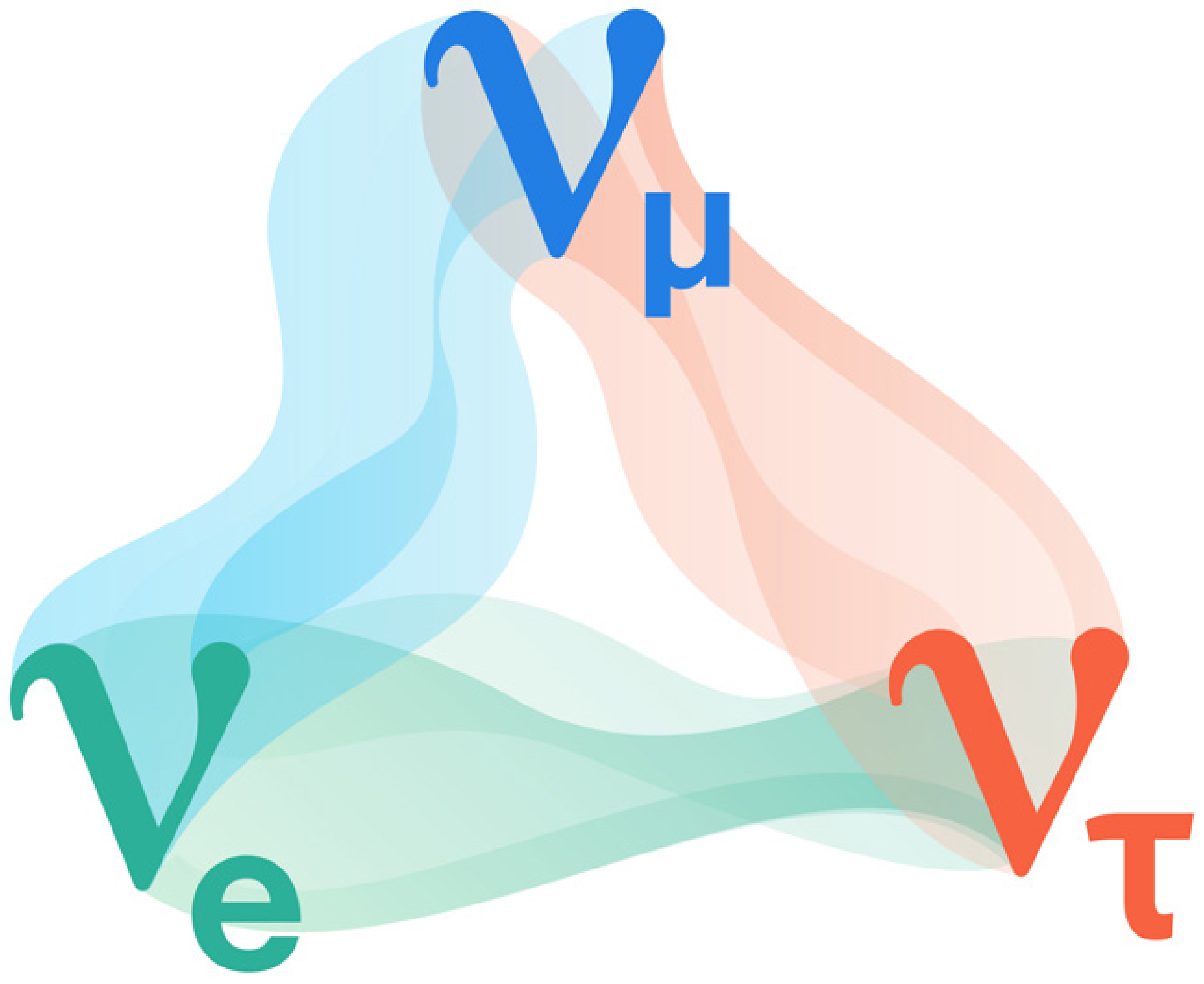
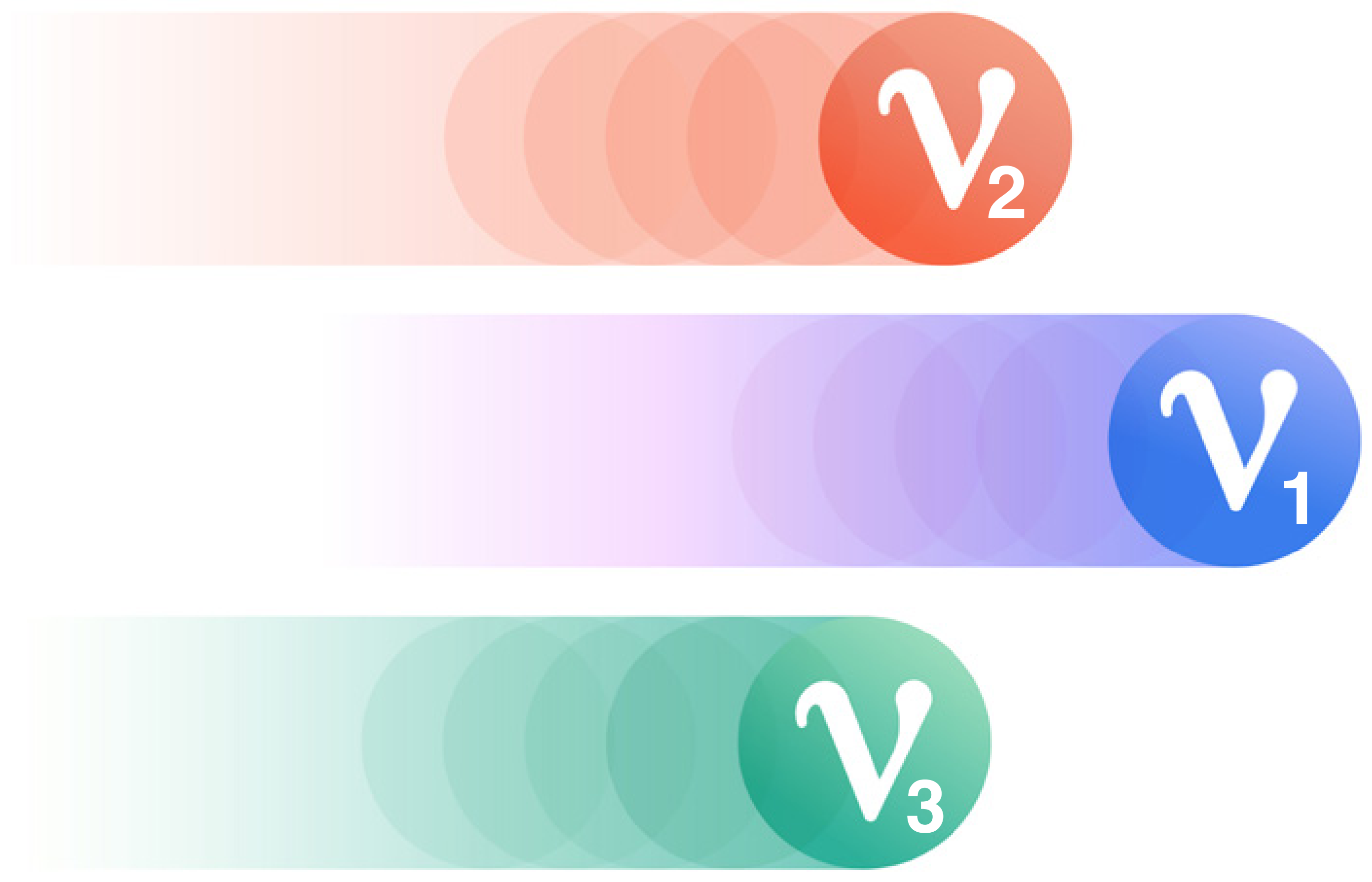
The Race for the Neutrino Mass Ordering

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



$$= U$$



U_pdg

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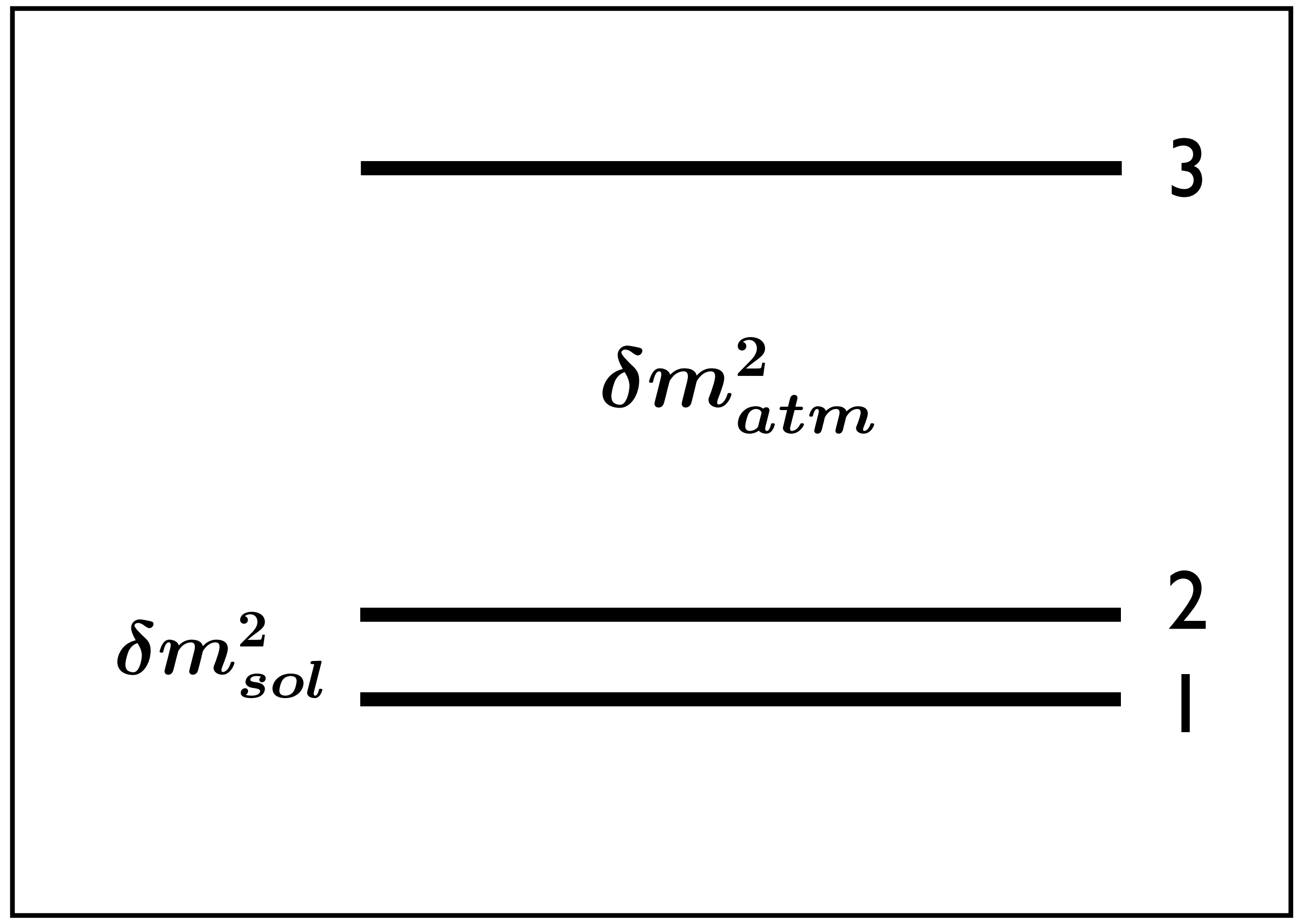
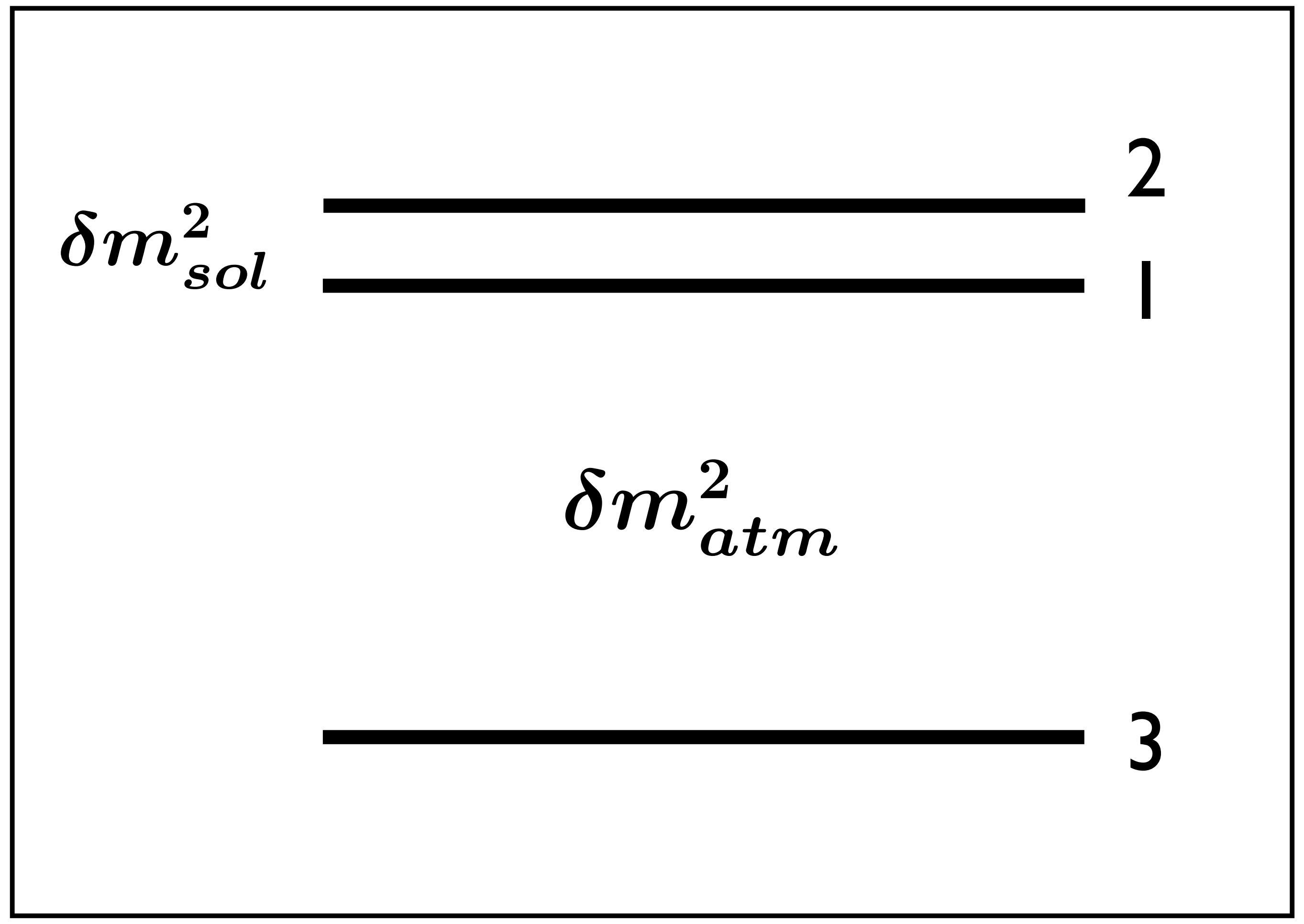


OR



The 2023 **EPS High Energy and Particle Physics Prize** is awarded to

Cecilia Jarlskog for the discovery of an invariant measure of CP violation in both quark and lepton sectors; and …

Quarks

$$J = (3.08 \pm 0.14) \times 10^{-5}$$

also used in SMEFT

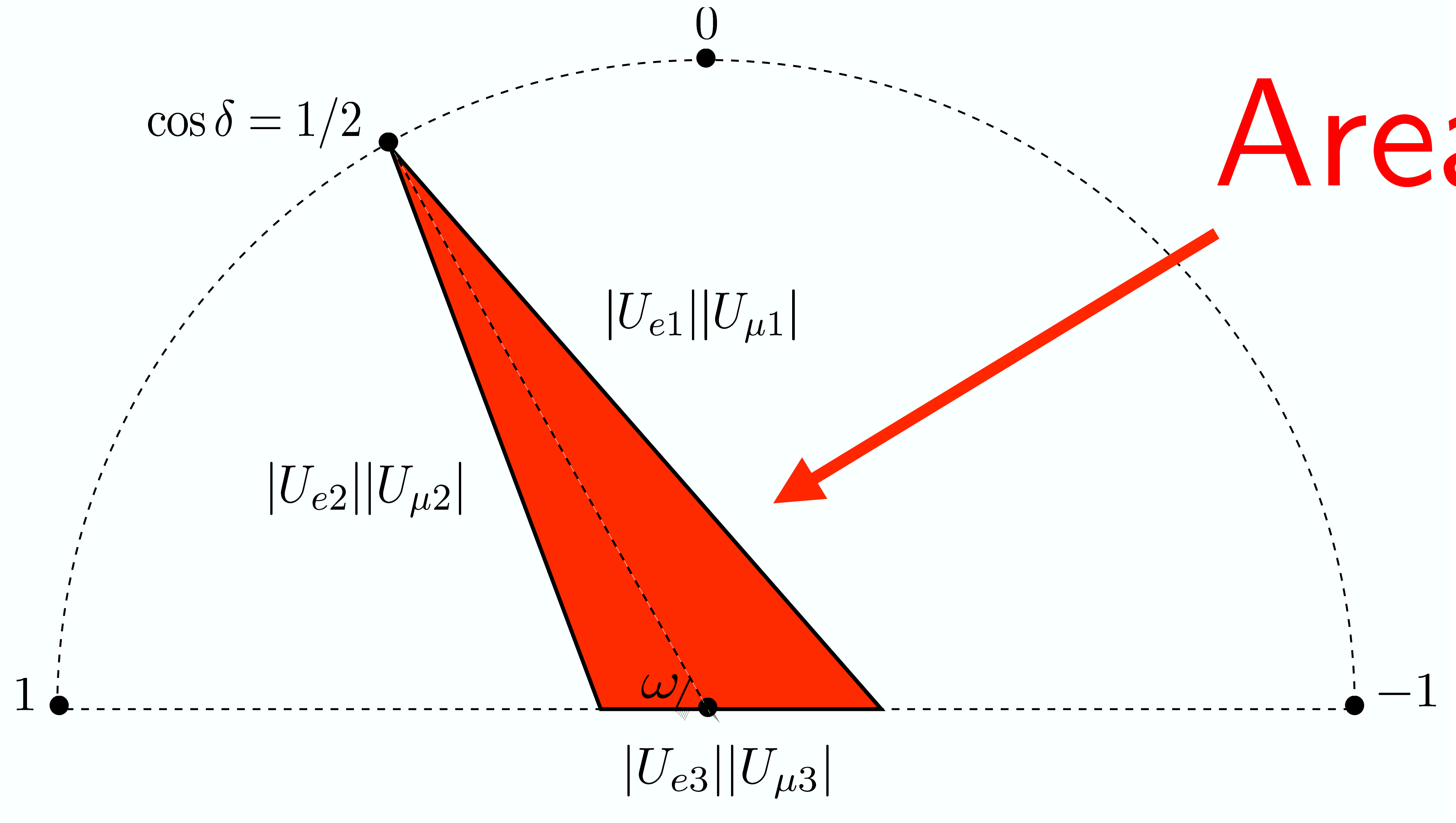
Jarlskog Invariant: 1985

$= 0, \pm 1$

$$J_{ij}^{\alpha\beta} \equiv \Im\{U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j}\} = J \sum_{k,\gamma} \epsilon_{ijk}\epsilon_{\alpha\beta\gamma}$$

$$J_{pdg} = s_{23}c_{23}\ s_{13}c_{13}^2\ s_{12}c_{12}\ \sin\delta$$

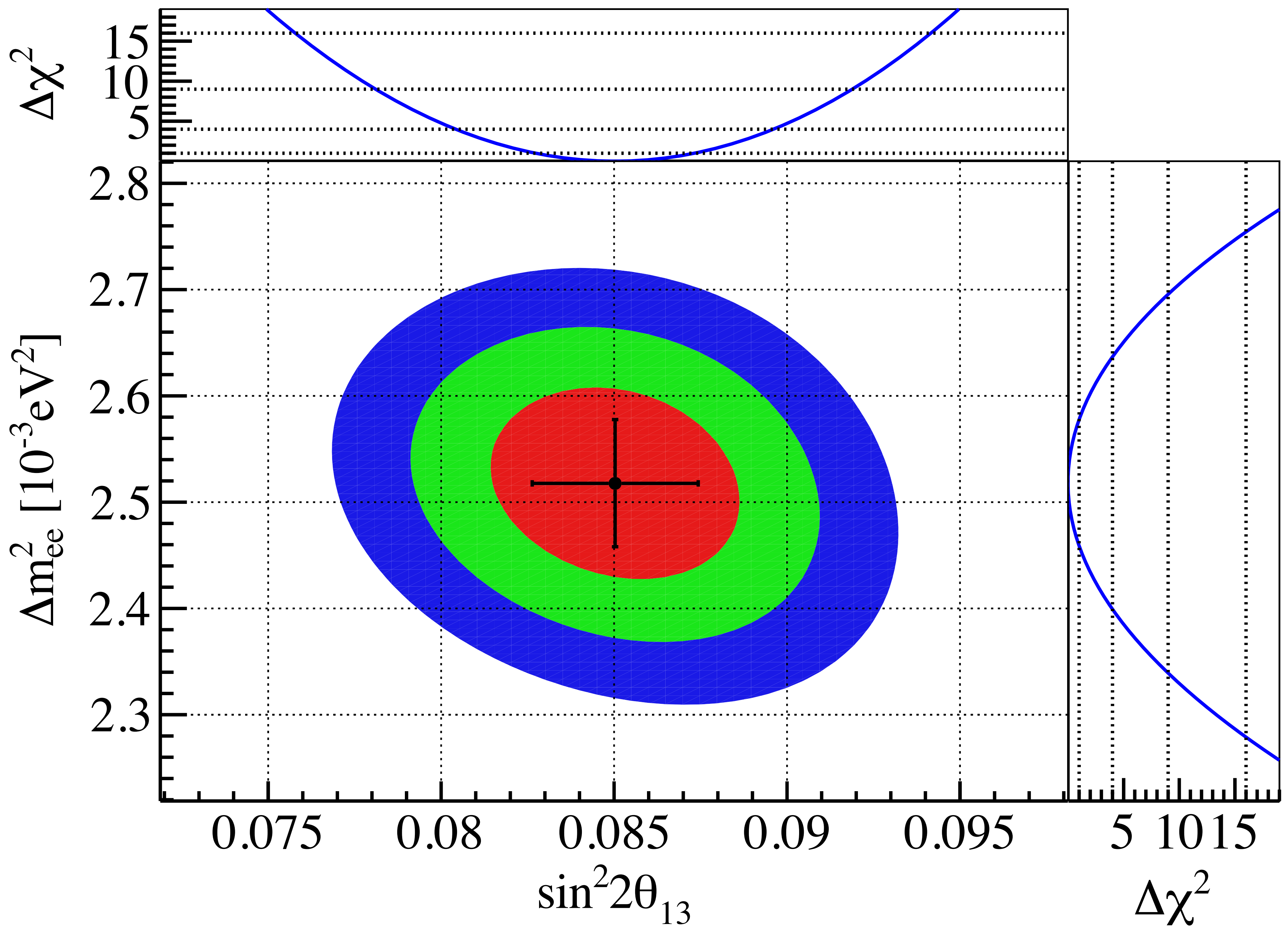
$$J_l = (3.36 \pm 0.06) \sin\delta_{CP} \times 10^{-2}$$



Area $= \frac{1}{2}\,|J|$

And the **Daya Bay and RENO collaborations** for the observation of short-baseline reactor electron-antineutrino disappearance, providing the first determination of the neutrino mixing angle Θ_{13}, which paves the way for the detection of CP violation in the lepton sector.

