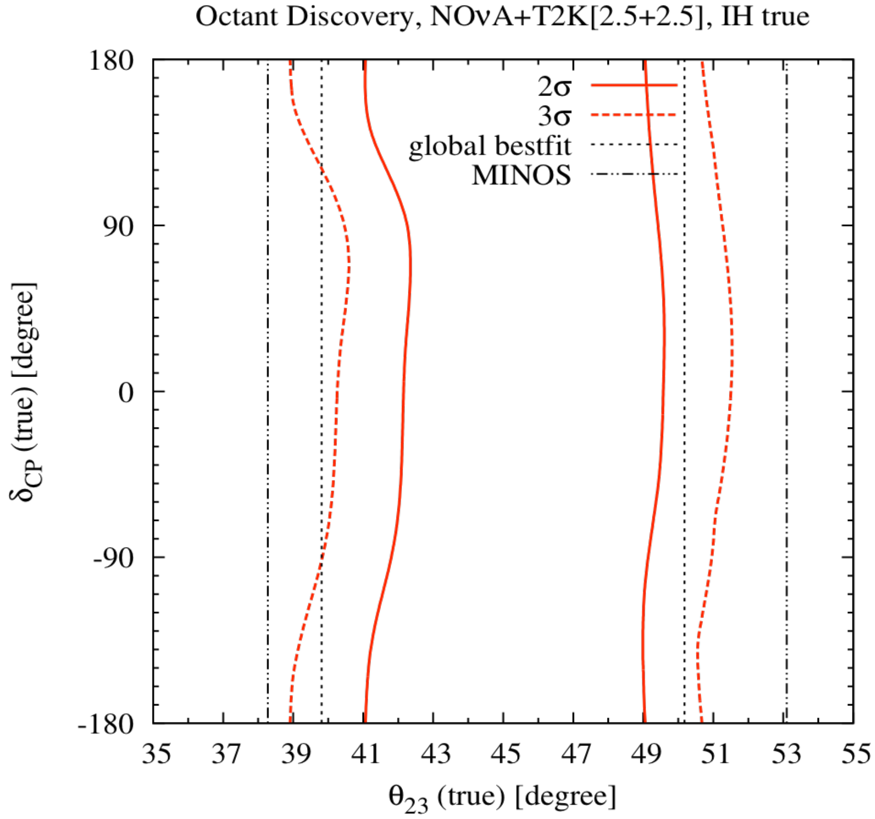
Strong motivation for anti-neutrino run in T2K

In these plots, atmospheric parameters are marginalized over

Courtesy C. Walter (T2K Collaboration) Talk at Neutrino 2014

Resolving Octant of θ_{23} with T2K and NOνA





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), 70 kton LArTPC (Phase2)

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Exploring the three flavor effects with future superbeams using liquid argon detectors

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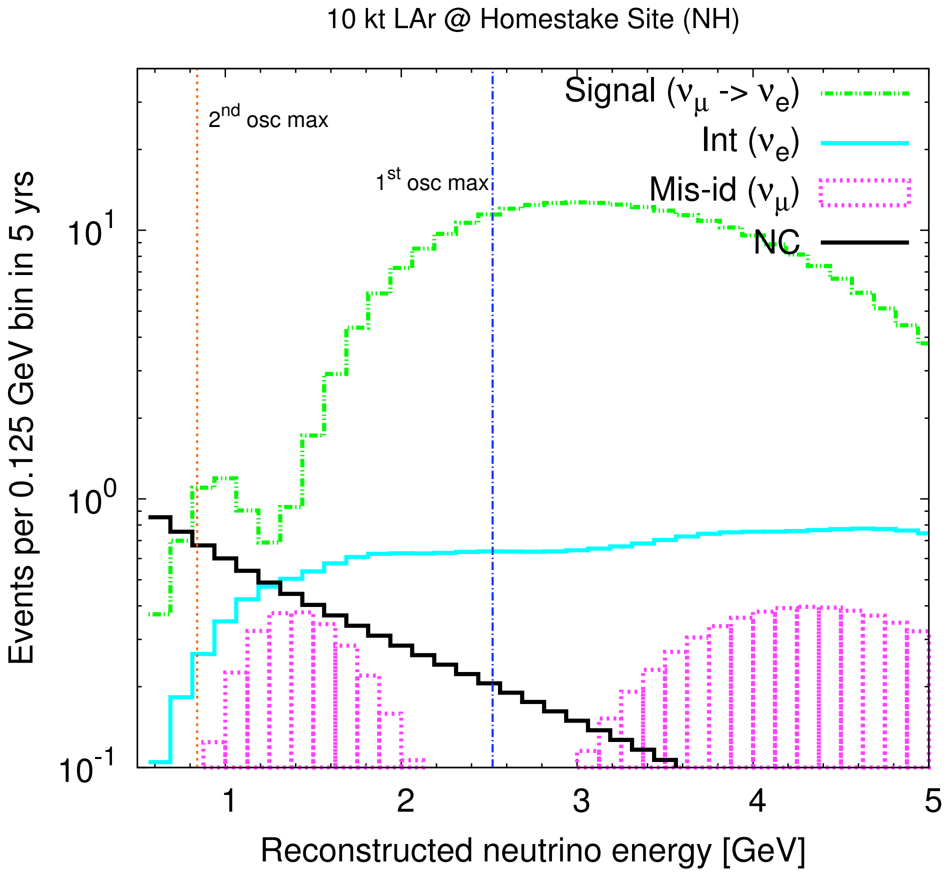
ABSTRACT: Recent measurement of a moderately large value of θ_{13} signifies an important breakthrough in establishing the standard three flavor oscillation picture of neutrinos. It has provided an opportunity to explore the sub-dominant three flavor effects in present and future long-baseline experiments. In this paper, we perform a comparative study of the physics reach of two future superbeam facilities, LBNE and LBNO in their first phases of run, to resolve the issues of neutrino mass hierarchy, octant of θ_{23}, and leptonic CP violation. We also find that the sensitivity of these future facilities can be improved significantly by adding the projected data from T2K and NOνA. Stand-alone LBNO setup

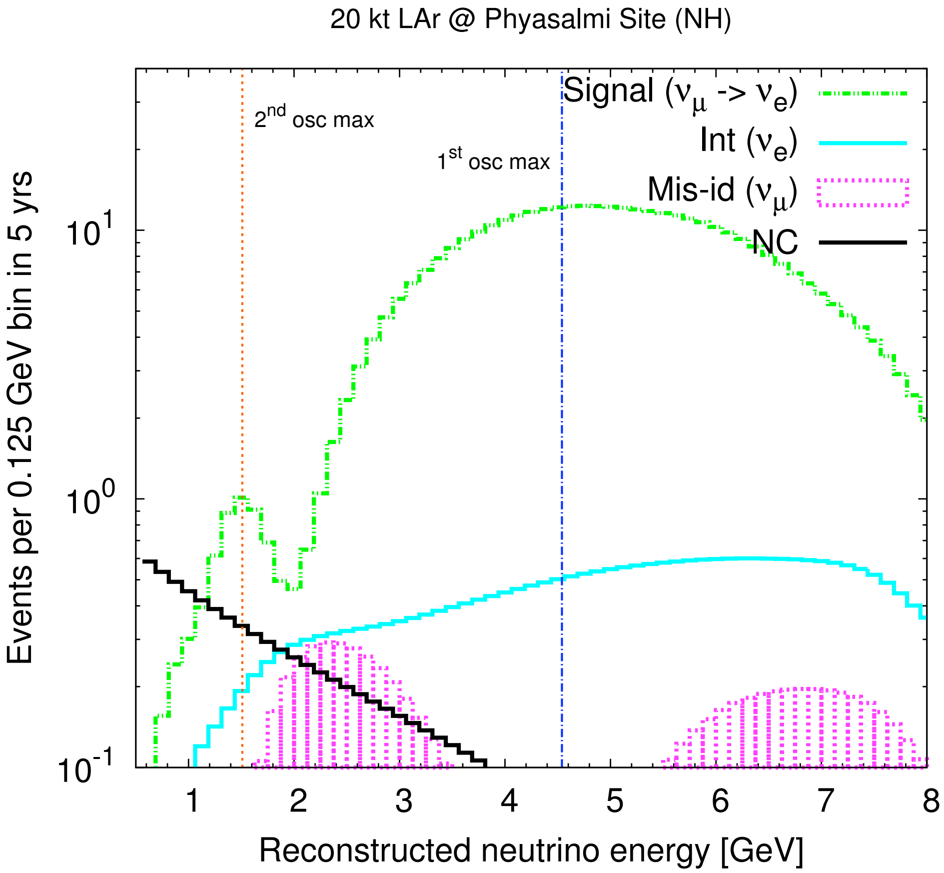
JHEP03(2014)087

These powerful future facilities are capable enough to settle the remaining fundamental unknowns in neutrino oscillation at high C.L., needed to claim the discovery

