# Recent Developments in Neutrino Oscillations & Future Roadmap

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# *The Standard Model: Massless Neutrinos*

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

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

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

3-fold repetition of the same representation!

- 3 *active* neutrinos: $\nu_e$ , $\nu_\mu$ , $\nu_\tau$
- 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: $m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

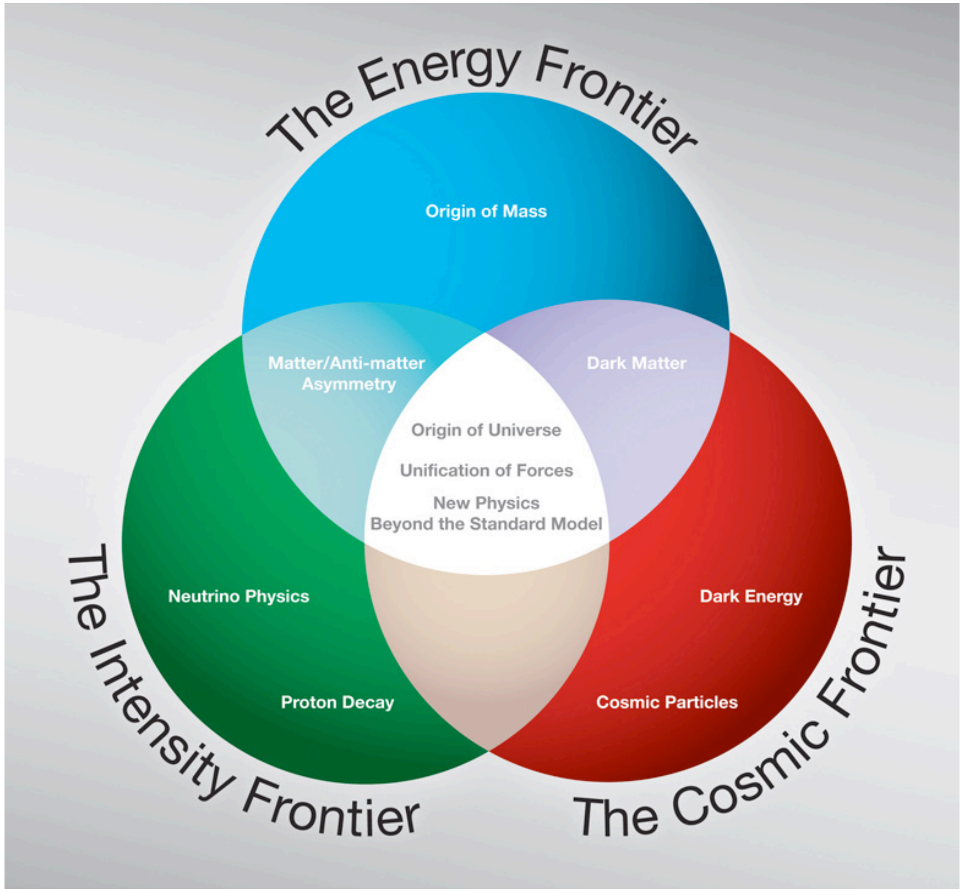
***Neutrinos are massless in the Basic SM***

- ❑ 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 $\theta_{13}$*




**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 $\theta_{13}$**

**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 $\theta_{13}$ has crucial consequences for future theoretical and experimental efforts**

**Non-zero $\theta_{13}$ is the gateway to discover leptonic CP violation & to measure $\delta_{CP}$**

# *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 $s_{ij} = \sin\theta_{ij}$

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

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

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

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

Three mixing angles: $\theta_{23}$ , $\theta_{13}$ , $\theta_{12}$ and one CP violating (Dirac) phase $\delta_{CP}$

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

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!

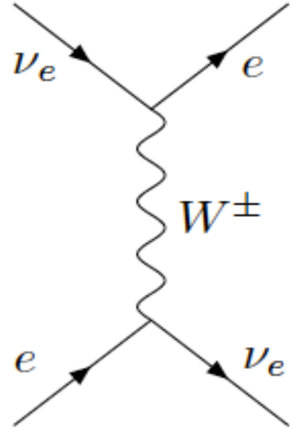
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*] \sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*] \sin 2\Delta_{ij}$$

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

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

2 independent mass splittings $\Delta m_{21}^2$ and $\Delta m_{32}^2$ , for anti-neutrinos replace $\delta_{CP}$ 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 $\nu_e$ with electrons creates an extra potential for $\nu_e$

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) , $\rho$ = 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***

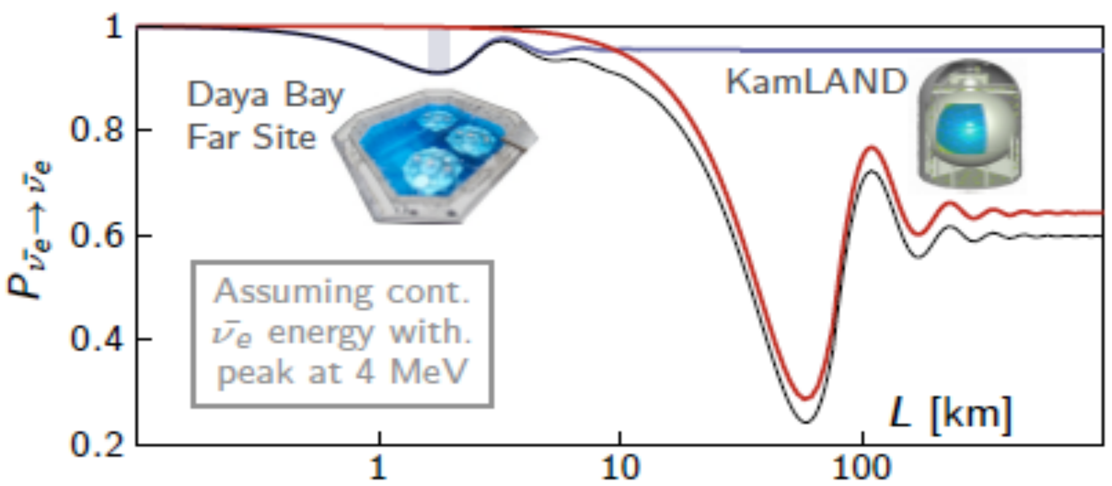
**Matter term modifies oscillation probability differently depending on the sign of $\Delta m^2$**

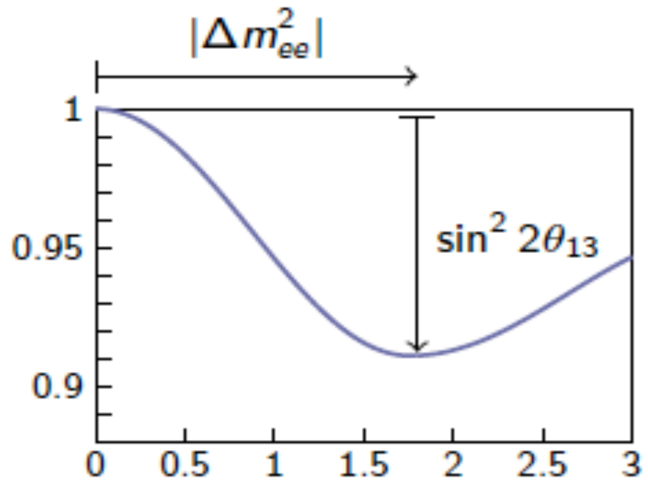
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – Matter effect***

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

→ ***Resonance occurs for neutrinos (anti-neutrinos) if $\Delta m^2$ is positive (negative)***

# *Short Baseline Reactor Neutrino Oscillation*




**$\theta_{13}$ measured by seeing the deficit of reactor anti-neutrinos at ~ 2 km**

**$\theta_{13}$ 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

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

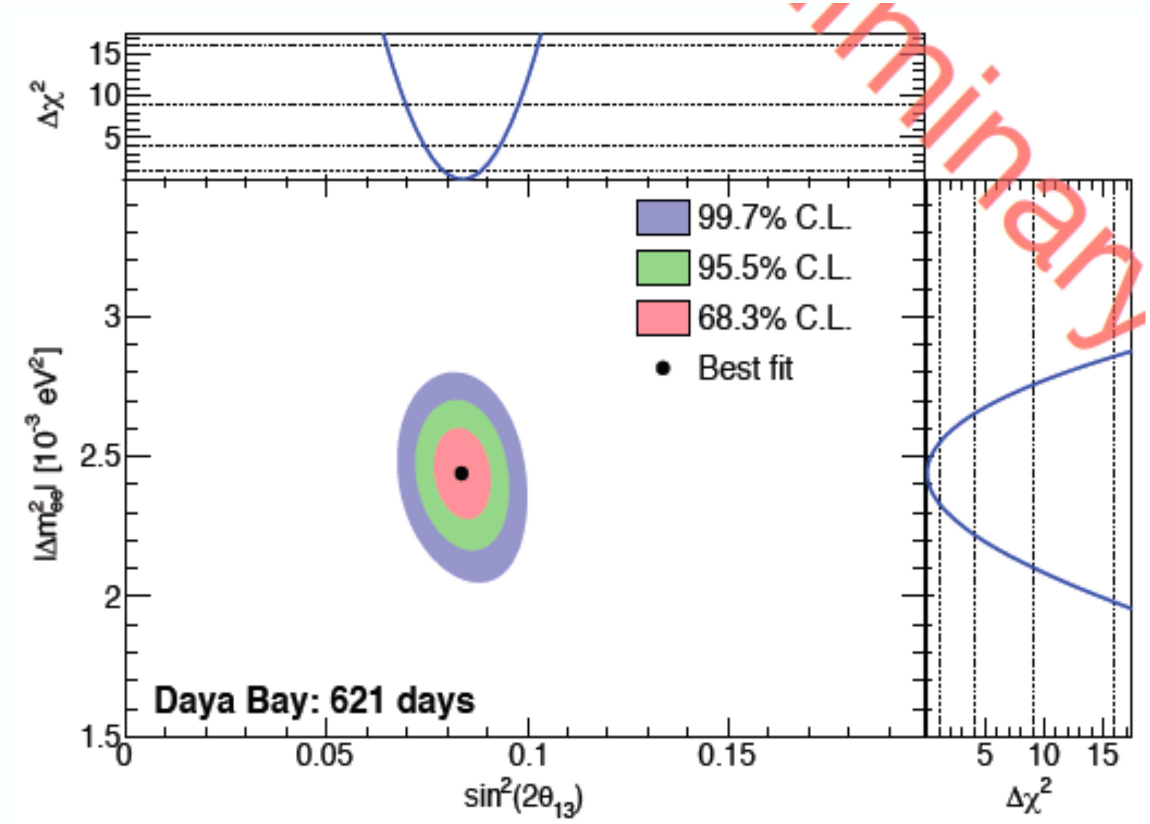
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5} \mathrm{eV}^2$$

+: Normal Hierarchy
−: Inverted Hierarchy

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

# *Latest Oscillation Results from Daya Bay*

Rate + Shape Oscillation Results [Announced in Neutrino 2014]




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

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

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

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

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

| | Normal MH $\Delta m^2_{32}$ [$10^{-3}$eV$^2$] | Inverted MH $\Delta m^2_{32}$ [$10^{-3}$eV$^2$] |
|---|---|---|
| From Daya Bay $\Delta m^2_{ee}$ | $2.39^{+0.10}_{-0.11}$ | $-2.49^{+0.10}_{-0.11}$ |
| 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 $\theta_{23}$ comes from: a) atmospheric neutrinos and b) accelerator neutrinos**

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

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

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

$$\sin^2 2\theta_{\text{eff}} = 4\cos^2\theta_{13}\sin^2\theta_{23}\left(1 - \cos^2\theta_{13}\sin^2\theta_{23}\right)$$ 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]**

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

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

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

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

# *Bounds on $\theta_{23}$ from the global fits*

**In $\nu_\mu$ 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 $\theta_{23}$:**

**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 $\theta_{23}$ belongs to LO (HO)**

**This is known as the octant ambiguity of $\theta_{23}$**

**Fogli and Lisi, hep-ph/9604415**

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

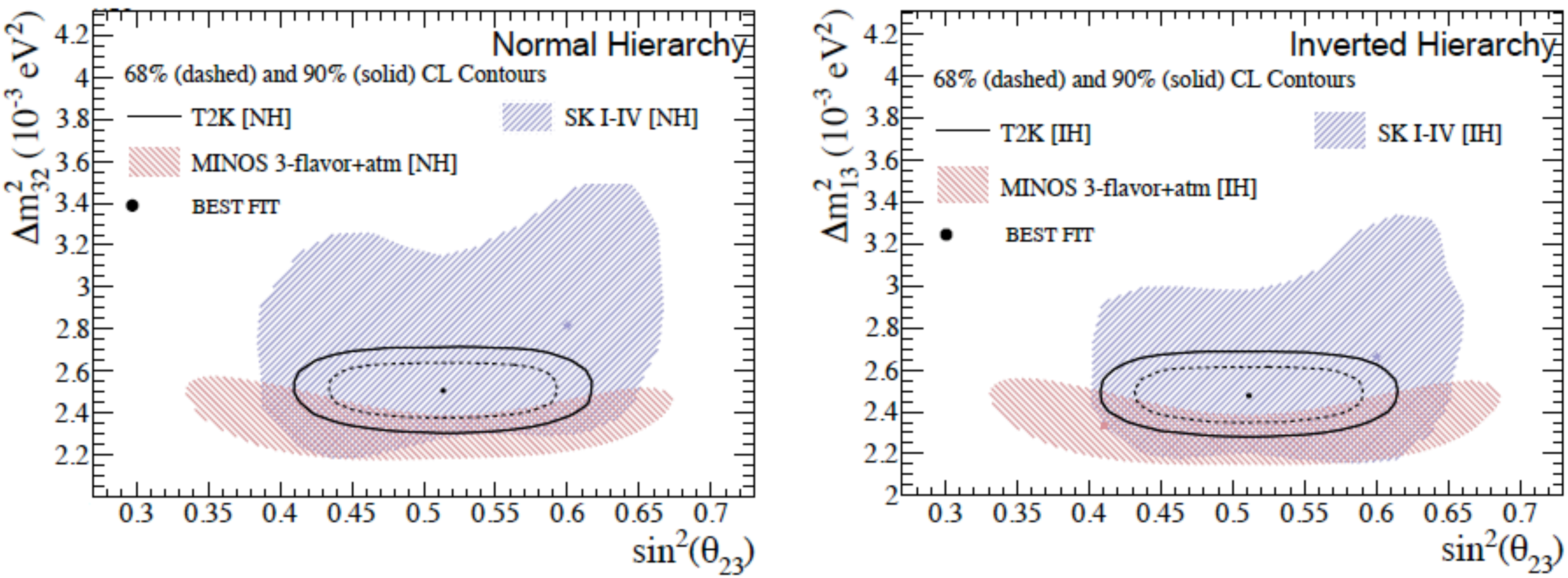
**Based on Gonzalez-Garcia, Maltoni, Salvado, Schwetz, http://www.nu-fit.org**

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

**$\nu_\mu$ to $\nu_e$ 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 ($\Delta m^2$ units $10^{-3}$ eV$^2$/c$^4$) |
|---|---|---|
| NH | $\sin^2\theta_{23}$ | $0.514^{+0.055}_{-0.056}$ |
| | $\Delta m^2_{32}$ | 2.51 ± 0.10 |
| IH | $\sin^2\theta_{23}$ | 0.511 ± 0.055 |
| | $\Delta m^2_{13}$ | 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**

# *Oscillation Parameters After Neutrino 2014*

| | bfp $\pm 1\sigma$ | $3\sigma$ range | Relative $1\sigma$ Precision |
|---|---|---|---|
| $\sin^2\theta_{12}$ | $0.304^{+0.012}_{-0.012}$ | $0.270 \rightarrow 0.344$ | 4% |
| $\theta_{12}/^\circ$ | $33.48^{+0.77}_{-0.74}$ | $31.30 \rightarrow 35.90$ | |
| $\sin^2\theta_{23}$ | $[0.451^{+0.001}_{-0.001}] \oplus 0.577^{+0.027}_{-0.035}$ | $0.385 \rightarrow 0.644$ | 9.6% |
| $\theta_{23}/^\circ$ | $[42.2^{+0.1}_{-0.1}] \oplus 49.4^{+1.6}_{-2.0}$ | $38.4 \rightarrow 53.3$ | |
| $\sin^2\theta_{13}$ | $0.0219^{+0.0010}_{-0.0011}$ | $0.0188 \rightarrow 0.0251$ | 4.8% |
| $\theta_{13}/^\circ$ | $8.52^{+0.20}_{-0.21}$ | $7.87 \rightarrow 9.11$ | |
| $\delta_{CP}/^\circ$ | $251^{+67}_{-59}$ | $0 \rightarrow 360$ | (Not Known) |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.50^{+0.19}_{-0.17}$ | $7.03 \rightarrow 8.09$ | 2.4% |
| $\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (N) | $[+2.458^{+0.002}_{-0.002}]$ | $+2.325 \rightarrow +2.599$ | 1.9% |
| $\frac{\Delta m^2_{32}}{10^{-3}\ \mathrm{eV}^2}$ (I) | $-2.448^{+0.047}_{-0.047}$ | $-2.590 \rightarrow -2.307$ | |

