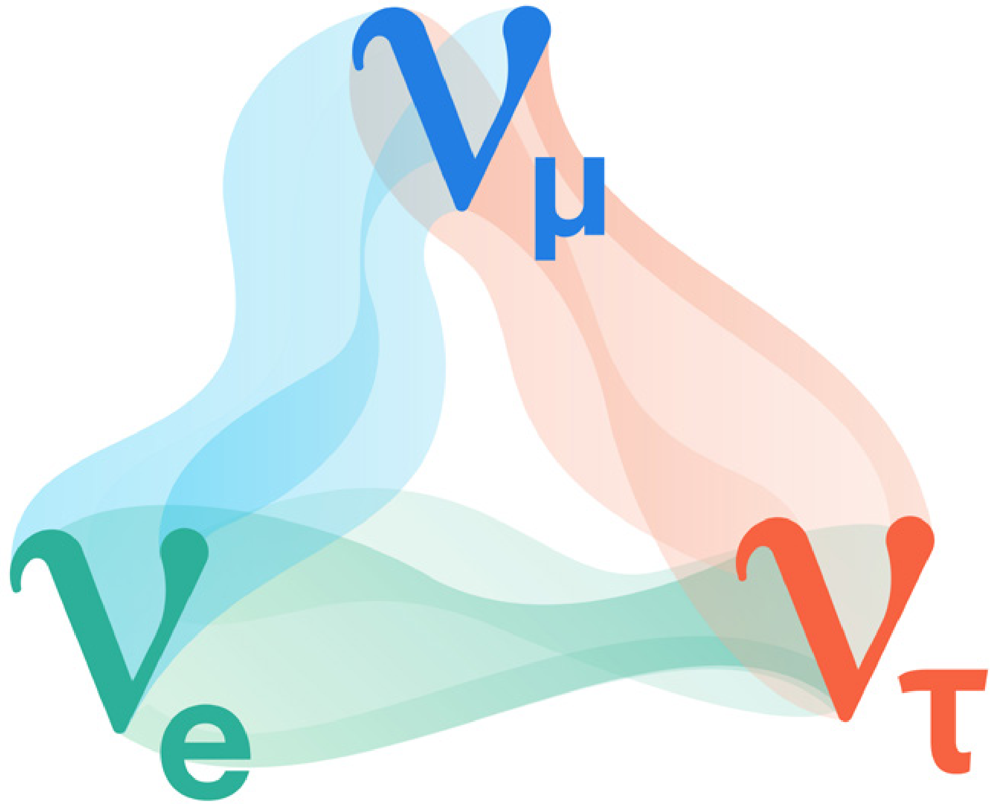
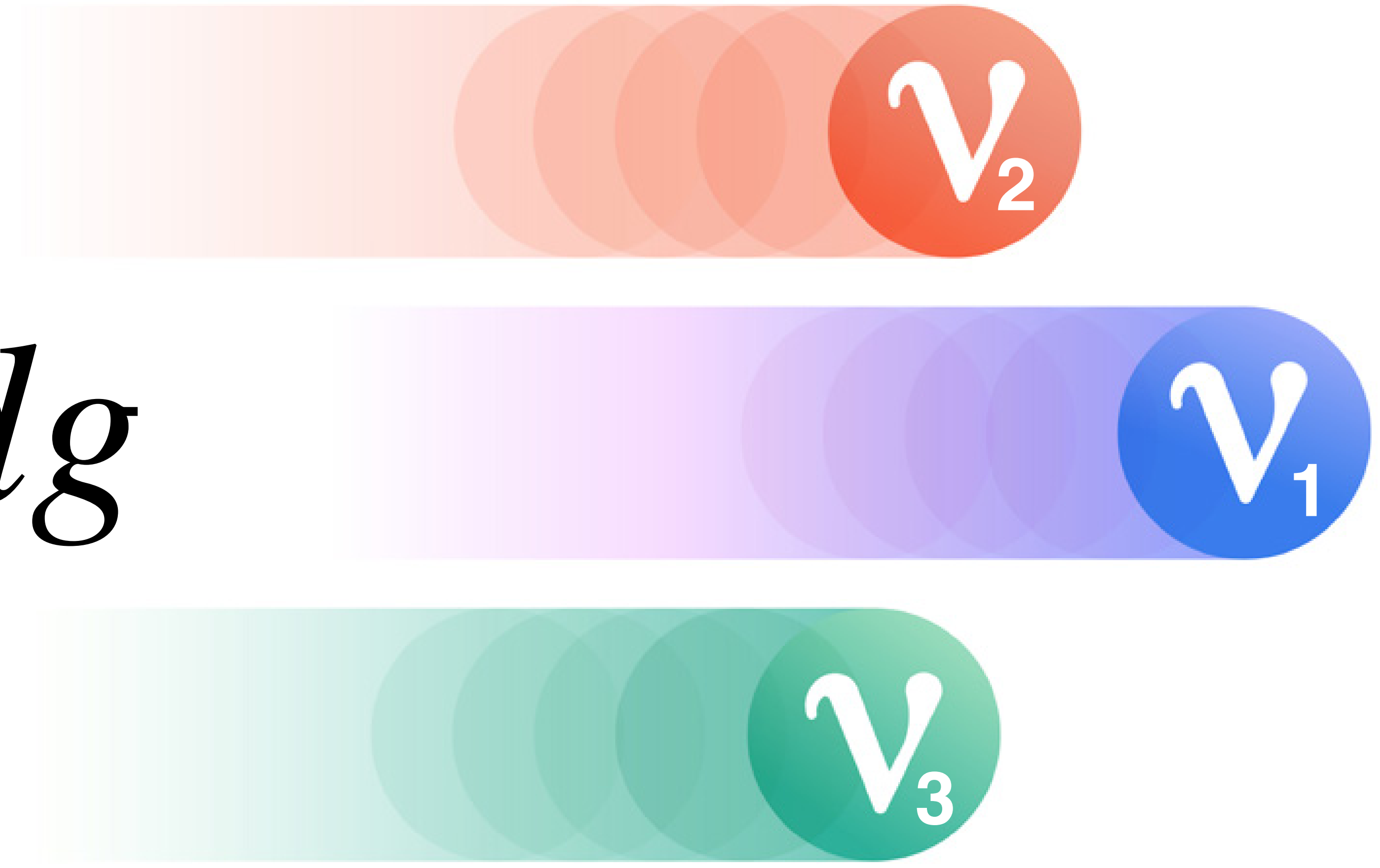
The Near Term Race for the Neutrino Mass Ordering

Stephen Parke: Theory-Fermilab
linktr.ee/stephen.parke

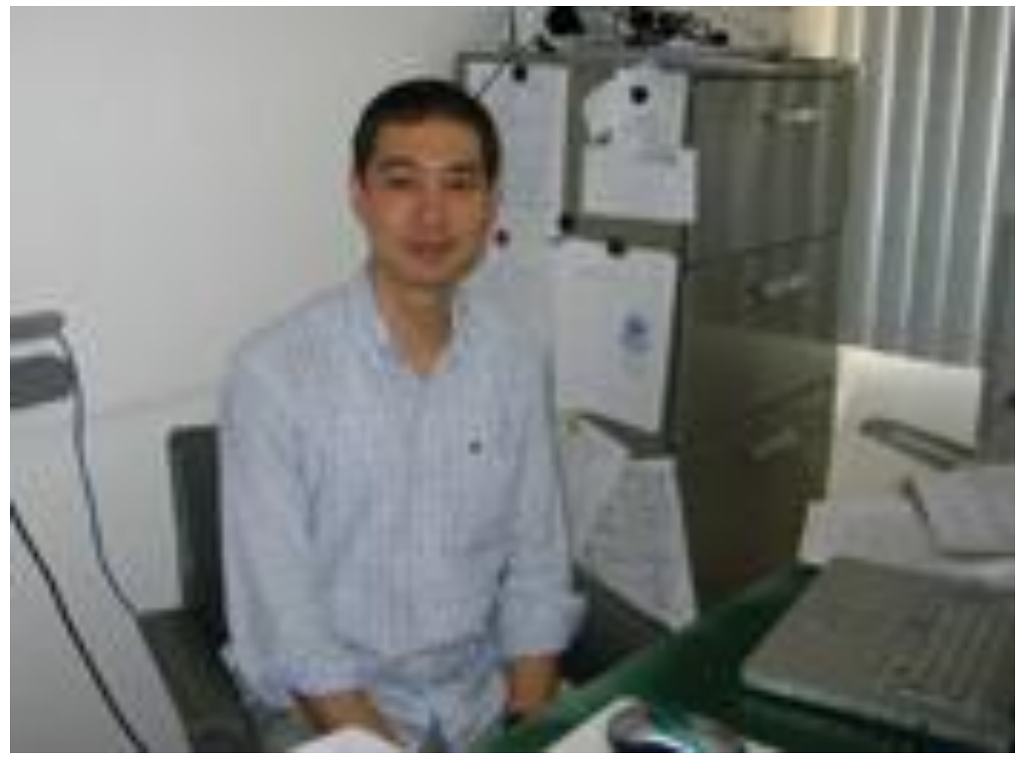


$$= U_{pdg}$$



with Hiroshi Nunokawa and Renata Zukanovich Fundal

(NPZ)



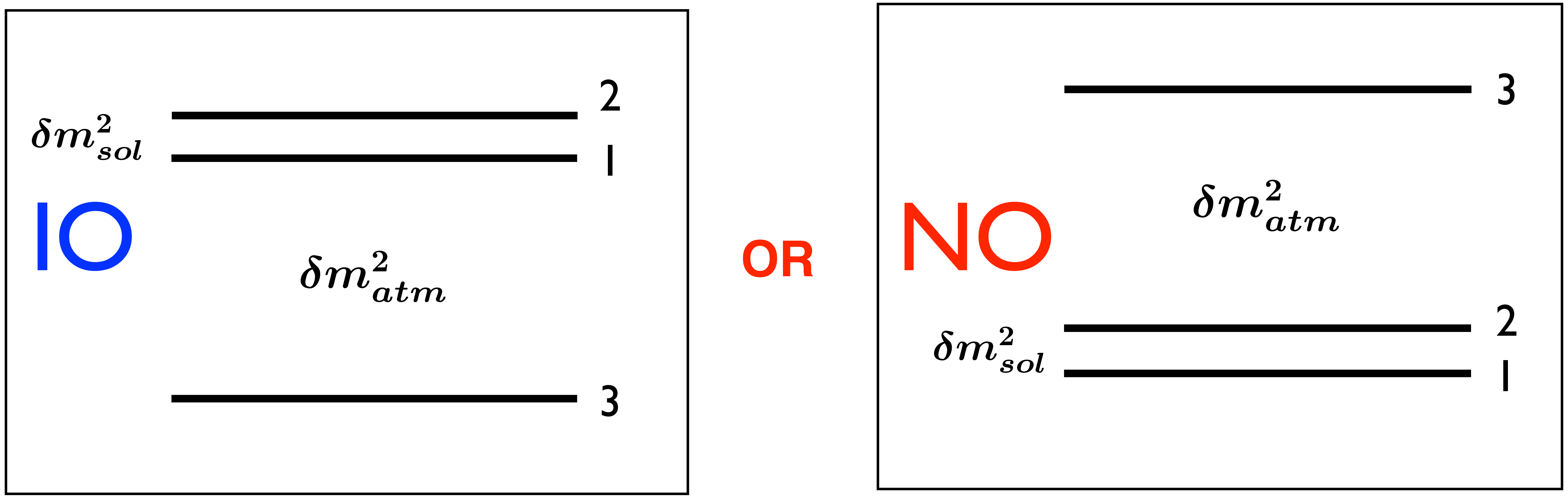
entitled in arXiv:2008.11280v1 as

Earliest Resolution to the Neutrino Mass Ordering?

Anatael Cabrera[*1,2,4], Yang Han[†1,2], Michel Obolensky[1], Fabien Cavalier[2], João Coelho[2], Diana Navas-Nicolás[2], Hiroshi Nunokawa[‡2,8], Laurent Simard[2], Jianming Bian[3], Nitish Nayak[3], Juan Pedro Ochoa-Ricoux[3], Bedřich Roskovec[7], Pietro Chimenti[§5,*], Stefano Dusini[¶6,*], Mathieu Bongrand[9,2], Rebin Karaparambil[9], Victor Lebrin[9], Benoit Viaud[9], Frederic Yermia[9], Lily Asquith[10], Thiago J. C. Bezerra[10], Jeff Hartnell[10], Pierre Lasorak[10], Jiajie Ling[11], Jiajun Liao[11], and Hongzhao Yu[11]

the Neutrino Mass Ordering

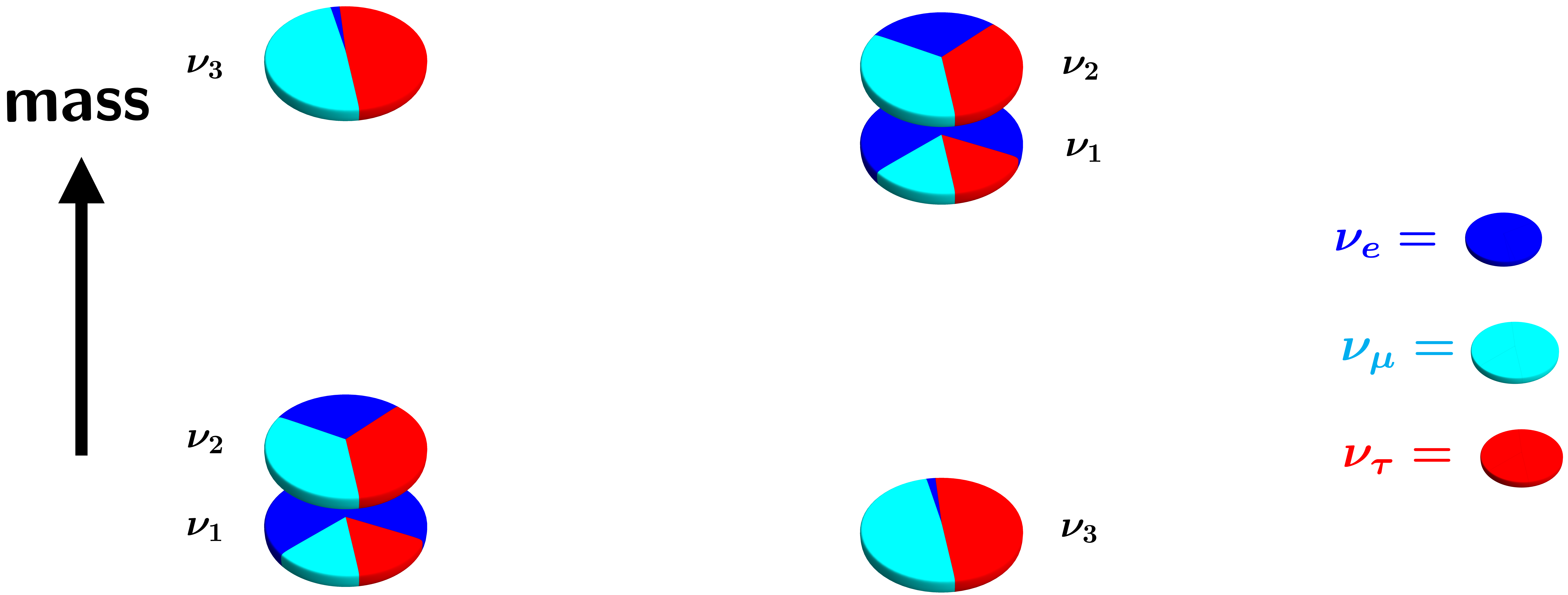
Define 1,2 & 3 such that: $|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$



SNO $m_2 > m_1$

KamLAND $|\Delta m^2_{21}| = |m_2^2 - m_1^2| = 7.5 \times 10^{-5}\ \mathrm{eV}^2$ $L/E = 15\ \mathrm{km/MeV} = 15,000\ \mathrm{km/GeV}$

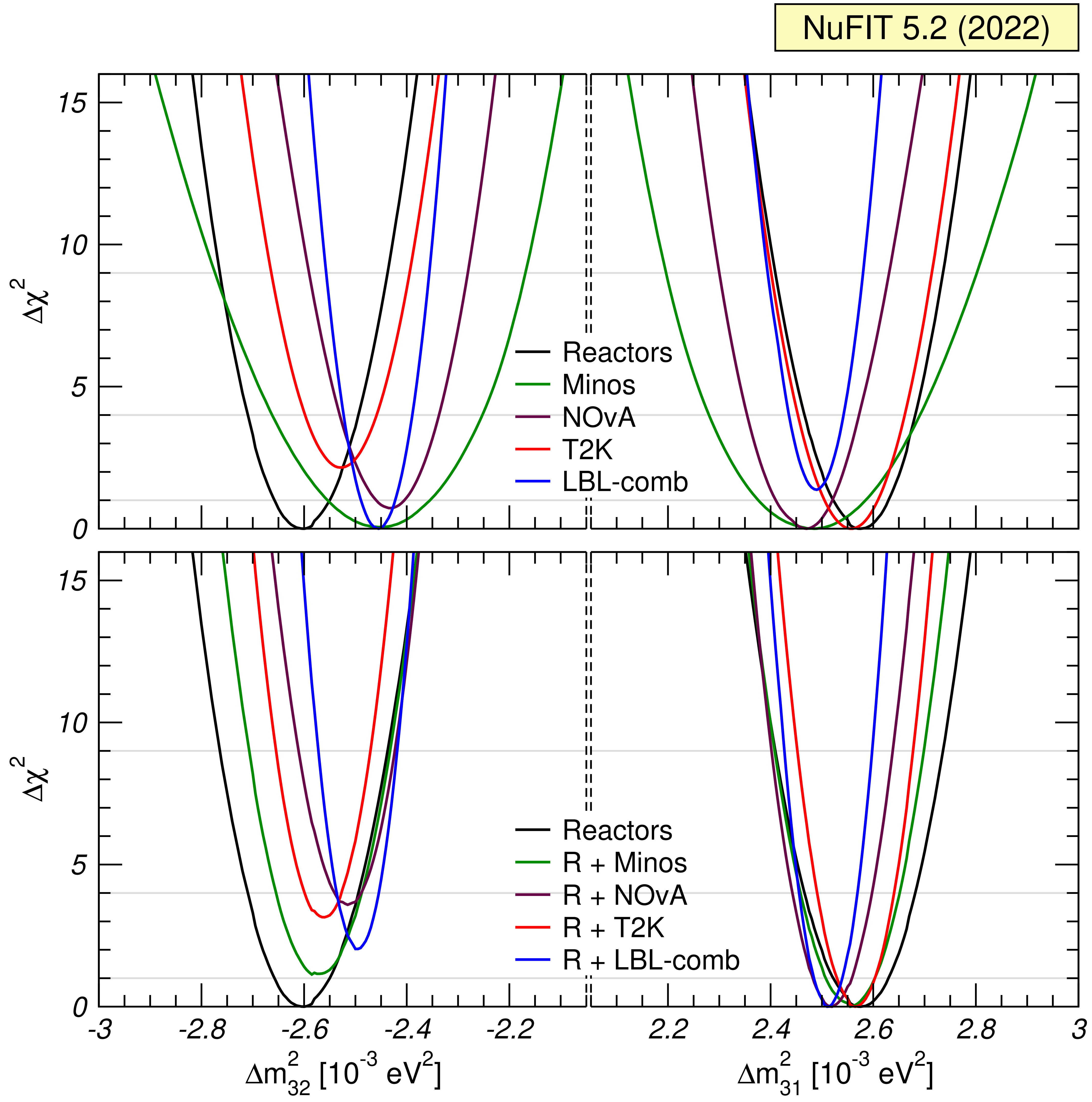
ν_3, ν_1/ν_2 Mass Ordering: −atmospheric mass ord



$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2 \qquad L/E = 0.5\ \mathrm{km/MeV} = 500\ \mathrm{km/GeV}$$

unknown: SK, T2K, NOvA, JUNO, T2HK, DUNE: ICECUBE, KM3NET/ORCA

Explain this figure + Future Prospects



www.nu-fit.org

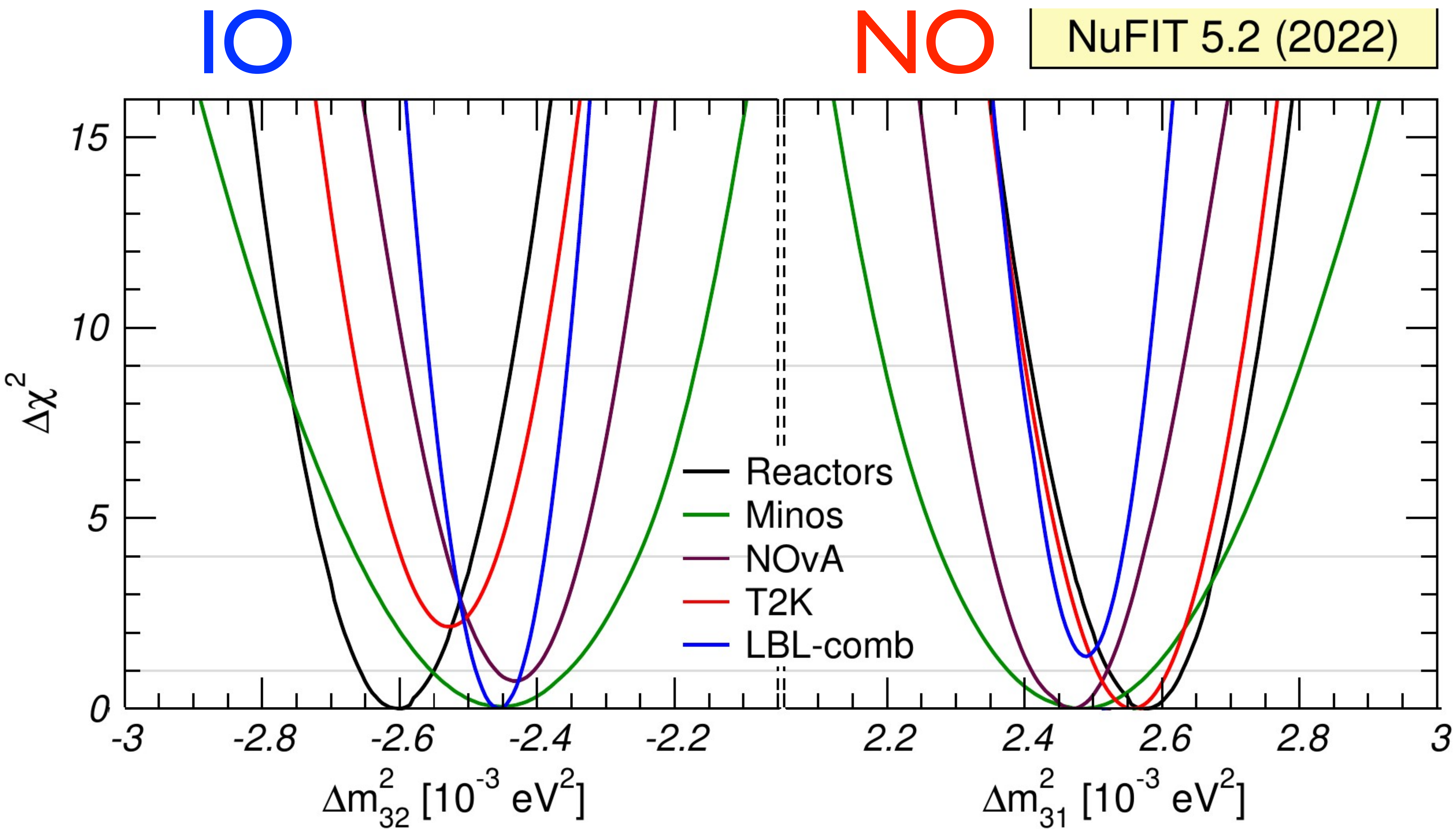
Current members:

- Ivan Esteban
- Concha Gonzalez Garcia
- Michele Maltoni
- Thomas Schwetz
- Albert Zhou

Former members:

- Johannes Bergström
- Alvaro Hernandez Cabezudo
- Ivan Martinez Soler
- Jordi Salvado

$$\frac{L}{E} \sim 500\ \frac{\text{km}}{\text{GeV}} = 0.5\ \frac{\text{km}}{\text{MeV}}$$



No preference
Or for NO

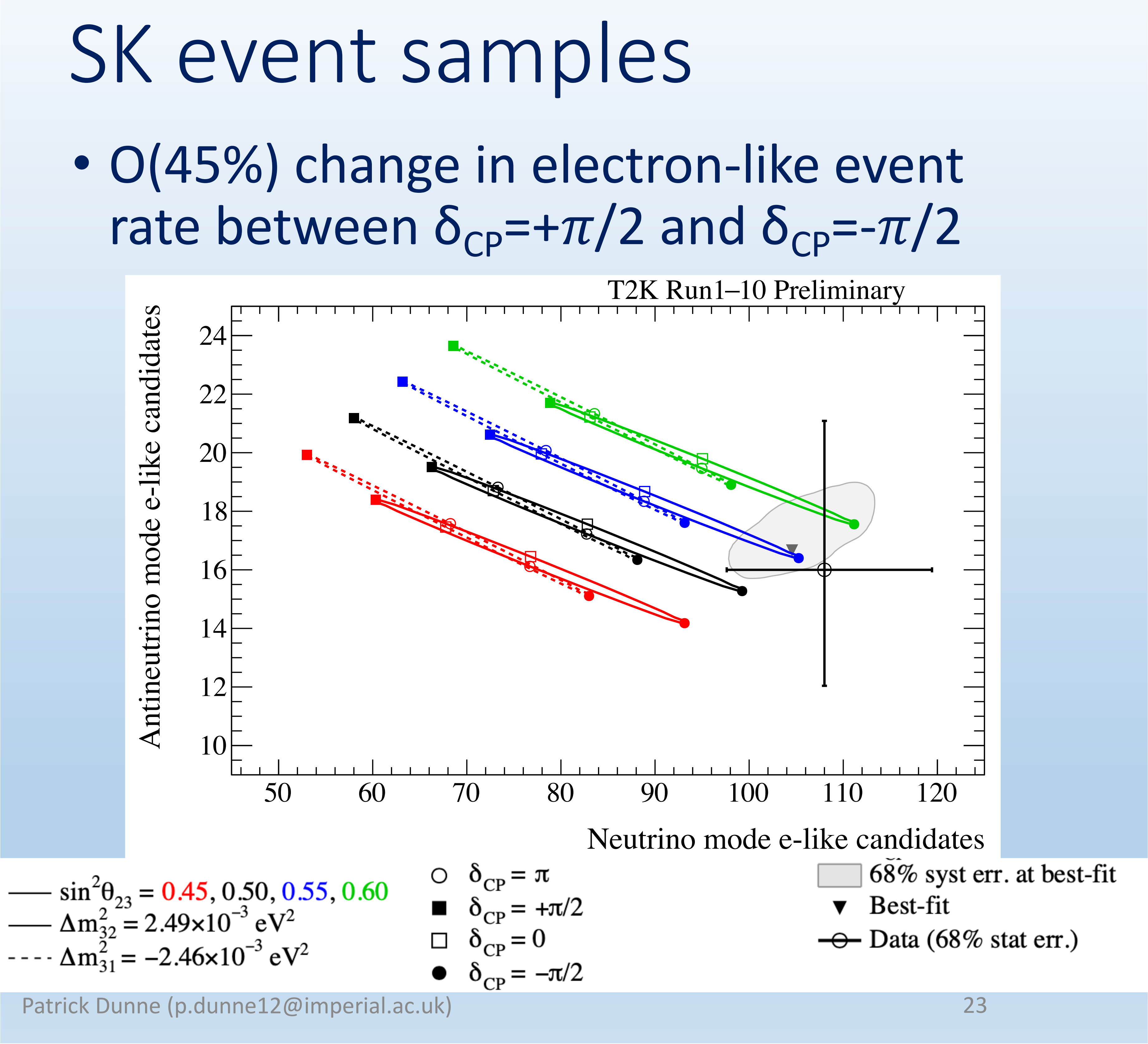
Except

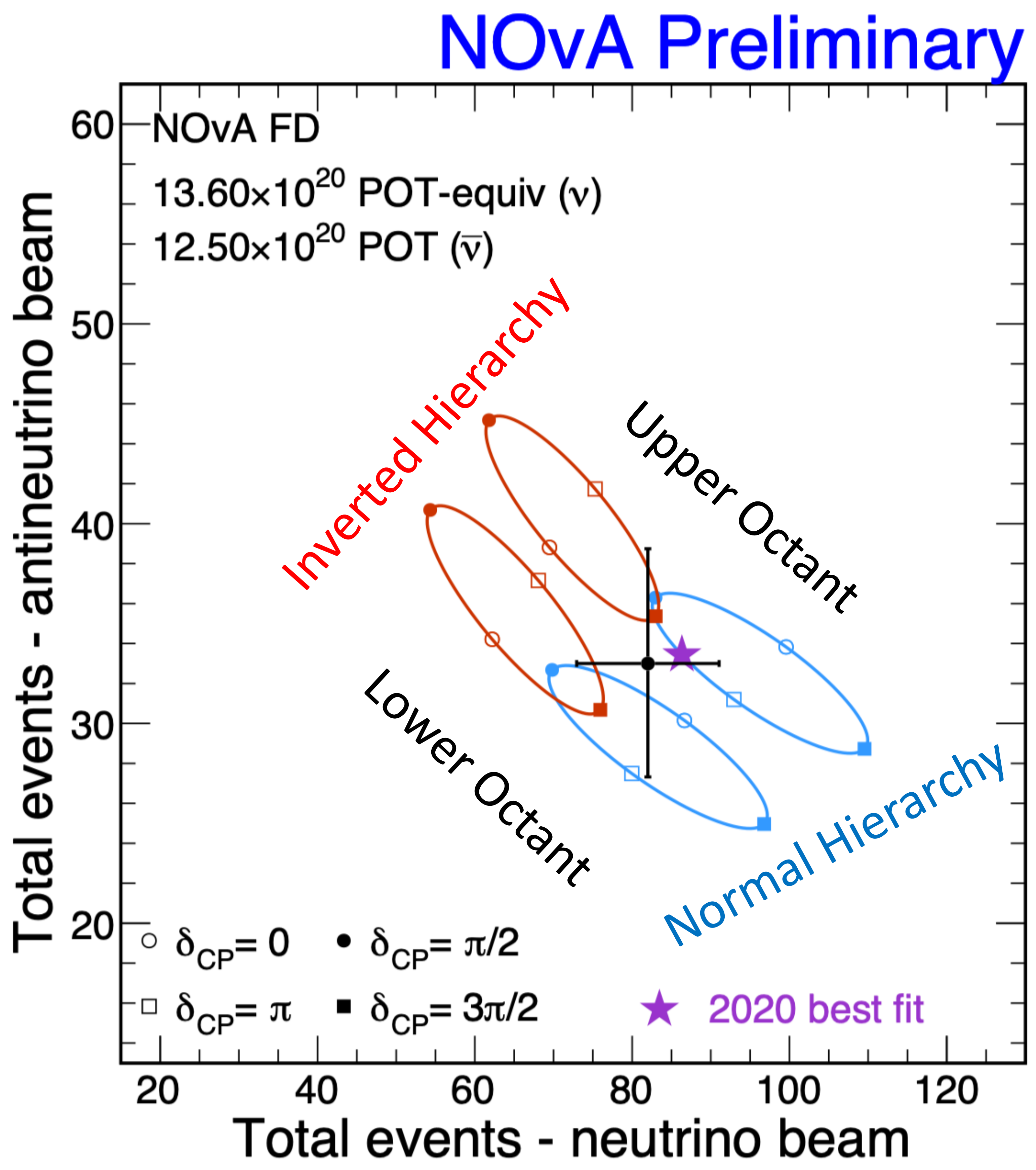
T2K + NOvA
Combined

By construction $\Delta\chi^2_{min}$ for either (or both) NO or IO at zero

T2K & NOvA Appearance Confusion:

Number of Events proportional to Oscillation Probability



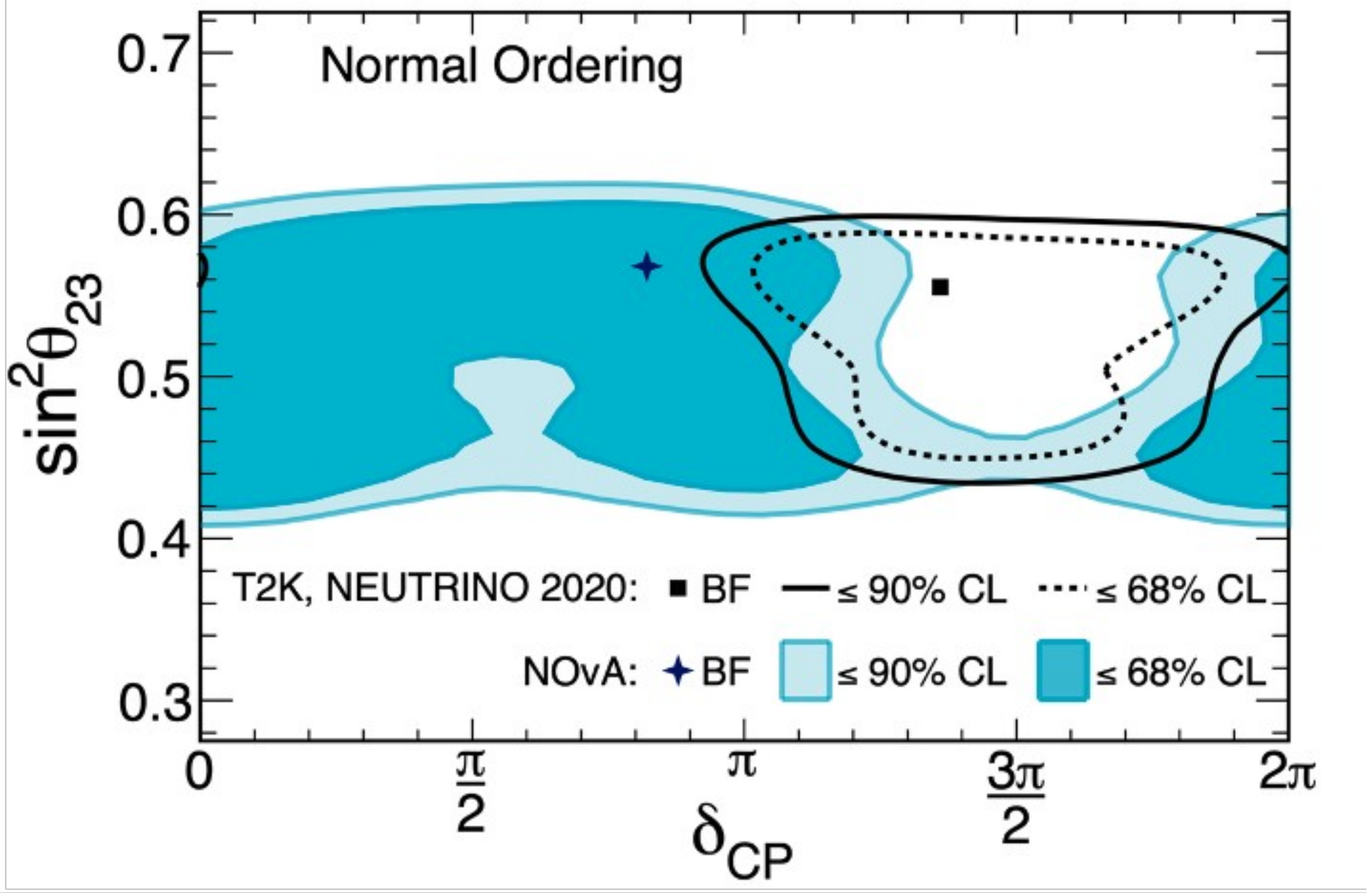


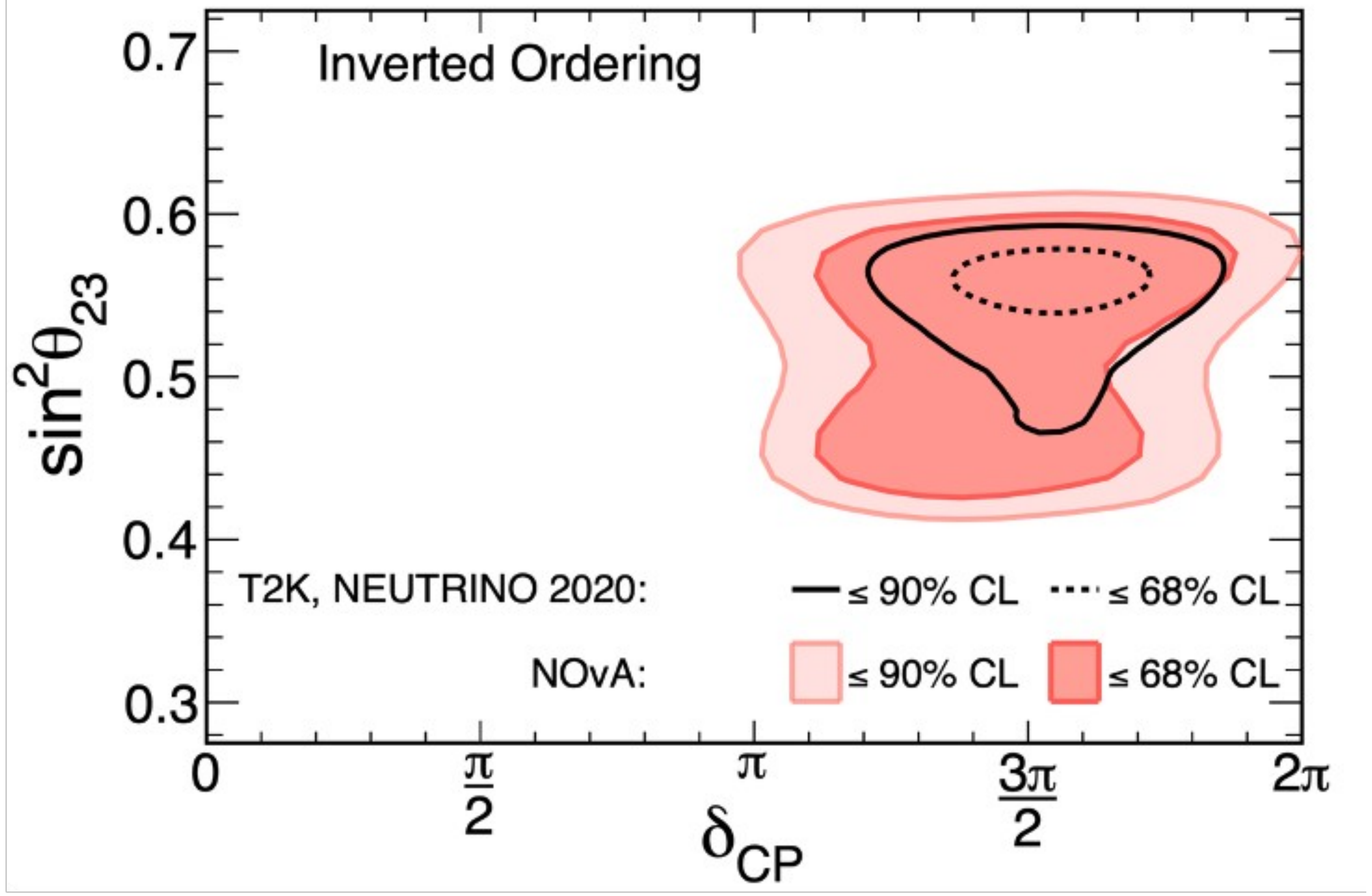
T2K NO prefer by ~2 units of χ^2

NOvA NO prefer by ~1 unit of χ^2

COMBINED

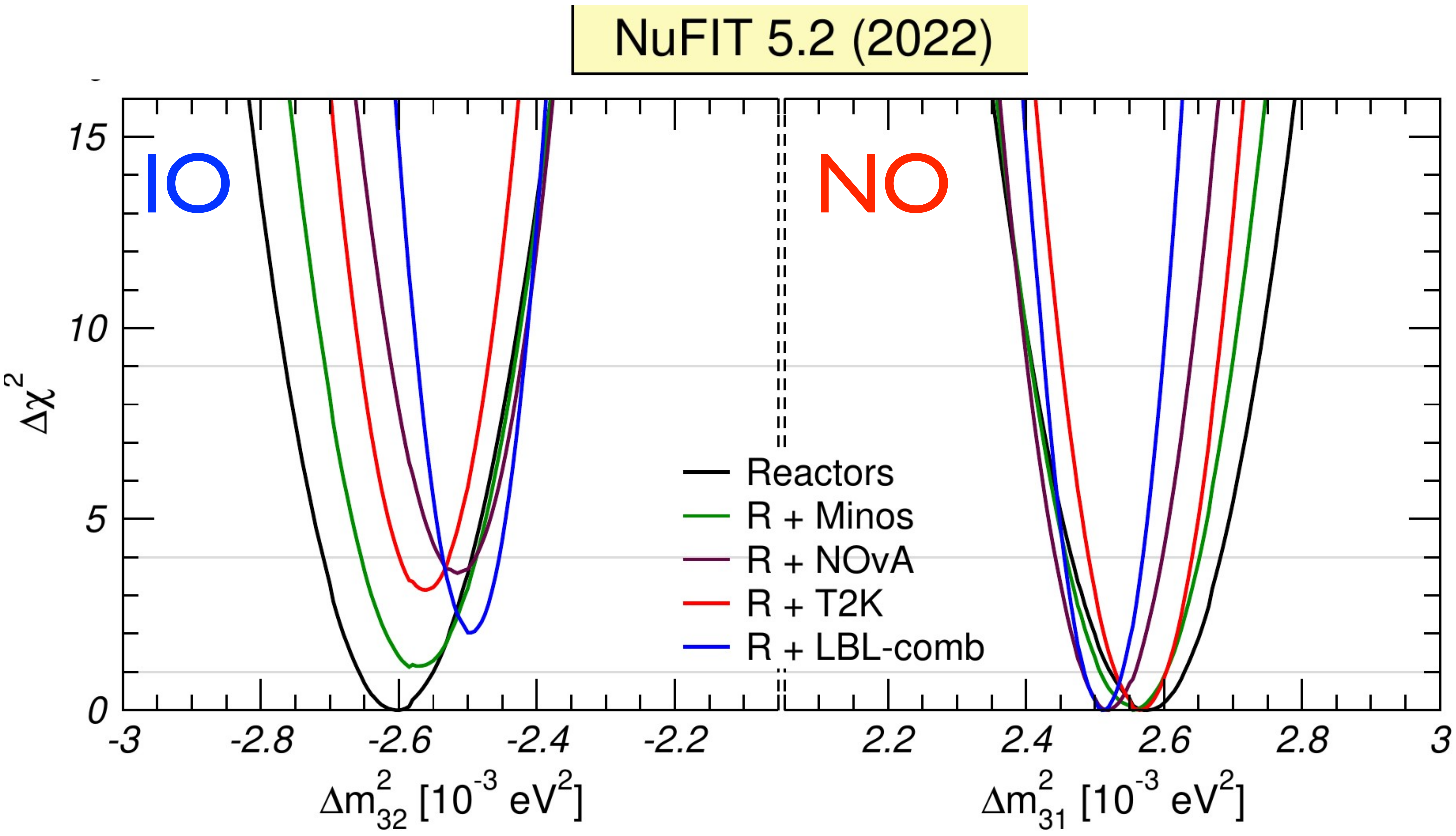
https://doi.org/10.5281/zenodo.6683827





IO prefer by ~1.6 unit of $\Delta\chi^2$

Kelly, Machado, SP, Perez, Zukanovich 2007.08526 plus other papers



Reactors + LBL
All
Prefer NO:

Even T2K + NOvA

For these Experiments the is a 'Mass Ordering Sum Rule:'

$$\left(|\Delta m^2_{32}|^{IO}_{DB} - |\Delta m^2_{32}|^{IO}_{\mu dis}\right) + \left(|\Delta m^2_{31}|^{NO}_{\mu dis} - |\Delta m^2_{31}|^{NO}_{DB}\right) = (2.4 - 0.9\widehat{\cos\delta})\%\ |\Delta m^2_{ee}|$$