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

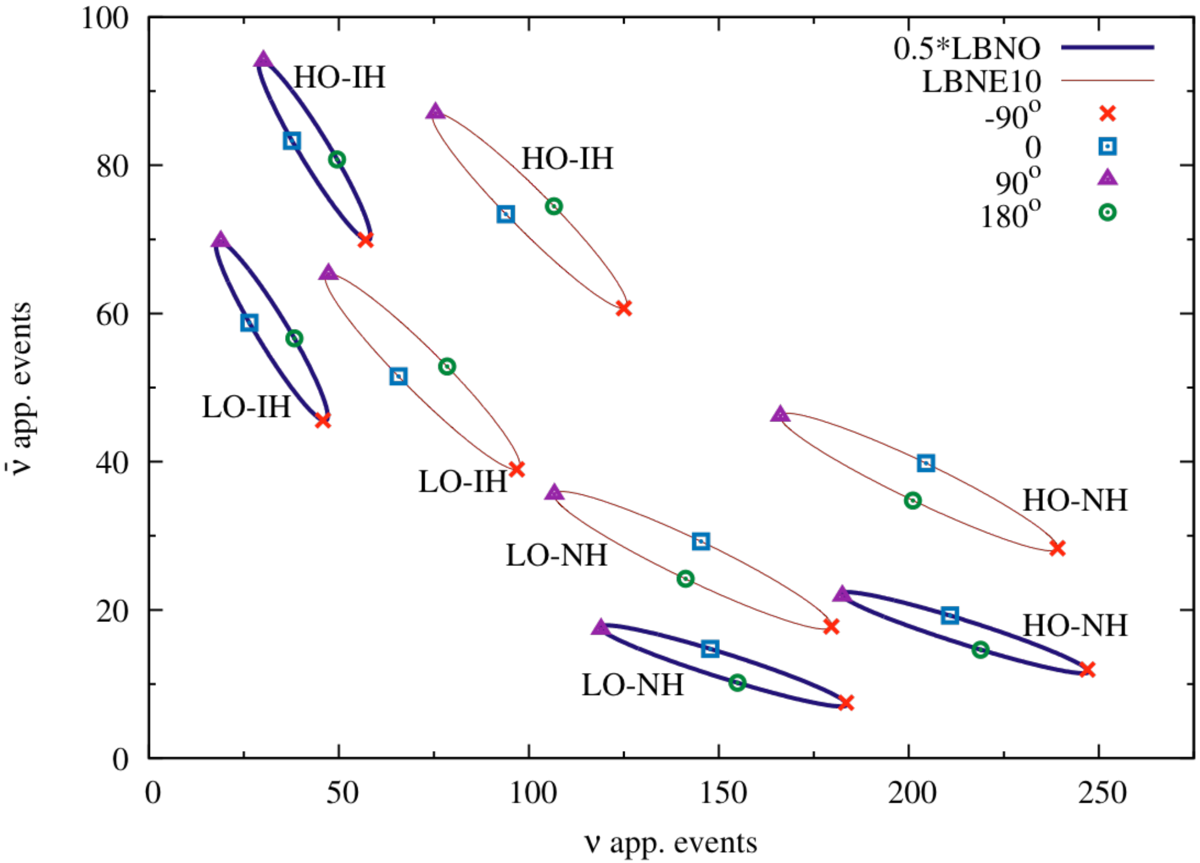
Event Spectrum in LBNE and LBNO Experiments





Review on long-baseline phenomenology, S.K. Agarwalla, arXiv: 1401.4705

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

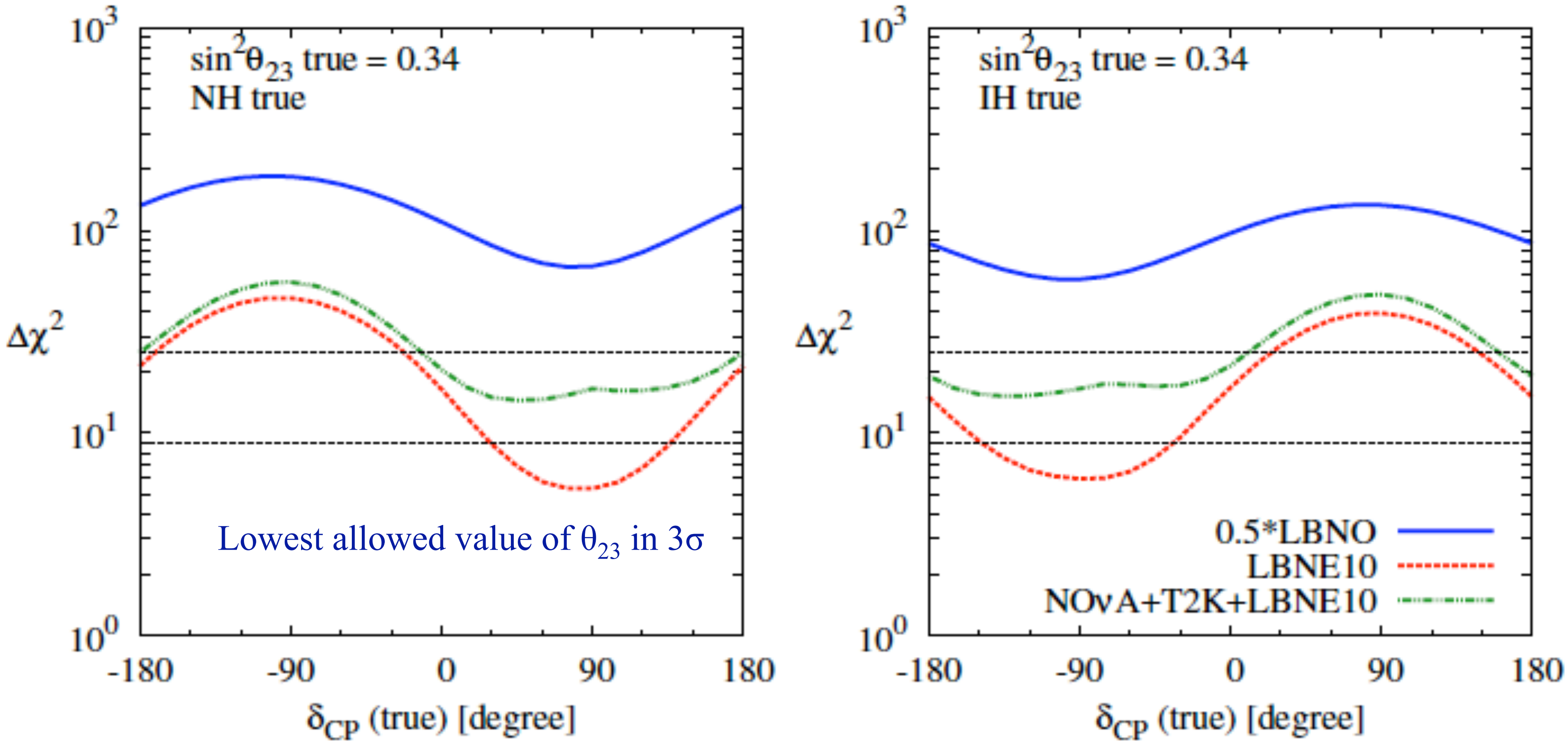
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

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

Median Hierarchy Discovery Potential with LBNE and LBNO

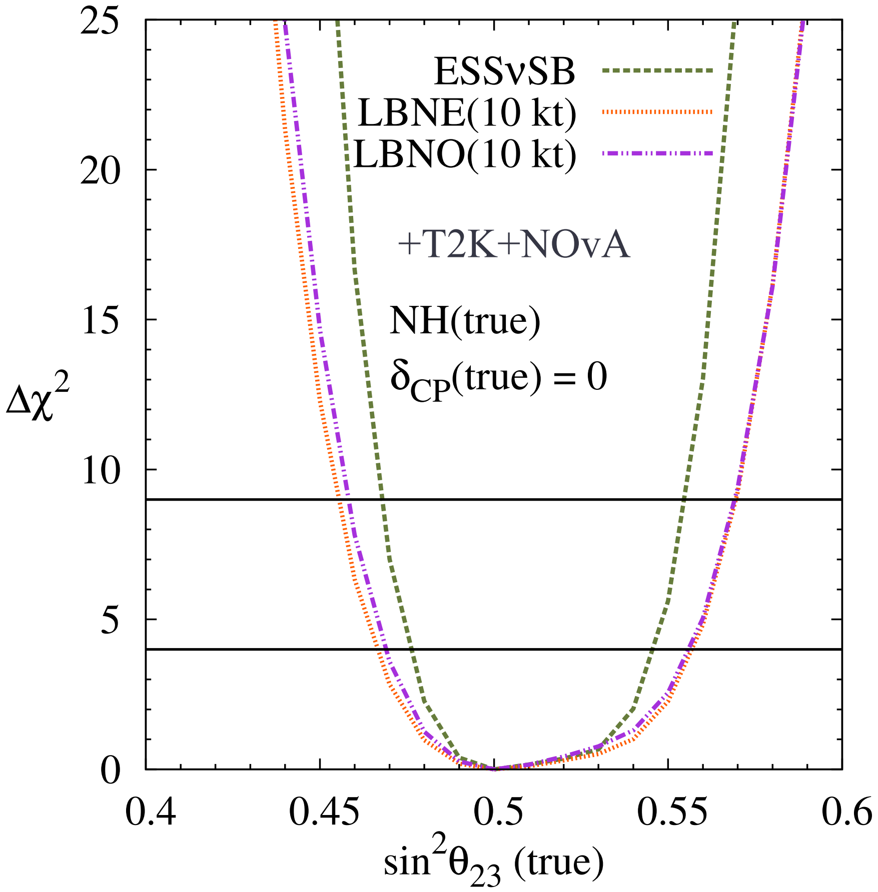


Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]
See also, arXiv:1312.6520 [hep-ph] from LAGUNA-LBNO Collaboration

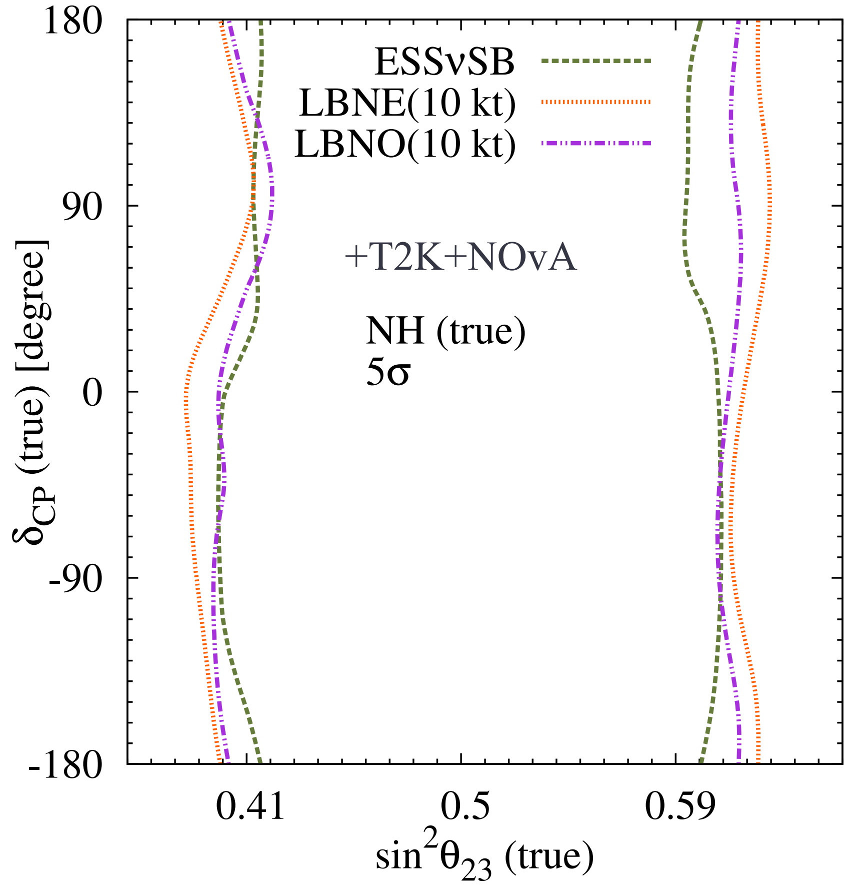
LBNO w/ 10 kt $> 7\sigma$ median hierarchy discovery irrespective of the choice of θ_{23}-δ_{CP}-hierarchy

