Neutrino Mass Hierarchy and CP-violation: How to get them?

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A Personal View of Sheldon Lee Glashow

Is observable CP violation confined to hadrons?

I would assign very high priority to experiments that could demonstrate the existence of CP violating effects in the neutrino sector

The other important mass-related issue is the binary choice between two orderings of neutrino masses

The accuracy with which oscillation parameters are already known surely suffices for the design of an experiment that can accomplish this goal

Particle Physics in the United States
A Personal View
Sheldon Lee Glashow
arXiv:1305.5482v1 [hep-ph]

!! Let us work together and resolve these fundamental issues !!

Neutrino Oscillations in 3 Flavors

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

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

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

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

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

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

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

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

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

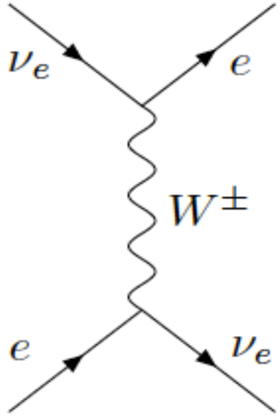
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin^2\Delta_{ij} - 2\sum_{i>j} \mathrm{Im}[U^*_{\alpha i} U_{\alpha j} U_{\beta i} U^*_{\beta j}] \sin 2\Delta_{ij}$$

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

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

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

Neutrino Oscillations in Matter



Neutrino propagation through matter modify the oscillations significantly

Coherent forward elastic scattering of neutrinos with matter particles

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

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

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

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

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

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

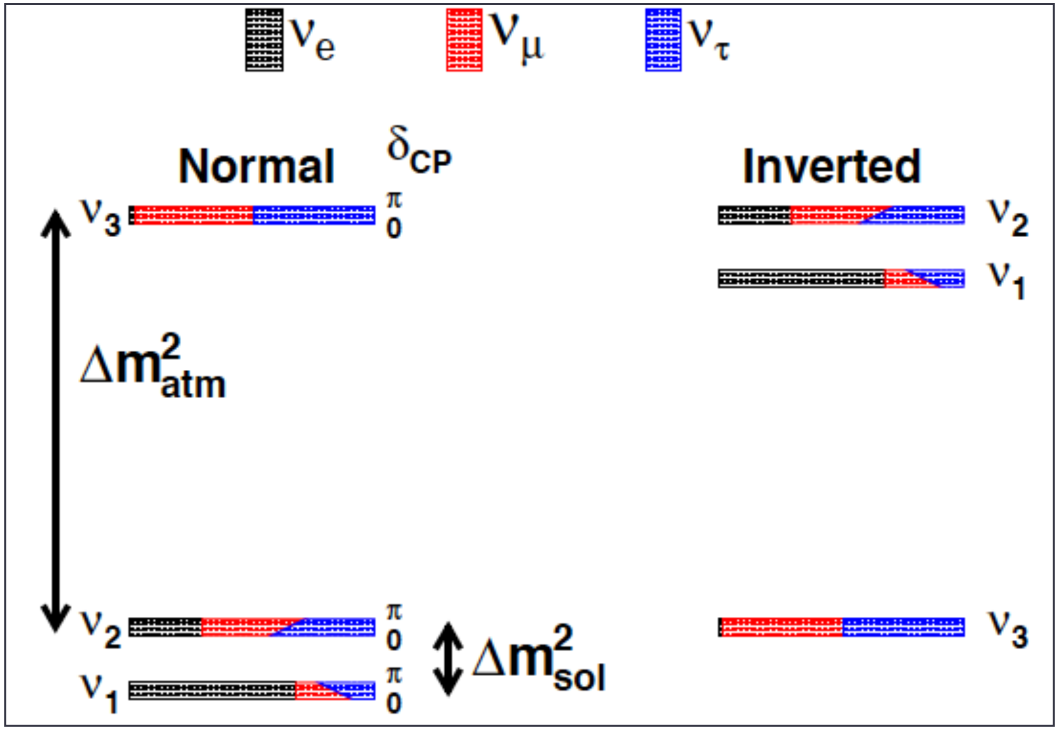
$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$ → ***Resonant conversion – Matter effect***

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

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

Neutrino Mass Hierarchy: Important Open Question

- The sign of Δm^2_{31} $(m_3^2 - m_1^2)$ is not known



$$\boxed{|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2}$$

ν_e component of ν_1 > ν_e component of ν_2 > ν_e component of ν_3

Neutrino mass spectrum can be normal or inverted hierarchical

We only have a lower bound on the mass of the heaviest neutrino

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

We currently do not know which neutrino is the heaviest

Mass Hierarchy Discrimination : A Binary yes-or-no type question

Leptonic CP-violation: Important Open Question

Is CP violated in the neutrino 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:

$$\Delta P_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta;\, L) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta;\, L) \quad (\alpha \neq \beta)$$

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

Accelerator long-baseline neutrino experiments

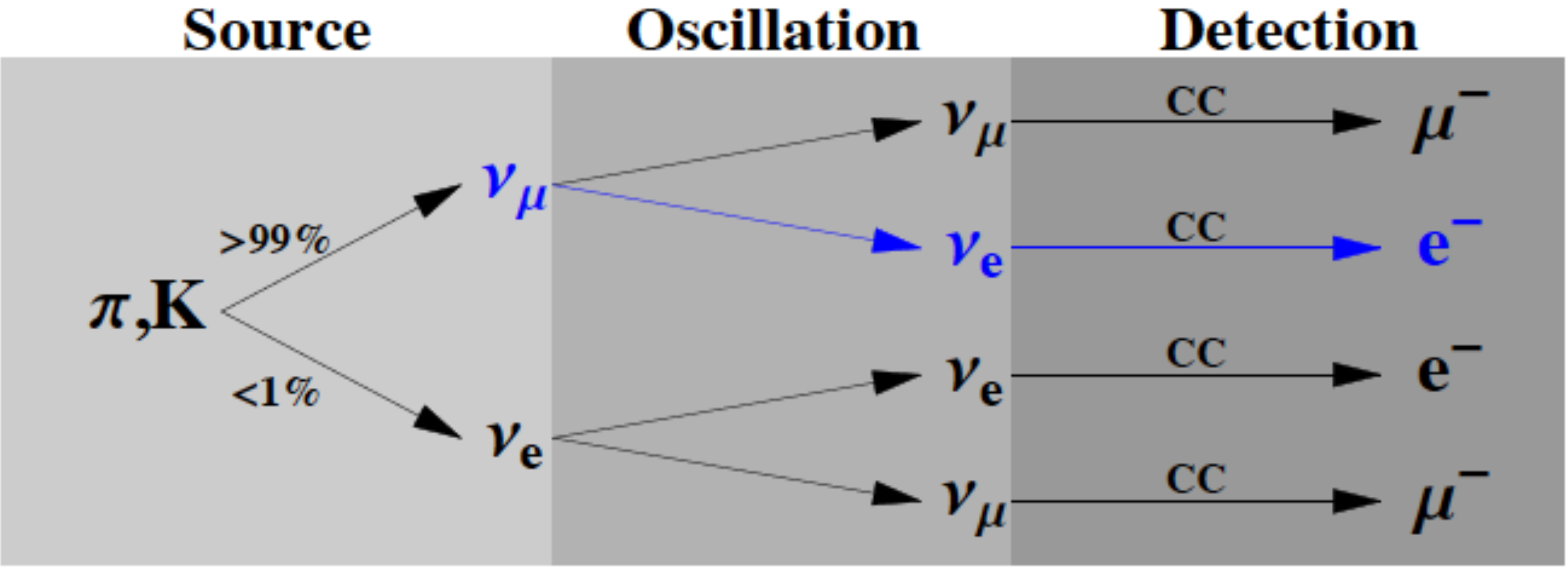
($\nu_\mu \rightarrow \nu_e$) and (anti-$\nu_\mu \rightarrow$ anti-ν_e)

T2K (Japan) & NOνA (USA) [running, off-axis]

DUNE (USA) [future, on-axis]

Hyper-Kamiokande (Japan) [future, off-axis]

Superbeams



Traditional approach: Neutrino beam from pion decay

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 $\underset{0.03}{\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}}$ and $\underset{0.3}{\sin 2\theta_{13}}$,

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

Resolves octant

where $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$,

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

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

changes sign with polarity
causes fake CP asymmetry!

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

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

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

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) =$$

← Our measurement

$$\frac{16A}{\Delta m_{31}^2} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$

← Matter Effects, small

$$- \frac{2AL}{E} \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$

← Matter Effects, ∞ L

$$- 8 \frac{\Delta m_{21}^2 L}{2E} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\delta \, s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}$$

← CPV, Our goal!

Here, $A = 2\sqrt{2} G_F n_e E = 7.6 \times 10^{-5} \mathrm{eV}^2 \cdot \frac{\rho}{\mathrm{g\,cm^{-3}}} \cdot \frac{E}{\mathrm{GeV}}$

How to proceed?

First possibility:

Choose small L (~ 200 km), so that matter effects are small

But, we want to work at oscillation maximum:

$$\frac{\Delta m_{31}^2 L}{4E} \sim \frac{\pi}{2} \quad \Rightarrow \quad E_\nu < 1 \text{ GeV}$$

Since, $\sigma \infty E_\nu$: we need a high flux at oscillation maximum

Off-axis beam: narrow range of neutrino energies

This is the working principle of Hyper-Kamiokande

How to proceed?

Second possibility:

Take large L (> 1000 km)

Estimate the matter effects, and settle the issue of Mass Hierarchy

But, we still want to work at oscillation maximum:

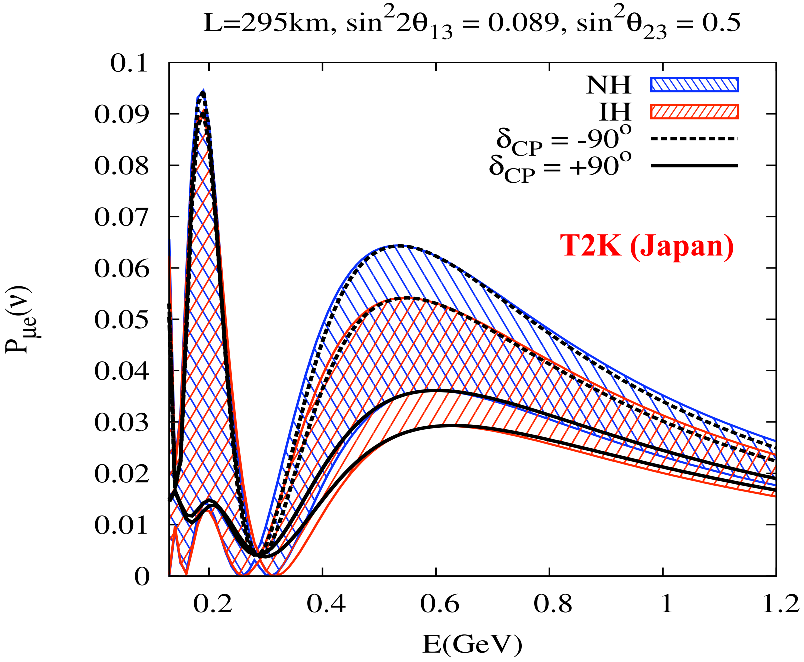
$$\frac{\Delta m^2_{31} L}{4E} \sim \frac{\pi}{2} \quad \rightarrow \quad E_\nu > 2\ \text{GeV}$$

Unfold CP-violation from matter effects through energy dependence

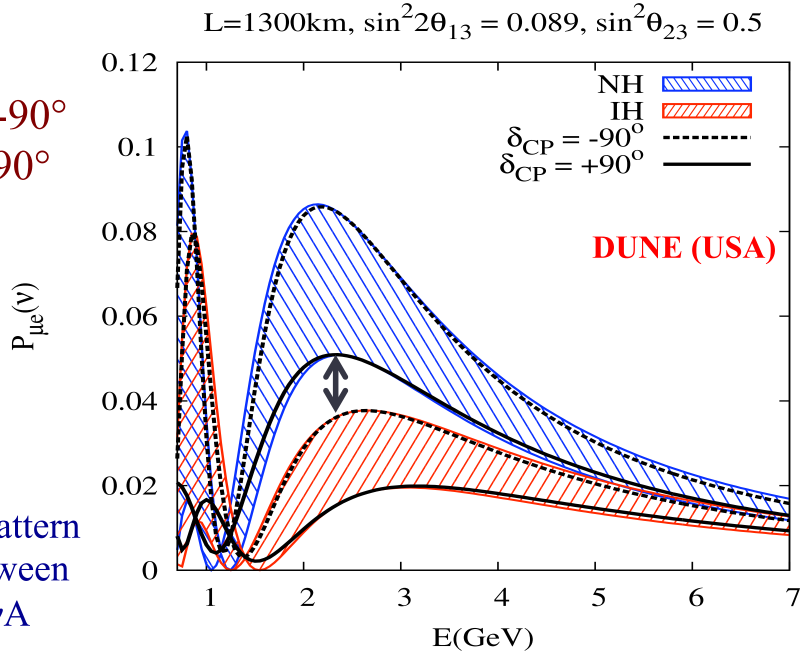
On-axis beam: wide range of neutrino energies

This is the working principle of DUNE

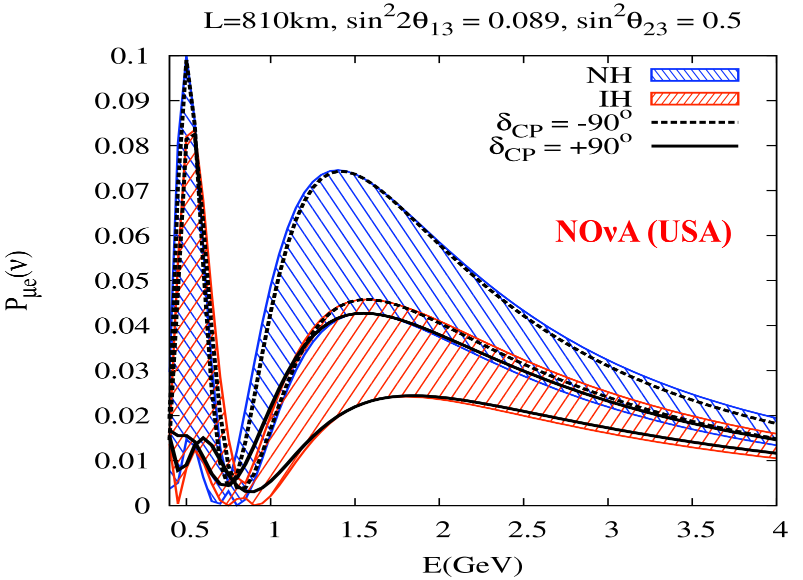
Hierarchy – δ_{CP} degeneracy in $\nu_\mu \rightarrow \nu_e$ oscillation channel



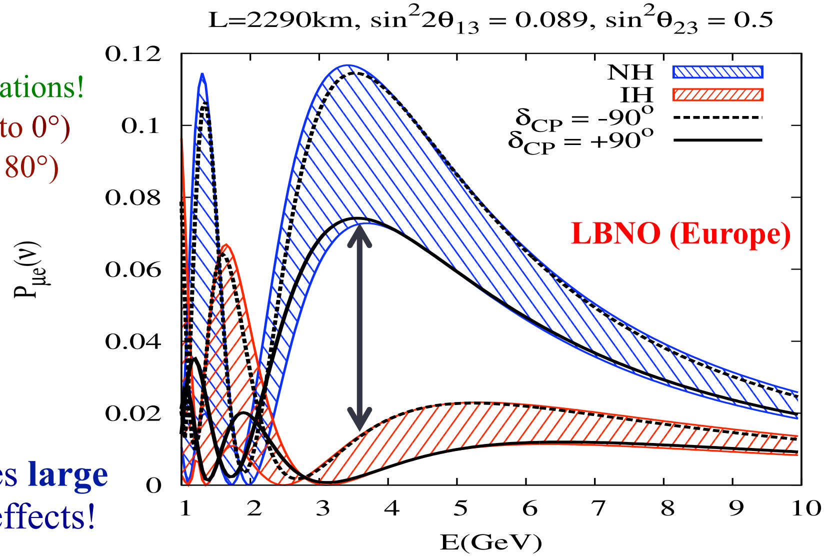
For ν:
Max: NH, -90°
Min: IH, 90°



Degeneracy pattern
different between
T2K & NOνA



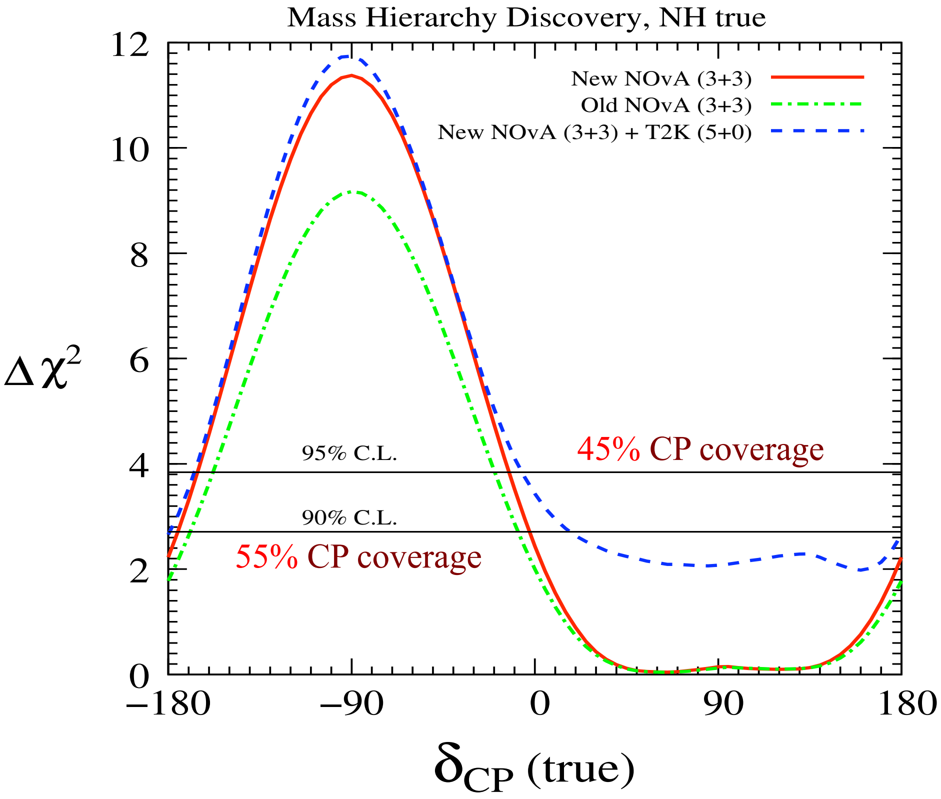
Favorable combinations!
NH, LHP (-180° to 0°)
IH, UHP (0° to 180°)

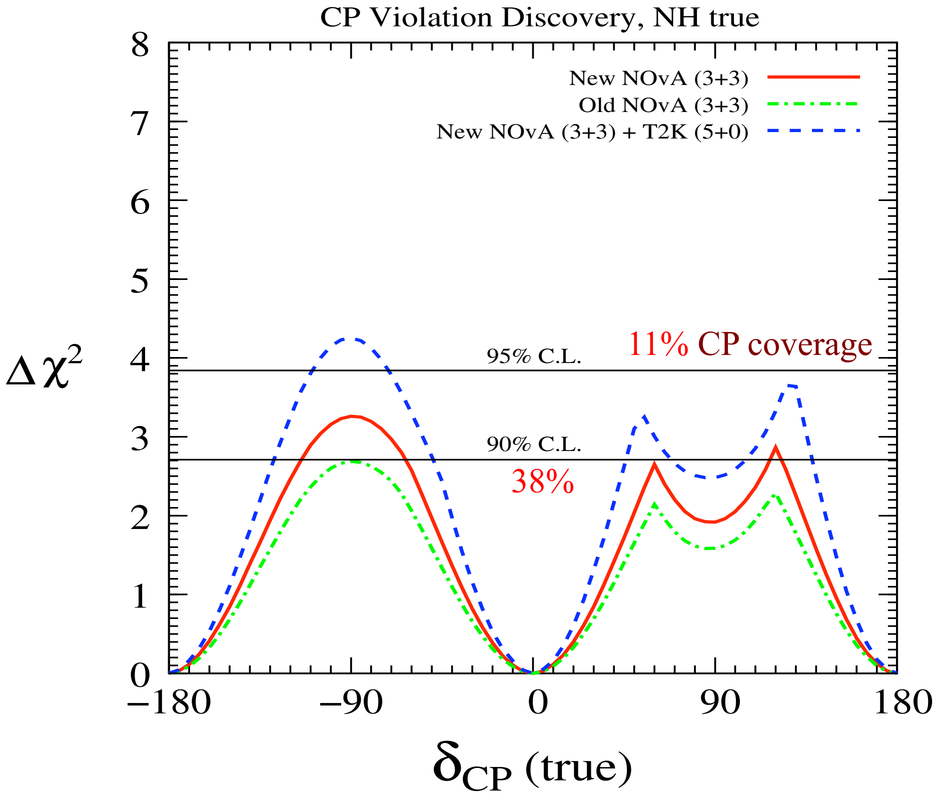


Large θ_{13} causes **large**
Earth matter effects!