If IO then ≈ 0

If NO then ≈ 0

+1.5 to +3.3 %

$$\widehat{\cos\delta} \equiv (\cos\delta^{NO} + \cos\delta^{IO})/2$$

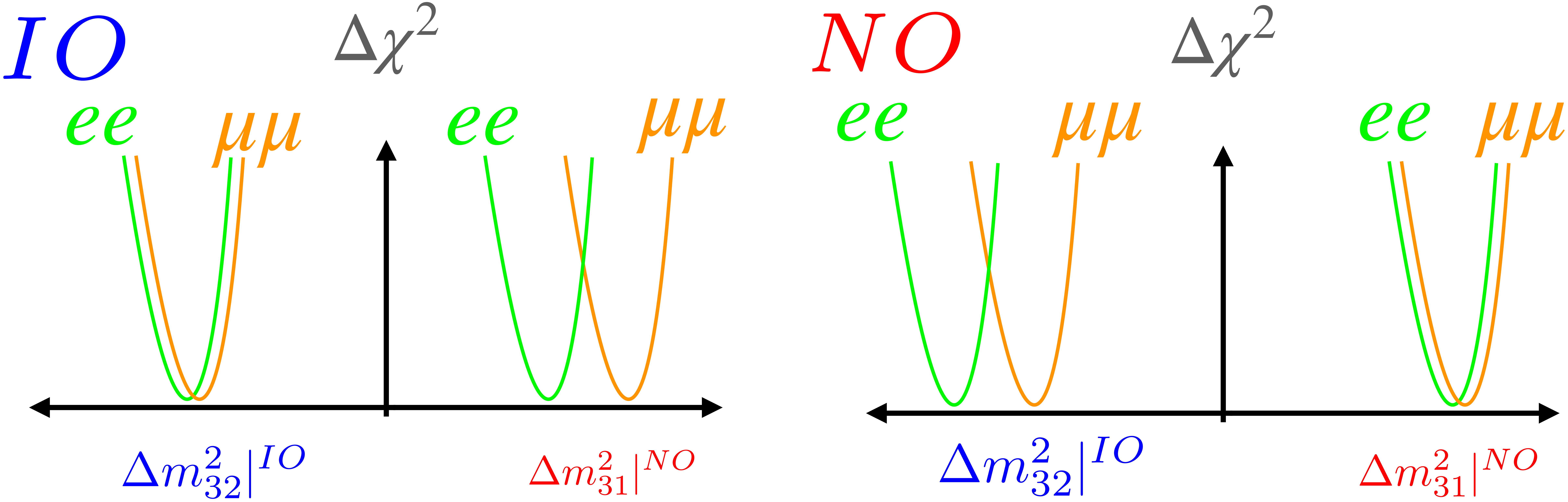
Not valid for ICECUBE, KM3Net/Orca

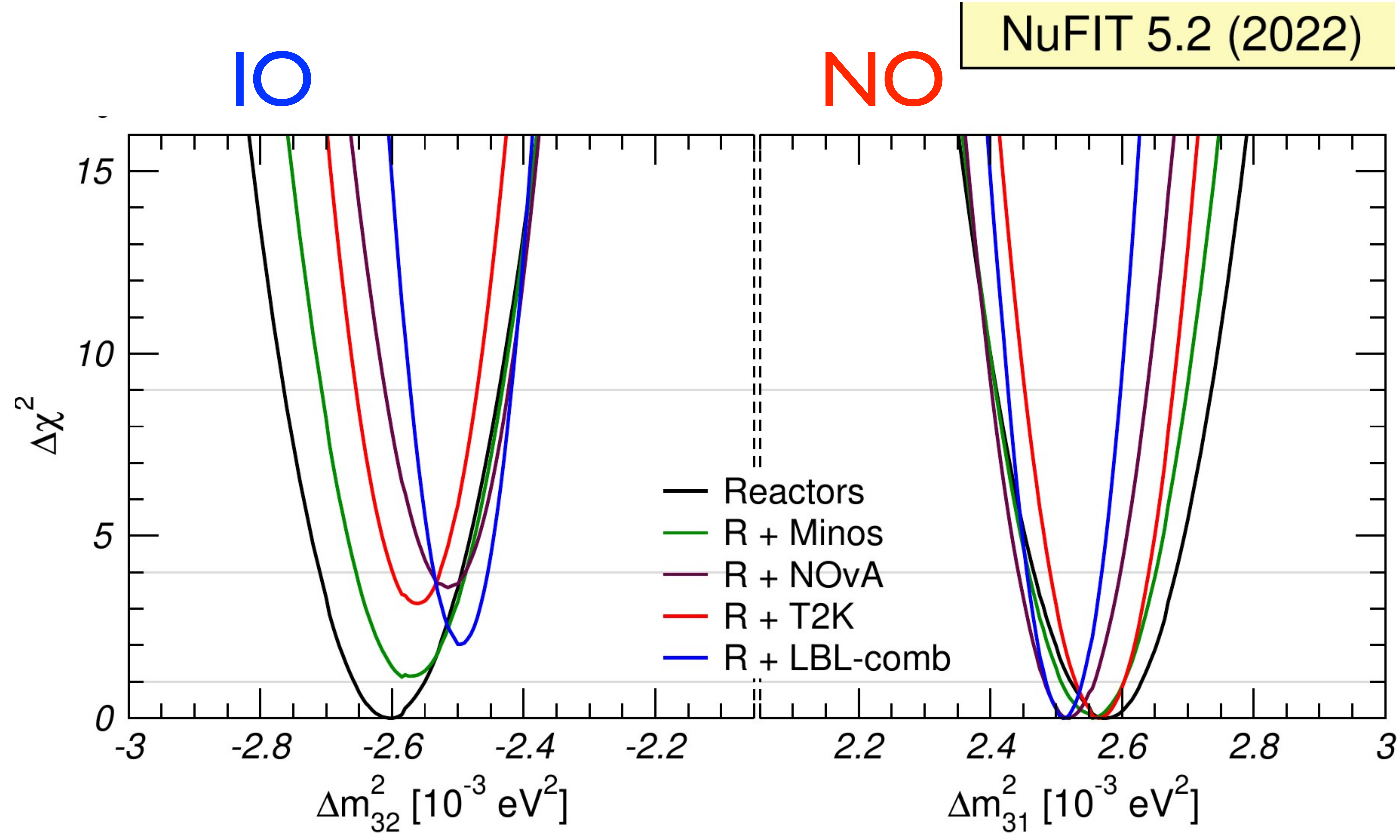
Needs tweak for JUNO

Unchanged if $31 \leftrightarrow 32$ in either or both MO's

$$\left(|\Delta m^2_{32}|^{IO}_{DB} - |\Delta m^2_{32}|^{IO}_{\mu dis}\right) + \left(|\Delta m^2_{31}|^{NO}_{\mu dis} - |\Delta m^2_{31}|^{NO}_{DB}\right) = (2.4 - 0.9\widehat{\cos\delta})\%\ |\Delta m^2_{ee}|$$

	$\|\Delta m^2_{32}\|^{IO}_{DB} - \|\Delta m^2_{32}\|^{IO}_{\mu dis}$	$\|\Delta m^2_{31}\|^{NO}_{\mu dis} - \|\Delta m^2_{31}\|^{NO}_{DB}$
NO	$(2.4 - 0.9\widehat{\cos\delta})\%$	≈ 0
IO	≈ 0	$(2.4 - 0.9\widehat{\cos\delta})\%$





$$\left(|\Delta m^2_{32}|^{IO}_{DB} - |\Delta m^2_{32}|^{IO}_{\mu dis}\right) + \left(|\Delta m^2_{31}|^{NO}_{\mu dis} - |\Delta m^2_{31}|^{NO}_{DB}\right) = (2.4 - 0.9\widehat{\cos\delta})\% \ |\Delta m^2_{ee}|$$

Another possible way to determine the Neutrino Mass Hierarchy

Hiroshi Nunokawa[1,*] Stephen Parke[2,†] and Renata Zukanovich Funchal[3‡]

arXiv:hep-ph/0503283v1 29 Mar 2005

in PRD

NPZ'05

Introduced Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ for disappearance experiments:

and that $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ implies NO

$|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$ implies IO

few % difference

$\bar{\nu}_e$ disappearance at an L/E $\sim$ 0.5 km/MeV

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$

$$\begin{aligned} P(\nu_e \to \nu_e) &= 1 - P_\odot - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) \\ &\approx 1 - P_\odot - \sin^2 2\theta_{13}(\sin^2\Delta_{3i} \; + (-1)^i\, \mathcal{O}(\Delta_{21})) \quad i = 1 \text{ or } 2 \\ &\approx 1 - P_\odot - \sin^2 2\theta_{13}(\sin^2\Delta_{ee} \; + \; \mathcal{O}(\Delta^2_{21})) \end{aligned}$$

note "2"

$$\Delta_{21} = \left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)\Delta_{31} = 0.03\,\frac{\pi}{2} = \frac{1}{20} \text{ and therefore } \Delta^2_{21} = \frac{1}{400}$$

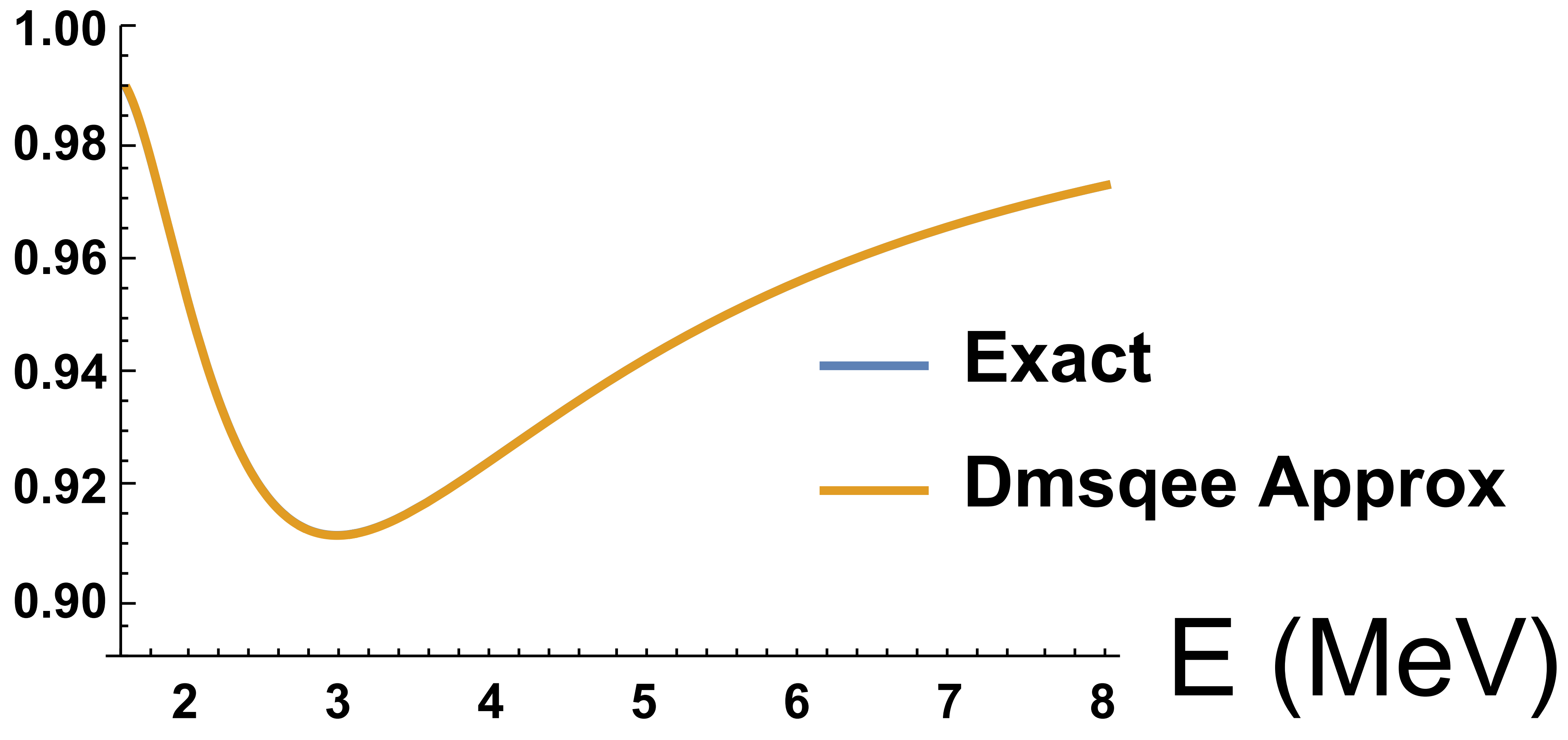
$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32} = m^2_3 - (c^2_{12}m^2_1 + s^2_{12}m^2_2)$$

ν_e average of Δm^2_{31} and Δm^2_{32}

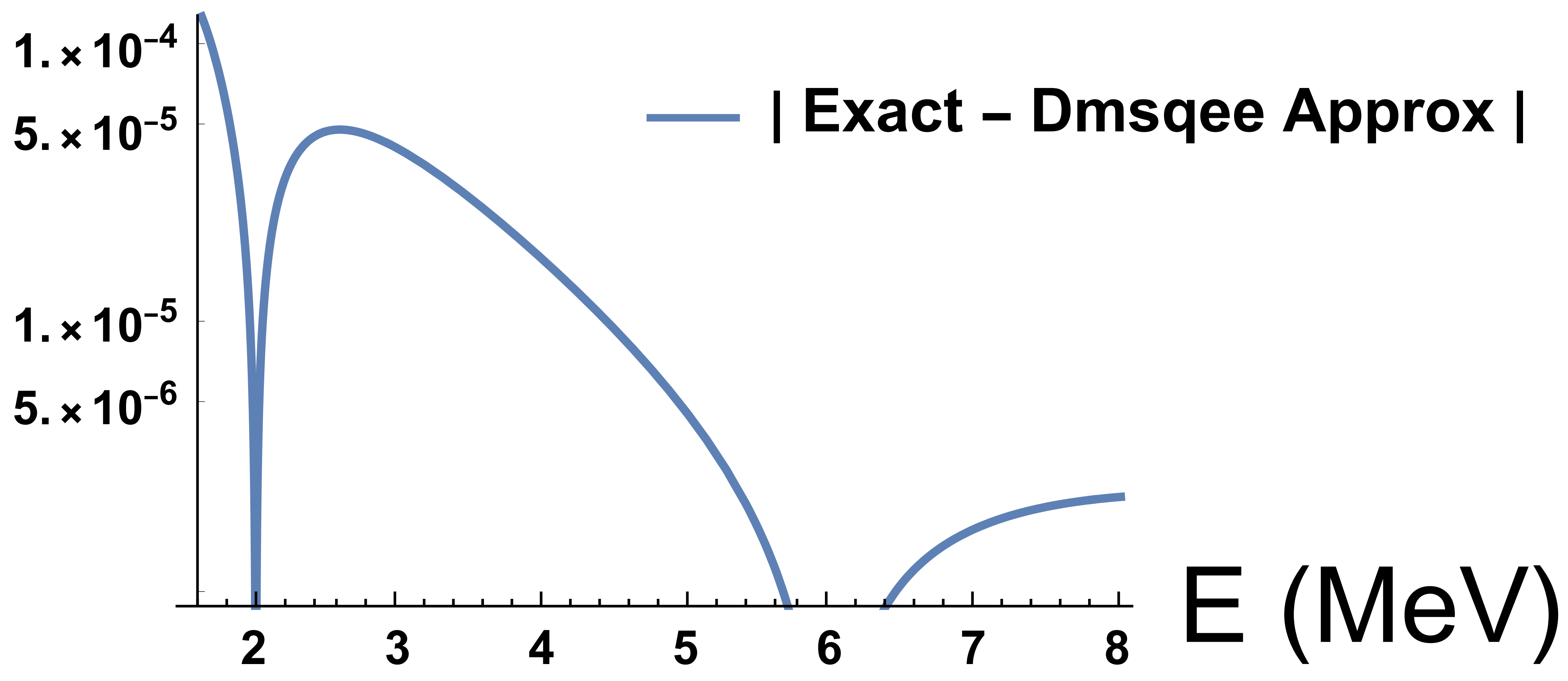
$$P_\odot = \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} = 0.002 \text{ when } \Delta_{31} = \frac{\pi}{2}$$

DAYA BAY OSCILLATION PROBABILITY:

Dis. Prob (Daya Bay)

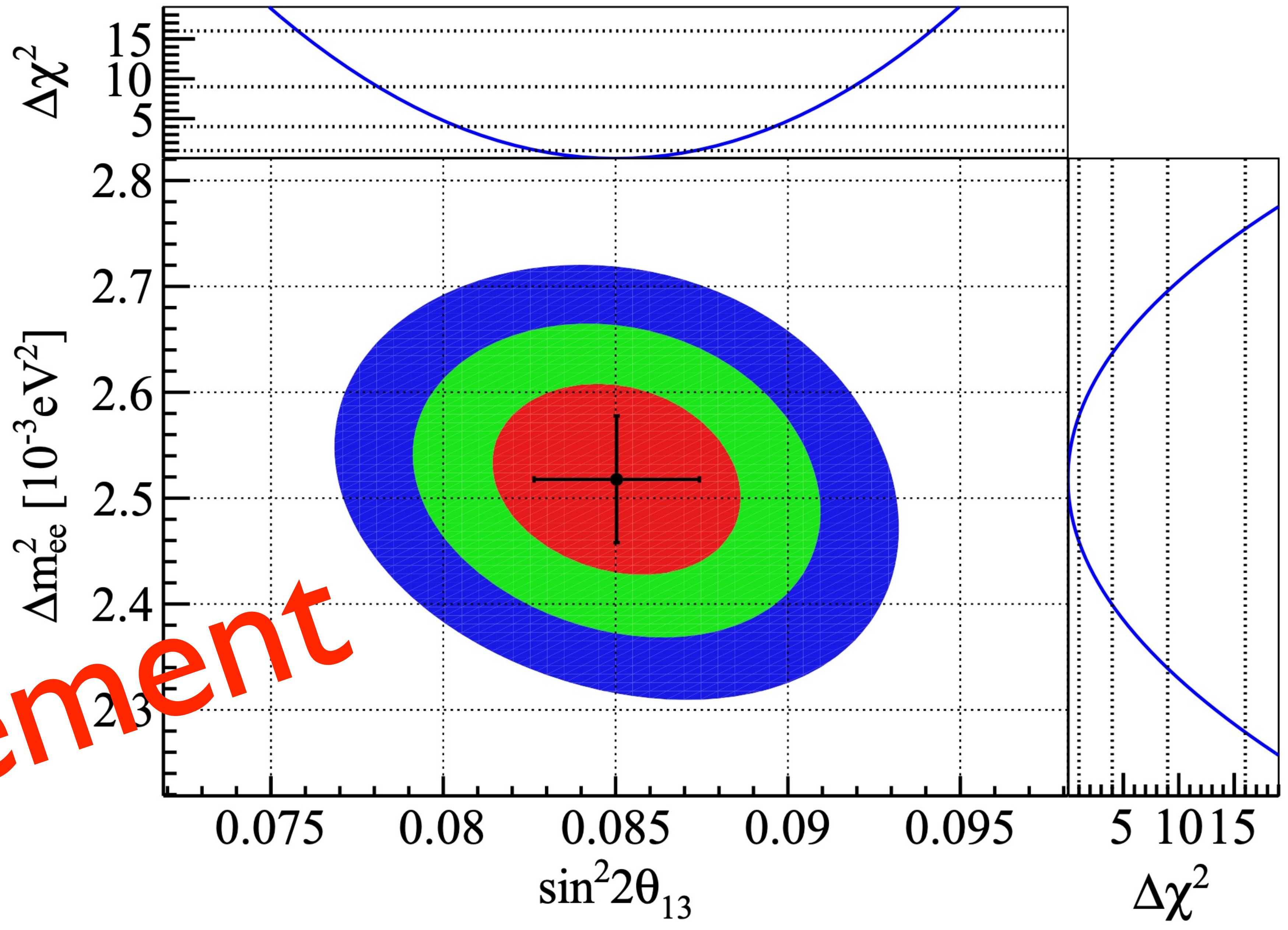


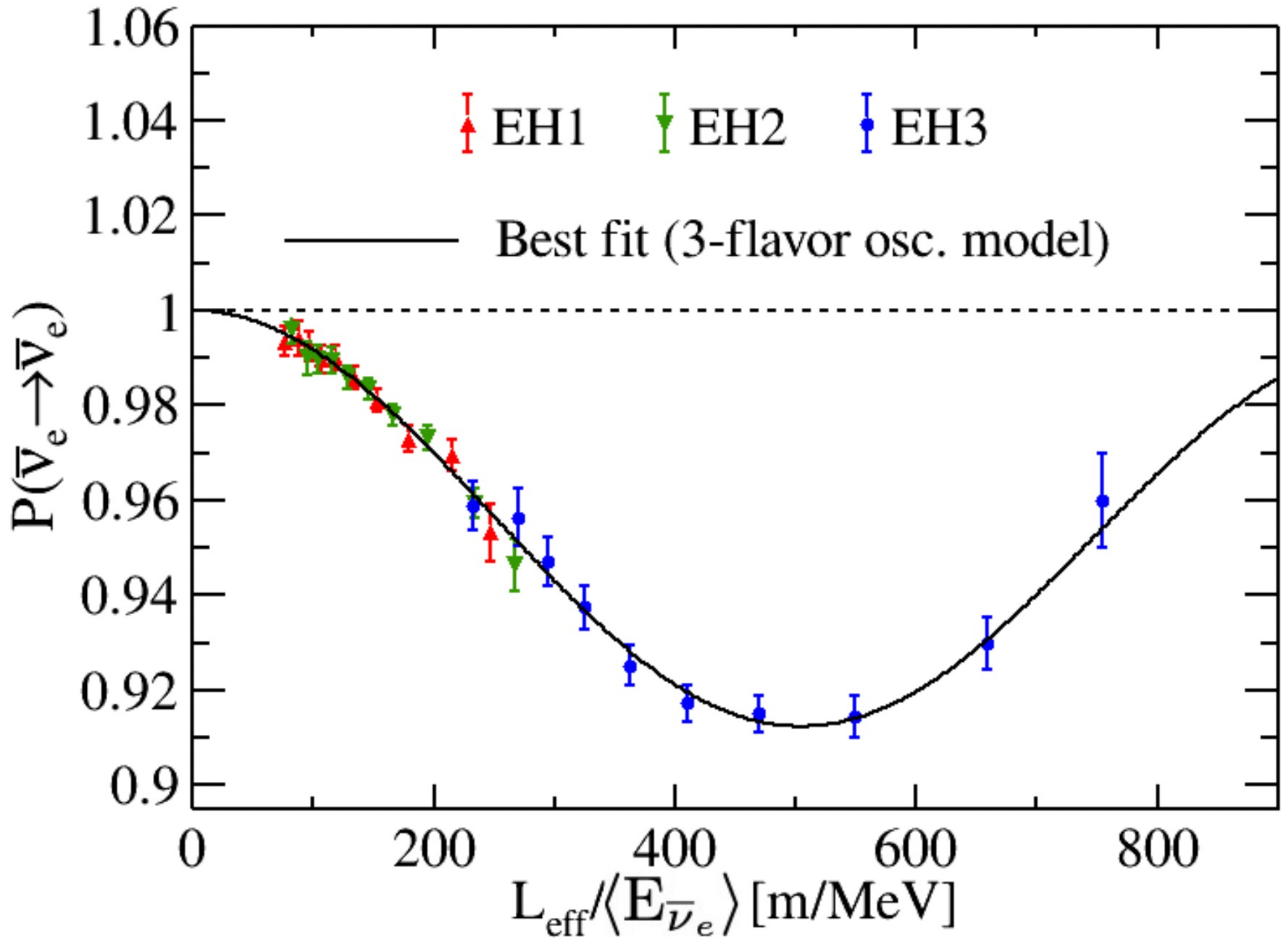
Delta Prob (Daya Bay)



$$P_{\text{NPZ}}(\nu_e \to \nu_e) \approx 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right)$$