2211.14988



$$|U_{e3}|^2 = \sin^2\theta_{13} = 0.0215\ (\pm 2.8\%)$$

$$|\Delta m^2_{ee}| = 2.52\ (\pm 2.4\%) \times 10^{-3}\ \text{eV}^2$$

note: $$\frac{\Delta m^2_{21}}{|\Delta m^2_{ee}|} = 3.0\%$$

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

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

Nunokawa, SP, Zukanovich hep/0503283

NO and IO orderings have same $|\Delta m^2_{ee}|$ within 2.4%

Outline of the MO Race

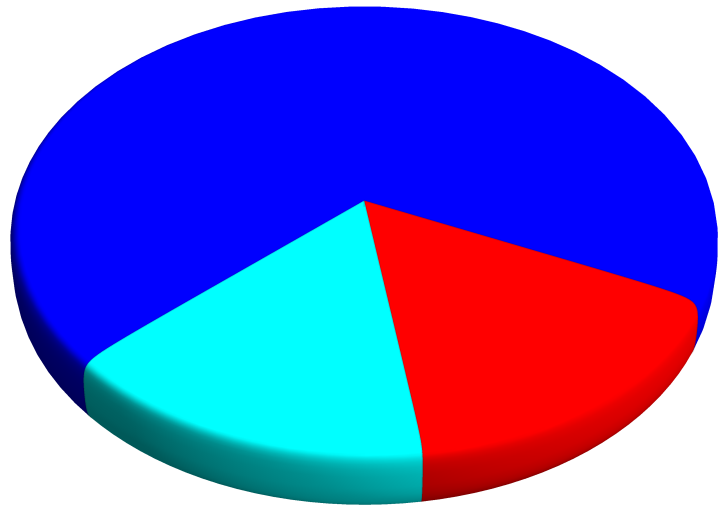
- The Neutrino Mass Ordering Question:
- Current Status: T2K, NOvA, Daya Bay, SK
- Mid-Decade: JUNO phase I
- Early Next Decade: JUNO phase II, DUNE

Neutrino Mass EigenStates or Propagation States:

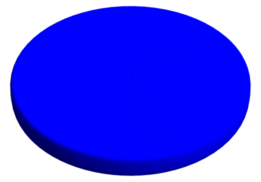
$$\text{Propagator } \nu_j \to \nu_k \;= \delta_{jk}\, e^{-i\left(\frac{m_j^2 L}{2E_\nu}\right)}$$

ν_1

most ν_e **68%**



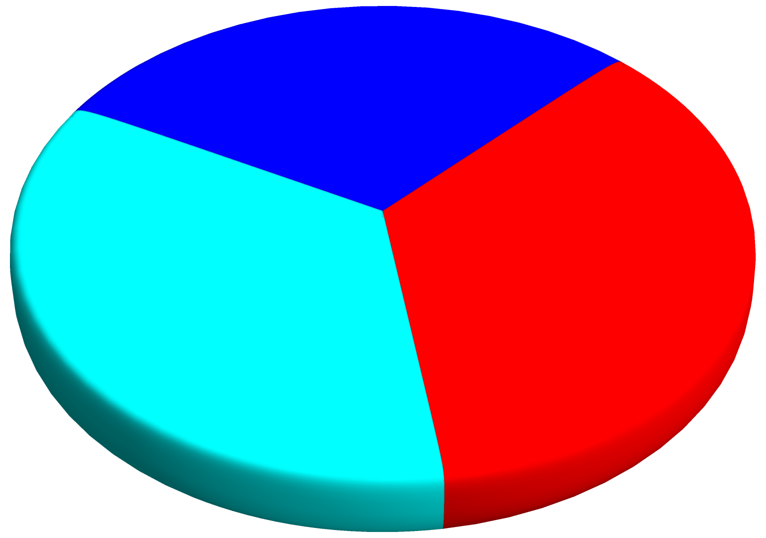
$\cos\delta, \theta_{23}$

$\nu_e =$ 

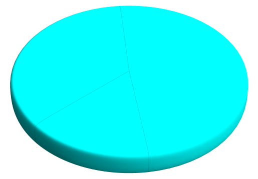
Solar Exp, SNO
KamiLAND
Daya Bay, RENO, …

ν_2

30 % ν_e



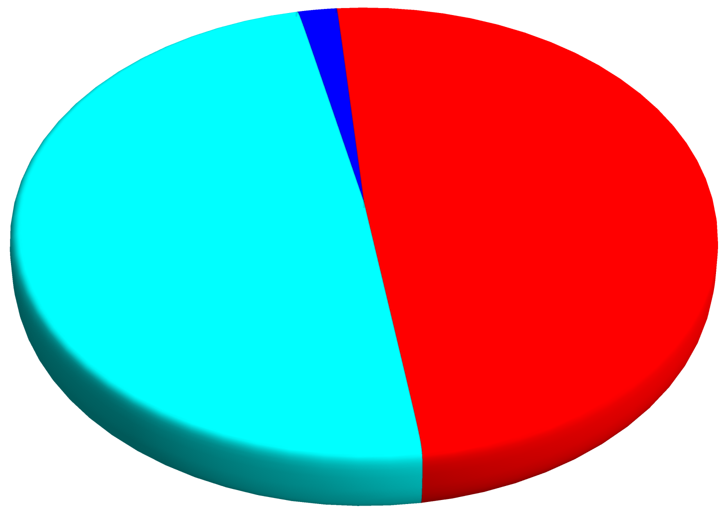
$\cos\delta, \theta_{23}$

$\nu_\mu =$ 

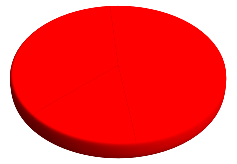
SuperK, K2K, T2K
MINOS, NOvA
ICECUBE

ν_3

least ν_e **2%**



θ_{23}

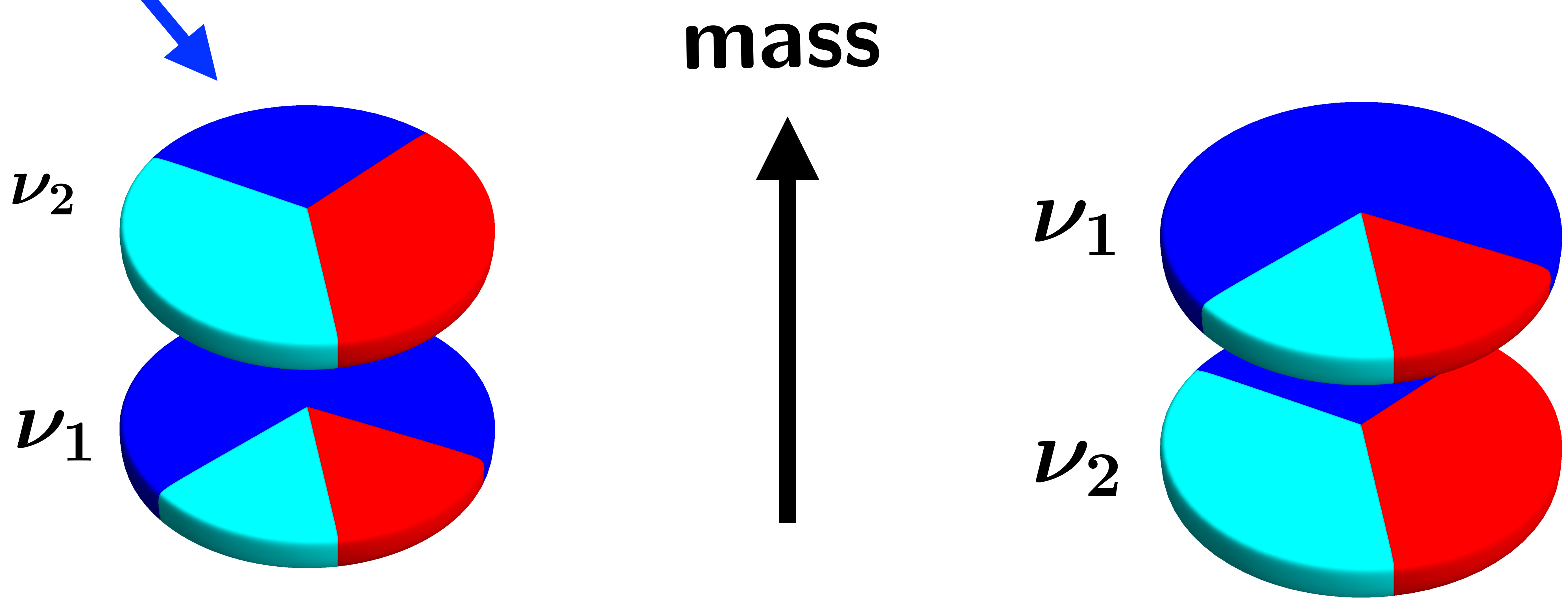
$\nu_\tau =$ 

Unitarity
SK, Opera
ICECUBE ?

$$|U_{e2}|^2 \approx 0.3 \approx \frac{CC}{NC}$$

$\nu_1, \;\nu_2$ Mass Ordering:

–solar mass ordering



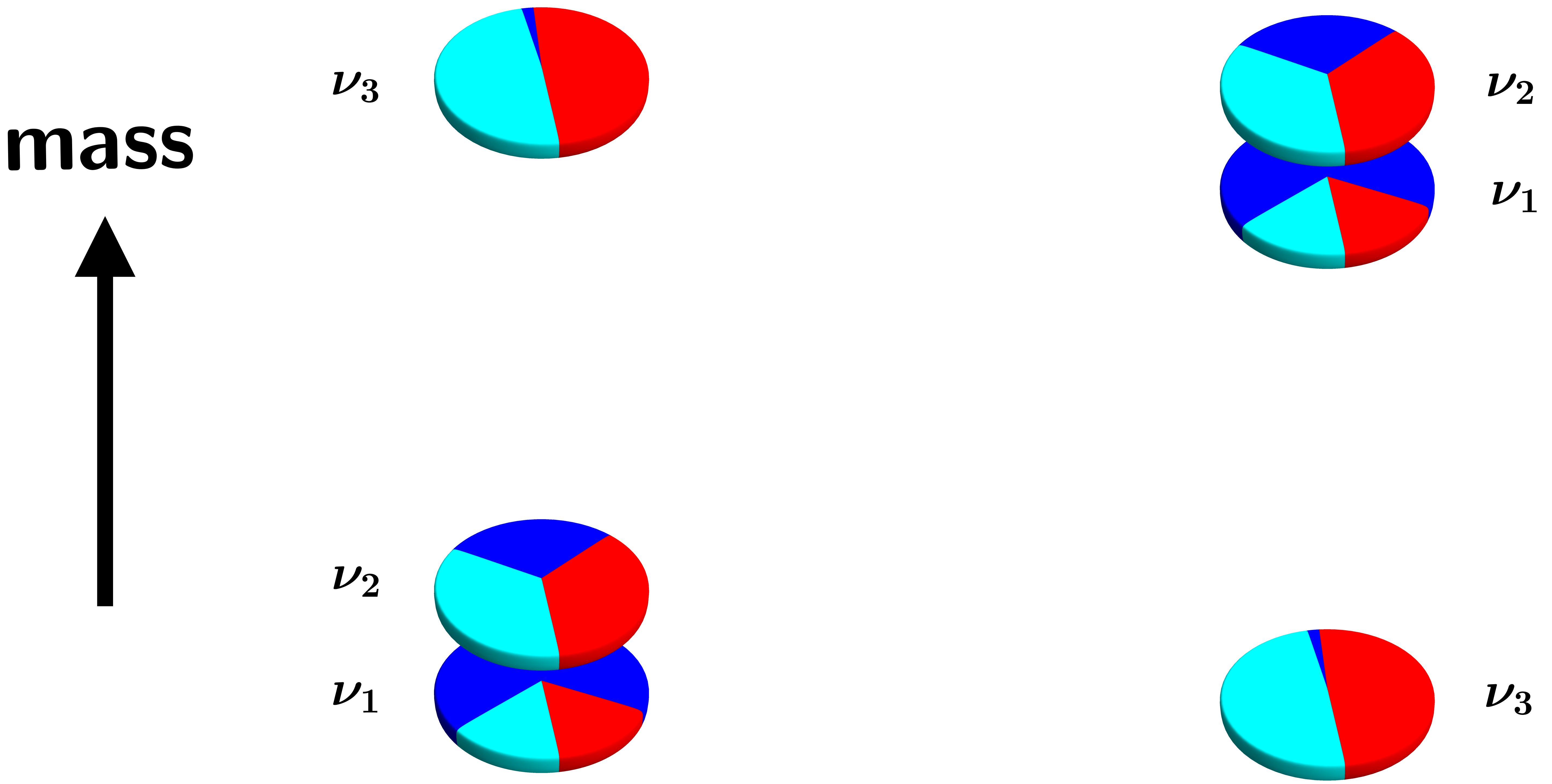
$|\Delta m^2_{21}| = |m^2_2 - m^2_1| = 7.5 \times 10^{-5}\ \mathrm{eV}^2$ $\quad$ $L/E = 15\ \mathrm{km/MeV} = 15,000\ \mathrm{km/GeV}$

SNO $\;m_2 > m_1$

$\nu_e =$ $\quad$ $\nu_\mu =$ $\quad$ $\nu_\tau =$

$\nu_3, \;\; \nu_1/\nu_2$ Mass Ordering:

–atmospheric mass ordering



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

unknown: SK, T2K, NOvA, JUNO, ICECUBE, DUNE, KNO, …

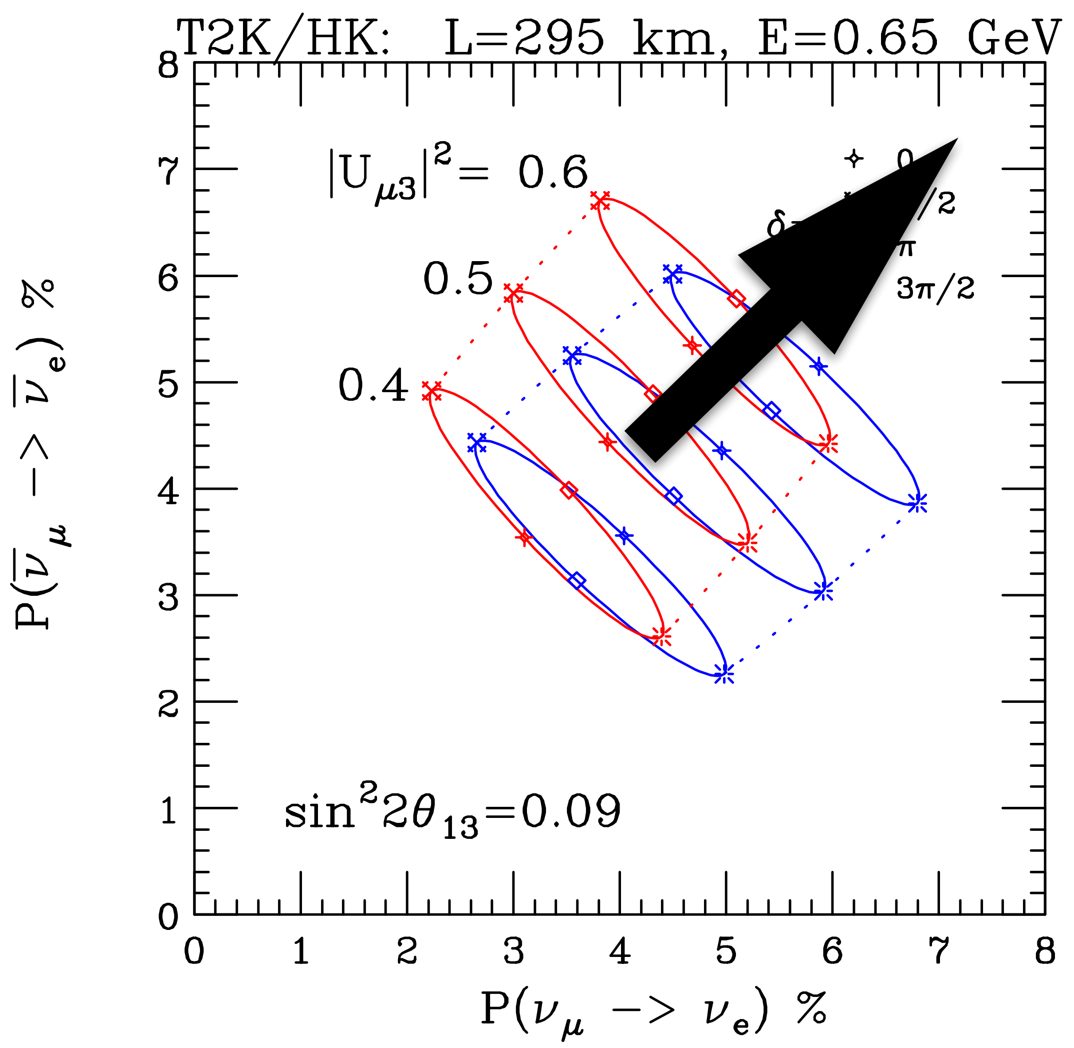
$\nu_e =$ $\qquad \nu_\mu =$ $\qquad \nu_\tau =$

Outline of the MO Race

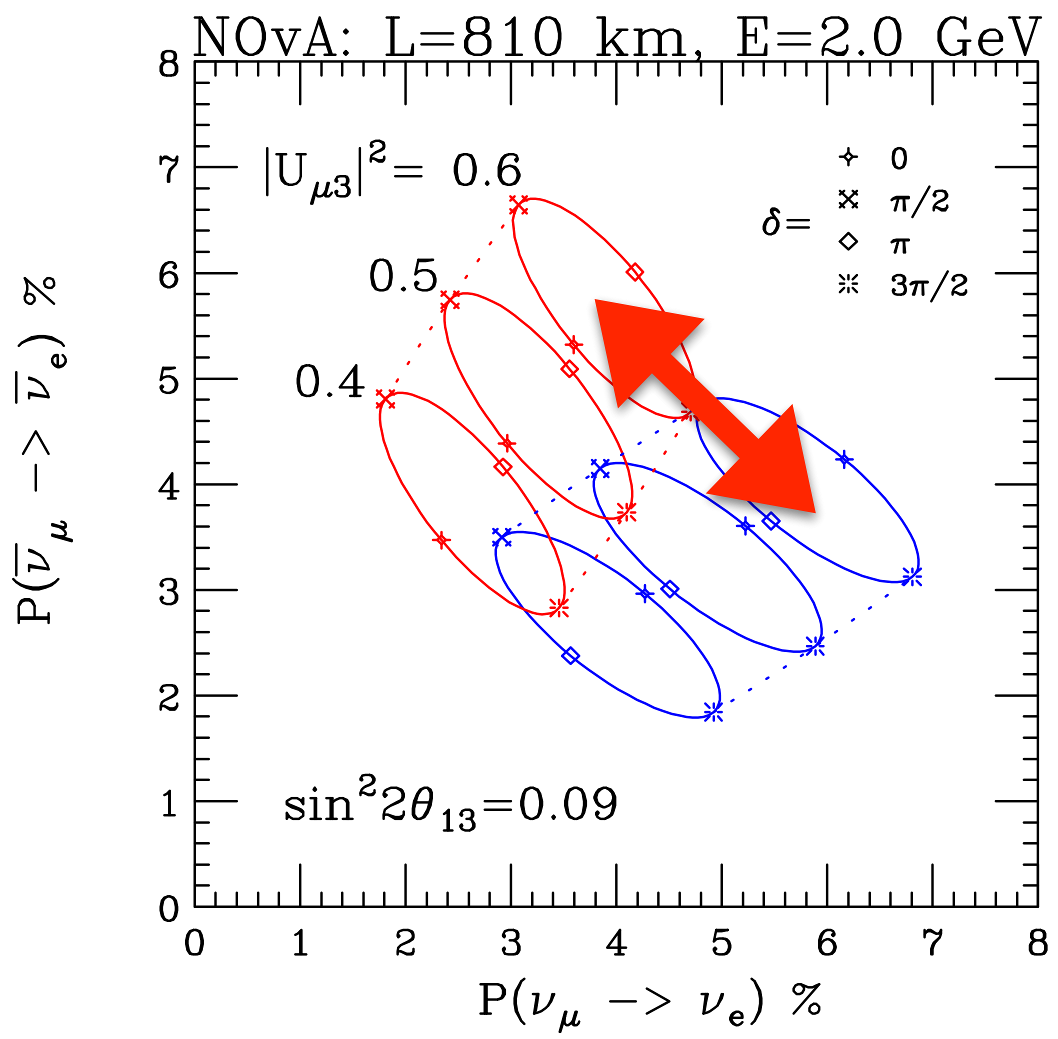
- Current Status: T2K, NOvA, Daya Bay, SK
  - Appearance
  - Disappearance
  - Combined

