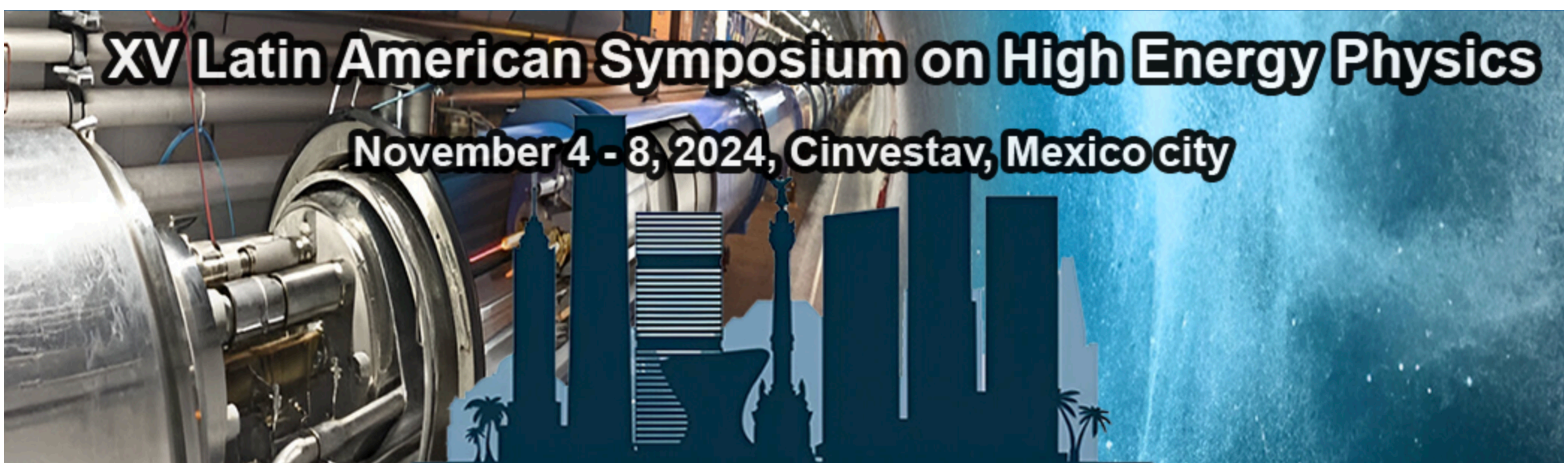
Global fits to three-neutrino oscillations

Mariam Tórtola
IFIC, CSIC/Universitat de València



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Neutrinos oscillate

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The three-flavour ν picture

neutrino mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

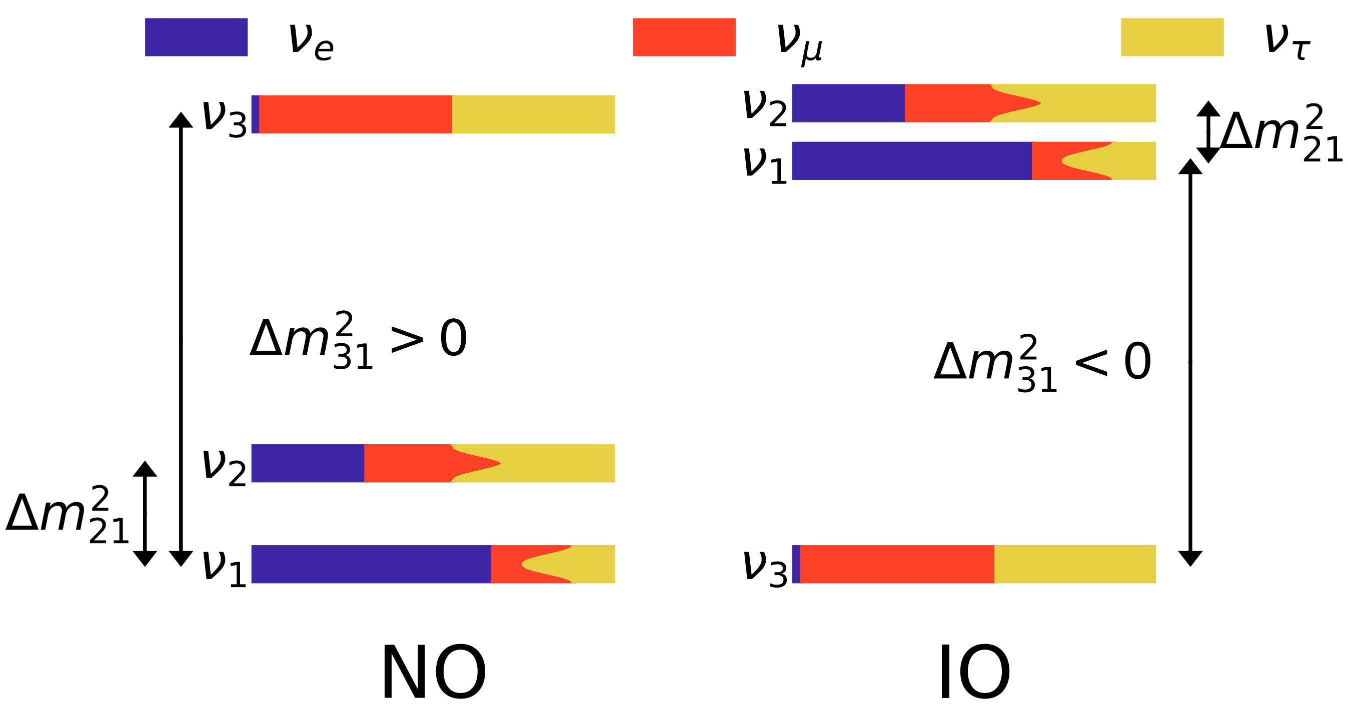
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

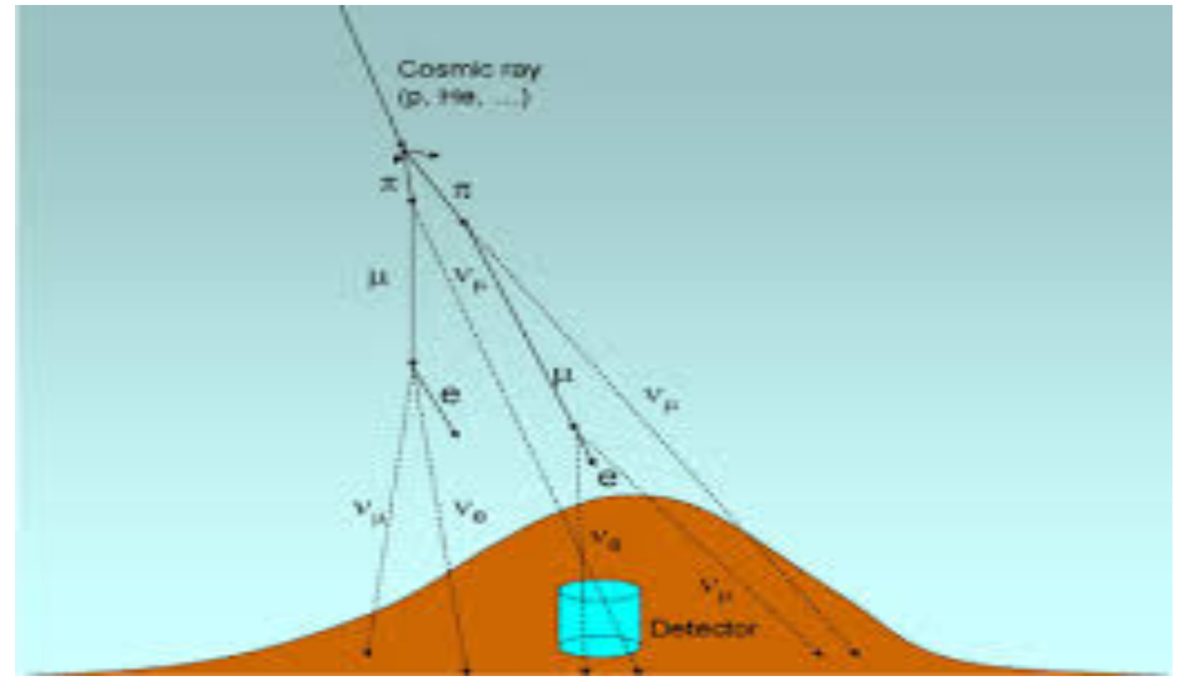
neutrino mass spectrum



Neutrino oscillations

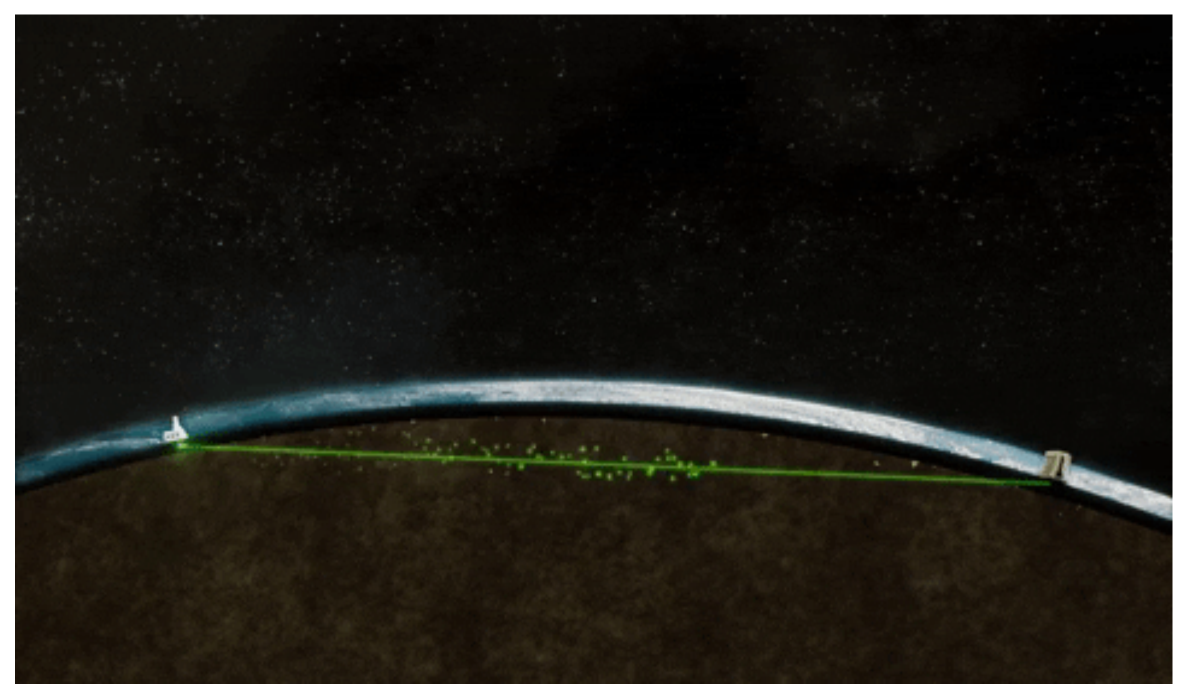
Solar neutrinos

Atmospheric neutrinos



Reactor neutrinos

Accelerator neutrinos



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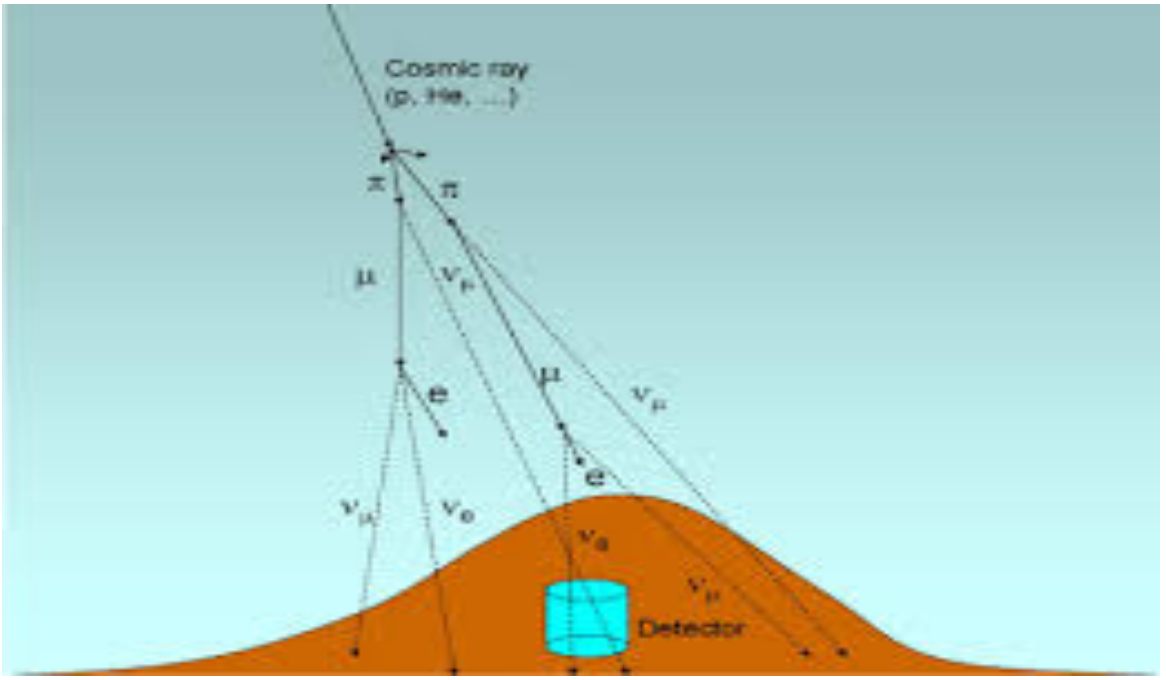

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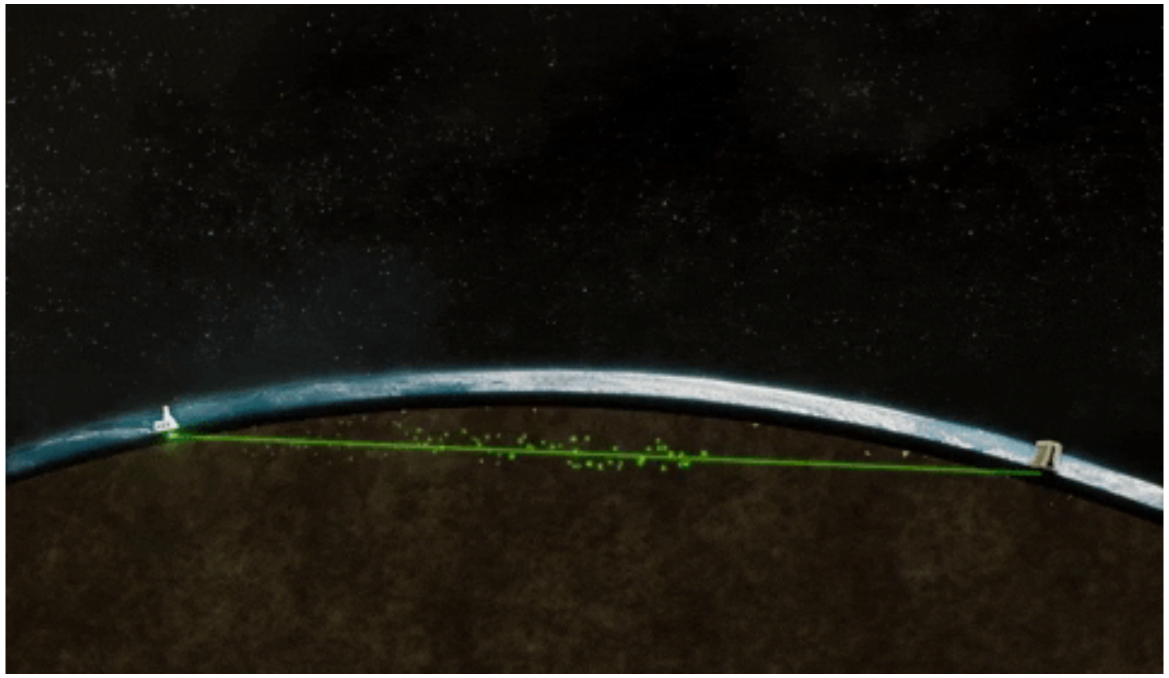
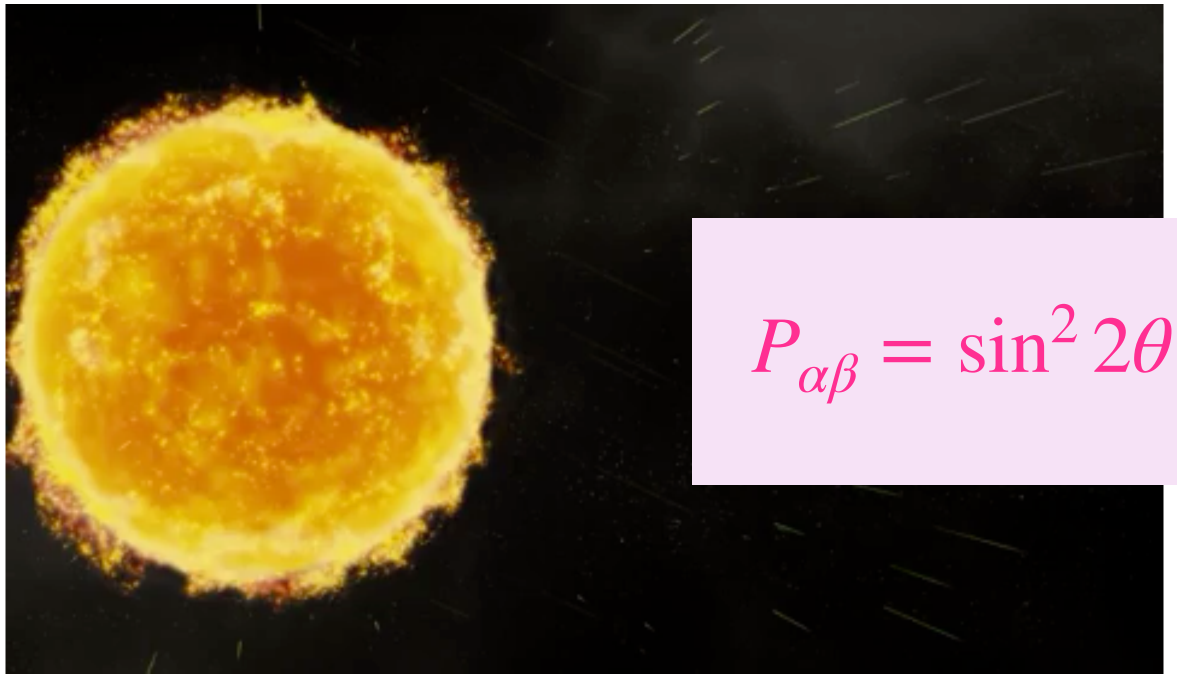
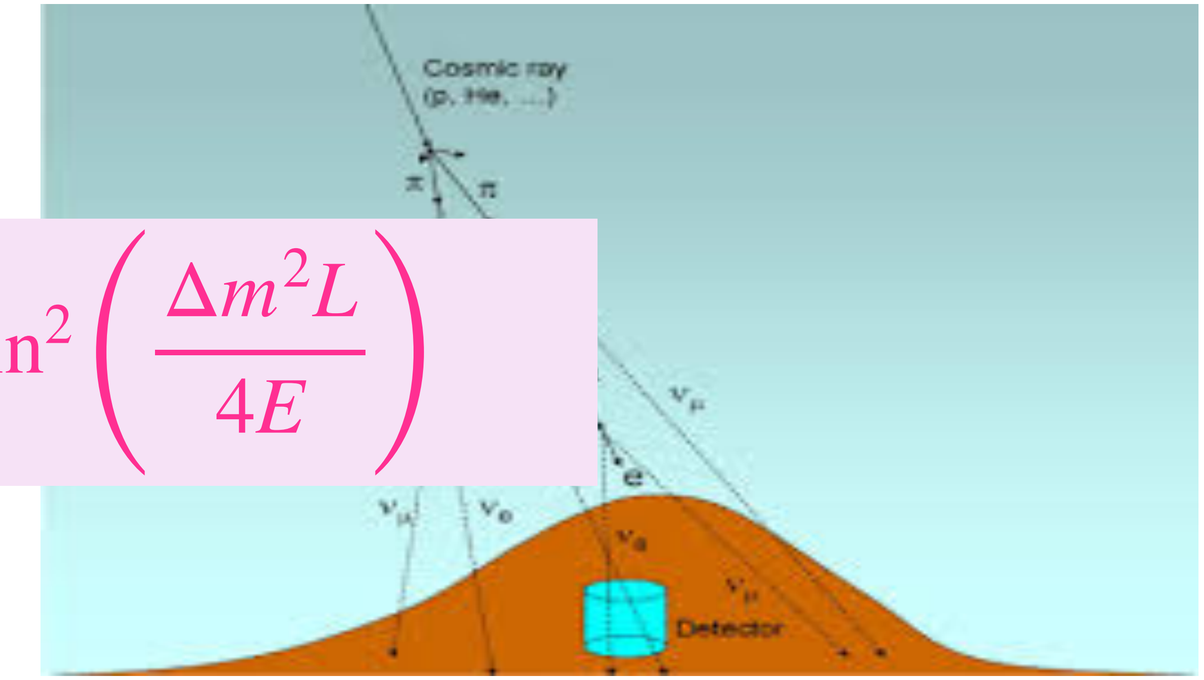


Neutrino oscillations

Solar sector: $\theta_{12}, \Delta m^2_{21}$



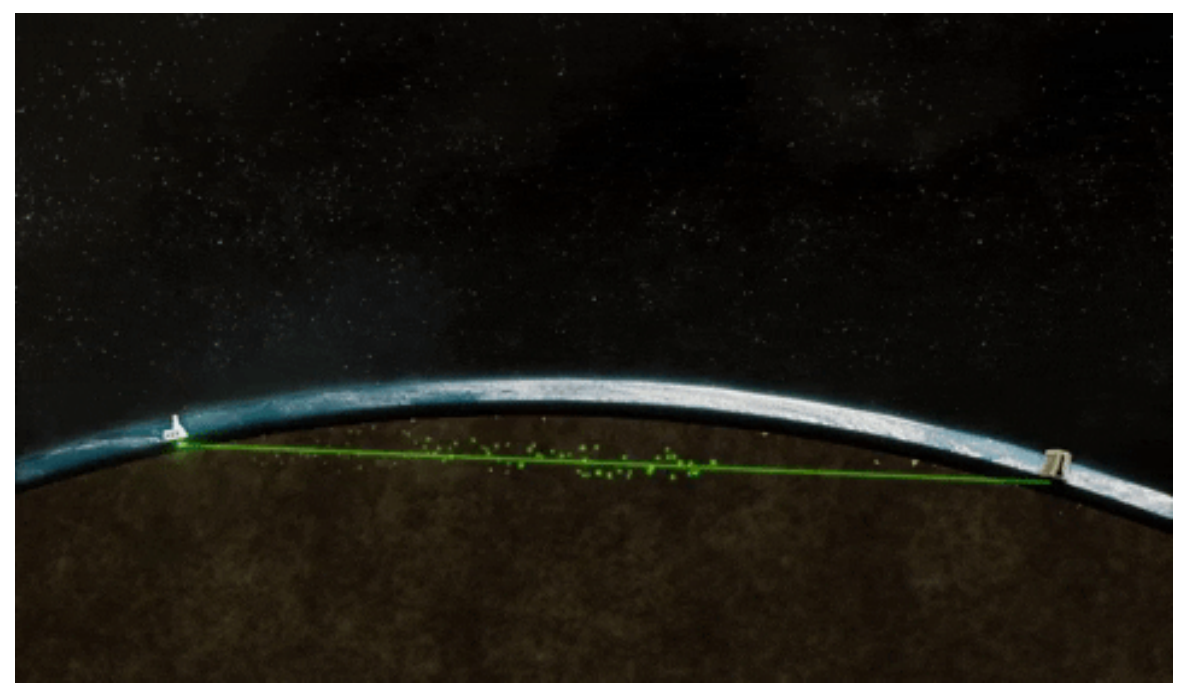
Atmospheric sector: $\theta_{23}, \Delta m^2_{31}$



$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Reactor sector (SBL): $\theta_{13}, \Delta m^2_{31}$

Accelerator sector: $\theta_{23}, \Delta m^2_{31}$



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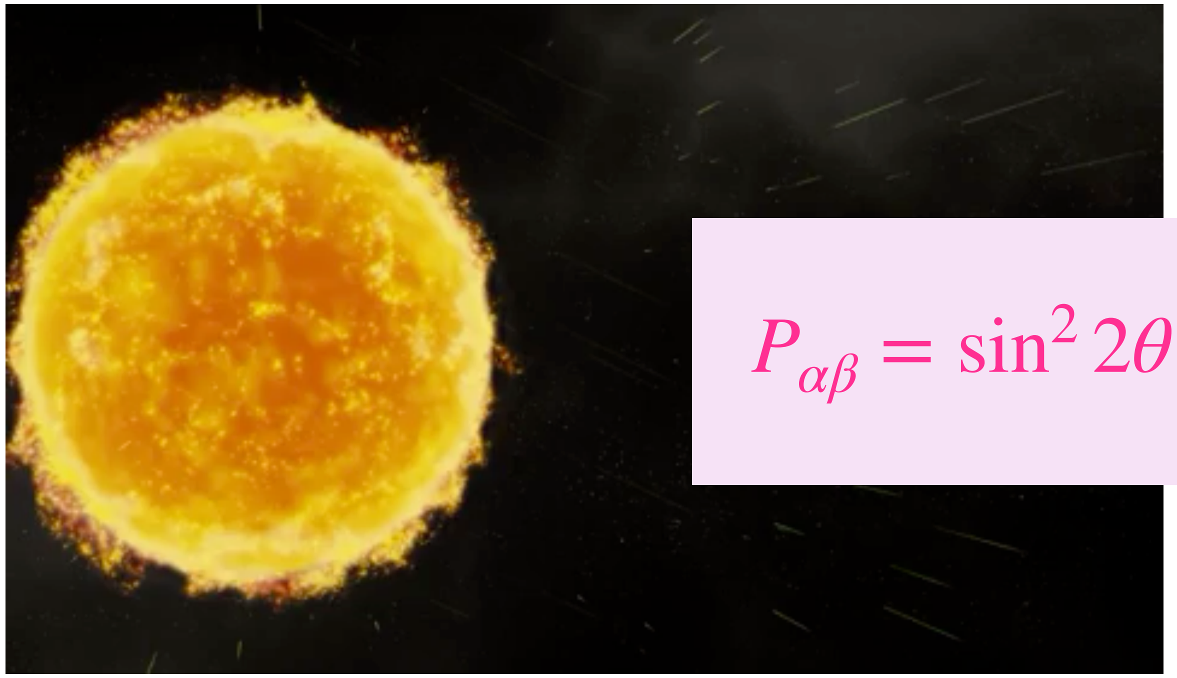

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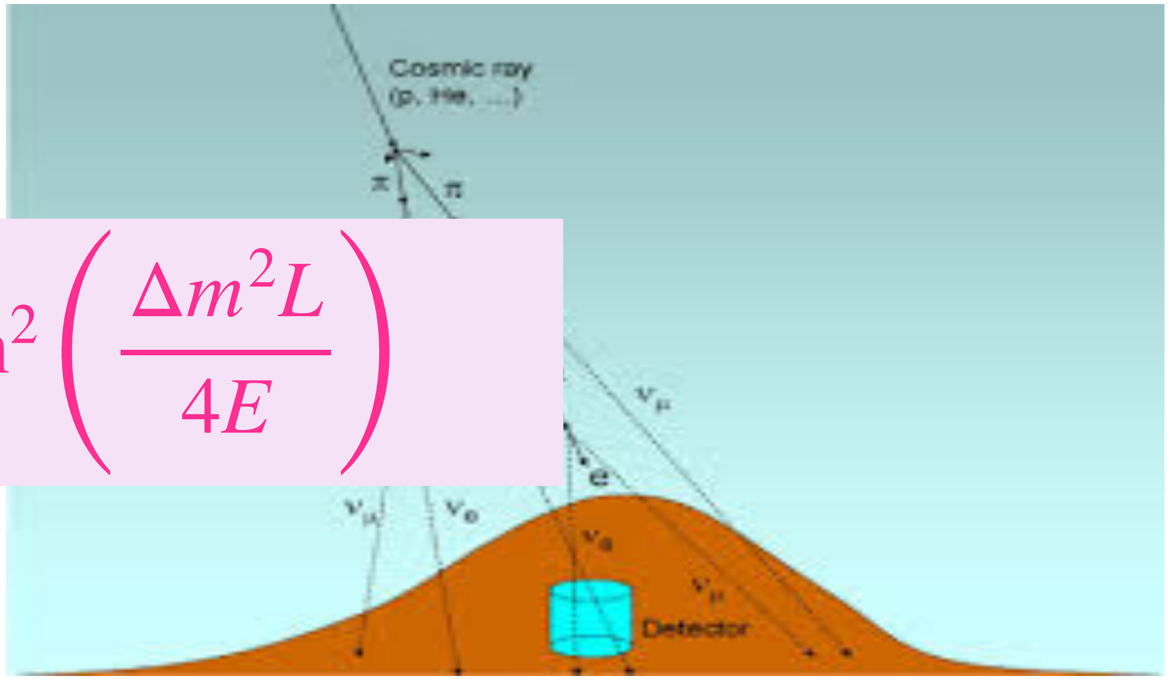

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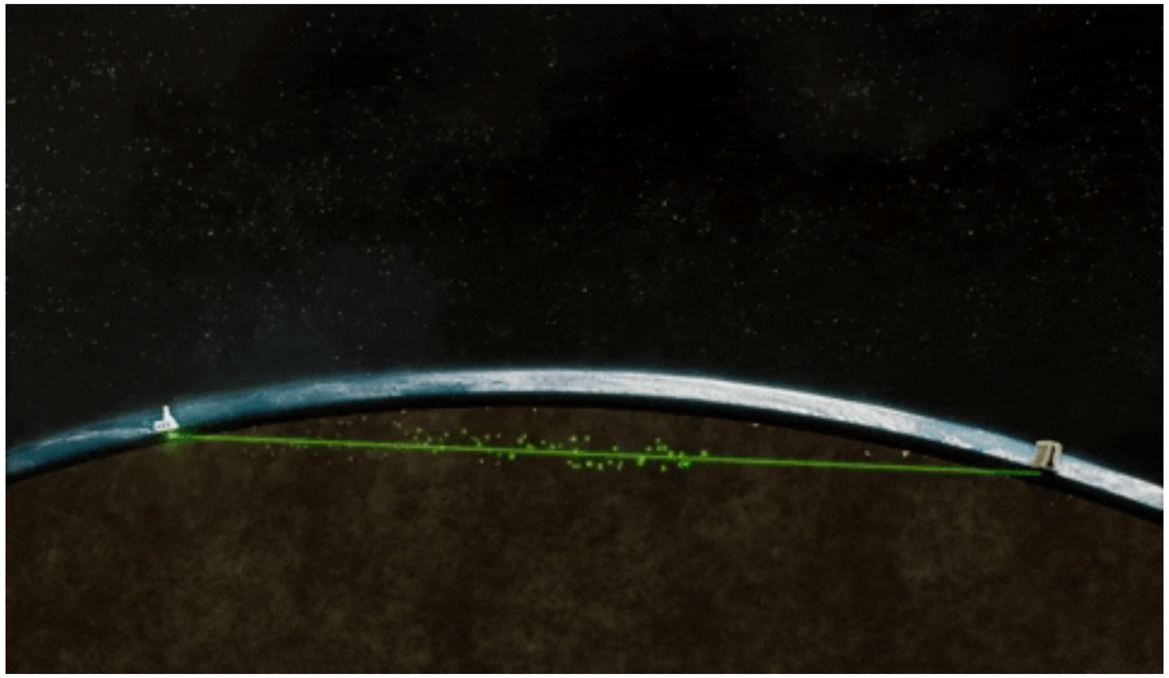
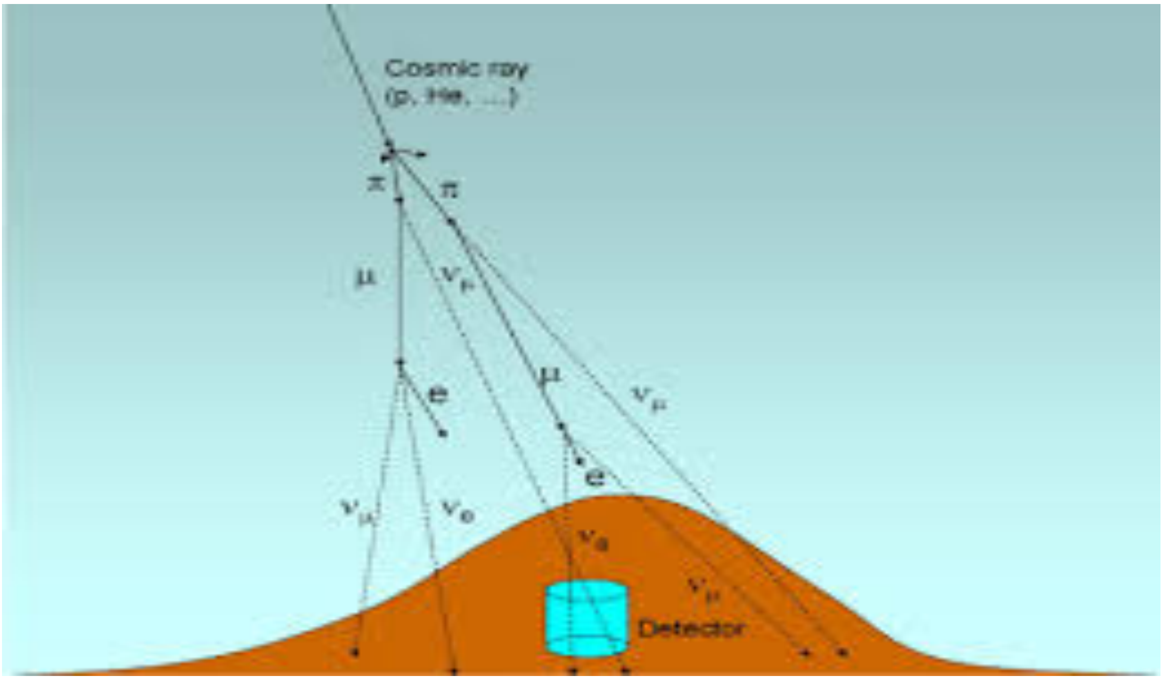