**Non-maximal $> 1.4\sigma$**

**Non-zero $> 10\sigma$**

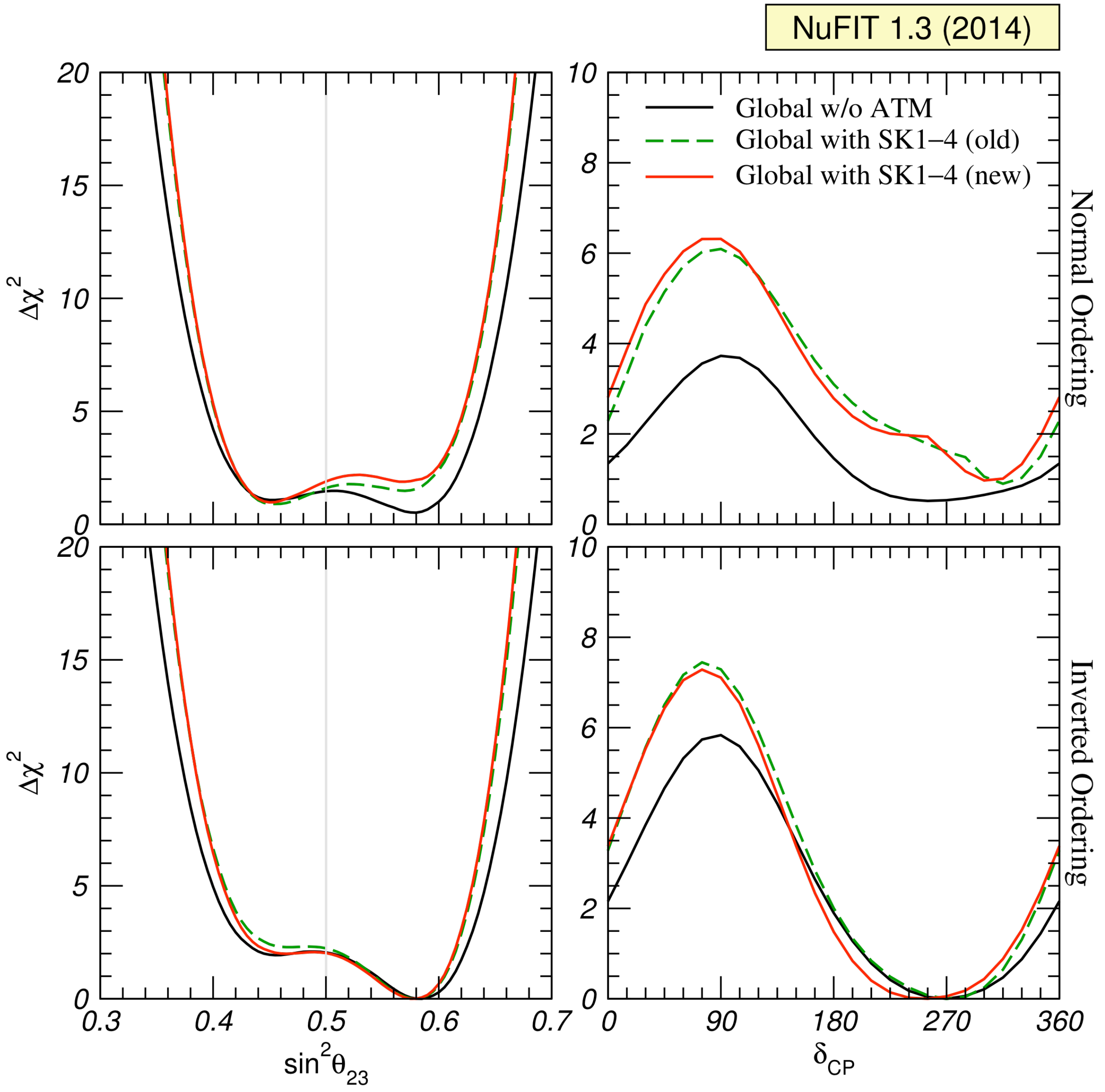
**$\sin\delta_{CP} < 0$ at 90% C.L.**

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

Based on the data available after Neutrino 2014 conference

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

# Role of Atmospheric Neutrinos in Global Fit

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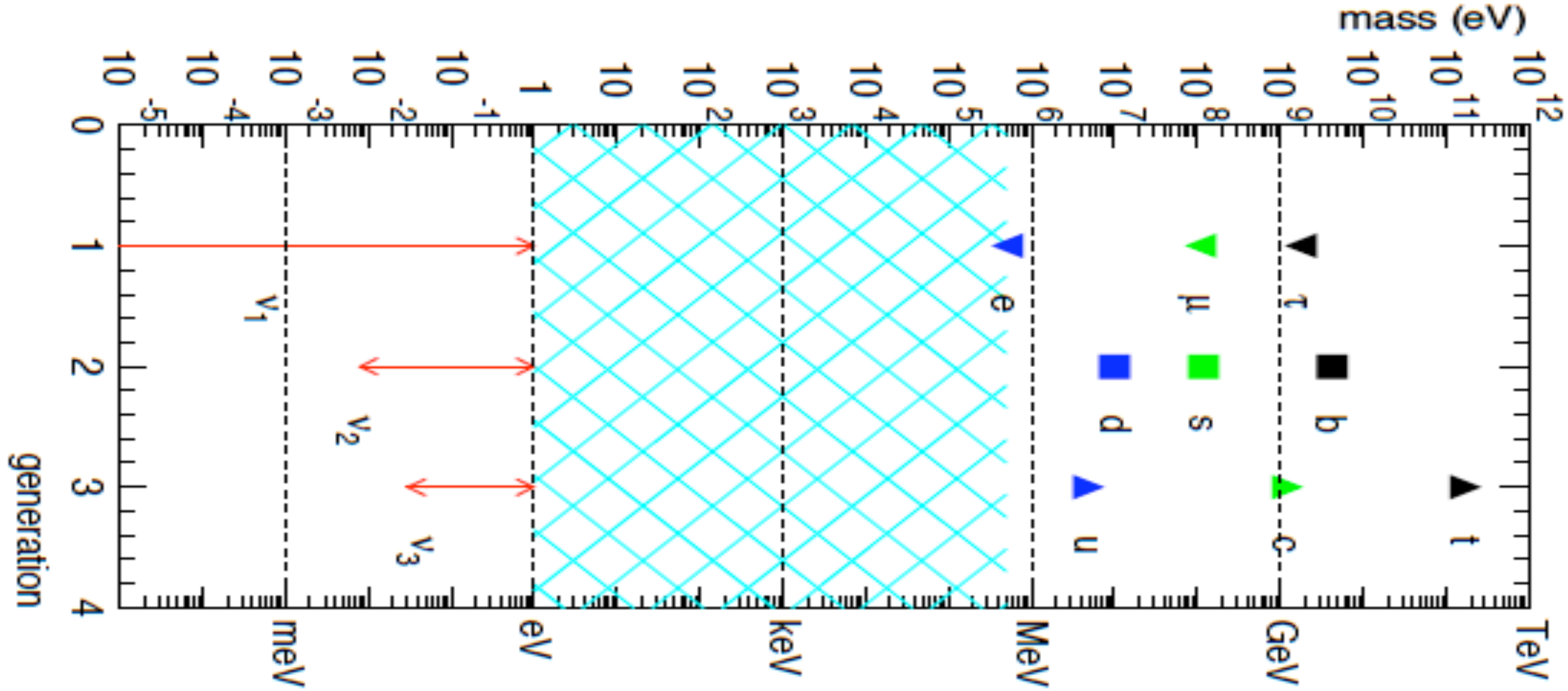
# The Two Fundamental Questions



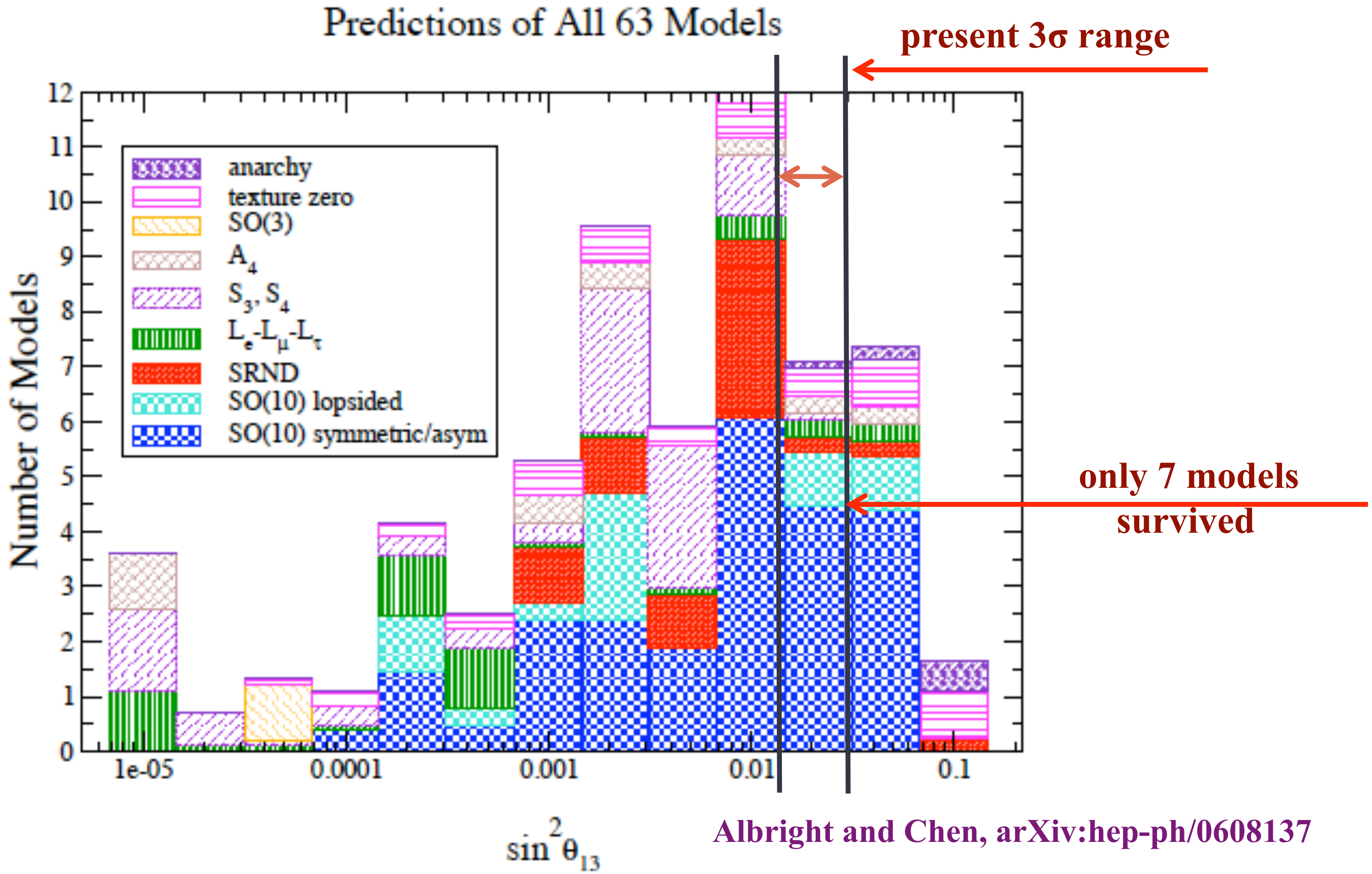

**Why are neutrinos so light?** **The origin of Neutrino Mass!**

| | Neutrinos (PMNS) | Quarks (CKM) |
|---|---|---|
| $\theta_{12}$ | 35° | 13° |
| $\theta_{32}$ | 43° | 2° |
| $\theta_{13}$ | 9° | 0.2° |
| $\delta$ | unknown | 68° |

**Why are lepton mixings so different from quark mixings?**

**The Flavor Puzzle!**

# *Latest Results on $\theta_{13}$ : 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 $\theta_{13}$

## 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 ($\nu$ mass matrix completely random): [Hal, Murayama, Weiner (99), de Gouvea, Murayama (03, 12)]

  It predicts: large $\theta_{13}$, okay with observed value of $\theta_{13}$

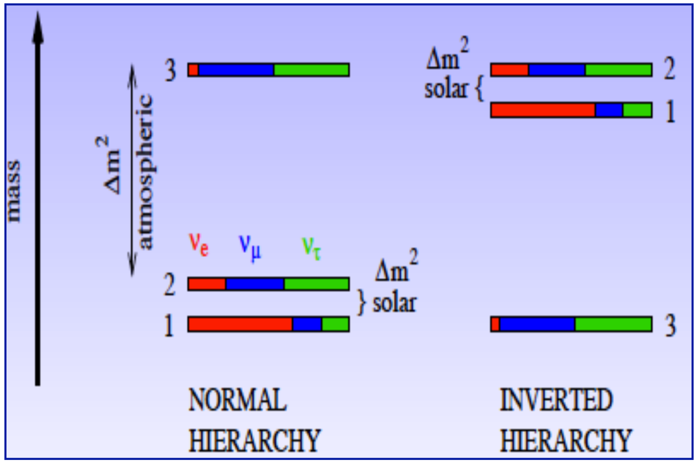
- Quark-Lepton Complementarity: [Minakata, Smirnov (94), Raidal (04)]

  Based on observation: $\theta_{12}$ (PMNS) + $\theta_{12}$ (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 $\theta_{23}$ 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 $\delta_{CP}$ 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 $\theta_{13}$, 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 $\theta_{13}$

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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

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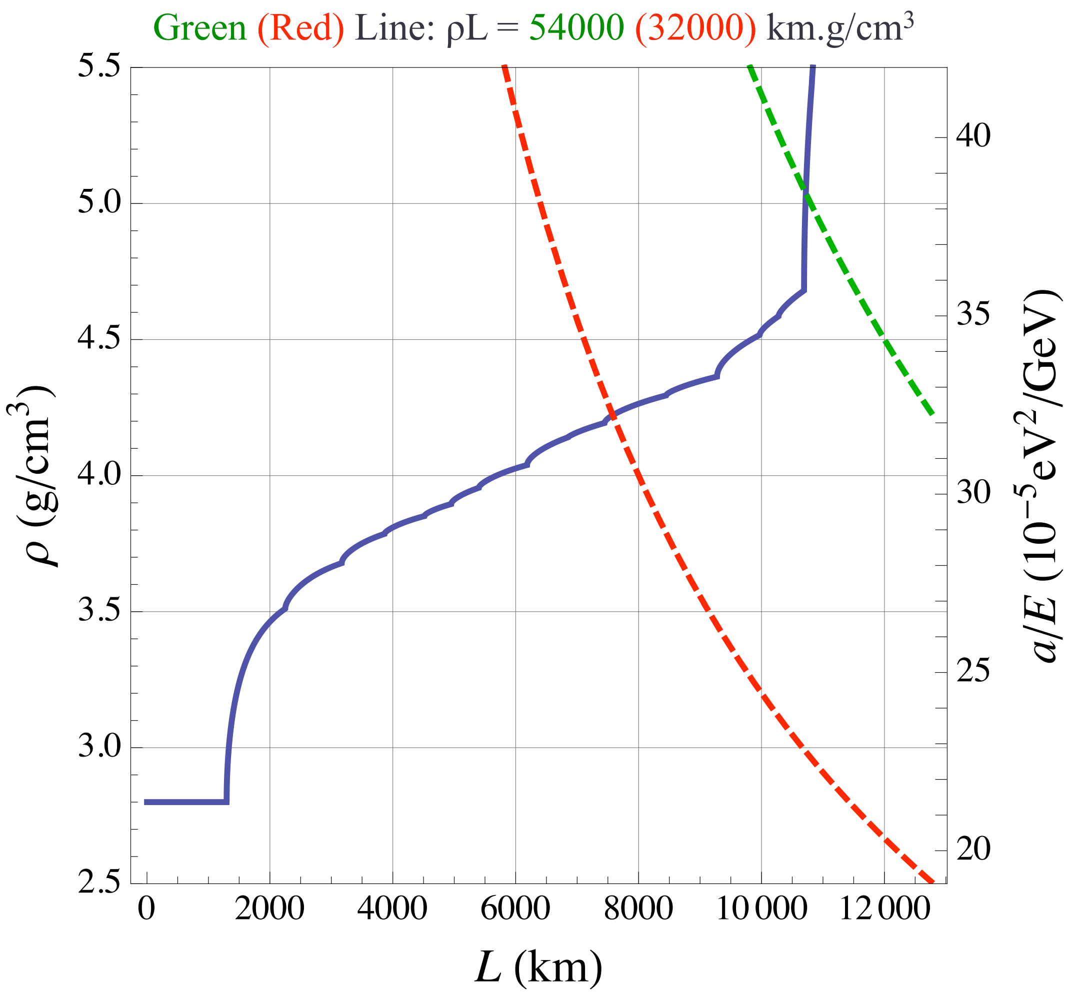
# *Matter Effect Parameter a*

$$a = 2\sqrt{2} G_F N_e E \quad = 7.63 \times 10^{-5} (\text{eV}^2) \left( \frac{\rho}{\text{g/cm}^3} \right) \left( \frac{E}{\text{GeV}} \right)$$




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 $\theta_{13}$, the running of $\theta_{23}$ and $\delta_{CP}$ can be neglected, simplifying the probability expression
- We need to rotate only $\theta_{12}$ and $\theta_{13}$

# 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

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

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

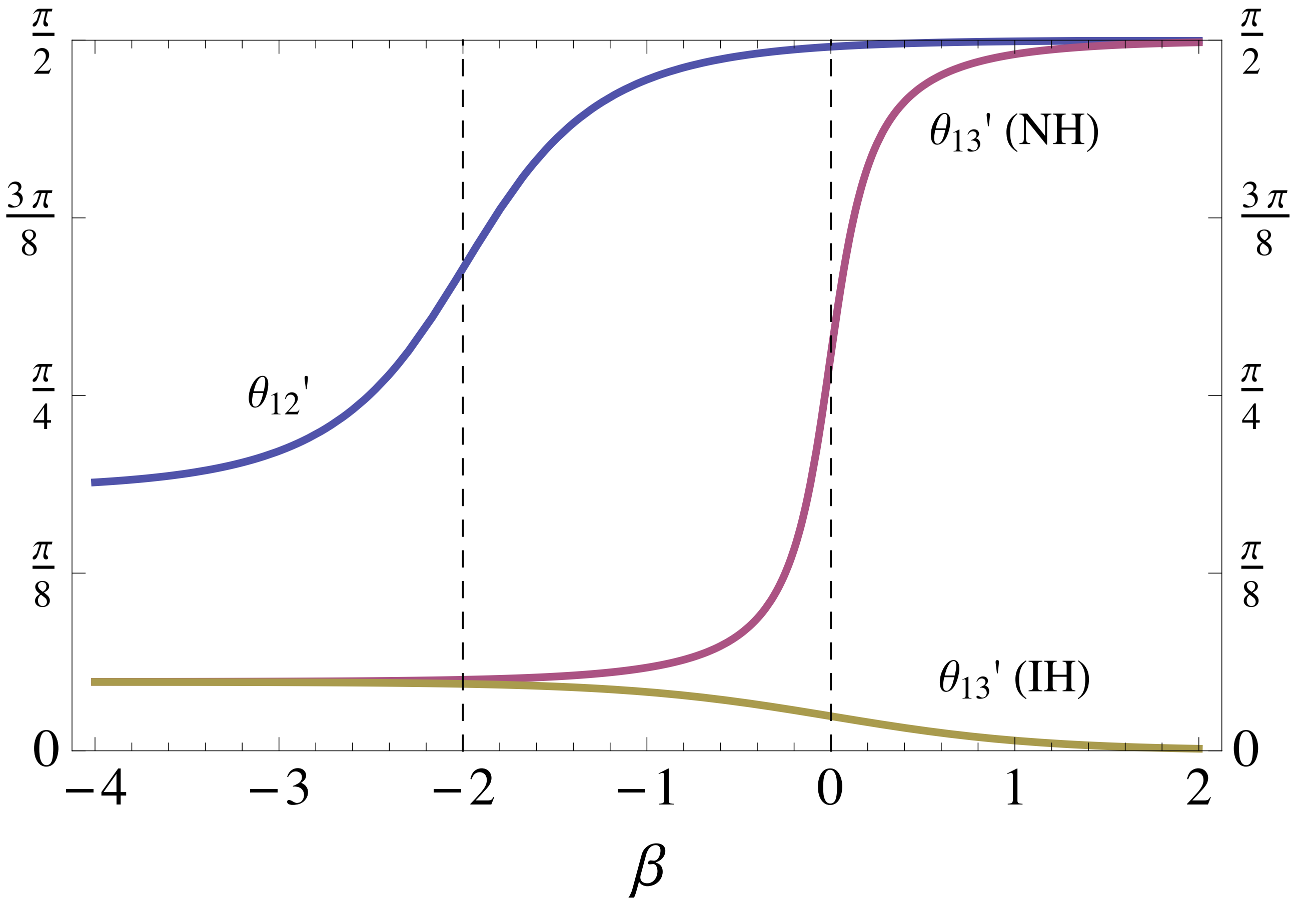
$$\lambda_2 = \lambda''_\mp$$

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

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

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

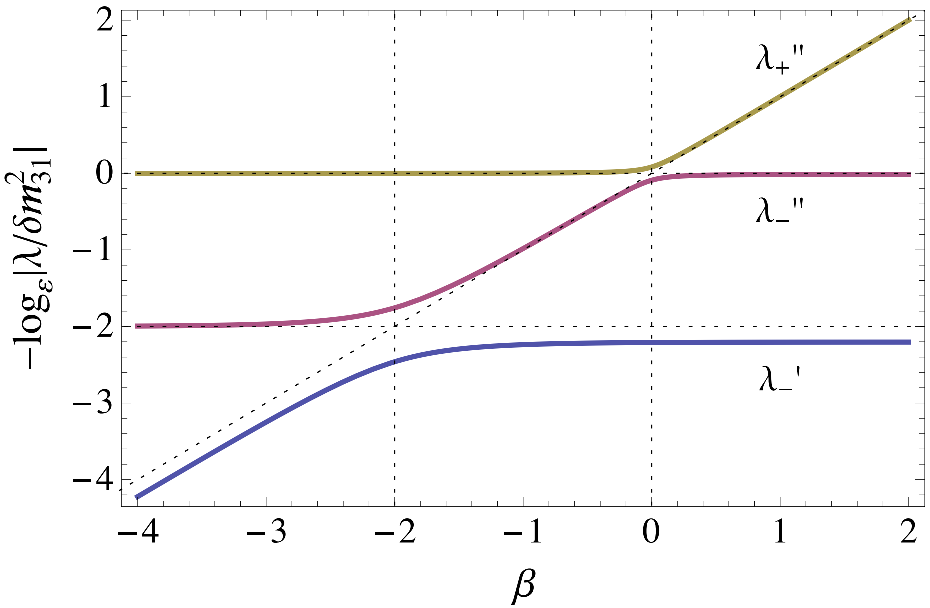
# *a-dependence of effective mixing angles*



