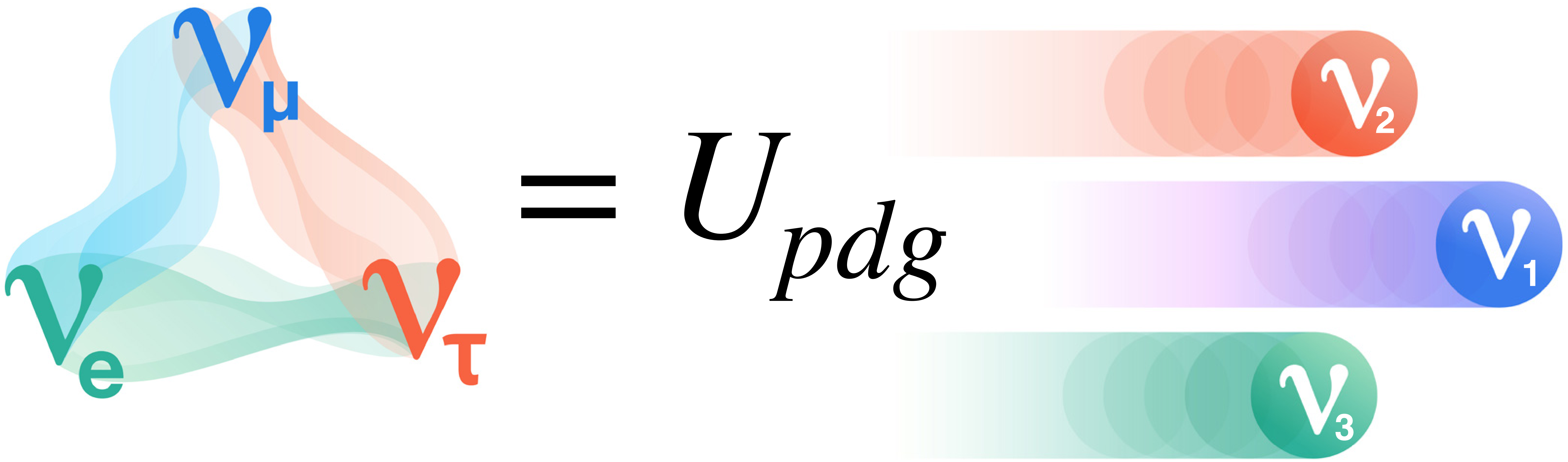
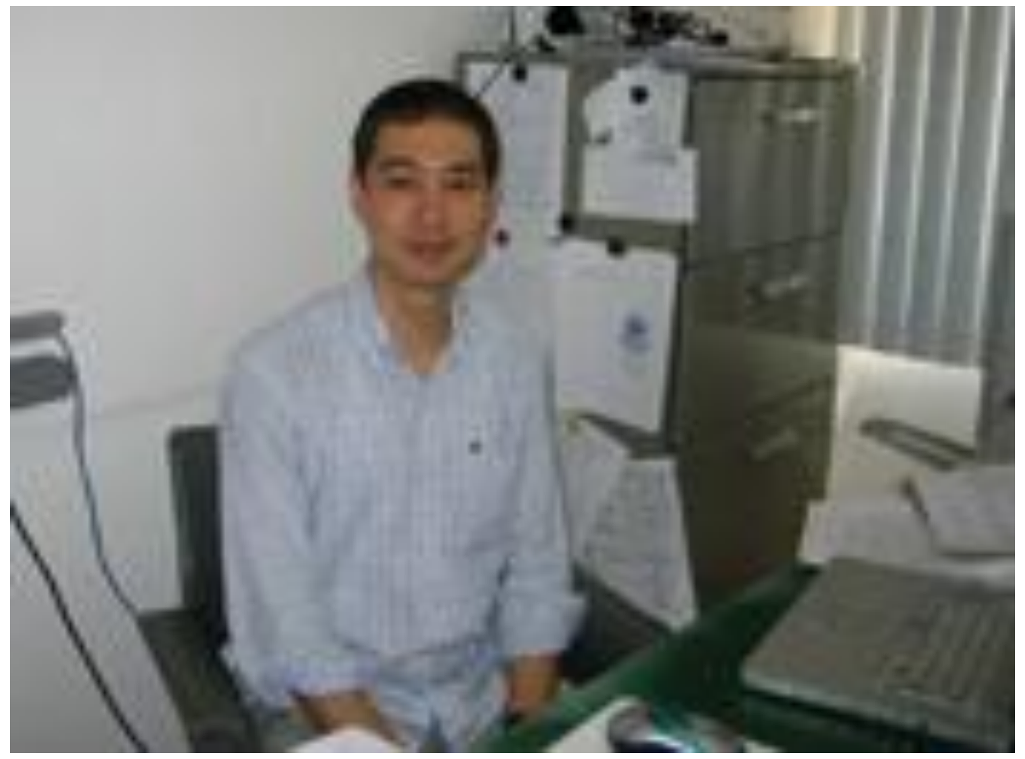
The Near Term* Race for the Neutrino Mass Ordering

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



* this decade



Another possible way to determine the Neutrino Mass Hierarchy

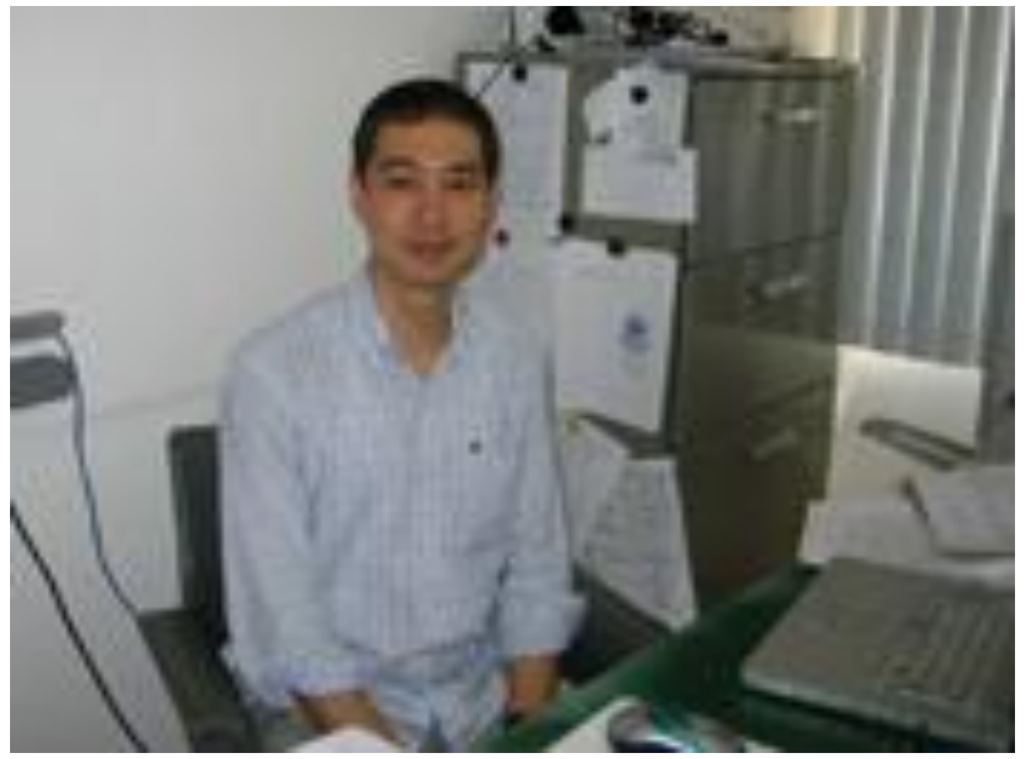
Hiroshi Nunokawa[1],[*] Stephen Parke[2],[†] and Renata Zukanovich Funchal[3‡]

arXiv:hep-ph/0503283v1 29 Mar 2005

in PRD

NPZ'05

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



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

few % difference

UPDATES:

The Smallness of Matter Effects in Long-Baseline Muon Neutrino Disappearance

Peter B. Denton[1,*] and Stephen J. Parke[2,†]

arXiv:2401.10326

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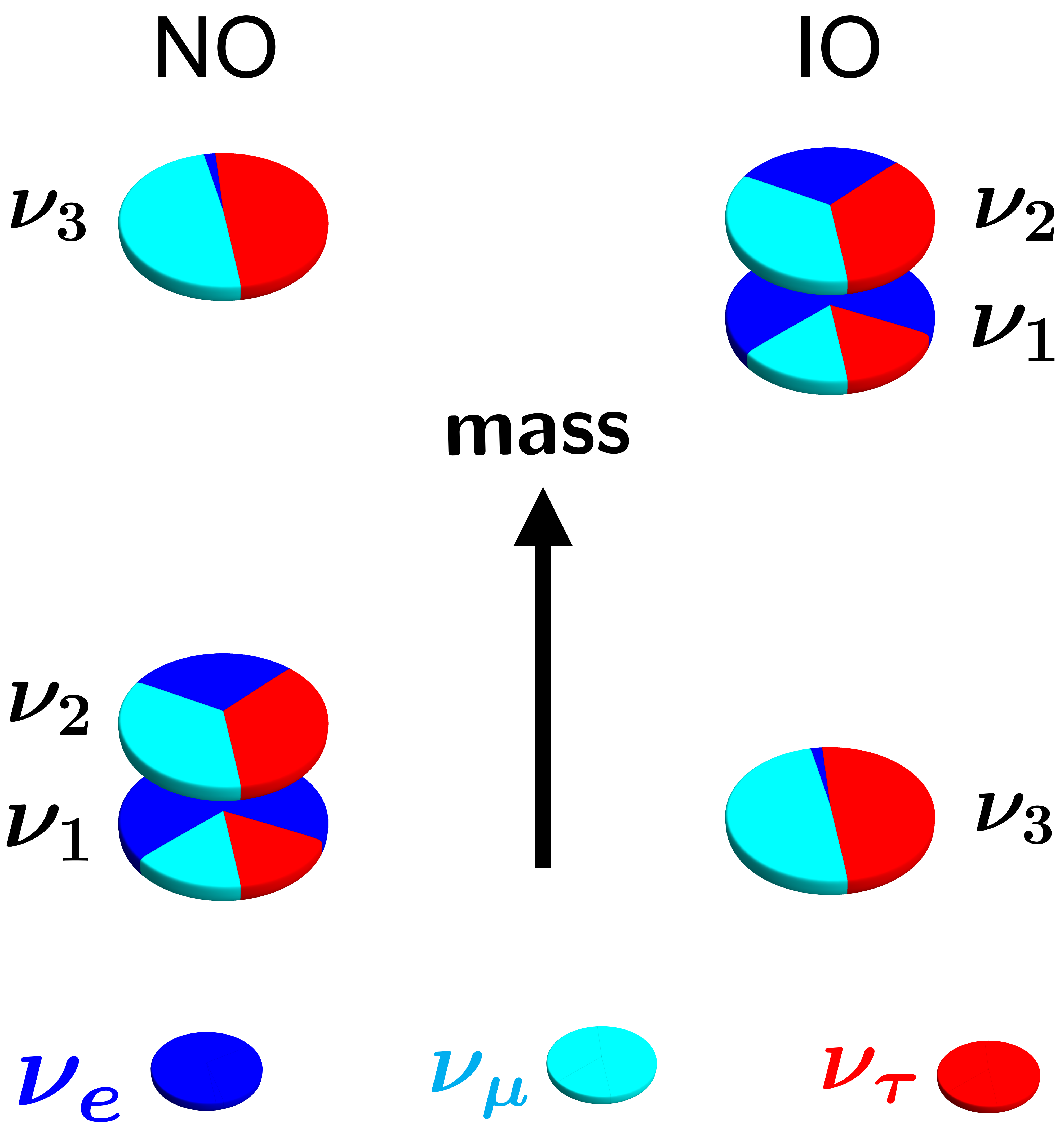
A Mass Ordering Sum Rule for the Neutrino Disappearance Channels in T2K, NOvA and JUNO

Stephen J. Parke* Renata Zukanovich Funchal†

arXiv:2404.08733

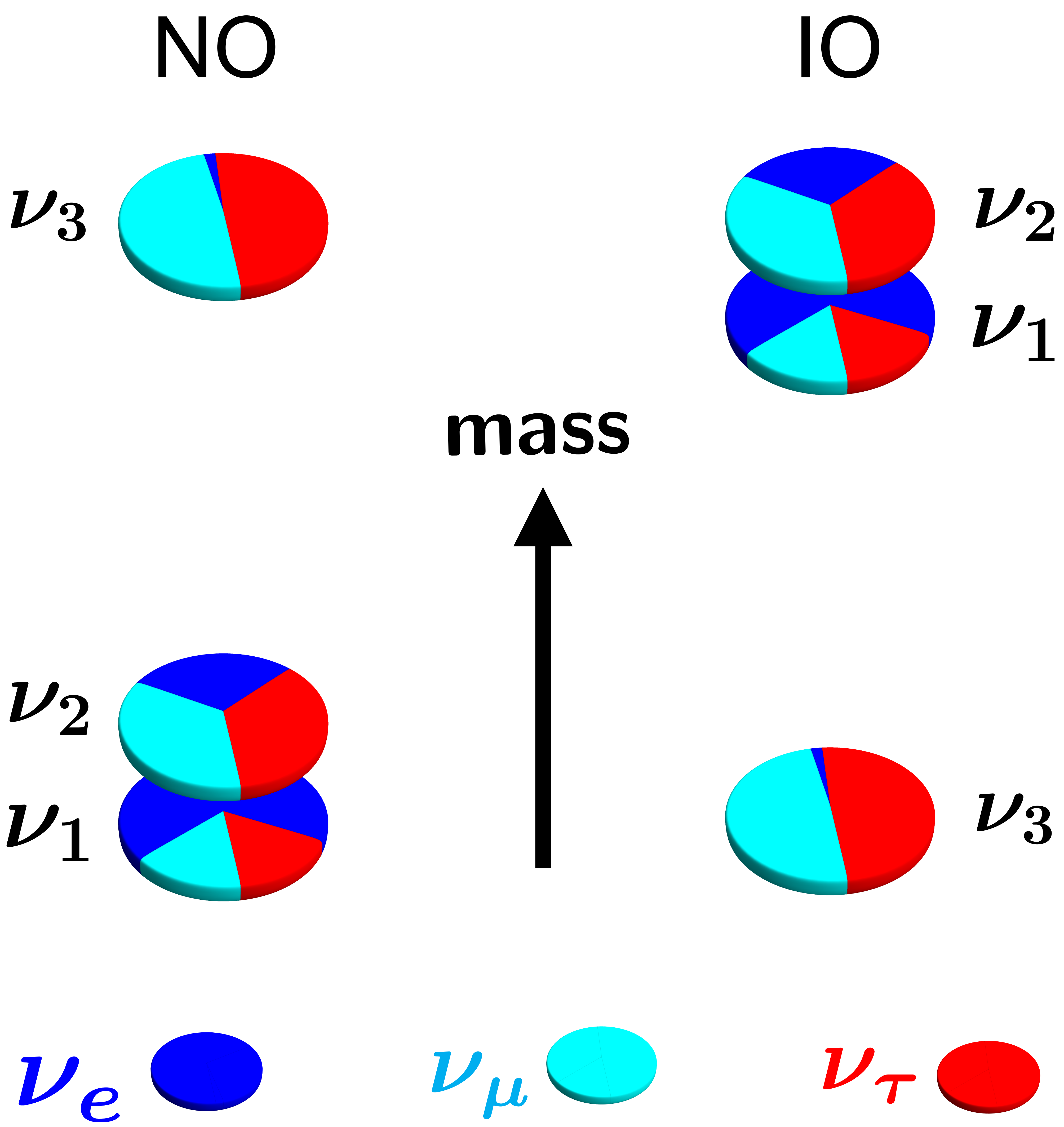
the Neutrino Mass Ordering



Define 1,2 & 3 such that:

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

the Neutrino Mass Ordering



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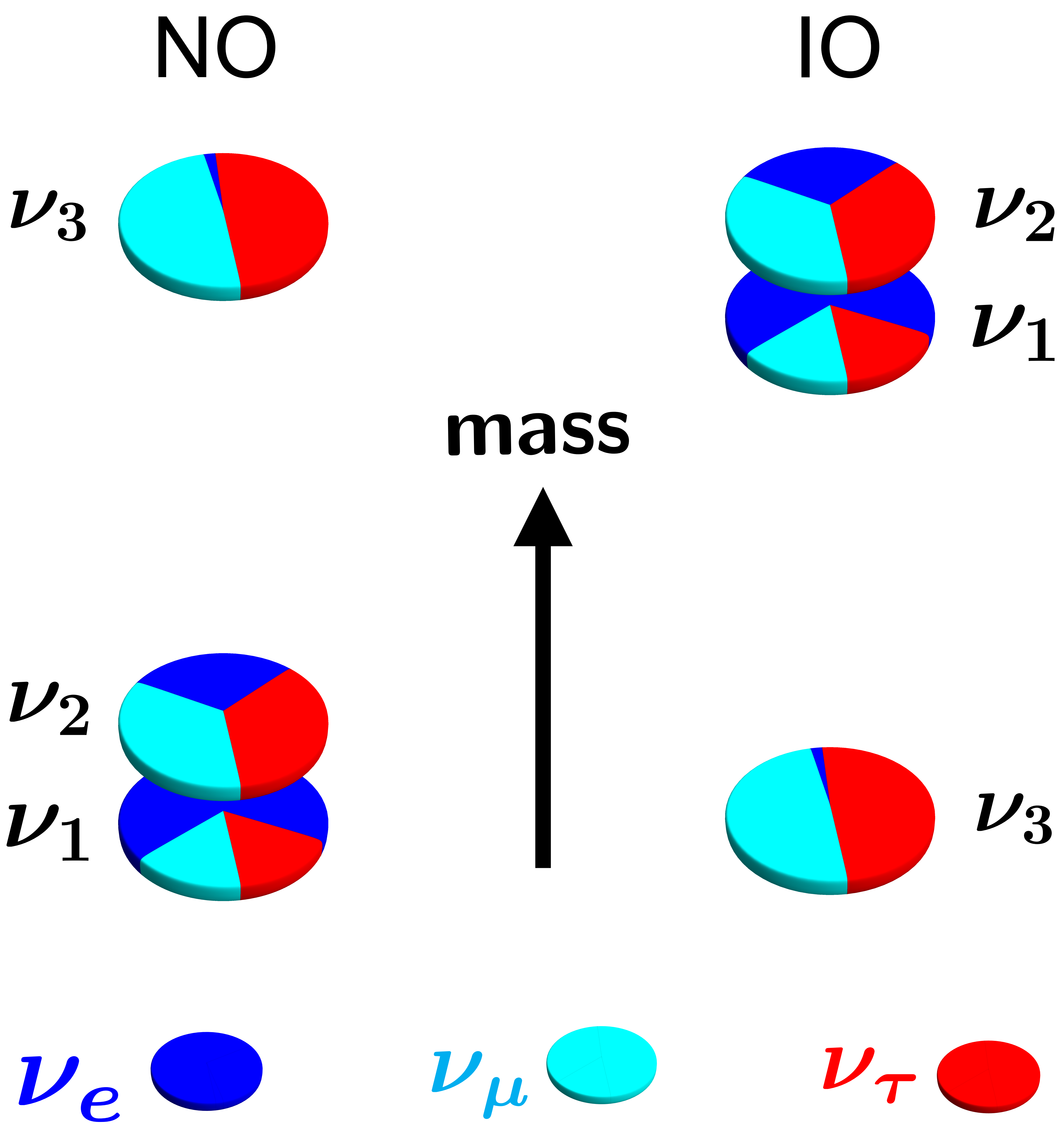
$$|U_{e1}|^2 > |U_{e2}|^2 > |U_{e3}|^2$$

SNO $m_2 > m_1$

$$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5} \text{ eV}^2$$

the Neutrino Mass Ordering



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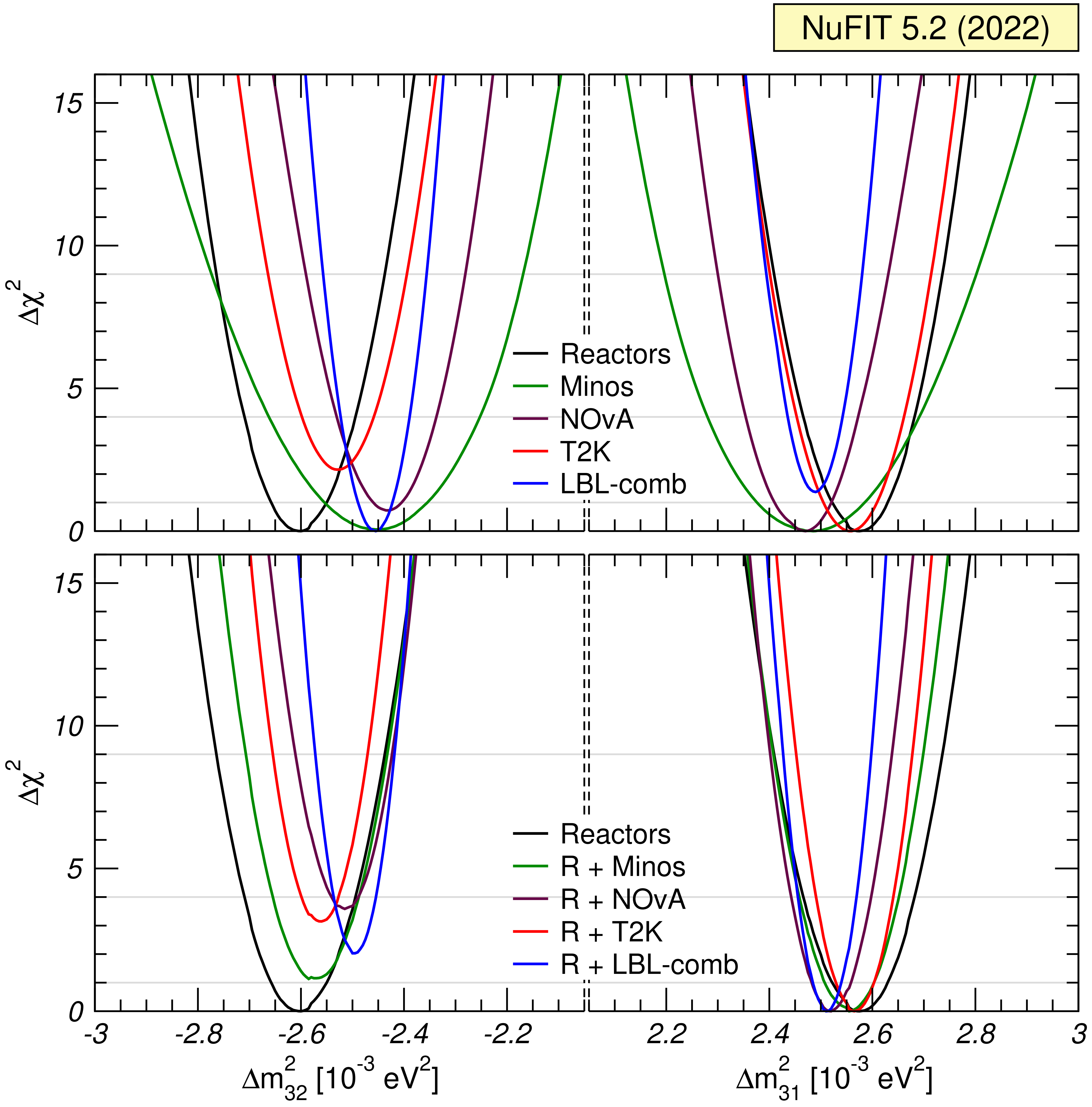
ν_3, ν_1/ν_2 Mass Ordering:

