Addressing Neutrino Mixing Models with T2HK and DUNE

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Work done in collaboration with

Sabya Sachi Chatterjee, S. T. Petcov, A. V. Titov

Eur. Phys. J. C (2018) 78: 286

arXiv:1711.02107 [hep-ph]

Studies along this direction:

S. T. Petcov (arXiv:1405.6006); I. Girardi et al., (arXiv:1410.8056, 1504.02402, 1504.00658, 1509.02502); P. Ballet et al., (arXiv:1308.4314, 1503.07543, 1410.7573, 1612.01999); S. S. Chatterjee et al., (arXiv:1712.03160, 1708.03290); M. Sruthiliya et al., (arXiv:1408.4392); K. Chakraborty et al., (arXiv:1804.02022); U. Dey et al., (arXiv:05808); N. Nath (arXiv:1805.05823)

The list is not complete.........(I apologize in advance if I have missed yours)

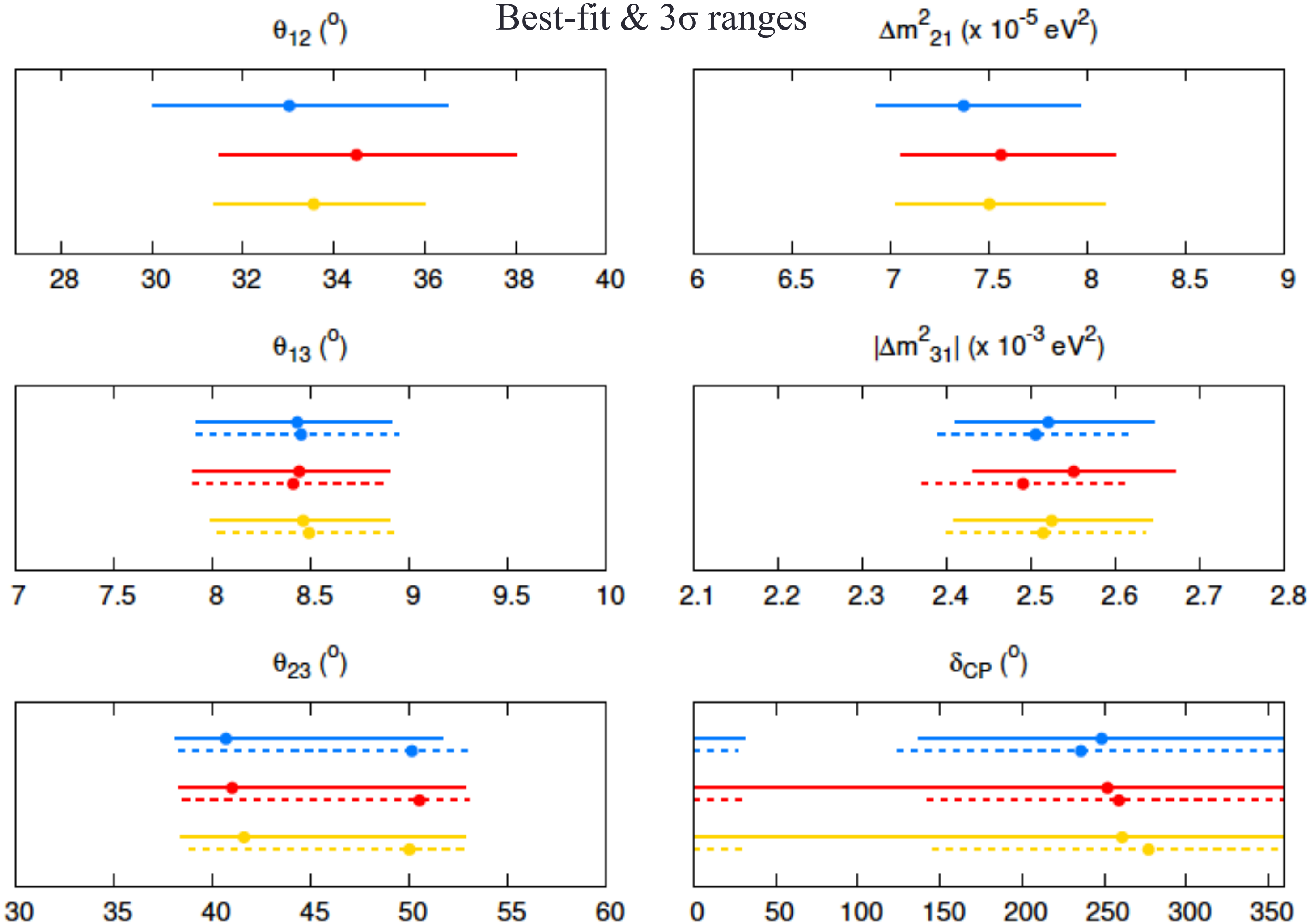
Present Status of Oscillation Parameters

Parameter	Best fit	1σ range	2σ range	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	2.97	2.81–3.14	2.65–3.34	2.50–3.54
$\frac{\sin^2\theta_{13}}{10^{-2}}$ (NO)	2.15	2.08–2.22	1.99–2.31	1.90–2.40
$\frac{\sin^2\theta_{13}}{10^{-2}}$ (IO)	2.16	2.07–2.24	1.98–2.33	1.90–2.42
$\frac{\sin^2\theta_{23}}{10^{-1}}$ (NO)	4.25	4.10–4.46	3.95–4.70	3.81–6.15
$\frac{\sin^2\theta_{23}}{10^{-1}}$ (IO)	5.89	4.17–4.48 $\oplus$ 5.67–6.05	3.99–4.83 $\oplus$ 5.33–6.21	3.84–6.36
δ_{CP} [°] (NO)	248	212–290	180–342	0–31 $\oplus$ 137–360
δ_{CP} [°] (IO)	236	202–292	166–338	0–27 $\oplus$ 124–360
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	7.37	7.21–7.54	7.07–7.73	6.93–7.96
$\frac{\Delta m^2_{31}}{10^{-3}\ \mathrm{eV}^2}$ (NO)	2.56	2.53–2.60	2.49–2.64	2.45–2.69
$\frac{\Delta m^2_{23}}{10^{-3}\ \mathrm{eV}^2}$ (IO)	2.54	2.51–2.58	2.47–2.62	2.42–2.66

Capozzi et al., (arXiv:1703.04471)

Similar Results from All Three Global Fit Studies

Best-fit & 3σ ranges

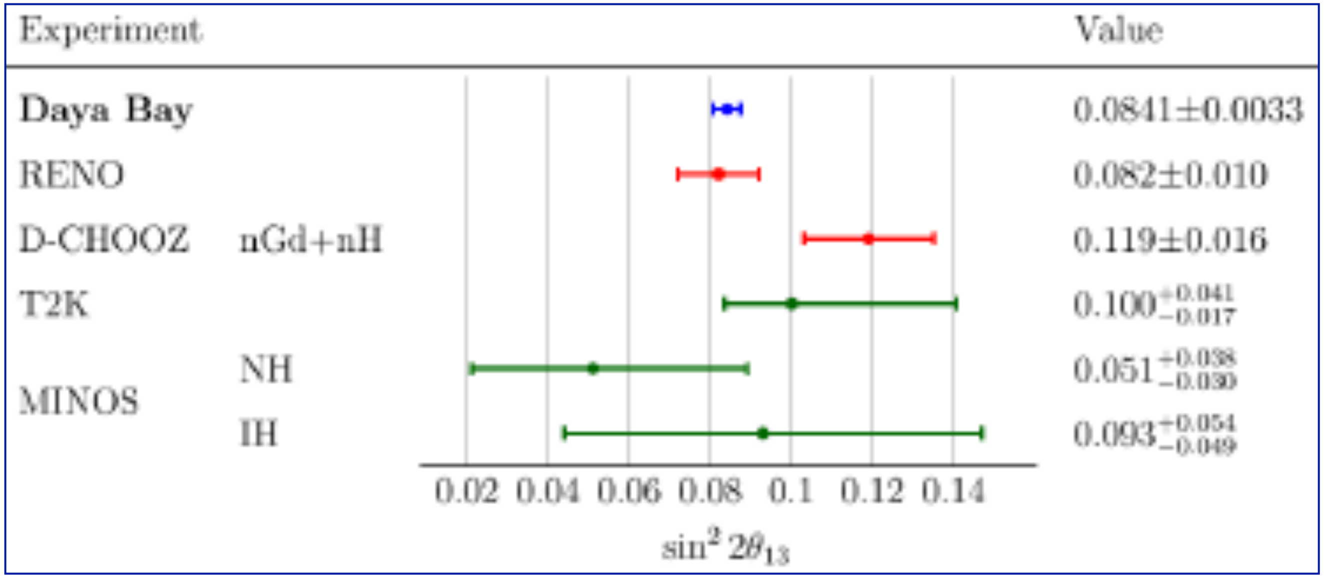


Courtesy: Monojit Ghosh, Sushant Raut

Blue: Capozzi et al., (1703.04471) **Red: Salas et al., (1708.01186)** **Yellow: NuFIT 3.0, (1611.01514)**

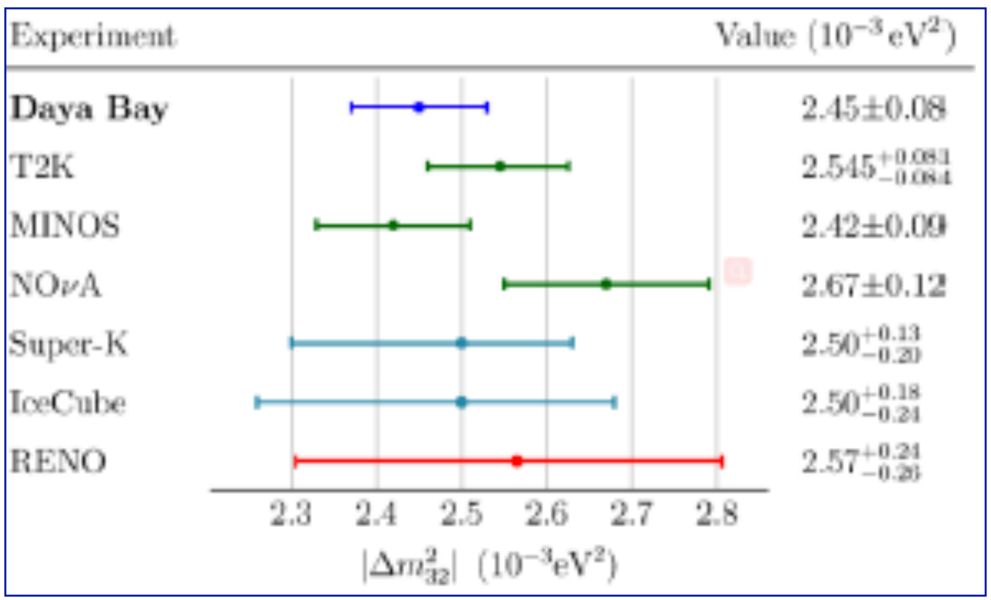
Solid: Normal Ordering, Dashed: Inverted Ordering

Complementarity Among Various Experiments



Daya Bay gives the most precise measurement of θ_{13}

Very useful for accelerator expts to measure δ_{CP}



Consistent $|\Delta m^2_{32}|$ between reactor, accelerator, and atmospheric experiments

Robustness of 3-flavor Paradigm!

Quark Mixing vs. Neutrino Mixing

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

PDG 2016

$$|U|_{3\sigma} = \begin{pmatrix} 0.799 \to 0.844 & 0.516 \to 0.582 & 0.140 \to 0.156 \\ 0.234 \to 0.502 & 0.452 \to 0.688 & 0.626 \to 0.784 \\ 0.273 \to 0.527 & 0.476 \to 0.705 & 0.604 \to 0.765 \end{pmatrix}$$

(PMNS)

NuFIT 3.1 (2017)

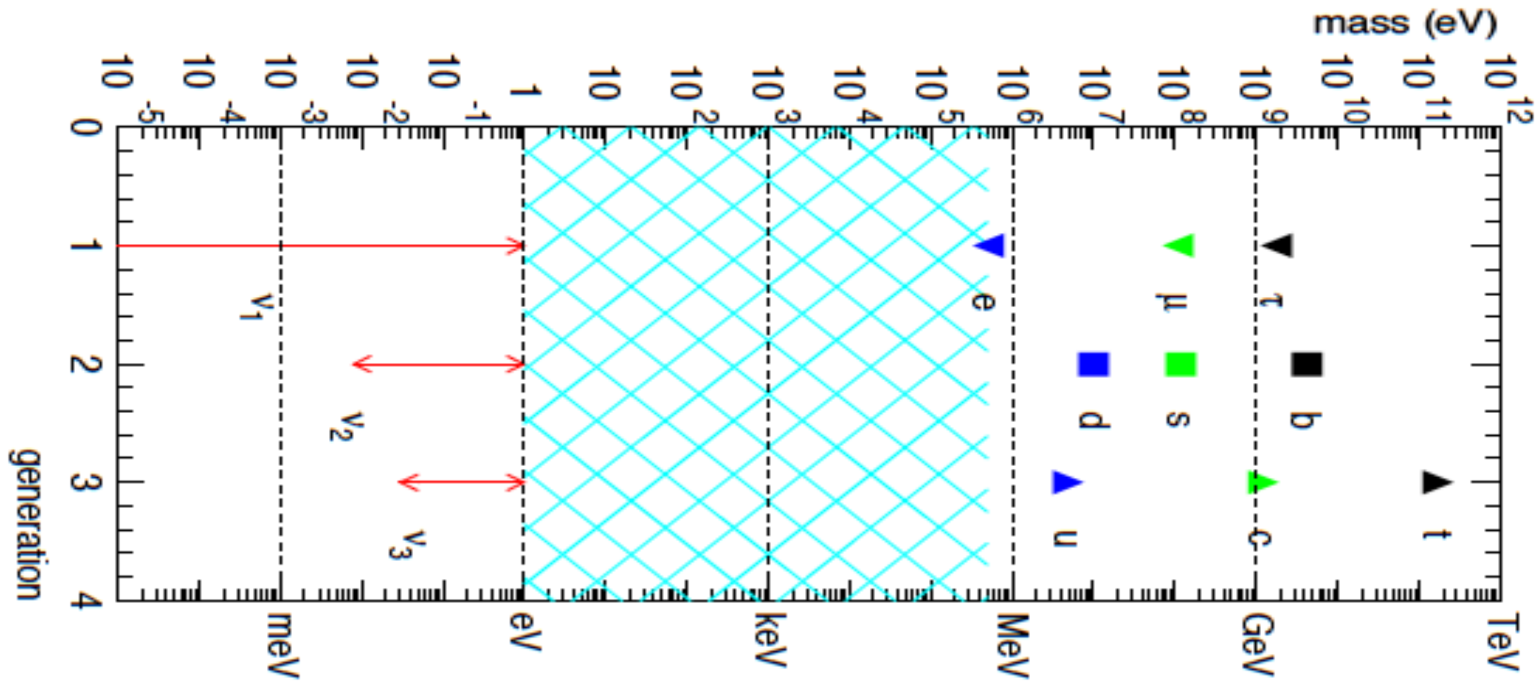
The goal is to achieve the CKM level precision for the PMNS
A Long Journey Ahead! But, the precision is improving rapidly for PMNS

Good News: There may be large CPV in neutrino sector than quark sector

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta_{CP}$$

$J_{CKM} \sim 3 \times 10^{-5}$, whereas J_{PMNS} can be as large as 3×10^{-2}

The Two Fundamental Questions



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

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

Why are lepton mixings so different from quark mixings?