Neutrino oscillations

Solar sector: θ_{12}, θ_{13}, Δm^2_{21}

Atmospheric sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



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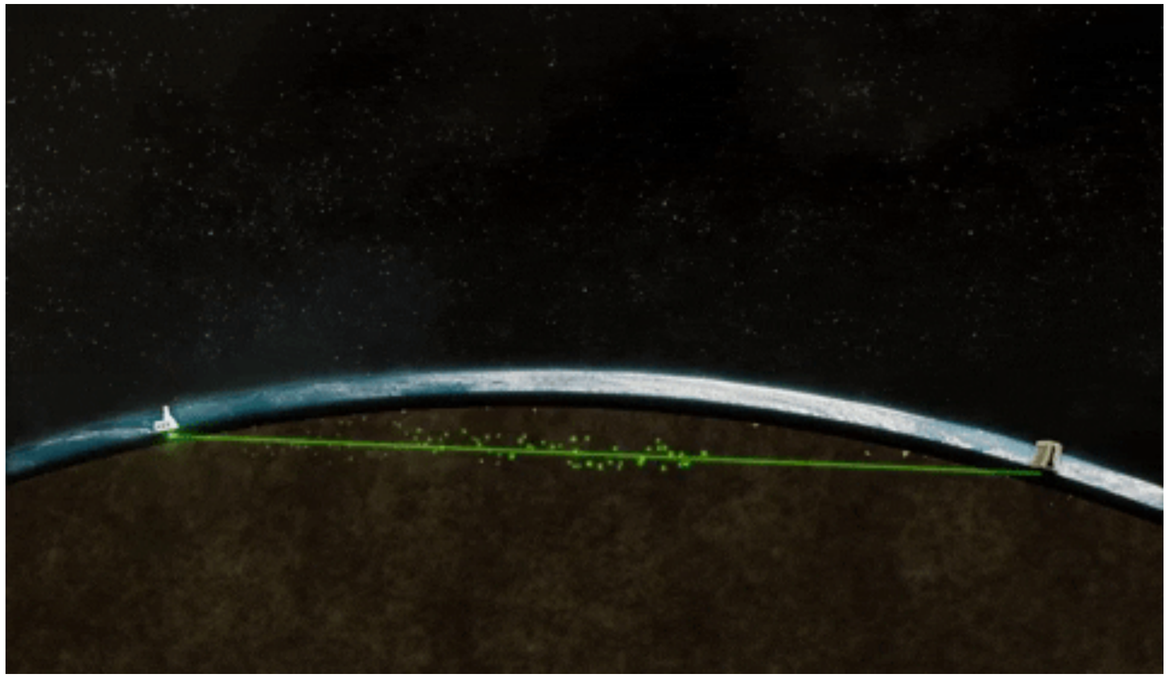

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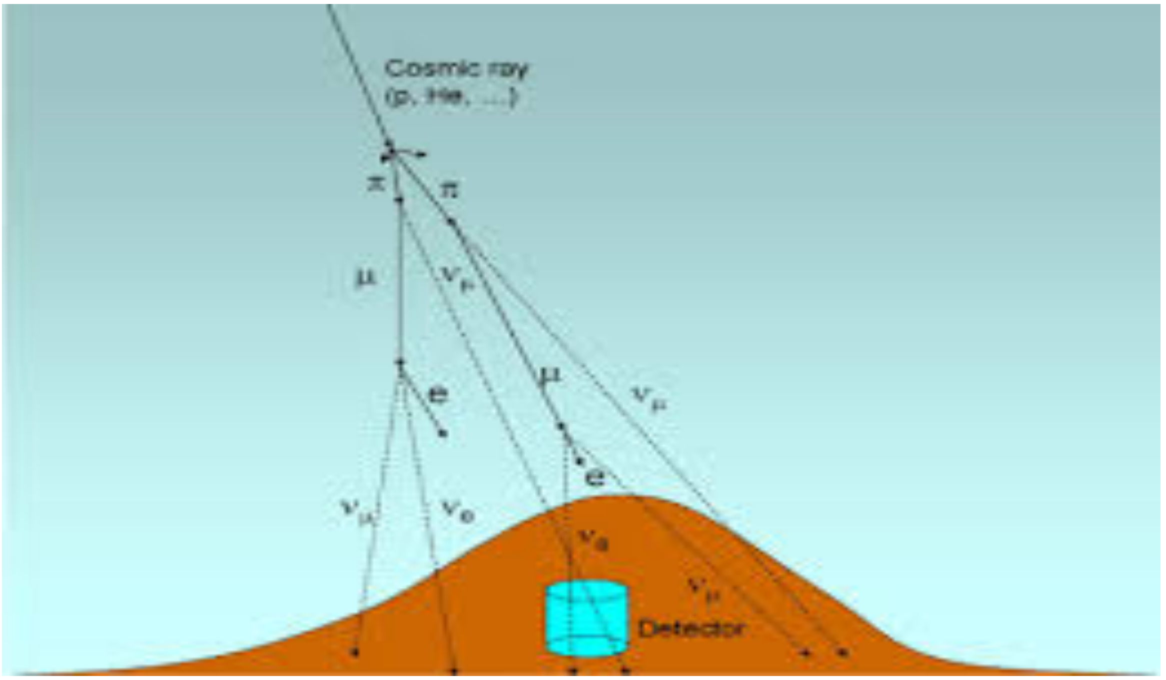

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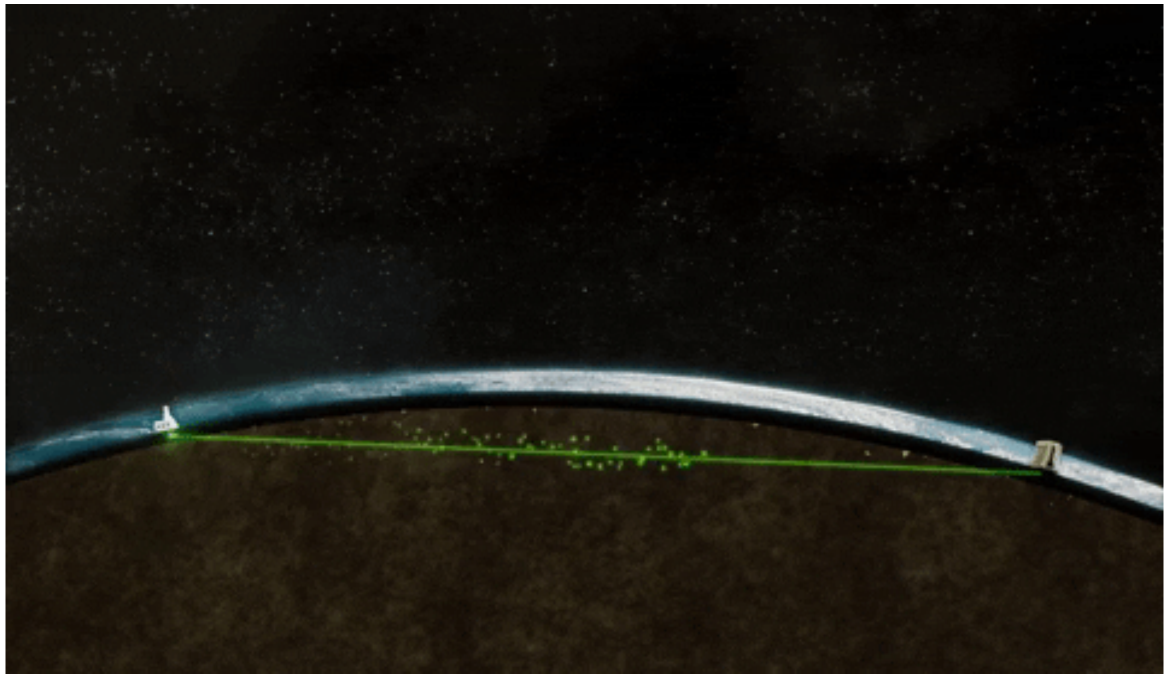
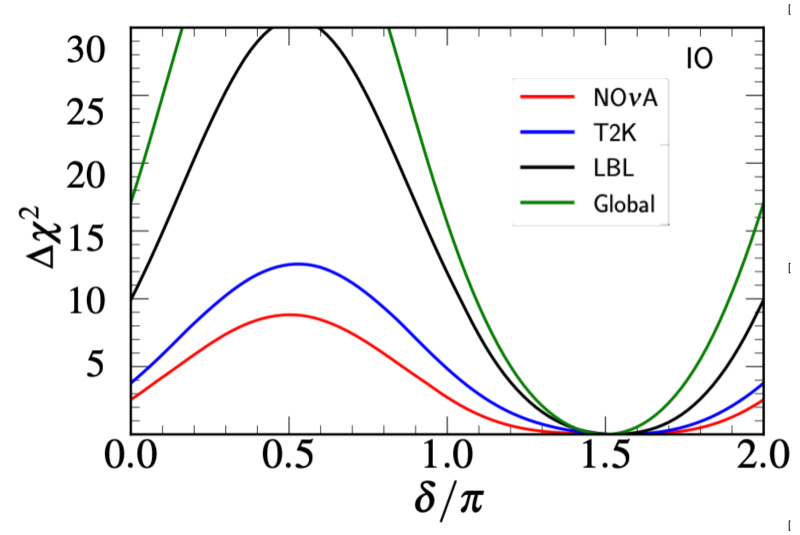


Why a global analysis?

1

Compensate low statistics in subleading oscillation effects searches

Ex: enhance sensitivity to MO and CP violation



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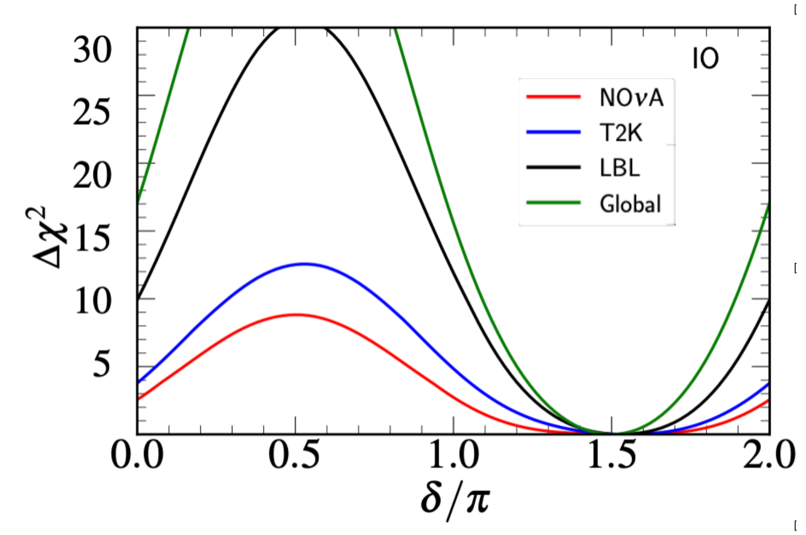

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Exploit synergies among experiments

Ex: solar params before KamLAND

Ex: $\theta_{13}\neq0$ before reactor measurement

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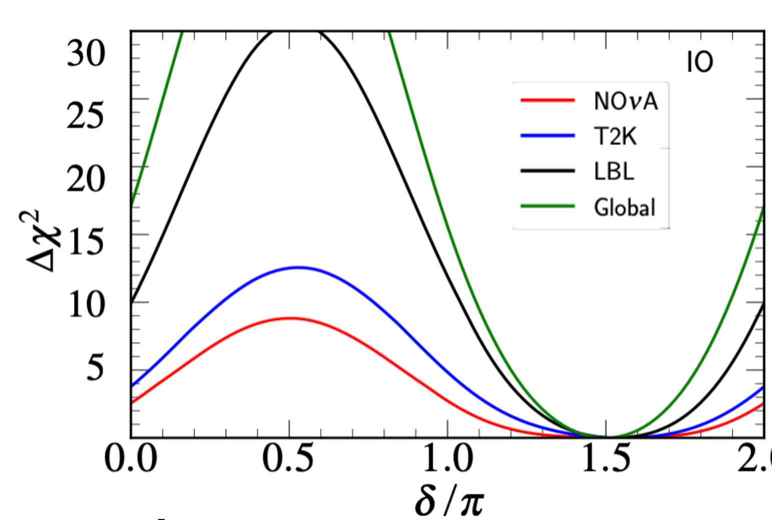

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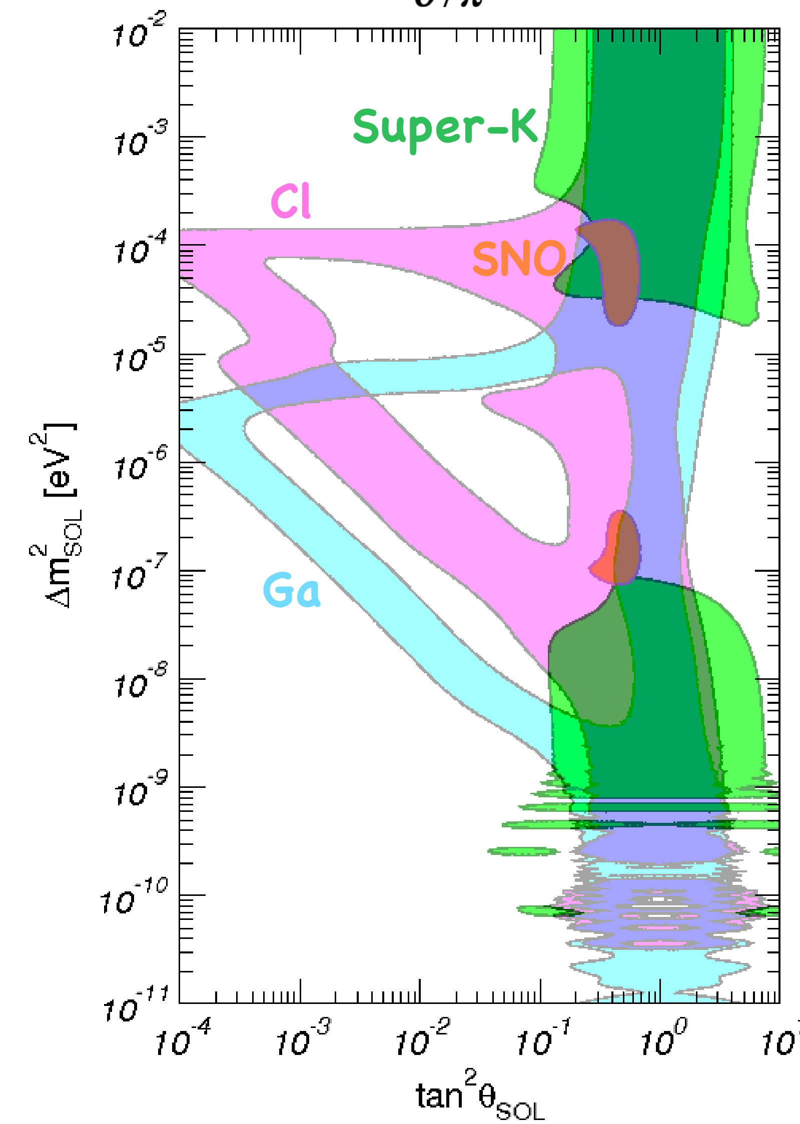

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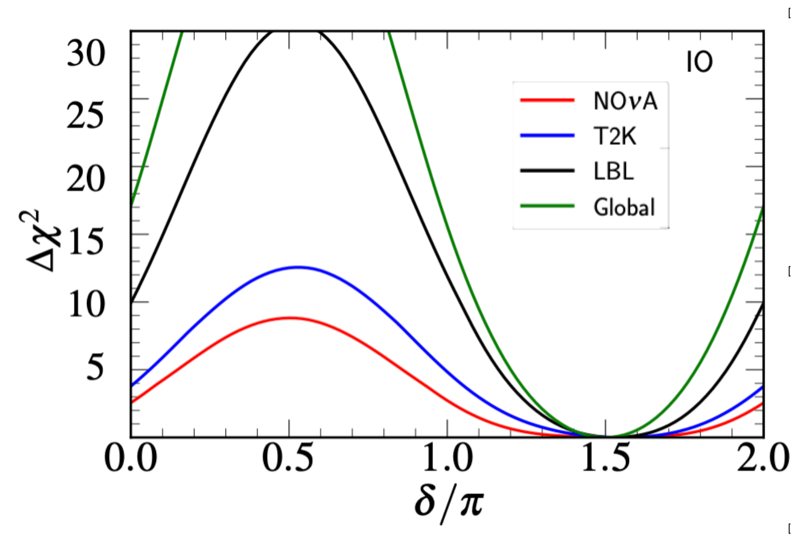

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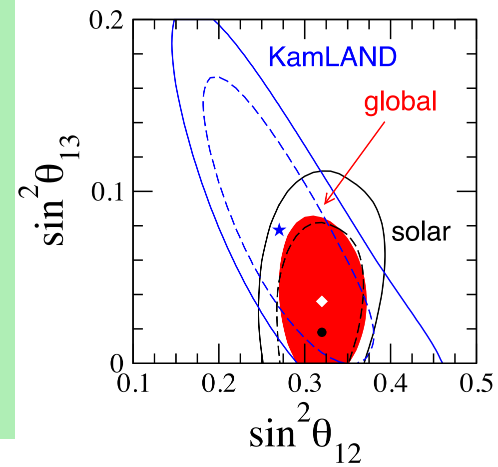

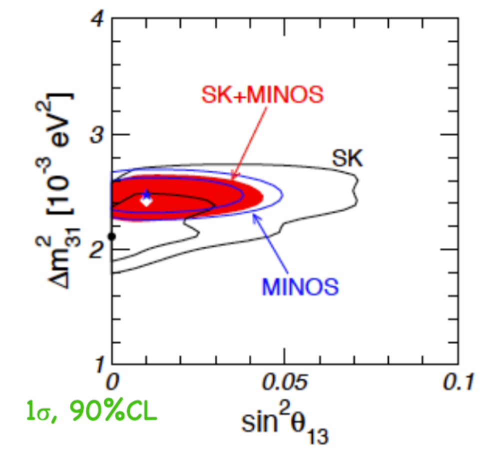

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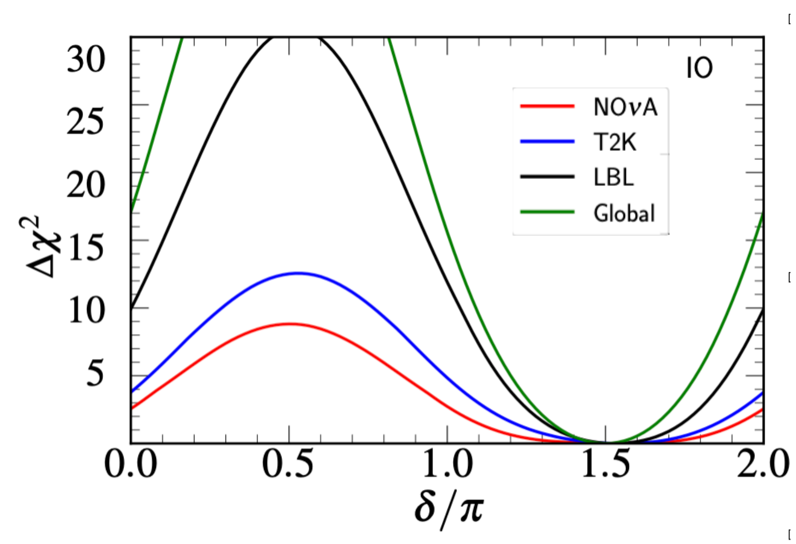

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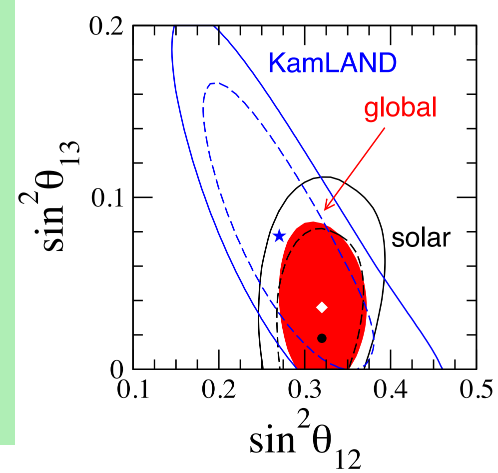

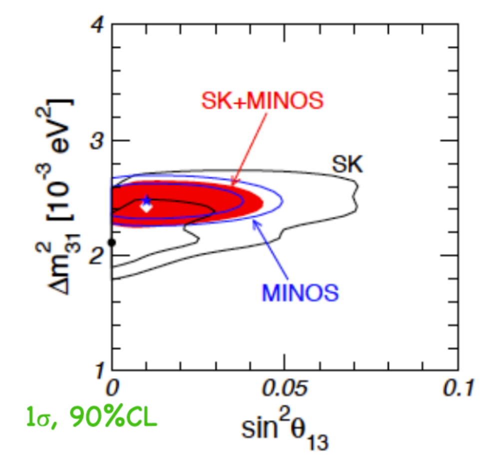

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Reveal tensions among data

Ex: Δm^2_{21} measurement in solar and KamLAND

Ex: δ_{CP} preference in NOvA and T2K (NO)

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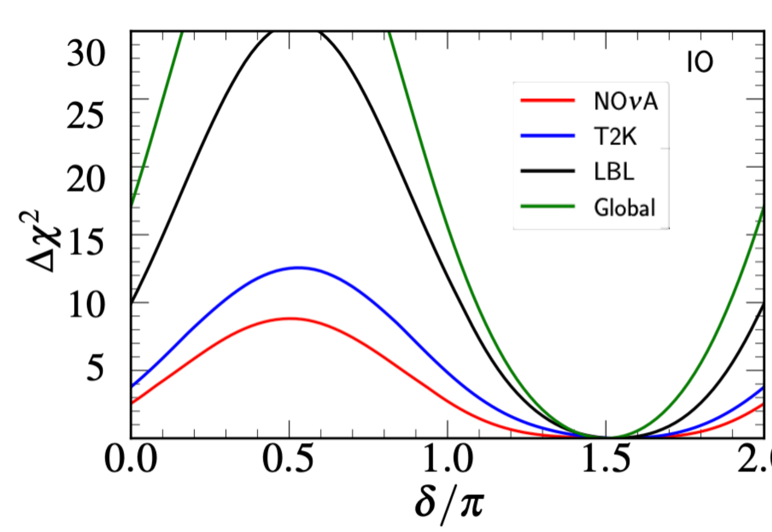

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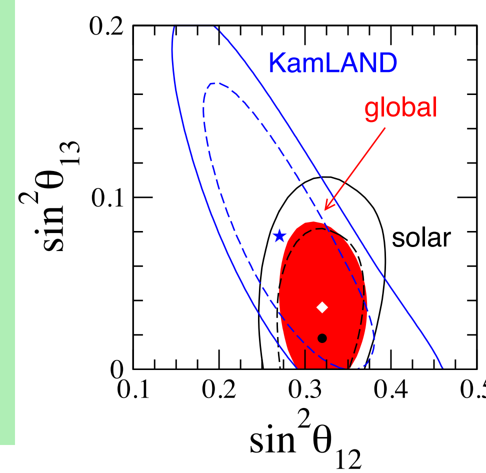

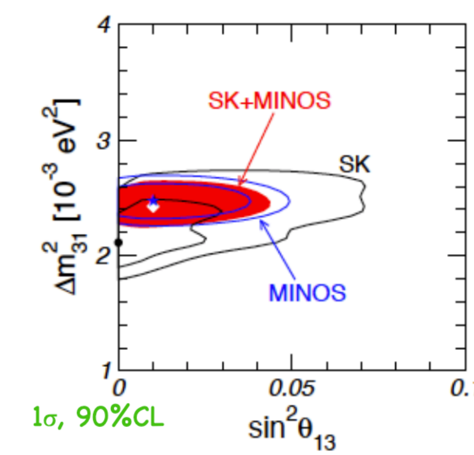

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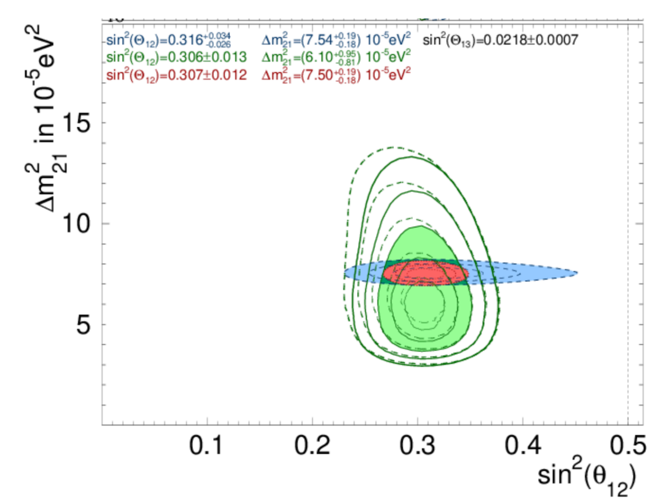

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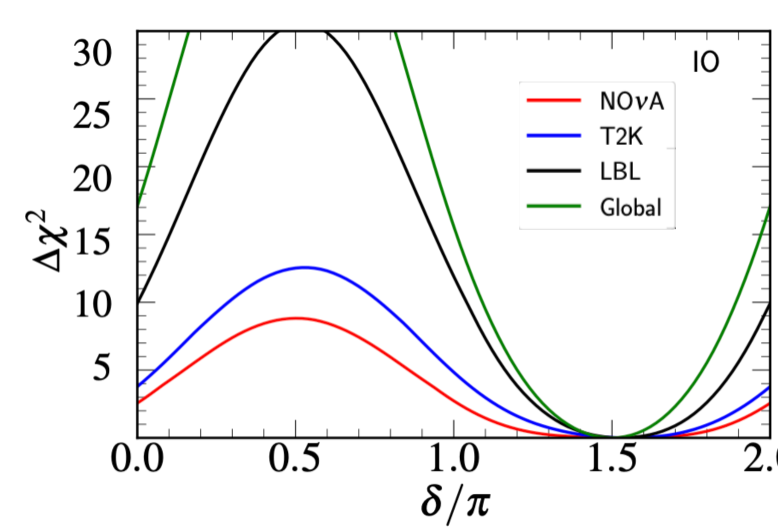

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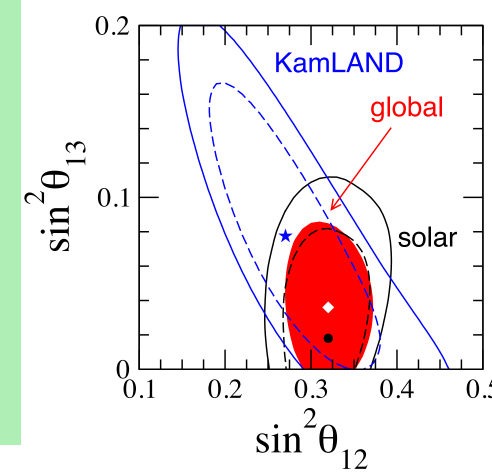

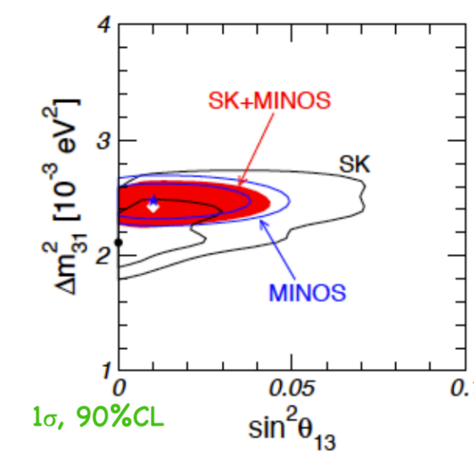

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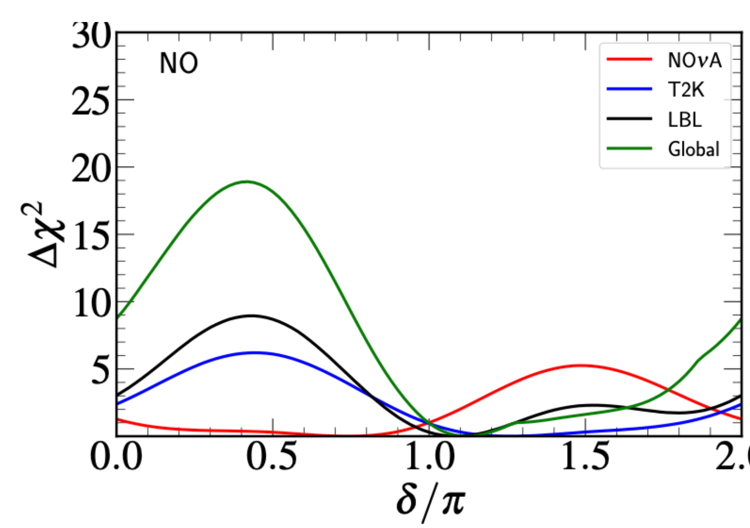
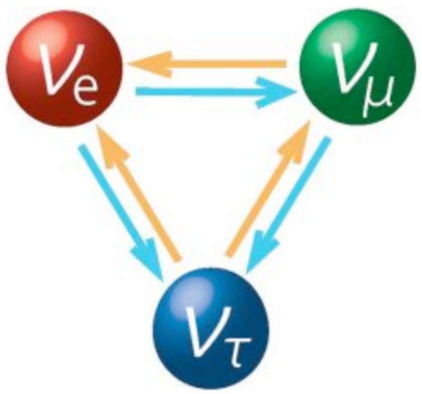


Three-neutrino global fits



Bari

Capozzi et al, PRD 104 (2021) 083031

NuFIT

Esteban et al, JHEP 09 (2020) 178
NuFIT 6.0 (2024) www.nu-fit.org

Valencia

de Salas et al, JHEP 02 (2021) 071
https://globalfit.astroparticles.es/

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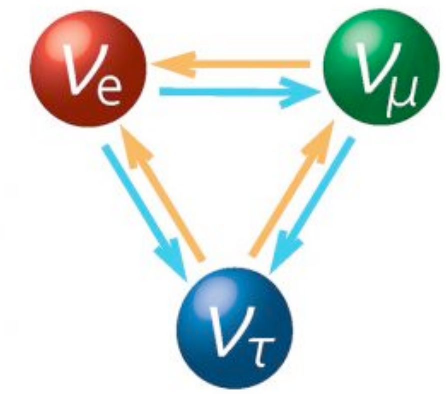

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Capozzi et al, PRD 104 (2021) 083031