–atmospheric mass ord

$$|\Delta m^2_{31}| = |m^2_3 - m^2_1| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

Explain this figure + Future Prospects

www.nu-fit.org



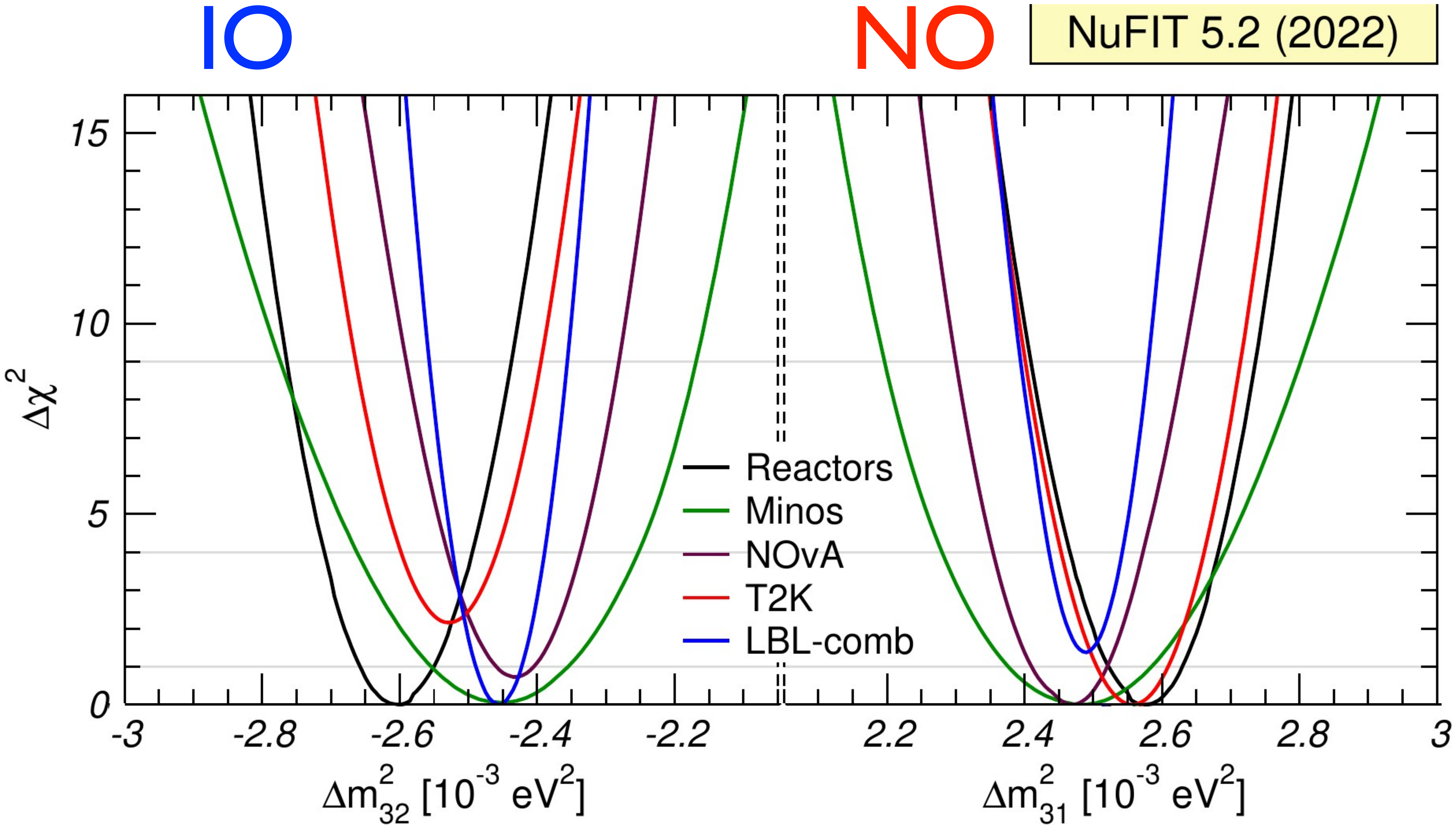
Current members:

Ivan Esteban
Concha Gonzalez Garcia
Michele Maltoni
Thomas Schwetz
Albert Zhou

Former members:

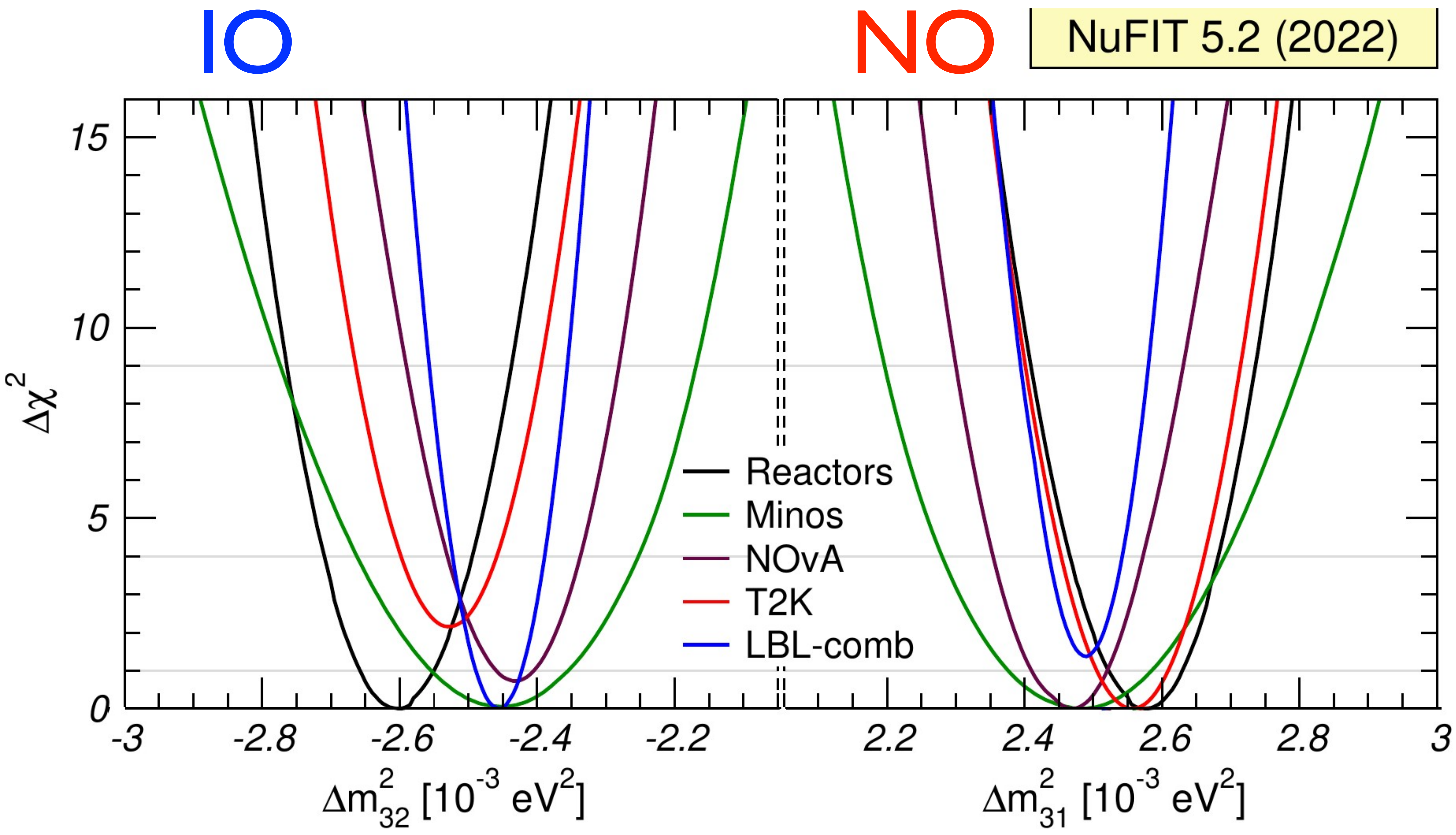
Johannes Bergström
Alvaro Hernandez Cabezudo
Ivan Martinez Soler
Jordi Salvado