Improved $\sin^2 2\theta_{13}$ and Δm^2_{32}





Measurement

Best-fit results: χ^2/ndf = 559/518

$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$ (2.8% precision)

$\pm c^2_{12}\Delta m^2_{21}$

Normal hierarchy: $\Delta m^2_{32} = +\,(2.466^{+0.060}_{-0.060}) \times 10^{-3}$ eV^2 (2.4% precision)

Inverted hierarchy: $\Delta m^2_{32} = -\,(2.571^{+0.060}_{-0.060}) \times 10^{-3}$ eV^2 (2.3% precision) 18

$$|\Delta m^2_{32}|^{IO} - |\Delta m^2_{32}|^{NO} = \quad + 2c^2_{12}\Delta m^2_{21} = 0.105 \times 10^{-3}\ \text{eV}^2$$

ν_μ disappearance at an L/E $\sim$ 500 km/GeV

$$\Delta m^2_{\mu\mu} \equiv \frac{|U_{\mu 1}|^2 \Delta m^2_{31} + |U_{\mu 2}|^2 \Delta m^2_{32}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2} = m^2_3 - \frac{|U_{\mu 1}|^2 m^2_1 + |U_{\mu 2}|^2 m^2_2}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

$$\approx \Delta m^2_{ee} - (\cos 2\theta_{12} - \sin\theta_{13} \cos\delta)\Delta m^2_{21}$$

$(\sin 2\theta_{12} \tan\theta_{23} \approx 1)$

ν_μ average of Δm^2_{31} and Δm^2_{32}

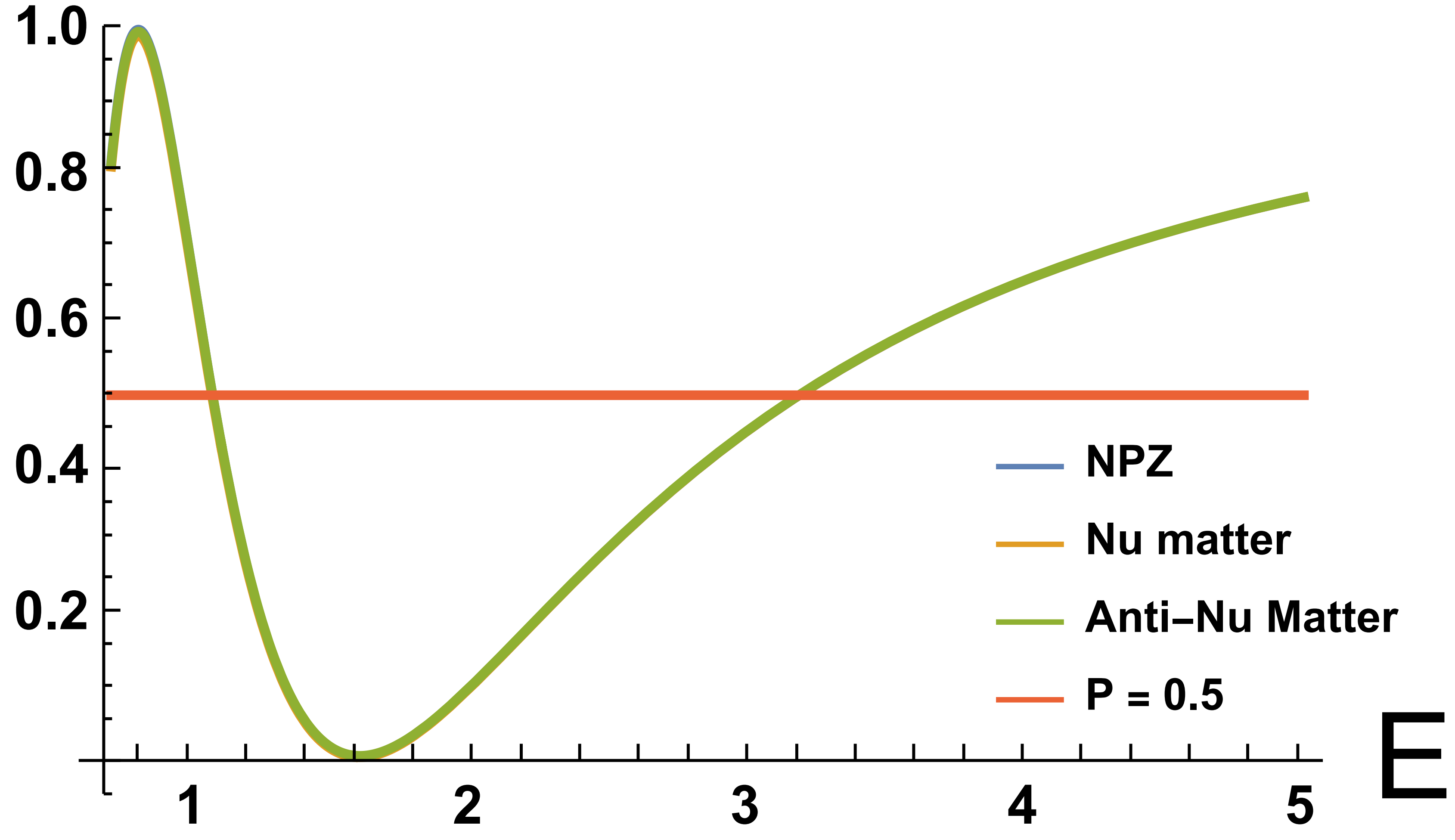
$|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ implies NO

$|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$ implies IO

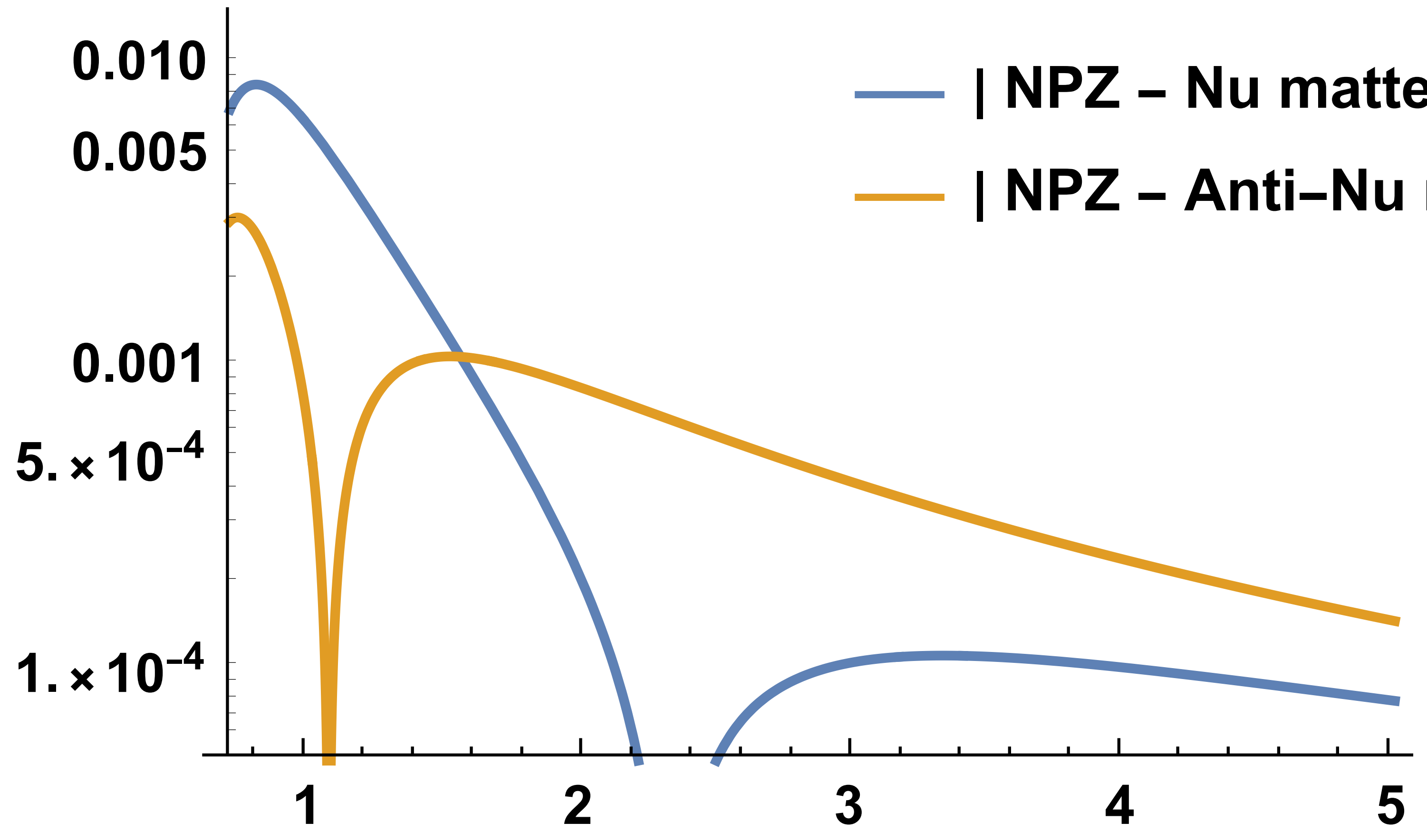
THIS IS IGNORING MATTER EFFECTS:

$$P_{\mathrm{NPZ}}(\nu_\mu \to \nu_\mu) \approx 1 - 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)\sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right)$$

Dis. Prob (NOvA)



Delta Prob (NOvA)



For Disappearance channel, only $|U_{\mu 3}|^2$ and $|\Delta m^2_{\mu\mu}|$ are measureable around first oscillation minimum.

To extract Δm^2_{32} , for 1% precision one needs $\mp \sin^2\theta_{12}\Delta m^2_{21}$ and for 0.5% level also $\mp \sin\theta_{13}\cos\delta\,\Delta m^2_{21}$

$$|\Delta m^2_{\mu\mu}| \approx |\Delta m^2_{32}|^{NO}_{\overline{IO}} \pm (s^2_{12} + s_{13}\cos\delta^{NO}_{\overline{IO}})\Delta m^2_{21} = |\Delta m^2_{31}|^{NO}_{\overline{IO}} \mp (c^2_{12} - s_{13}\cos\delta^{NO}_{\overline{IO}})\Delta m^2_{21}$$

T2K:

Parameter	With reactor constraint	
	Normal ordering	Inverted ordering
$\delta_{\rm CP}$ (rad.)	$-1.97^{+0.97}_{-0.62}$	$-1.44^{+0.56}_{-0.59}$
$\sin^2\theta_{13}/10^{-3}$	—	—
$\sin^2\theta_{23}$	$0.561^{+0.019}_{-0.038}$	$0.563^{+0.017}_{-0.032}$
$\Delta m^2_{32}/10^{-3}\,(\mathrm{eV}^2)$	$2.494^{+0.041}_{-0.058}$	—
$\lvert\Delta m^2_{31}\rvert/10^{-3}\,(\mathrm{eV}^2)$	—	$2.463^{+0.042}_{-0.056}$

± 0.05 (2%)

$$|\Delta m^2_{31}|^{IO} - |\Delta m^2_{32}|^{NO} = -(\cos 2\theta_{12} - 2s_{13}\widehat{\cos\delta})\Delta m^2_{21}$$

$$|-2.463| - +2.494 \approx -(0.4 - 0.30\widehat{\cos\delta}) \times 0.075$$

$$-0.031 = -\begin{pmatrix} 0.008 & \widehat{\cos\delta} = 1 \\ 0.030 & \widehat{\cos\delta} = 0 \\ 0.053 & \widehat{\cos\delta} = -1 \end{pmatrix}$$

$$|\Delta m^2_{\mu\mu}| \approx |\Delta m^2_{32}|^{\frac{NO}{IO}} \pm (s^2_{12} + s_{13}\cos\delta^{\frac{NO}{IO}})\Delta m^2_{21} = |\Delta m^2_{31}|^{\frac{NO}{IO}} \mp (c^2_{12} - s_{13}\cos\delta^{\frac{NO}{IO}})\Delta m^2_{21}$$

NOvA:

Parameter	Normal ord. UO	Normal ord. LO	Inverted ord. UO	Inverted ord. LO
$\Delta m^2_{32}(10^{-3}\ \mathrm{eV}^2)$	$+2.41 \pm 0.07$	$+2.39$	-2.45	-2.44
$\sin^2\theta_{23}$	$0.57^{+0.03}_{-0.04}$	0.46	0.56	0.46
$\delta_{\mathrm{CP}}(\pi)$	$0.82^{+0.27}_{-0.87}$	0.07	1.52	1.41

± 0.07

$$|\Delta m^2_{32}|^{IO} - |\Delta m^2_{32}|^{NO} = (2s^2_{12} + s_{13}\cos\delta^{NO} + s_{13}\cos\delta^{IO})\Delta m^2_{21}$$

UO $$|-2.45| - +2.41 \approx (0.6 + 0.15\cos\delta^{NO} + 0.15\cos\delta^{IO}) \times 0.075$$

$$0.04 \approx 0.045 - 0.008$$

LO $$|-2.44| - +2.39 \approx (0.6 + 0.15\cos\delta^{NO} + 0.15\cos\delta^{IO}) \times 0.075$$

$$0.05 \approx 0.045 + 0.007$$

agrees to the accuracy provided !

Matter Effect:

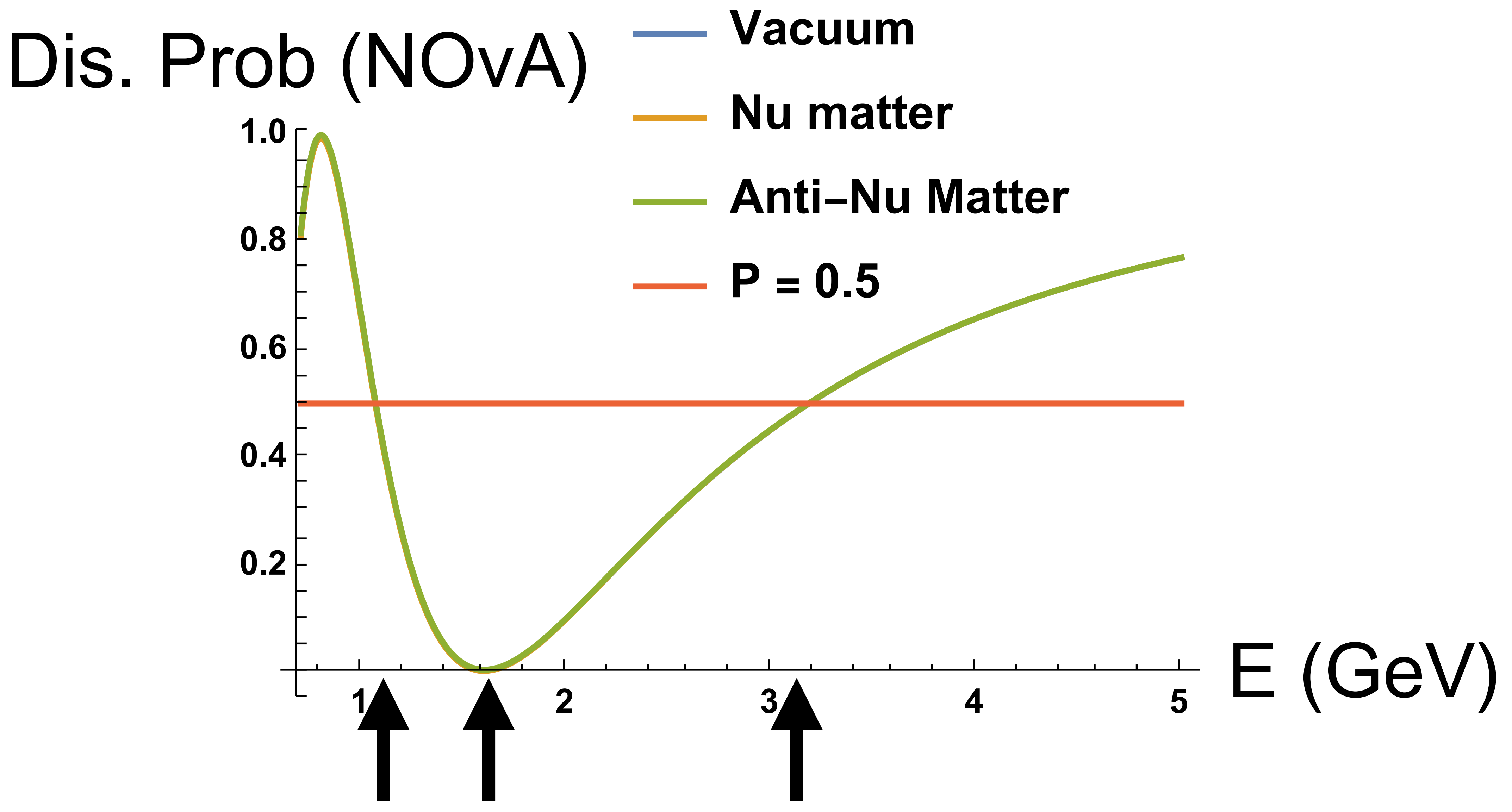
Daya Bay: $\dfrac{E_\nu}{12\text{ GeV}} < 10^{-3}$ irrelevant

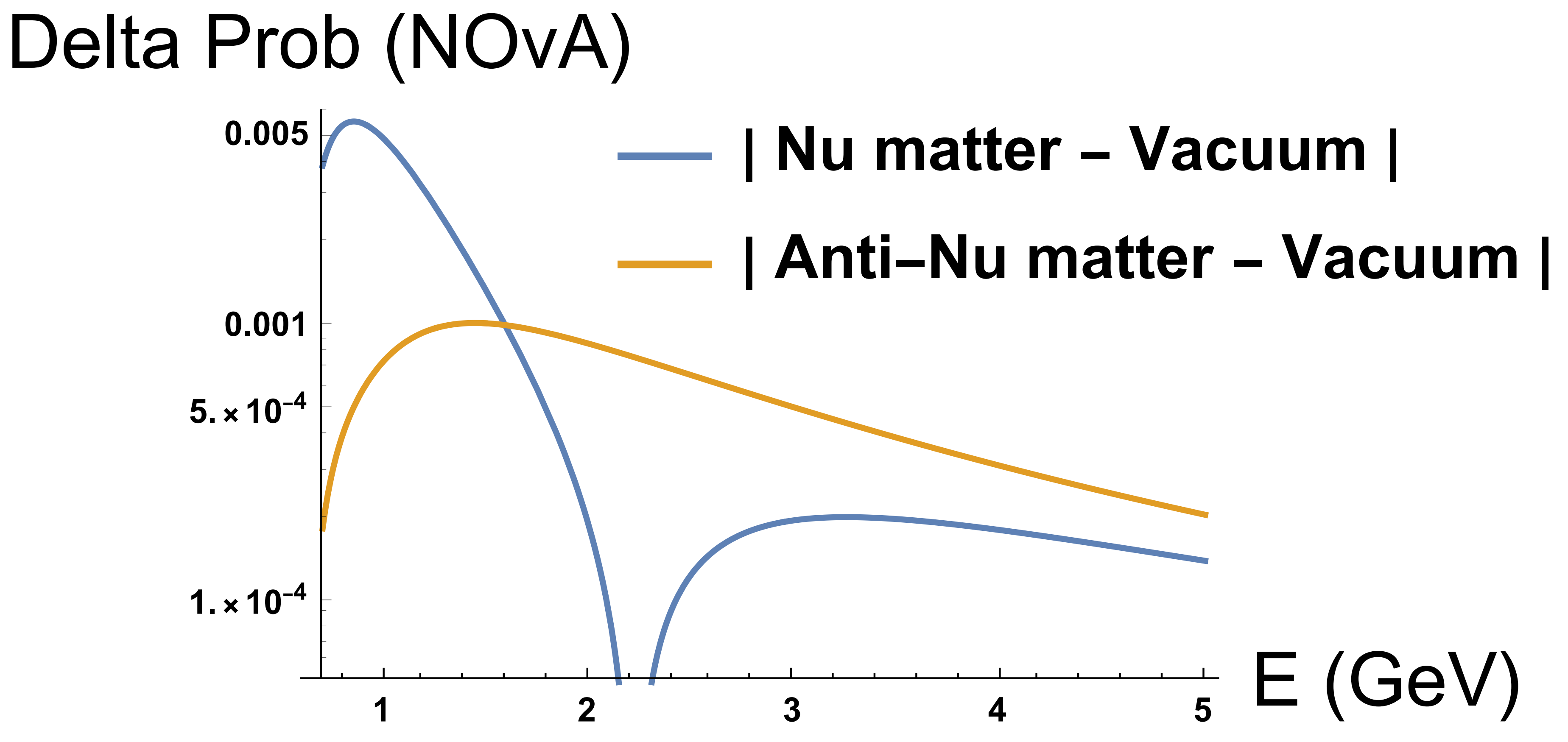
NOvA Disappearance: $\dfrac{E_\nu}{12\text{ GeV}} \approx 0.2$

