Neutrino physics overview

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Neutrino oscillations overview

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Outline

- Current status of the **standard three-neutrino** framework

  ⇒ based on **de Salas et al, JHEP 02 (2021) 071 [arXiv:2006.11237]**

  ⇒ updated with the results presented in Neutrino 2020 Conference

  ⇒ figures and $\chi 2$ tables publicly available at the website:

  https://globalfit.astroparticles.es/

  https://doi.org/10.5281/zenodo.4593330

  See also: Esteban et al. (NuFIT), Lisi et al.

  ⇒ Discussion of results presented in Neutrino 2022

- Future prospects in neutrino oscillations:

  ⇒ near future & next generation neutrino oscillation experiments

- Beyond the standard three-neutrino scenario:

  ⇒ can BSM physics improve oscillation fits?

The three-flavour ν picture

neutrino mixing

$$U_{3\times 3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

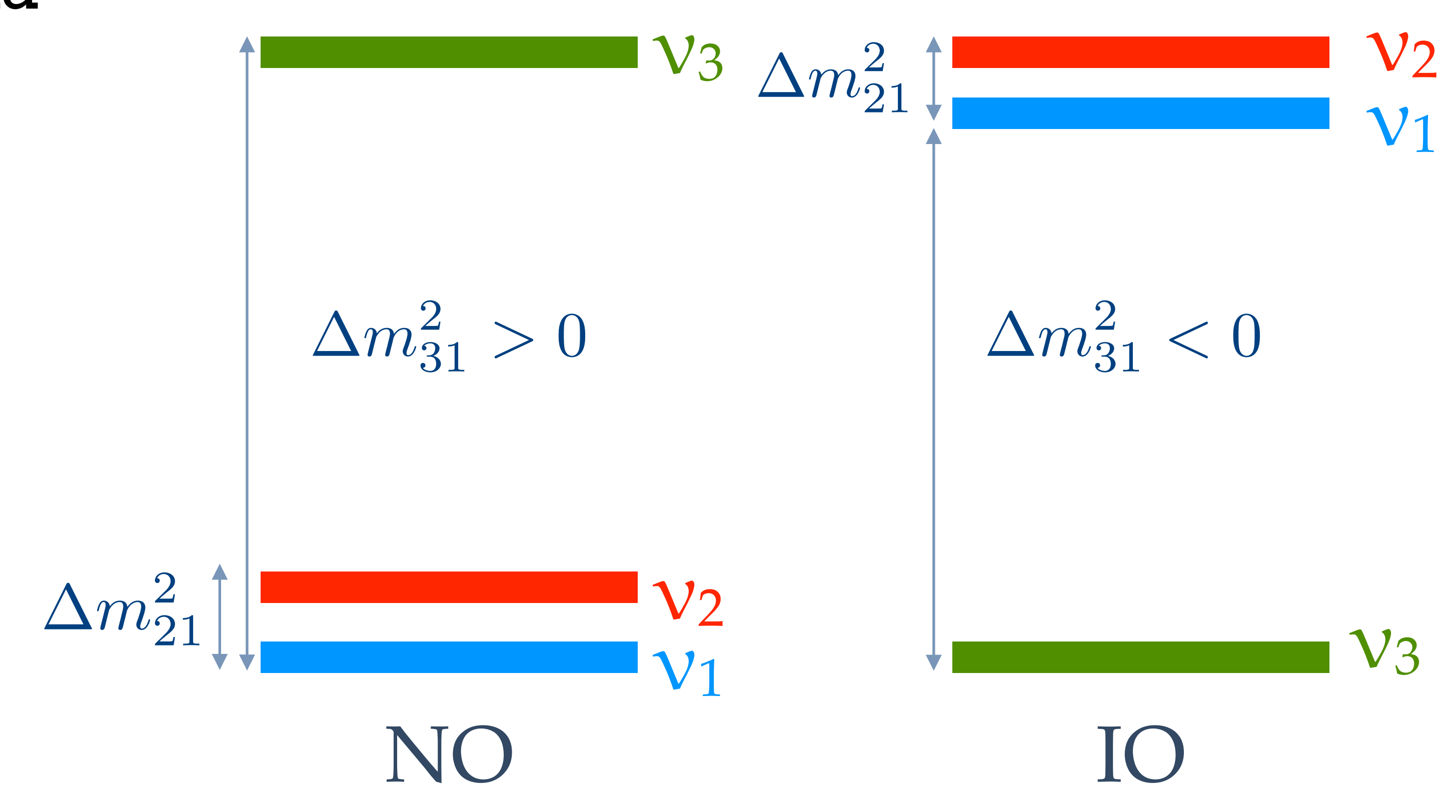
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$$\Delta m^2_{21}, \Delta m^2_{31}$$

neutrino mass spectrum



Neutrino mixing and 0νββ

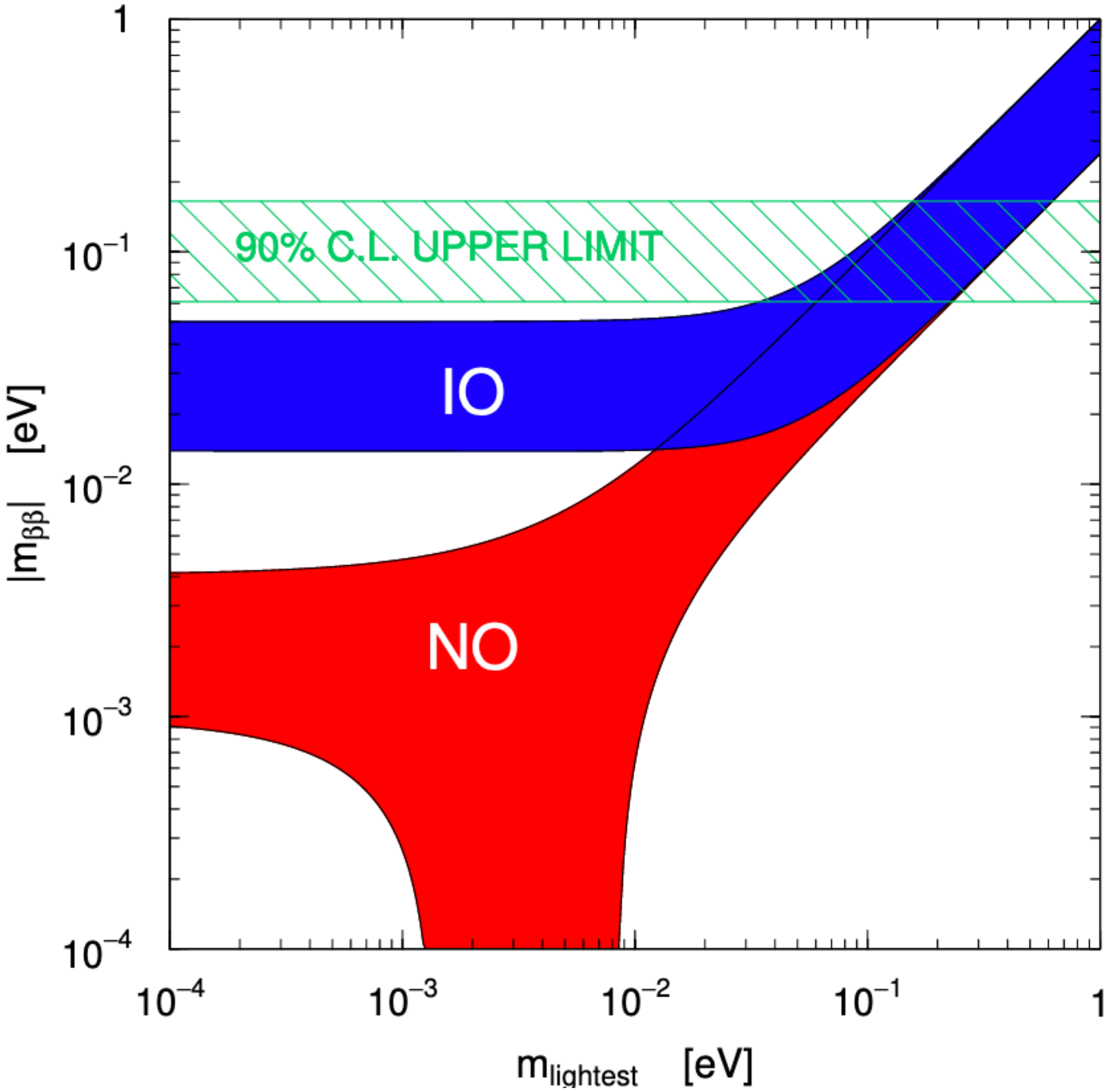
- If neutrinoless double beta decay is mostly due to the exchange of light Majorana neutrinos:

$$\Gamma_{0\nu\beta\beta} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

- Effective Majorana neutrino mass:

$$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

$\Rightarrow$ sensitive to Majorana phases α_i



$$U = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -e^{i\delta}c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three-neutrino mixing

✦ Currently, we have evidence for neutrino oscillations in atmospheric, solar, reactor and accelerator experiments

✦ Each type of experiment is sensitive to different mixing parameters:

$$U_{3\times 3} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric + accelerator disapp	SBL reactor + accelerator app	solar + KamLAND
Δm^2_{31}	Δm^2_{31}	Δm^2_{21}

Experimental data

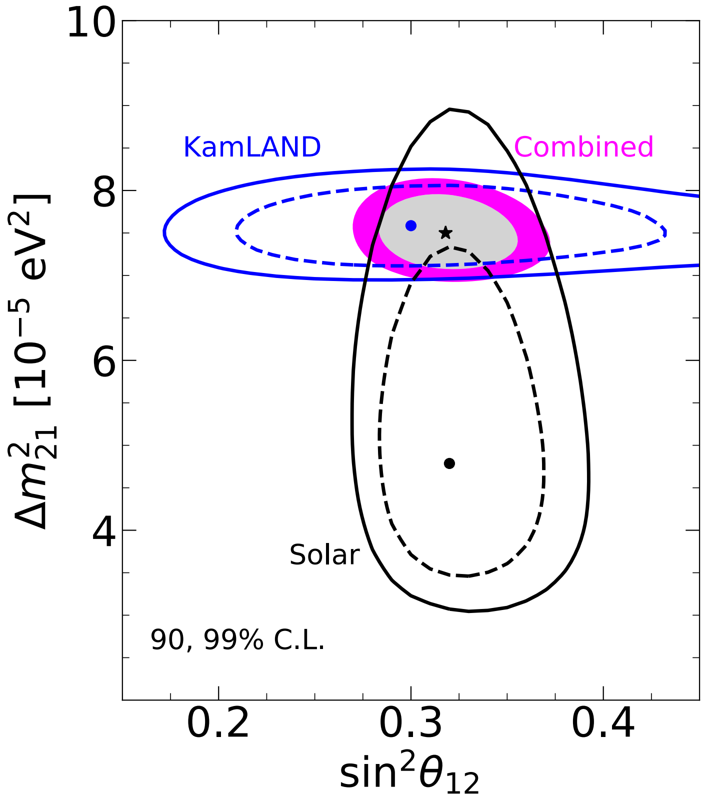
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

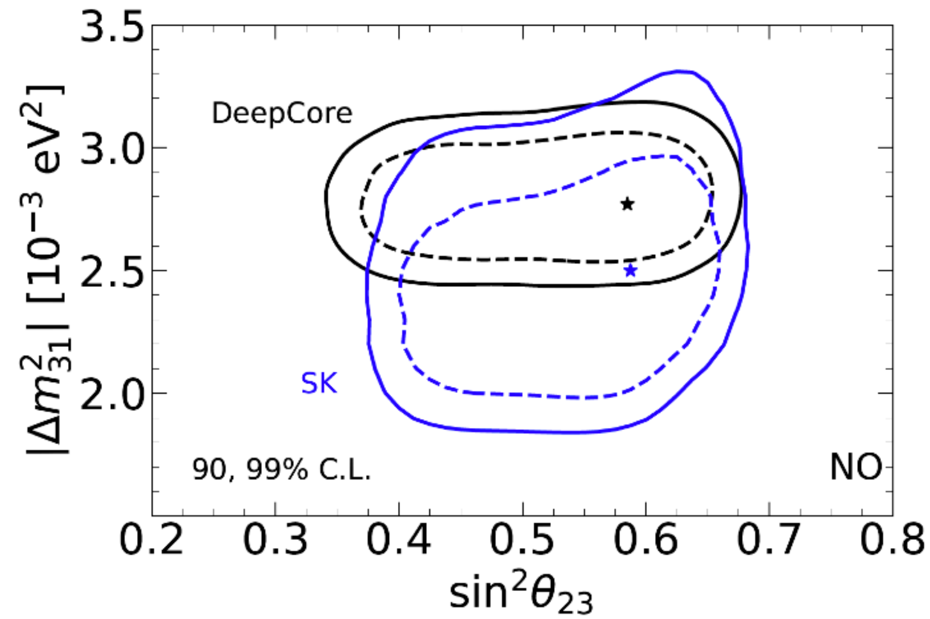
solar sector

Cl, Ga, SK

SNO, Borexino

KamLAND





atmospheric results

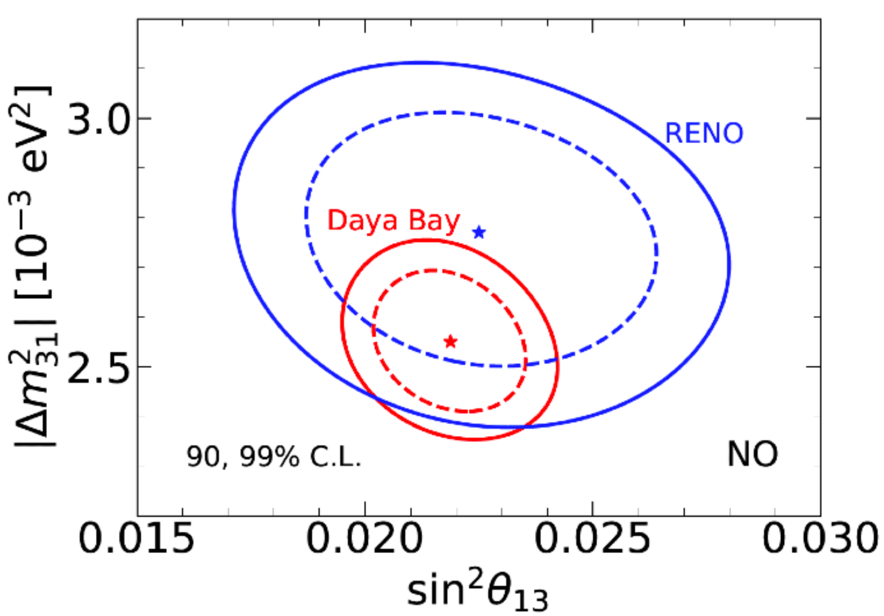
Super-K

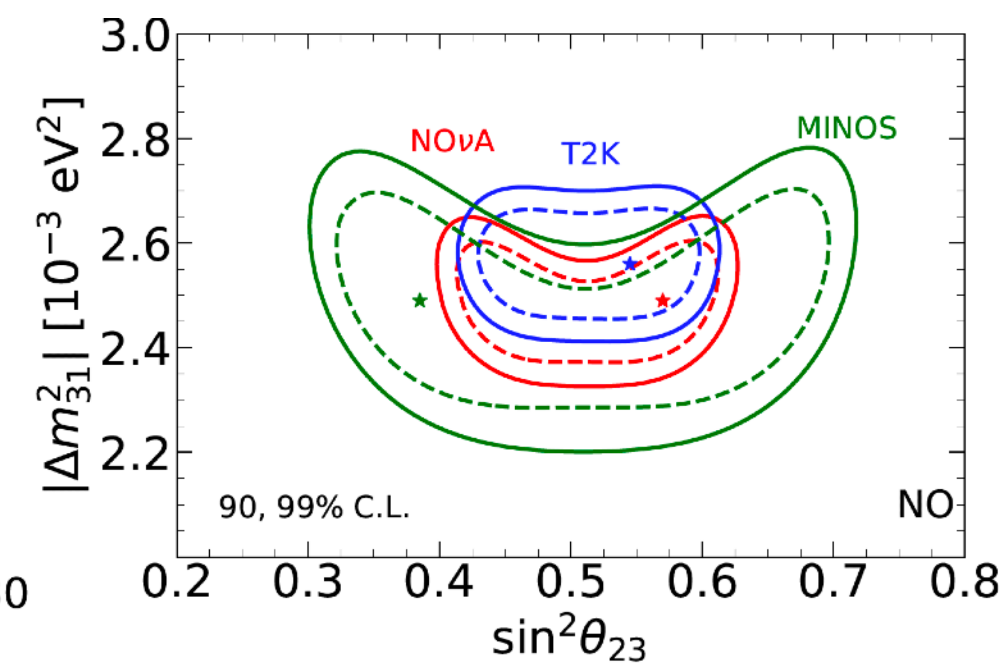
IC-DeepCore

SBL reactors

Daya Bay

RENO





LBL experiments

MINOS

T2K

NOvA

Neutrino oscillation parameters

de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]

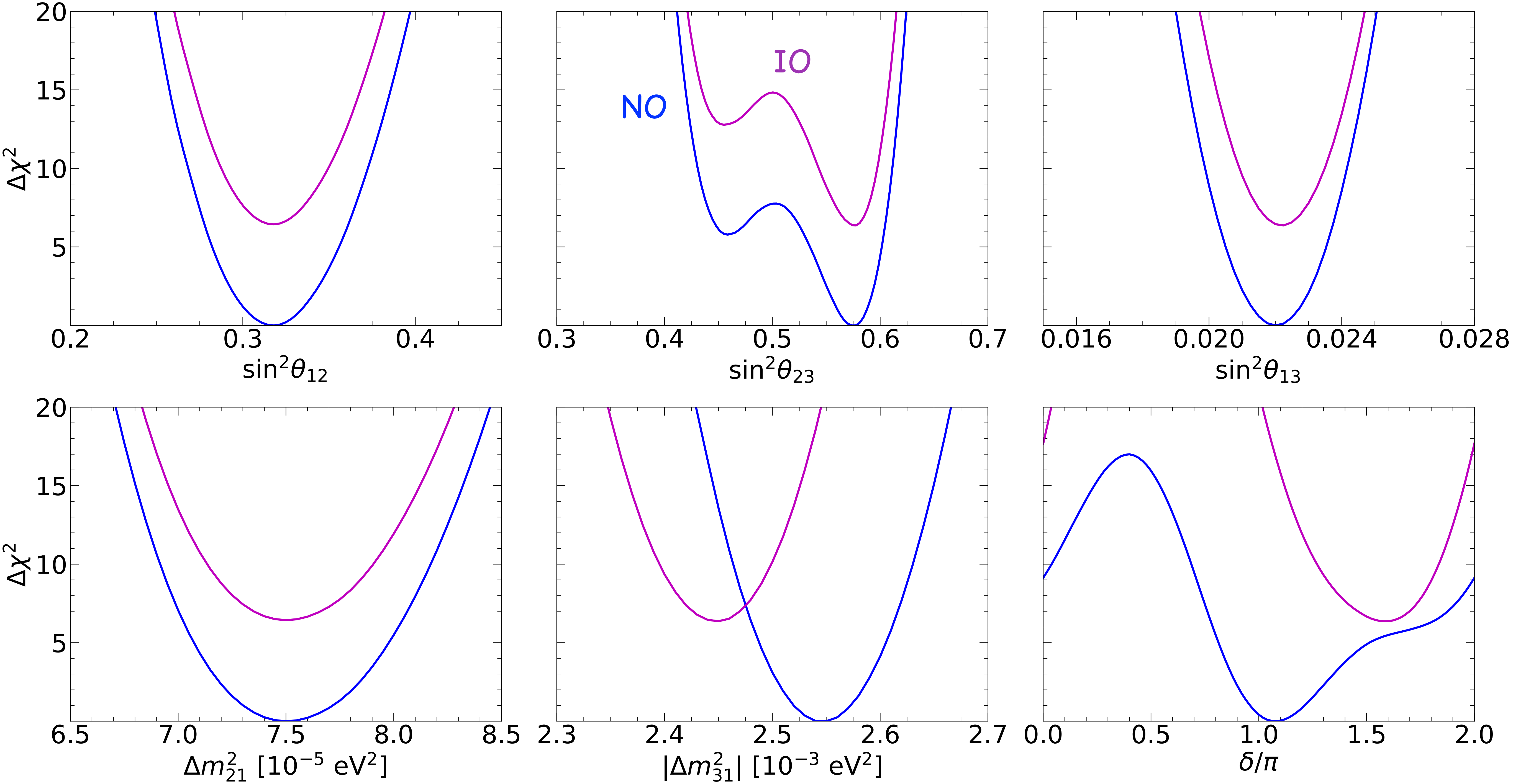
See also NuFIT and Bari group analyses

https://globalfit.astroparticles.es/

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1.1%
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.37–2.53	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71–3.69	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	5.74 ± 0.14	4.34–6.10	5.1%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	4.33–6.08	
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.000–2.405	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.018–2.424	
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.71–1.99	20%
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.11–1.96	9.0%

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



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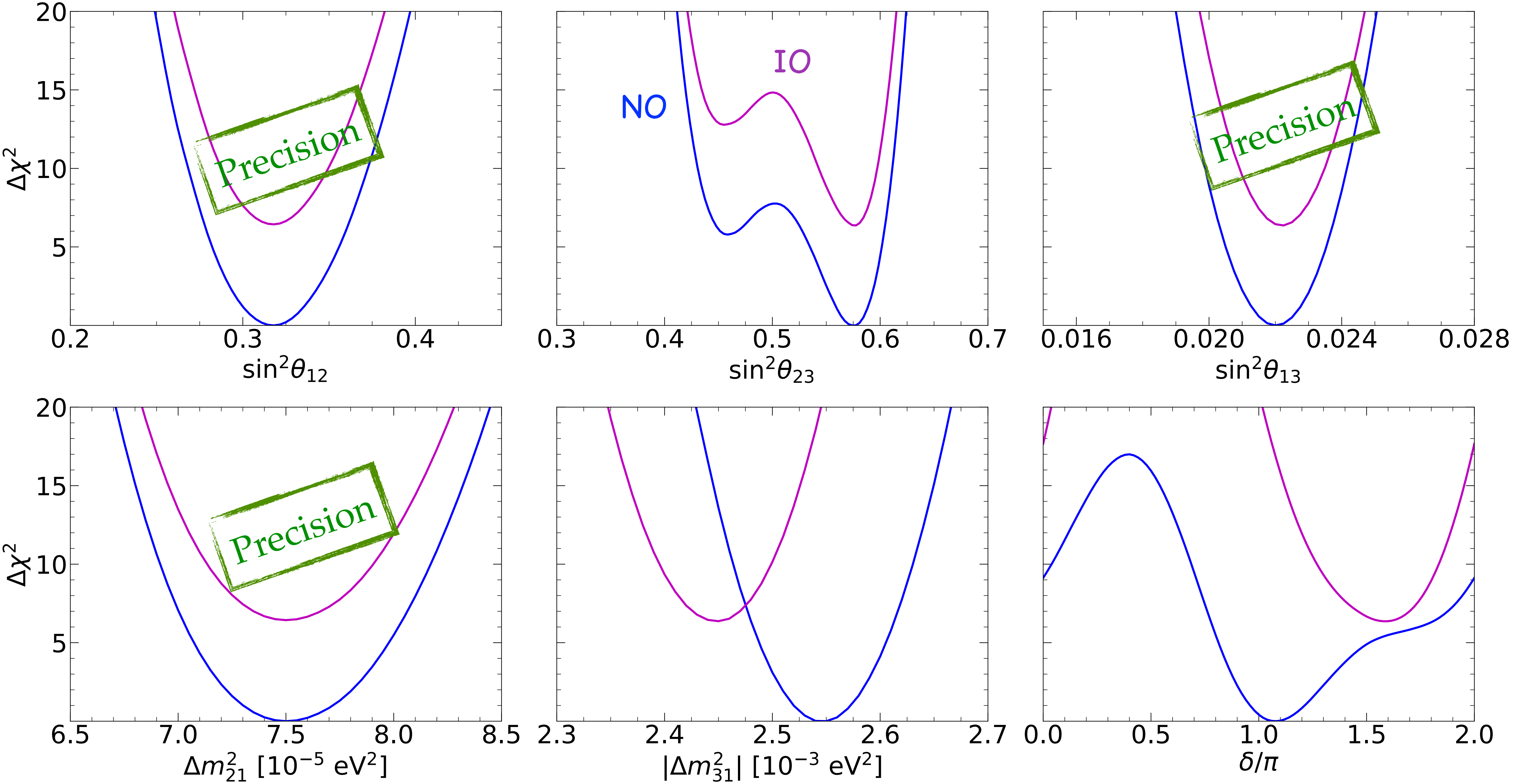

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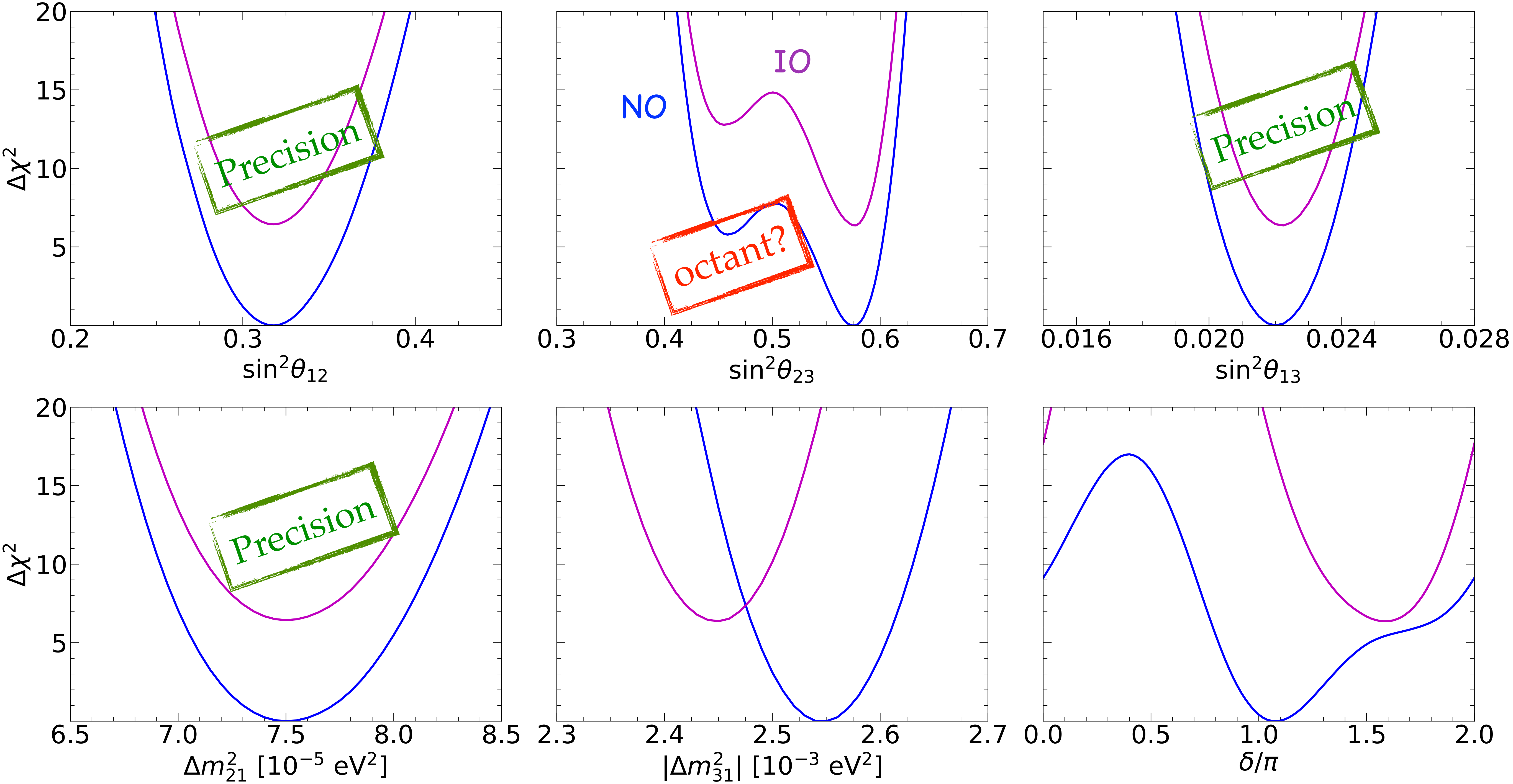

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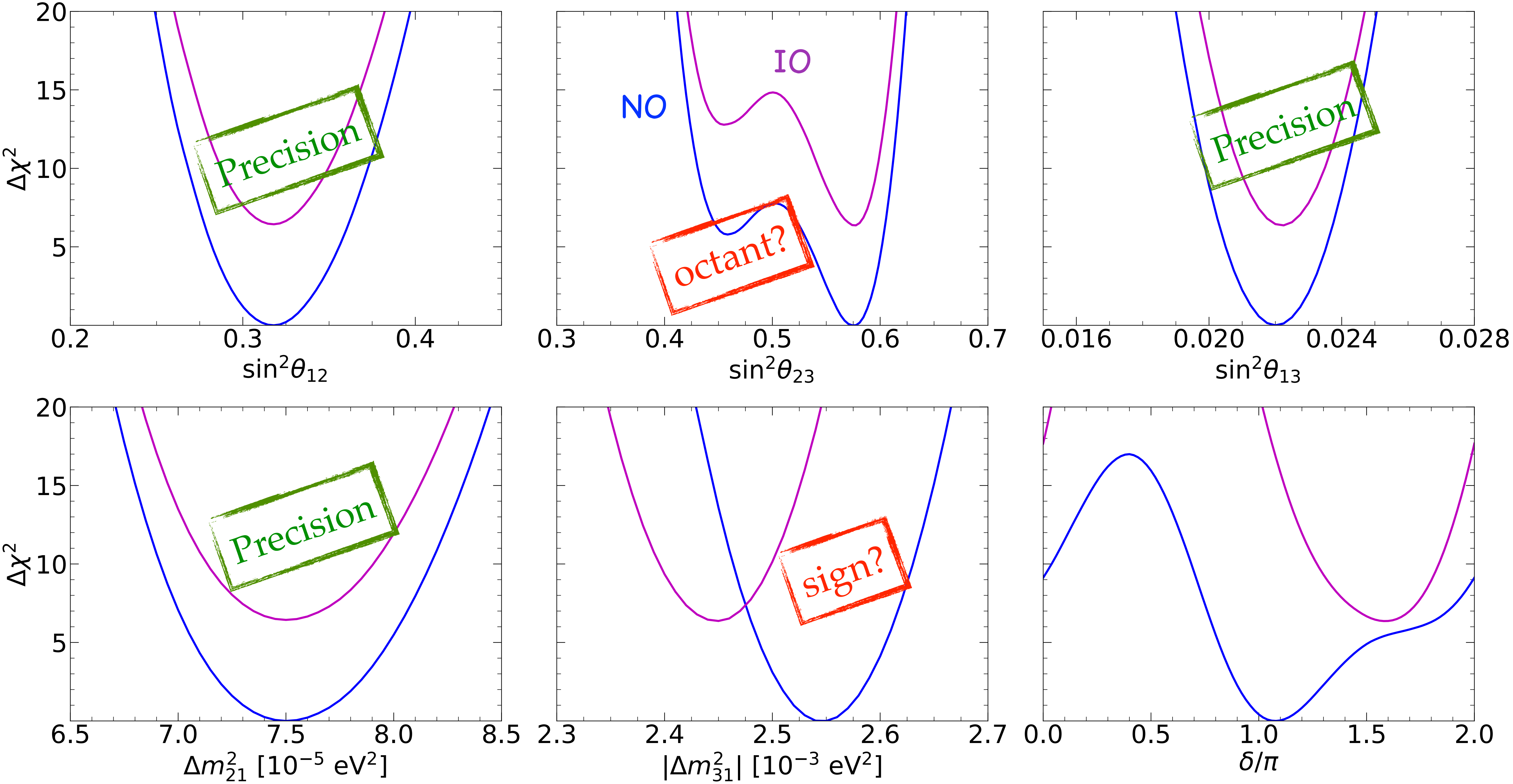

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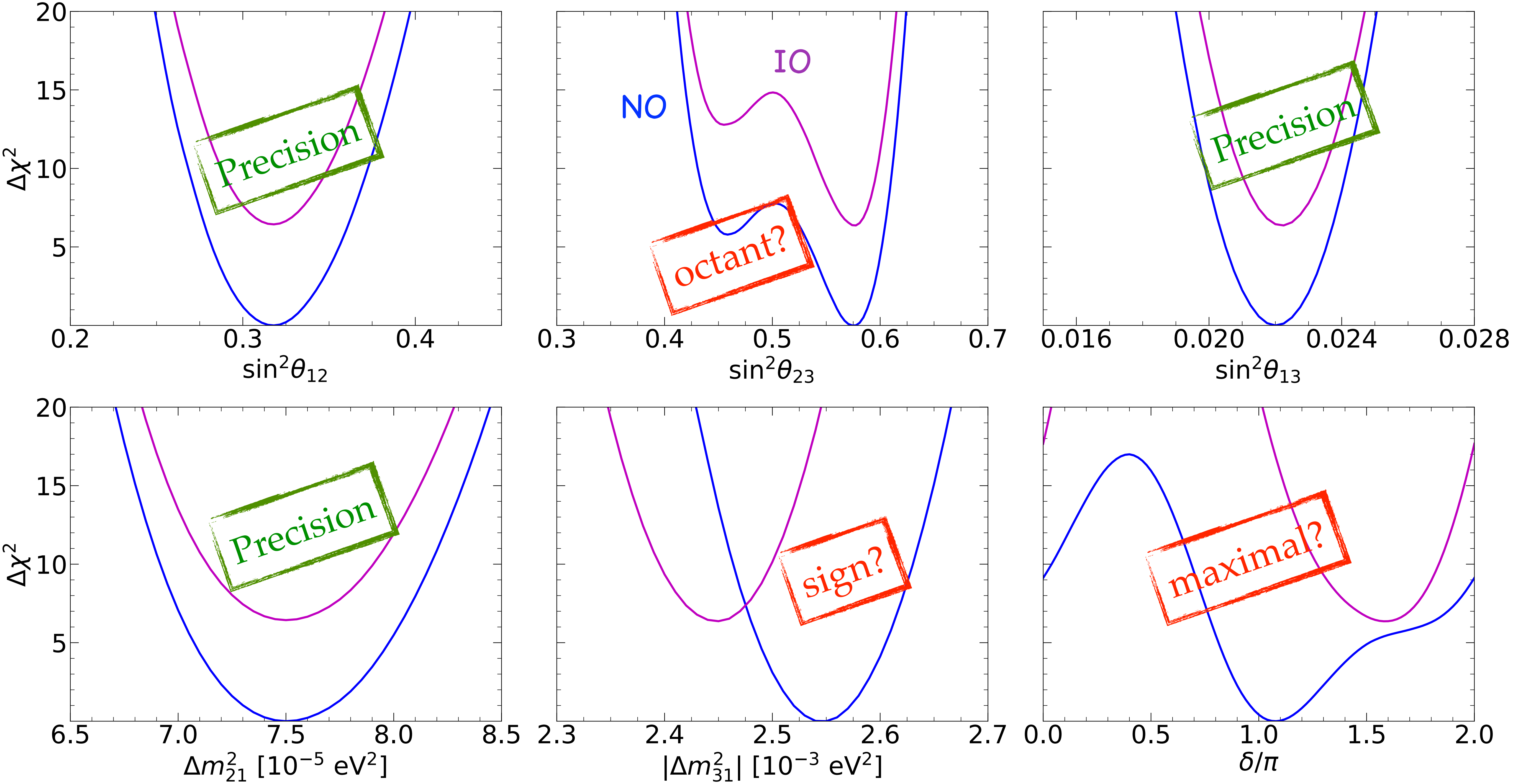