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



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

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



No preference
Or for NO

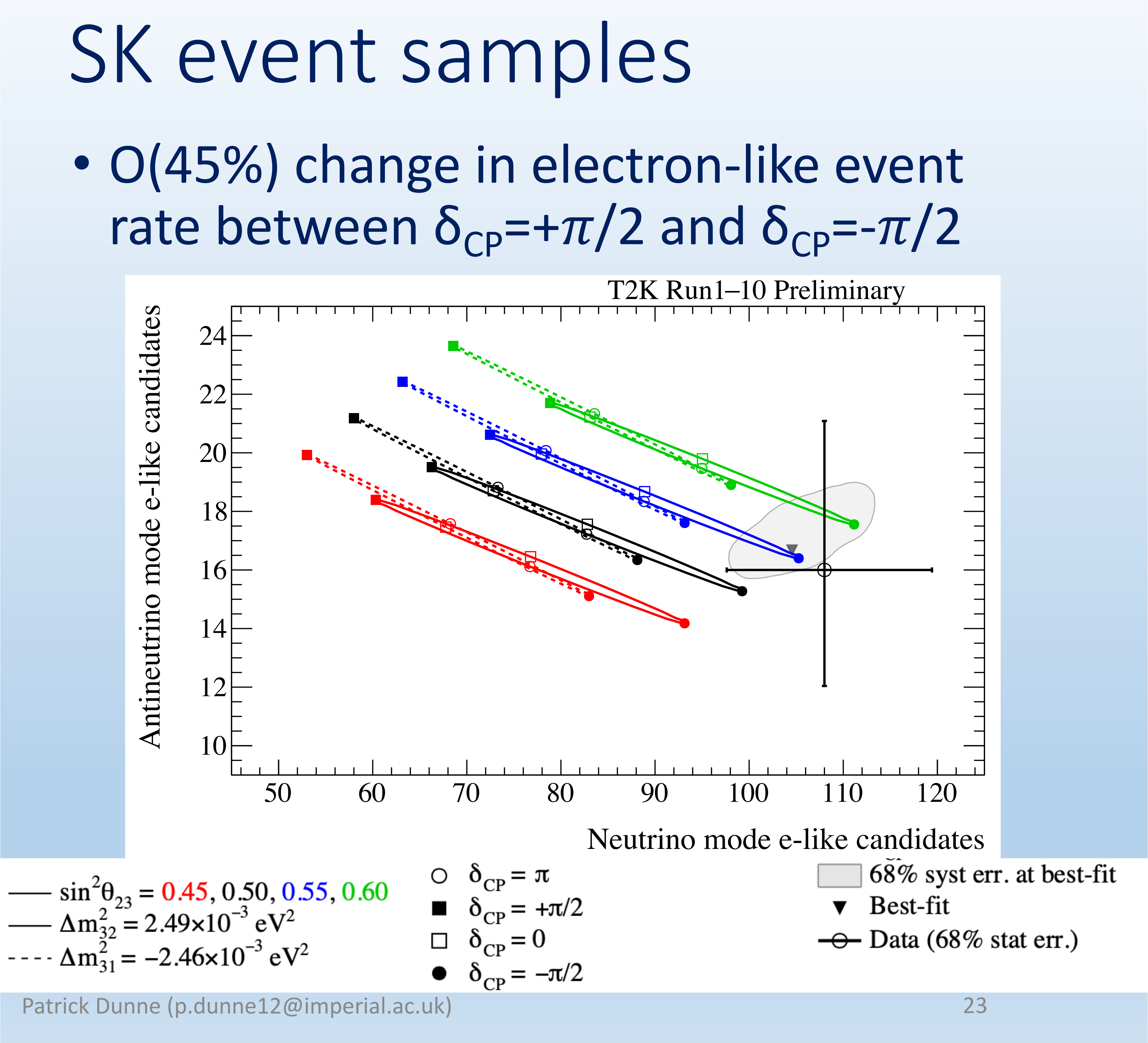
Except

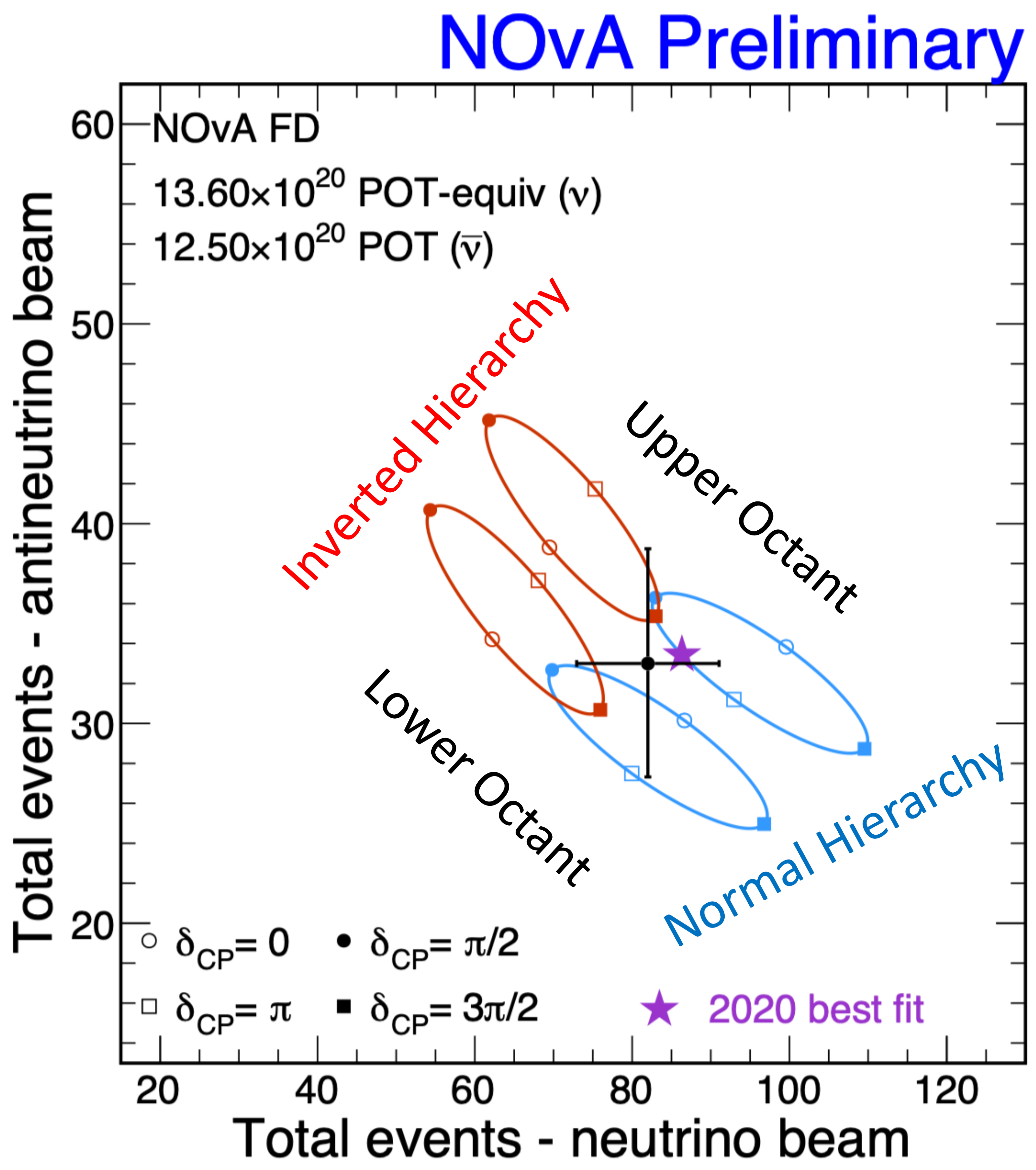
T2K + NOvA
Combined

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



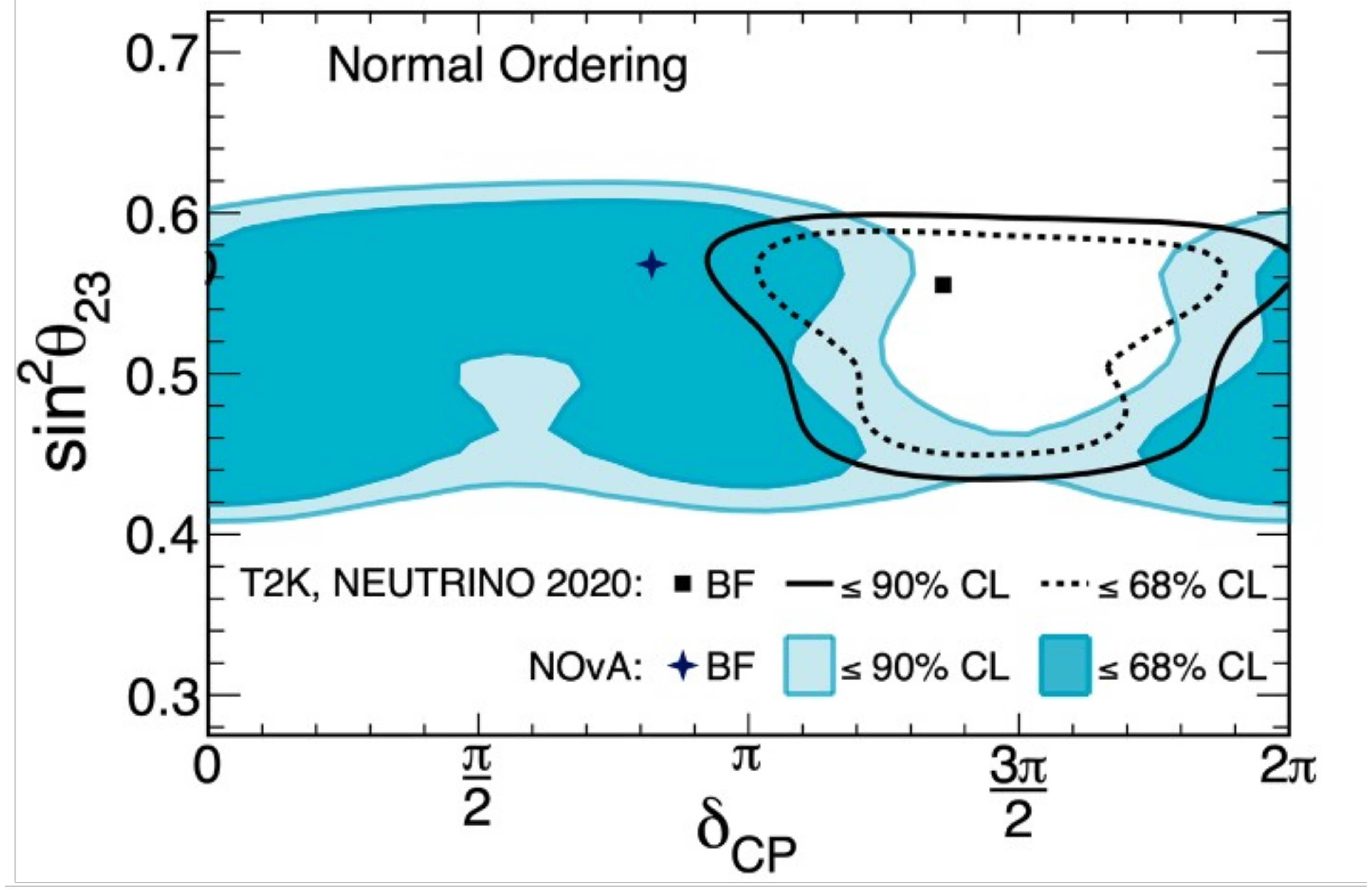


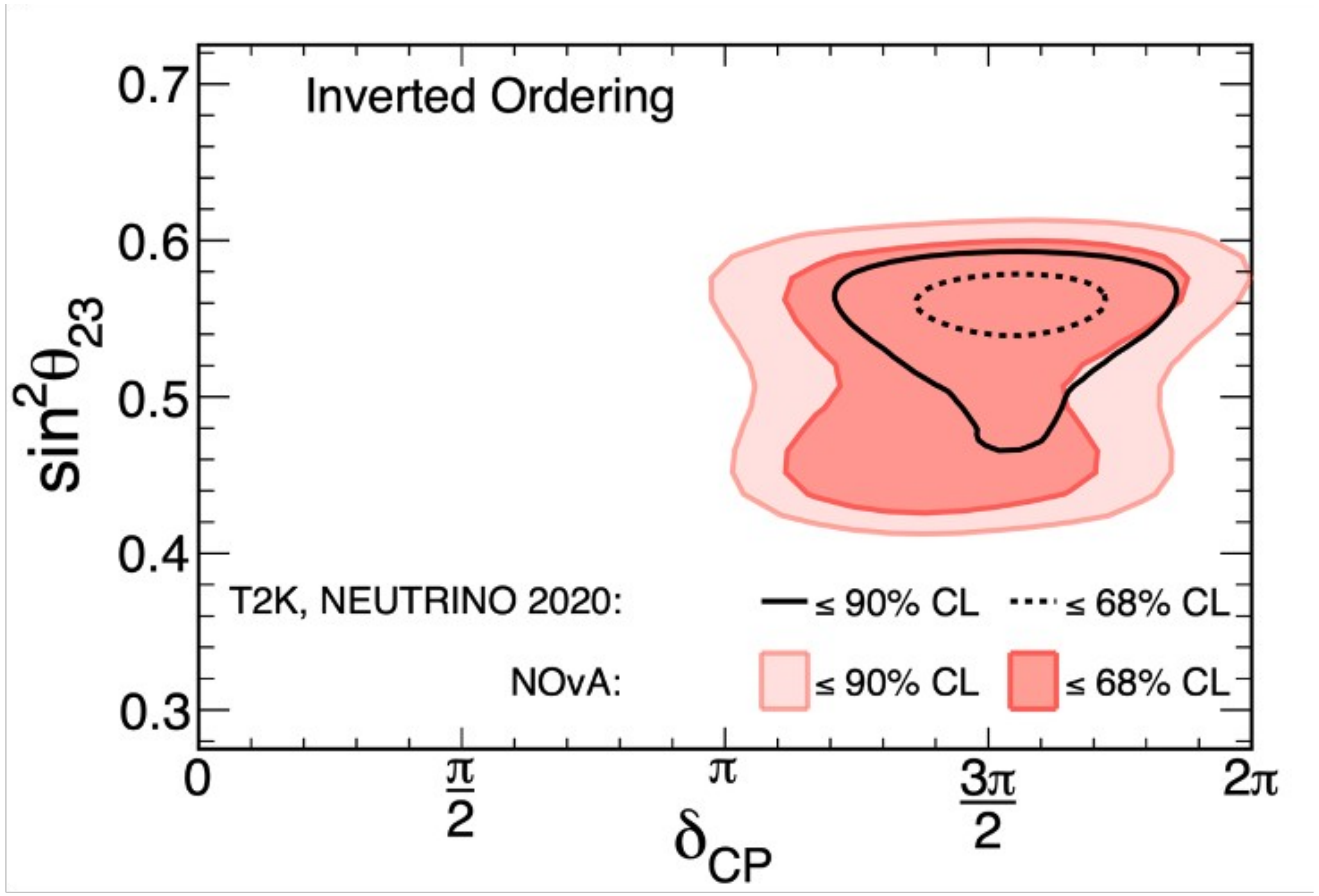
T2K NO prefer by ~2 units of χ^2

NOvA NO prefer by ~1 unit of χ^2

COMBINED

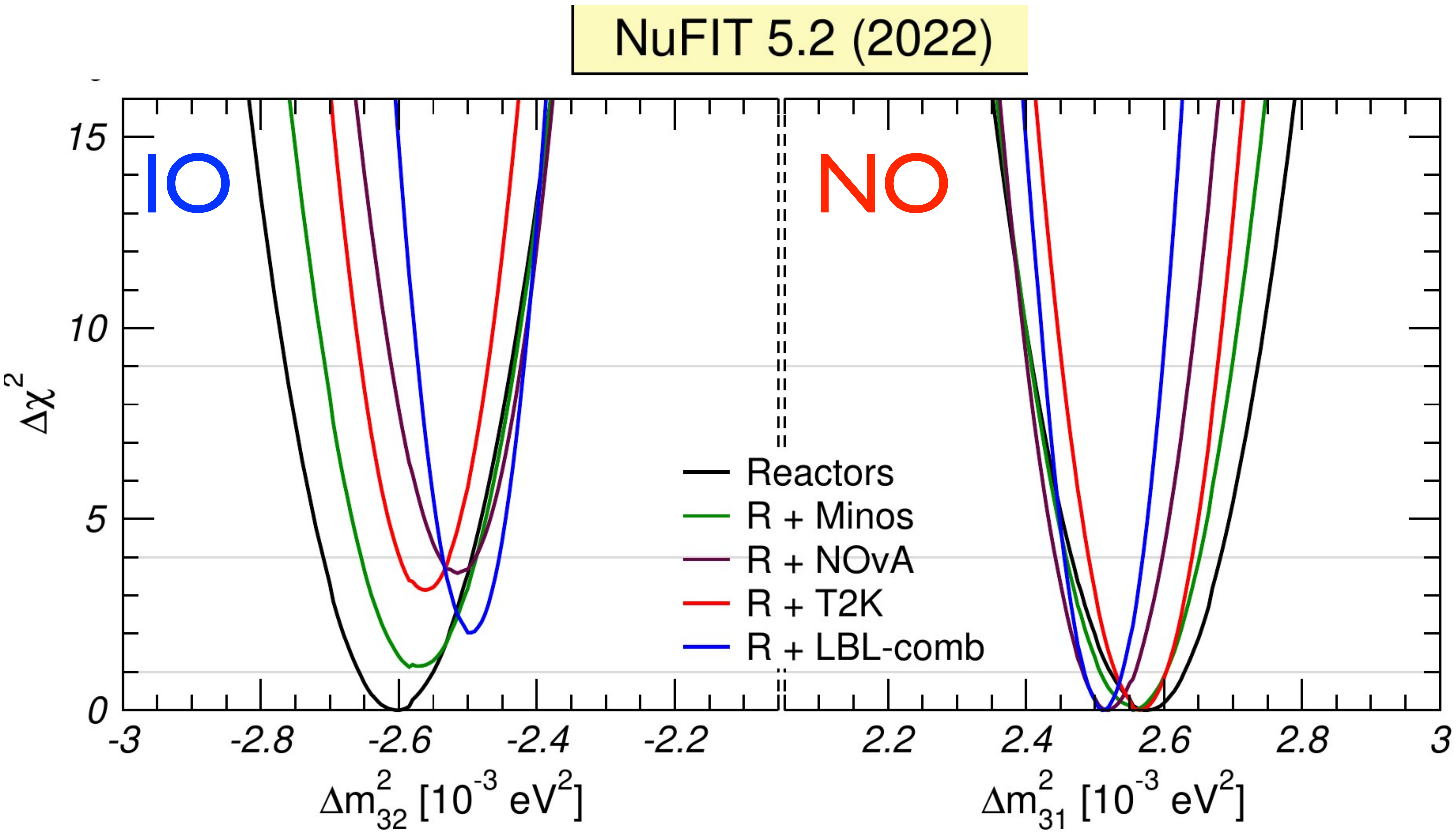
https://doi.org/10.5281/zenodo.6683827



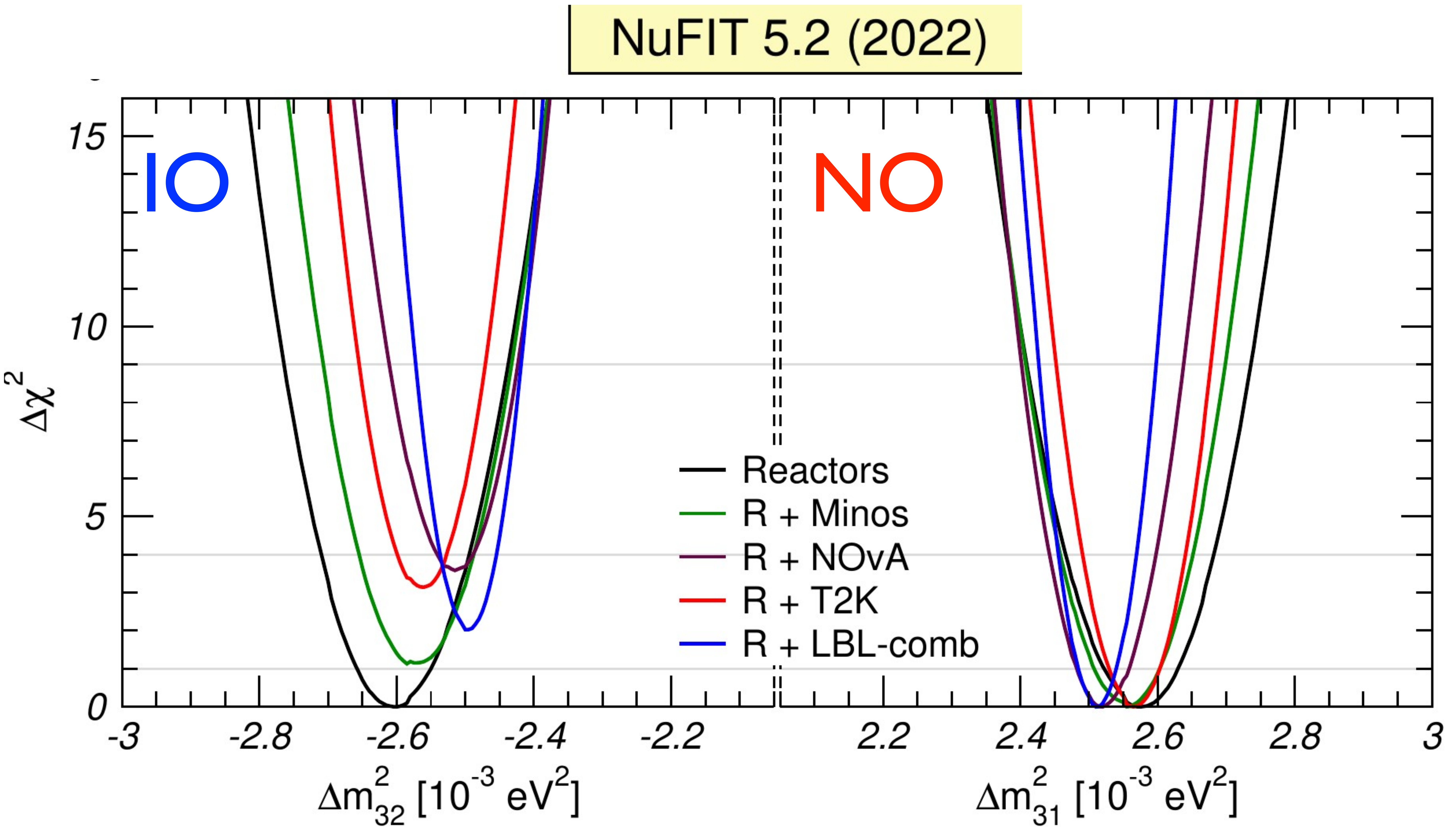


IO prefer by ~1.6 unit of $\Delta\chi^2$

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



NuFIT 5.2 (2022)
IO
NO
Reactors
R + Minos
R + NOvA
R + T2K
R + LBL-comb
$\Delta\chi^2$
Δm^2_{32} [10^{-3} eV^2]
Δm^2_{31} [10^{-3} eV^2]



Reactors + LBL
All
Prefer NO:

Even T2K + NOvA

Sum Rule:

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

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

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

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

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If IO then ≈ 0

If NO then ≈ 0

+1.5 to +3.3 %

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+1.5 to +3.3 %

Valid for some but not all
ICECUBE, KM3Net/Orca.
Needs tweak for JUNO

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

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

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NO	$(2.4 - 0.9\widehat{\cos\delta})\%$	≈ 0
IO	≈ 0	$(2.4 - 0.9\widehat{\cos\delta})\%$

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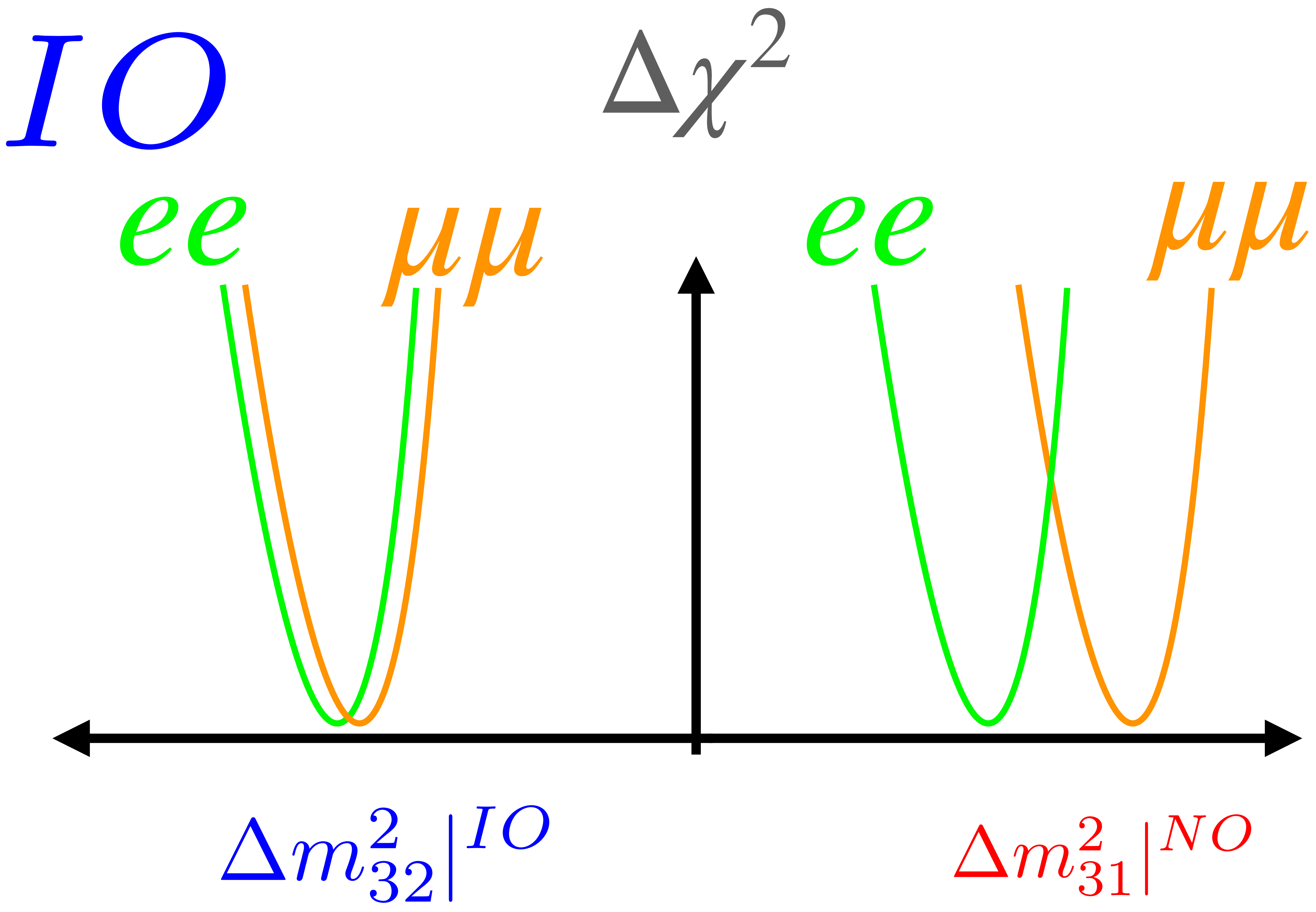

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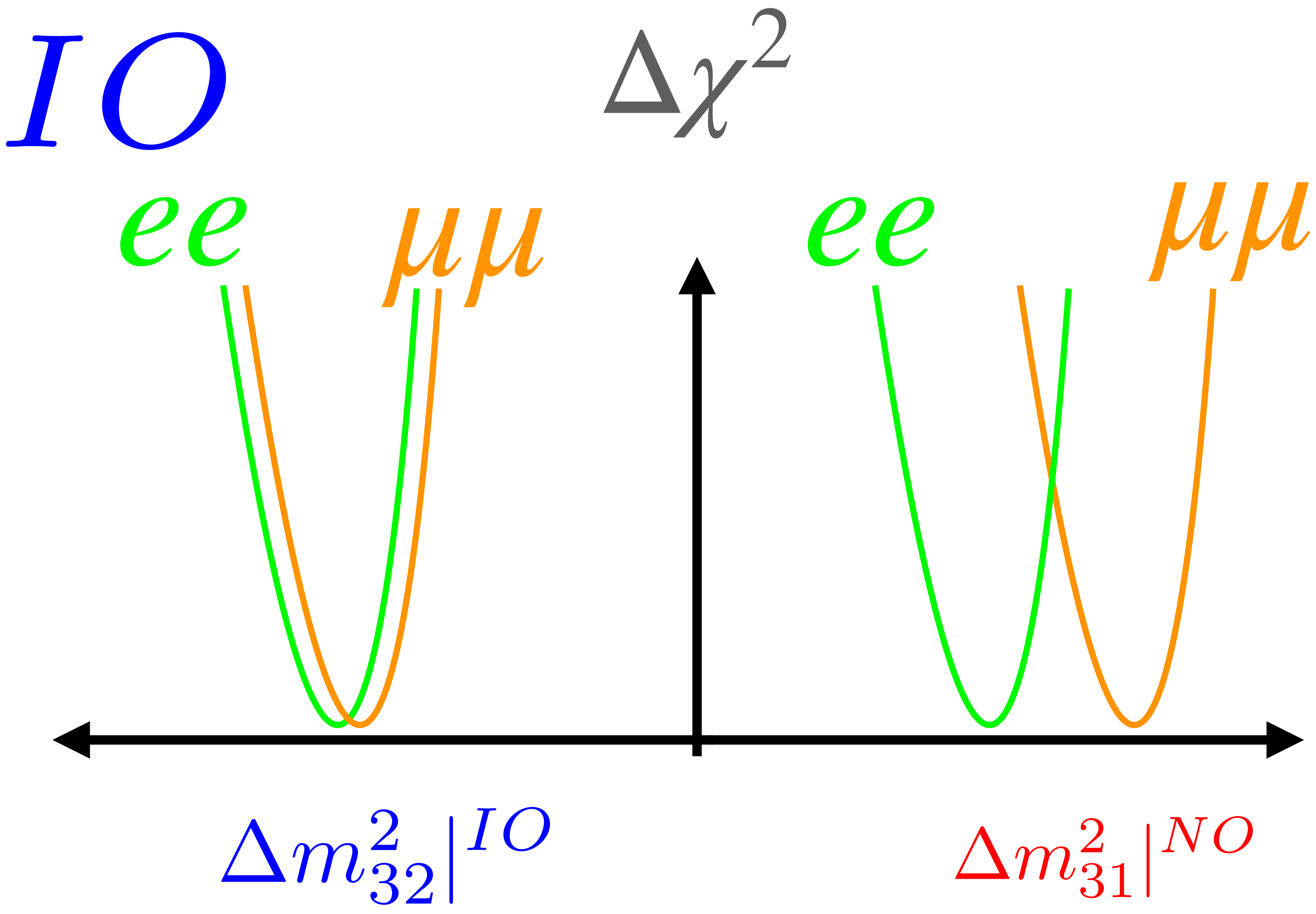