Agarwalla, Prakash, Raut, Sankar, 2012-2013

Mass Hierarchy & CP-Violation Discovery with T2K and NOνA



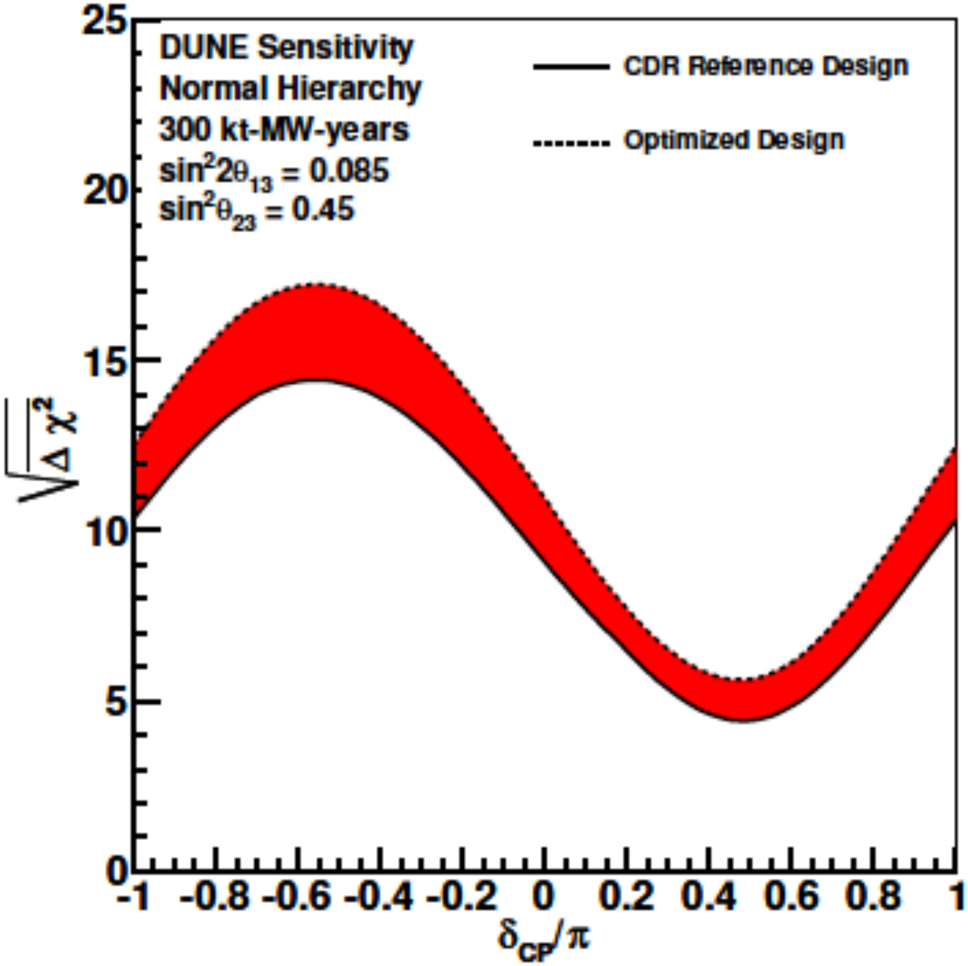


Agarwalla, Prakash, Raut, Sankar, arXiv: 1208.3644
See also, Huber, Lindner, Schwetz, Winter, arXiv: 0907.1896;
Machado, Minakata, Nunokawa, Funchal, arXiv: 1307.3248;
Ghosh, Ghosal, Goswami, Raut, arXiv: 1401.7243

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

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

Mass Hierarchy Discovery Potential at DUNE



$$\Delta\chi^2_{MH} \;=\; \chi^2_{IH} - \chi^2_{NH} \; \text{(true normal hierarchy)}$$

Exposure needed to have MH discovery at 5σ for 100% values of the CP phase

CDR reference beam design:

→ 400 kt • MW • year

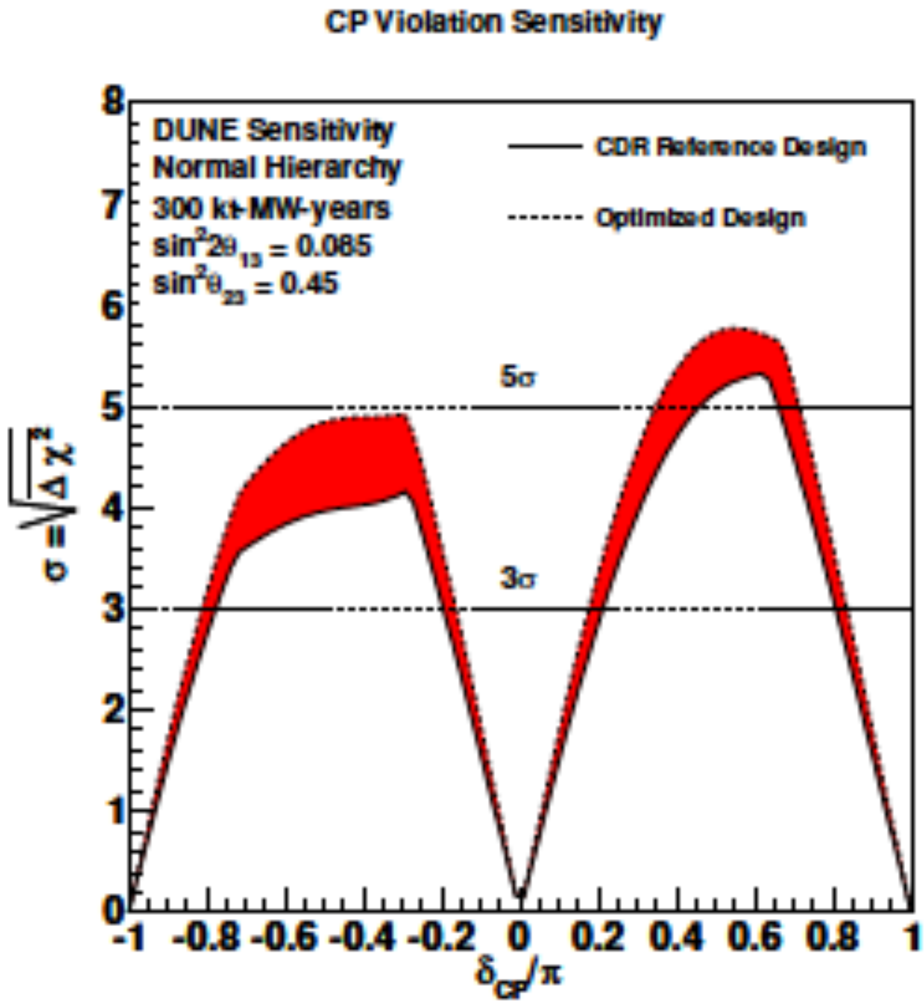
Optimized beam design:

→ 230 kt • MW • year

Talk by B. Choudhary and M.V. Diwan

DUNE CDR Physics Overview, arXiv:1512.06148 [physics.ins-det]

CP-Violation Discovery Potential at DUNE



Exposure needed to have CP-violation

Significance	CDR Reference Design
3σ for 75% of $\delta_{\rm CP}$ values	1320 kt · MW · year
5σ for 50% of $\delta_{\rm CP}$ values	810 kt · MW · year

$$\Delta\chi^2_{CPV} = Min[\Delta\chi^2_{CP}(\delta^{test}_{\rm CP}=0), \Delta\chi^2_{CP}(\delta^{test}_{\rm CP}=\pi)], \text{ where}$$

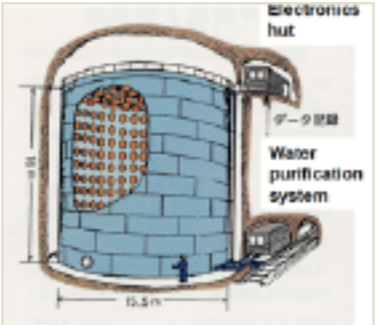
$$\Delta\chi^2_{CP} = \chi^2_{\delta^{test}_{\rm CP}} - \chi^2_{\delta^{true}_{\rm CP}}.$$

DUNE CDR Physics Overview, arXiv:1512.06148 [physics.ins-det]

Hyper-Kamiokande

Hyper-Kamiokande is the proposed 3rd generation large water Cherenkov detector in the Kamioka mine

Kamiokande
(1983-1996)

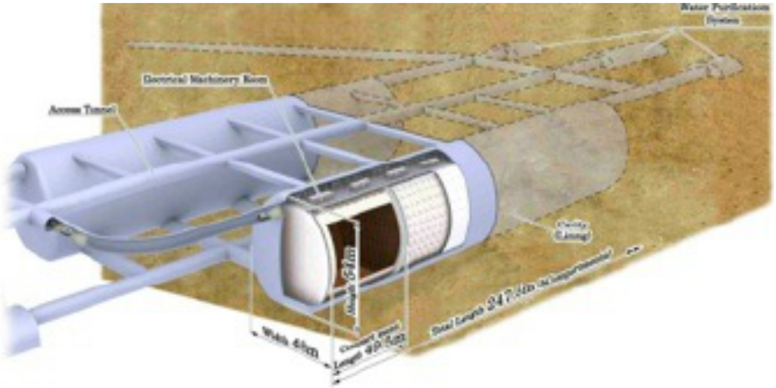


3 kton

Super-Kamiokande
(1996-)

50 kton

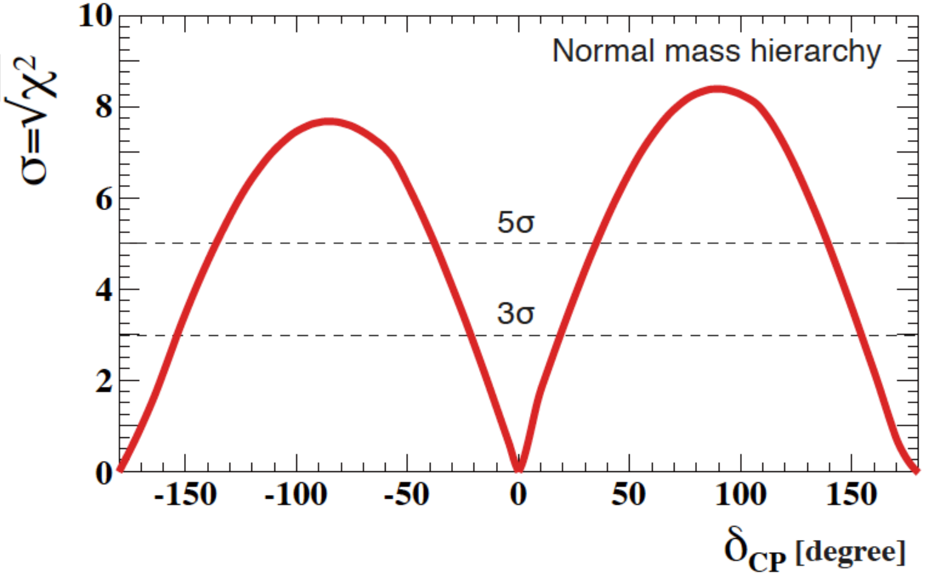
Hyper-Kamiokande
(202?-)

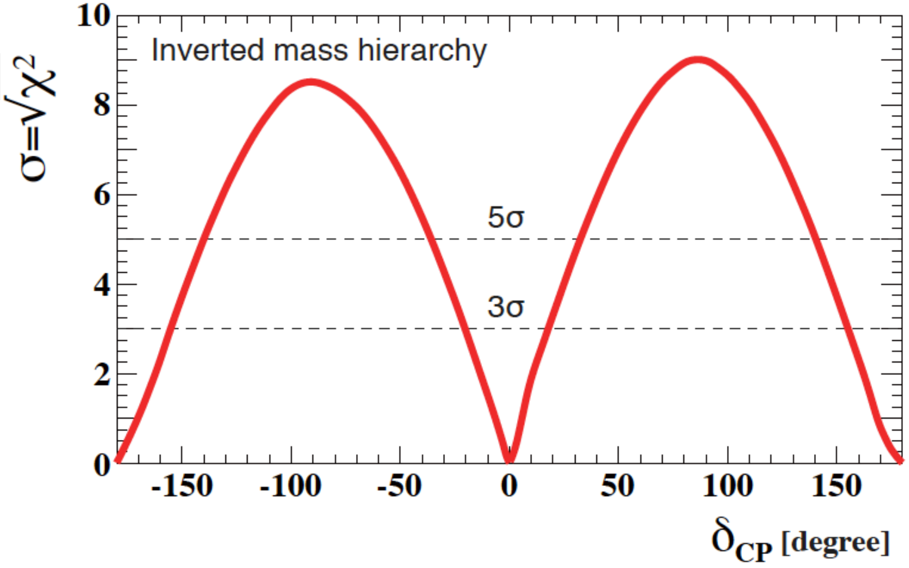


1 Mton

- **Inner detector volume: 0.74 Mton**
- **Fiducial volume: 0.56 Mton**
- **Photomultiplier tubes: 99,000 20” inner detector and 25,000 8” outer detector**

CP-Violation Discovery Potential at Hyper-K





- **Hyper-K is off-axis, narrow-band beam, 295 km baseline**
- **10 years @ 750 kW or 5 years at 1.5 MW**
- **Assume Mass Hierarchy is already known**
- **Beam sharing: neutrinos:anti-neutrinos = 1:3**
- **CPV coverage: 76% at 3σ or 58% at 5σ**

Hyper-K Overview, arXiv:1412.4673v2 [physics.ins-det]

Other Sources for Mass Hierarchy Measurements

- **Atmospheric neutrino experiments**

  1) Water based: Super-K [running], Hyper-K, PINGU, ORCA [proposed]
  2) Liquid Argon based: DUNE [proposed]
  3) Iron Calorimeter: ICAL at INO [proposed]

- **Reactor medium-baseline anti-neutrino experiments**

  JUNO, RENO-50 [proposed]

- **Dark horse (Cosmology)**

  CMB, & its B-mode, LSS (Projects: MS-DESI, Euclid, LSST, Stage-IV CMB)

- **From β-decay endpoint & from the study of 0νββ**

- **From Supernova (Rise Time Analysis)**

Atmospheric neutrino experiments (wide range of E & L for free)

(Super-K, Hyper-K, PINGU, ORCA, DUNE)

Category 1:

$$(\nu_\mu \rightarrow \nu_\mu) + (\nu_e \rightarrow \nu_\mu) = \text{observable } \mu^-$$

$$+$$

$$(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_\mu) + (\text{anti-}\nu_e \rightarrow \text{anti-}\nu_\mu) = \text{observable } \mu^+$$

Category 2:

$$(\nu_e \rightarrow \nu_e) + (\nu_\mu \rightarrow \nu_e) = \text{observable } e^-$$

$$+$$

$$(\text{anti-}\nu_e \rightarrow \text{anti-}\nu_e) + (\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e) = \text{observable } e^+$$

No Charge-Identification: therefore $(\mu^- + \mu^+)$ and $(e^- + e^+)$

But, on top of μ^-/μ^+, e^-/e^+ can also be detected (extra source of MSW effect)

Atmospheric neutrino experiments (wide range of E & L for free)

(Magnetized Iron Calorimeter @ India-based Neutrino Observatory)

Category 1:

$$(\nu_\mu \rightarrow \nu_\mu) + (\nu_e \rightarrow \nu_\mu) = \text{observable } \mu^-$$

Category 2:

$$(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_\mu) + (\text{anti-}\nu_e \rightarrow \text{anti-}\nu_\mu) = \text{observable } \mu^+$$

Excellent Charge-Identification: μ^- and μ^+ are separately detected

Electron detection not possible with present design

Oscillation Probabilities with One Mass Scale Dominance

take $\Delta m^2_{21} = 0$

$A = 2\sqrt{2} G_F N_e E_\nu$

$$\boxed{\begin{aligned} P^{approx}_{\mu\mu} = 1 &- \sin^2\theta^M_{13}\sin^2 2\theta_{23}\sin^2\frac{[(\Delta m^2_{31}+A)-(\Delta m^2_{31})^M]L}{8E_\nu} \\ &- \cos^2\theta^M_{13}\sin^2 2\theta_{23}\sin^2\frac{[(\Delta m^2_{31}+A)+(\Delta m^2_{31})^M]L}{8E_\nu} \\ &- \sin^2 2\theta^M_{13}\sin^4\theta_{23}\sin^2\frac{(\Delta m^2_{31})^M L}{4E_\nu}, \end{aligned}}$$

$$\boxed{P^{approx}_{e\mu} = \sin^2 2\theta^M_{13}\sin^2\theta_{23}\sin^2\frac{(\Delta m^2_{31})^M L}{4E_\nu}}$$

where

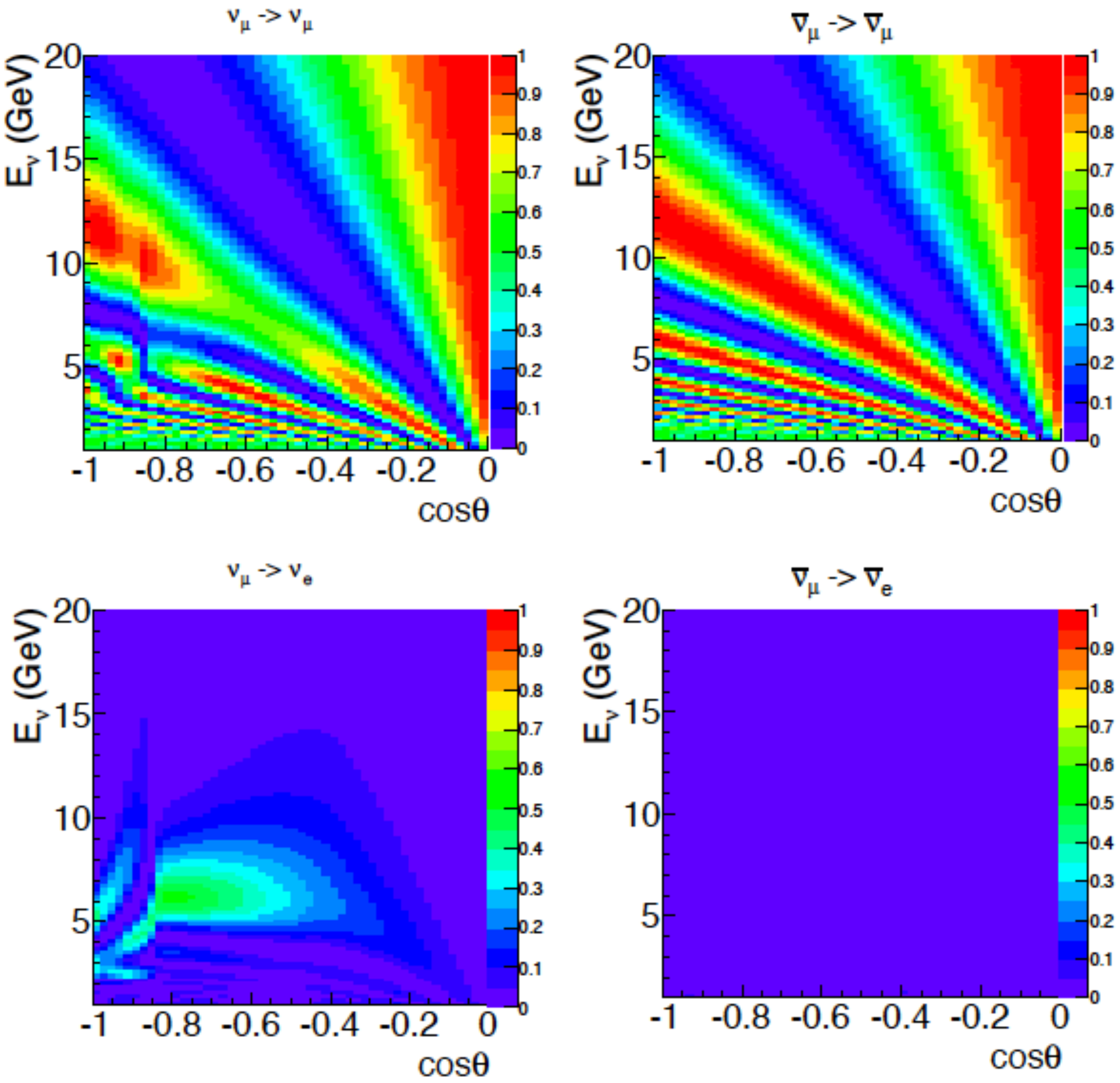
$$(\Delta m^2_{31})^M = \left((\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + \Delta m^2_{31}\sin^2 2\theta_{13}\right)^{1/2},$$

$$\sin^2 2\theta^M_{13} = \frac{\Delta m^2_{31}\sin^2 2\theta_{13}}{\left((\Delta m^2_{31}\cos 2\theta_{13} - A)^2 + \Delta m^2_{31}\sin^2 2\theta_{13}\right)}.$$