Correlations btw $\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$

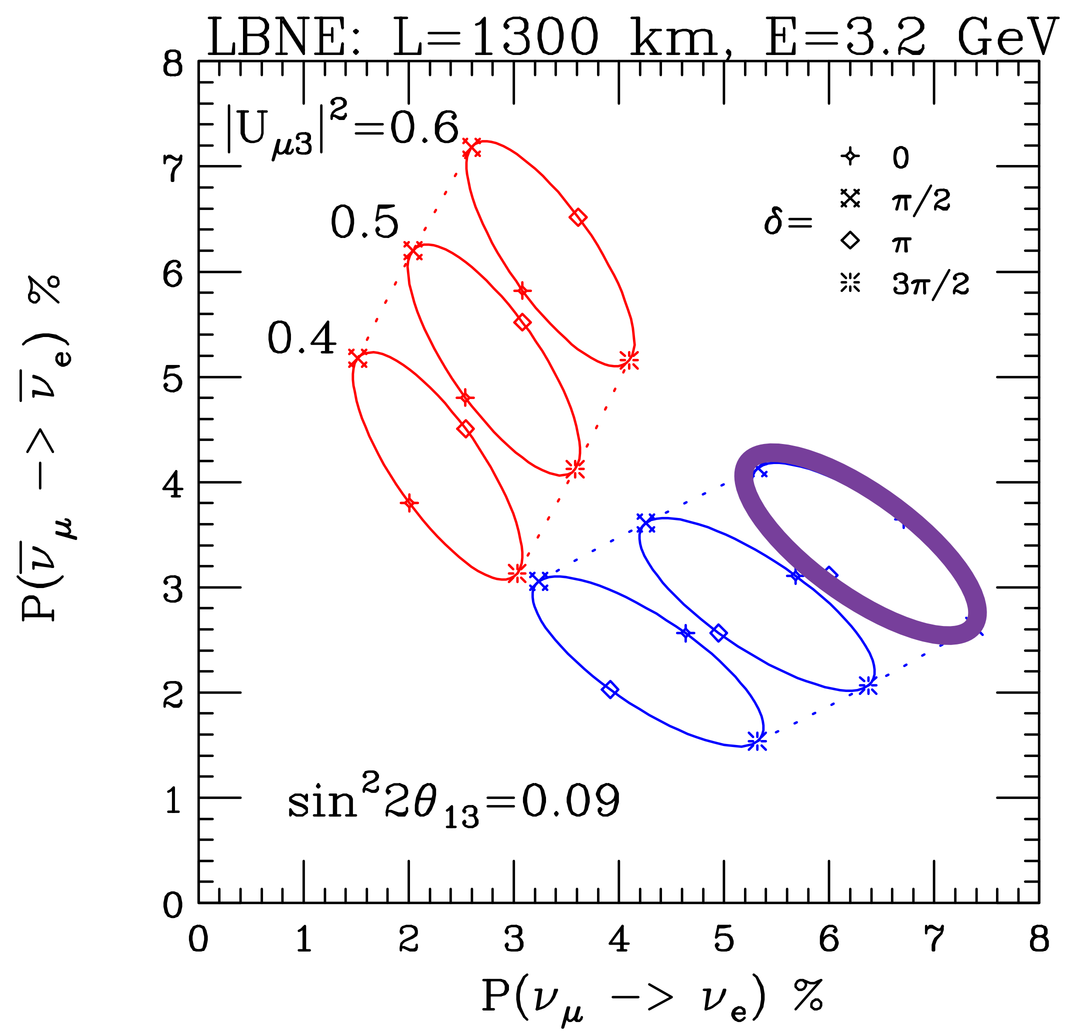
T2K/HK

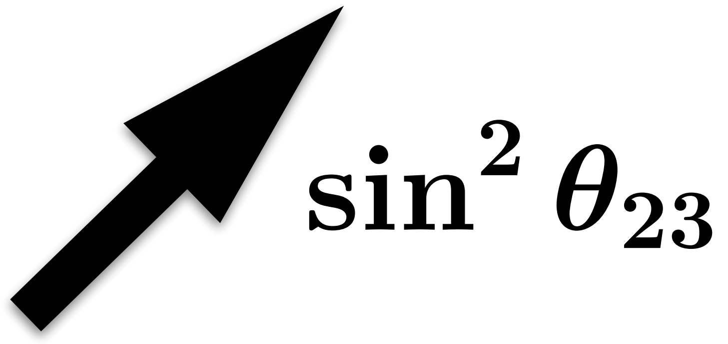


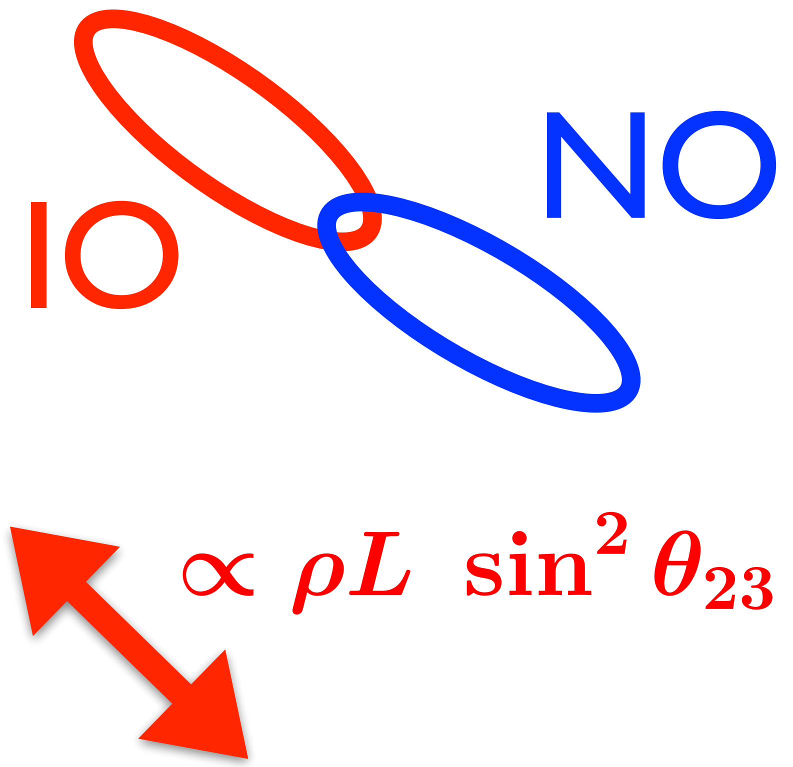
NOvA

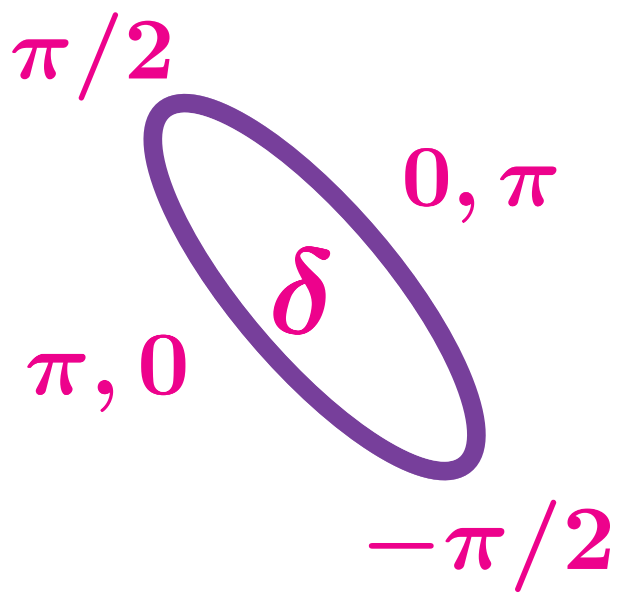


DUNE Same L/E as NOνA





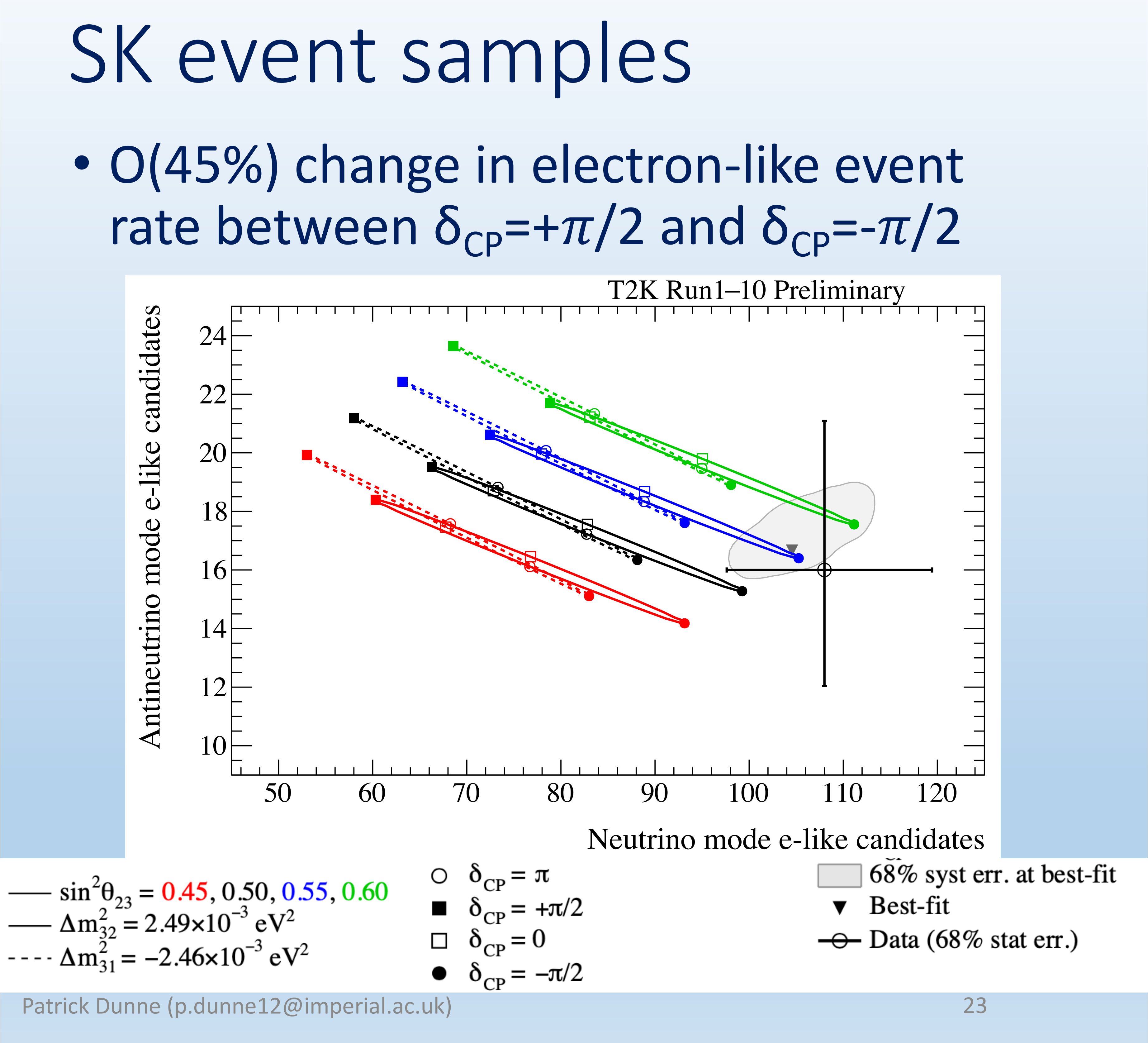


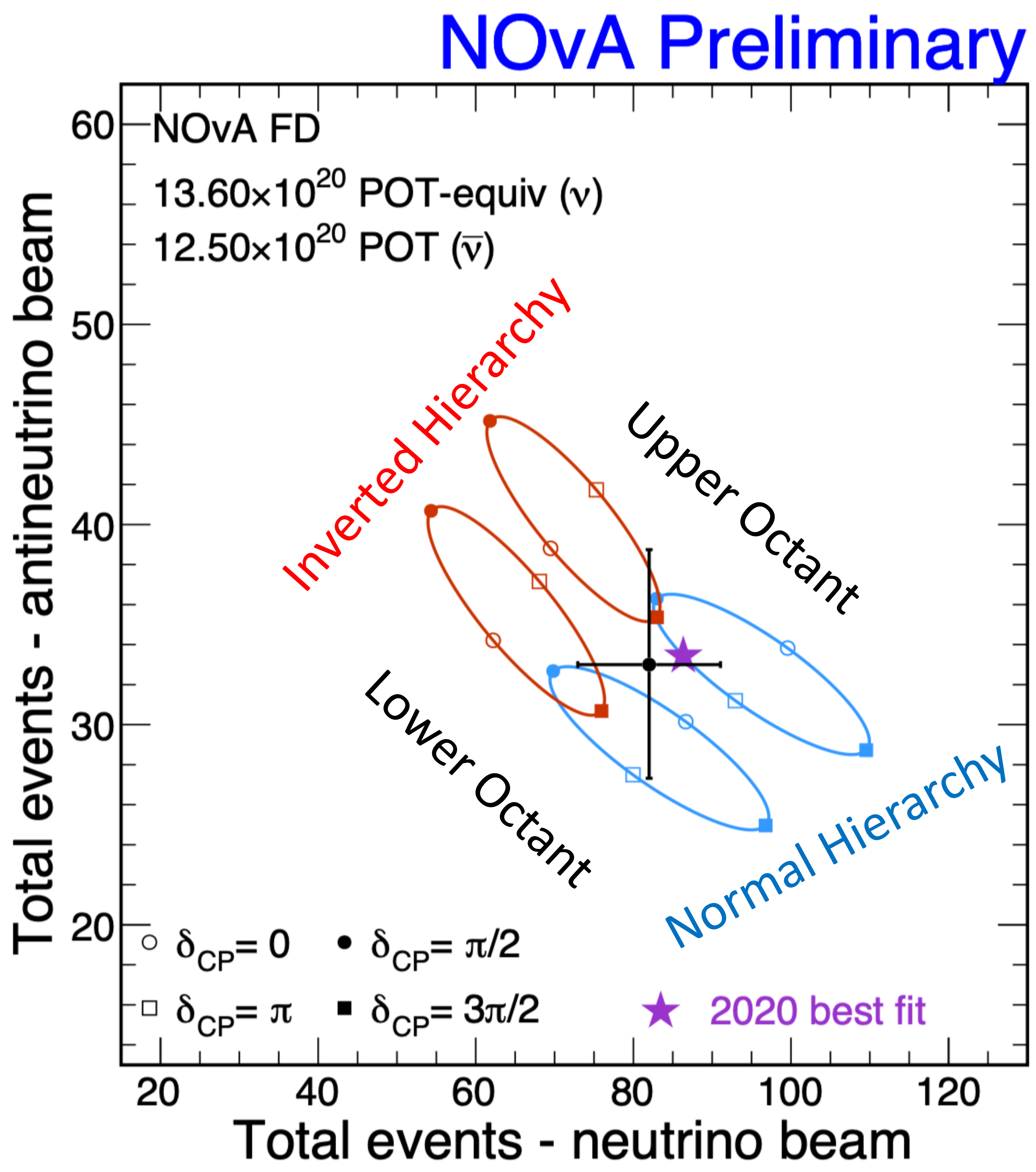


arXiv:hep-ph/020417

T2K & NOvA

Number of Events proportional to Oscillation Probability



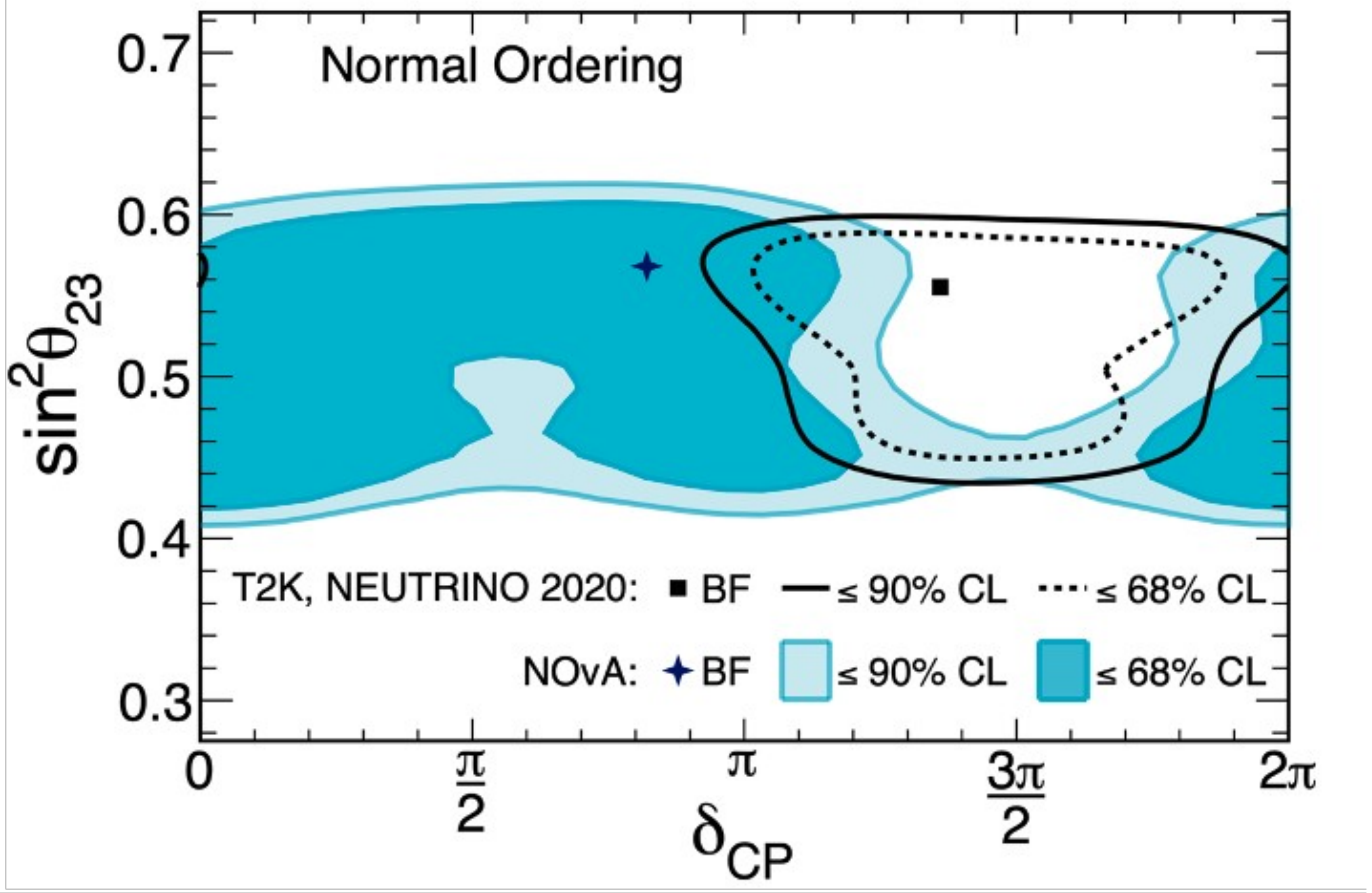


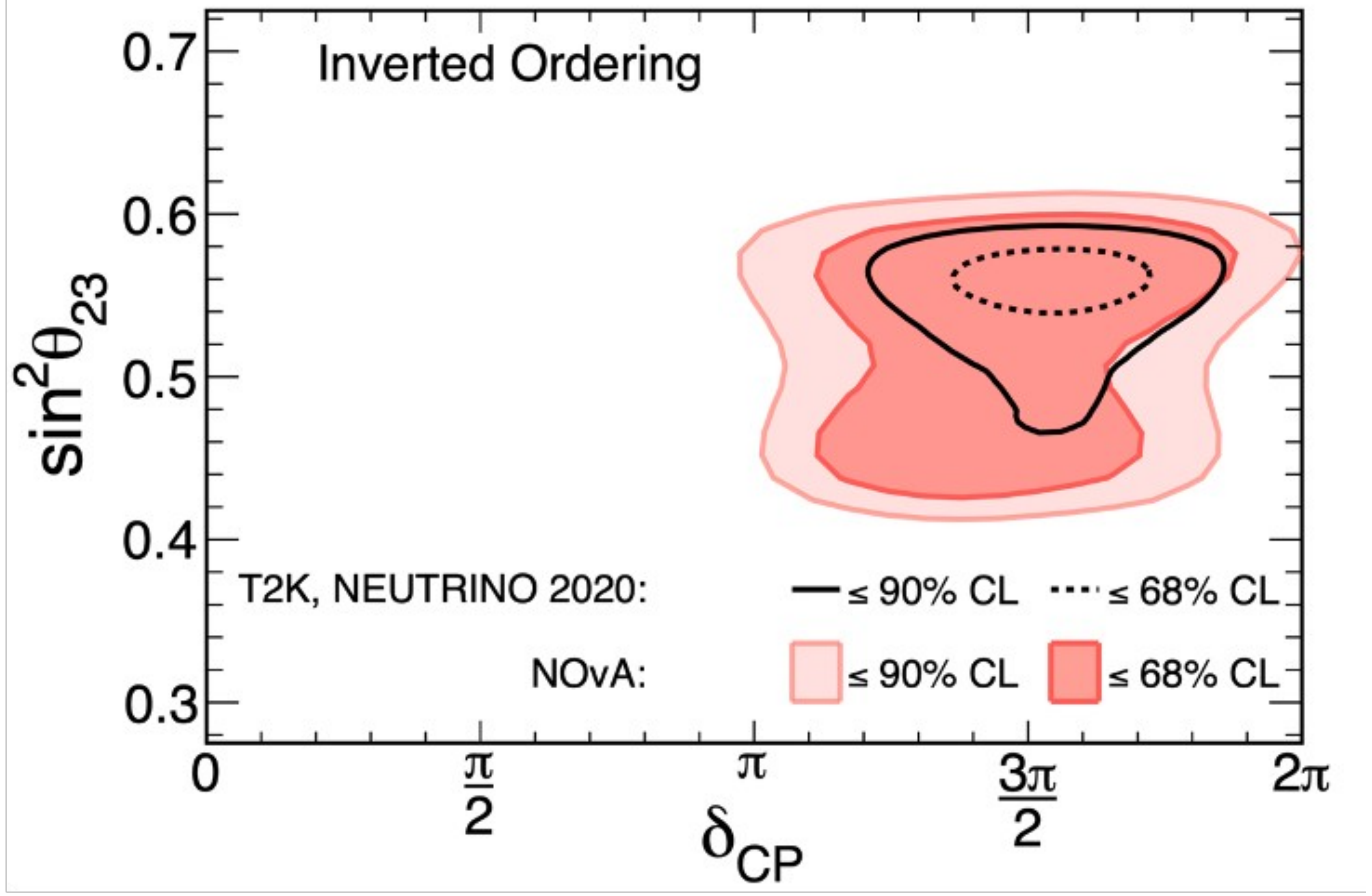
T2K NO prefer by ~2 units of χ^2

NOvA NO prefer by ~1 unit of χ^2

COMBINED

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

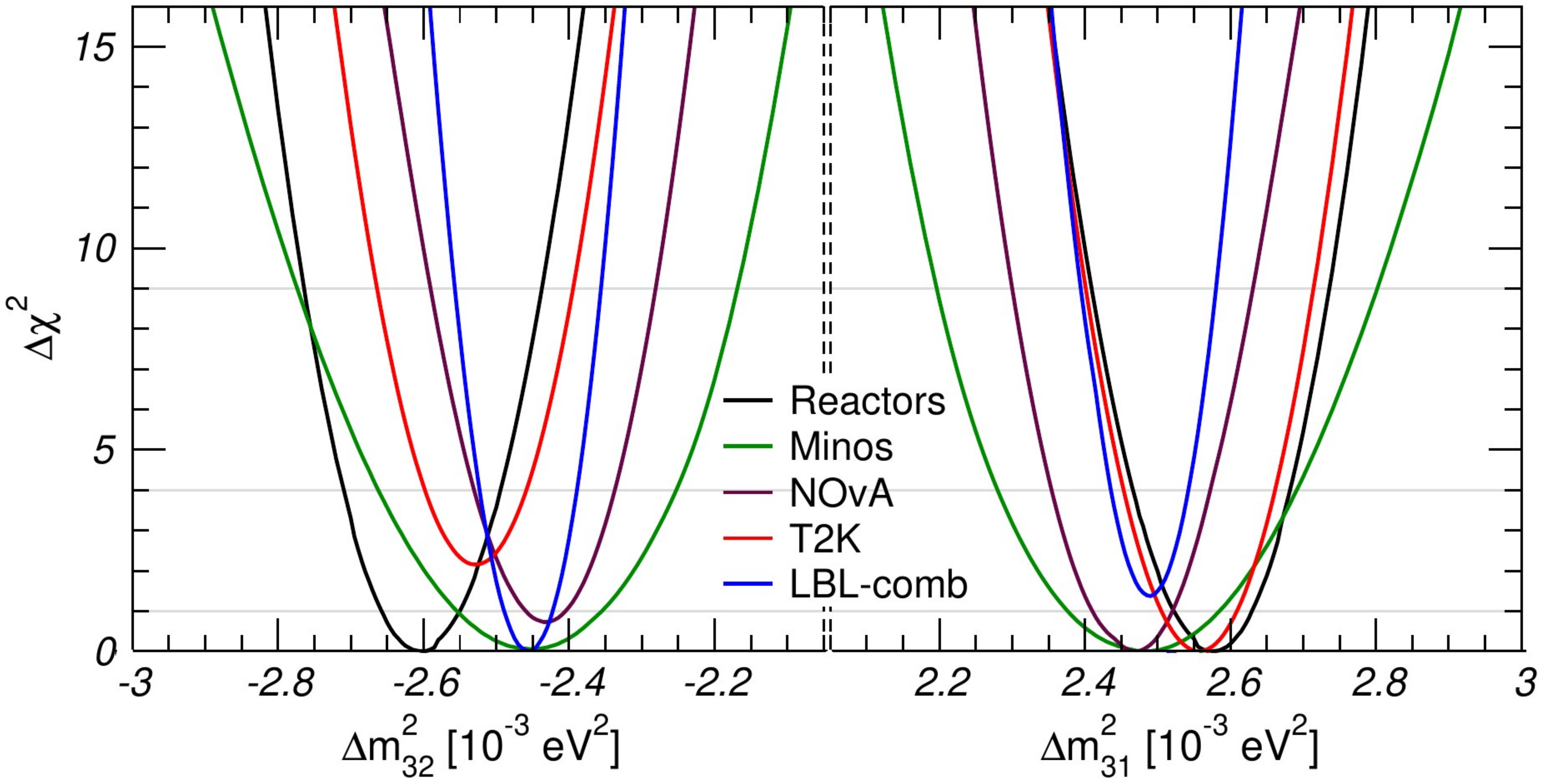




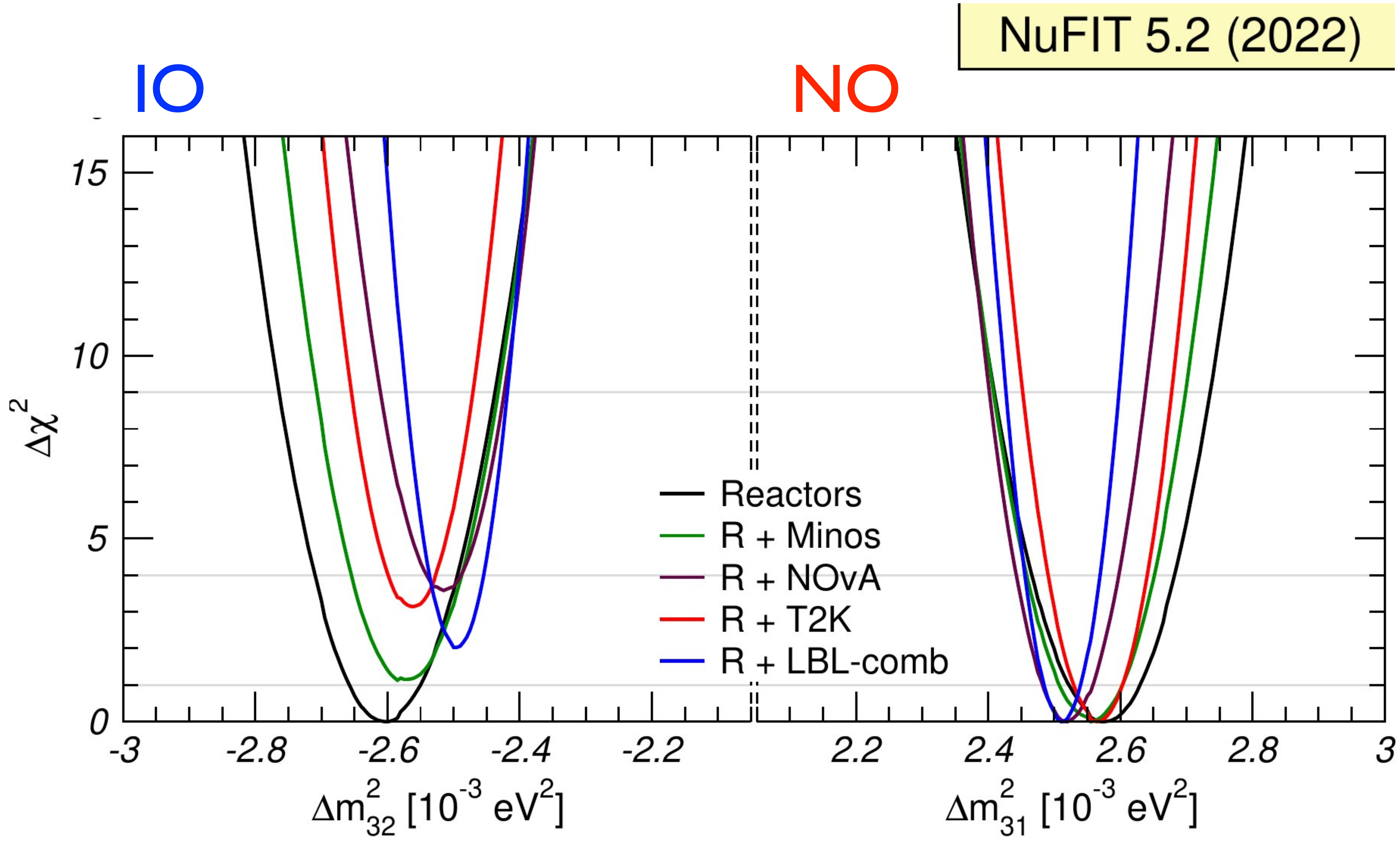
IO prefer by ~1.6 unit of $\Delta\chi^2$

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

IO NO NuFIT 5.2 (2022)



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



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

Another possible way to determine the Neutrino Mass Hierarchy

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

Also PRD

NPZ'05

arXiv:hep-ph/0503283v1 29 Mar 2005

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

NPZ'05 in a Nutshell

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

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

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

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

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

note "2"

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

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

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 Δm^2_{ee} Saga

For an effective Δm^2,   L/E independence is a necessary requirement !

$$\textbf{What is } \Delta m^2_{ee} \textbf{ ?}$$

SP   arXiv:1601.07464

ν_μ disappearance at an L/E ~ 500 km/GeV

$$\Delta m^2_{\mu\mu} \equiv \frac{|U_{\mu 1}|^2 \Delta m^2_{31} + |U_{\mu 2}|^2 \Delta m^2_{32}}{|U_{\mu 1}|^2 + |U_{\mu 2}|^2}$$

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

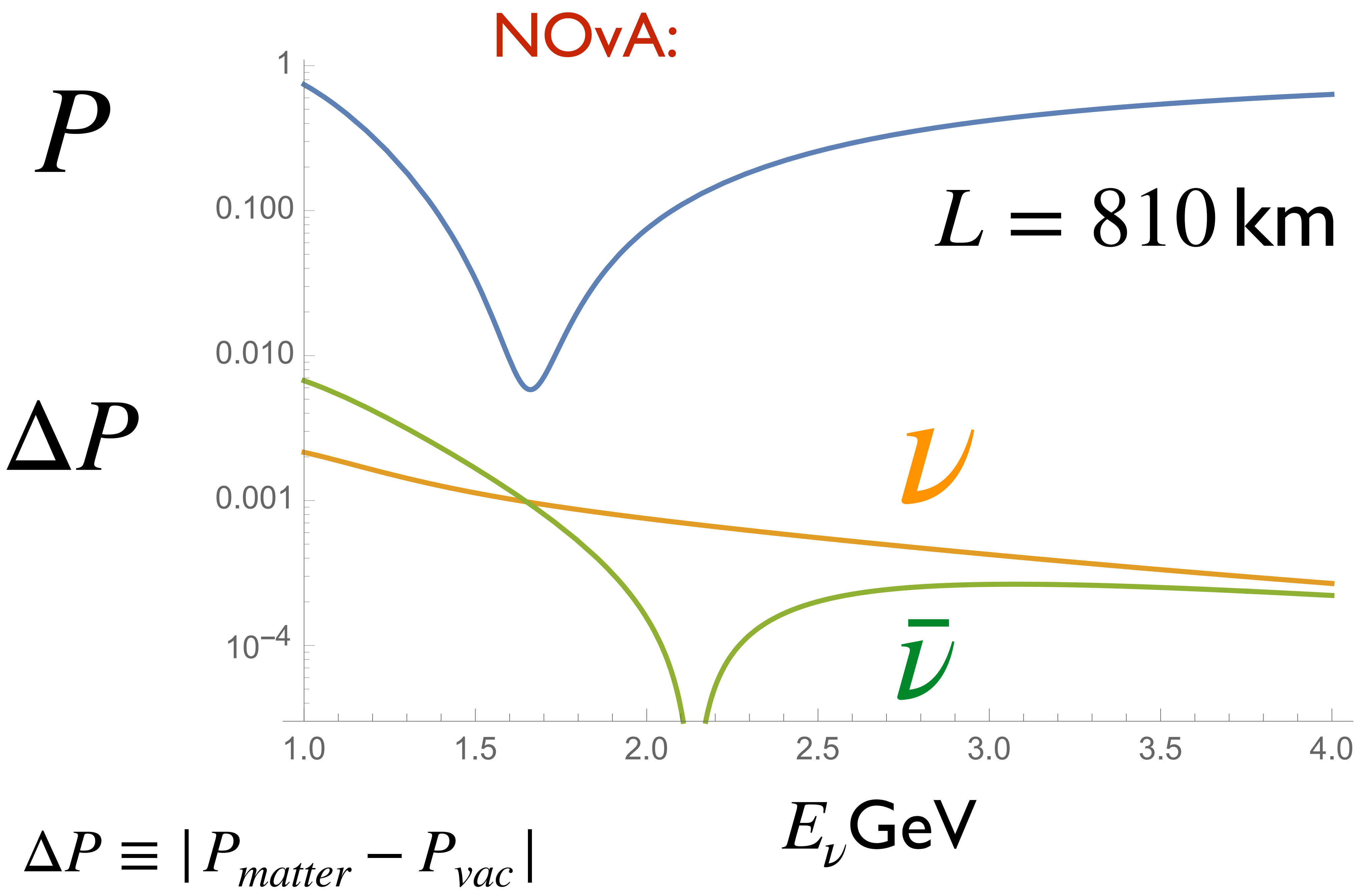
$$\approx \Delta m^2_{ee} - (\cos 2\theta_{12} - \sin\theta_{13}\cos\delta)\Delta m^2_{21}$$

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

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

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

Nunokawa, SP, Zukanovich hep/0503283



this is in vacuum, but for ν_μ disappearance matter effects are very small due to cancellations between $\nu_\mu \to \nu_e$ and $\nu_\mu \to \nu_\tau$ for θ_{13} effects:

$$|U_{\mu 3}|^2(1 - |U_{\mu 3}|^2) = s^2_{23}c^2_{23} - s^2_{13}\cos 2\theta_{23} + s^4_{13}s^4_{23}$$

both s^2_{13} and $\cos 2\theta_{23}$ are small.