The Flavor Puzzle!

Motivation

Do we understand the origin of patters of neutrino oscillation parameters revealed by oscillation experiments? Very challenging problem!

It is a part of the more general fundamental problem in particle physics of understanding the origin of flavor – the patterns of quark, charged lepton and ν masses, and quark and lepton mixing

High-precision measurements of oscillation parameters may shed light on the origin of observed pattern of ν mixing and flavor

This would be possible if the observed form of neutrino (and possibly quark) mixings were determined by an underlying discrete symmetry

Striking features of discrete symmetry approach to ν mixing & lepton flavor:

→ It leads to fixed predictions of some ν mixing angles and δ_{CP}

→ Interesting correlations among some of the mixing angles and/or between mixing angles and δ_{CP} – known as neutrino mixing **'sum rules'**

$$U_{\text{PMNS}} = U_e^\dagger U_\nu$$

$$U_e^\dagger M_e M_e^\dagger U_e = \text{diag}\left(m_e^2, m_\mu^2, m_\tau^2\right) \qquad U_\nu^T M_\nu U_\nu = \text{diag}\left(m_1, m_2, m_3\right)$$

M_e (M_ν) is the charged lepton (Majorana neutrino) mass matrix

U_e (U_ν) diagonalizes the charged lepton (neutrino) mass matrix

Idea: the main contribution to the PMNS matrix comes from U_ν

U_ν is assumed to be fixed (up to phases from the right)

$$U_\nu = \tilde{U}_\nu Q_0 \,, \quad Q_0 = \text{diag}\left(1, e^{i\frac{\xi_{21}}{2}}, e^{i\frac{\xi_{31}}{2}}\right)$$

$\tilde{U}_\nu$ is assumed to have a symmetry form which is dictated by, or associated with, a flavour (discrete) symmetry, e.g., A_4, S_4, A_5, T′

The Framework

$\tilde{U}_\nu$, in particular, has one of the following symmetry forms: tri-bimaximal (**TBM**), bimaximal (**BM**), golden ratio A (**GRA**), golden ration B (**GRB**), hexagonal (**HG**) ……

$$U_{\rm BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix} \qquad U_{\rm TBM} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \\ -\sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix}$$

$$\tilde{U}_\nu = R_{23}(\theta^\nu_{23})\, R_{12}(\theta^\nu_{12})\,, \quad \theta^\nu_{23} = -\pi/4$$

Symmetry form	θ^ν_{12} [°]
BM S_4	45
TBM A_4/S_4	$\arcsin(1/\sqrt{3}) \approx 35$
GRA A_5	$\arctan(1/\phi) \approx 32$
GRB D_{10}	$\arccos(\phi/2) = 36$
HG D_{12}	30

golden ratio:

$\phi = (1+\sqrt{5})/2$

$\theta^\nu_{13} = 0 \Rightarrow$ corrections needed!

Charged lepton corrections, i.e., non-trivial matrix U_e diagonalising the charged lepton mass matrix

$$U_e^\dagger = \tilde{U}_e^\dagger \, \Psi \,, \quad \Psi = \mathrm{diag}\left(1, e^{-i\psi}, e^{-i\omega}\right)$$

$\tilde{U}_e$ is, in general, a CKM-like 3 × 3 unitary matrix Frampton, Petcov, Rodejohann, *NPB* **687** (2004) 31

The considered set-up corresponds to pattern where

$$G_e \text{ is fully broken and } G_\nu = Z_n,\ n > 2 \text{ or } Z_n \times Z_m,\ n, m \geq 2$$

Examples: $\tilde{U}_e = R_{23}^{-1}(\theta_{23}^e)\, R_{12}^{-1}(\theta_{12}^e)$ Marzocca, Petcov, Romanino, Sevilla, *JHEP* **05** (2013) 073; Petcov, *NPB* **892** (2015) 400

$$\cos\delta = \frac{\tan\theta_{23}}{\sin 2\theta_{12} \sin\theta_{13}} \left[\cos 2\theta_{12}^\nu + \left(\sin^2\theta_{12} - \cos^2\theta_{12}^\nu\right)\left(1 - \cot^2\theta_{23}\, \sin^2\theta_{13}\right)\right]$$

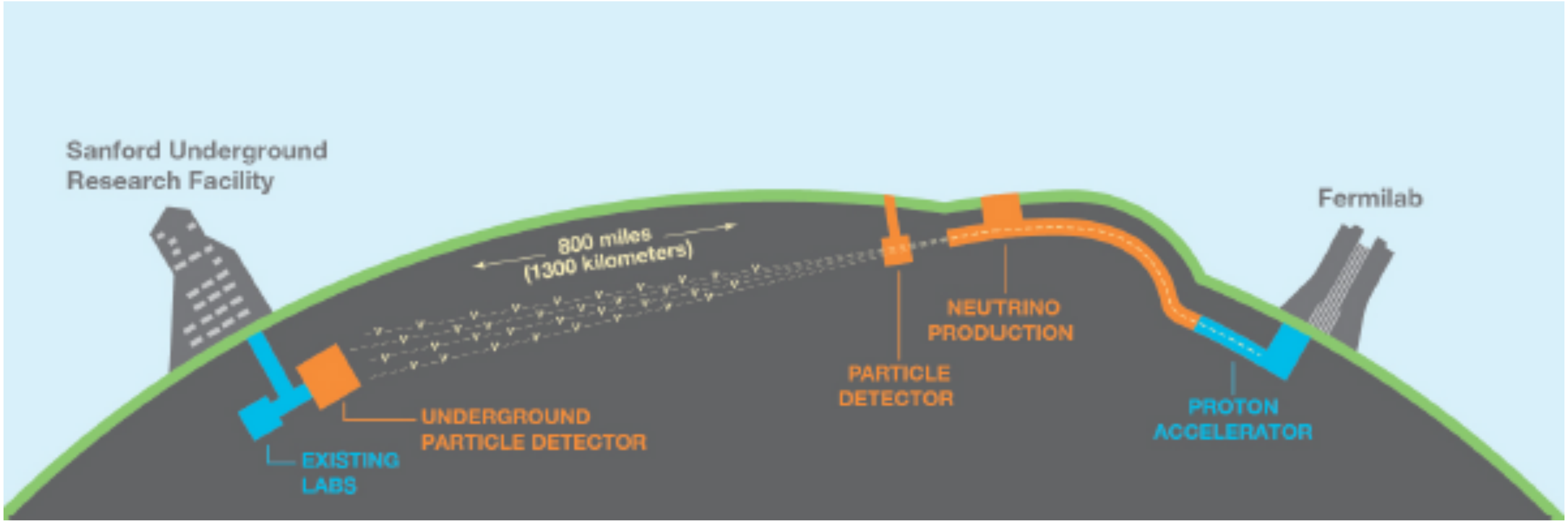
Petcov, *NPB* **892** (2015) 400

Predictions for CP-Phase and its intervals

Sum Rule: $$\cos\delta_{CP} = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\,\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + \left(\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12}\right)\left(1 - \cot^2\theta_{23}\,\sin^2\theta_{13}\right)\right]$$

Symmetry form	θ^{ν}_{12} [°]	$\cos\delta_{CP}$	δ_{CP} [°]
BM	45	unphysical	unphysical
TBM	$\arcsin(1/\sqrt{3}) \approx 35$	−0.16	$99 \vee 261$
GRA	$\arctan(1/\phi) \approx 32$	0.21	$78 \vee 282$
GRB	$\arccos(\phi/2) = 36$	−0.24	$104 \vee 256$
HG	30	0.39	$67 \vee 293$

Symmetry form	Intervals for δ_{CP} [°] obtained varying		
	θ_{12} in 3σ	θ_{23} in 3σ	θ_{13} in 3σ
BM	$150–180 \vee 180–210$	unphysical	unphysical
TBM	$79–119 \vee 241–281$	$98–107 \vee 253–262$	$98–101 \vee 259–262$
GRA	$57–95 \vee 265–303$	$76–78 \vee 282–284$	$77.6–77.9 \vee 282.1–282.4$
GRB	$84–125 \vee 235–276$	$102–114 \vee 246–258$	$103–106 \vee 254–257$
HG	$45–84 \vee 276–315$	$60–68 \vee 292–300$	$66–68 \vee 292–294$



www.dunescience.org

Deep Underground Neutrino Experiment planned in the USA

Liquid Argon TPC of 35 kt (fiducial mass)

Total 6×10^{21} p.o.t. (5 years in ν mode and 5 years in anti-ν mode)

Total exposure of 248 kt·MW·year

Tokai to Hyper-Kamiokande Experiment planned in the Japan

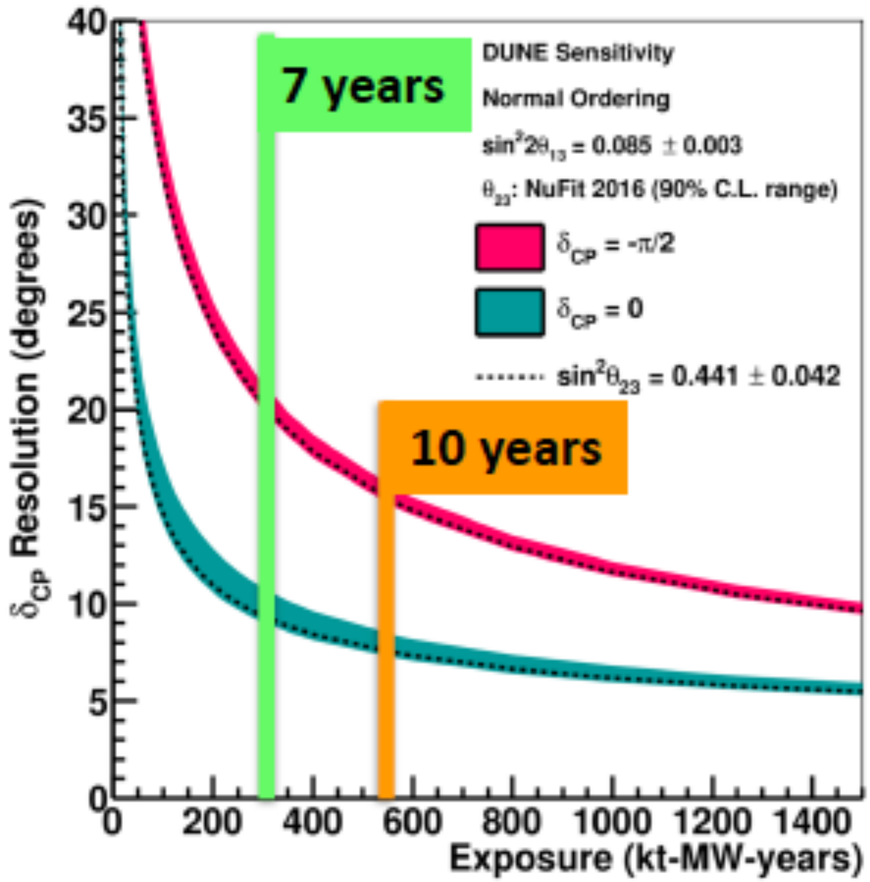
Water Cherenkov detector of 560 kt (fiducial mass)

Total 15.6×10^{21} p.o.t. (ν and anti-ν run-time ratio is 1:3)