Choubey, Roy, hep-ph/0509197v2

- If θ_{13} would have been zero, there is no Earth matter effect
- No discrimination between NH and IH
- Recently discovered moderately large θ_{13} ➔ good news for MH

Neutrino Mass Hierarchy Signature



Neutrino Oscillograms

These plots are for NH

For IH, the neutrino & anti-neutrino patterns are exchanged

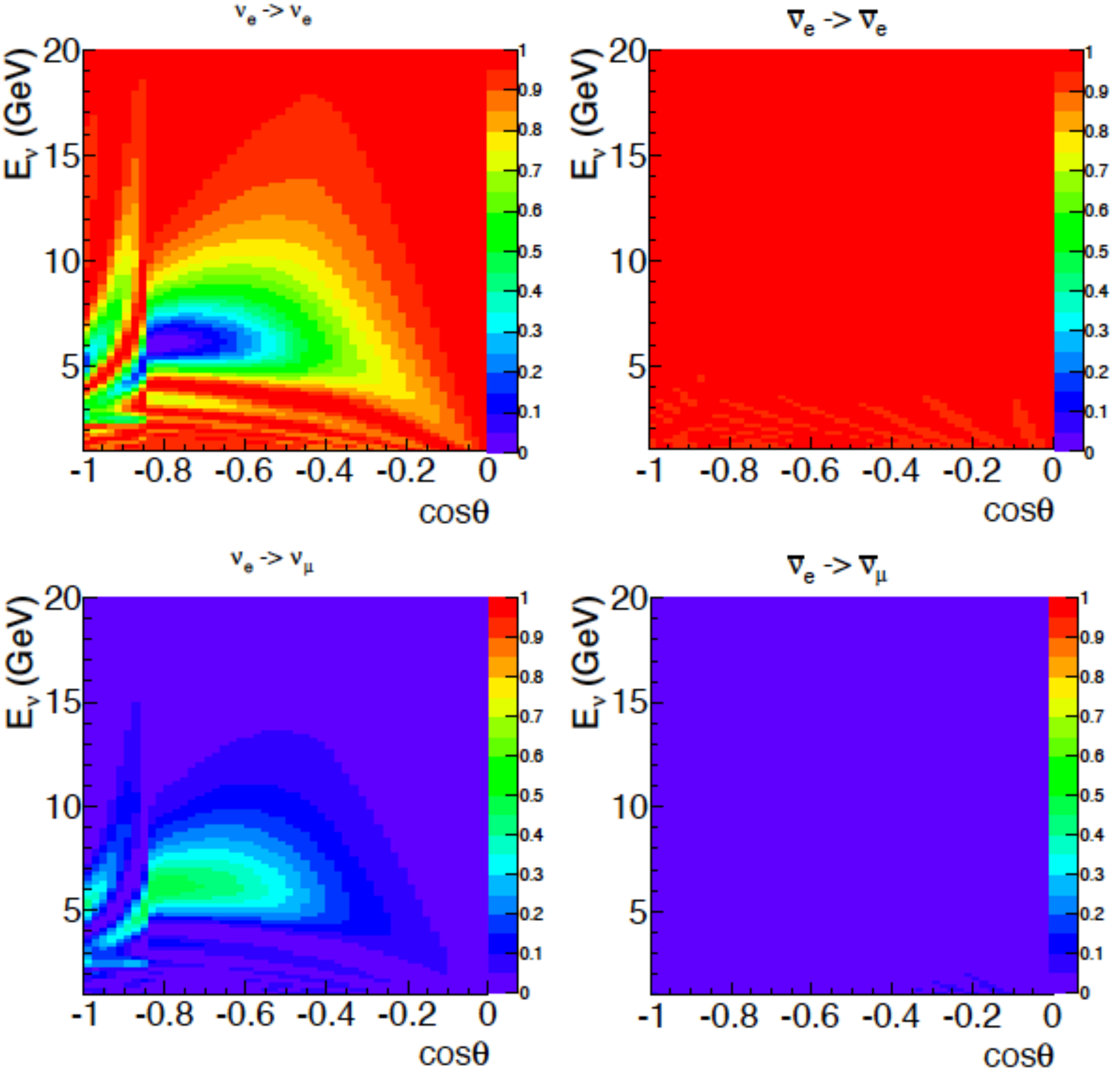
Crucial for MSW effect:

Energy:
2 GeV to 8 GeV

Baseline:
2000 km to 8000 km

Qian, Vogel,
arXiv:1505.01891v3 [hep-ex]

Neutrino Mass Hierarchy Signature



Neutrino Oscillograms

These plots are for NH

For IH, the neutrino & anti-neutrino patterns are exchanged

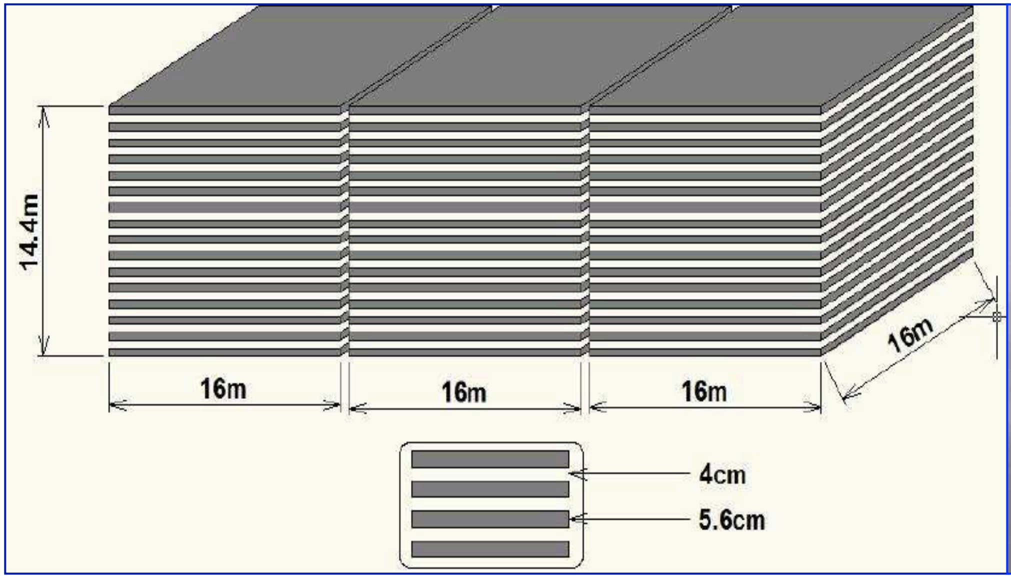
Qian, Vogel, arXiv:1505.01891v3 [hep-ex]

Detector Characteristics

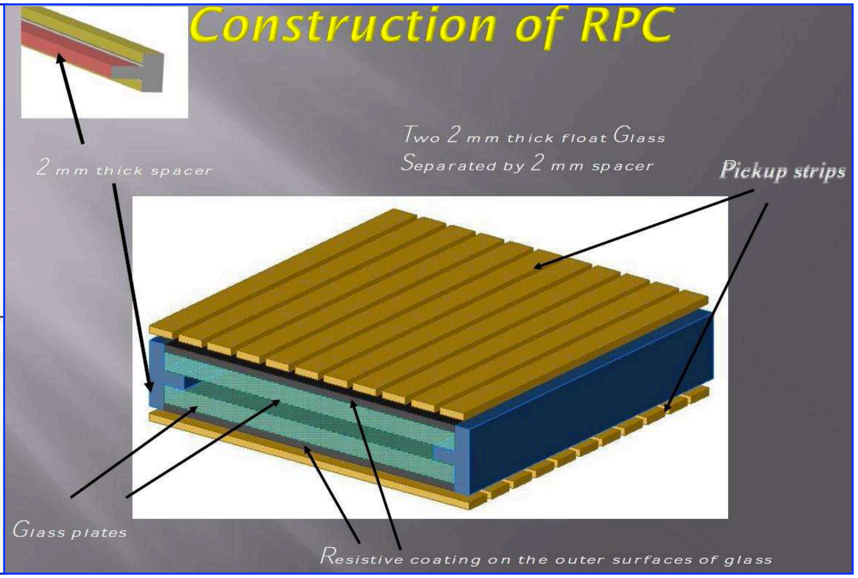
- *Should have large target mass (50 – 100 kt)*
- *Good tracking and Energy resolution (tracking calorimeter)*
- *Good directionality for up/down discrimination (nano-second time resolution)*
- *Charge identification (need to have uniform, homogeneous magnetic field)*
- *Ease of construction & Modularity*
- *Complementary to the other existing and proposed detectors*

Our choice

Magnetized iron (target mass): ICAL



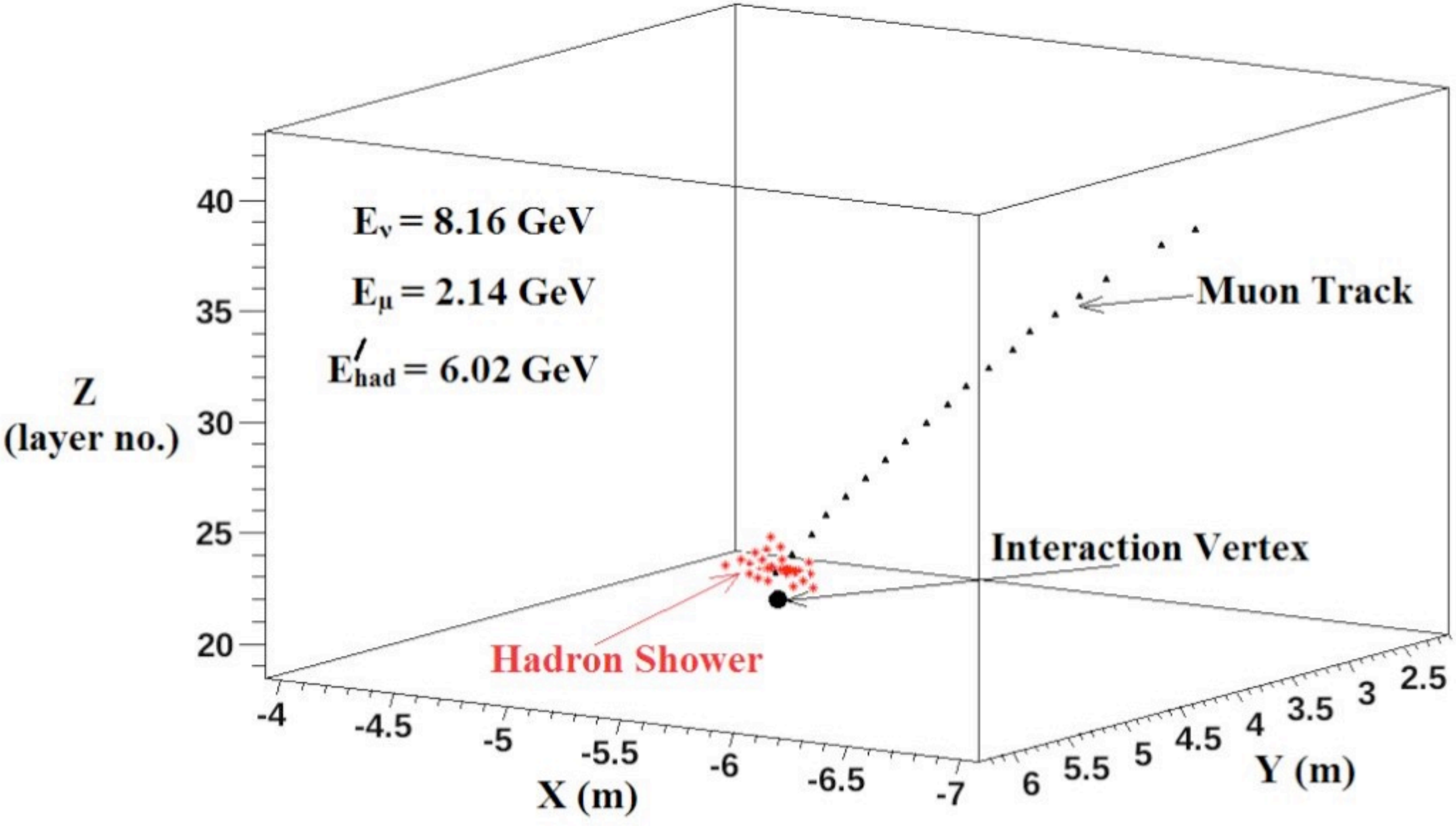
RPC (active detector element)



Specifications of the ICAL Detector

No of modules	*3*
Module dimension	*16 m X 16 m X 14.4m*
Detector dimension	*48.4 m X 16 m X 14.4m*
No of layers	*150*
Iron plate thickness	*5.6cm*
Gap for RPC trays	*4 cm*
Magnetic field	*1.4 Tesla*
RPC unit dimension	*195 cm x 184 cm x 2.4 cm*
Readout strip width	*3 cm*
No. of RPCs/Road/Layer	*8*
No. of Roads/Layer/Module	*8*
No. of RPC units/Layer	*192*
Total no of RPC units	*28800*
No of Electronic channels	3.7×10^6

Event Display Inside the ICAL Detector

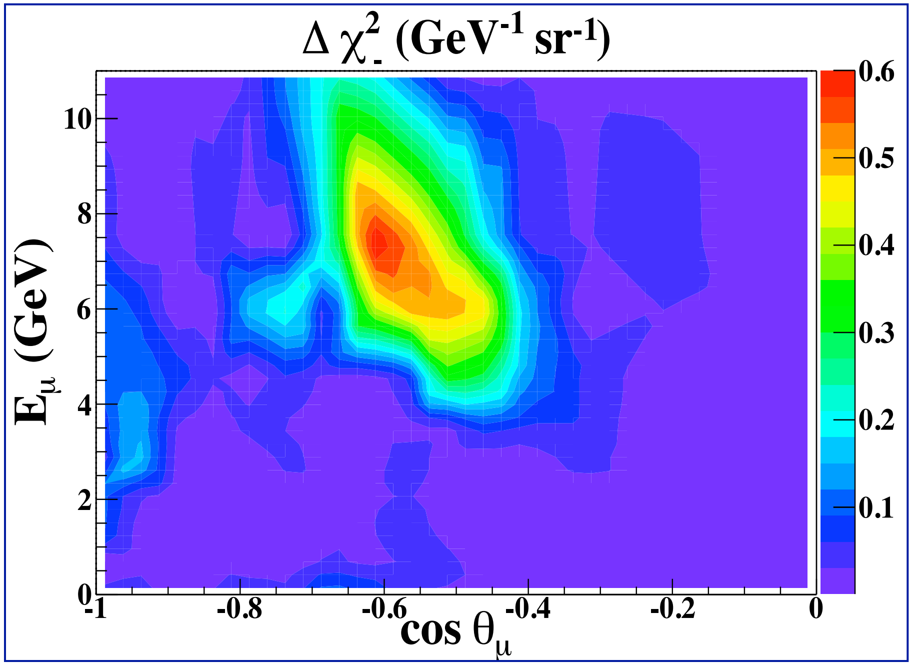


Using GEANT4 simulation

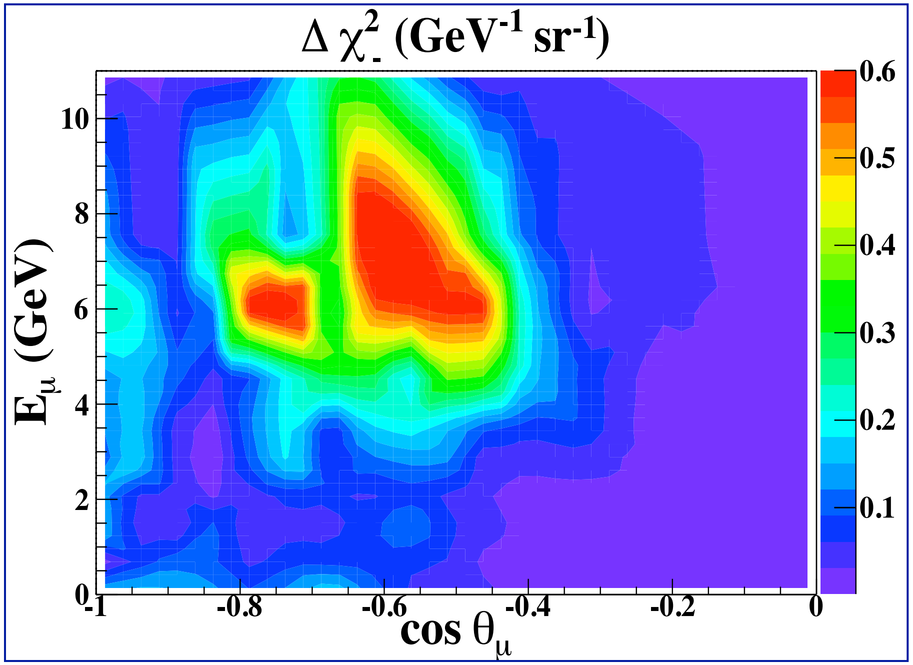
Devi, Thakore, Agarwalla, Dighe, arXiv:1406.3689 [hep-ph] (INO Collaboration)