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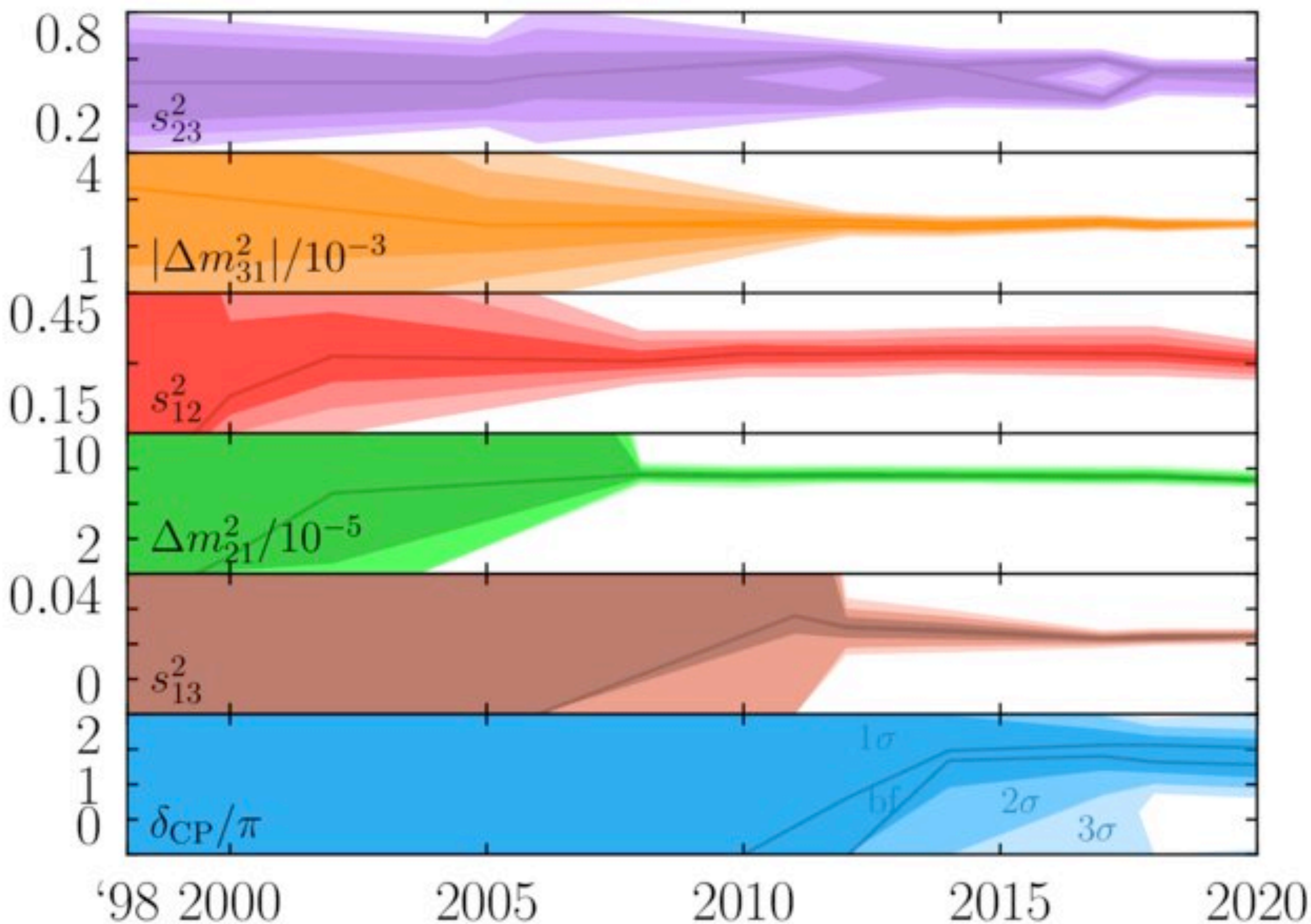
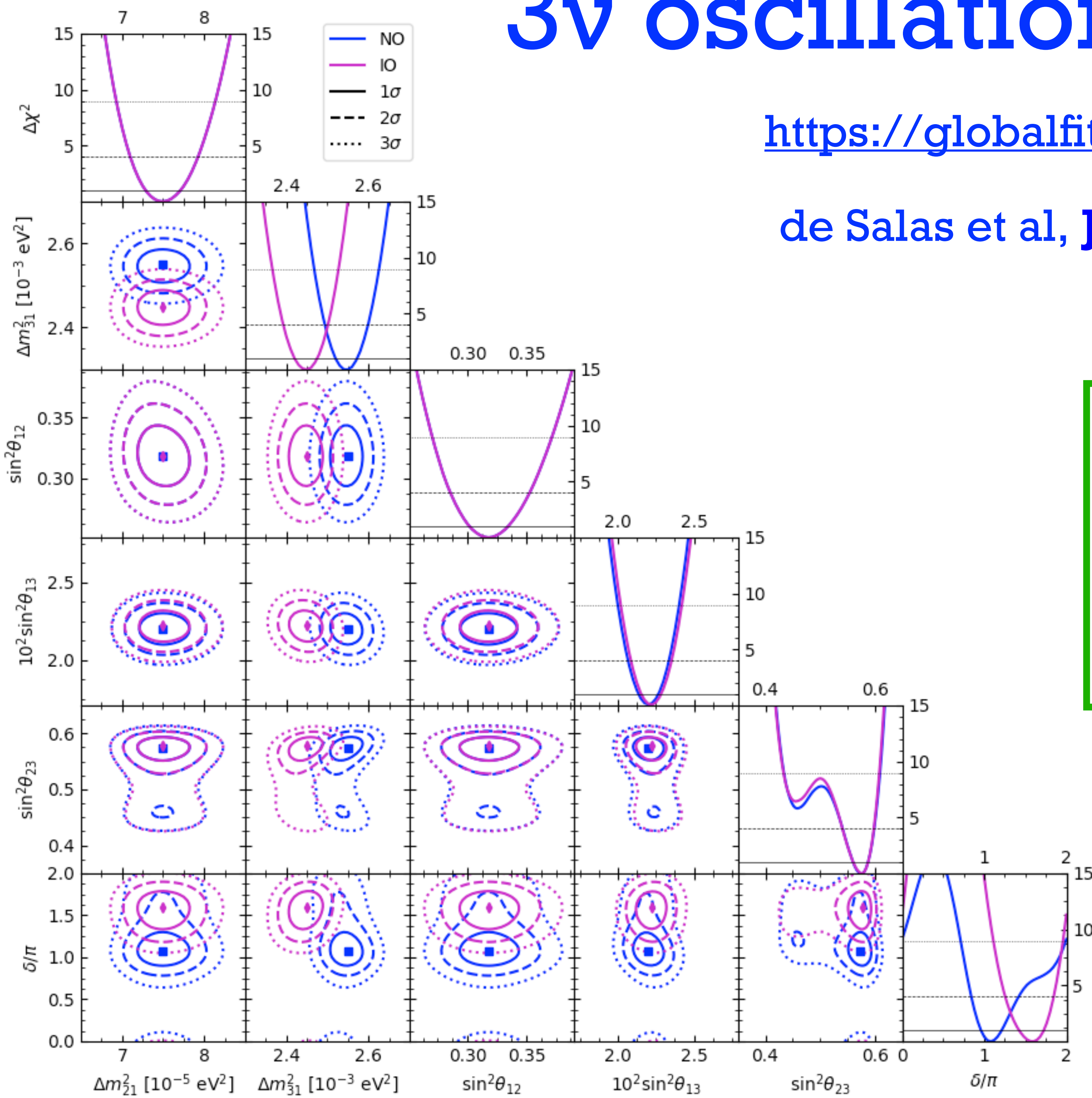
Three-neutrino oscillation parameters



Denton et al, Snowmass Neutrino Frontier: NF01 Report [arXiv:2212.00809]

3ν oscillations global fit



https://globalfit.astroparticles.es/

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

Updated here with…

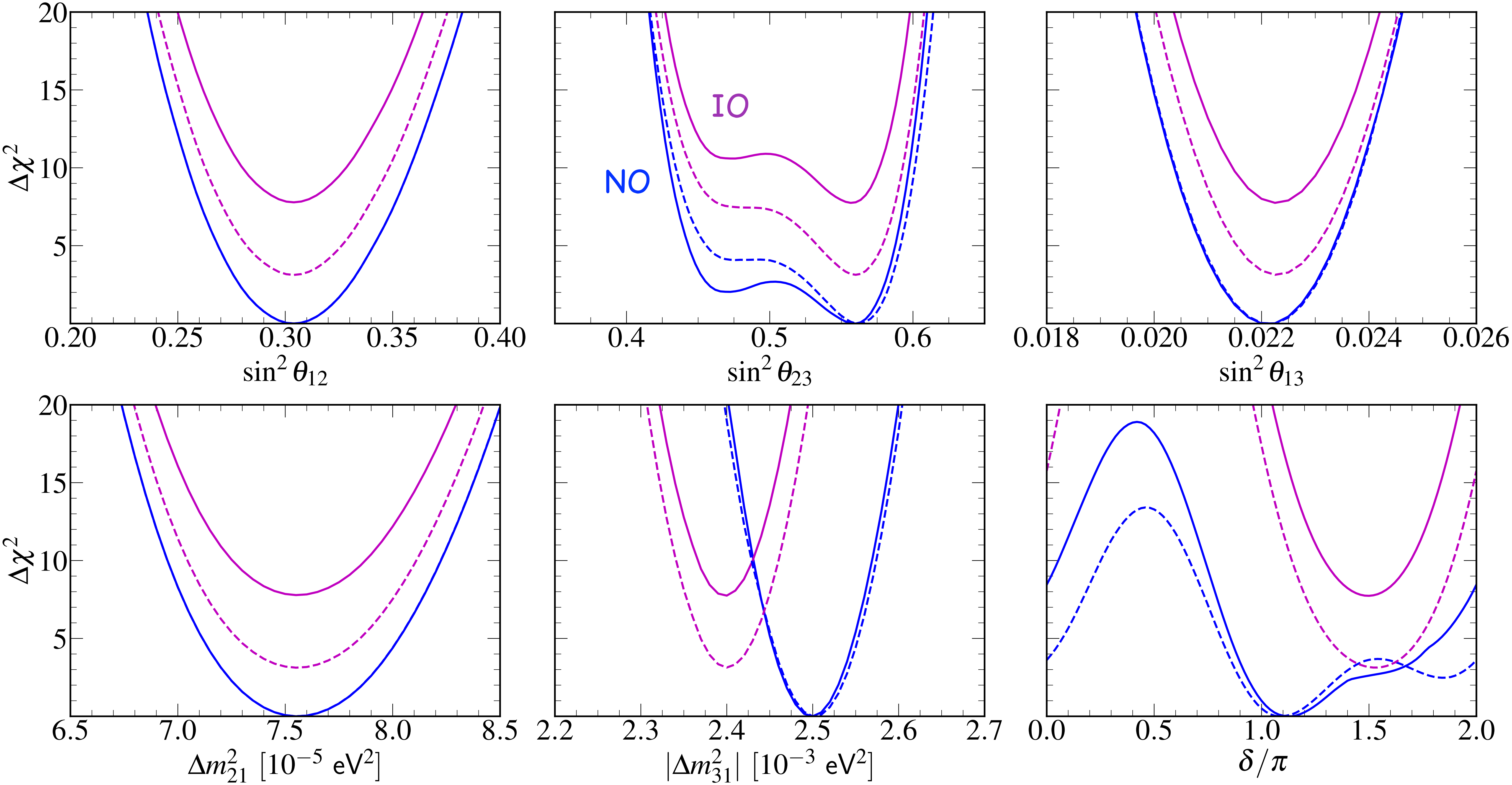
- Standard Solar Model B23
- SK-IV solar data
- Daya Bay full dataset
- RENO full dataset
- Full SK I-V atmos χ^2 tables
- DeepCore 9yr data

Not yet included…

- Latest T2K & NOvA results presented in Nu'24

Global fit to ν oscillation parameters

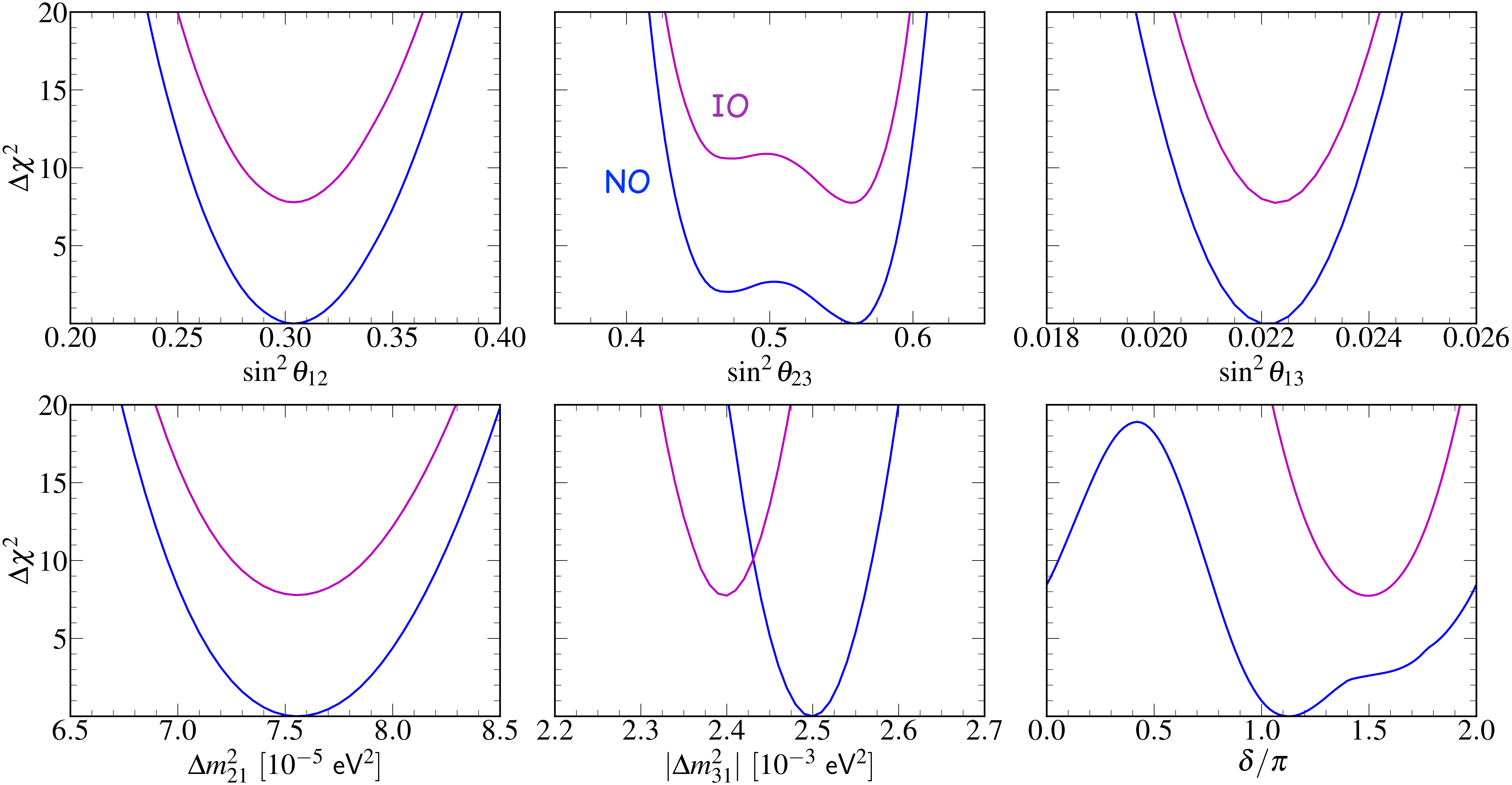
— w SK-atm - - - w/o SK.atm



SSM HZ model - MB22m

$\Delta\chi^2$(IO-NO) = 7.7 w SK-atm $\Delta\chi^2$(IO-NO) = 3.1 w/o SK-atm

Global fit to ν oscillation parameters



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with SK atmospheric

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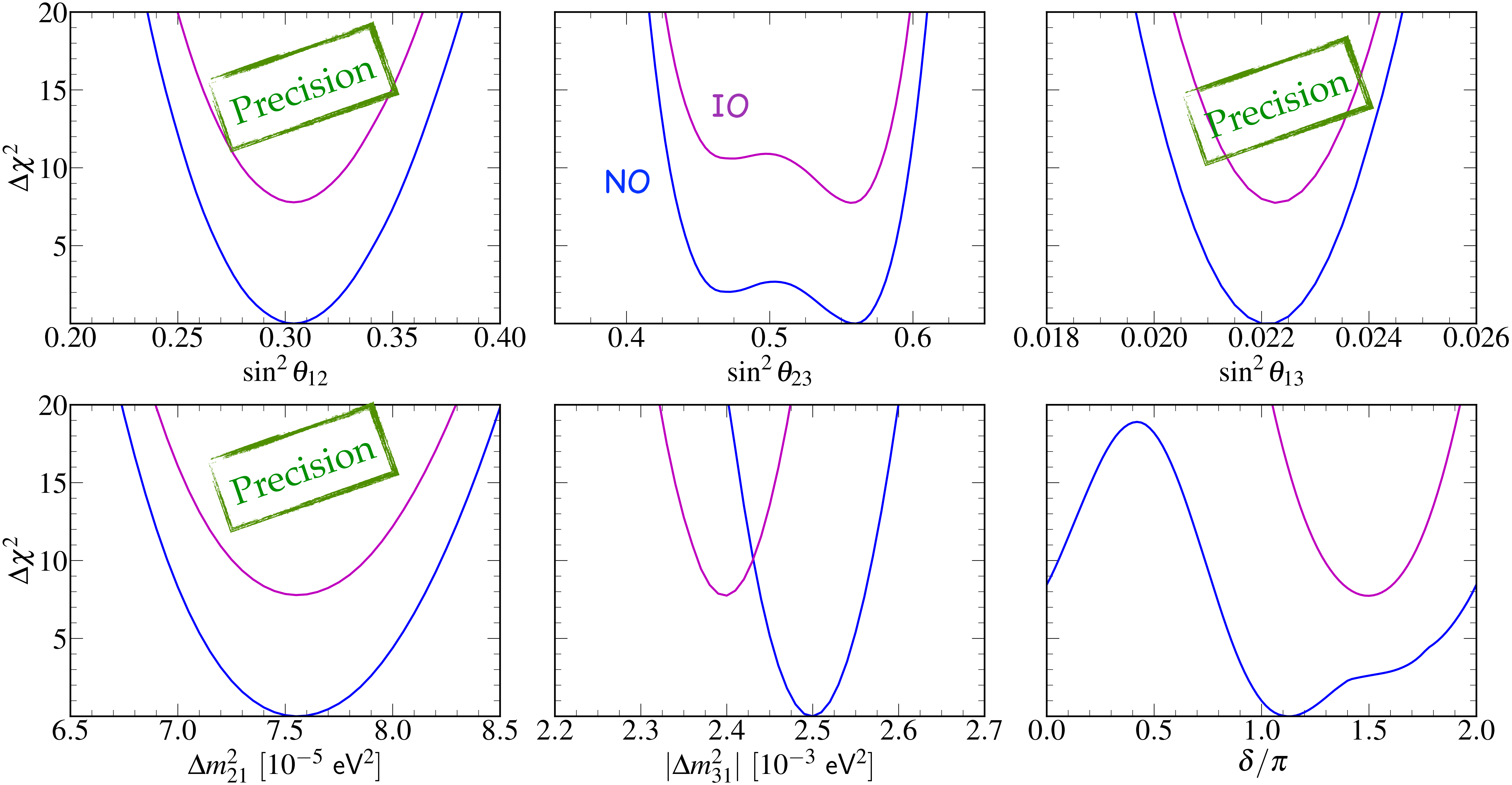

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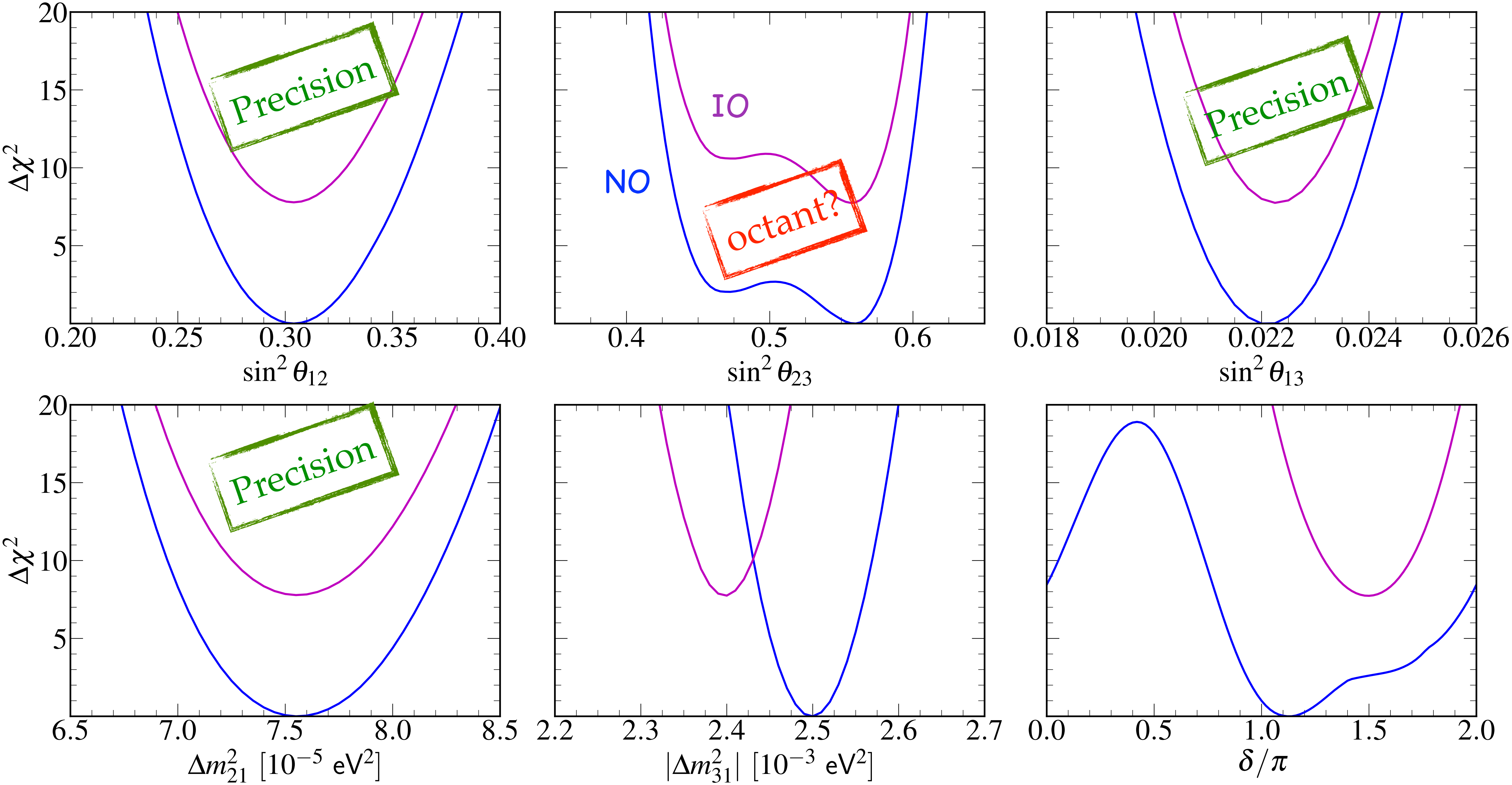

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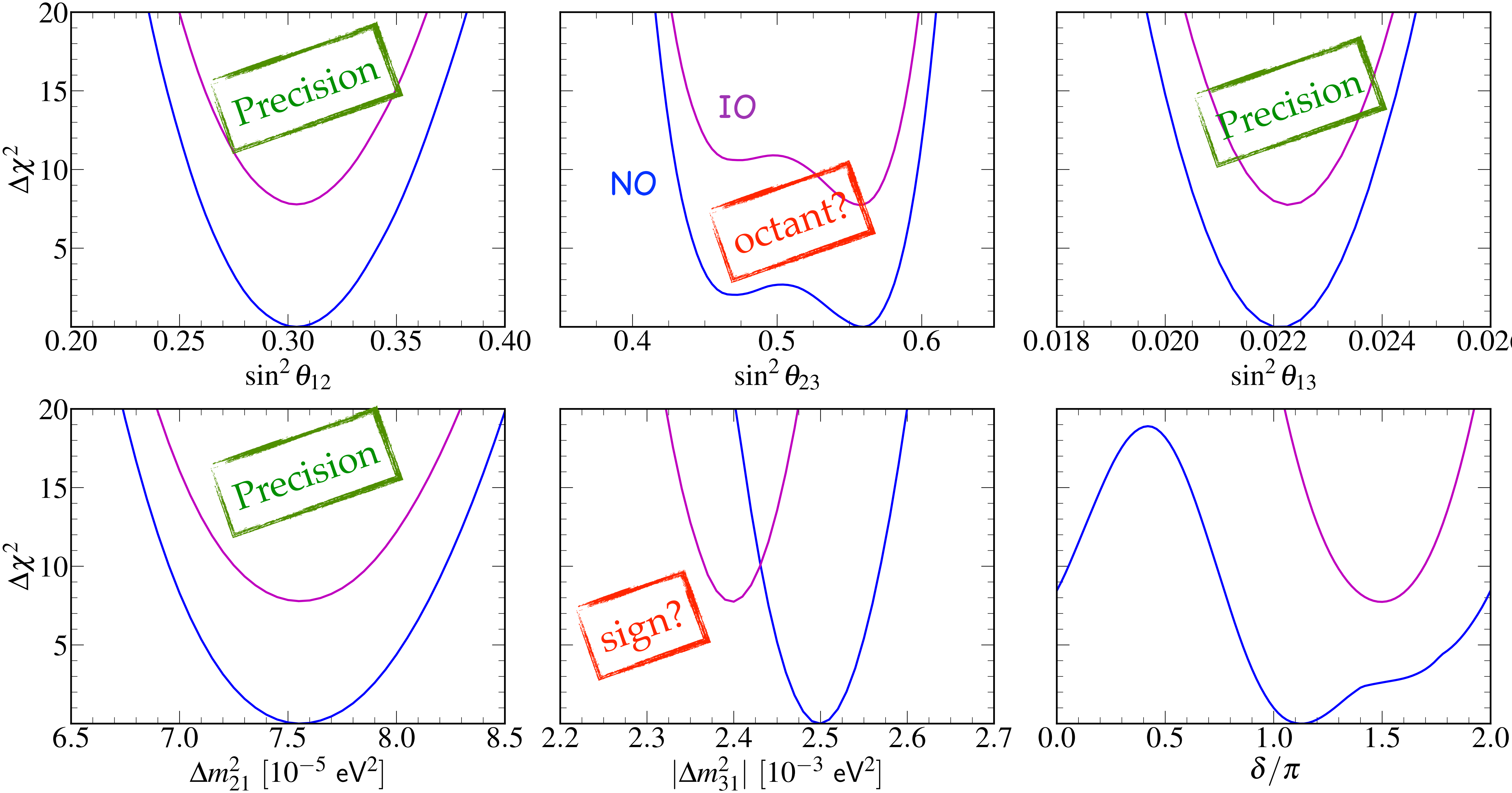

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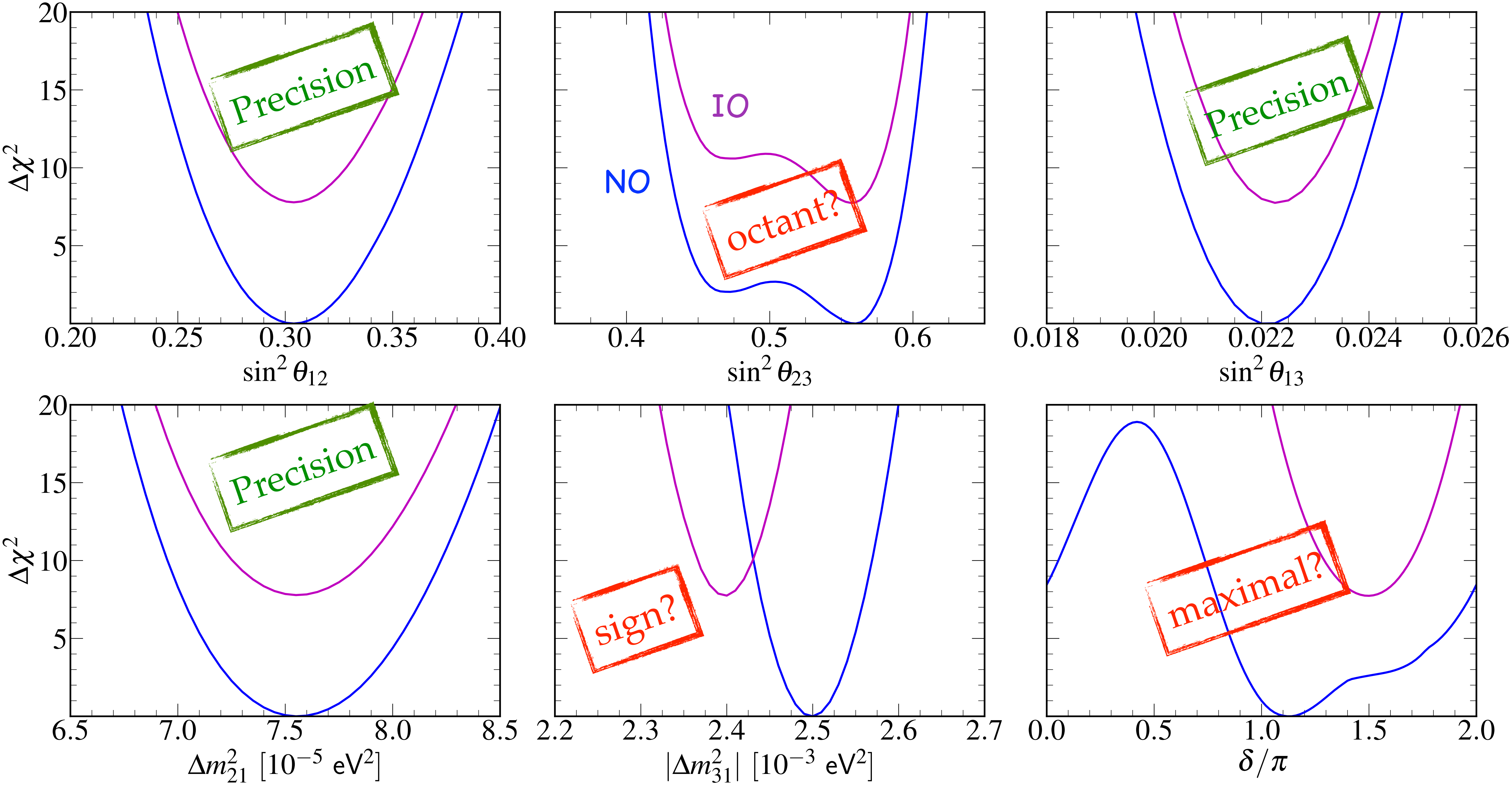