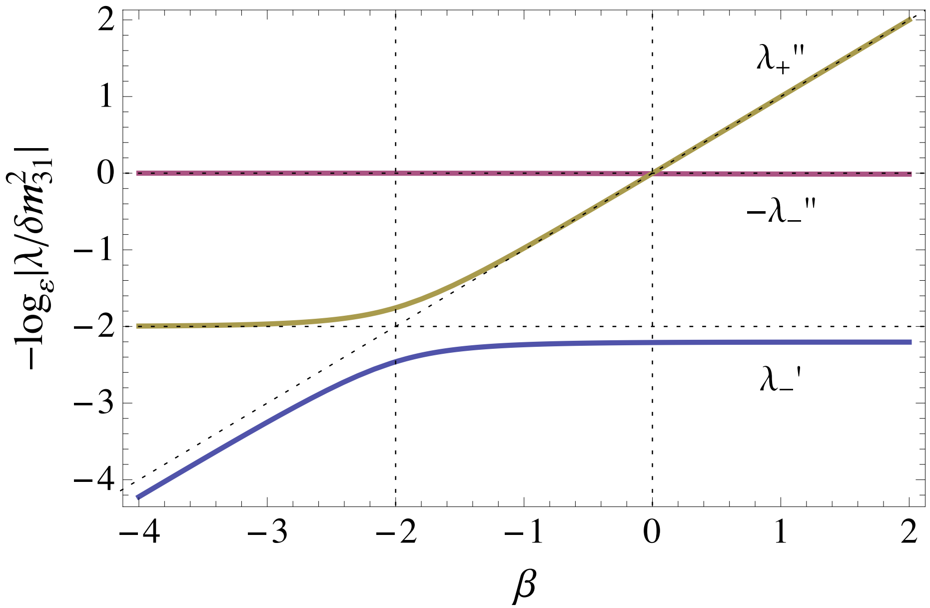

$$\frac{a}{|\delta m_{31}^2|} = \varepsilon^{-\beta}, \qquad \varepsilon = \sqrt{\frac{\delta m_{21}^2}{|\delta m_{31}^2|}} \approx 0.17$$

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

# a-dependence of effective mass-squared differences



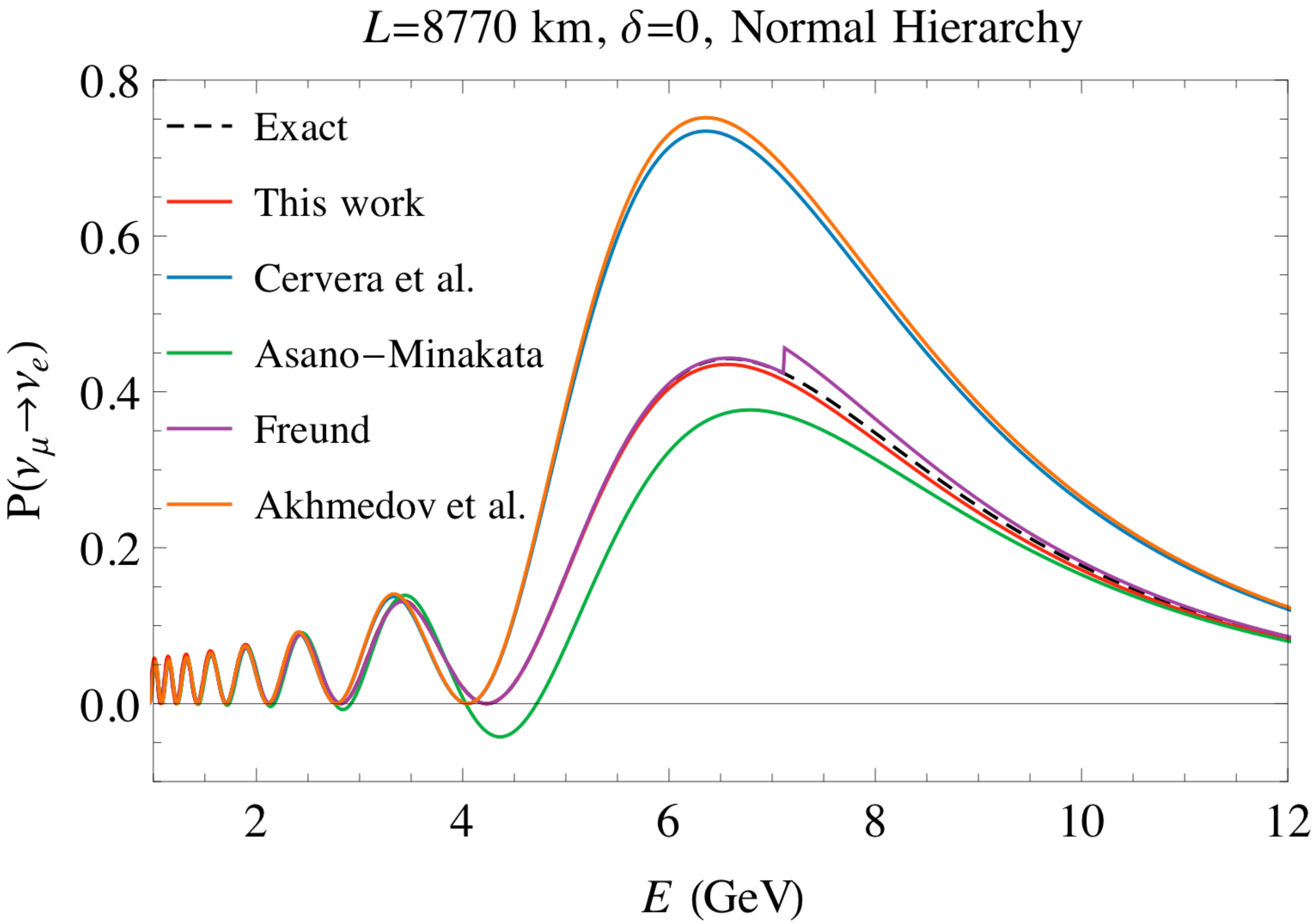

Normal Hierarchy




Inverted Hierarchy

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

# *Accuracy of Our Method and Comparison with Existing Literature*

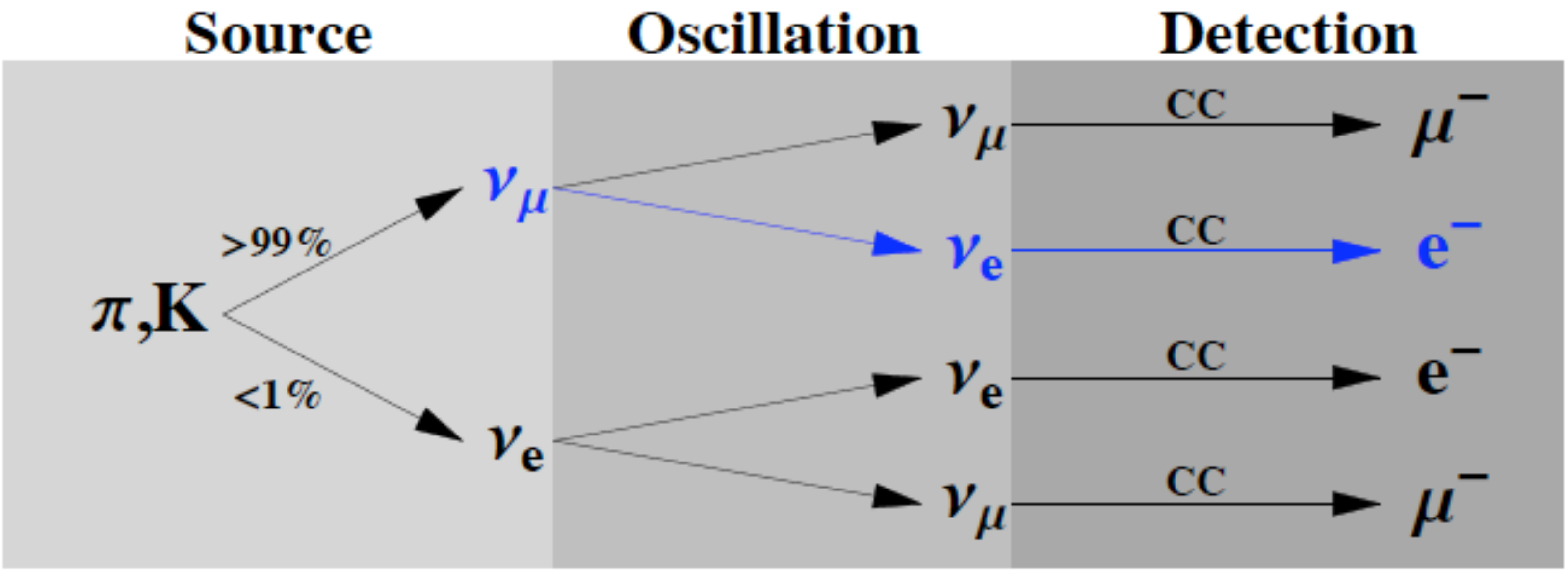



**Agarwalla, Kao, Takeuchi, JHEP 1404, 047 (2014)**

Other analytical expressions suffer in accuracy due to their reliance on expansion in $\theta_{13}$, or in simplicity when higher order terms in $\theta_{13}$ 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 (2.5º off-axis, 1st Osc. Max = 0.6 GeV)

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

Detector: Super-Kamiokande (22.5 kton fiducial volume)

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

NuMI Beam: 0.7 MW, Total $3.6 \times 10^{21}$ 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),

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

$\sin^2 2\theta_{13}$: 0.09 — $\theta_{13}$ Driven

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

$\alpha \sin 2\theta_{13}$: 0.009 — 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

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

$\alpha^2$: 0.0009 — Solar Term

Resolves octant ($\sin^2\theta_{23}$)

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($\Delta m^2_{31}$) 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 – $\delta_{CP}$) & (Octant – $\delta_{CP}$) degeneracy! How can we break them?**

# *Physics Potential of T2K & NOνA in light of large $\theta_{13}$*

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ACCEPTED: *November 22, 2012*
PUBLISHED: *December 14, 2012*

**Potential of optimized NO$\nu$A for large $\theta_{13}$ & combined performance with a LArTPC & T2K**

**Sanjib Kumar Agarwalla,[a] Suprabh Prakash,[b] Sushant K. Raut[b,c] and S. Uma Sankar[b,d]**

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ABSTRACT: NO$\nu$A experiment has reoptimized its event selection criteria in light of the recently measured moderately large value of $\theta_{13}$. 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 $\delta_{CP}$, NO$\nu$A sensitivity to mass hierarchy and leptonic CP violation is

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**Resolving the octant of $\theta_{23}$ with T2K and NO$\nu$A**

**Sanjib Kumar Agarwalla,[a,b] Suprabh Prakash[c] and S. Uma Sankar[c]**

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[b] *Instituto de Física Corpuscular, CSIC-Universitat de València, Apartado de Correos 22085, E-46071 Valencia, Spain*
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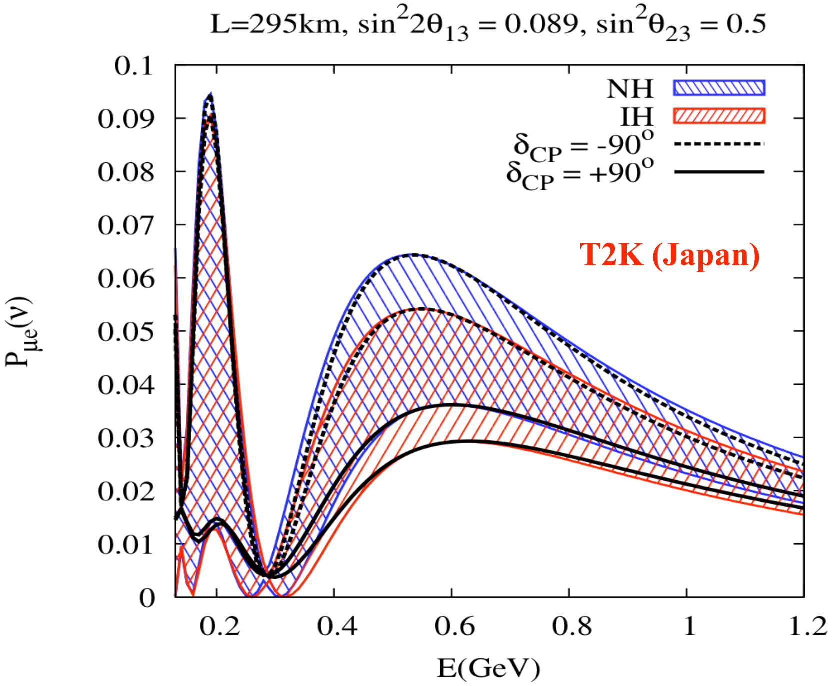
ABSTRACT: Preliminary results of MINOS experiment indicate that $\theta_{23}$ is not maximal. Global fits to world neutrino data suggest two nearly degenerate solutions for $\theta_{23}$: one in the lower octant (LO: $\theta_{23} < 45°$) and the other in the higher octant (HO: $\theta_{23} > 45°$). $\nu_\mu \to \nu_e$ 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 NO$\nu$A experiments. Because of the hierarchy-$\delta_{CP}$ degeneracy and the octant-$\delta_{CP}$ degeneracy, the impact of hierarchy on octant resolution has to be taken into account.

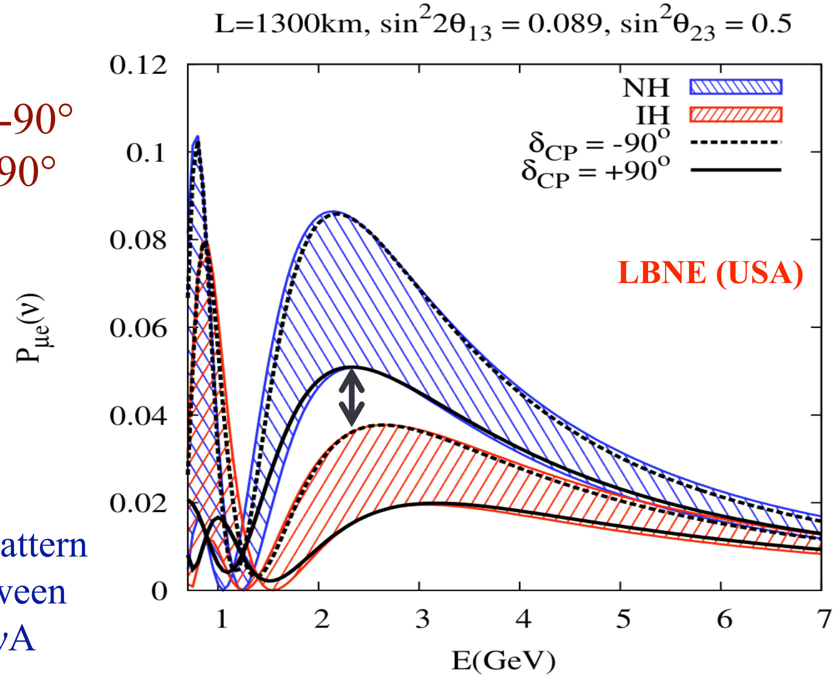
JHEP07(2013)131

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

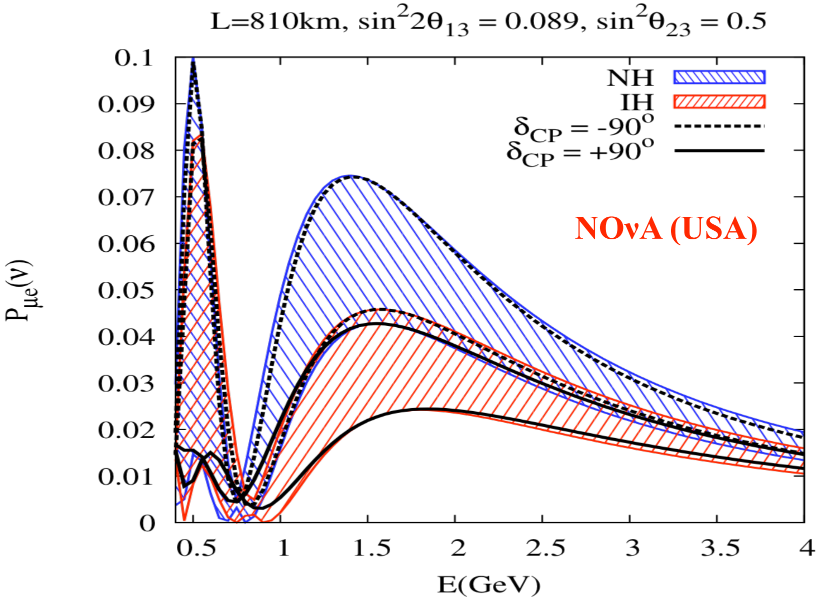
# *Hierarchy – $\delta_{CP}$ degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel*




For ν:
Max: NH, -90°
Min: IH, 90°

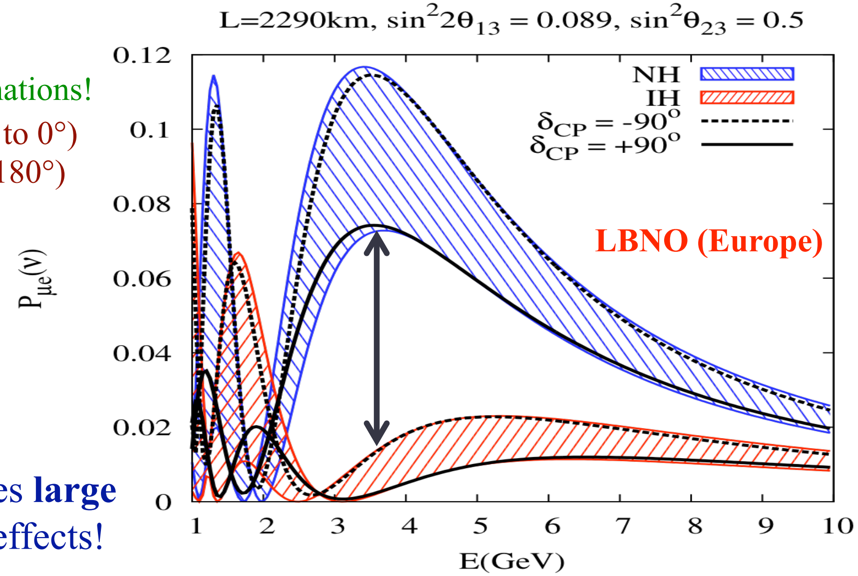



Degeneracy pattern different between T2K & NOνA



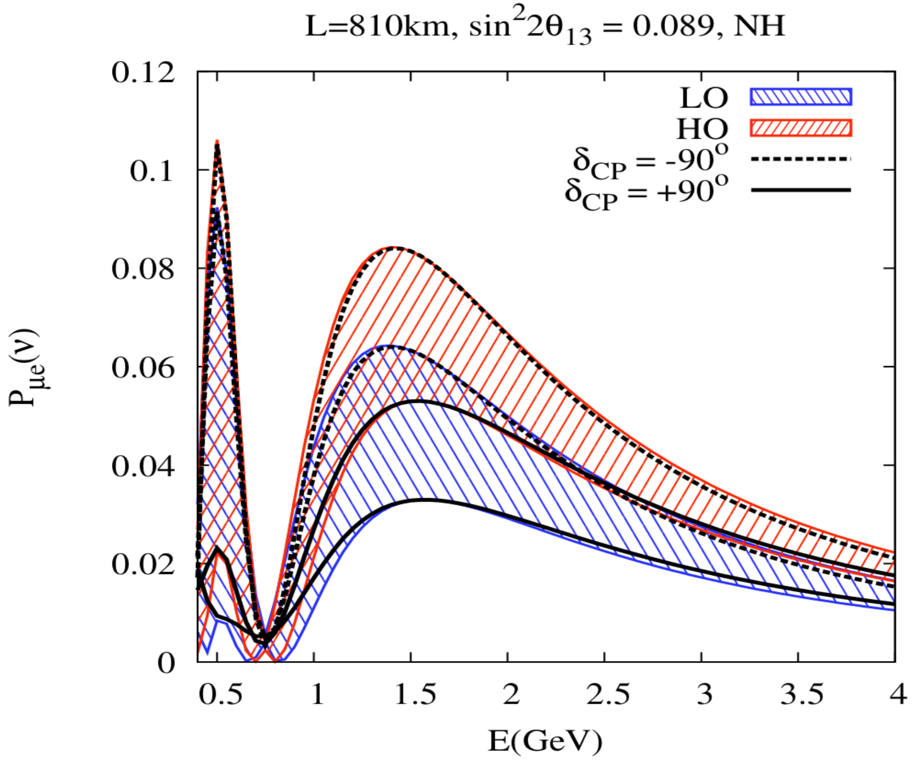

Favorable combinations!
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

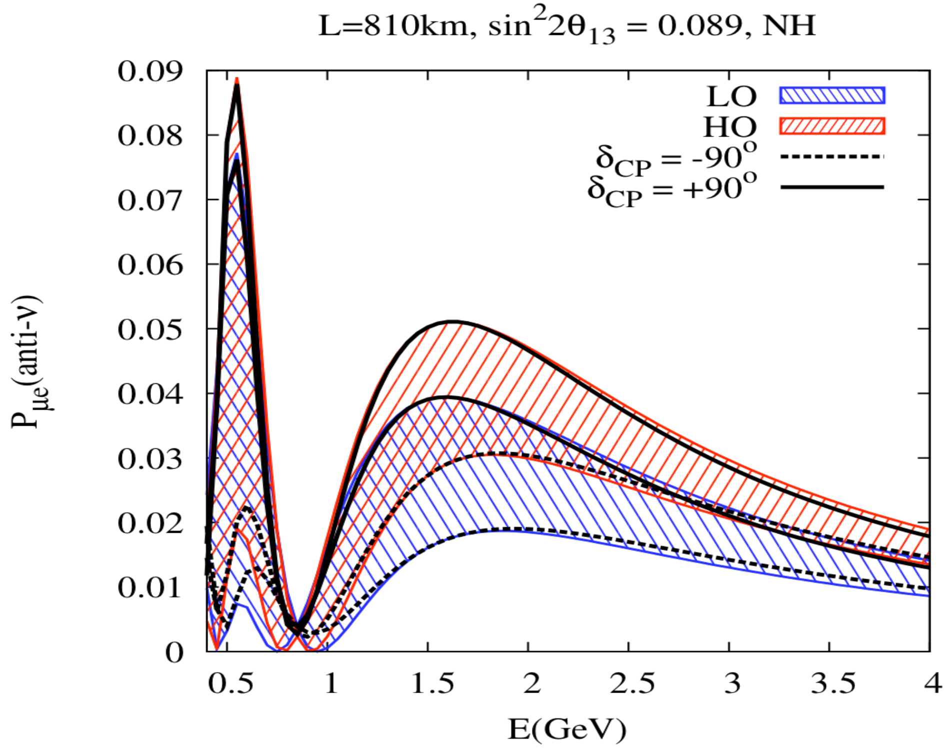
Large $\theta_{13}$ causes **large** Earth matter effects!