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:

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

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

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

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

If IO then 0

If NO then 0

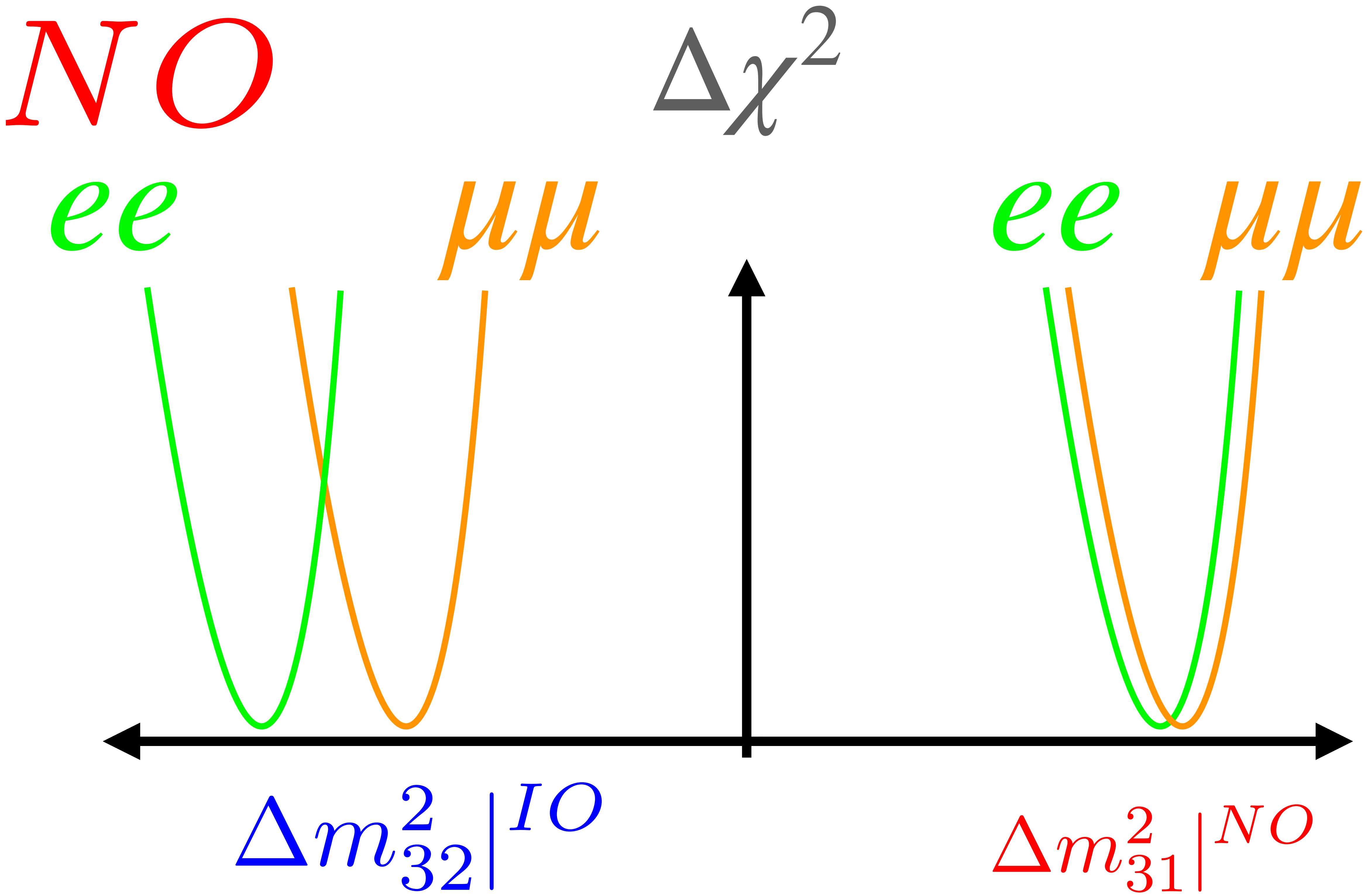
$$(\Delta m^2_{32}|^{IO}_{\mu dis} - \Delta m^2_{32}|^{IO}_{DB}) + (\Delta m^2_{31}|^{NO}_{\mu dis} - \Delta m^2_{31}|^{NO}_{DB}) = (2.4 - 0.9\cos\delta)\% \ \Delta m^2_{ee}$$

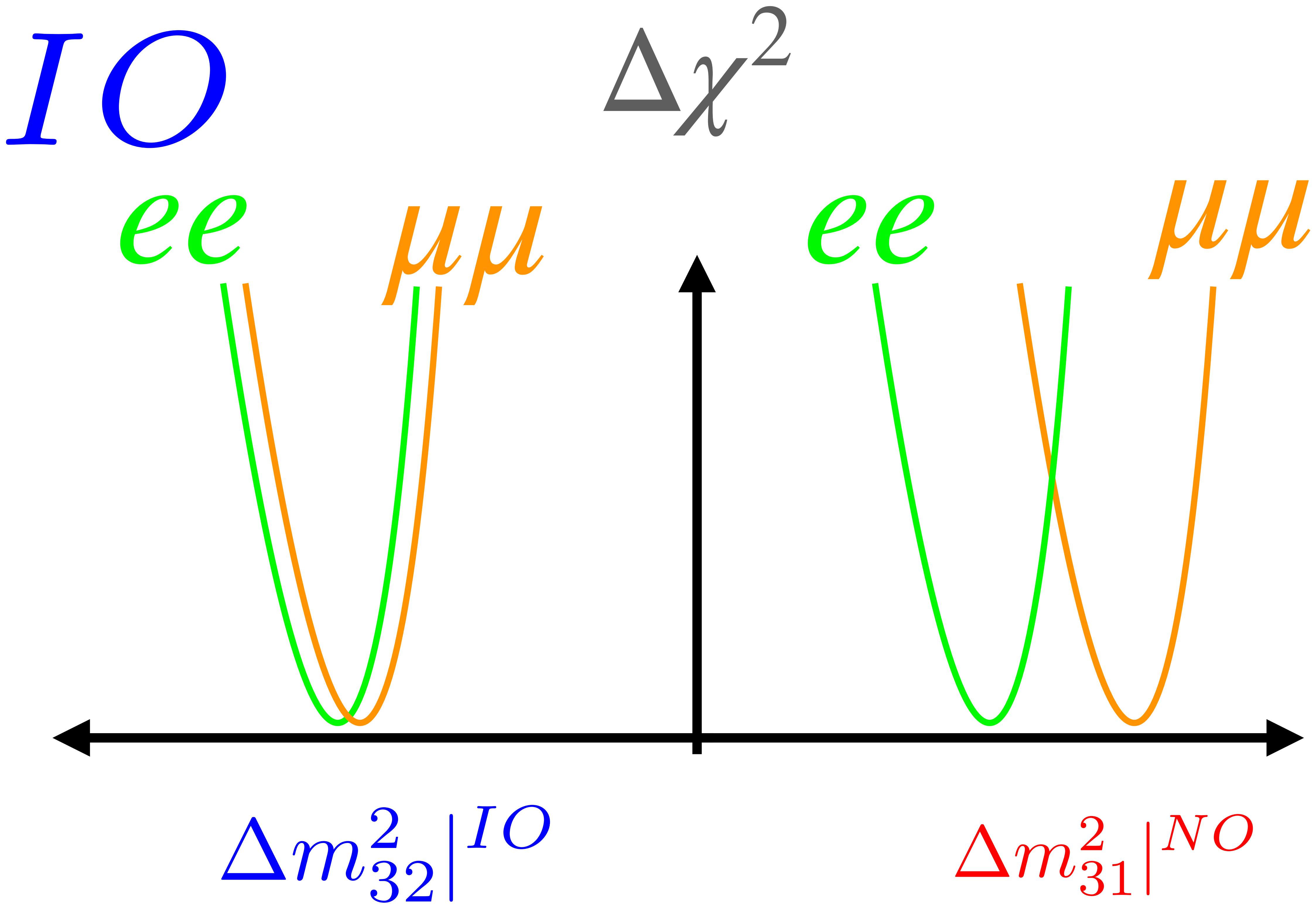
1.5 to 3.3 %

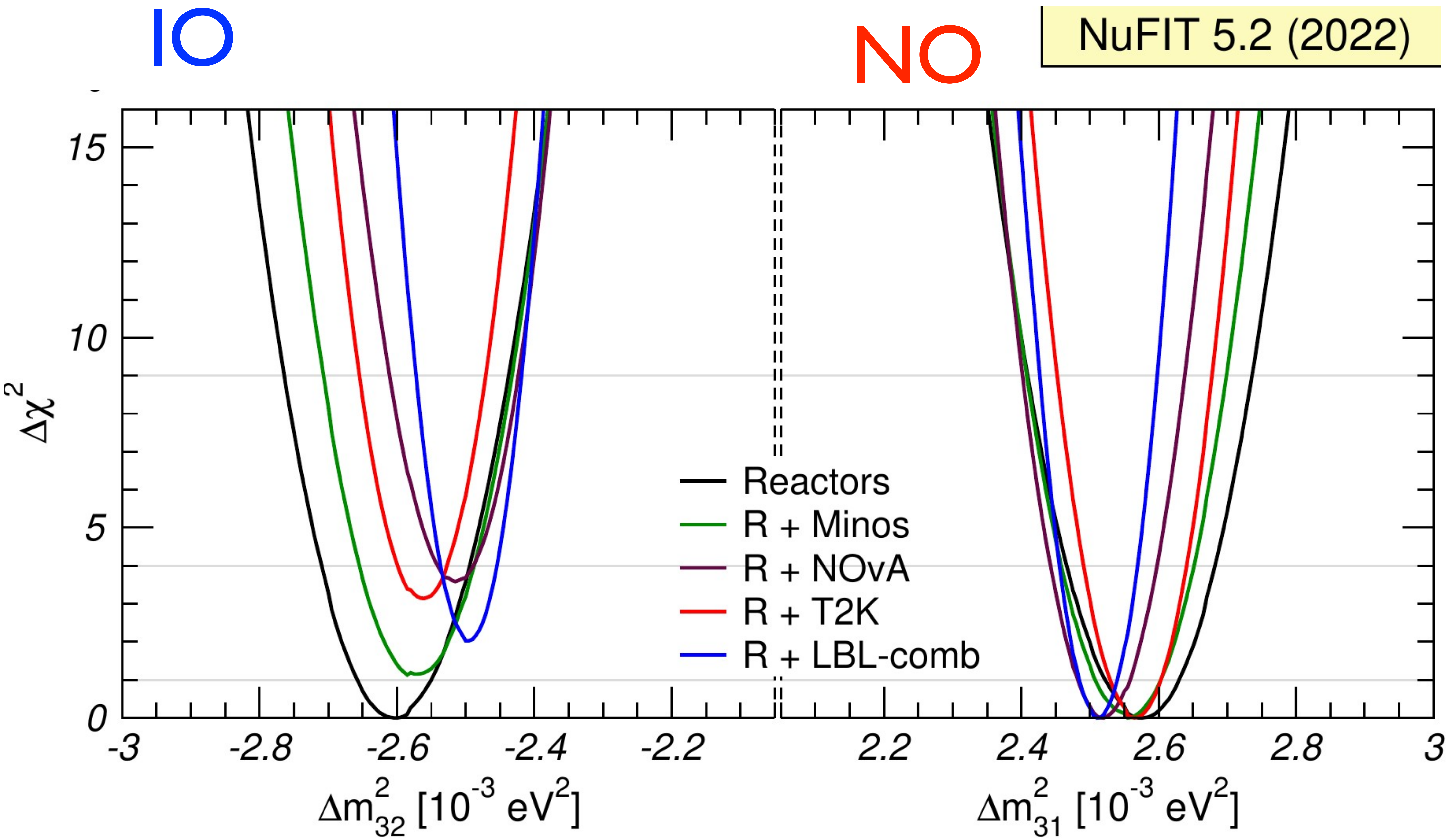
Unchanged if $31 \leftrightarrow 32$ in either or both MO's

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

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

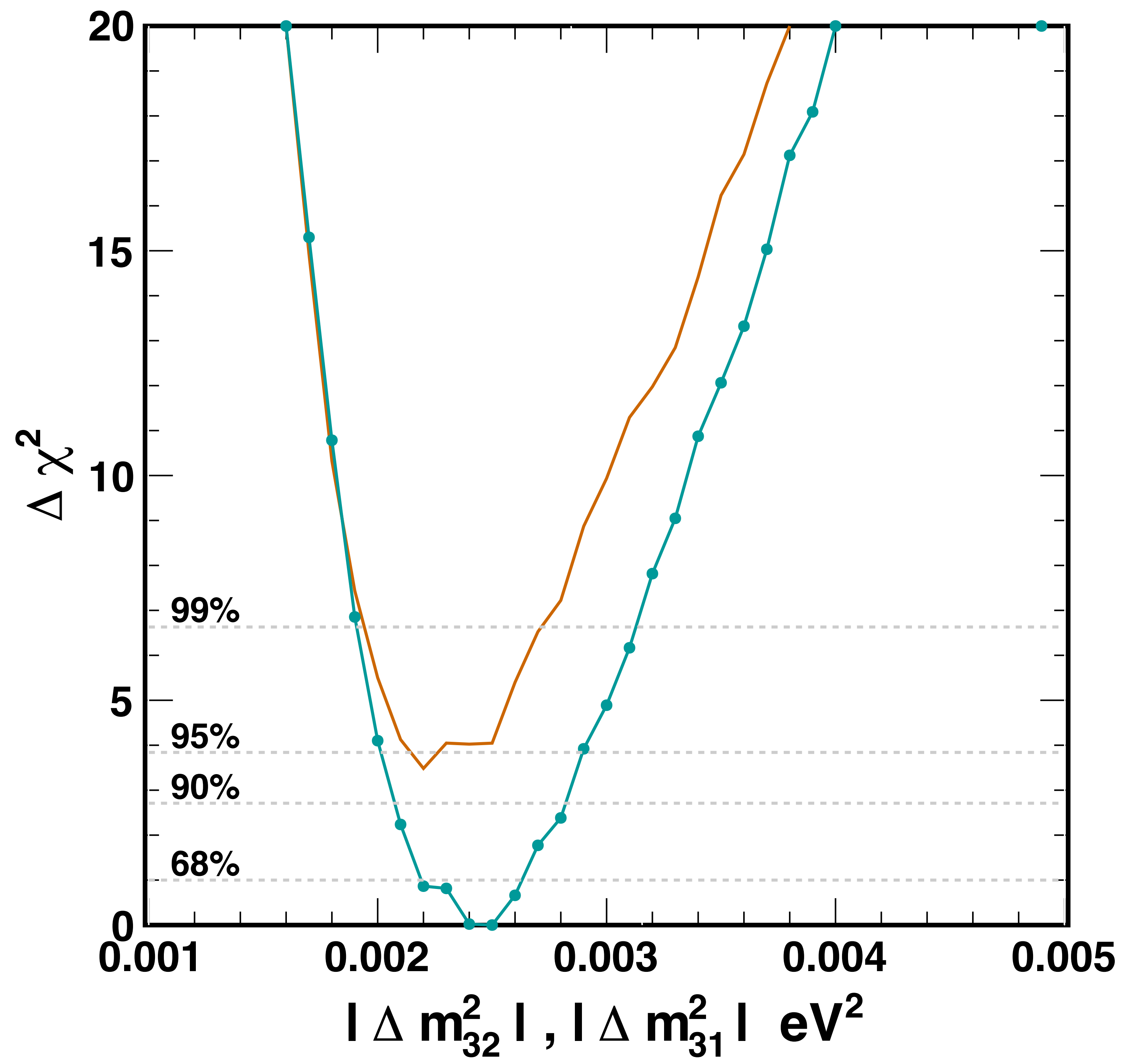


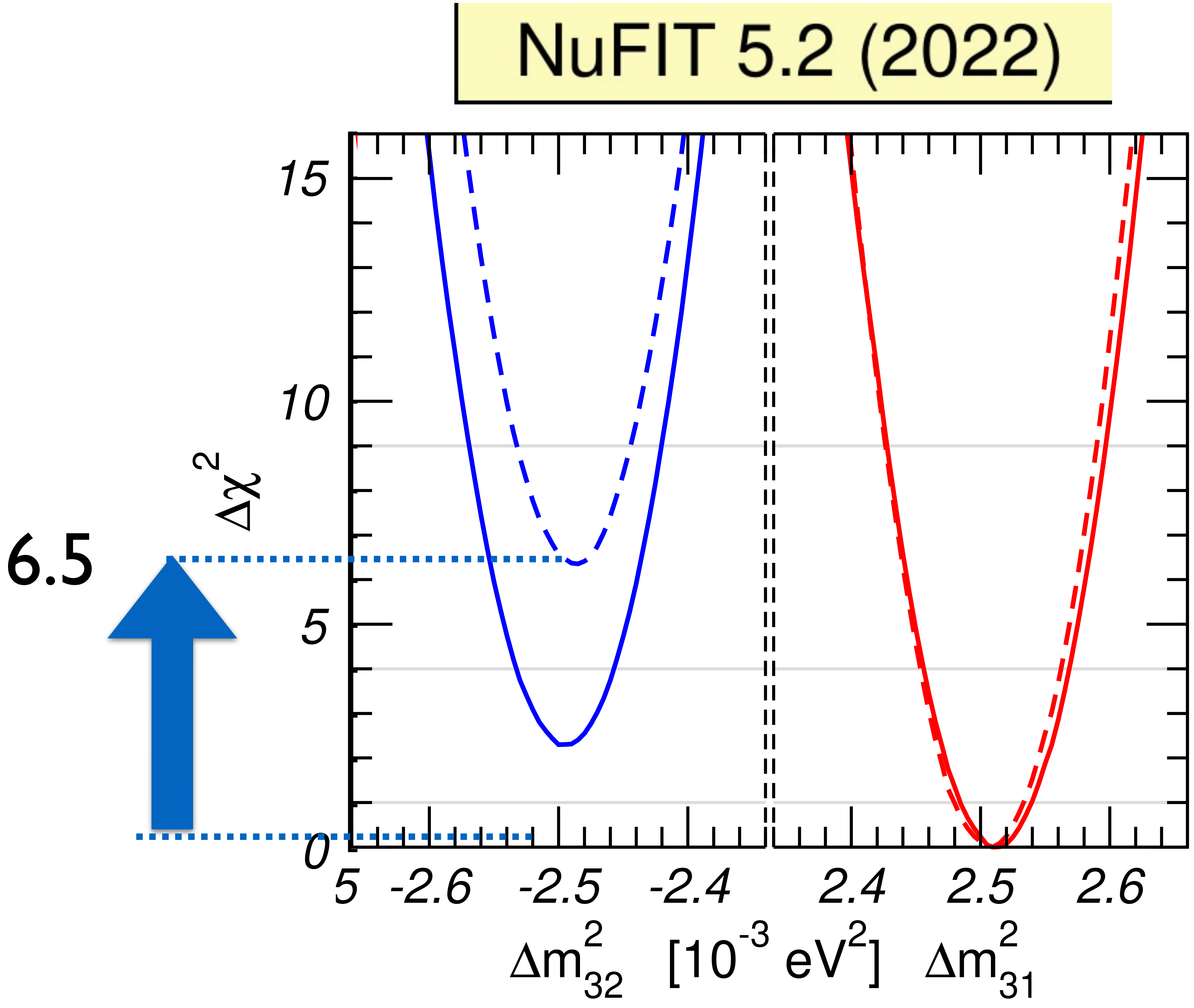




Hinting at NO and $\cos\delta \leq 0$

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)

Outline of the MO Race

- Mid-Decade: JUNO phase I
  - Precision measurement of Δm^2_{ee} and $(\sin^2 \theta_{12}, \Delta m^2_{21})$

(update 2204.13249)

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.