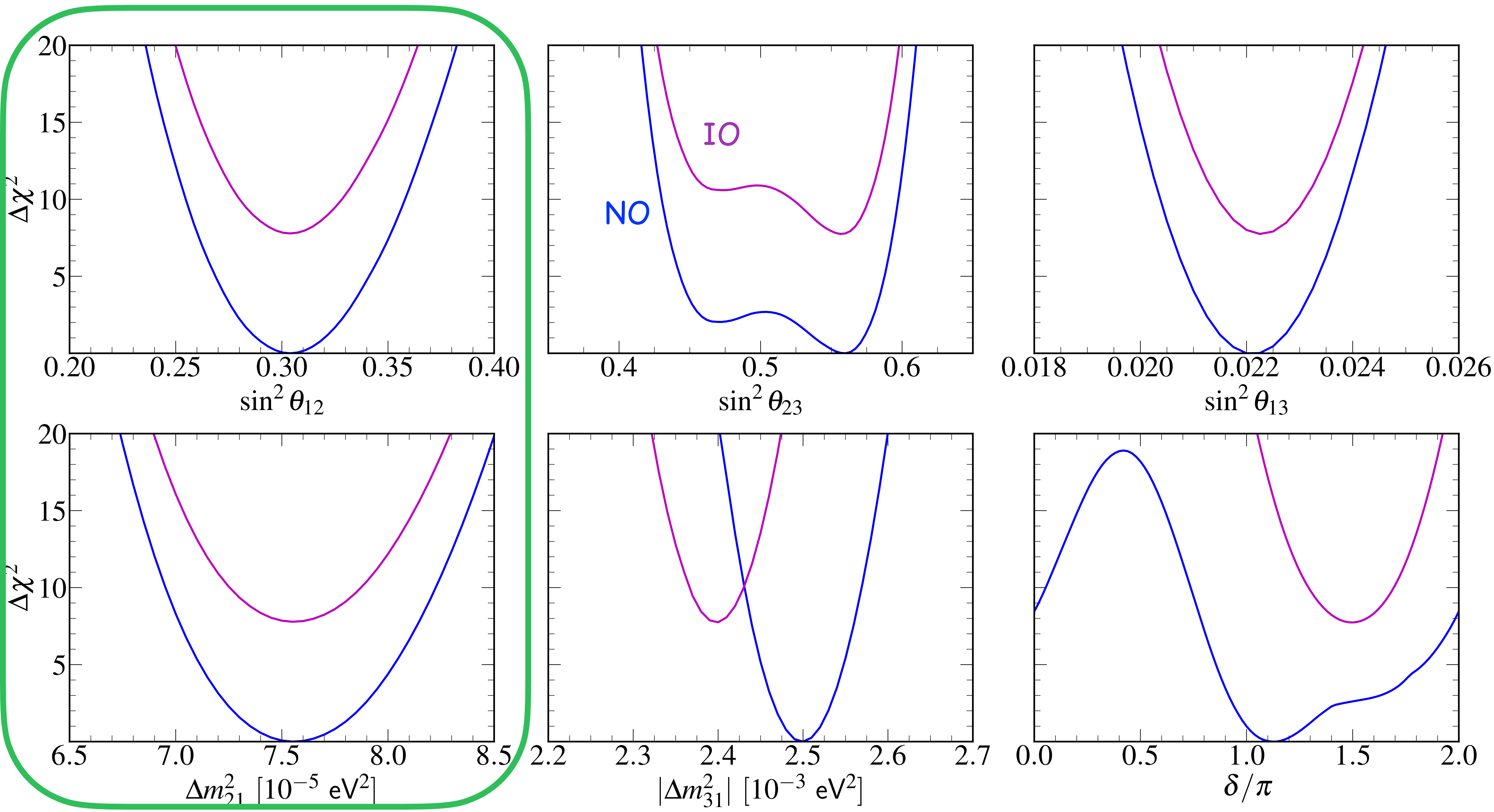
SSM HZ model - MB22m **with SK atmospheric** $\Delta\chi^2$(IO-NO) = 7.7

Global fit to ν oscillation parameters

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncert	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	**2.7 %**	
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50±0.02	2.43–2.57	**0.9 %**	mass ordering?
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.40±0.02	2.33-2.46		
$\sin^2\theta_{12}/10^{-1}$	3.04±0.16	2.57–3.55	**5.4%**	
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.60^{+0.13}_{-0.22}$	4.32–5.96	**4.8%**	octant?
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.57^{+0.14}_{-0.20}$	4.34–5.93		
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.07}_{-0.04}$	2.05–2.38	**2.5%**	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.23^{+0.05}_{-0.06}$	2.06–2.39		
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	**10-18%**	maximal CP violation??
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87		

SSM HZ model - MB22m **with SK atmospheric**

Global fit to ν oscillation parameters



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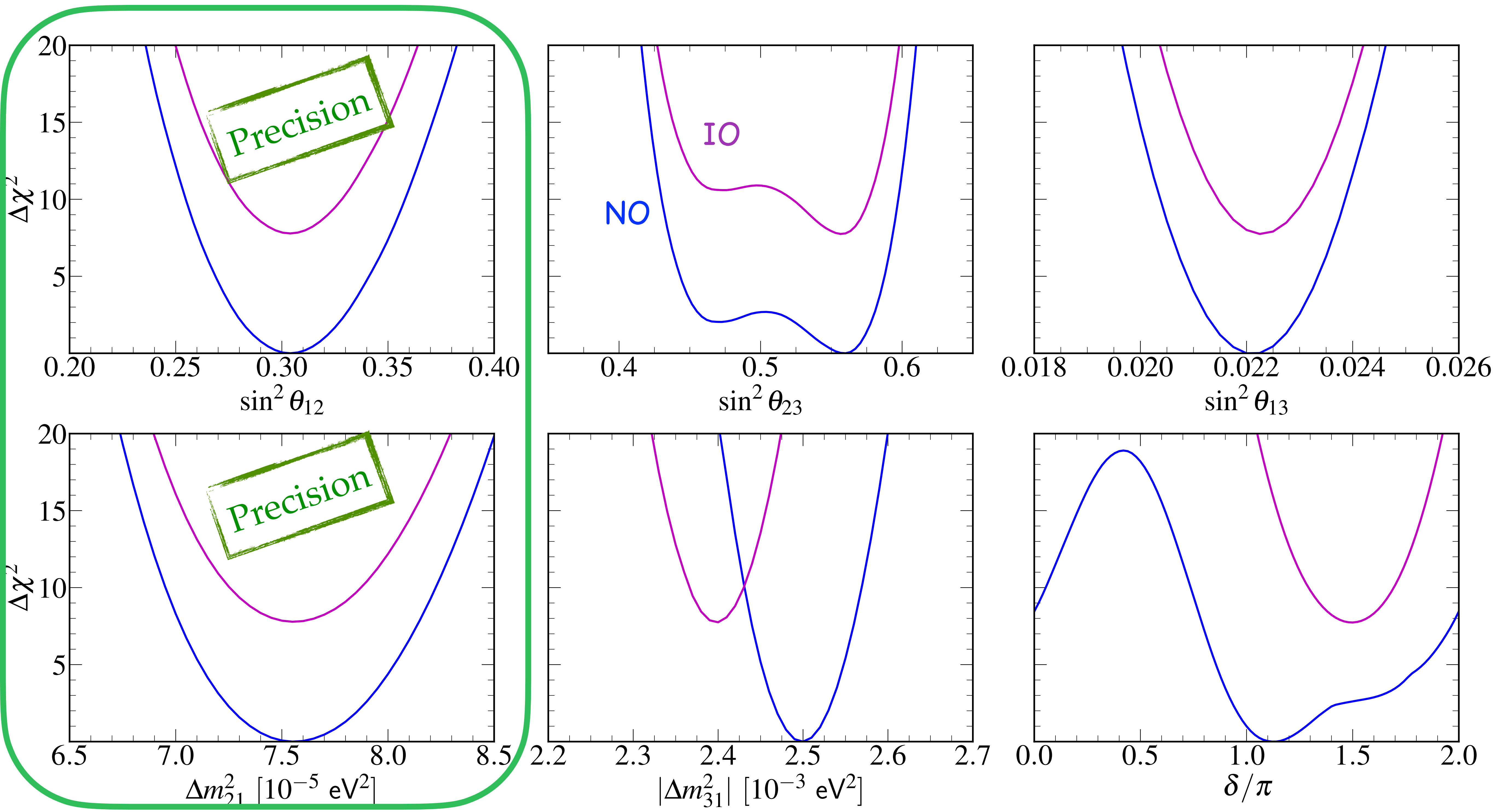

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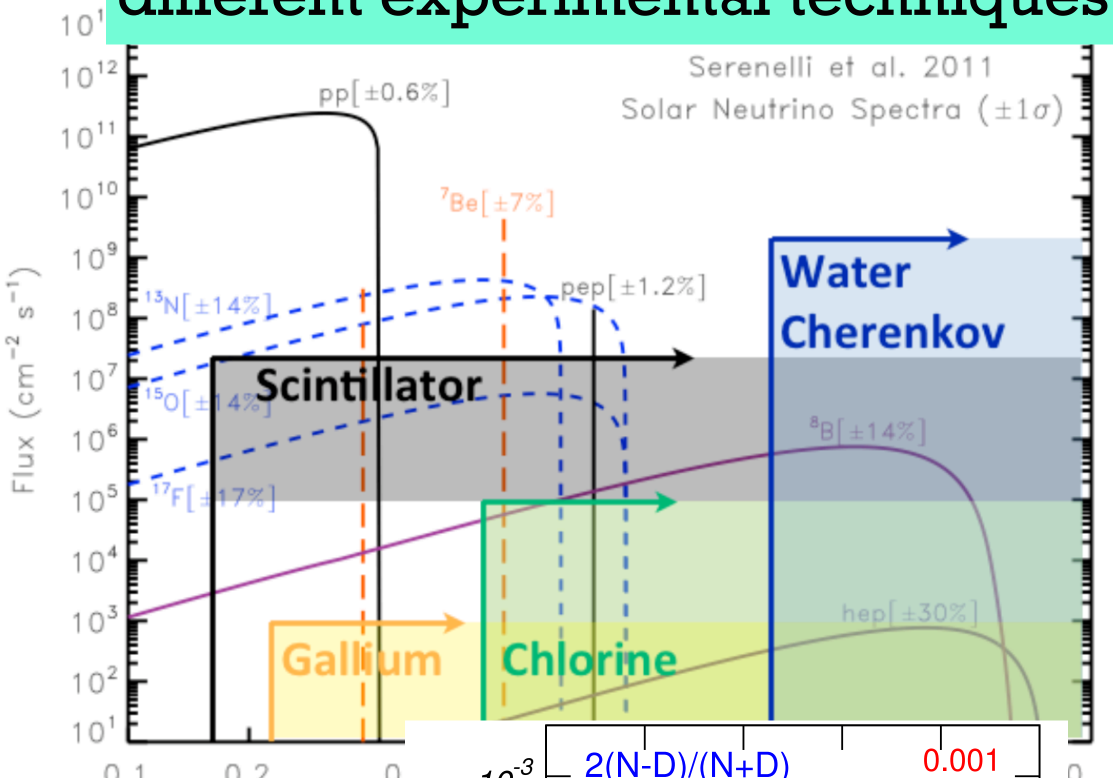
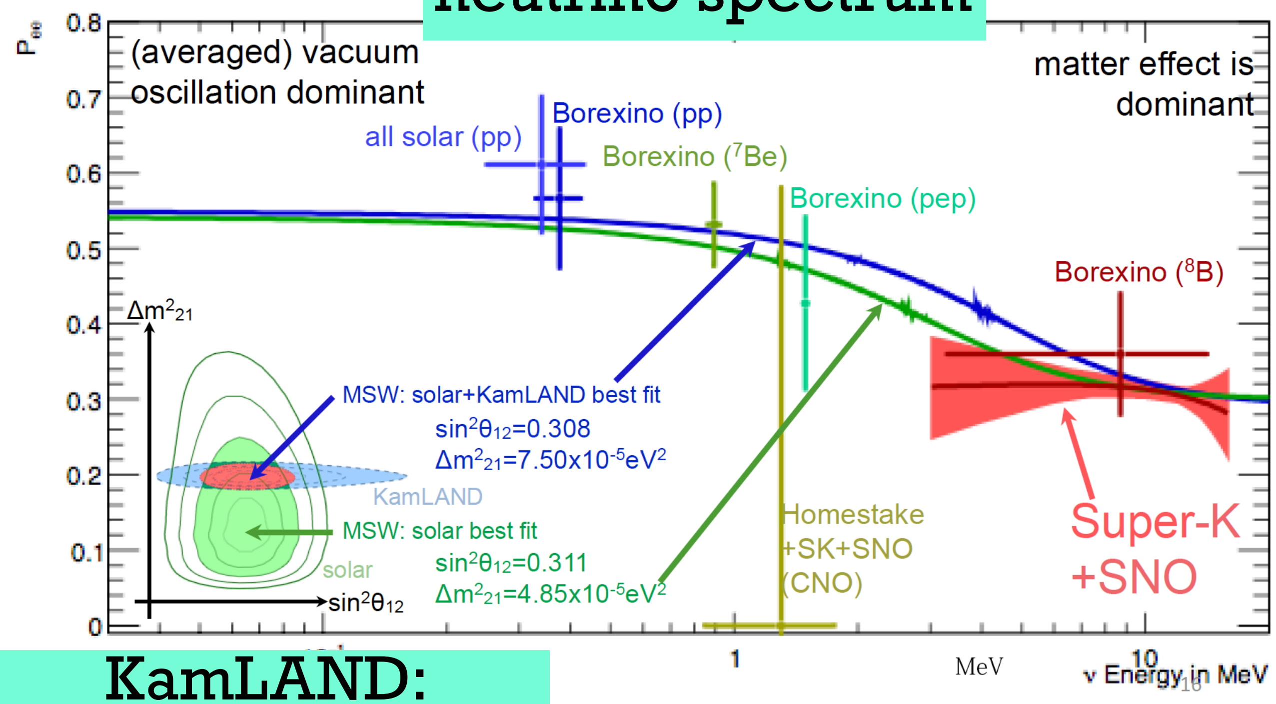
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

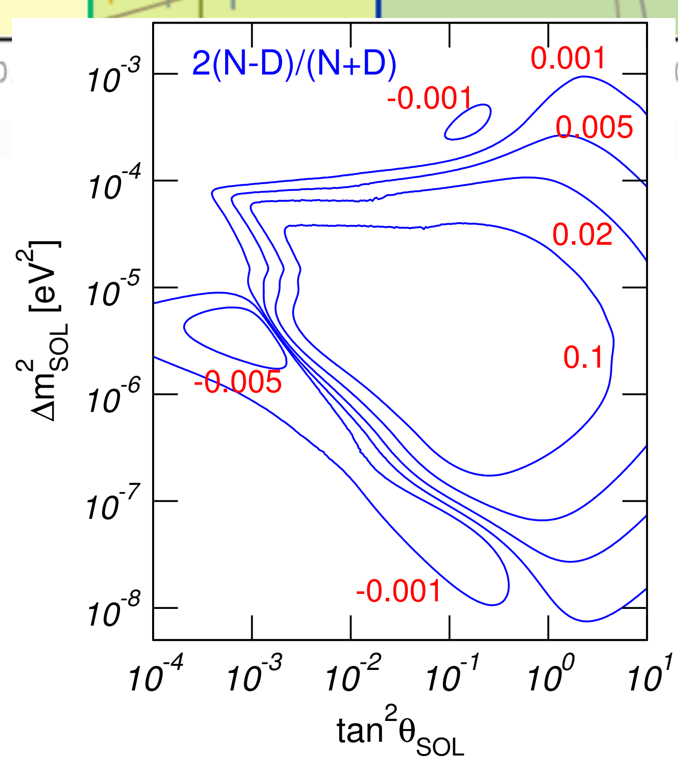
different experimental techniques



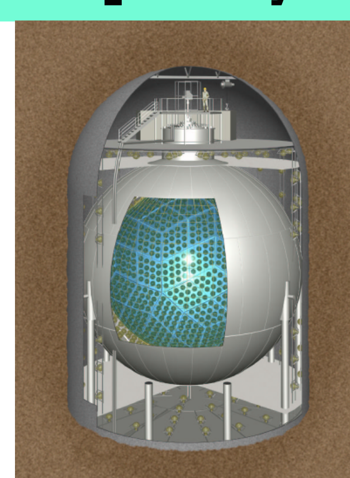
neutrino spectrum

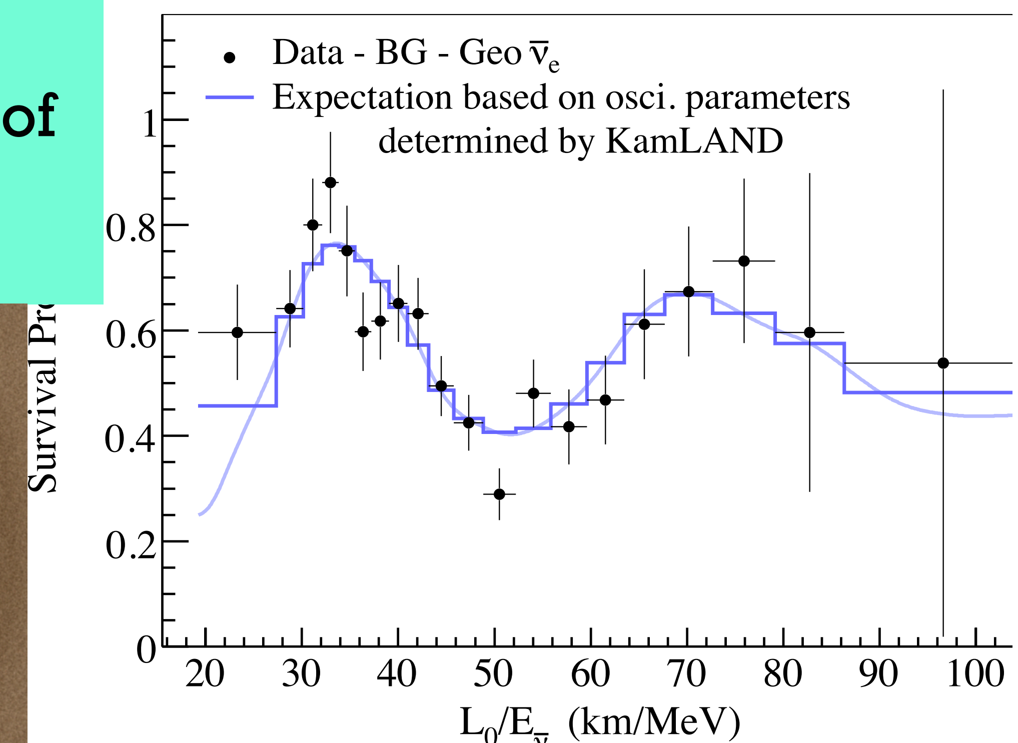


day/night asymmetry



KamLAND: precise measurement of oscillation frequency





The solar sector

New Results

Standard Solar Models B23/SF-III

Herrera & Serenelli (2023)
https://doi.org/10.5281/zenodo.10174170

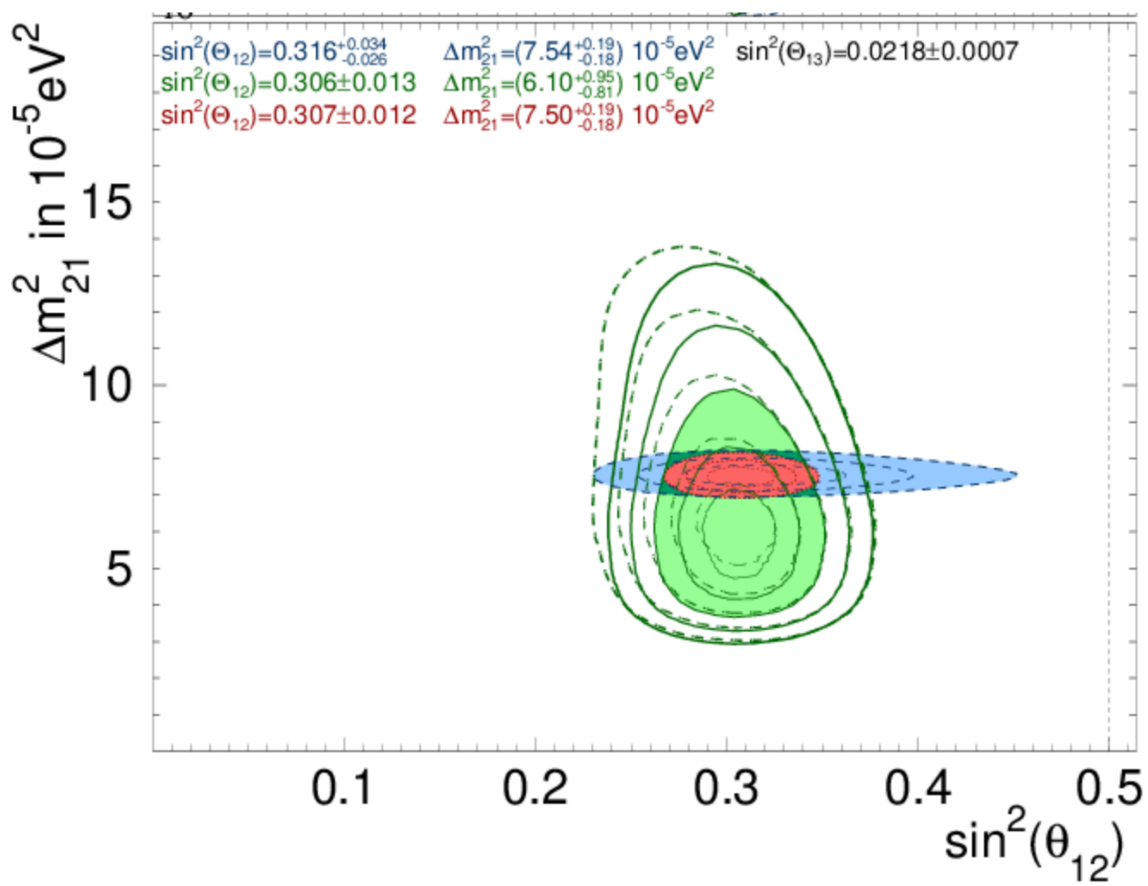
- "GS98" :: Grevesse & Sauval (1998), Space Sci. Rev., 85, 161.
- "AGSS09" :: Asplund et al. (2009), ARA&A, 47, 481.
- "C11" :: Caffau et al. (2011), Sol. Phys., 268, 255.
- "AAG21" :: Asplund et al. (2021), A&A 653, A141.
- "MB22m" :: Magg et al. (2022), A&A 661, A140. (Meteoritic)
- "MB22p" :: Magg et al. (2022), A&A 661, A140. (Photospheric)

✦ MB22m: high Z

✦ AAG21: low Z

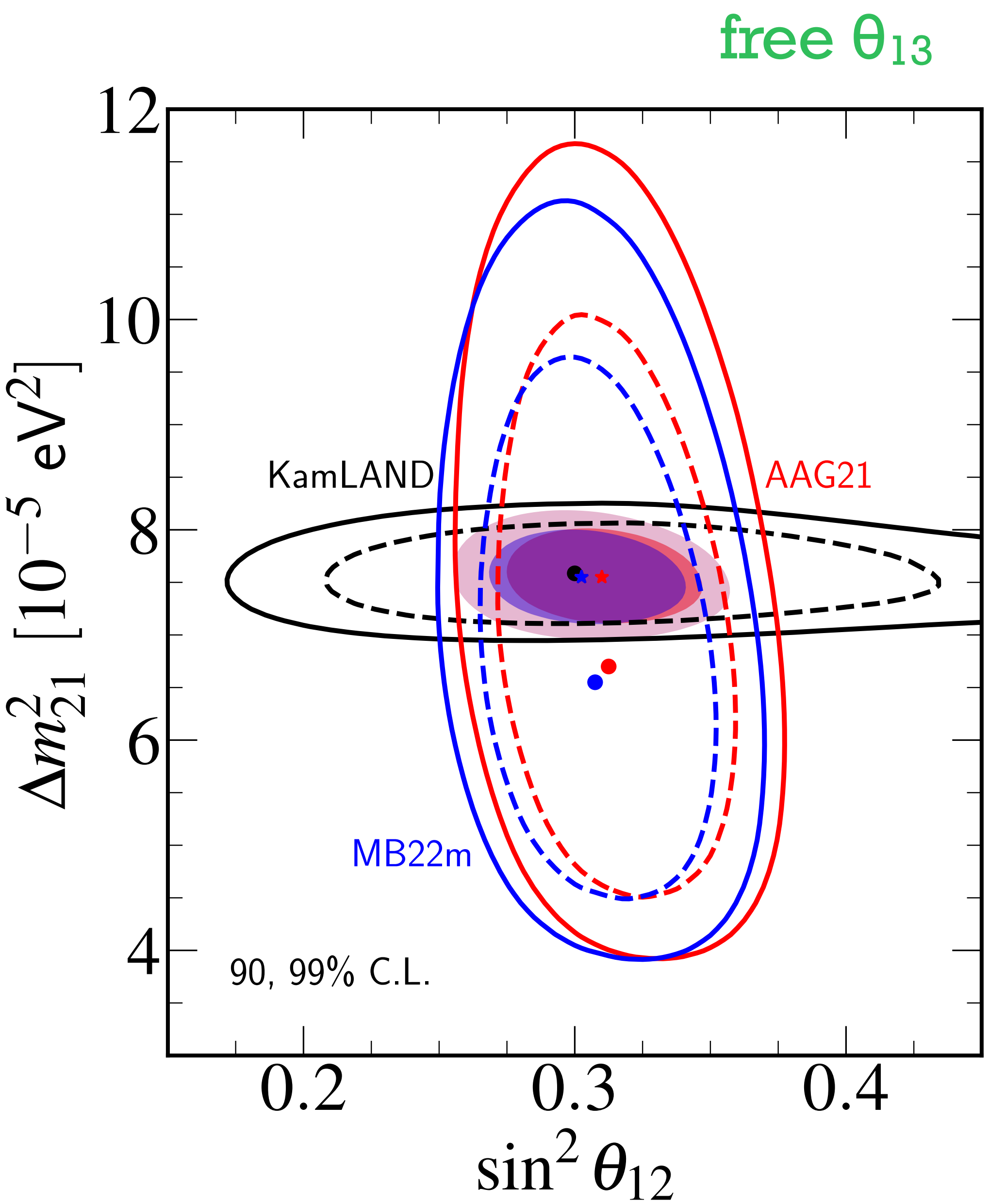
Super-K IV D/N spectrum (2970 days)

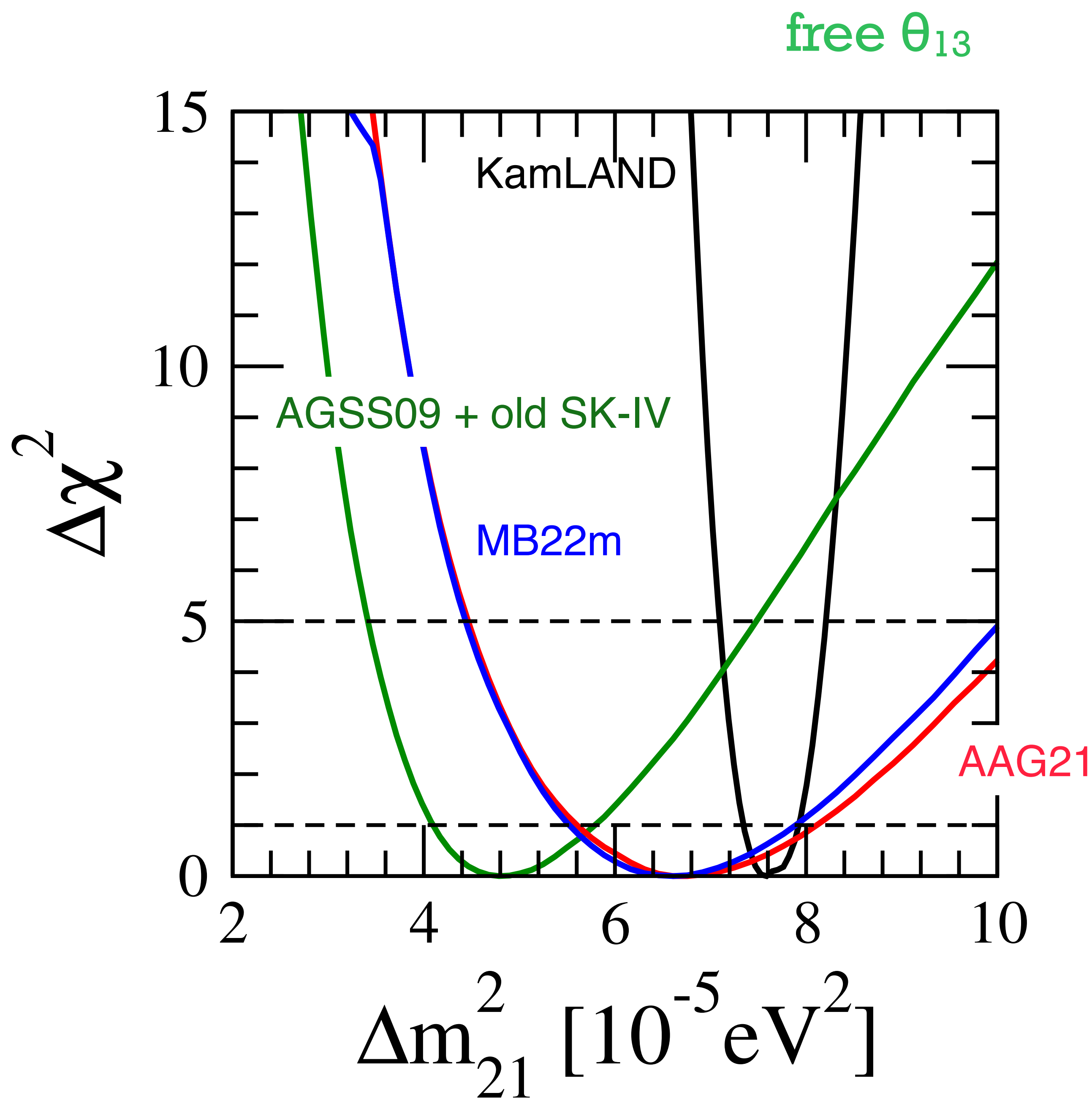
SK Collab, PRD 109 (2024) 092001



~1.5σ deviation wrt Δm^2_{21} measured in KamLAND (fixed θ_{13})

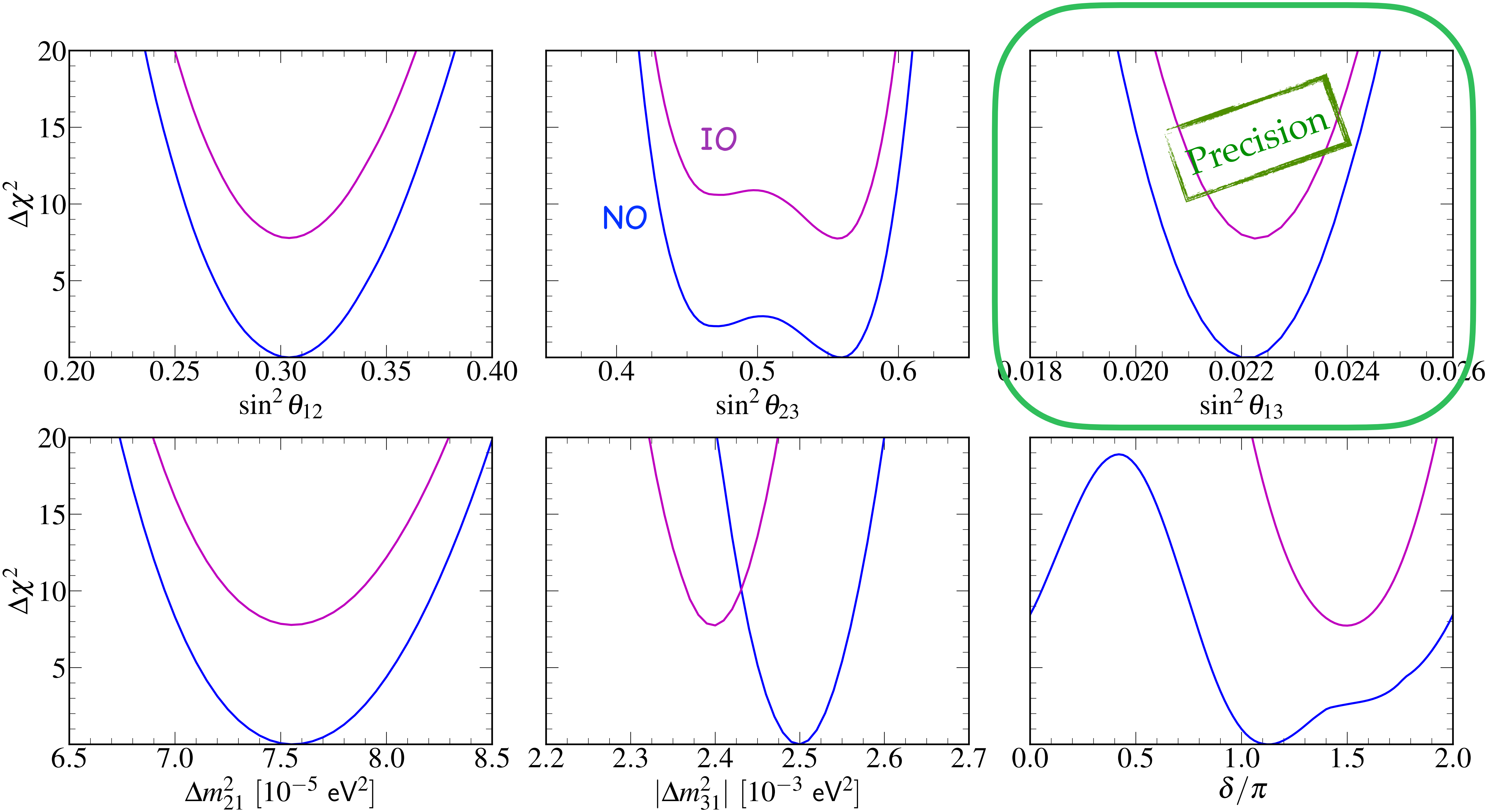
The solar sector





- θ_{12} measurement dominated by solar data
- Δm^2_{21} better measured by KamLAND.
- new SK-IV data reduce the tension in Δm^2_{21} measurement ($\sim 2\sigma \rightarrow \sim 1\sigma$ deviation)