LBNE w/ 10 kt + T2K + NOνA $>$ 3σ median hierarchy discovery for any parameter choice

Probing 2-3 Mixing Angle with LBNE and LBNO



Discovery potential of non-maximal θ_{23}

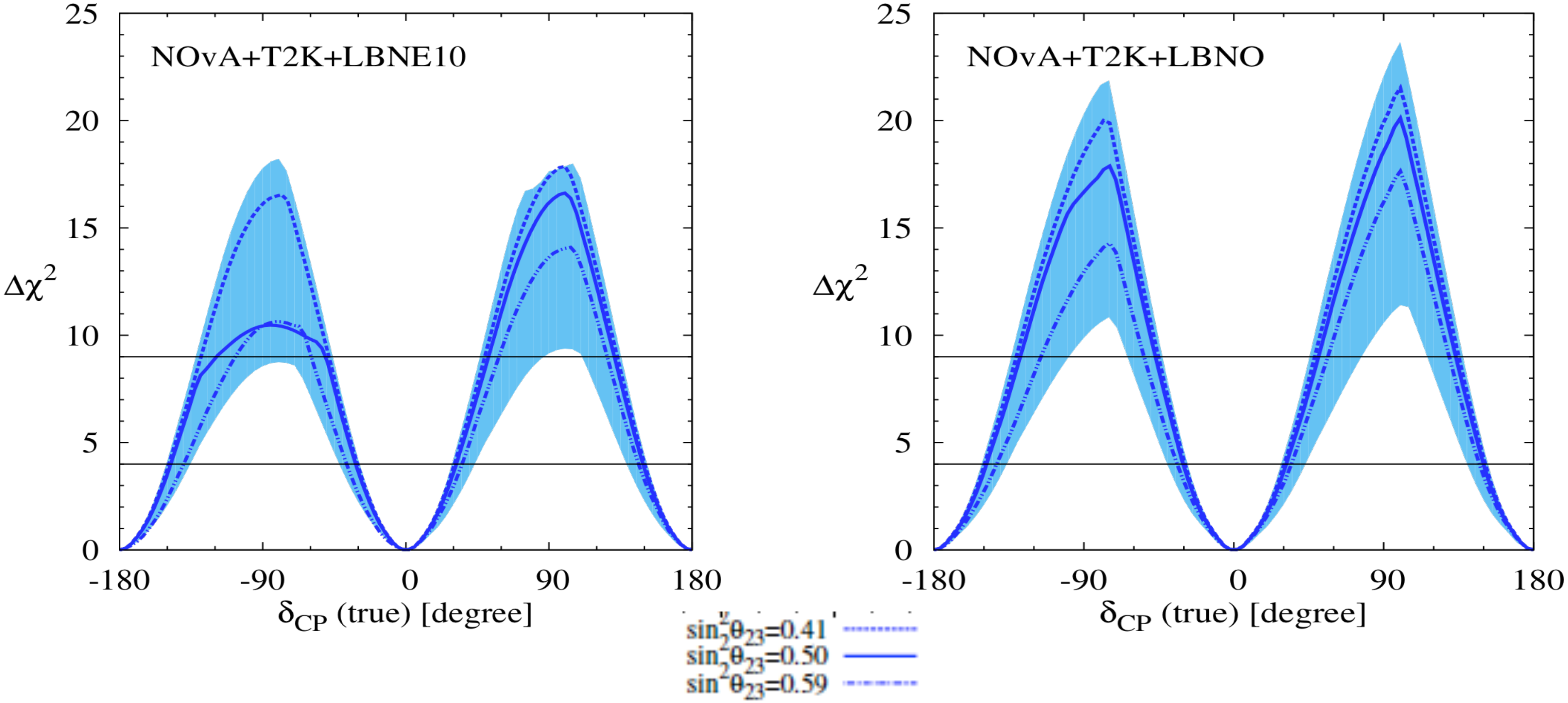


Octant Discovery potential

Agarwalla, Choubey, Prakash, arXiv:1406.2219 [hep-ph]

If $\sin^2\theta_{23} \leq 0.39$ or $\sin^2\theta_{23} \geq 0.62$, octant can be resolved at 5σ irrespective of δ_{CP}

CP violation Discovery with LBNE and LBNO



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

Assuming maximal mixing as true choice

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

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*

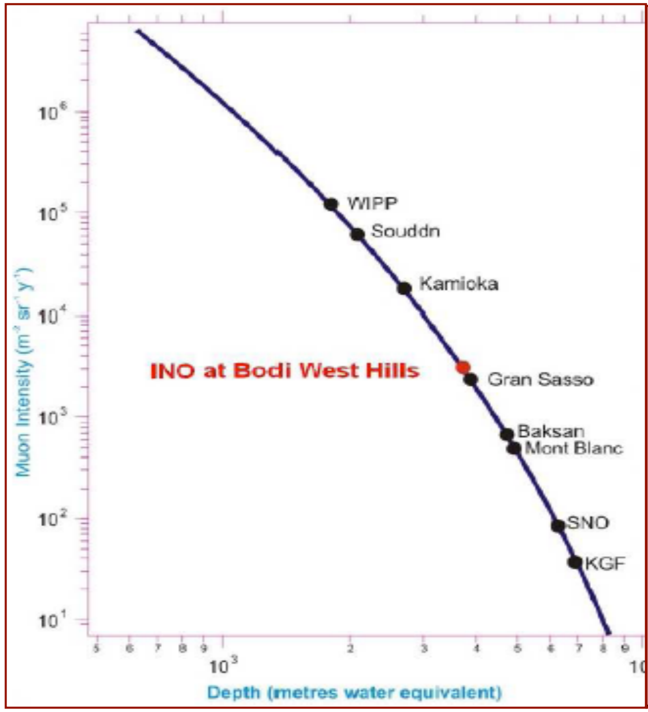
- *A mega-science project (~250 M$) in India, jointly funded (50:50) by the Department of Atomic Energy and the Department of Science and Technology*

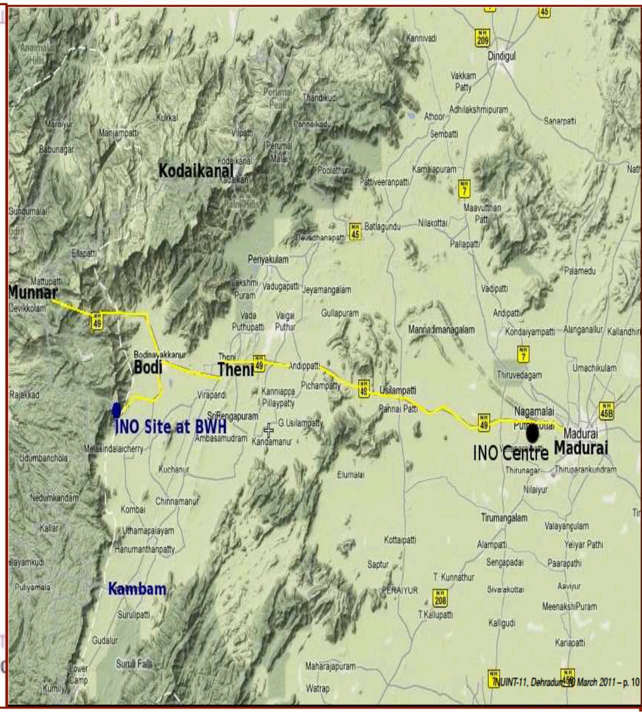
- ***INO project was discussed and approved by the Atomic Energy Commission on 17th August, 2013 at New Delhi***

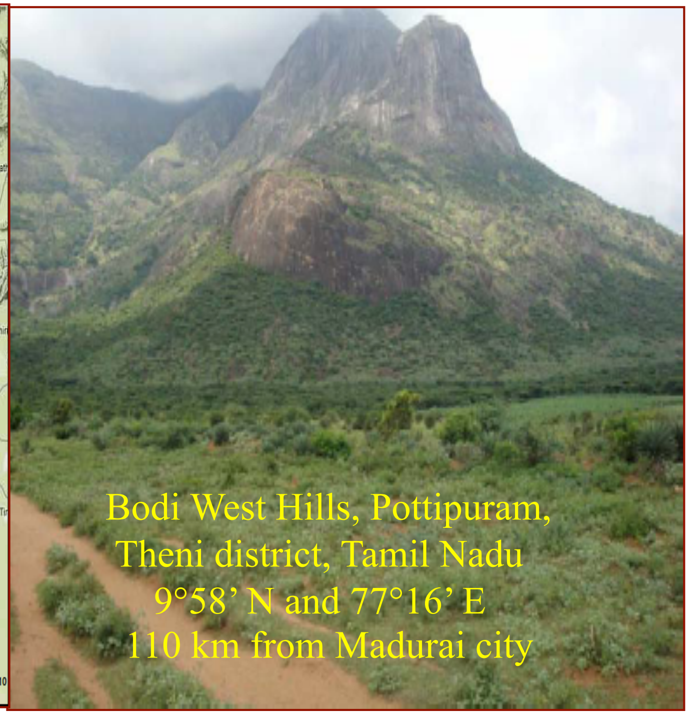
- *Regarding Final approval: Clearance from the Cabinet expected soon*