**Agarwalla, Prakash, Raut, Sankar, 2012-2013**

# *Octant – $\delta_{CP}$ degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel*



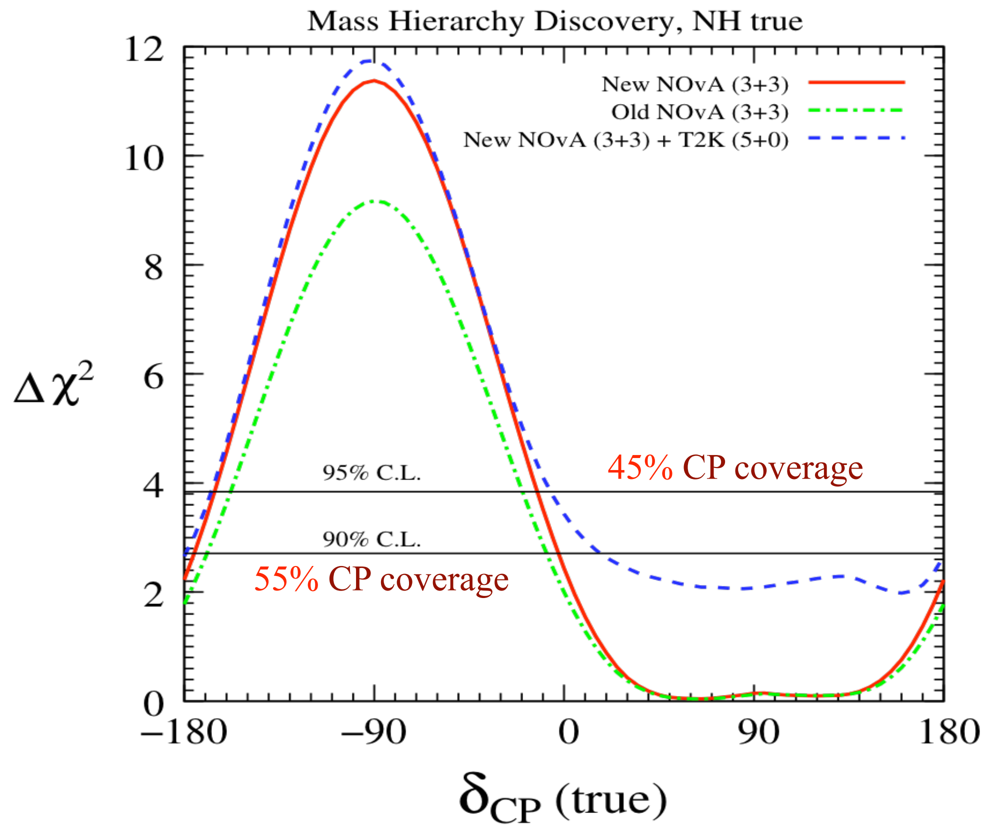

For neutrino:
Maximum: HO, -90°
Minimum: LO, 90°

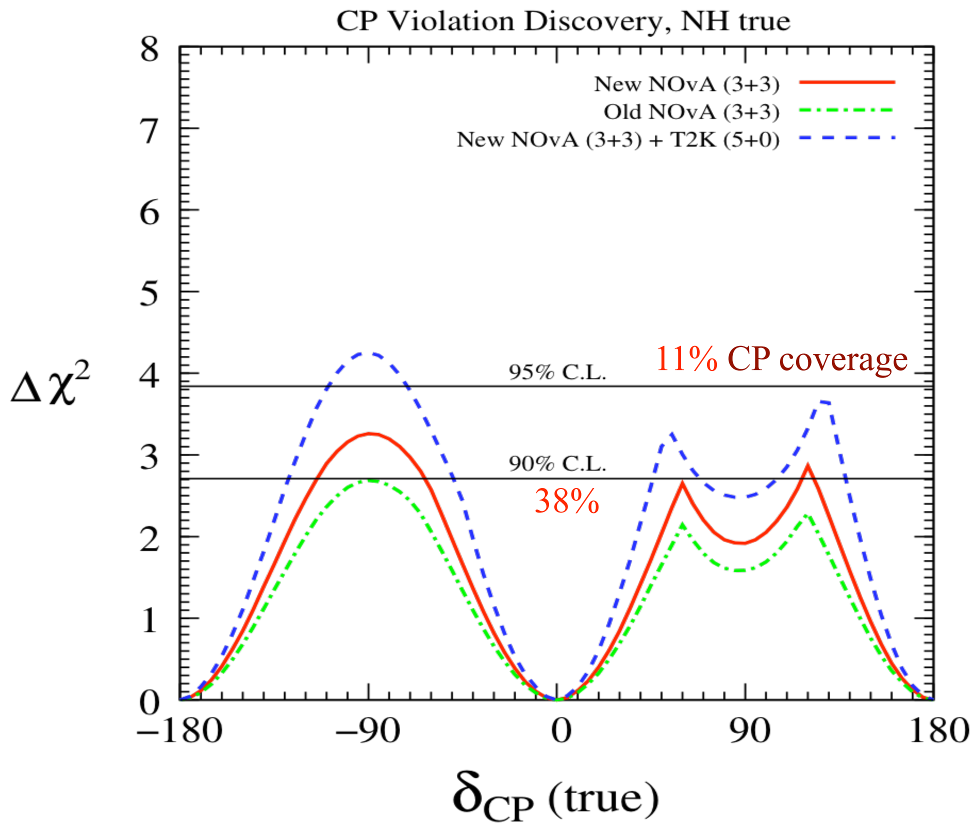
For anti-neutrino:
Maximum: HO, 90°
Minimum: LO, -90°

**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*



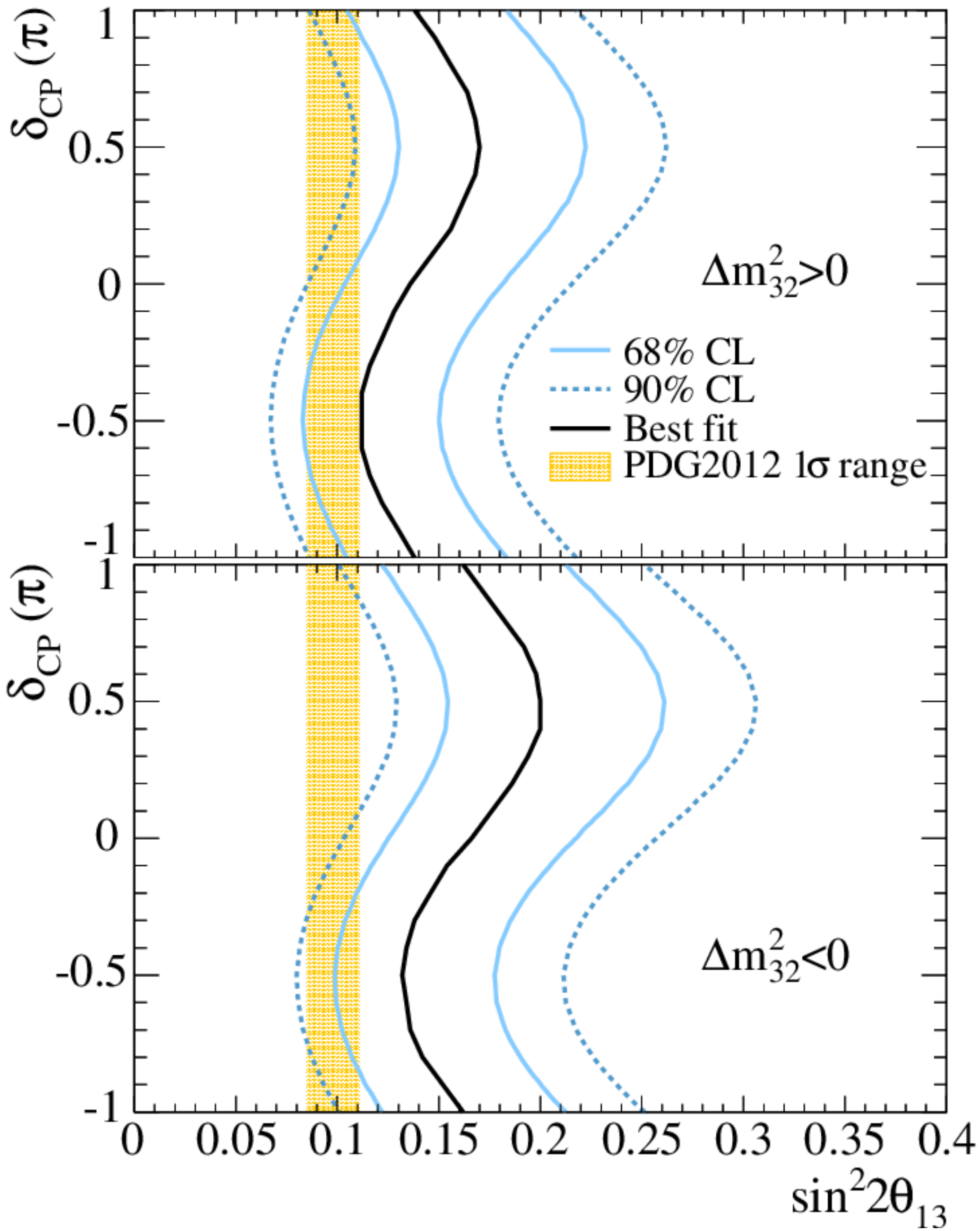




**Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644**
**See also, Huber, Lindner, Schwetz, Winter, arXiv: 0907.1896;**
**Machado, Minakata, Nunokawa, Funchal, arXiv: 1307.3248;**
**Ghosh, Ghosal, Goswami, Raut, arXiv: 1401.7243**

**Adding data from T2K and NOvA is useful to kill the intrinsic degeneracies**

CP asymmetry ∞ $1/\sin2\theta_{13}$, large $\theta_{13}$ increases statistics but reduces asymmetry, Systematics are important

# *Important Synergy between Reactor and Accelerator data*




**First hint of $\delta_{CP}$ combining Reactor and Accelerator data**

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

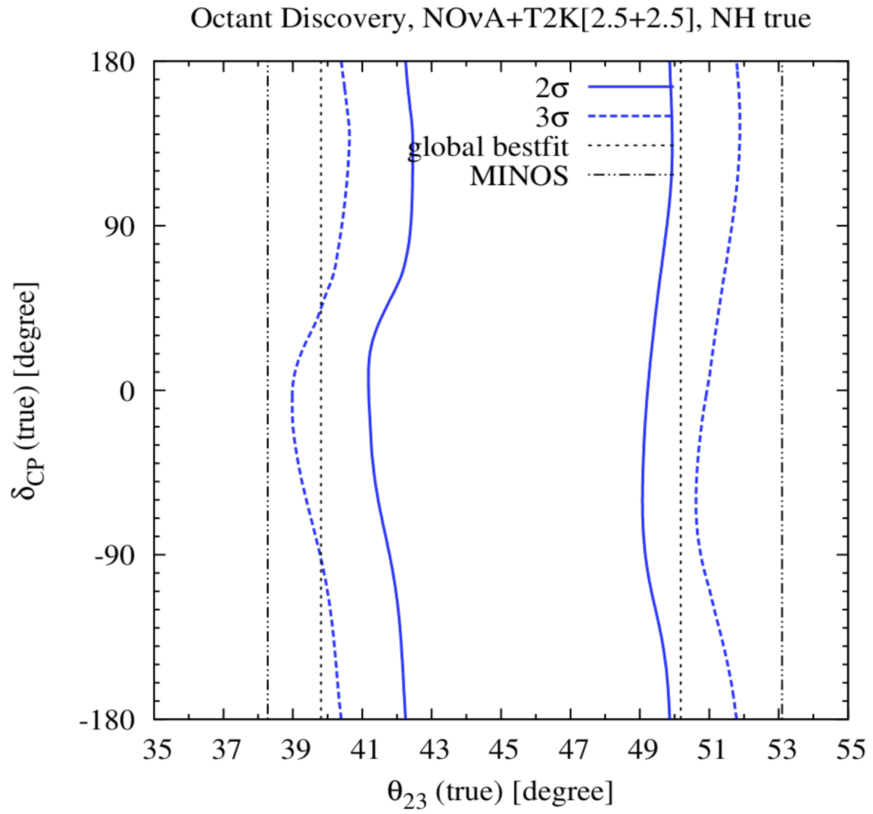
- ★ **Is Nature very kind to us?**
- ★ **Are we very lucky?**
- ★ **Is CP violated maximally?**

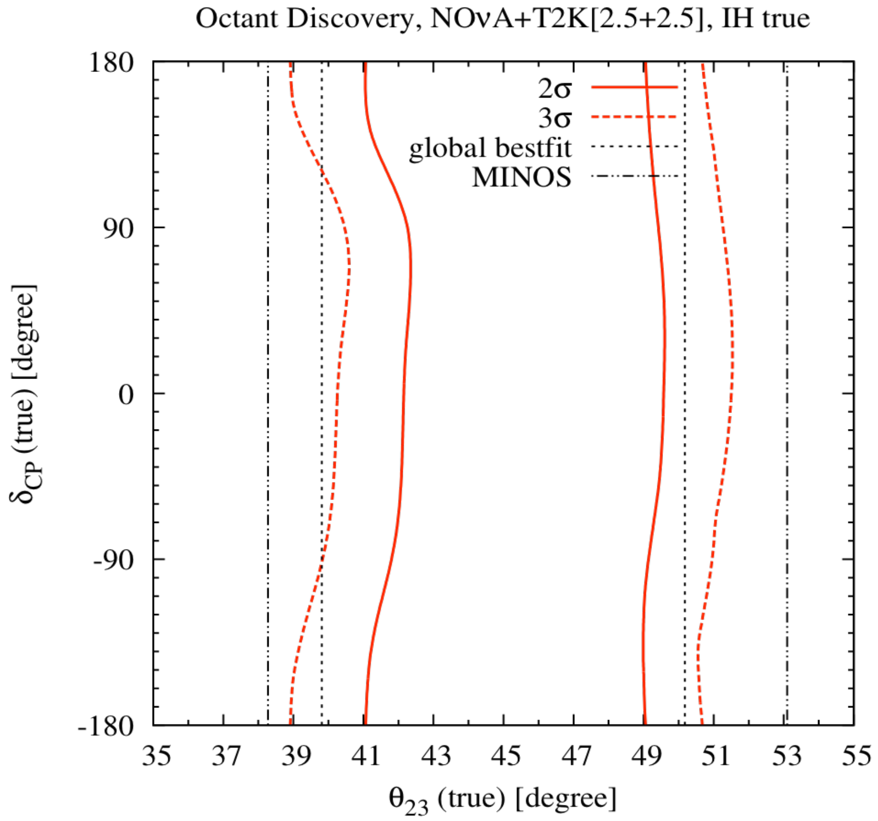
**Strong motivation for anti-neutrino run in T2K**

**In these plots, atmospheric parameters are marginalized over**

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

# *Resolving Octant of $\theta_{23}$ 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 $2\sigma$ irrespective of $\delta_{CP}$

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

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

# Future Facilities for Long Baseline Neutrino Experiments

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

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

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

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

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

Detector: 20 kton LArTPC (Phase1), 70 kton LArTPC (Phase2)

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PUBLISHED: *March 20, 2014*

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

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[b] *Department of Physics, Indian Institute of Technology Bombay, Mumbai 400076, India*

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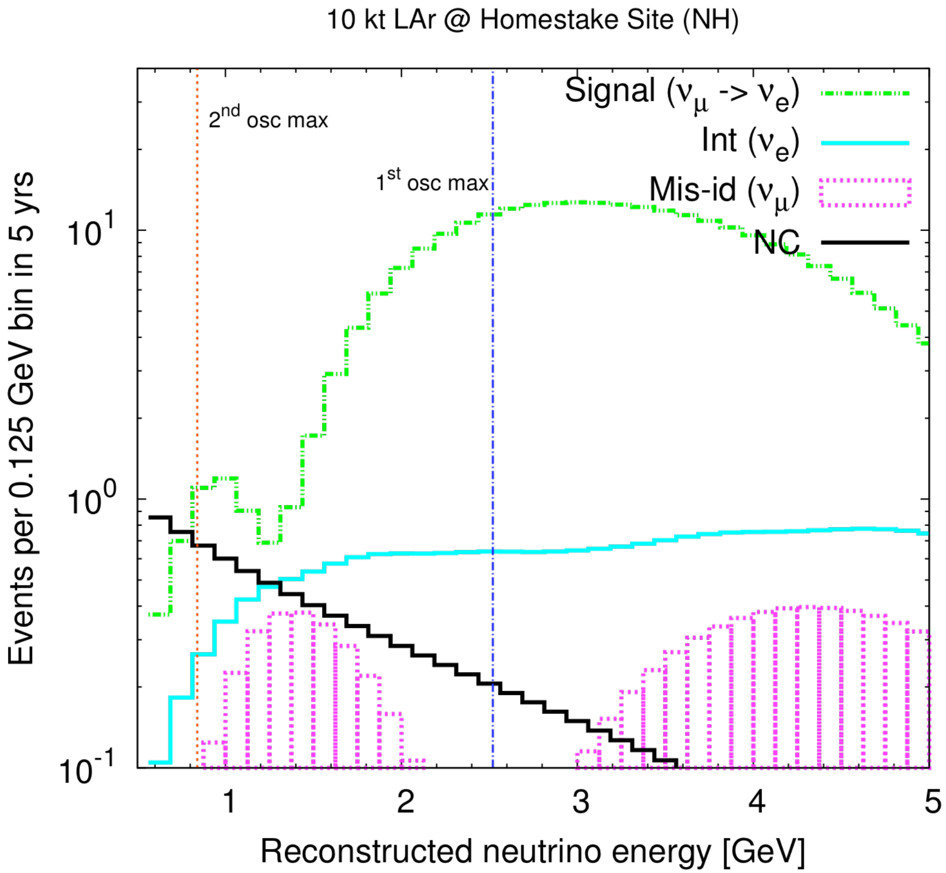
ABSTRACT: Recent measurement of a moderately large value of $\theta_{13}$ signifies an important breakthrough in establishing the standard three flavor oscillation picture of neutrinos. It has provided an opportunity to explore the sub-dominant three flavor effects in present and future long-baseline 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 $\theta_{23}$, 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 NO$\nu$A. Stand-alone LBNO setup

