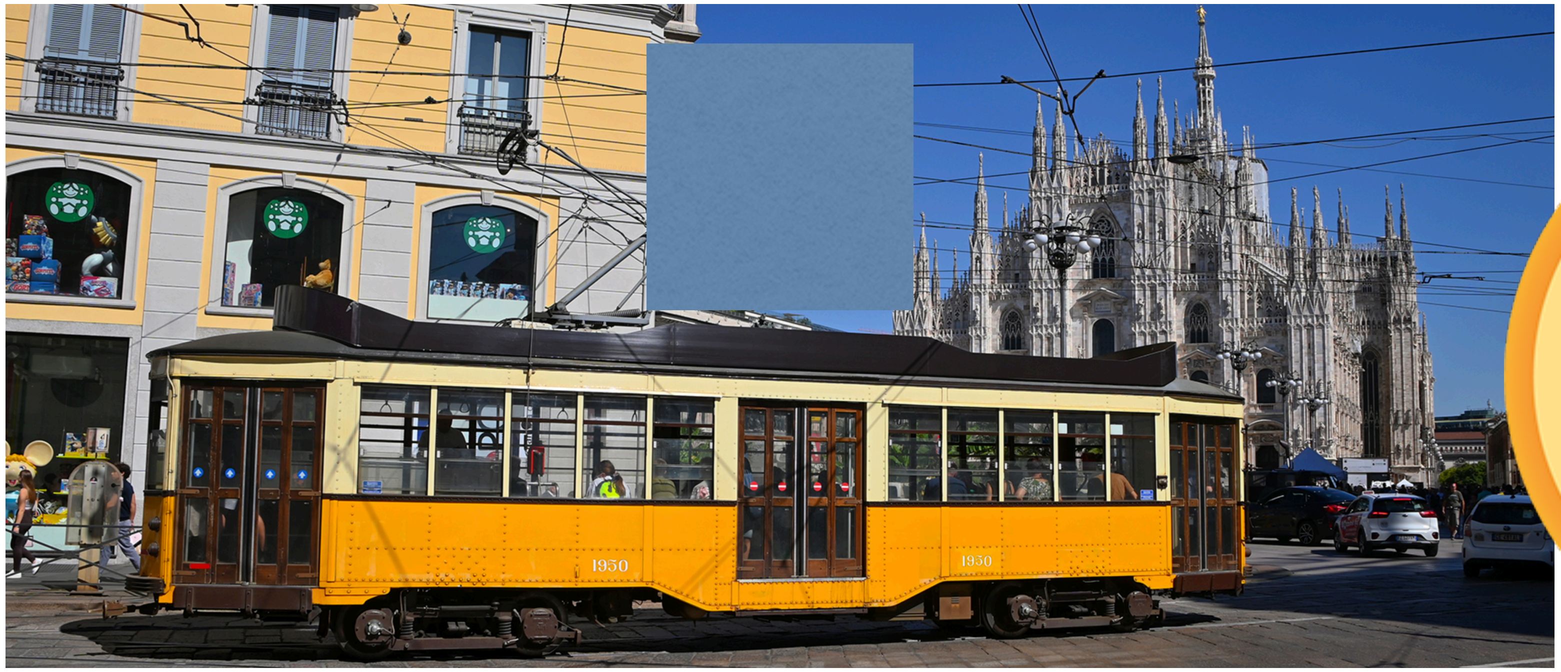
Global analysis of three-neutrino oscillations

Mariam Tórtola
IFIC, CSIC/Universitat de València



XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024 Milan, Italy

Current global analysis of three-neutrino oscillations

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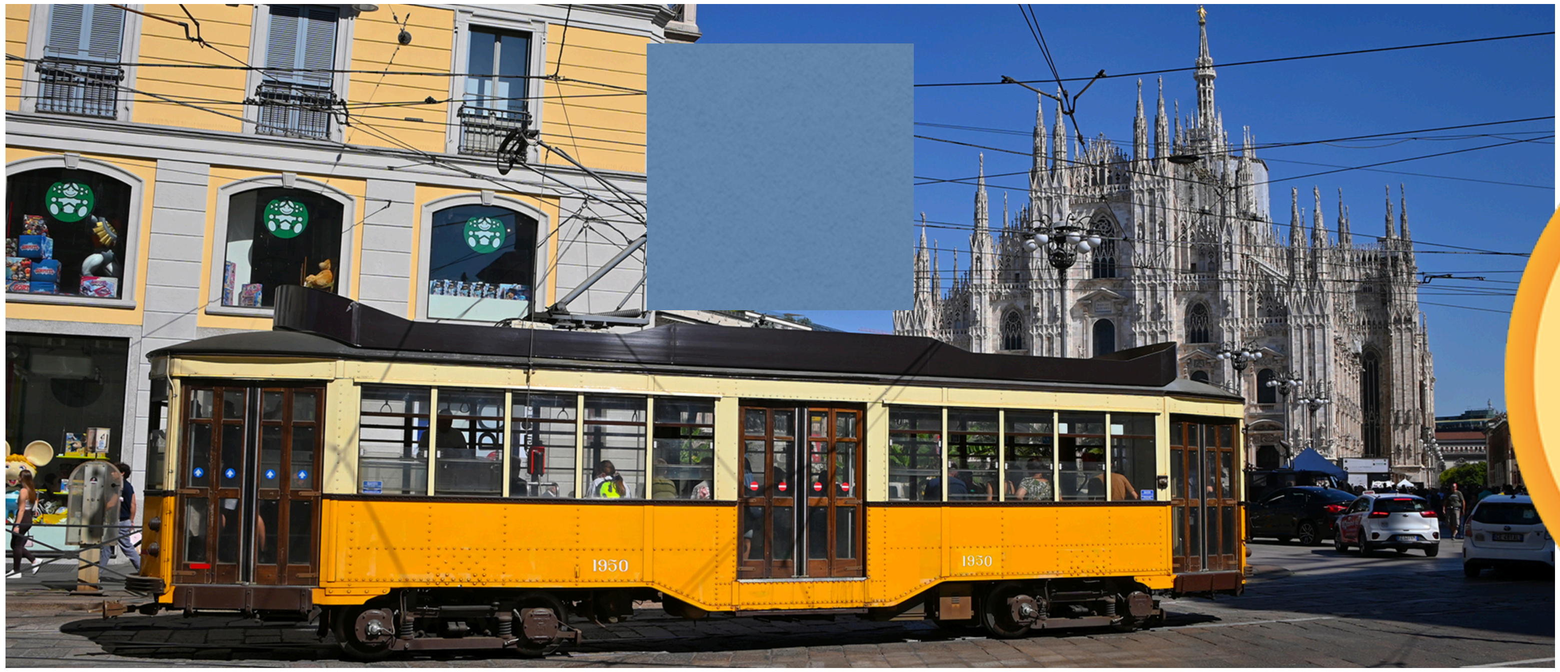

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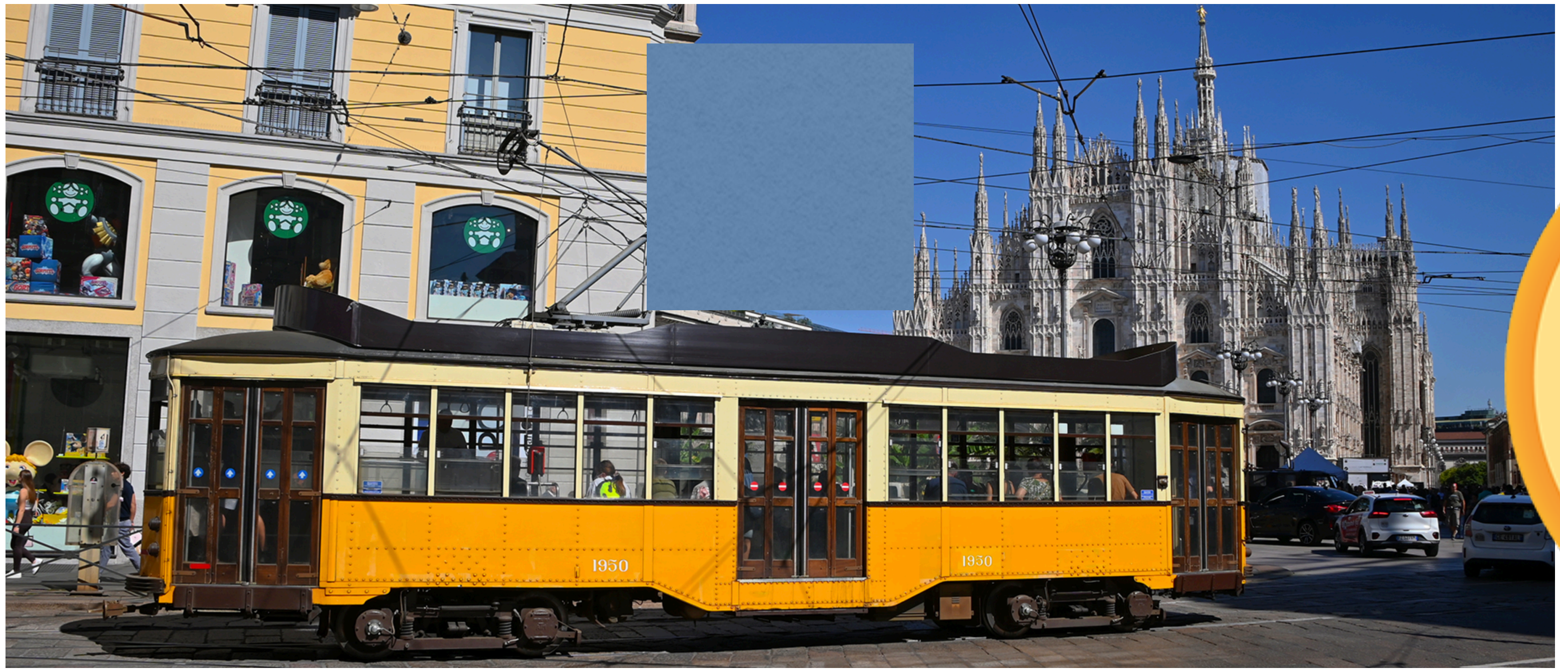

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GENERALITAT VALENCIANA
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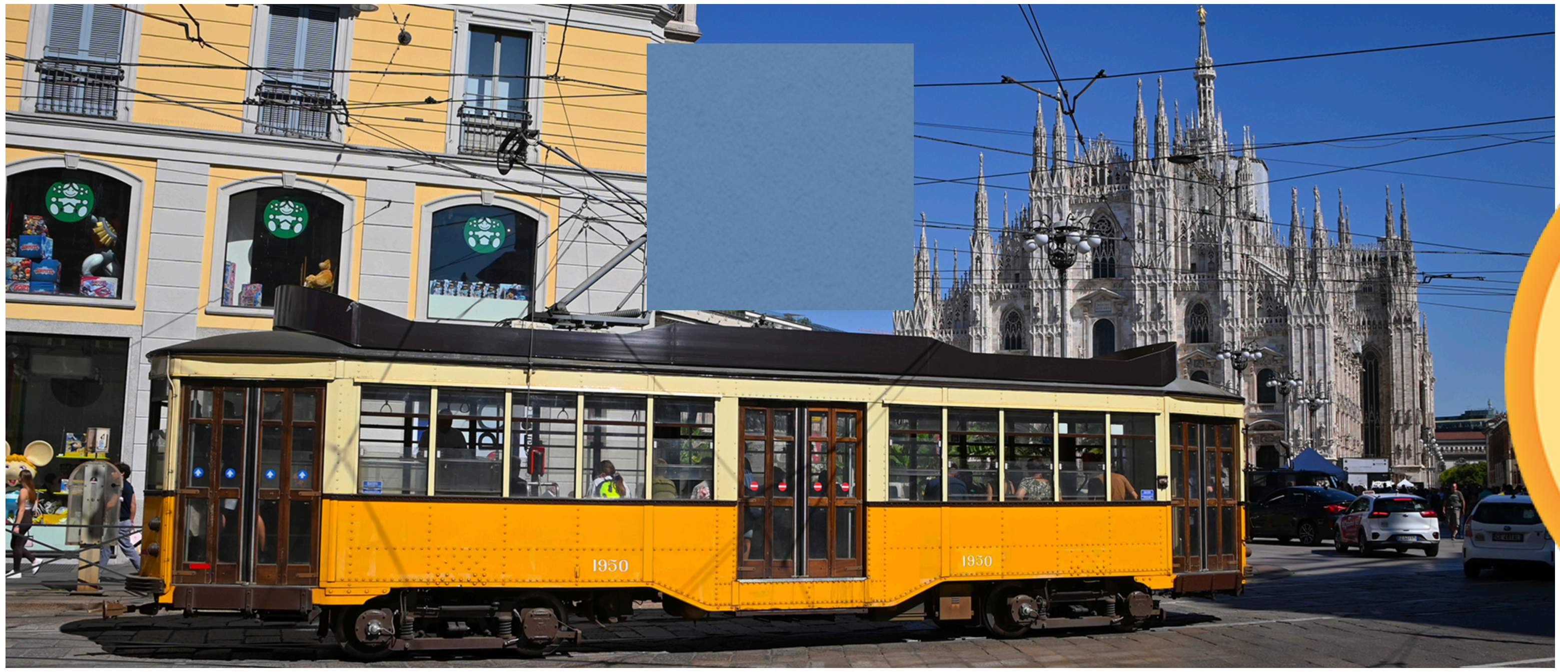