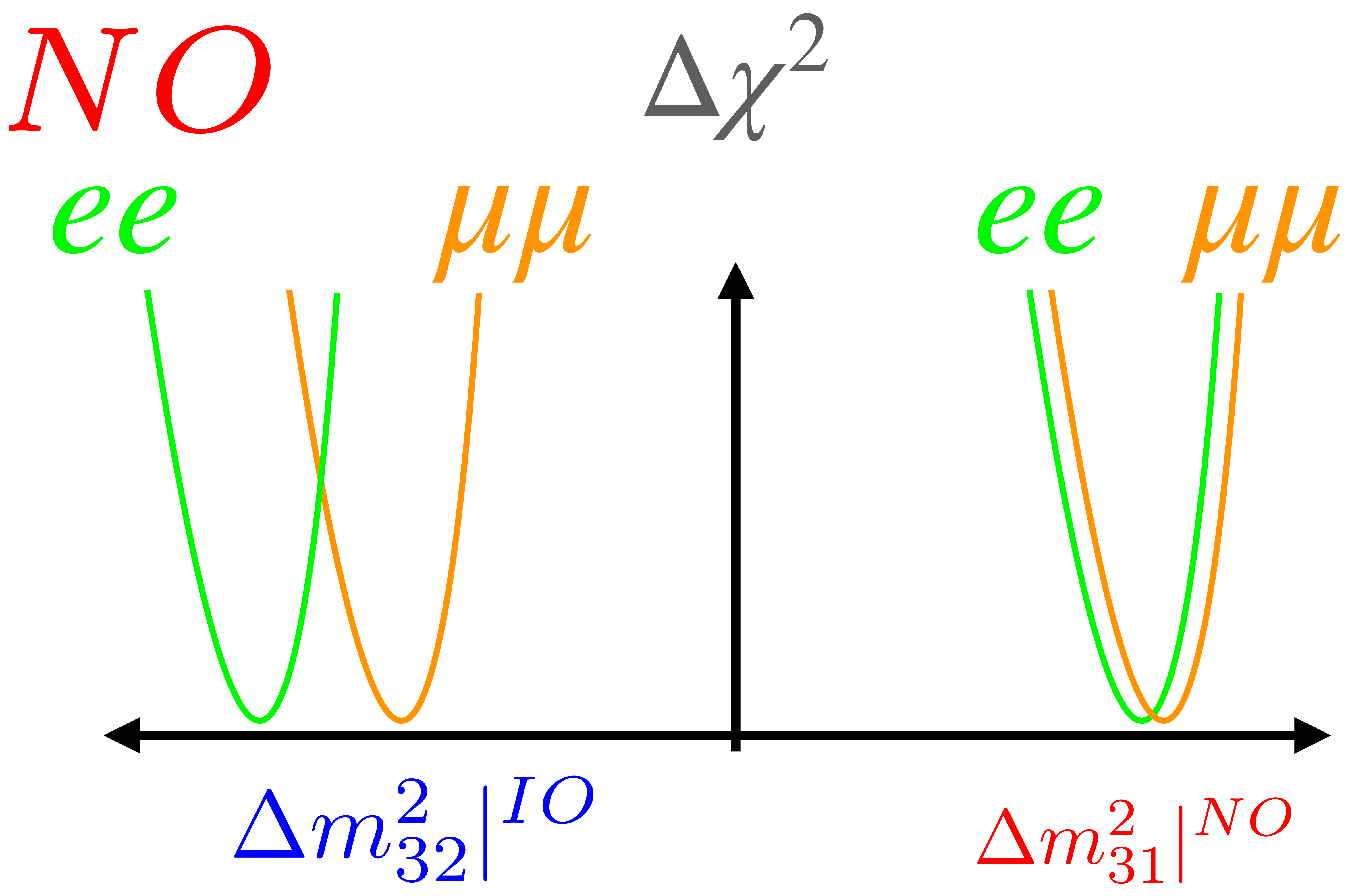

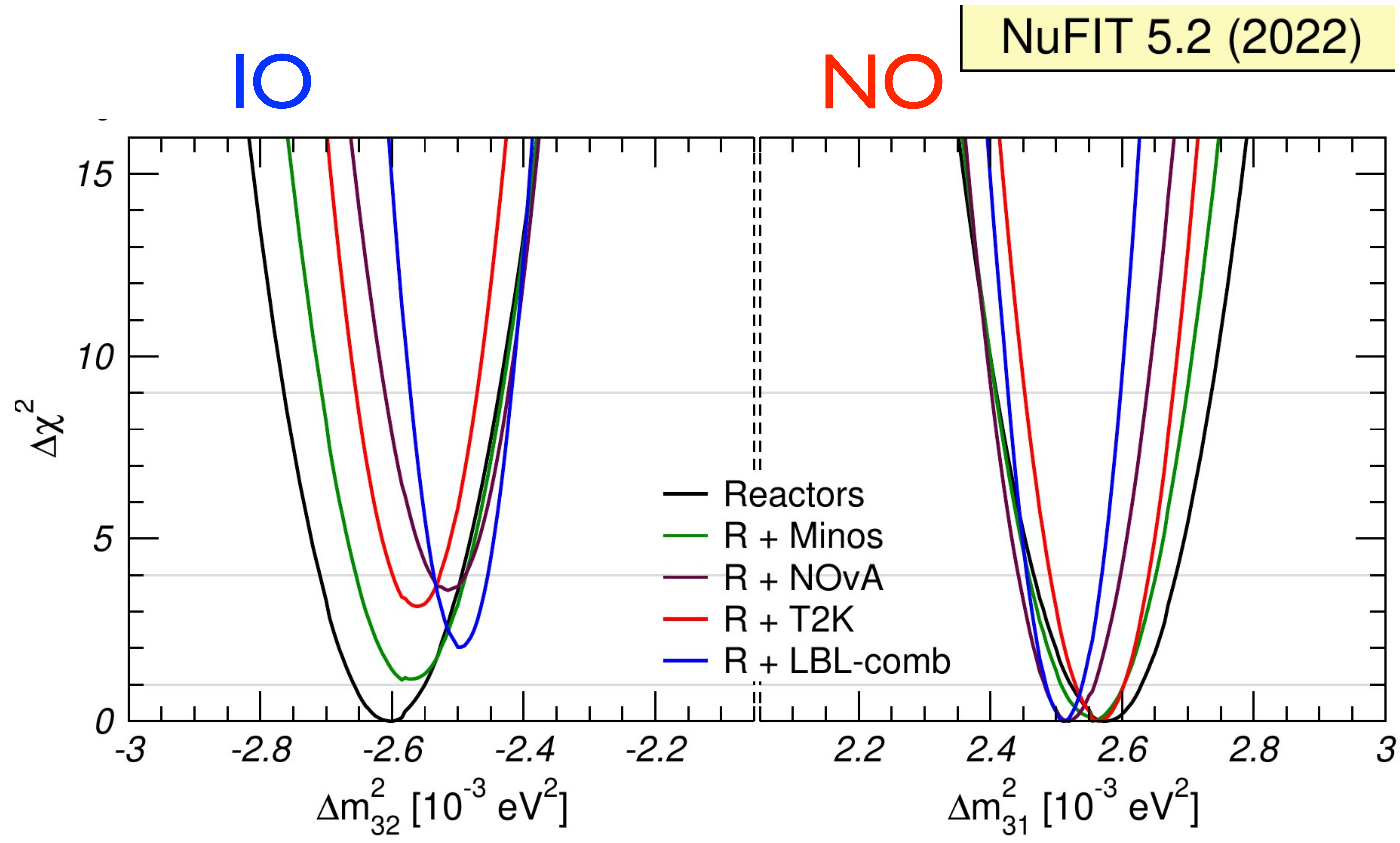

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few % difference

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

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

$$P(\nu_e \to \nu_e) = 1 - P_\odot - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\approx 1 - P_\odot - \sin^2 2\theta_{13}(\sin^2\Delta_{3i} + (-1)^i\, \mathcal{O}(\Delta_{21})) \quad i = 1 \text{ or } 2$$

$$\approx 1 - P_\odot - \sin^2 2\theta_{13}(\sin^2\Delta_{ee} + \mathcal{O}(\Delta^2_{21}))$$

note "2"

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

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

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

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

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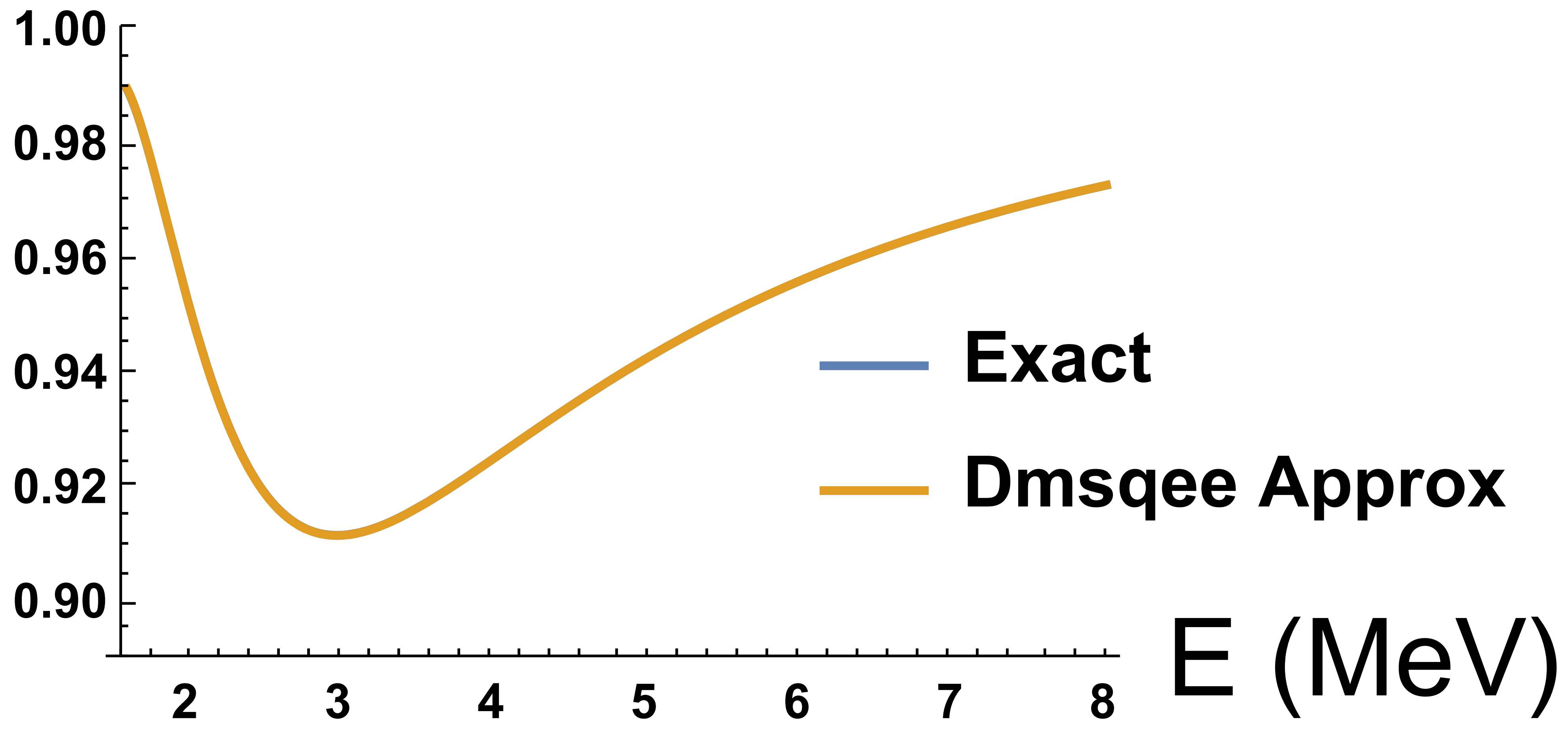
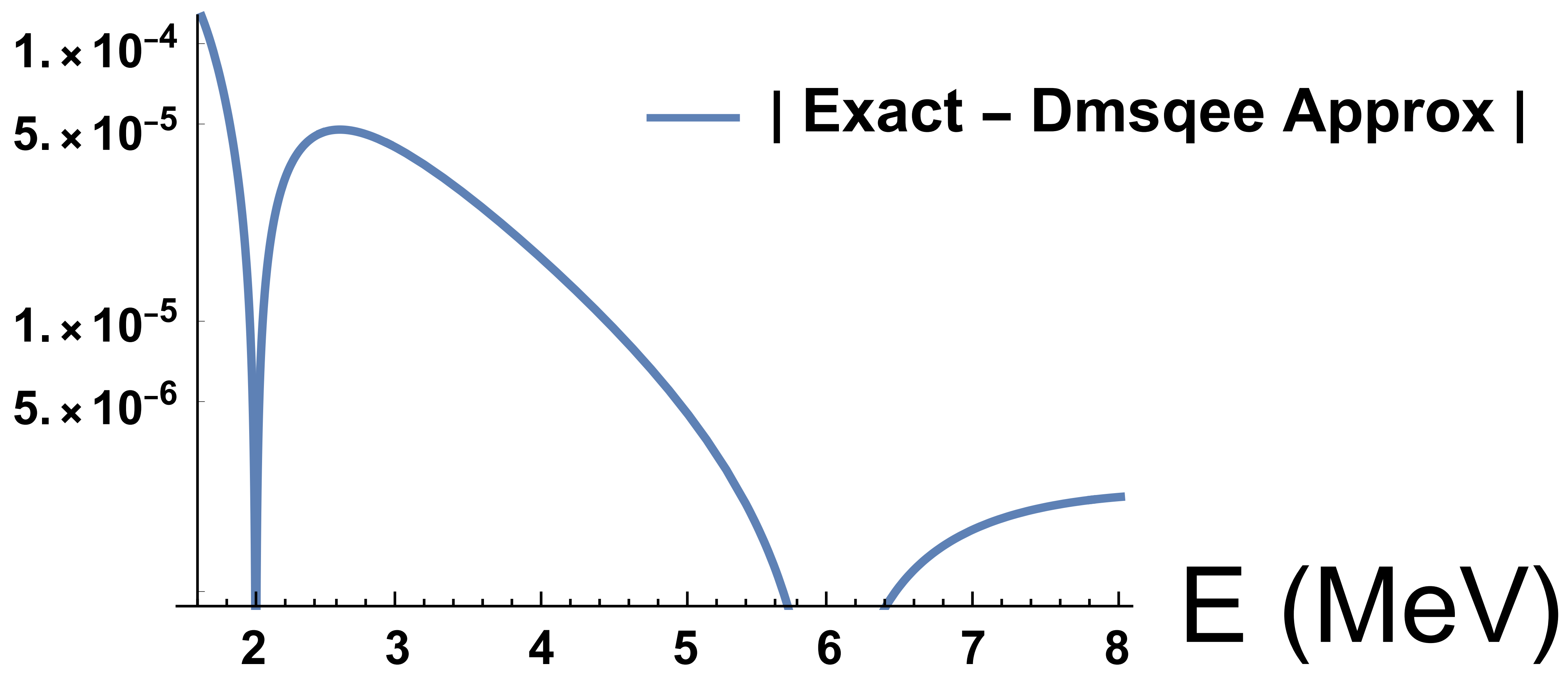
DAYA BAY OSCILLATION PROBABILITY:

Dis. Prob (Daya Bay)

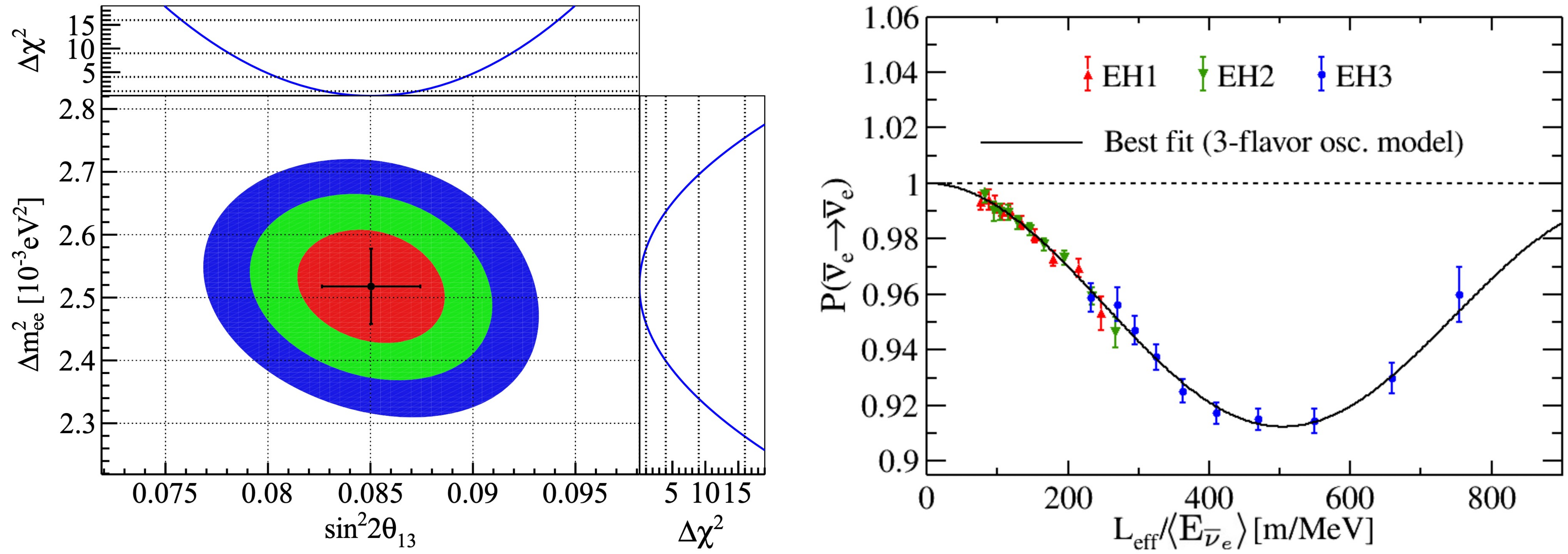


Delta Prob (Daya Bay)



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

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



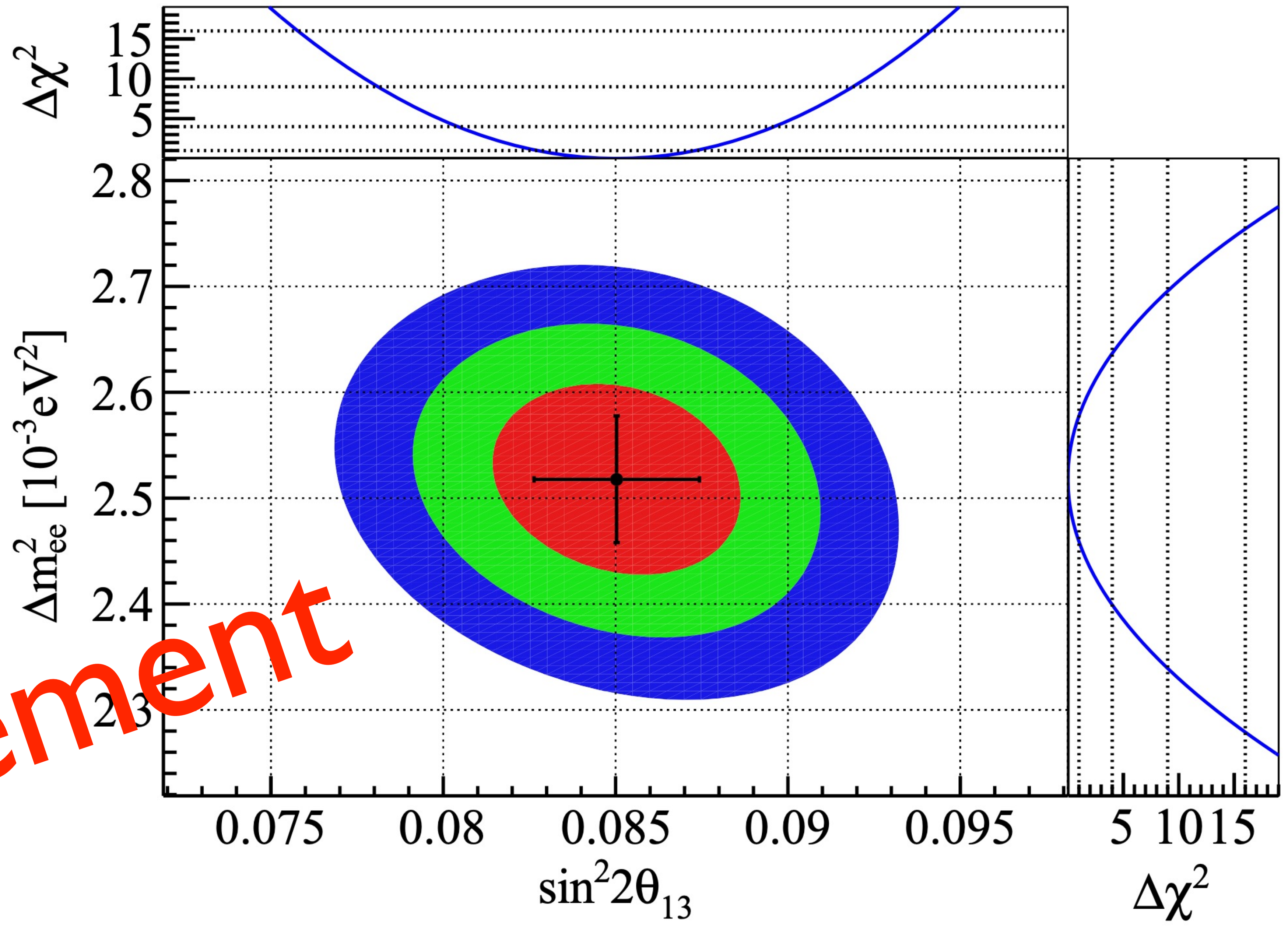
Best-fit results: χ^2/ndf = 559/518

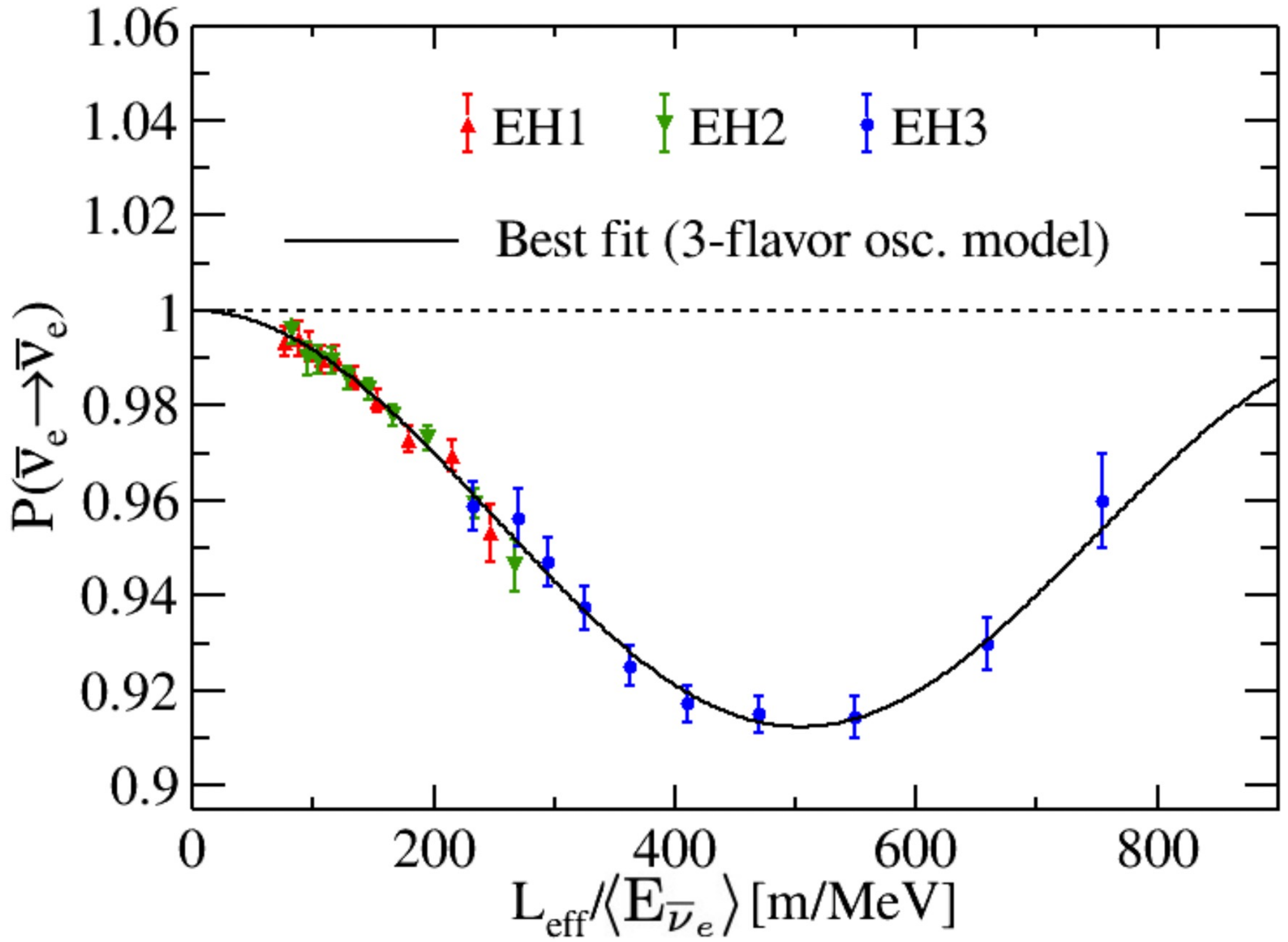
$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$ (2.8% precision)