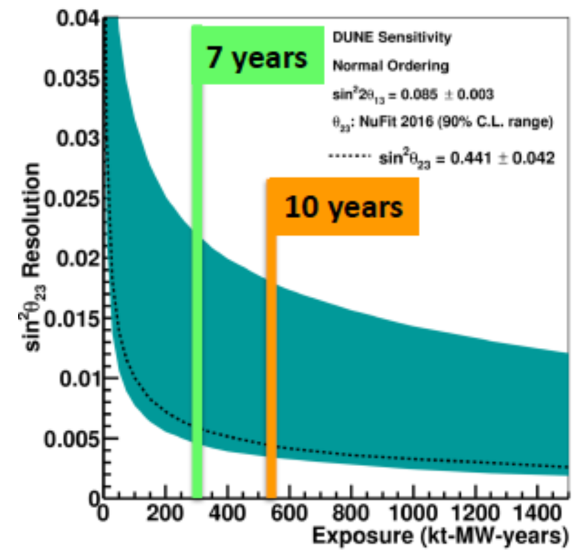
Total exposure of 4200 kt·MW·year

Precise Measurements of Oscillation Parameters

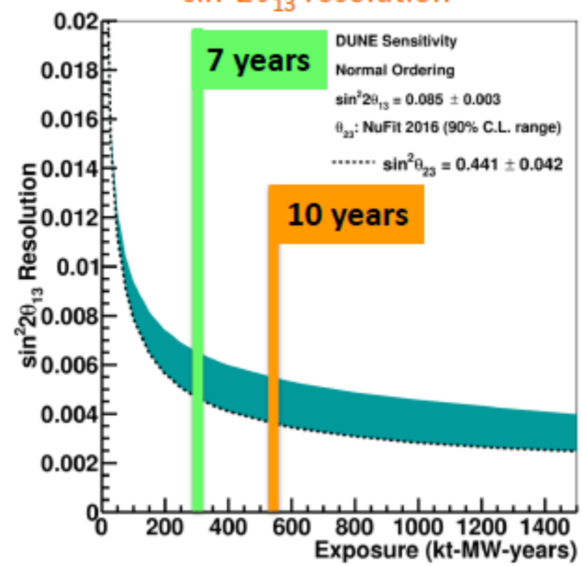
δ_{CP} Resolution



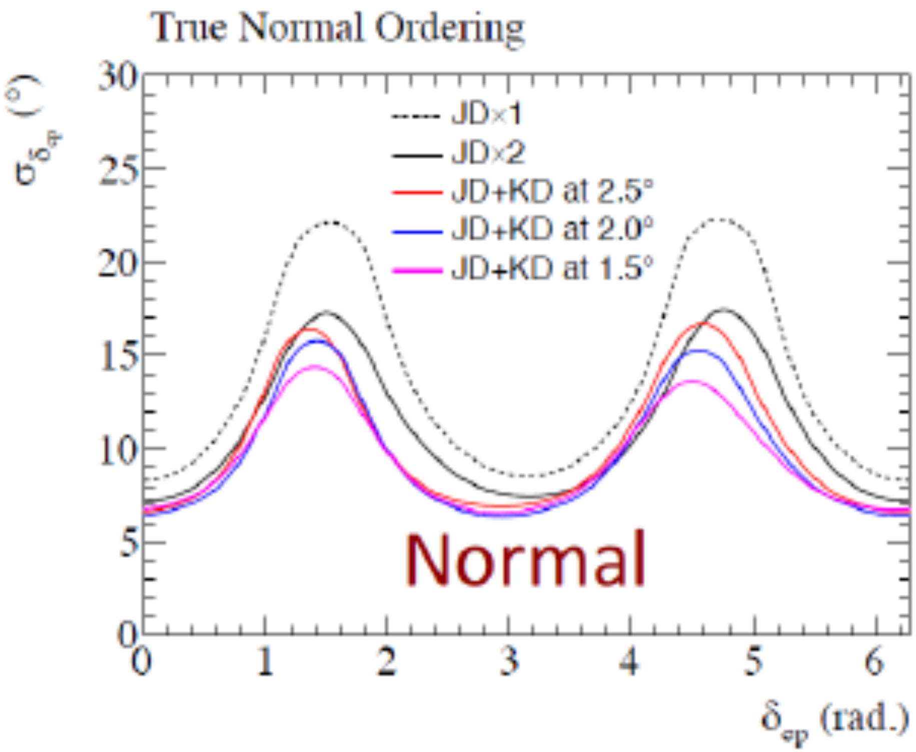
$\sin^2\theta_{23}$ resolution

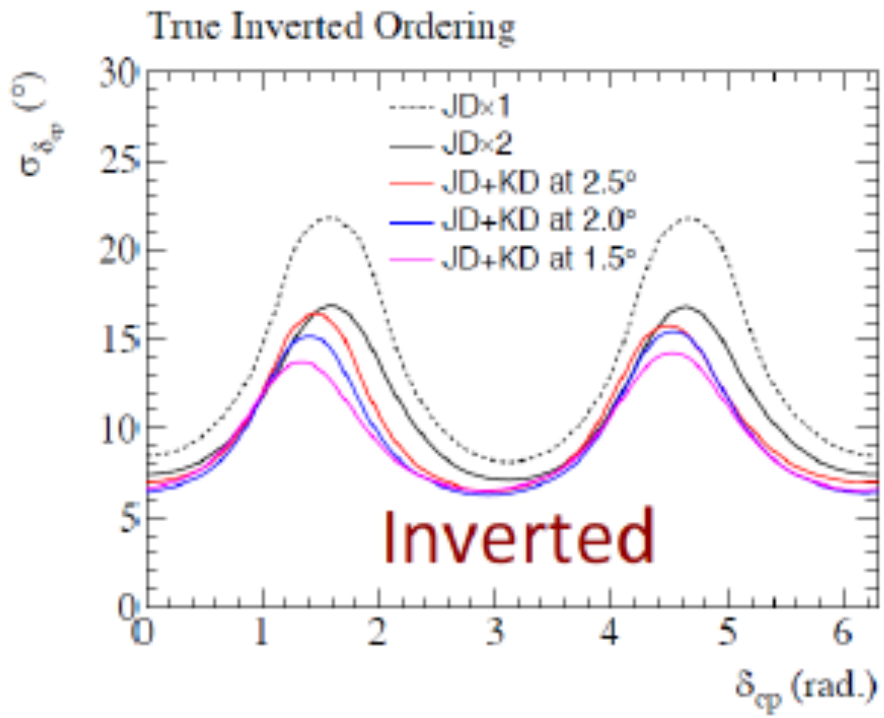


$\sin^2 2\theta_{13}$ resolution



DUNE CDR (see also talk by Nuno Barros)

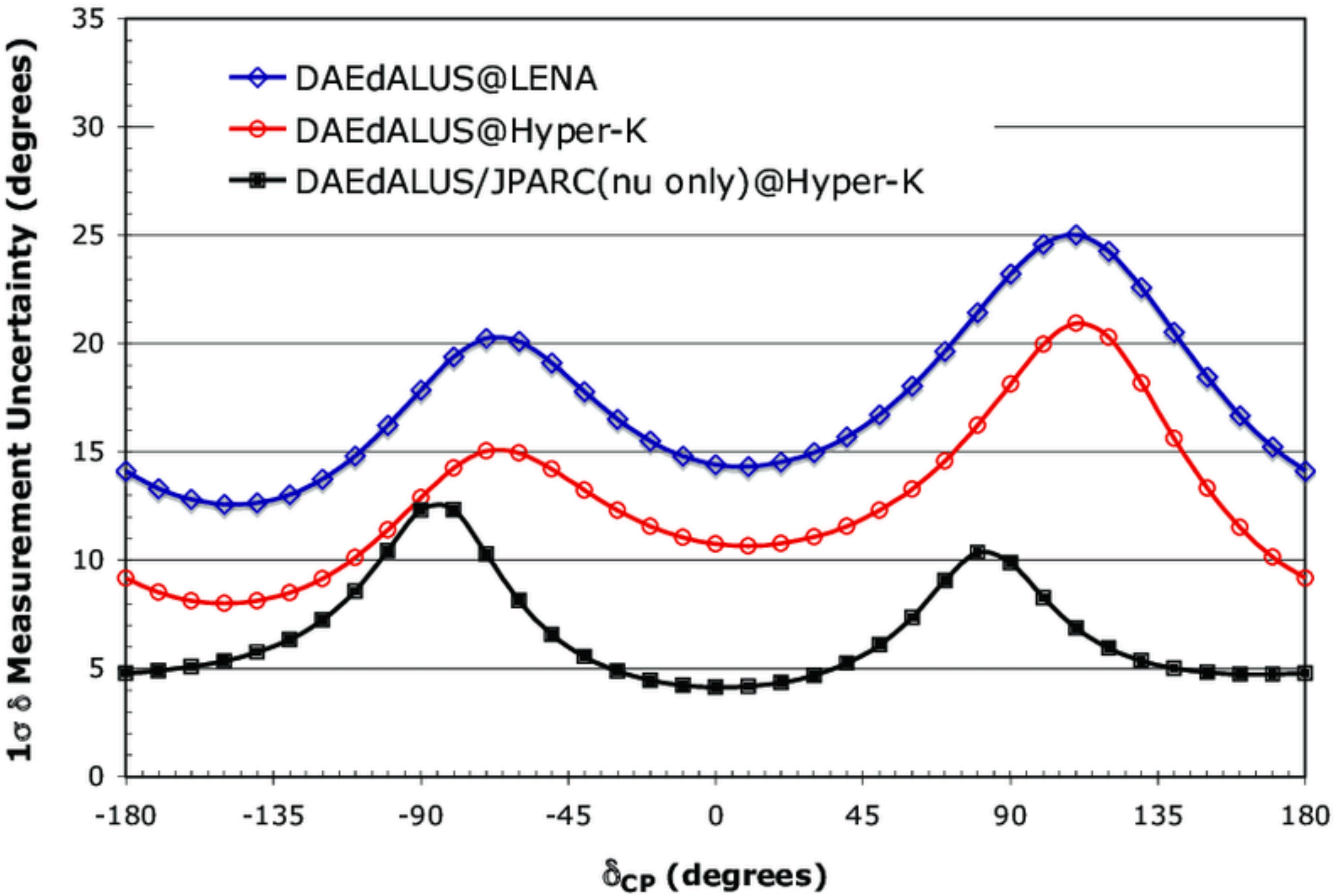




JD x 1:	**HK 1 tank, Japan**	**σ(δ) = 22 deg**
JD x 2:	**HK 2 tanks, Japan**	**σ(δ) = 17 deg**
JD + KD:	**HK 1tank (Japan + HK 1 tank (Korea)**	**σ(δ) = 13-14 deg**

arXiv:1611.06118 (see also talk by Yury Kudenko)

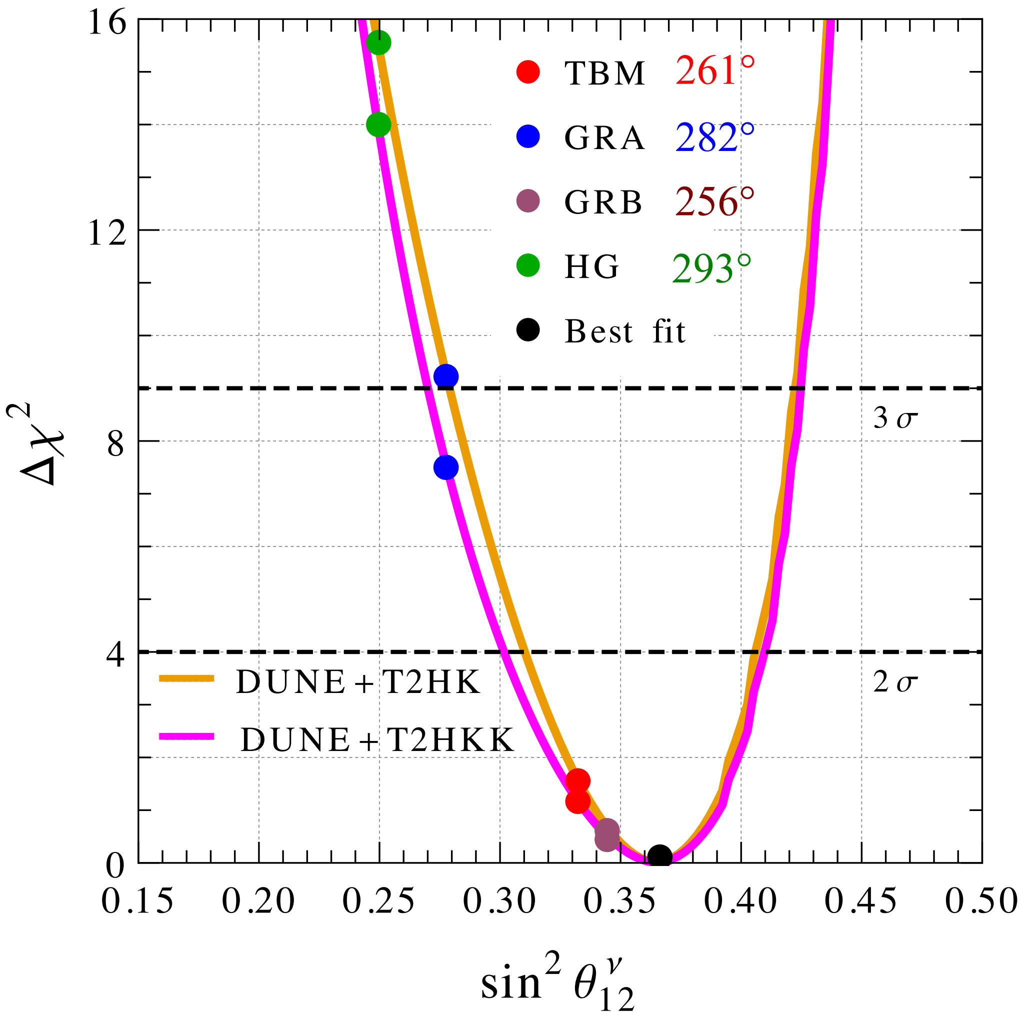
Precise Measurements of Oscillation Parameters



DAEδALUS/IsoDAR Collaboration (see talk by Spencer N. Axani at NuFact 2018)

Compatibility Among Symmetry Forms and Present Best-fit Values

Sum Rule: $\cos\delta_{CP} = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\,\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + \left(\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12}\right)\left(1 - \cot^2\theta_{23}\,\sin^2\theta_{13}\right)\right]$



black dot: current best-fit value of $\delta_{CP} = 248°$ which means $\sin^2\theta^{\nu}_{12} = 0.364$ $(\Delta\chi^2 = 0)$

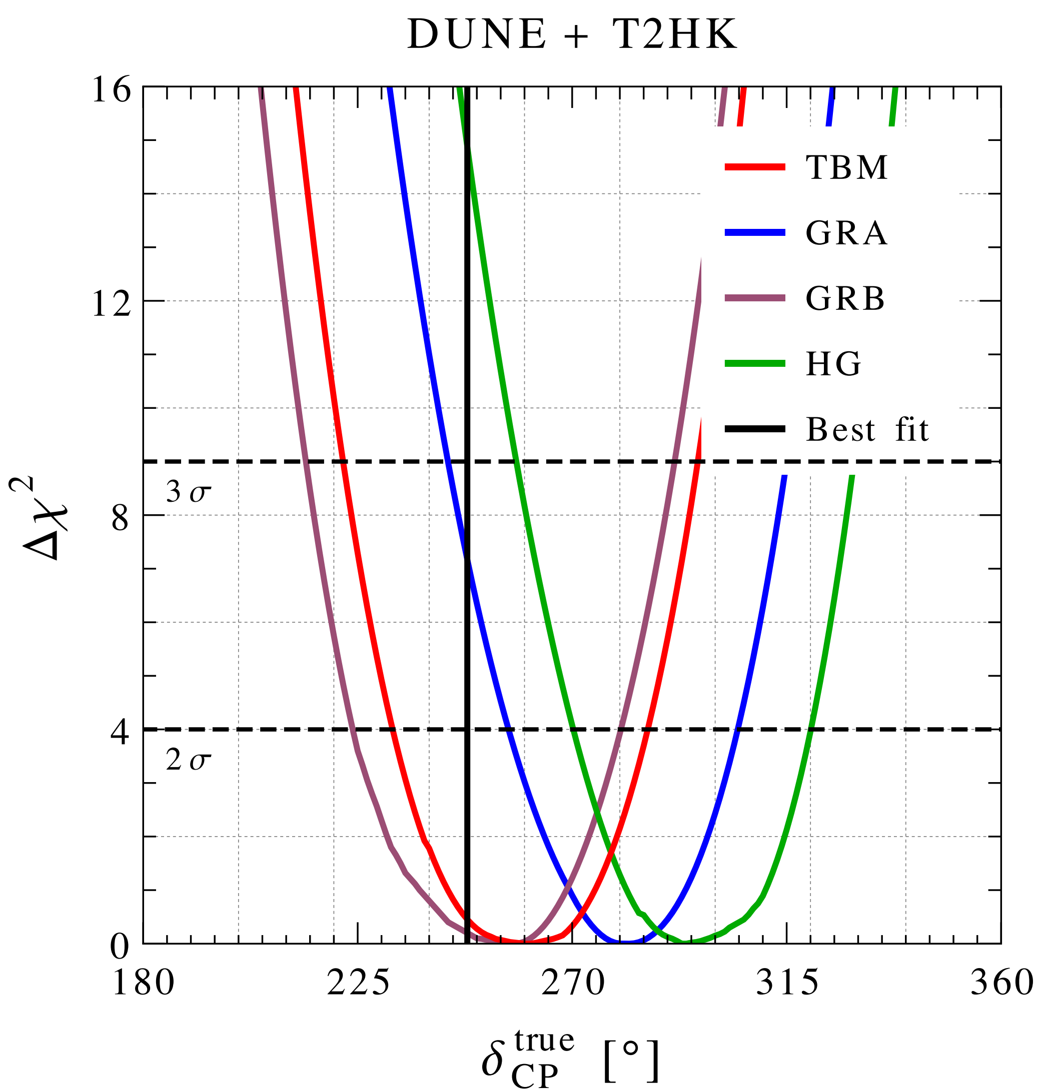
GRB and TBM compatible at around 1σ C.L.