- *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



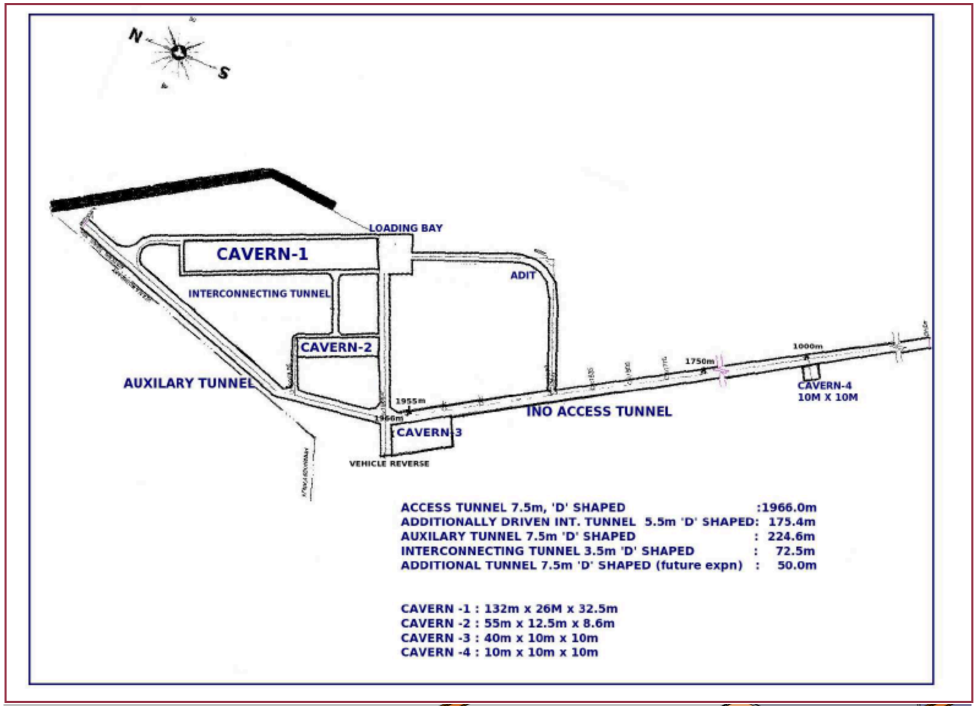


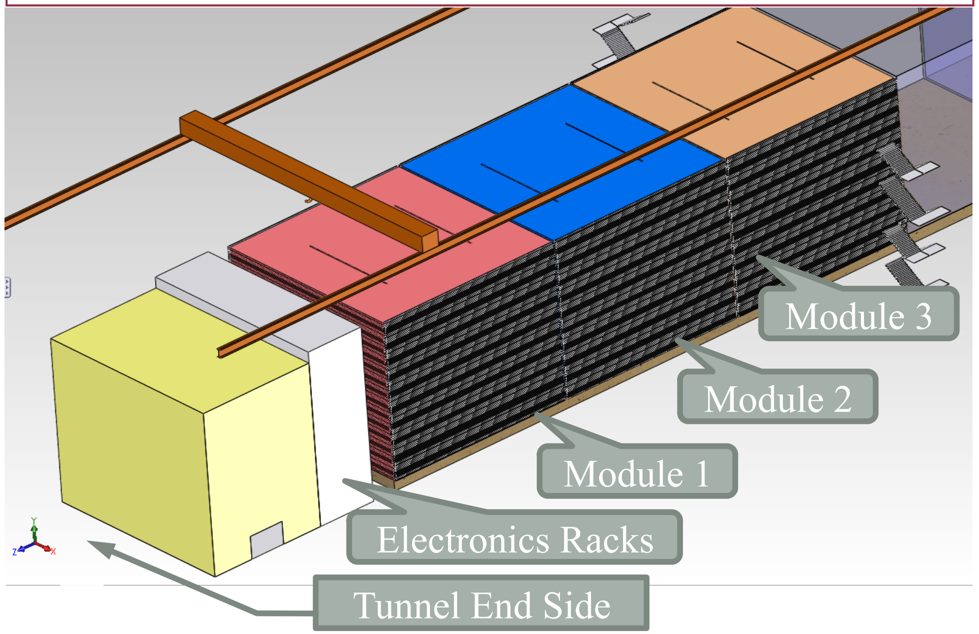


- ***Transport:*** *Flat terrain with good access from major roads*
- ***Geotechnical Issues:*** *Good rock quality, Cavern set in massive Charnockite rock under the 1589 m peak, Vertical cover approx. 1289 m, Tunnel length 1.91 km*
- ***Environmental Issues:*** *Portal set outside the Reserved Forest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

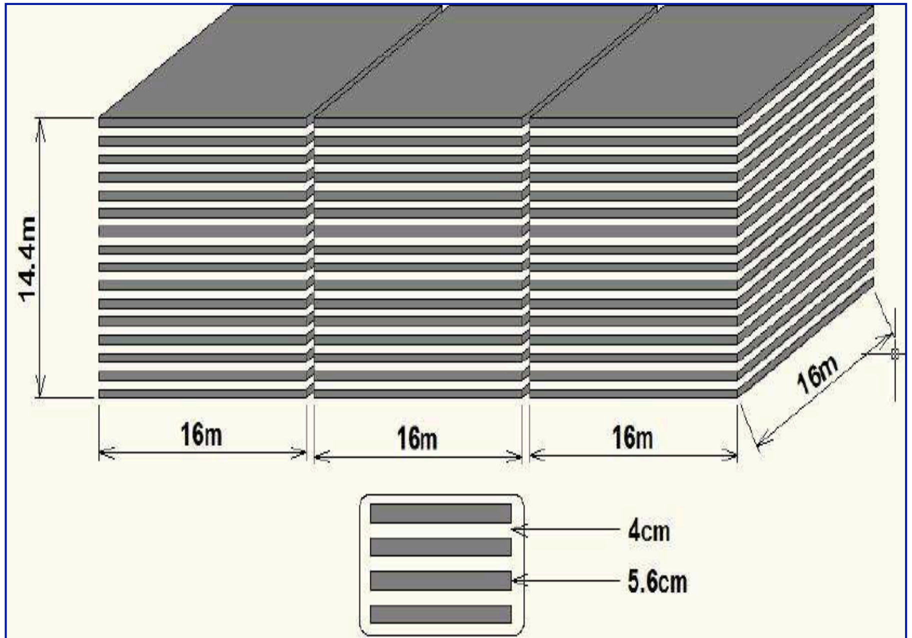
Approved projects under INO

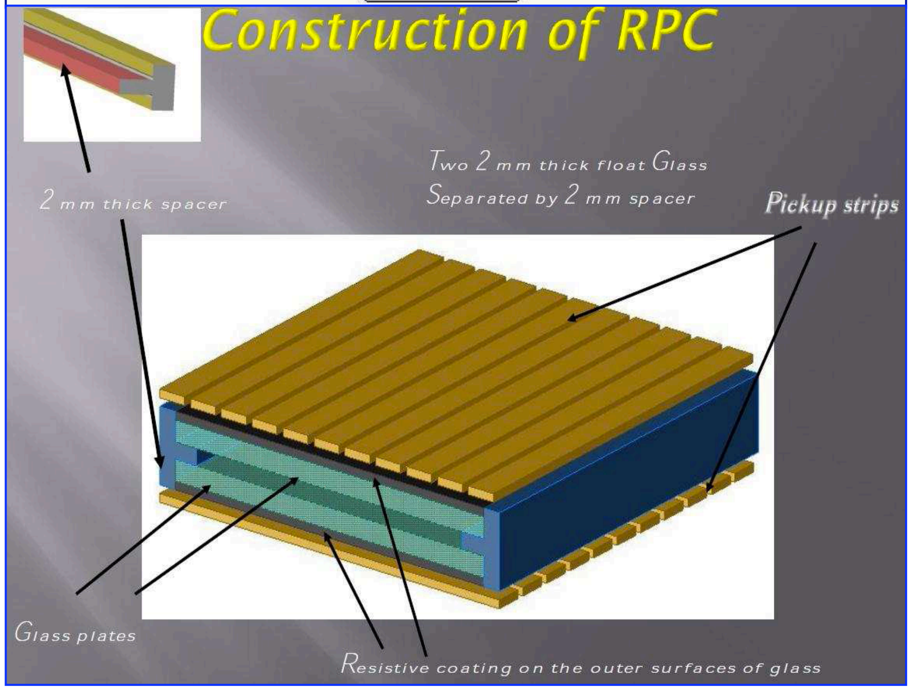
- *Come up with an underground lab & surface facilities near Pottipuram village in Theni district of Tamil Nadu*
- *Build massive 50 kt magnetized Iron calorimeter (ICAL) detector to study properties of atmospheric neutrinos*
- *Construction of INO centre at Madurai: Inter-Institutional Centre for High 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: 2019*