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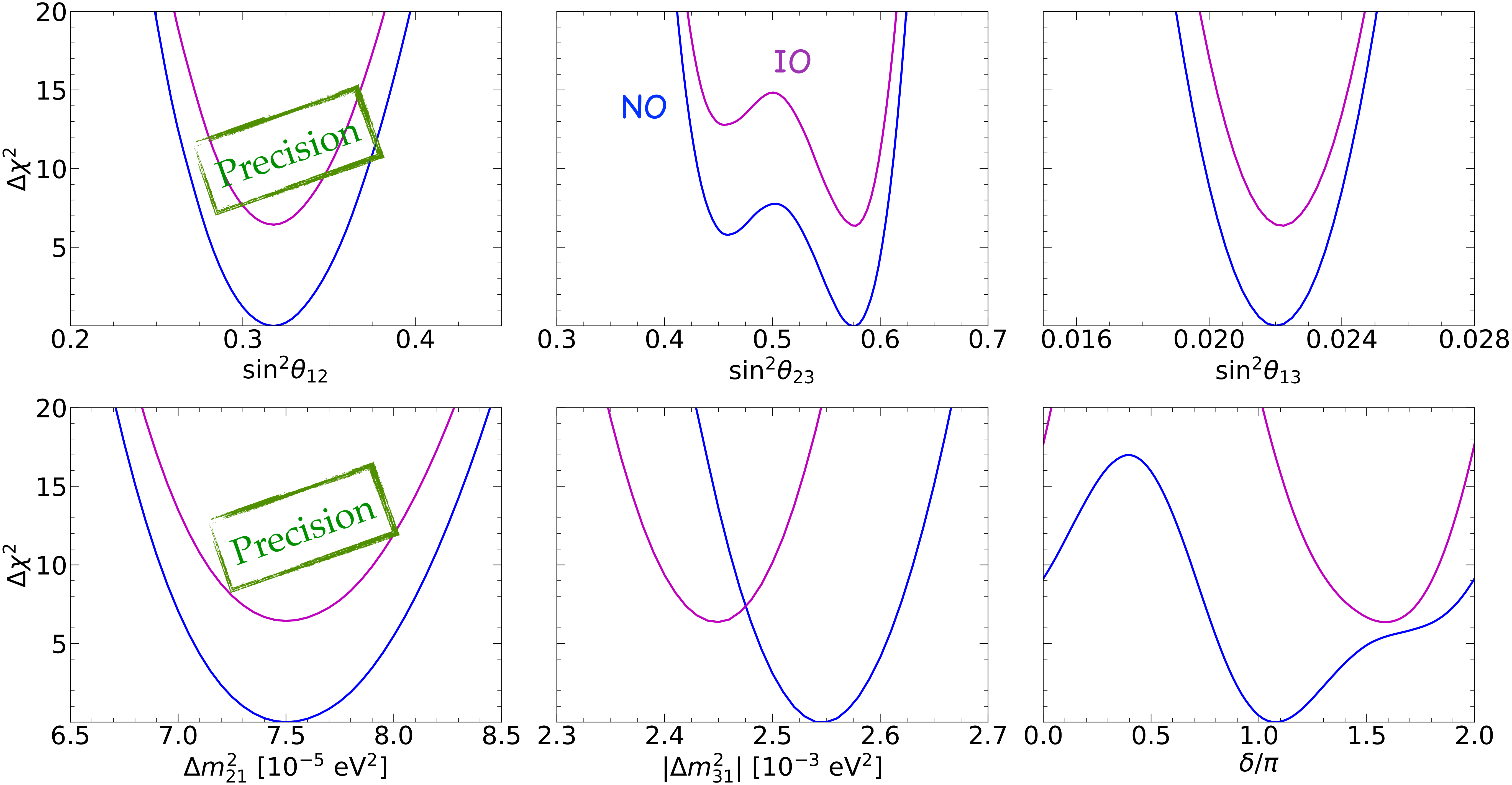
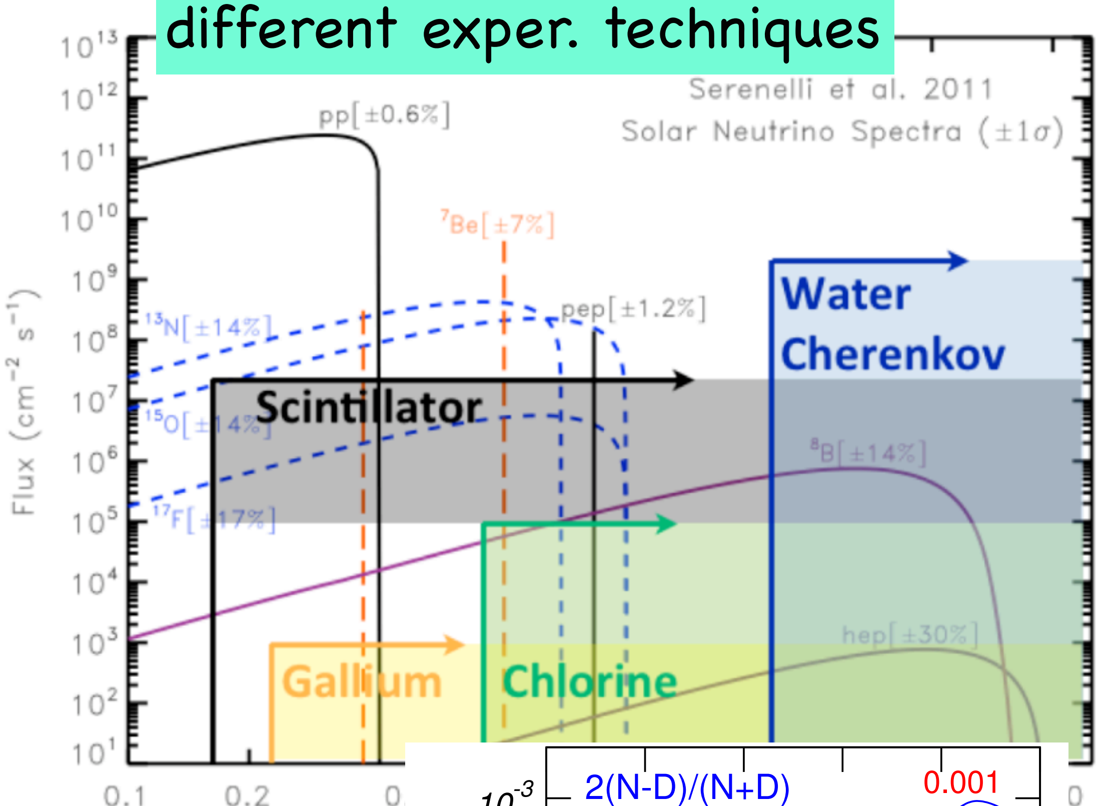


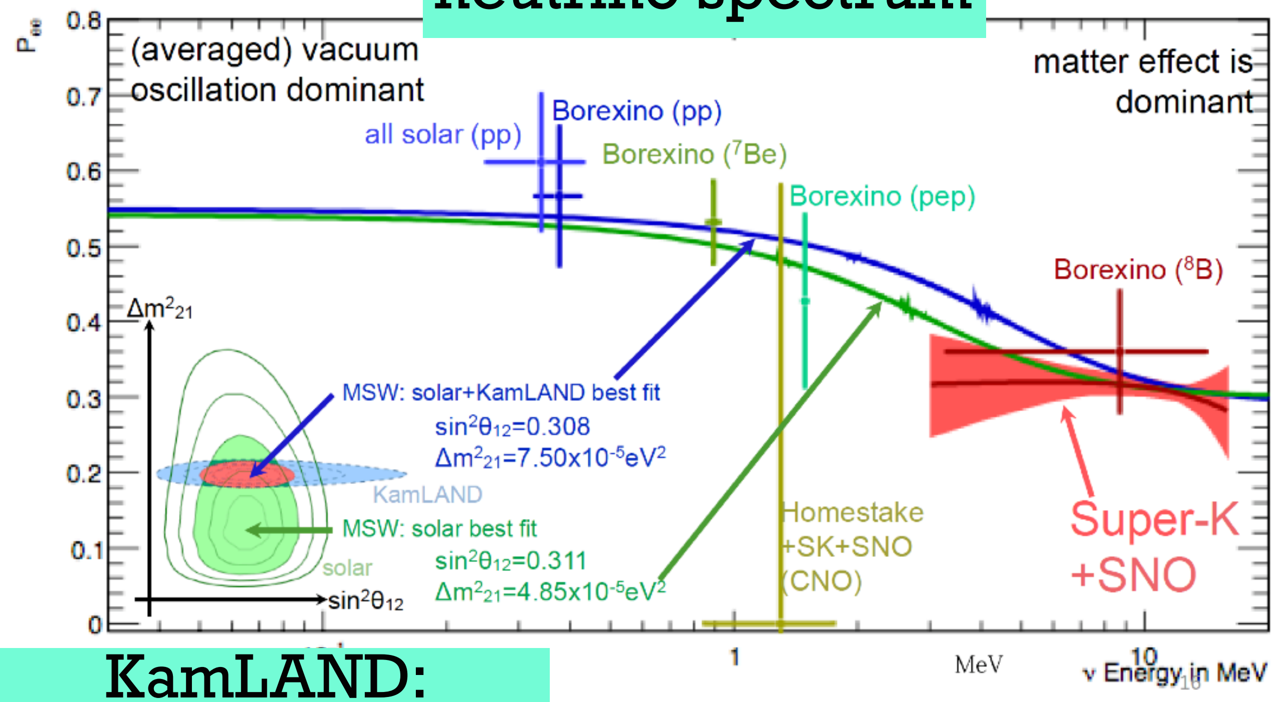
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

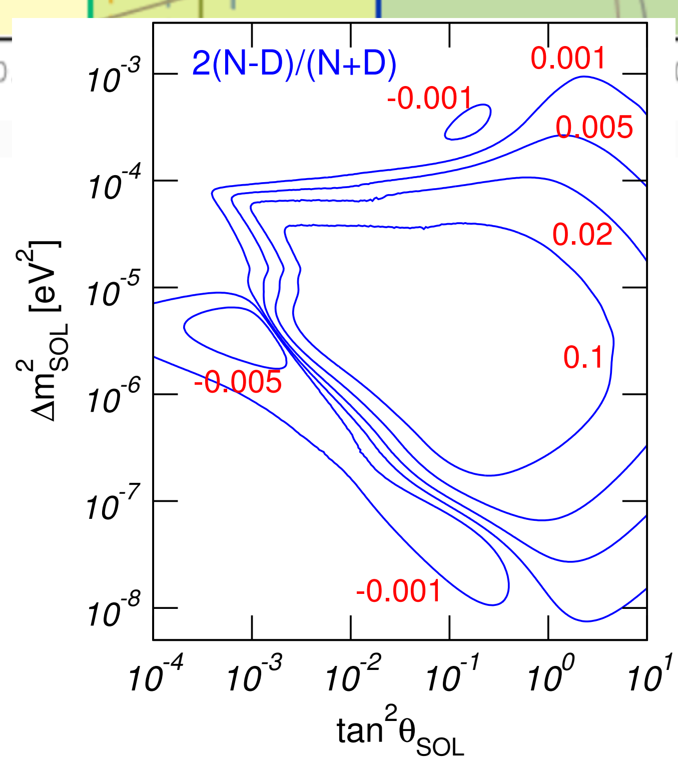
different exper. techniques



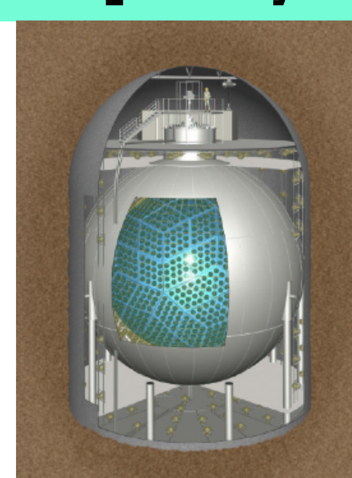
neutrino spectrum

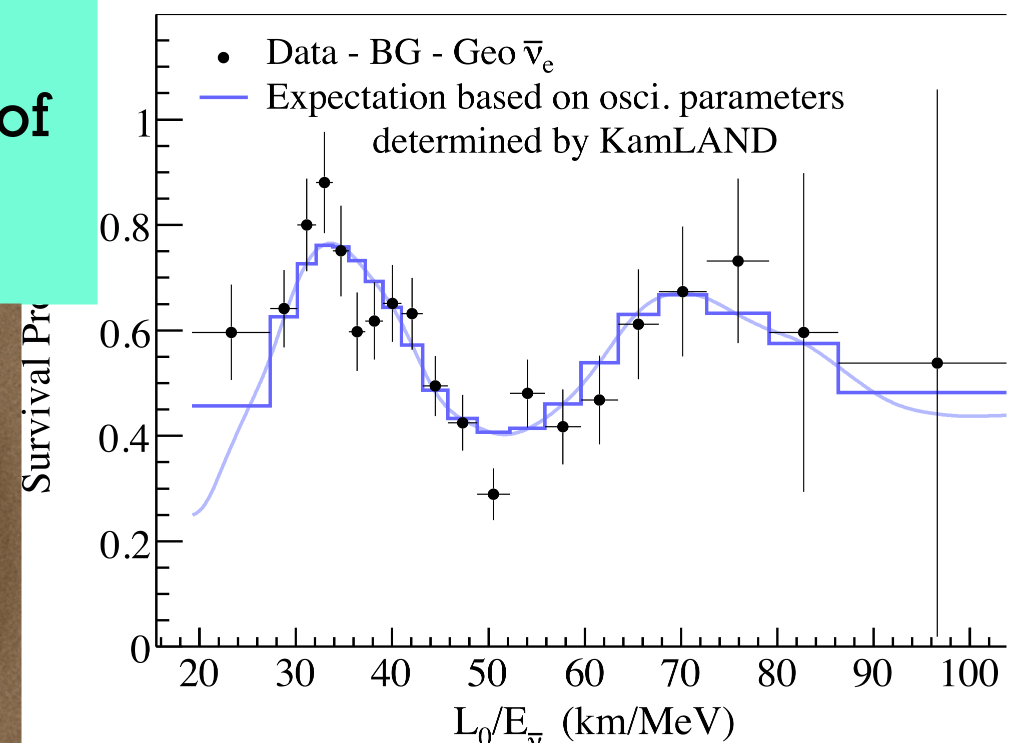


day/night asymmetry

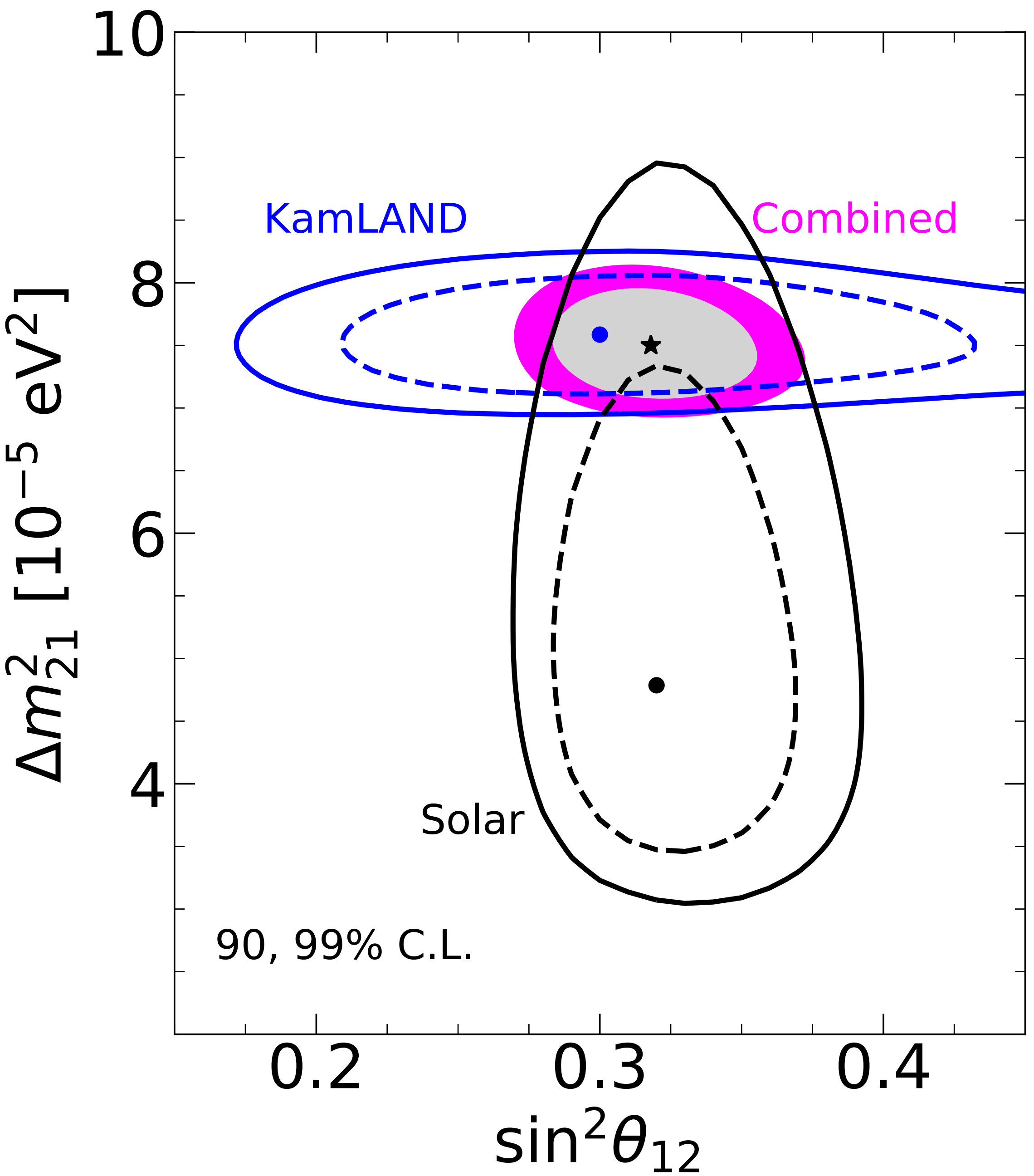


KamLAND: precise measurement of oscillation frequency





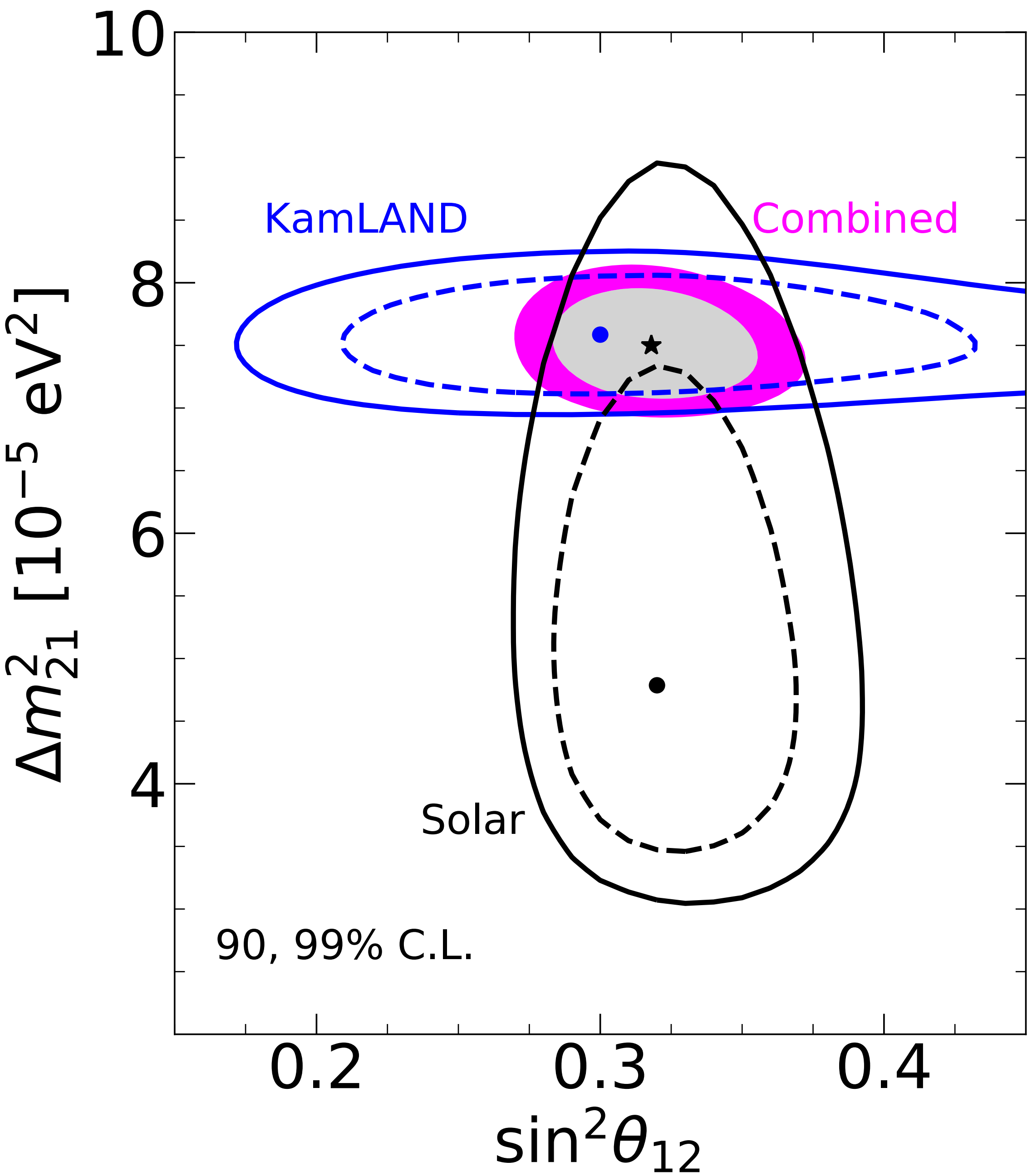
The solar sector



de Salas et al, **JHEP 02 (2021) 071**
[arXiv:2006.11237]

- θ_{12} measurement is dominated by solar neutrino data
- Δm^2_{21} is better measured by KamLAND.
- 2σ mismatch between the values of Δm^2_{21} measured by solar and KamLAND

The solar sector



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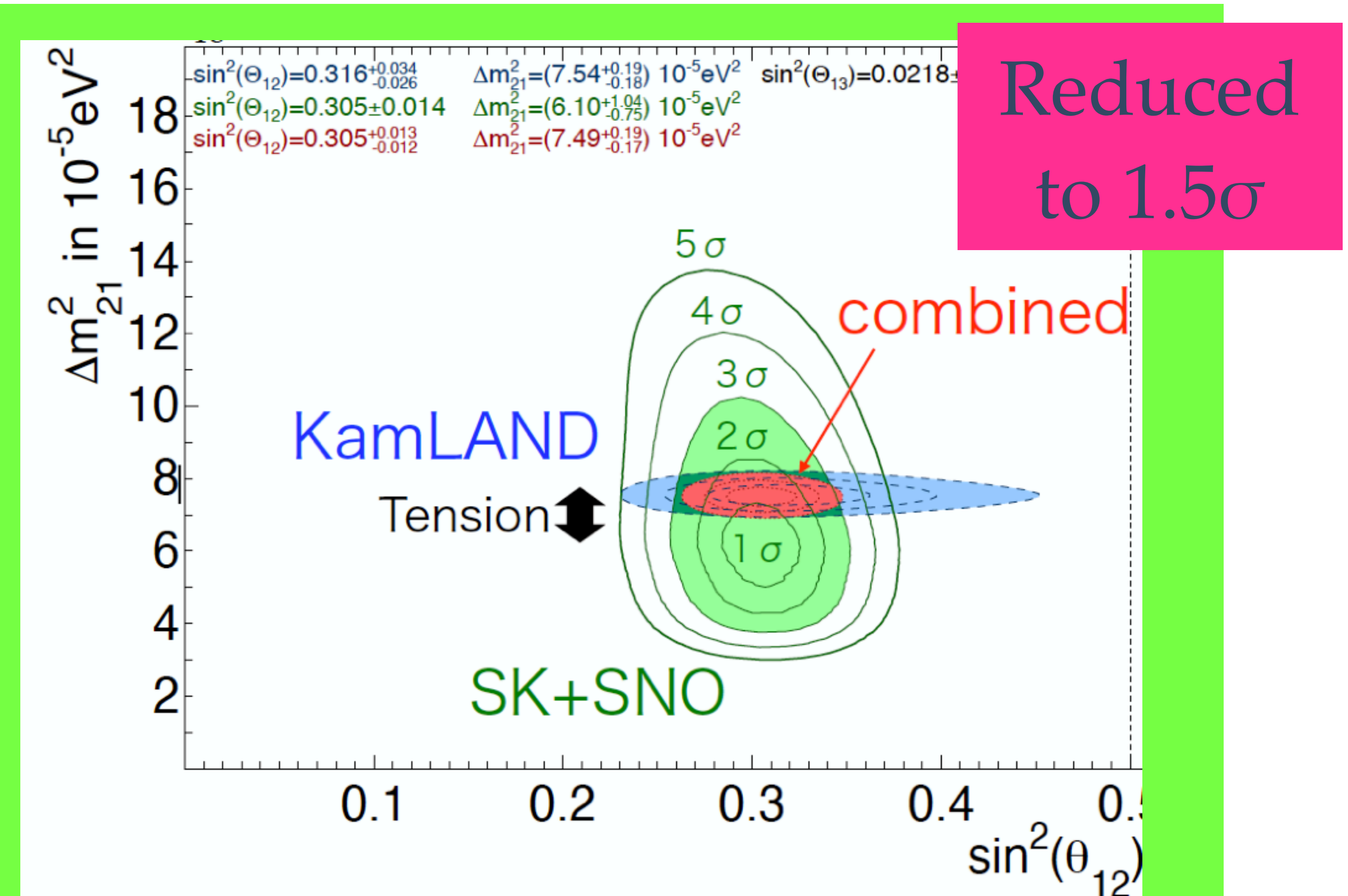
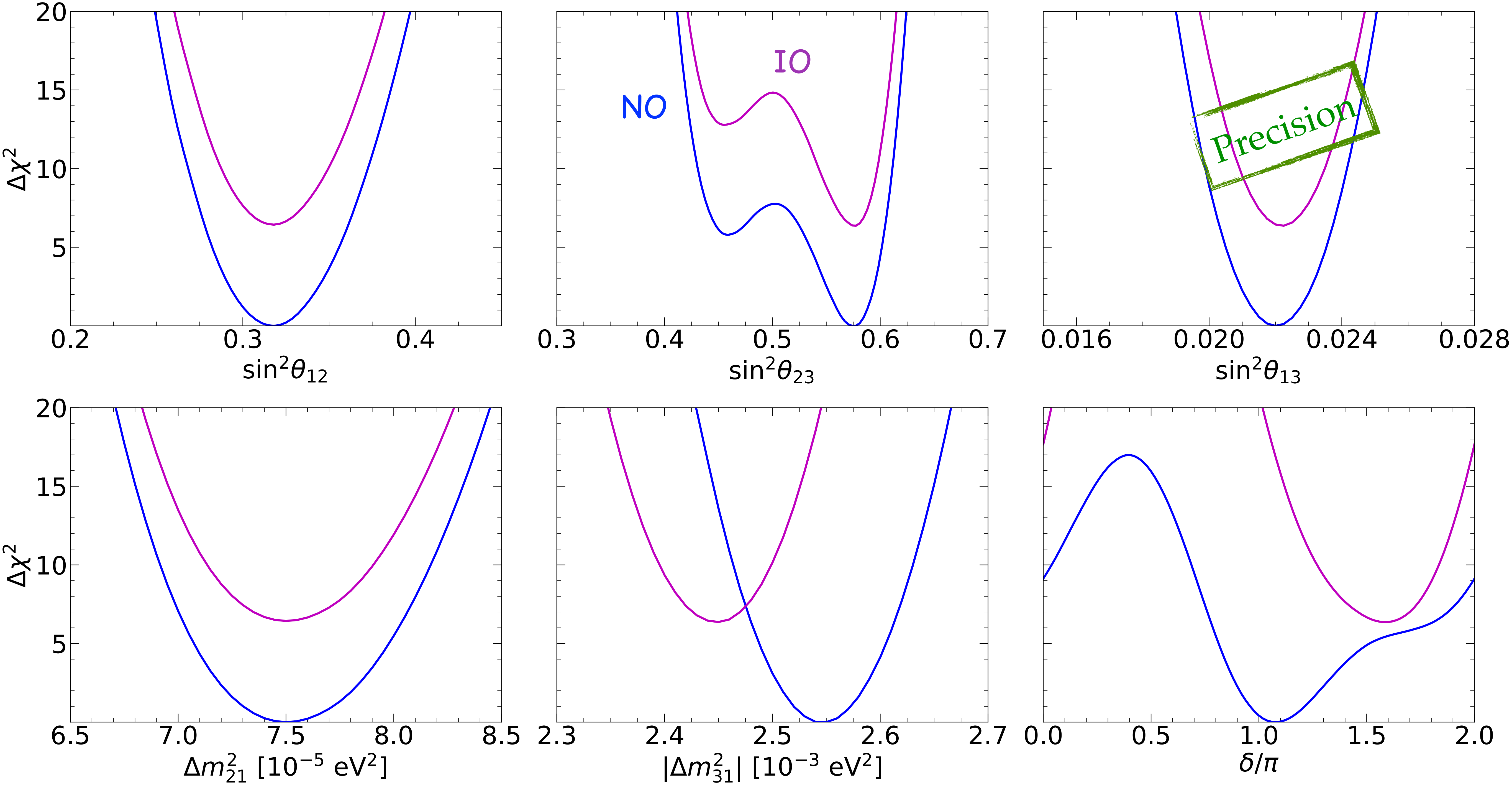


Y. Koshio, Neutrino-2022

Global fit to ν oscillation parameters

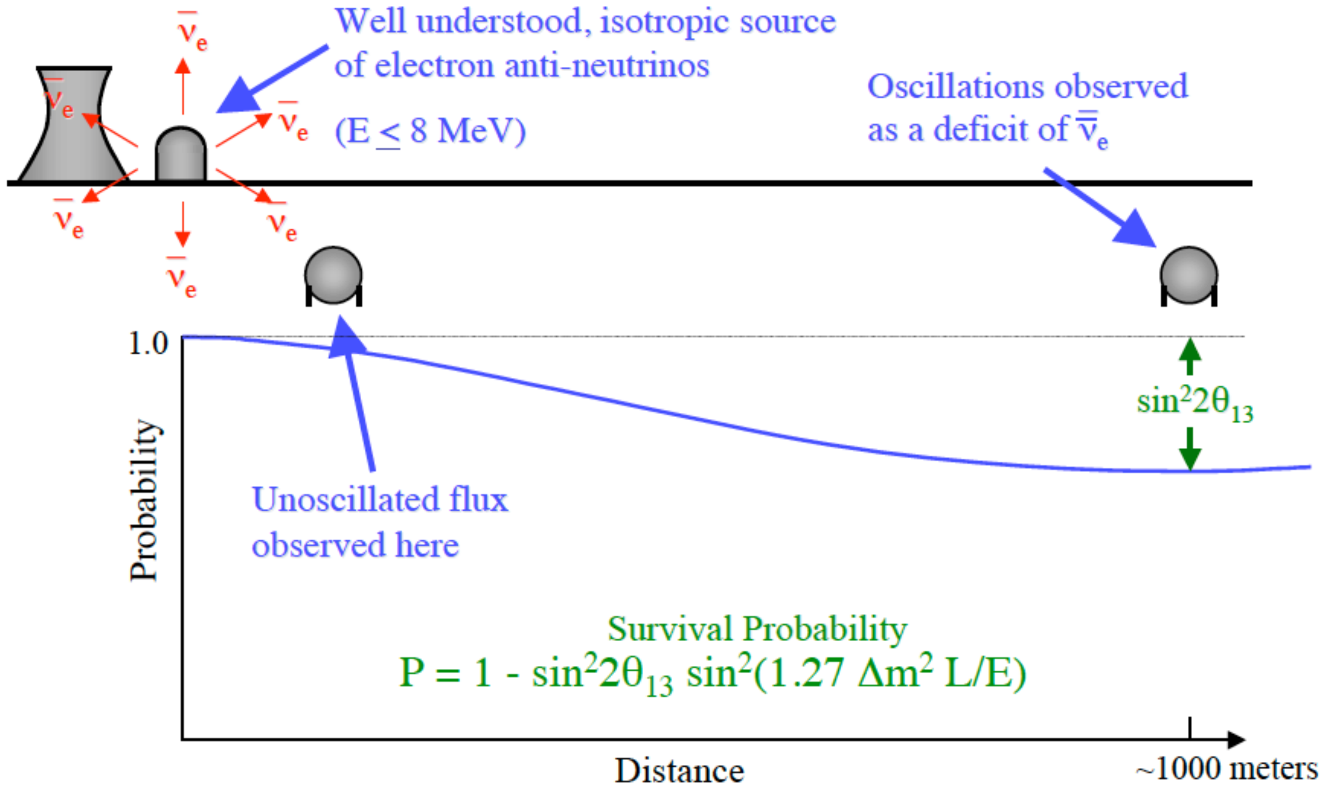
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The reactor sector

New generation of SBL reactor experiments

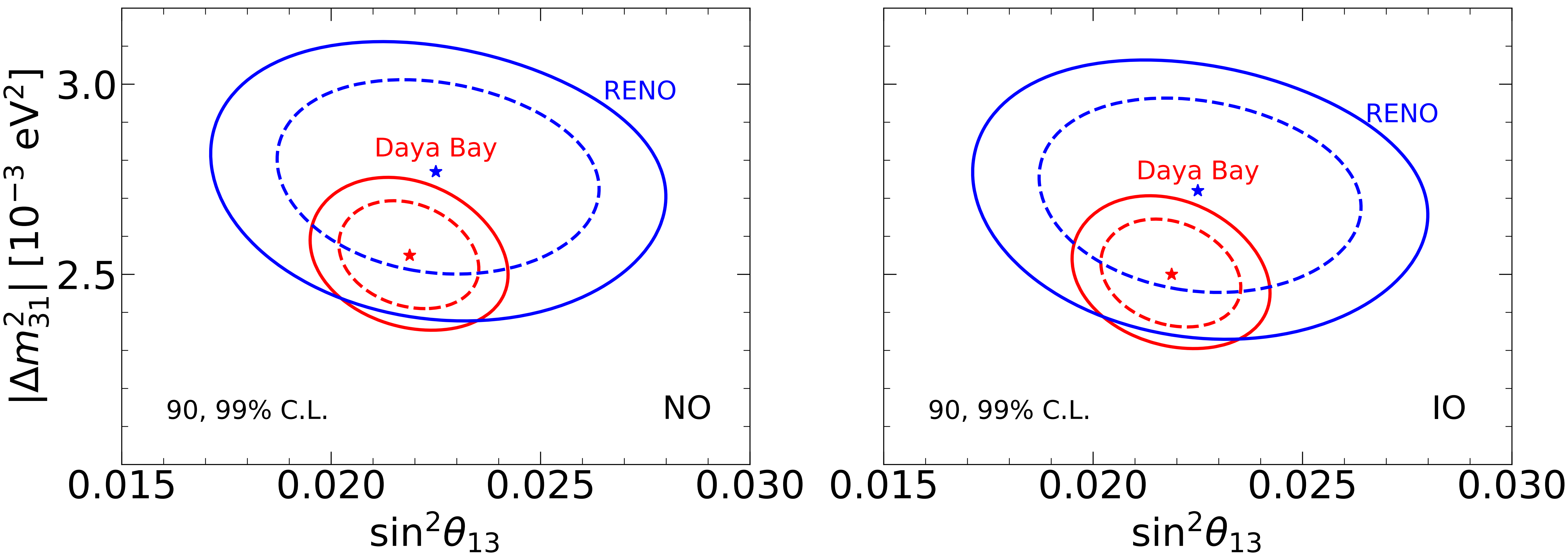
- more powerful reactors
- larger detector volume
- 2-8 detectors at 100 m – 1 km