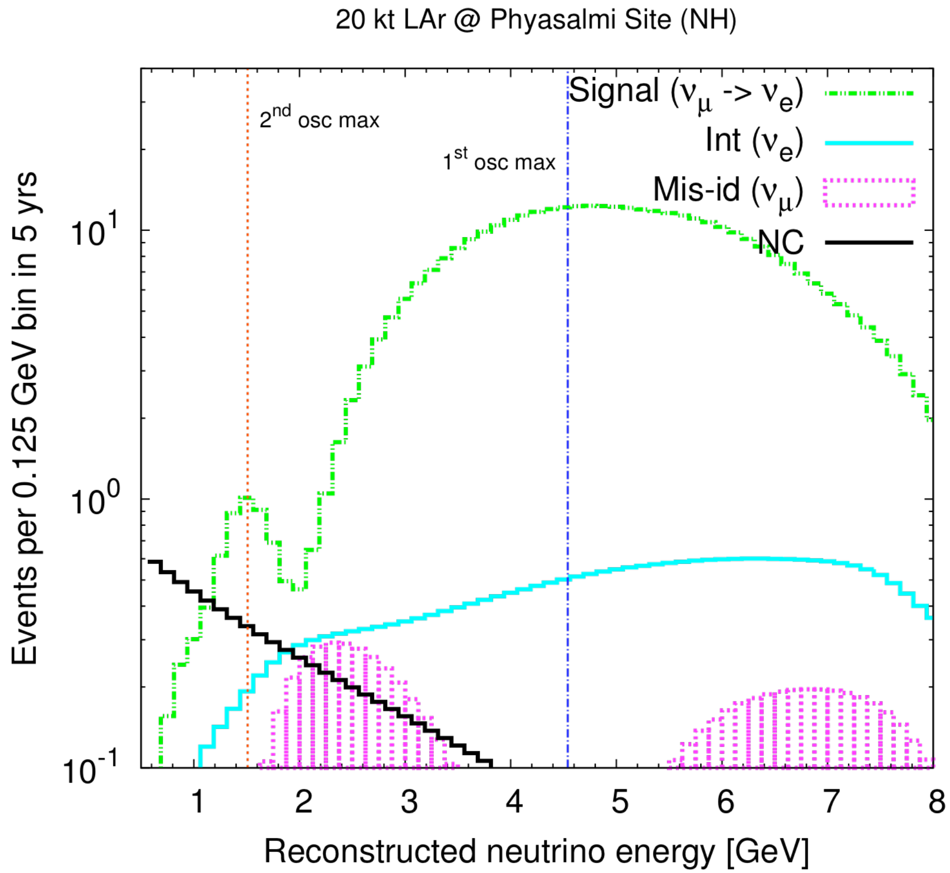
JHEP03(2014)087

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

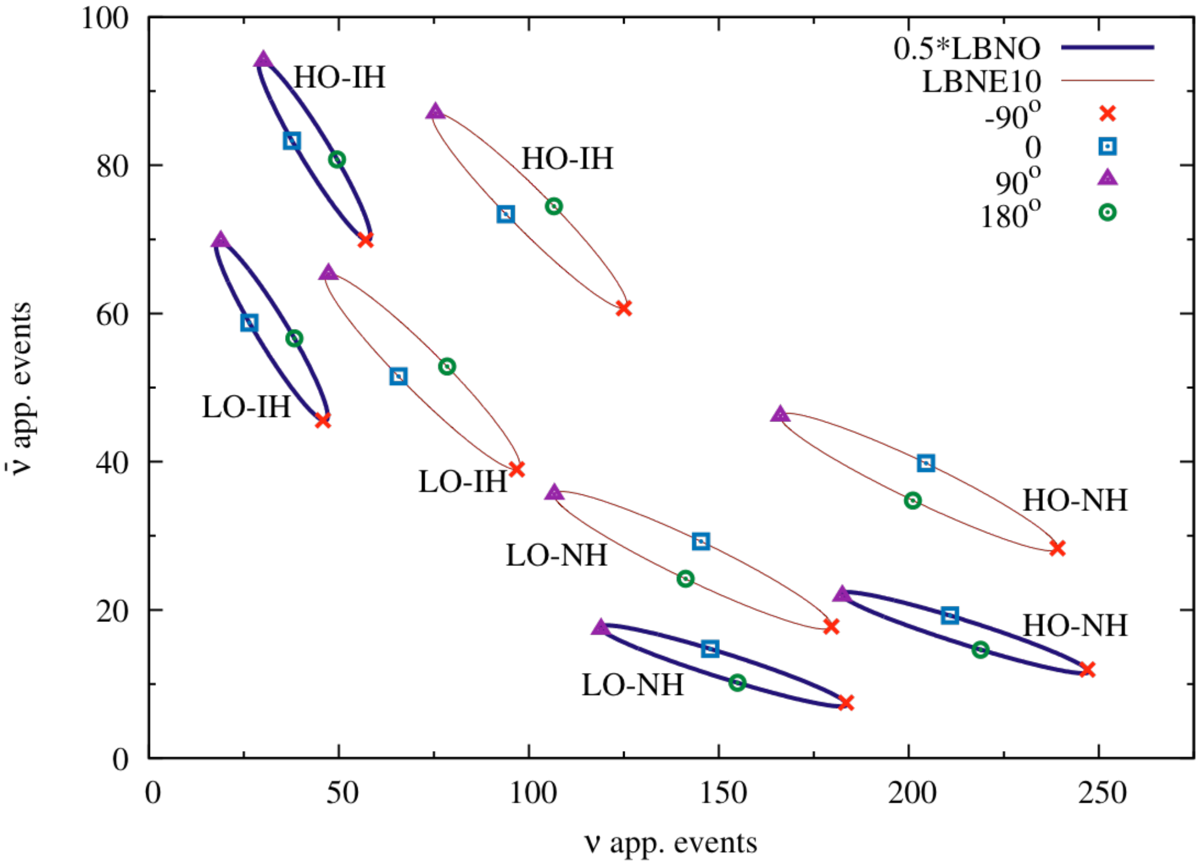
# Event Spectrum in LBNE and LBNO Experiments




**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

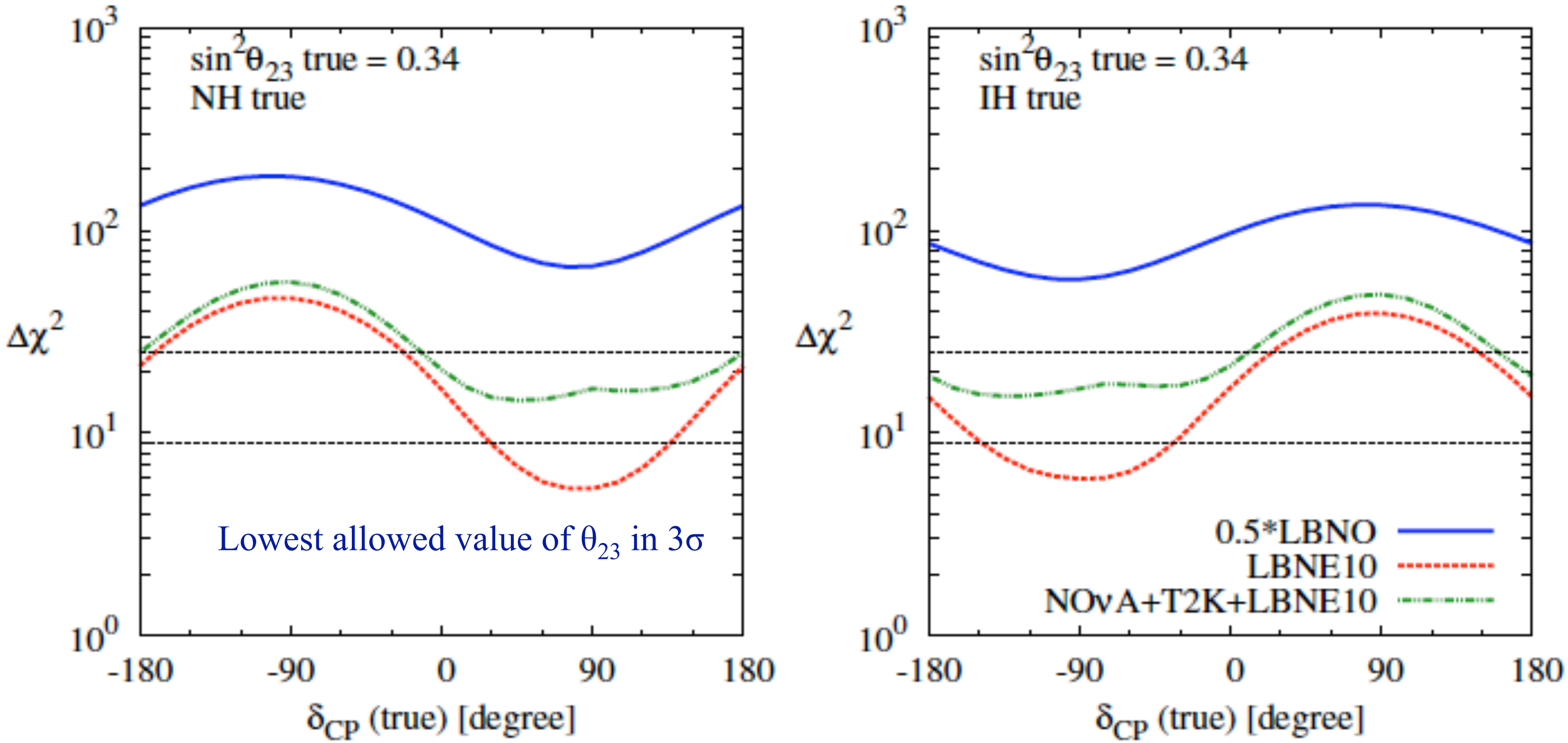
**Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]**

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*

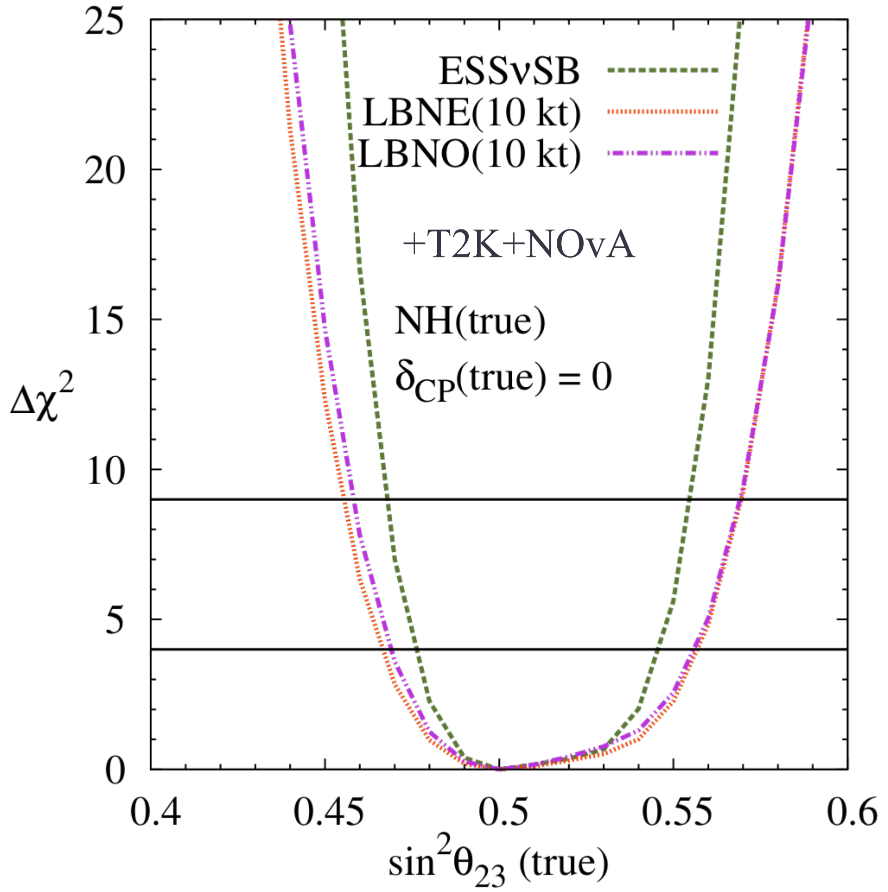



**Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]**
**See also, arXiv:1312.6520 [hep-ph] from LAGUNA-LBNO Collaboration**

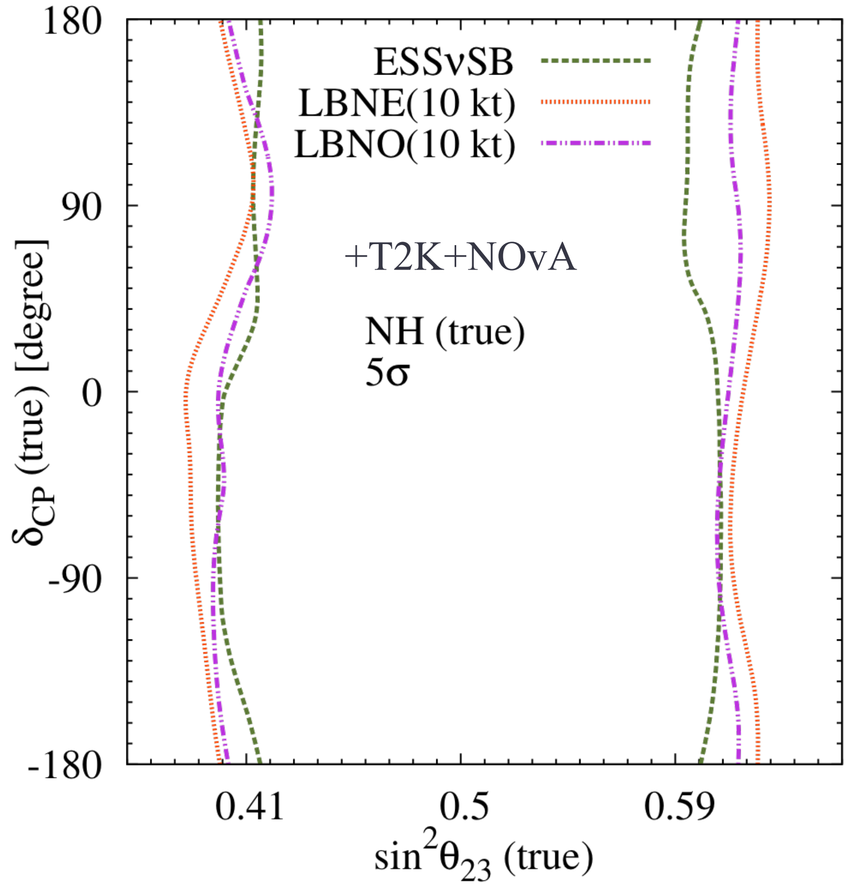
LBNO w/ 10 kt > $7\sigma$ median hierarchy discovery irrespective of the choice of $\theta_{23}$-$\delta_{CP}$-hierarchy

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

# *Probing 2-3 Mixing Angle with LBNE and LBNO*




**Discovery potential of non-maximal $\theta_{23}$**

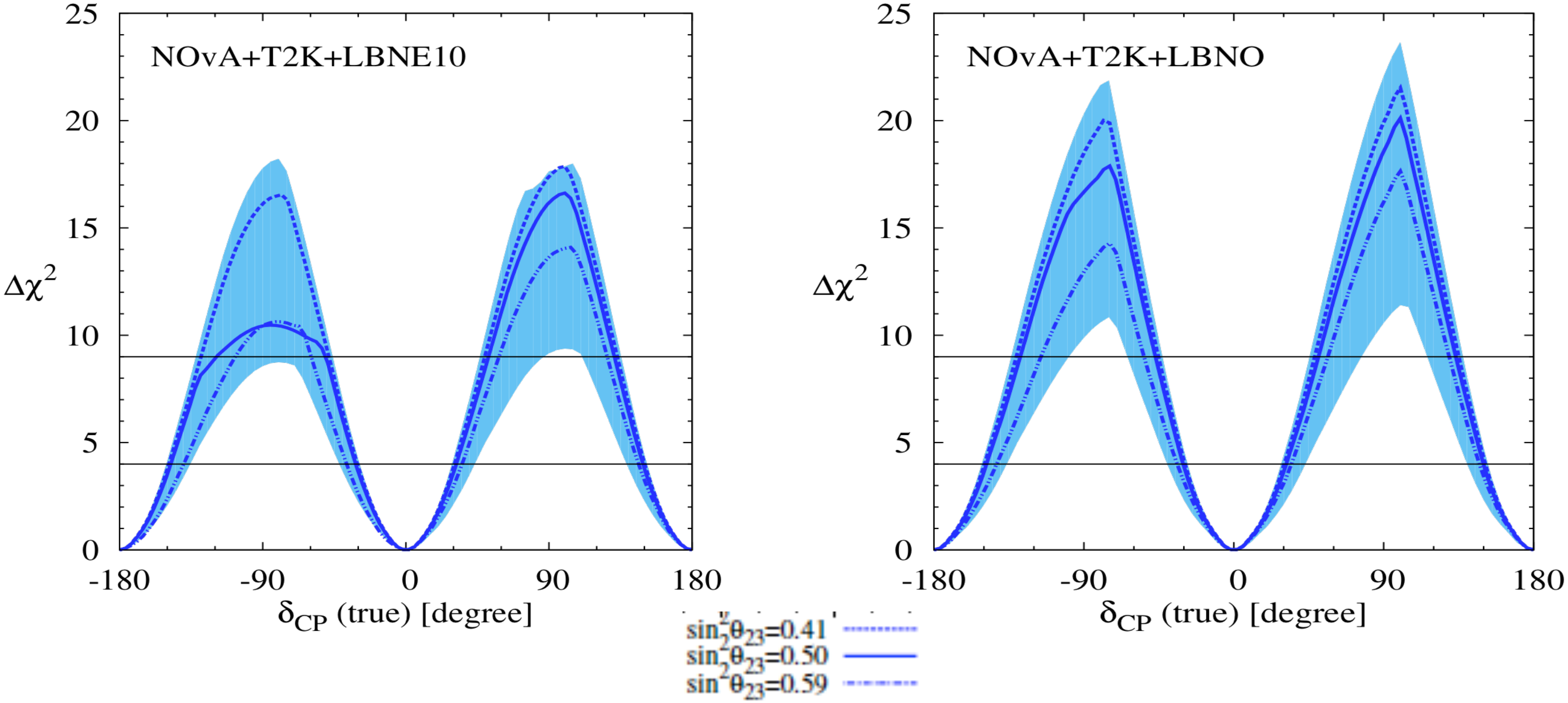



**Octant Discovery potential**

**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 $5\sigma$ irrespective of $\delta_{CP}$

# *CP violation Discovery with LBNE and LBNO*




| Setups | Fraction of $\delta_{CP}$(true) | |
|---|---|---|
| | $2\sigma$ confidence level | $3\sigma$ confidence level |
| LBNE10 (10 kt) | 0.51 | 0.03 |
| LBNE10 + T2K + NO$\nu$A | 0.63 | 0.43 |
| LBNO (20 kt) | 0.51 | 0.23 |
| LBNO + T2K + NO$\nu$A | 0.69 | 0.46 |