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

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





Measurement

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

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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

$$\Delta m^2_{\mu\mu} \equiv \frac{|U_{\mu 1}|^2 \Delta m^2_{31} + |U_{\mu 2}|^2 \Delta m^2_{32}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2} = m_3^2 - \frac{|U_{\mu 1}|^2 m_1^2 + |U_{\mu 2}|^2 m_2^2}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

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

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

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

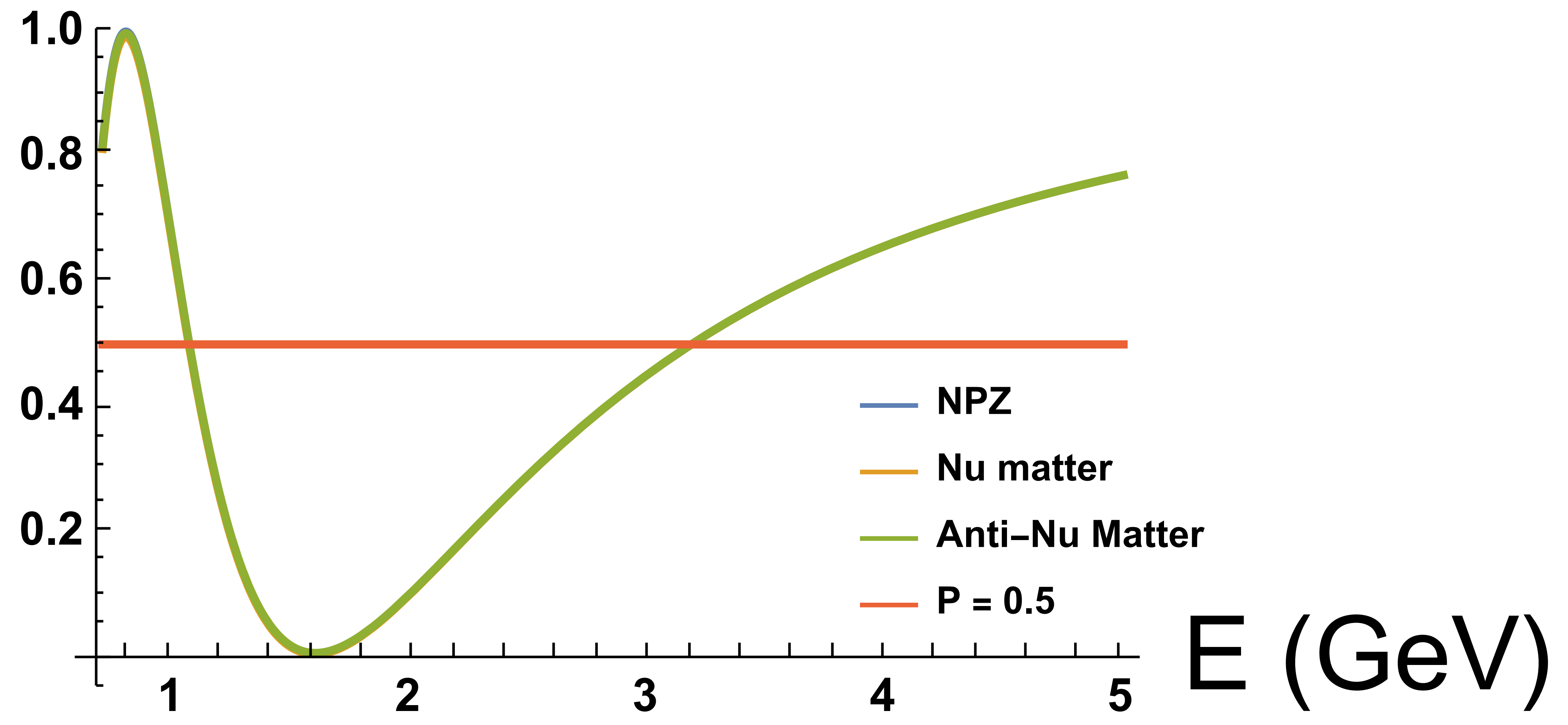
$|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ implies NO

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

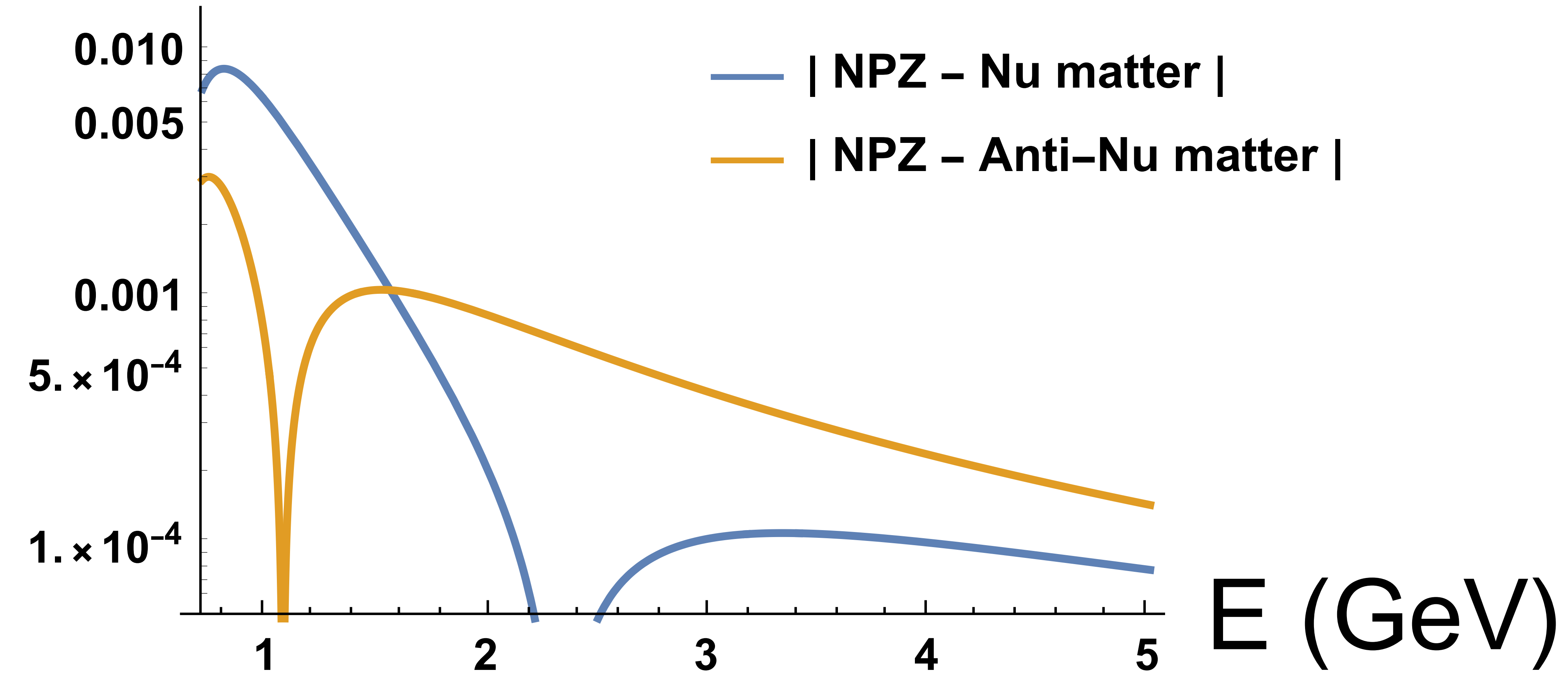
THIS IS IGNORING MATTER EFFECTS:

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

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 $\mp \sin\theta_{13} \cos\delta\, \Delta m^2_{21}$

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

T2K:

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

± 0.05 (2%)

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

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

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

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

NOvA:

Parameter	Normal ord. UO	Normal ord. LO	Inverted ord. UO	Inverted ord. LO
$\Delta m^2_{32}(10^{-3}\ \text{eV}^2)$	$+2.41 \pm 0.07$	$+2.39$	-2.45	-2.44
$\sin^2\theta_{23}$	$0.57^{+0.03}_{-0.04}$	0.46	0.56	0.46
$\delta_{\text{CP}}(\pi)$	$0.82^{+0.27}_{-0.87}$	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: $\frac{E_\nu}{12 \text{ GeV}} < 10^{-3}$ irrelevant

Matter Effect:

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

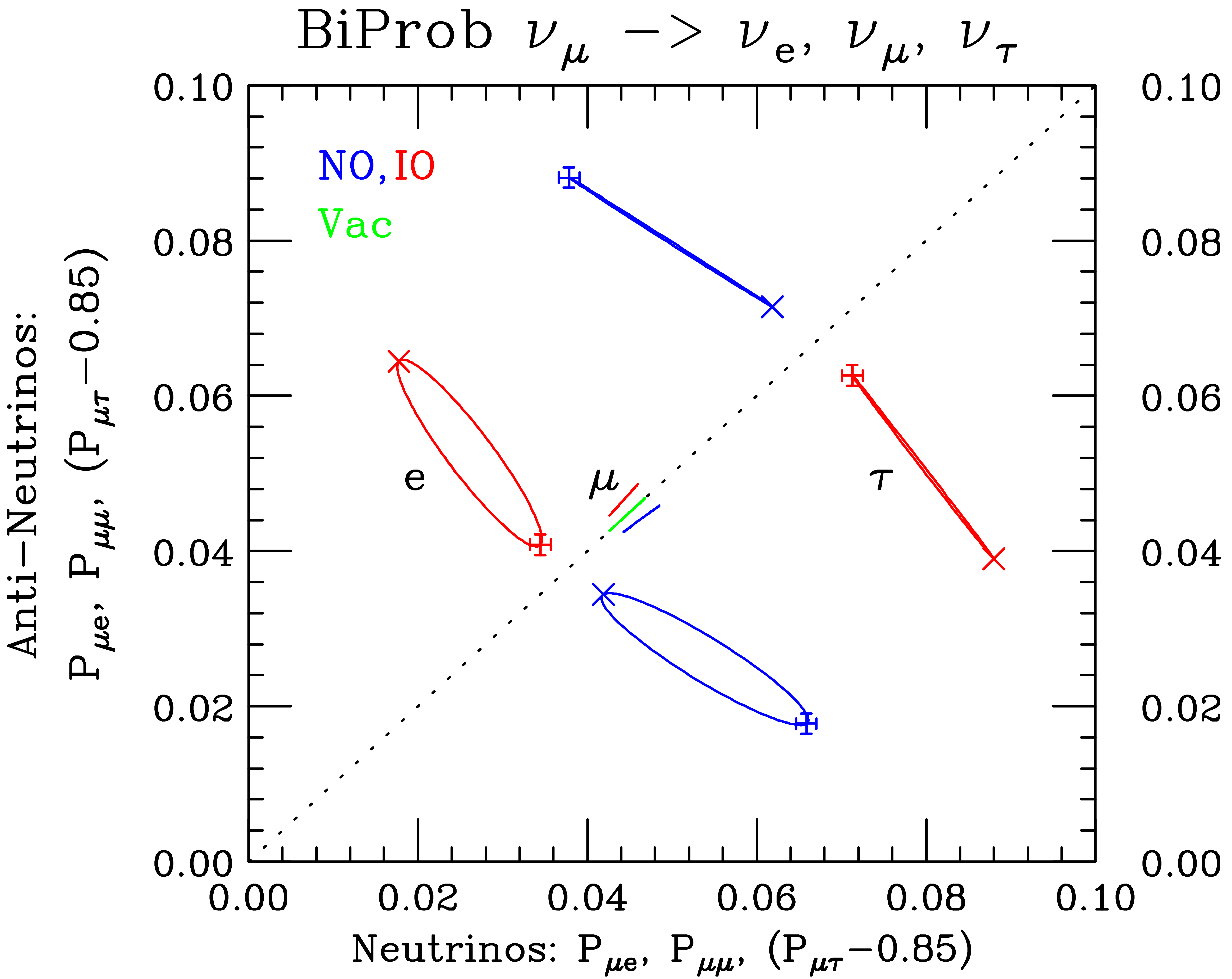
NOvA Disappearance: $\frac{E_\nu}{12\ \text{GeV}} \approx 0.2$

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

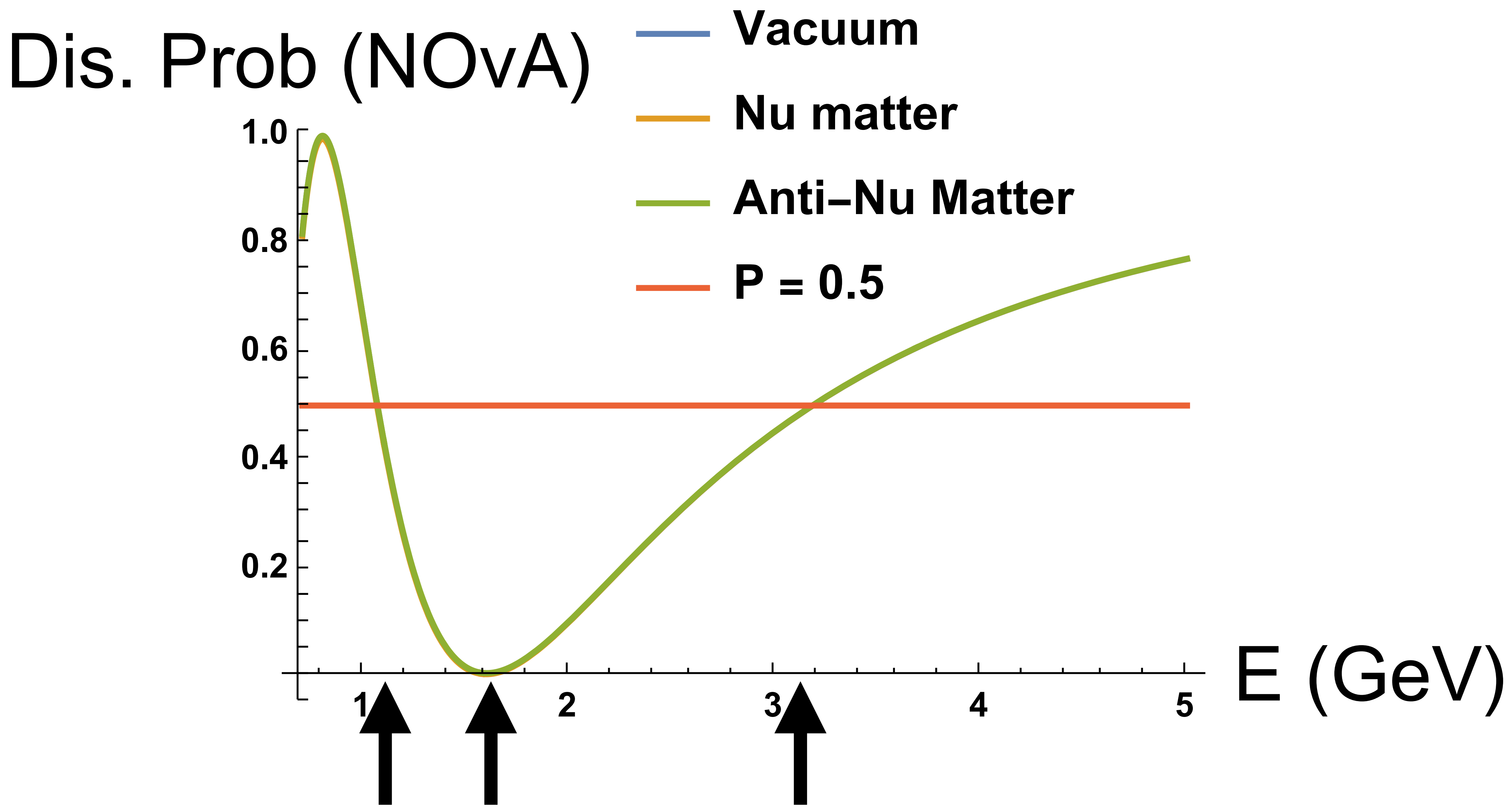
Combined approx. 0.002 !