Global fit to ν oscillation parameters

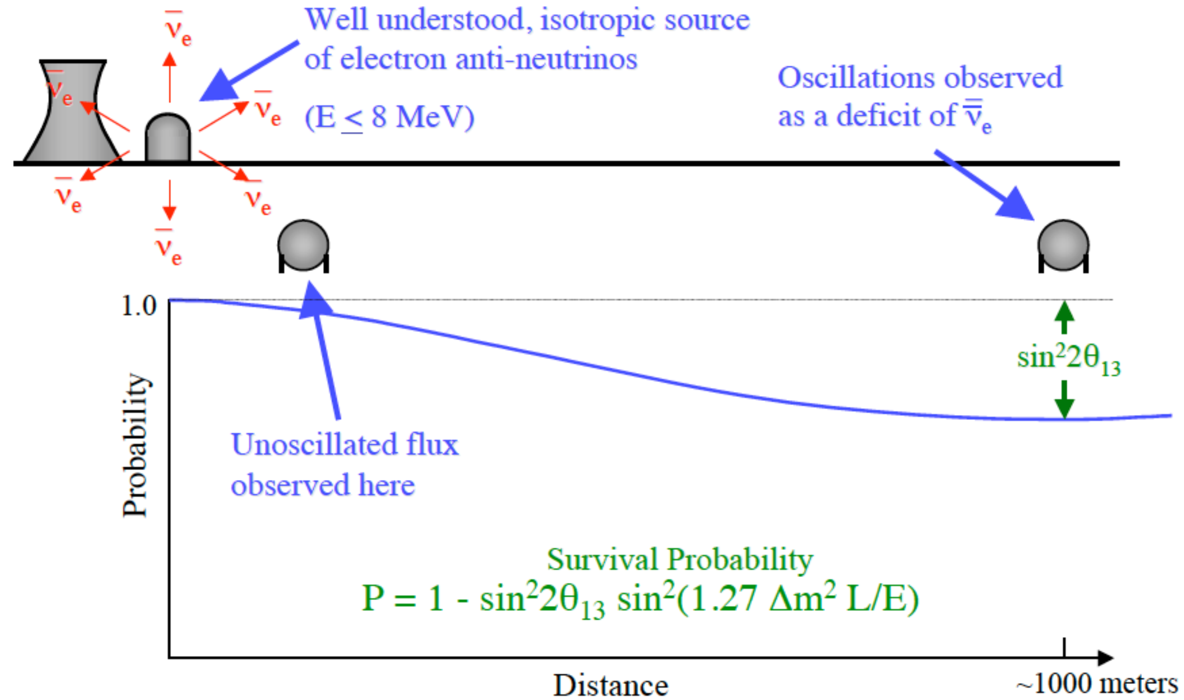


SSM HZ model - MB22m **with SK atmospheric** $\Delta\chi^2$(IO-NO) = 7.7

The reactor sector

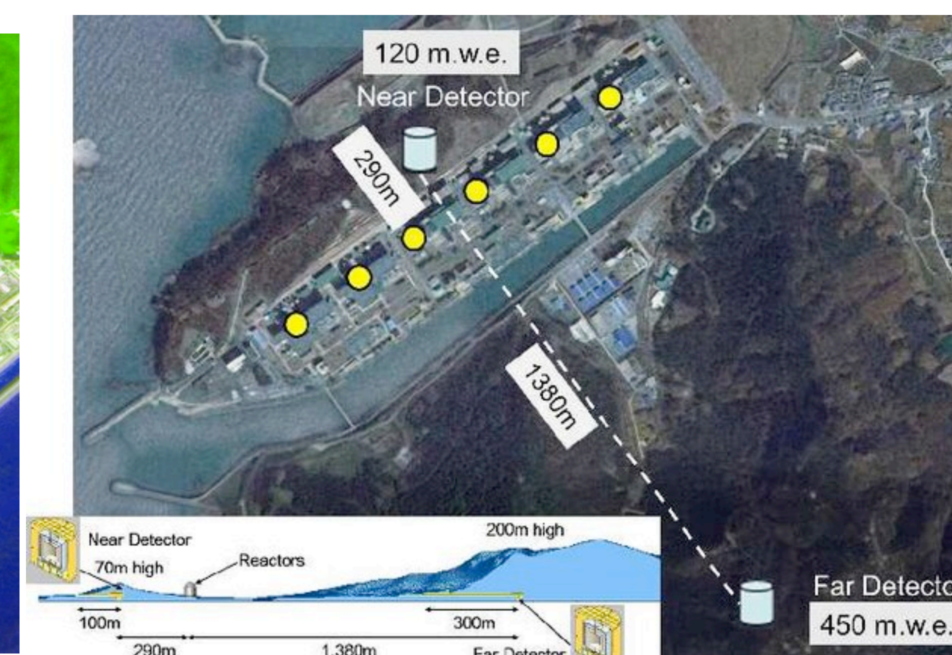
km-baseline reactor experiments:

- very powerful reactors (multi-core)
- large detector volume (kton)
- 2-8 detectors at 100 m – 1 km



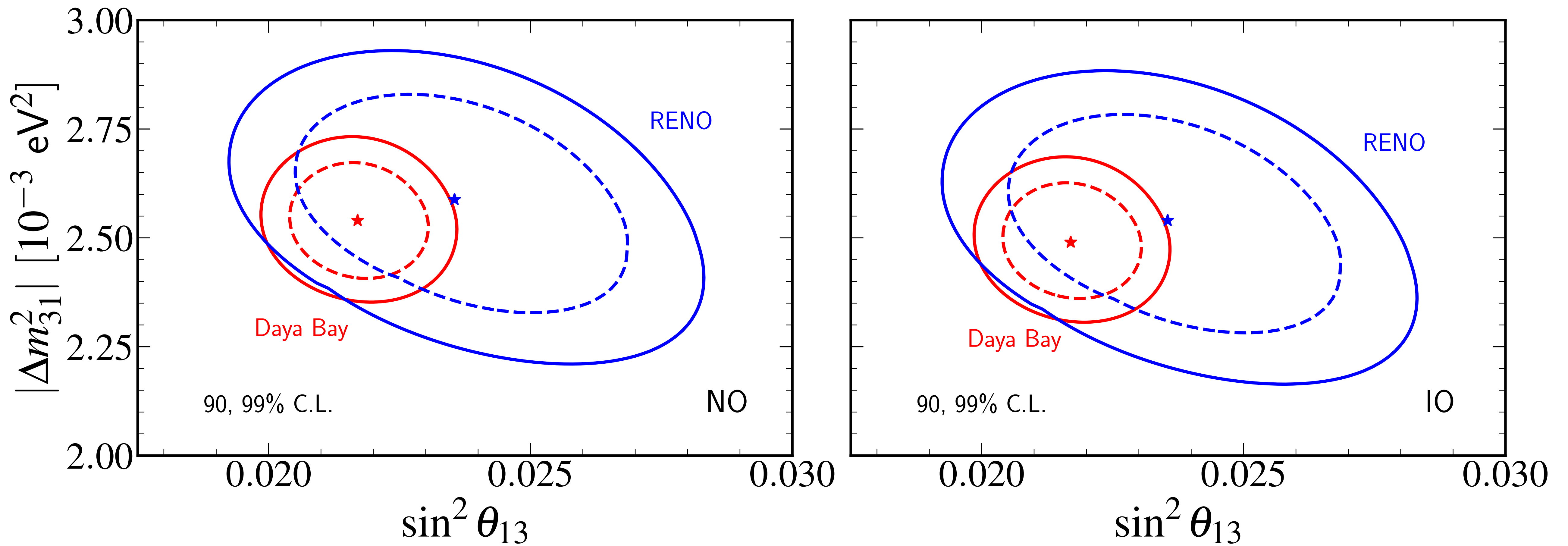
2 cores + 1 ND + 1 FD

6 cores + 4 ND + 4FD



6 cores + 1 ND + 1 FD

The reactor sector



- **Daya Bay:** 3158-day data: $\sin^2 2\theta_{13} = 0.0853 \pm 0.0024$ (2.8%)

[Daya Bay Collaboration] PRL 130 (2023),161802

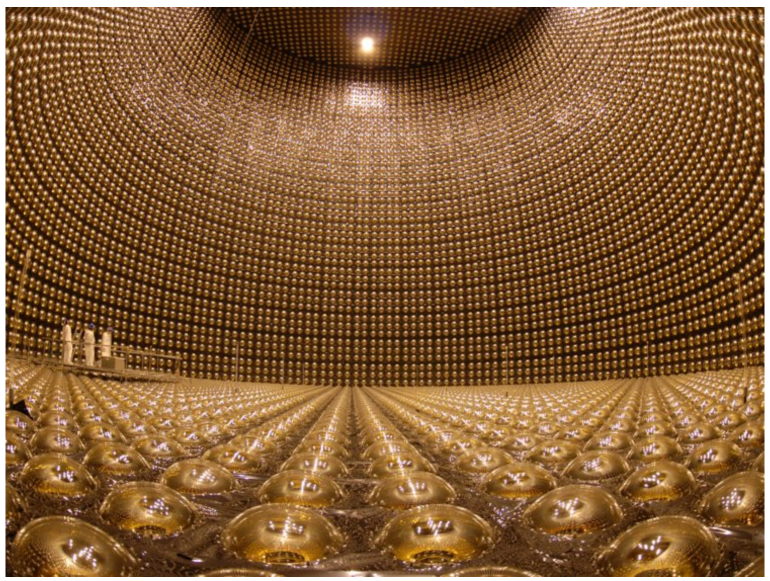
- **RENO**: 3800-day data: $\sin^2 2\theta_{13} = 0.0920 \pm 0.0059$ (6.4%)

S. Jeon [RENO Collaboration] @ ICHEP2024

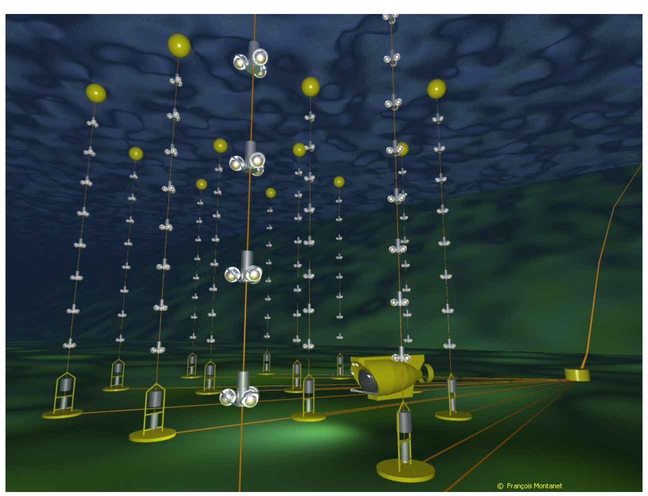
The atmospheric sector

Atmospheric experiments

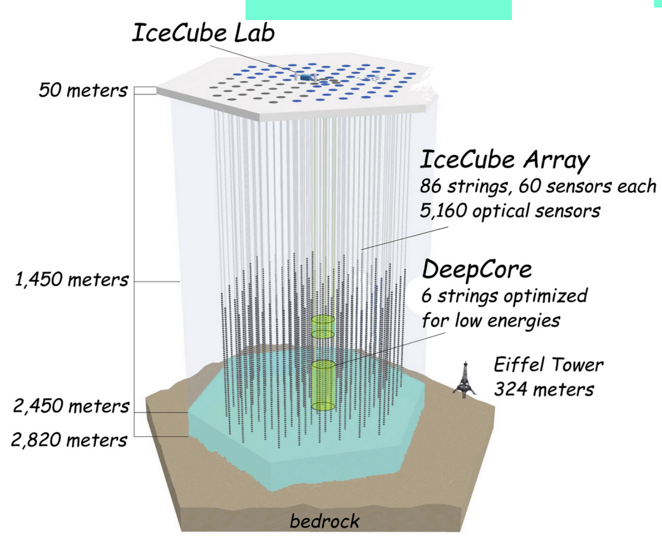
Super-Kamiokande



ANTARES & KM3NeT

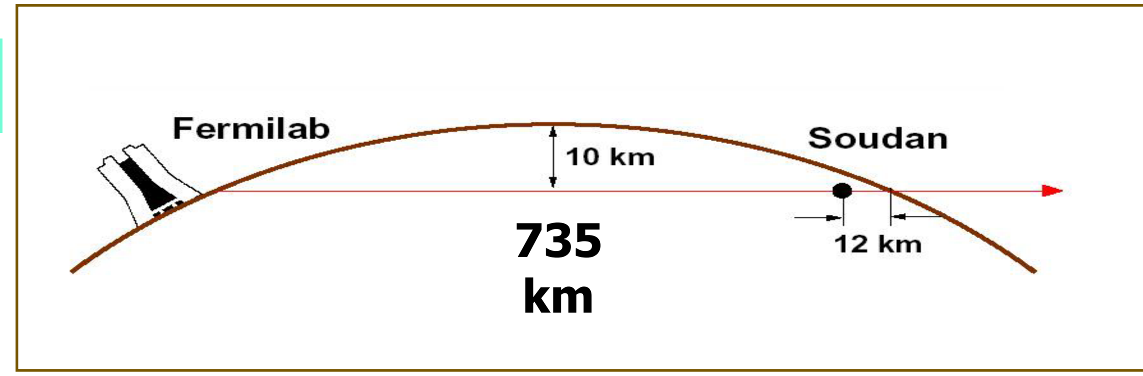


IceCube

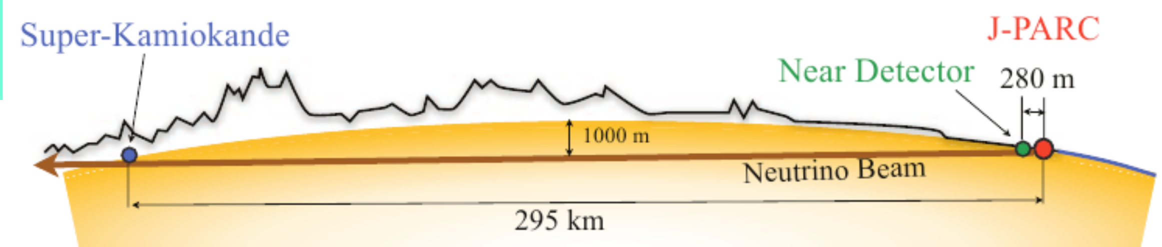


Accelerator long-baseline experiments

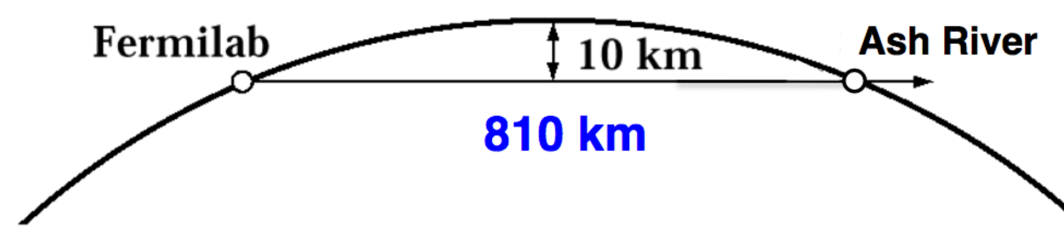
MINOS



T2K



NOvA



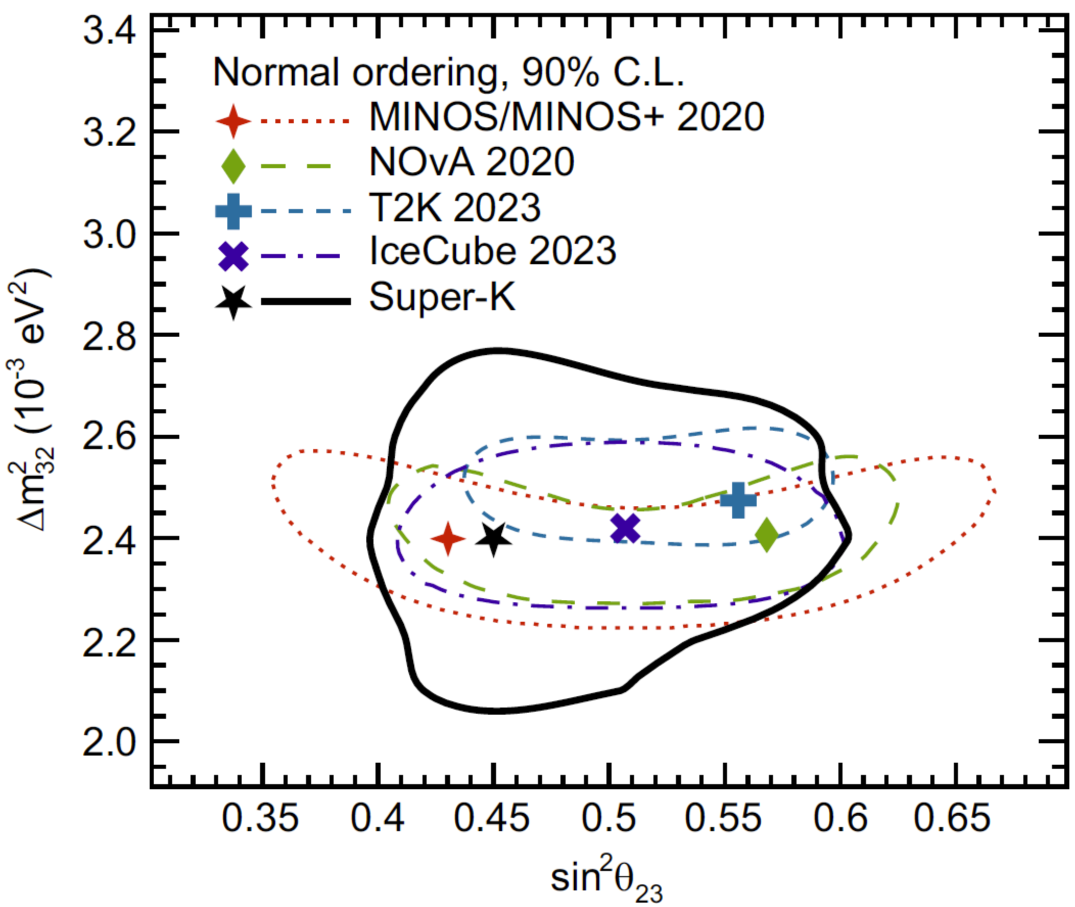
→ consistent with atmospheric data

→ atm ν oscillations confirmed by lab exps

The atmospheric sector

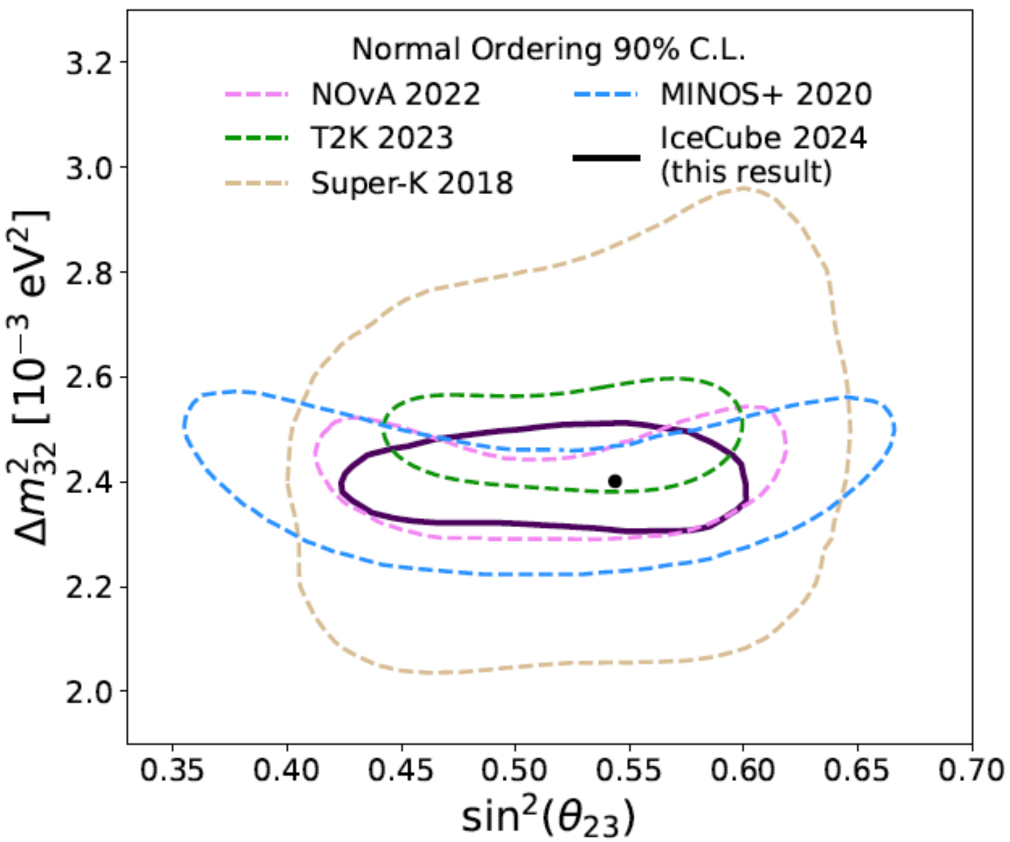
New Results

Super-K I-V atmospheric data
(6511.3 live days, expanded FV)



SK Collab, PRD 109 (2024) 072014

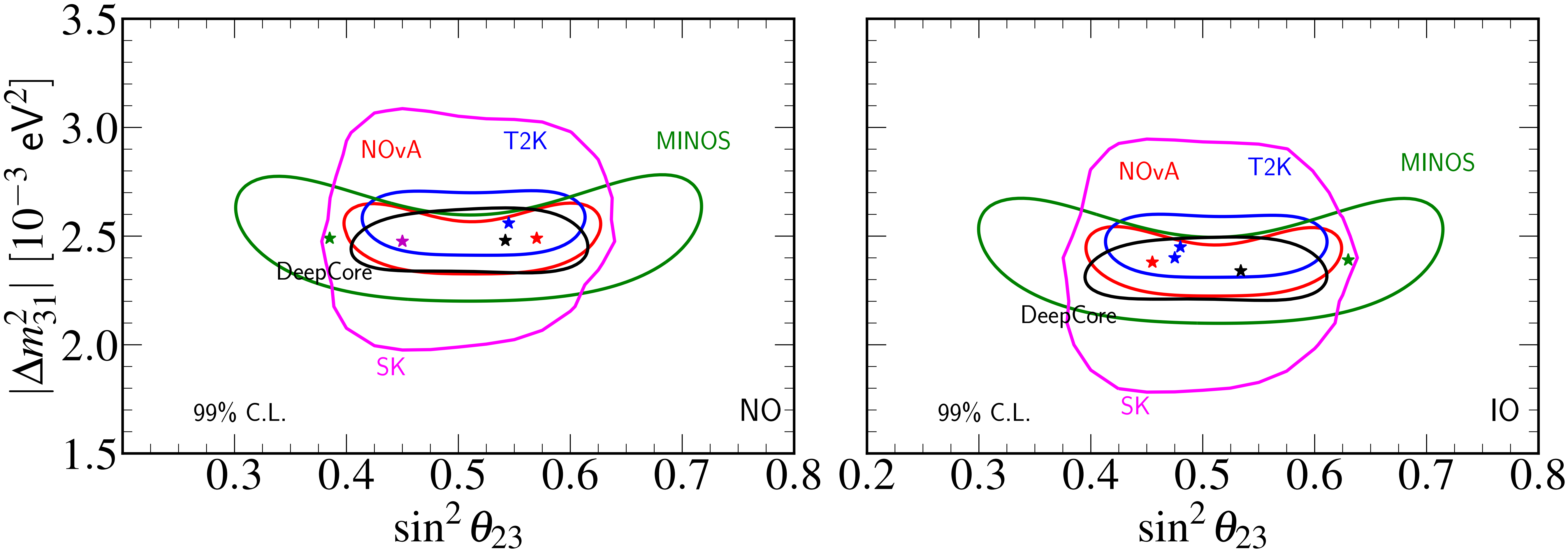
IceCube DeeCore 9.3 yrs



IceCube Collab, arXiv:2405.02163

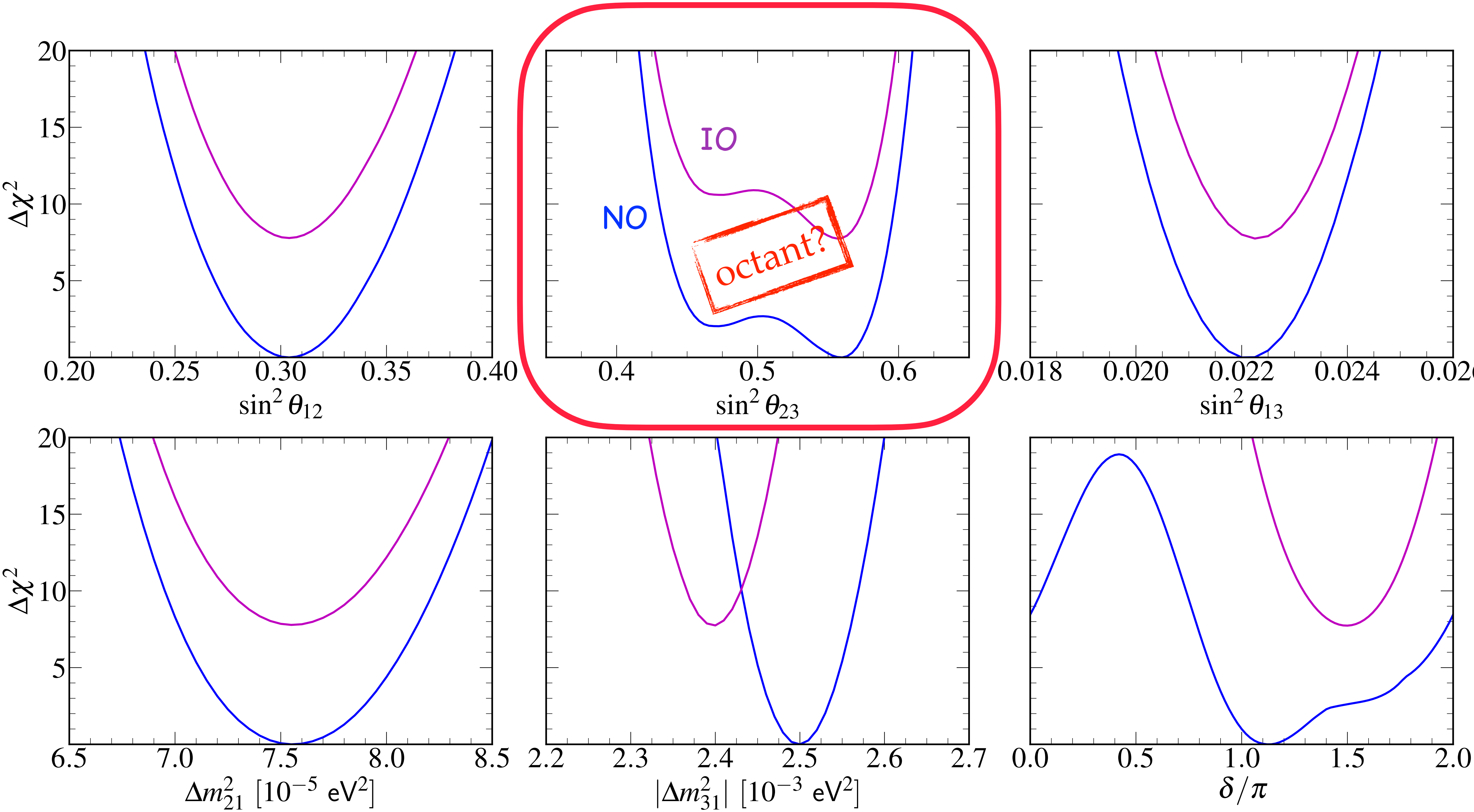
The atmospheric sector

($\sin^2\theta_{23}$ - Δm^2_{31}) regions (99% CL) from individual experiments



- ✦ Great agreement among all the experiments
- ✦ Best sensitivity obtained at T2K (closely followed by NOvA and DeepCore)
- ✦ IC-DeepCore starts being competitive with LBL accelerator experiments

Global fit to ν oscillation parameters

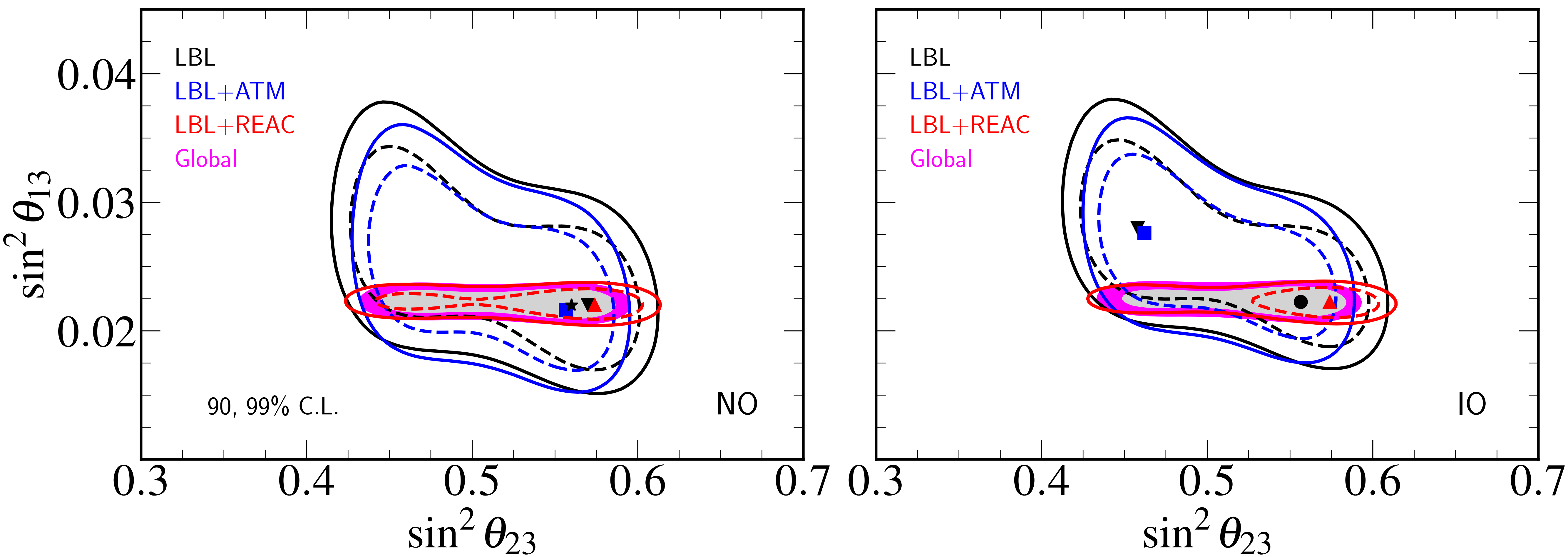


SSM HZ model - MB22m

with SK atmospheric

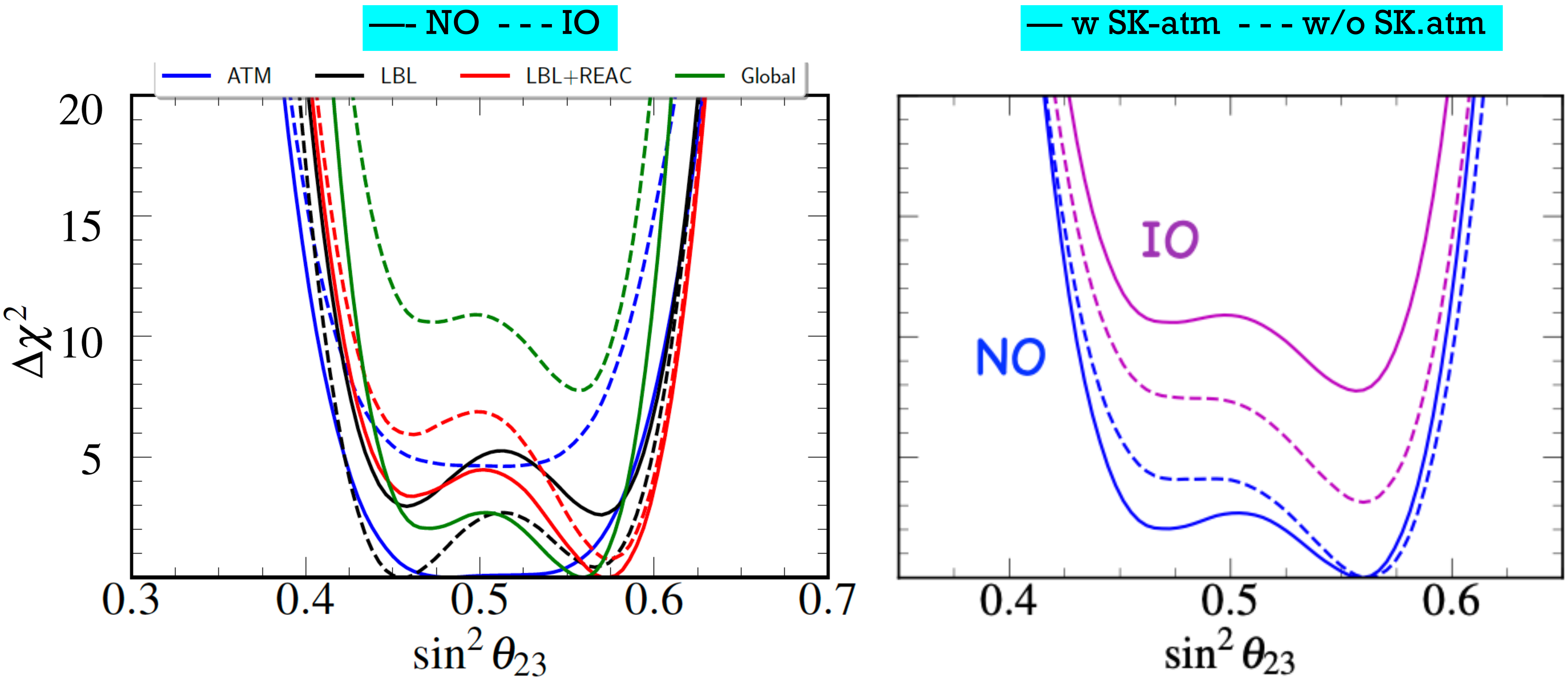
$\Delta\chi^2$(IO-NO) = 7.7

The octant of θ_{23}



- **LBL** combination slightly prefer UO (NO) and LO(IO) with $\Delta\chi^2 = 0.3\text{-}0.4$
- LBL + ATM prefers UO (NO) and LO(IO) with $\Delta\chi^2 \sim 0.3\text{-}1$
- REAC breaks the degeneracy in favor of UO (NO and IO) with $\Delta\chi^2 \sim 3.5\text{-}5.2$ over LO
- Global analysis show a milder preference for UO with $\Delta\chi^2 \sim 2.0$ (2.9) for NO (IO)