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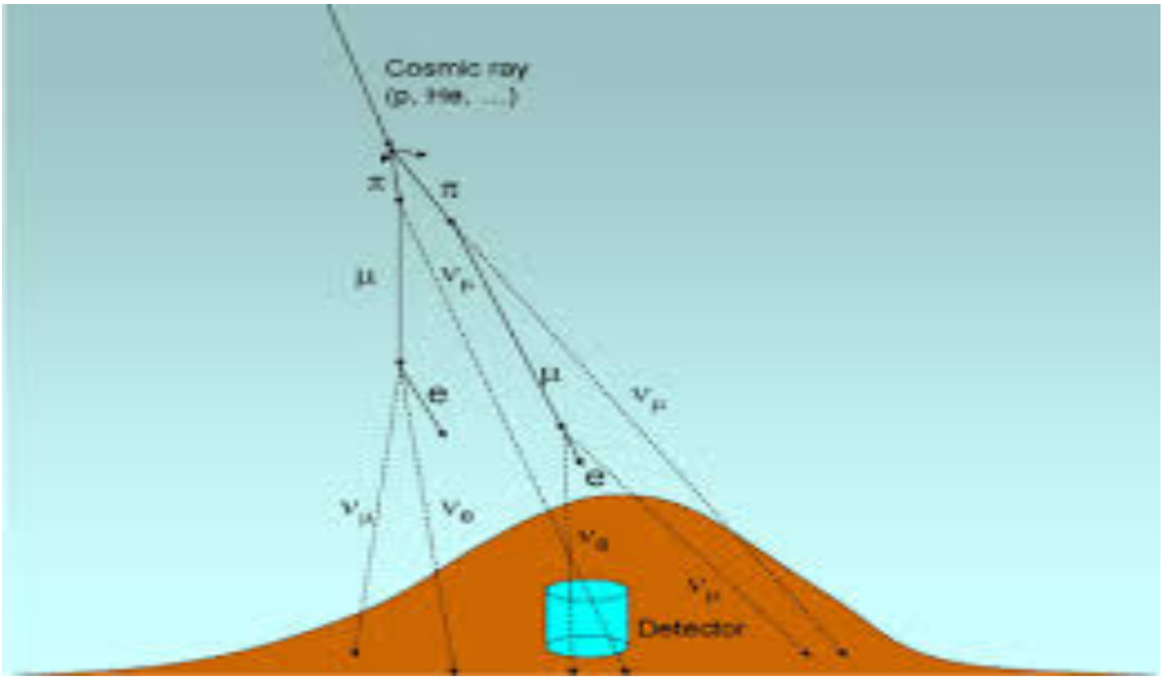
Neutrinos oscillate

© Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrino oscillations

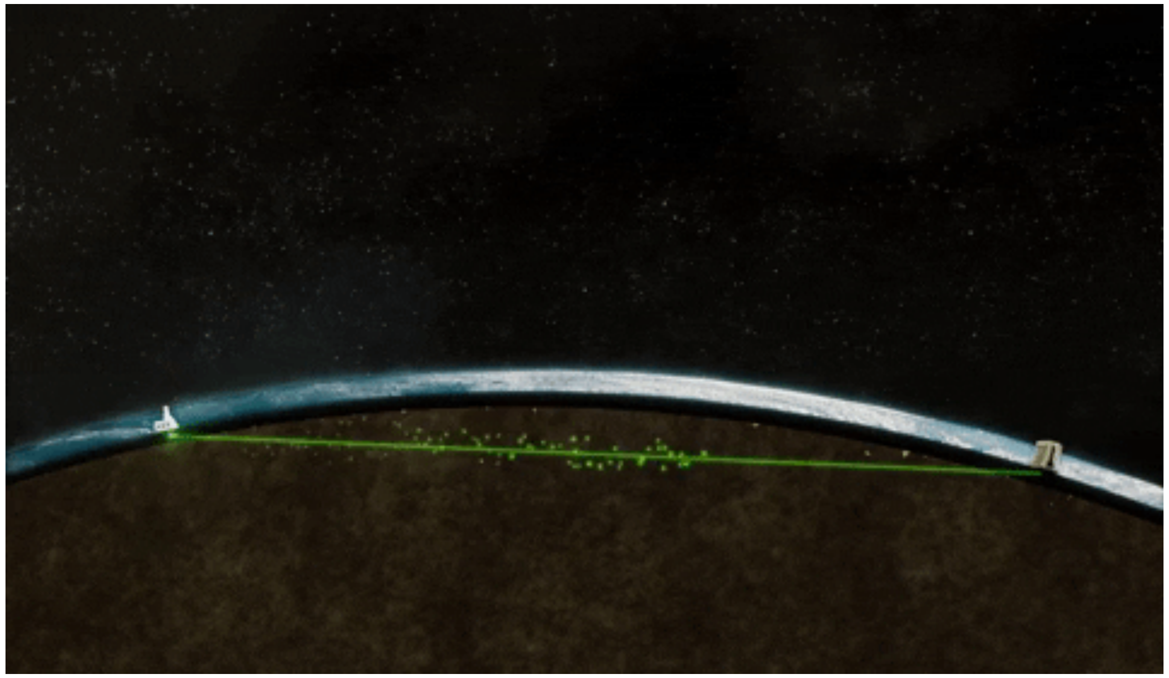
Solar neutrinos

Atmospheric neutrinos



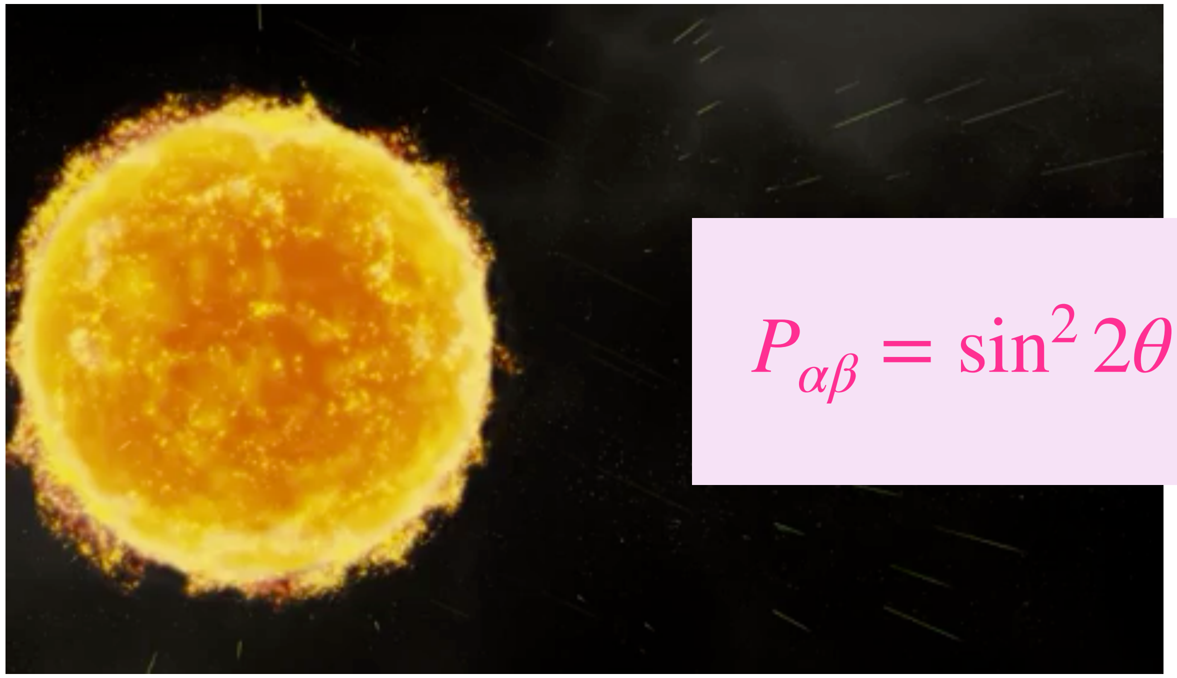
Reactor neutrinos

Accelerator neutrinos

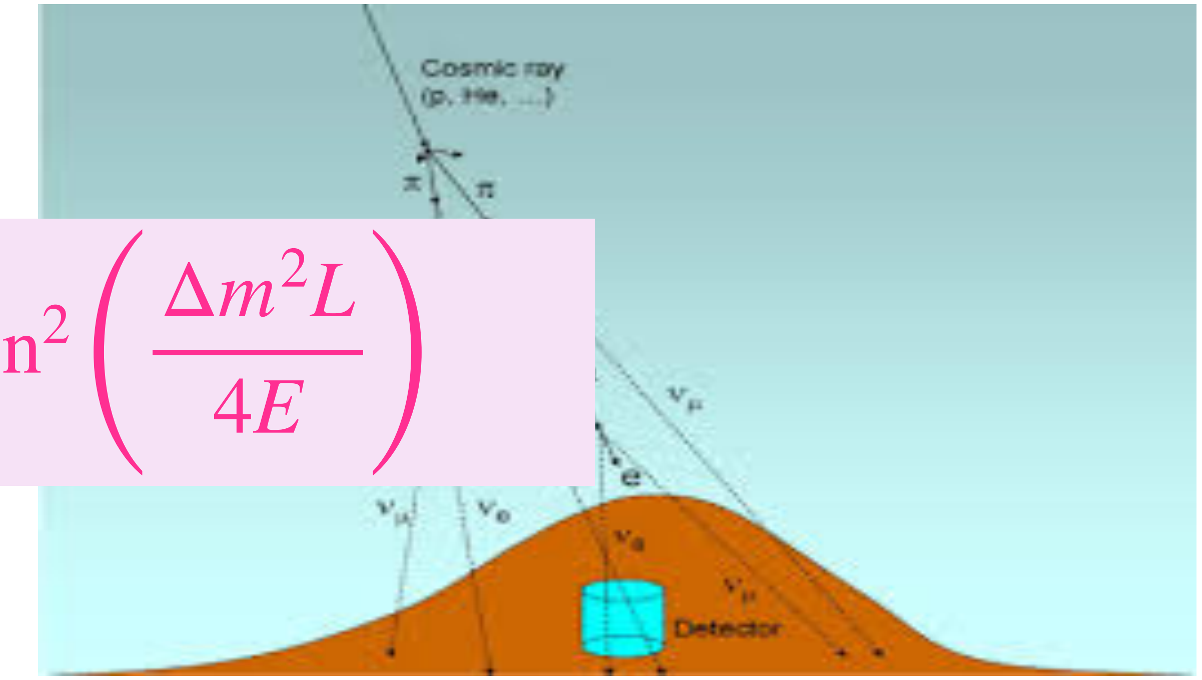


Neutrino oscillations

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



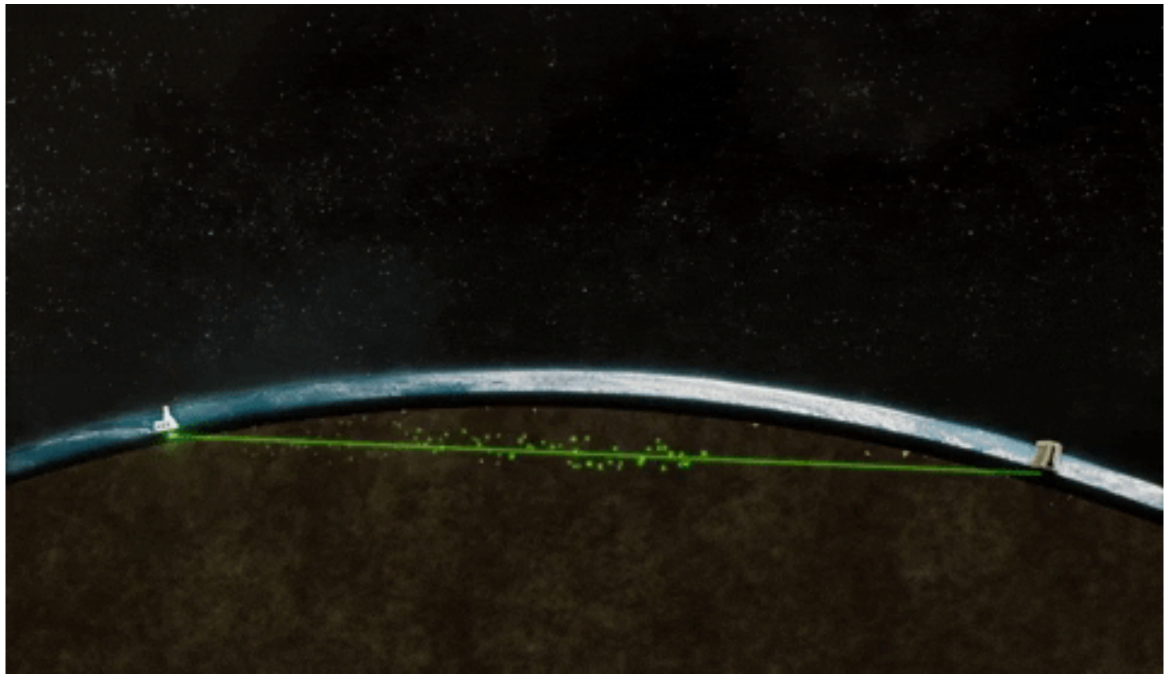
Atmospheric sector: $\theta_{23}, \Delta m^2_{31}$



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

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

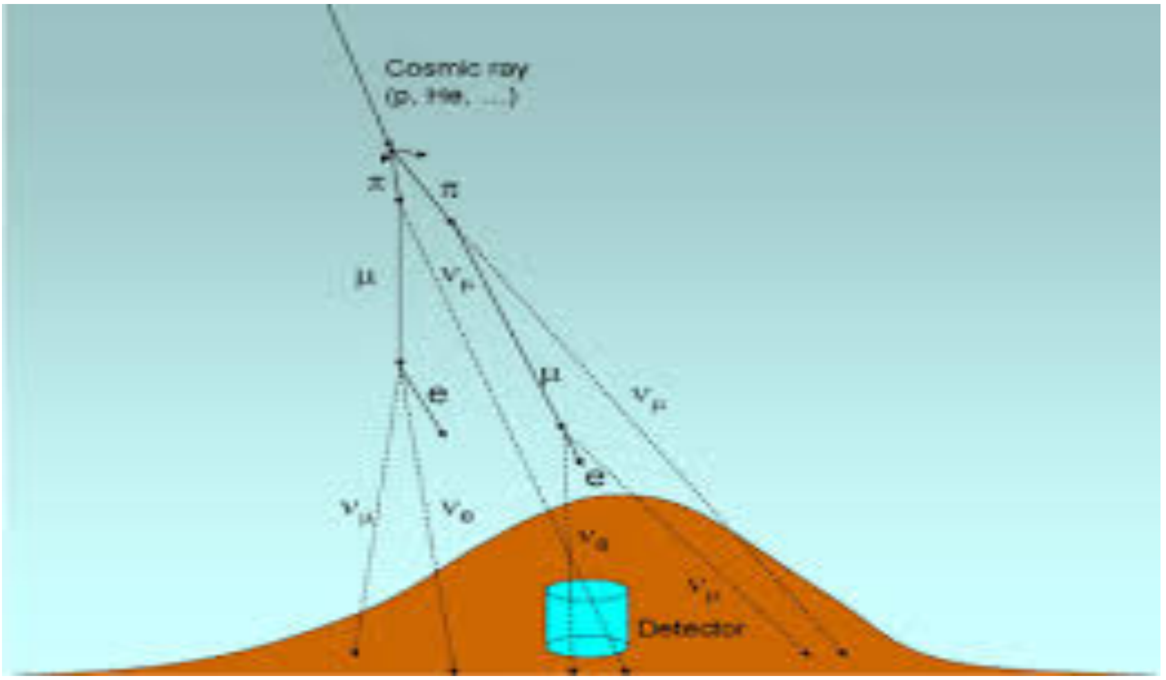
Accelerator sector: $\theta_{23}, \Delta m^2_{31}$



Neutrino oscillations

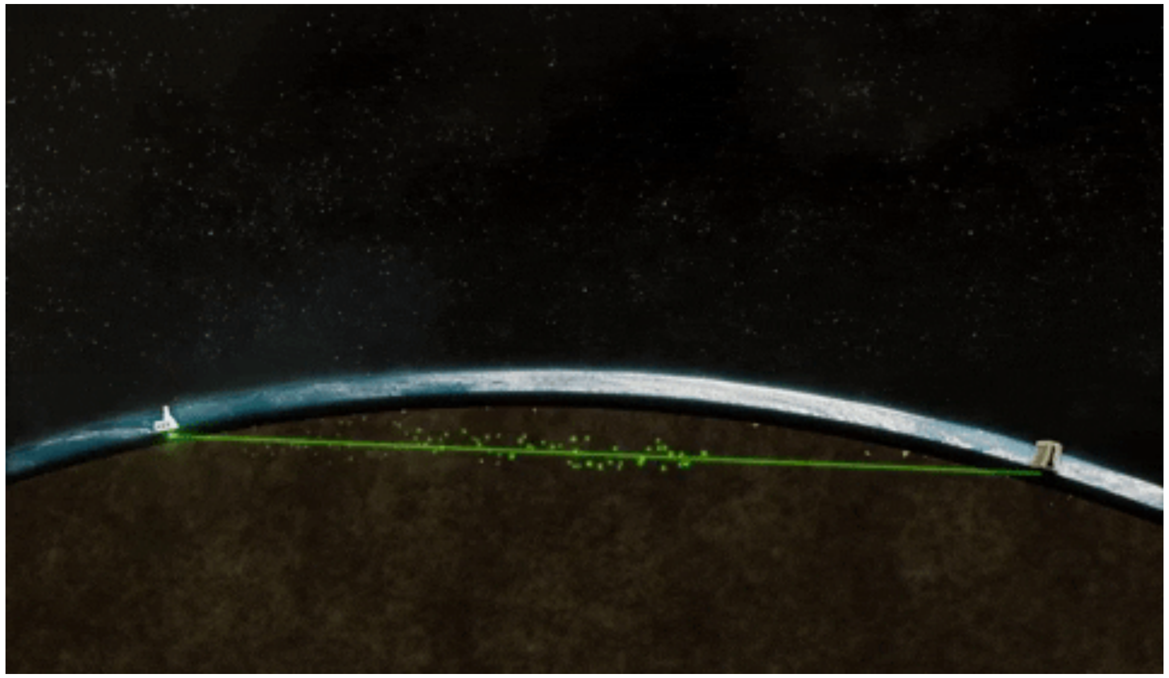
Solar sector: θ_{12}, θ_{13}, Δm^2_{21}

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



Reactor sector: θ_{13}, Δm^2_{31}

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



The three-flavour ν picture

neutrino mixing

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

neutrino mass spectrum

✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}

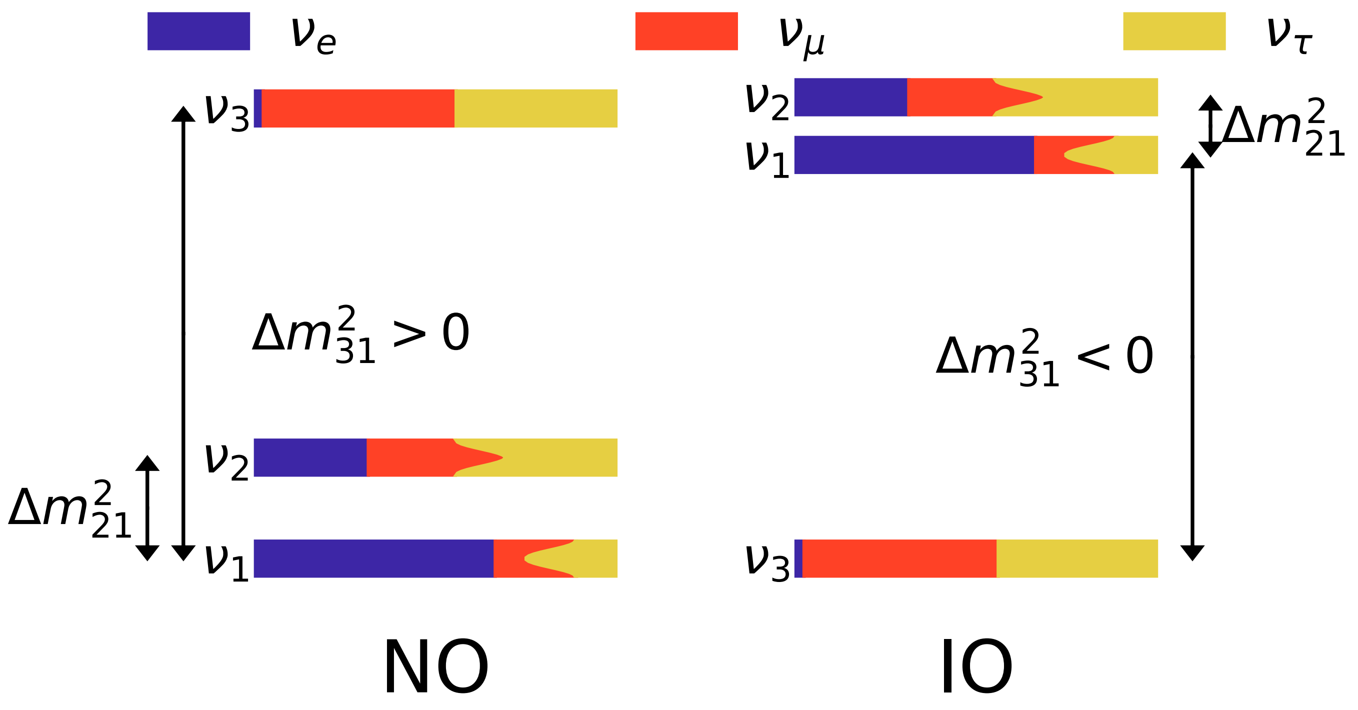
✓ 3 CP phases: 1 Dirac + 2 Majorana

✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

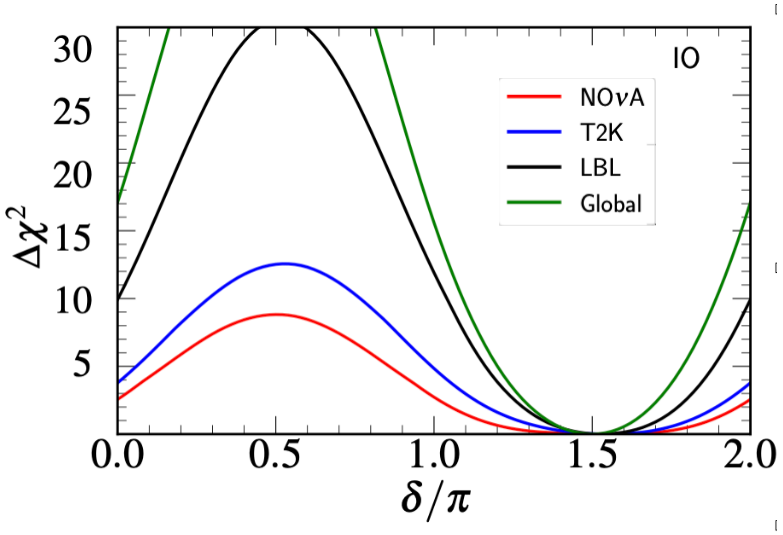


Why a global analysis?