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

2011-2014: A productive phase for INO

Several milestones achieved

Physics Issues with ICAL-INO in Phase 1

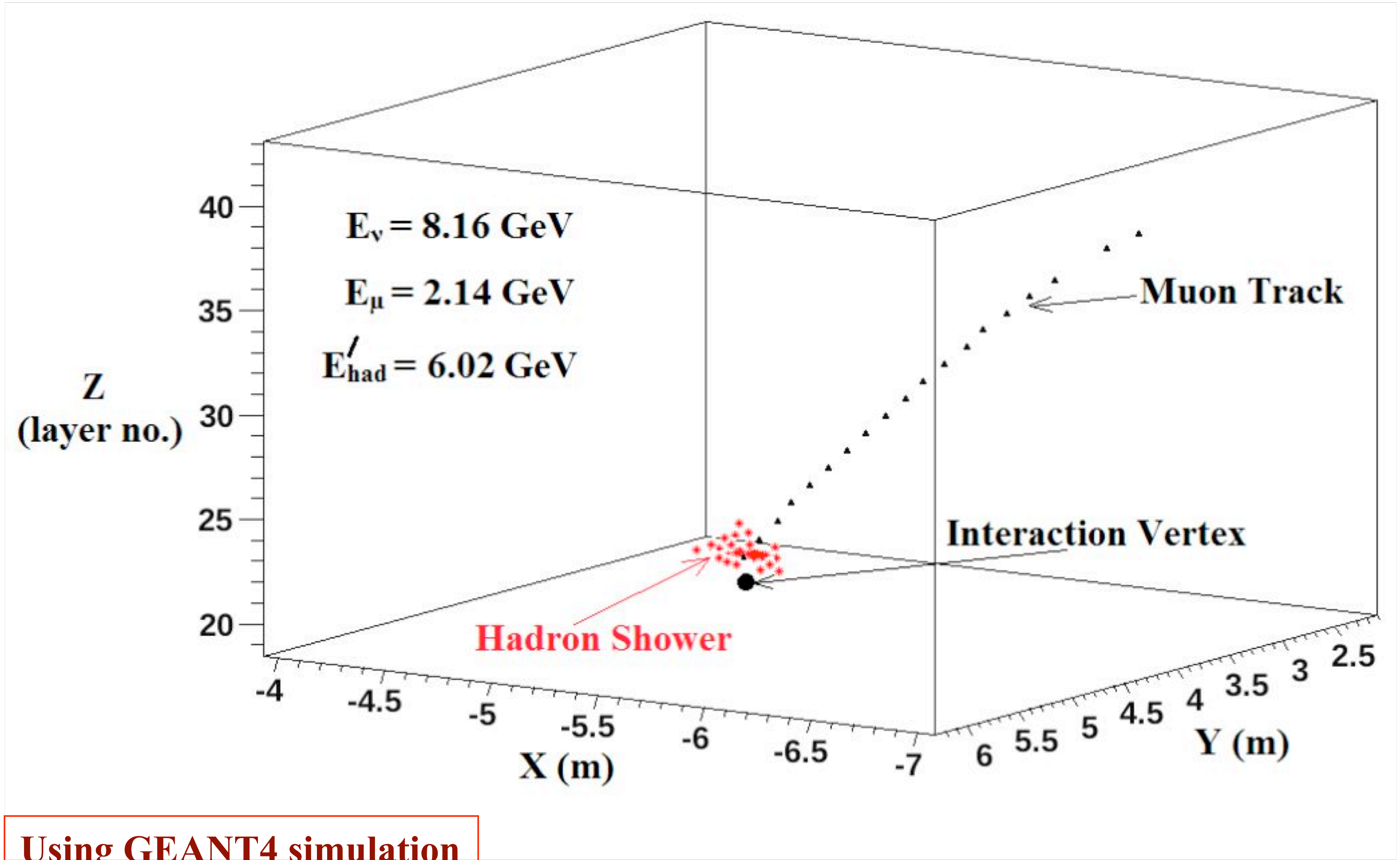
Study Atmospheric neutrinos w/ a wide range of Baselines & Energies

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***

Event Display Inside the ICAL Detector

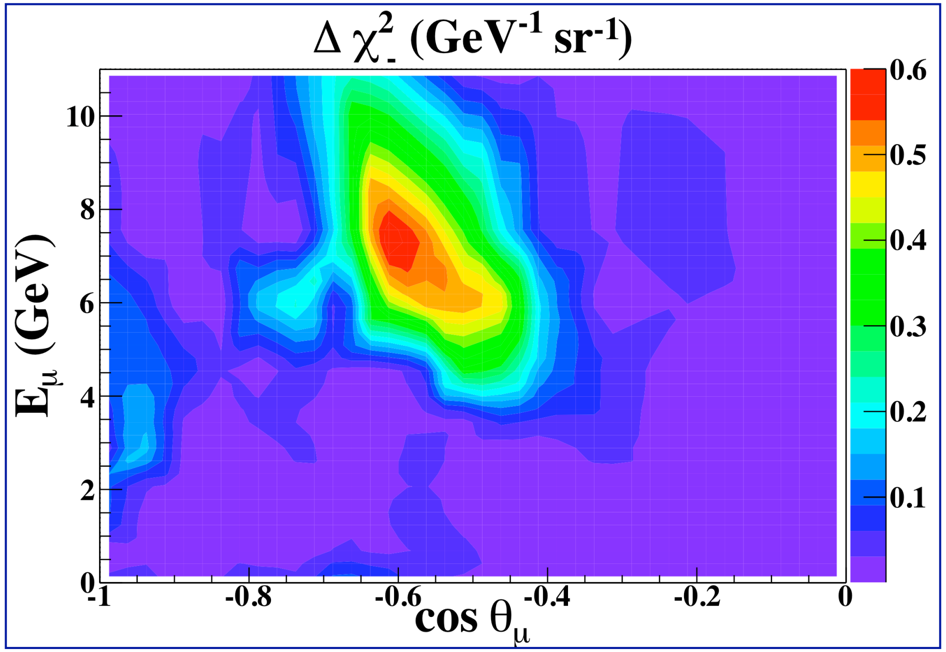


Using GEANT4 simulation

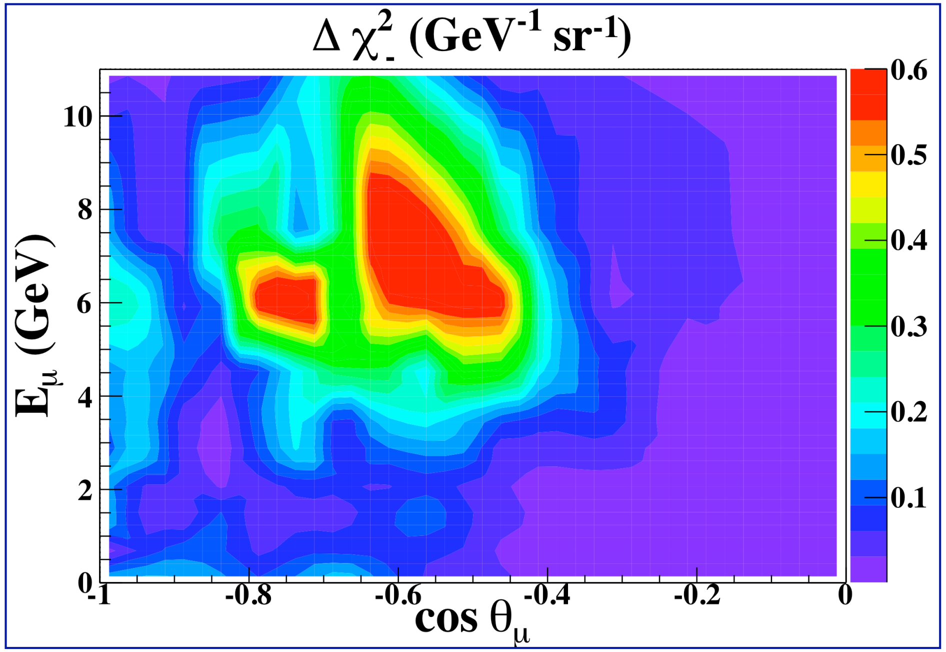
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Neutrino Mass Hierarchy Discrimination

Distribution of $\Delta\chi^2$ [χ^2 (IH) - χ^2 (NH)] for mass hierarchy discrimination considering μ^- events



Hadron energy information not used

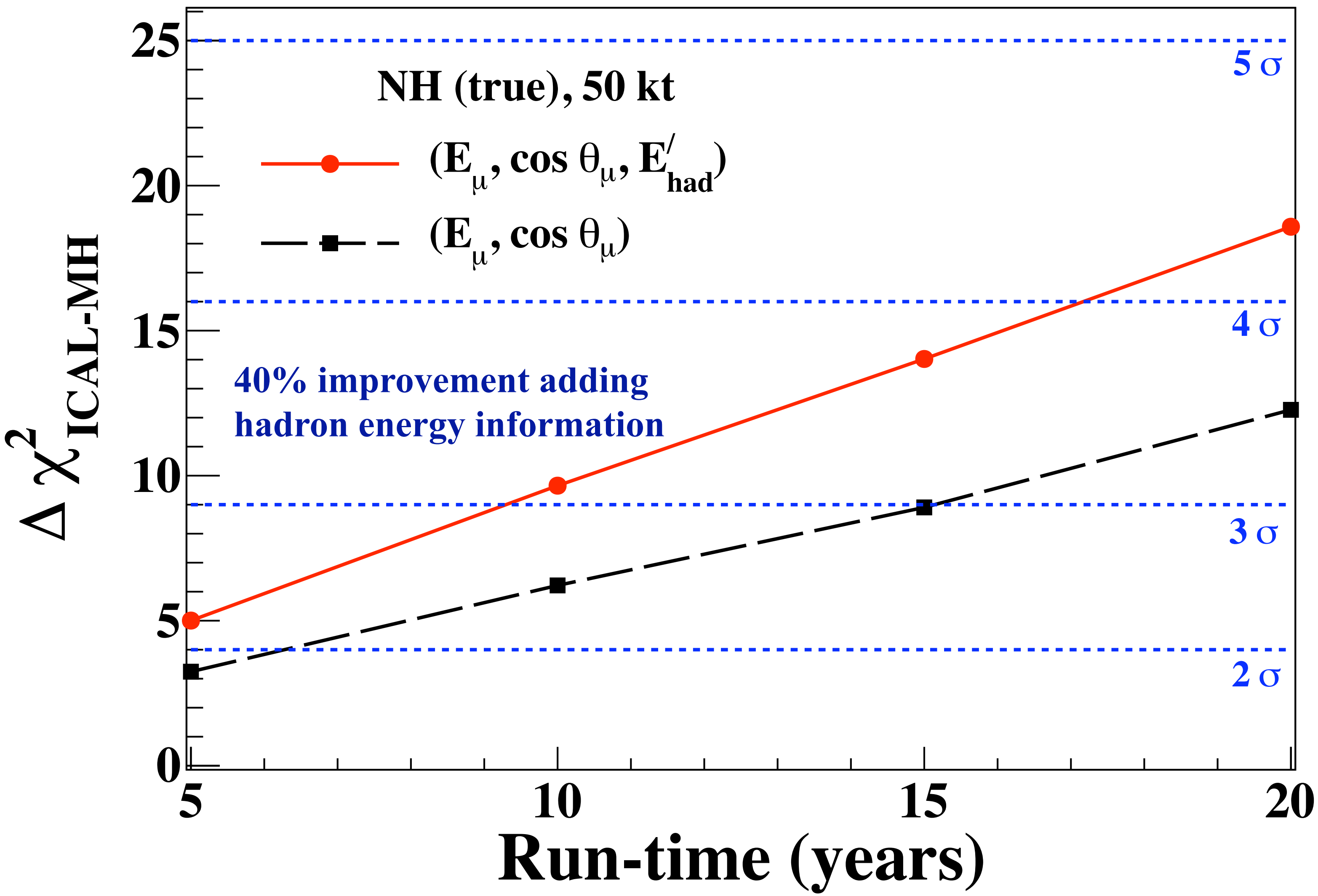


Hadron energy information used

Observable	Range	Bin width	Total bins	
E_μ (GeV)	$[1, 4)$	0.5	6	10
	$[4, 7)$	1	3	
	$[7, 11)$	4	1	
$\cos\theta_\mu$	$[-1.0, -0.4)$	0.05	12	21
	$[-0.4, 0.0)$	0.1	4	
	$[0.0, 1.0]$	0.2	5	
$E'_{\rm had}$ (GeV)	$[0, 2)$	1	2	4
	$[2, 4)$	2	1	
	$[4, 15)$	11	1	