6 cores + 4 ND + 4FD 2 cores + 1 ND + 1 FD 6 cores + 1 ND + 1 FD

The reactor sector

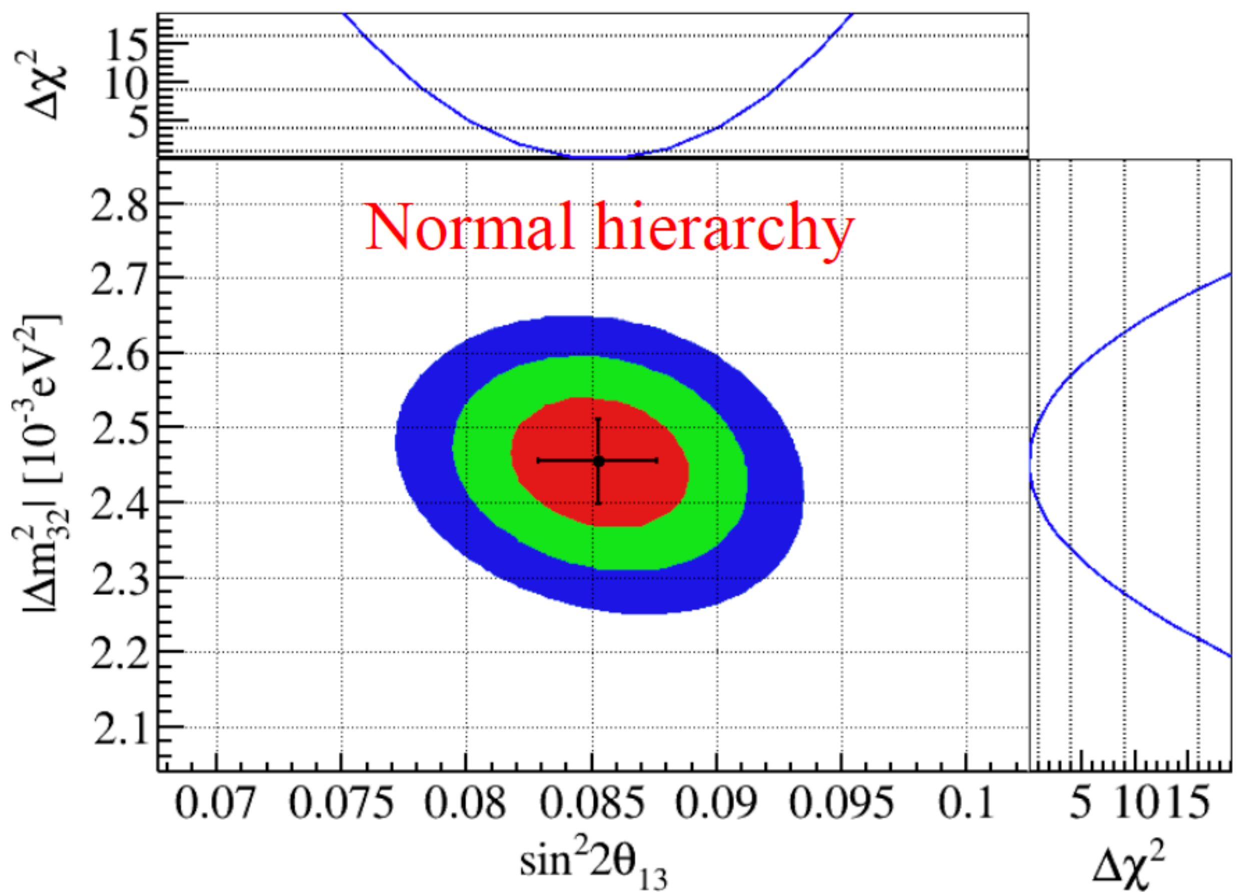
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]

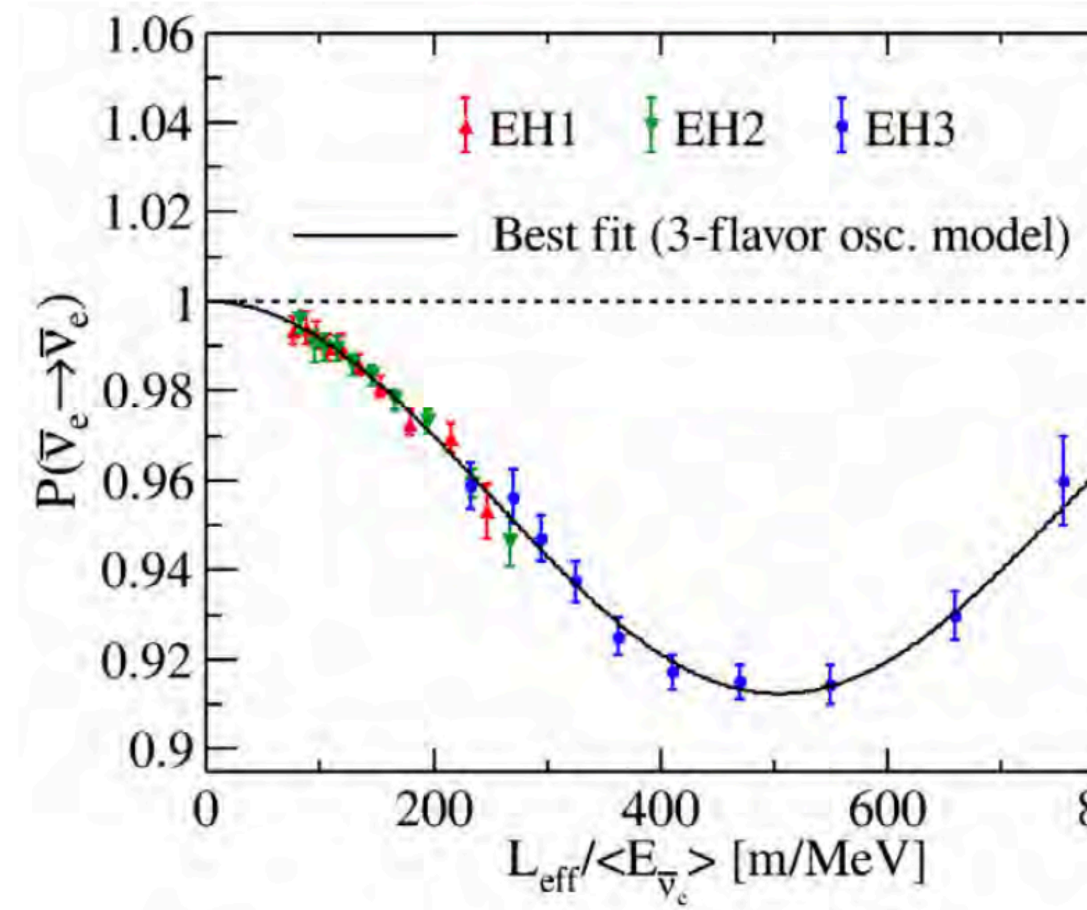


- Daya Bay: 1958-day data: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (3.4%)
- RENO: 2900-day data: $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ (7%)

Precision dominated by Daya Bay

The reactor sector





Best-fit results: $\chi^2/\text{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

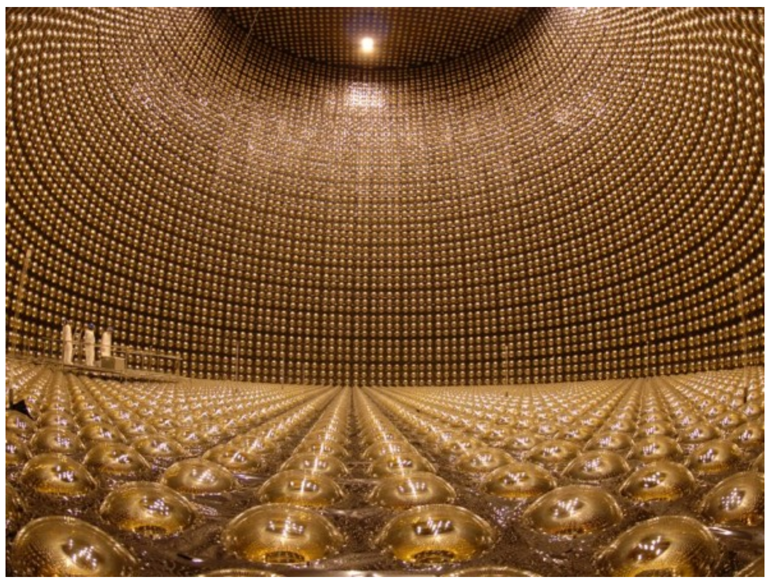
Daya Bay: 3158-day data

K. Luk, Neutrino-2022

The atmospheric sector

Atmospheric experiments

Super-Kamiokande



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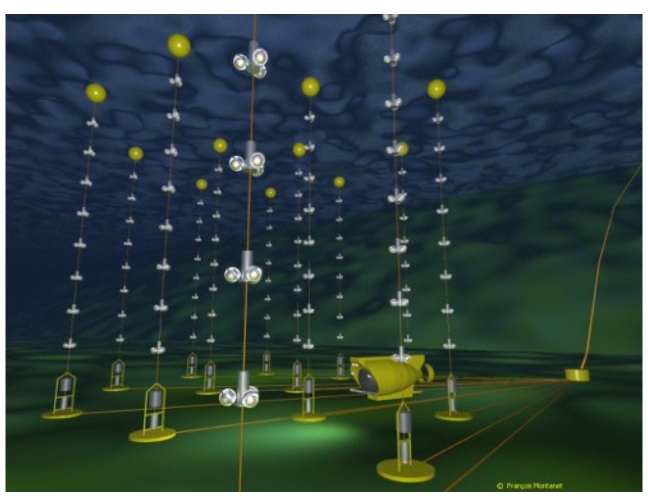
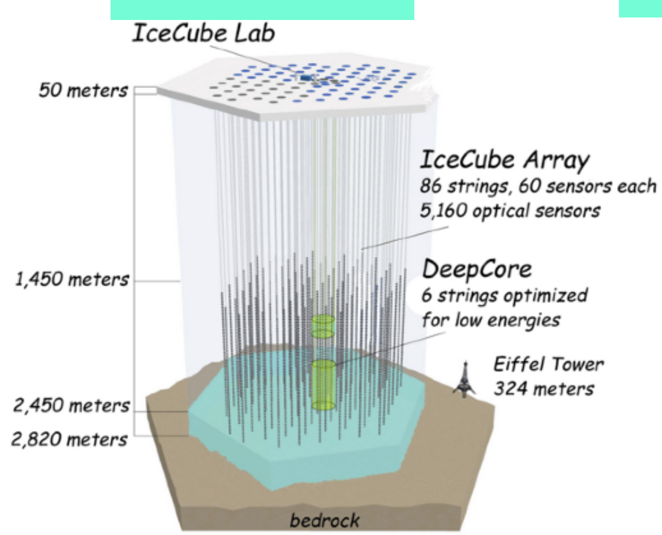
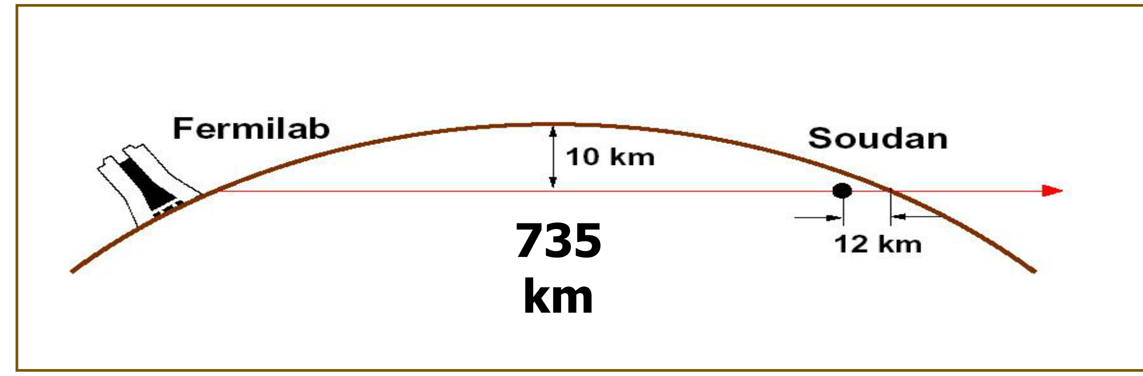


IceCube

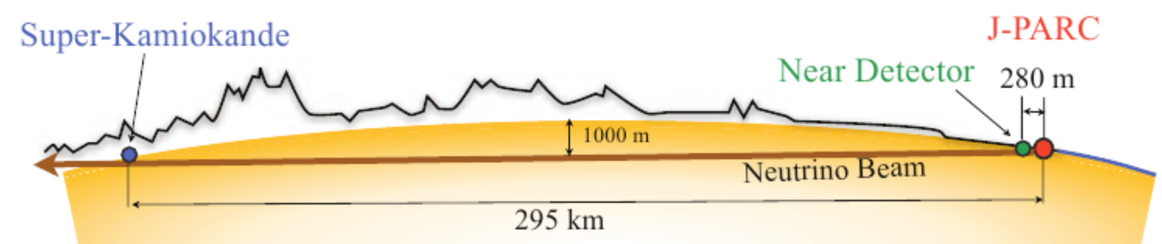


Accelerator long-baseline experiments

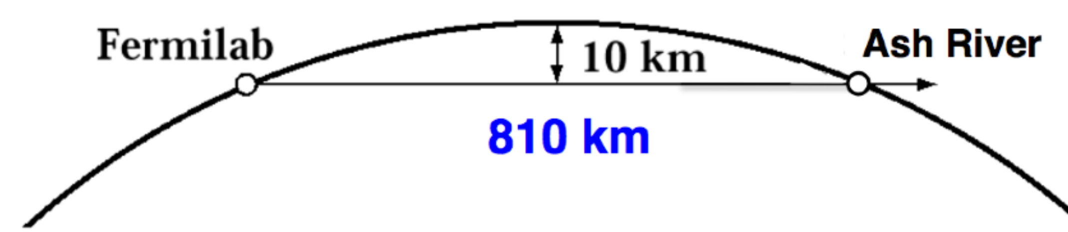
MINOS



T2K



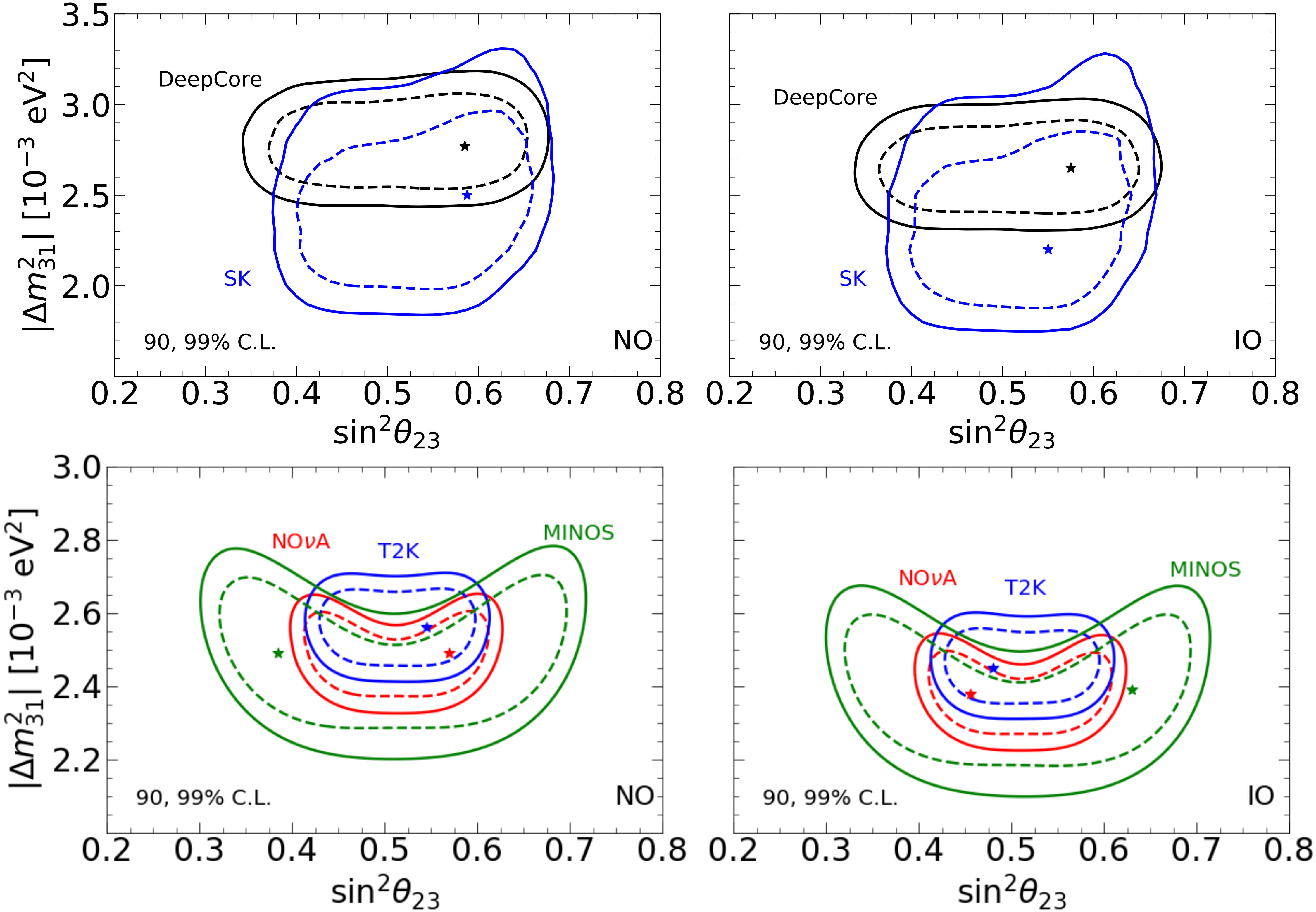
NOvA



→ consistent with atmospheric data

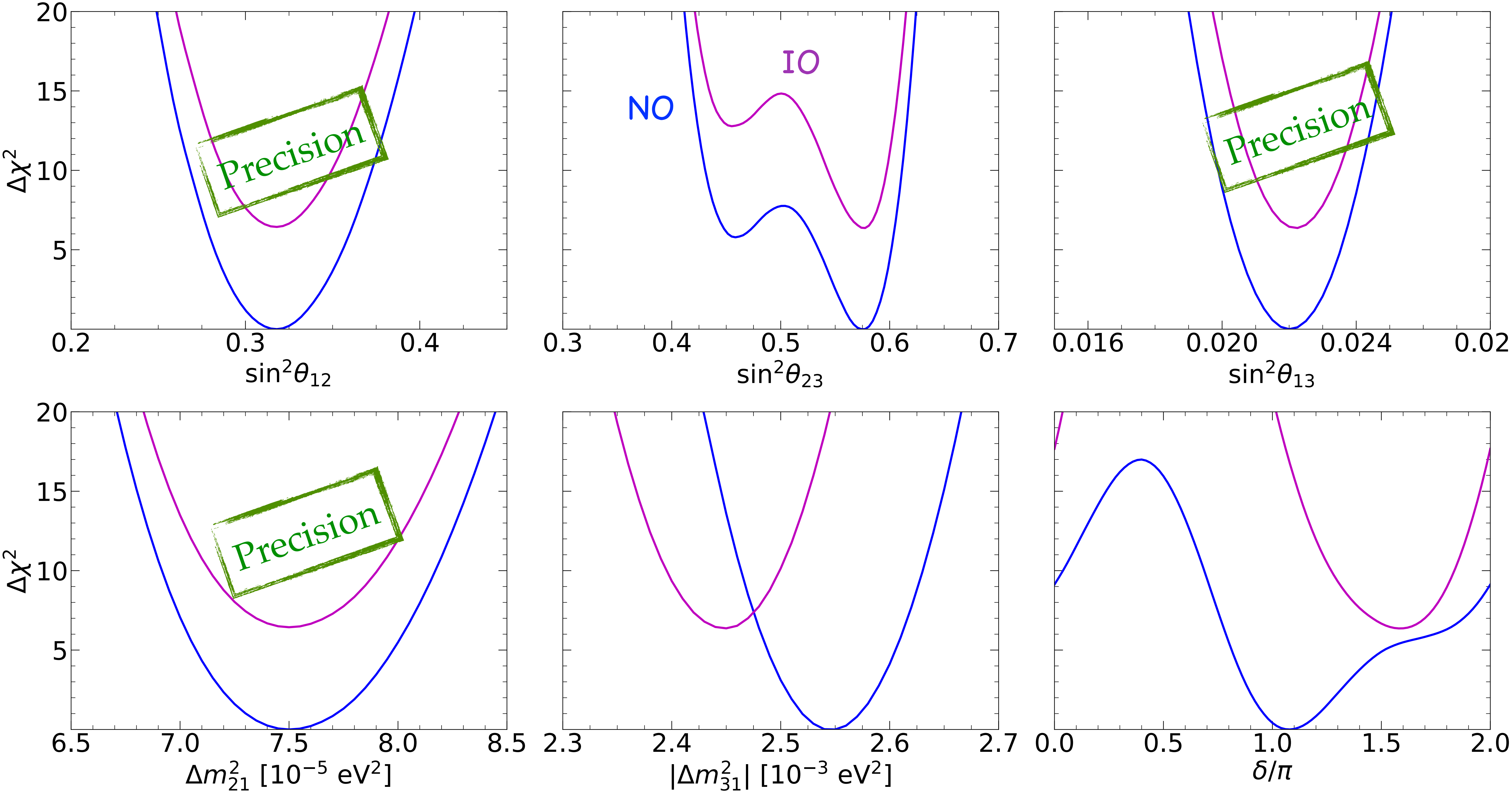
→ atm ν oscillations confirmed by lab exps

The atmospheric sector



Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]



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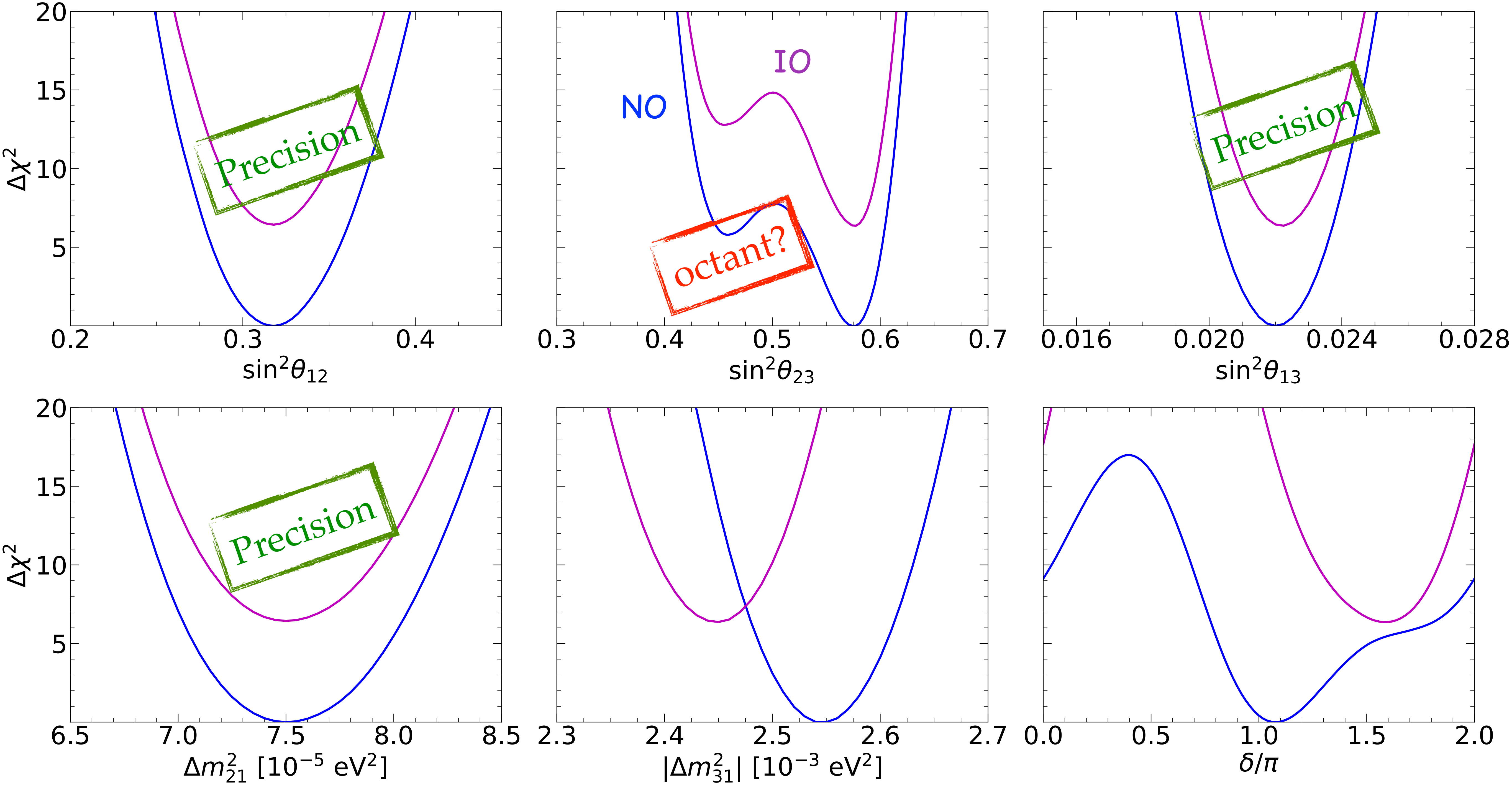
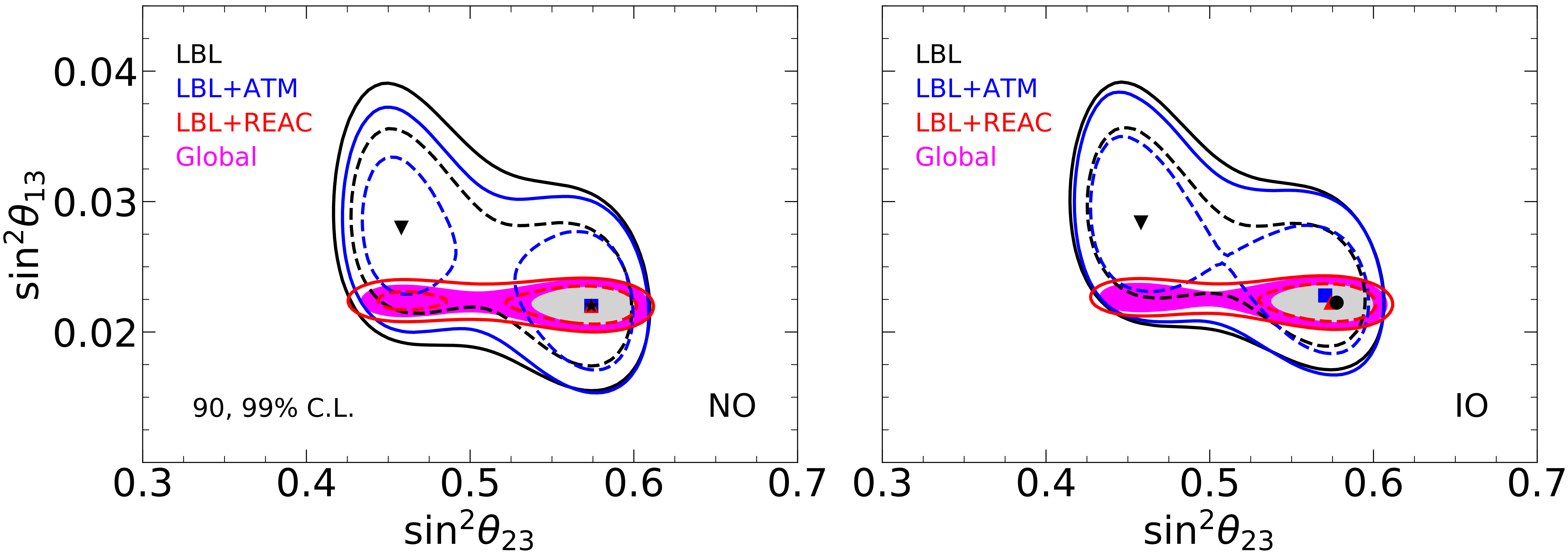


The octant of θ_{23}

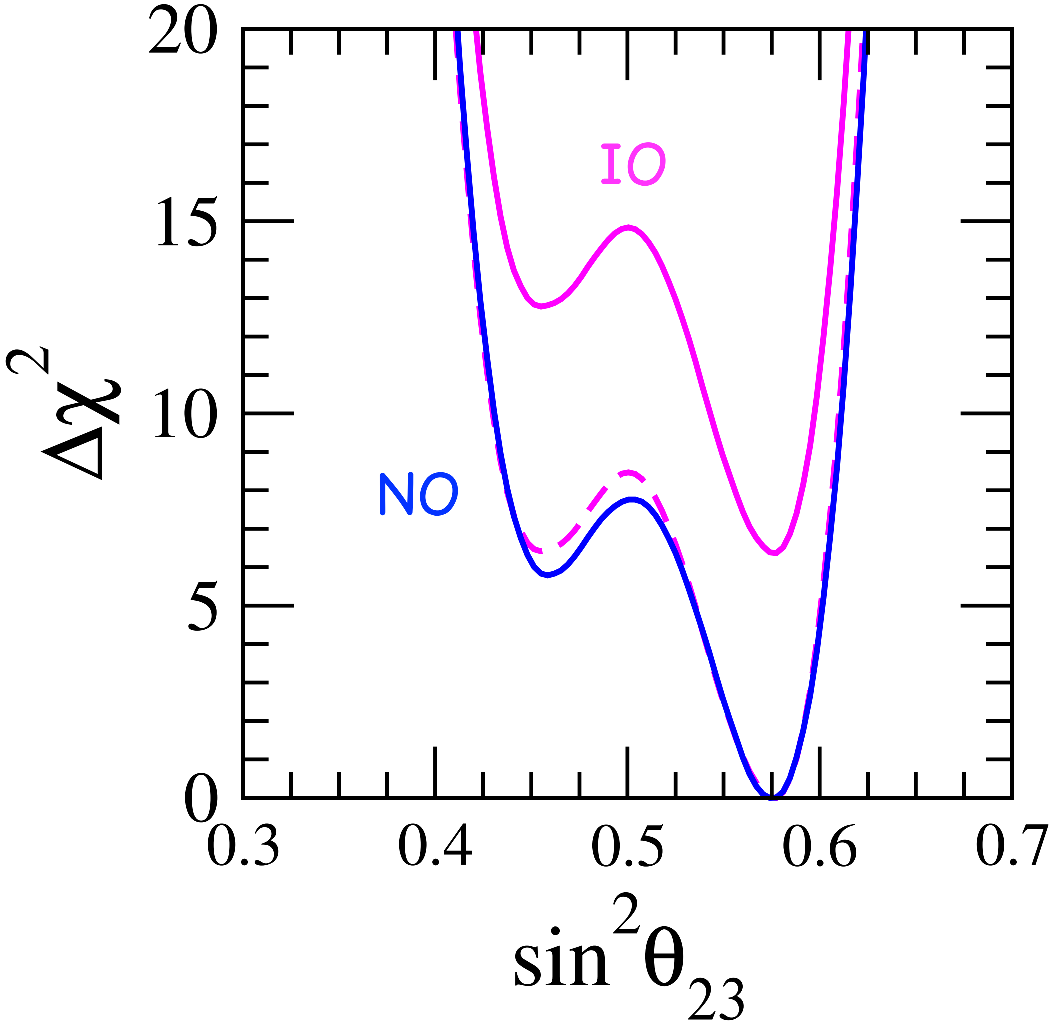
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



- The combination of LBL experiments prefers $\theta_{23} < 45°$ for both orderings
- The combination with atmospheric data shifts the preferred θ_{23} to the second octant
- The combination with SBL reactors also breaks the degeneracy in favor of 2nd octant

The octant of θ_{23}

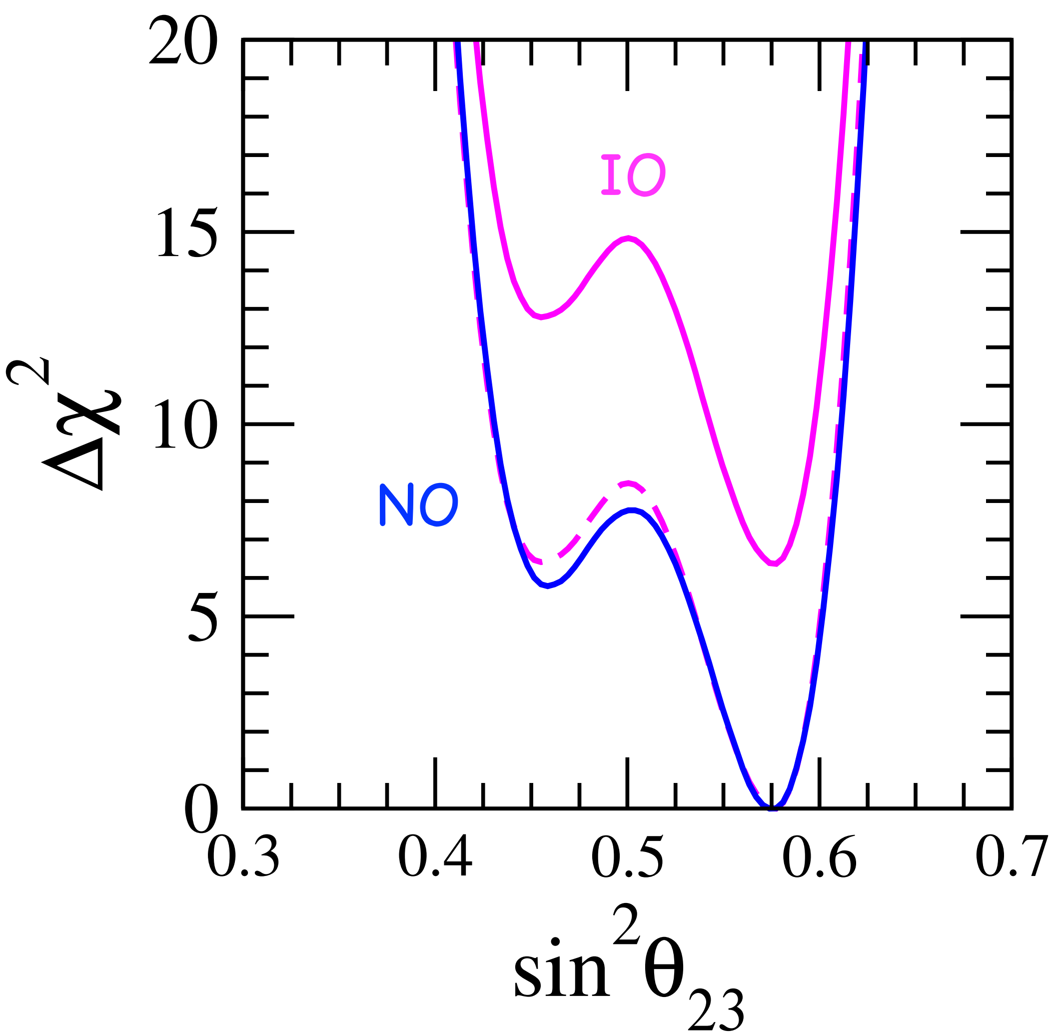
de Salas et al, JHEP 02 (2021) 071



Values at the 1st octant disfavored
with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)