Neutrino Mass Hierarchy Discrimination

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



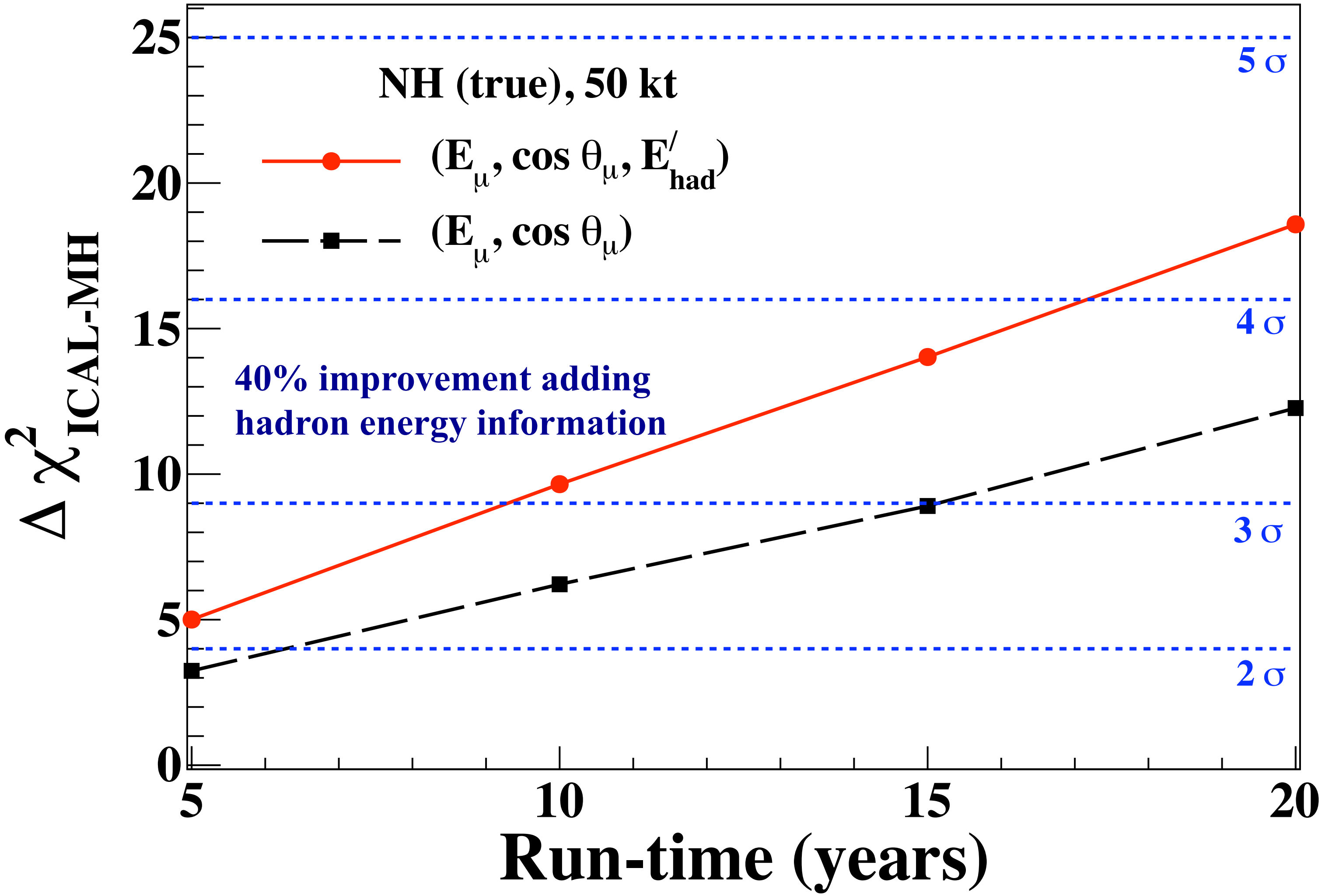
Hadron energy information not used



Hadron energy information used

- 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

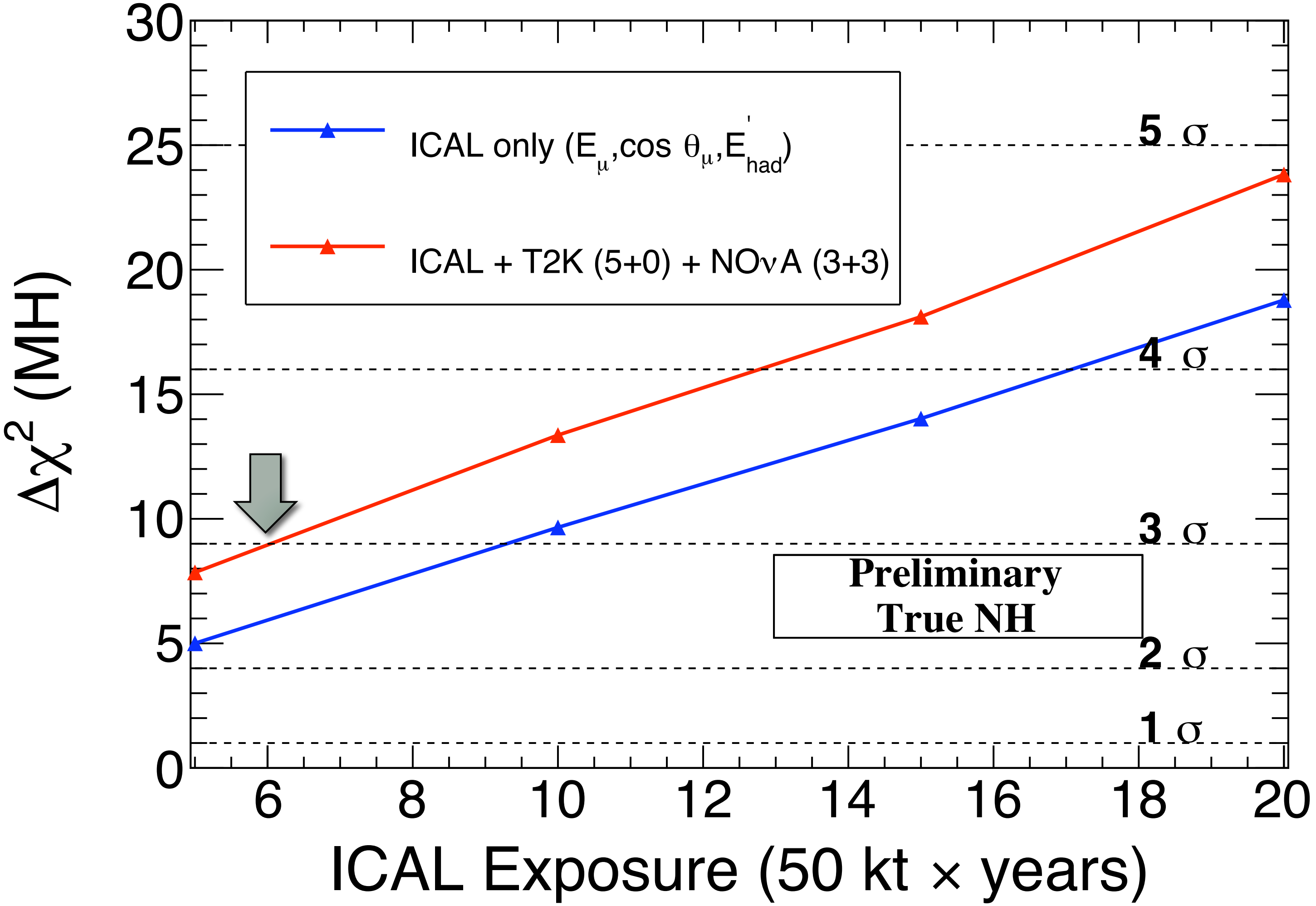


Median Sensitivity

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+NOνA



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

3σ median sensitivity can be achieved in 6 years

Reactor medium-baseline anti-neutrino experiments

anti-$\nu_e \rightarrow$ anti-ν_e

JUNO (China) & RENO-50 (Korea)

The Jiangmen Underground Neutrino Observatory (JUNO)

Located in Kaiping, Jiangmen, Guangdong Province, China, 53 km far from Yangiang and Taishan nuclear power plants

- **20 kiloton liquid scintillator detector**
- **Requires unprecedented 3% energy resolution at 1 MeV**
- **700-meter deep underground**

Project Status

JUNO has been approved

Geological survey completed in 2013

Contract of the engineering design, purchase, and construction was signed in April 2014

Land was delivered afterwards

Civil engineering design is nearly finished

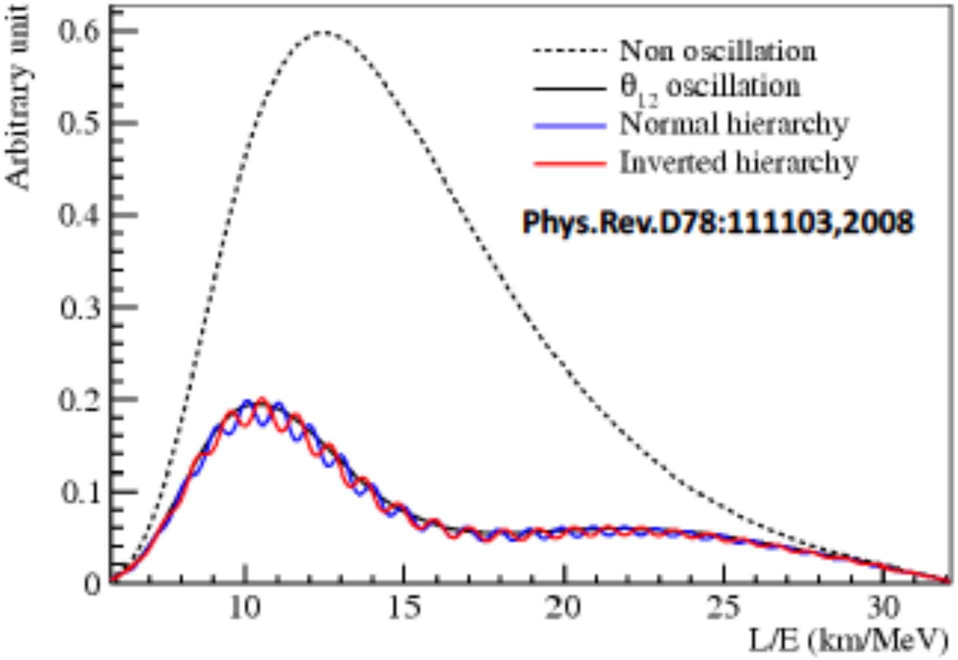
Groundbreaking ceremony at the experiment site in January 2015

JUNO Collaboration, Miao He, arXiv: 1412.4195v1

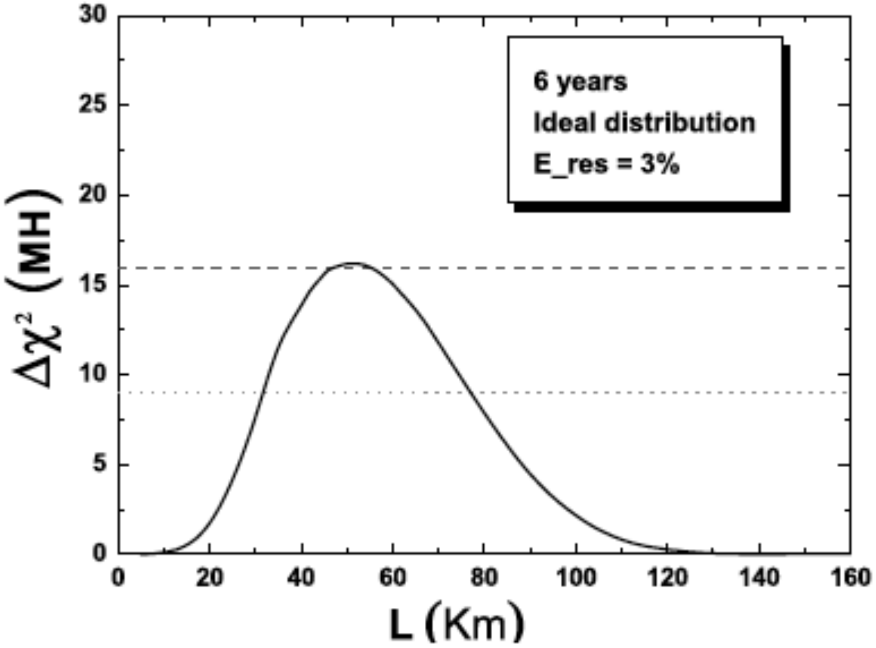
Interference effects in JUNO

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\ - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\ - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\ \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

Only the last term depends on the mass hierarchy.
Plus sign is for NH.
Minus sign is for IH

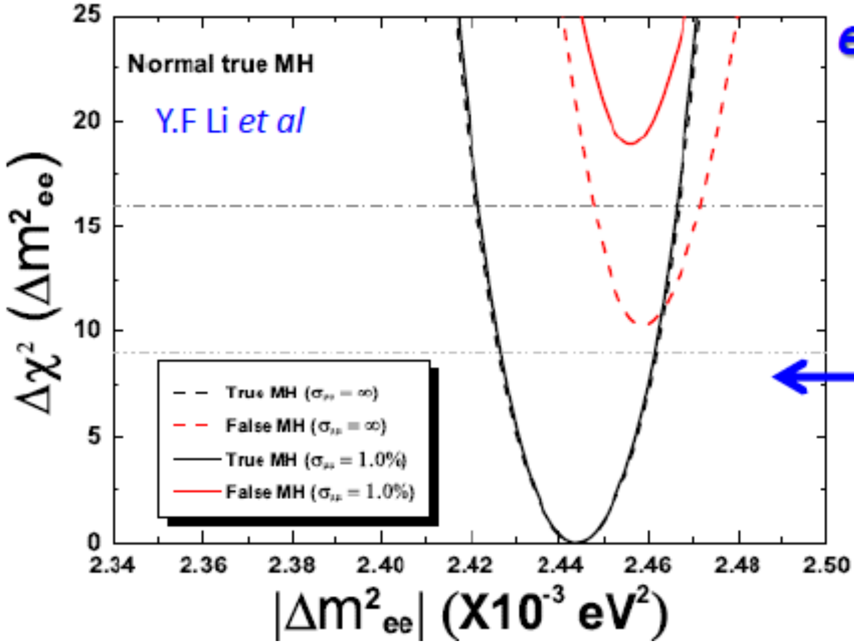


Phys.Rev.D78:111103,2008



Li, Cao, Wang, Zhan, arXiv: 1303.6733v2

Medium-baseline Reactor Oscillation Experiments

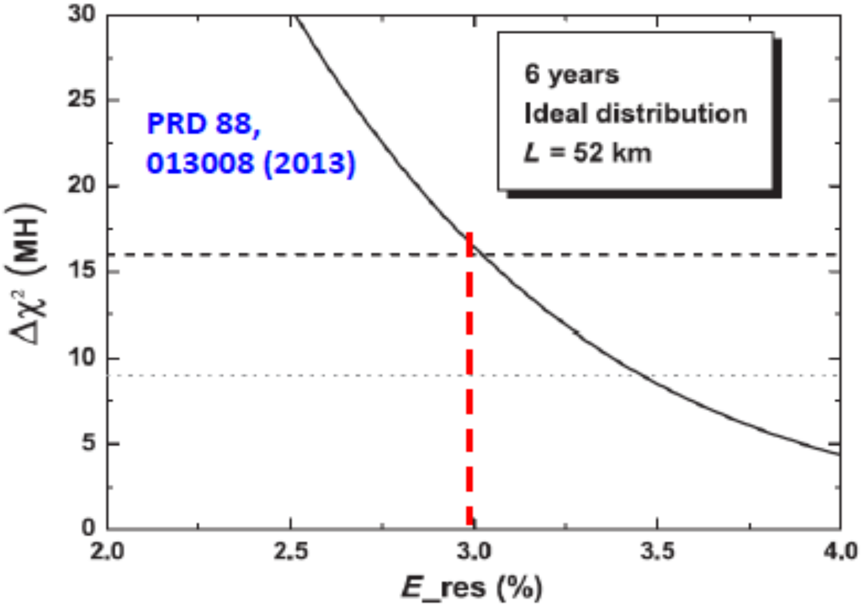


e.g JUNO **MH sensitivity with 6 years' data:**

Ref: Y.F Li et al, PRD 88, 013008 (2013)	**Relative Meas.**	**[(a)]Use absolute Δm^2**
Ideal case	**4σ**	**5σ**
[(b)]Realistic case	**3σ**	**4σ**

[(a)] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level

[(b)] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc



	Current	**e.g JUNO**
Δm^2_{12}	~3%	~0.5%
Δm^2_{23}	~4%	~0.6%
$\sin^2\theta_{12}$	~7%	~0.7%
$\sin^2\theta_{23}$	~15%	N/A
$\sin^2\theta_{13}$	~6%→ ~4%	~ 15%

Courtesy Liangjian Wen, talk at Neutrino 2014

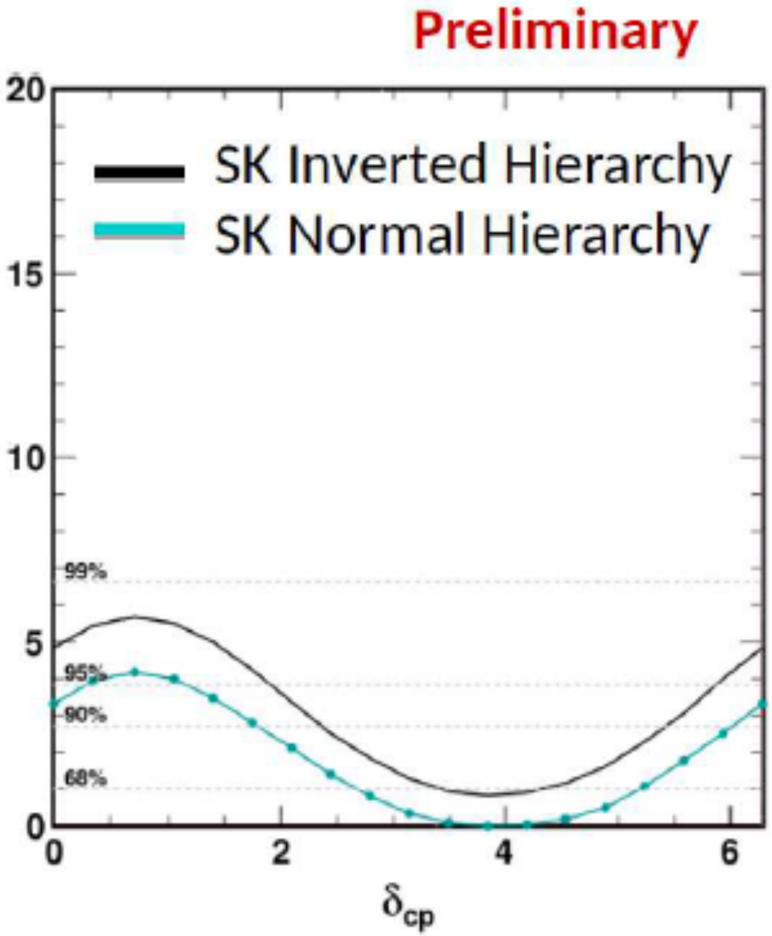
Concluding Remarks

- **Recent discovery of moderately large θ_{13} have established the 3-flavor paradigm**
- **Discovery of non-zero θ_{13} signifies an important breakthrough in deciding the future neutrino roadmap to unravel neutrino mass hierarchy and leptonic CP-violation**
- **Race for the MH discovery has received tremendous boost with large θ_{13}**
- **With non-zero θ_{13}, we can also explore leptonic CP-violation using appearance channel**
- **Long-baseline experiments such as DUNE can measure both MH and CPV in a single experiment using their energy dependence with sufficient amount of exposure**
- **Hyper-K can access CPV and measure CP phase free from the matter effect which is complementary to the strategy of the DUNE experiment**
- **ICAL@INO, PINGU, ORCA would provide a very rich dataset in the multi-GeV range & these data would be sensitive to the Earth's matter effect, key for MH**
- **Proposed JUNO experiment can also explore MH free from θ_{23}, δ_{CP}, and matter effect**

We have a rich, diverse, and well defined neutrino roadmap to explore MH and CPV

Thank you

Mass Hierarchy in Super-Kamiokande



θ_{13} fixed to PDG average, but its uncertainty is included as a systematic error

Normal hierarchy favored at:
$\chi^2_{IH} - \chi^2_{NH} = -0.9$

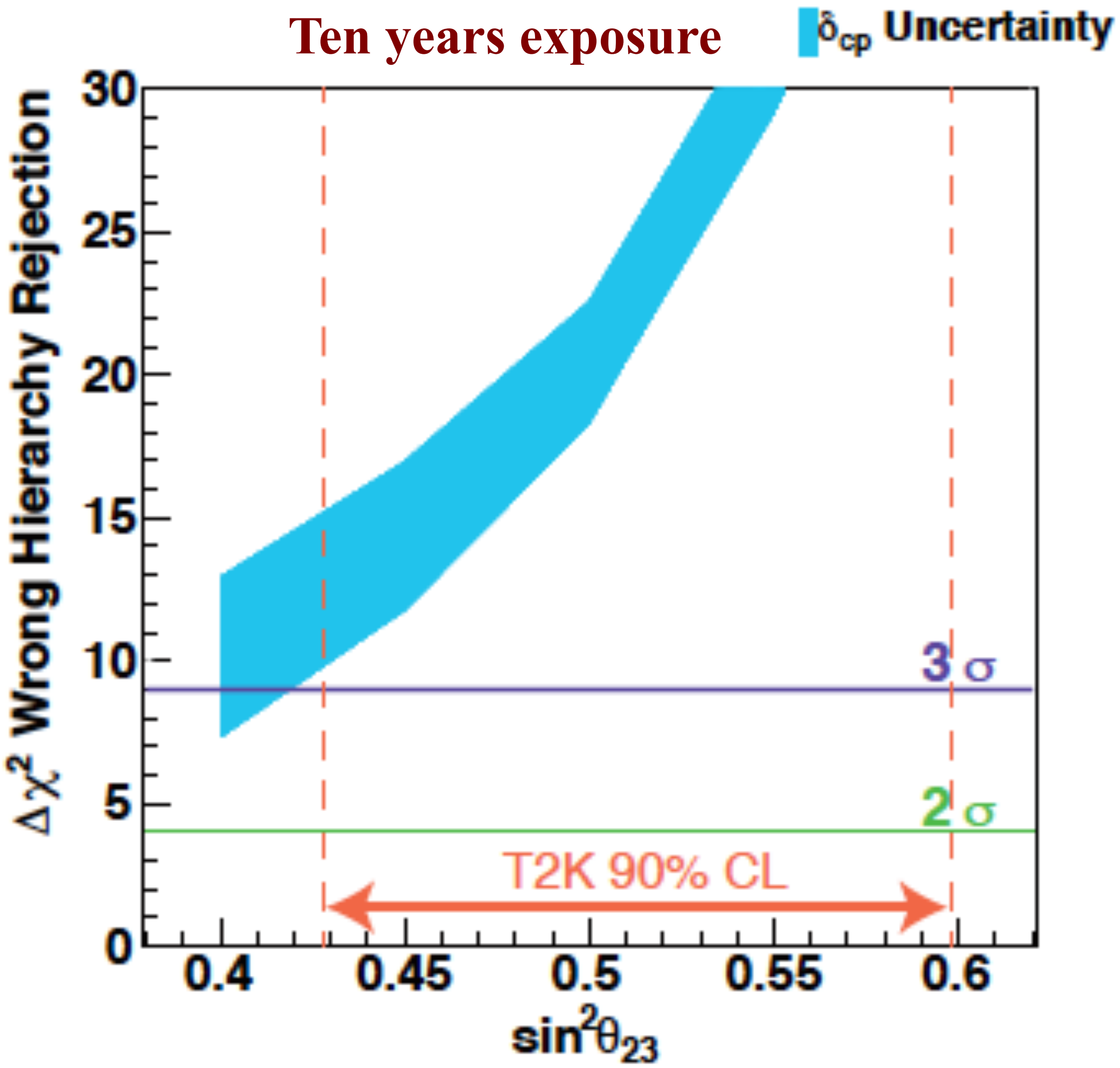
Still statistics limited,
expected reach by 2025 is 1.3σ