- Further subdivide the events into four hadron energy bins
- Hadron energy carries crucial information
- Correlation between hadron energy and muon momentum is very important

Identifying Neutrino Mass Hierarchy with ICAL

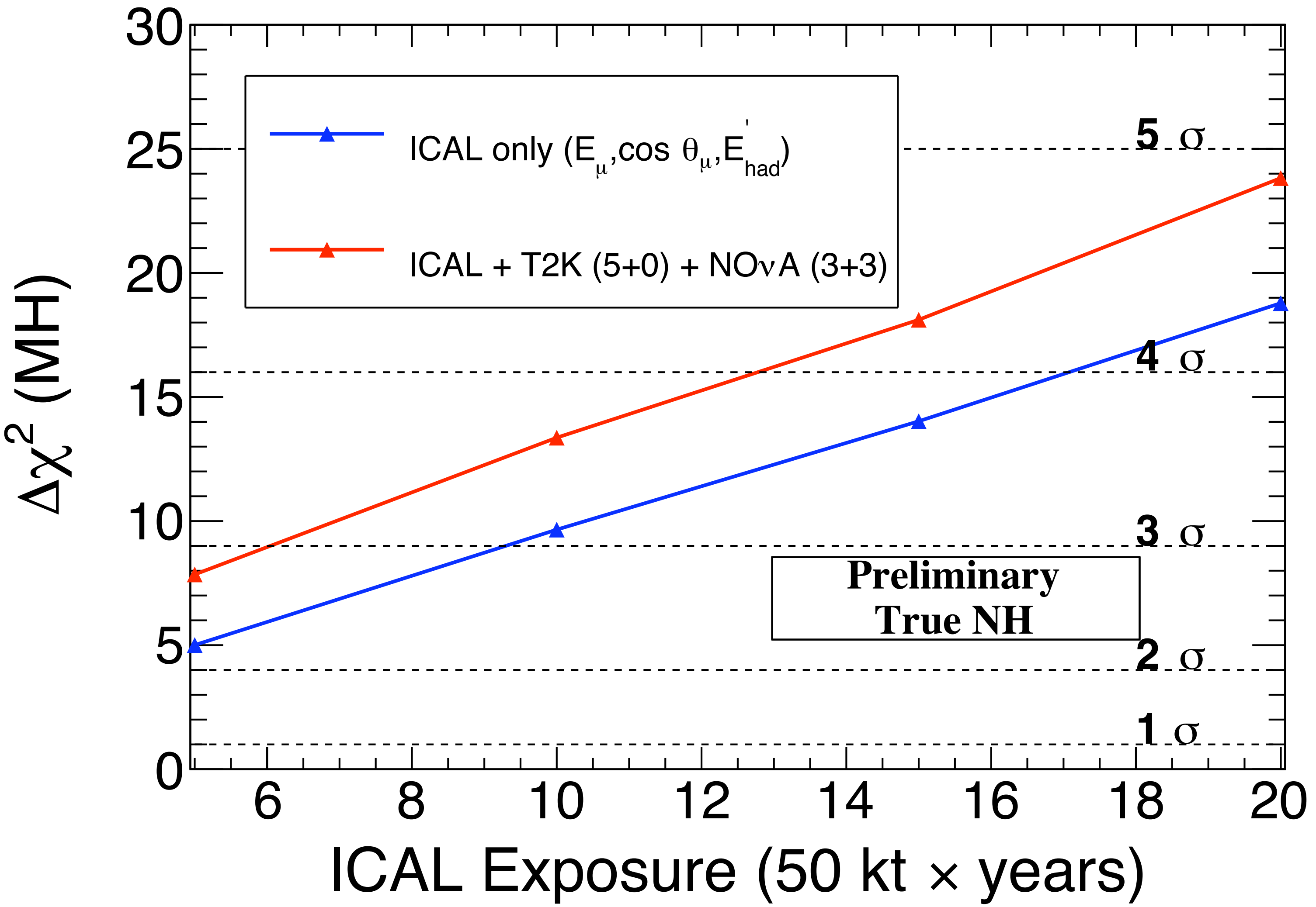


Median Sensitivity

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

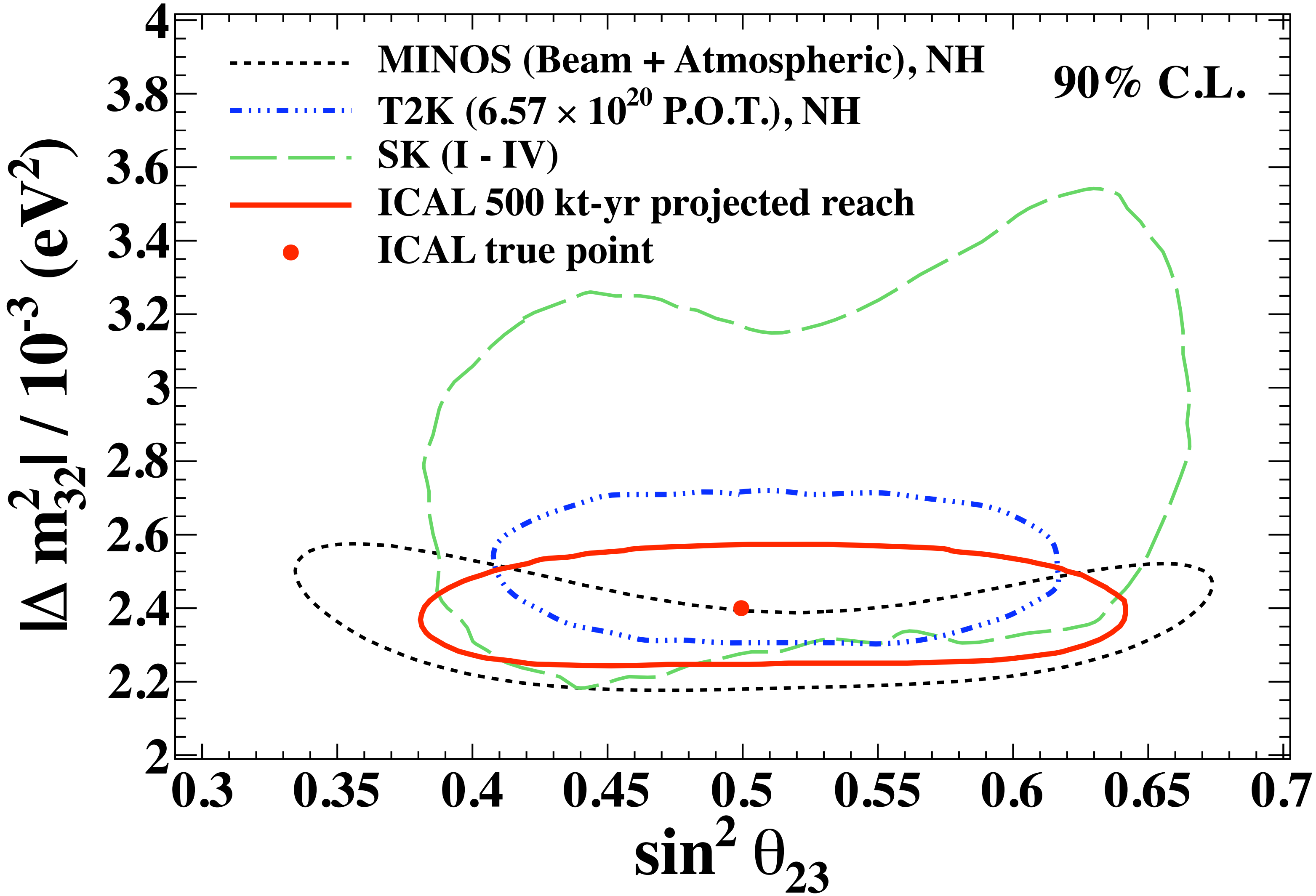
50 kt ICAL can rule out the wrong hierarchy with $\Delta\chi^2 \approx 9.5$ in 10 years

MH Discovery with ICAL+T2K+NOvA



Devi, Thakore, Agarwalla, Dighe, work in progress (INO Collaboration)

3σ median sensitivity can be achieved in 6 years



Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

ICAL expected precision on atmospheric mass splitting is far superior than SK

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:

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

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

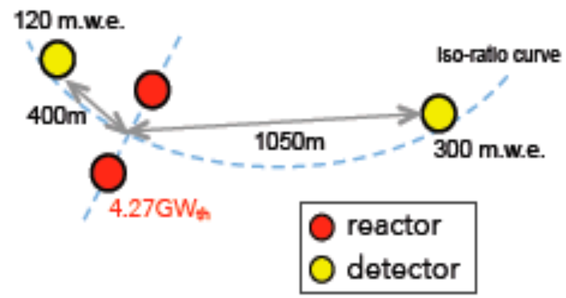
$$|V|_{\text{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046}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

!! Let us work together and achieve it !!

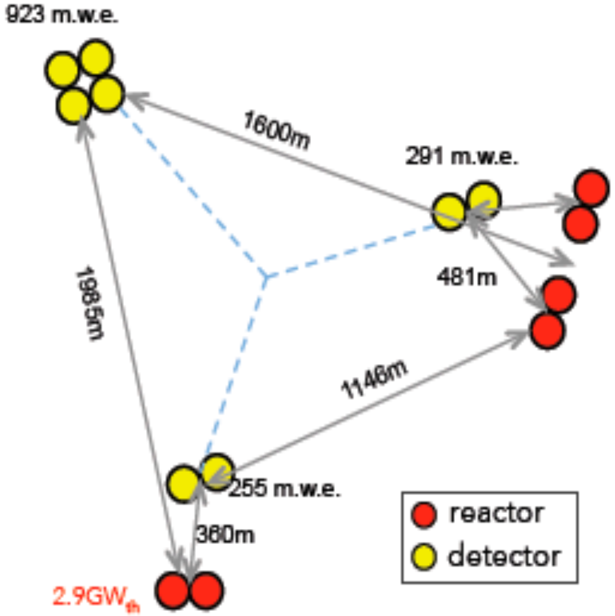
Thank you!