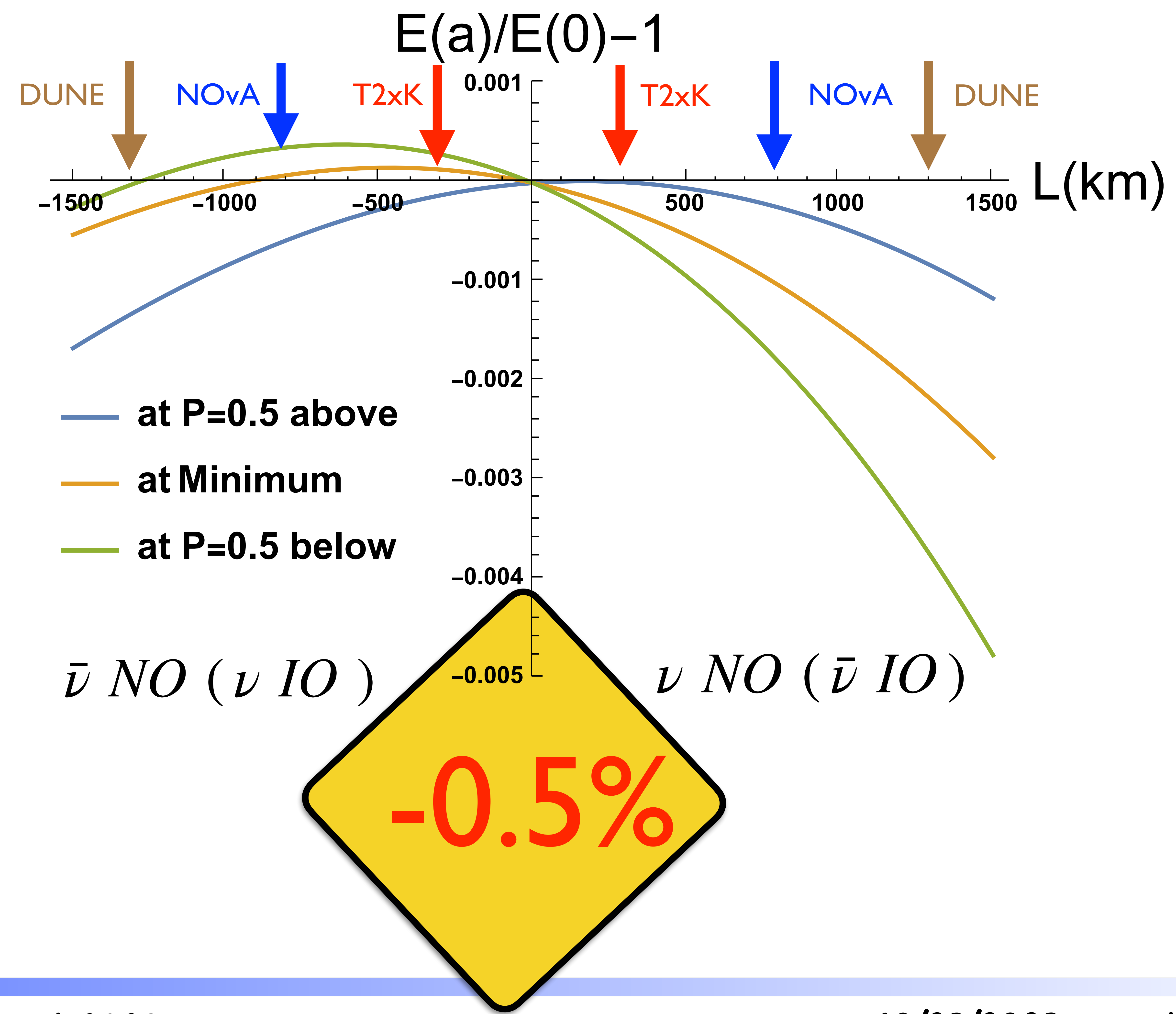
But further suppressed by s_{13}^2 and $(1 - 2|U_{\mu 3}|^2)$

Combined approx. 0.002 !

NOvA matter effects in the disappearance channel:







ν_e Disappearance:

$|\Delta m^2_{ee}|$ same for both orderings

Daya Bay:

ν_μ Disappearance:

$|\Delta m^2_{\mu\mu}|$ same for both orderings

NOvA, T2K:

$$|\Delta m^2_{32}|^{IO}_{DB} = |\Delta m^2_{31}|^{NO}_{DB} + \cos 2\theta_{12}\Delta m^2_{21}$$

$$|\Delta m^2_{32}|^{IO}_{\mu dis} = |\Delta m^2_{31}|^{NO}_{\mu dis} - (\cos 2\theta_{12} - 2\sin\theta_{13}\widehat{\cos\delta})\Delta m^2_{21}$$

$$\cos 2\theta_{12} \approx 0.40$$

$$\cos 2\theta_{12} - 2\sin\theta_{13}\cos\delta \approx 0.40 - 0.30\cos\delta$$

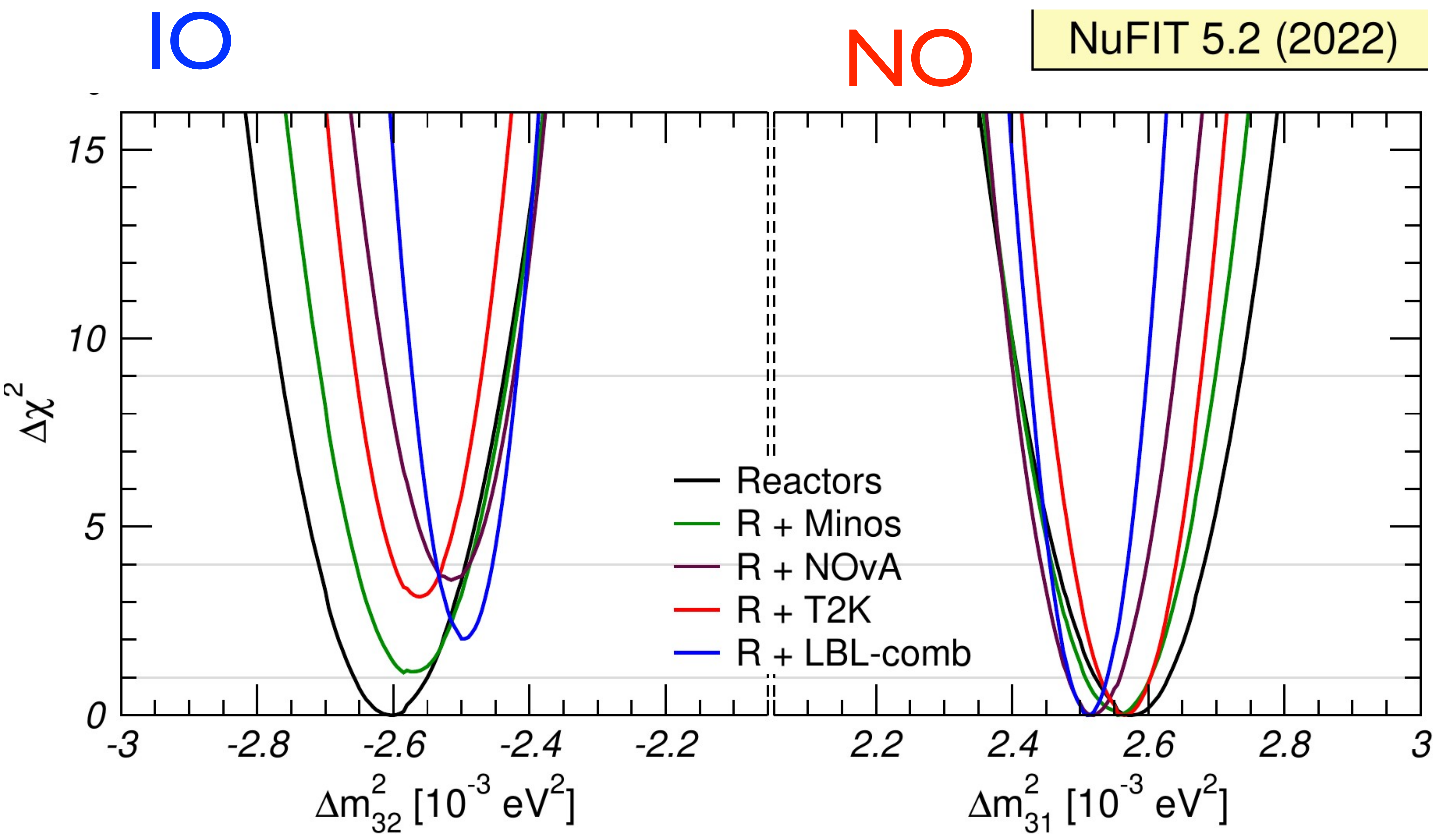
If IO then 0

If NO then 0

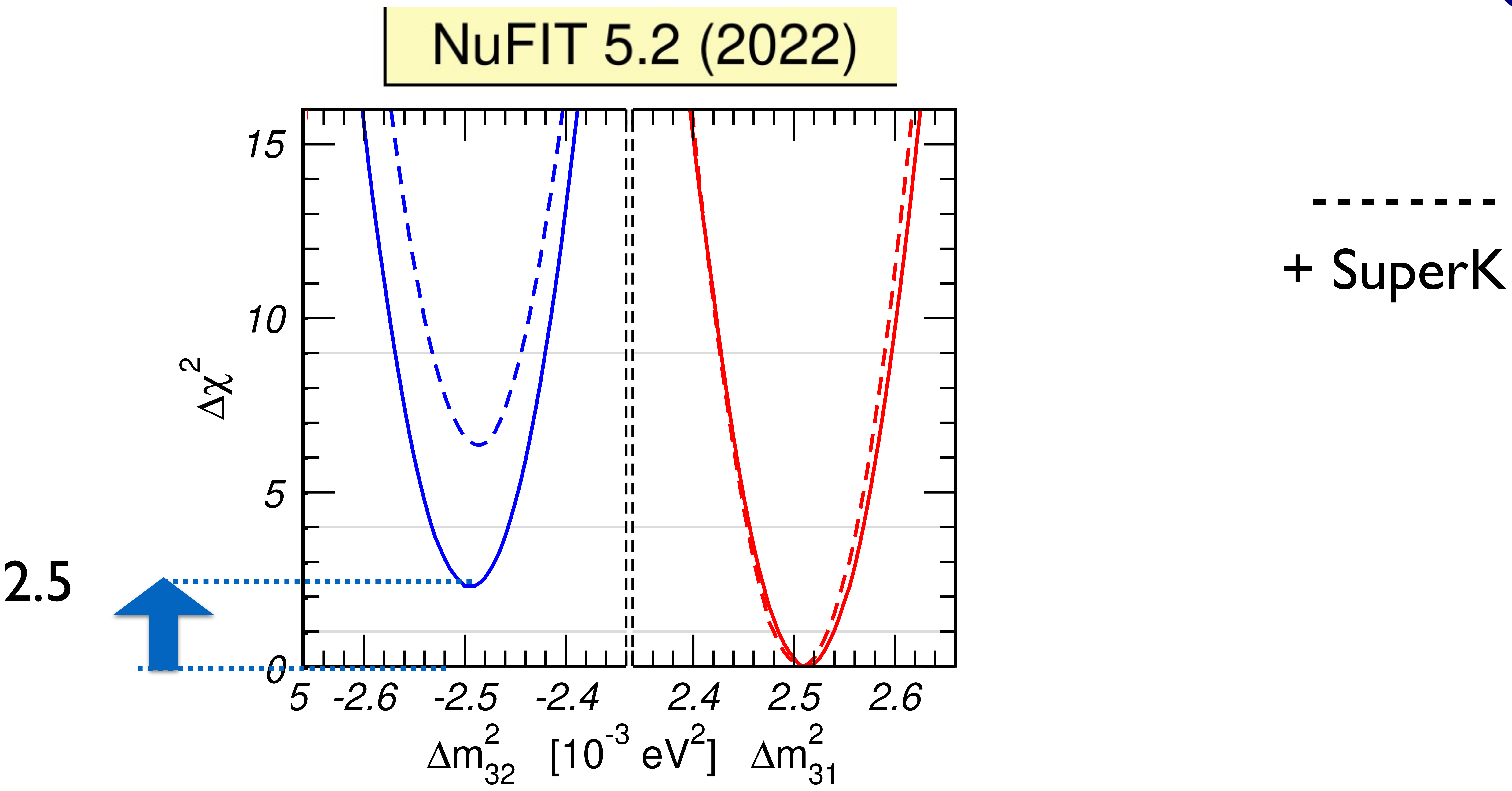
$$\left(|\Delta m^2_{32}|^{IO}_{DB} - |\Delta m^2_{32}|^{IO}_{\mu dis}\right) + \left(|\Delta m^2_{31}|^{NO}_{\mu dis} - |\Delta m^2_{31}|^{NO}_{DB}\right) = (2.4 - 0.9\widehat{\cos\delta})\%\ |\Delta m^2_{ee}|$$

1.5 to 3.3 %

Unchanged if $31 \leftrightarrow 32$ in either or both MO's

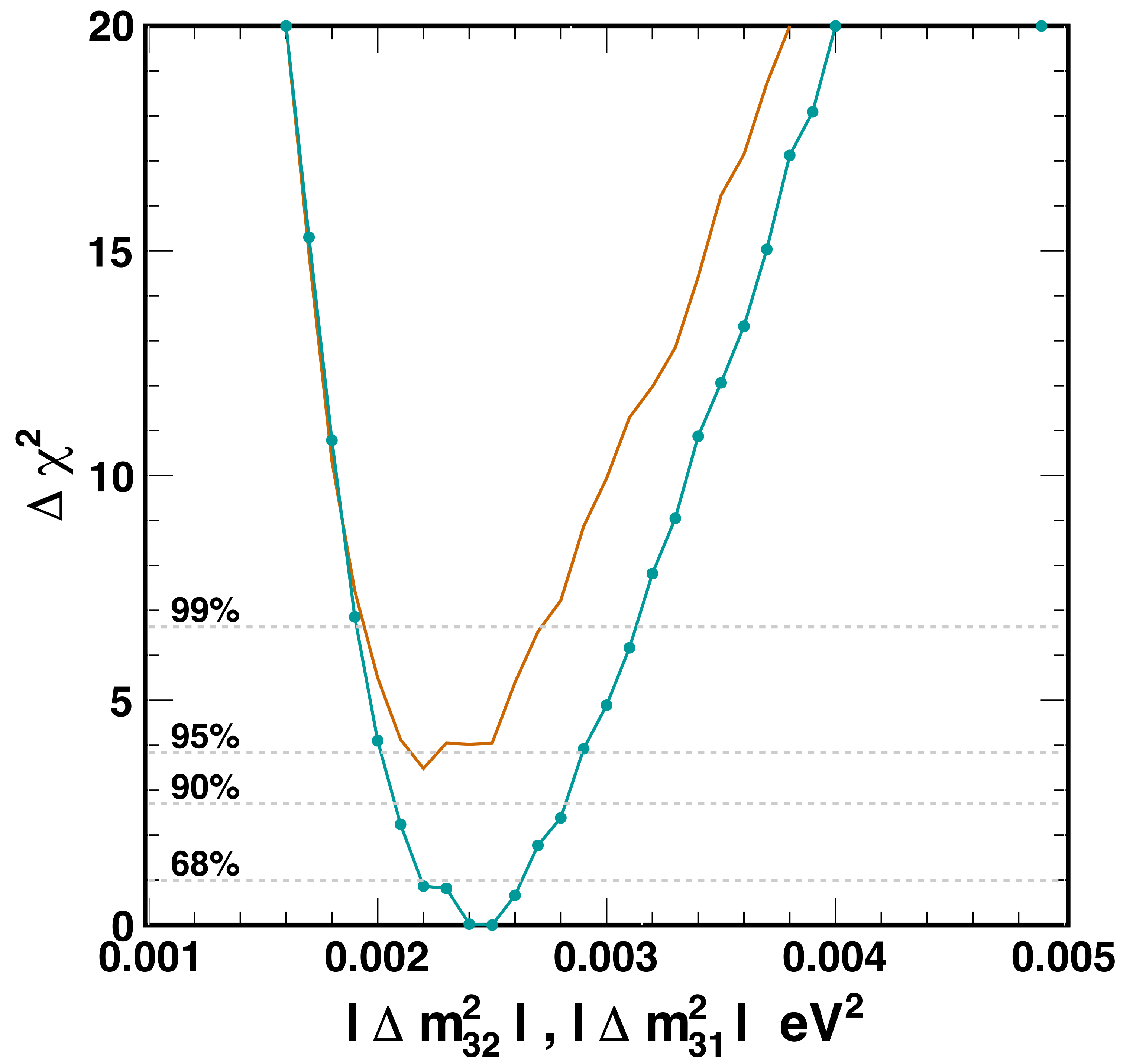


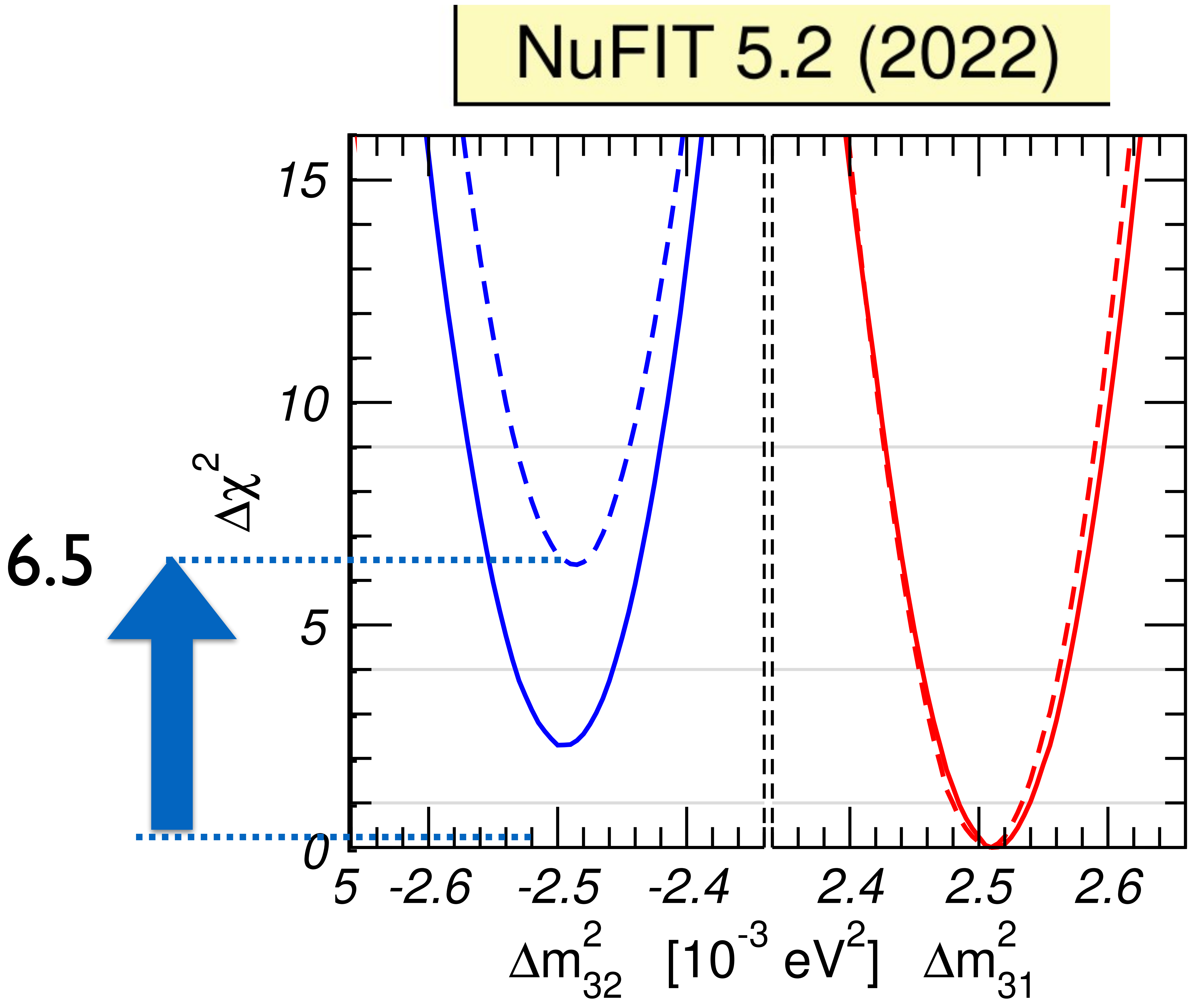
Hinting at NO and $\cos\delta \leq 0$



2.5 approx -1.6 (App LBL) +4.1 (Dis LBL)

add SuperKamiokaNDE arXiv:1710.09126

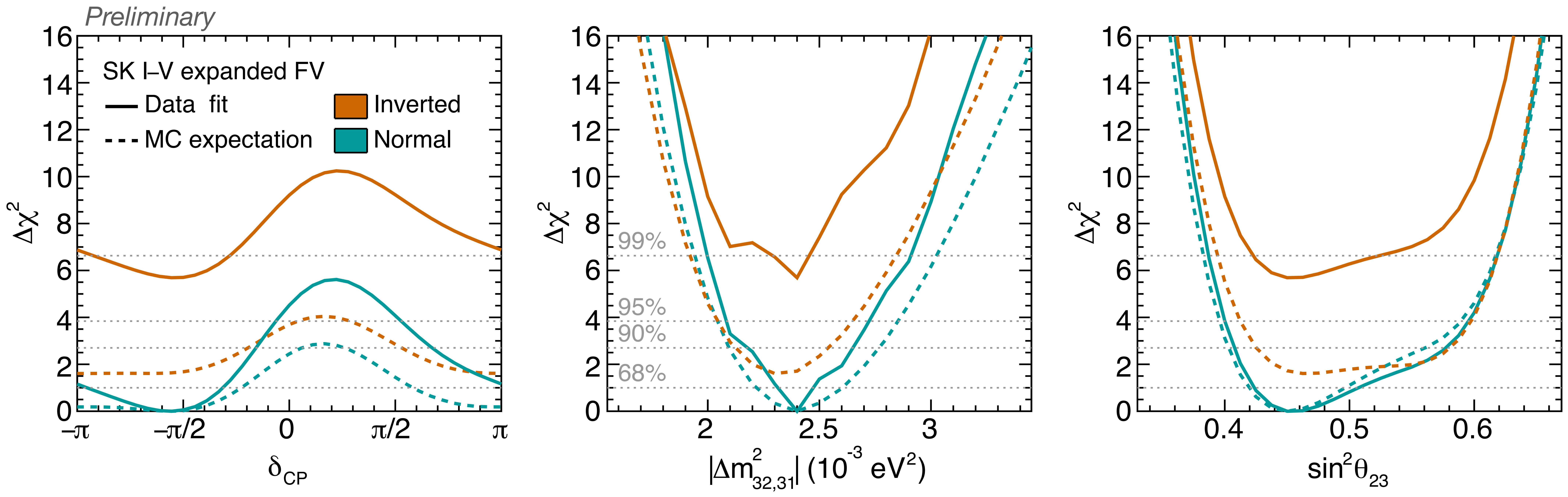




NO preference with $\Delta\chi \sim 4.0$

6.5 approx +4.0 (SK) -1.6 (App LBL) +4.1 (Dis LBL)

SK I–V Atmospheric Oscillation Results



SK 2023 best fit: Normal ordering, $\delta_{CP} \sim -\pi/2$, $\Delta m^2_{32} \sim 2.4 \times 10^{-3}$ eV^2, $\sin^2\theta_{23} \sim 0.45$

Mass ordering: $\Delta\chi^2_{\text{I.O. - N.O.}} \sim 5.7$*

With reactor constraint: $\sin^2\theta_{13} = 0.0220 \pm 0.0007$

NEXT STEP: JUNO

JUNO

Fig. 1. Map of the local area around the experimental site of JUNO, located on the South-West part of the Guangzhou city in China.