The octant of θ_{23}

de Salas et al, JHEP 02 (2021) 071



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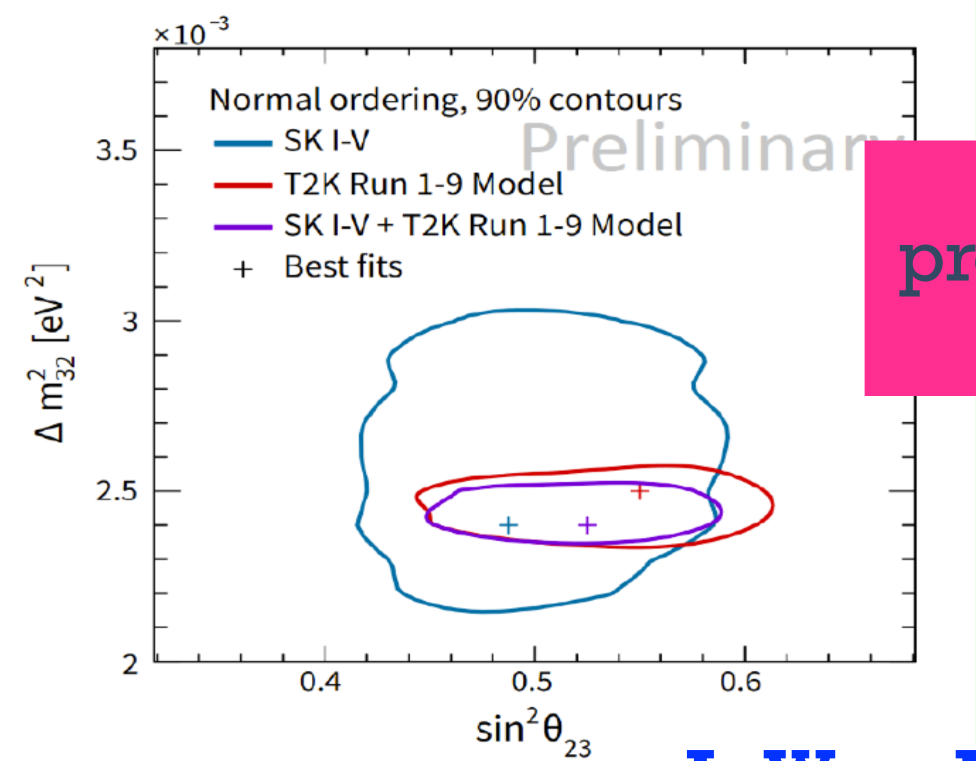
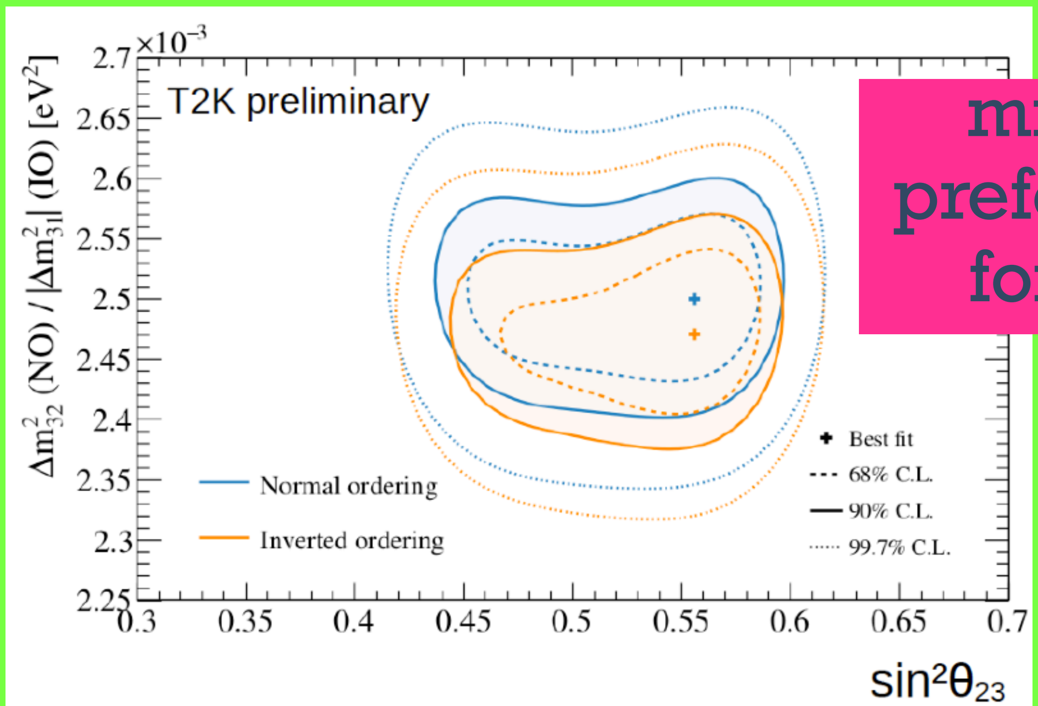


slight preference for LO

L. Wan, Nu 2022

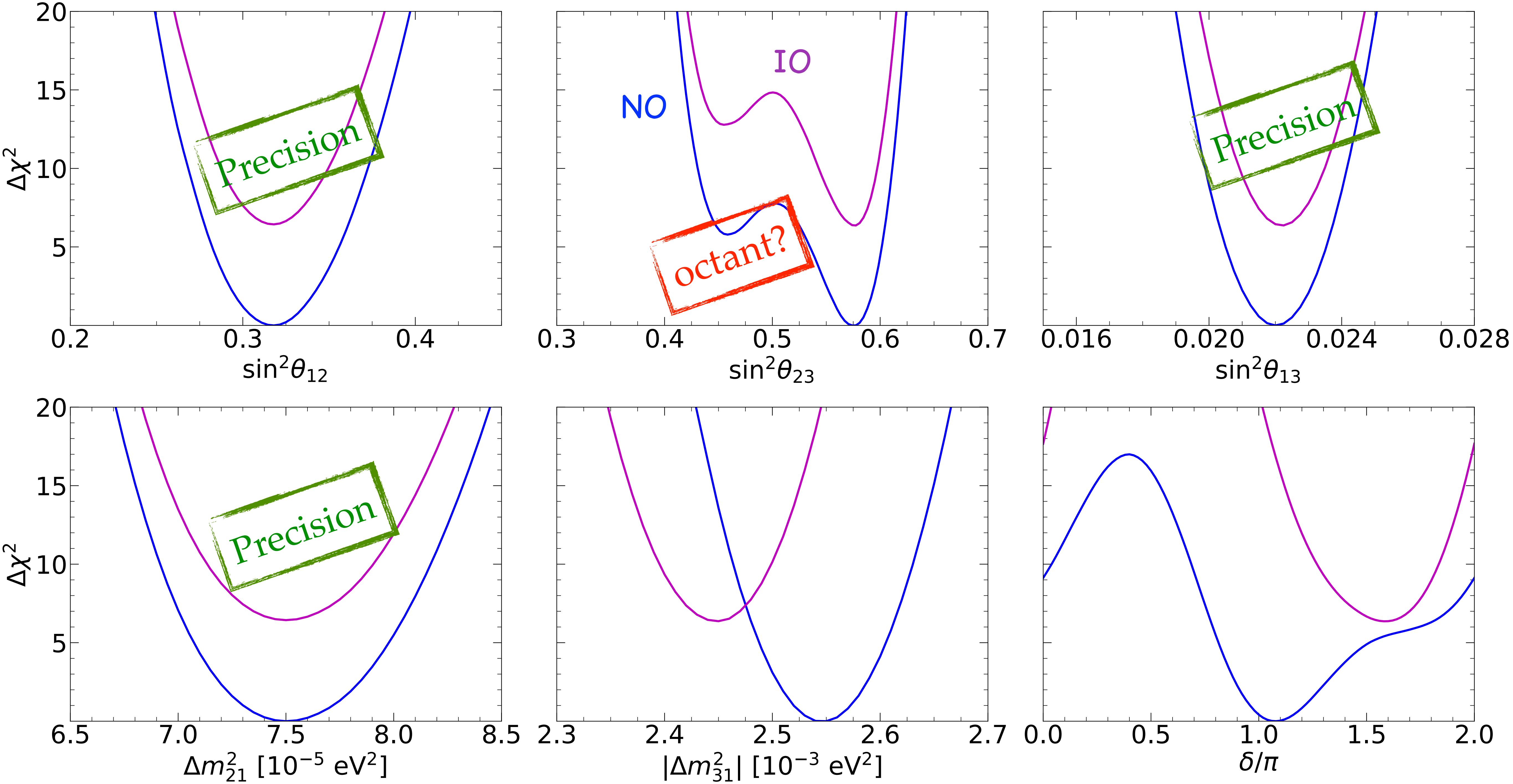


milder preference for UO

C. Bronner, Nu 2022

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



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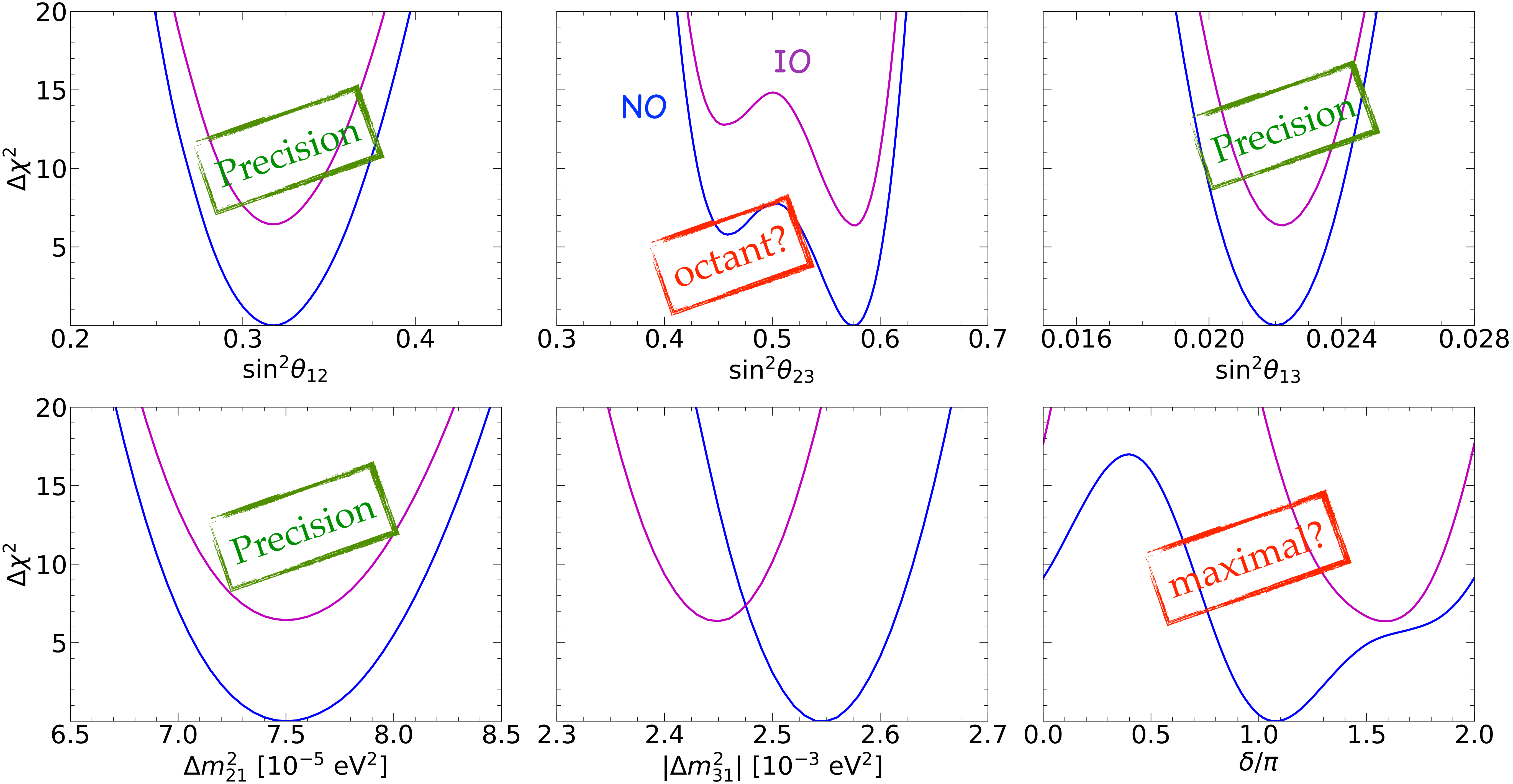
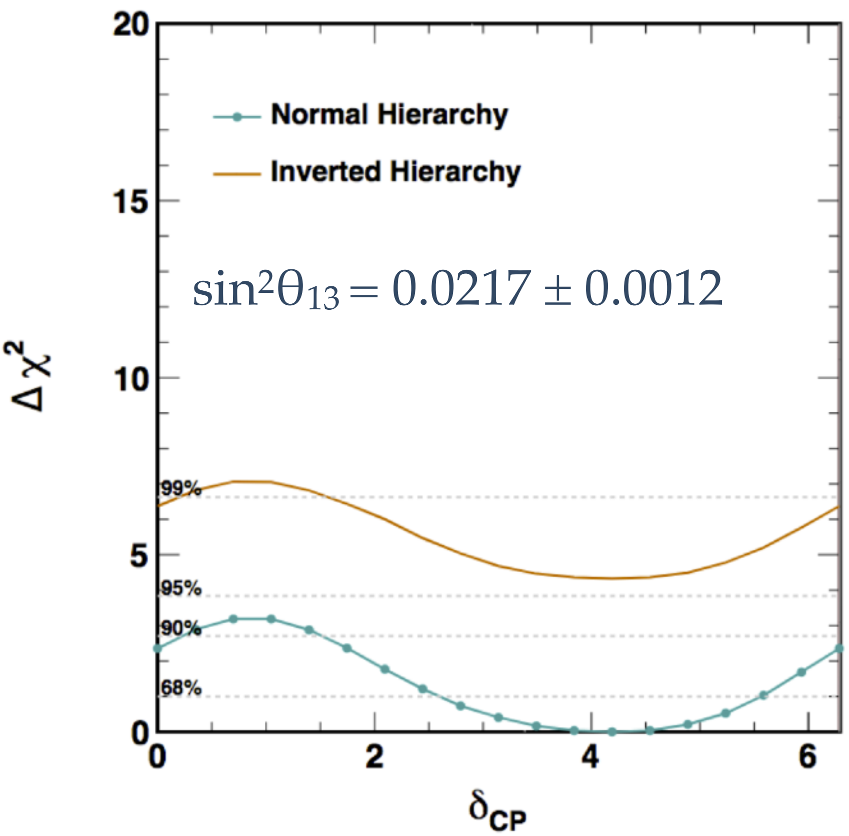


The CP phase

Super-Kamiokande (atm)



- δ_{BF} = 1.5π (1.2π) for NO (IO)
- preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

T2K

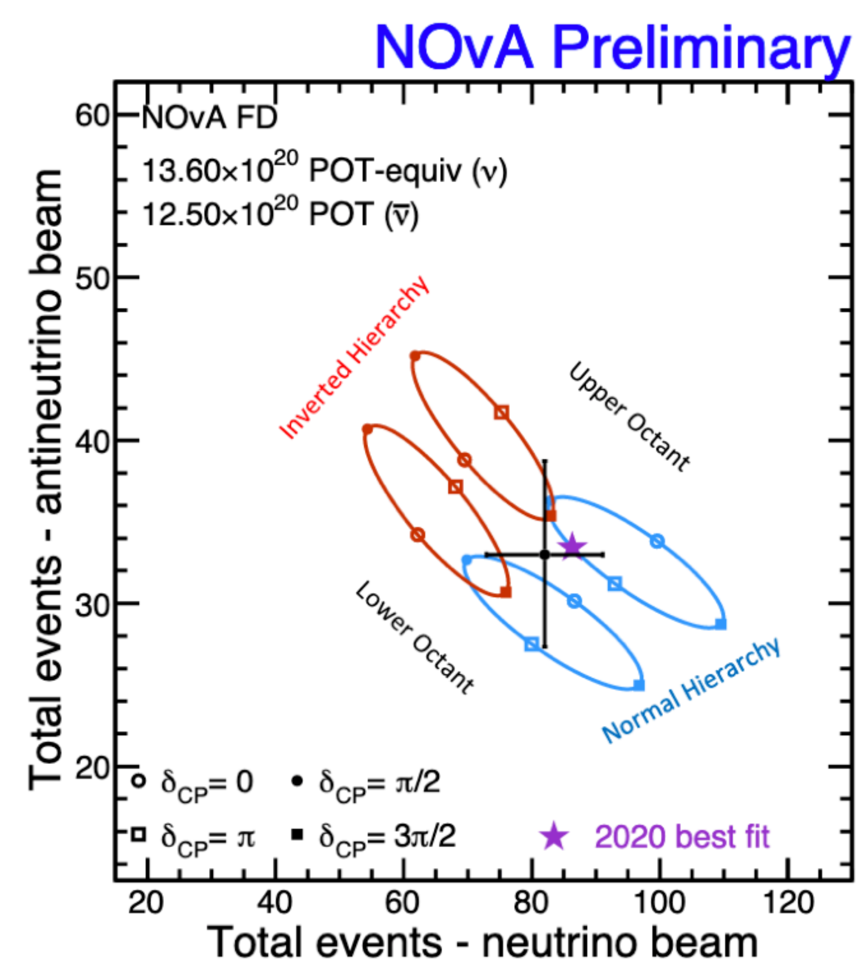
H. Tanaka, TAUP 2019

$\delta_{BF} \simeq 3\pi/2$ due to better agreement with observed ν_e and ν_e events

T2K (NO)		-π/2	0	+π/2	π	OBS
ν mode	1Re 0 d.e.	74.5	62.3	50.6	62.8	75
	1Re 1 d.e.	7.0	6.1	4.9	5.9	15
$\bar{\nu}$ mode	1Re 0 d.e.	17.1	19.6	21.7	19.3	15

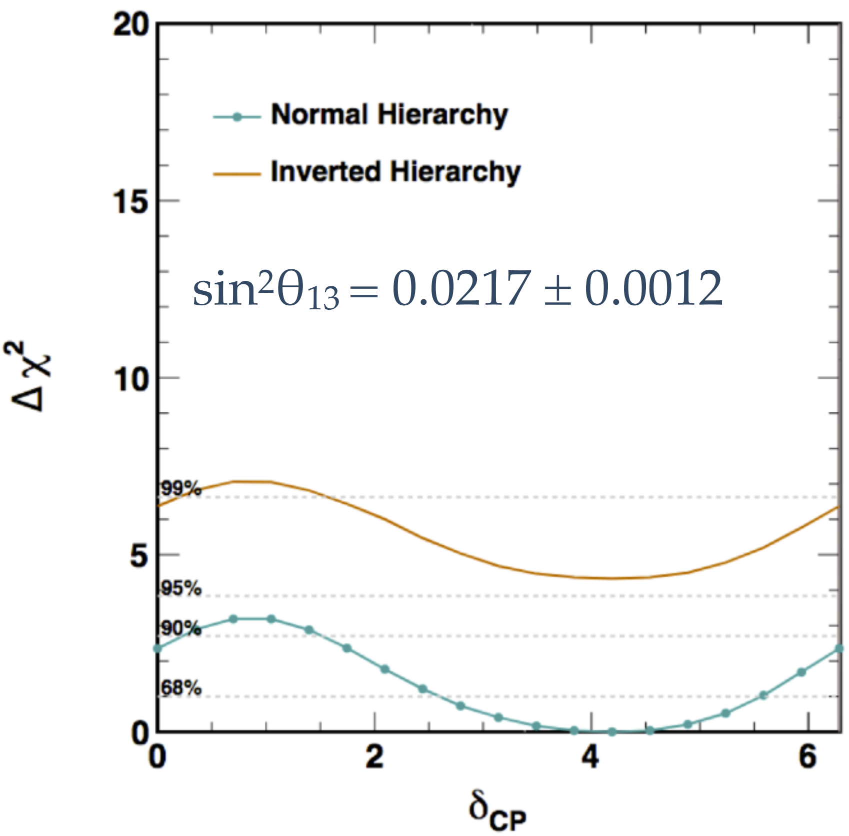
NOvA

P Vahle, TAUP 2021



The CP phase

Super-Kamiokande (atm)



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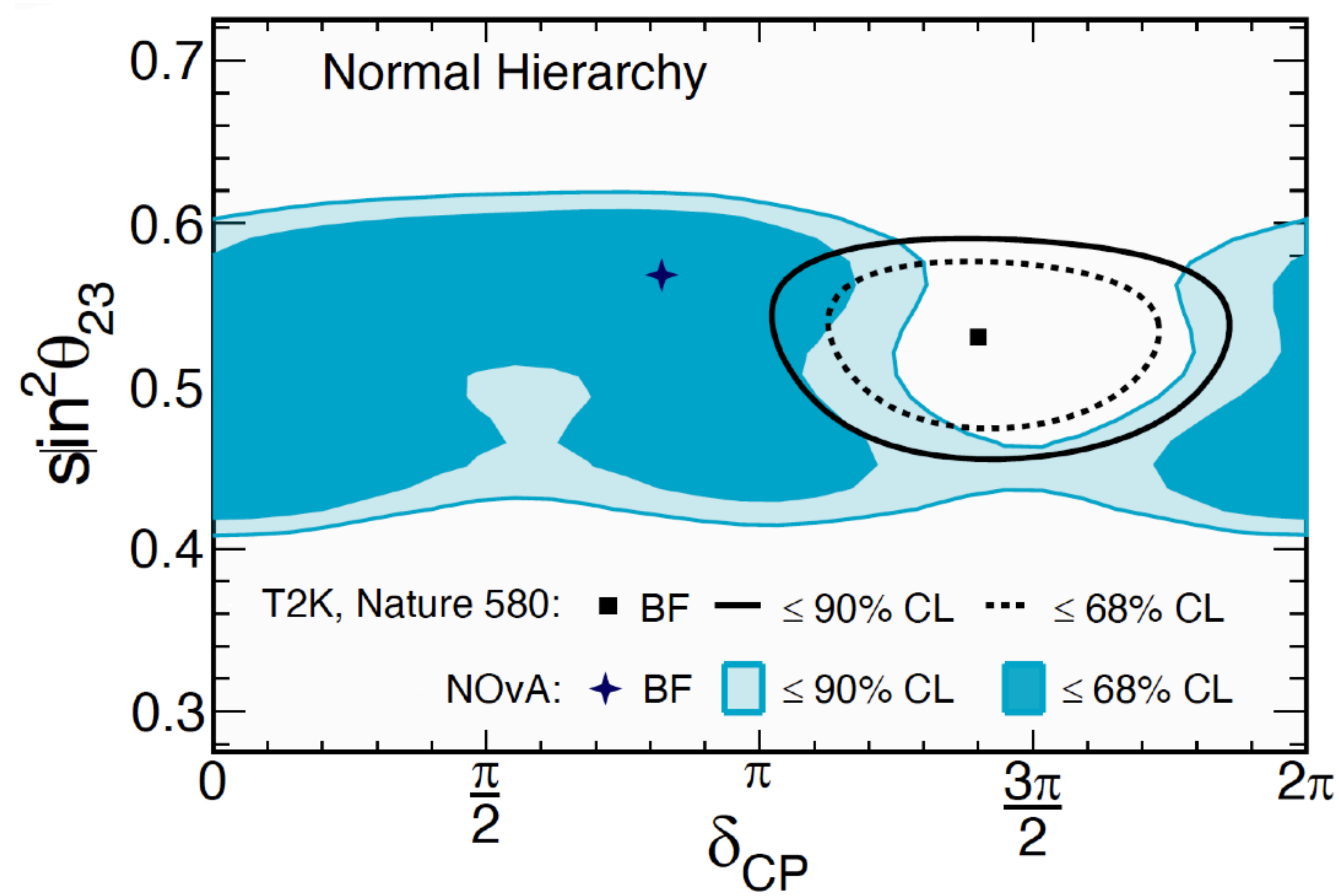
SK Collab. PRD97 (2018)

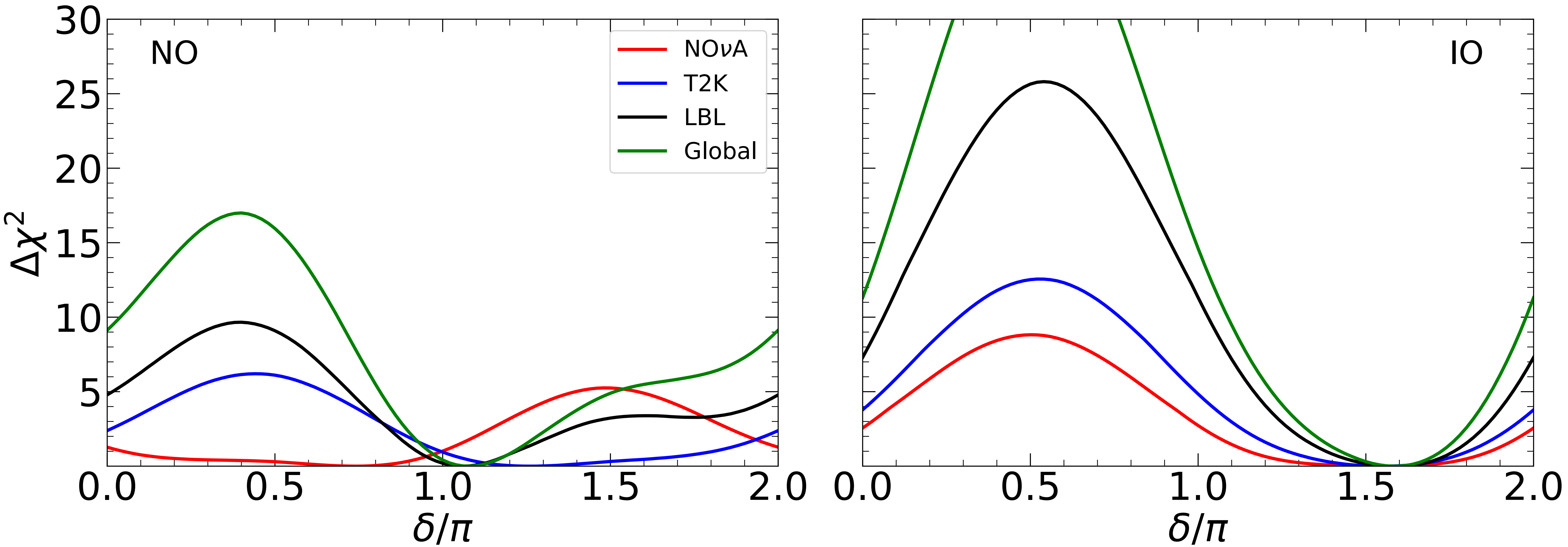
Slight tension between T2K and NOvA results for NO



A. Himmel, Neutrino 2020

The CP phase

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



- NO: there is a tension between NOvA and T2K and SK atmospheric results

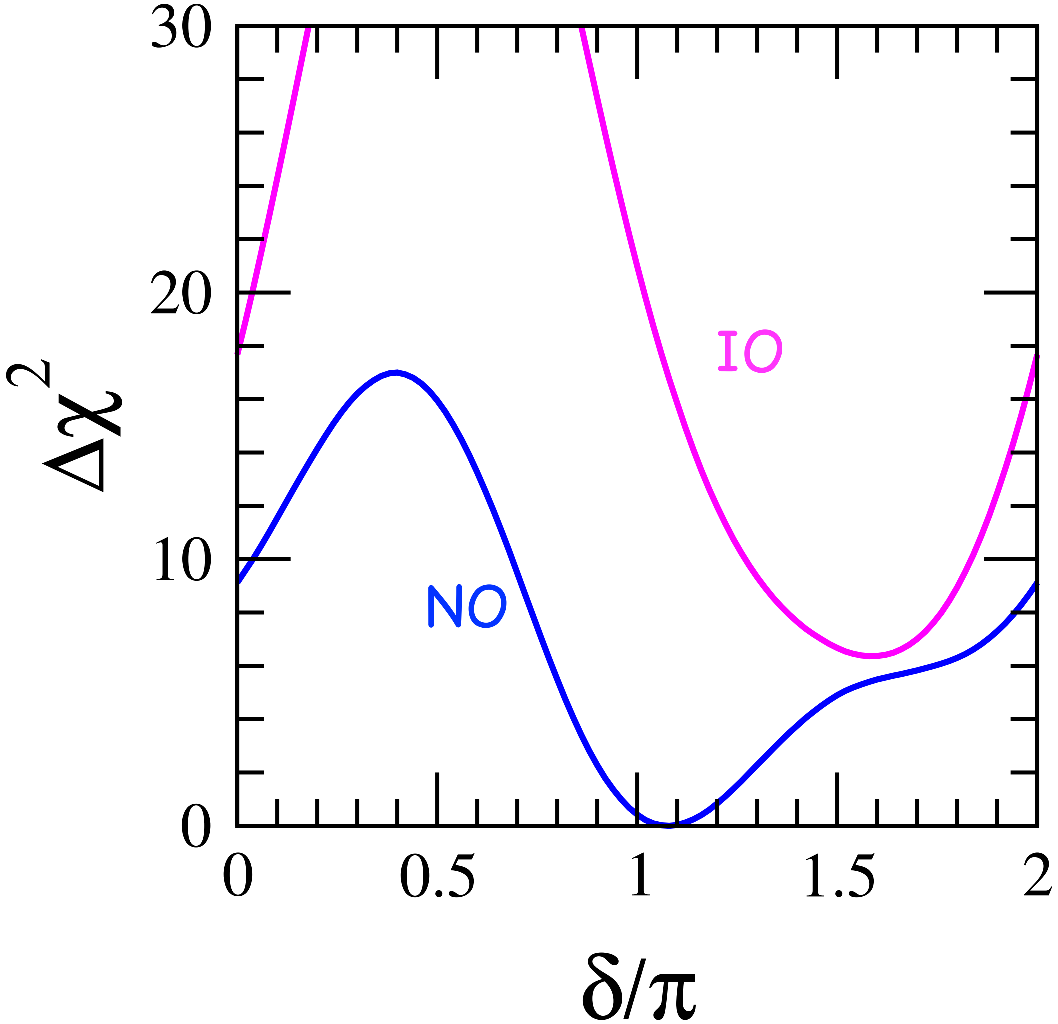
  $\delta_{BF} = 1.08\pi$; $\delta = \pi/2$ (0) disfavored at 4.0σ (3.0σ); $\delta = 3\pi/2$ with $\Delta\chi^2 = 4.9$

- IO: all experiments prefer $\delta \approx 3\pi/2$

  $\delta_{BF} = 1.58\pi$; $\delta = \pi/2$ (π) disfavored at 6.2σ (3.8σ);

The CP phase

de Salas et al, JHEP 02 (2021) 071



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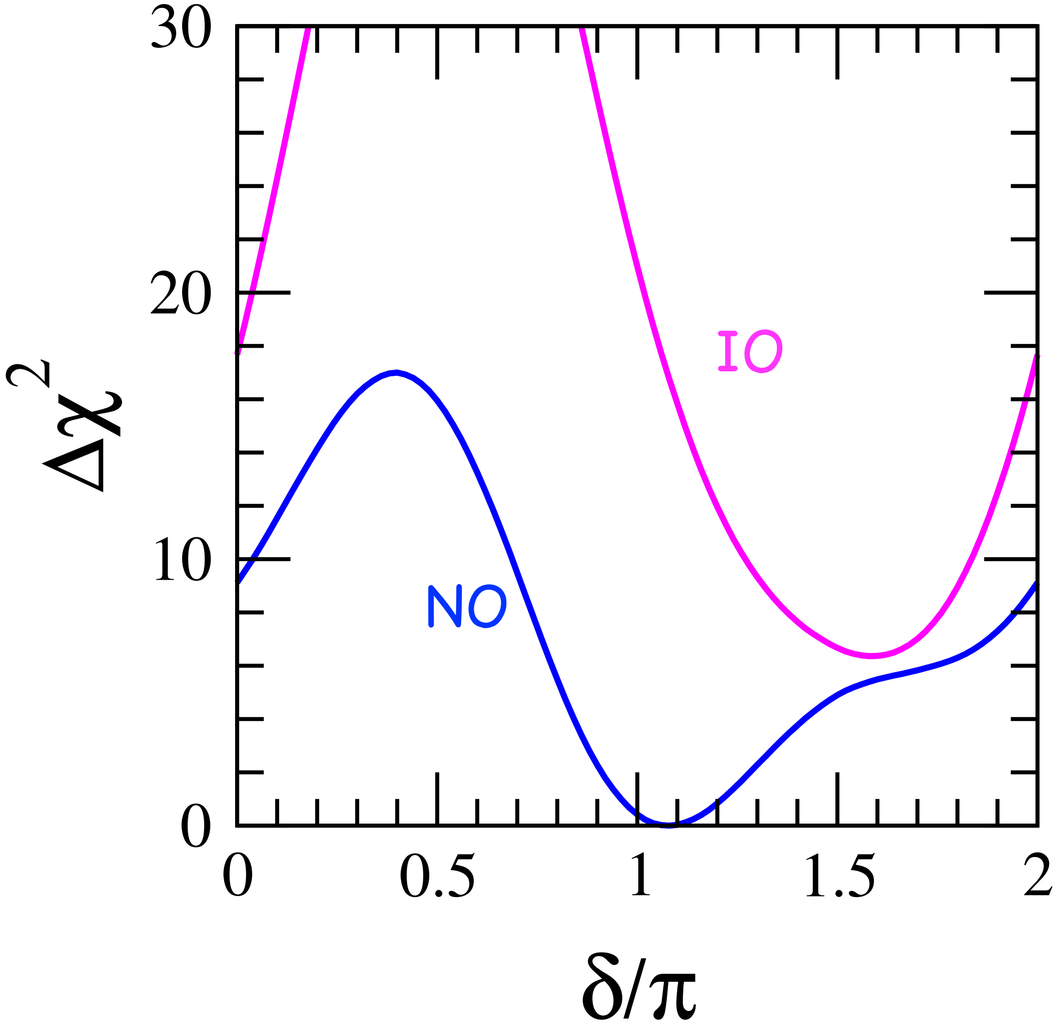