1

Compensate low statistics in subleading oscillation effects searches

Ex: enhance sensitivity to MO and CP violation



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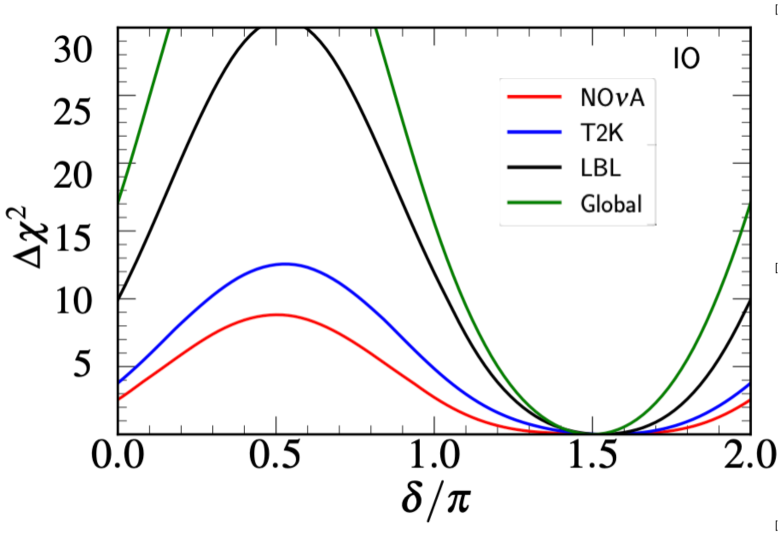

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Exploit synergies among experiments

Ex: solar params before KamLAND

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

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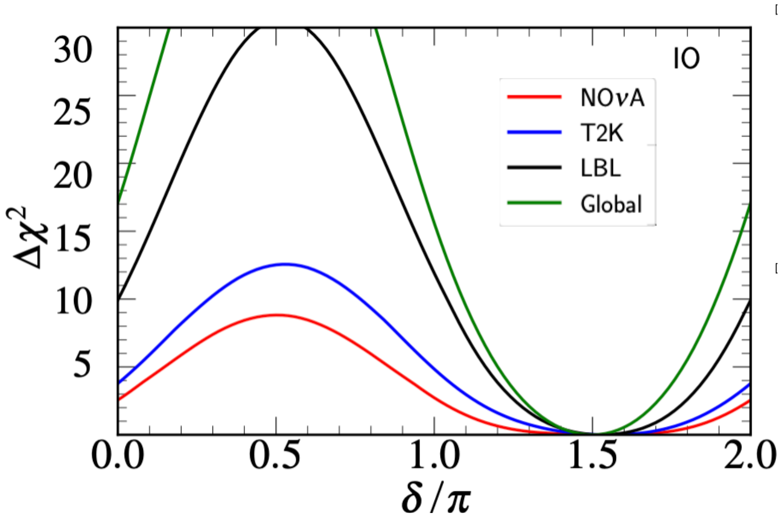

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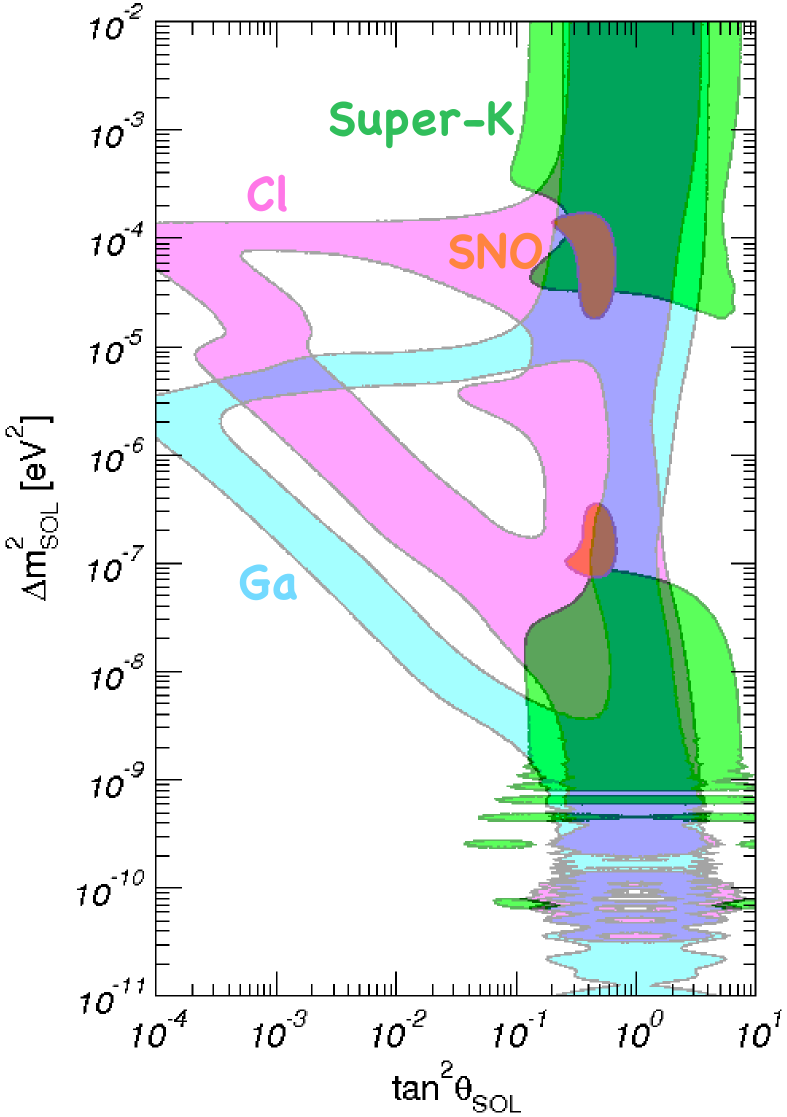

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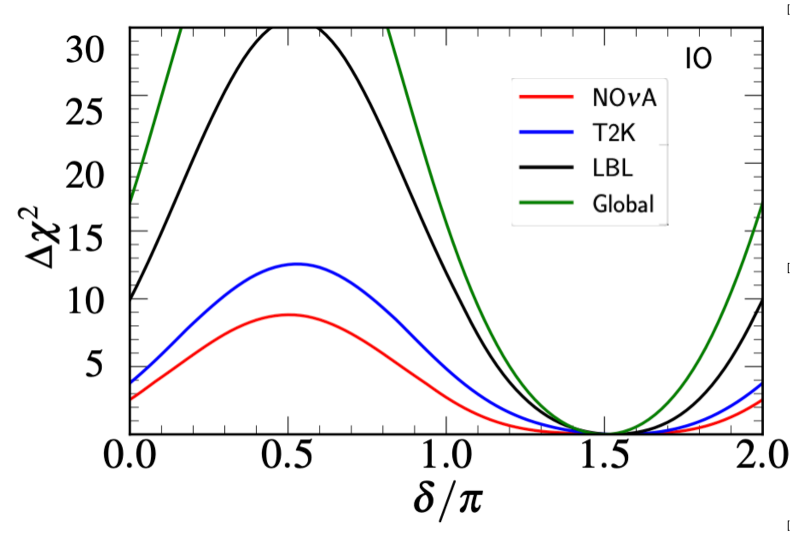

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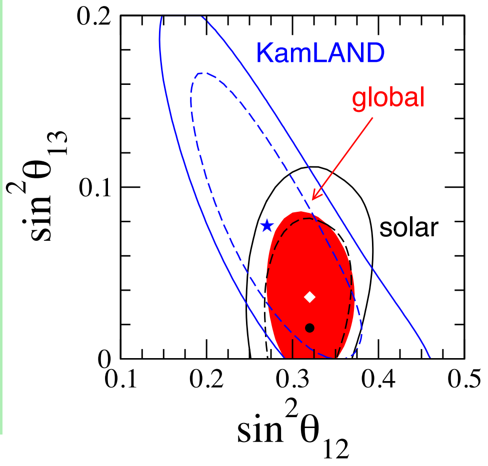

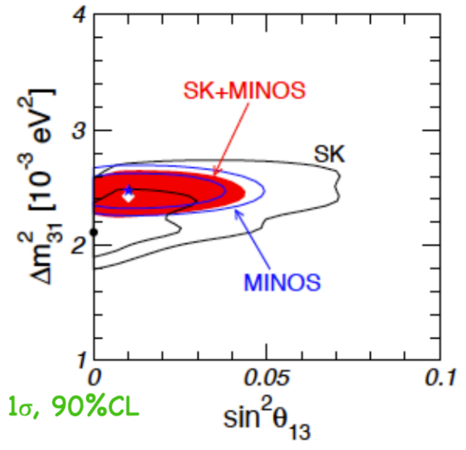

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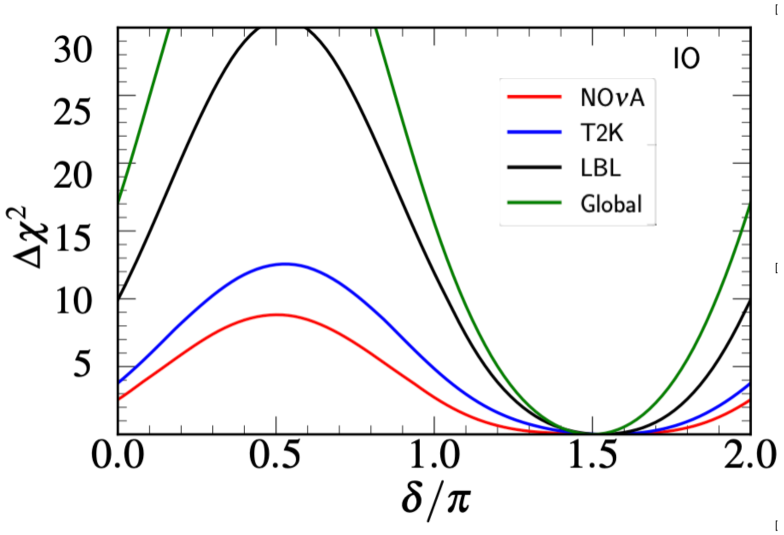

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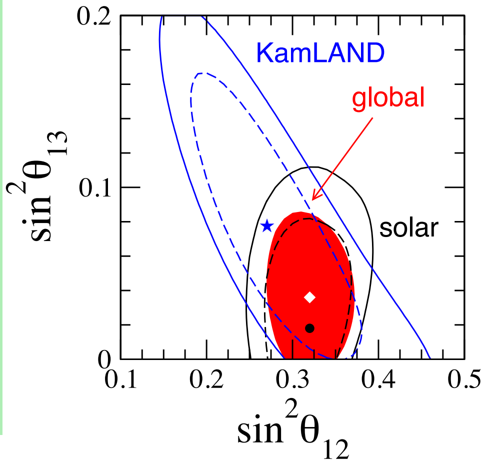

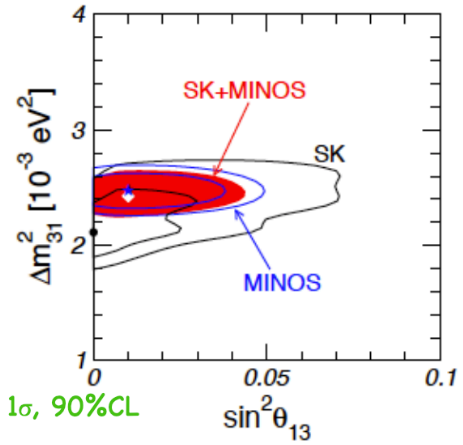

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Ex: Δm^2_{21} measurement in solar and KamLAND