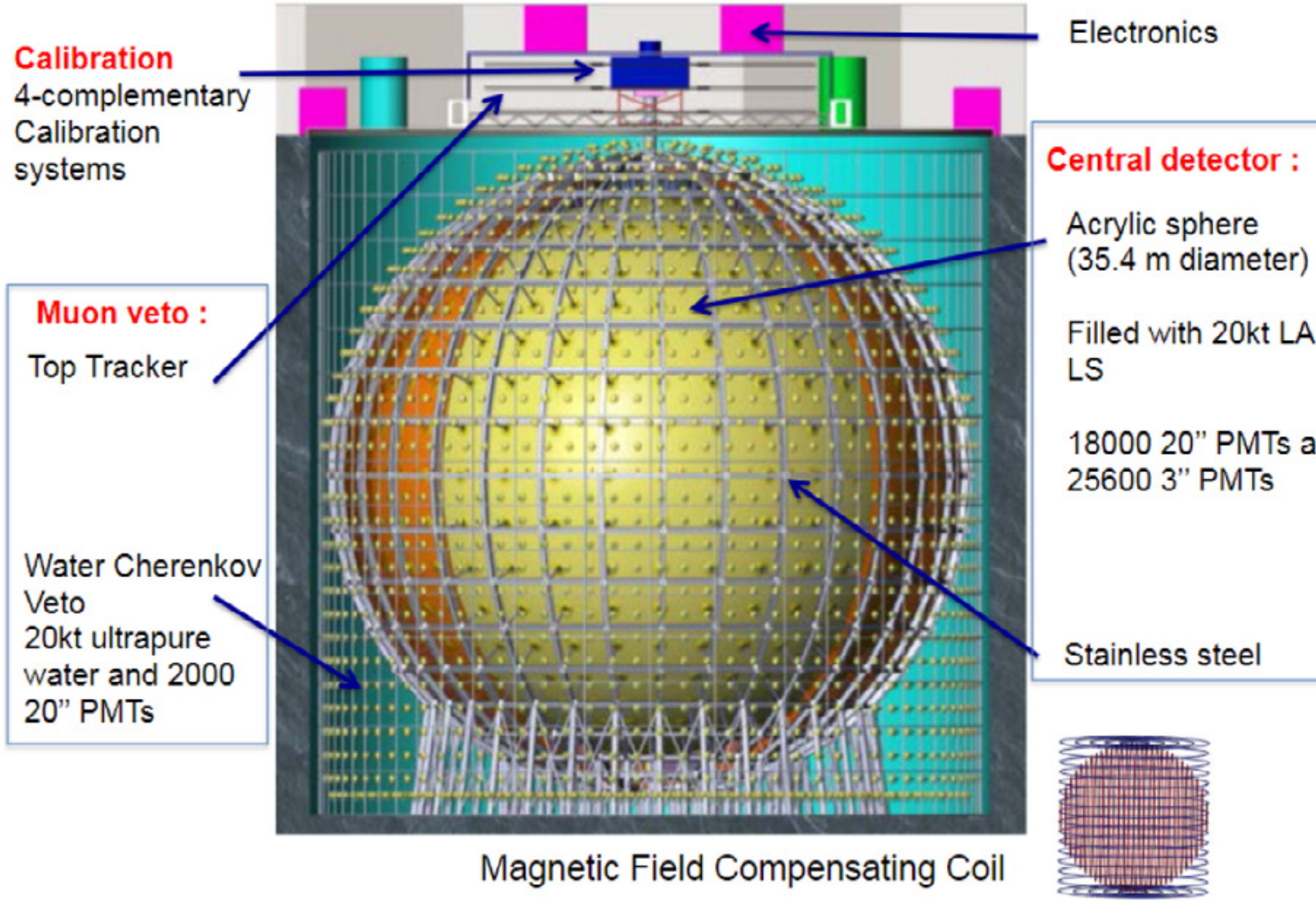
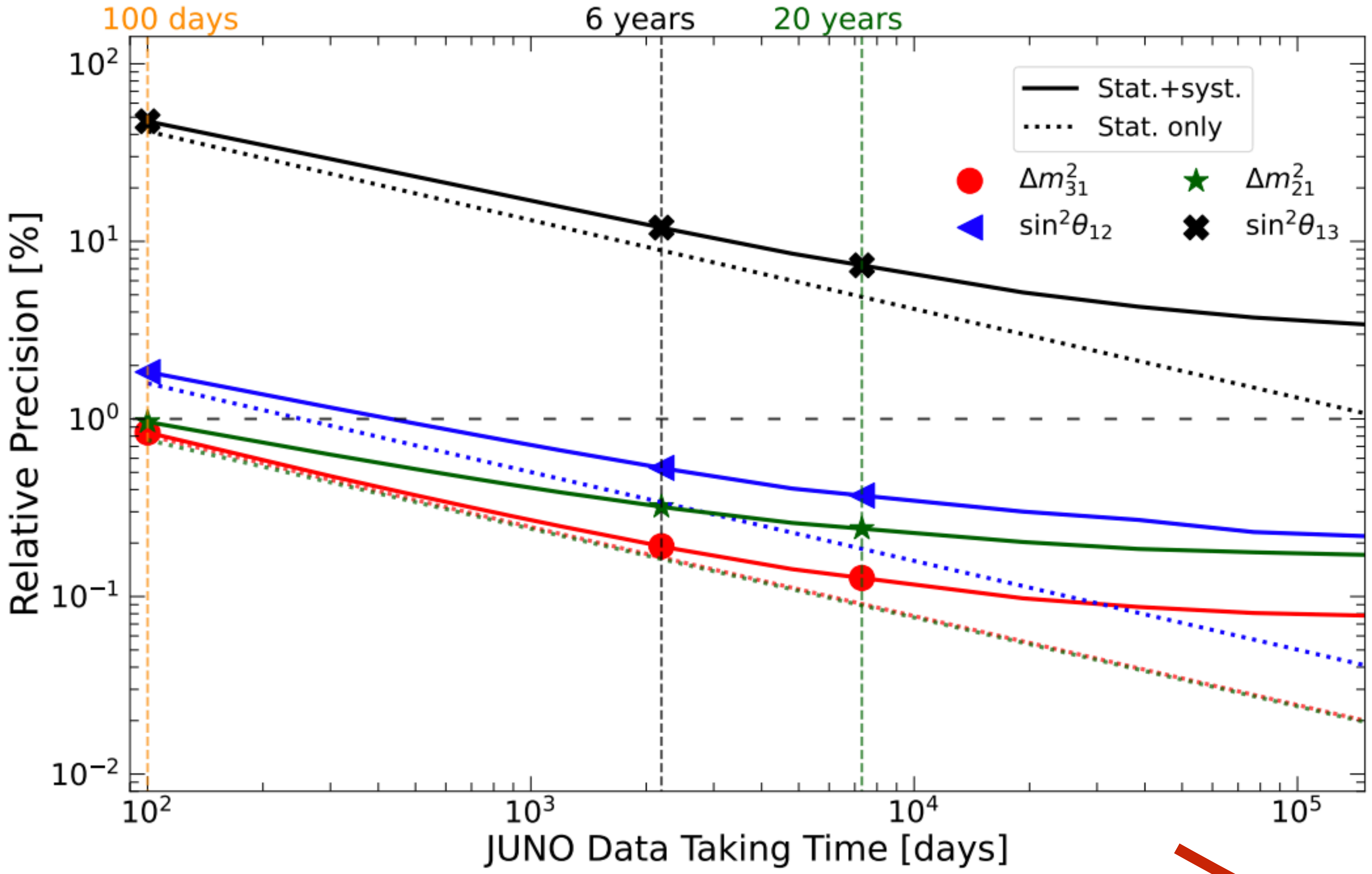


Fig. 4. Schematic view of the JUNO detector.

Reactor	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6	TS-C1	TS-C2	DB	HZ
Power (GW_{th})	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline (km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

Time Evolution of JUNO measurements



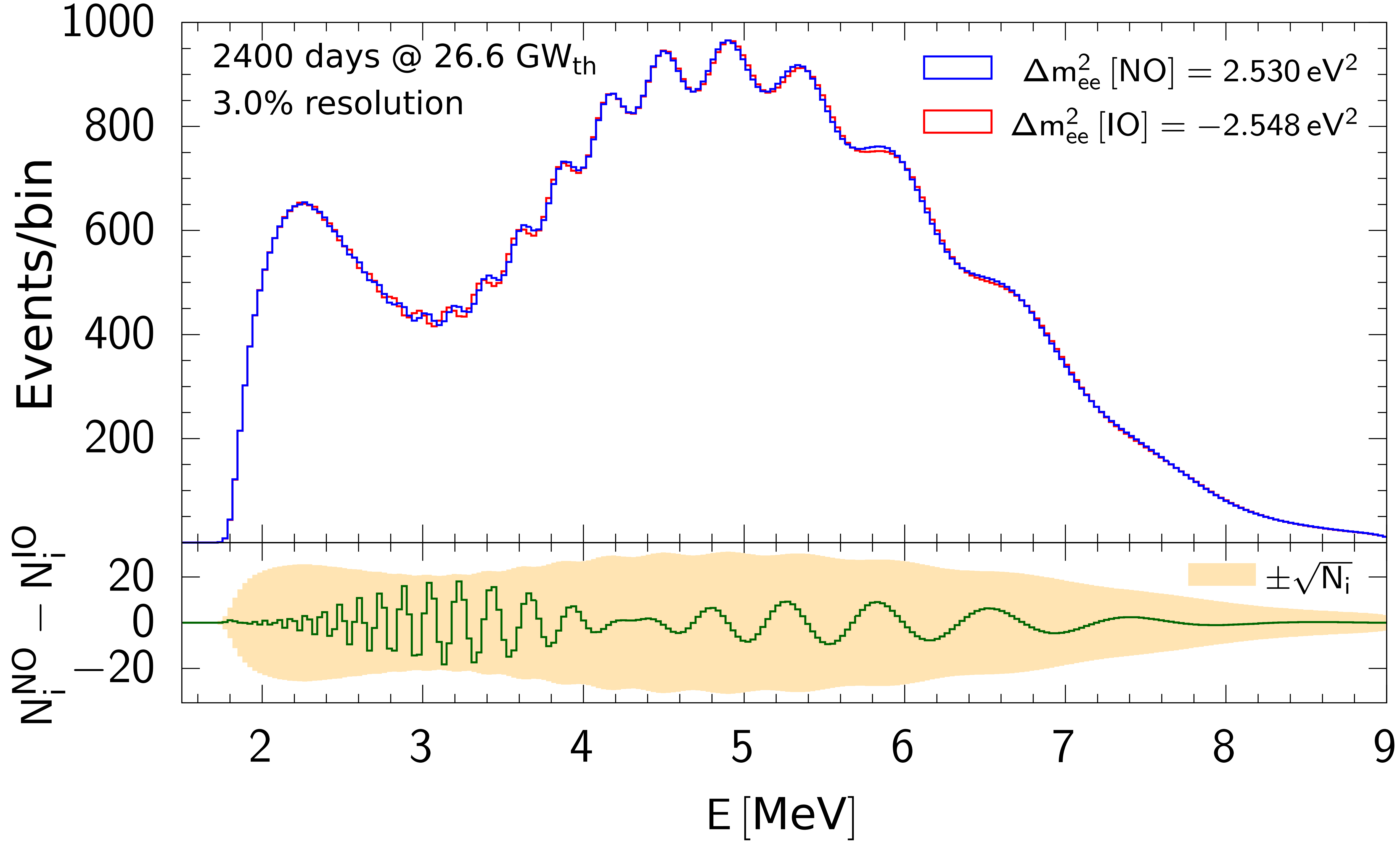
JUNO_update_2204.13249

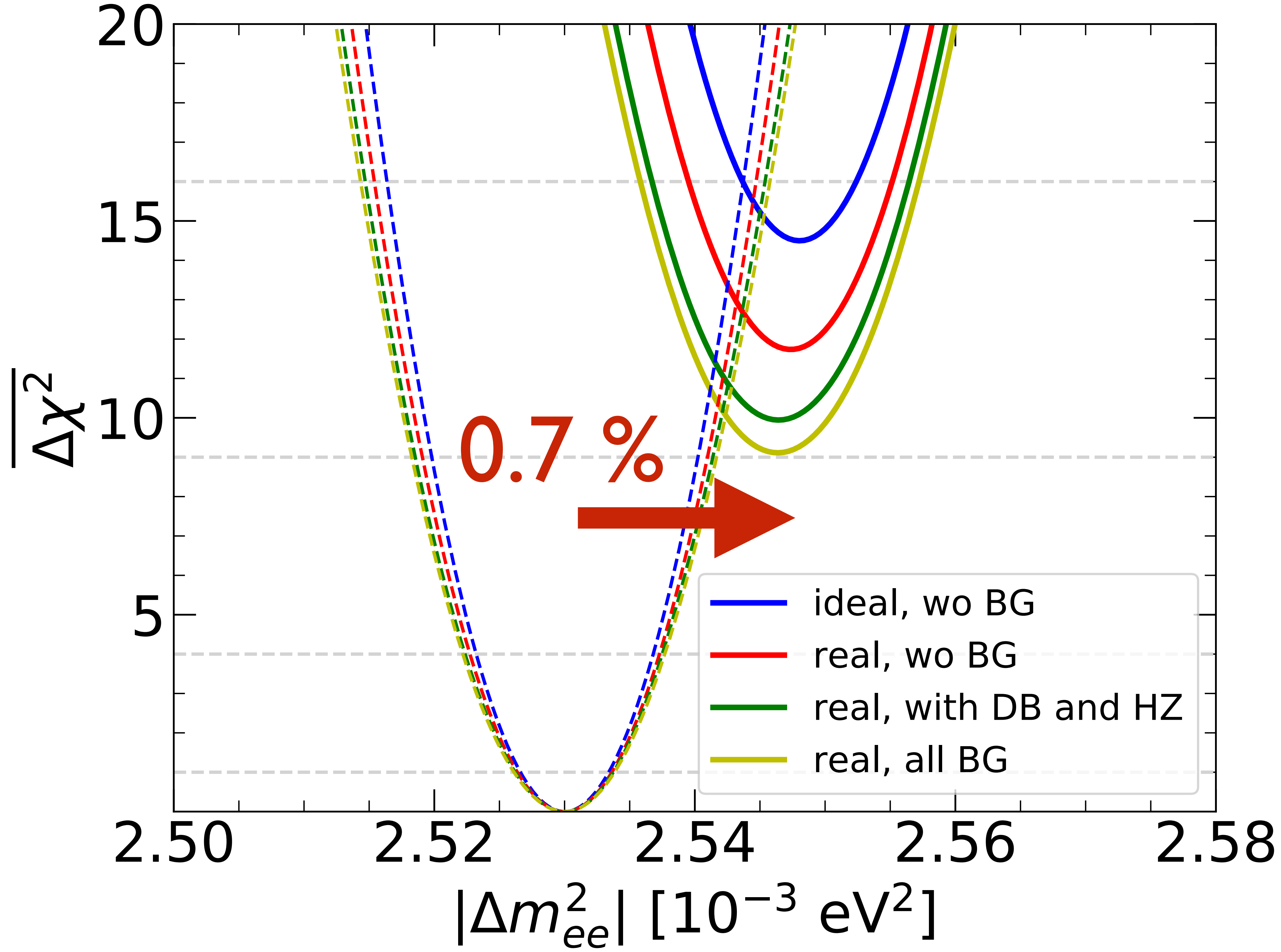
Time	% on Δm^2_{atm}	$\overline{\lvert\chi^2_{NO} - \chi^2_{IO}\rvert}$
100 days	1.0	0.25
4 years	0.3	3.4
8 years	0.2	6.7
12 Years	0.15	10.0

Forero, SP, Ternes, Zukanovich 2107.12410

JUNO Events Spectra

Real Baseline Distribution + Backgrounds





8 years, 26.6 GW_th
baseline exactly 52.5 km
3.0 % resolution

Forero, SP, Ternes, Zukanovich 2107.12410

If $|\Delta m^2_{32}|(IO) = |\Delta m^2_{32}|(NO)$, then $|\Delta m^2_{ee}|(IO) = 2.428$

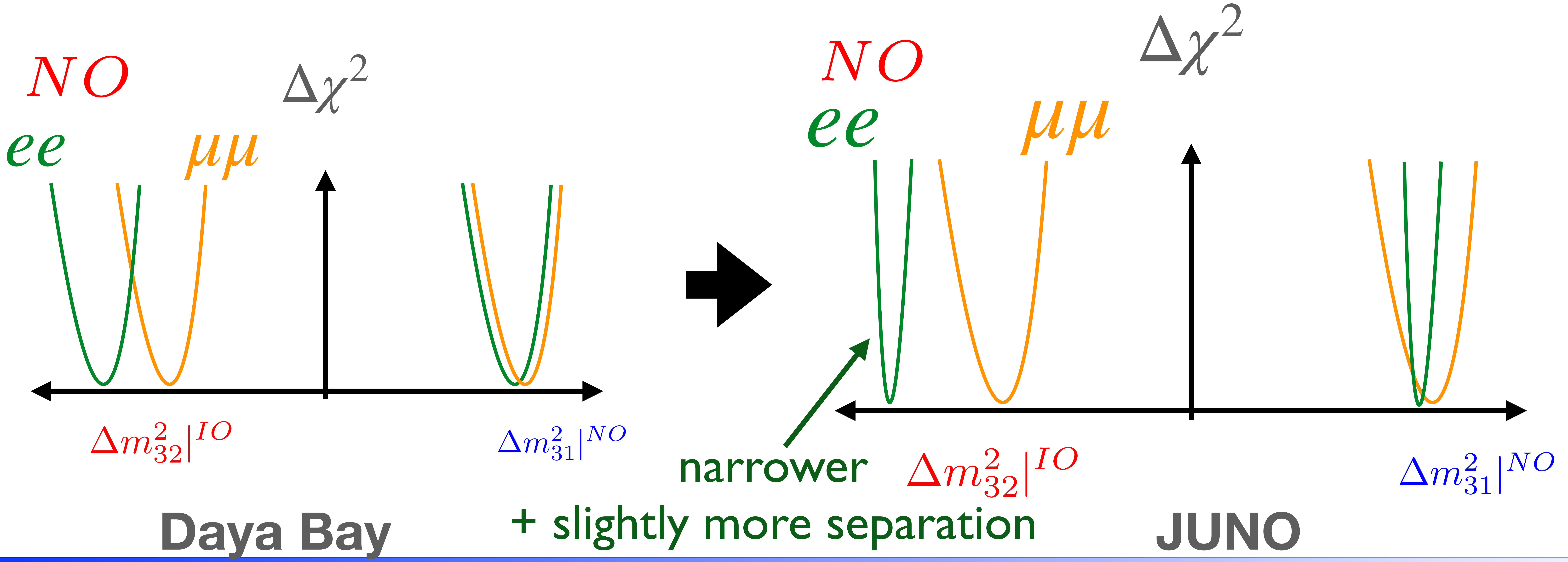
If $|\Delta m^2_{31}|(IO) = |\Delta m^2_{31}|(NO)$, then $|\Delta m^2_{ee}|(IO) = 2.578$