The octant of θ_{23}

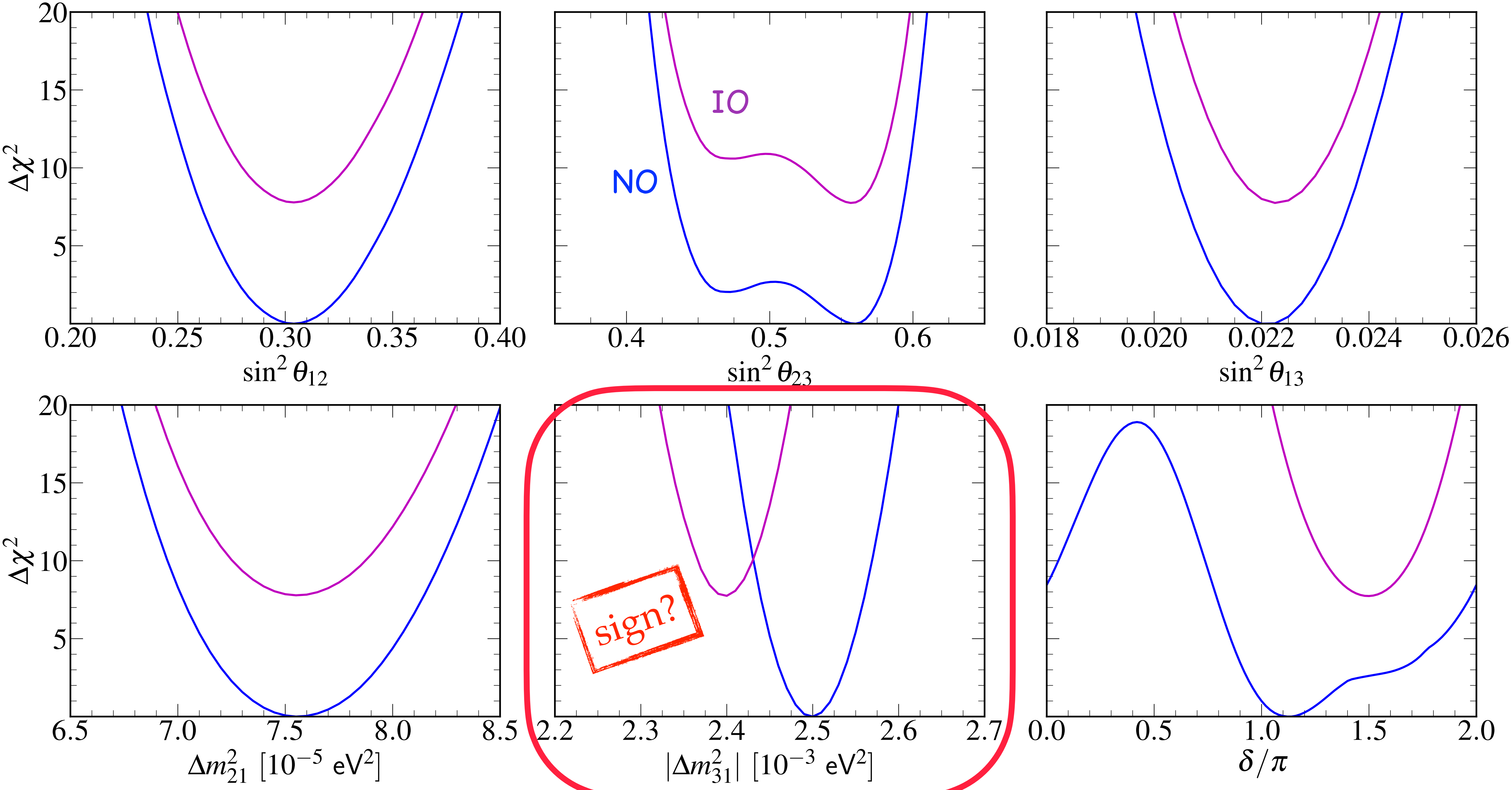


✦ Lower-octant slightly disfavoured with $\Delta\chi^2 \geq 2.0$ (2.9) for NO (IO)

$\Rightarrow$ w/o SK: LO more disfavoured, with $\Delta\chi^2 \sim 4.2$

✦ Maximal mixing disfavoured with $\Delta\chi^2 =$ 2.5 (3.1) for NO (IO)

Global fit to ν oscillation parameters



SSM HZ model - MB22m

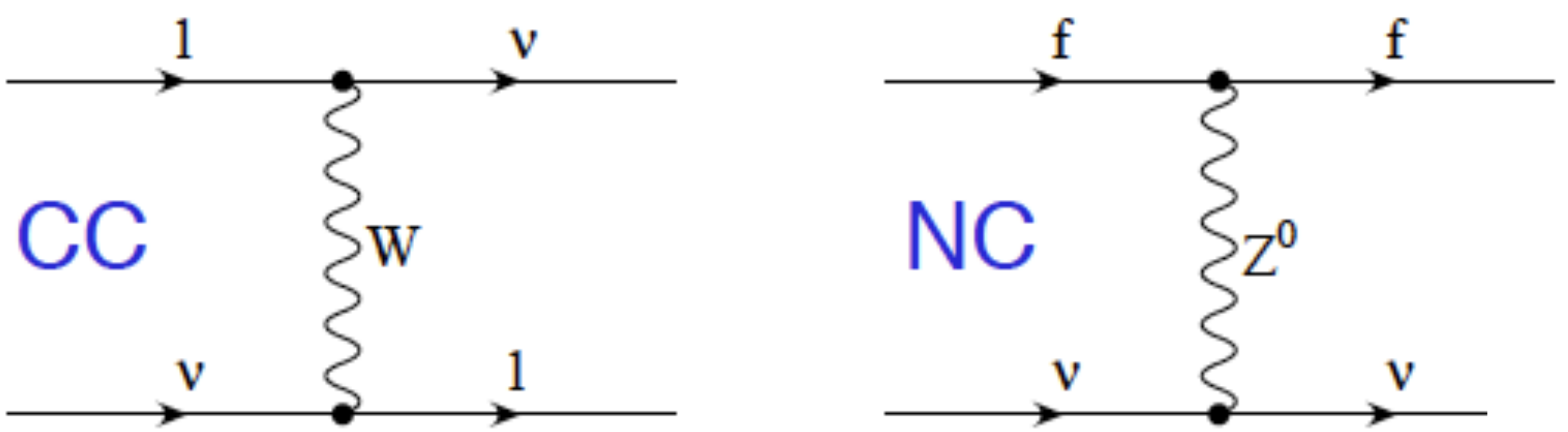
with SK atmospheric

$\Delta\chi^2$(IO-NO) = 7.7

Matter effects on neutrino oscillations

✦When neutrinos pass trough matter, the interactions with the particles in the medium induce an **effective potential** for neutrinos.

L. Wolfenstein, 1978



$$V_{\rm matt} = \pm\sqrt{2}G_F\,{\rm diag}(N_e - \frac{1}{2}N_n, -\frac{1}{2}N_n, -\frac{1}{2}N_n)$$

(+) neutrinos
(-) antineutrinos

→ modifies the **mixing between flavor states and mass eigenstates**, leading to a different oscillation probability with respect to vacuum oscillations.

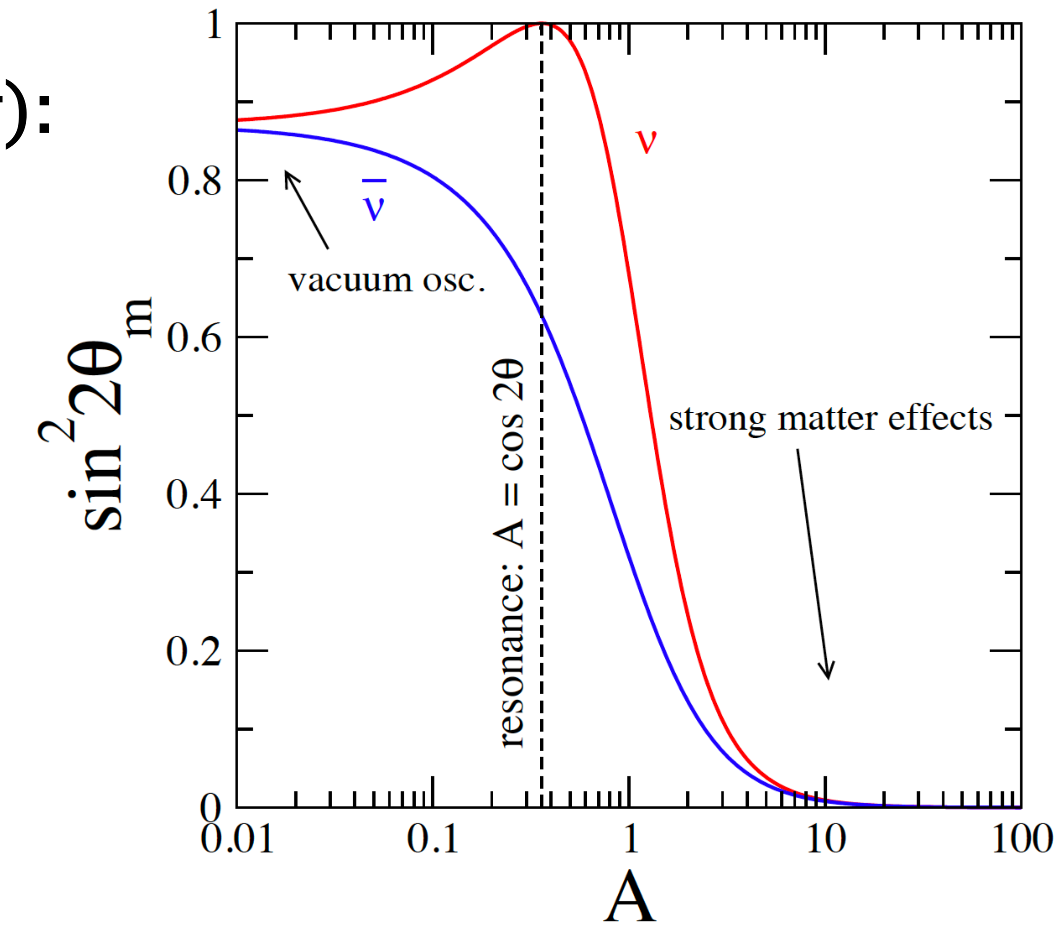
Matter effects in solar neutrinos

- Mixing angle in matter (constant density):

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta}{\sin^2 2\theta + (\cos 2\theta \mp A)^2}$$

(-) neutrinos (+) antineutrinos

with: $$A = \frac{2EV_{CC}}{\Delta m^2} = \frac{2\sqrt{2}G_F E N_e}{\Delta m^2}$$

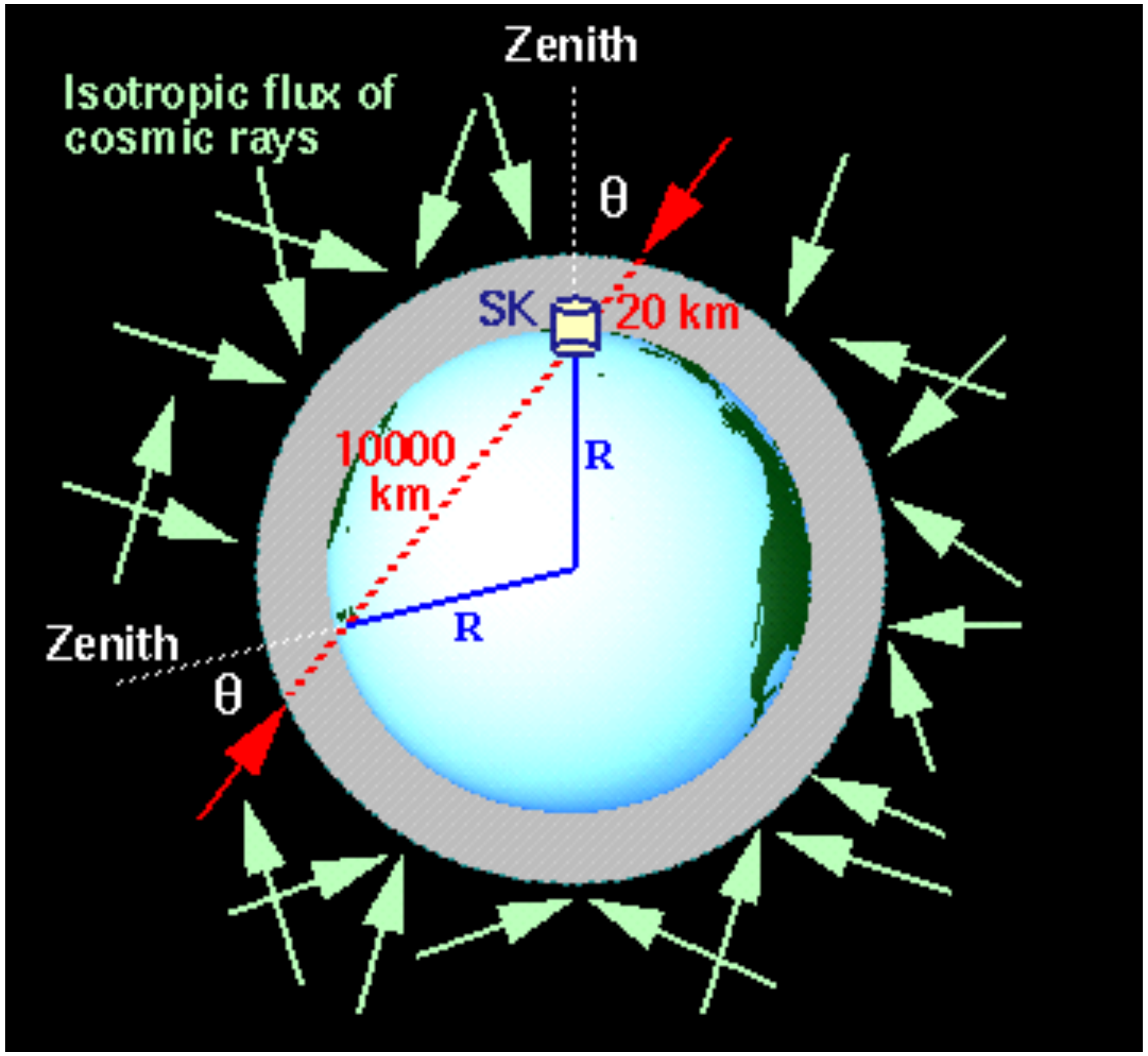


→ **resonance condition** (MSW effect) A = cos2θ is satisfied for neutrinos for $\Delta m^2 > 0$ and antineutrinos for $\Delta m^2 < 0$.

- Matter effects observed in solar neutrino data in agreement with the presence of a resonance as predicted above:

→ since solar neutrinos are ν_e: $\Delta m^2_{21} > 0 \rightarrow m_2 > m_1$

Matter effects in atmospheric ν's



✦ Atmospheric neutrinos interact with the Earth mantle and core

✓ no matter effects in $\nu_\mu \to \nu_\tau$ channel

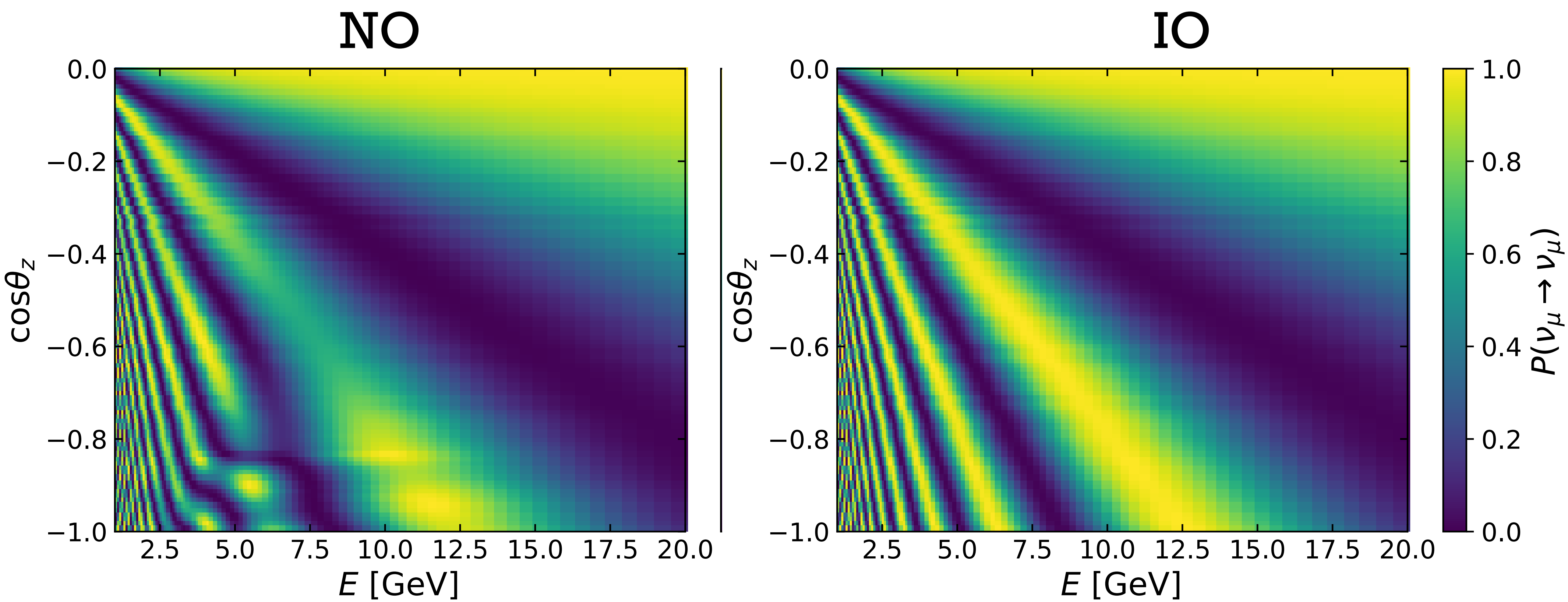
✓ MSW resonance in $\nu_\mu \to \nu_e$ channel

$$\tan 2\theta_m = \frac{\frac{\Delta m^2}{4E} \sin 2\theta}{\frac{\Delta m^2}{4E} \cos 2\theta \mp \sqrt{2} G_F N_e}$$

(-) neutrinos (+)antineutrinos

➙ Matter effects on the atmospheric neutrino flux are sensitive to the mass ordering

Matter effects in atmospheric ν's



de Salas et al, arXiv:1806.11051

At E~ 3-8 GeV: MSW resonance for neutrinos and NO mass spectrum

For antineutrinos ⟹ the resonance appears in IO

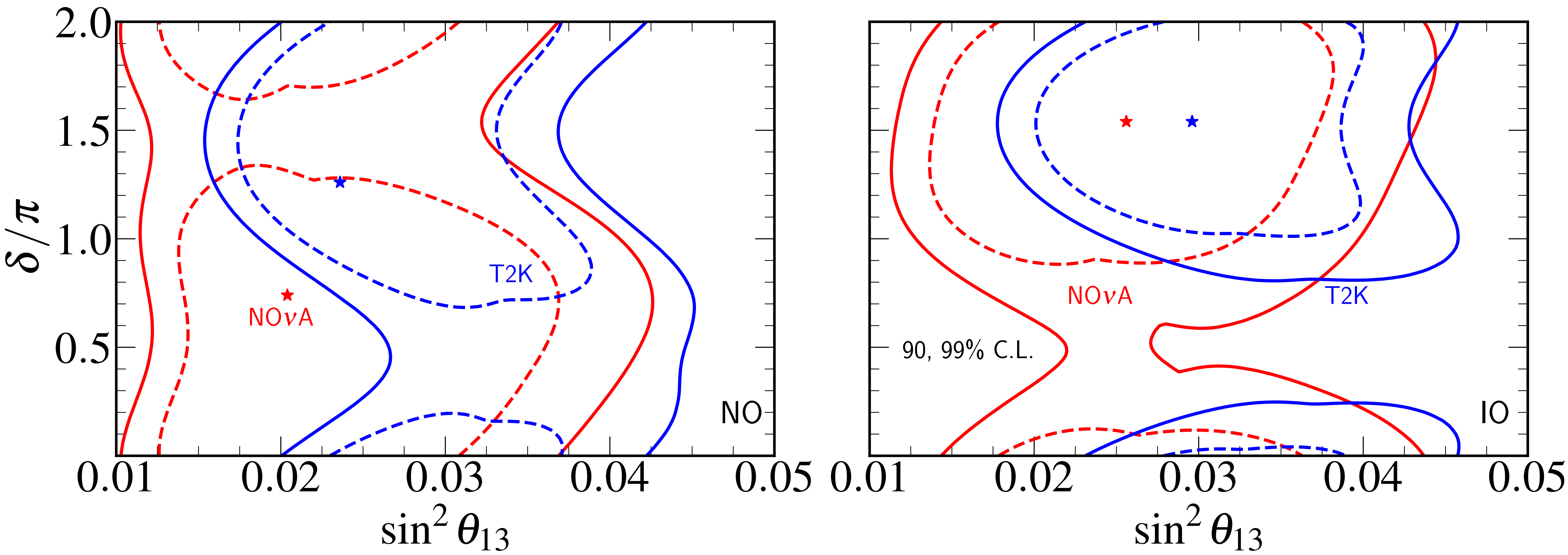
These matter effects are harder to observe since $P_{\mu e} \propto \theta_{13}$

➙ sign(Δm^2_{31}) unknown

The mass ordering

- ✦ T2K and NOvA separate analyses prefer **NO** with $\Delta\chi^2 \approx 0.2$-0.4

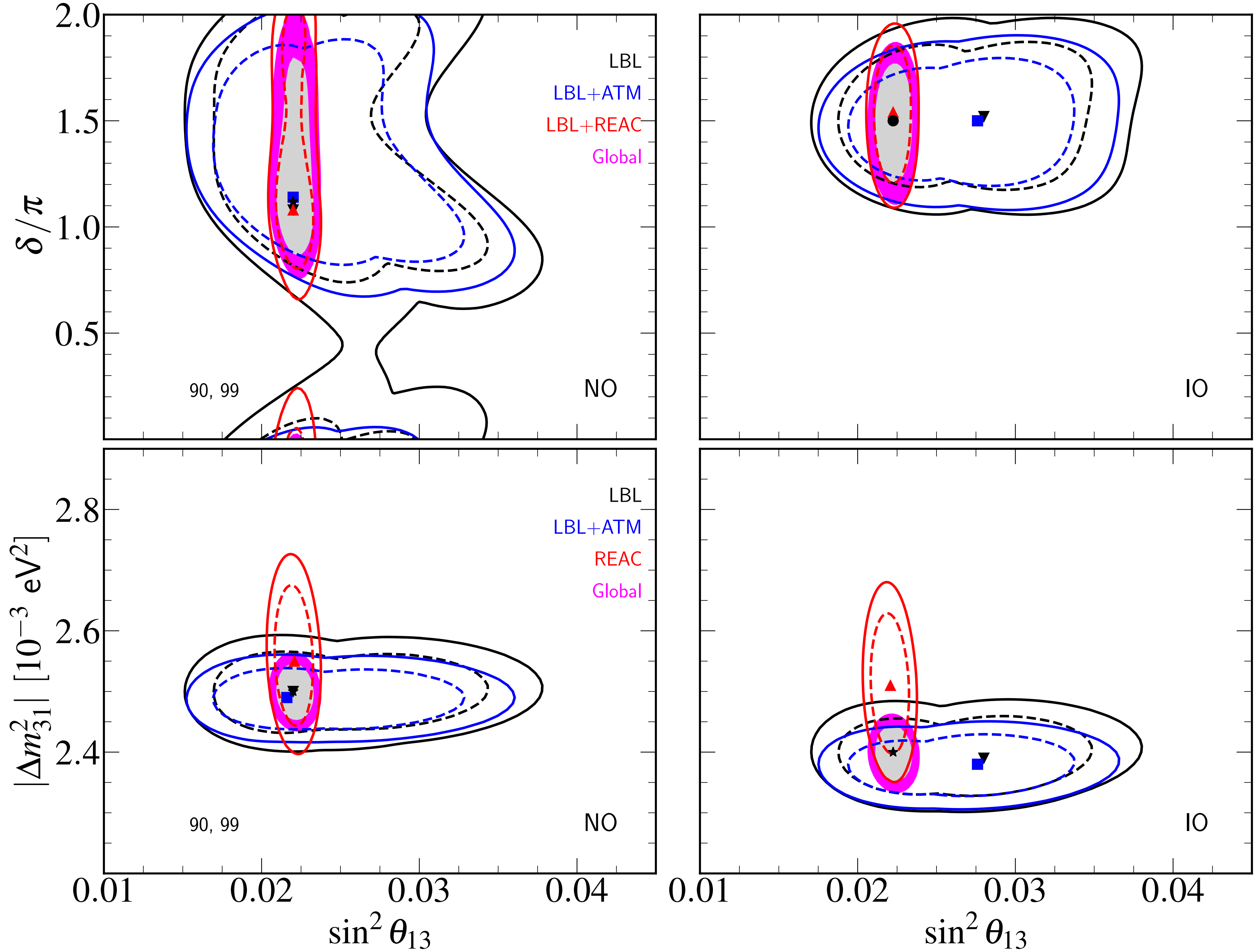
Tension between T2K and NOvA results in NO



➙ The LBL combination (T2K + NOvA + MINOS) prefer **IO** with $\Delta\chi^2 \approx 2.6$

The mass ordering

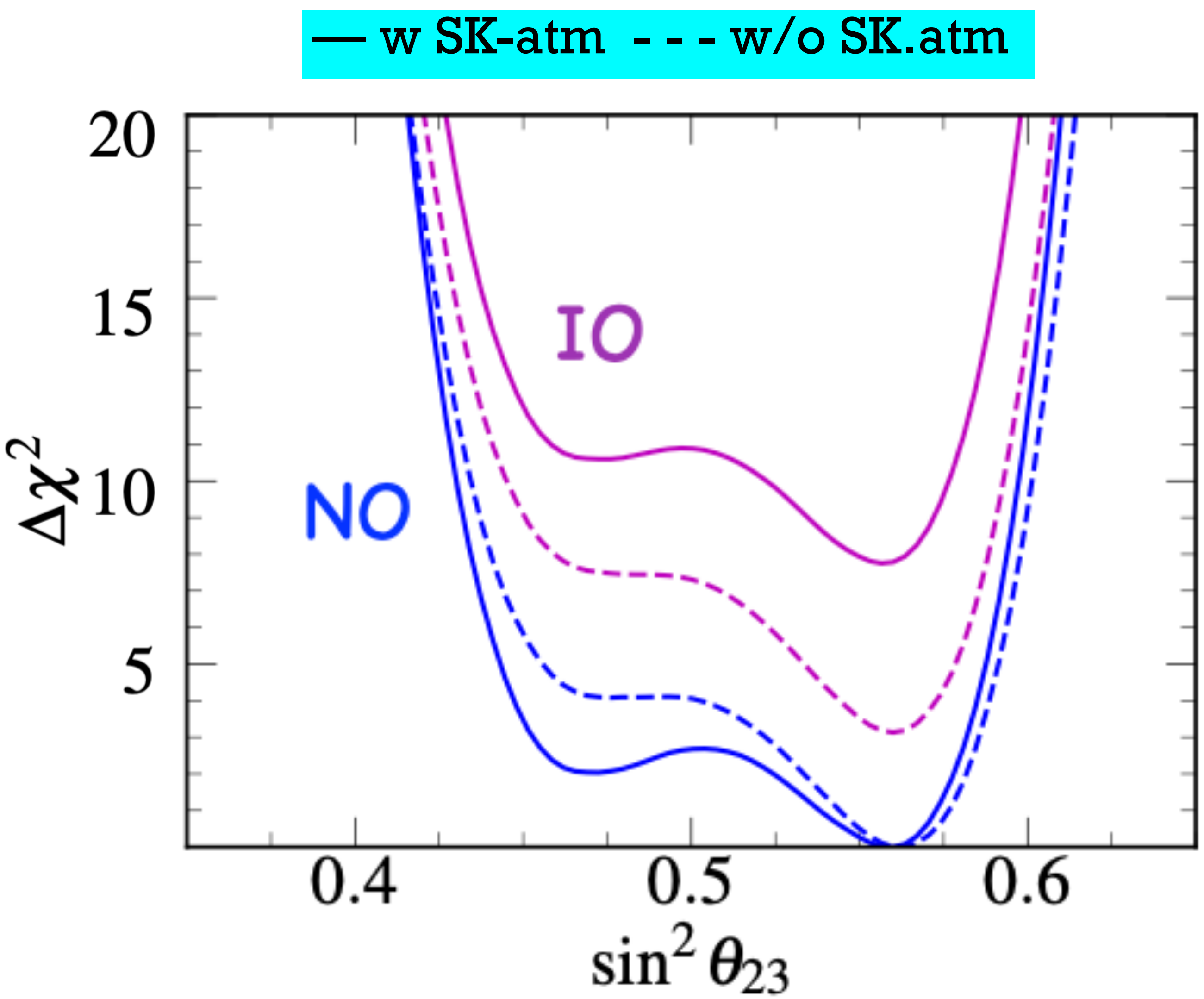
Tension between LBL and NOvA results in IO