GRA and HG disfavored at more than 2.7σ and 3.7σ C.L.

the coloured dots corresponding to the values of $\sin^2\theta^{\nu}_{12}$ which characterise the GRB (violet), TBM (red), GRA (blue) and HG (green) symmetry forms.

Compatibility with Any True Value of the CP-Phase

Sum Rule: $\cos\delta_{CP} = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + \left(\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12}\right)\left(1-\cot^2\theta_{23}\sin^2\theta_{13}\right)\right]$



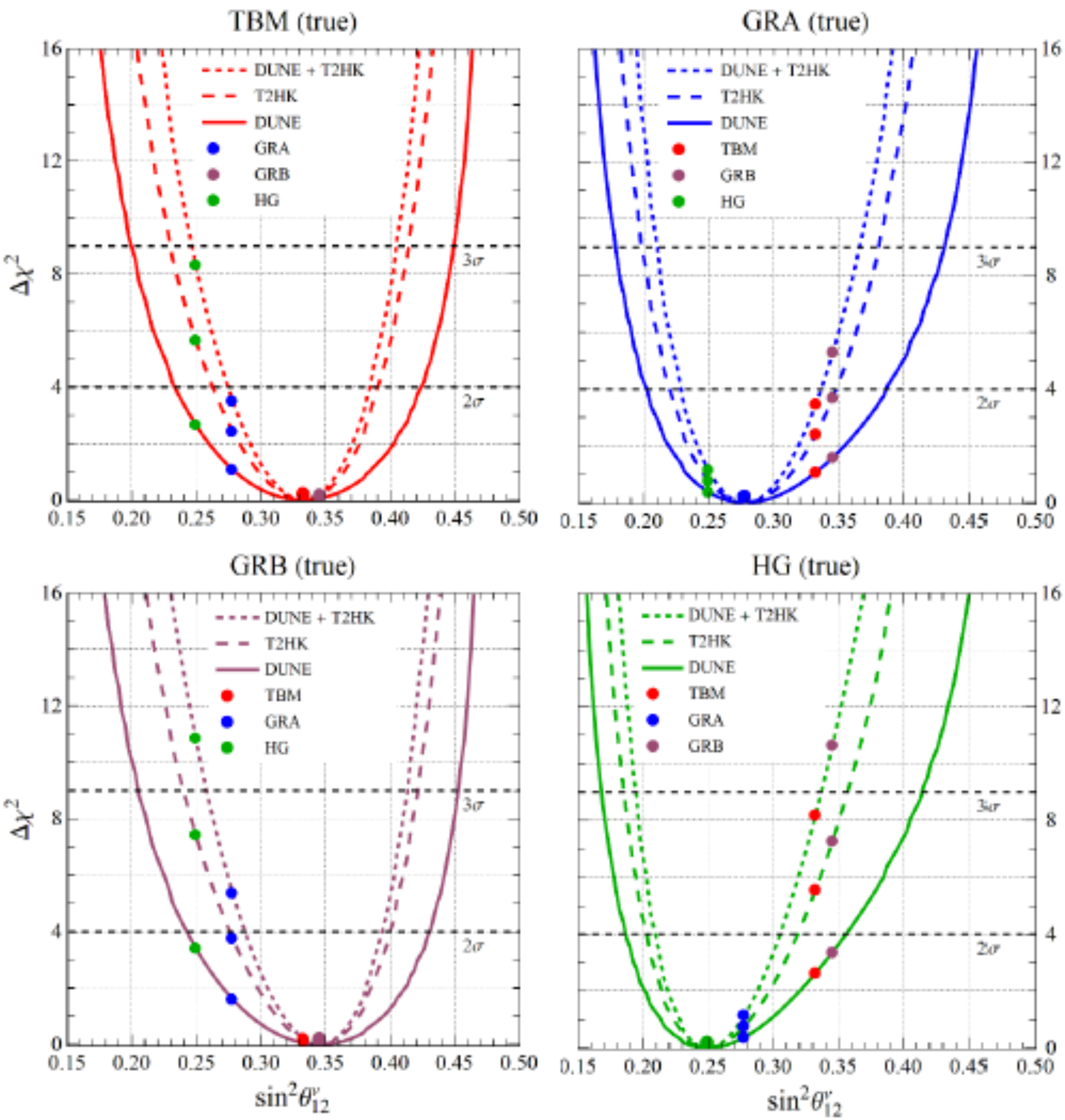
Black vertical line: current best-fit value of $\delta_{CP} = 248°$ for NO

For each symmetry form, a significant region in δ_{CP} gets disfavored at > 3σ

Draw a vertical line at any possible true δ_{CP} to see at what C.L. any given symmetry form is compatible with that true δ_{CP}

A Gaussian prior of 0.7% (at 1σ) on $\sin^2\theta_{12}$ as expected from JUNO is imposed

Distinguishing Between Various Symmetry Forms



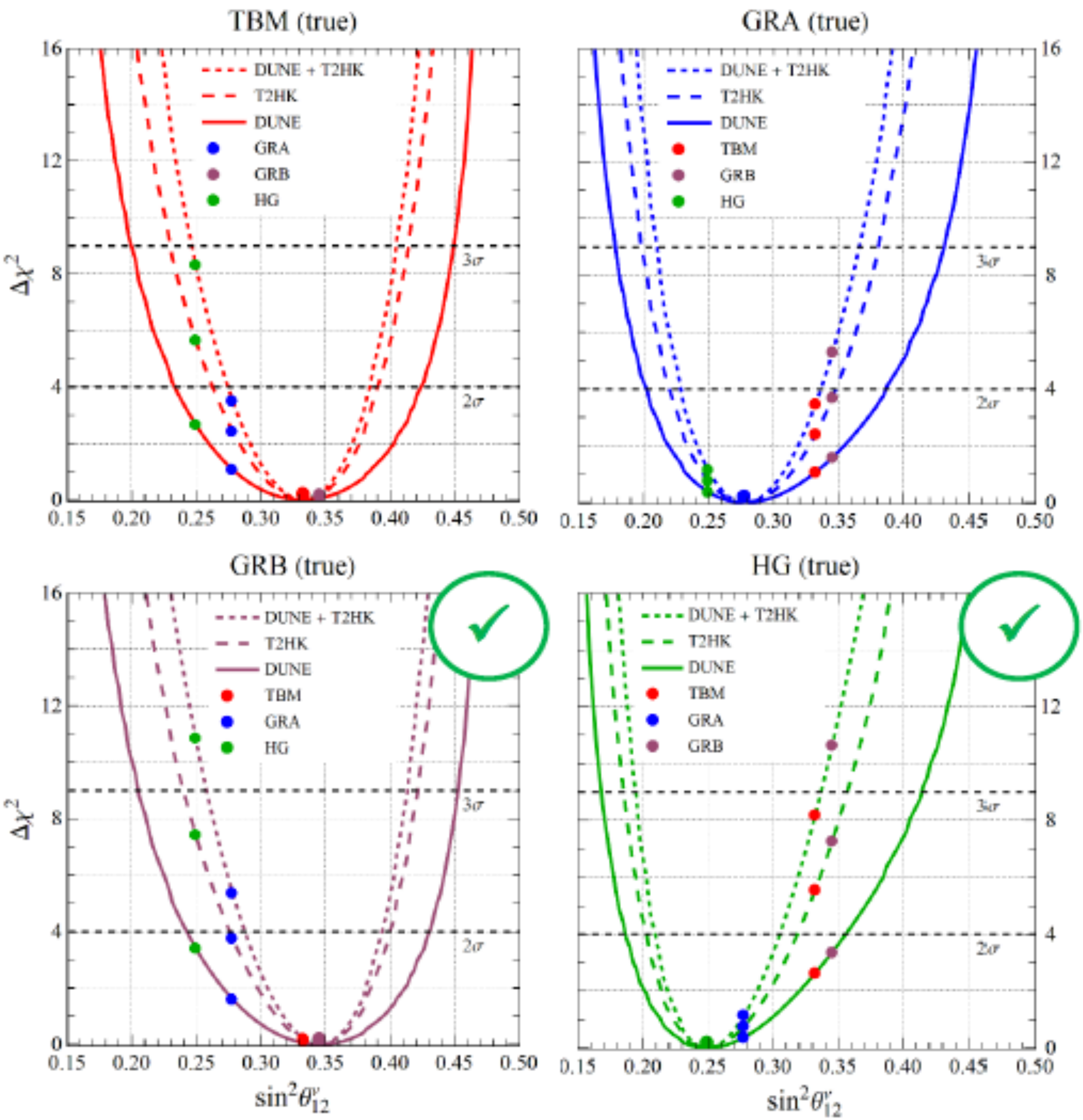
TBM → 261° ($\sin^2\theta_{12}^\nu \approx 0.33$)

GRA → 282° ($\sin^2\theta_{12}^\nu \approx 0.28$)

GRB → 256° ($\sin^2\theta_{12}^\nu \approx 0.35$)

HG → 293° ($\sin^2\theta_{12}^\nu \approx 0.25$)

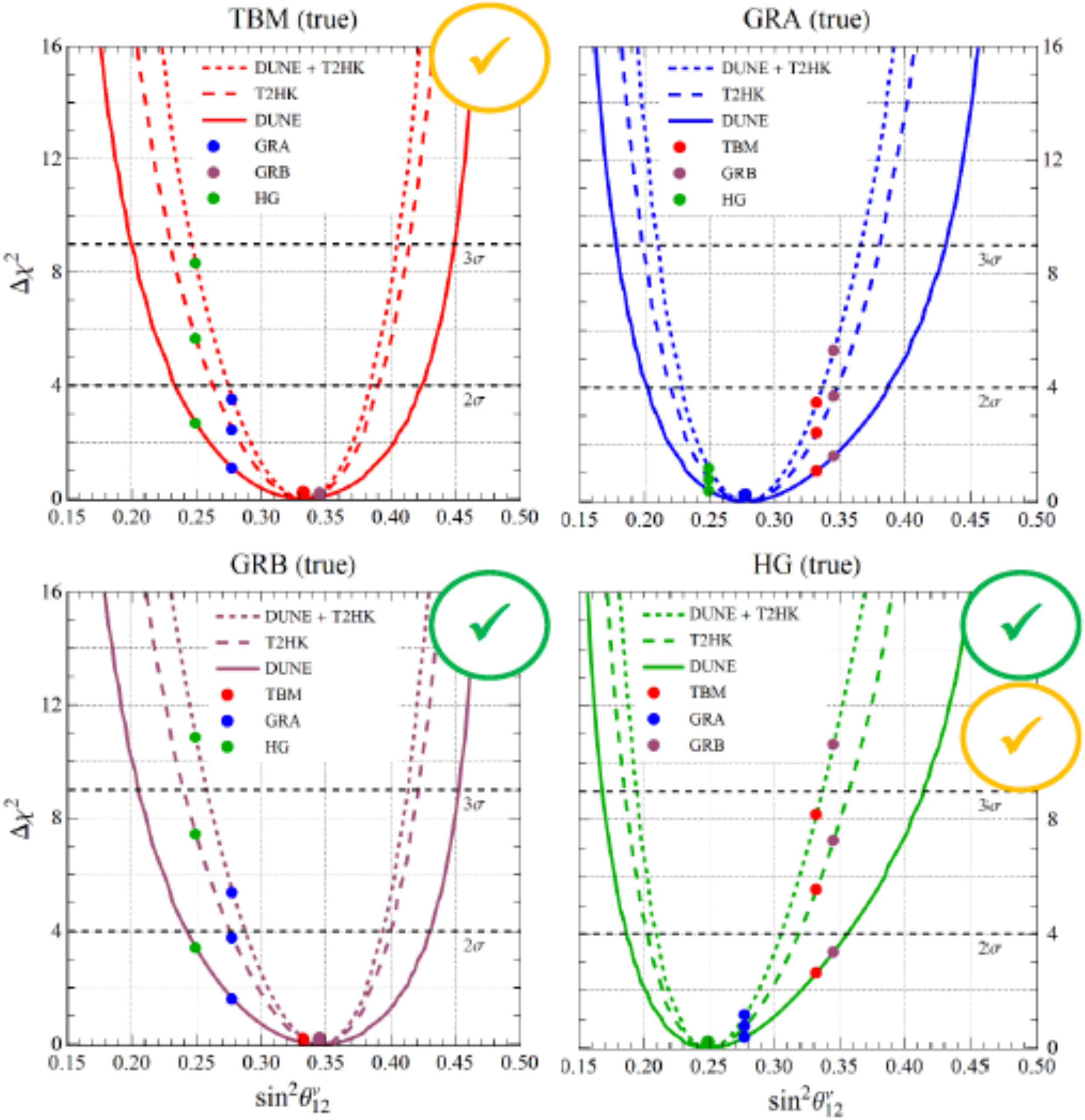
Distinguishing Between Various Symmetry Forms



DUNE + T2HK:

GRB–HG $> 3\sigma$

Distinguishing Between Various Symmetry Forms

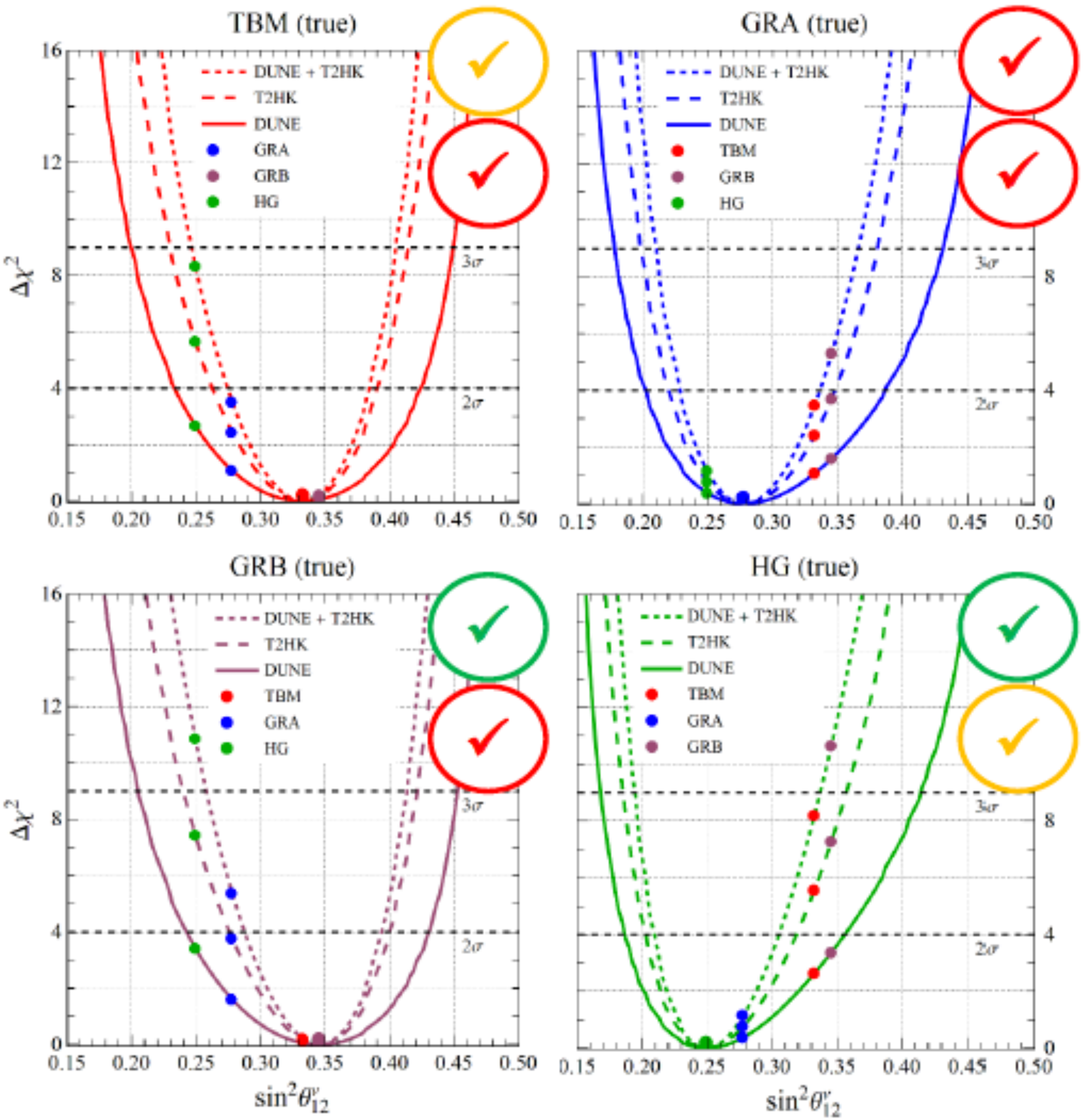


DUNE + T2HK:

GRB–HG $> 3\sigma$

TBM–HG $\lesssim 3\sigma$

Distinguishing Between Various Symmetry Forms



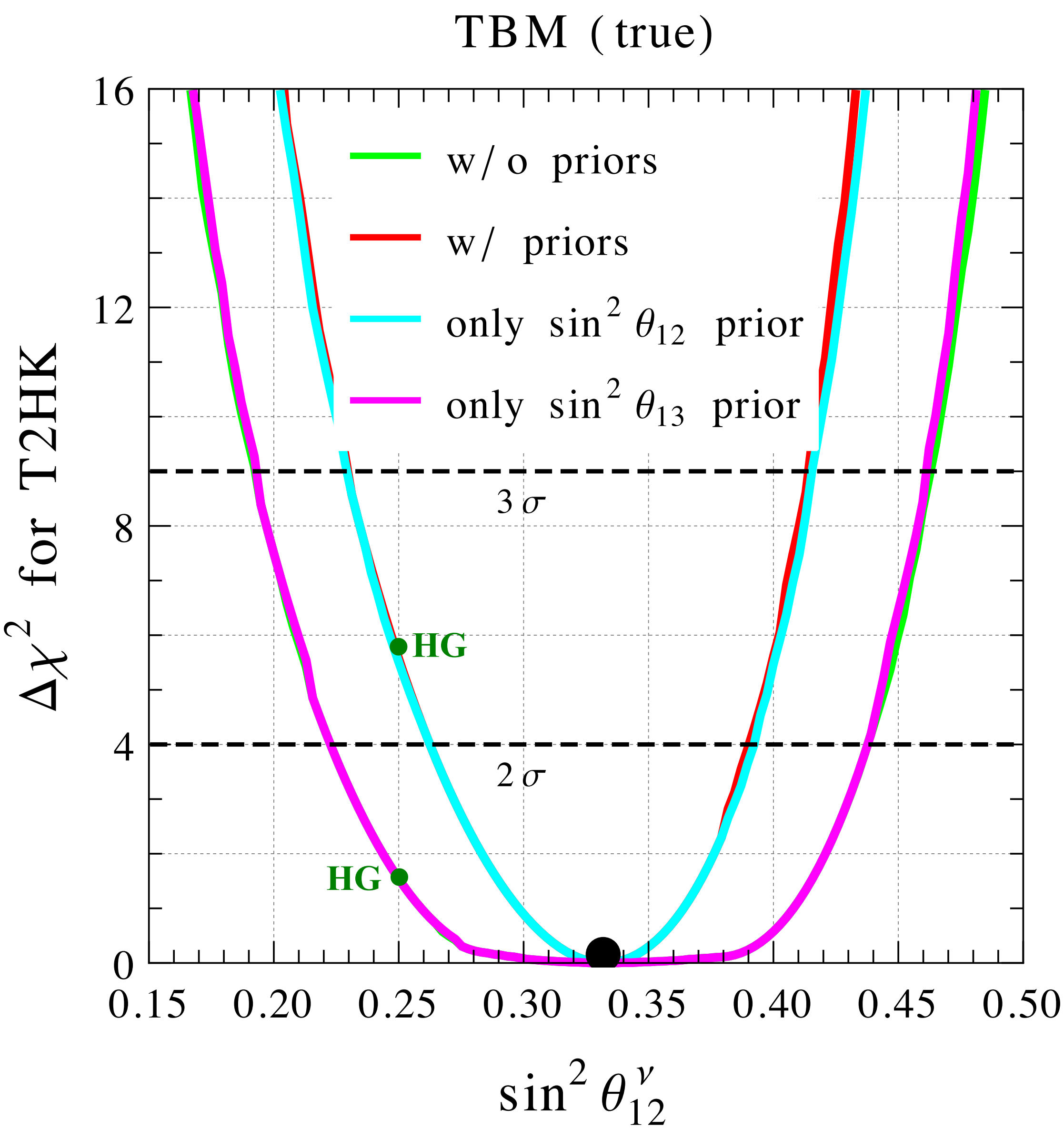
DUNE + T2HK:

GRB–HG $> 3\sigma$

TBM–HG $\lesssim 3\sigma$

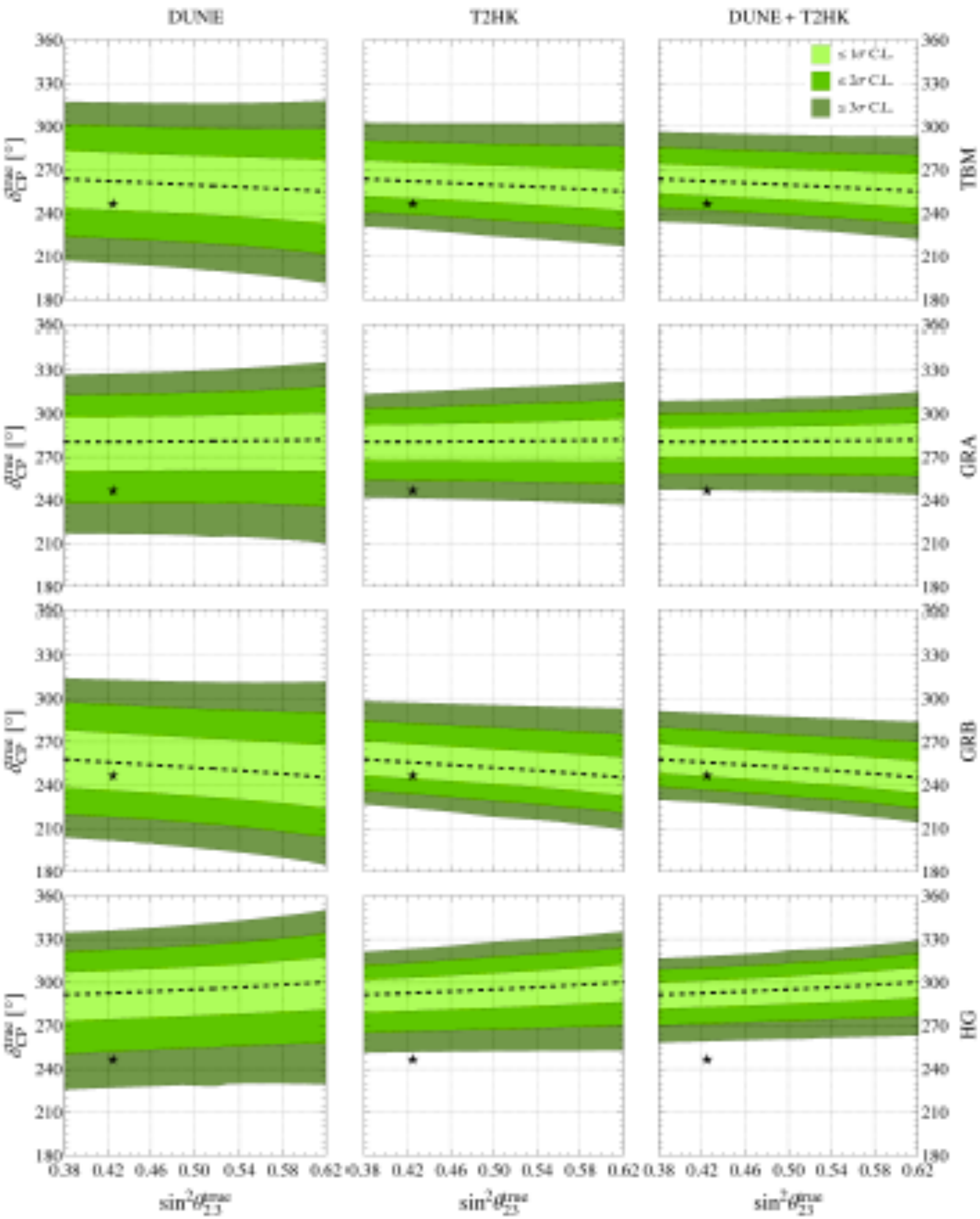
GRB–GRA $\gtrsim 2\sigma$

TBM–GRA $\lesssim 2\sigma$



- Gaußian prior of 0.7% (at 1σ) on $\sin^2\theta_{12}$ as expected from JUNO
- Gaußian prior of 3% (at 1σ) on $\sin^2\theta_{13}$ as expected by the end of Daya Bay's run

← Effect of the prior on $\sin^2\theta_{12}$ important synergy between JUNO and LBL experiments



Star indicates the present best-fit value

For all symmetry forms: a significant part of the parameter space gets disfavored at more than 3σ for DUNE+T2HK

Concluding Remarks

Asked what single mystery, if he could choose, he would like to see solved in his lifetime, Weinberg doesn't have to think for long: he wants to be able to explain the observed pattern of quark and lepton masses

From "*Model Physicist*", *CERN Courier*, 13 October 2017

www.cerncourier.com

Let us build next-generation high-precision machines to measure the neutrino mass-mixing parameters with utmost accuracy to shed light on the long-standing flavor puzzle!

Thank you!

Details of Statistical Analysis: Long-baseline Experiments

Poissonian χ^2 function:

$$\chi^2 = \min_{\xi_s,\xi_b}\left[2\sum_{i=1}^{n}(\tilde{y}_i - x_i - x_i \ln\frac{\tilde{y}_i}{x_i}) + \xi_s^2 + \xi_b^2\right]$$

n is the total number of reconstructed energy bins

Total number of bckg events

$$\tilde{y}_i(\{\omega\},\{\xi_s,\xi_b\}) = N_i^{th}(\{\omega\})\,[1+\pi^s\xi_s] + N_i^b(\{\omega\})\,[1+\pi^b\xi_b]$$

Predicted number of CC signal events in the i-th energy bin for a set of oscillation parameters ω

Systematic errors on the signal and bckg events: 5% (5%) and 5% (10%) for DUNE (T2HK)

"Pulls" due to the systematic error on the signal and bckg

$$x_i = N_i^{ex} + N_i^b$$

Number of observed CC events

Number of bckg events

$$\chi^2_{\rm total} = \chi^2_{\nu_\mu\to\nu_e} + \chi^2_{\overline{\nu}_\mu\to\overline{\nu}_e} + \chi^2_{\nu_\mu\to\nu_\mu} + \chi^2_{\overline{\nu}_\mu\to\overline{\nu}_\mu} + \chi^2_{\rm prior}$$

$$\chi^2_{\rm prior} = \left(\frac{\sin^2\theta_{12} - \sin^2\theta_{12}^{\rm true}}{\sigma(\sin^2\theta_{12})}\right)^2 + \left(\frac{\sin^2\theta_{13} - \sin^2\theta_{13}^{\rm true}}{\sigma(\sin^2\theta_{13})}\right)^2$$

Event Rates at DUNE and T2HK

Number of expected electron events in the i-th energy bin in the detector:

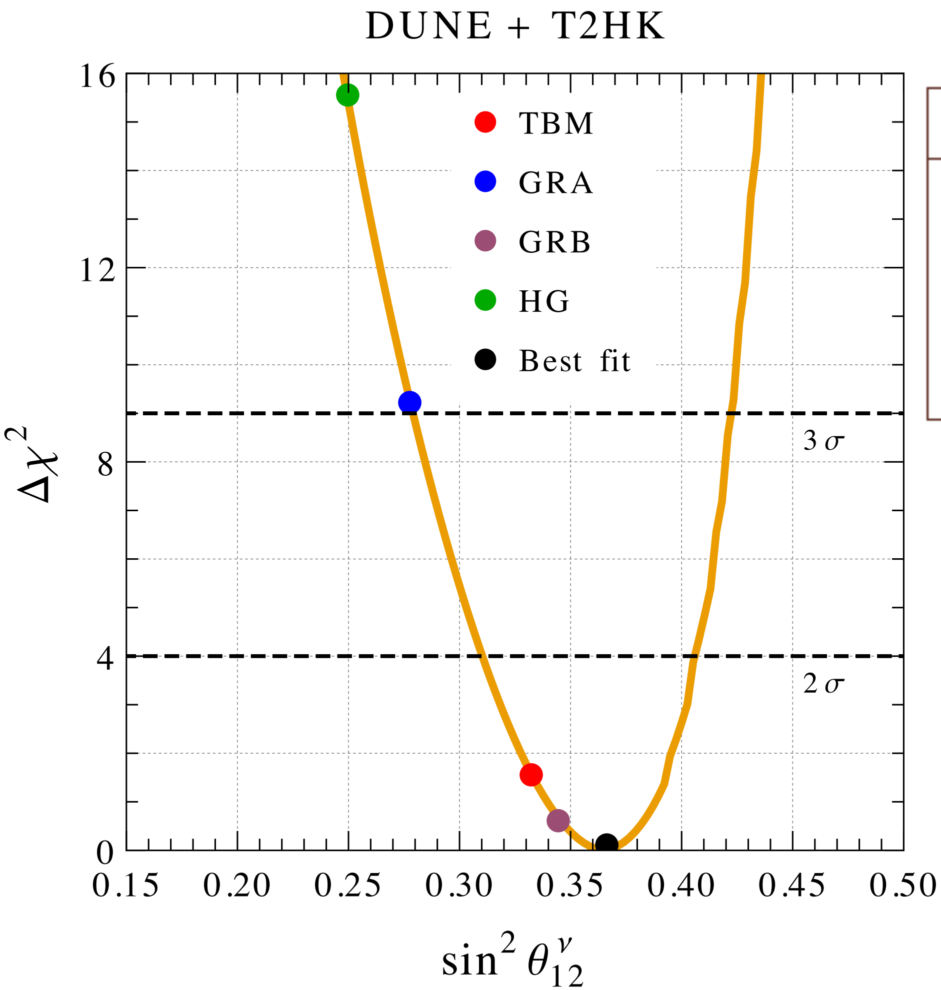
$$N_i = T\, n_n\, \epsilon \int_0^{E_{\max}} dE \int_{E_{A_i}^{\min}}^{E_{A_i}^{\max}} dE_A\, \phi(E)\, \sigma_{\nu_e(E)}\, R(E, E_A)\, P_{\mu e}(E)$$

Mode (Channel)	**DUNE (248 kt · MW · year)**		**T2HK (4200 kt · MW · year)**	
	Signal	Background	Signal	Background
	CC	Int+Mis-id+NC=Total	CC	Int+Mis-id+NC=Total
ν (appearance)	614	125+29+24=178	2852	530+13+173=716
ν (disappearance)	5040	0+0+24=24	20024	12+44+1003=1059
$\bar{\nu}$ (appearance)	60	43+10+7=60	1383	627+11+265=903
$\bar{\nu}$ (disappearance)	1807	0+0+7=7	27447	14+5+1287=1306

Total signal and background event rates for DUNE and T2HK set-ups assuming NO, $\delta = 248^\circ$, and $\sin^2\theta_{23} = 0.425$. All other oscillation parameters are fixed to their best fit values corresponding to NO. Here "Int" means intrinsic beam contamination, "Mis-id" represents mis-identified muon events.