If $|\Delta m^2_{32}|(IO) = |\Delta m^2_{31}|(NO)$, then $|\Delta m^2_{ee}|(IO) = 2.503$

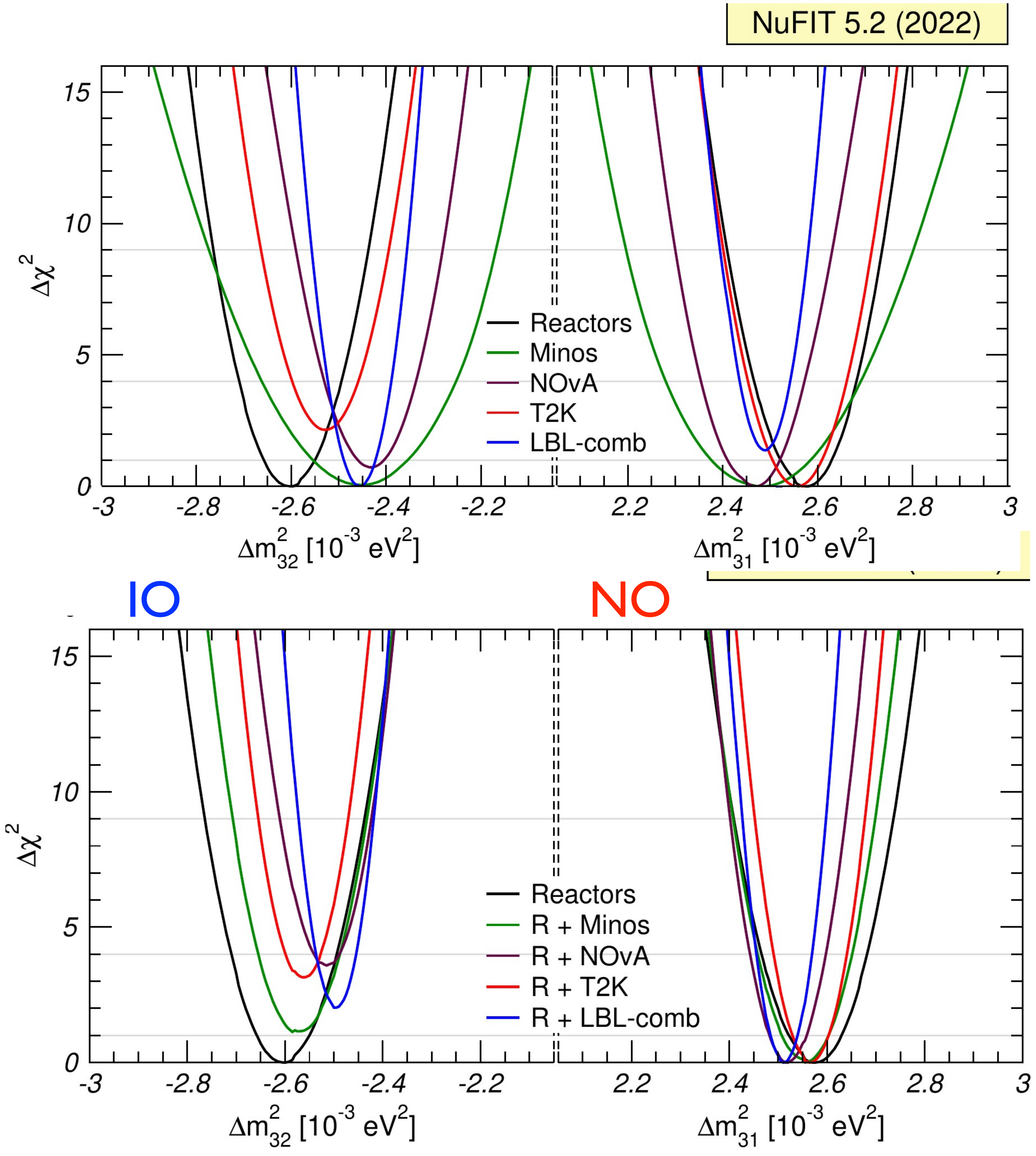
For JUNO: $|\Delta m^2_{ee}|^{IO} = 1.007\ |\Delta m^2_{ee}|^{NO}$

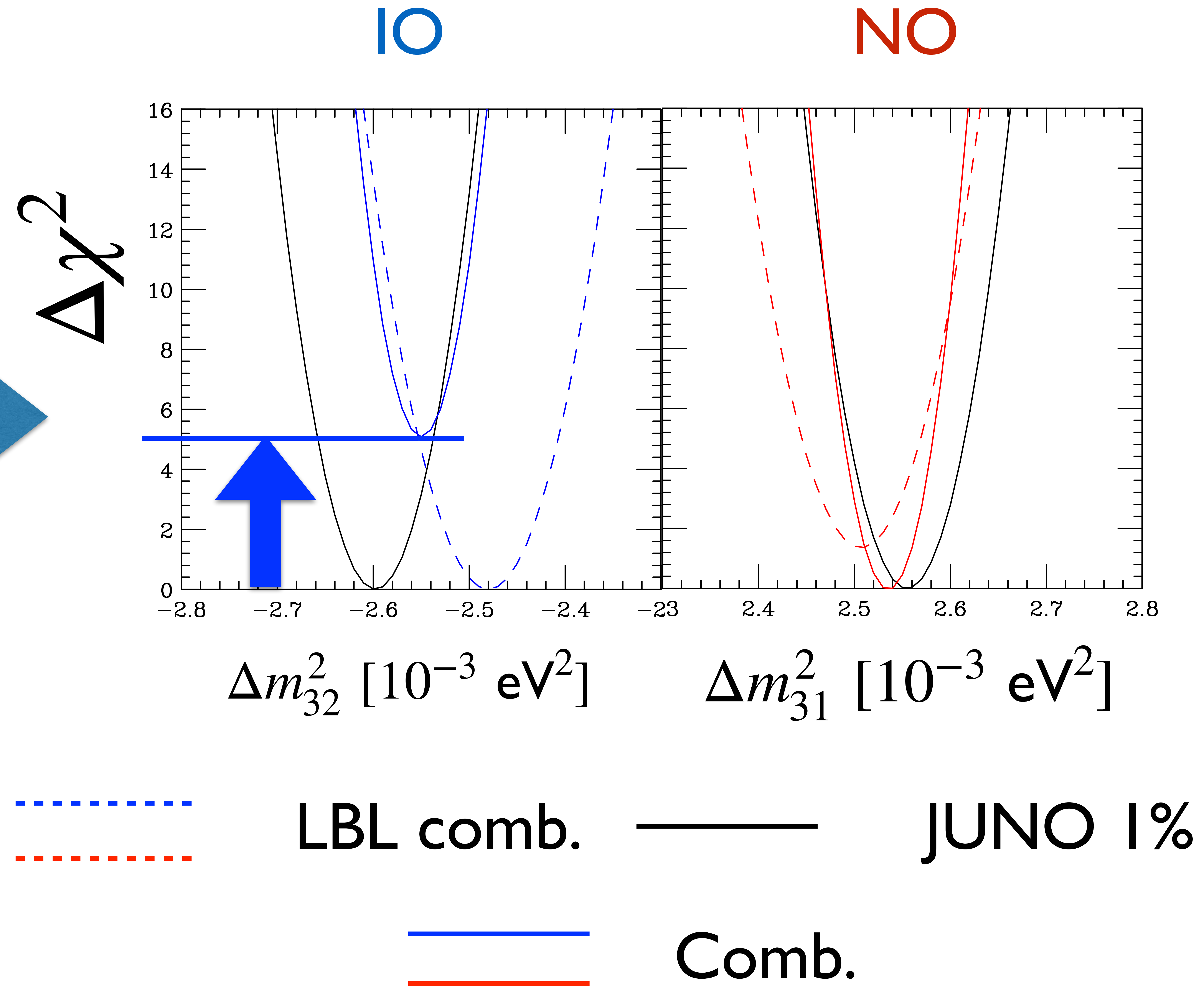
$$\left(|\Delta m^2_{32}|^{IO}_{Ju} - |\Delta m^2_{32}|^{IO}_{\mu dis}\right) + \left(|\Delta m^2_{31}|^{NO}_{\mu dis} - |\Delta m^2_{31}|^{NO}_{Ju}\right) = (3.3 - 0.9\widehat{\cos\delta})\%\ |\Delta m^2_{ee}|$$

and experimental uncertainty on $|\Delta m^2_{ee}|$ drops to <1%. (Daya Bay 2.4%).

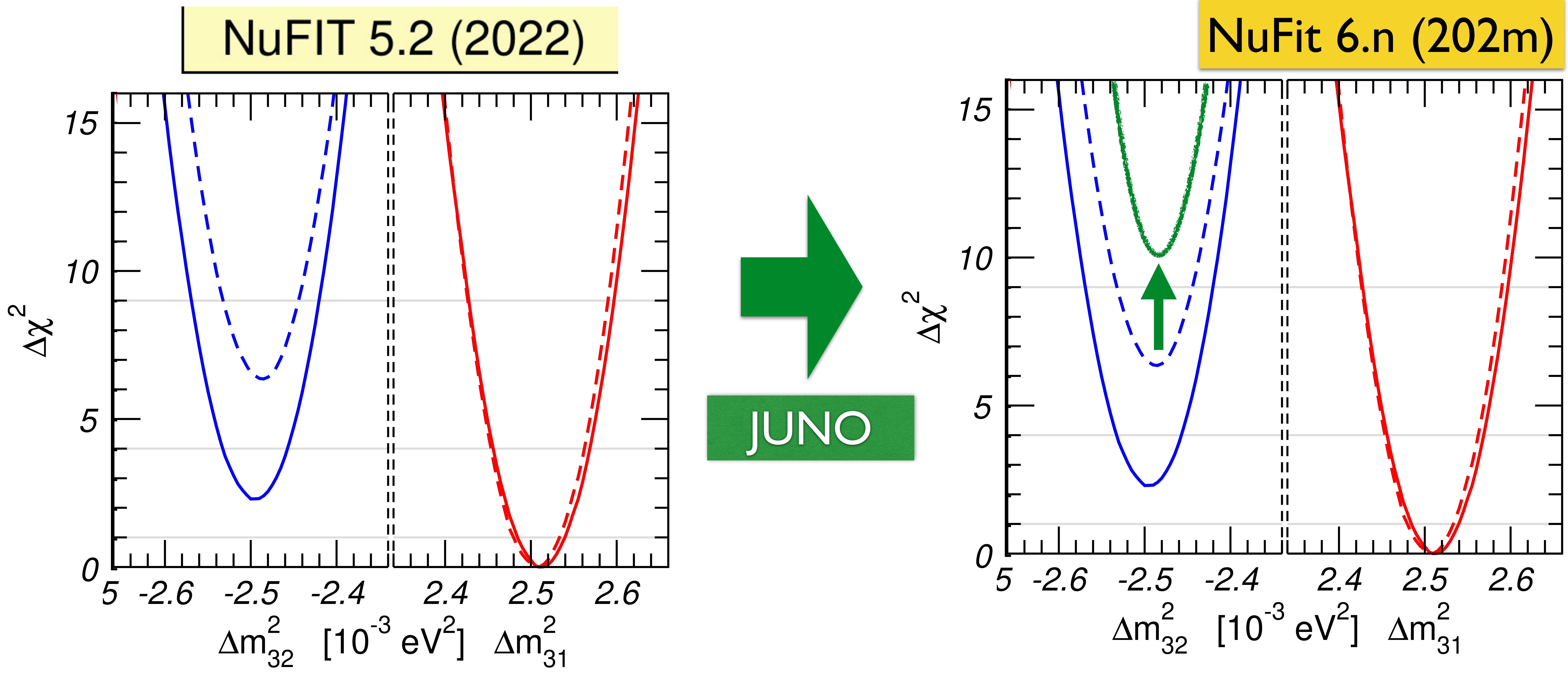


Preliminary NPZ++





Effect of JUNO's presicion measurement on Δm^2_{ee}



my guess: Global Fits > 3σ at Nu 2026

Further Synergies:

JUNO-ICECUBE UPGRADES 1911.06745

JUNO-KM3NET 2108.06293

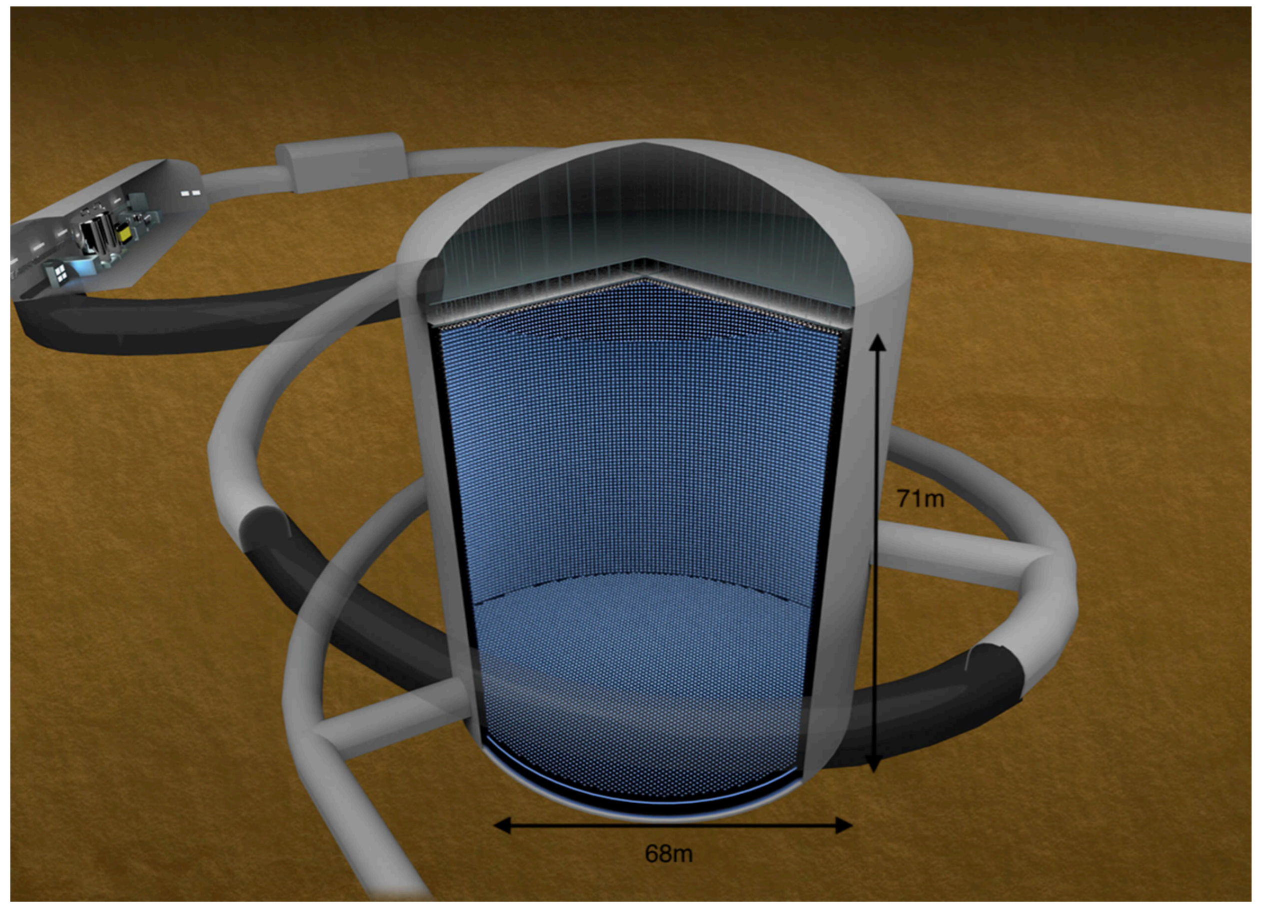
Single Experiments:

JUNO 1507.05613

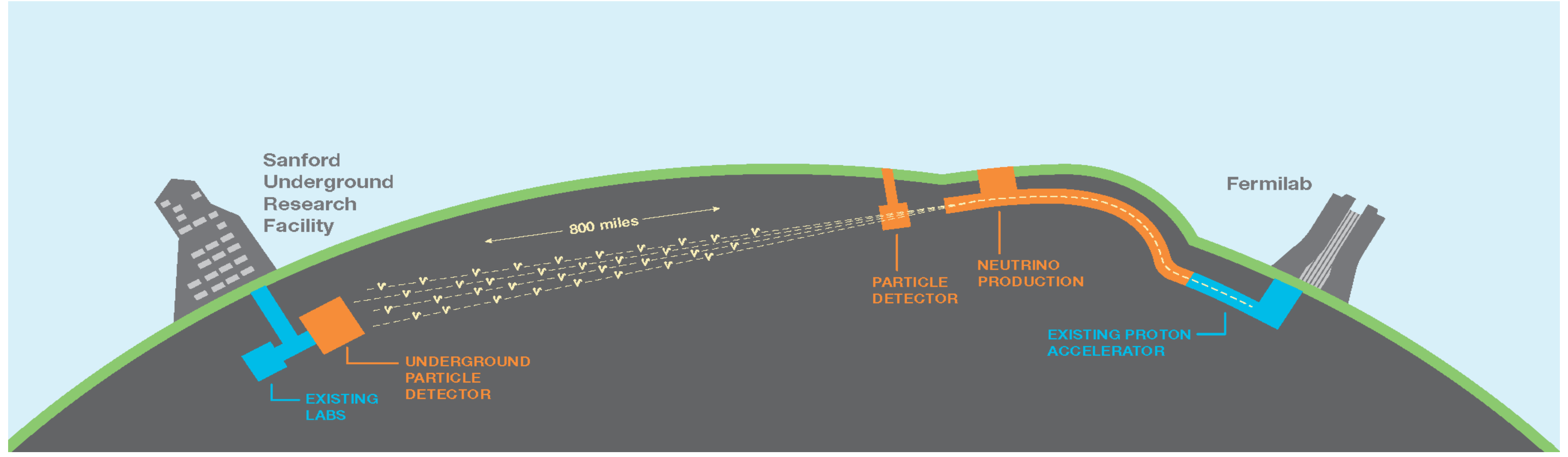
no MO update in
JUNO 2204.13249

See also
FPTZ:2107.12410

HyperK:



DUNE:



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- **Nu 2024: June 16 - 22**

Summary:

- Circa Nu 2026: Global fits, including JUNO's precision Δm^2 measurement may give us Neutrino Mass Ordering $> 3\sigma$.
    - Precision Disappearance Δm^2 measurements will make significant contributions (NPZ '05)
- Circa Nu 202x: Synergies of JUNO with ICECUBE/PINGU, KM3NET …..
- Circa Nu 203x: JUNO, HK and DUNE will each have Neutrino Mass Ordering $> 3\sigma$ in a single experiment
- A Year Later: DUNE $> 5\sigma$ for Neutrino Mass Ordering

Extras

$$|\Delta m^2_{ee}| \equiv |\Delta m^2_{32}|^{NO}_{IO} \pm c^2_{12}\Delta m^2_{21}$$

$$\equiv |\Delta m^2_{31}|^{NO}_{IO} \mp s^2_{12}\Delta m^2_{21}$$

Daya Bay (10^{-3} eV^2)

$$|\Delta m^2_{32}|^{IO} - |\Delta m^2_{32}|^{NO} = \quad + 2c^2_{12}\Delta m^2_{21}$$

$$|-2.571| \quad - \quad +2.466 \quad \approx \quad +2 \times 0.7 \times 0.075 = 0.105$$

$$\pm 0.060$$

Perfect agreement !