Assuming maximal mixing as true choice

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

# *Physics Issues with ICAL-INO*

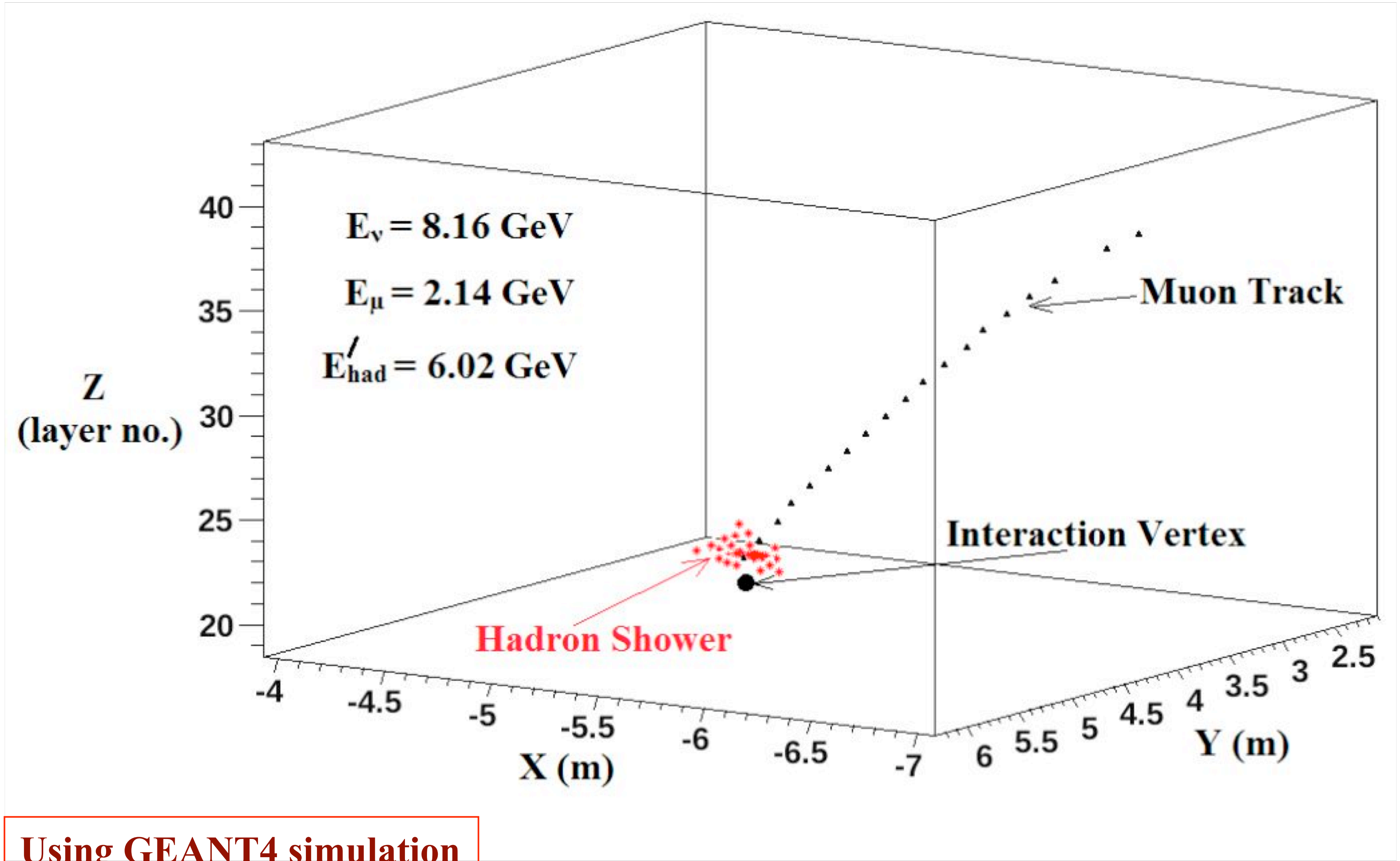
**Study Atmospheric neutrinos w/ a wide range of Baselines & Energies**

**Recent discovery of large $\theta_{13}$ : A good 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***

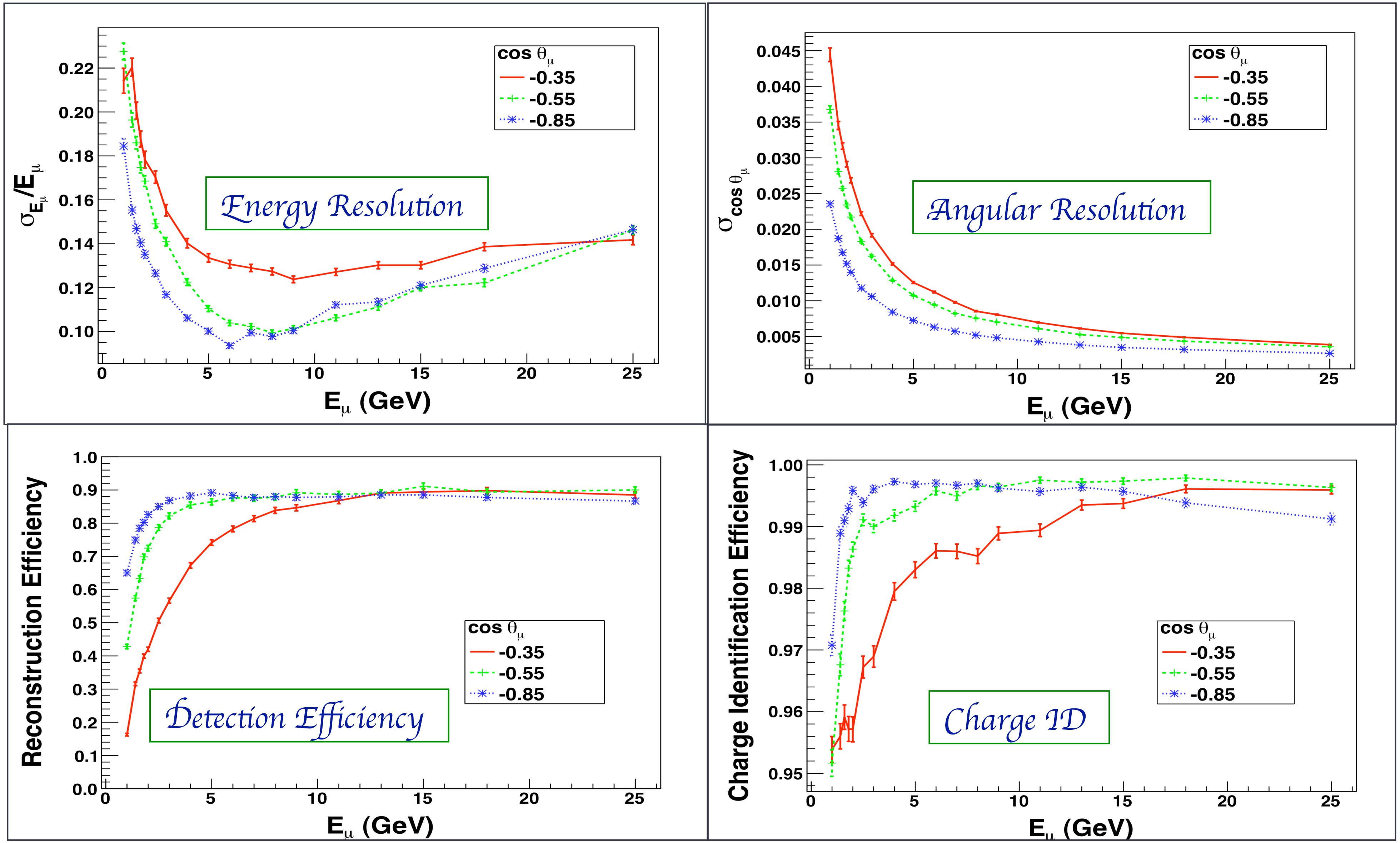
# *Event Display Inside the ICAL Detector*




**Using GEANT4 simulation**

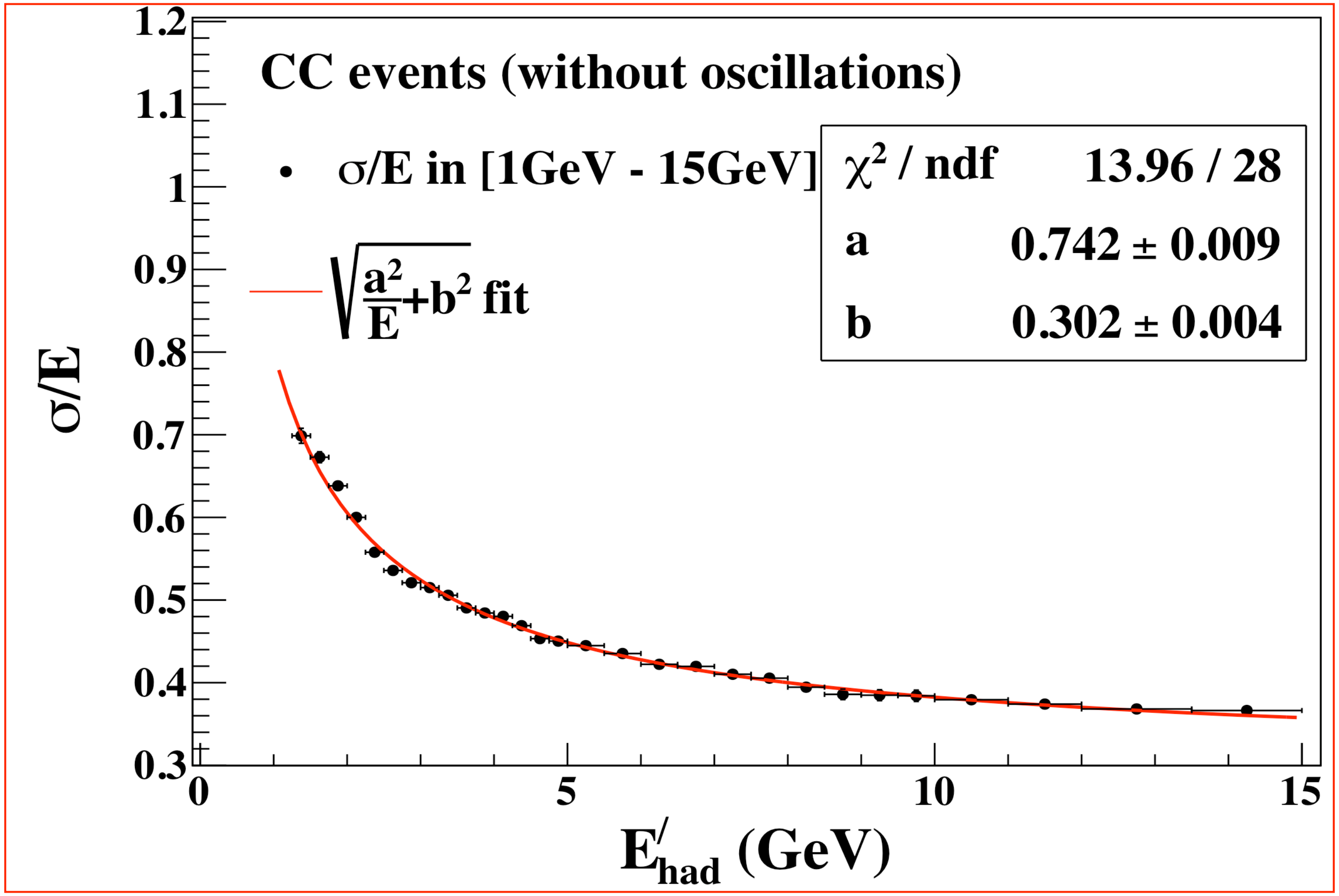
**Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)**

# Muon Efficiencies and Resolutions




Animesh Chatterjee, Meghna K.K., Kanishka Rawat, Tarak Thakore etal., arXiv:1405.7243 [physics.ins-det]

# Hadron Energy Response of ICAL




**$E'_h = E_\nu - E_\mu$ (from hadron hit calibration)**

**Hadron energy resolution: 85% at 1 GeV and 36% at 15 GeV**

Moon Moon Devi, Anushree Ghosh, Daljeet Kaur, Lakshmi S. Mohan etal., JINST 8 (2013) P11003

# The $\chi^2$ Analysis

We define the Poissonian $\chi^2_-$ for $\mu^-$ events as :

$$\chi^2_- = \min_{\xi_l} \sum_{i=1}^{N_{E'_{\rm had}}} \sum_{j=1}^{N_{E_\mu}} \sum_{k=1}^{N_{\cos\theta_\mu}} \left[ 2(N_{ijk}^{\rm theory} - N_{ijk}^{\rm data}) - 2N_{ijk}^{\rm data} \ln\left(\frac{N_{ijk}^{\rm theory}}{N_{ijk}^{\rm data}}\right)\right] + \sum_{l=1}^{5} \xi_l^2 \,,$$

where

$$N_{ijk}^{\rm theory} = N_{ijk}^0 \left(1 + \sum_{l=1}^{5} \pi_{ijk}^l \xi_l\right) .$$

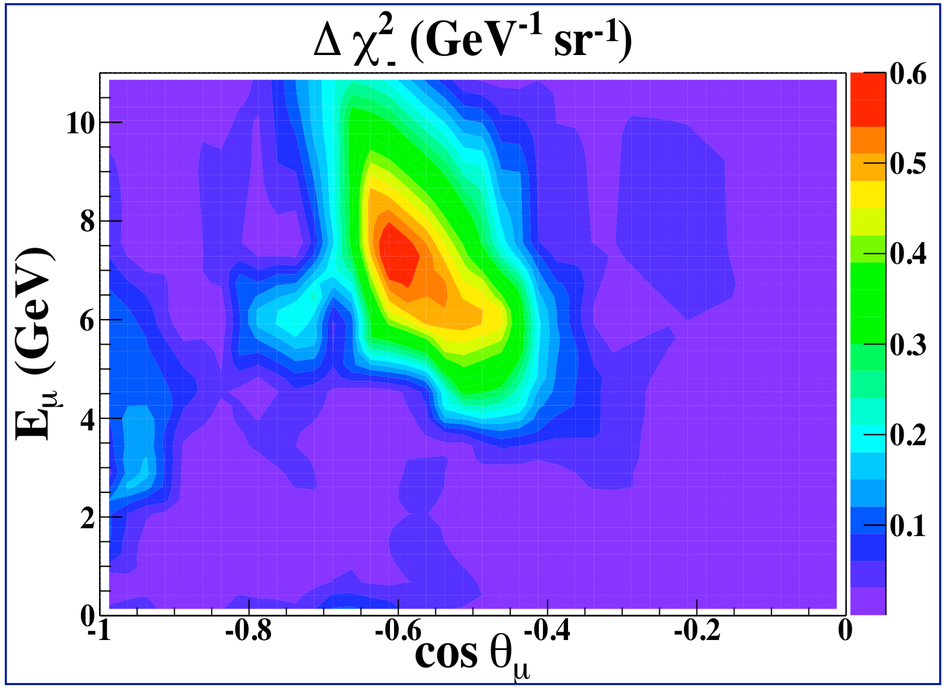
| Observable | Range | Bin width | Total bins | |
|---|---|---|---|---|
| $E_\mu$ (GeV) | $[1,4)$ | 0.5 | 6 | 10 |
| | $[4,7)$ | 1 | 3 | |
| | $[7,11)$ | 4 | 1 | |
| $\cos\theta_\mu$ | $[-1.0,-0.4)$ | 0.05 | 12 | 21 |
| | $[-0.4,0.0)$ | 0.1 | 4 | |
| | $[0.0,1.0]$ | 0.2 | 5 | |
| $E'_{\rm had}$ (GeV)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

1) Overall 5% systematic uncertainty
2) Overall flux normalization: 20%
3) Overall cross-section normalization: 10%

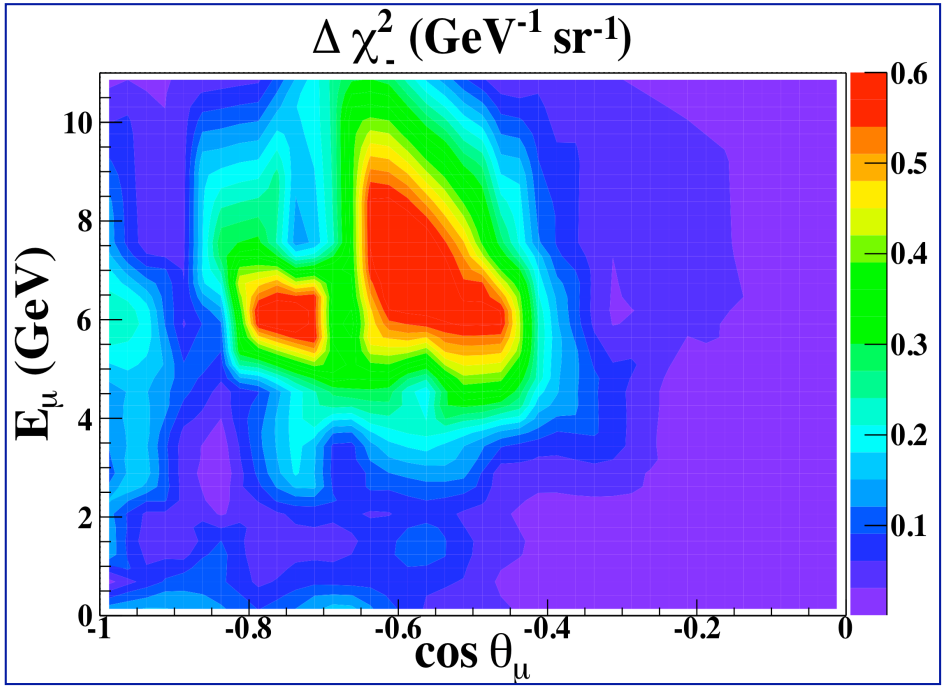
4) 5% uncertainty on the zenith angle dependence of the fluxes
5) Energy dependent tilt factor:
$\Phi_\delta(E) = \Phi_0(E)\,[E/E_0]^\delta \approx \Phi_0(E)\,[1+\delta \ln E/E_0]$
where $E_0 = 2$ GeV and
$\delta$ is the $1\sigma$ systematic error of 5%