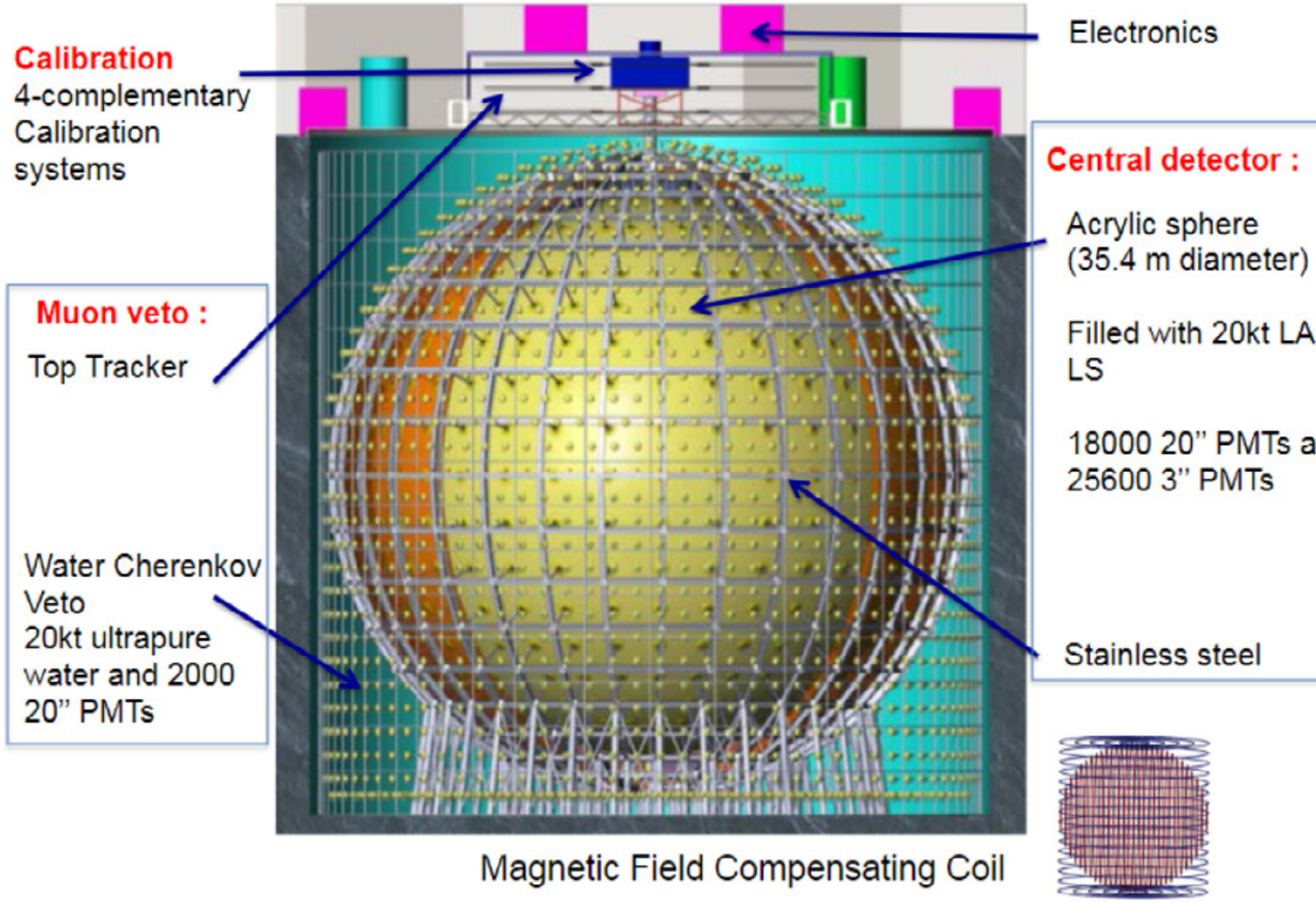
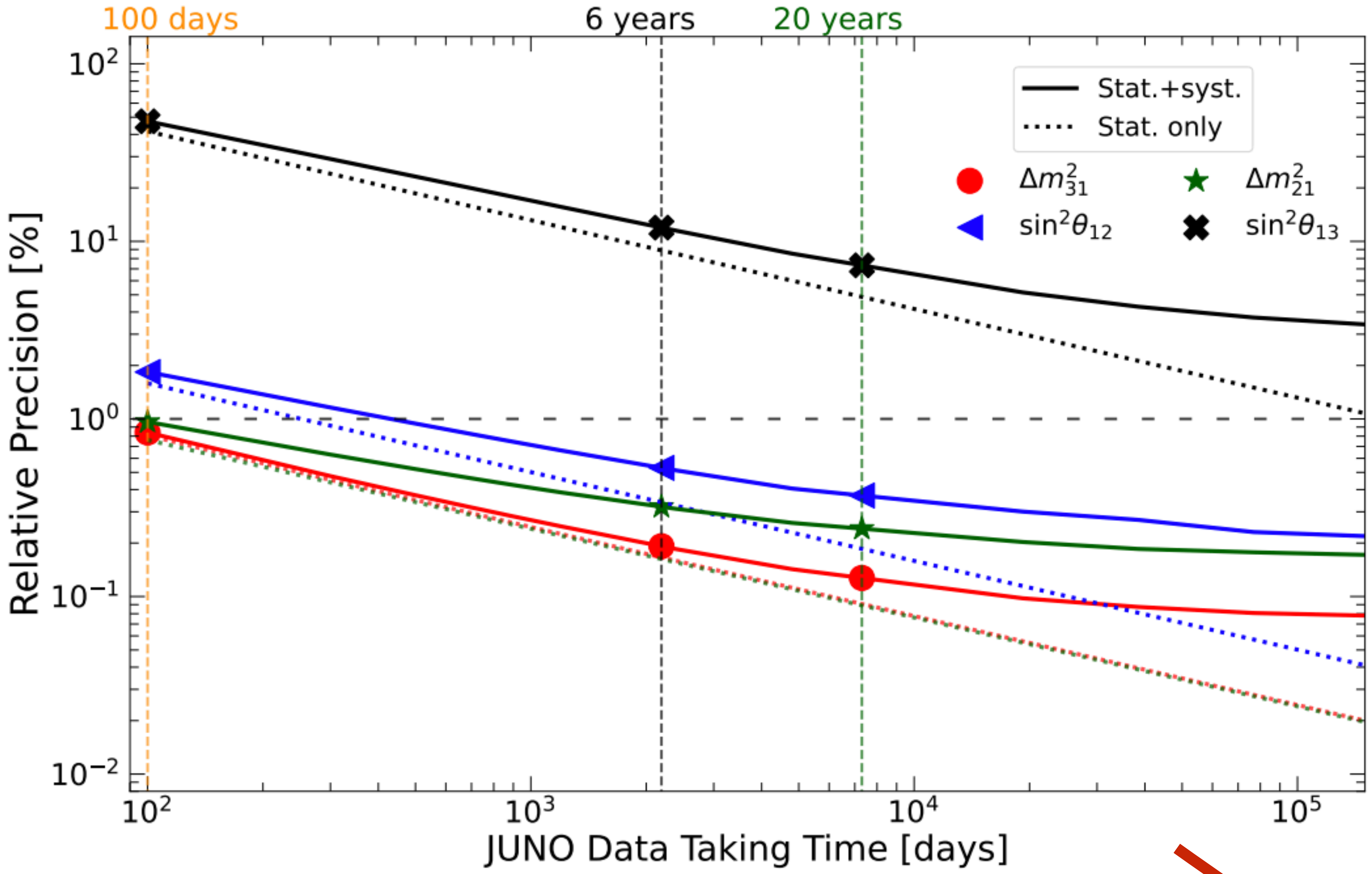


Fig. 4. Schematic view of the JUNO detector.

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

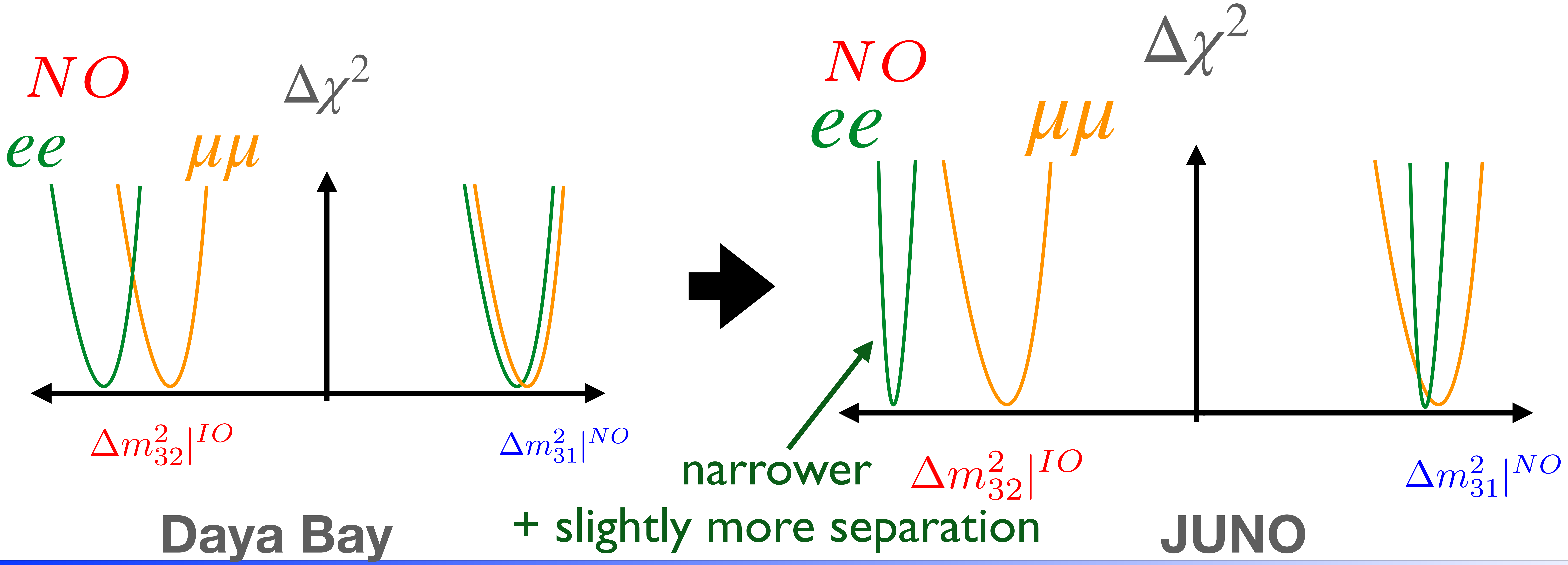
Time	% on Δm^2_{atm}	$\overline{\lvert\chi^2_{NO} - \chi^2_{IO}\rvert}$
100 days	1.0	0.25
4 years	0.3	3.4
8 years	0.2	6.7
12 Years	0.15	10.0

later

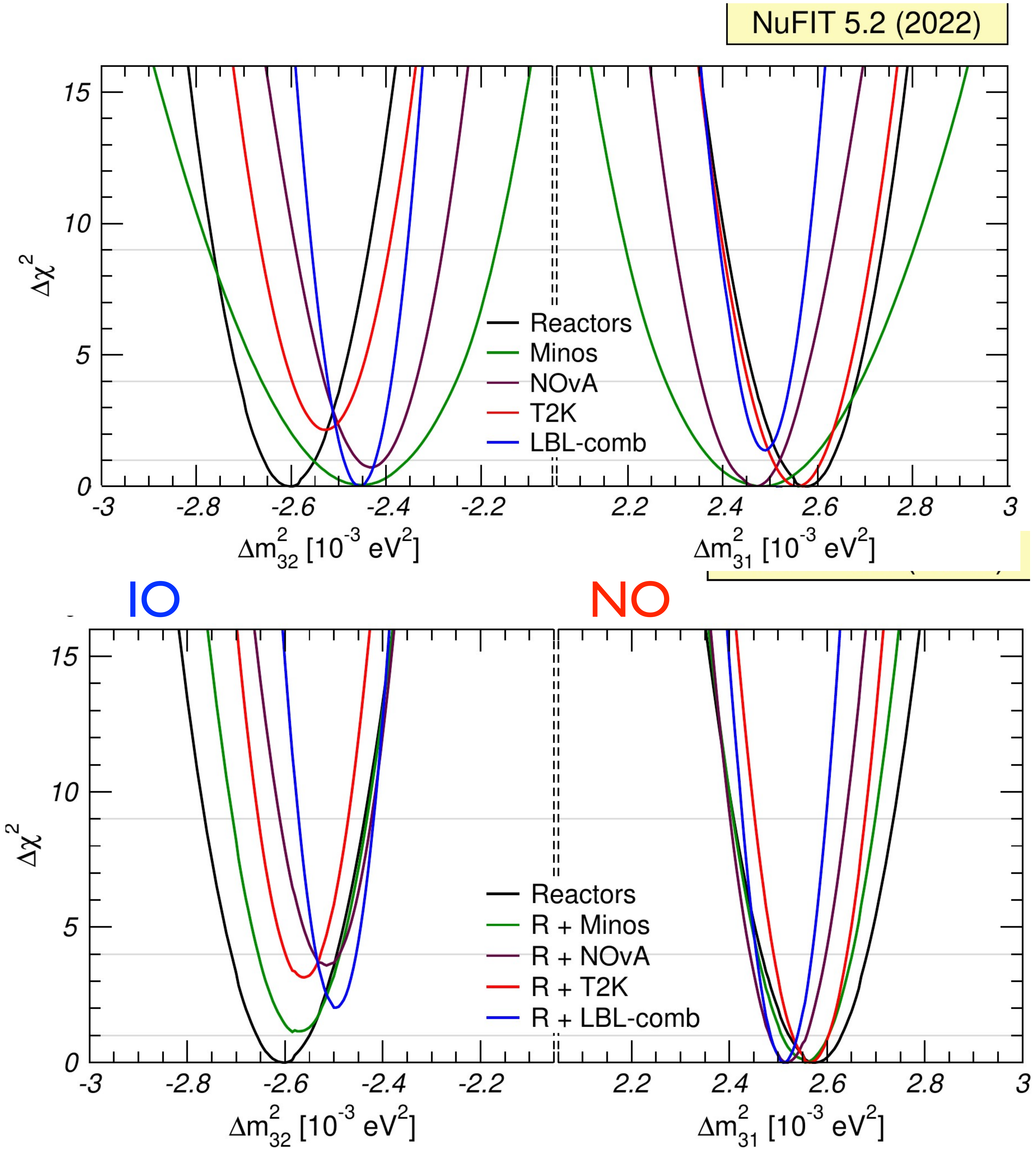
For JUNO: $|\Delta m^2_{ee}|^{IO} = 1.007\ |\Delta m^2_{ee}|^{NO}$

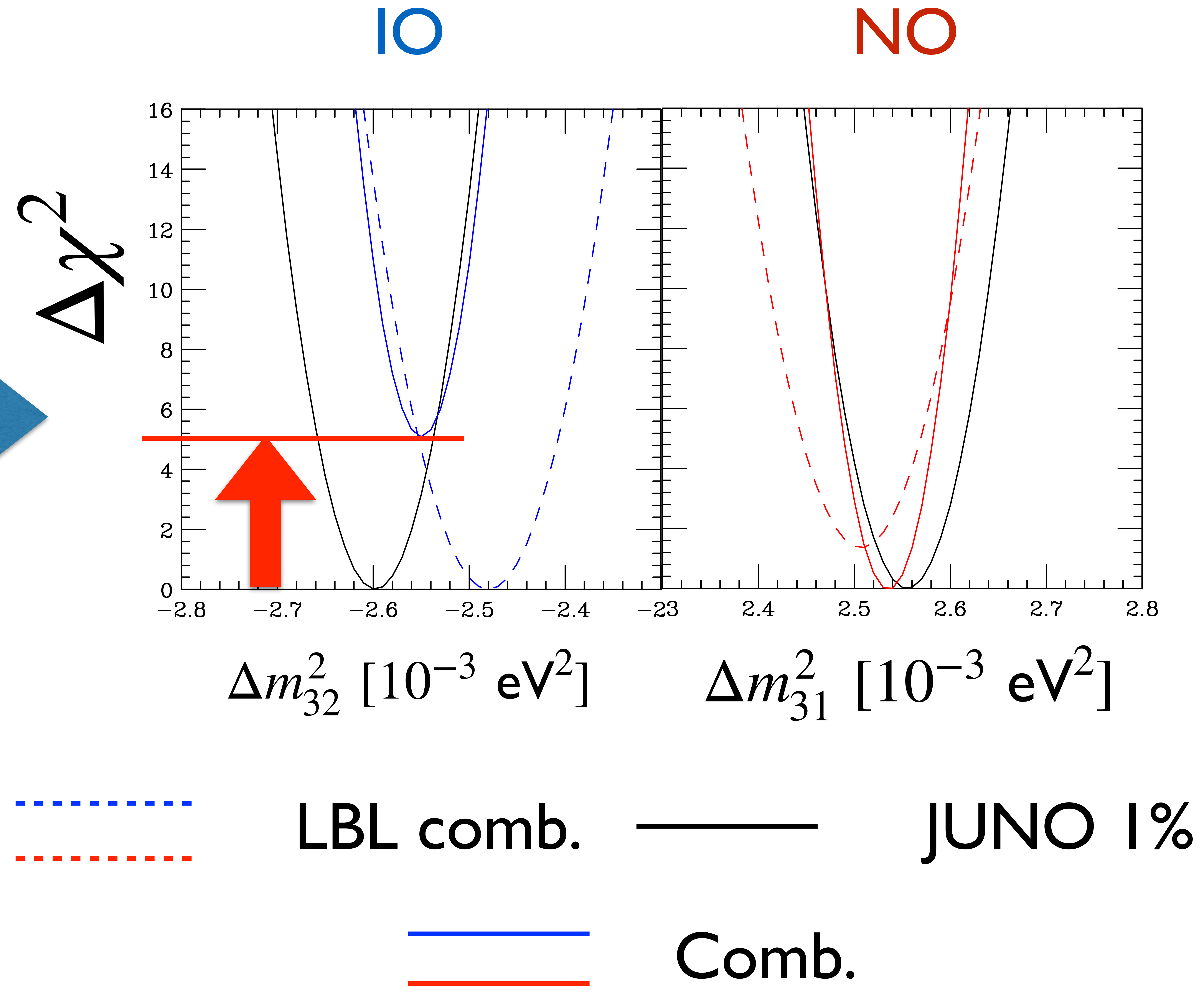
then $(2.4 - 0.9\cos\delta)\% \rightarrow (3.1 - 0.9\cos\delta)\%$

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

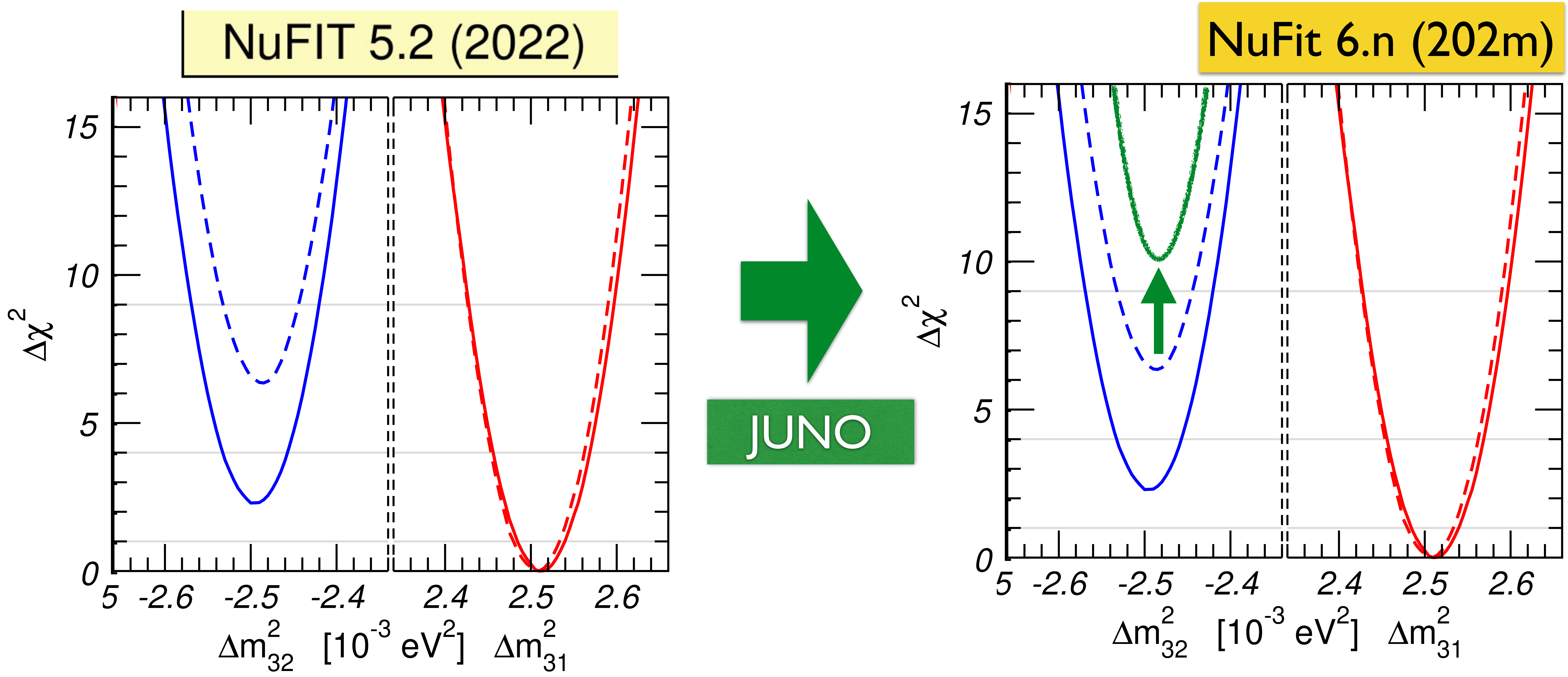


Preliminary NPZ++





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



my guess: Global Fits > 3σ at Nu 2026

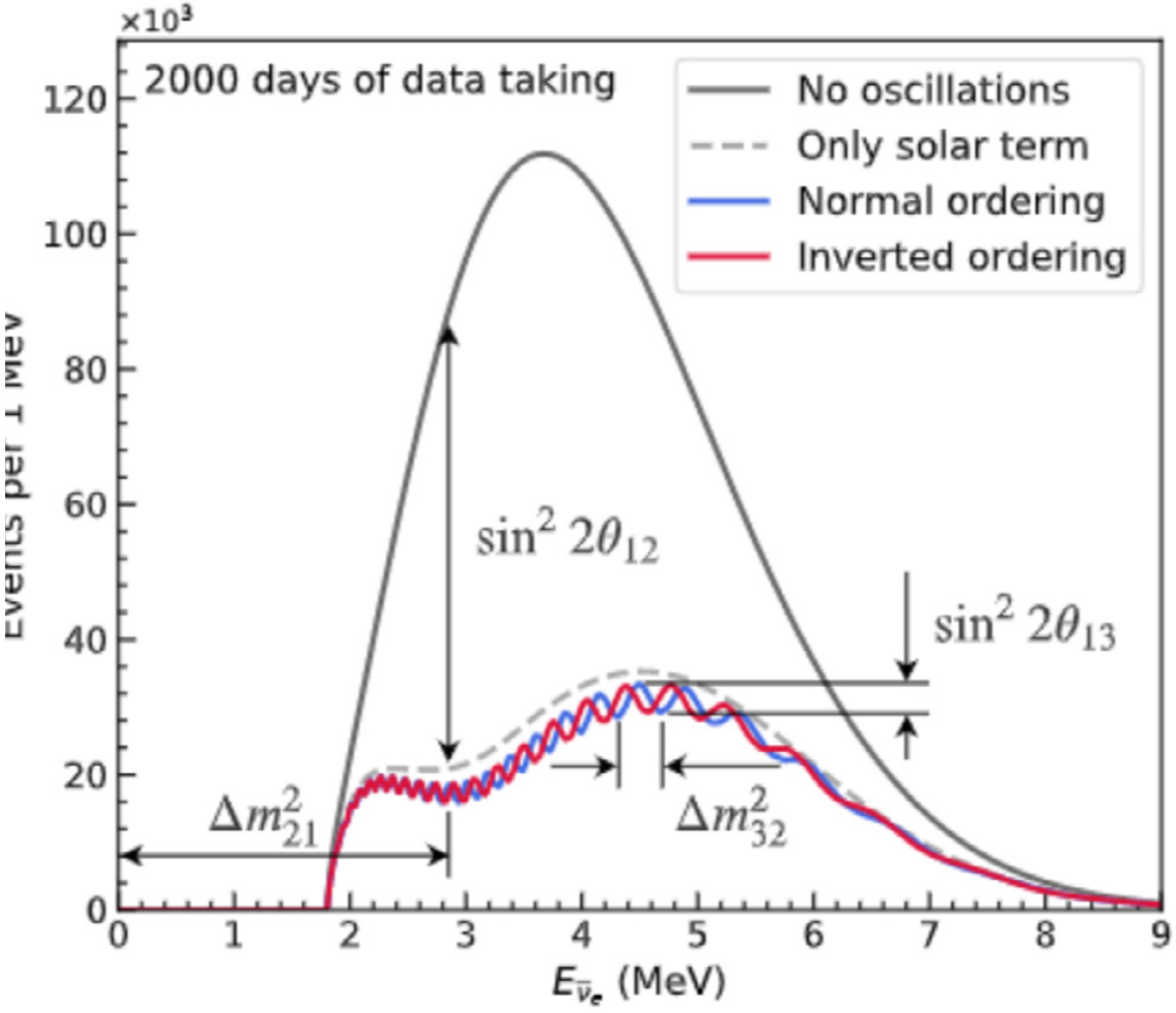
Outline of the MO Race

- Early Next Decade:
  - JUNO phase II
    - JUNO:1507.05613. / FPTZ: 2107.12410
  - DUNE

reproduced

JUNO Spectra assuming $|\Delta m^2_{32}|$ is the same for both NO/IO.

If you let $|\Delta m^2_{32}|(IO)$ be slightly different than $|\Delta m^2_{32}|(NO)$ then the θ_{13}wiggles sit more on top of one other, significantly reducing the $\Delta\chi^2$.



. **2.** Energy spectra expected to be recorded by JUNO after 2000 days of data ing, in case of no oscillation, and in case of normal and inverted mass hierarchy ootheses.