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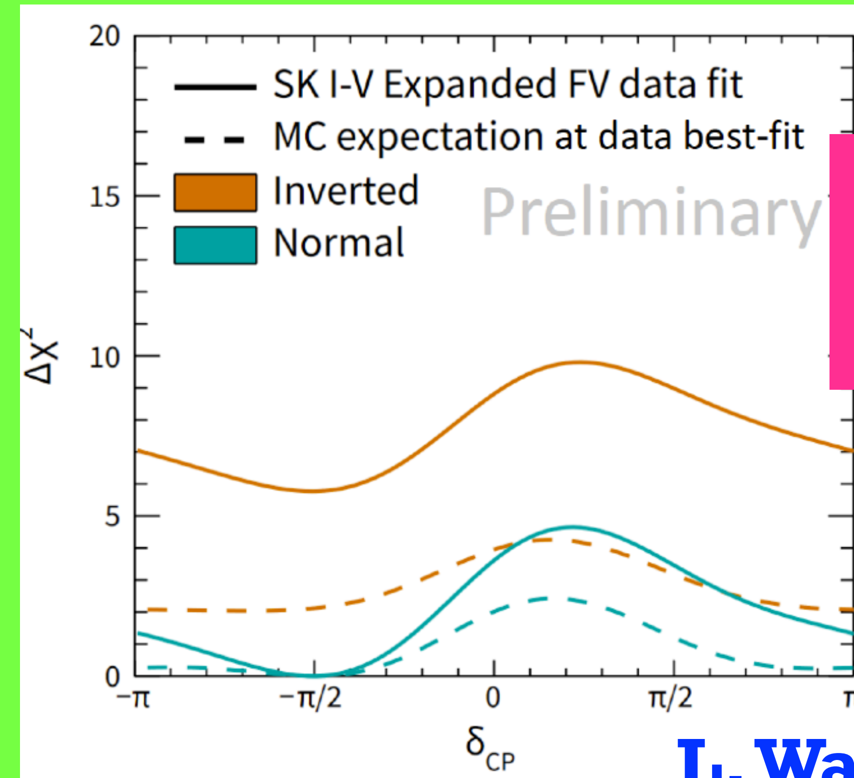
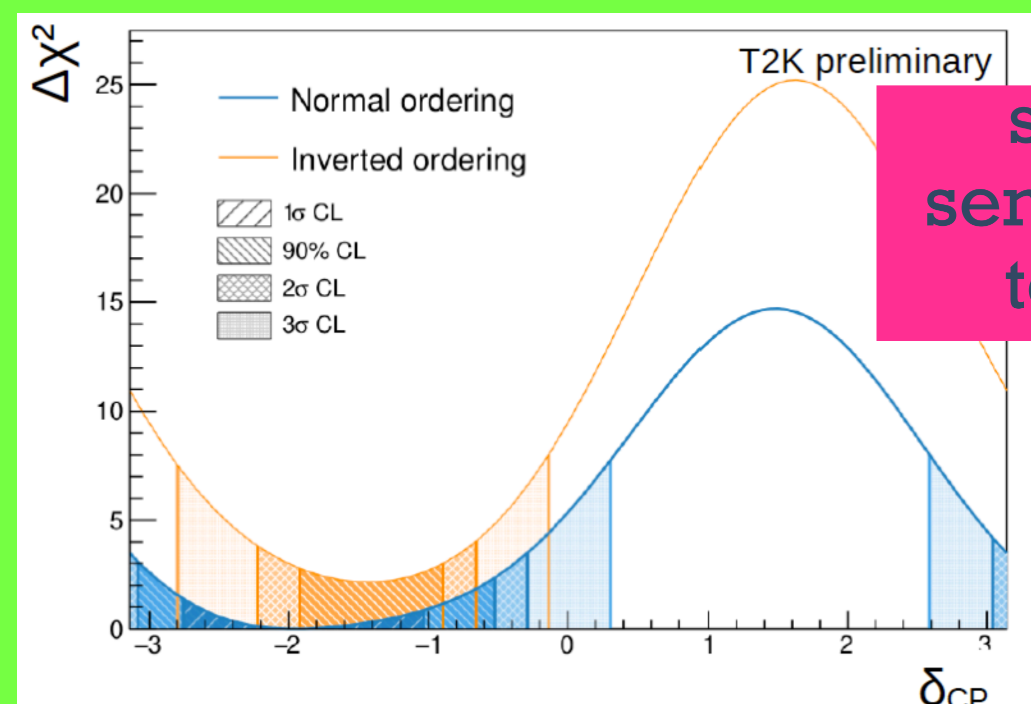


improved sensitivity to δ_{CP}

L. Wan, Nu 2022

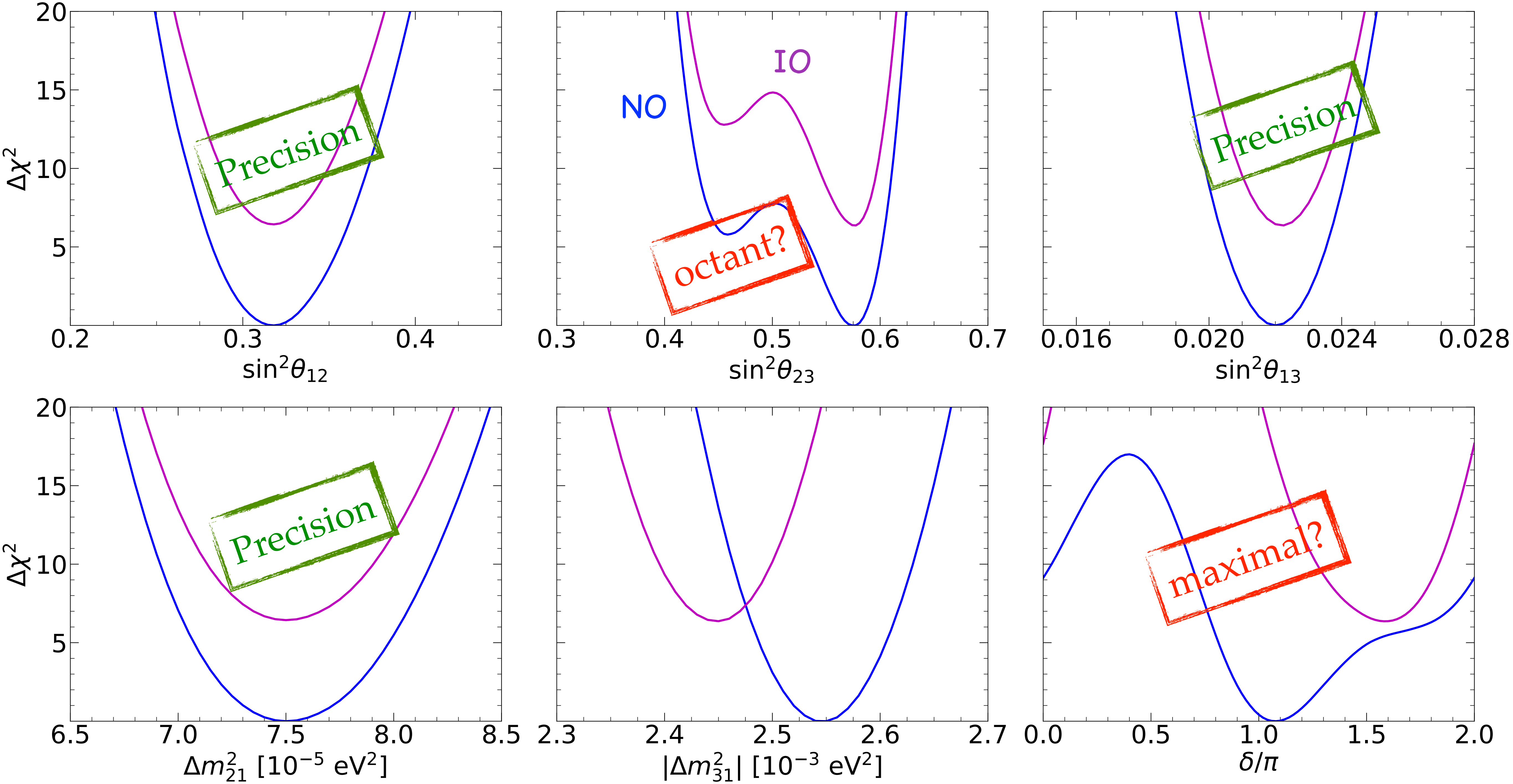


same sensitivity to δ_{CP}

C. Bronner, Nu 2022

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



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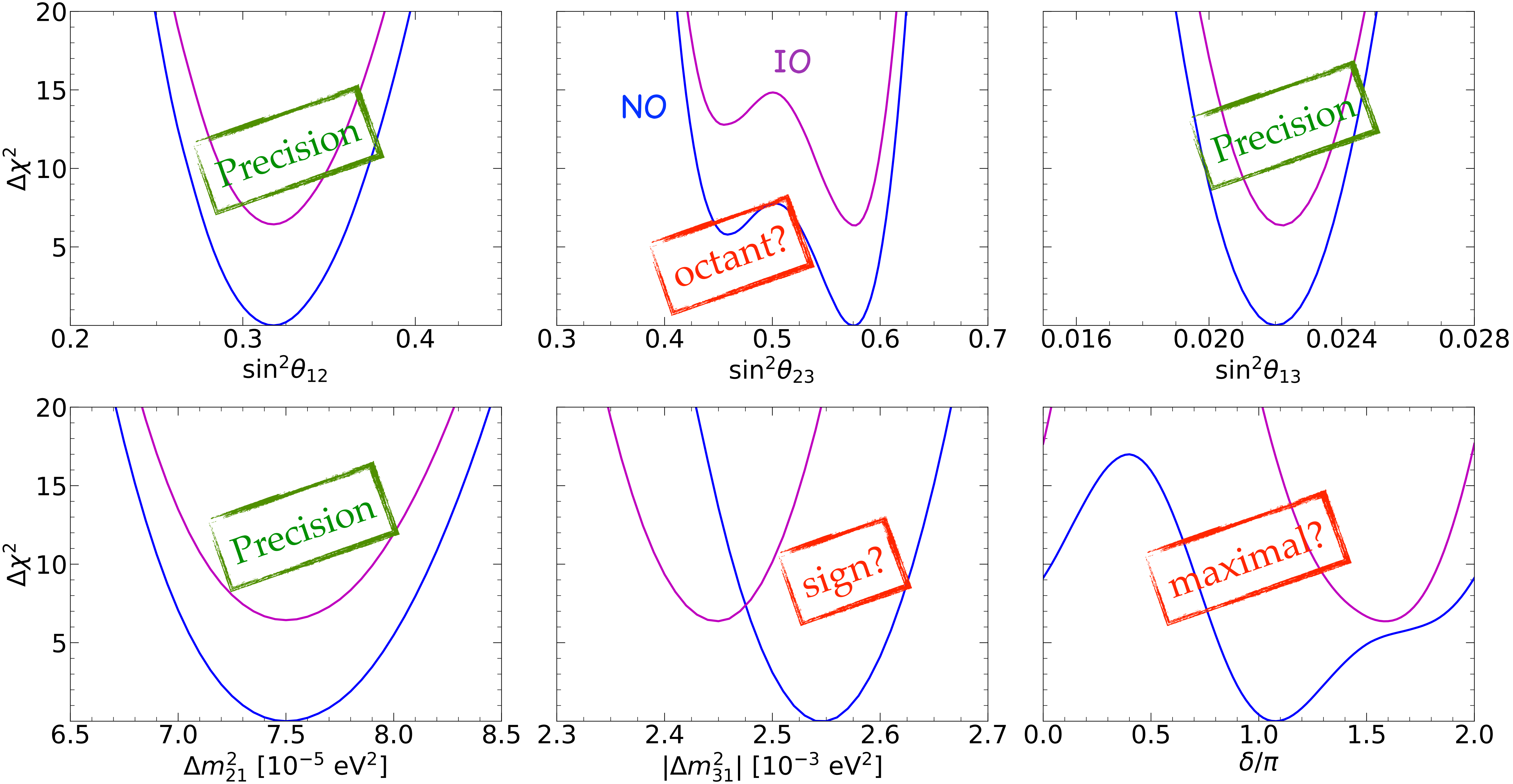


The mass ordering

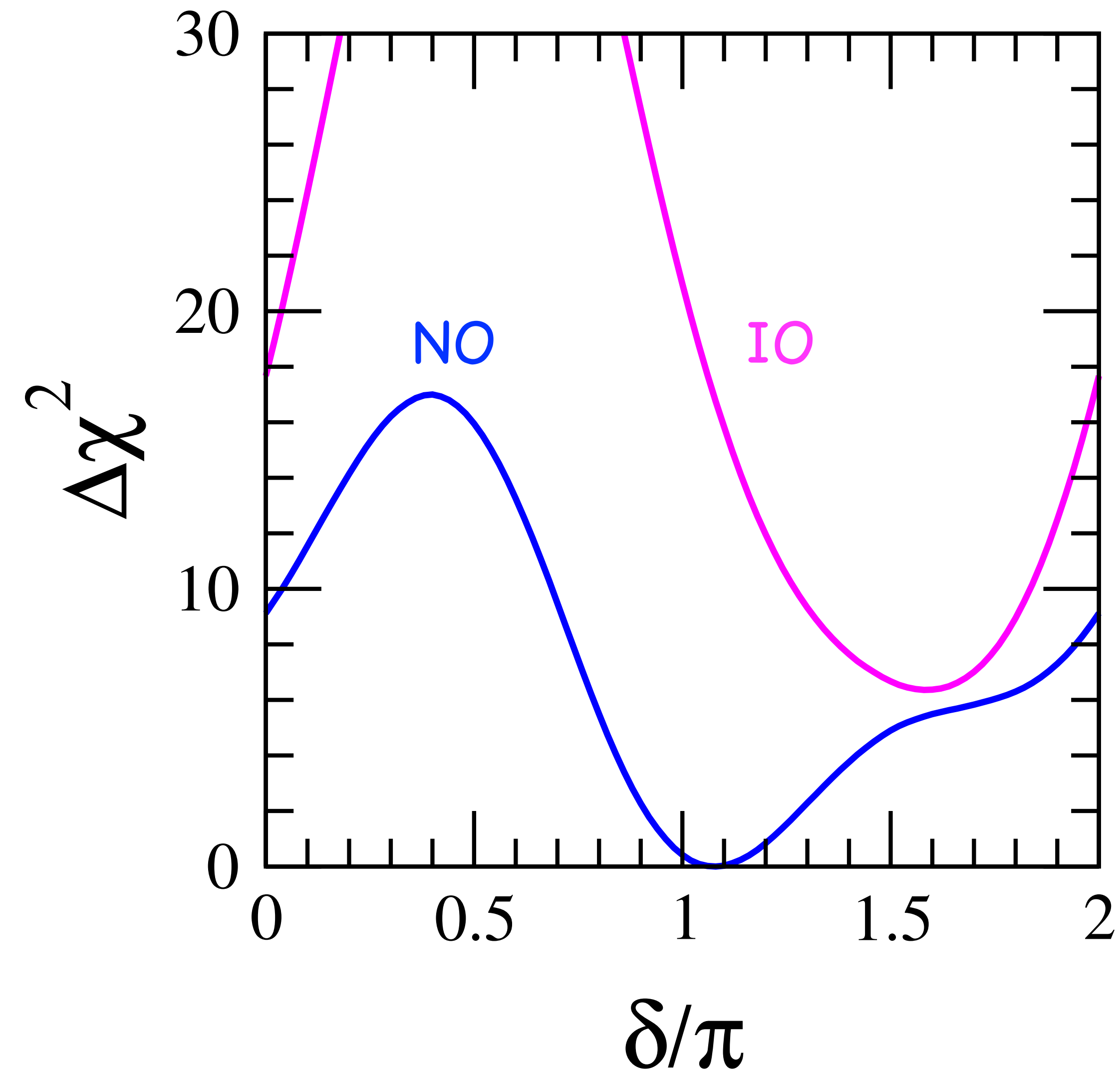
- T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.4$

- T2K + NOvA combined prefer IO with $\Delta\chi^2 \approx 2.4$ (tension in δ for NO)

- LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.4$ (tension in Δm^2_{31} measurement in IO)

- Atmos. sensitivity: Super-K ($\Delta\chi^2 \approx 3.5$) and DeepCore ($\Delta\chi^2 \approx 1.0$)

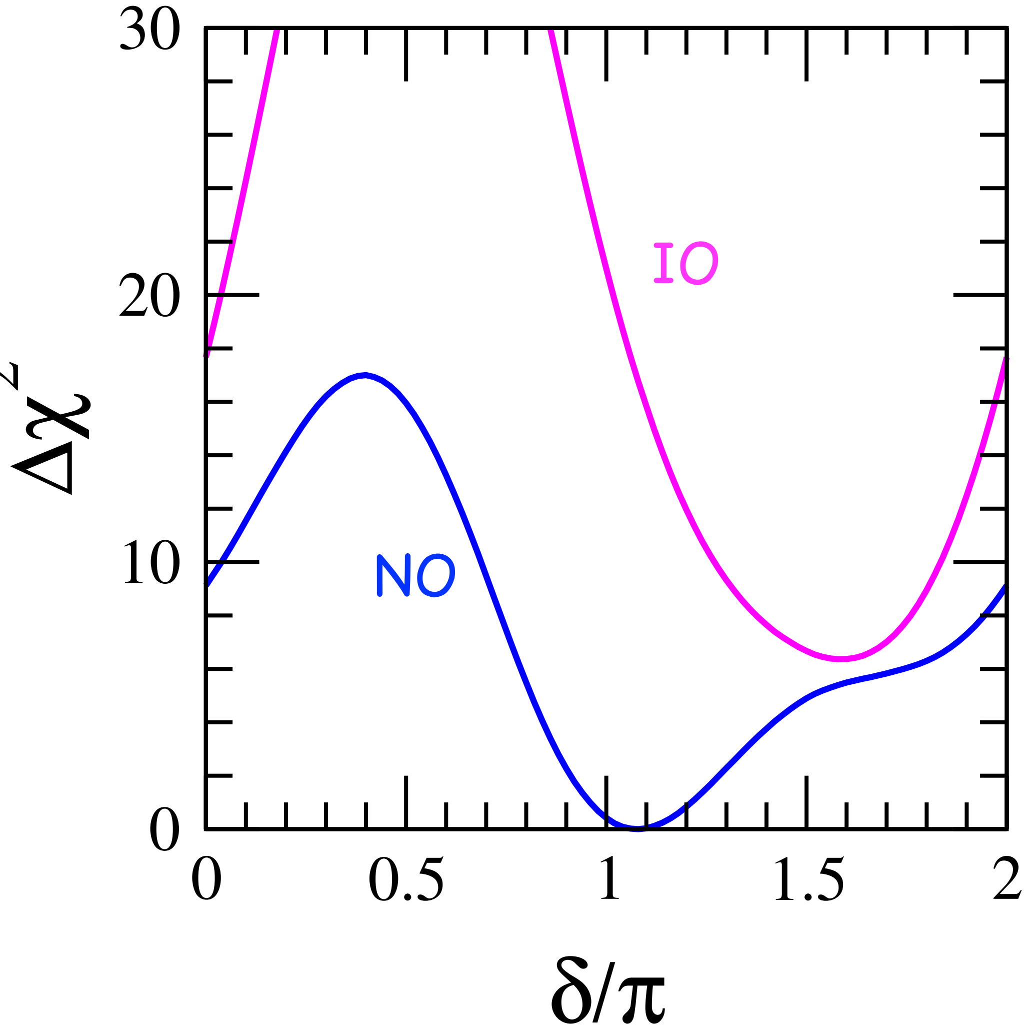
- Global fit: $\Delta\chi^2 = 6.4 \rightarrow$ 2.5σ preference for NO



de Salas et al, **JHEP 02 (2021) 071**

The mass ordering

de Salas et al, JHEP 02 (2021) 071



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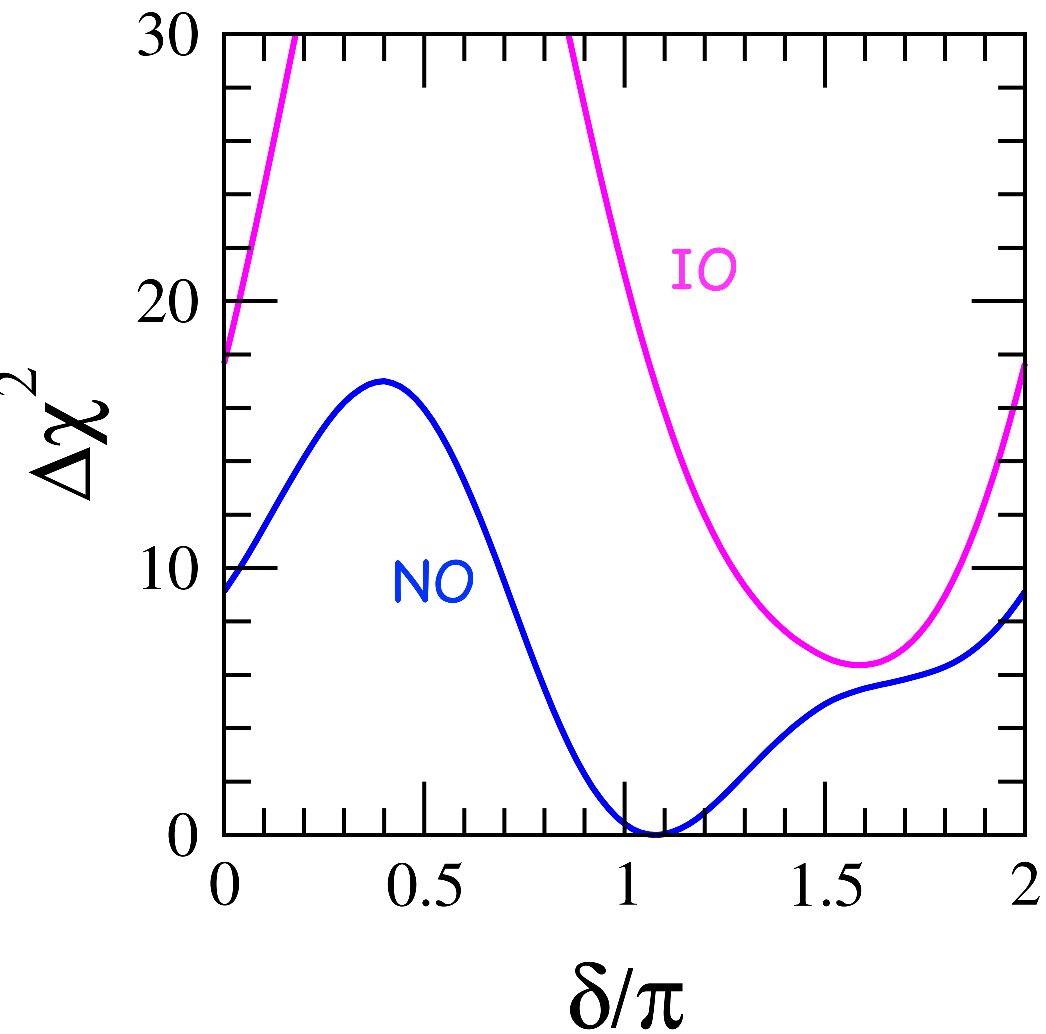
de Salas et al, JHEP 02 (2021) 071



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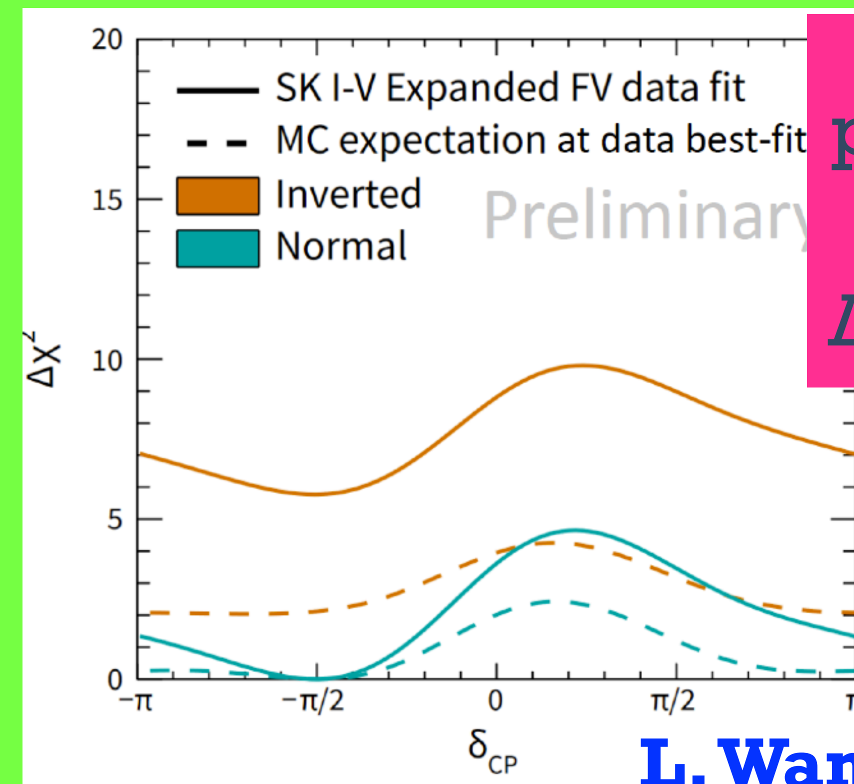
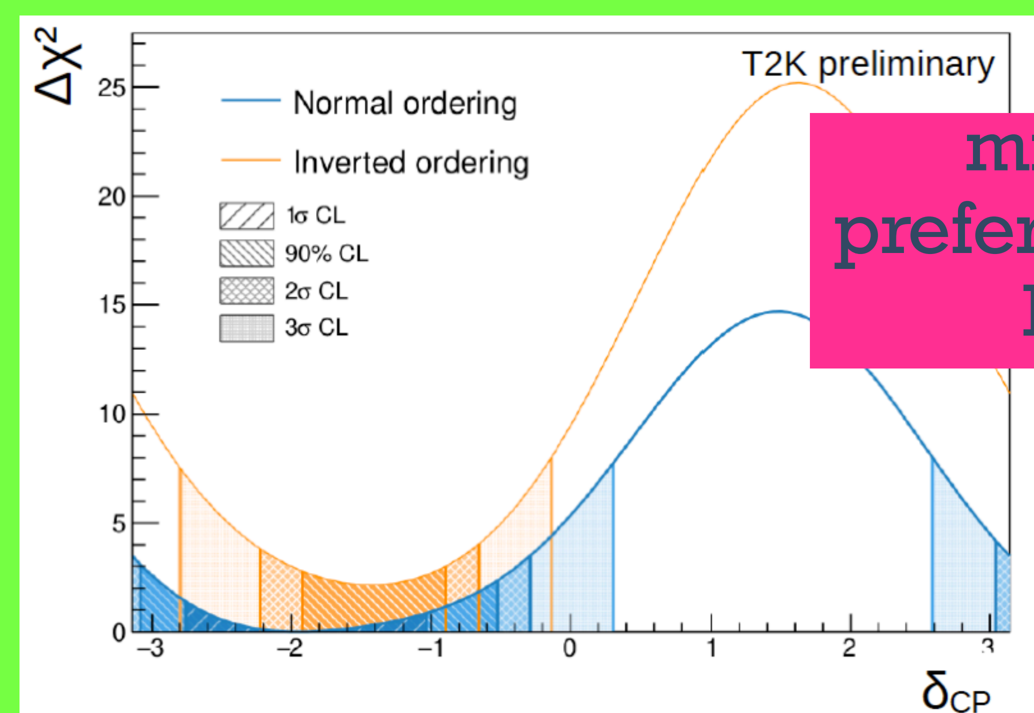


higher preference for NO:

$\Delta\chi^2 = 3.5 \rightarrow 5.8$

L. Wan, Nu 2022



milder preference for NO

C. Bronner, Nu 2022

Other inputs for mass ordering?

de Salas et al, JHEP 02 (2021) 071

Experimental sensitivity to neutrino masses:

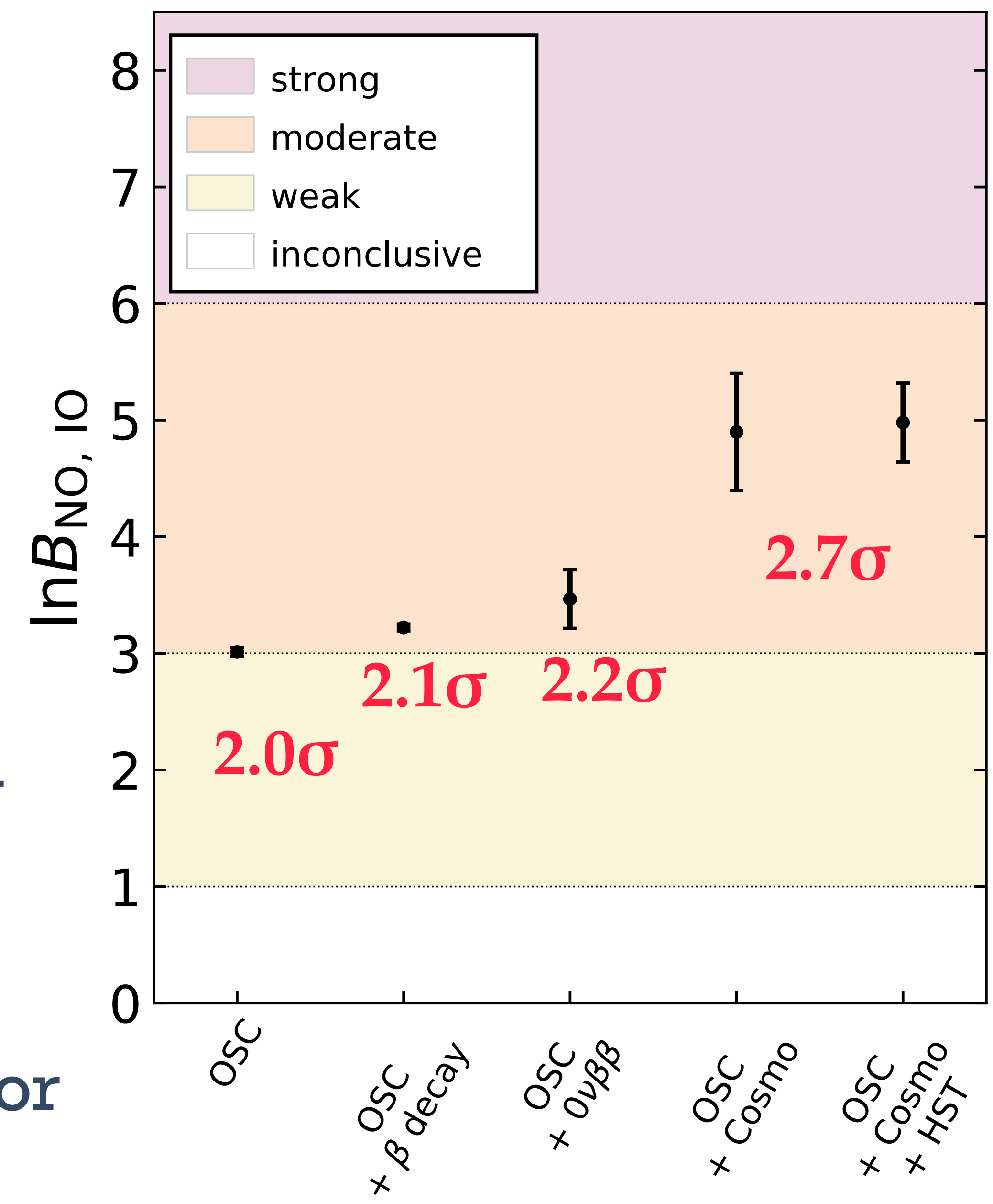
- ν-oscillations: Δm^2_{ij}
- β-decay: $m_\beta = f(m_i, \theta_{ij})$
- 0νββ: $m_{\beta\beta} = f(m_i, \theta_{ij}, \phi_i)$
- cosmology: Σm_i

Results from the combined bayesian analysis:

⇒ weak/moderate preference for NO driven by oscillation data (2.0σ)

⇒ β-decay and 0νββ have little impact on MO.