ν_e Disappearance:

$|\Delta m^2_{ee}|$ same for both orderings

Daya Bay:

ν_μ Disappearance:

$|\Delta m^2_{\mu\mu}|$ same for both orderings

NOvA, T2K:

$$\pm = NO/IO$$

$$\Delta m^2_{32} = \pm|\Delta m^2_{ee}| - \cos^2\theta_{12}\Delta m^2_{21}$$

$$\Delta m^2_{31} = \pm|\Delta m^2_{ee}| + \sin^2\theta_{12}\Delta m^2_{21}$$

$$-\Delta m^2_{32}|^{IO}_{DB} = \Delta m^2_{31}|^{NO}_{DB} + \cos 2\theta_{12}\Delta m^2_{21}$$

$$\Delta m^2_{32} = \pm|\Delta m^2_{\mu\mu}| - \sin^2\theta'_{12}\Delta m^2_{21}$$

$$\Delta m^2_{31} = \pm|\Delta m^2_{\mu\mu}| + \cos^2\theta'_{12}\Delta m^2_{21}$$

$$-\Delta m^2_{32}|^{IO}_{\mu dis} = \Delta m^2_{31}|^{NO}_{\mu dis} - \cos 2\theta'_{12}\Delta m^2_{21}$$

$$\cos 2\theta_{12} \approx 0.40$$

$$\cos 2\theta'_{12} = \cos 2\theta_{12} - 2s_{13}\cos\delta \approx 0.40 - 0.30\cos\delta$$

If IO then 0

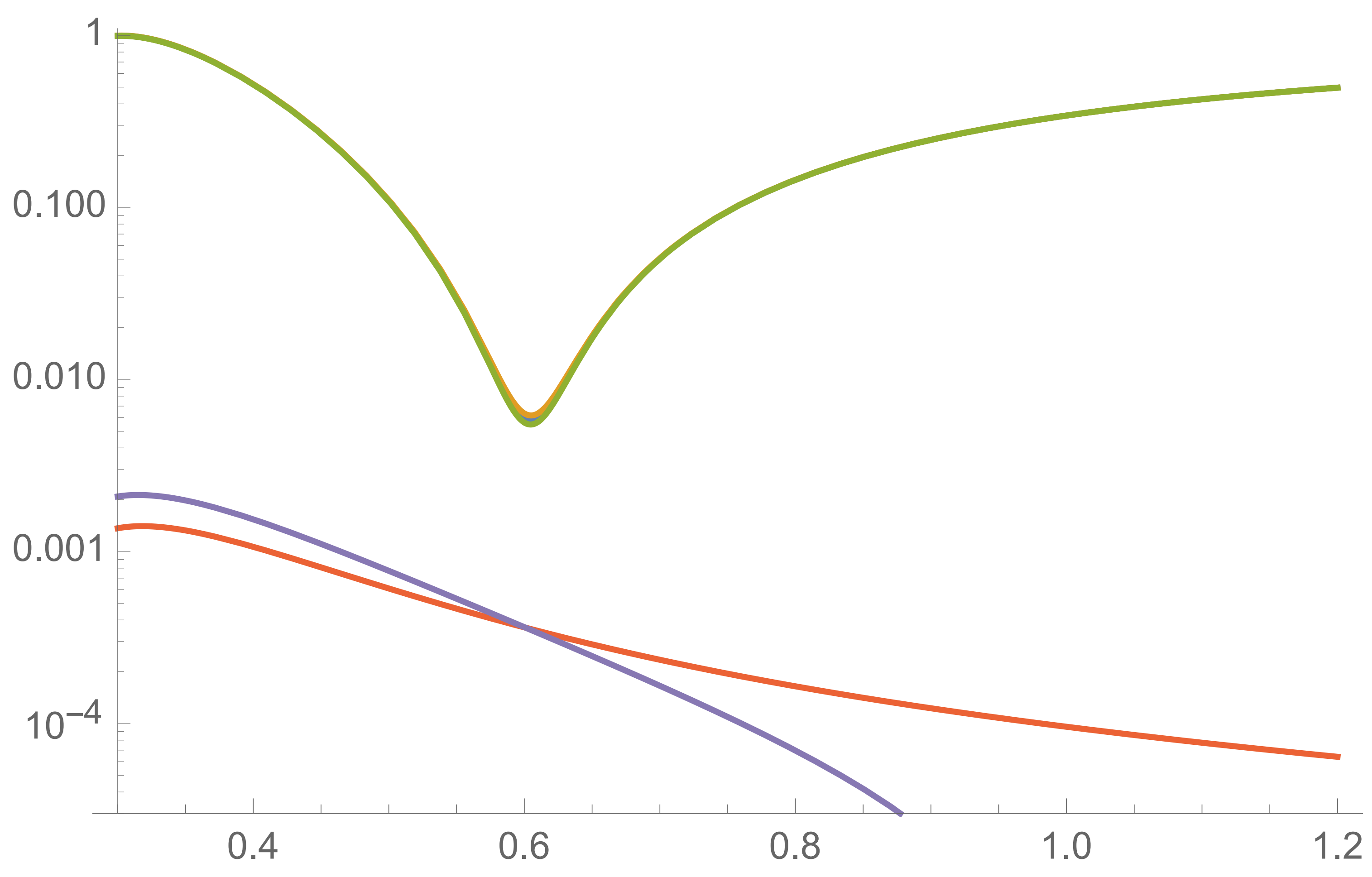
If NO then 0

$$(\Delta m^2_{32}|^{IO}_{\mu dis} - \Delta m^2_{32}|^{IO}_{DB}) + (\Delta m^2_{31}|^{NO}_{\mu dis} - \Delta m^2_{31}|^{NO}_{DB}) = (2.4 - 0.9\cos\delta)\%\ \Delta m^2_{ee}$$

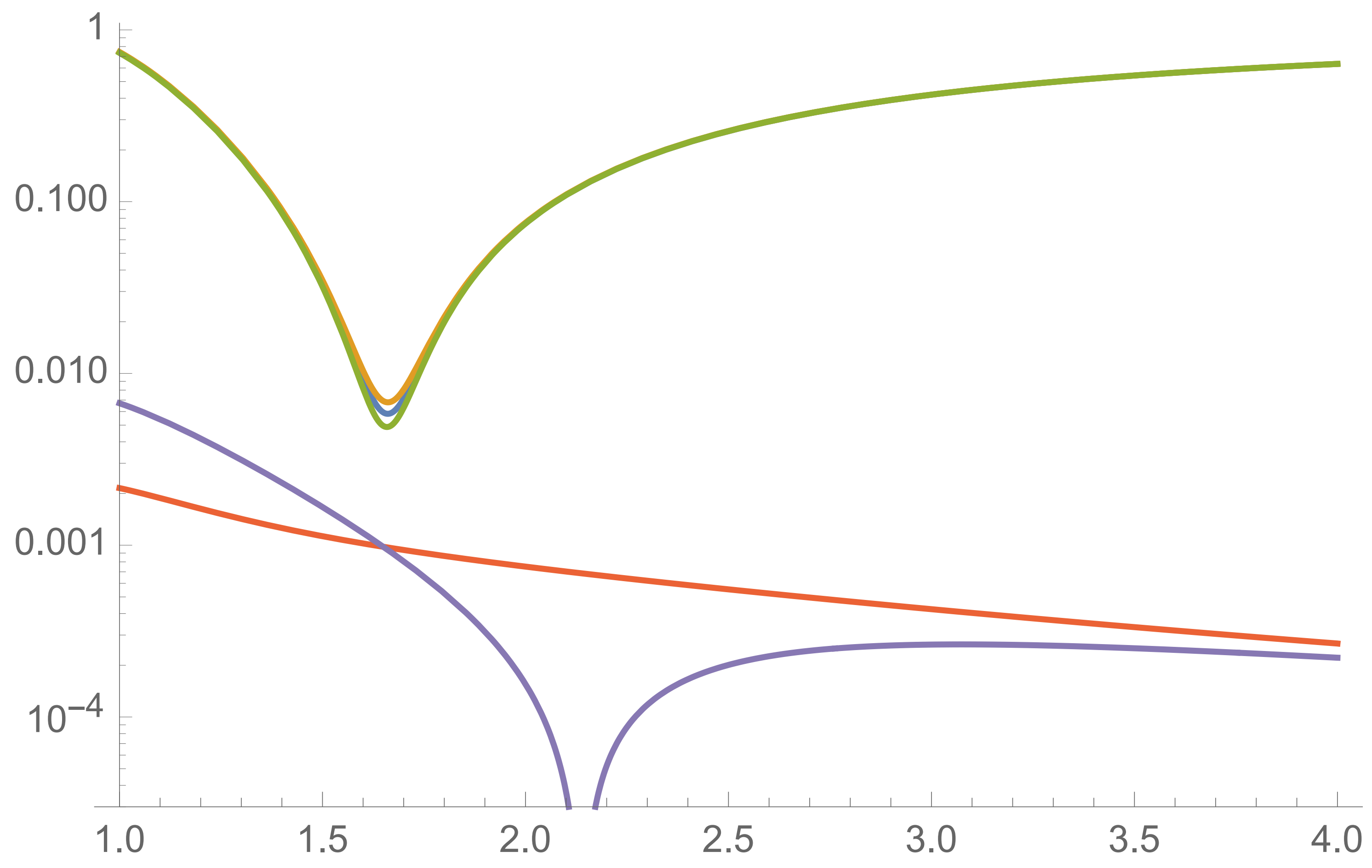
Unchanged if 31 $\leftrightarrow$ 32 in either or both MO's

1.5 to 3.3 %

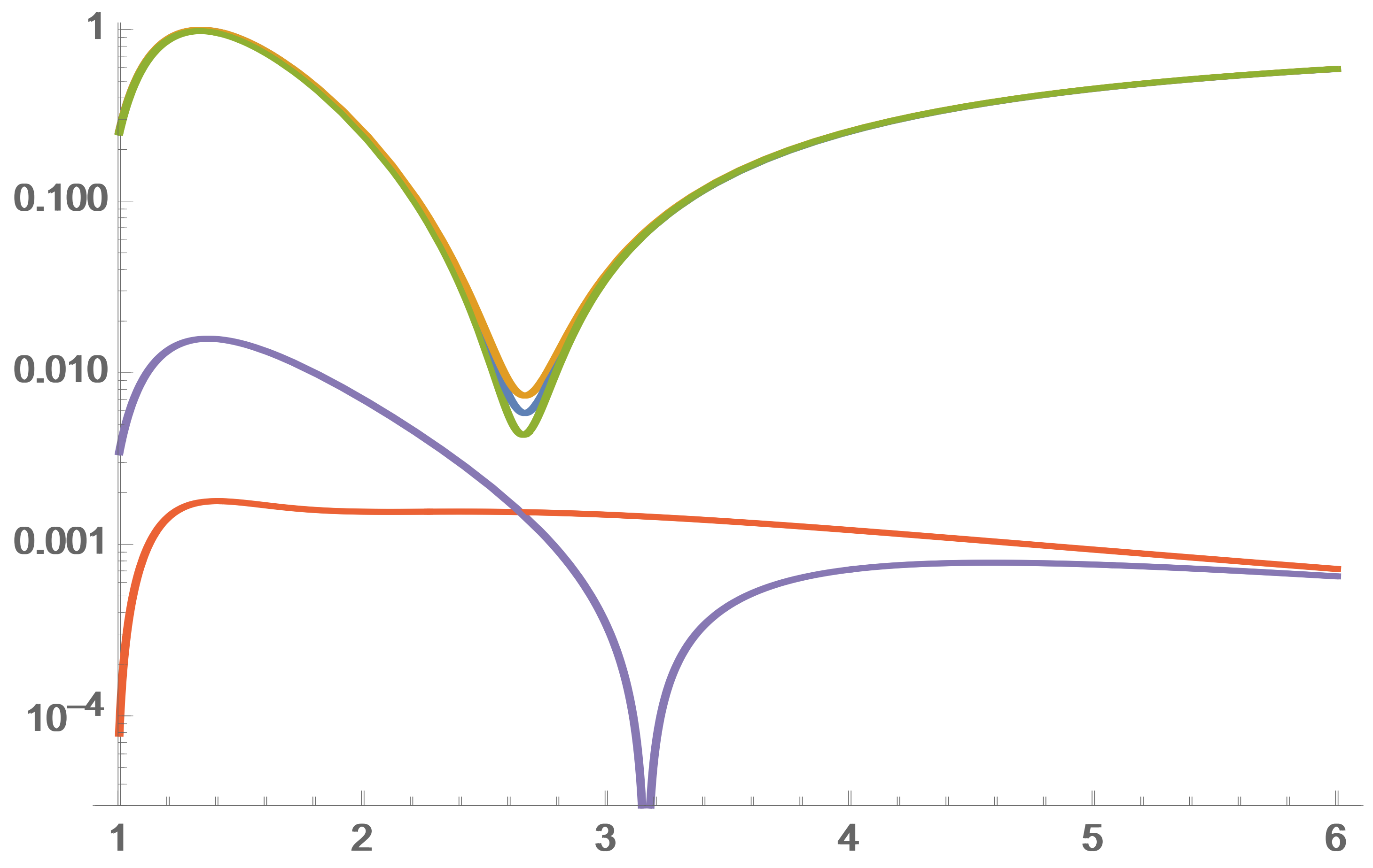
Vacuum v Matter:



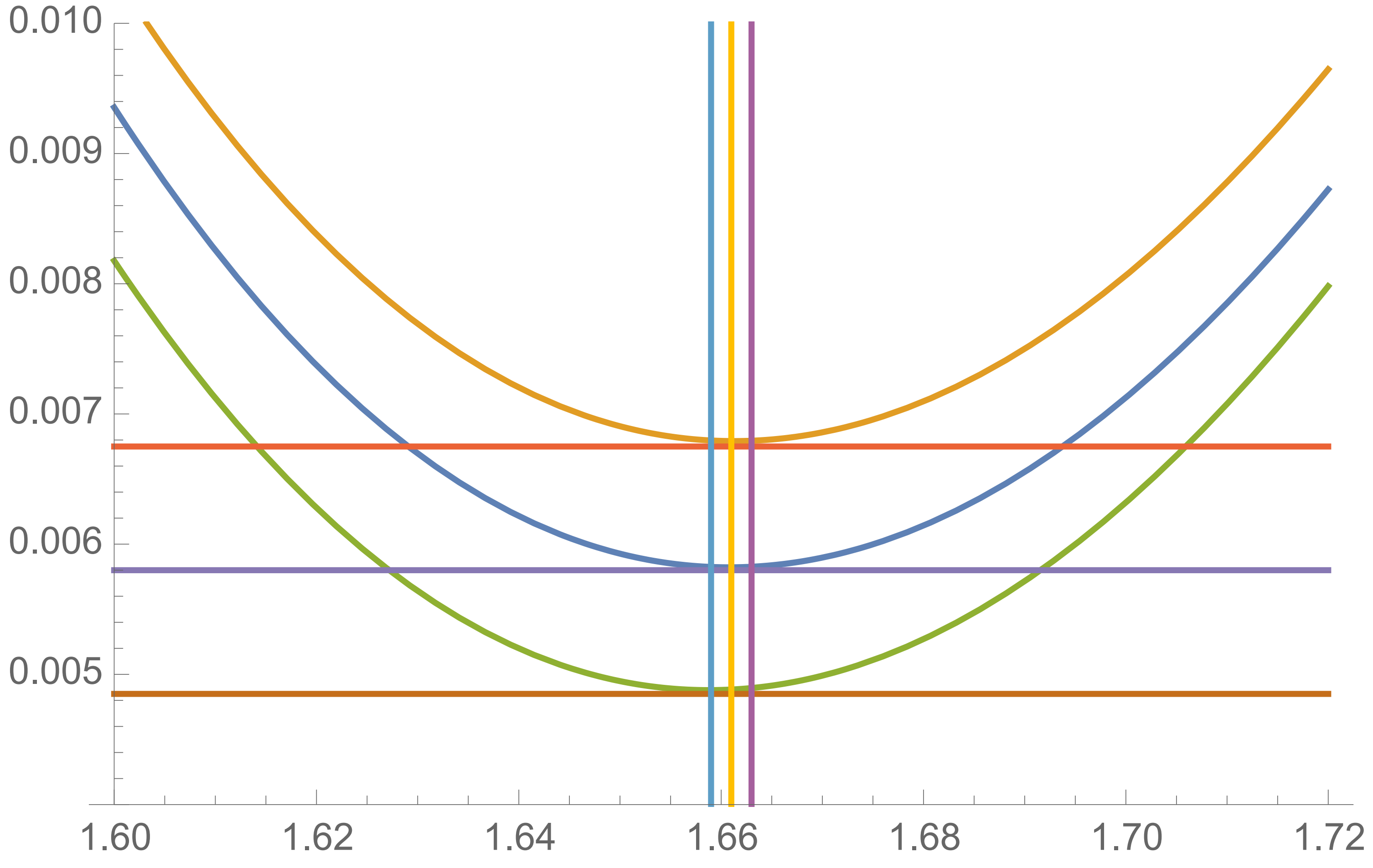
T2K

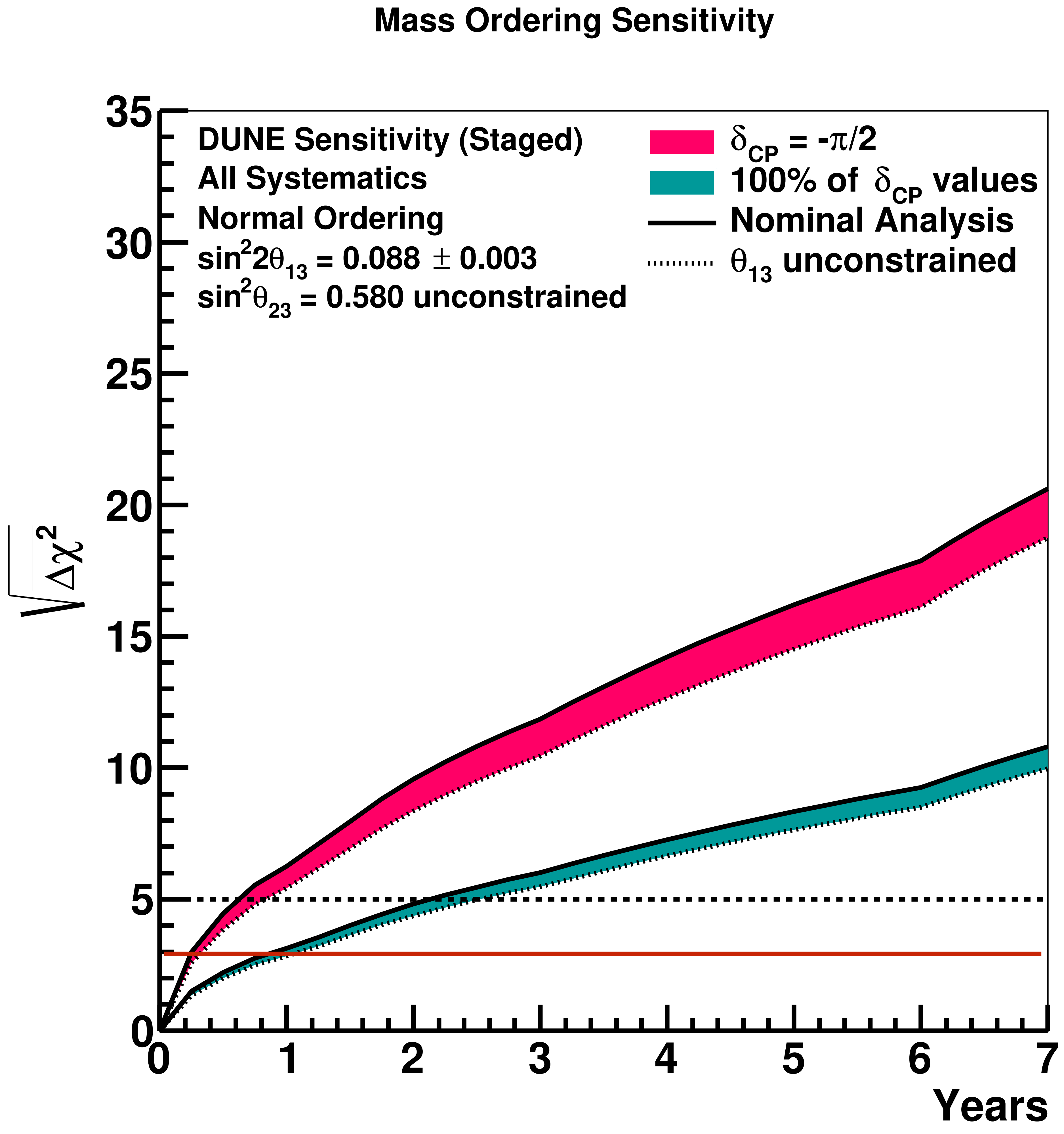


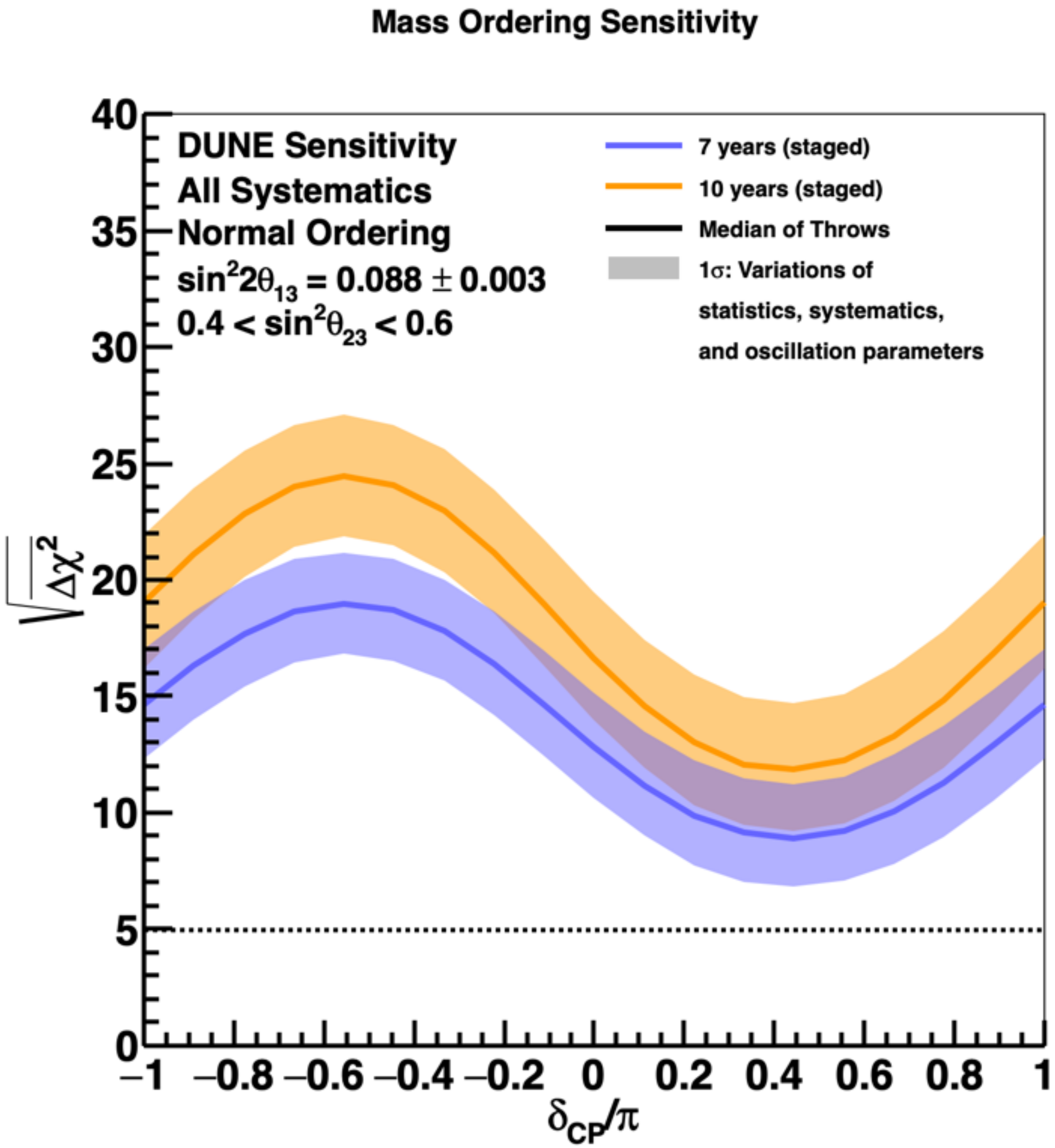
NOvA



DUNE







one (two) year > 3 σ (> 5 σ) for all values of δ_{CP}