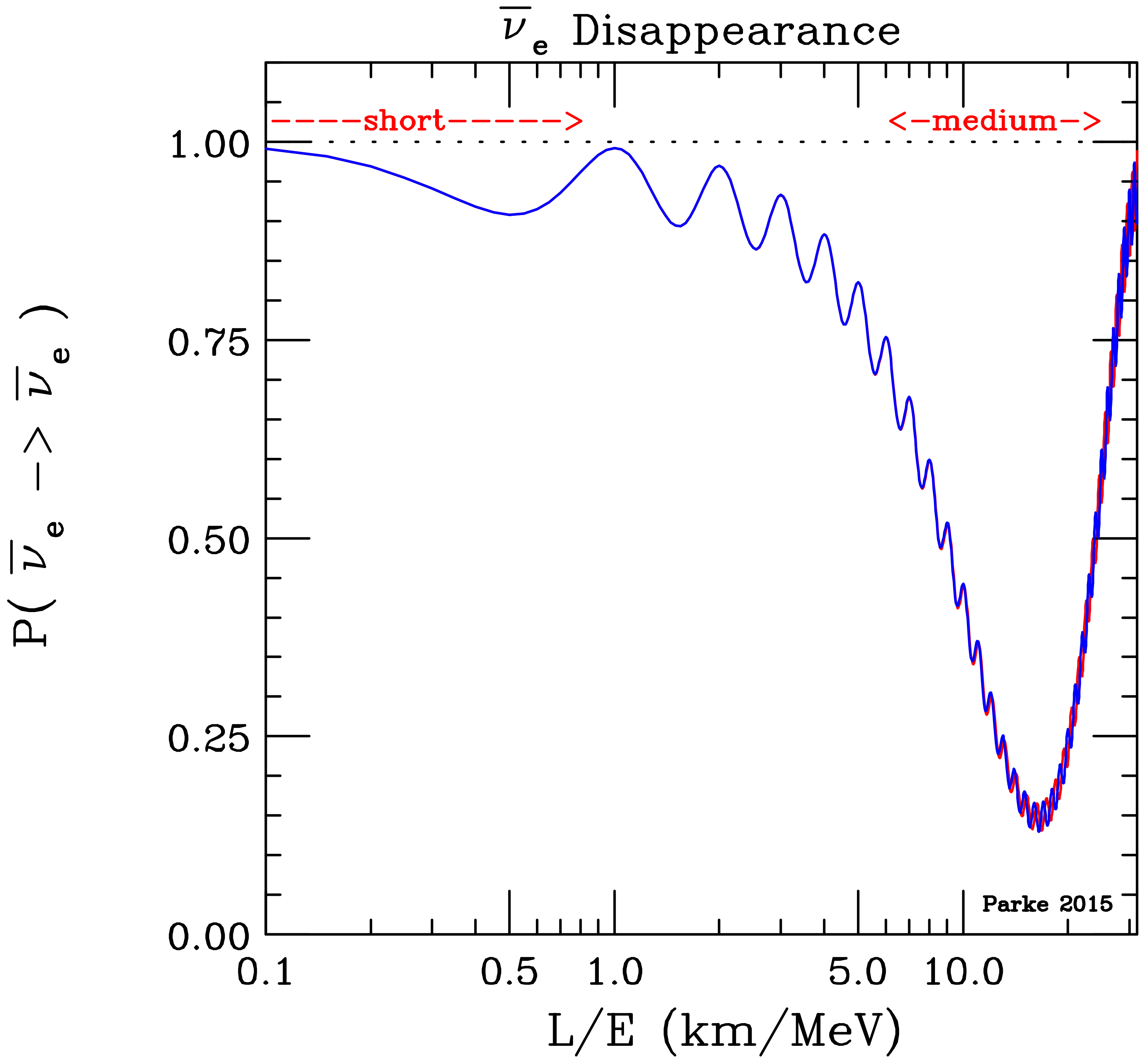
Petcov et al: hep-ph/0112074, hep-ph/0306017, arXiv:1701.06328, PDG-2018

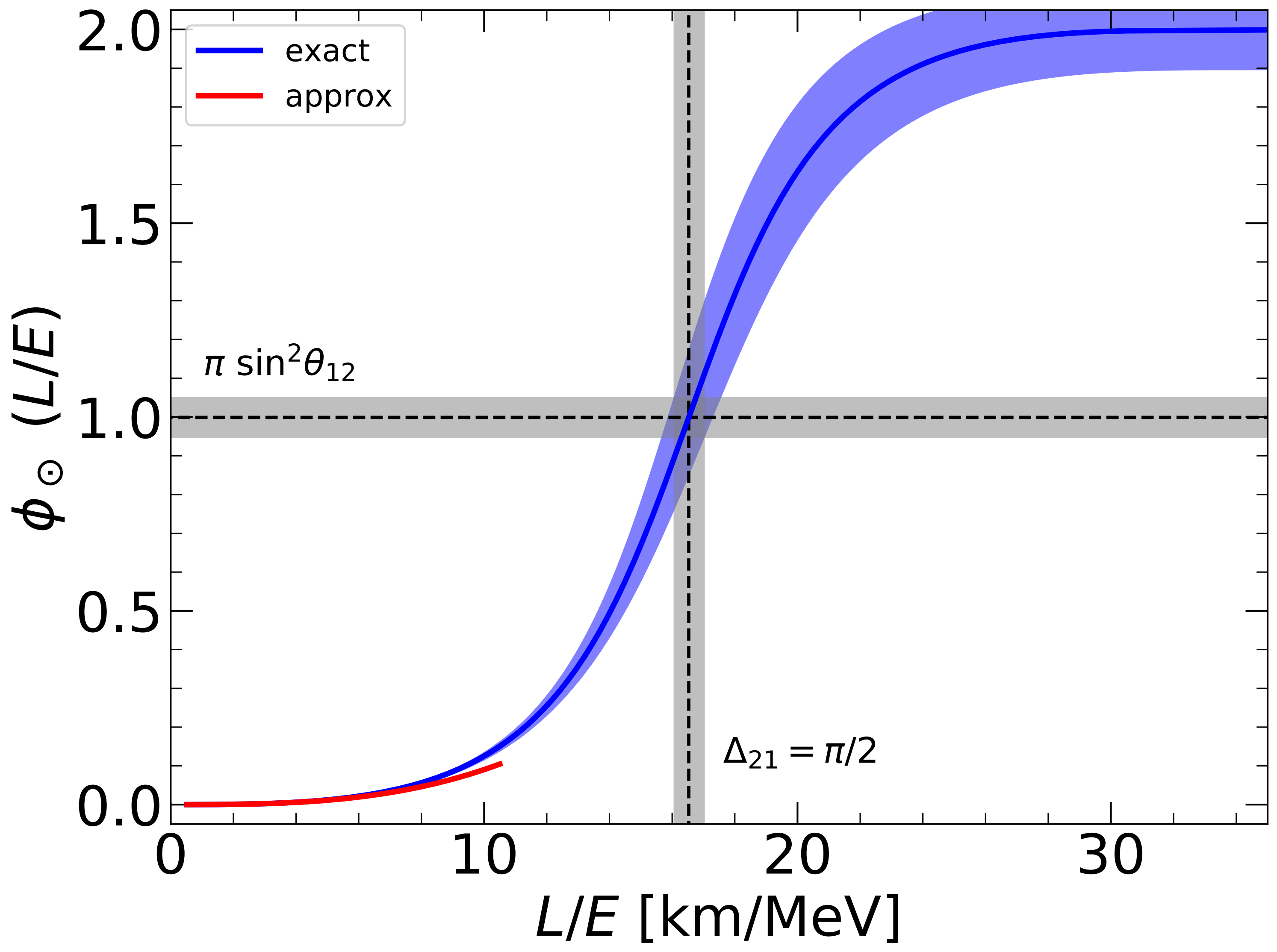
JUNO θ_{13} Wiggles:

Phase Advance(NO) / Retardation(IO)

$$1 - P(\bar{\nu}_e \to \bar{\nu}_e) = 4c_{13}^4 s_{12}^2 c_{12}^2 \sin^2\Delta_{21} + 2s_{13}^2 c_{13}^2 \left(1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2\Delta_{21}} \cos\left[2|\Delta_{ee}| \pm \Phi(\Delta_{21})\right]\right)$$

Amplitude modulation





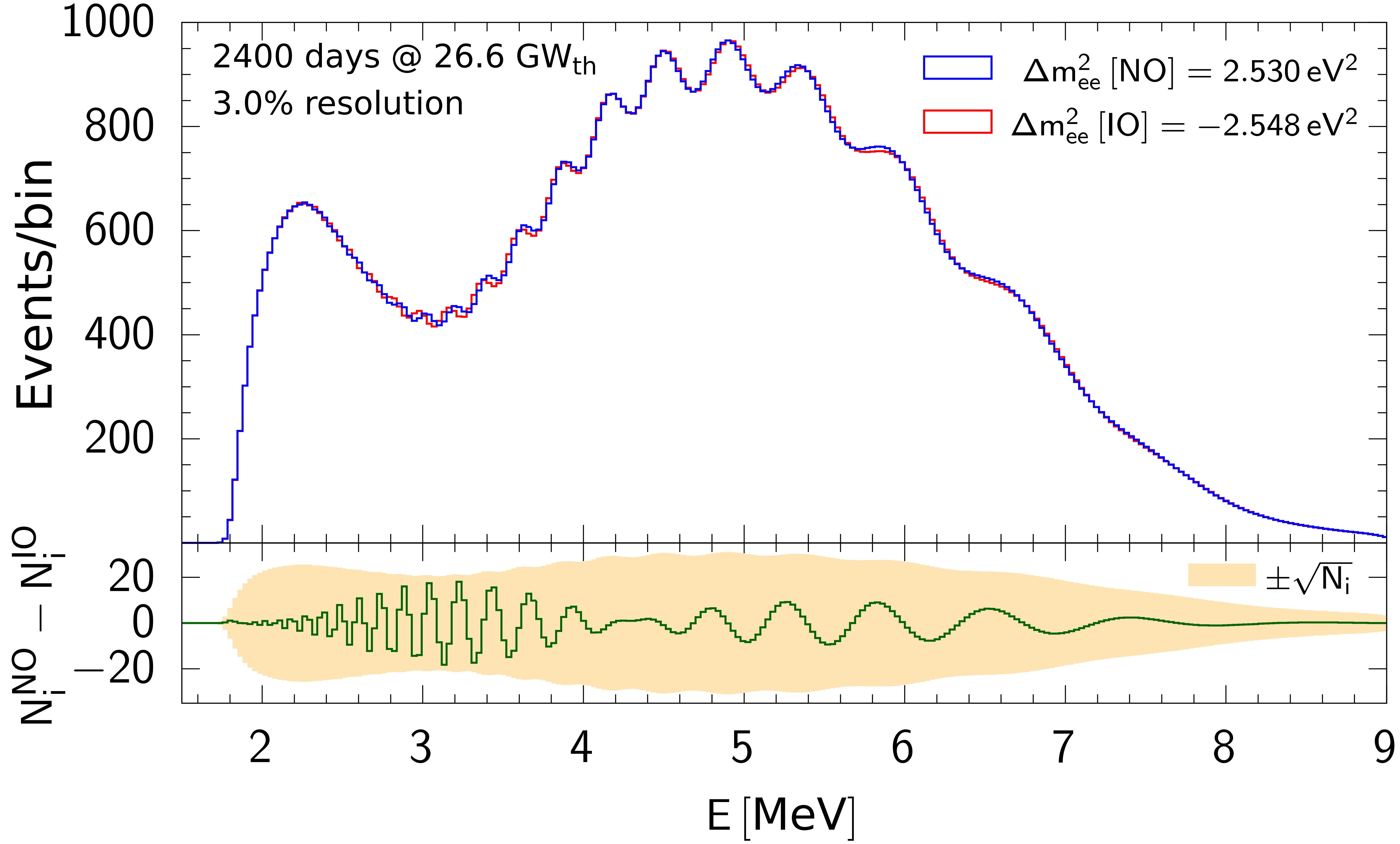
$$\Phi(\Delta_{21}) = \arctan(\cos 2\theta_{12} \tan\Delta_{21}) - \cos 2\theta_{12}\Delta_{21} = \mathcal{O}(\Delta_{21}^3)$$

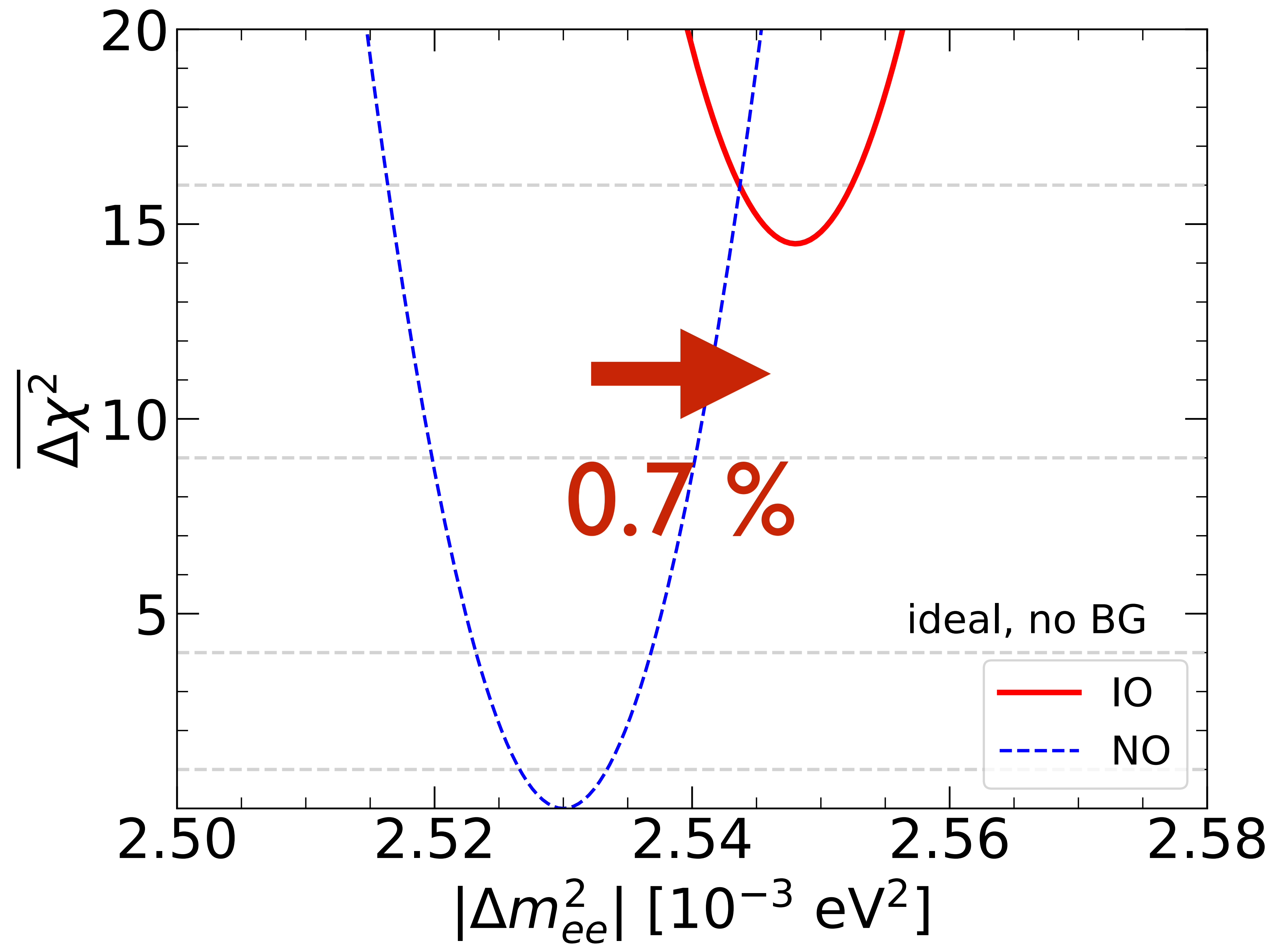
$$\Phi(\Delta_{21} = \pi/2) = \pi \sin^2\theta_{12}$$

Minakata, Nunokawa, SP, Zukanovich hep/0701151

JUNO Events Spectra

No backgrounds, No Systematics





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

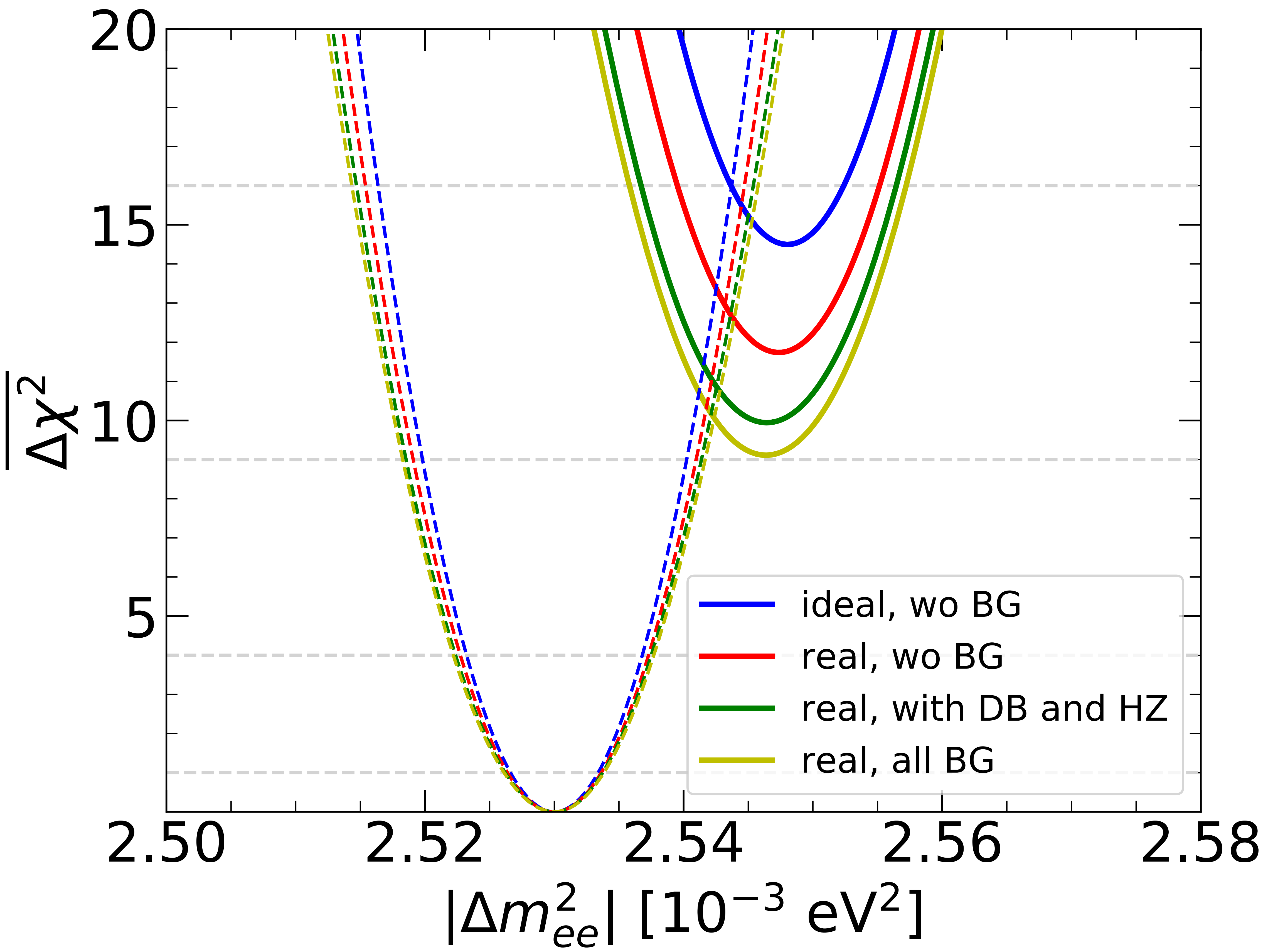
If $|\Delta m^2_{32}|(IO) = |\Delta m^2_{32}|(NO)$, then $|\Delta m^2_{ee}|(IO) = 2.428$

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

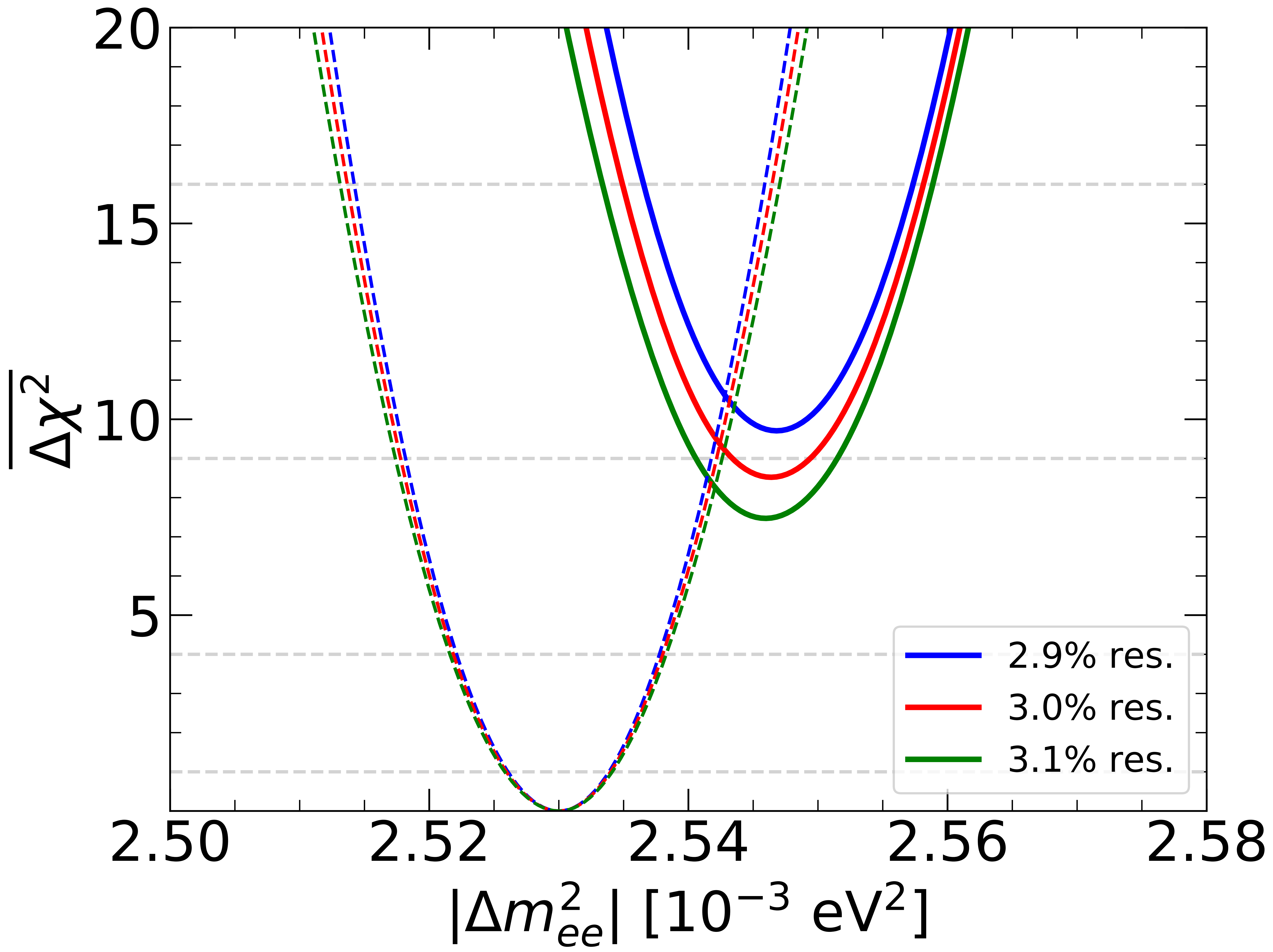
Real Baseline Distribution + Backgrounds



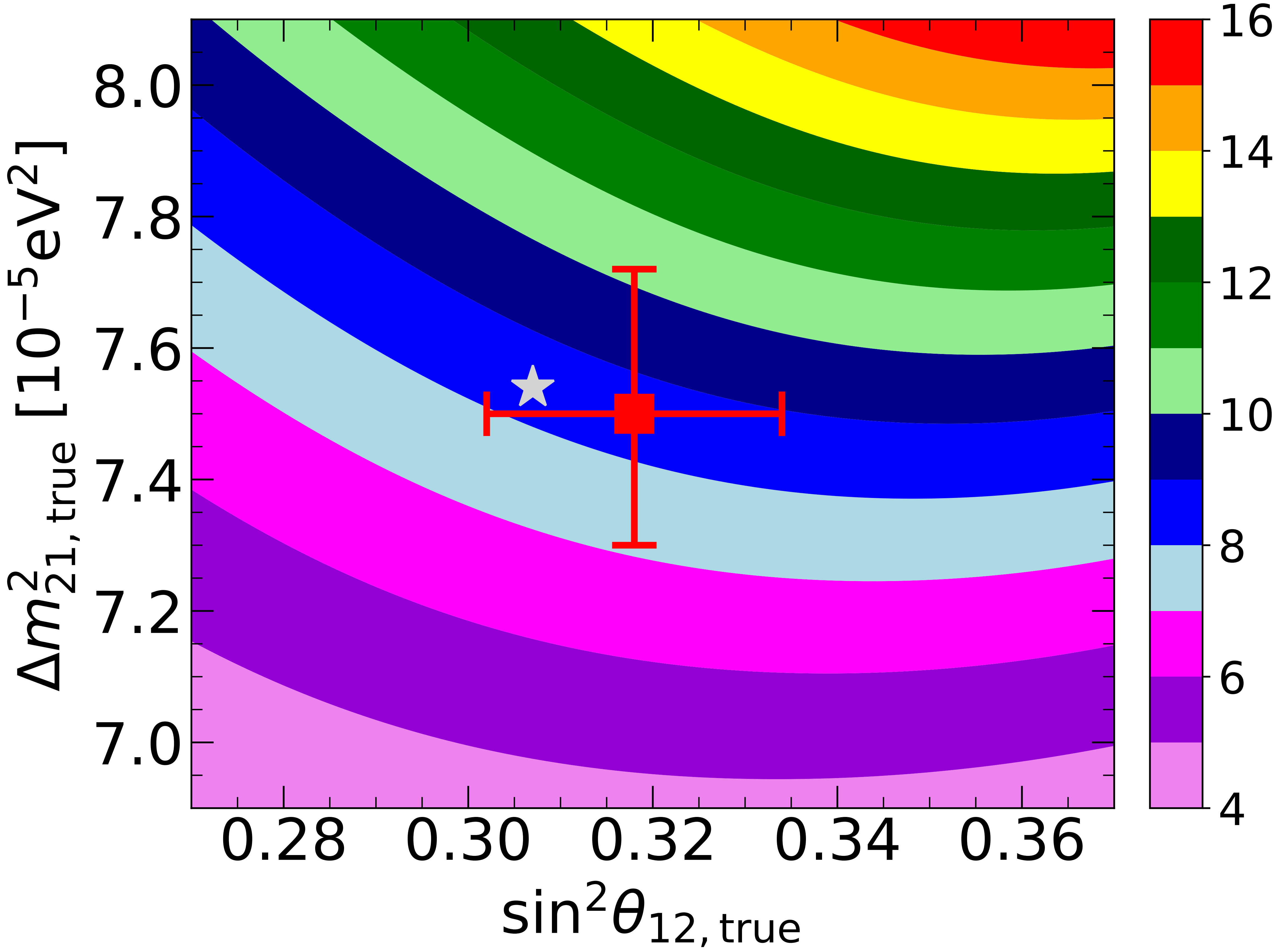
Forero, SP, Ternes, Zukanovich 2107.12410