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

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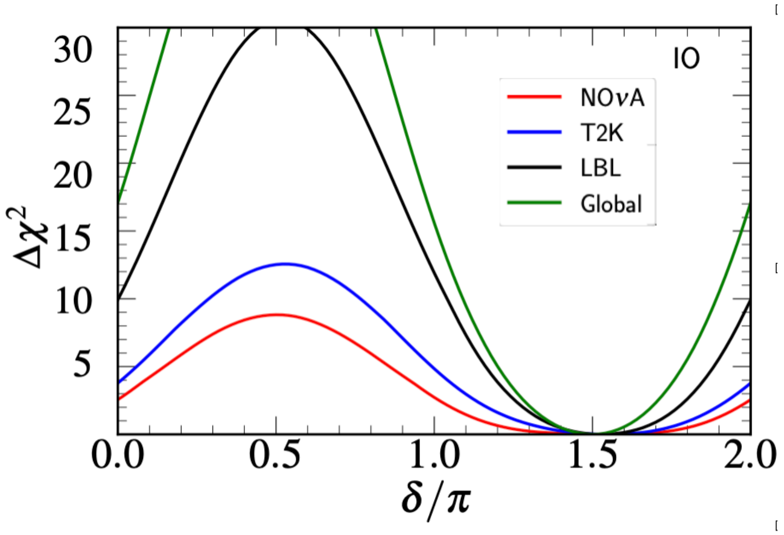

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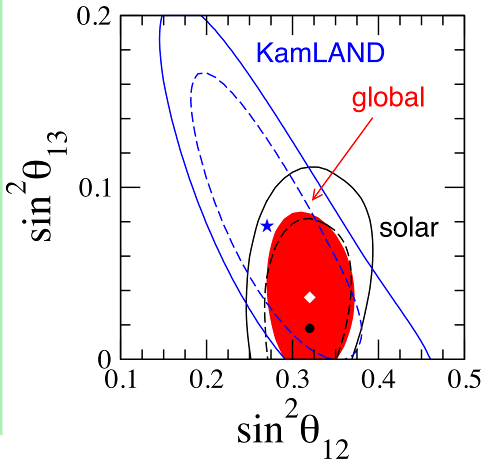

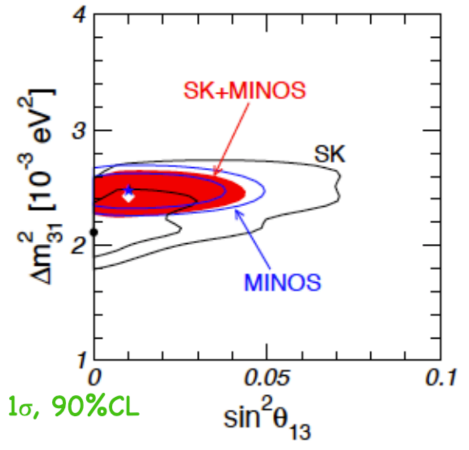

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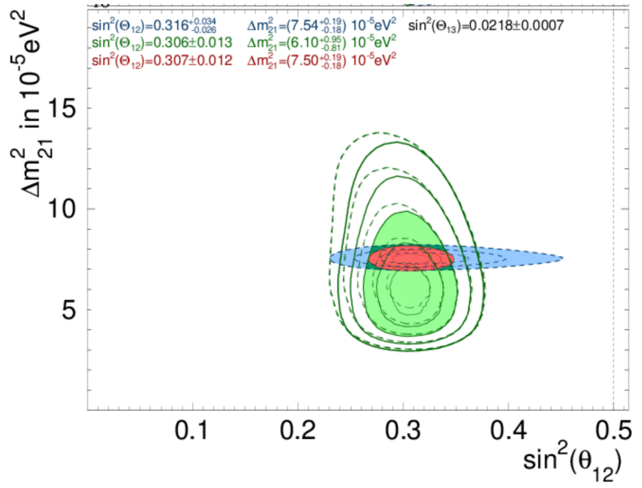

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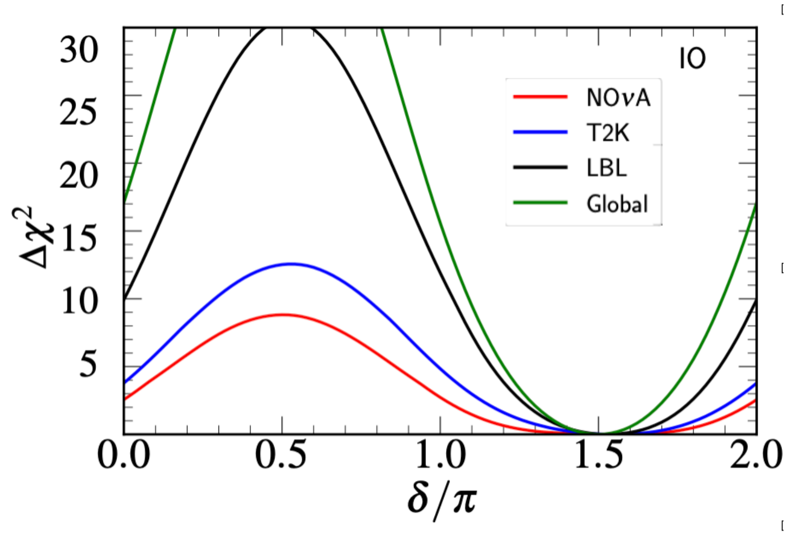

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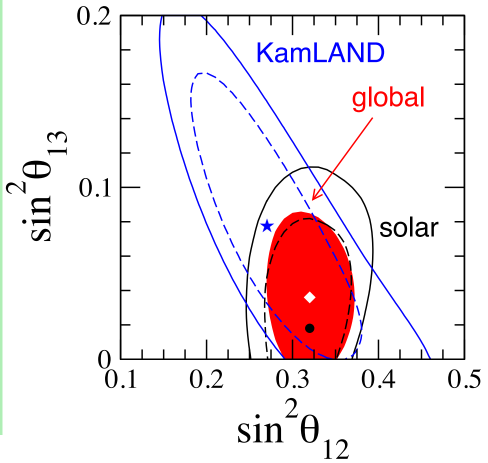

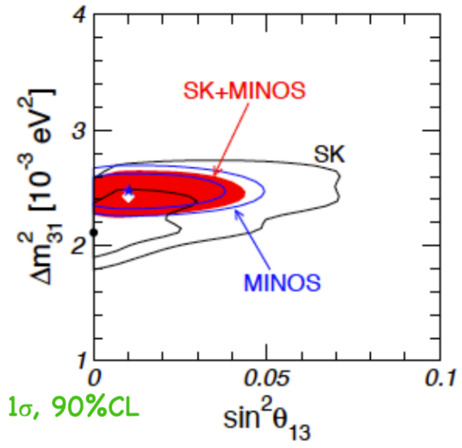

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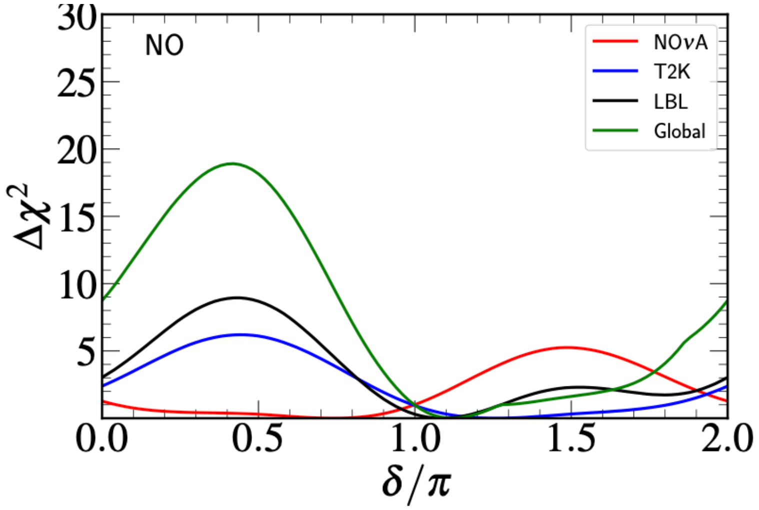
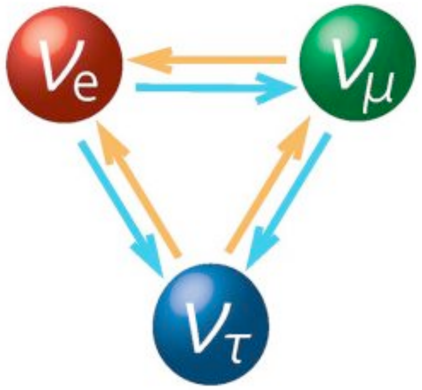


Three-neutrino global fits



Bari

Capozzi et al, PRD 104 (2021) 083031

NuFIT

Esteban et al, JHEP 09 (2020) 178
NuFIT 5.3 (2024) www.nu-fit.org

Valencia

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

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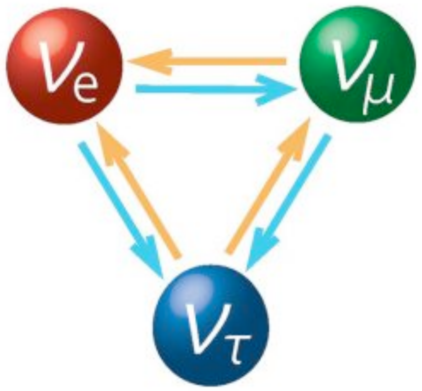

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Capozzi et al, PRD 104 (2021) 083031

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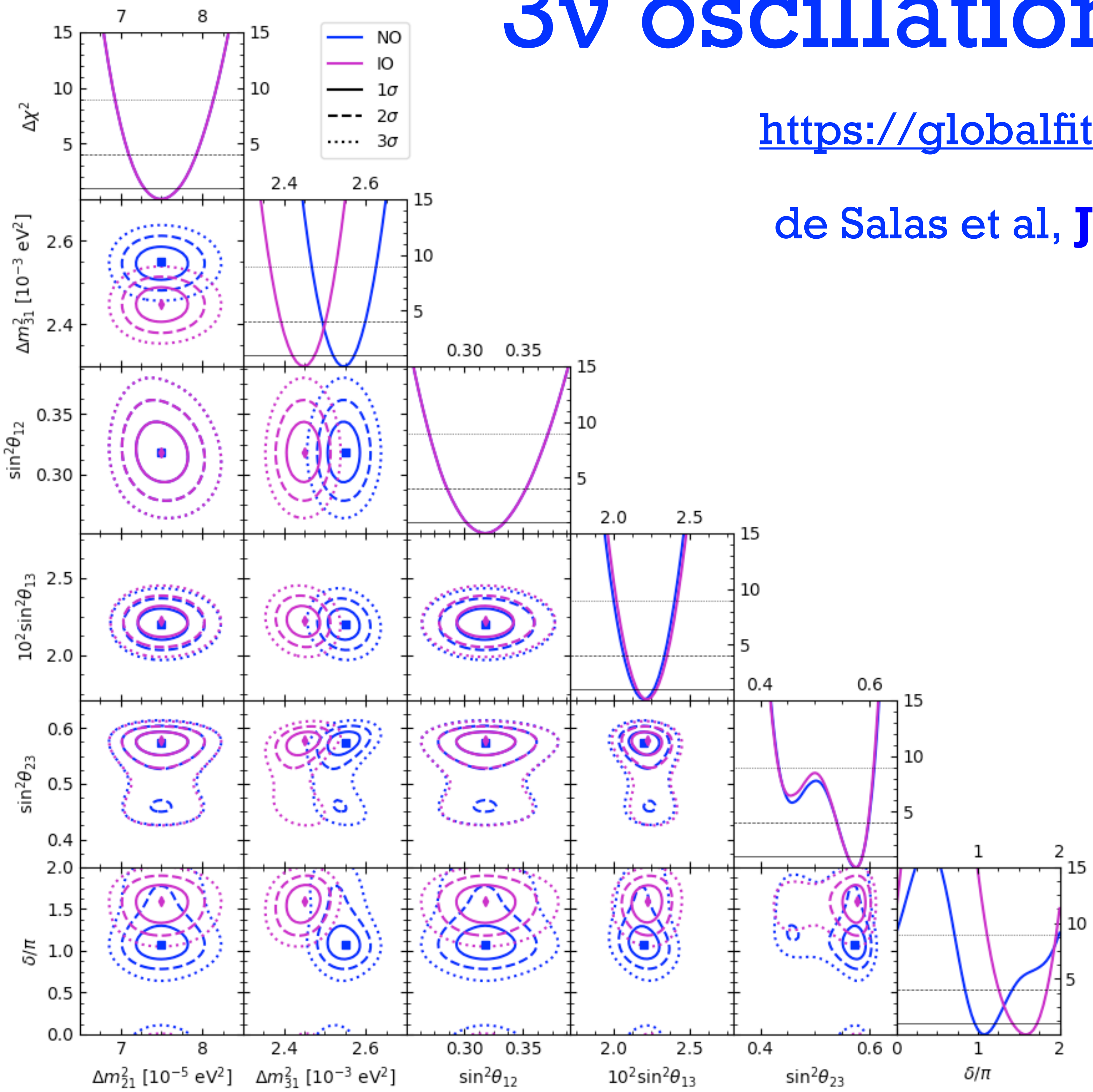
3ν oscillations global fit