- LBL and REAC data show better agreement in NO

- LBL + REAC prefer **NO** with $\Delta\chi^2 \approx 0.7$

The mass ordering



- T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.2$-0.4
- **LBL** prefer IO with $\Delta\chi^2 \approx 2.6$ (tension NO)
- LBL + REAC prefer NO with $\Delta\chi^2 \approx 0.7$ (tension in Δm^2_{31} measurement in IO)
- SK-atm prefers NO with $\Delta\chi^2 = 5.69$ (5.23) for θ_{13} constrained (free)
- From the global fit: $\Delta\chi^2$ (IO-NO)= 7.7 (3.1) w SK-atm (w/o SK-atm)

  assuming Wilk's theorem: 2.8σ (1.8σ) **preference for NO** w SK-atm (w/o SK-atm)

Neutrino mass scale

Neutrino oscillations

$$\sum m_\nu|_{\rm NO} \gtrsim 0.06\,{\rm eV}$$

$$\sum m_\nu|_{\rm IO} \gtrsim 0.1\,{\rm eV}$$

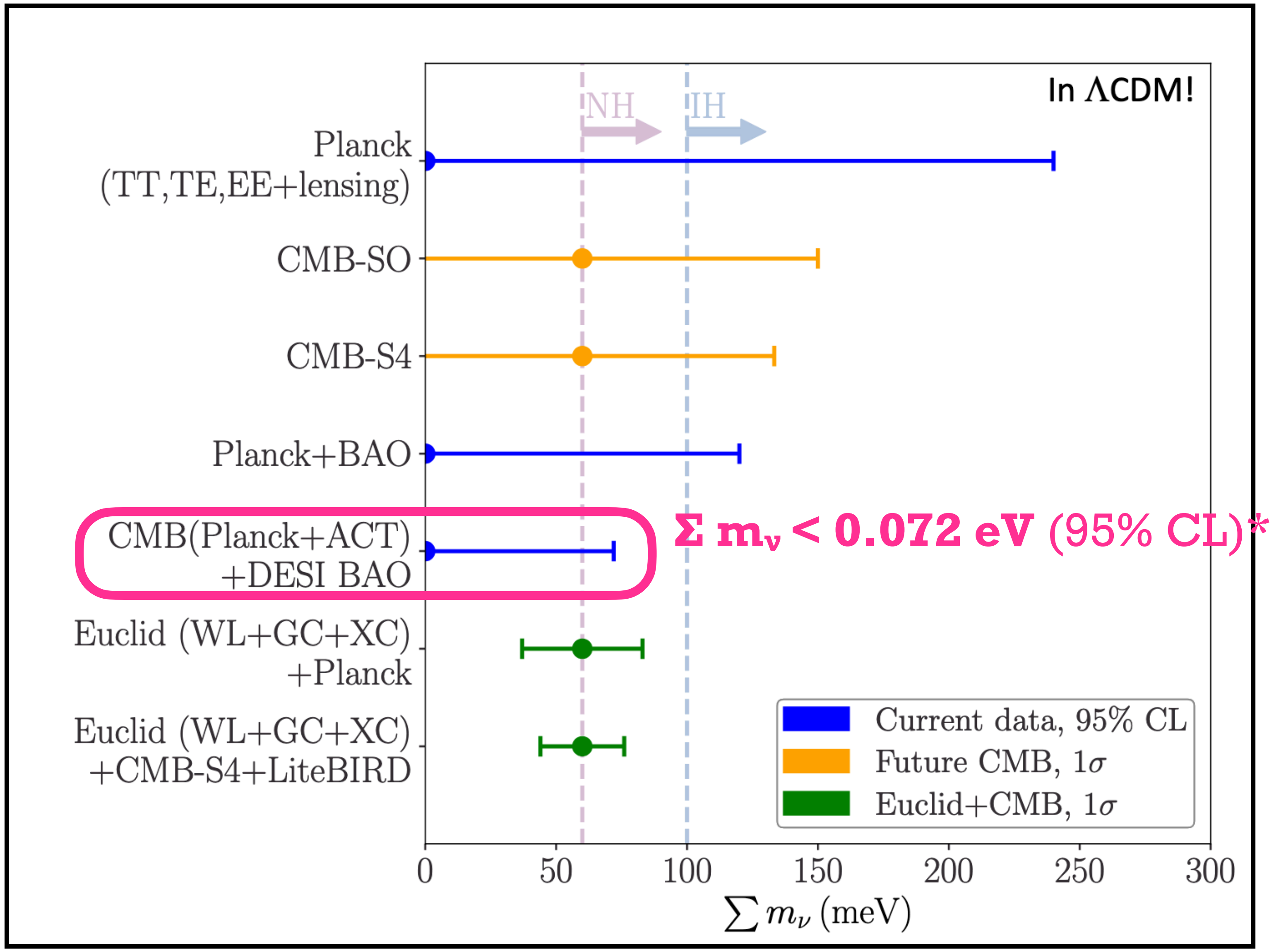
Direct constraints

✦ new world-best direct neutrino mass constraint from KATRIN:

m_β < 0.45 eV (90% CL)

C. Wiesinger @ ICHEP 2024

Cosmological constraints



Σ m_ν < 0.072 eV (95% CL)*

M. Archidiacono @ Neutrino 2024

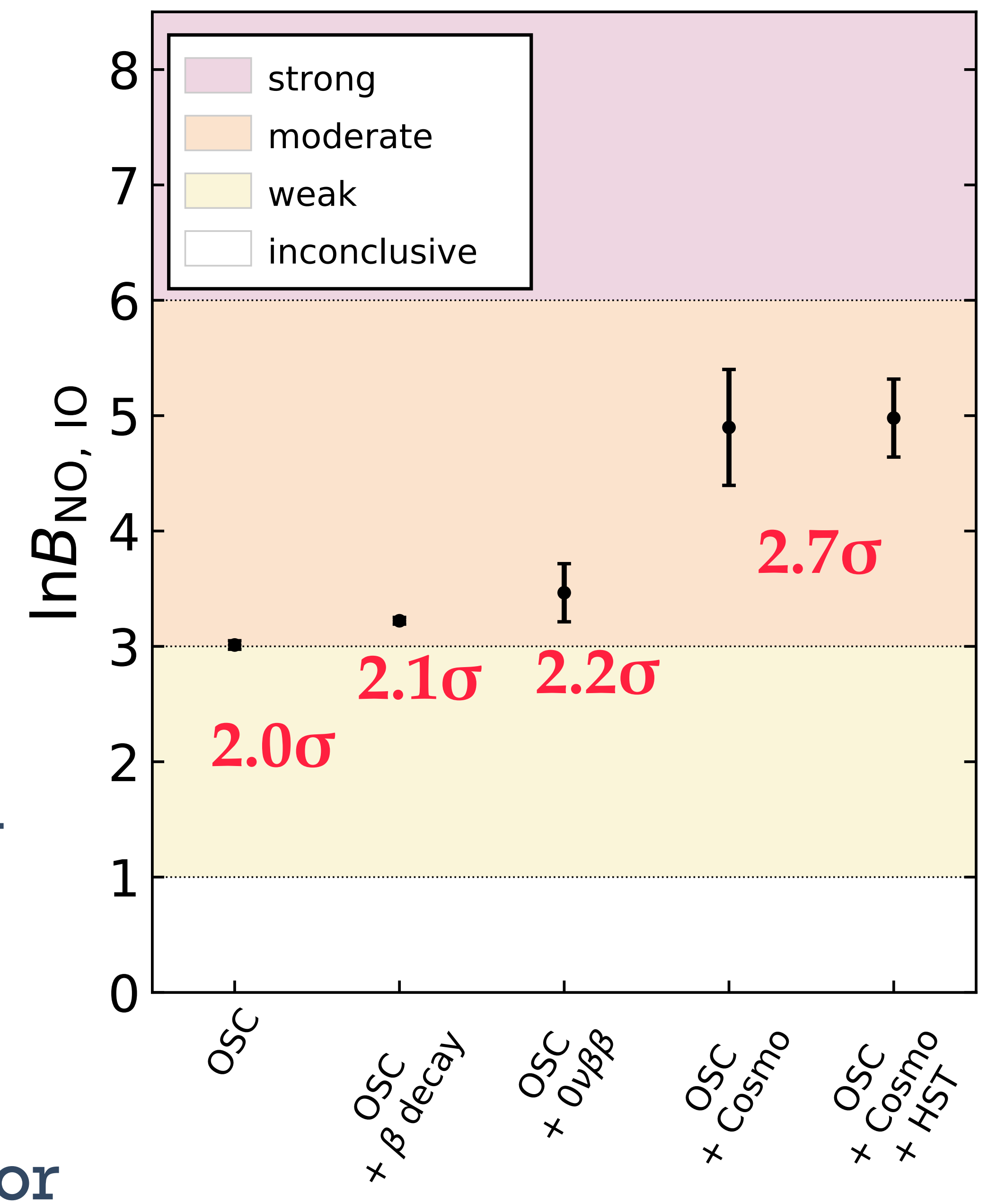
* Relaxed to **Σ m_ν < 0.11 eV** (Naredo-Tuero, arXiv:2407.13831)

The mass ordering

de Salas et al, JHEP 02 (2021) 071

Experimental sensitivity to neutrino masses:

- ν-oscillations: Δm^2_{ij}
- β-decay: $m_\beta = f(m_i,\theta_{ij})$ **m_β < 1.1 eV** (90% CL)
- 0νββ: $m_{\beta\beta} = f(m_i,\theta_{ij},\phi_i)$
- Cosmology: Σm_i **$\Sigma\, m_\nu$ < 0.12 (0.15) eV** NO (IO) (95%CL)



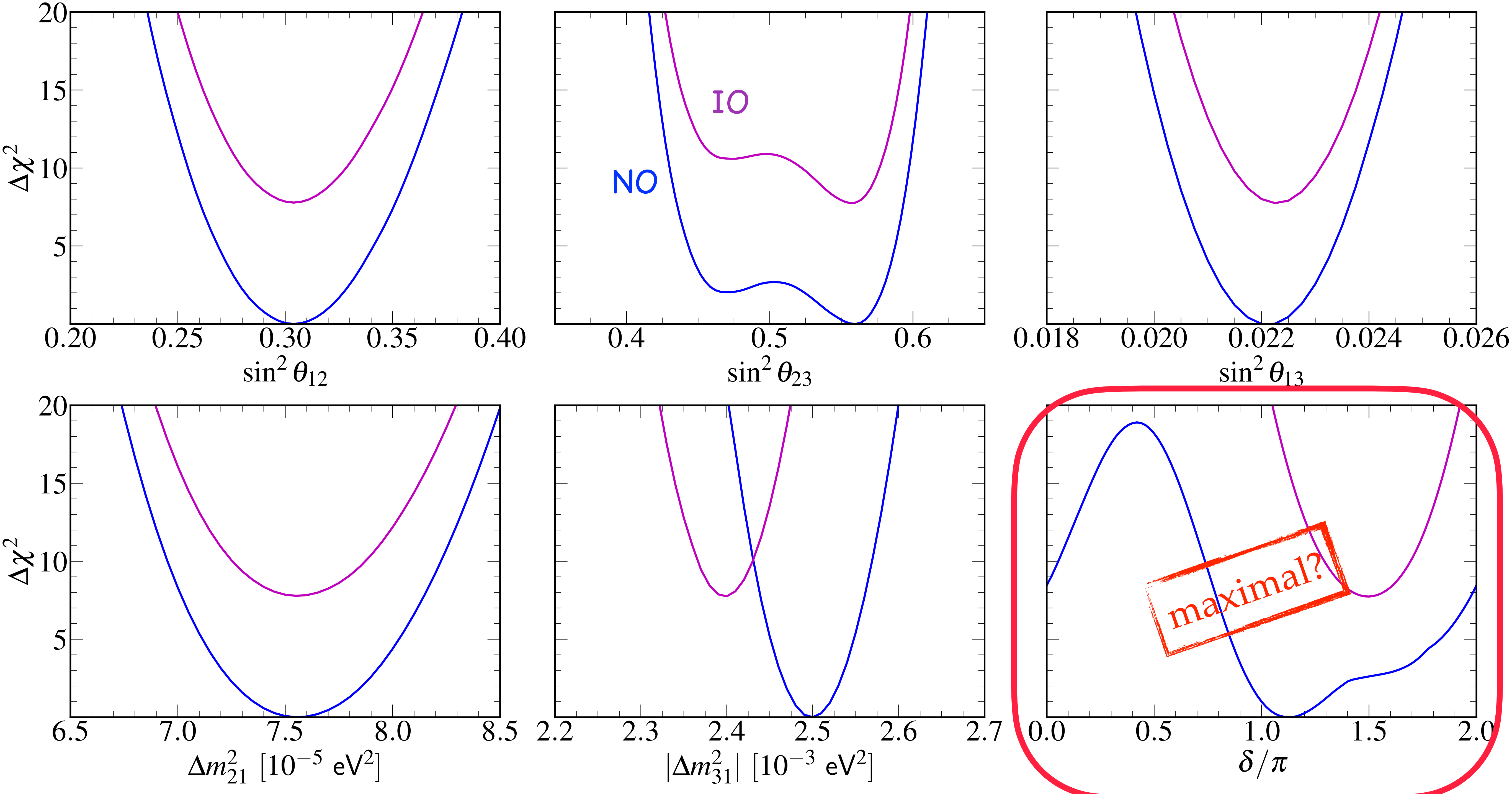
Results from the combined bayesian analysis:

⇒ 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

Global fit to ν oscillation parameters



SSM HZ model - MB22m

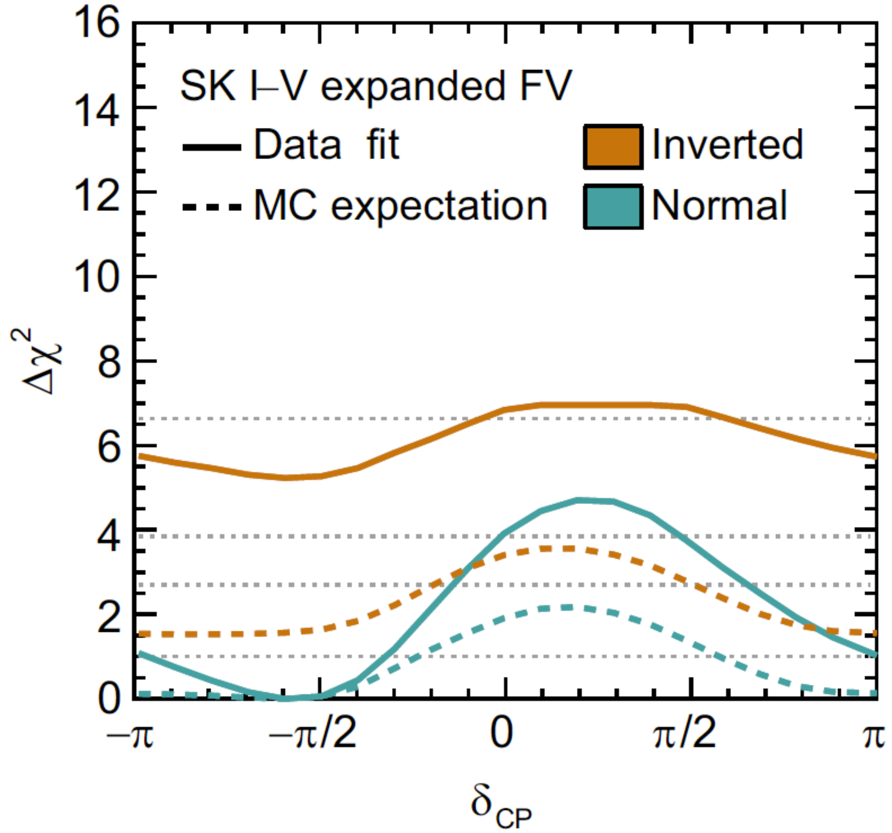
with SK atmospheric

$\Delta\chi^2$(IO-NO) = 7.7

The CP phase

H. Tanaka, TAUP 2019

Super-Kamiokande (atm)



✦ δ_{BF} = 1.4π (NO and IO)

✦ preference driven by ν_e excess in sub-GeV amb multi-GeV e-like samples

SK Collab, PRD 109 (2024) 072014

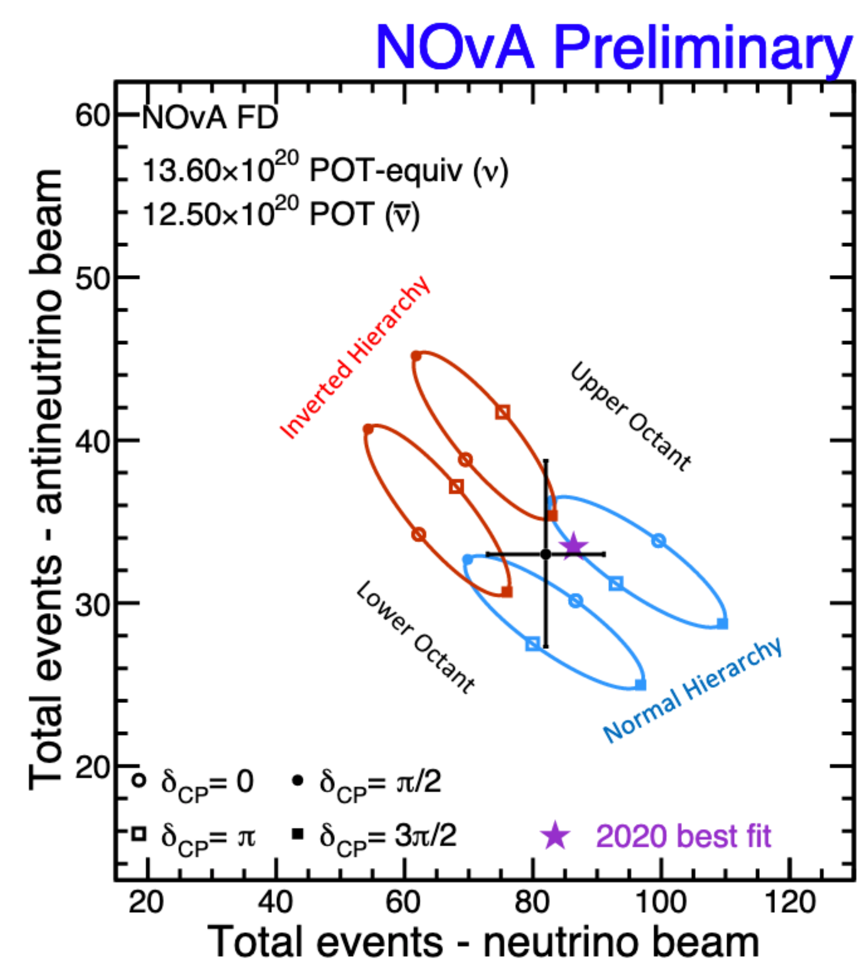
T2K

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

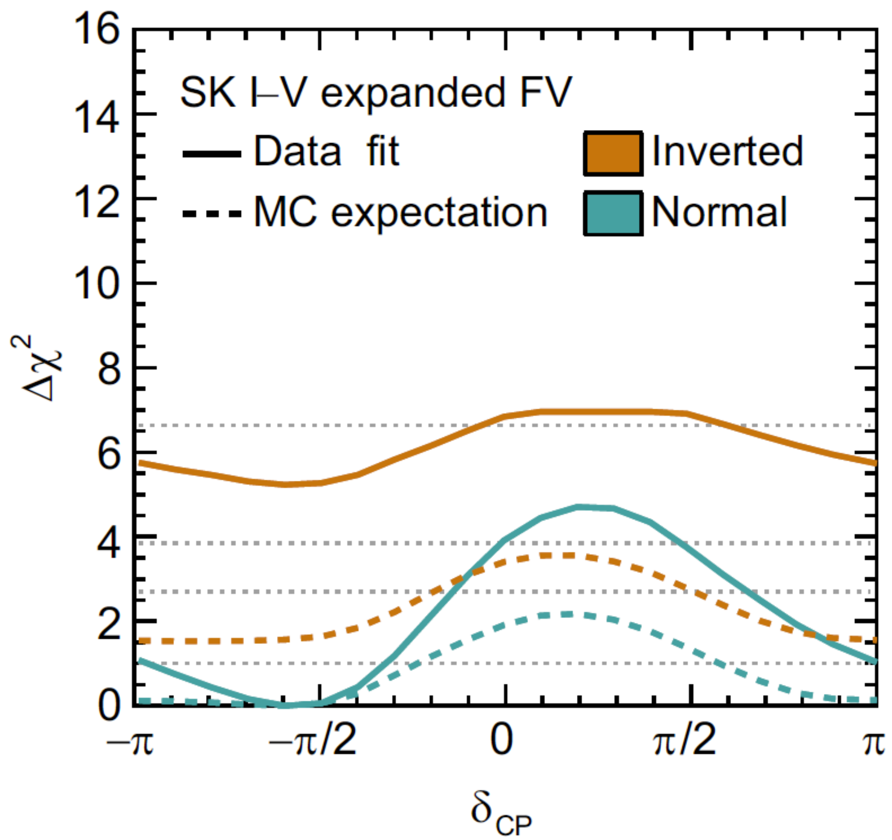
No strong asymmetry in the ν_e / $\bar{\nu}_e$ app rates



P Vahle, TAUP 2021

The CP phase

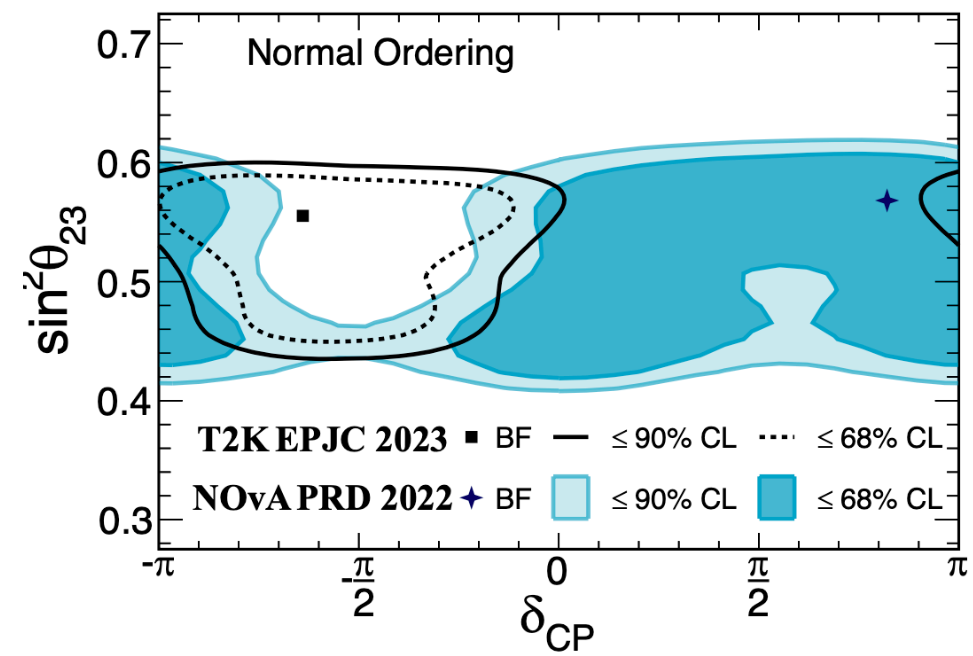
Super-Kamiokande (atm)

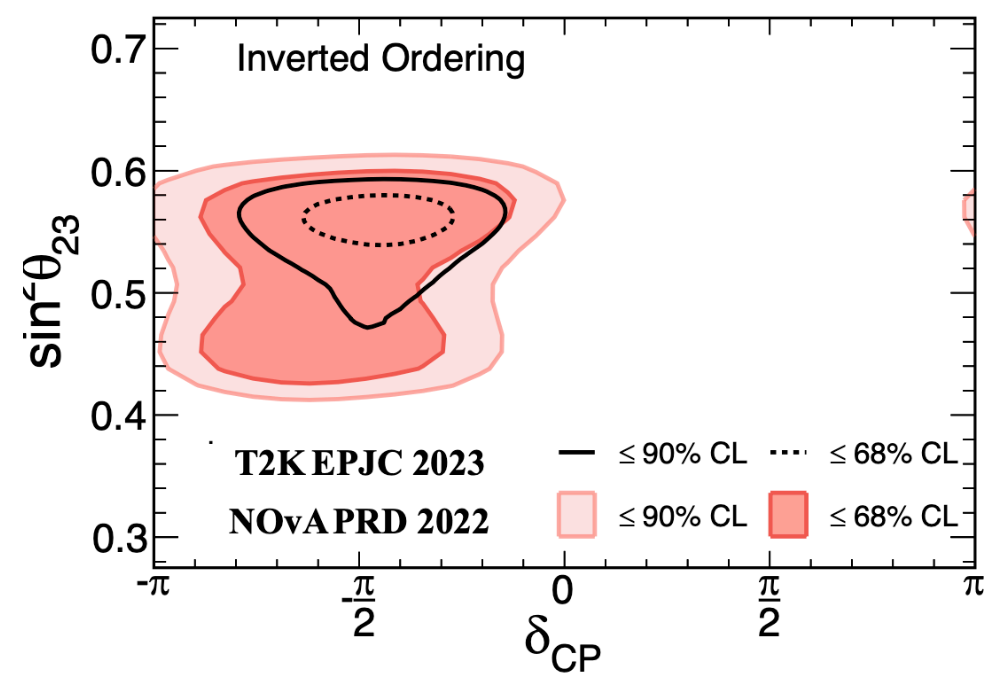


- ✦ $\delta_{BF} = 1.4\pi$ (NO and IO)
- ✦ preference driven by ν_e excess in sub-GeV amb multi-GeV e-like samples

SK Collab, PRD 109 (2024) 072014

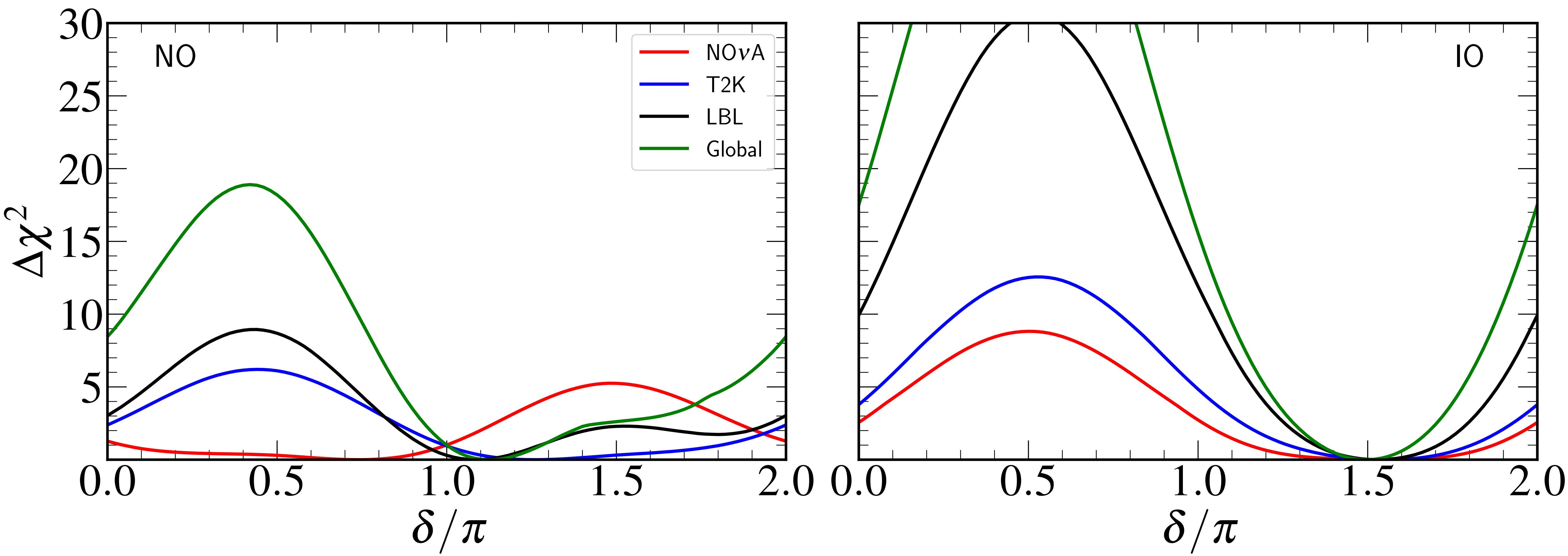
Slight tension T2K & NOvA for NO





A. Booth, 2024

The CP phase



- NO: mismatch between NOvA and T2K and SK atmospheric results

  $\delta_{BF} = 1.12\pi$; $\delta = \pi/2$ (0) disfavored at 4.3σ (2.9σ)

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

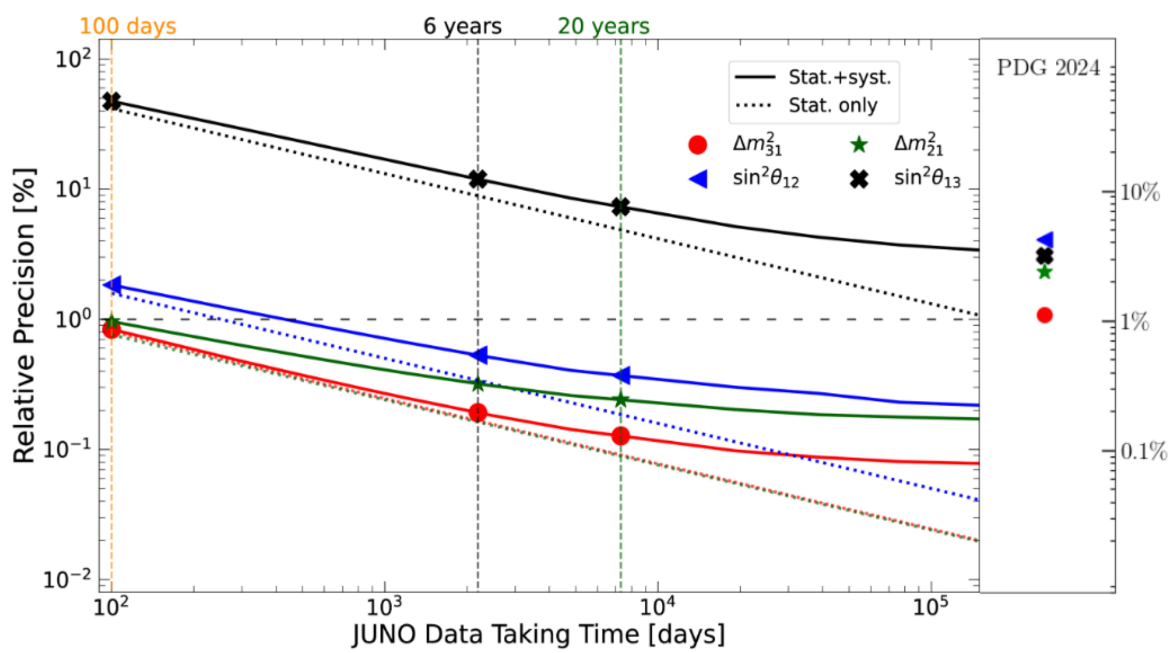
  $\delta_{BF} = 1.5\pi$; $\delta = \pi/2$ (π) disfavored at 6.8σ (3.9σ)