Oscillation Data and Neutrino Mixing Schemes

Sum Rule: $\cos\delta_{CP} = \frac{\tan\theta_{23}}{\sin 2\theta_{12}\sin\theta_{13}}\left[\cos 2\theta^{\nu}_{12} + (\sin^2\theta_{12} - \cos^2\theta^{\nu}_{12})(1 - \cot^2\theta_{23}\sin^2\theta_{13})\right]$



Symmetry form	θ^{ν}_{12} [°]	$\cos\delta_{CP}$	δ_{CP} [°]
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$U_{PMNS} = U_e^{\dagger} U_{\nu}$ golden ratio: $\phi = (1+\sqrt{5})/2$

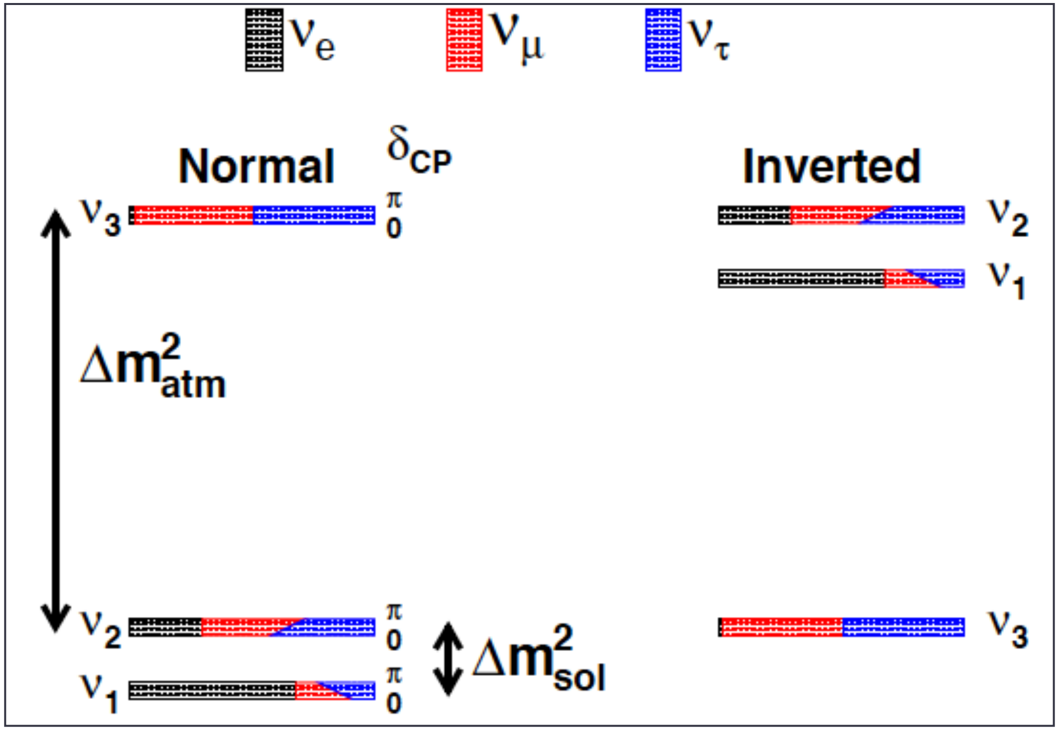
black dot: current best-fit value of $\delta_{CP} = 248°$ which means $\sin^2\theta^{\nu}_{12} = 0.364$ $(\Delta\chi^2 = 0)$

Agarwalla, Chatterjee, Petcov, Titov, arXiv:1711.02107

the coloured dots corresponding to the values of $\sin^2\theta^{\nu}_{12}$ which characterise the GRB (violet), TBM (red), GRA (blue) and HG (green) symmetry forms.

Neutrino Mass Hierarchy: Important Open Question

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



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

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

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

We currently do not know which neutrino is the heaviest

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

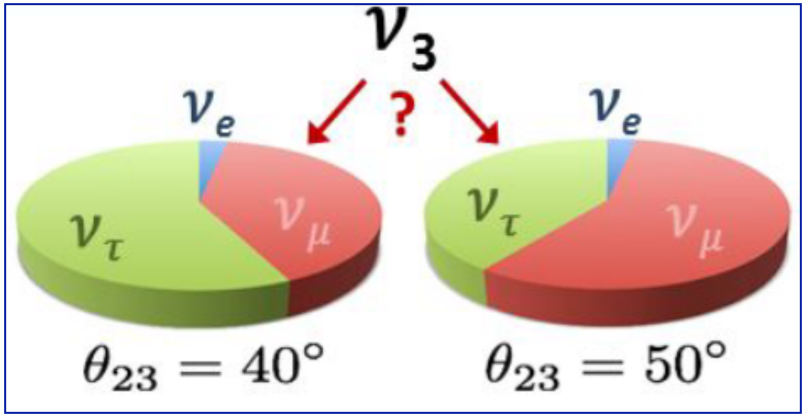
Octant of 2-3 Mixing Angle: Important Open Question

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

→ *If $\sin^2 2\theta_{23}$ differs from 1 (recent hints), we get two solutions for θ_{23}*

→ *One in lower octant (LO: $\theta_{23} < 45$ degree)*

→ *Other in higher octant (HO: $\theta_{23} > 45$ degree)*



Octant ambiguity of θ_{23}

Fogli and Lisi, hep-ph/9604415

ν_μ to ν_e oscillation channel can break this degeneracy
preferred value would depend on the choice of neutrino mass hierarchy

Leptonic CP-violation: Important Open Question

Is CP violated in the neutrino sector, as in the quark sector?

Mixing can cause CPV in ν sector, provided $\delta_{CP} \neq 0°$ and $180°$

Need to measure the CP-odd asymmetries:

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

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4J_{CP} \times \left[\sin\left(\frac{\Delta m^2_{21}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{32}}{2E}L\right) + \sin\left(\frac{\Delta m^2_{13}}{2E}L\right)\right]$$

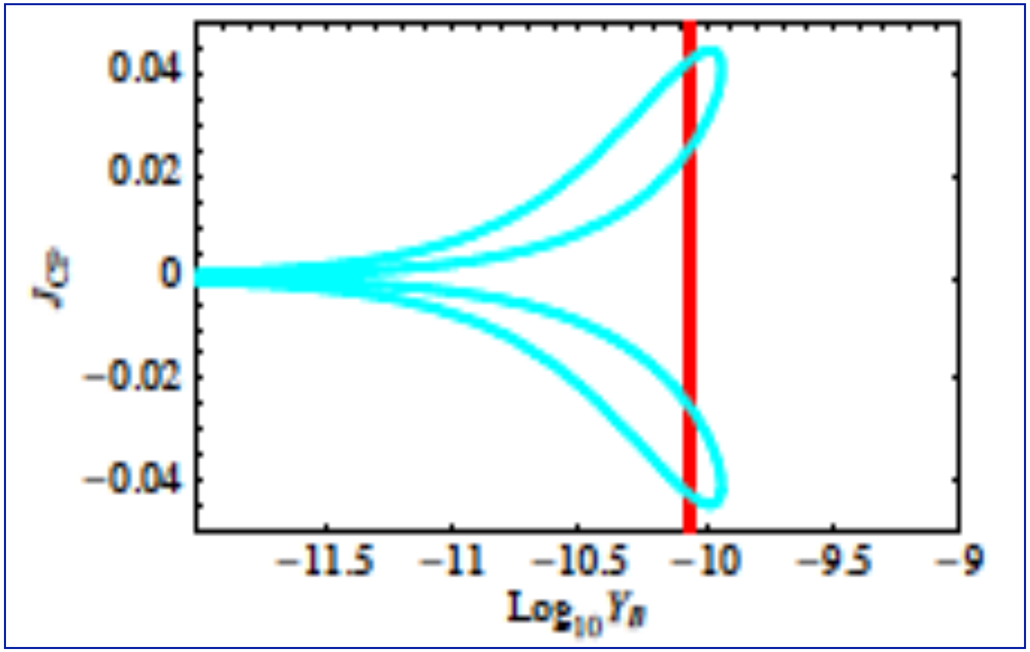
Jarlskog CP-odd Invariant → $J_{CP} = \frac{1}{8}\cos\theta_{13}\,\sin 2\theta_{13}\,\sin 2\theta_{23}\,\sin 2\theta_{12}\,\sin\delta_{CP}$

Three-flavor effects are key for CPV, need to observe interference

Conditions for observing CPV:

1) *Non-degenerate masses* ✔
2) *Mixing angles $\neq 0°$ and $90°$* ✔
3) *$\delta_{CP} \neq 0°$ and $180°$ (Hints)*

Large CPV: Boost for Leptogenesis



Pascoli, Petcov, Riotto, arXiv:hep-ph/0609125

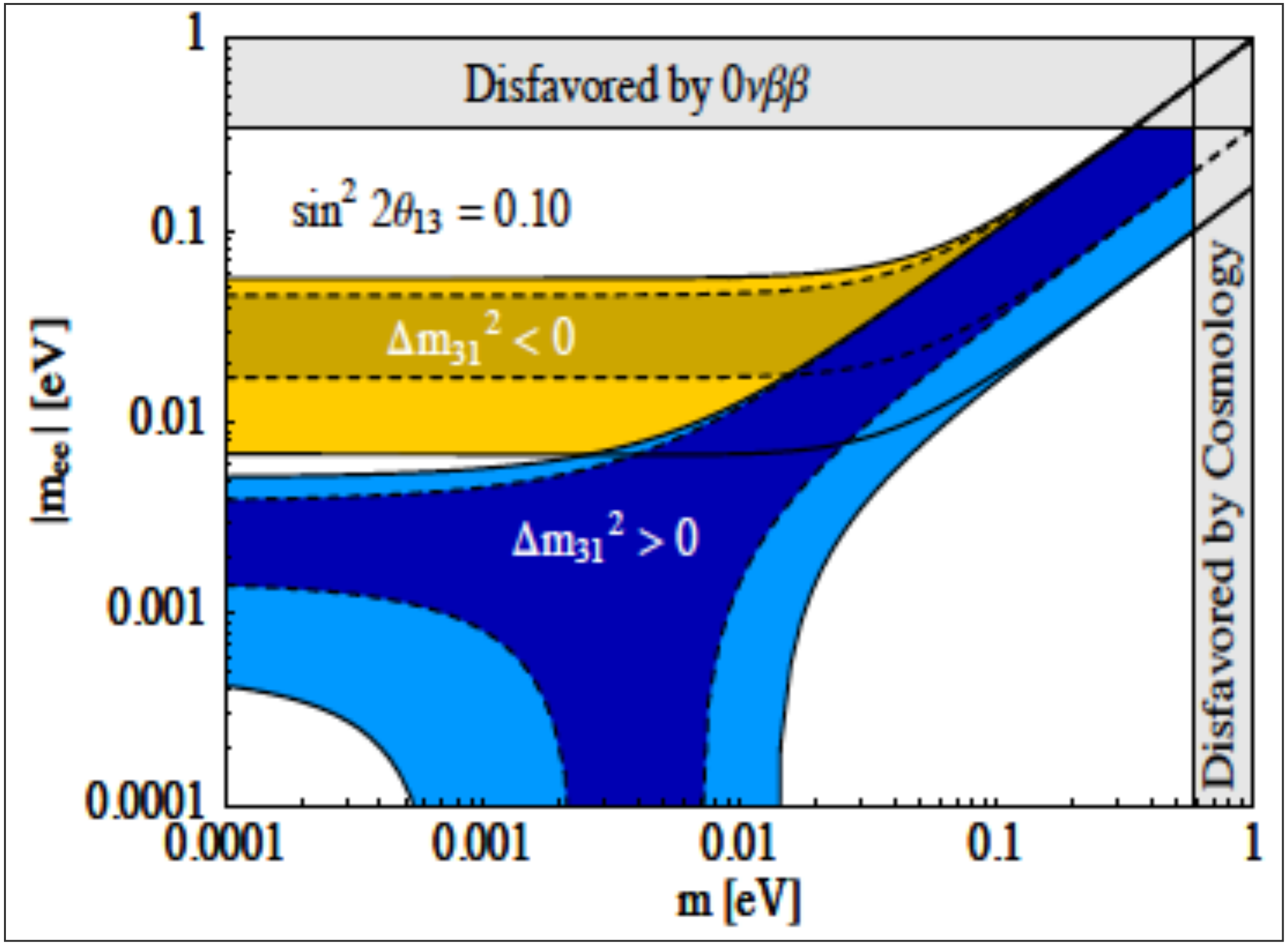
Large CPV would not establish the Leptogenesis mechanism, but it may have an impact on it

δ_{CP} alone may be sufficient to generate the observed amount of Baryon Asymmetry provided $|\sin\theta_{13} \sin\delta_{CP}| > 0.11$

~ 0.15

~ -1.0 (hints)