Roger Wendell, Talk at Neutrino 2014

Fit (517 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($\times 10^{-3}$)
SK (NH)	559.8	0.025	3.84	0.57	2.6
SK (IH)	560.7	0.025	3.84	0.57	2.5

MH in Hyper-Kamiokande with Atmospheric Neutrinos

Ten years exposure



arXiv: 1412.4673v2 [physics.ins-det]

Future Megaton-class Water Cherenkov Detectors

Good Particle-Id helps to discriminate between muons and electrons

Low threshold in energy helps of probe sub-GeV event samples

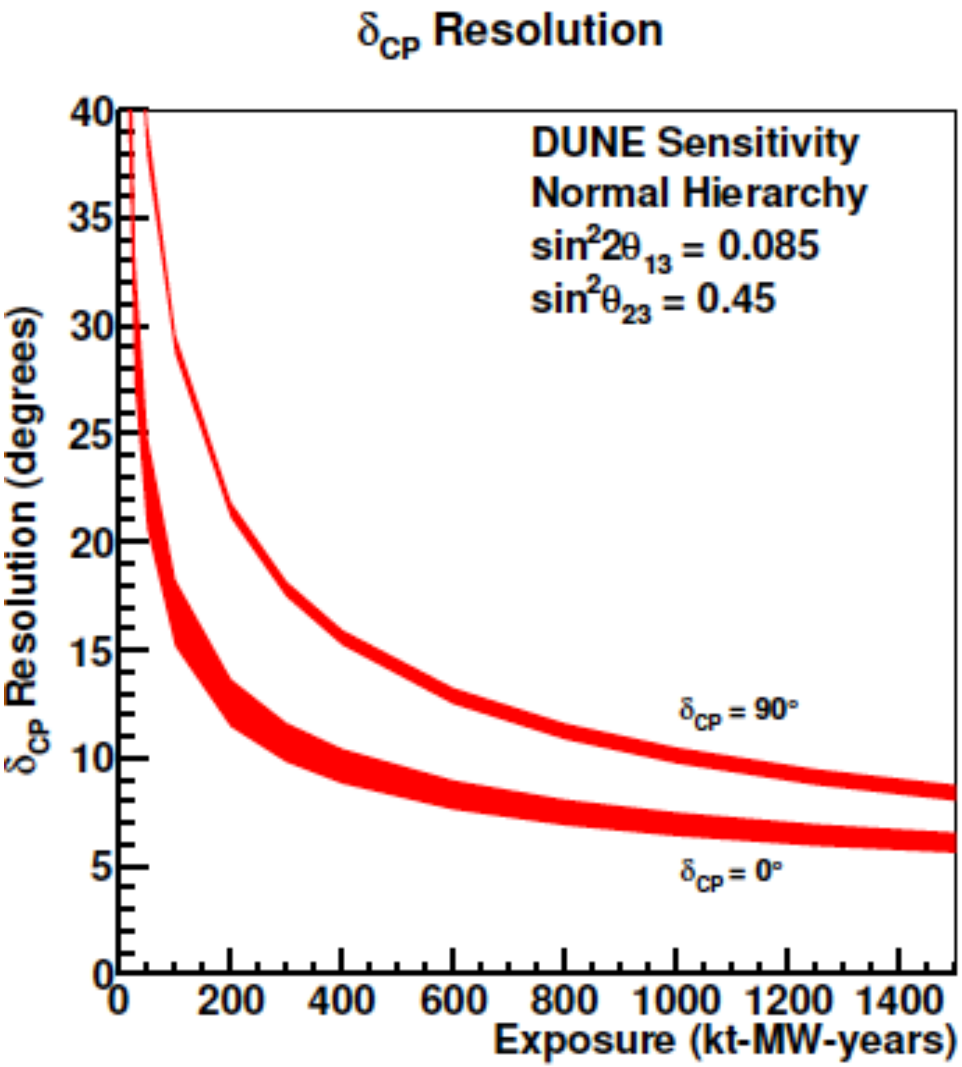
Good angular resolution

Huge Statistics

Statistical separation of ν_e from anti-ν_e in single ring event sample

~ 4.4σ discovery of MH expected in 10 years for maximal mixing

Measurement of CP phase at DUNE



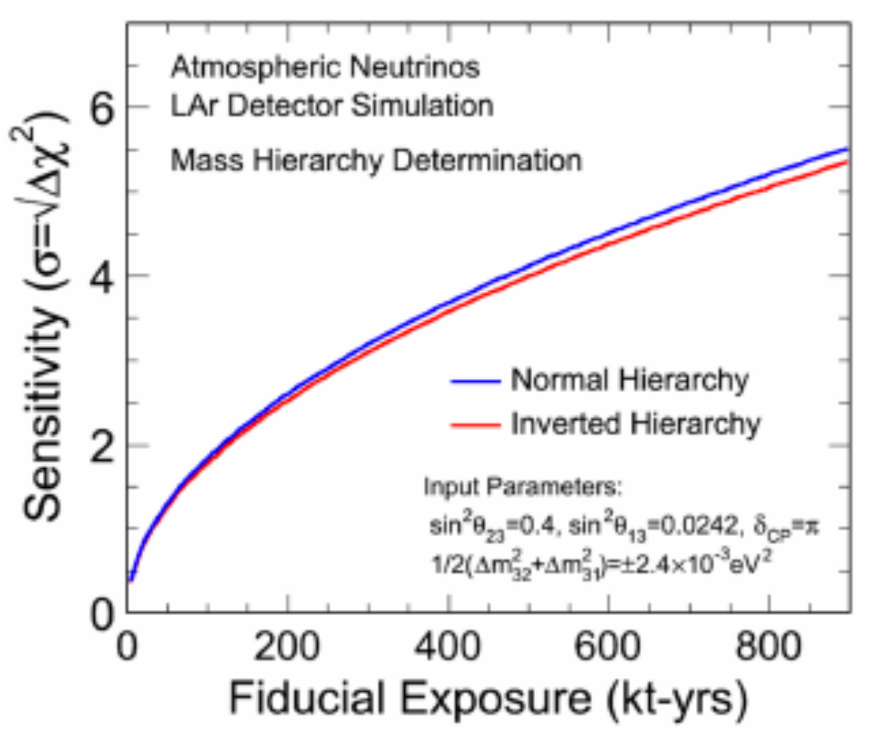
Uncertainty on CP phase

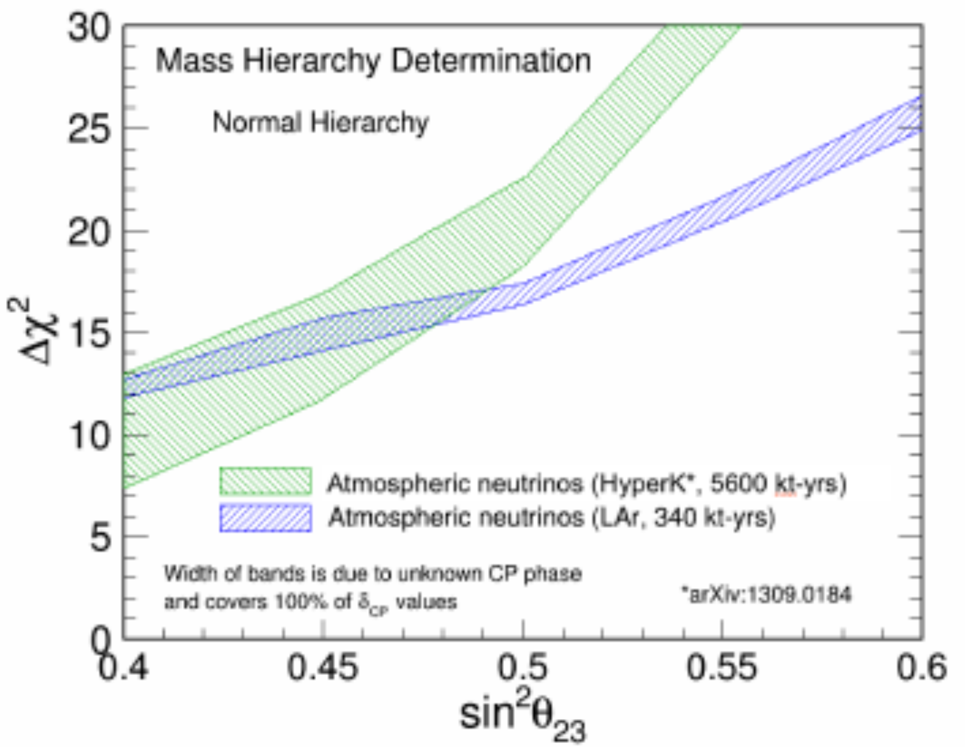
Aim:

To achieve a precision comparable to the quark sector

DUNE CDR Physics Overview, arXiv:1512.06148 [physics.ins-det]

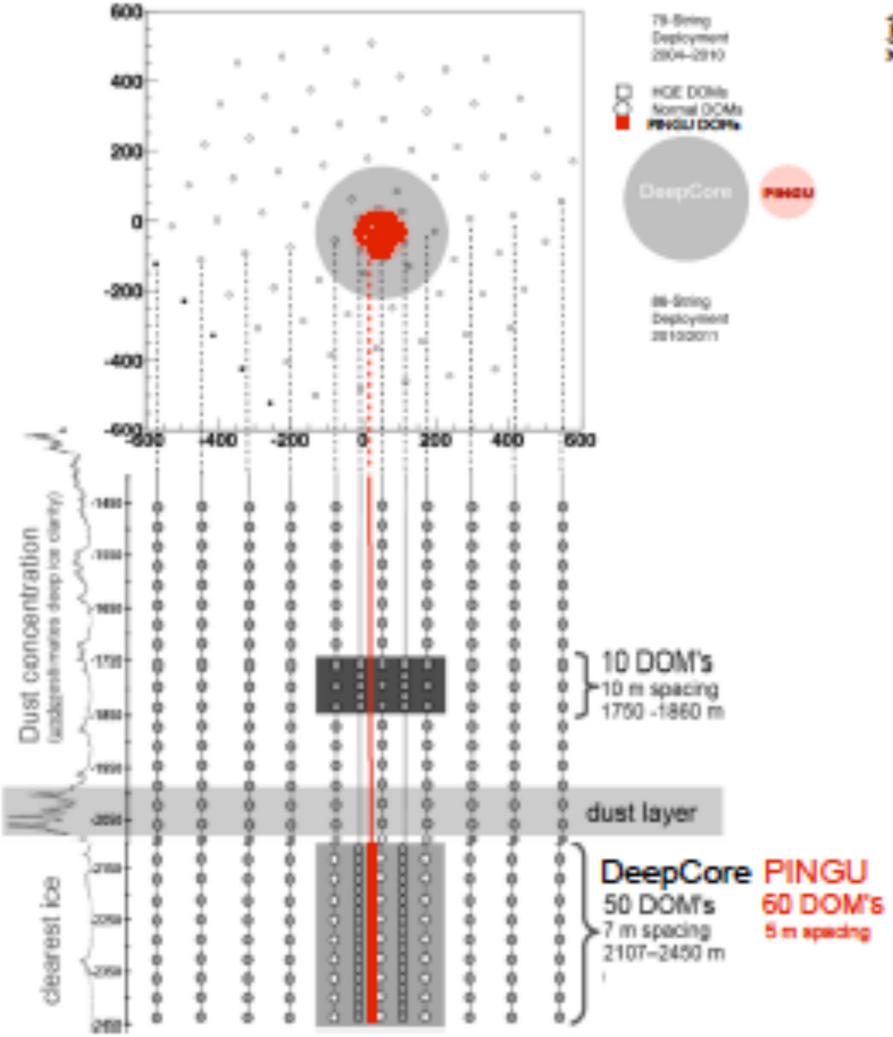
Mass Hierarchy in DUNE with Atmospheric Neutrinos

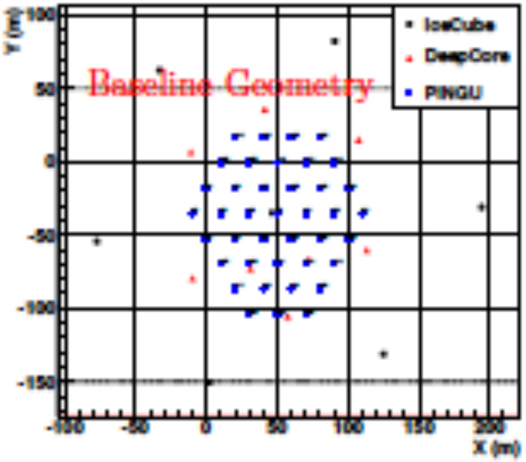


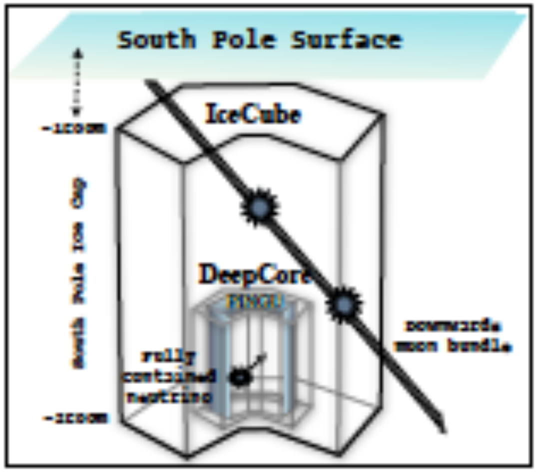


DUNE Physics Overview, arXiv: 1512.06148v2 [physics.ins-det]

The Precision IceCube Next Generation Upgrade (PINGU)



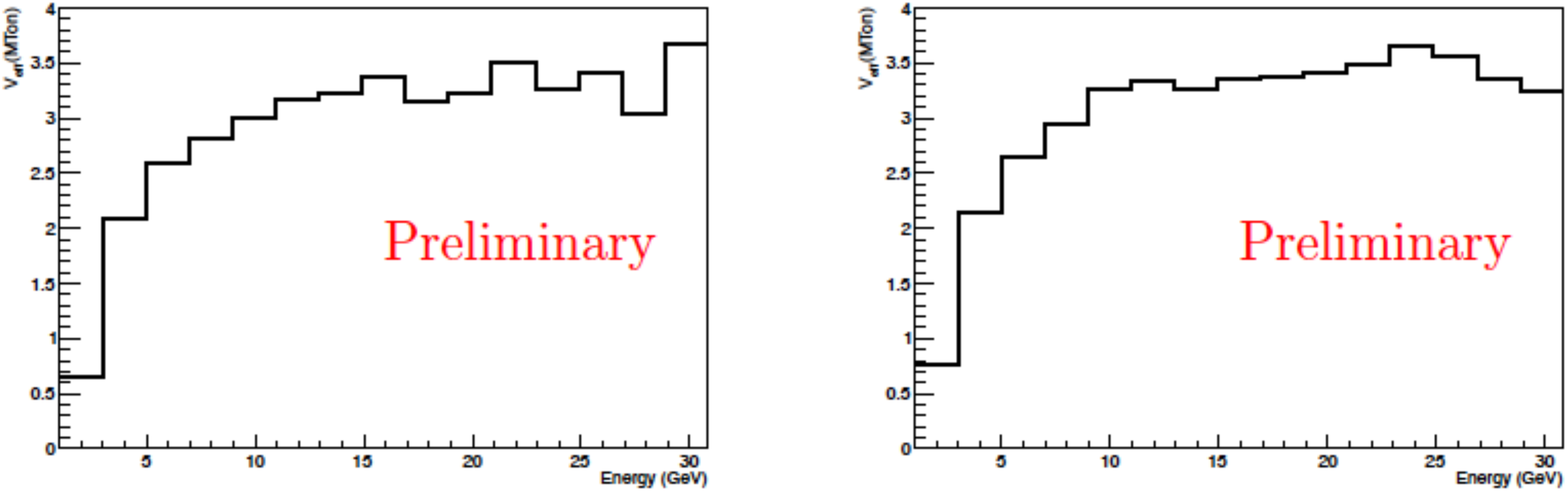




PINGU would add an array of 40 strings each with 60 optical modules to the DeepCore

PINGU, Letter of Intent, arXiv: 1401.2046v1

The Precision IceCube Next Generation Upgrade (PINGU)



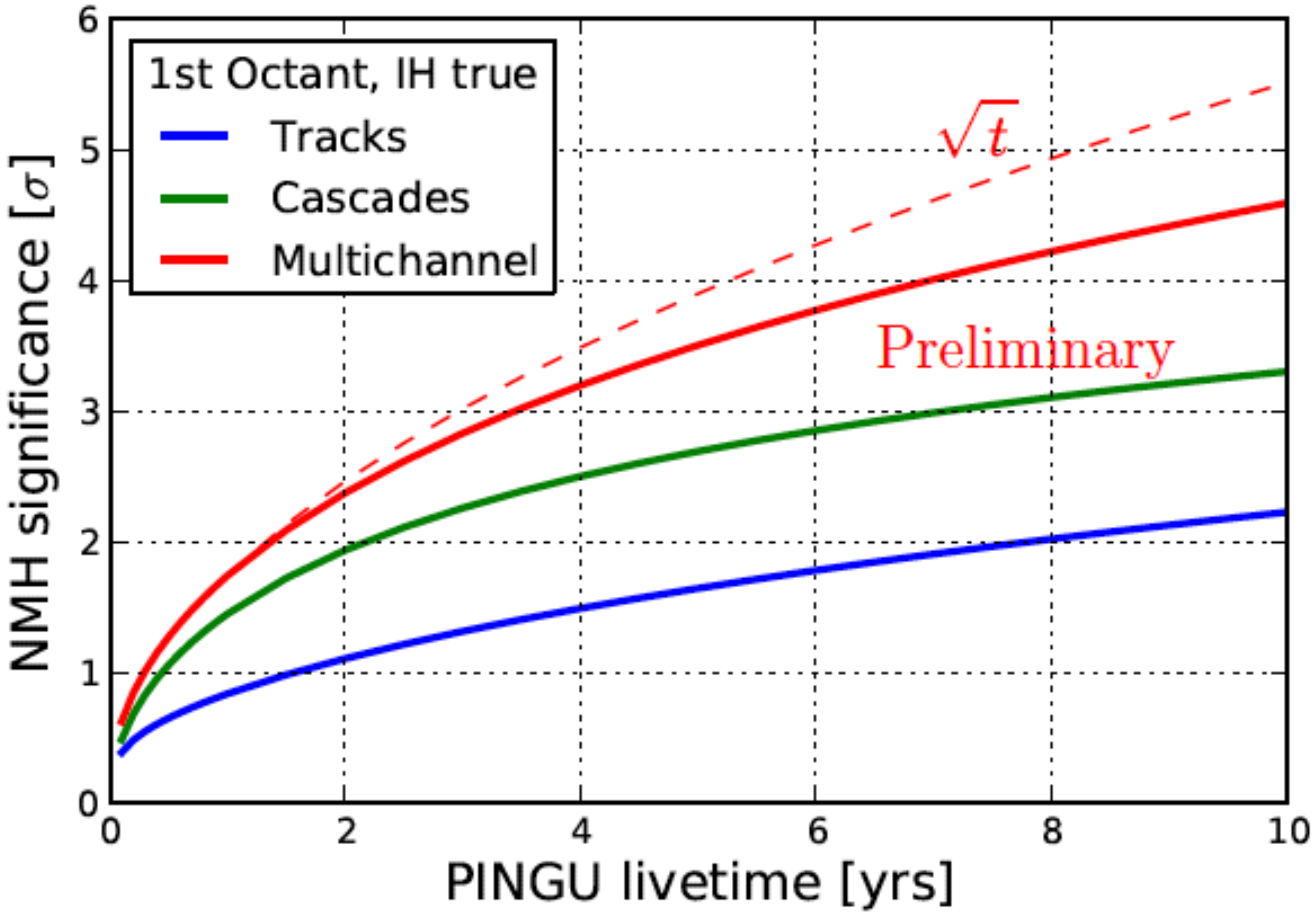
(a) $V_{\rm eff}(\nu_\mu)$

(b) $V_{\rm eff}(\nu_e)$

PINGU, Letter of Intent, arXiv: 1401.2046v1

- ○ Huge statistics
- ○ Good Particle-Id helps to distinguish muons & electrons
- ○ Good angular resolution for muons
- ○ Good energy resolution for electrons

Mass Hierarchy in PINGU



PINGU, Letter of Intent, arXiv: 1401.2046v1

3σ discovery in 3 years of run

Mass Hierarchy in ORCA

- **Similar expectations from the Oscillation Research with Cosmics in the Abyss (ORCA) experiment like PINGU**

- **It uses the deep-sea neutrino telescope technology developed for the KM3NeT project**

- **ORCA is expected to deploy large 3-dimensional arrays of photo-sensors to detect Cherenkov lights in the deep Mediterranean Sea**