Neutrino oscillations in the near future

See P. Ochoa-Ricoux's talk

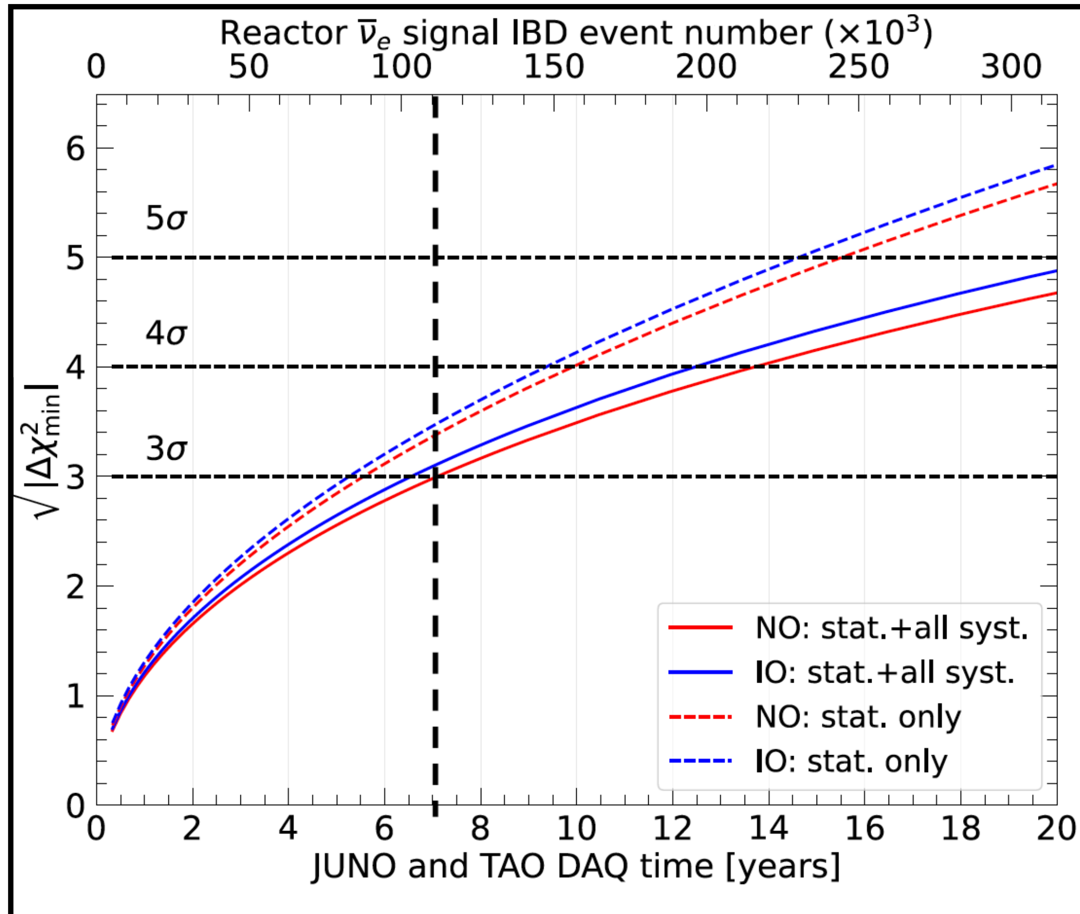
JUNO ➤ precision and mass ordering

V. Cerrone @ NOW 2024



	PDG 2024	JUNO 100 days	JUNO 6 years
Δm^2_{31}	1.1%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5%
$\sin^2\theta_{13}$	3.2%	47.9%	12%

Chinese Phys. C 46 123001

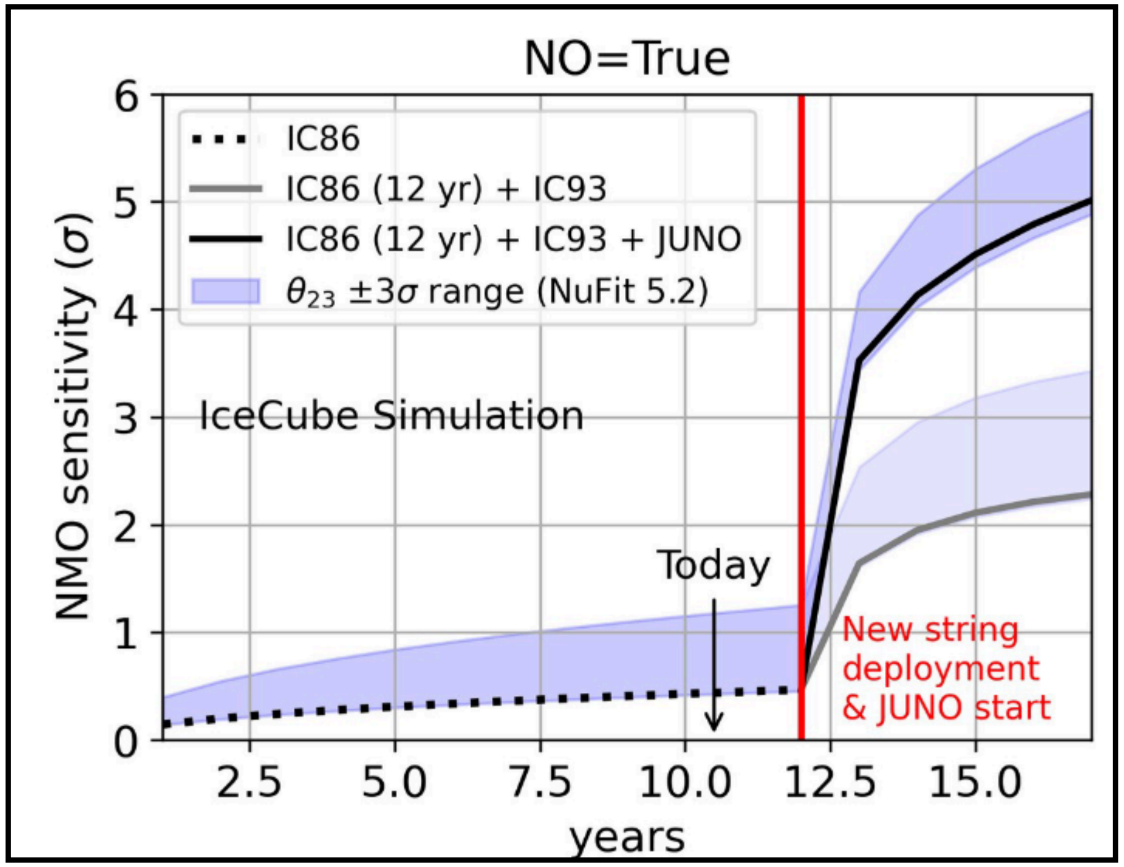


- 3σ sensitivity in ~7 years of data
- Combined analysis with atmospheric experiments will enhance the sensitivity

Neutrino oscillations in the near future

IceCube Upgrade + JUNO

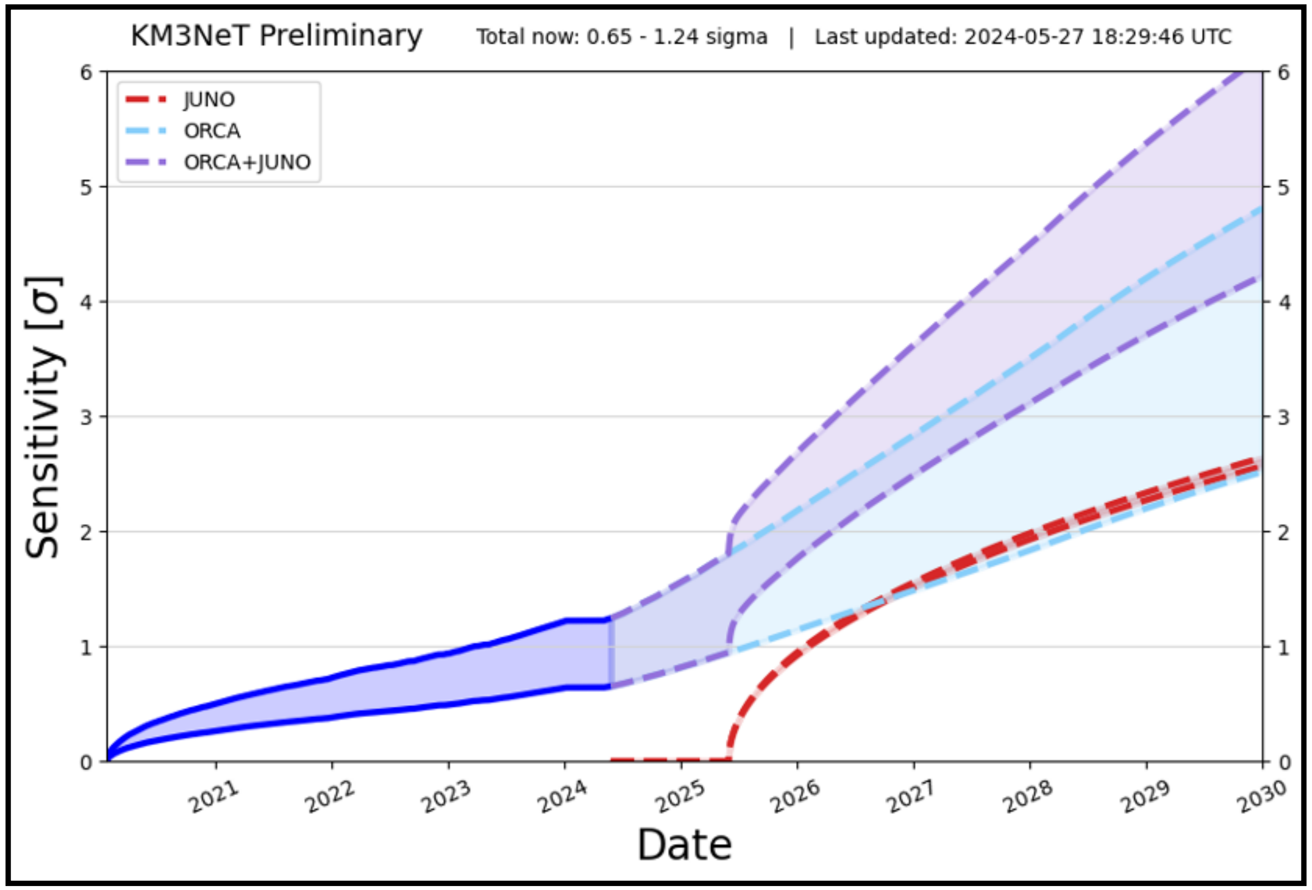
A. Terliuk @ NOW 2024



- Up to 3σ sensitivity to neutrino mass ordering (5σ with JUNO)

ORCA + JUNO

P. Migliozzi @ NOW 2024

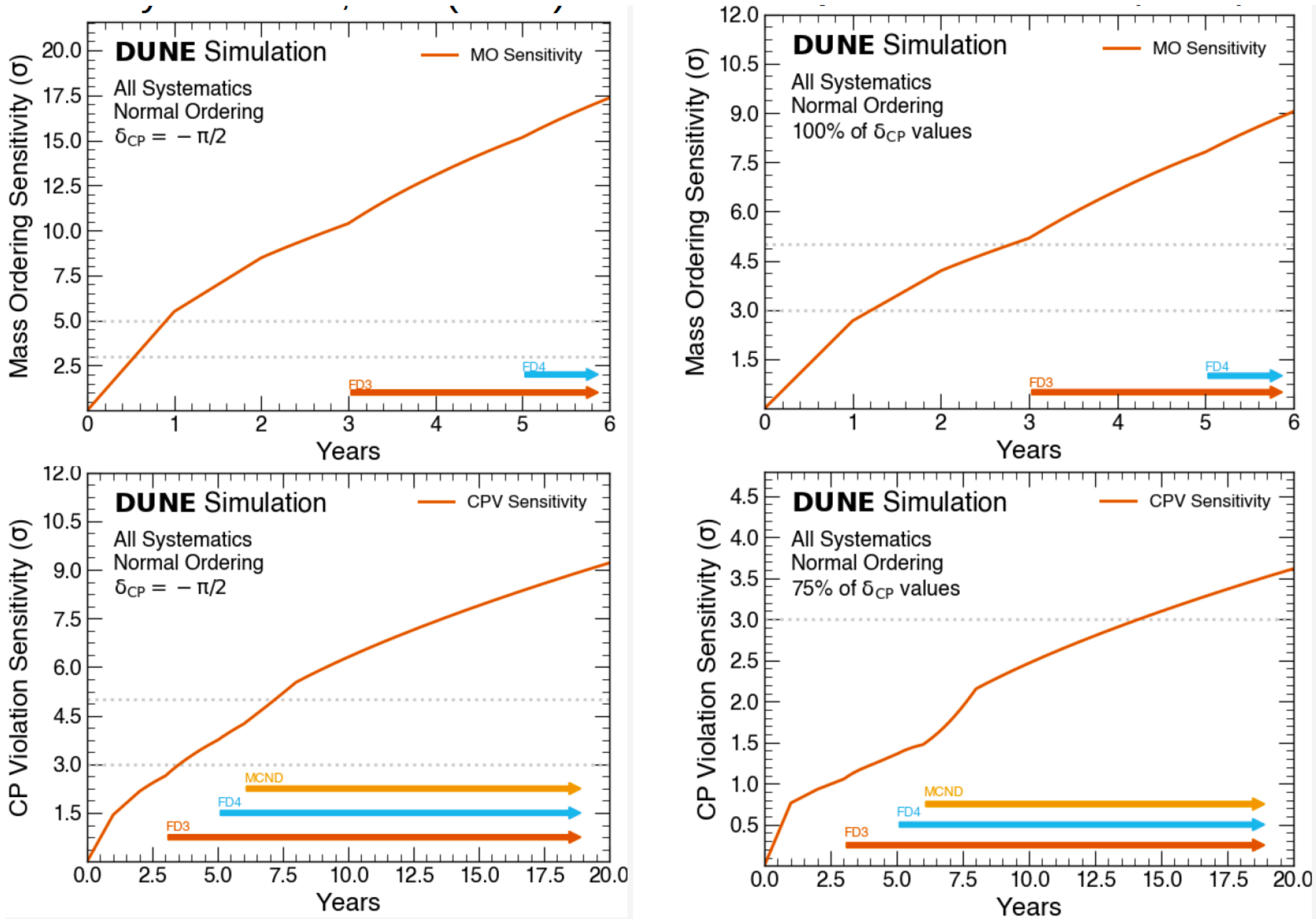


- 4-6σ sensitivity to neutrino MO by 2030 (below 3σ with JUNO only)

Next generation of ν experiments

DUNE

C. Marshall@ Neutrino'24



Ultimate precision in δ_{CP}: 6-16°

✦ Best-case oscillation scenarios:

>5σ mass ordering sensitivity in 1 year

>3σ CPV sensitivity in 3.5 years

✦ Worst-case oscillation scenarios:

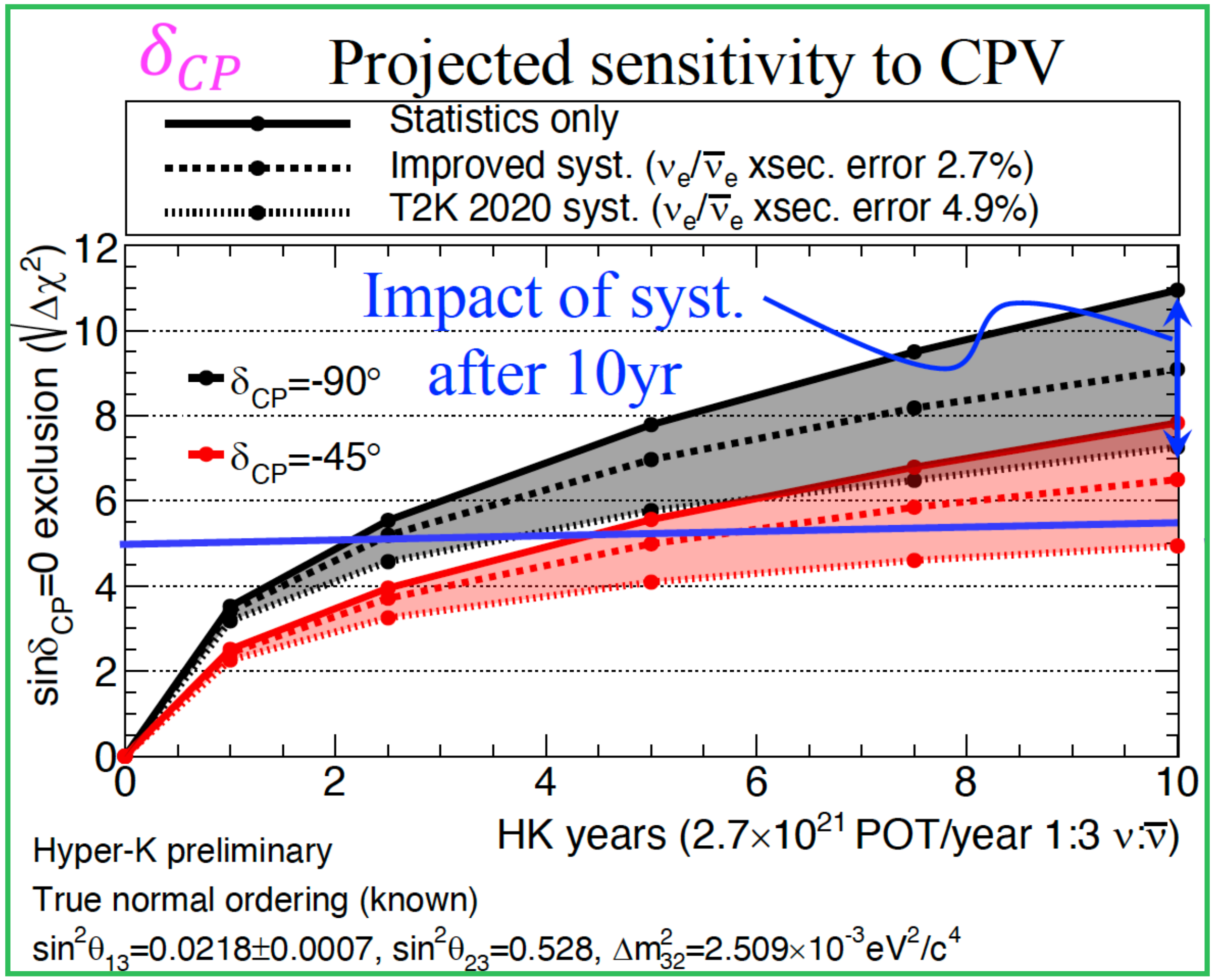
>5σ mass ordering sensitivity in 3 years

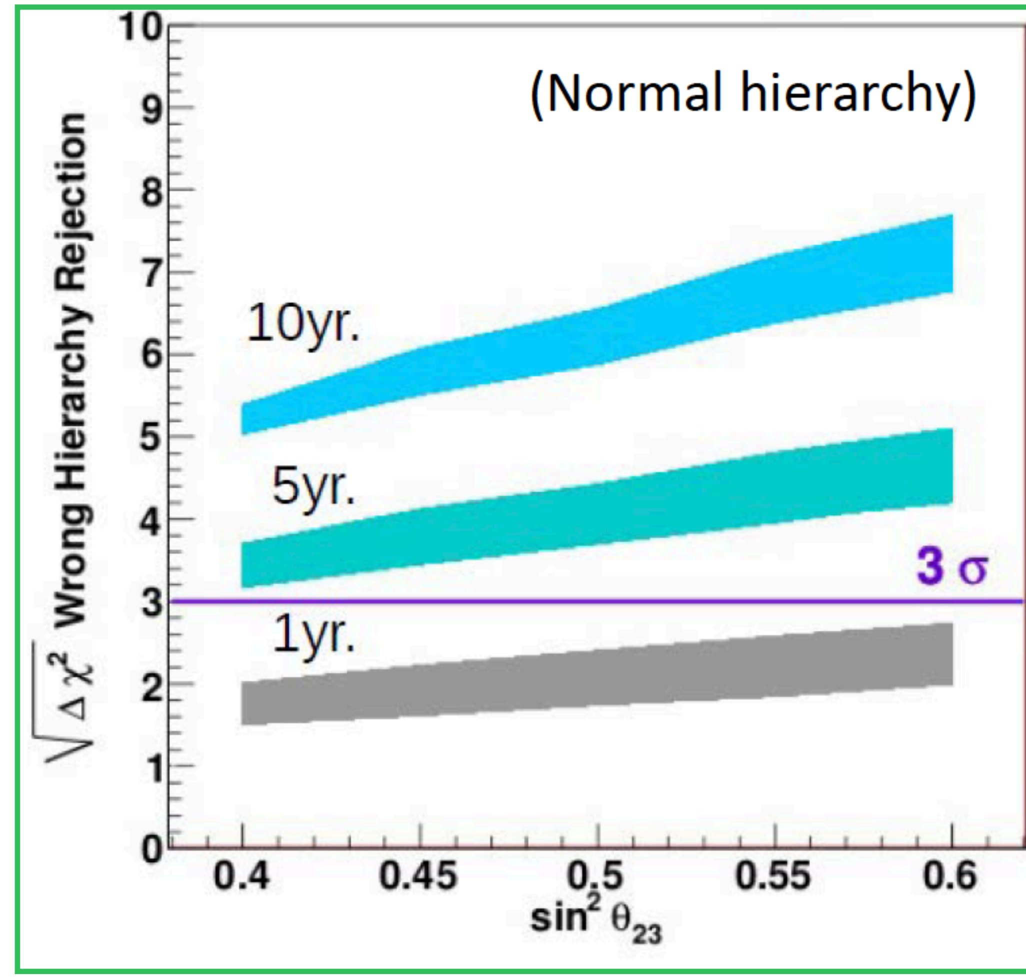
+10yr: CPV over 75%of δ_{CP} values at >3σ

Next generation of ν experiments

Hyper-Kamiokande

S. Moriyama @ Neutrino'24



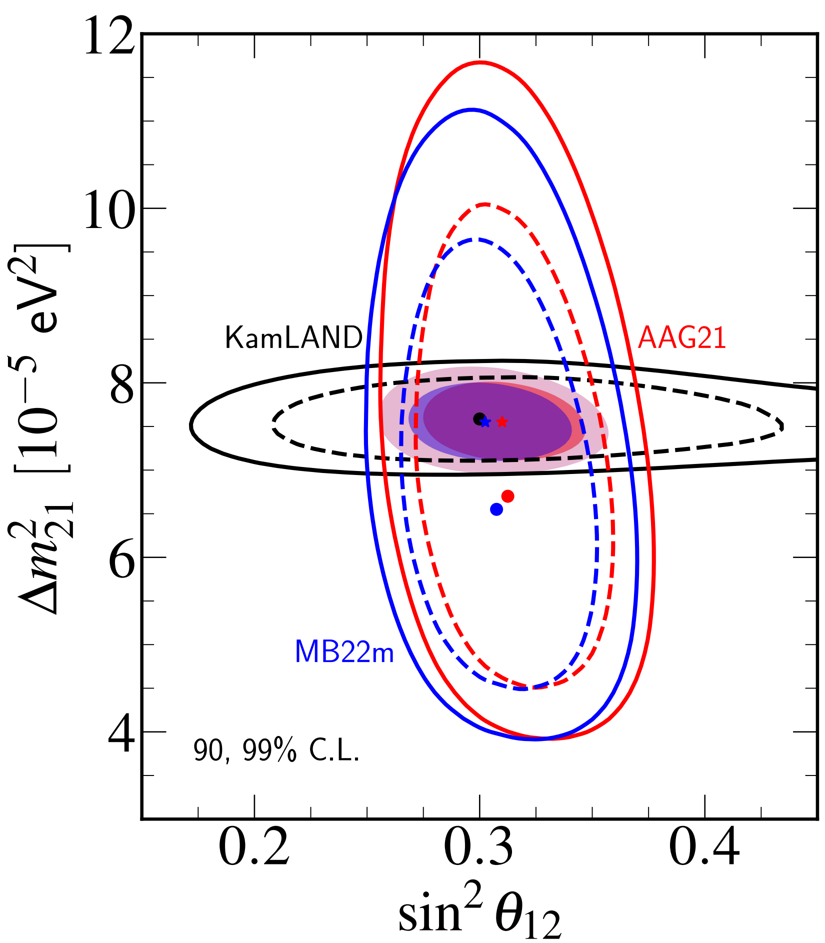


- >5σ CPV discovery for >60% of δ_{CP}
- 1σ resolution of δ_{CP} in 10 yrs: ~20° (~6°) for δ_{CP} = –90° (0°)

- >5σ sensitivity to mass ordering for all values of θ_{23} for NO

Tensions in global fits to 3ν oscillations ?

The solar-KamLAND Δm^2_{21} tension



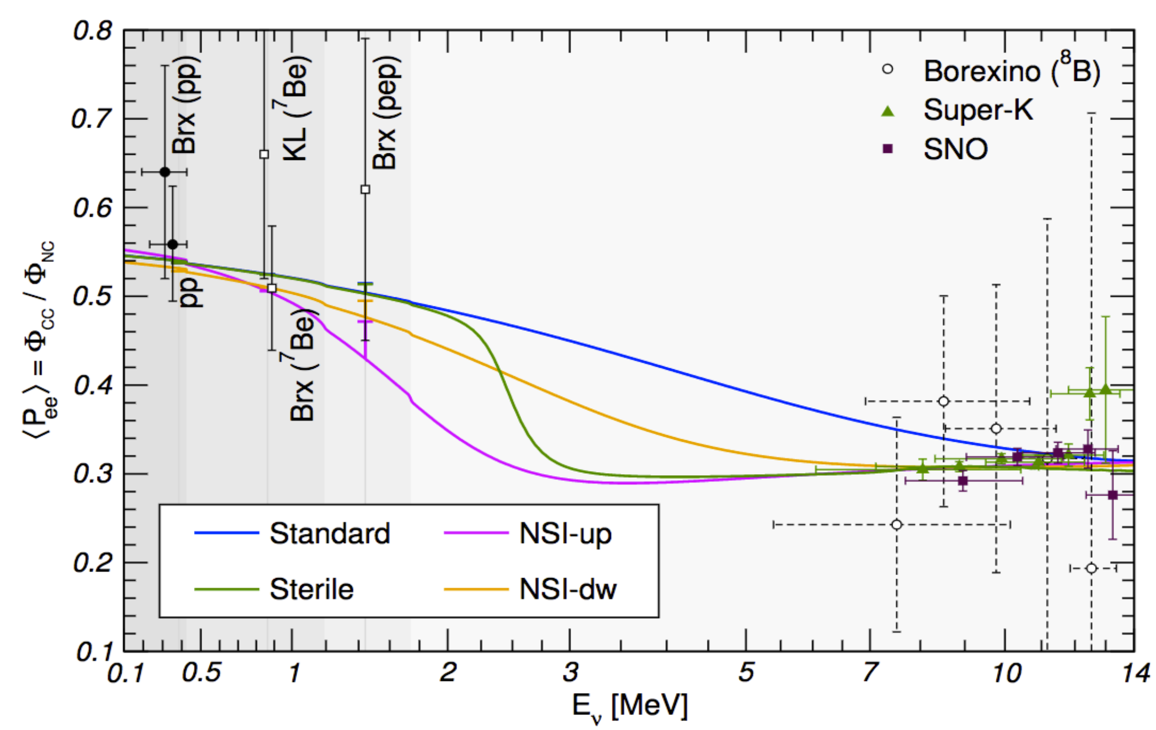
⇒ tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ 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

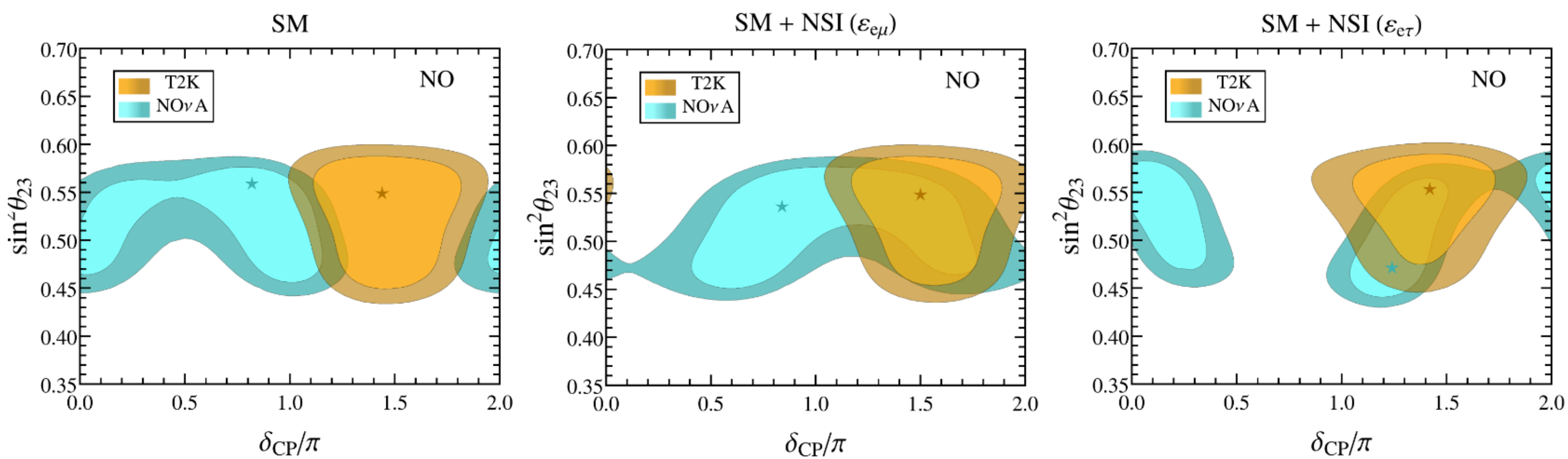


Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

The T2K-NOvA δ_{CP} tension

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

✦ Maximal CP-violating NSI couplings $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ of order ~ 0.1-0.2 may reconcile T2K and NOvA results.



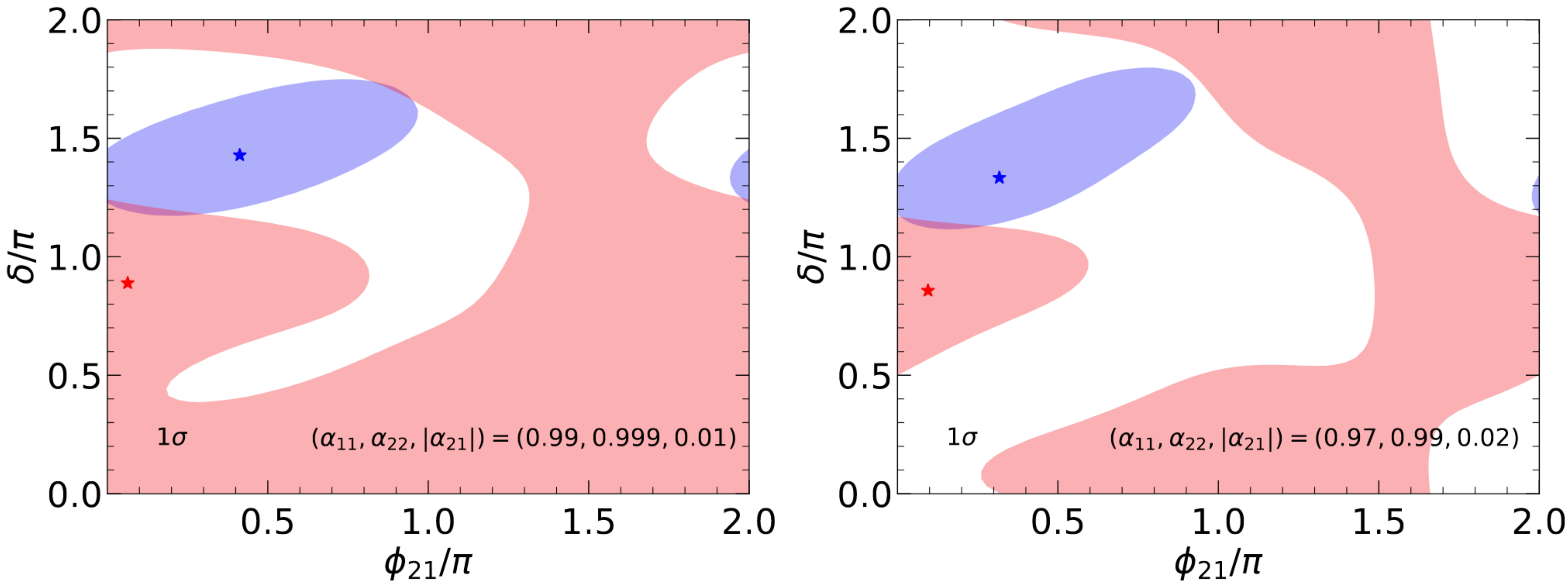
$|\varepsilon_{e\mu}| = 0.125$
$\varphi_{e\mu} = 1.35\pi$

$|\varepsilon_{e\tau}| = 0.22$
$\varphi_{e\tau} = 1.70\pi$

Chatterjee and Palazzo, arXiv:2409.10599
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 (ϕ_{21})
- The tension is not alleviated since the new phase affects equally T2K & NOvA

Summary

- Global fits to neutrino oscillations exploit complementarities of data sets to enhance the sensitivity of individual experiments, improving our knowledge of the three-neutrino oscillation picture.

- From the updated three-neutrino global fit:
  - ✓ precise determinations for most parameters (~ 1 - 5%)
  - ✓ slight preference for θ_{23} >45° - LO disfavoured by $\Delta\chi^2 \geq 2.0$ (2.9) for NO (IO)
  - ✓ normal ordering preferred over IO with $\Delta\chi^2 = 7.7$ (3.1) w SK (w/o SK)
  - ✓ $\delta_{BF} = 1.12\pi$ (1.5π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.3σ (6.8σ) for NO (IO)

- In the near future, global fits (JUNO+) will be useful to enhance sensitivities.

- Next generation experiments (DUNE, HyperK) will provide sensitivities above 3σ for CPV and mass ordering

- Tensions among datasets revealed by global fits might point to the existence of new physics BSM.