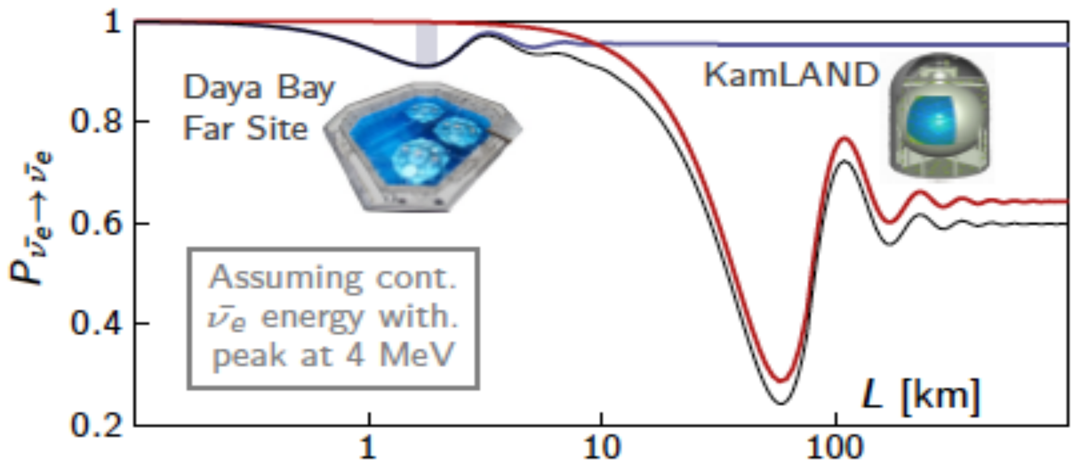
Connection between 0νββ and Neutrino Mass Ordering

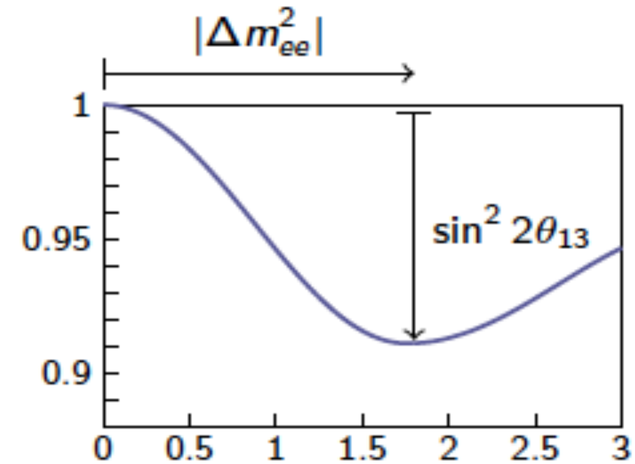


Lindner, Merle, Rodejohann , hep-ph/0512143

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

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

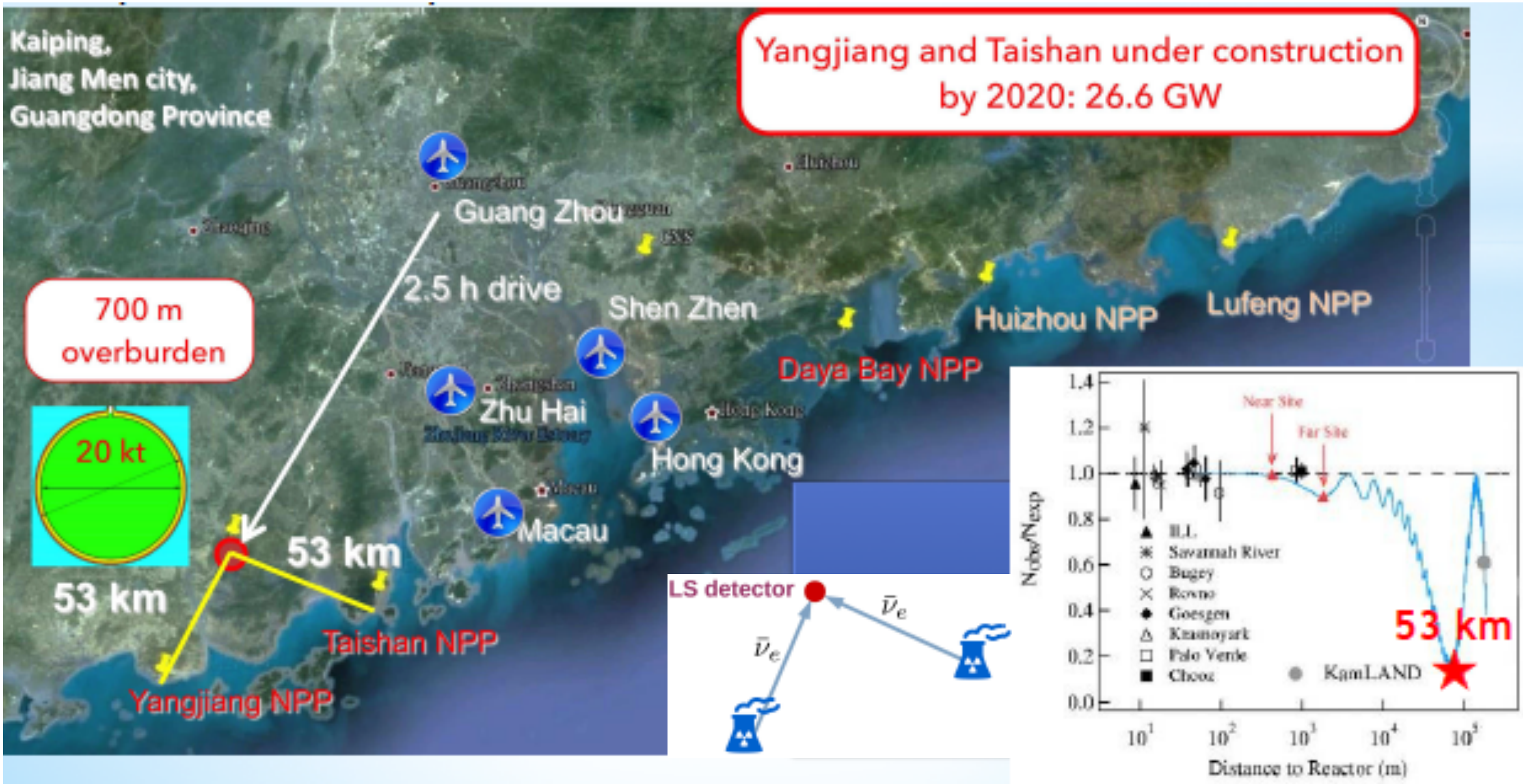
$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

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

+: Normal Hierarchy
−: Inverted Hierarchy

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

The Jiangmen Underground Neutrino Observatory (JUNO)



- **20 kt liquid scintillator detector with unprecedented 3% energy resolution at 1 MeV**
- **Neutrino Mass Ordering measurement & improve precision on oscillation parameters**

Interference effects in JUNO

The electron antineutrino survival probability in vacuum :

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

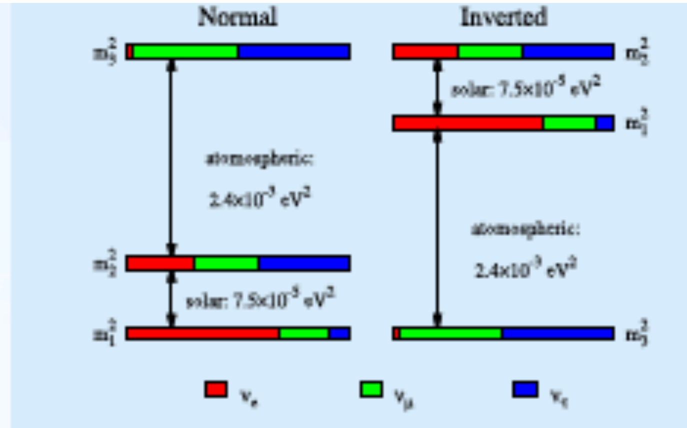
Depending on the NMH, the oscillation frequency differs :

$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \qquad \omega P_{31} > \omega P_{32} \\
\mathrm{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \qquad \omega P_{31} < \omega P_{32}
\end{aligned}
$$

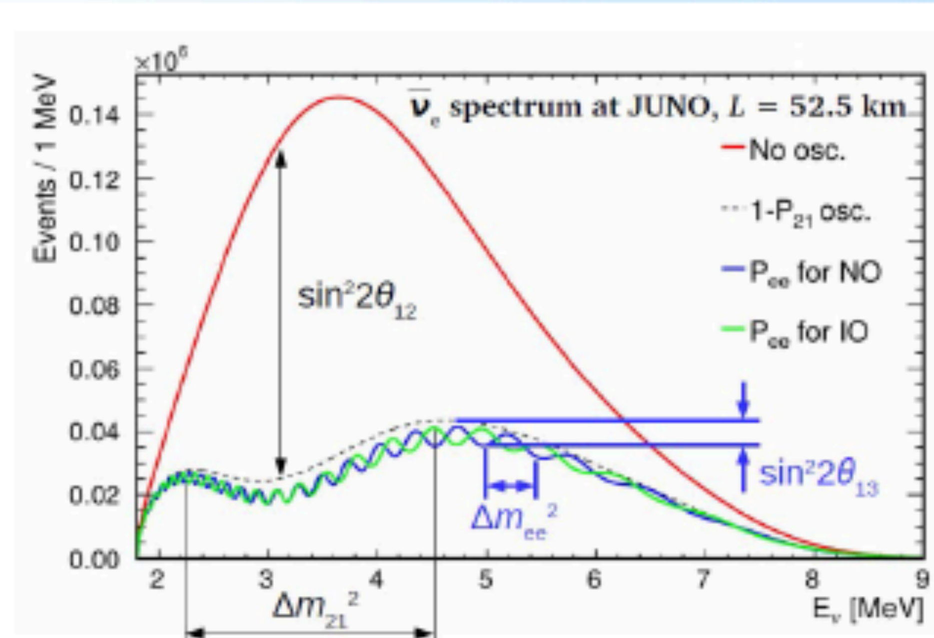
The L/E spectrum contains the NMH information

3σ mass hierarchy in 6 years

Key issues :
- energy resolution and energy scale
- Large statistics

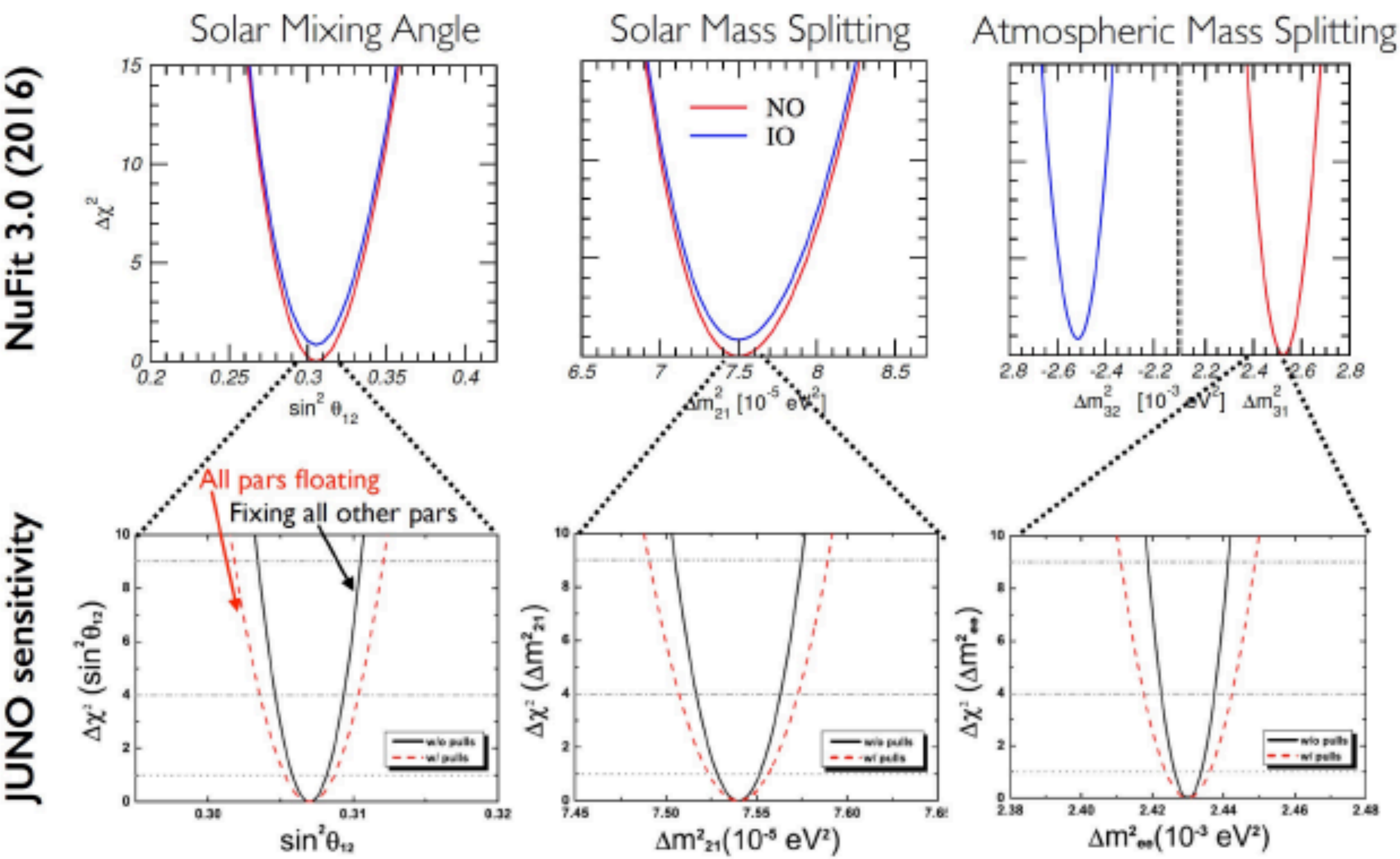


JUNO antineutrino energy spectrum:



Courtesy: Barbara Clerbaux, NuFact 2017

High-Precision Measurement of Oscillation Parameters in JUNO



$\sin^2(\theta_{12})$: 0.54% Δm^2_{21}: 0.24% Δm^2_{ee}: 0.27%

J. Phys. G 43 (2016) 030401

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

The appearance probability $(\nu_\mu \rightarrow \nu_e)$ in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ (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) → θ_{13} Driven

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

($\alpha \sin 2\theta_{13}$: 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