- **A 3 to 5σ MH sensitivity is targeted for a ~ 20 Mton•year overall exposure given the neutrino detecting threshold around 5 GeV**

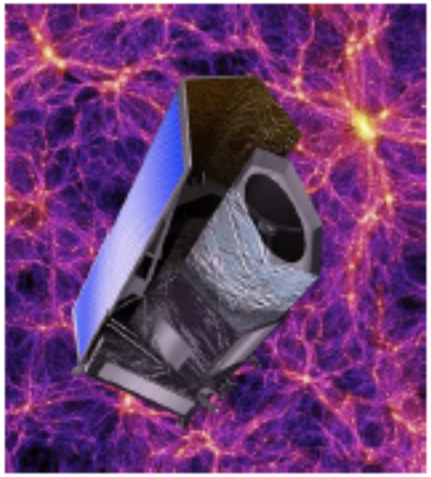
Ulrich F. Katz, The ORCA Option for KM3NeT, arXiv:1402.1022 (2014)

Cosmological Observations

CMB, and its B-mode, LSS

Cosmological Observations

Planck (CMB)
operating now



Euclid (LSS, lensing in visible, near-IR)
adopted as an ESA mission last year; launch in 2020

POLARBEAR (CMB *B-mode*)
operating now

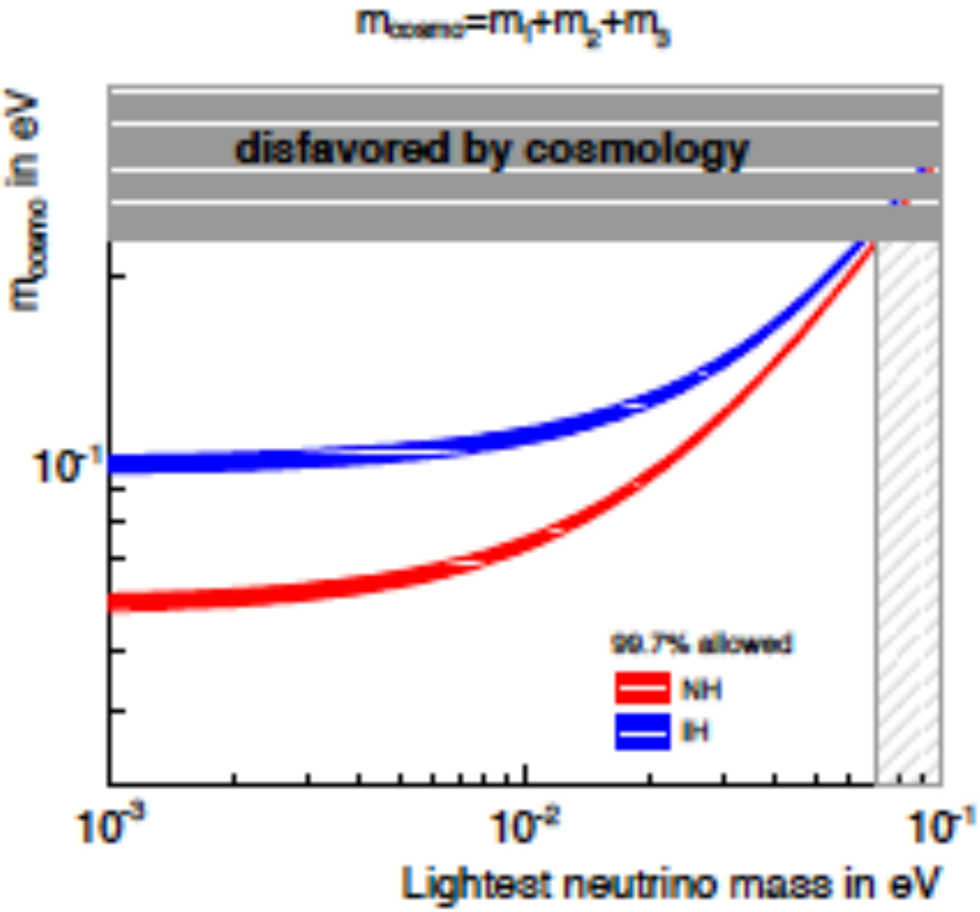
Square Kilometer Array (LSS vs. redshift via 21 cm)
Phase I start-up circa 2019
(at longer timescales: "Omniscope")

Start of operations, ranging from 2018 to 2022

Forecast uncertainties on Σm_ν begin at 20 meV (c. 2025) and improve to ~ 10 meV (c. 2030) with past data sets taken in combination with future ones

R. N. Cahn etal, arXiv: 1307.5487 (2013)

Cosmological Data

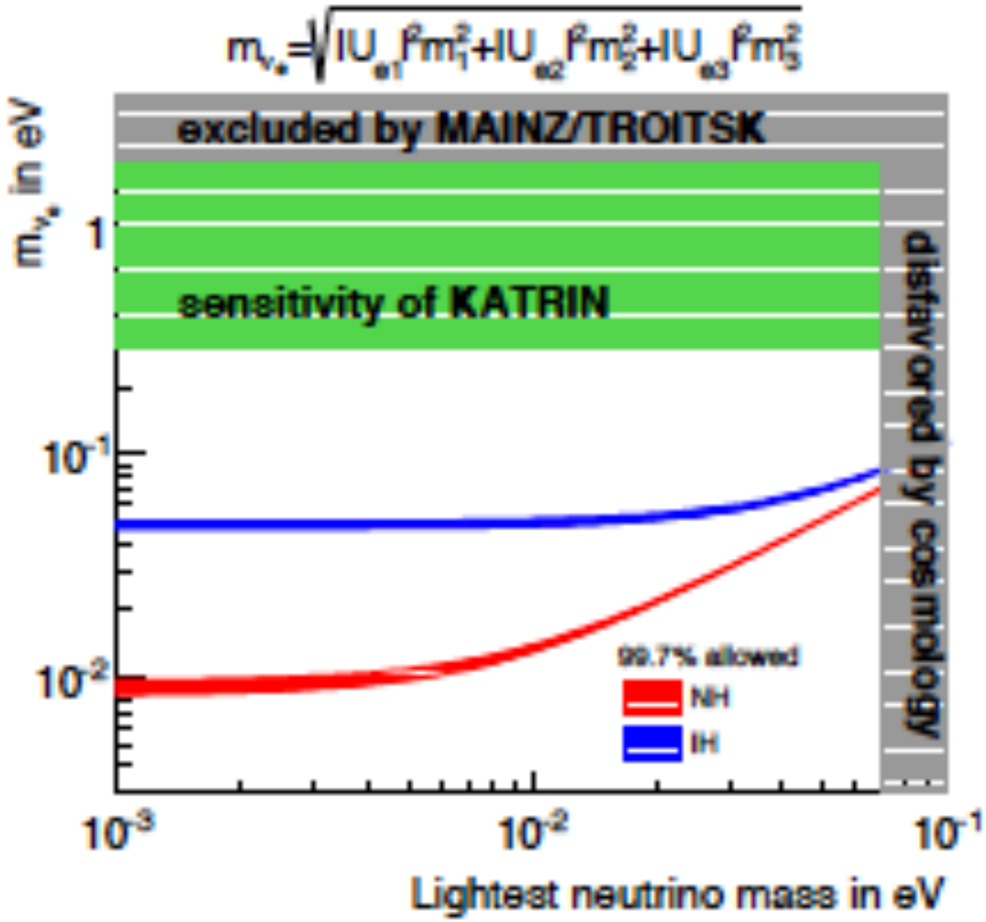


In cosmology, the sum of the neutrino masses $m_{cosmos} = \Sigma m_\nu$ could be determined

If that mass is below the minimum mass of ~ 0.1 eV corresponding to the IH, the existence of the NH is indicated

$$m_{cosmos} = \begin{cases} m_L + \sqrt{m_L^2 + \Delta m_{21}^2} + \sqrt{m_L^2 + |\Delta m_{31}^2|} & \text{(Normal Hierarchy)} \\ m_L + \sqrt{m_L^2 + |\Delta m_{32}^2|} + \sqrt{m_L^2 + |\Delta m_{31}^2|} & \text{(Inverted Hierarchy)} \end{cases}$$

MH from β-decay endpoint

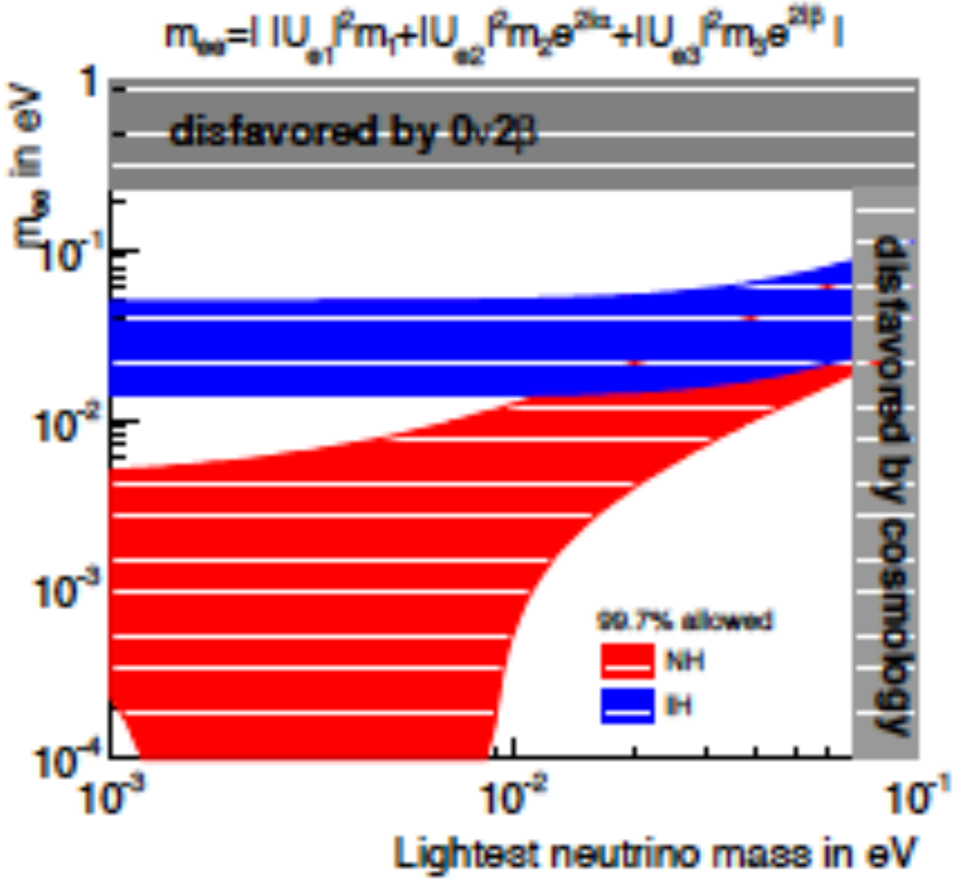


If the effective neutrino mass is measured to be smaller than ~ 0.05 eV corresponding to the minimum value of the IH, the existence of the NH is suggested

$$m_{\nu_e} = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$$

$$m_{\nu_e} = \begin{cases} \sqrt{m_L^2 + c_{13}^2 s_{12}^2 \Delta m_{21}^2 + s_{13}^2 |\Delta m_{31}^2|} & \text{(Normal Hierarchy)} \\ \sqrt{m_L^2 + c_{13}^2 c_{12}^2 |\Delta m_{31}^2| + c_{13}^2 s_{12}^2 |\Delta m_{32}^2|} & \text{(Inverted Hierarchy)} \end{cases}$$

MH from 0νββ-decay

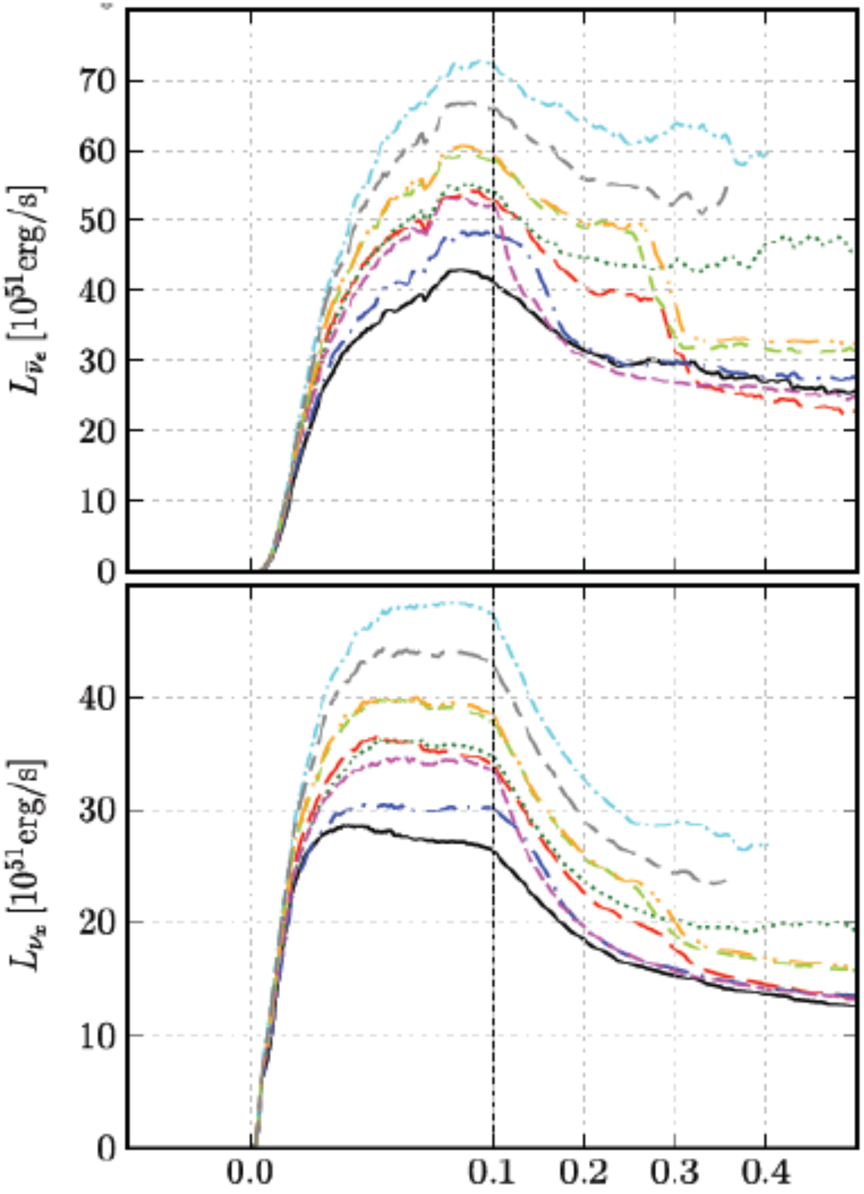


If the deduced Majorana neutrino mass is again below its minimal value corresponding to the IH, then the NH is implied

$$m_{ee} = ||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{2\alpha i} + |U_{e3}|^2 m_3 e^{2\beta i}|$$

$$m_{ee}^2 = \begin{cases} (c_{12}^2 c_{13}^2 m_L + c_{13}^2 s_{12}^2 \sqrt{m_L^2 + \Delta m_{21}^2} \cos 2\alpha + s_{13}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} \cos 2\beta)^2 + & \\ (c_{13}^2 s_{12}^2 \sqrt{m_L^2 + \Delta m_{21}^2} \sin 2\alpha + s_{13}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} \sin 2\beta)^2 & \text{(Normal Hierarchy)} \\ (c_{12}^2 c_{13}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} + c_{13}^2 s_{12}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} \cos 2\alpha + s_{13}^2 m_L \cos 2\beta)^2 + & \\ (c_{13}^2 s_{12}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} \sin 2\alpha + s_{13}^2 m_L \sin 2\beta)^2 & \text{(Inverted Hierarchy)} \end{cases}$$

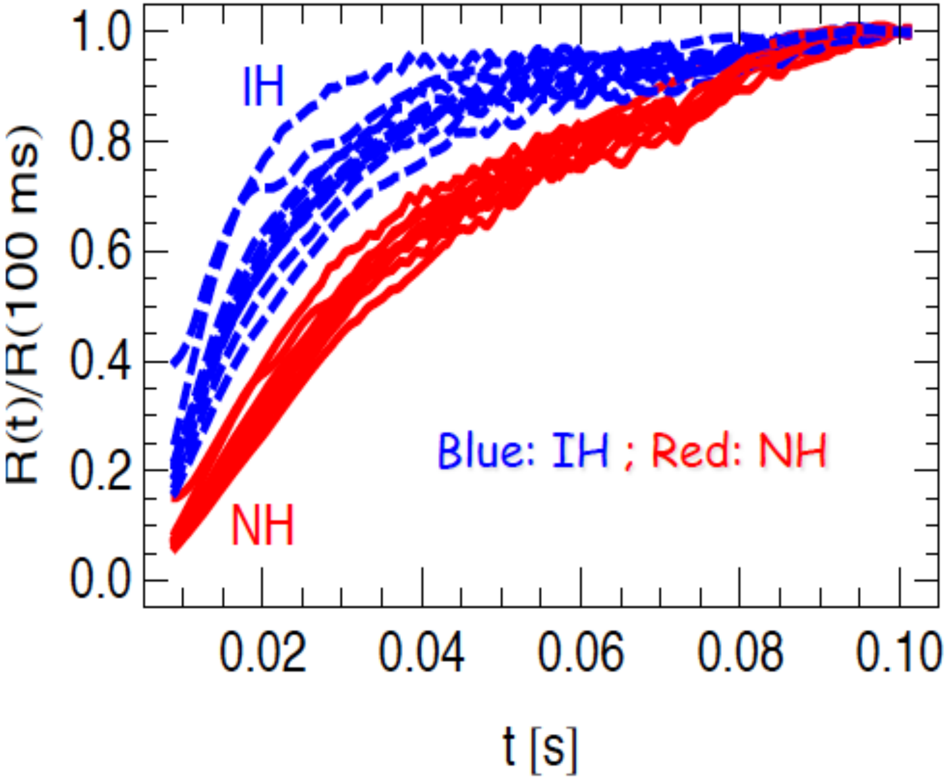
MH from Supernova: Rise Time Analysis



Garching group, 2011

Normalized Count rate :

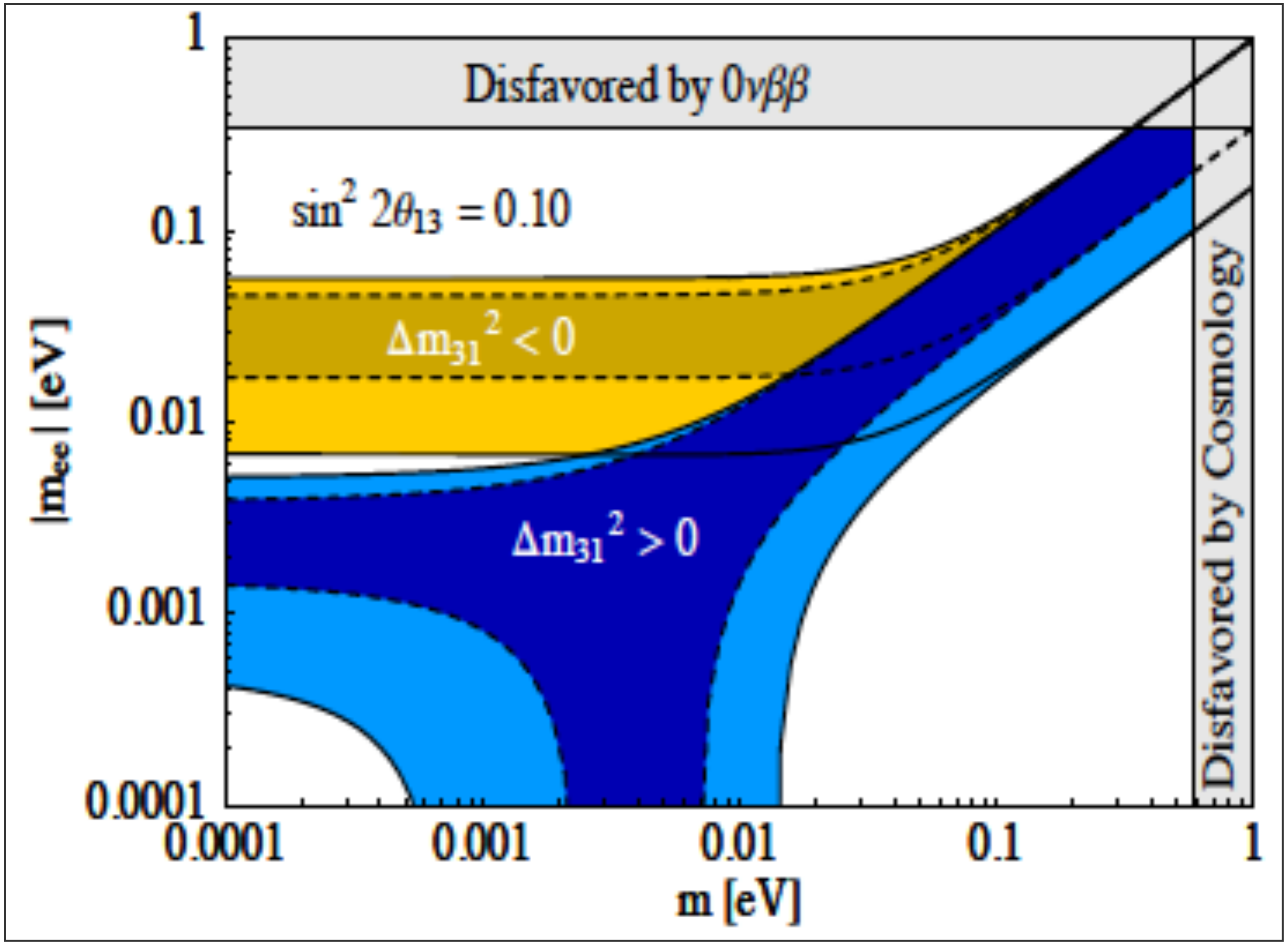
10 different models (12 $M_\odot$-40 $M_\odot$)