⇒ cosmological data enhances the preference for NO from 2.0σ to 2.7σ



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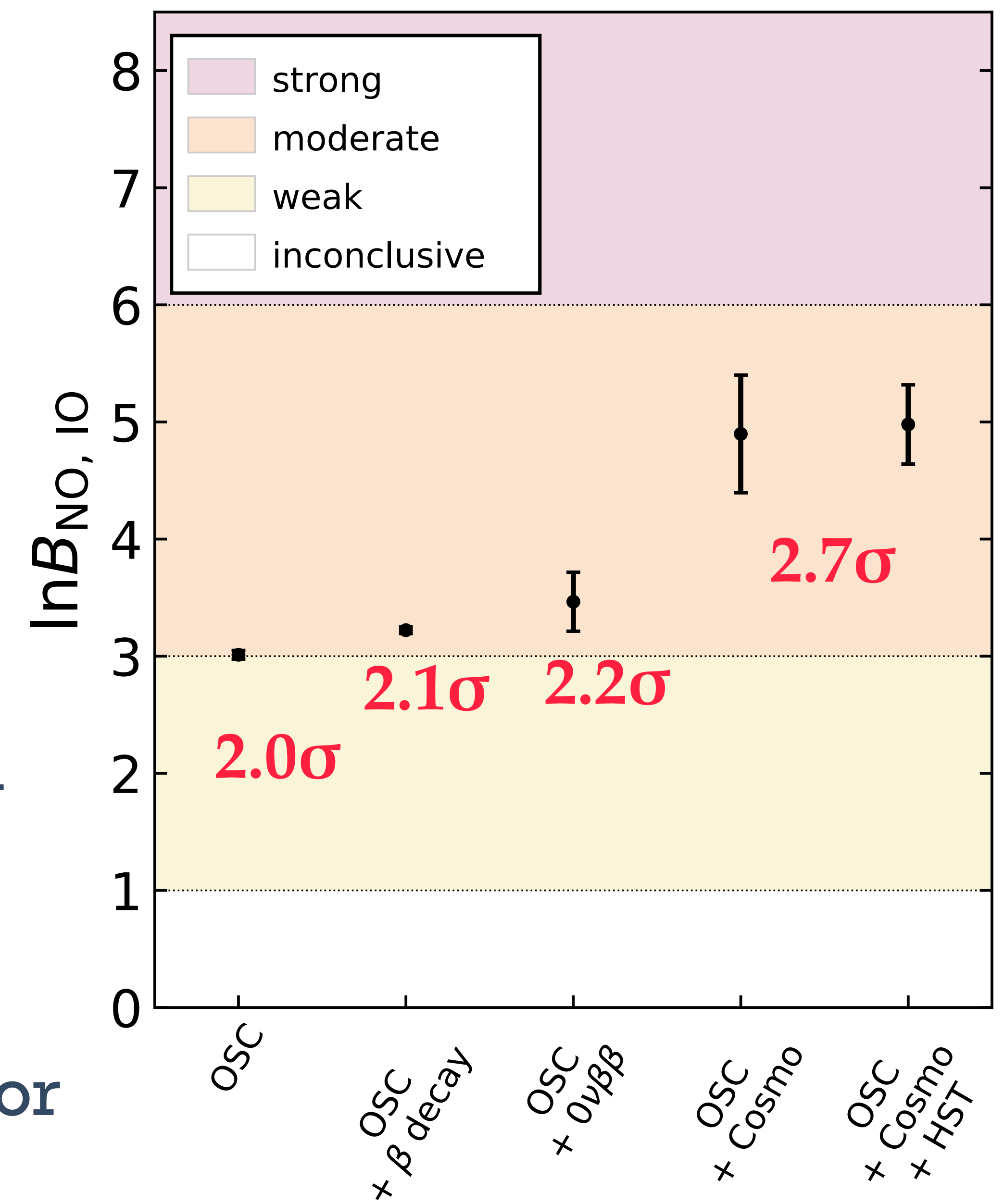
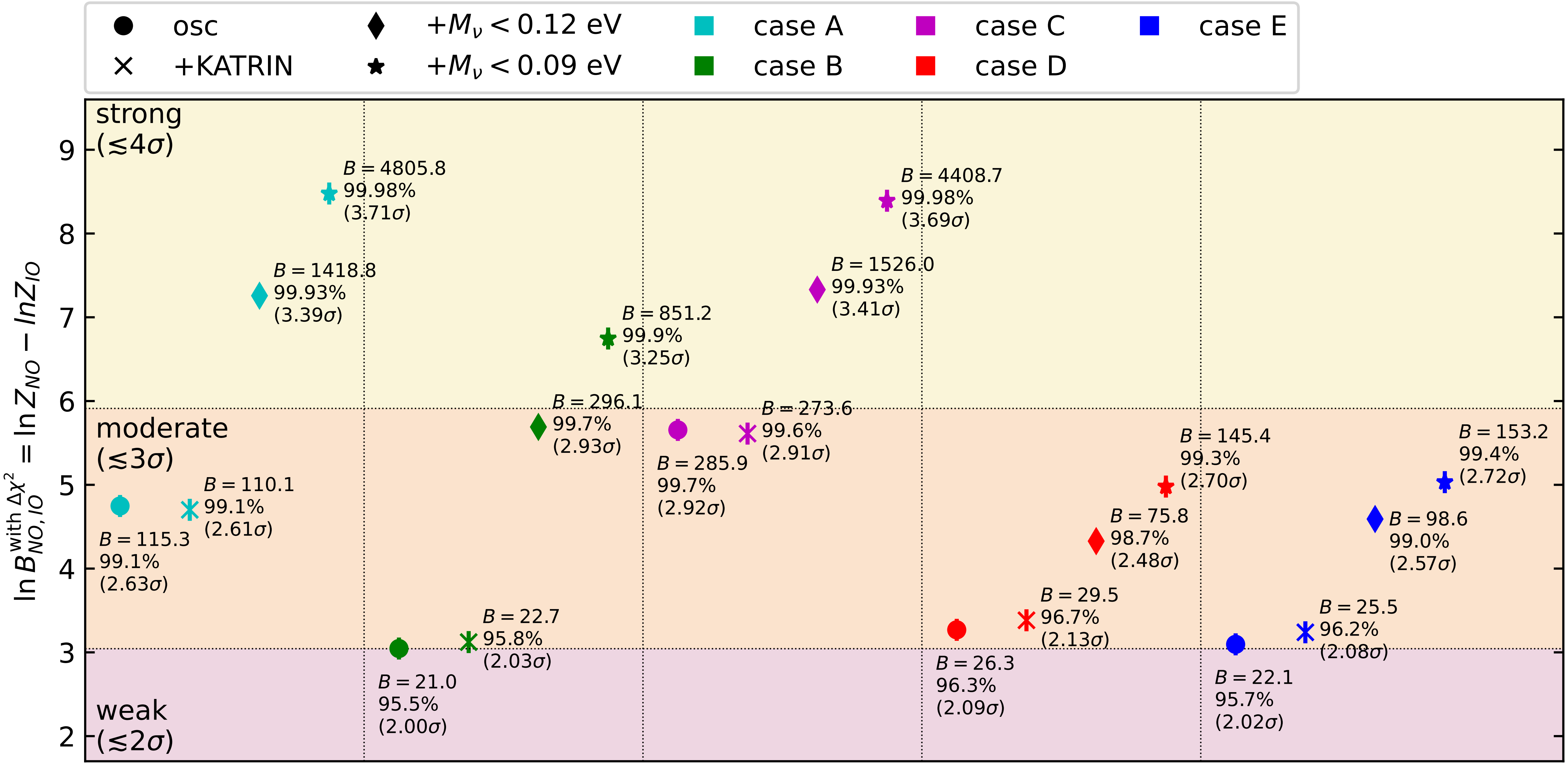
de Salas et al, JHEP 02 (2021) 071



Jiménez et al, 2203.14247 → Decisive evidence for NO from cosmology

Preference for NO (with OSC)

Gariazzo et al, 2205.02195



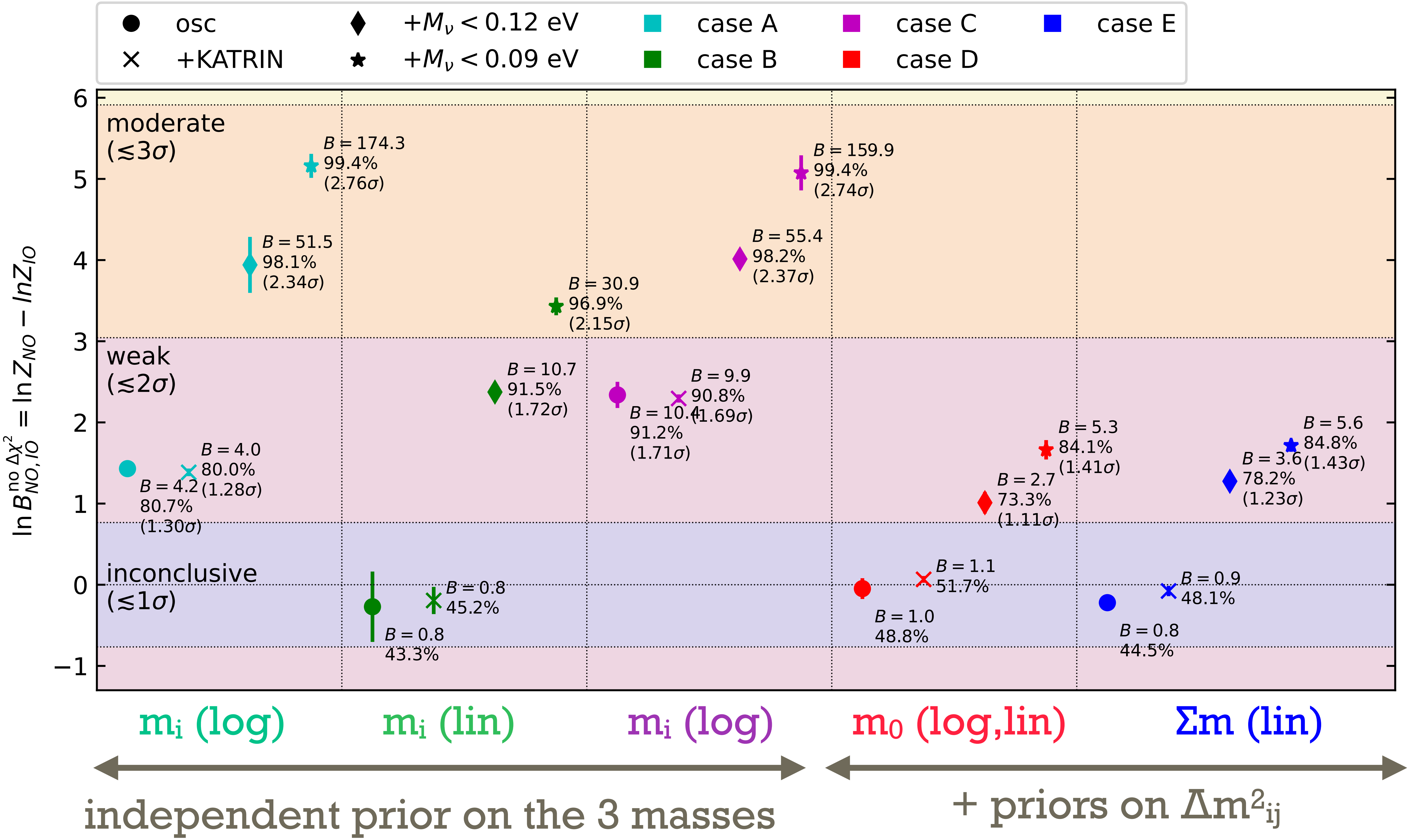
m_i (log) m_i (lin) m_i (log) m_0 (log,lin) Σm (lin)

independent prior on the 3 masses

+ priors on Δm^2_{ij}

Preference for NO (without OSC)

Gariazzo et al, 2205.02195



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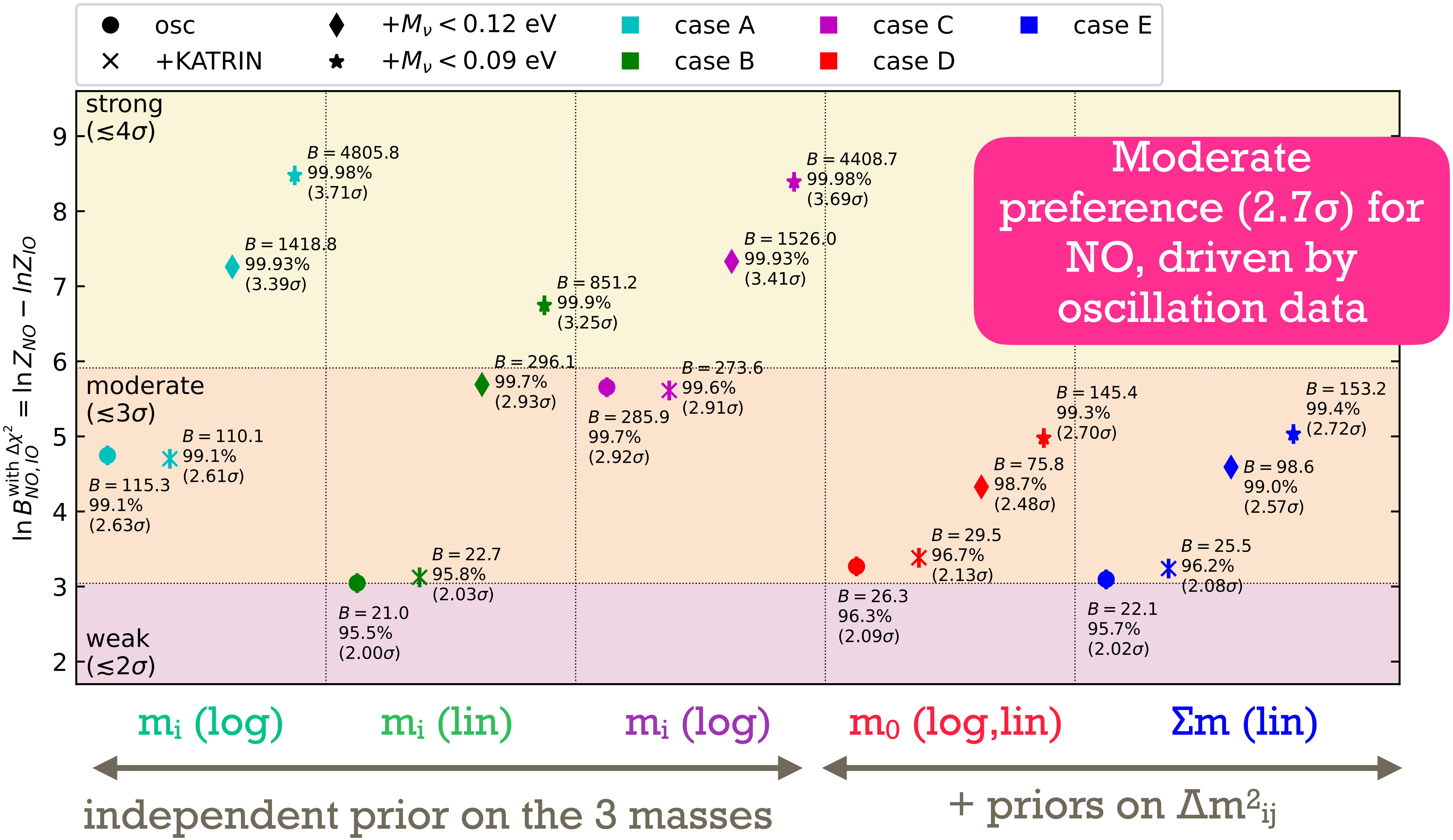
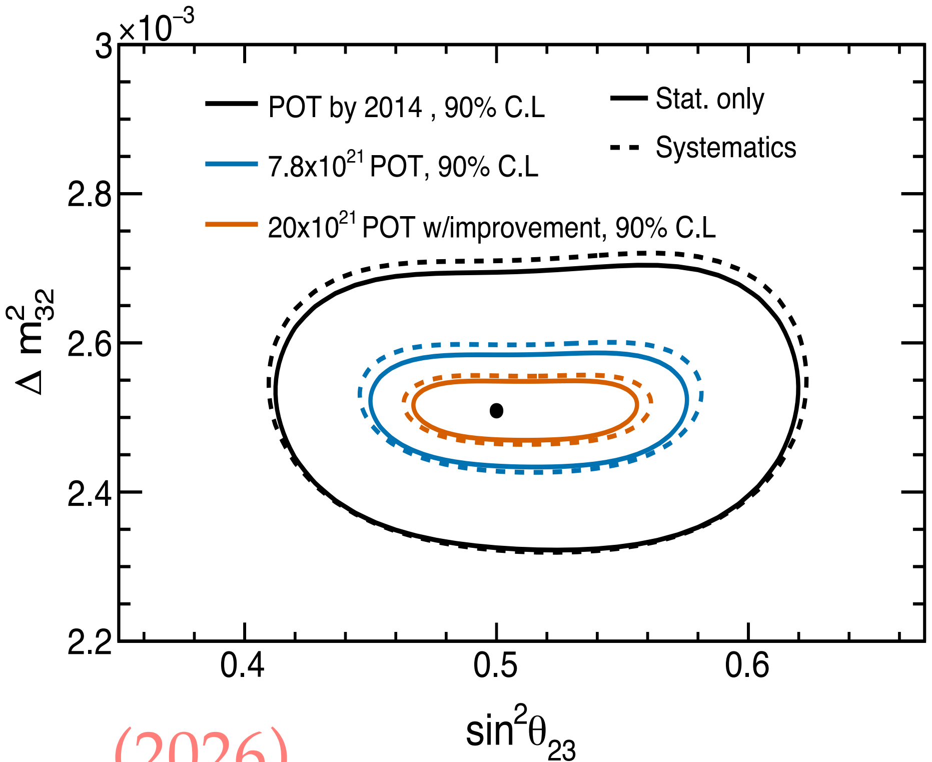


Future prospects in neutrino oscillations

Prospects for precision

T2K

Abe et al, 1609.04111

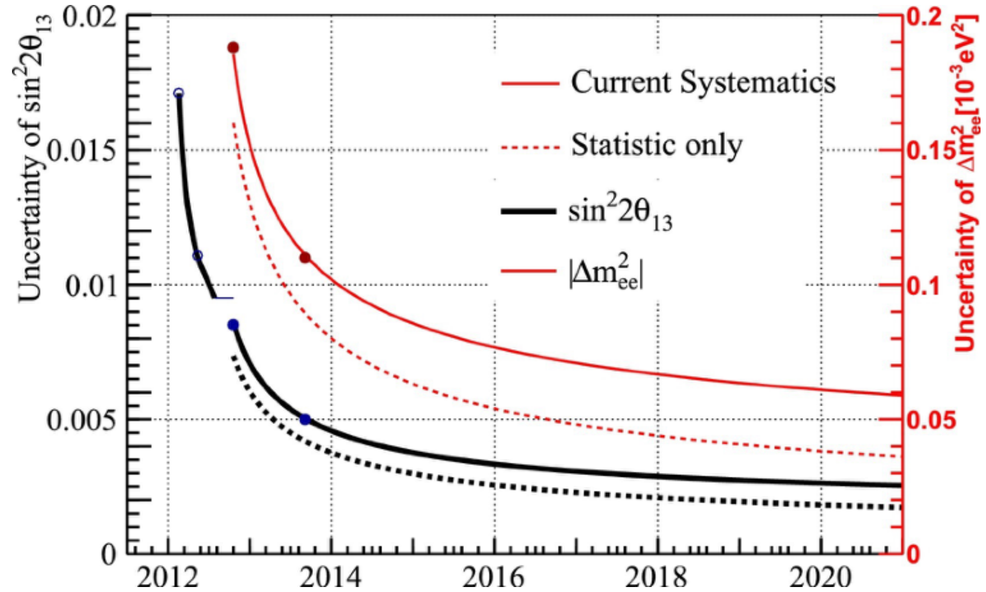


(2026)

~1% precision on Δm^2_{32}

~1-3% precision on $\sin^2\theta_{23}$

DayaBay

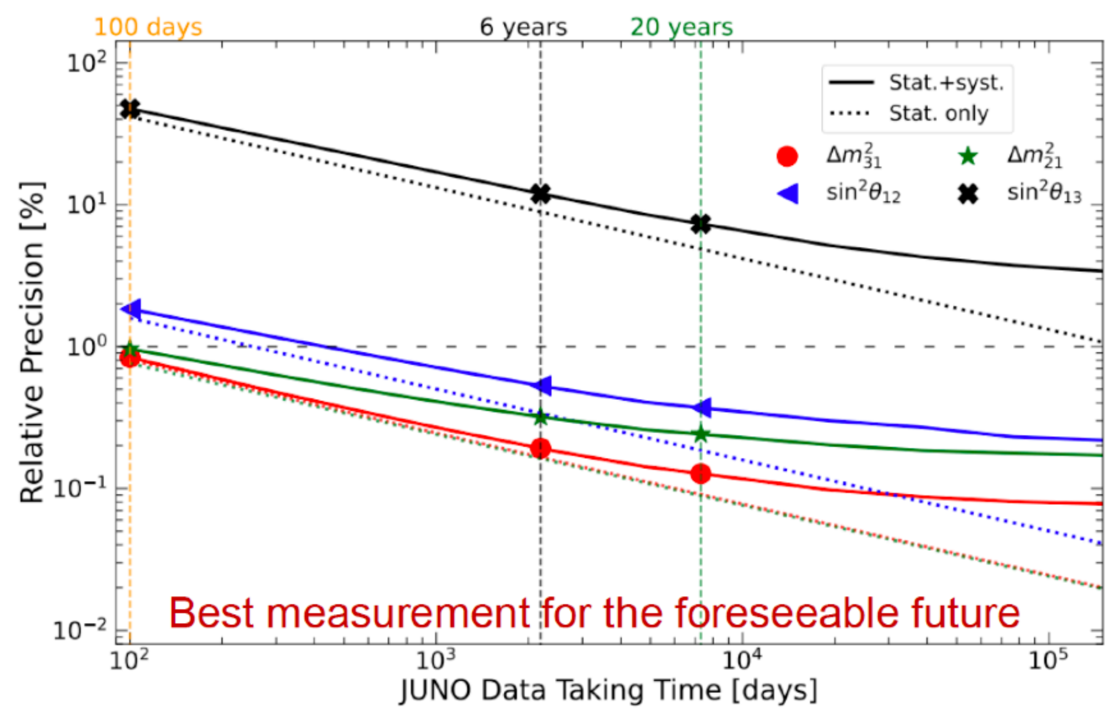


Cao and Luk, 1605.01502

< 3% precision in $\sin^2 2\theta_{13}$ and Δm^2_{ee}

2.7% in $\sin^2 2\theta_{13}$
[Z, Yu, TAUP'21]

JUNO



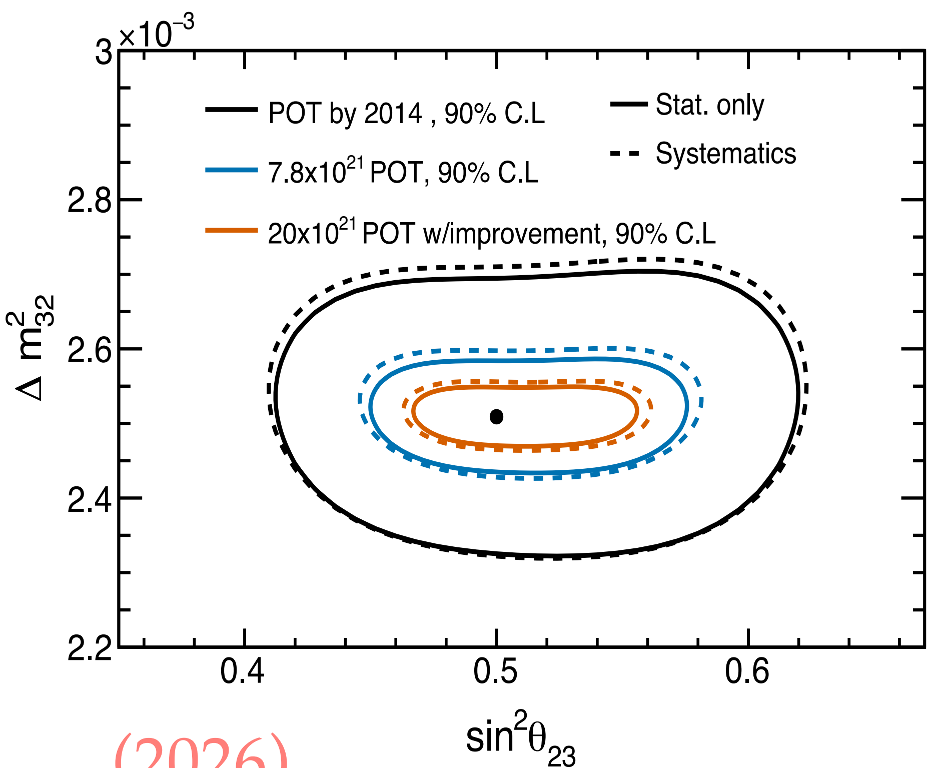
6 years:

< 0.5% precision on $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

J. Zhao, Neutrino 2022

Prospects for precision

T2K **Abe et al, 1609.04111**



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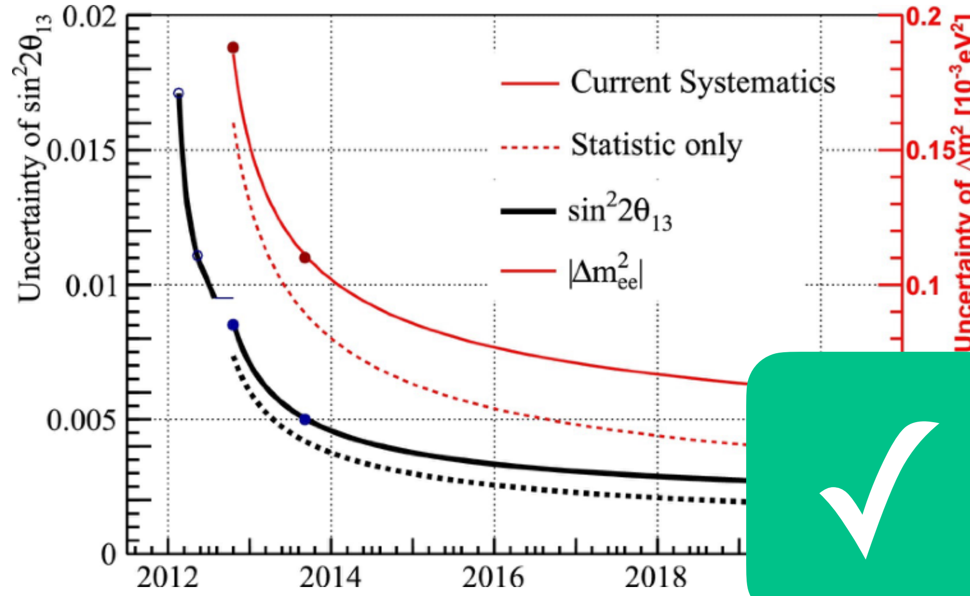

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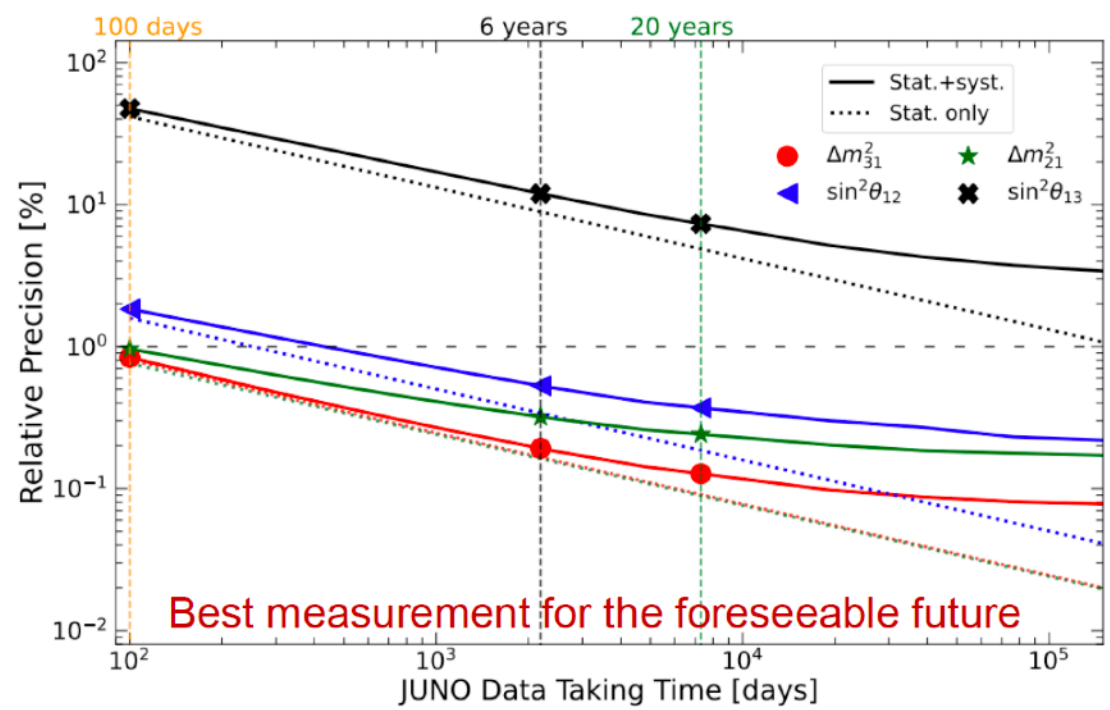
JUNO



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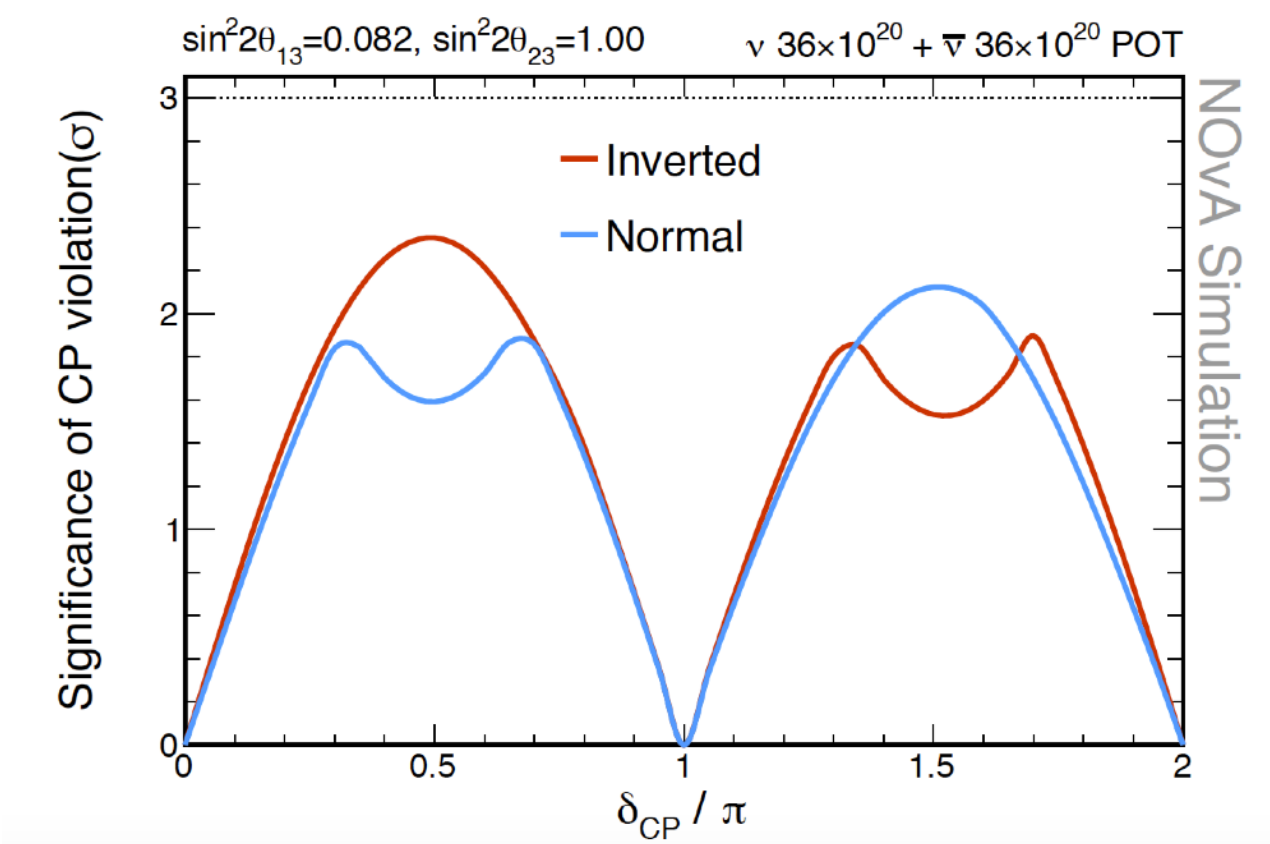
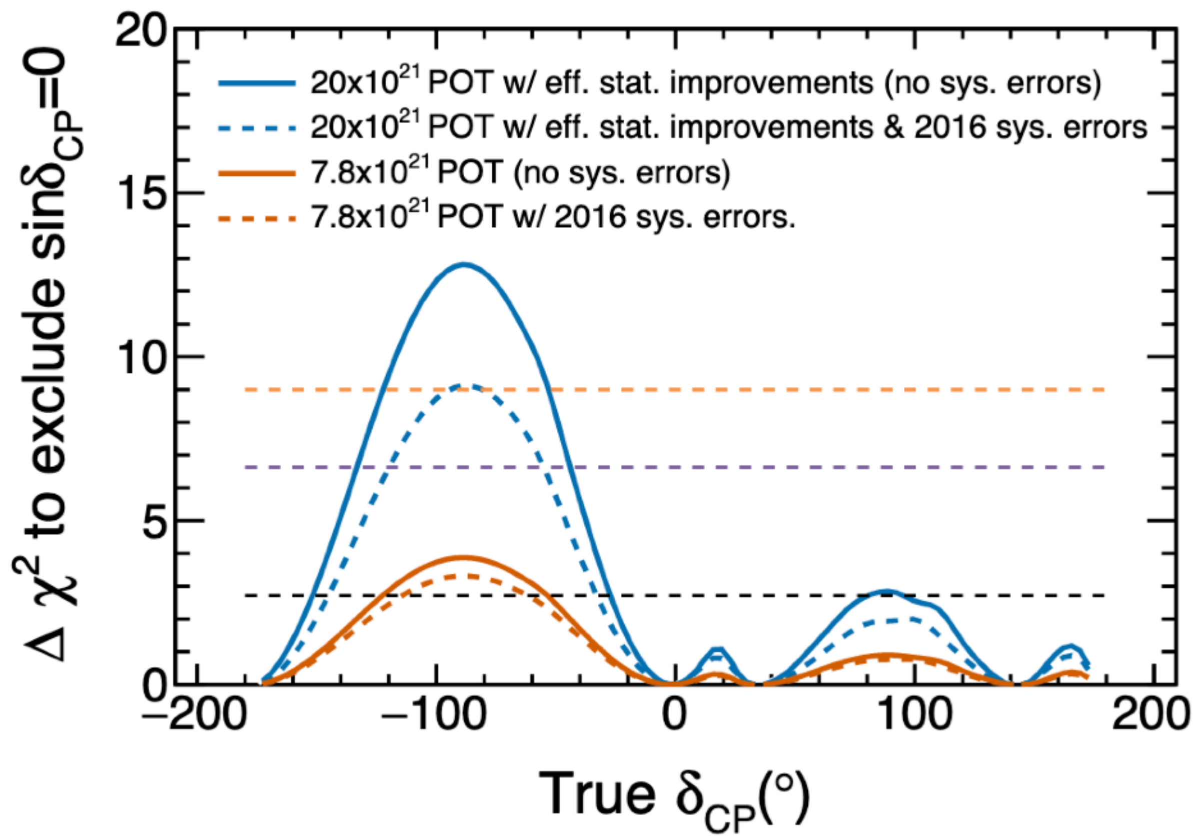
J. Zhao, Neutrino 2022

Prospects for CP violation

NOvA M. Sánchez, Neutrino'18
P. Vahle, TAUP'21



T2K Abe et al, 1609.04111

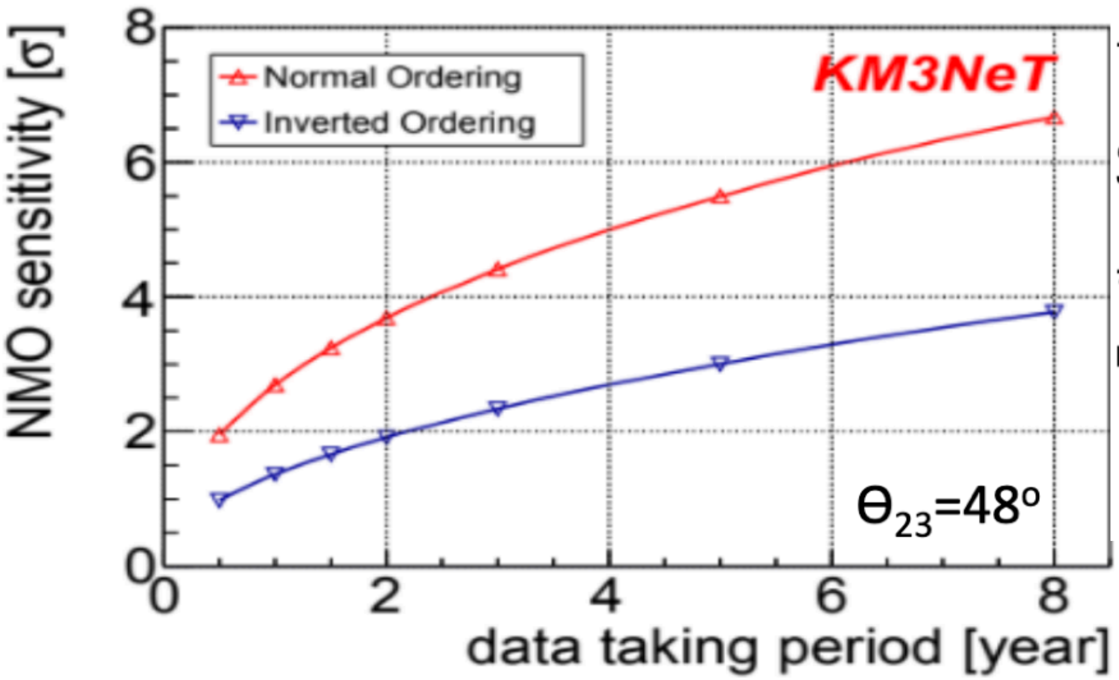


✦by 2026 (60-70 x 10^{20} POT):
~ 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