Backup Slides: Currently Running Reactor θ_{13} Experiments

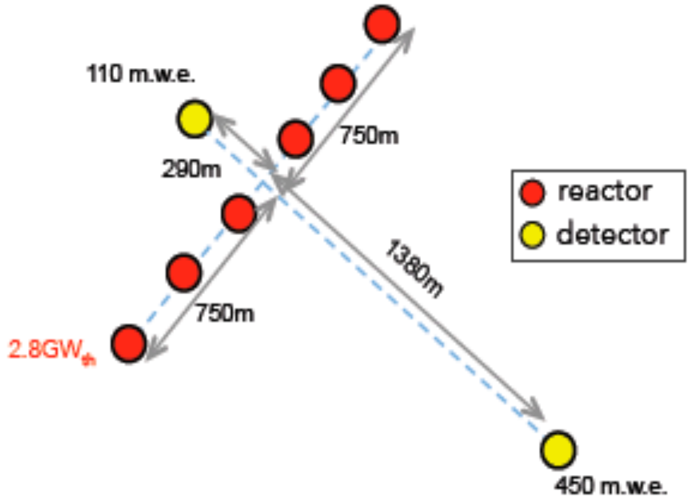
Double Chooz (France)



Daya Bay (China)



RENO (Korea)

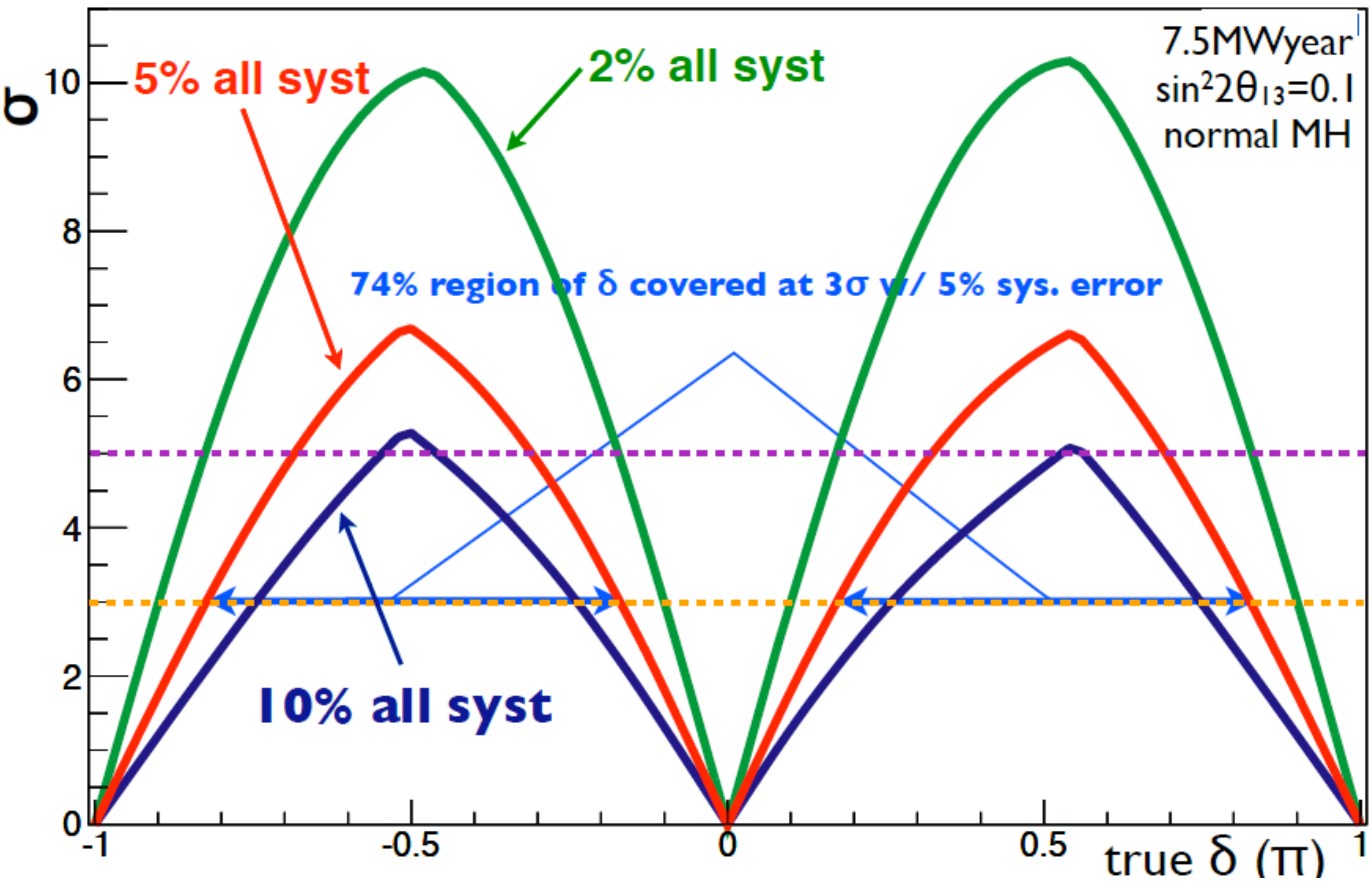


Backup Slides: Key Features of three Reactor Experiments

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

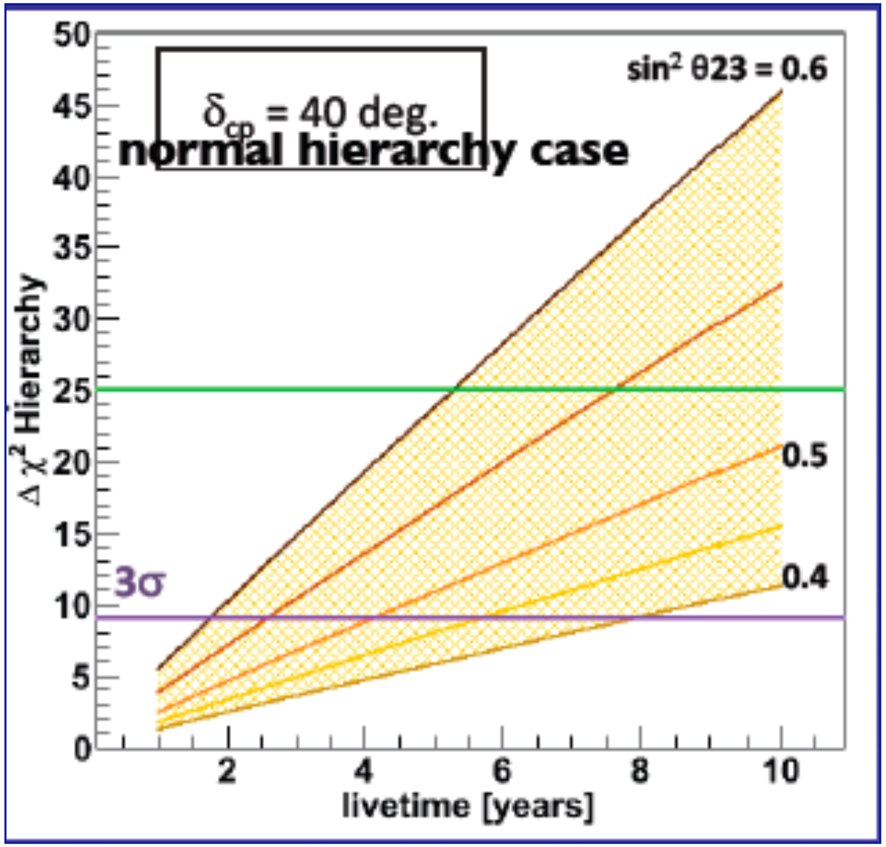
Daya Bay Strategy: Go strong, big and deep!

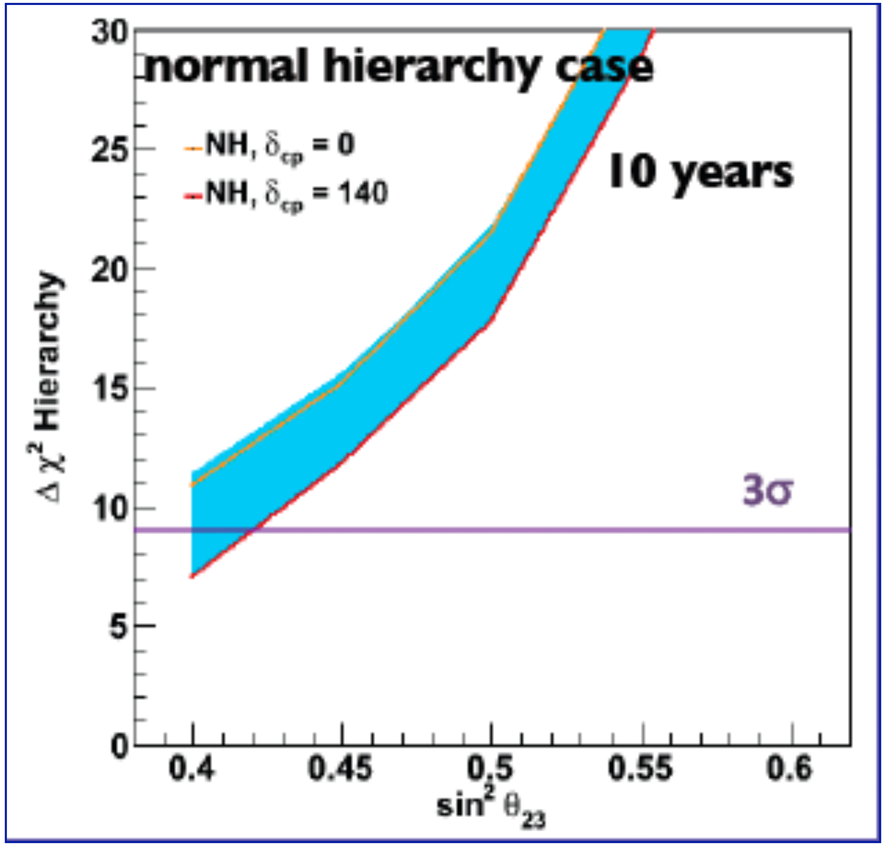
Backup Slides: CPV Discovery in T2HK Setup (w/ MH known)