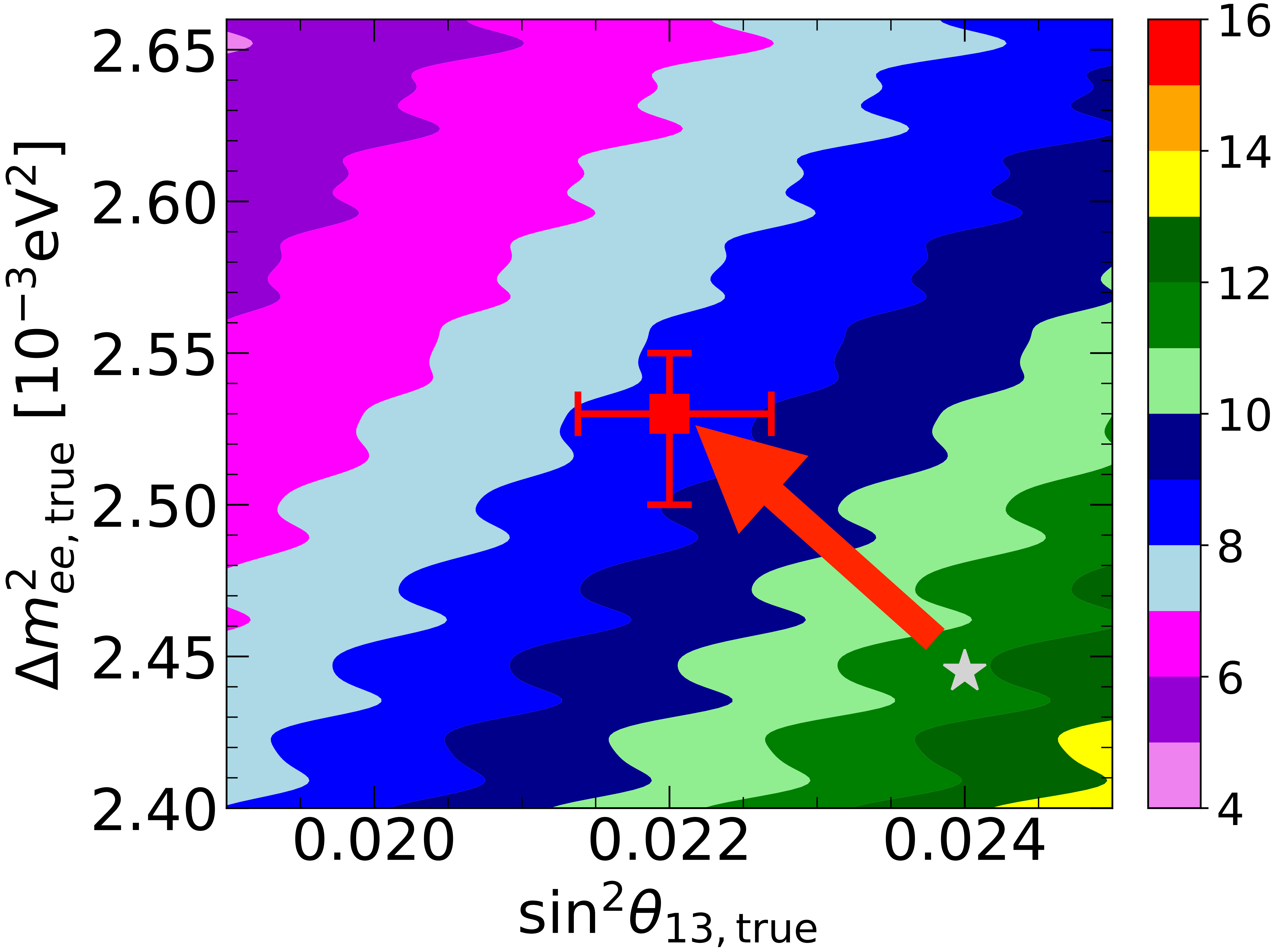
Reactor	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6	TS-C1	TS-C2	DB	HZ
Power (GW_{th})	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline (km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

Energy Resolution Effect:



Parameter Sensitivity: $\Delta\chi^2$ distributions

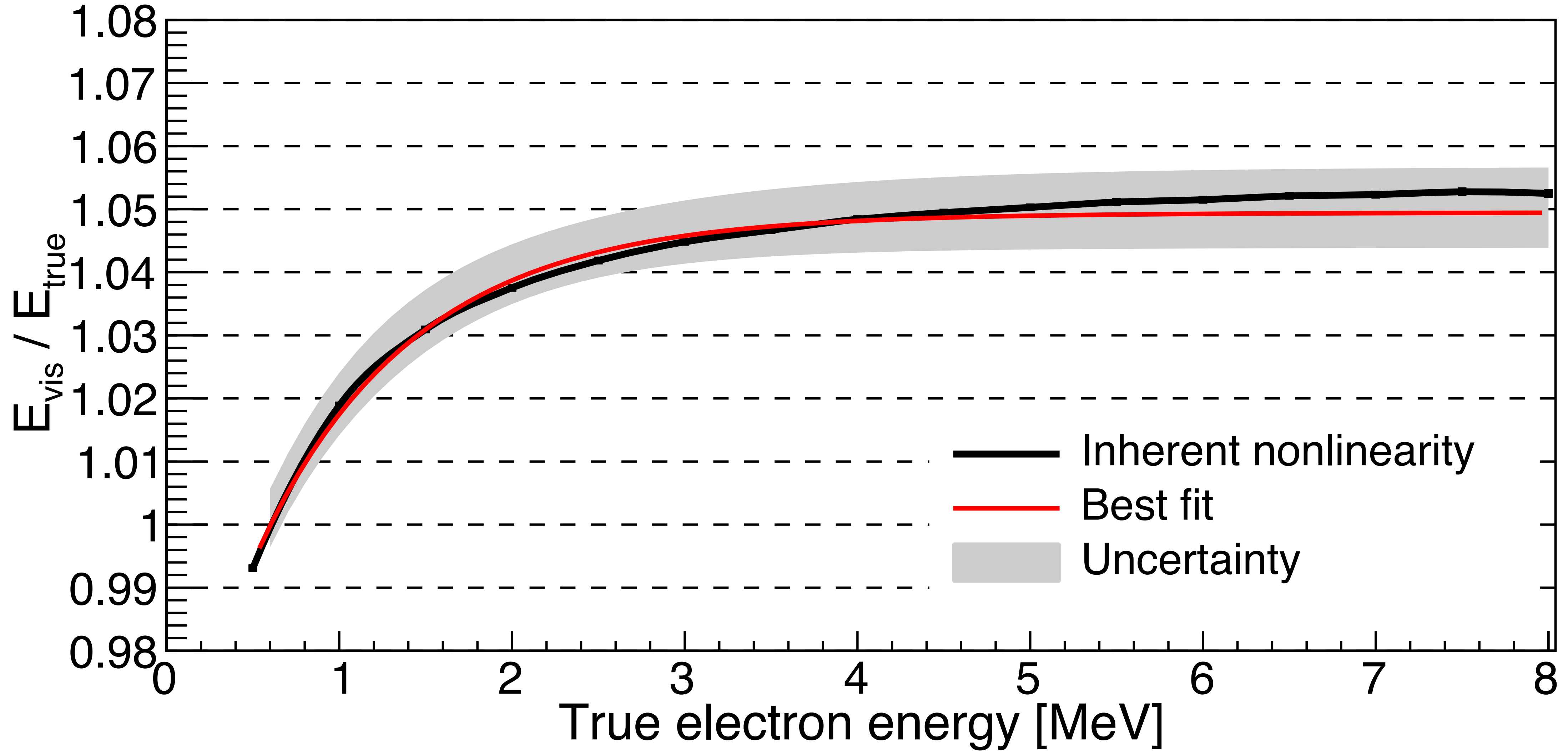




Daya Bay results moved best fit point from * to +

Non-linear Energy Response

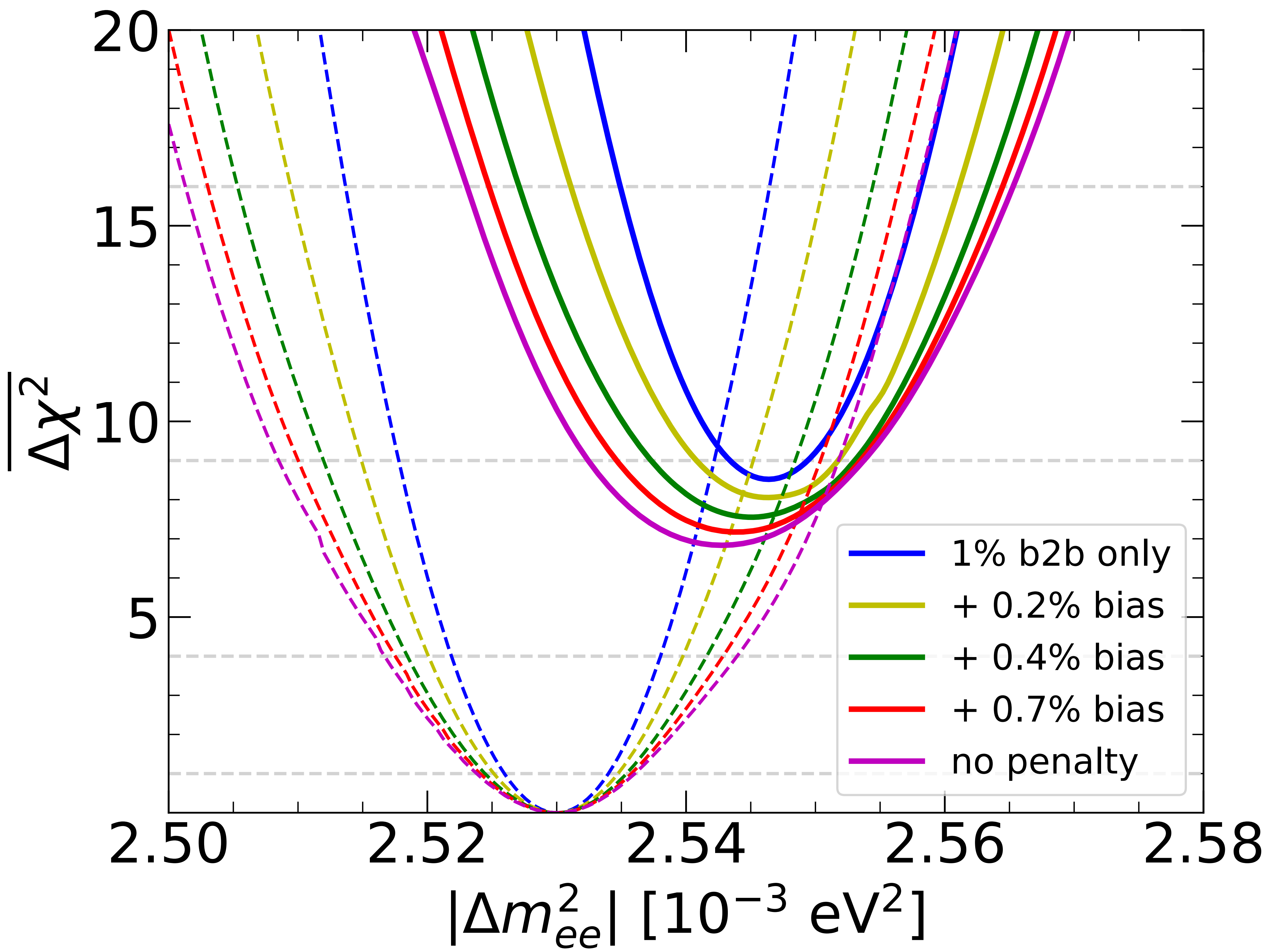
JUNO_2011.06405



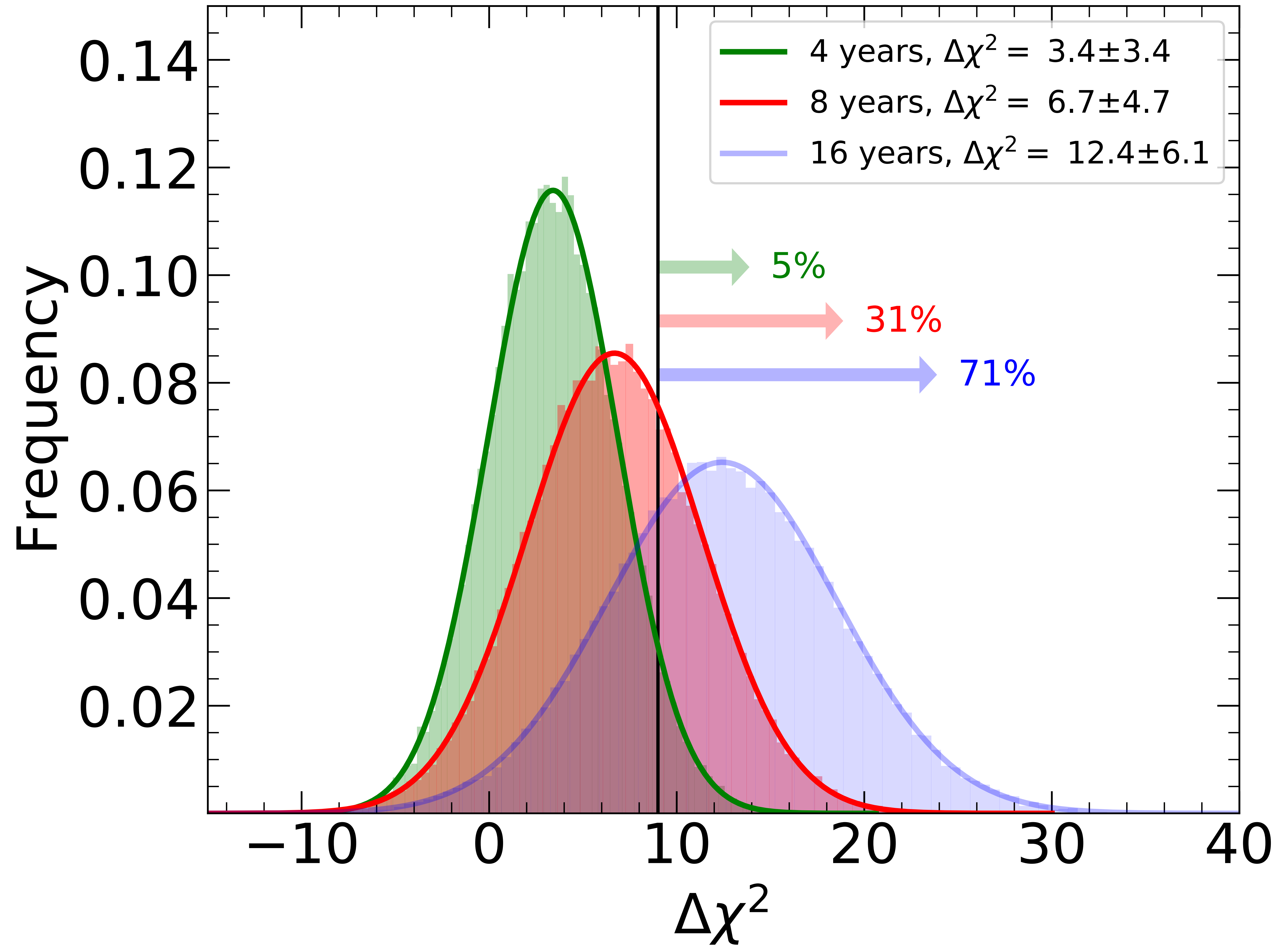
(c) Electron non-linearity

$$E_p = \frac{E^{\mathrm{vis}}}{f_{\mathrm{NL}}(a_1, a_2, a_3, a_4; E_p)}$$

$$f_{\mathrm{NL}}(a_1, a_2, a_3, a_4; E_p) \equiv \frac{a_1 + a_2\,(E_p/\mathrm{MeV})}{1 + a_3\ \exp\left(-a_4\,(E_p/\mathrm{MeV})\right)}$$



JUNO probability of determining Mass Ordering



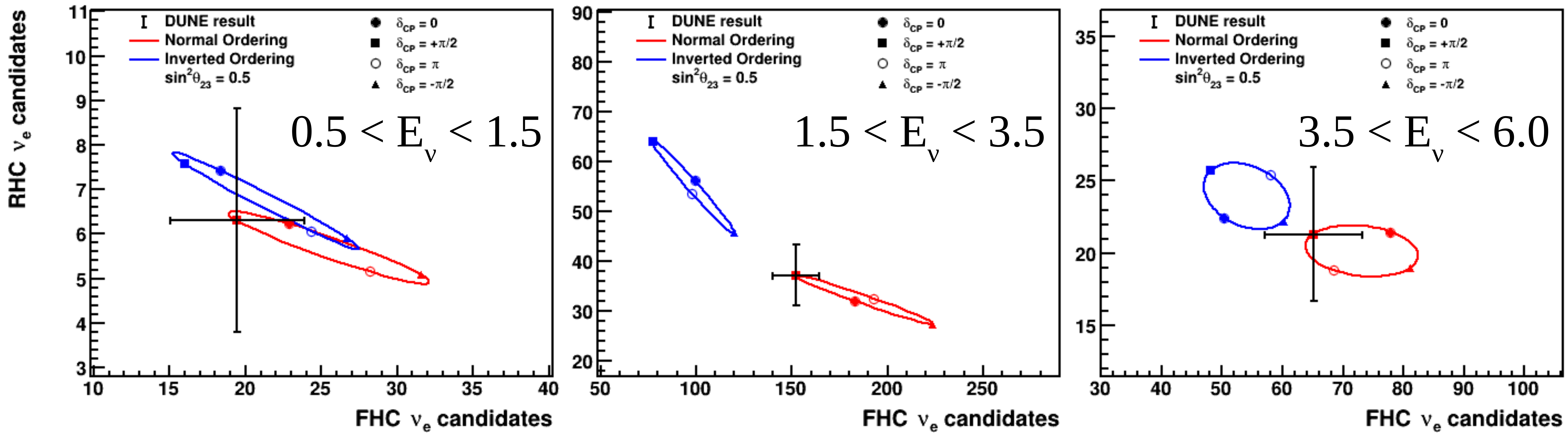
Time	% on Δm^2_{atm}	$\overline{\lvert\chi^2_{NO} - \chi^2_{IO}\rvert}$
100 days	1.0	0.25
4 years	0.3	3.4
8 years	0.2	6.7
12 Years	0.15	10.0

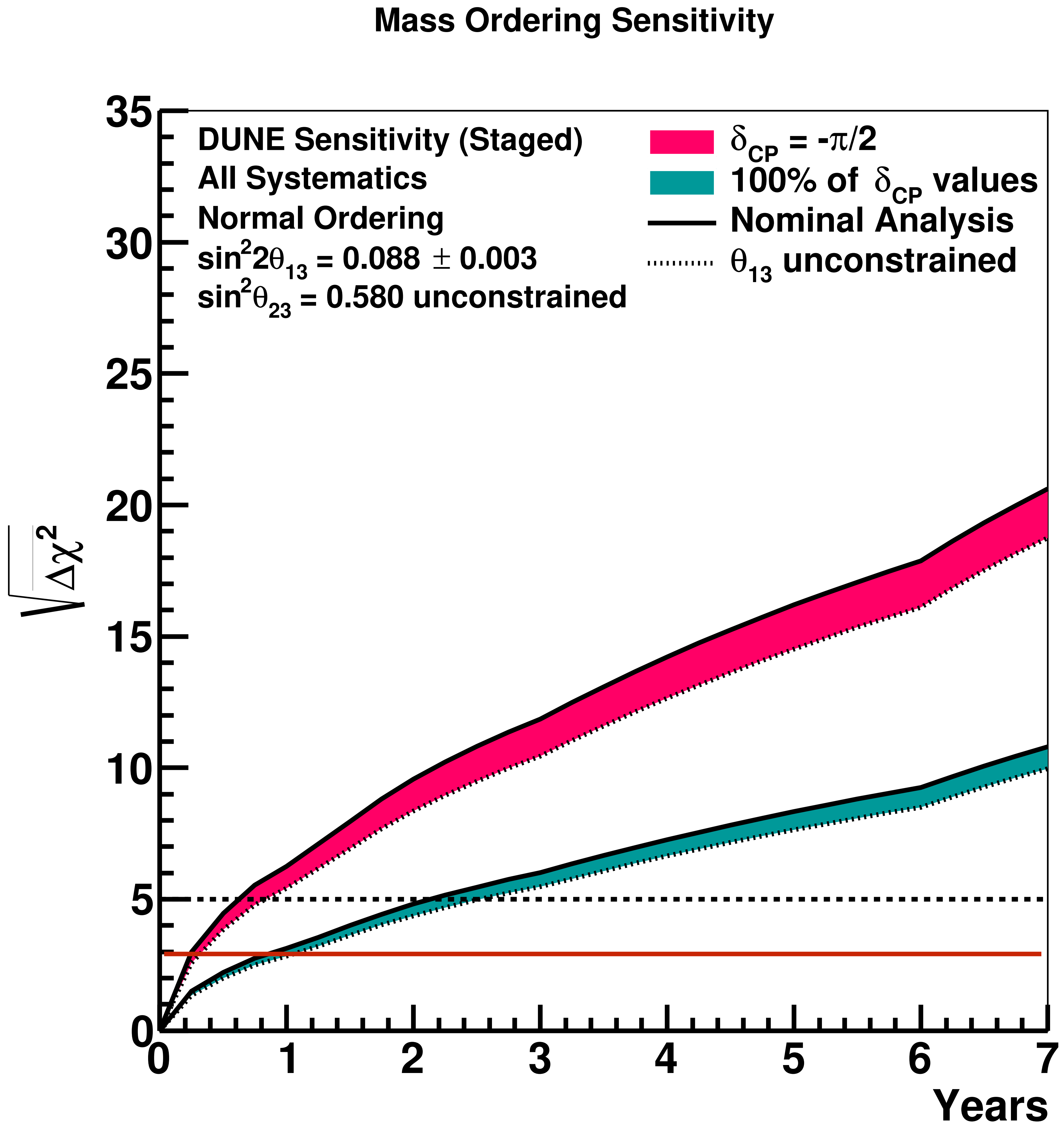
$\Delta\chi^2 \sim 0.85$ / year

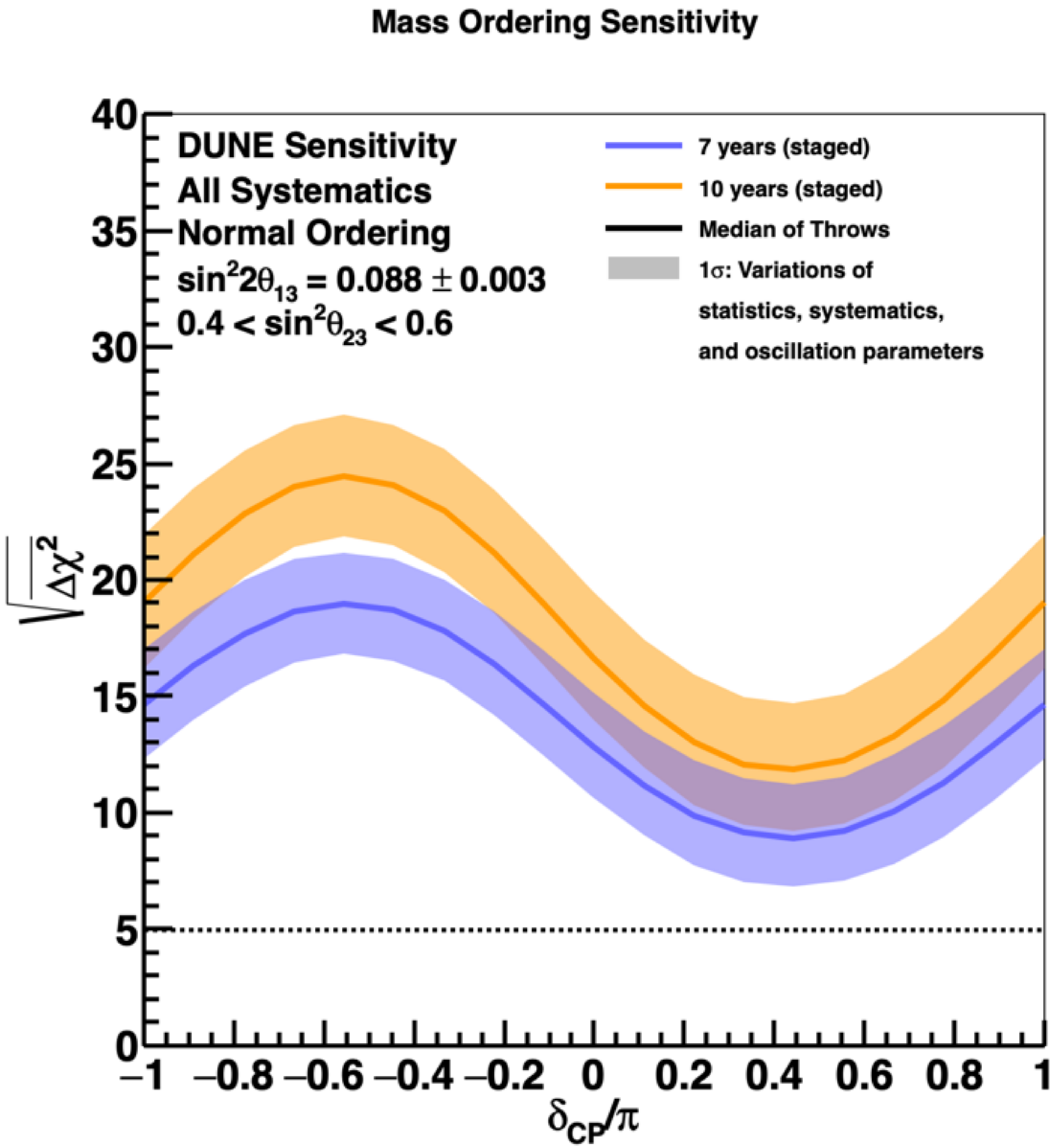
Outline of the MO Race

- Early Next Decade:
  - DUNE

Experimentalist Bi-Event Plot
For DUNE







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

Summary:

- Circa Nu 2026: Global fits, including JUNO's precision Δm^2_{ee} measurement will give us Neutrino Mass Ordering $> 3\sigma$.
  - Precision Disappearance Δm^2 measurements will make significant contributions (NPZ '05)
- Circa Nu 203x: JUNO & DUNE will each have Neutrino Mass Ordering $> 3\sigma$ in a single experiment - a race !
- A Year Later: DUNE $> 5\sigma$ for Neutrino Mass Ordering

Comment for P5:

“Success” builds on “Success”

Lots of examples:

Gedanken exp: Braidwood, BTeV, SSC

Using 2014-P5 metric, DUNE phase I is not a “Success”

for guaranteed “Success”

full DUNE phase II + ACE are needed

This is building for future “Successes”

Extras

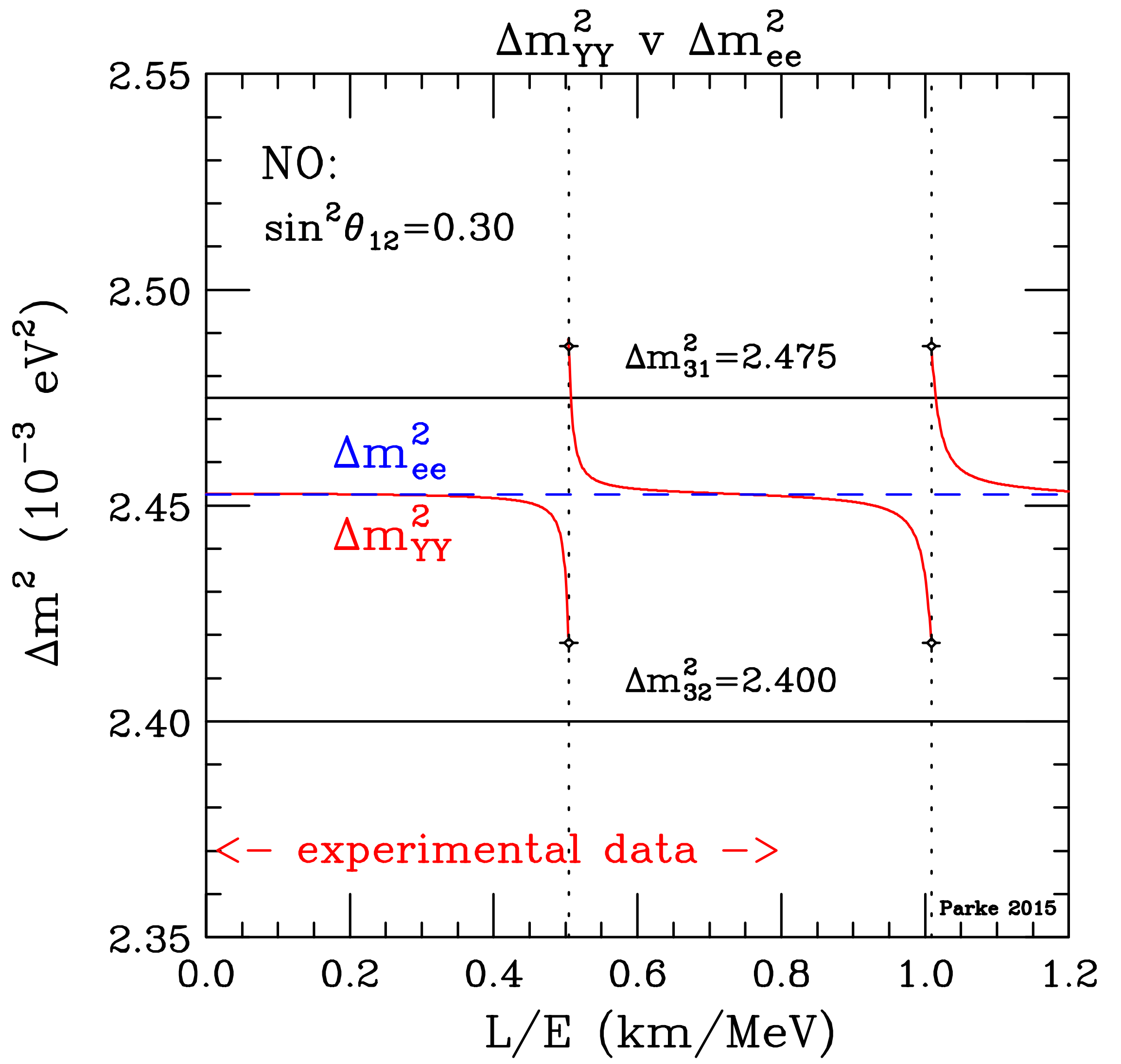
Daya Bay:

1.

$$\sin^2 \Delta_{YY} \equiv \cos^2\theta_{12} \ \sin^2\Delta_{31} + \sin^2\theta_{12} \ \sin^2\Delta_{32}.$$

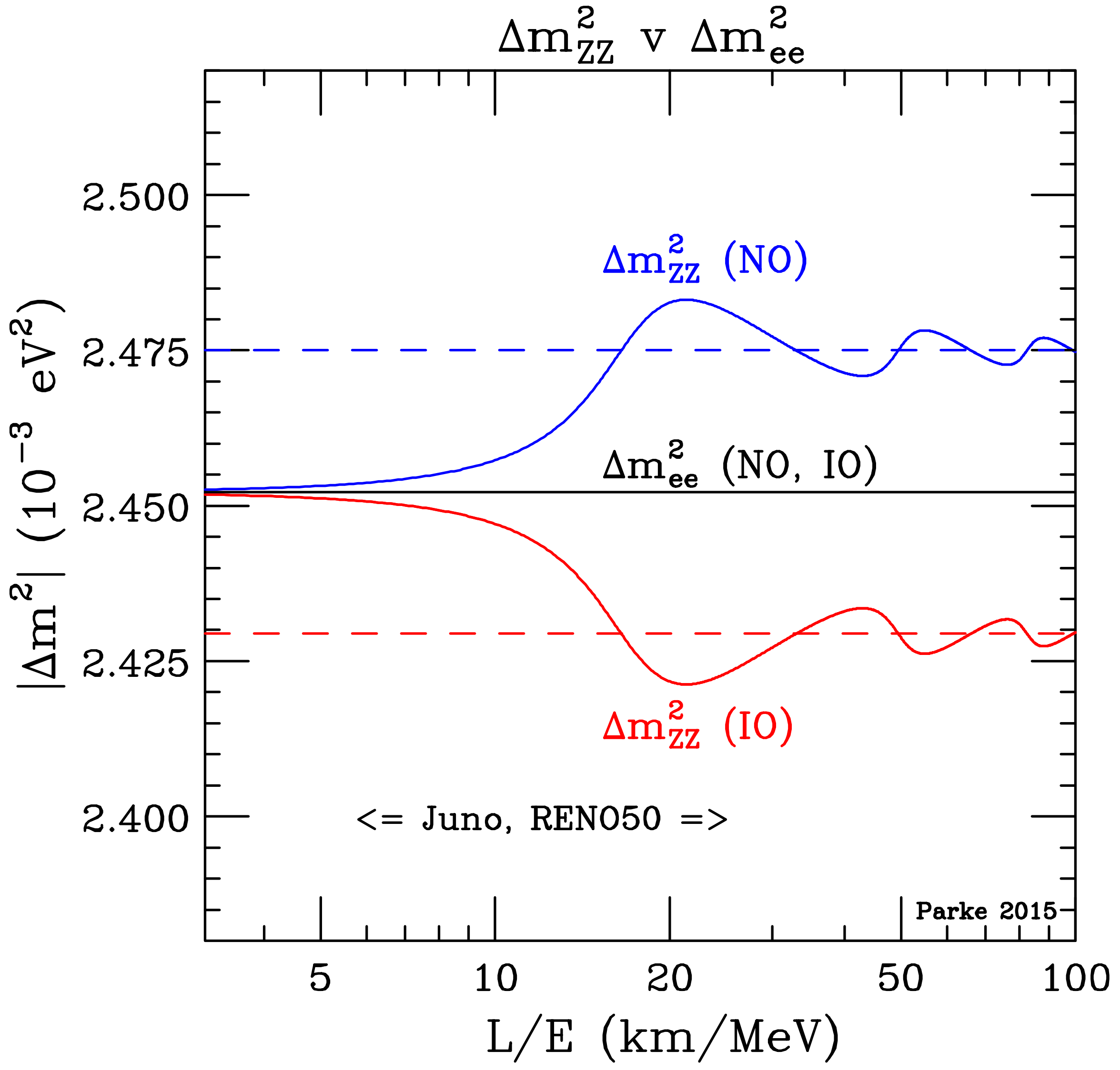
which implies that

$$\Delta m^2_{YY} \equiv \left(\frac{4E}{L}\right) \arcsin\left[\sqrt{(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})}\right].$$



2.

$$\Delta m^2_{ZZ} \equiv \frac{2E}{L}\left(\Delta_{31} + \Delta_{32} + \arctan[\cos 2\theta_{12} \tan\Delta_{21}]\right)$$



3.

$$\Delta m^2_{ee} \equiv \frac{\partial}{\partial(L/2E)}\left(\Delta_{31} + \Delta_{32} + \arctan[\cos 2\theta_{12} \tan\Delta_{21}]\right)\Bigg|_{L/2E=0} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

NPZ'05

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

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

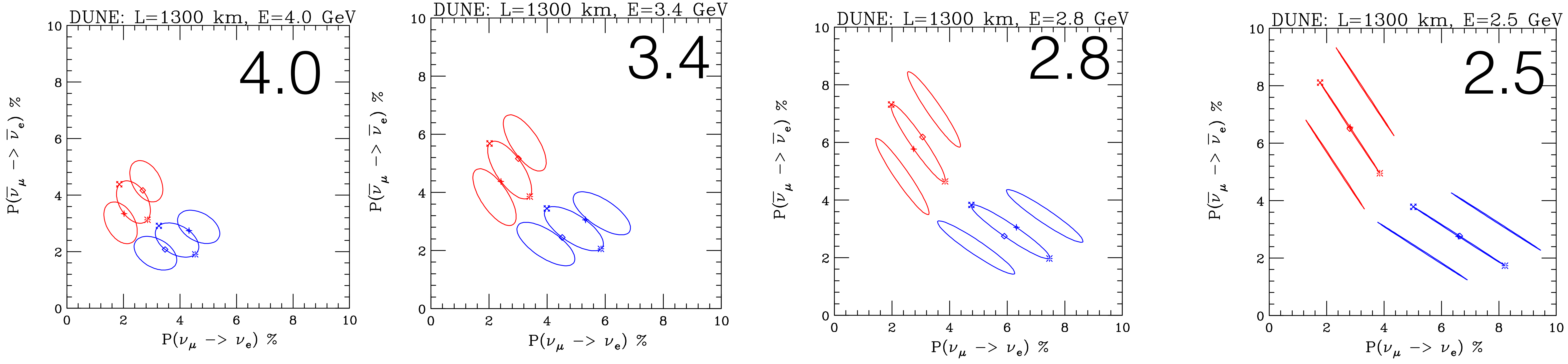
Unchanged if $31 \leftrightarrow 32$ in either or both MO's

1.5 to 3.3 %

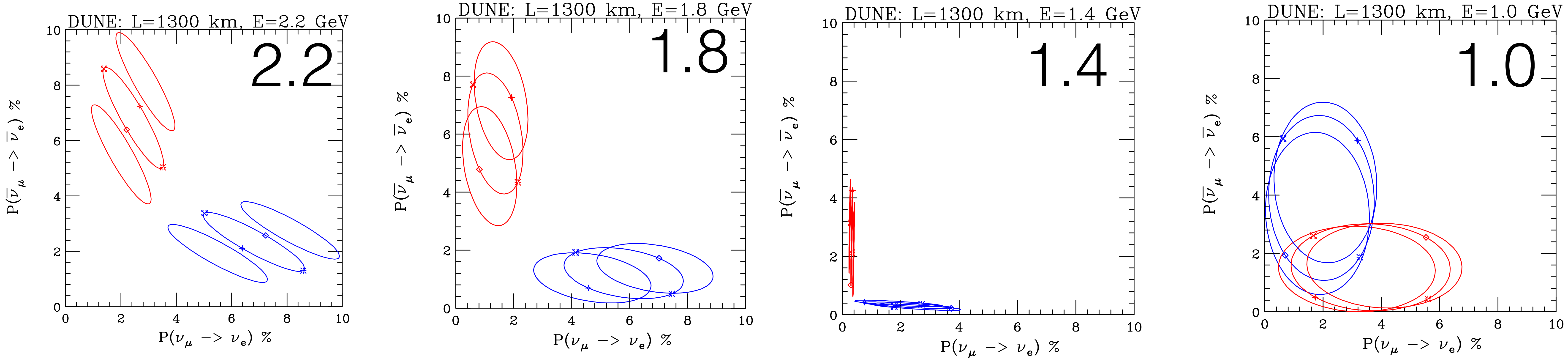
DUNE bi-Probability Diagrams:

Normal Ordering — Inverted Ordering

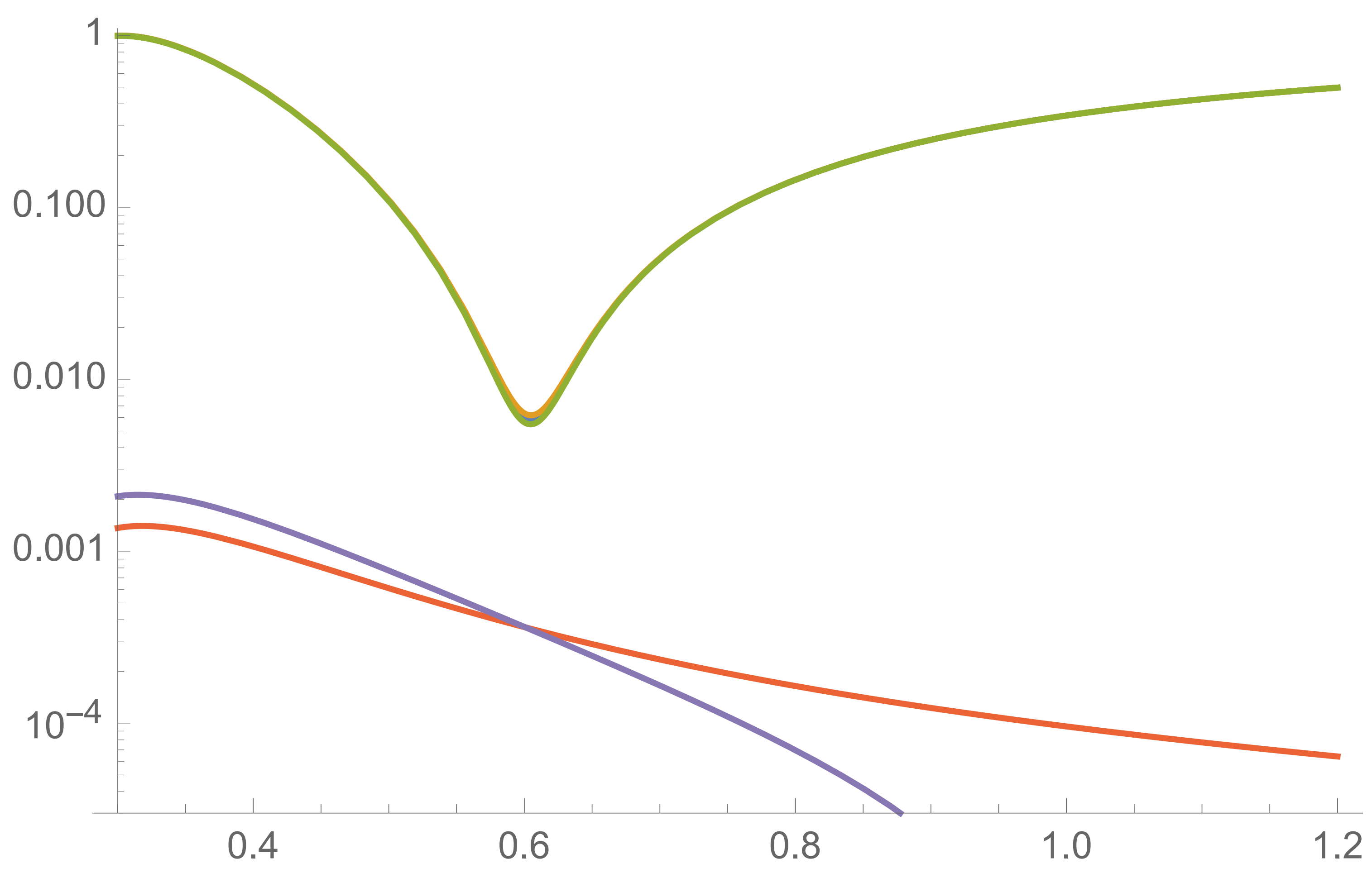
VOM



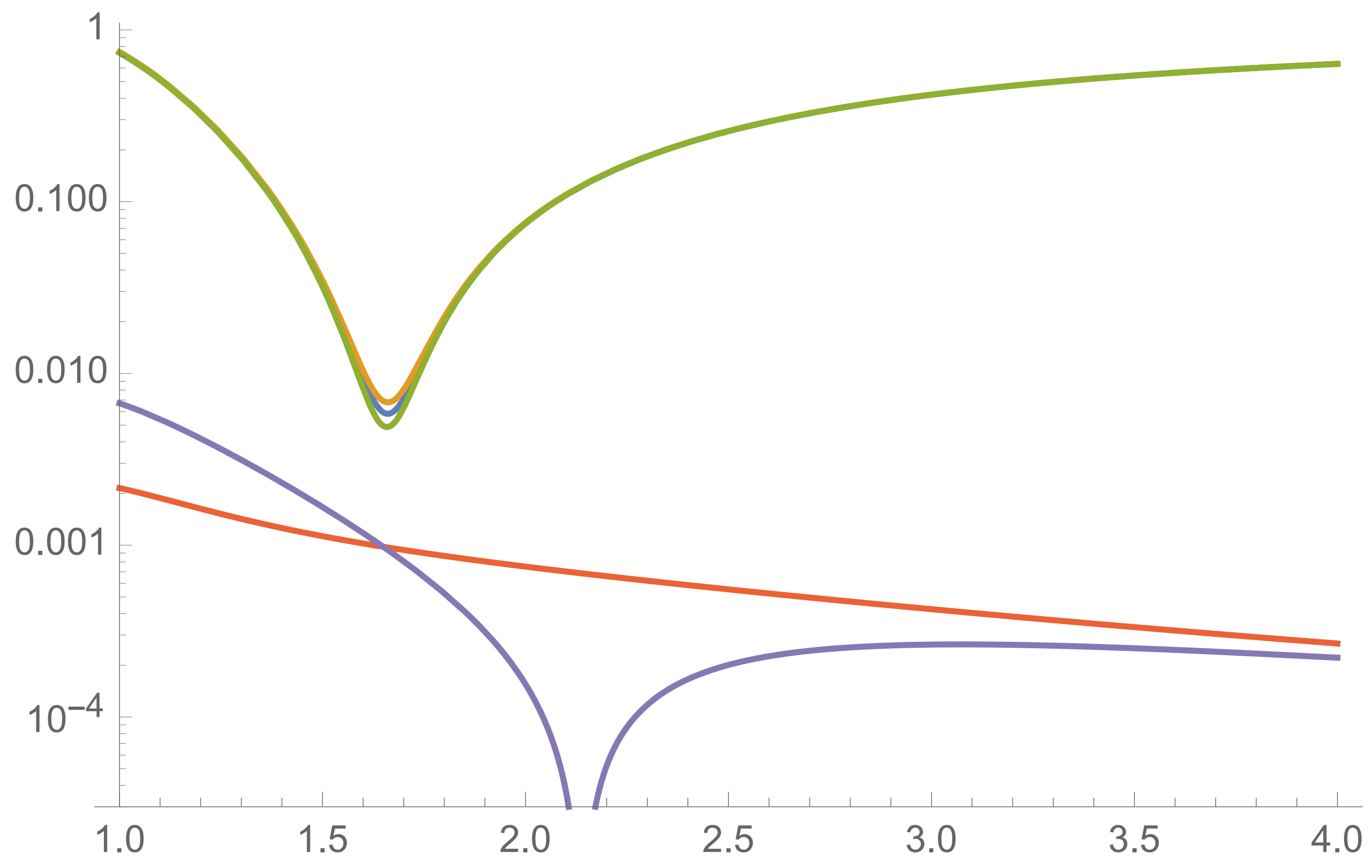
near Osc Min



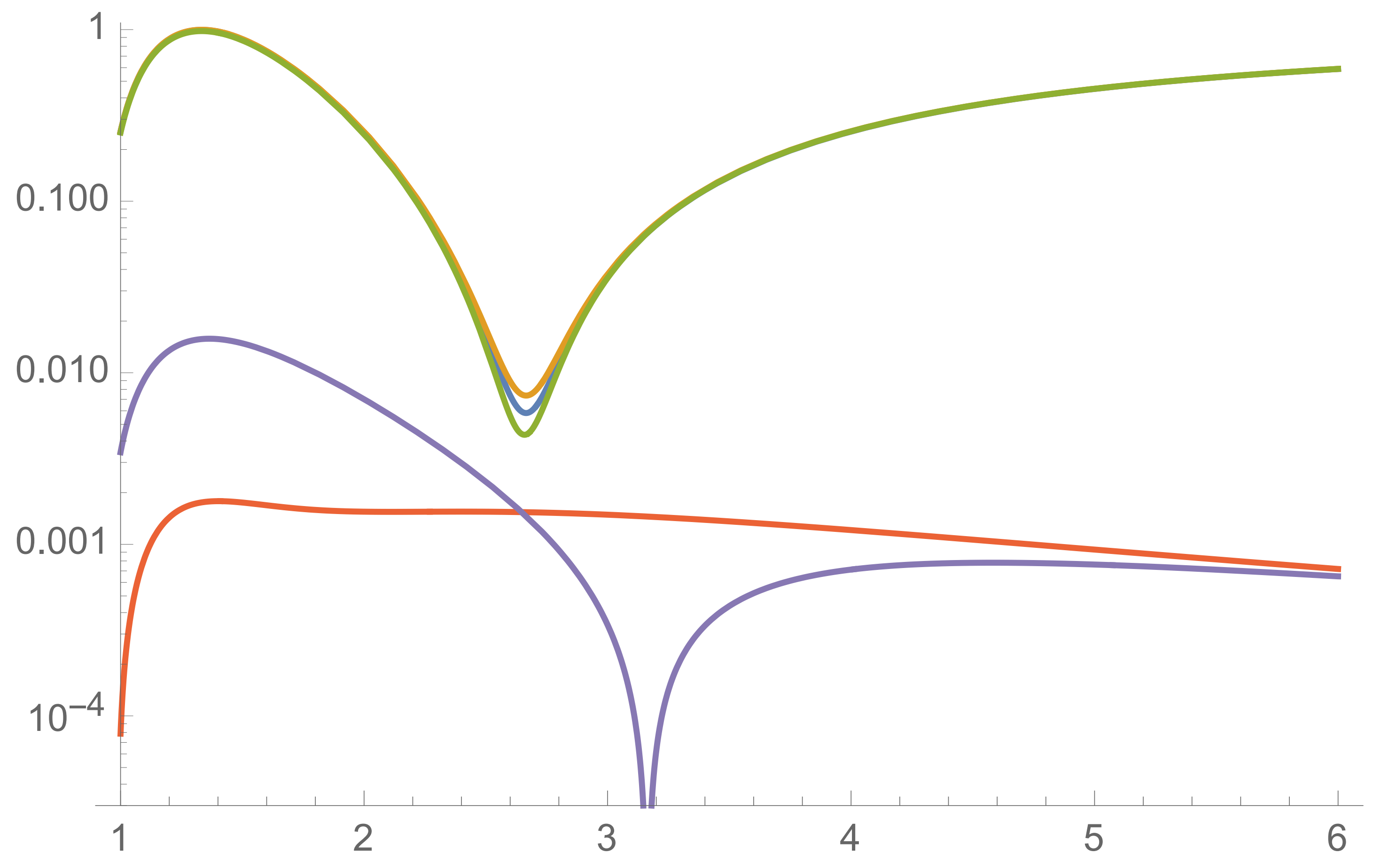
Vacuum v Matter:



T2K



NOvA



DUNE