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

(α^2: 0.0009) → Solar Term

$\sin^2\theta_{23}$ → Resolves octant

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

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

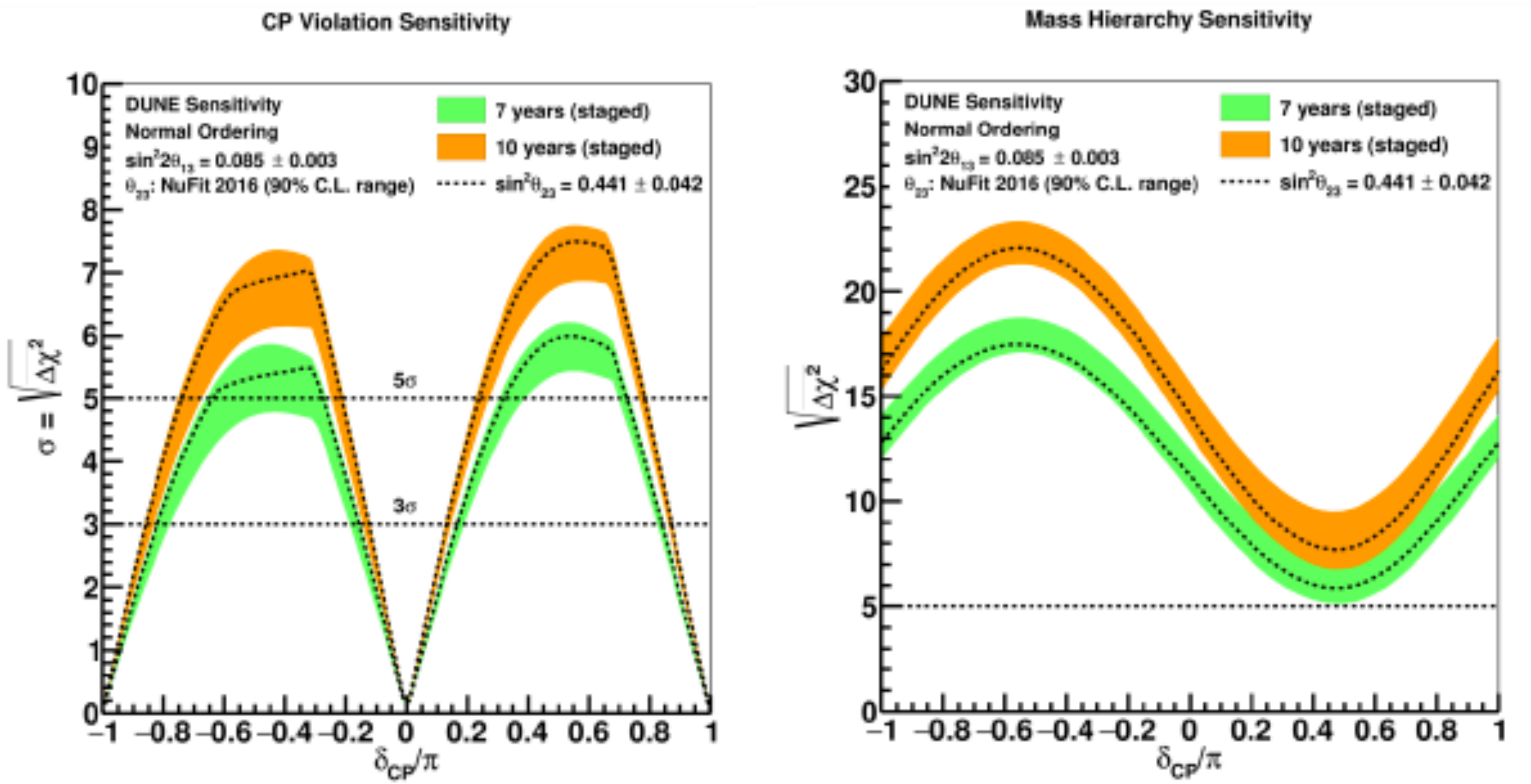
changes sign with sgn(Δm^2_{31}) key to resolve hierarchy!

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?

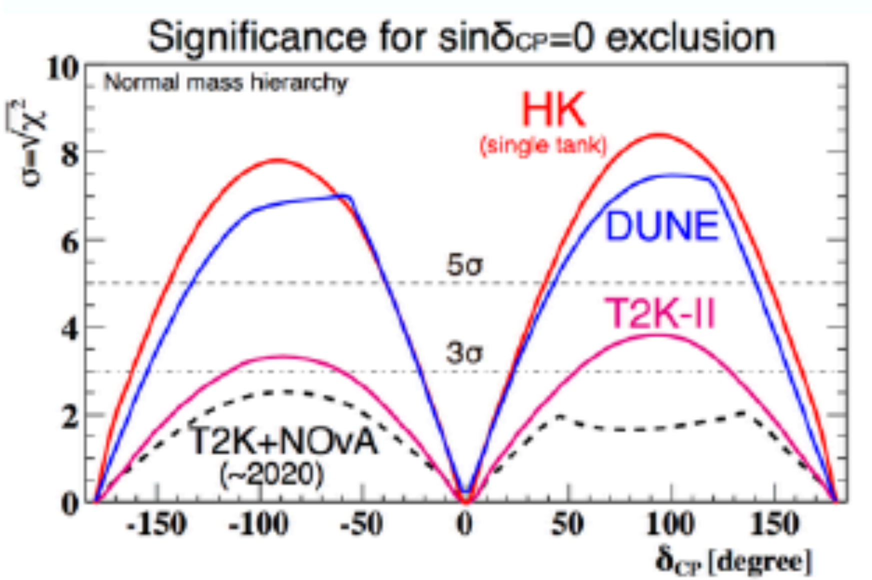
Deep Underground Neutrino Experiment (DUNE)

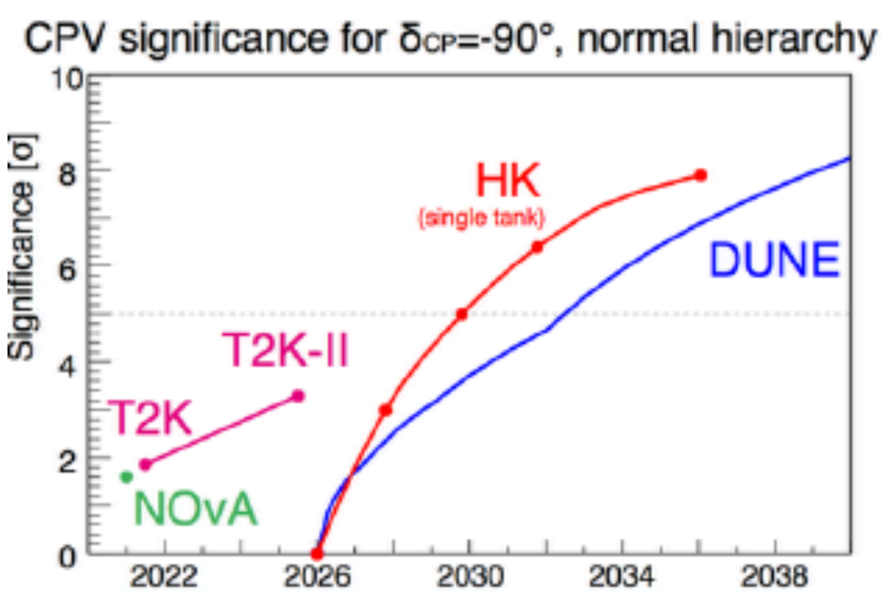


Exposure (kt-MW-years)	Exposure (years)
171	5
300	**7**
556	**10**
984	15

Talk by Dorota Stefan (DUNE Collaboration) at NNN, 2017

Tokai to Hyper-Kamiokande (T2HK)





Single tank: 187 kt fiducial

Expected sensitivity in Hyper-K

(1.3 MW × 10 years, $\nu : \overline{\nu} = 1 : 3$)

significance for $\sin\delta_{CP} = 0$ exclusion

~8σ significance if $\delta_{CP} = \pm 90°$

~6σ significance if $\delta_{CP} = \pm 45°$

Observe CP violation for 58% of δ_{CP} space with 5σ

uncertainty on δ_{CP}

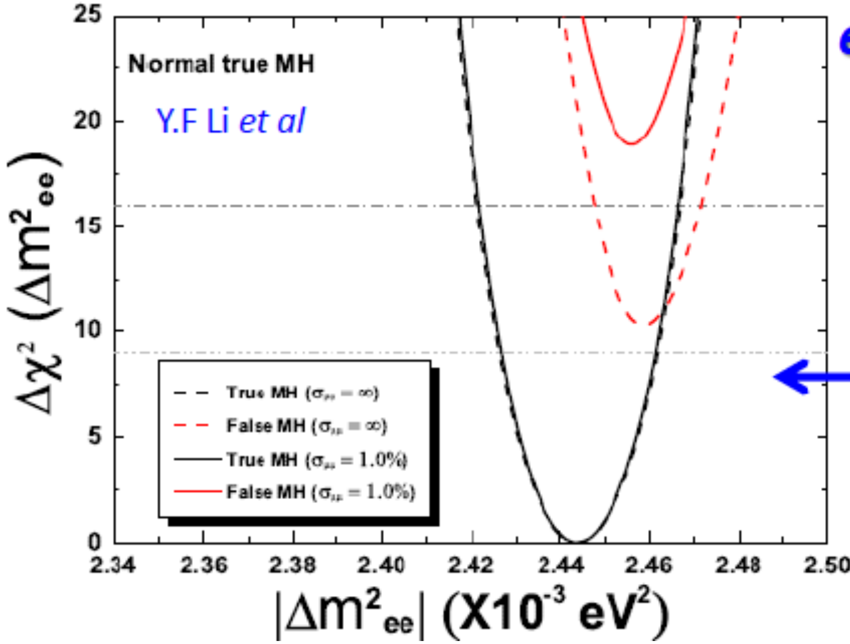
22° for $\delta_{CP} = \pm 90°$

7° for $\delta_{CP} = 0°/180°$

assuming 3-4% systematic uncertainty smaller than 5-6% in T2K (2017)

Talk by I. Shimizu (Hyper-K Collaboration) at NNN, 2017

JUNO Physics Goals

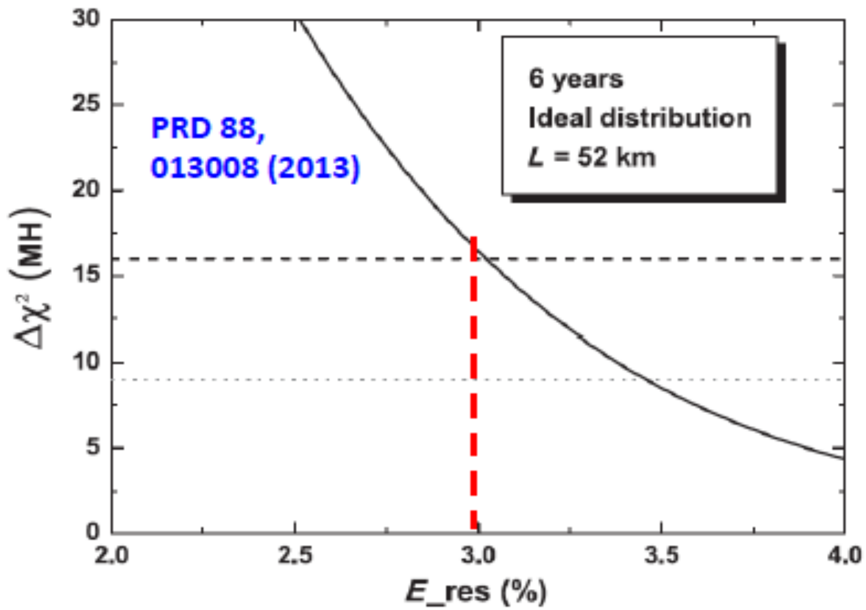


e.g JUNO **MH sensitivity with 6 years' data:**

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



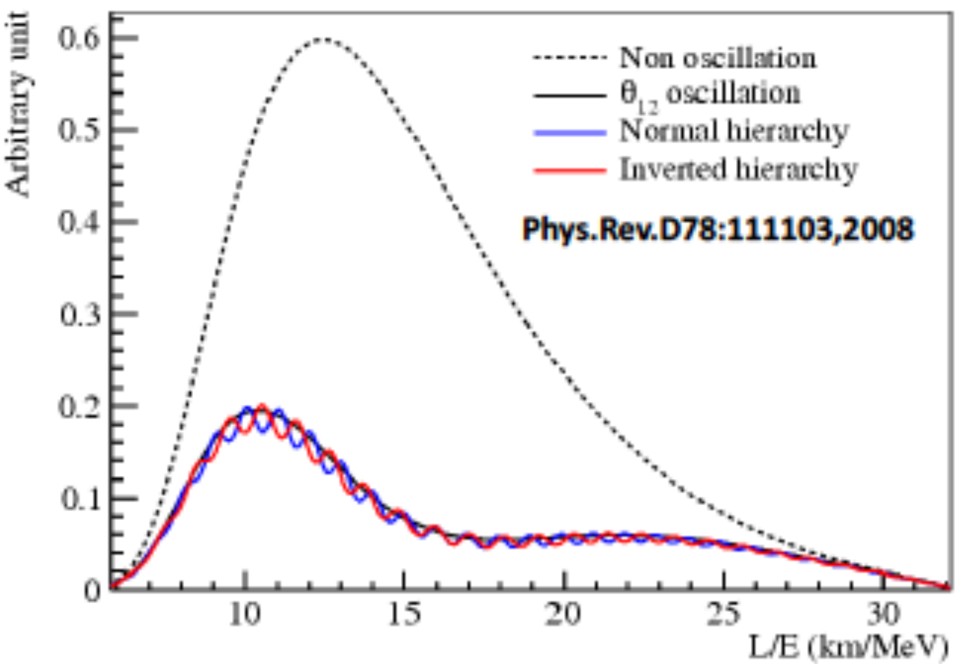
	Current	e.g JUNO
Δm^2_{12}	~3%	~0.5%
Δm^2_{23}	~4%	~0.6%
$\sin^2\theta_{12}$	~7%	~0.7%
$\sin^2\theta_{23}$	~15%	N/A
$\sin^2\theta_{13}$	~6% → ~4%	~ 15%

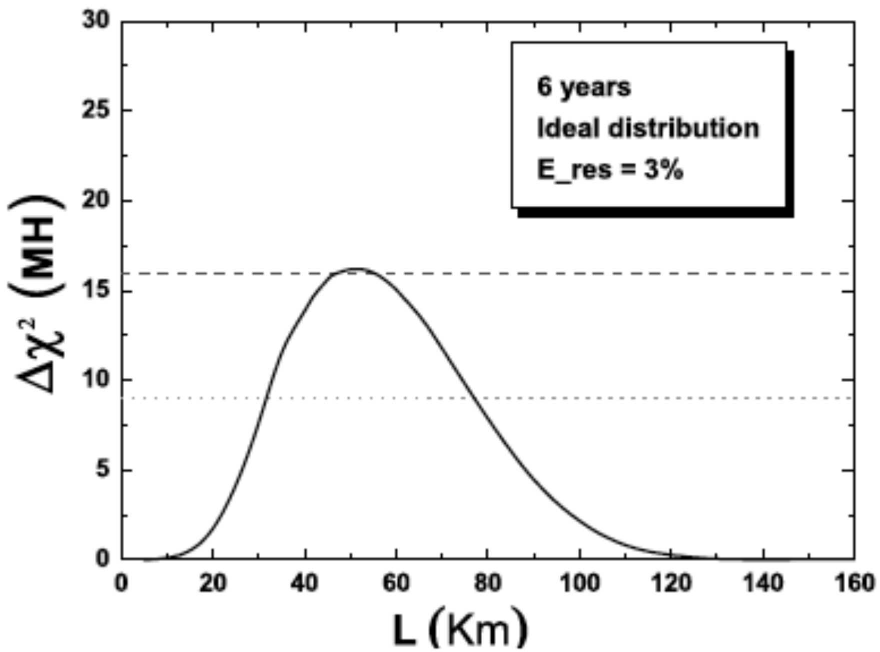
Courtesy Liangjian Wen, talk at Neutrino 2014

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





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