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

Backup Slides: MH Discovery in T2HK 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]

The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

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

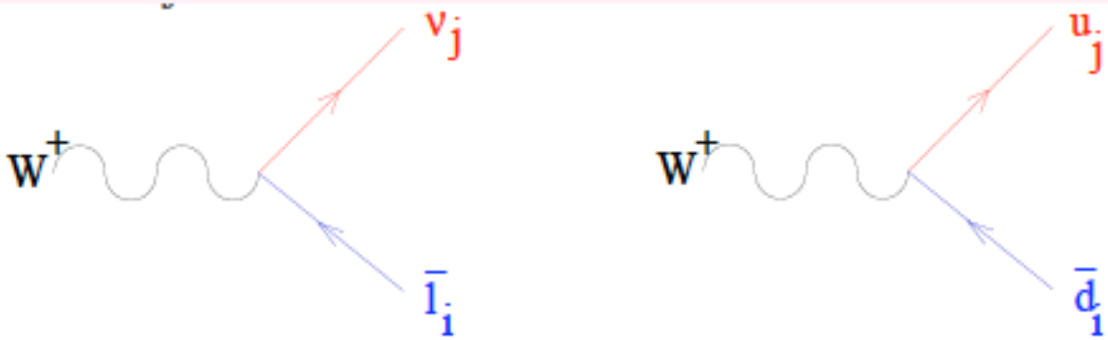
$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  * 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)

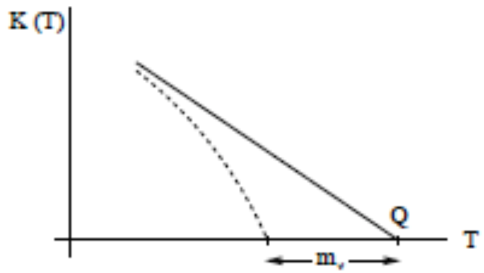
$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(U_{\text{LEP}}^{ij} \, \overline{\ell^i} \, \gamma^\mu \, L \, \nu^j \; + \; U_{\text{CKM}}^{ij} \, \overline{U^i} \, \gamma^\mu \, L \, D^j \right) \; + \; h.c.$$



Courtesy to Concha Gonzalez-Garcia

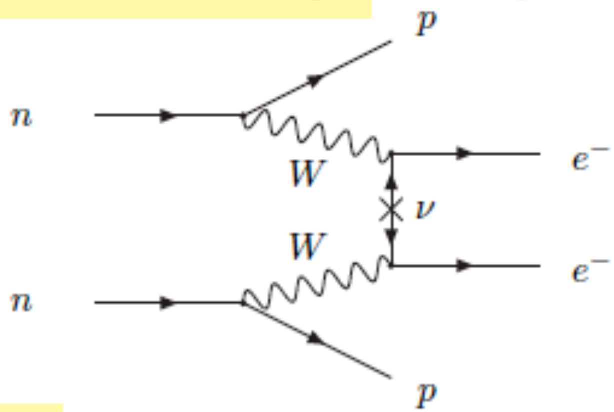
Neutrino Mass Scale

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



$$m^2_{\nu_e} = \sum m^2_j |U_{ej}|^2 = c^2_{13}c^2_{12}m^2_1 + c^2_{13}s^2_{12}m^2_2 + s^2_{13}m^2_3$$

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



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

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

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

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	> 1.6×10^{25} (90%CL)	*EXO-200†††*	< 0.14 – 0.38
^{150}Nd	> 1.8*10^{22} (90%CL)	NEMO-3	

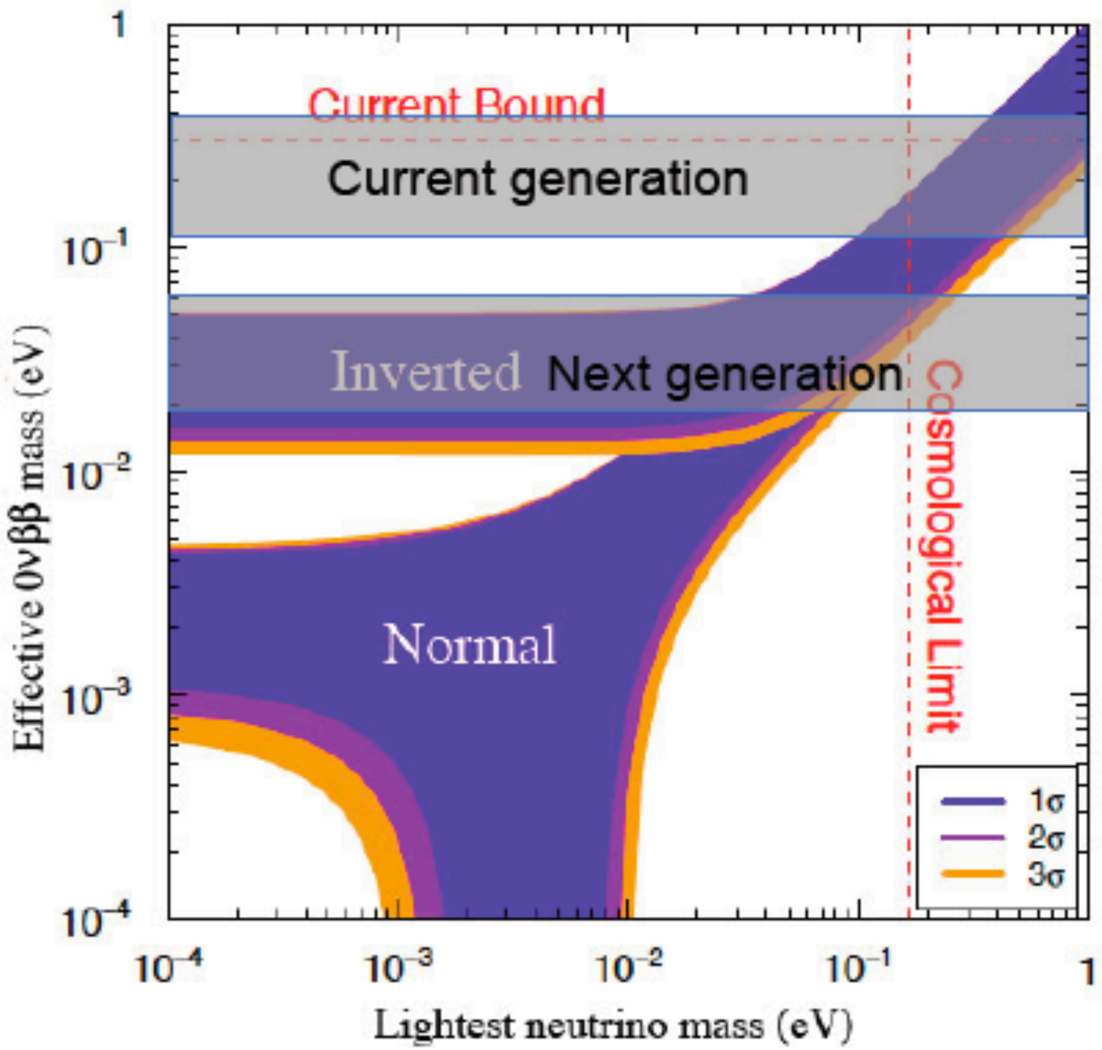
Courtesy to Liang Yang

[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!

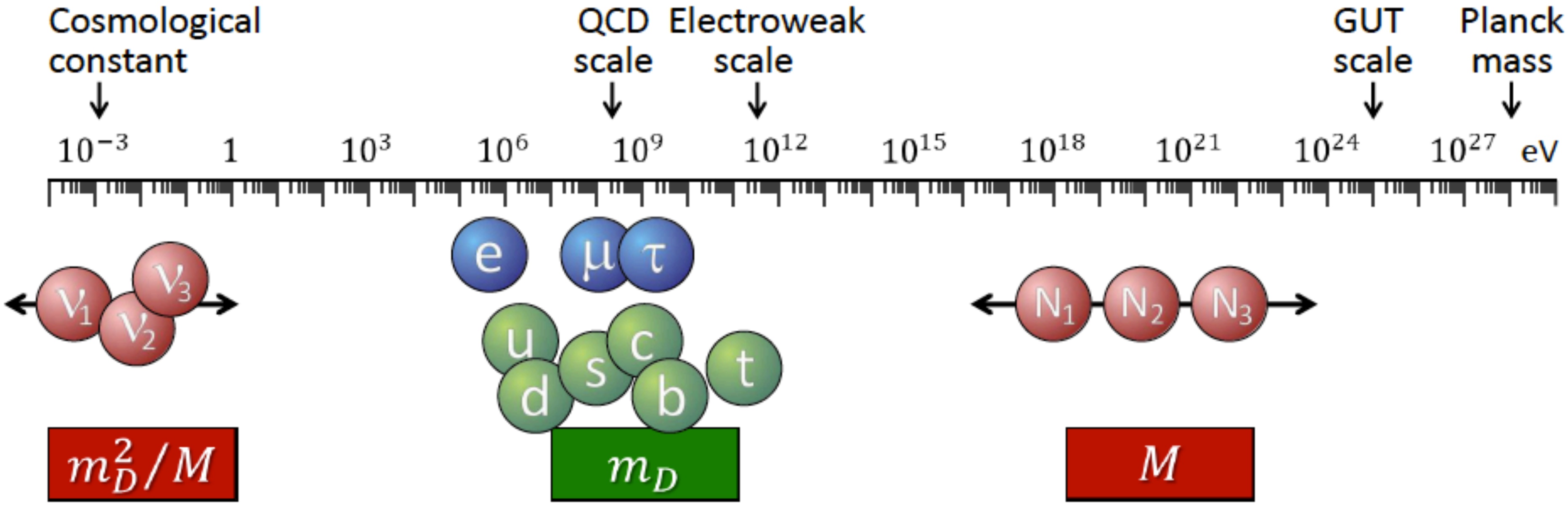
Experimental Sensitivity to Neutrino Mass

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



arXiv:1203.5250v1

Courtesy to Liang Yang



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