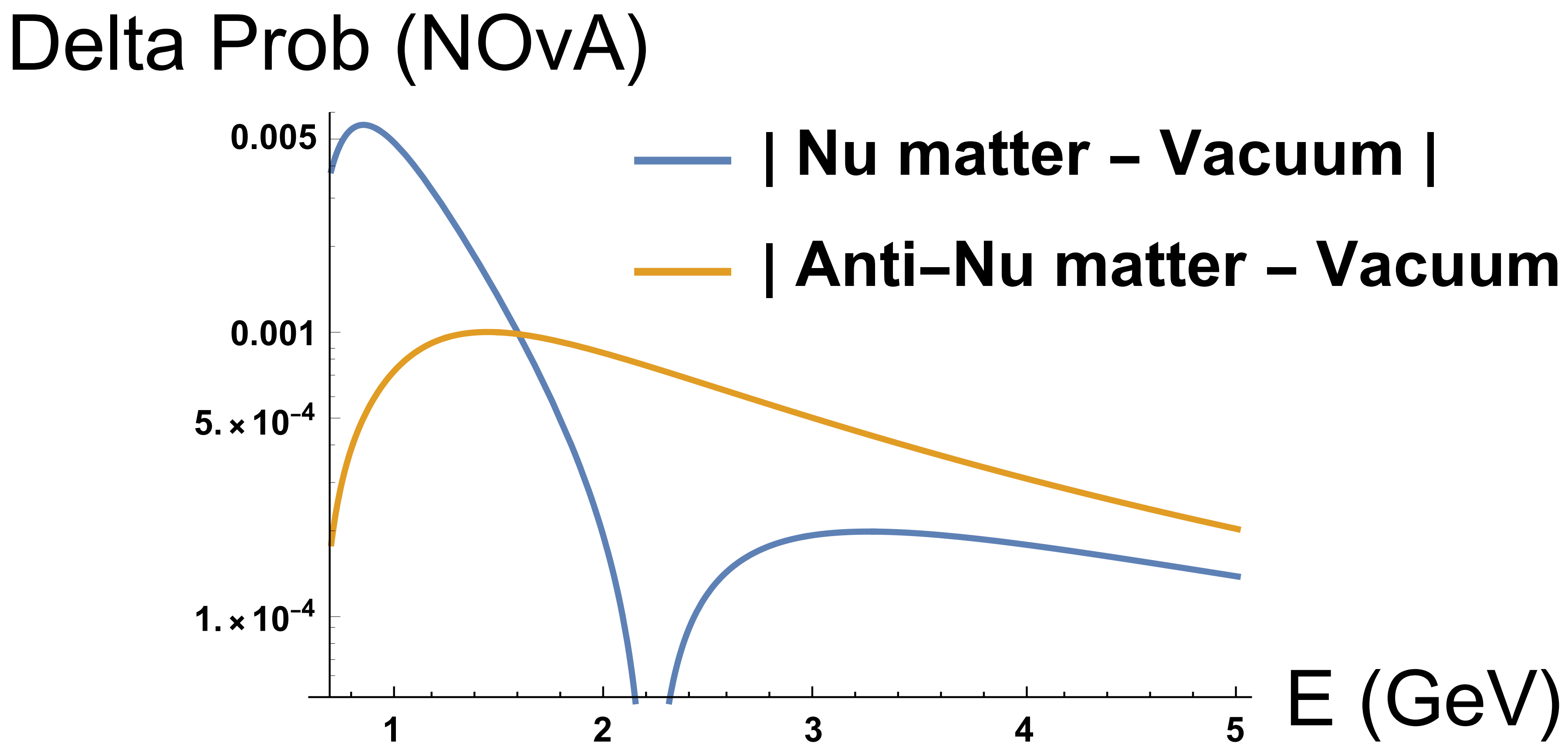
DUNE:
3 GeV

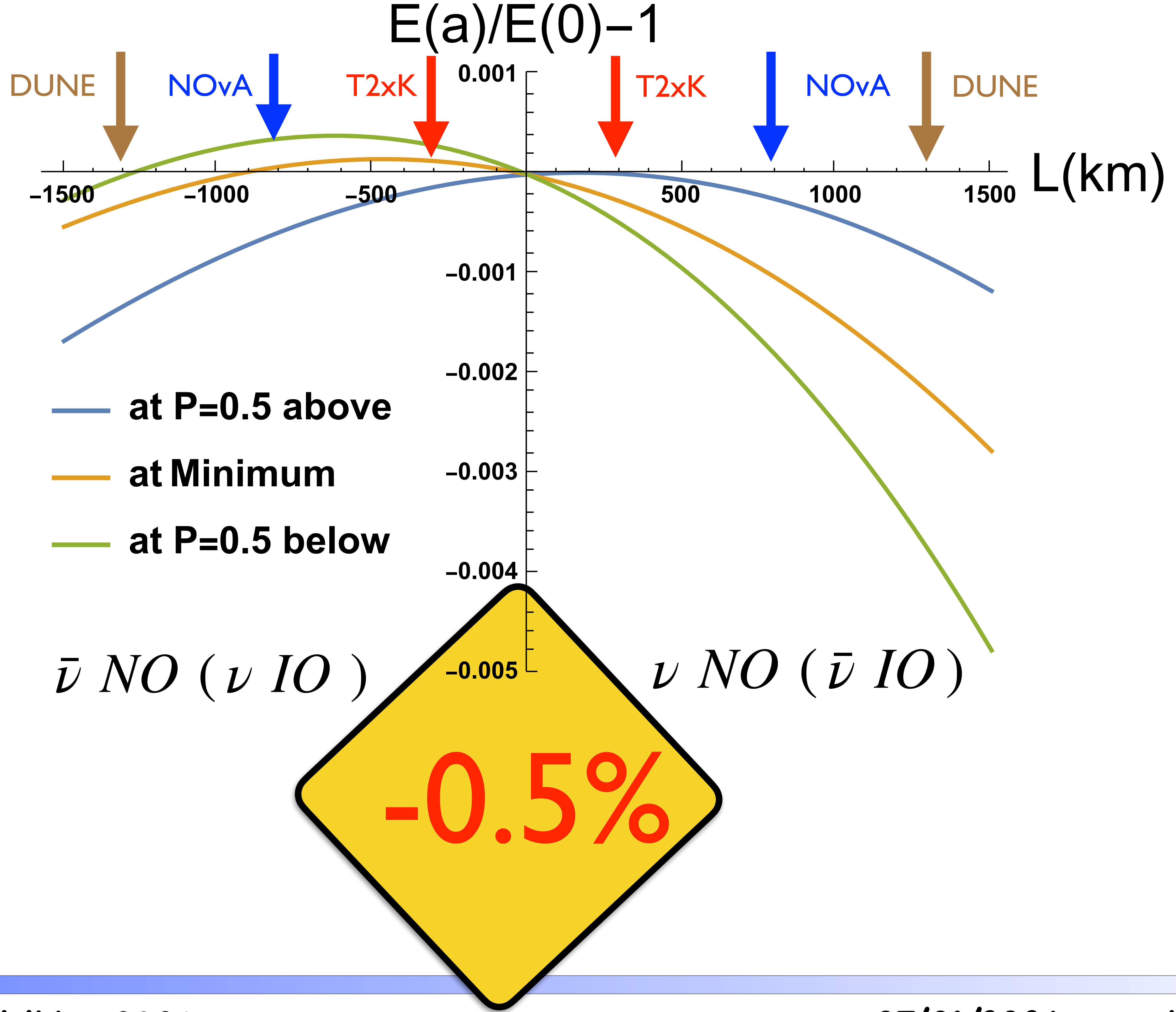
arXiv:2401.10326



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

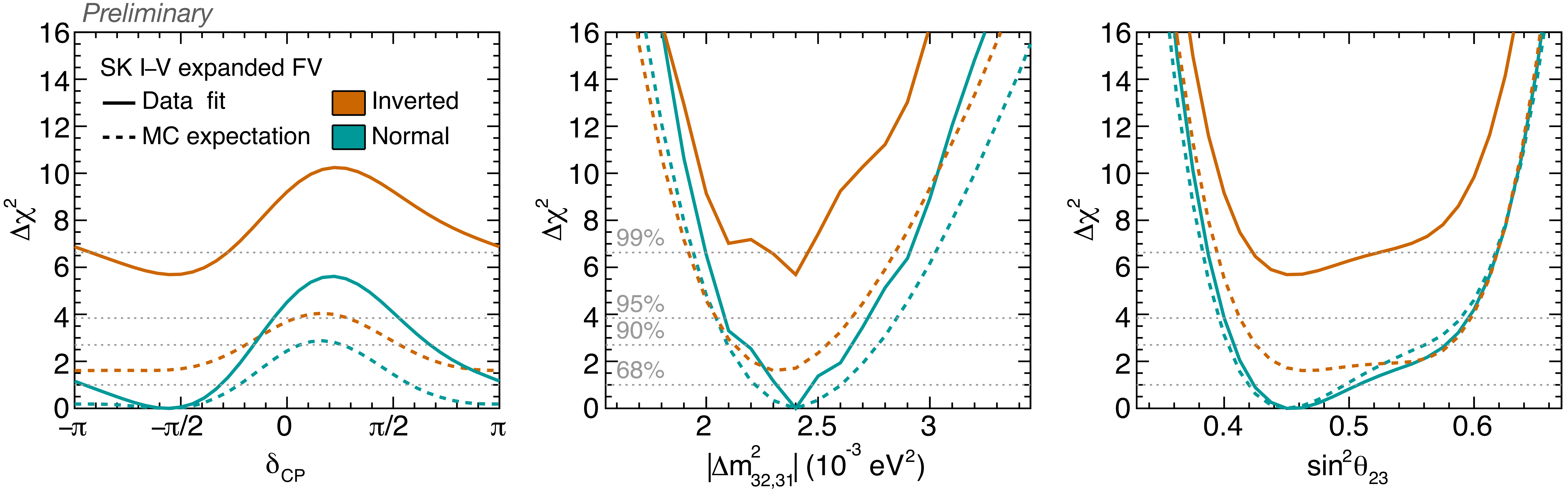
If NO then 0

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

1.5 to 3.3 %

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

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

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

2023/10/12 Super-K Neutrino Results & Gd Status, Thomas Wester, NNN2023 14

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.

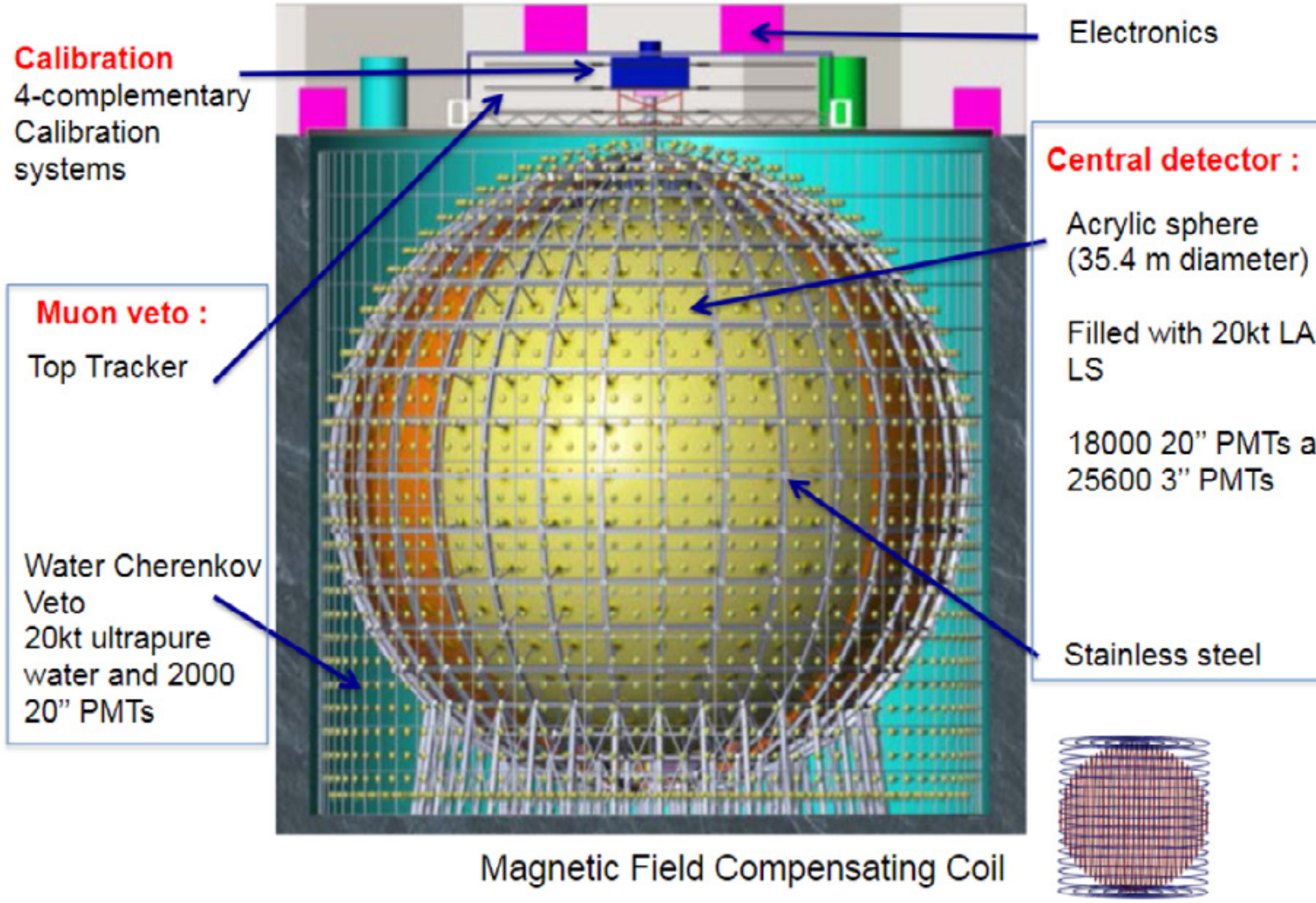
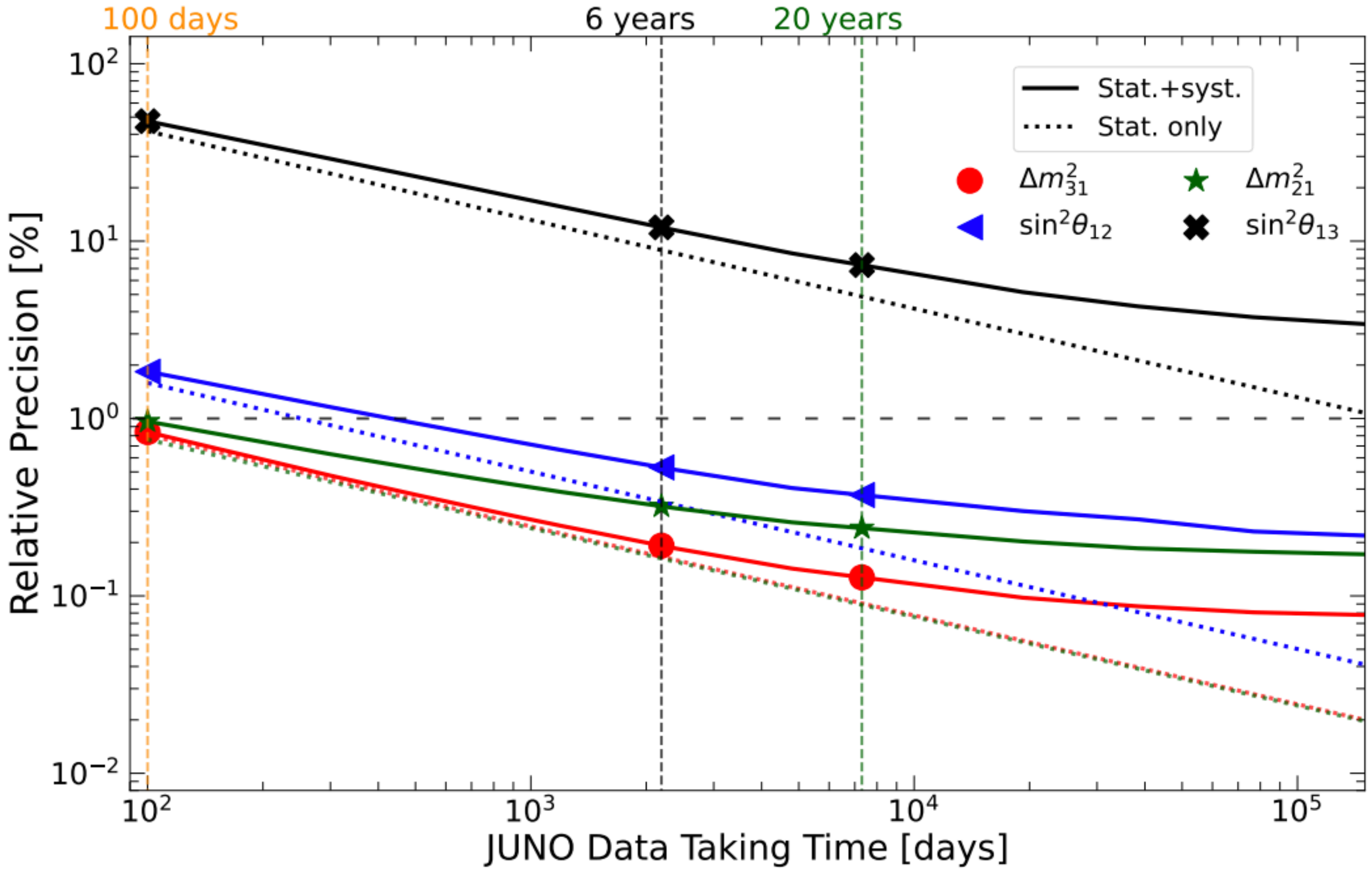


Fig. 4. Schematic view of the JUNO detector.

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

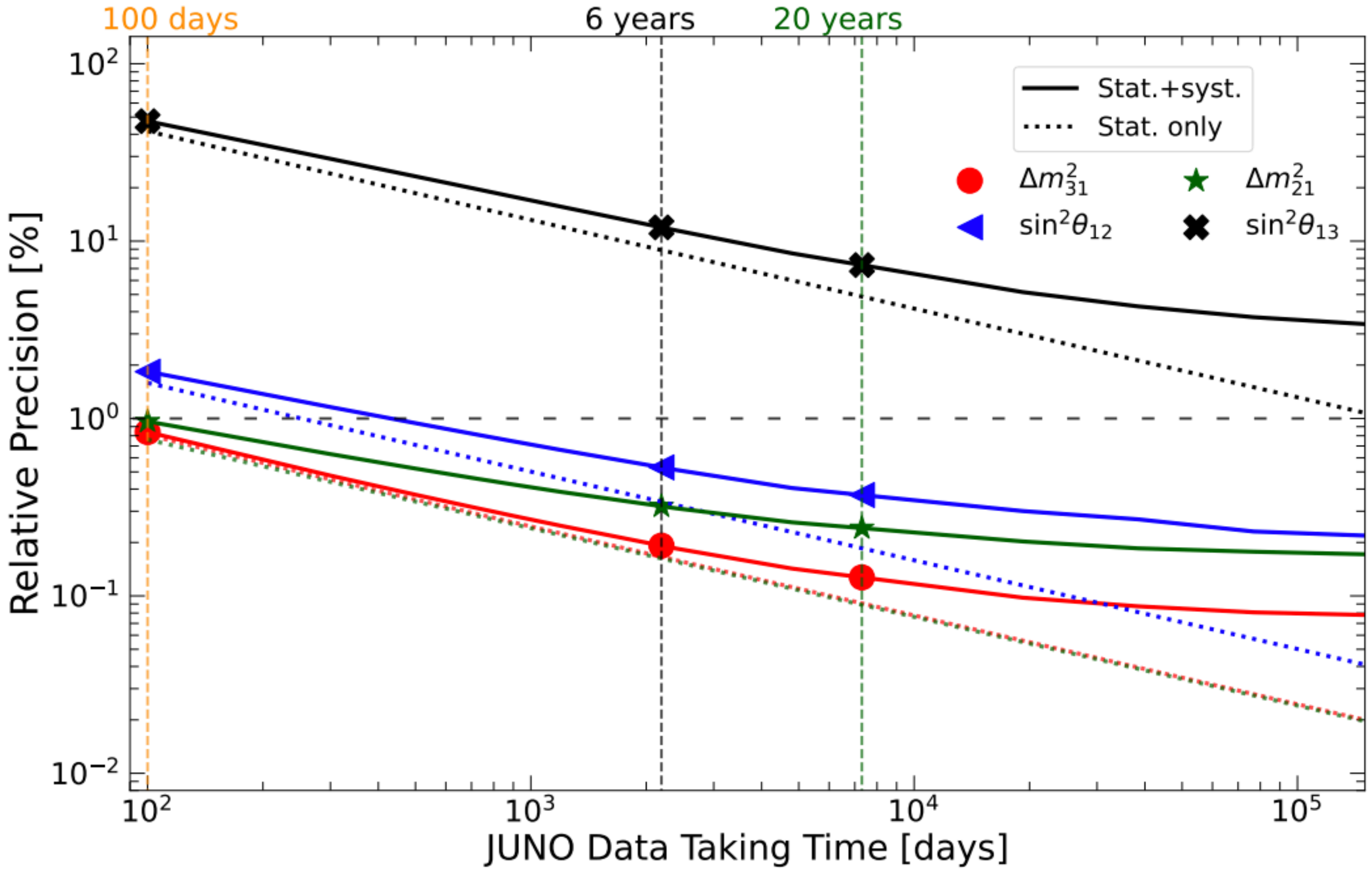
JUNO_update_2204.13249



Time	% on Δm^2_{atm}
100 days	1.0
4 years	0.3
8 years	0.2
12 Years	0.15

Time Evolution of JUNO measurements

JUNO_update_2204.13249

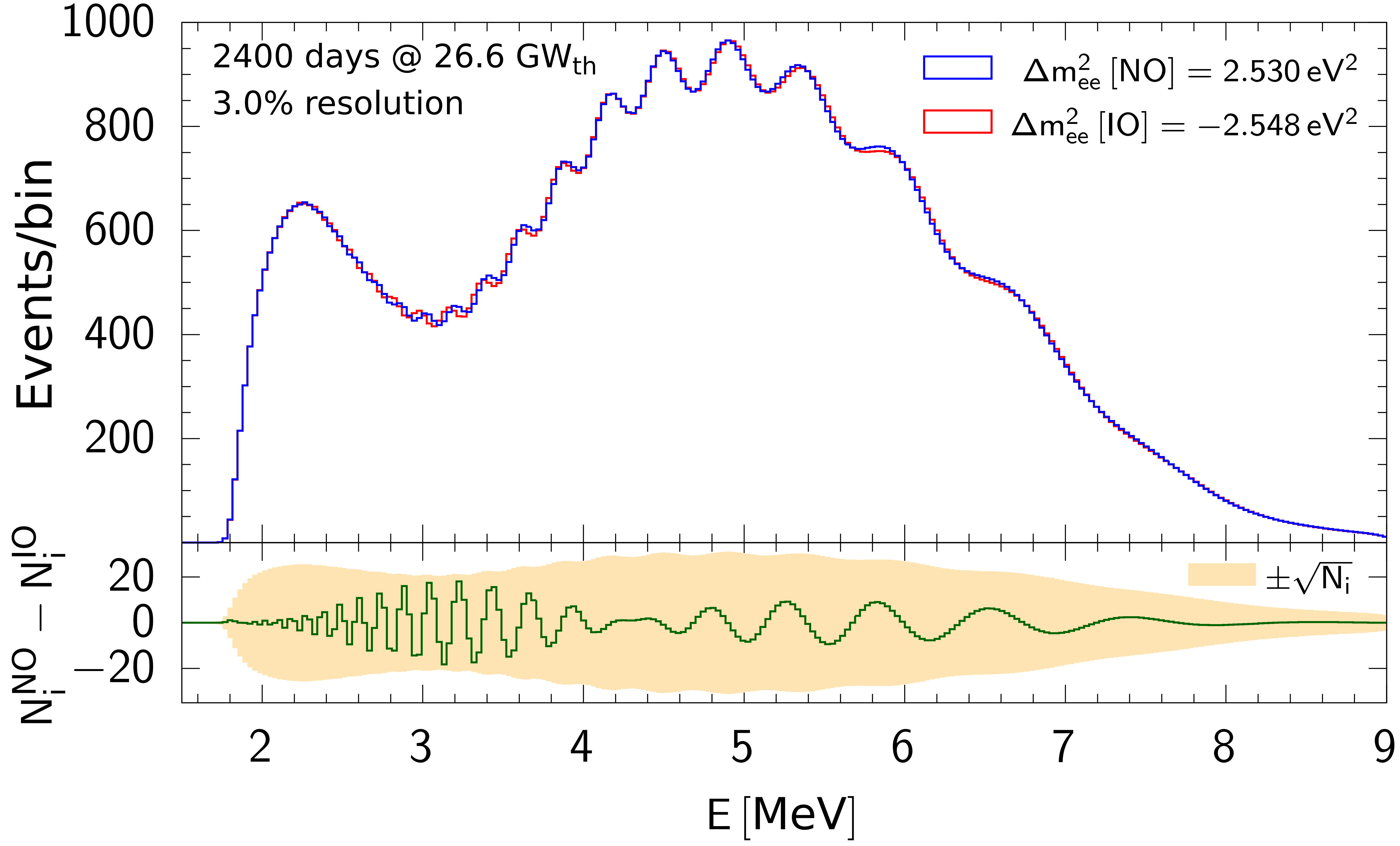


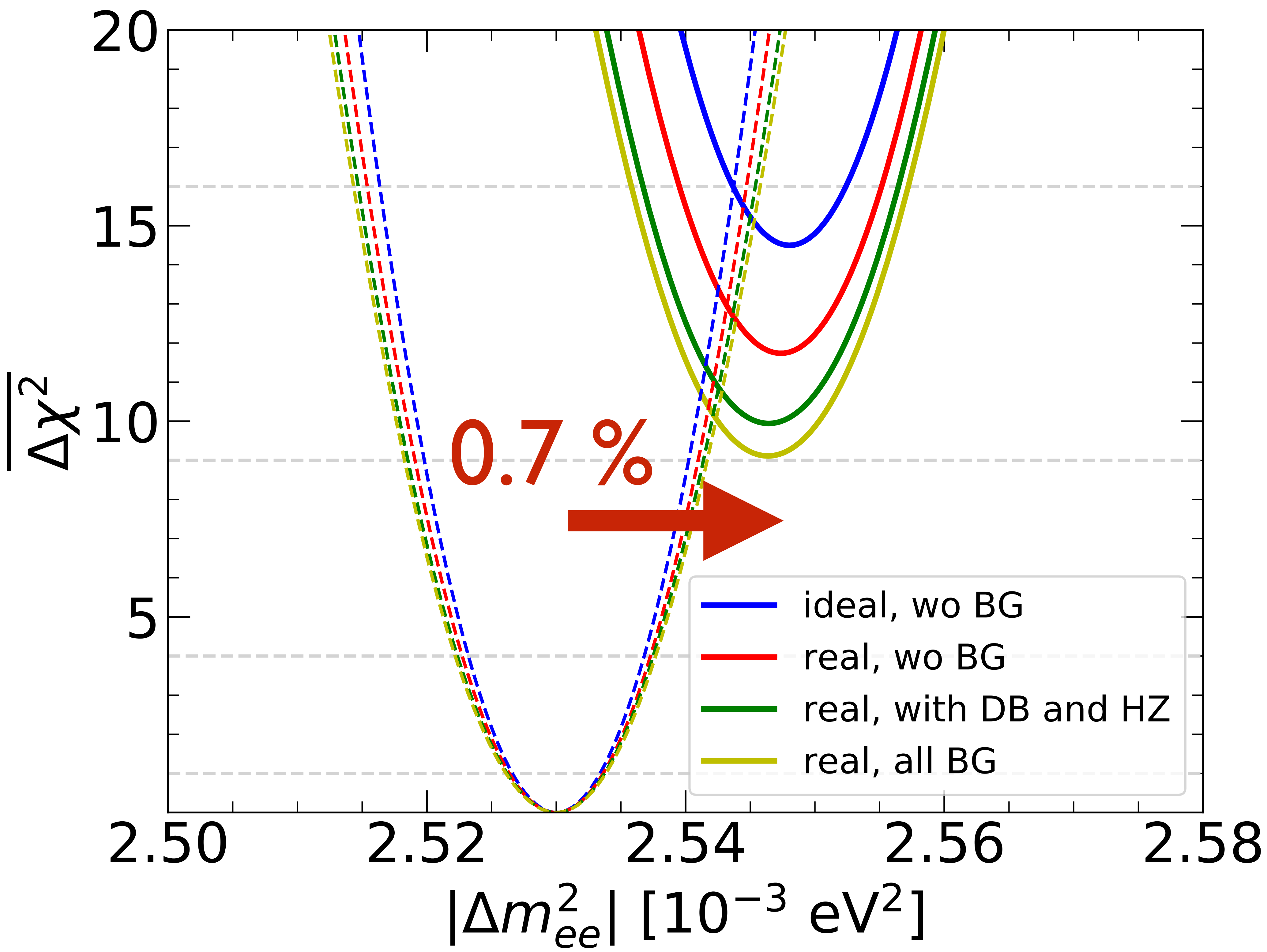
Time	% on Δm^2_{atm}
100 days	1.0
4 years	0.3
8 years	0.2
12 Years	0.15