✦by 2026 (20×10^{21} POT):
> 3σ sensitivity on CP violation for 3π/2

Prospects for mass ordering

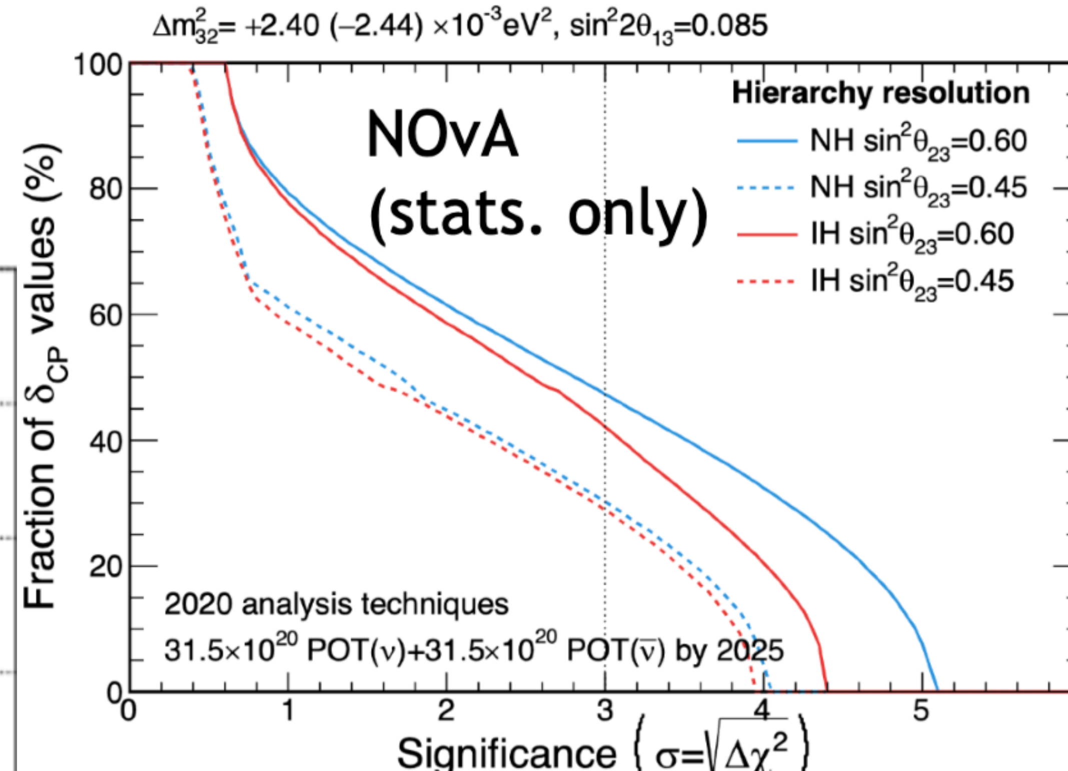
ORCA



✦ 3σ determination of MO in 4-5 yr

A. Heijboer, Neutrino 2022

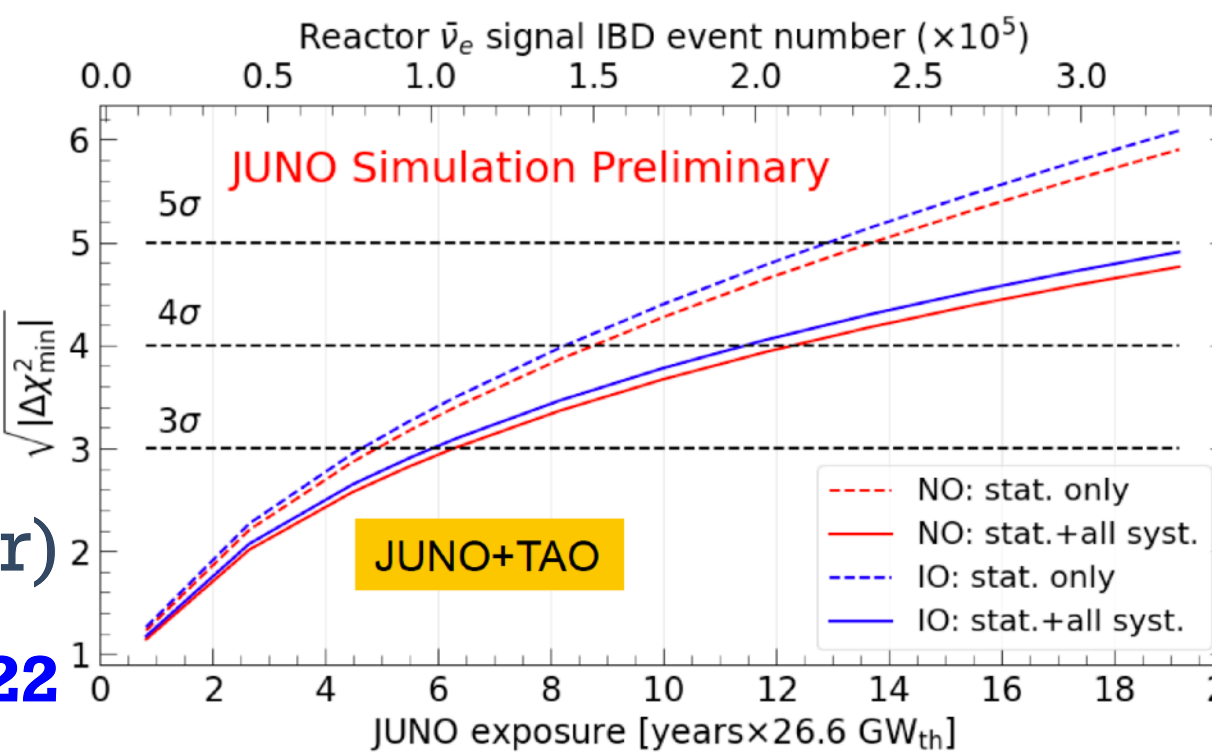
NOvA



P. Vahle, TAUP'21

✦ 2026: 3σ sensitivity for 30-50% of δ

JUNO

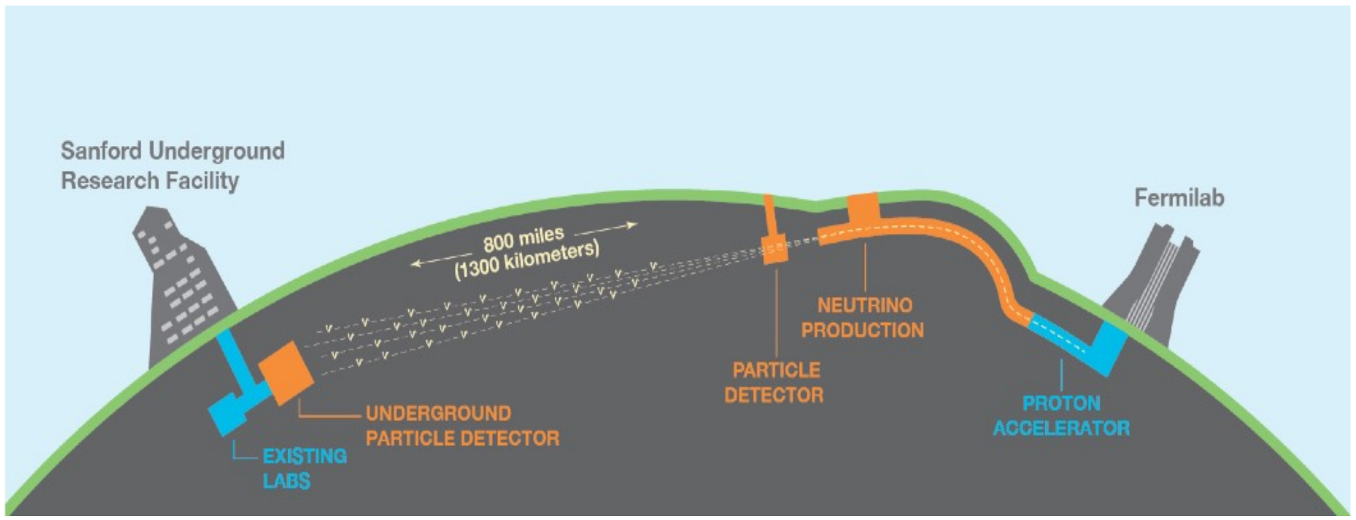


✦ 3σ sensitivity (6 yr)

J. Zhao, Neutrino 2022

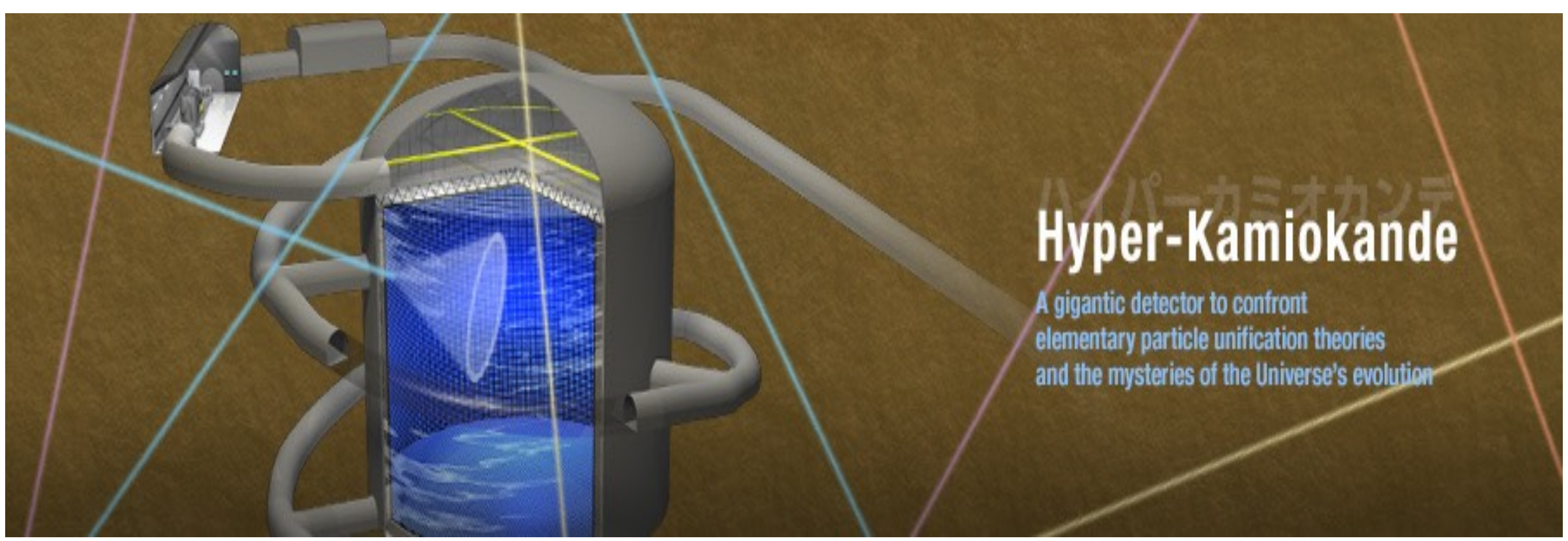
Next generation of ν experiments

DUNE



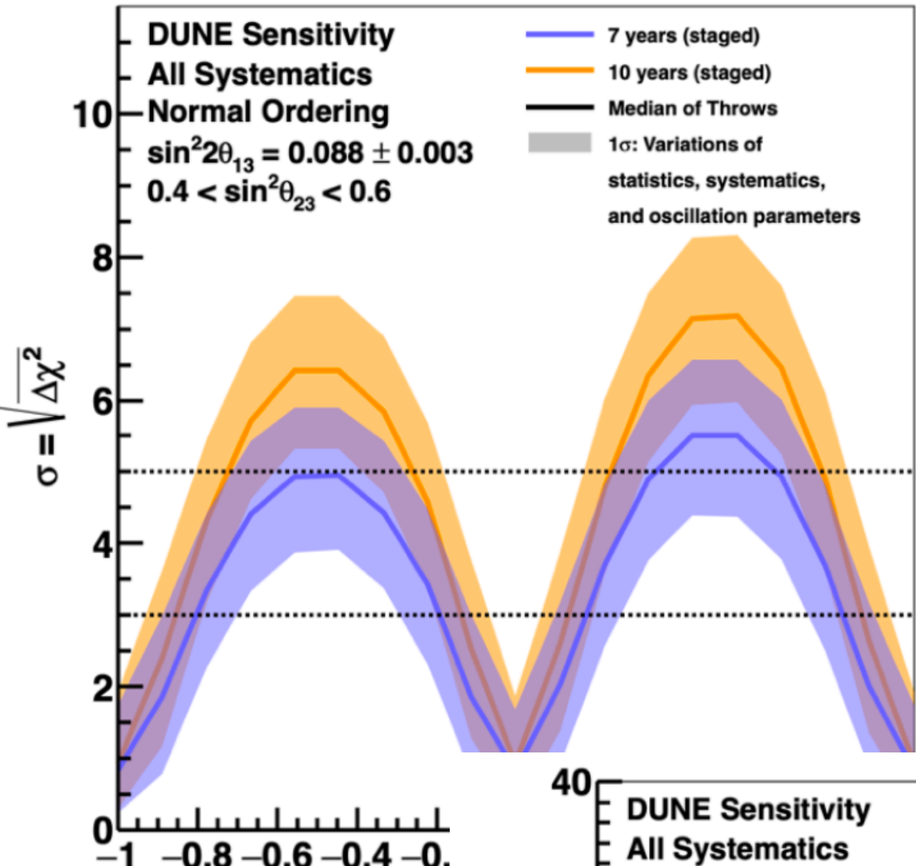
- 1.2 MW wide-band beam from FNAL to SURF (1300km)
- 4x10 kt Liquid Argon TPCs
- capability to probe 2nd oscillation max
- great sensitivity to mass ordering

Hyper-Kamiokande

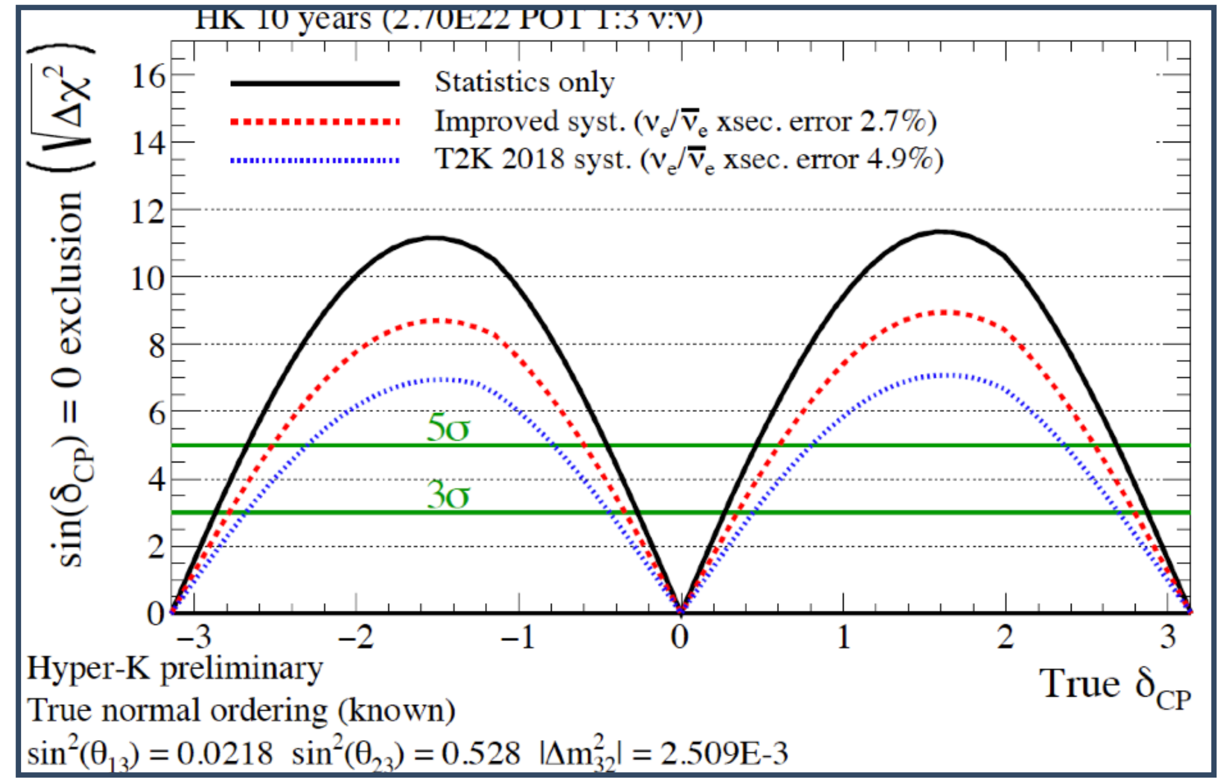


- 188 kton water Cerenkov
- T2HK: great sensitivity to δ_{CP}
- T2HKK (1100km) will have similar sensitivities as DUNE

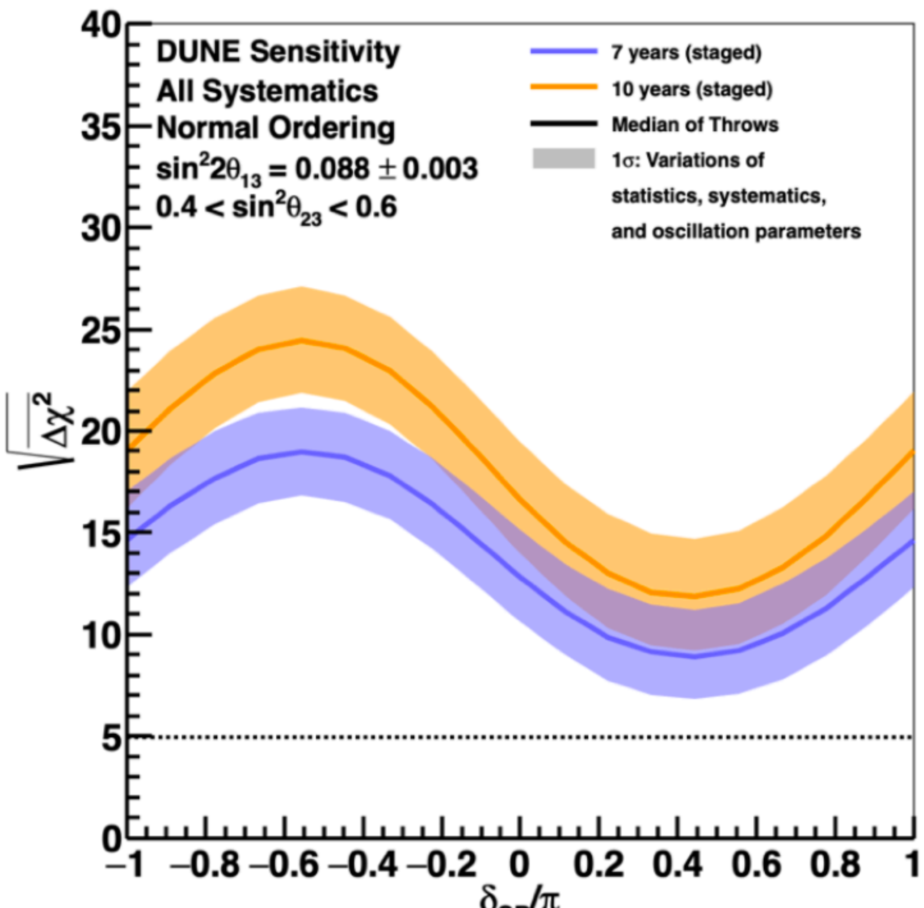
Next generation of ν experiments

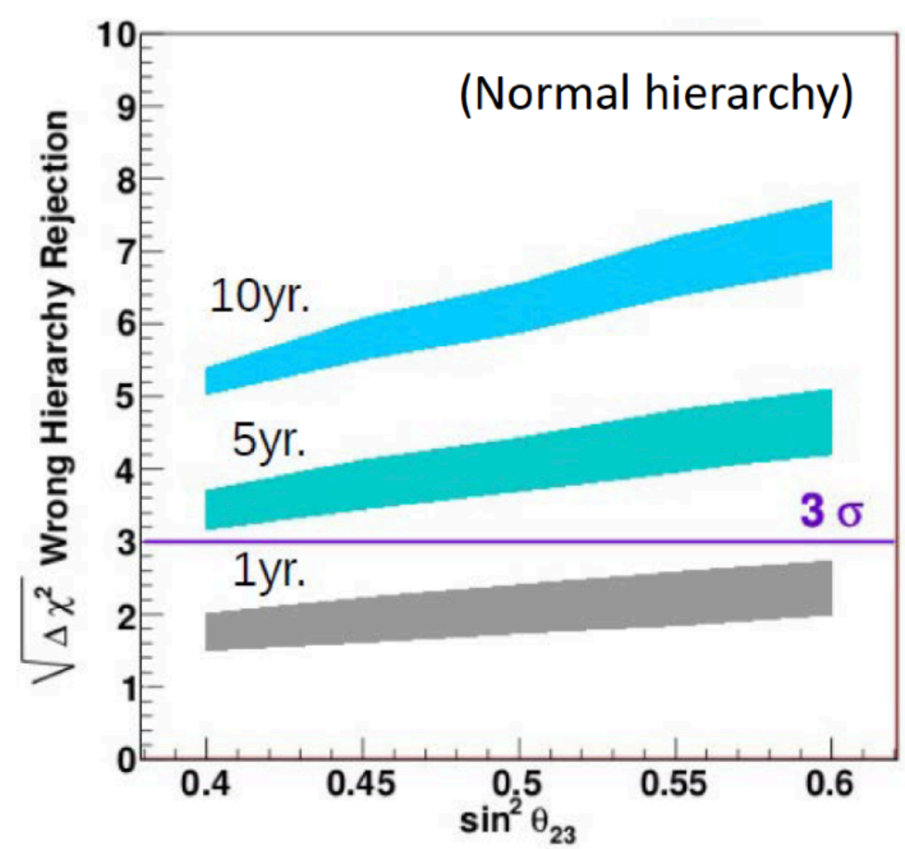


Hyper-K



DUNE





Beyond the standard three-neutrino scenario

Beyond the 3-neutrino scenario

- Neutrino results suggest the presence of **physics BSM** to explain:
  - ✓ light neutrino masses (mass generation mechanism)
  - ✓ large neutrino mixing compared to quark sector (flavour problem)
  - ✓ short-distance anomalies (LSND, reactor and Ga anomalies)

- Many different **BSM scenarios** analyzed in the literature:
  - ✓ neutrino non-standard interactions (NSI) with matter
  - ✓ exotic neutrino electromagnetic properties
  - ✓ presence of light sterile neutrinos
  - ✓ mixing with heavy sterile neutrinos: non-unitary neutrino mixing

⇒ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

Non-unitary light neutrino mixing

- Most models of neutrino masses include **new extra heavy states**

Ex: type I seesaw, inverse seesaw $\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$ $\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$

→ (3x3) light neutrino mixing matrix U is **non-unitary** in general

- NxN **non-unitary mixing matrix** described with $2N^2$-(2N-1) parameters

→ 13 parameters are needed to describe a non-unitary (3x3) matrix

→ besides the 4 standard ones (θ_{ij} and δ_{CP}), 9 more parameters are needed

- General parameterization for non-unitary NxN mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix} \quad \text{with} \quad N = N^{NP}U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

Escrihuela et al, PRD92 (2015)

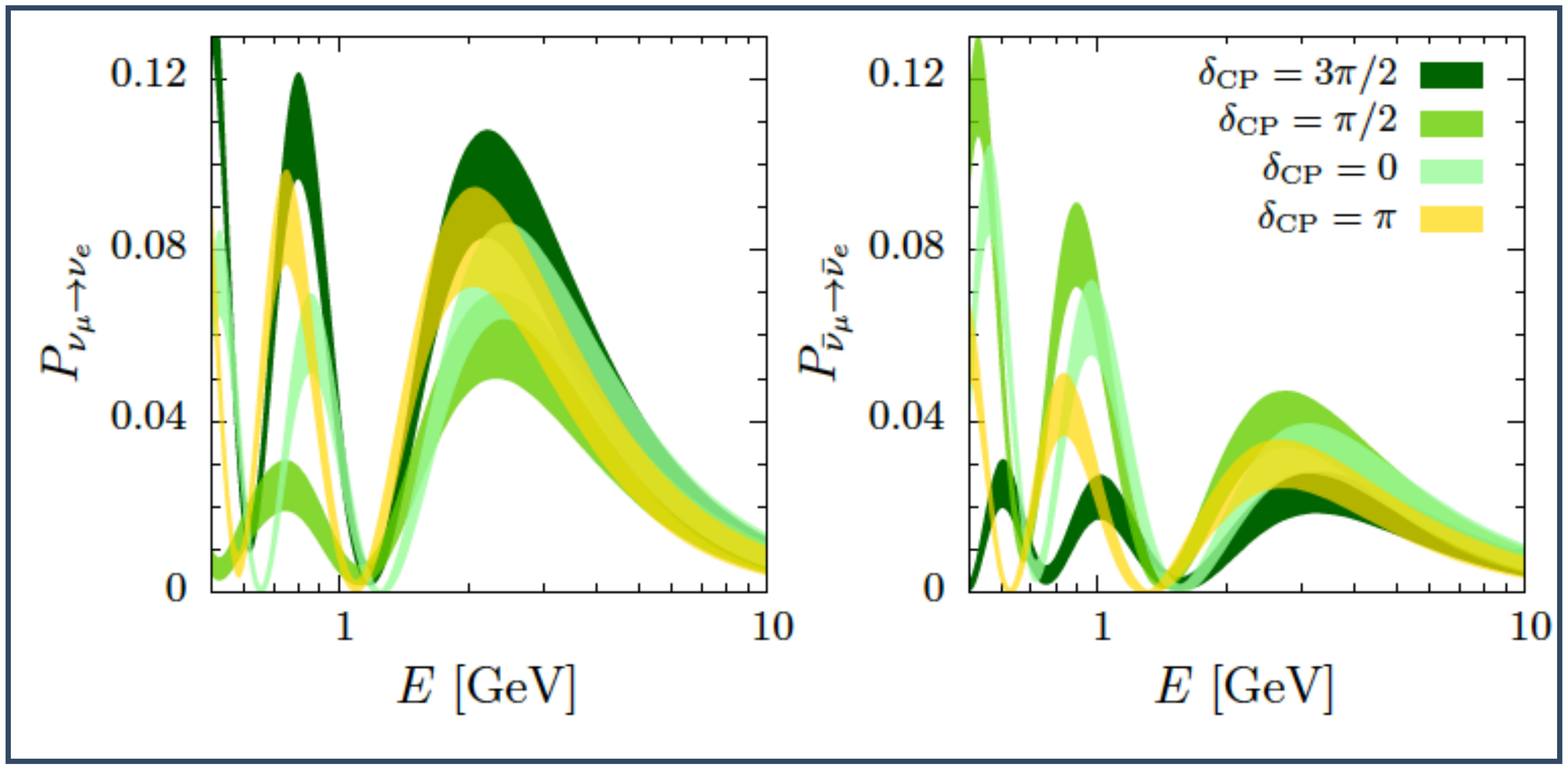
See also Xing, PRD2012 for n=6

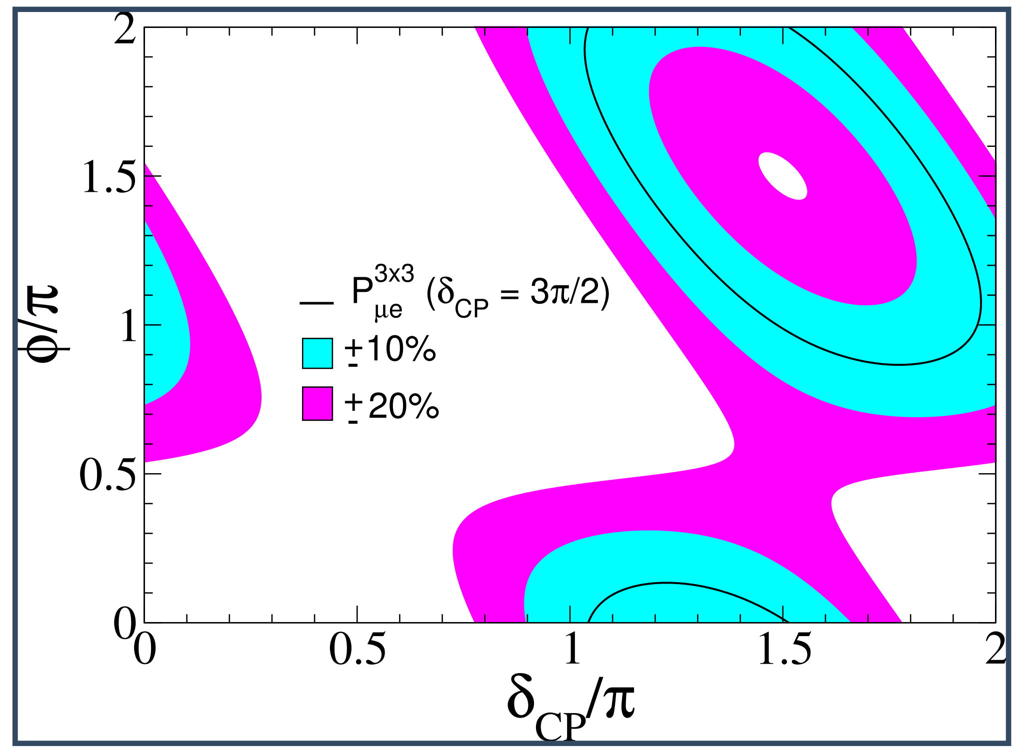
→ α_{ii} real, α_{ij} complex: 9 new parameters

NU neutrino oscillations in DUNE

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2 \alpha_{22}|\alpha_{21}| P_{\mu e}^{I} + \alpha_{11}^2 |\alpha_{21}|^2$$ **with** $P^{I}_{\mu e}(\phi)$

The new phases (ϕ) will modify the standard oscillation picture in LBL experiments, such as DUNE



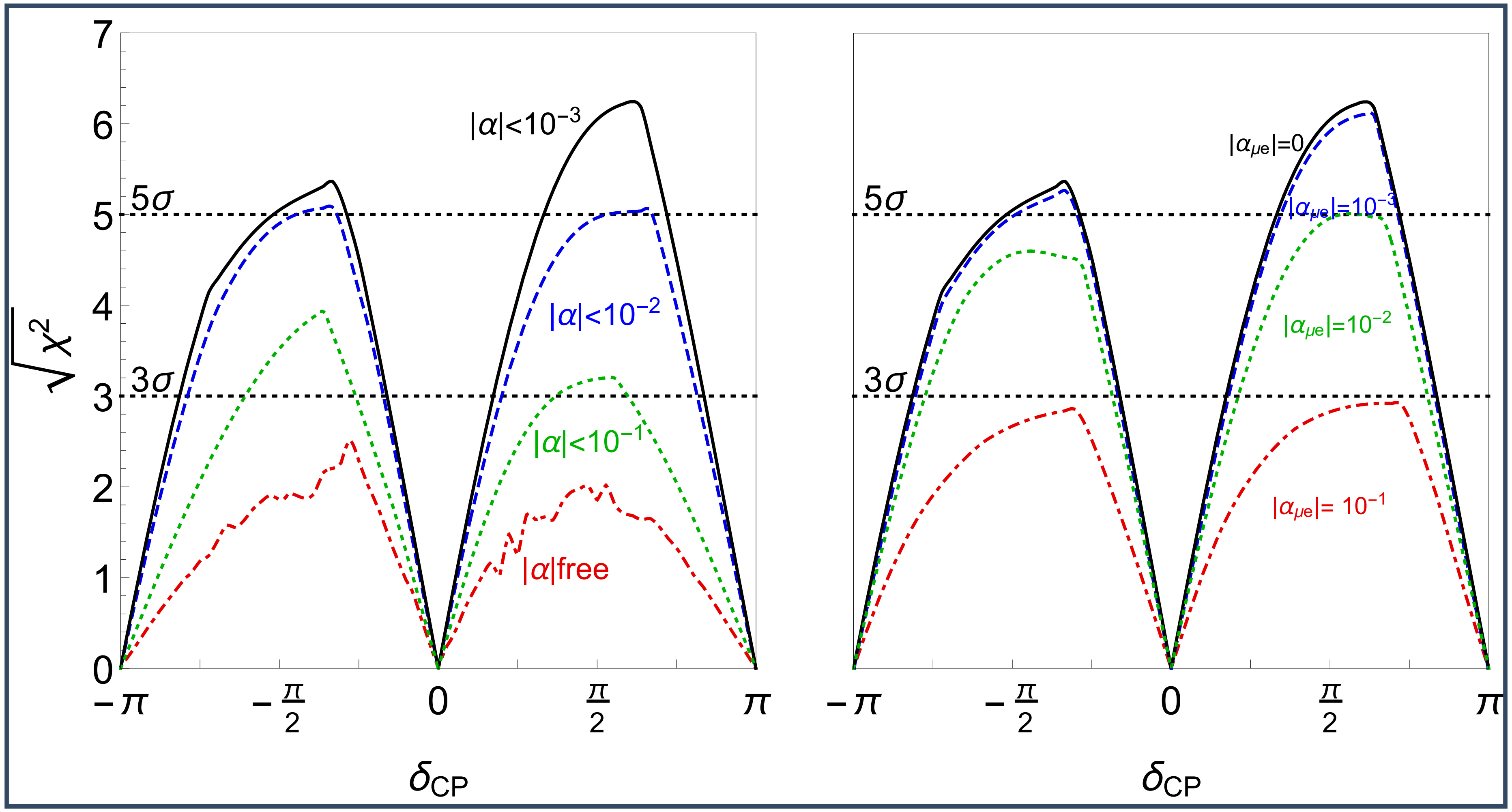


Escrihuela et al, NJP 2017

Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV spoil sensitivity to δ

DUNE CP sensitivity with NU



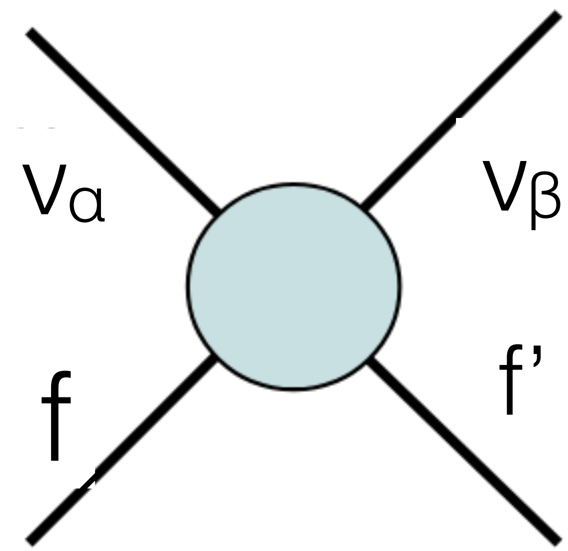
Fernández-Martínez et al (DUNE-BSM Working Group)