# *Neutrino Mass Hierarchy Discrimination*

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



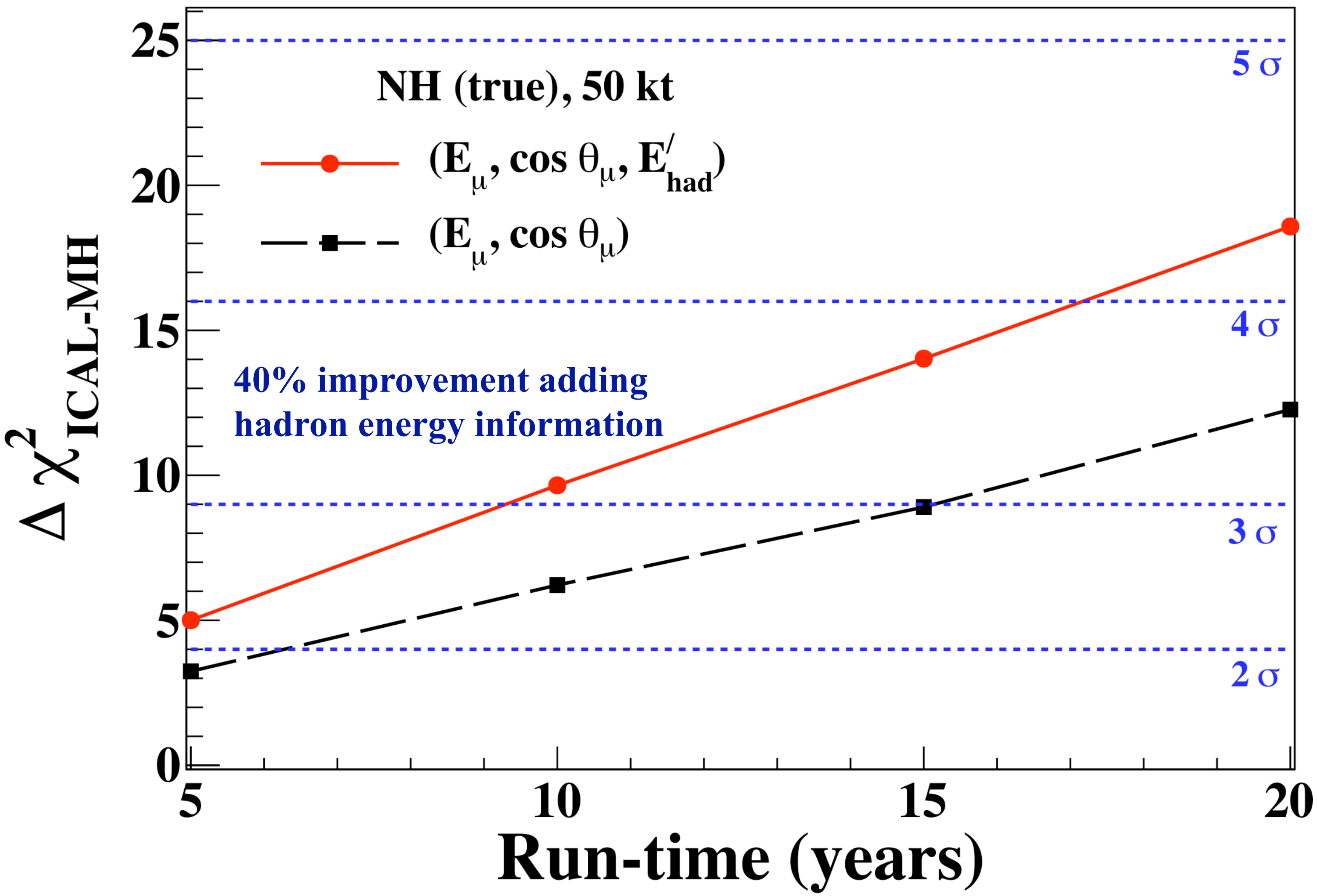

Hadron energy information not used




Hadron energy information used

- 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*

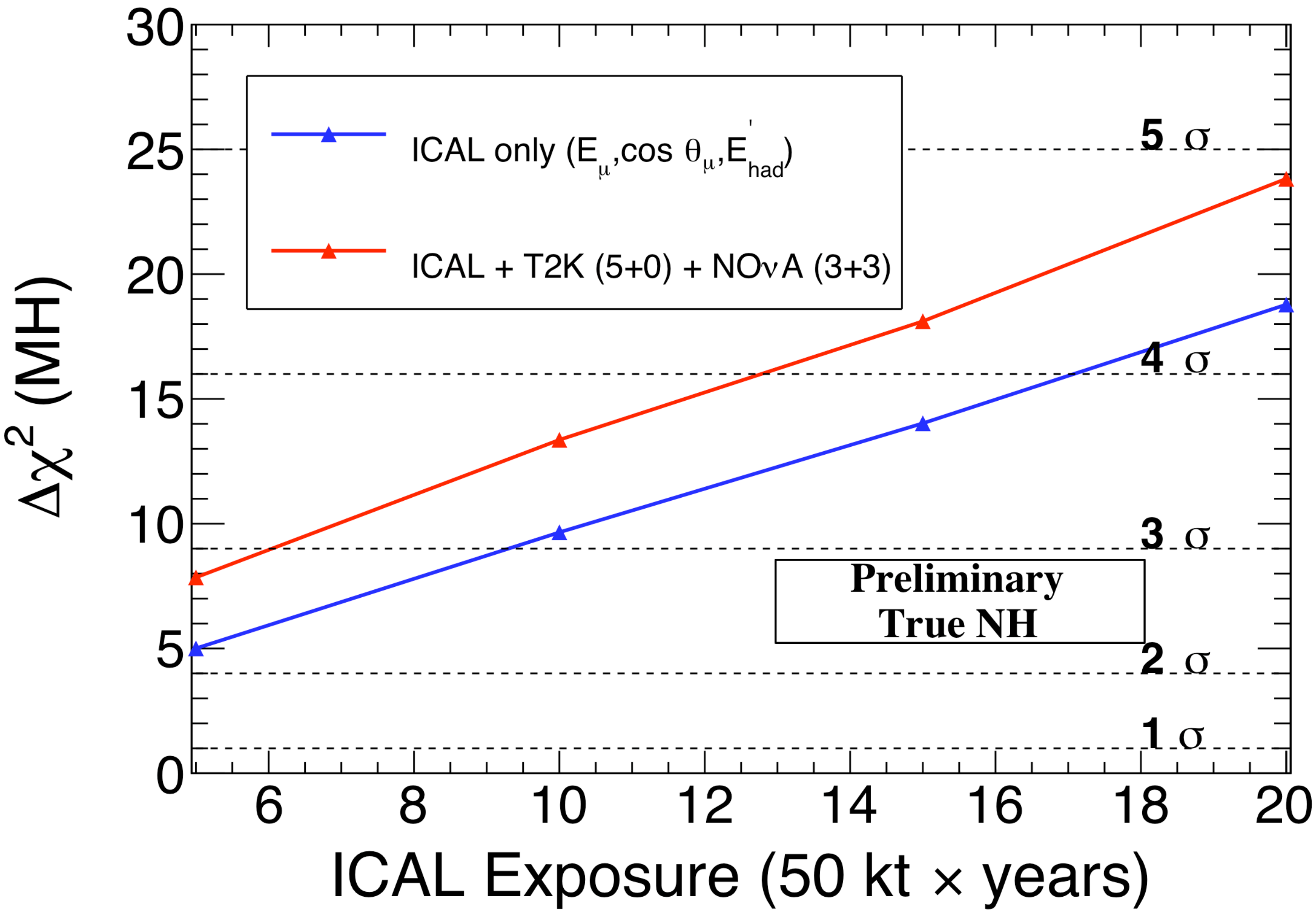



**Median Sensitivity**

**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

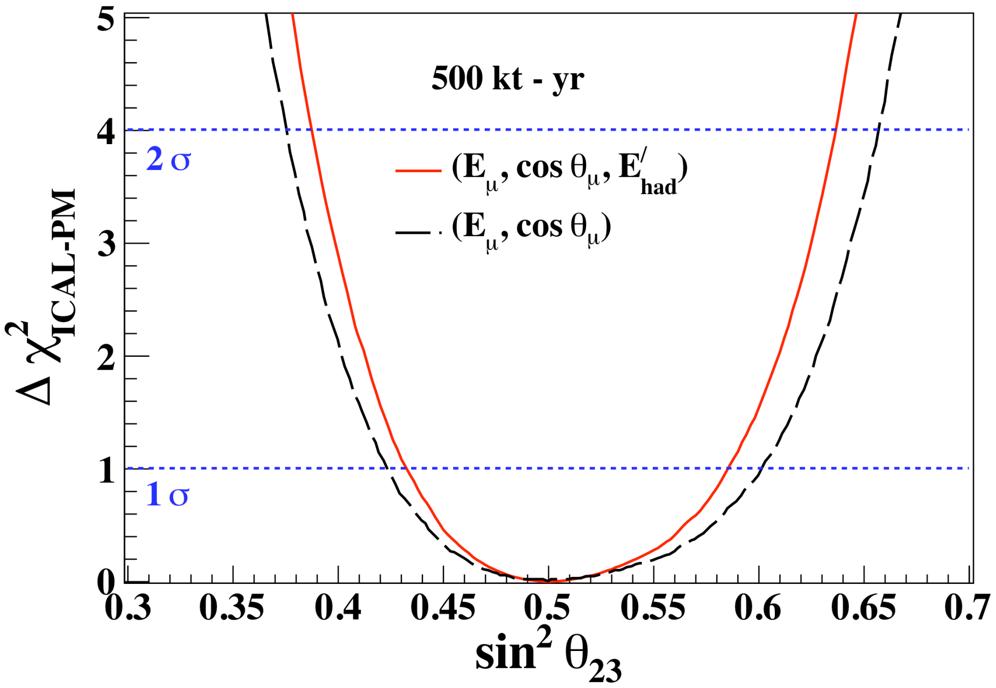
# MH Discovery with ICAL+T2K+NOvA



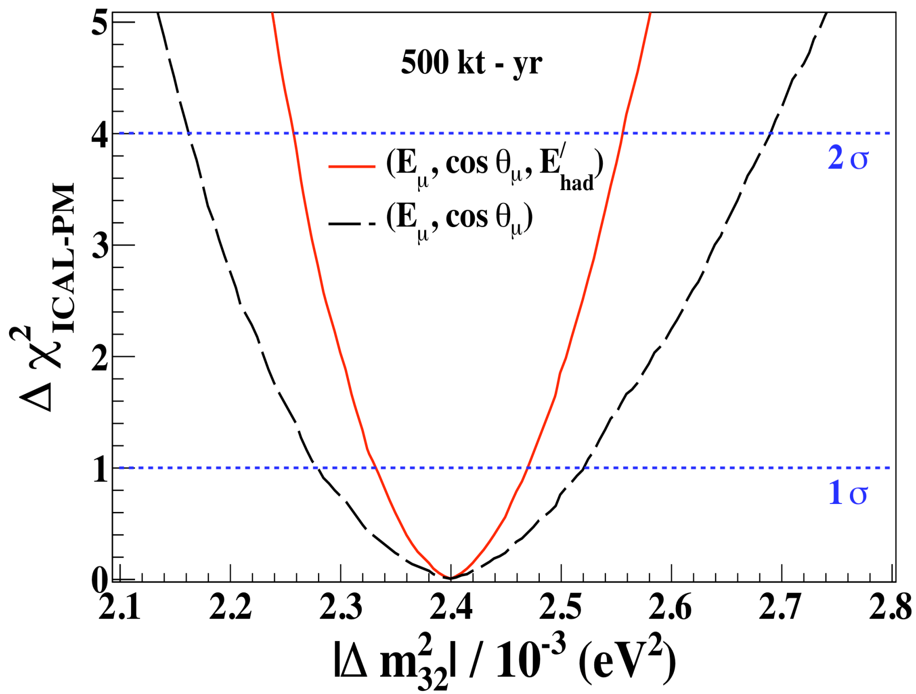

Devi, Thakore, Agarwalla, work in progress (INO Collaboration)

3σ median sensitivity can be achieved in 6 years

# *Precision of Atmospheric Oscillation Parameters*



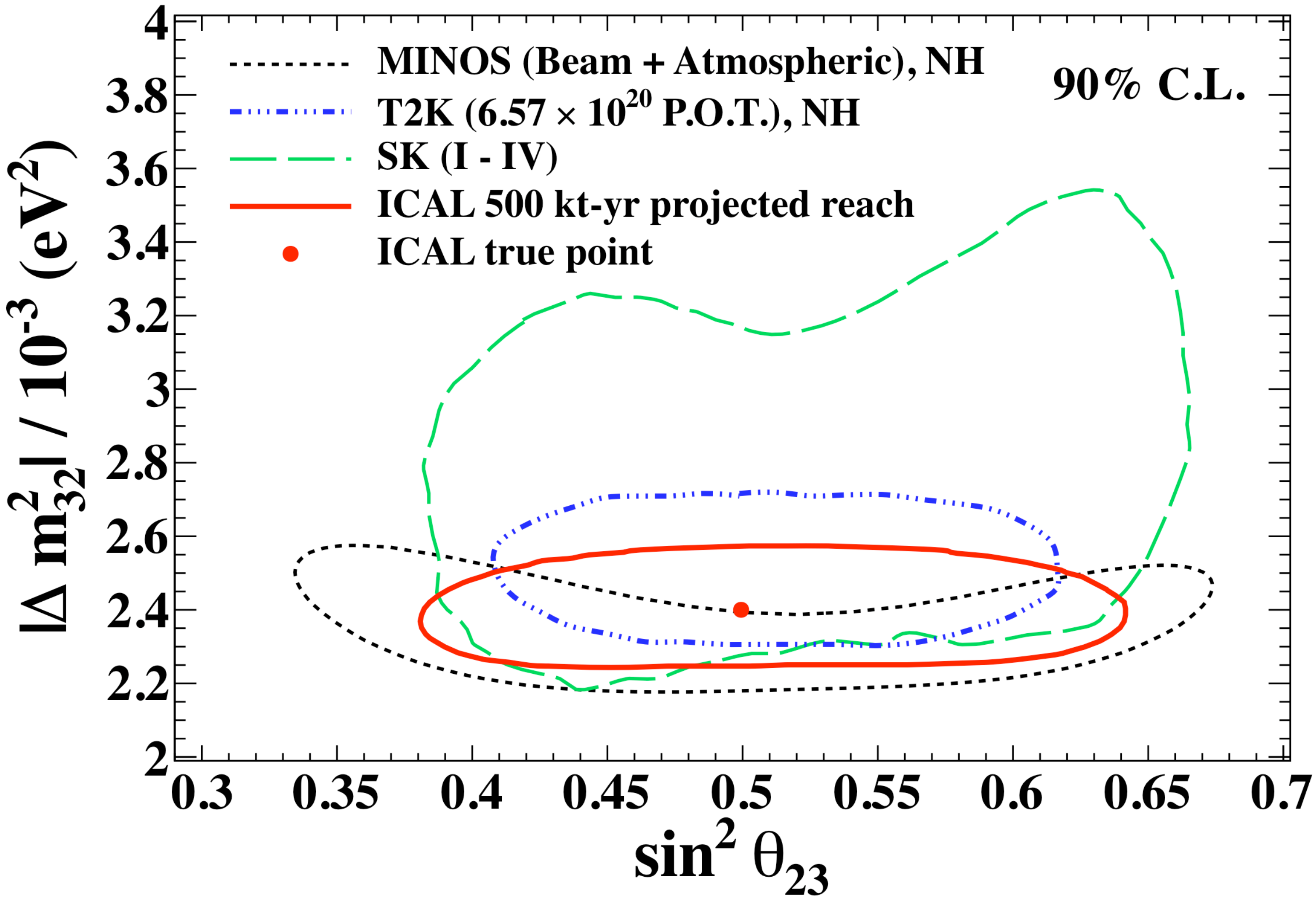

**Relative 1σ precision: 12%**




**Relative 1σ precision: 2.9%**

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

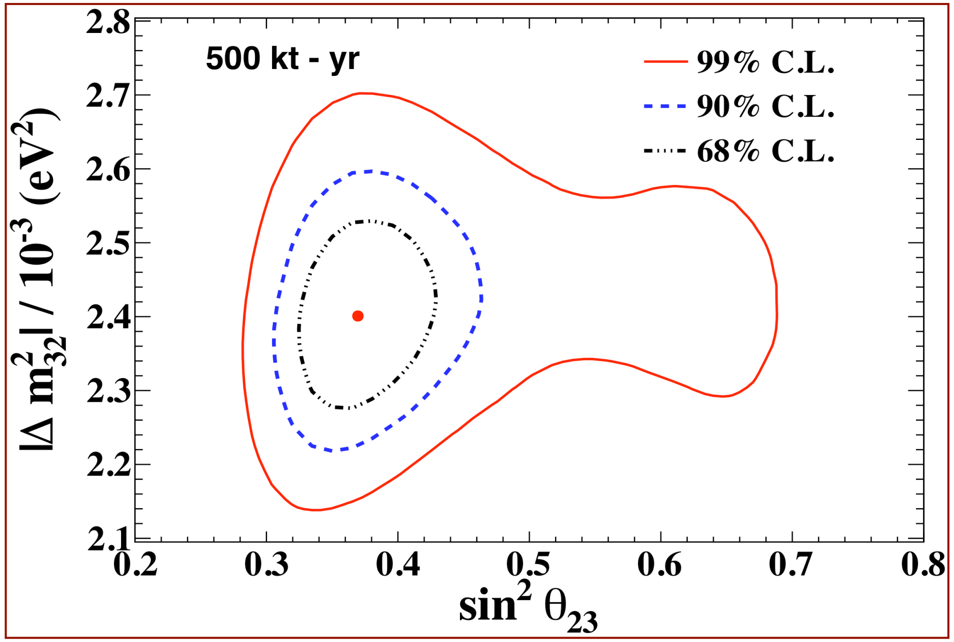
Significant improvement in the precision measurement of atmospheric mass splitting by adding hadron energy information with muon momentum

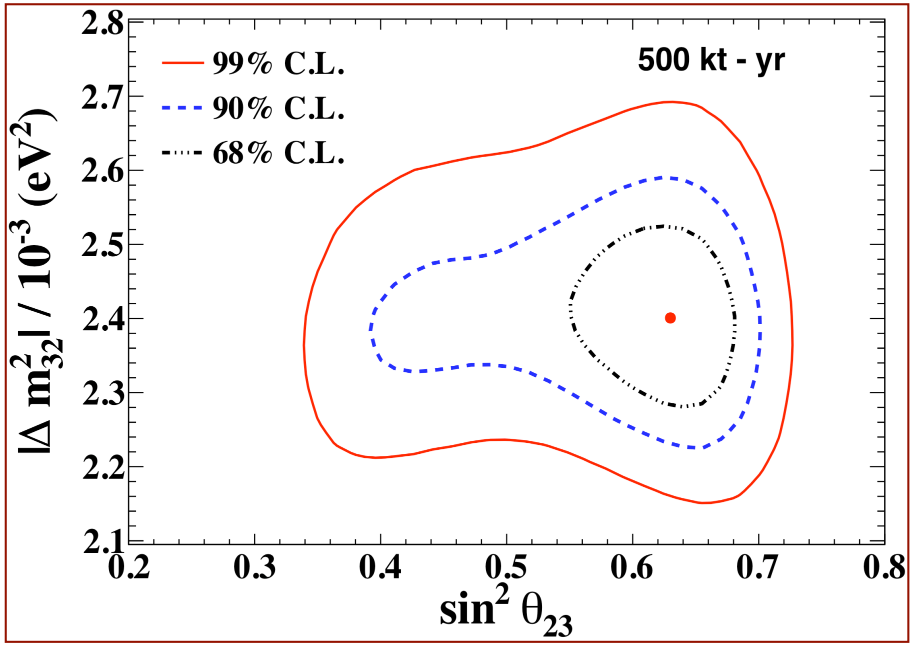


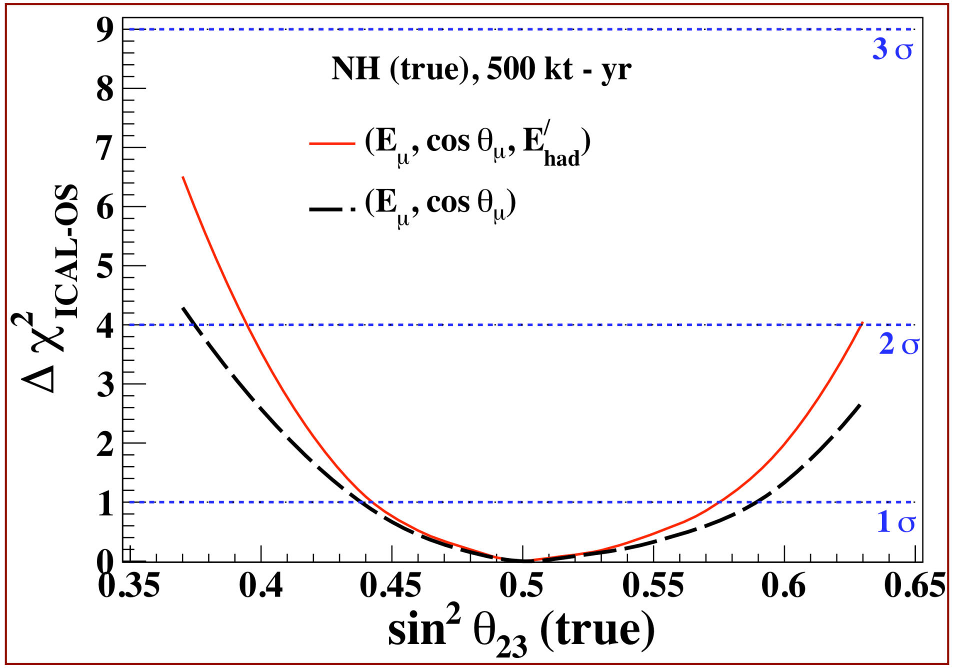

Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

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

# *Octant of $\theta_{23}$ with ICAL-INO*




**Median 2σ discovery of $\theta_{23}$ octant is possible if $\theta_{23}$ is sufficiently away from maximal value**

**Devi, Thakore, Agarwalla, Dighe, arXiv: 1406.3689 (INO Collaboration)**

# *Concluding Remarks*

*Recent discovery of $\theta_{13}$ 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:***

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

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

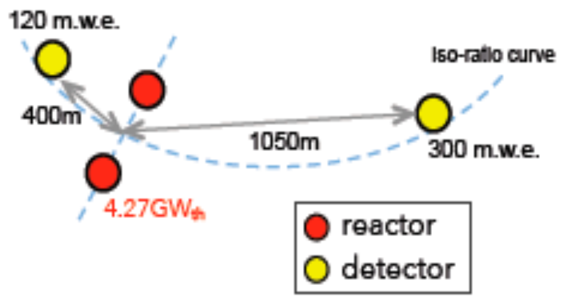
$$|V|_{\text{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\ (8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046}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

***!! Let us work together and achieve it !!***

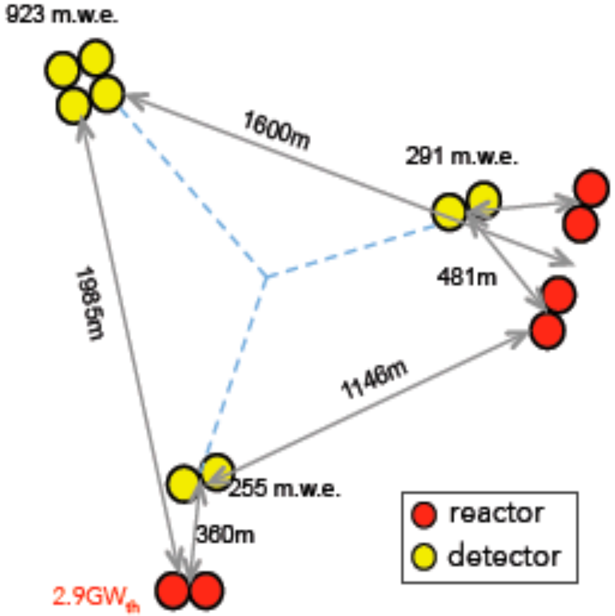
Thank you!