500+ years

JUNO Events Spectra

Real Baseline Distribution + Backgrounds





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

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 $|\Delta m^2_{ee}|(IO) = 2.503$

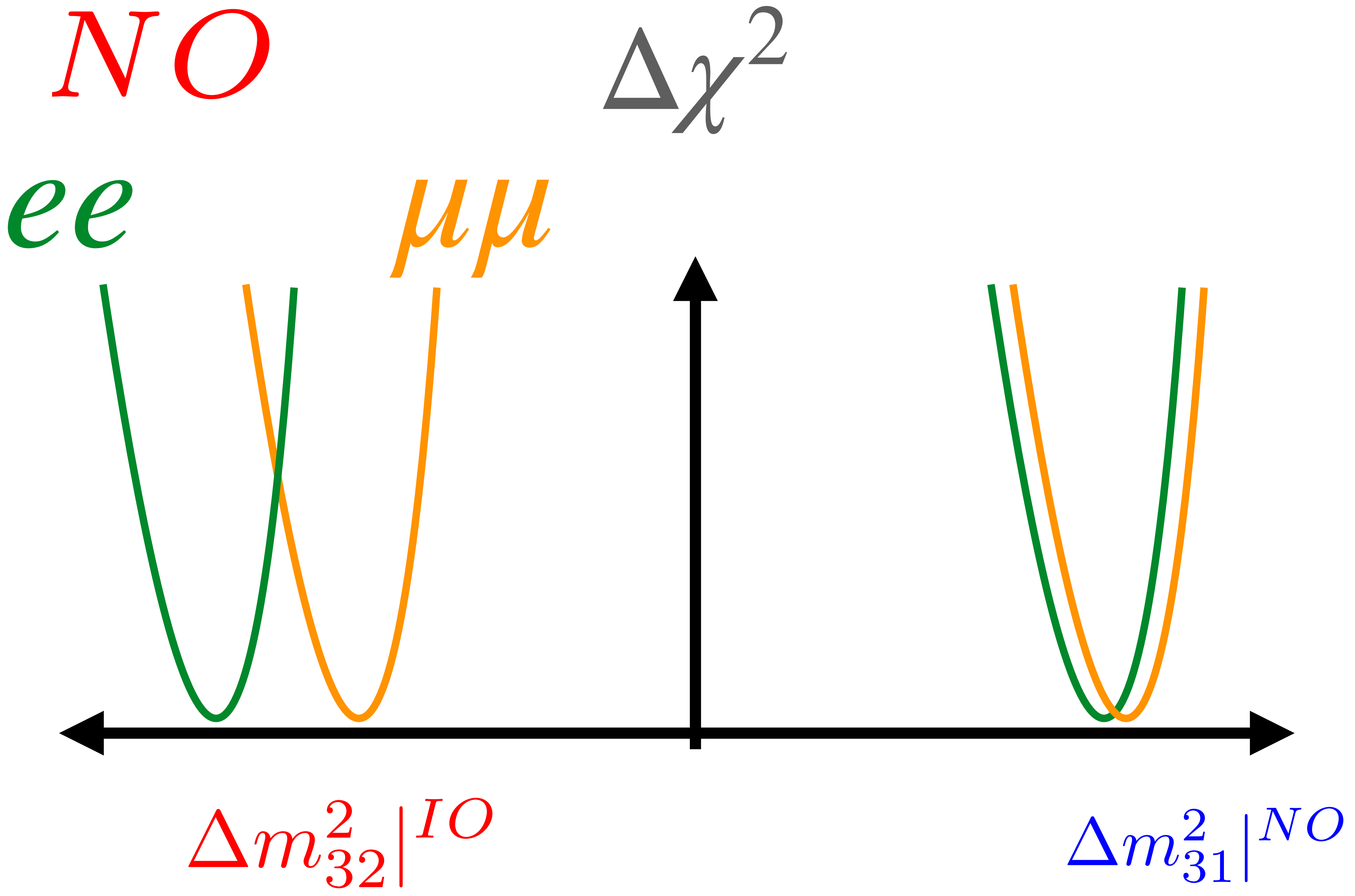
Forero, SP, Ternes, Zukanovich 2107.12410

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%).

NO

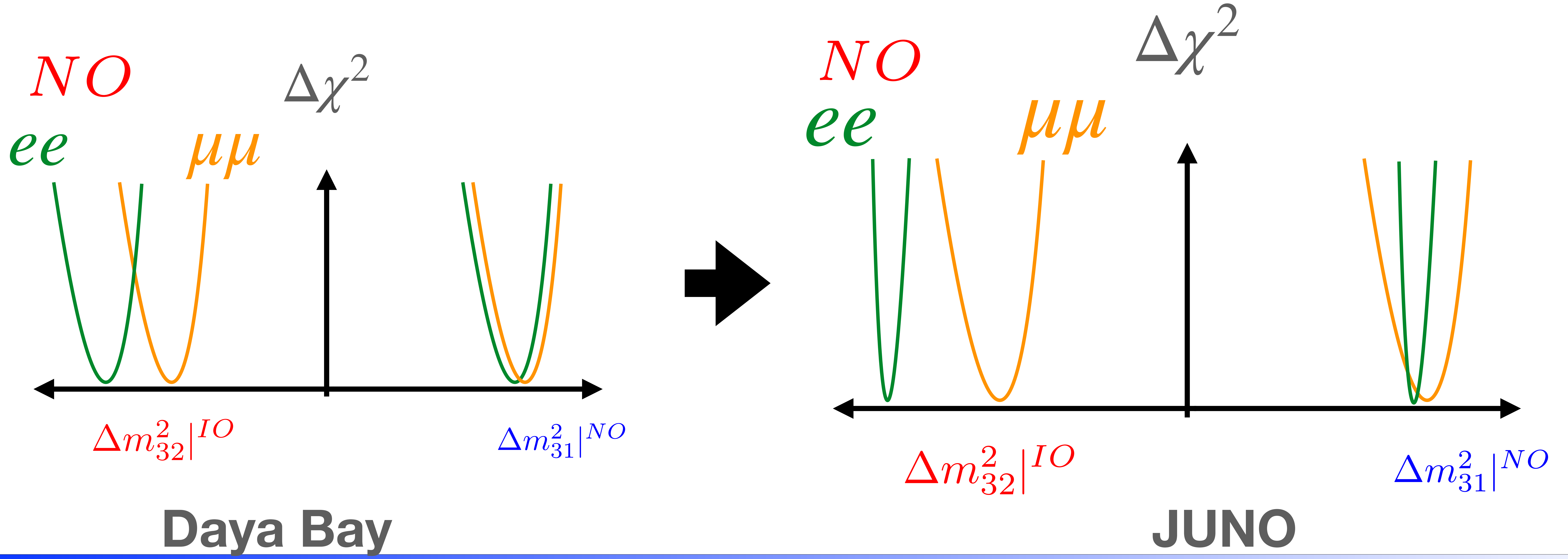


Daya Bay

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

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

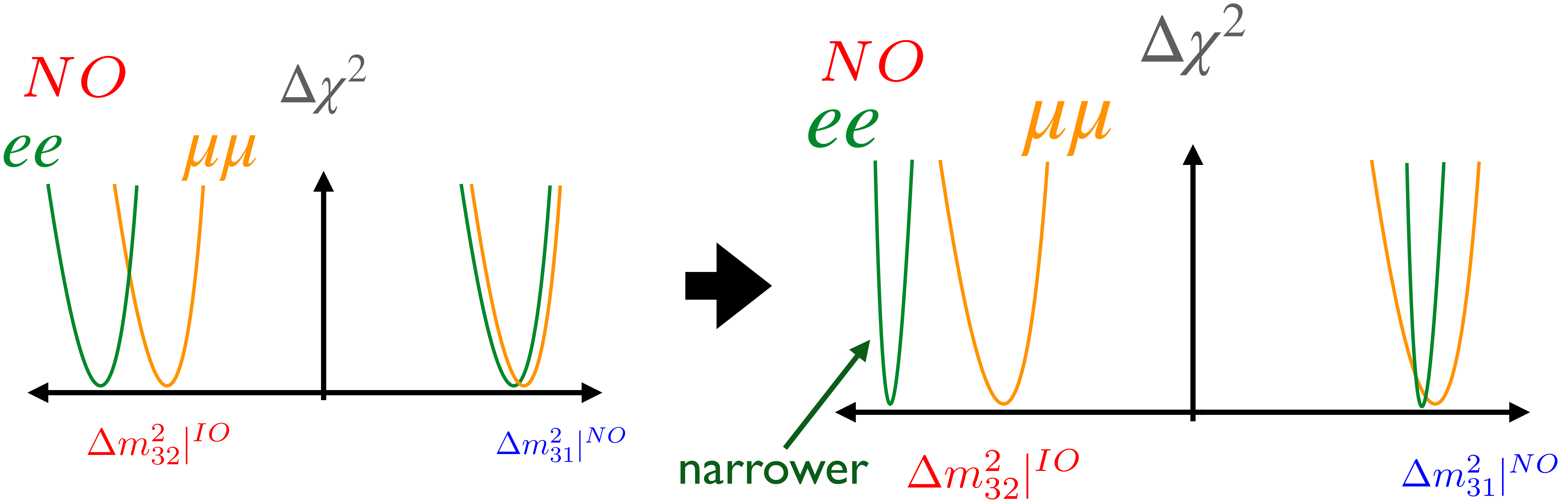
and experimental uncertainty on $|\Delta m^2_{ee}|$ drops to <1%. (Daya Bay 2.4%).



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%).



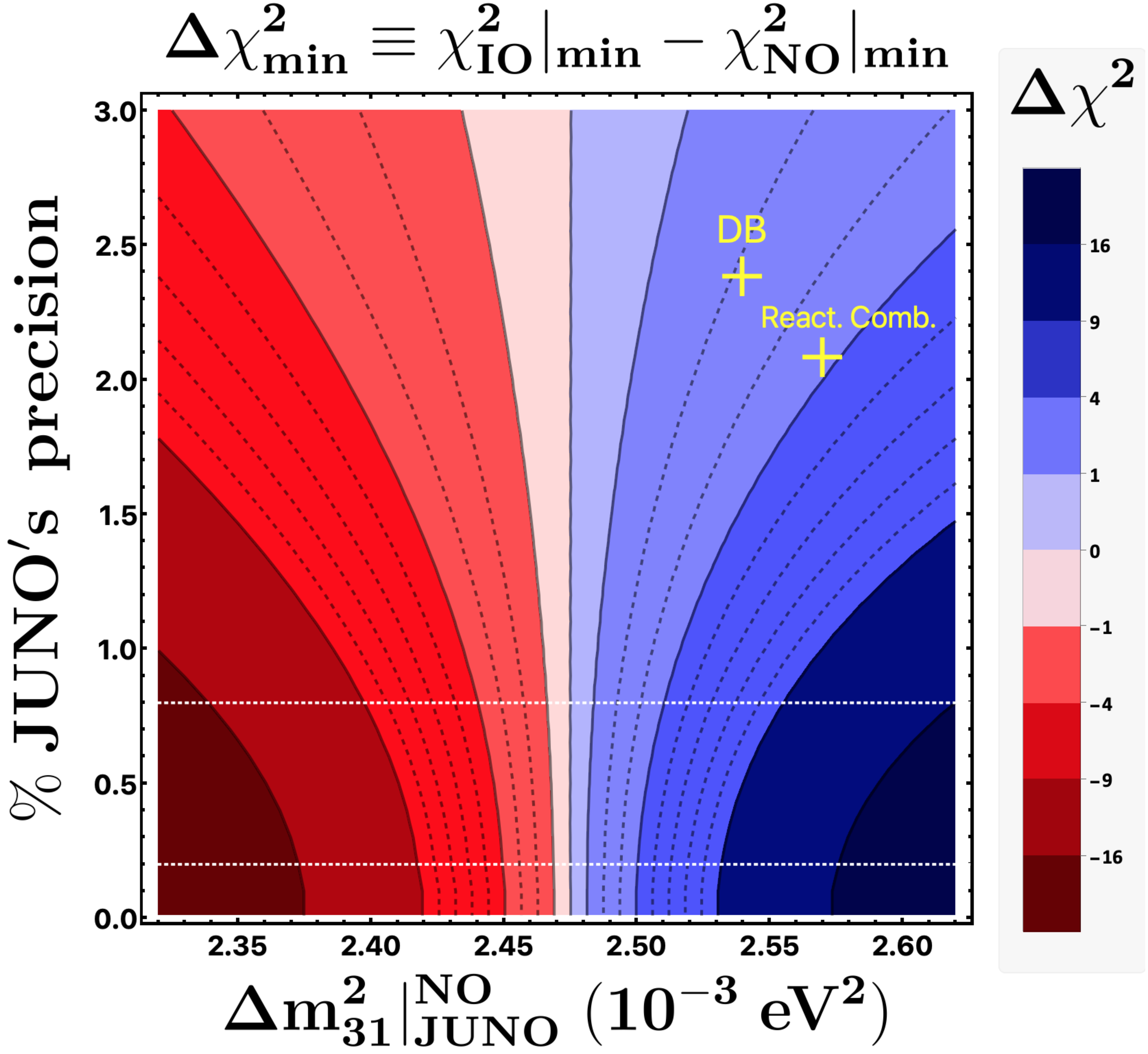
Daya Bay

+ slightly more separation

JUNO

A Mass Ordering Sum Rule for the Neutrino Disappearance Channels in T2K, NOvA and JUNO

arXiv:2404.08733



100 days

6 years

Further Synergies:

JUNO-ICECUBE UPGRADES 1911.06745

JUNO-KM3NET 2108.06293

Further Synergies:

JUNO-ICECUBE UPGRADES 1911.06745 JUNO-KM3NET 2108.06293

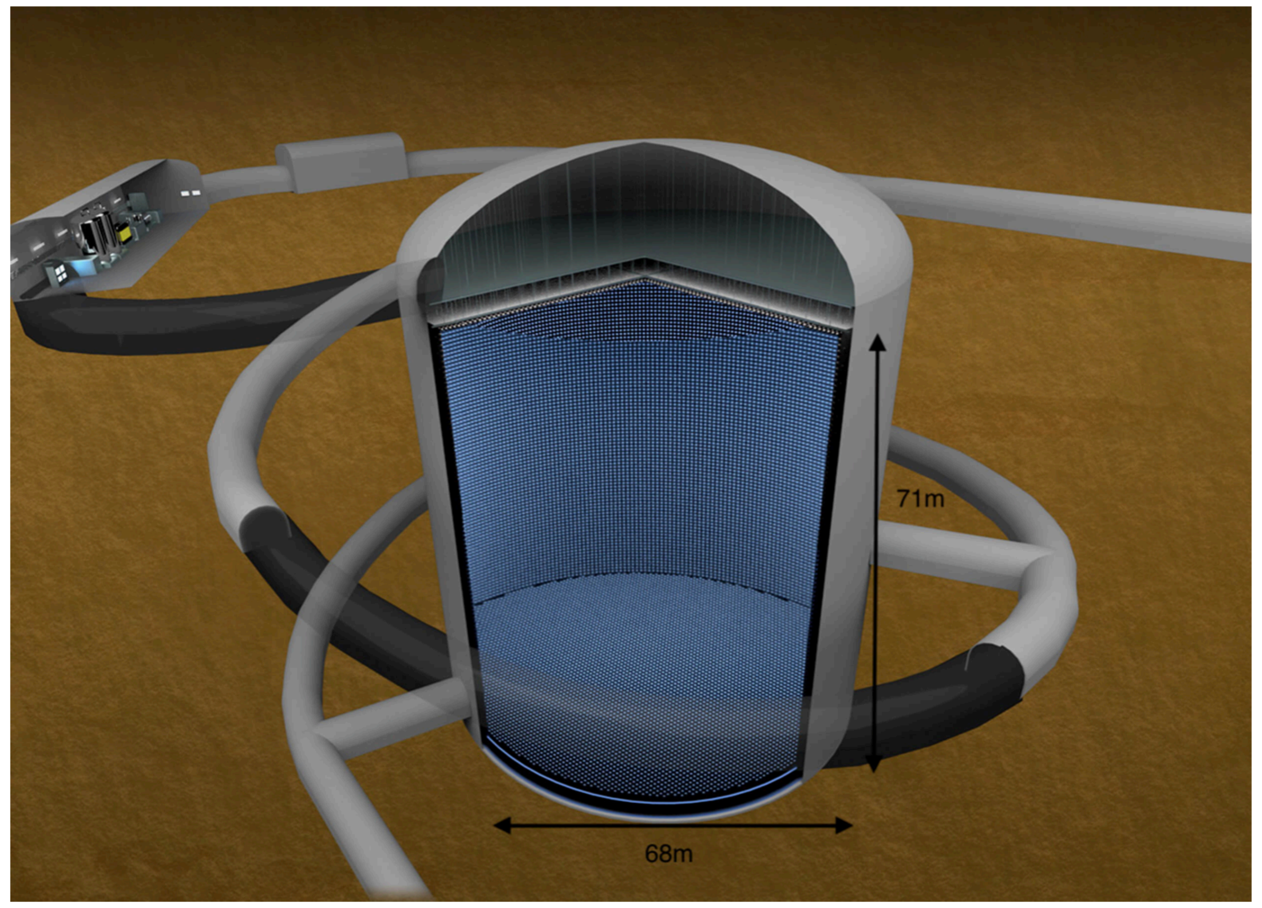
Single Experiments:

JUNO 1507.05613

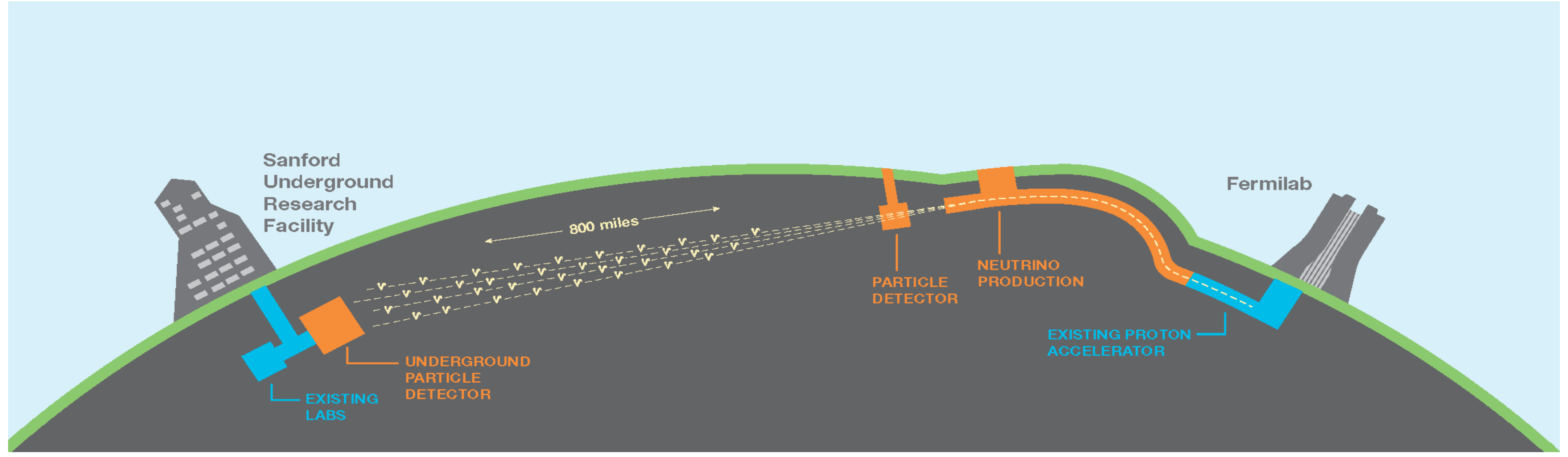
no MO update in
JUNO 2204.13249

See also
FPTZ:2107.12410

HyperK:



DUNE:



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

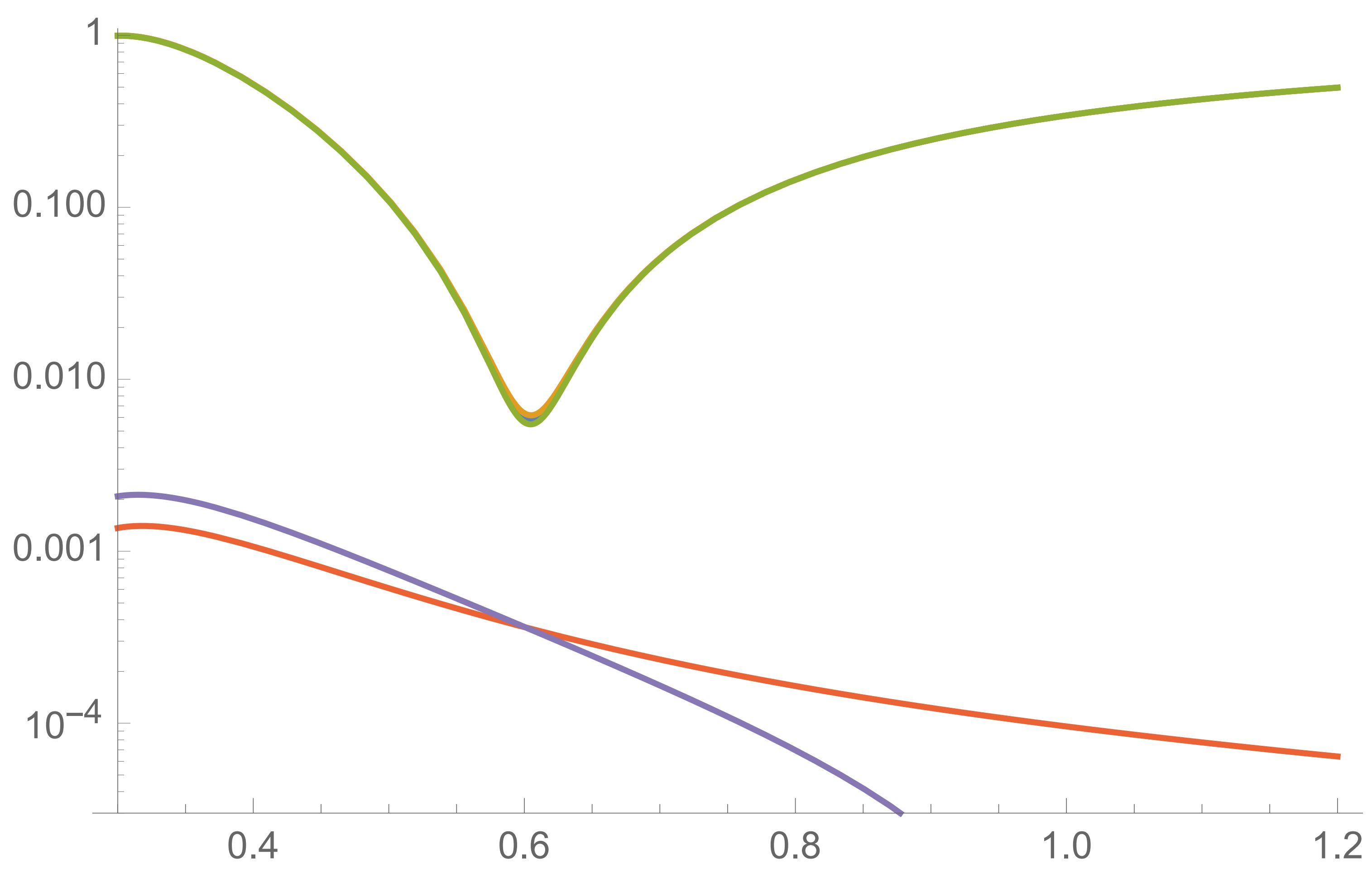
If NO then 0

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

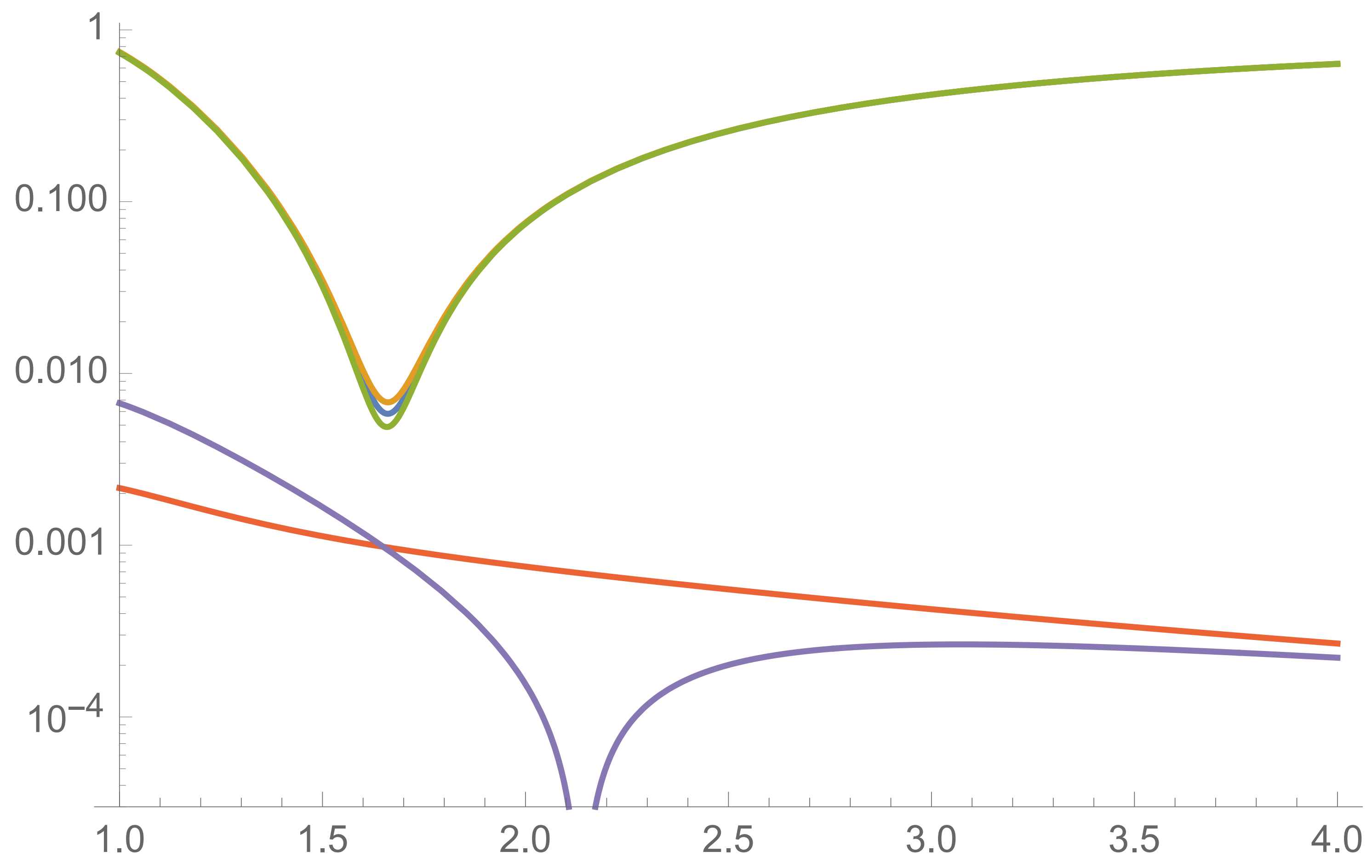
1.5 to 3.3 %

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

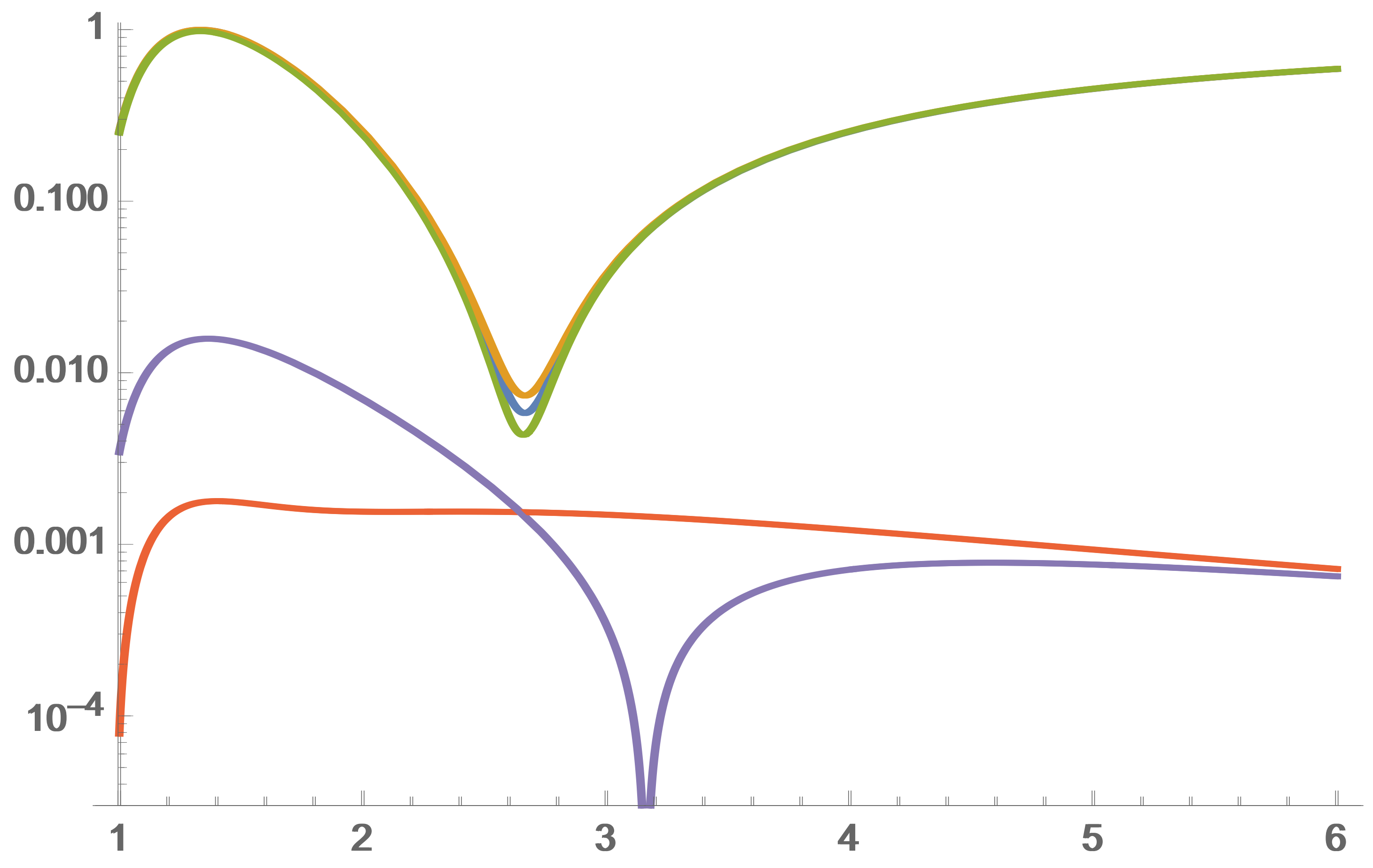
Vacuum v Matter:



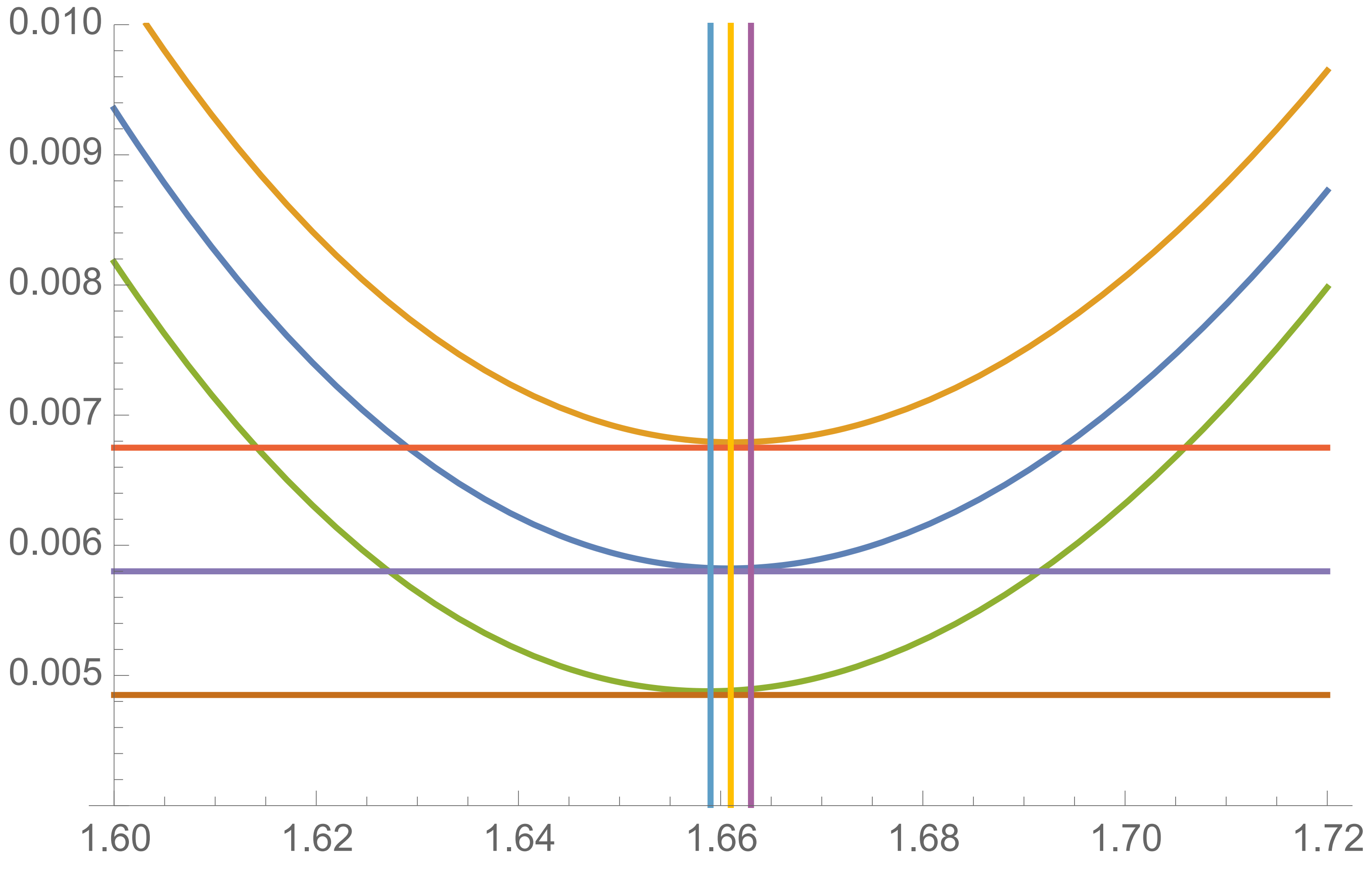
T2K

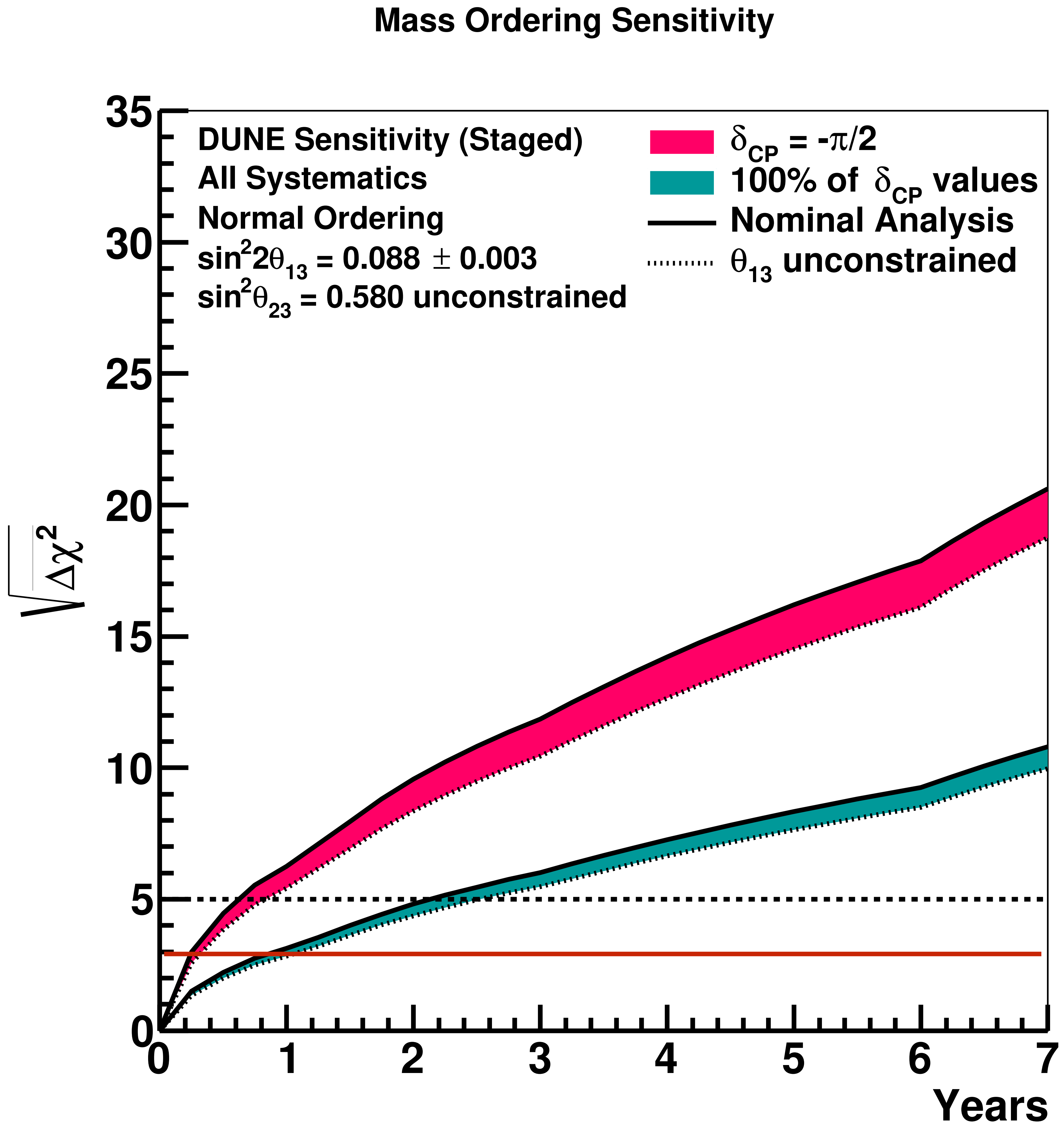


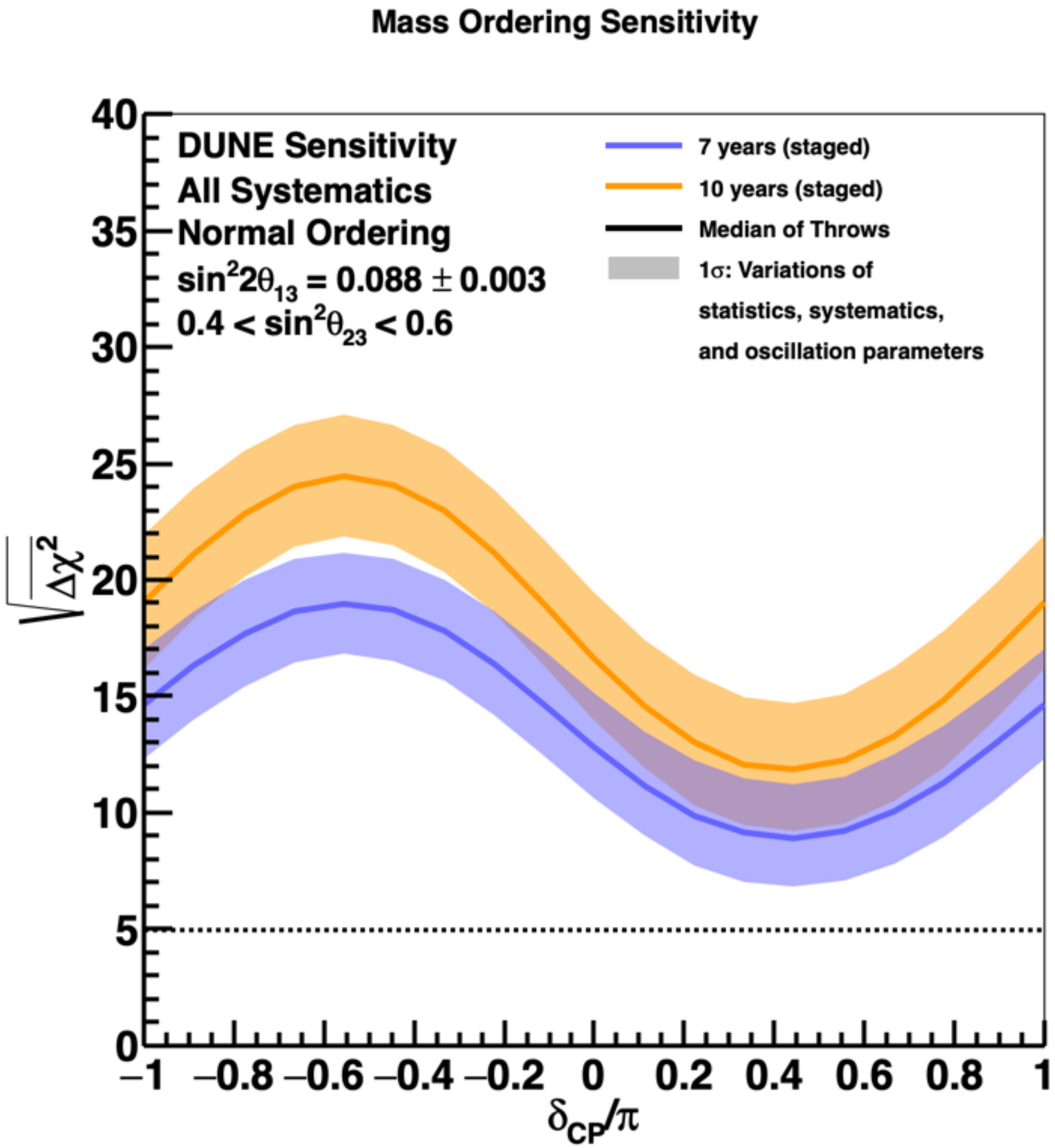
NOvA



DUNE







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