https://globalfit.astroparticles.es/

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



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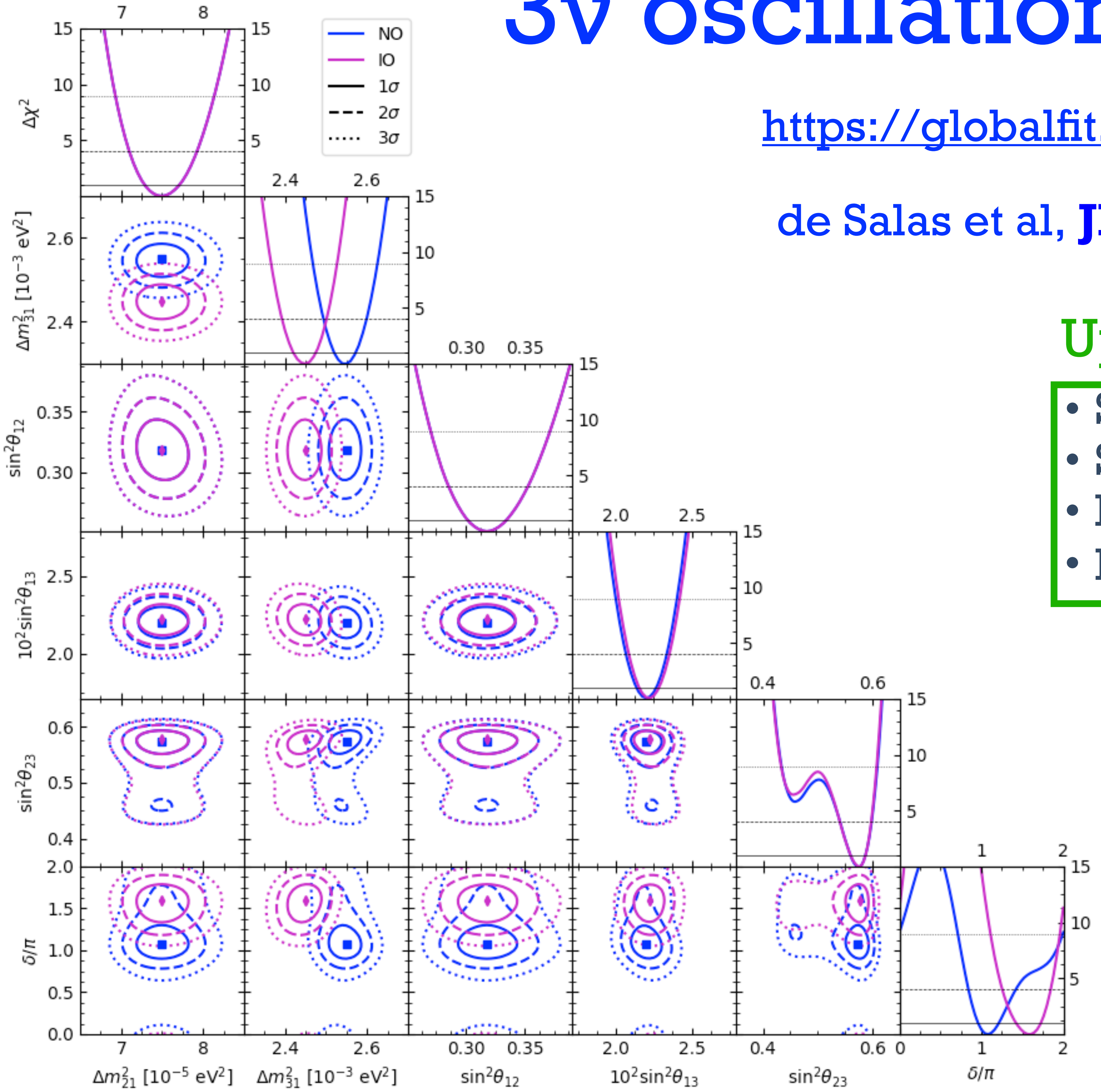


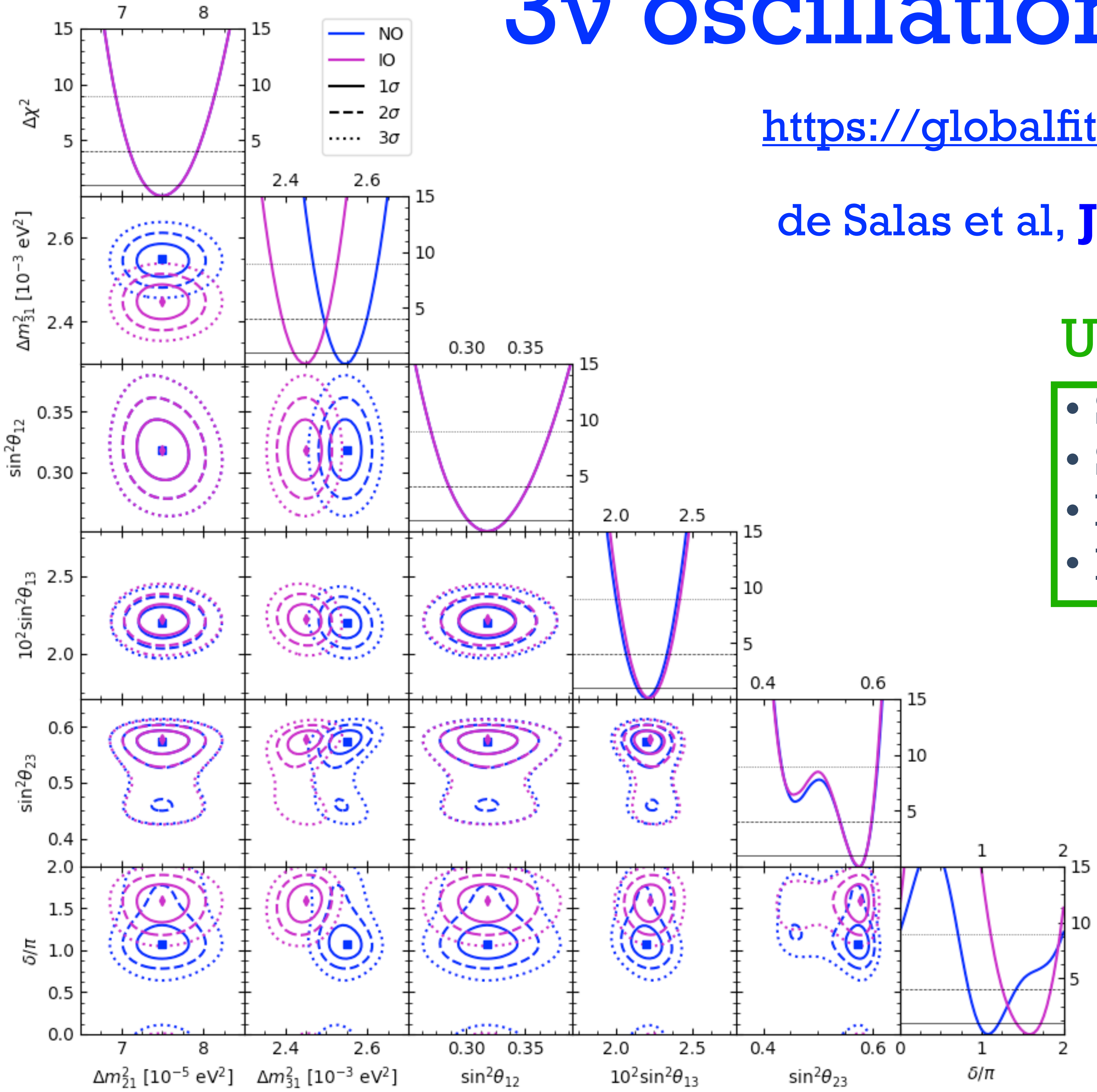
https://globalfit.astroparticles.es/

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

Updated here with…

- SSM B23 / SF-III
- SK-IV solar data
- Daya Bay full dataset
- Full SK I-V atmos χ^2 tables

3ν oscillations global fit



https://globalfit.astroparticles.es/

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

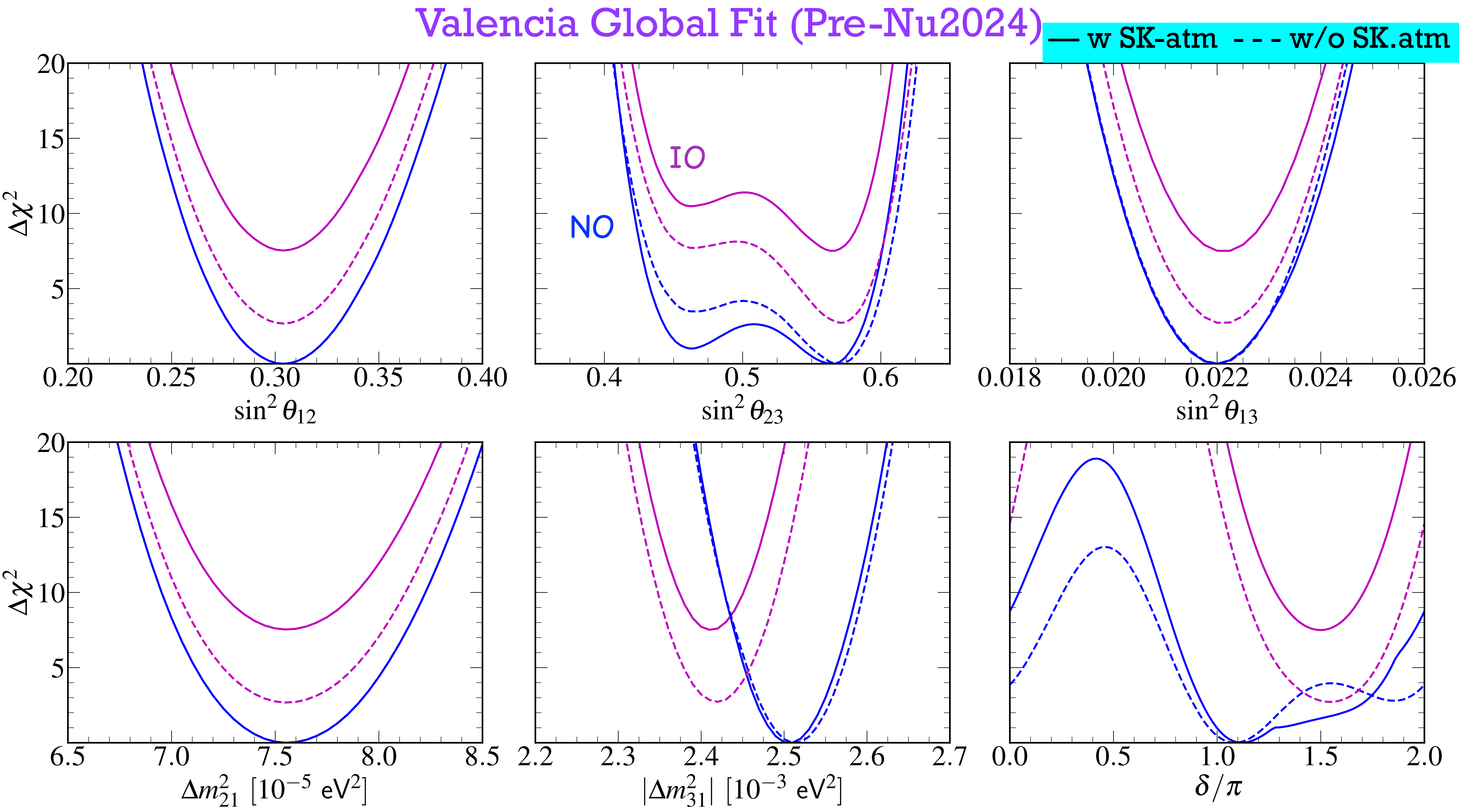
Updated here with…

- SSM B23 / SF-III
- SK-IV solar data
- Daya Bay full dataset
- Full SK I-V atmos χ^2 tables