# *Backup Slides: Currently Running Reactor $\theta_{13}$ Experiments*

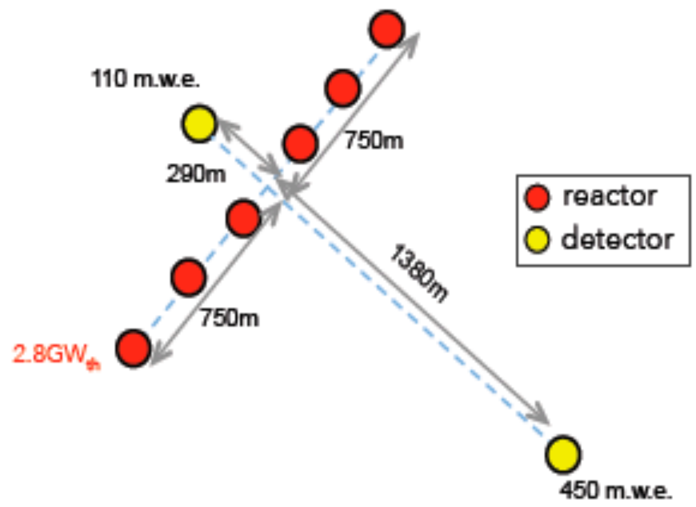
## Double Chooz (France)




## Daya Bay (China)




## RENO (Korea)

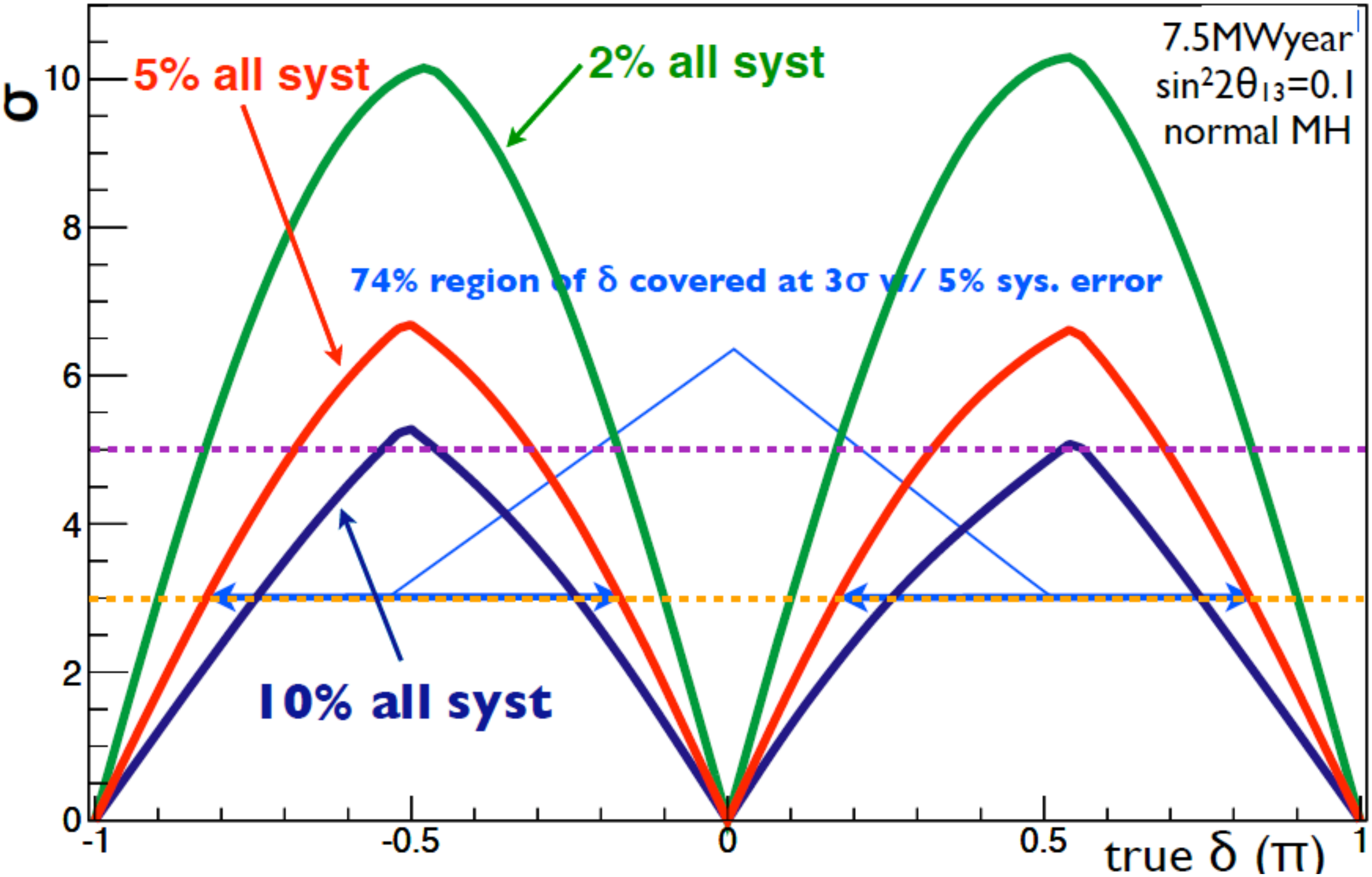


# *Backup Slides: Key Features of three Reactor Experiments*

| 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 |

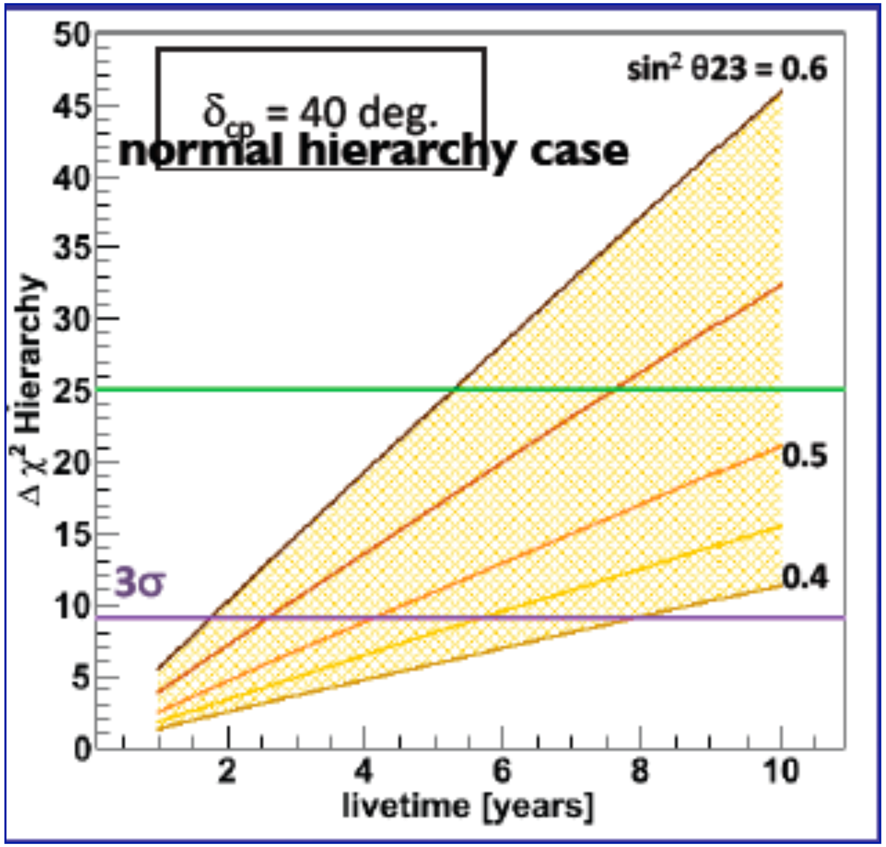
**Daya Bay Strategy: Go strong, big and deep!**

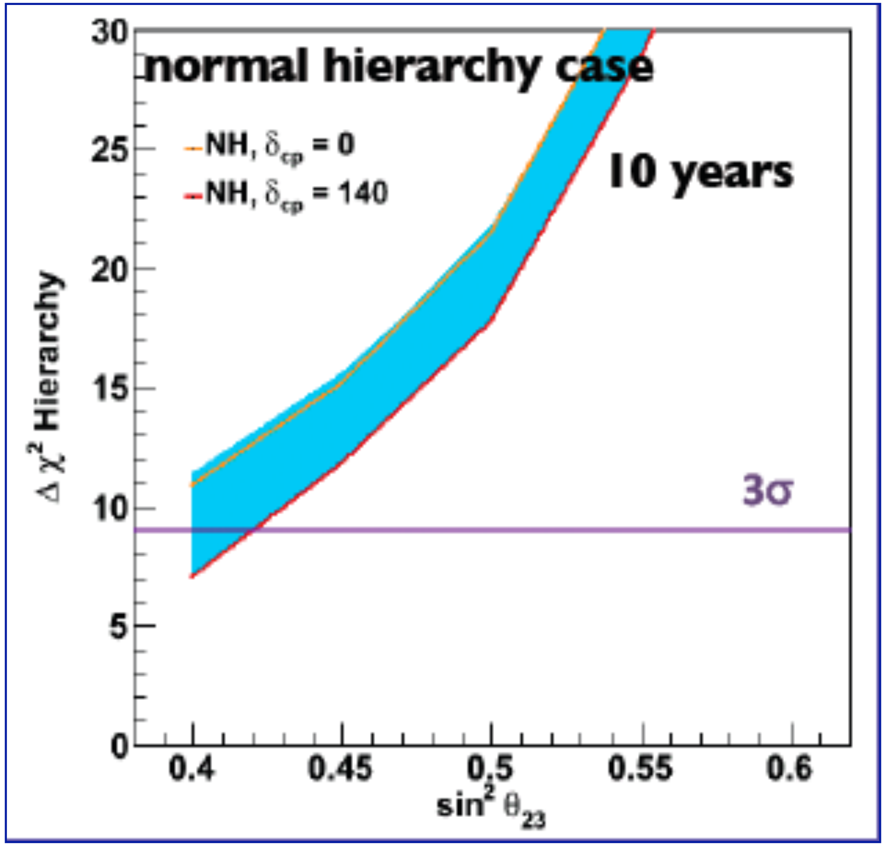
# *Backup Slides: CPV Discovery in T2HK Setup (w/ MH known)*




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

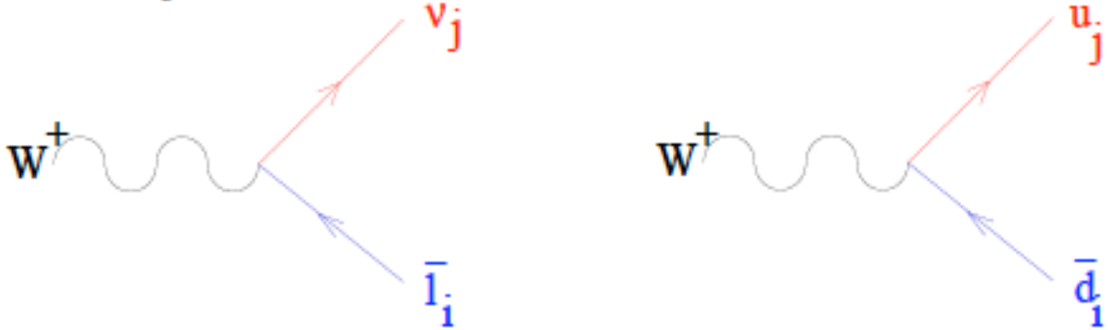
$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu_L} \nu_R + h.c.$$

  $*$ 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)

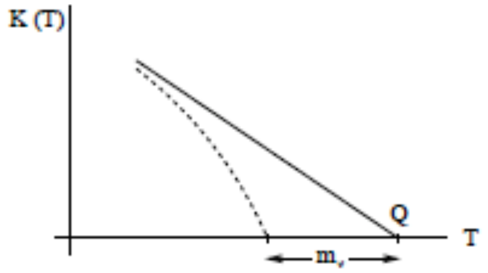
$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left( U_{\rm LEP}^{ij}\, \overline{\ell^i}\, \gamma^\mu\, L\, \nu^j \ + \ U_{\rm CKM}^{ij}\, \overline{U^i}\, \gamma^\mu\, L\, D^j \right) \ + \ h.c.$$




Courtesy to Concha Gonzalez-Garcia

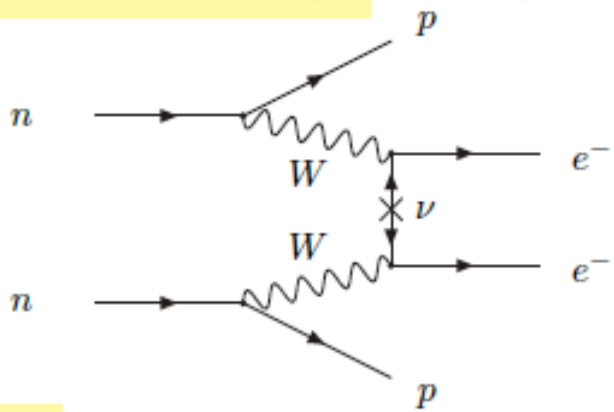
# Neutrino Mass Scale

**Single $\beta$ decay** : Dirac or Majorana $\nu$ mass modify spectrum endpoint




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

**$\nu$-less Double-$\beta$ decay:** $\Leftrightarrow$ Majorana $\nu' s$ sensitive to Majorana phases




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

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

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

**COSMO** Neutrino mass (Dirac or Majorana) modify the growth of structures $\quad \sum m_i$

**Courtesy to Concha Gonzalez-Garcia**

# Experimental Limits

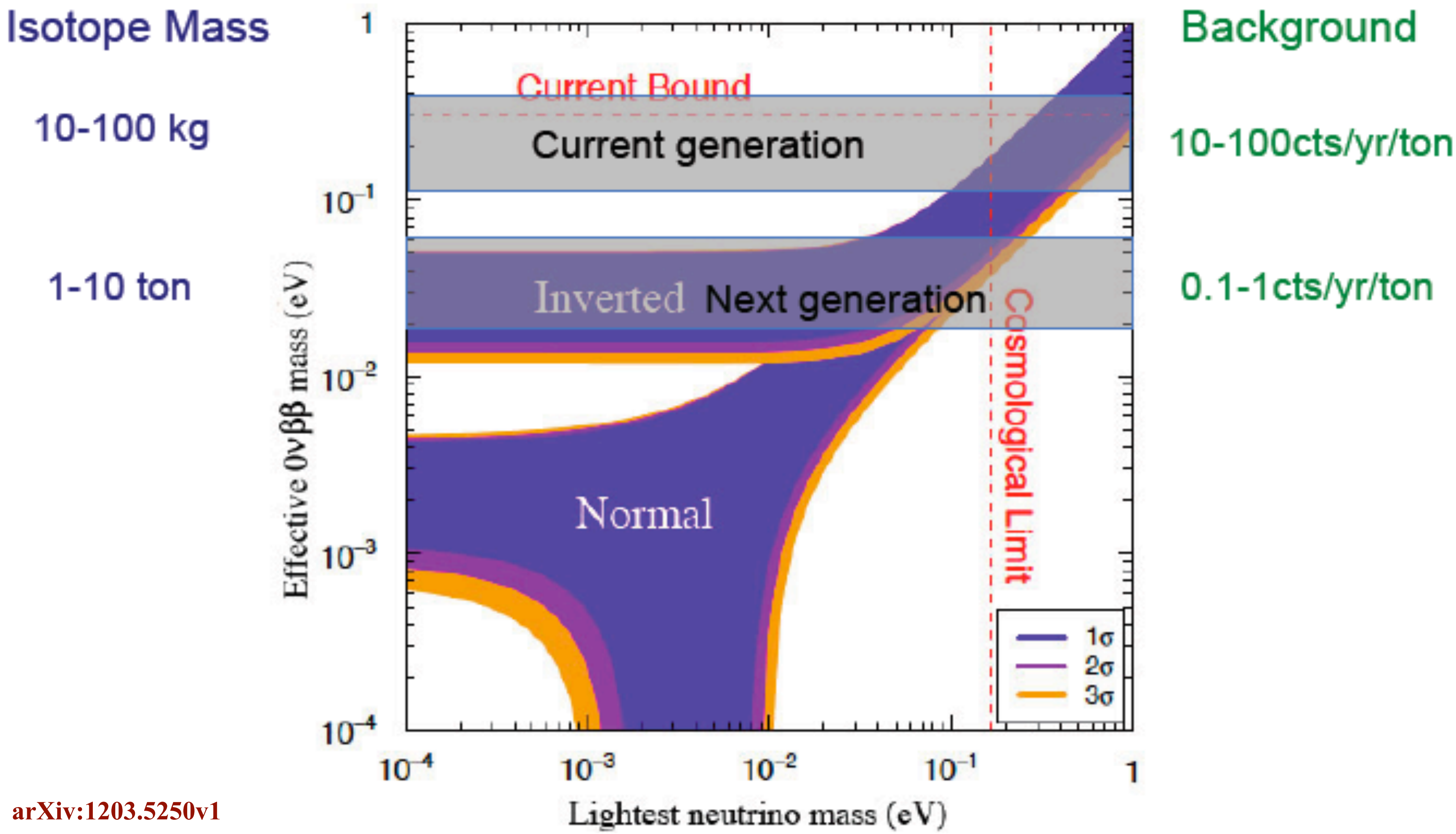
| Isotope | $0\nu\beta\beta$ half life | Experiment | <m> eV |
|---|---|---|---|
| $^{48}Ca$ | $> 1.4*10^{22}$ (90%CL) | ELEGANT-VI | < 7 - 44 |
| $^{76}Ge$ | $> 1.9*10^{25}$ (90%CL) | Heidelberg-Moscow | < 0.35 |
| $^{76}Ge$ | $2230^{+440}_{-310}$ (90%CL) | Subset of HM coll. | 0.32 +/- 0.03 |
| $^{76}Ge$ | $> 2.1*10^{25}$ (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!

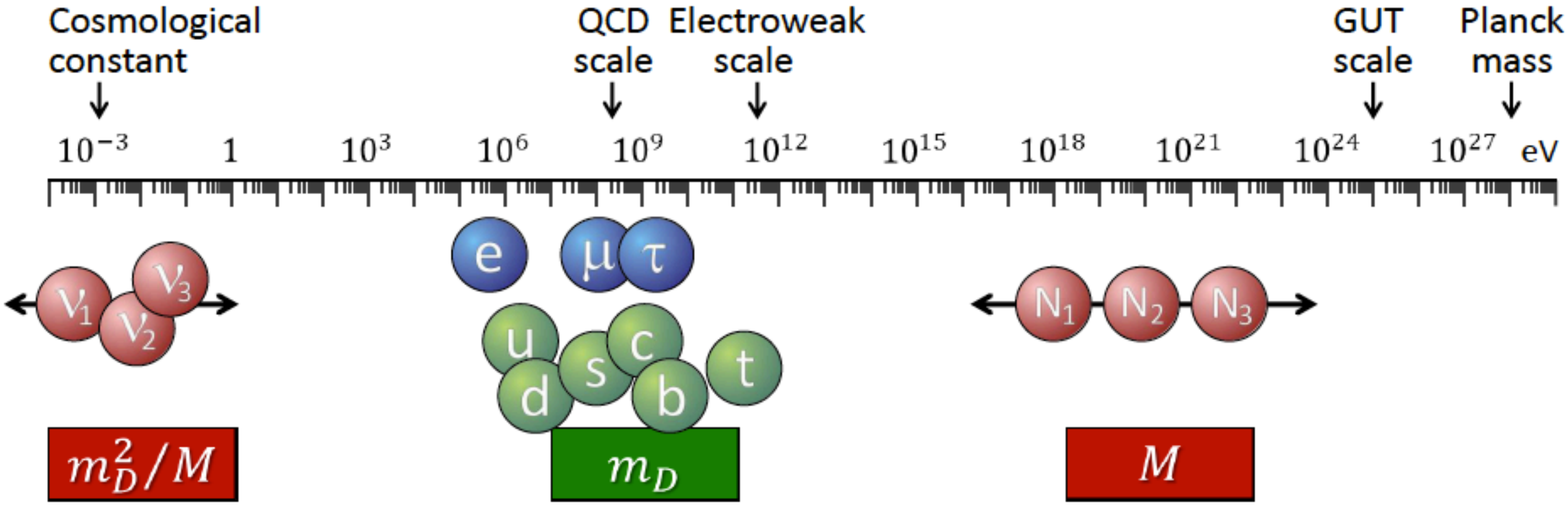
# Experimental Sensitivity to Neutrino Mass




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

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

Diagonalization

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

One light and one heavy Majorana neutrino

**Courtesy to George Raffelt**