→ The sensitivity to CP violation might be spoiled in the absence of priors on NU

→ With priors based on current bounds (10^{-3}-10^{-2}), the effect is less dramatic

Neutrino NSI with matter

- NSI appear in models of neutrino masses
- Information about the size of NSI could be very useful for neutrino model building
- NSI may affect oscillation parameters



⇒ precision measurements at current experiments
⇒ sensitivity reach of upcoming experiments(degeneracies)

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)$$

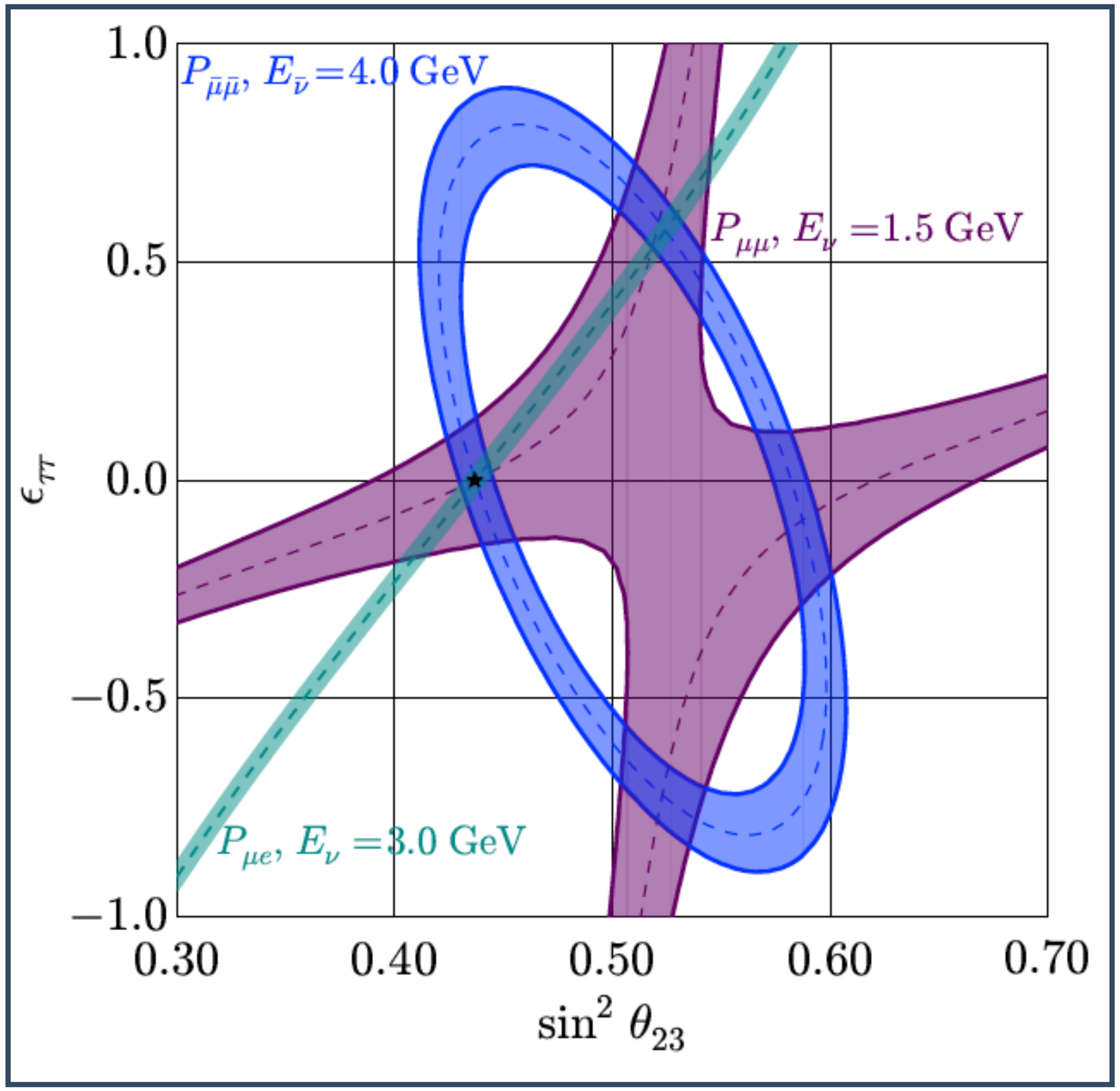
$\epsilon_{\alpha\beta} \neq 0$ → NSI violate lepton flavor (FC-NSI)

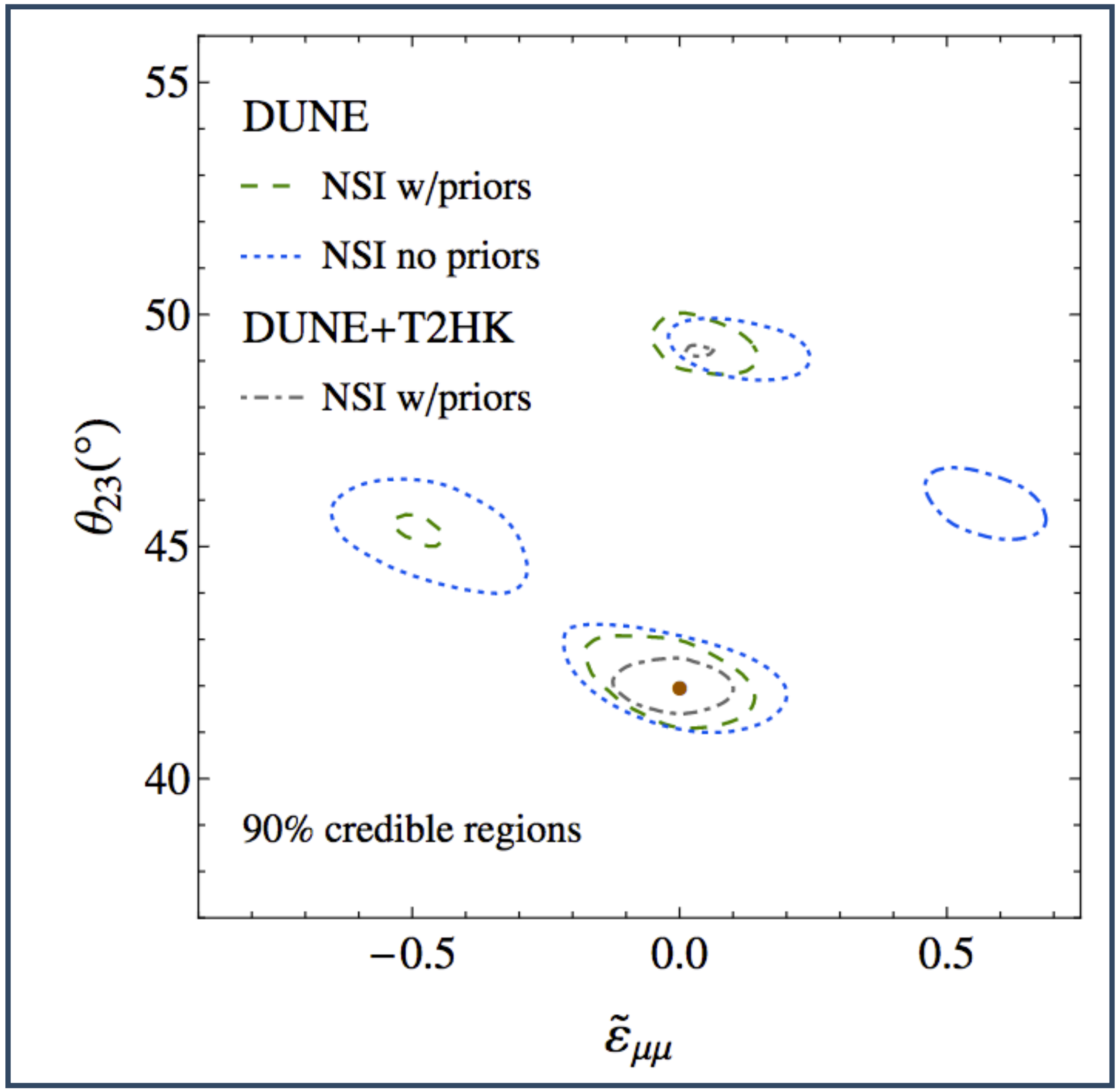
$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0$ → NSI violate lepton universality (NU-NSI)

⇒ mainly affecting neutrino propagation in matter
(but also detection in Super-K & Borexino)

NSI at future LBL experiments

(θ_{23}-$\epsilon_{\tau\tau}$) degeneracy in DUNE



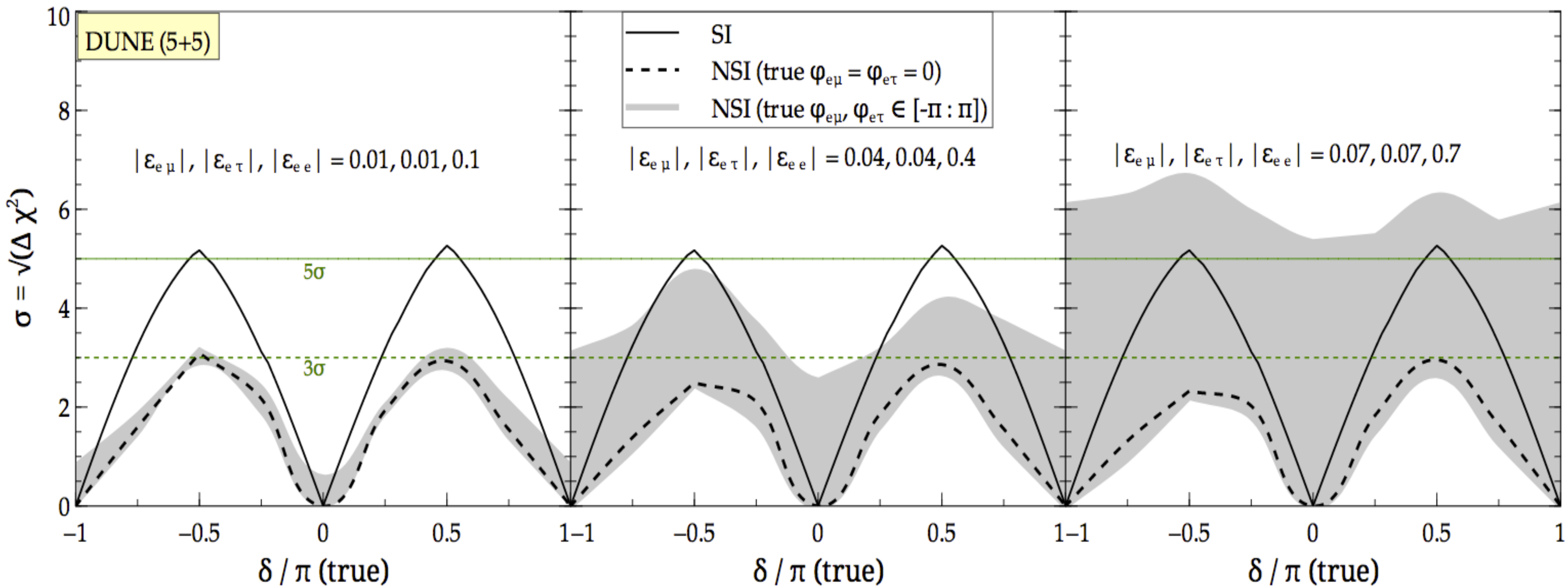


Gouvea and Kelly, NPB 2016

Coloma, JHEP 2016

NSI at future LBL experiments

NSI significantly spoil sensitivity to CP violation in DUNE



Masud and Mehta, PRD 2016

NSI at future LBL experiments

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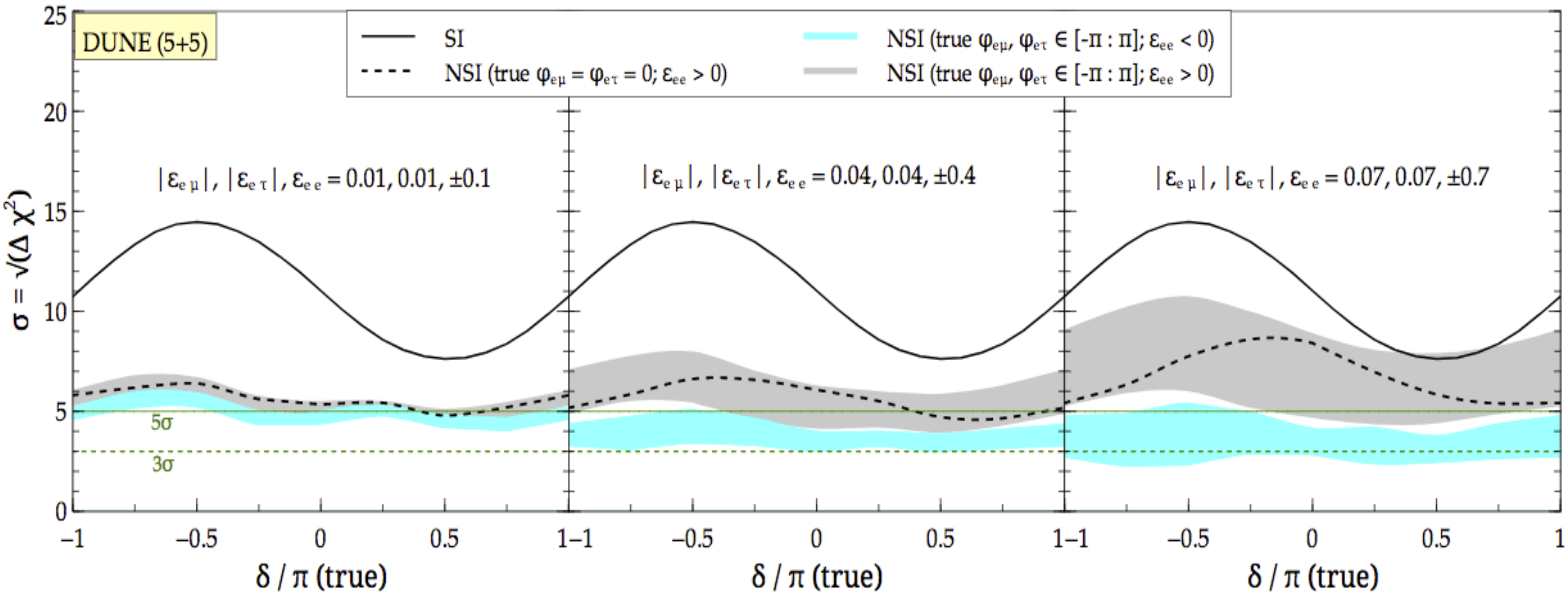

Masud and Mehta, PRD 2016

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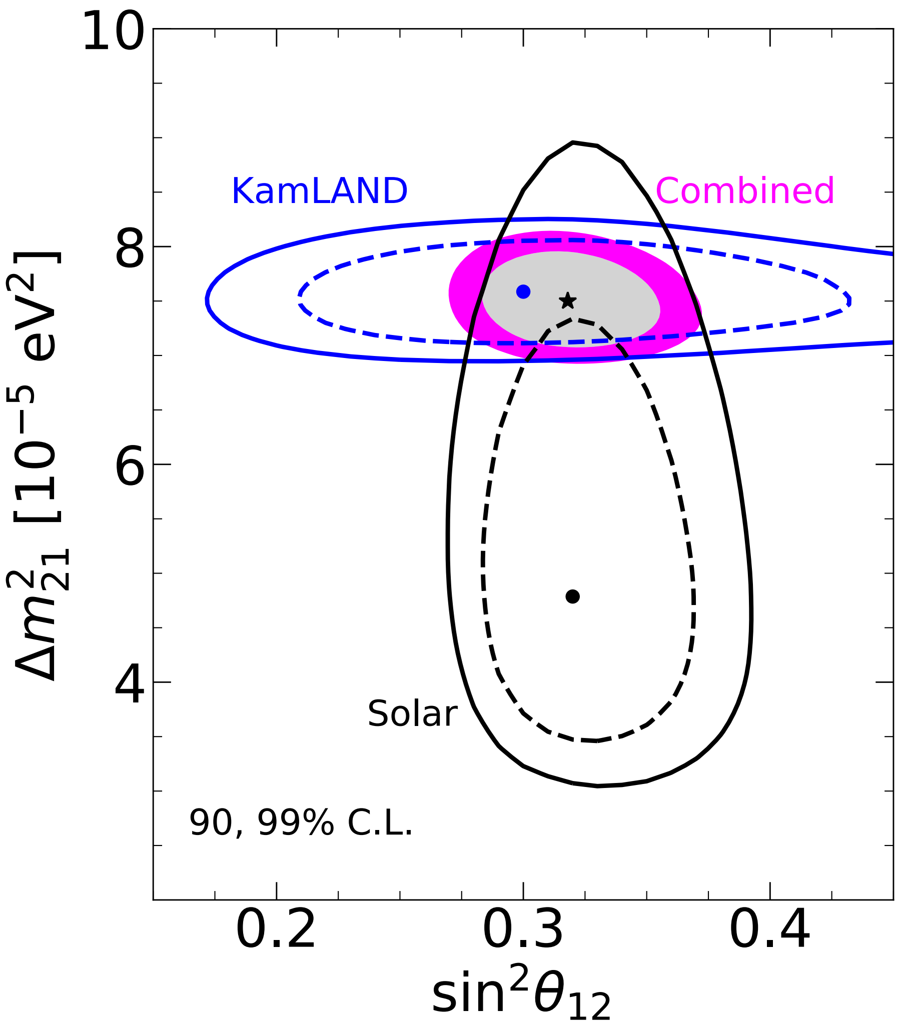
Can they also help reducing the current tensions?

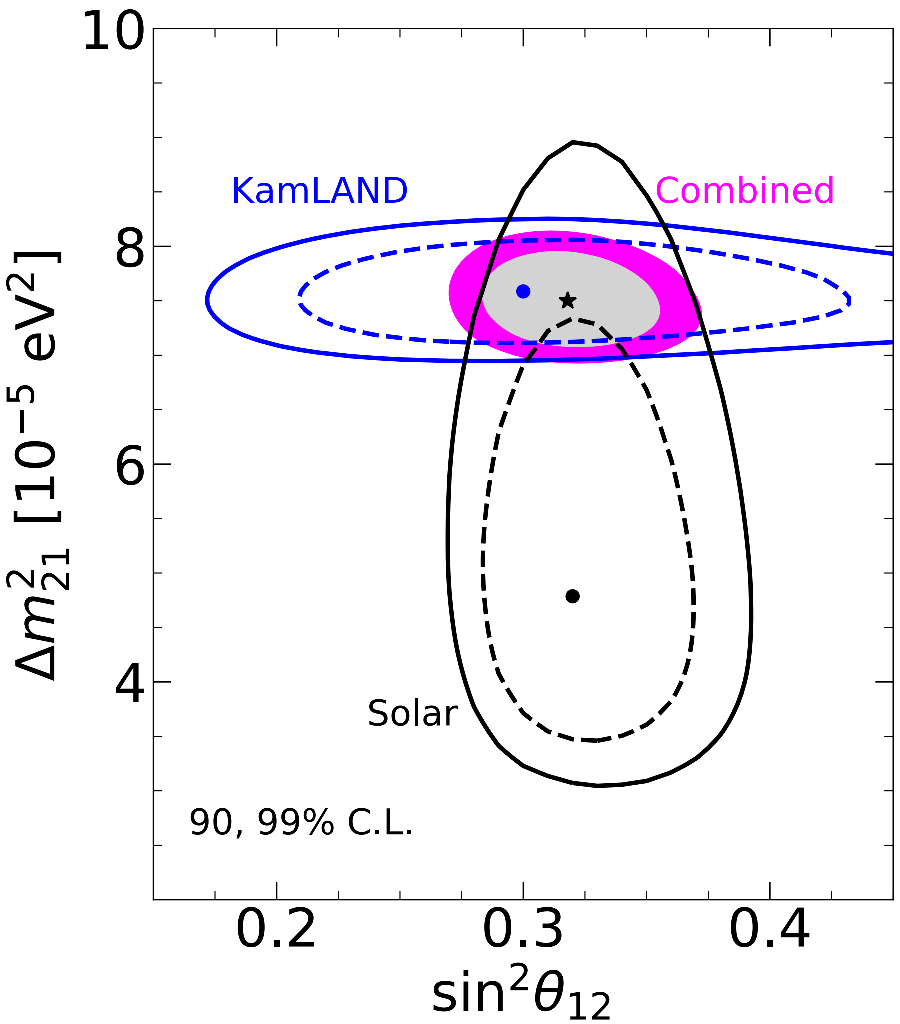
The solar-KamLAND Δm^2_{21} tension



⇒ 2σ (1.5σ) tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ Δm^2_{21} preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

The solar-KamLAND Δm^2_{21} tension



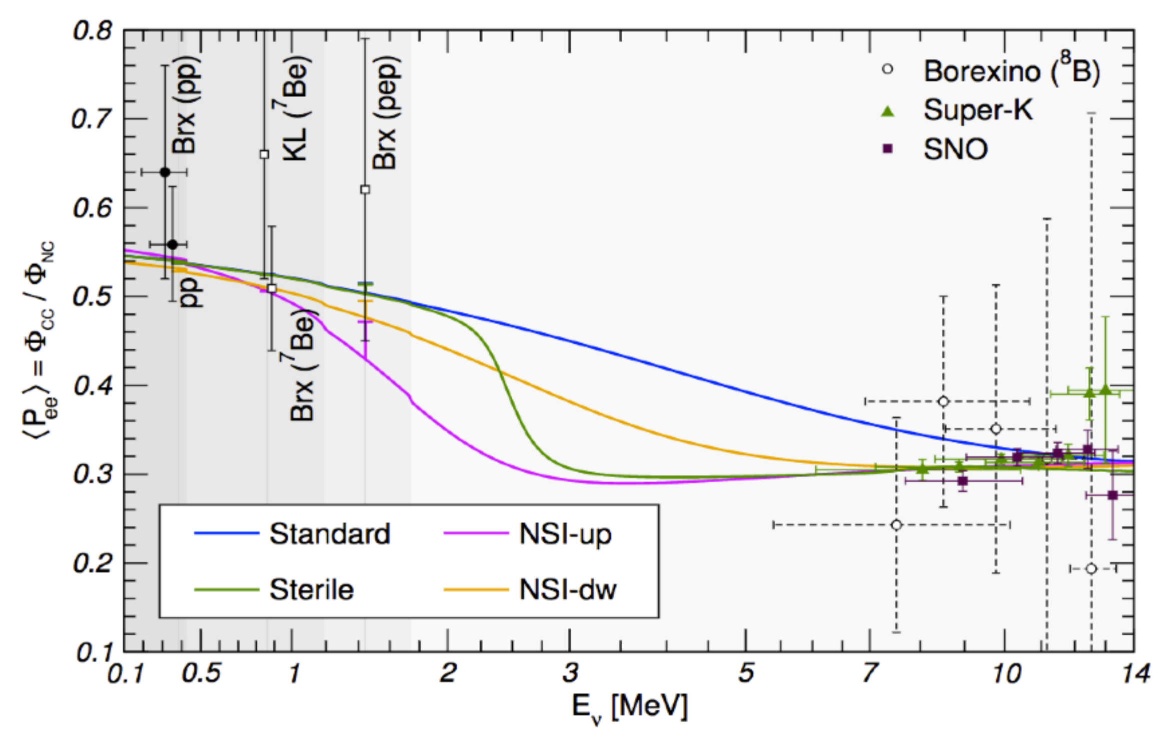
⇒ 2σ (1.5σ) tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ Δm^2_{21} preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

✦ NSI (ε ~0.3) can reconcile both results:

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected

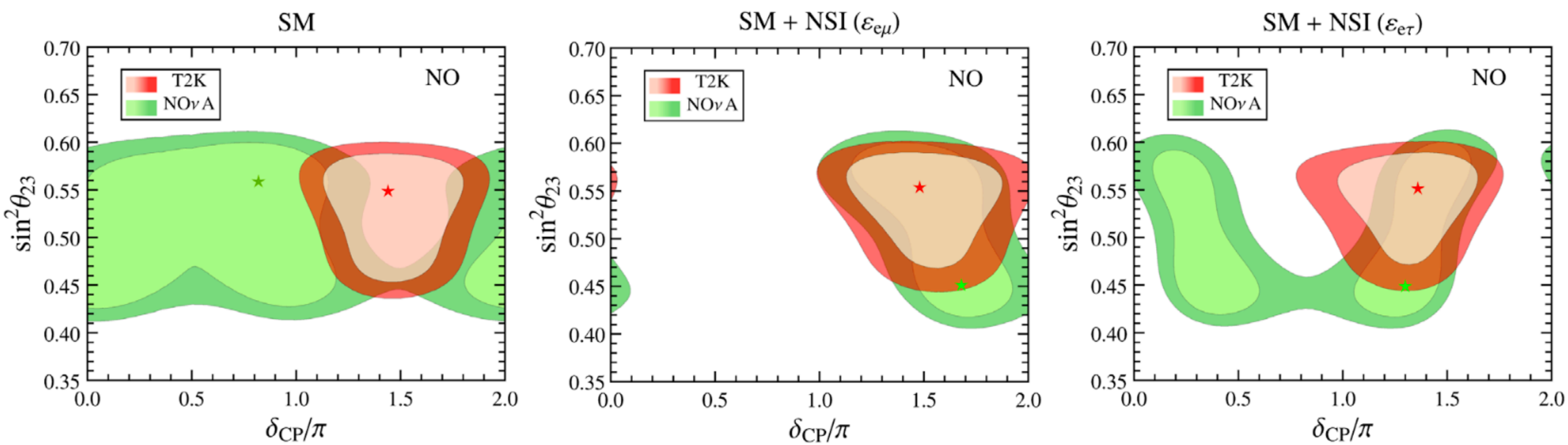


Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

The T2K-NOvA δ_{CP} tension

✦ NSI may include new sources of CP violation besides δ_{CP}: $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \exp(i\phi_{\alpha\beta})$

✦ CP-violating NSI with a new complex phase $\phi_{e\mu}$ or $\phi_{e\tau}$ close to maximal with NSI couplings $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ of the order of 0.2 may reconcile T2K and NOvA results.

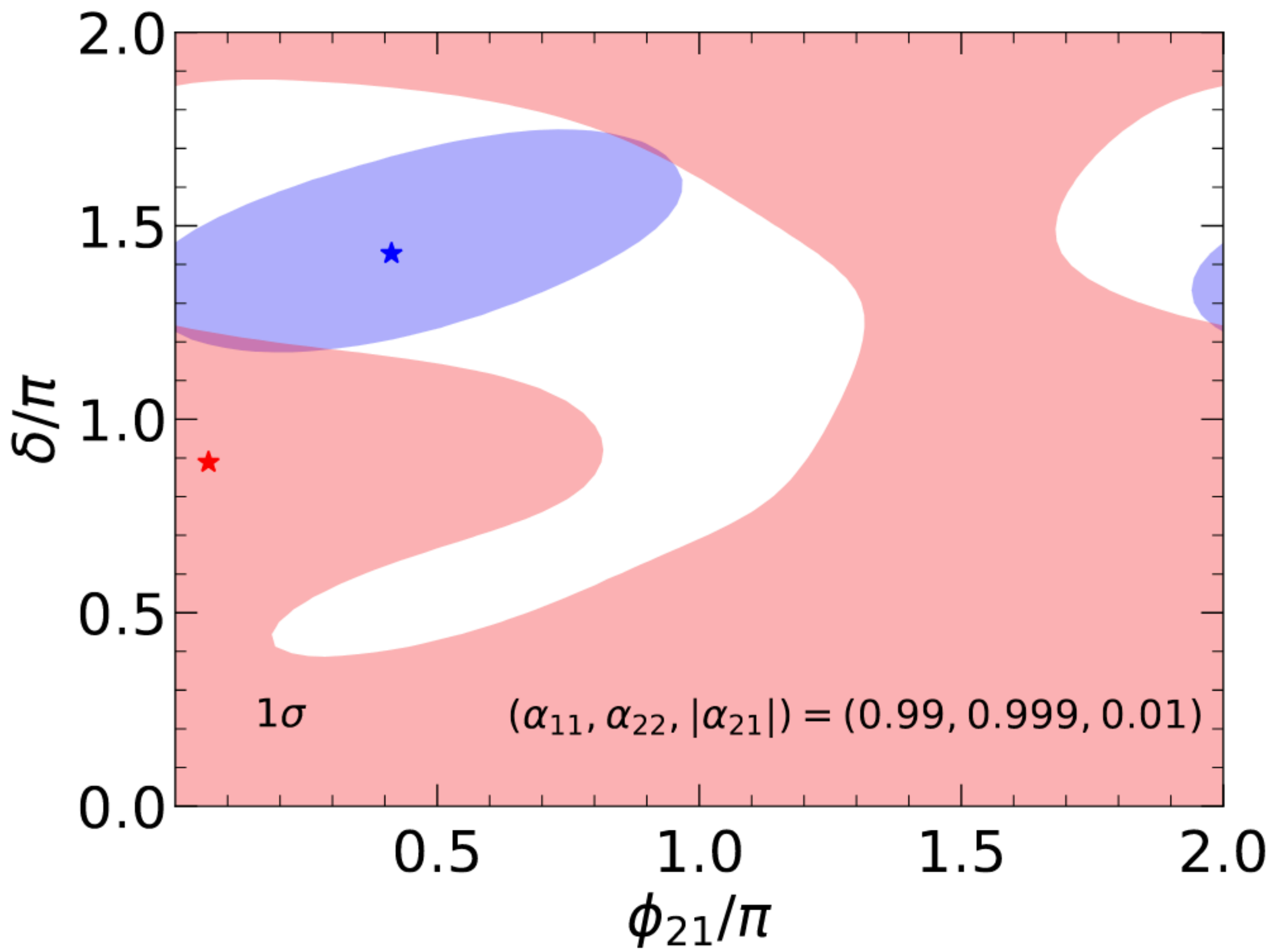


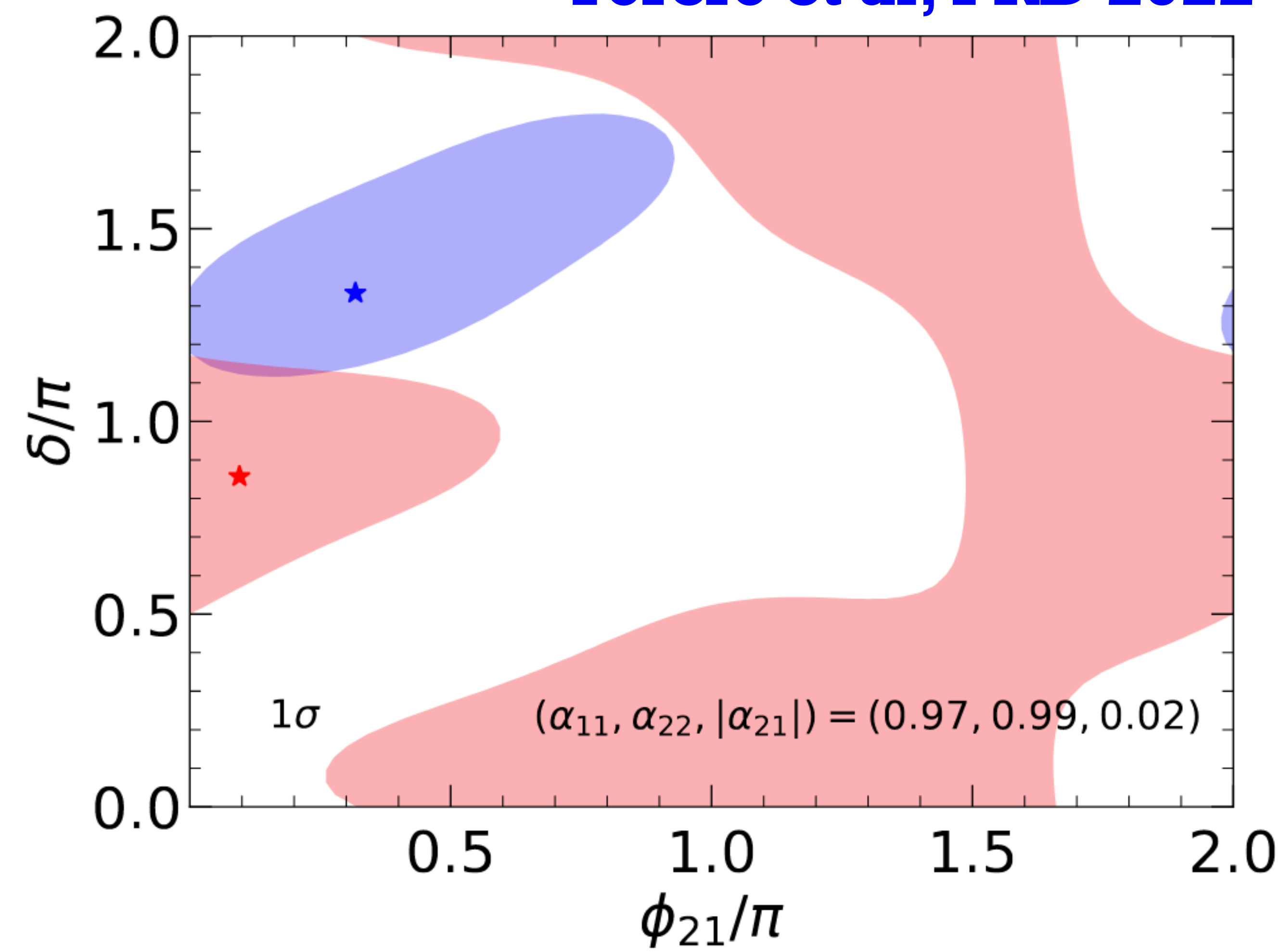
Chatterjee and Palazzo, PRL 2021 **Denton et al, PRL 2021**

The T2K-NOvA δ_{CP} tension

Non-unitary mixing analysis of T2K and NOvA (normal ordering)

Forero et al, PRD 2022





- NU includes additional sources of CP violation.
- No significant deviation from unitary mixing is found: updated bounds with LBL and SBL ⇒MINOS improves current neutrino limits!

⇒ The tension is not alleviated in the context of NU neutrino mixing

Summary

✦ Current status of three-neutrino oscillation parameters:

✓ very precise and robust determinations for most of them (1.3-10%)

✓ preference for $\theta_{23} > 45°$, 1st octant value disfavoured with $\Delta\chi^2 \geq 5.8$ (6.4)

✓ $\delta_{BF} = 1.08\pi$ (1.58π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.0σ (6.2σ)

✓ 2.5σ hint for normal ordering from atmospheric, LBL and reactor data

✓ sensitivity on mass ordering driven by oscillation data so far.

✦ New results presented in Neutrino 2022 may change some results:

✓ Daya Bay achieved expected final sensitivity on $\sin^2 2\theta_{13}$

✓ Small changes expected in CP violation, atmospheric octant and mass ordering

✦ By 2025/2026:

✓ oscillation parameters will be measured with 0.6-3% precision

✓ θ_{23} octant can be resolved at more than 3σ (for some values)

✓ $2\text{-}3\sigma$ sensitivity to CP violation at NOvA and T2K

✓ 3σ sensitivity to MO from reactor, accelerator and nu-telescopes

⇒ sensitivities above 3σ from a single experiment: DUNE, Hyper-Kamiokande

✦ New physics BSM may affect the current description of neutrino oscillations relaxing tensions or worsening the precision of measurements.