Not included…

- Latest DeepCore results
- 10yr NOvA results
- + Nu'24

Global fit to ν oscillation parameters

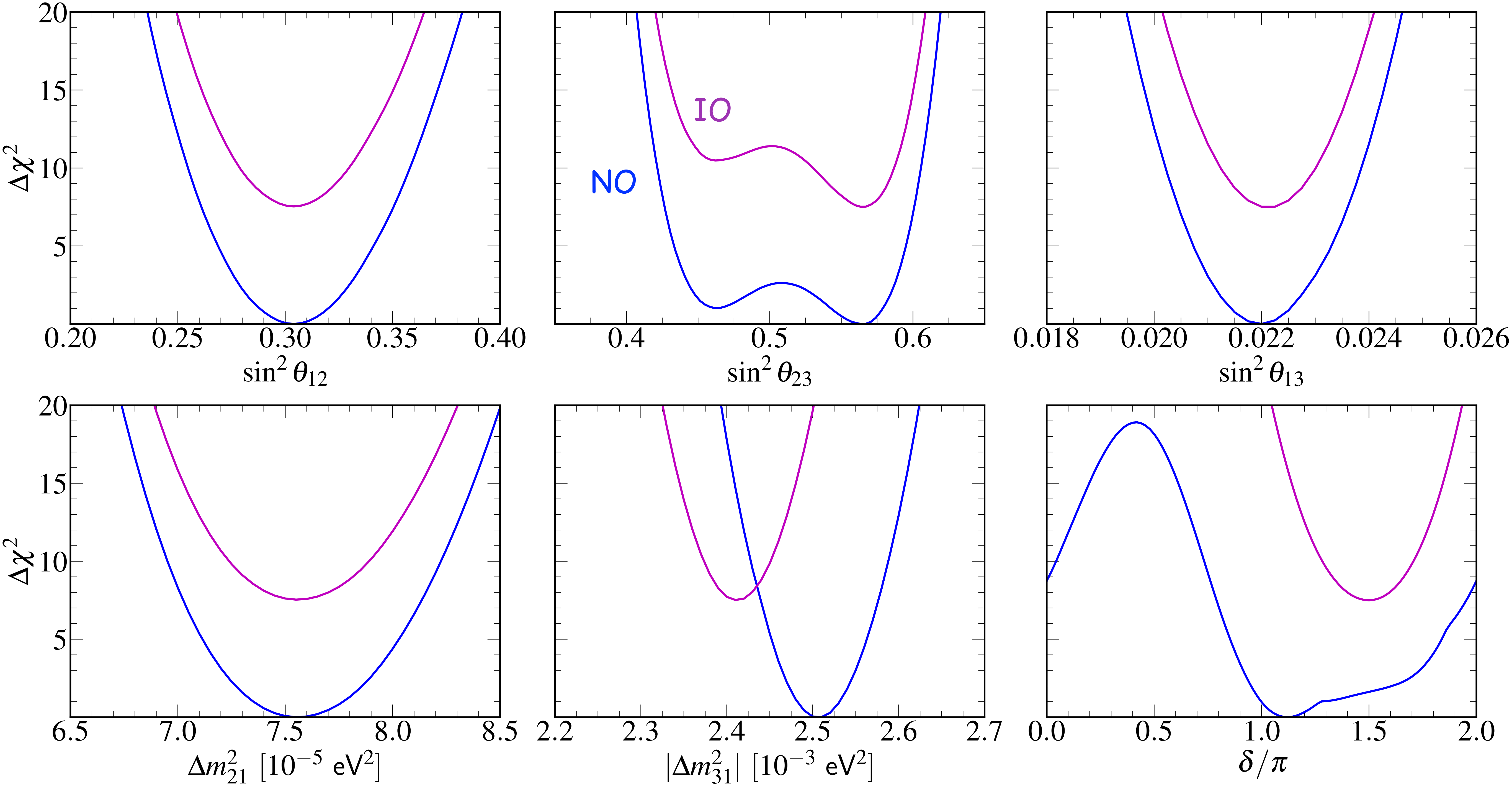


SSM HZ model - MB22m

$\Delta\chi^2$(IO-NO) = 7.5 w SK-atm $\Delta\chi^2$(IO-NO) = 2.7 w/o SK-atm

Global fit to ν oscillation parameters

Valencia Global Fit (Pre-Nu2024)



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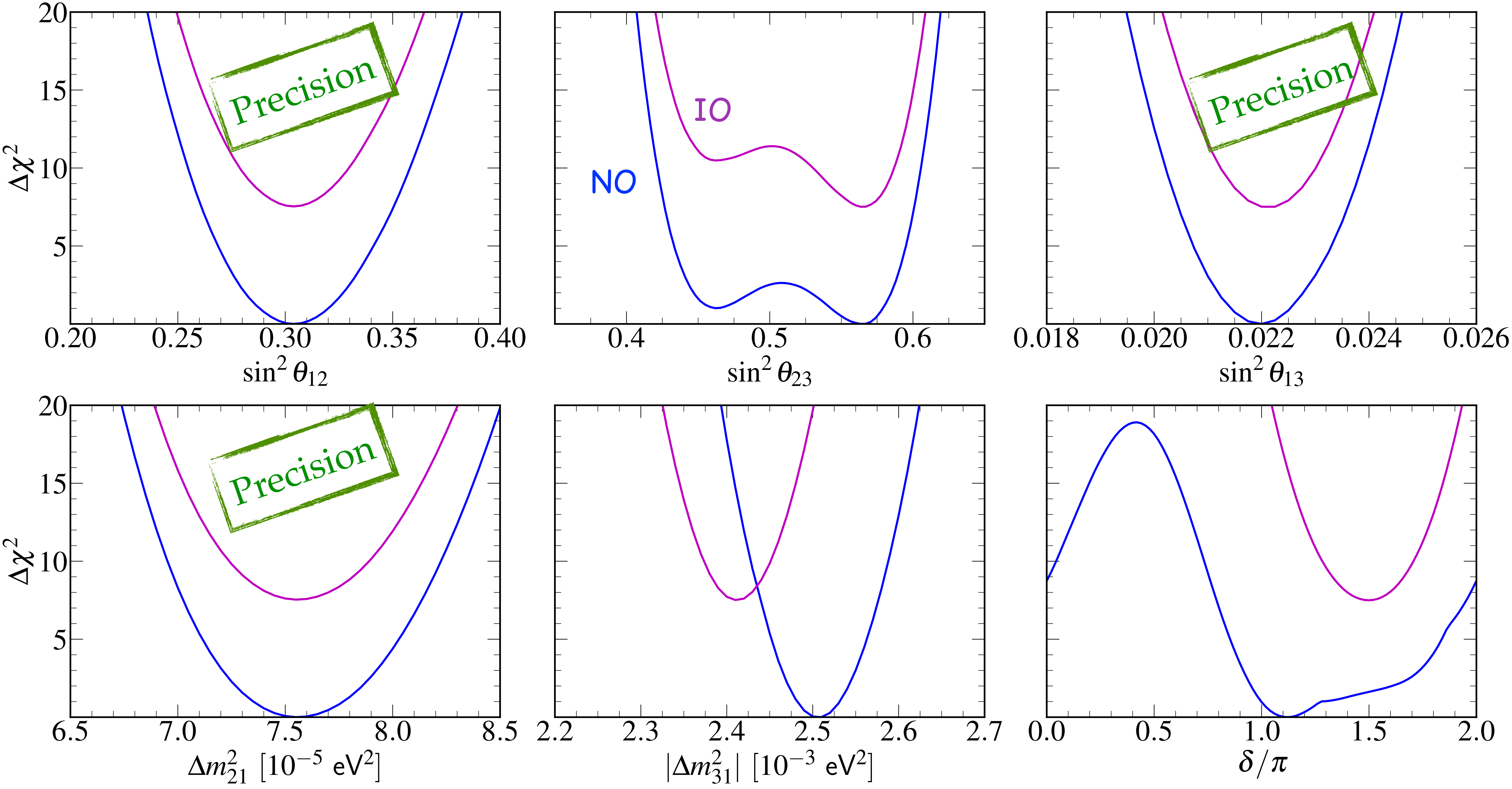

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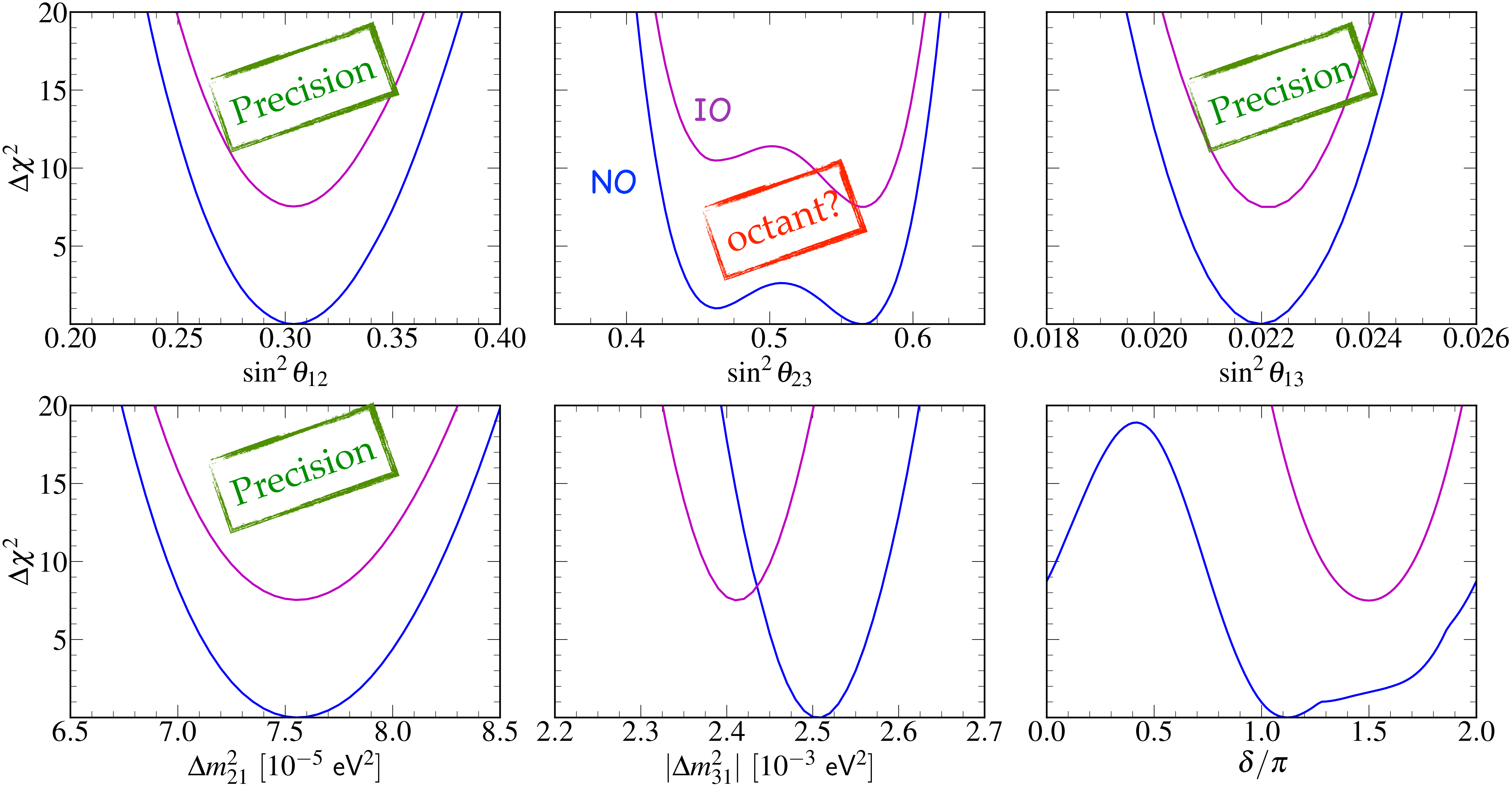