Flux in IH rises faster than NH

Serpico etal, PRD 85 (2012) 085031

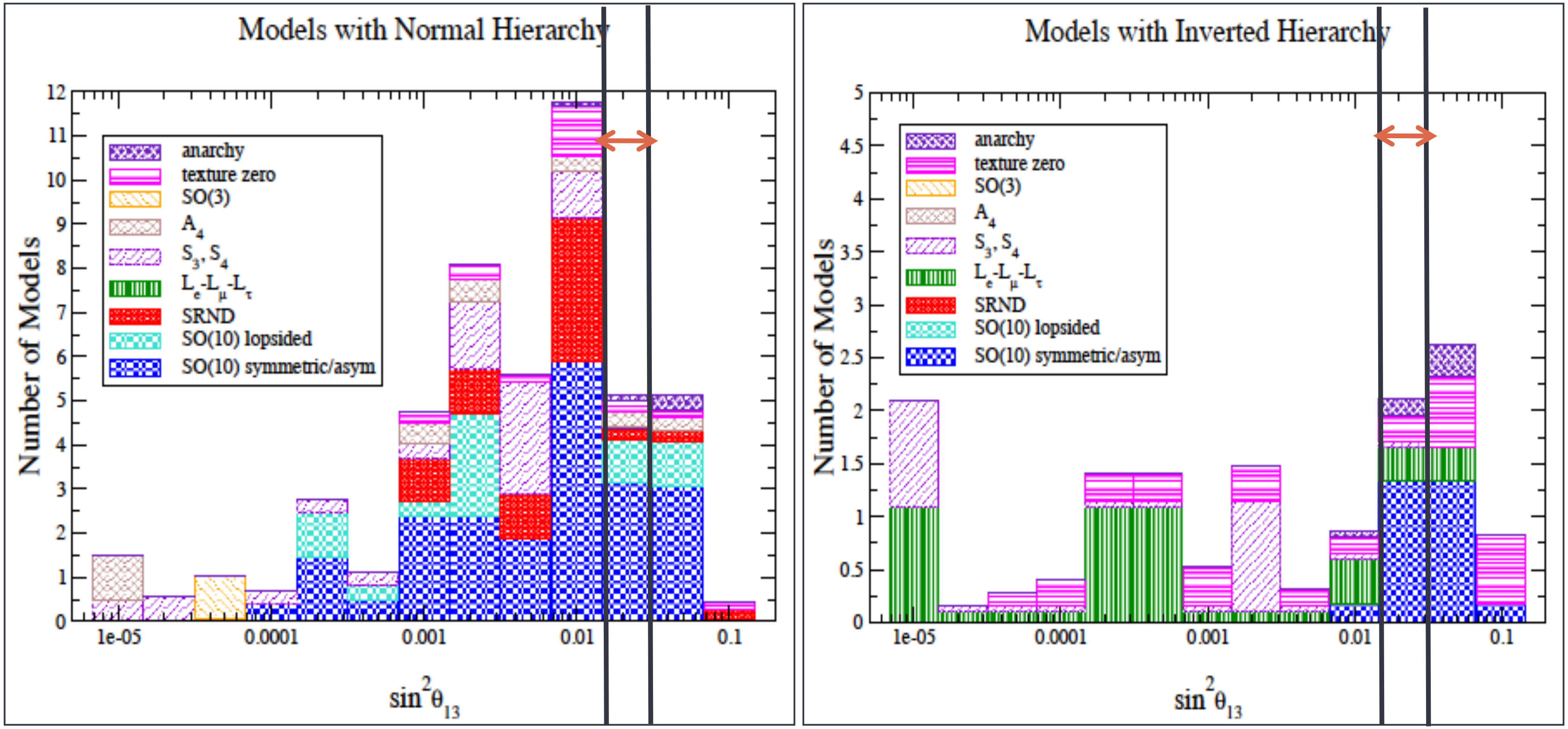
Connection between 0νββ and Neutrino Mass Ordering



Lindner, Merle, Rodejohann , hep-ph/0512143

If hierarchy is inverted, & yet no 0νββ is observed in the very far future,
strong hint that neutrinos are not Majorana particles

Why do we care about Neutrino Mass Ordering?

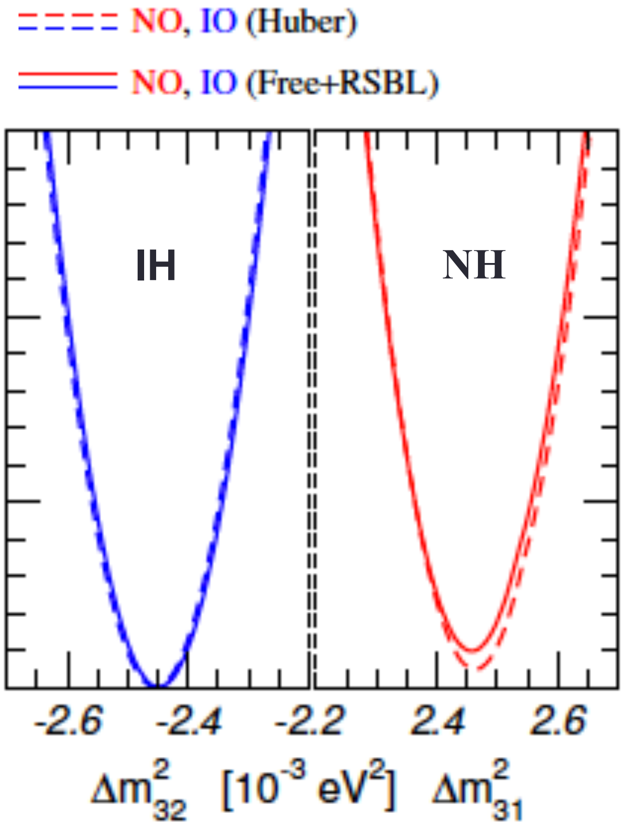


only 7 models survived

Albright and Chen, hep-ph/0608137

- Dictates the structure of neutrino mass matrix
- Essential for the underlying theory of neutrino masses and mixing
- Acts as a powerful discriminator between various neutrino mass models

Information on Neutrino Mass Hierarchy from the Global Fit



Gonzalez-Garcia, Maltoni, Schwetz, arXiv:1512.06856v1

Statistical significance of the preference for IH over NH is quite small, $\Delta\chi^2 \leq 1$

But in Capozzi, Lisi, Marrone, Montanino, Palazzo, arXiv:1601.07777v1

NH is slightly favored over IH:

$\Delta\chi^2$ (IH-NH) = +0.98 (with NOvA LID data set, 6 appearance events)

$\Delta\chi^2$ (IH-NH) = +2.80 (~ 90% C.L.) (with NOvA LEM data set, 11 appearance events)

T2K and NOνA

Current Generation Experiments:

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

J-PARC Beam: 0.75 MW, 30 GeV proton energy

Total 7.8×10^{21} p.o.t., with 50% ν and 50% anti-ν

Detector: SK (22.5 kton fiducial volume)

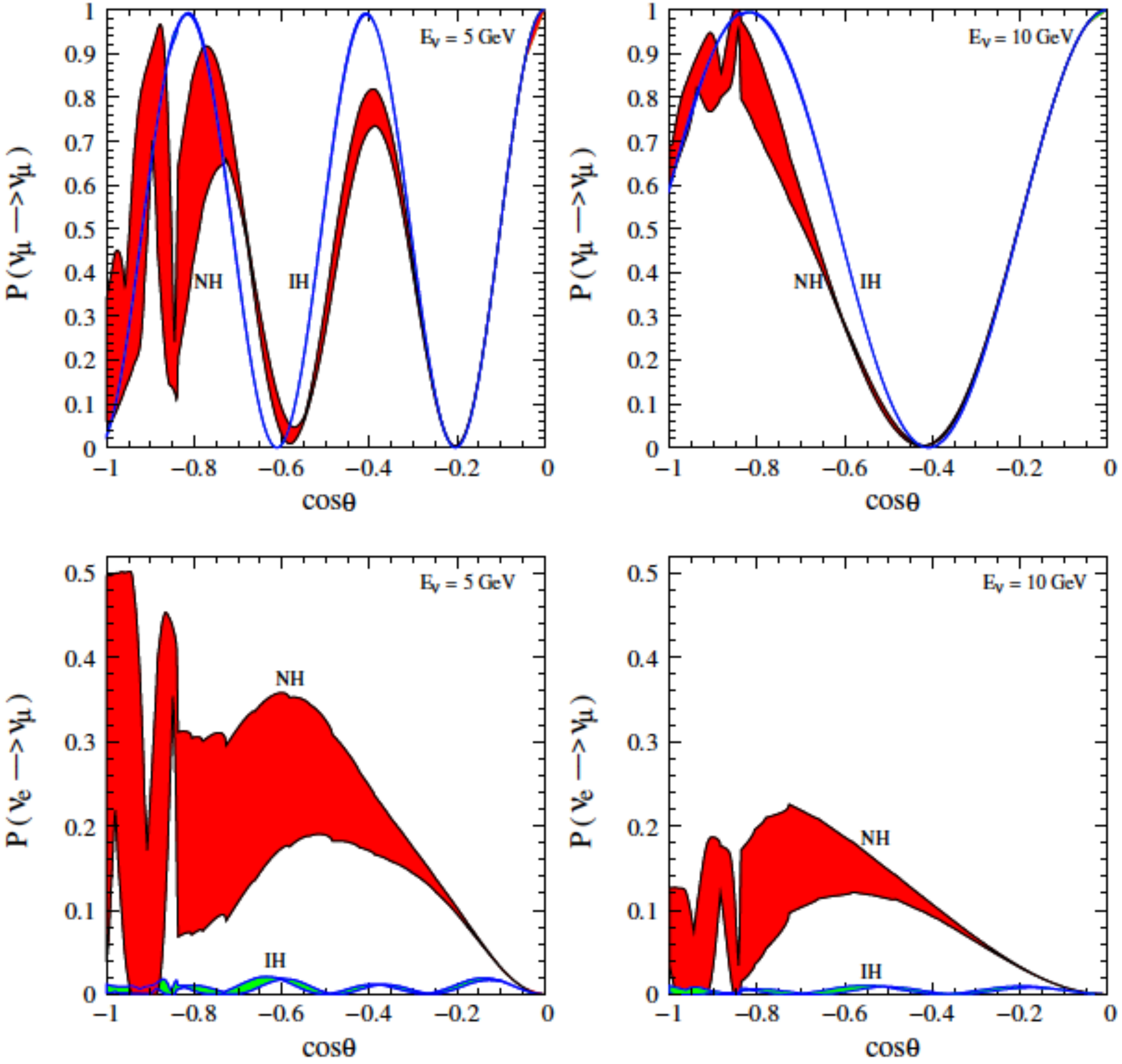
FNAL to Ash River (NOνA) : 810 km (0.8° off-axis, 1st Osc. Max = 1.7 GeV)

NuMI Beam: 0.7 MW, 120 GeV proton energy

Total 3.6×10^{21} p.o.t., 3 yrs ν + 3 yrs anti-ν

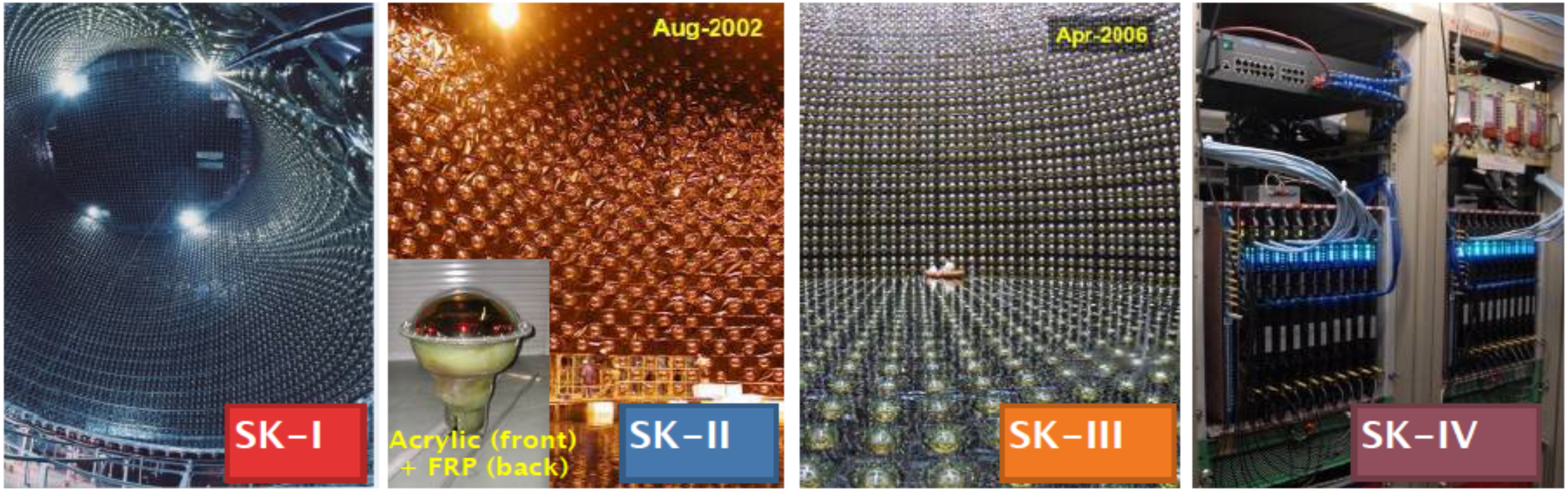
Detector: 14 kton Totally Active Scintillator Detector (TASD)

Matter effect in Atmospheric Experiments



S. K. Agarwalla, EILH-2016, AMU, Aligarh, India, 2^{nd} November, 2016

Super-Kamiokande (SK)

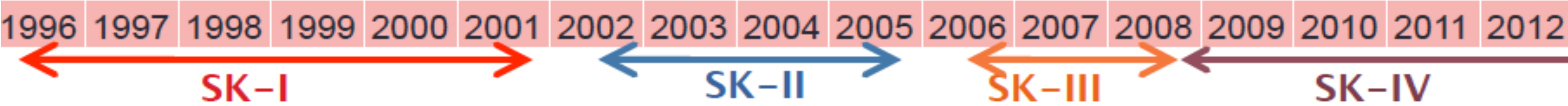


11146 ID PMTs (40% coverage)

5182 ID PMTs (19% coverage)

11129 ID PMTs (40% coverage)

Electronics Upgrade



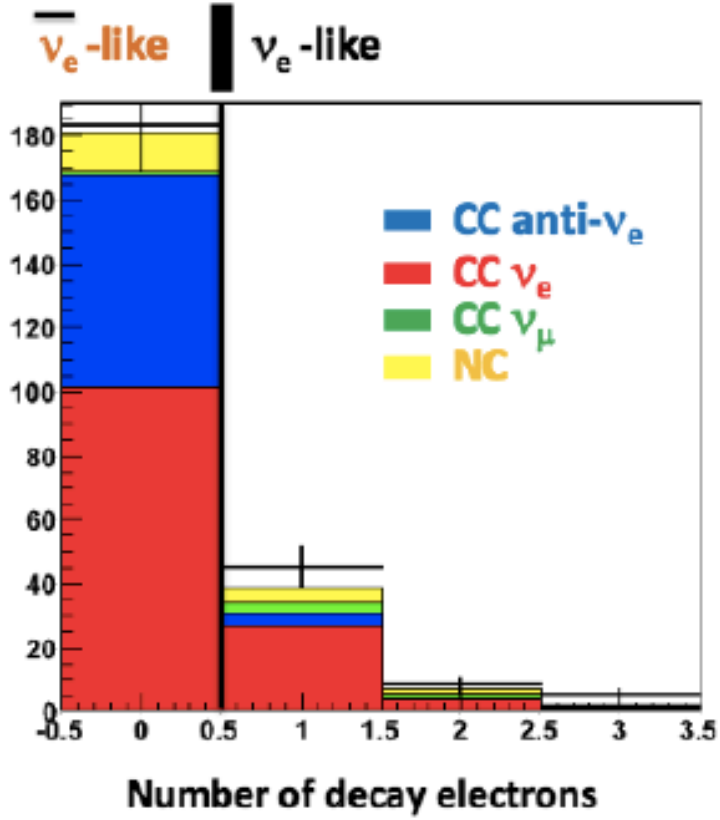
- > 38,000 atmospheric neutrino events collected in SK-I+II+III+IV
- Recently, SK performed three-flavor fit to ν_μ and ν_e atmospheric samples
- Sub-leading oscillation effects are important in wide range of L & E
- Possible to determine mass hierarchy if we can separate ν_e and anti-ν_e
- Separate ν_e from anti-ν_e in single ring sample using number of decay electrons

MH in SK with Atmospheric Neutrinos

- **Upward-going neutrinos with an energy range of 2-10 GeV experience an enhanced $\nu_\mu \rightarrow \nu_e$ osc. probability**
- **This enhancement exists only for neutrinos if the hierarchy is normal, and only for anti-neutrinos if the hierarchy is inverted**
- **SK probe the hierarchy by looking for an excess in the upward-going event rate of high energy e-like samples**
- **Separation between the single ring sample of ν_e and anti-ν_e is the key**

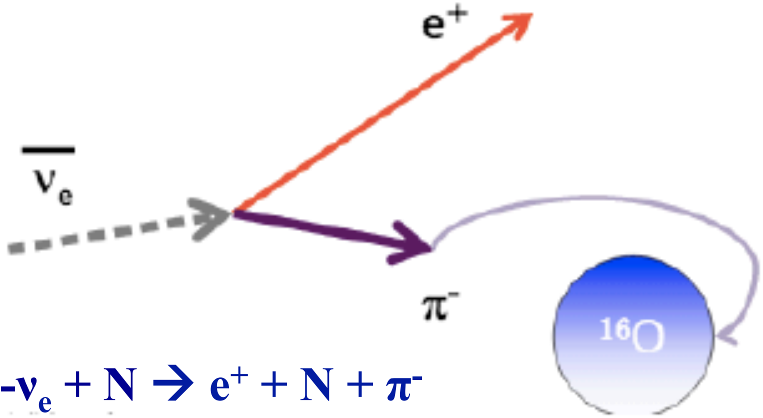
Electron neutrino and anti-neutrino separation in SK

Sample selection: Multi-GeV Single Ring anti-ν_e and ν_e-like



☐ Separate neutrinos from anti-neutrinos in the single-ring sample using the number of observed decay electrons

☐ The outgoing π^- from an anti-neutrino CC-1 π event can be absorbed on a ^{16}O nuclei before it decays. The lack of an outgoing muon means there is no possibility of a subsequent Michel (decay) electron



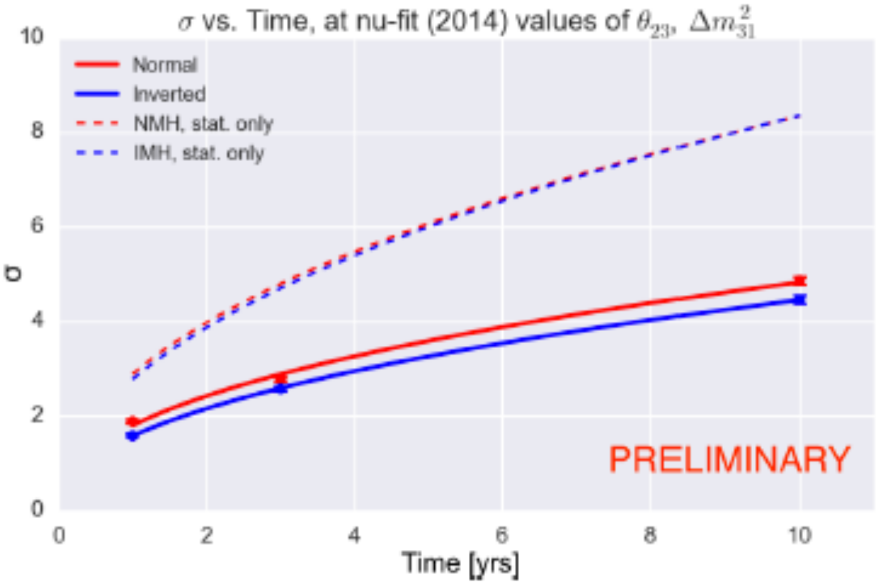
(Multi-ring events are in general more complicated separation is done using a likelihood)

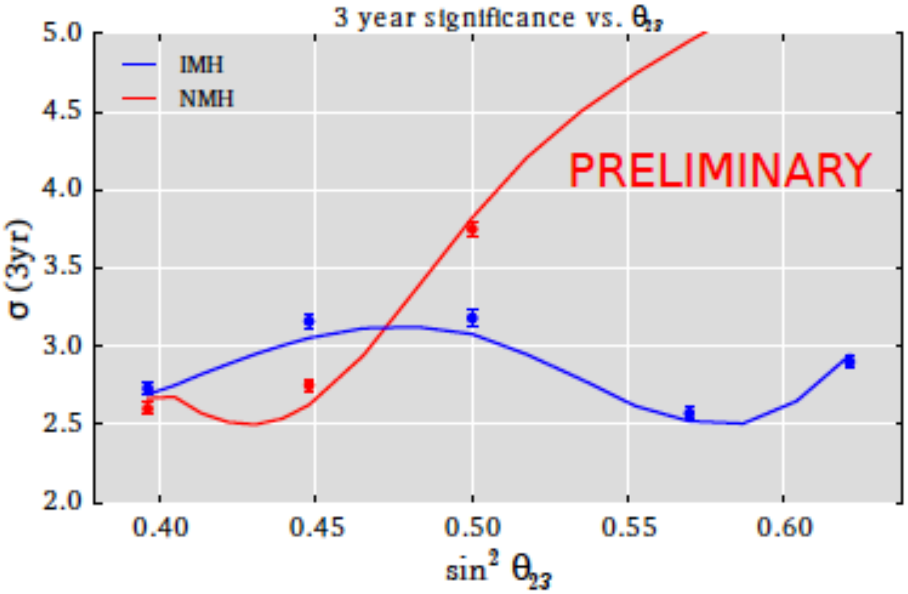
$$\text{anti-}\nu_e + N \rightarrow e^+ + N + \pi^-$$

$$\nu_e + N \rightarrow e^- + N + \pi^{+,0}$$

Roger Wendell, NNN 2012

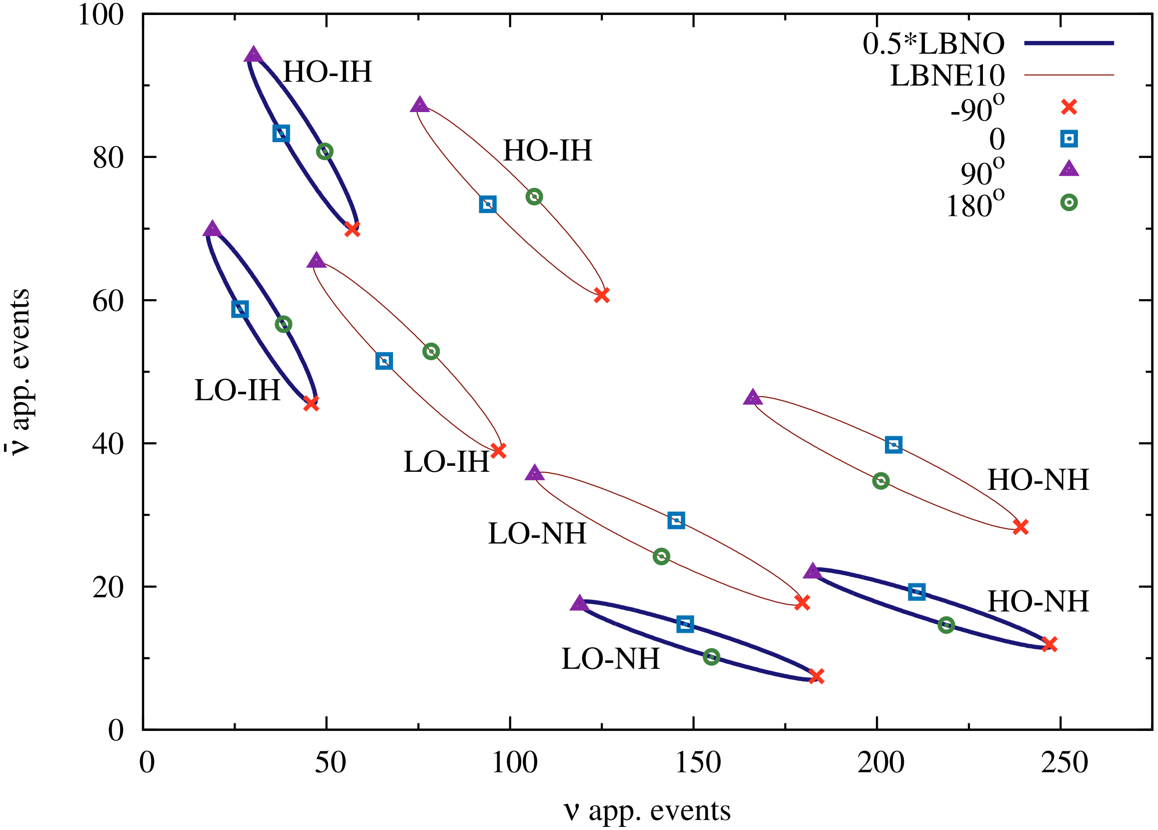
Mass Hierarchy in PINGU





From DeepCore to PINGU, J.P. Yanez, arXiv: 1601.05245v1 [hep-ex]

Future Superbeam Expts with LAr Detector: DUNE & 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

DUNE with 10 kt LArTPC

For LO, hierarchy discovery is limited

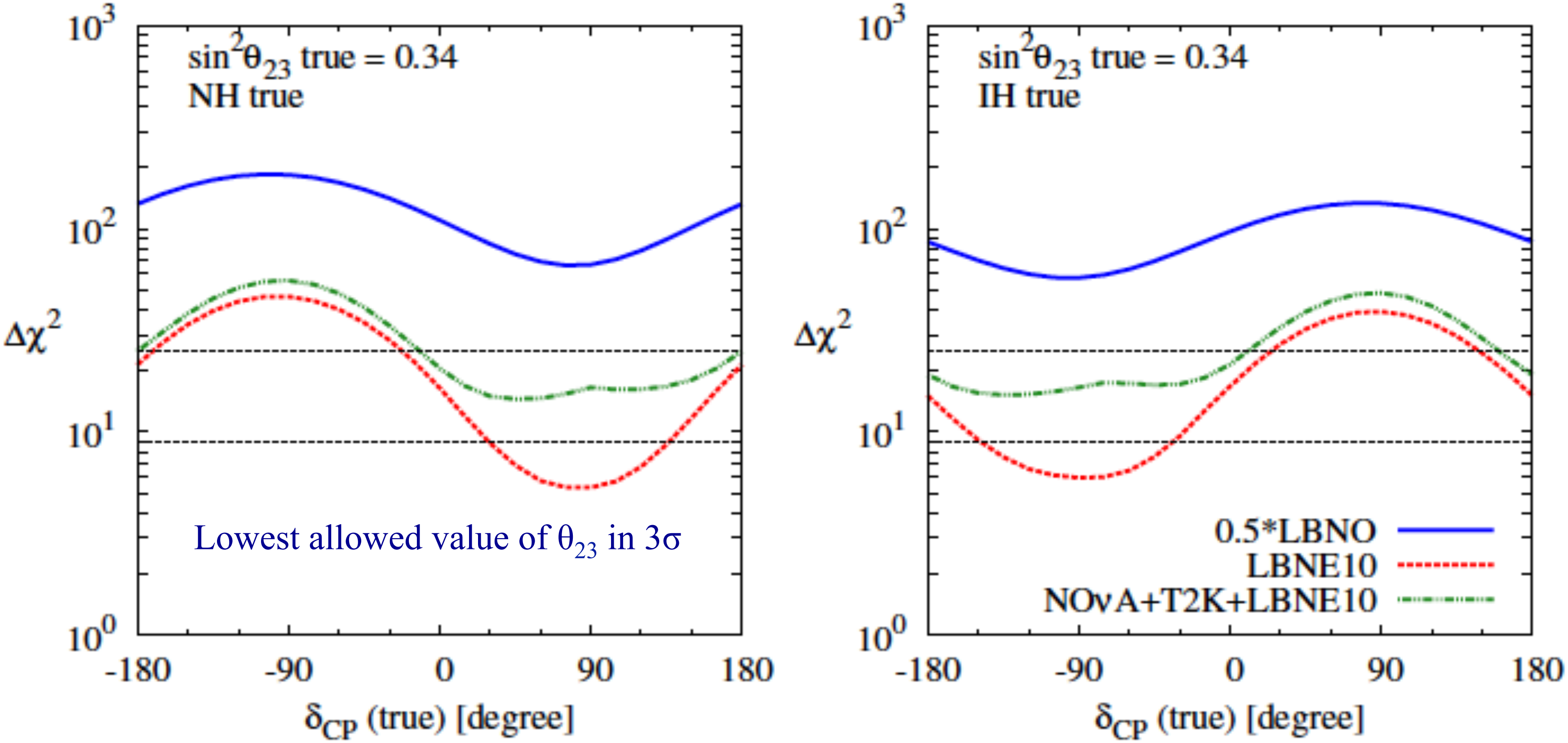
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]

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 DUNE and LBNO



Lowest allowed value of θ_{23} in 3σ

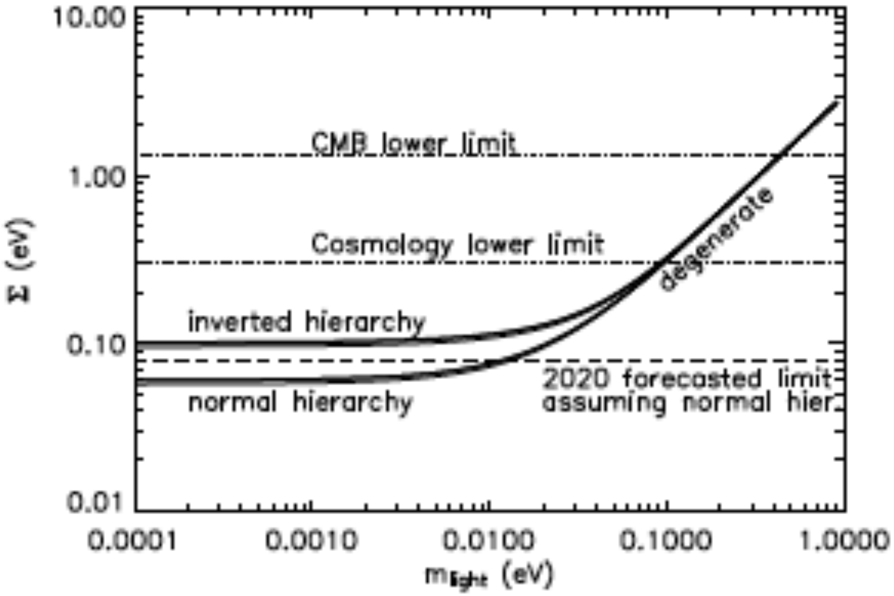
DUNE exposure: 70.8 kt • MW • year

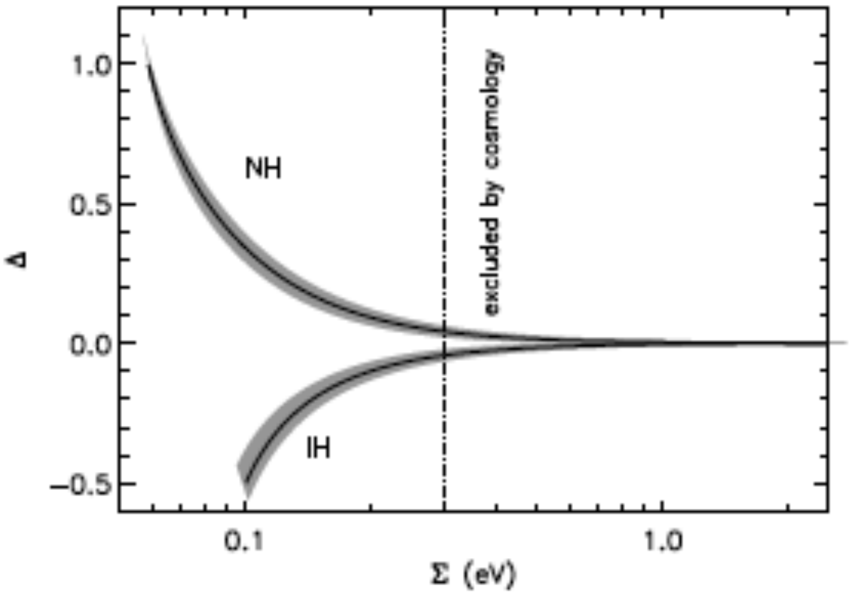
Agarwalla, Prakash, Sankar, arXiv:1304.3251 [hep-ph]
See also, arXiv:1312.6520 [hep-ph] from LAGUNA-LBNO Collaboration

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

DUNE w/ 10 kt + T2K + NOvA > 3σ median hierarchy discovery for any parameter choice

Cosmological Observations





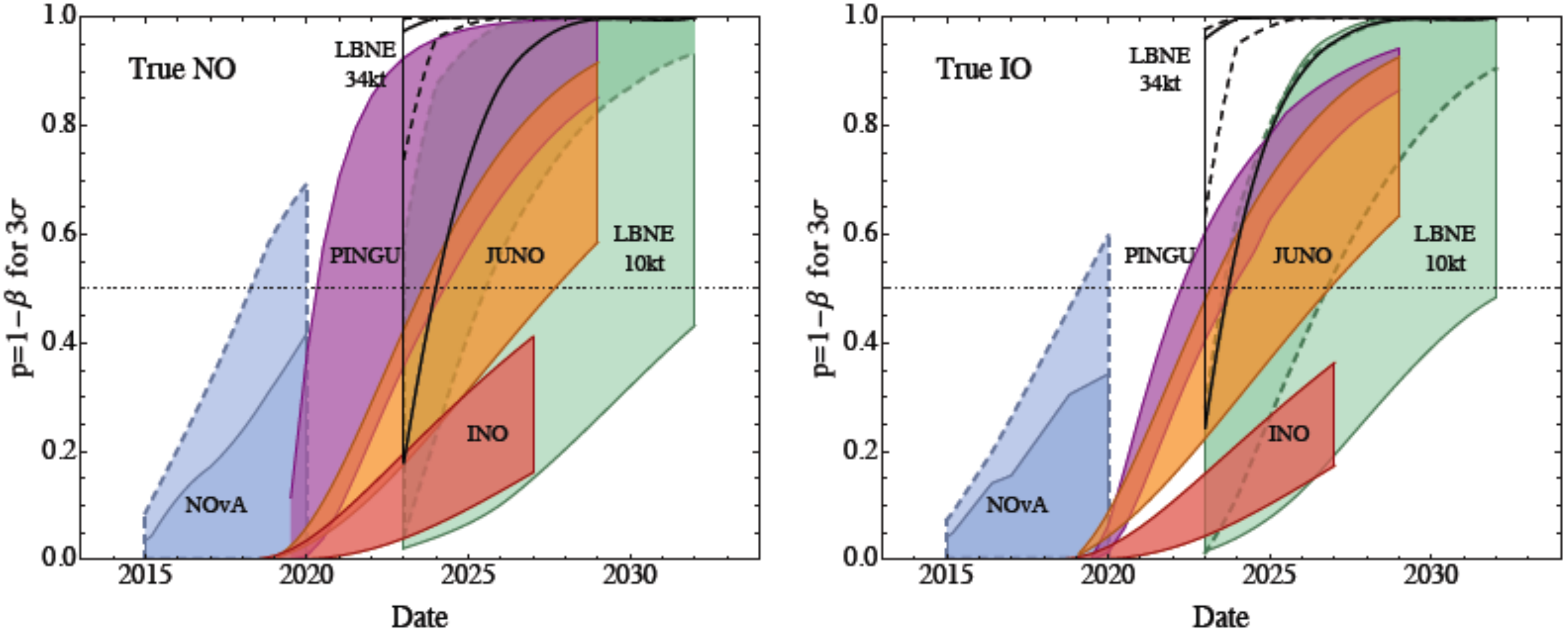
Jimenez, Kitching, Pena-Garay, Verde, JCAP05 (2010) 035
See also, Oyama, Shimizu, Kohri, PLB 718, 1186 (2013)
See also, F. De Bernardis etal, PRD 80, 123509 (2009)

$$\text{NH}: \quad \Sigma = 2m + M \quad \Delta = (M - m)/\Sigma$$
$$\text{IH}: \quad \Sigma = m + 2M \quad \Delta = (m - M)/\Sigma$$

m: lightest neutrino mass
M: heaviest neutrino mass

Precise measurement of the shape of the matter power spectrum from LSS and weak gravitational lensing can shed light on mass hierarchy

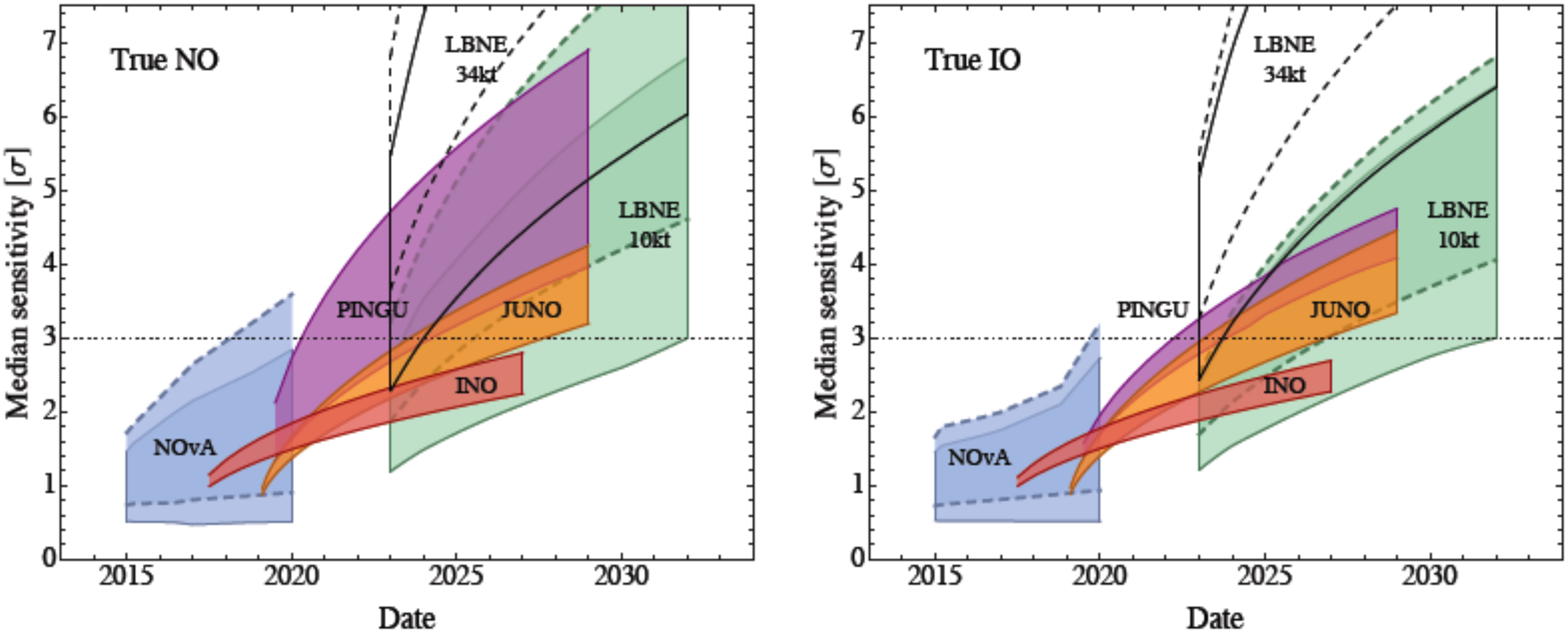
Probability of Rejecting Wrong ordering at 3σ



Blennow, Coloma, Huber, Schwetz, arXiv:1311.1822v2

Bands have different meanings:
For NOvA and LBNE: Different true values of CP phases
For INO and PINGU: 2-3 mixing angle between 40 degree and 50 degree
For JUNO: Energy resolution between 3% and 3.5%

Comparison of Experiments – Median Sensitivity



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