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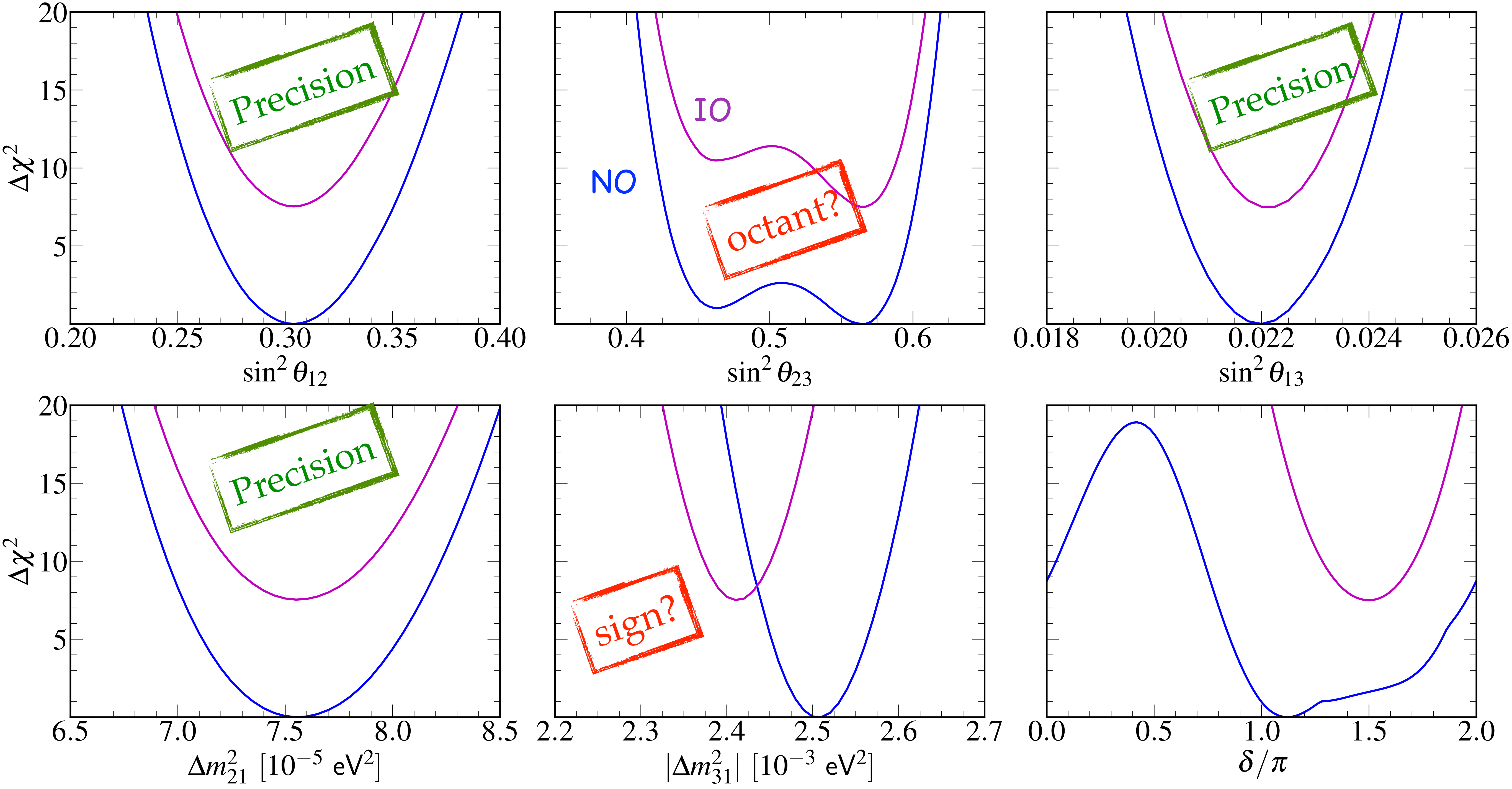

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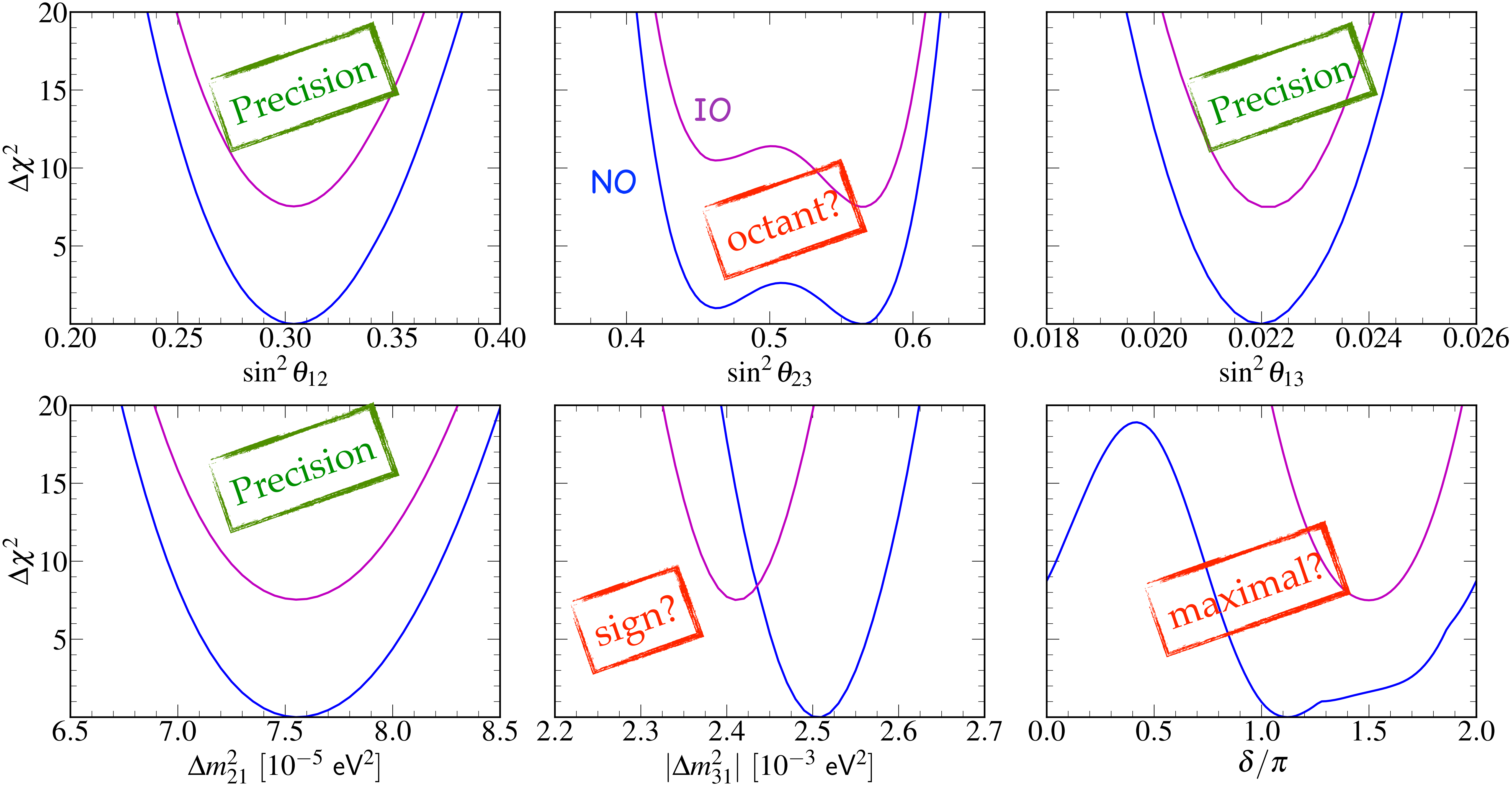

SSM HZ model - MB22m

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$\Delta\chi^2$(IO-NO) = 7.5

Global fit to ν oscillation parameters

Valencia Global Fit (Pre-Nu2024)

parameter	best fit $\pm$ 1σ	3σ range	relative 1σ uncert	
Δm^2_{21} $[10^{-5}\text{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	**2.7 %**	
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	**1.0 %**	mass ordering?
$\|\Delta m^2_{31}\|$ $[10^{-3}\text{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34-2.49		
$\sin^2\theta_{12}/10^{-1}$	$3.04^{\pm}0.16$	2.57–3.55	**5.4%**	
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	**3-4%**	octant?
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03		
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	**2.6%**	
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38		
δ/π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	**10-15%**	maximal CP violation??
δ/π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87		

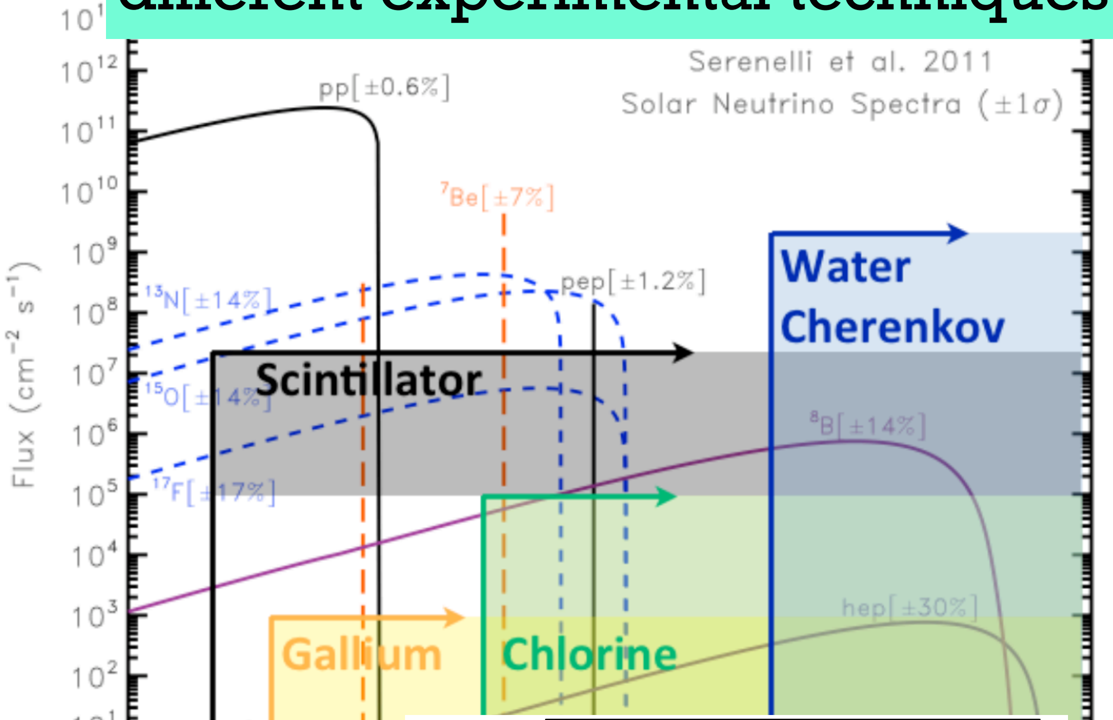
SSM HZ model - MB22m

with SK atmospheric

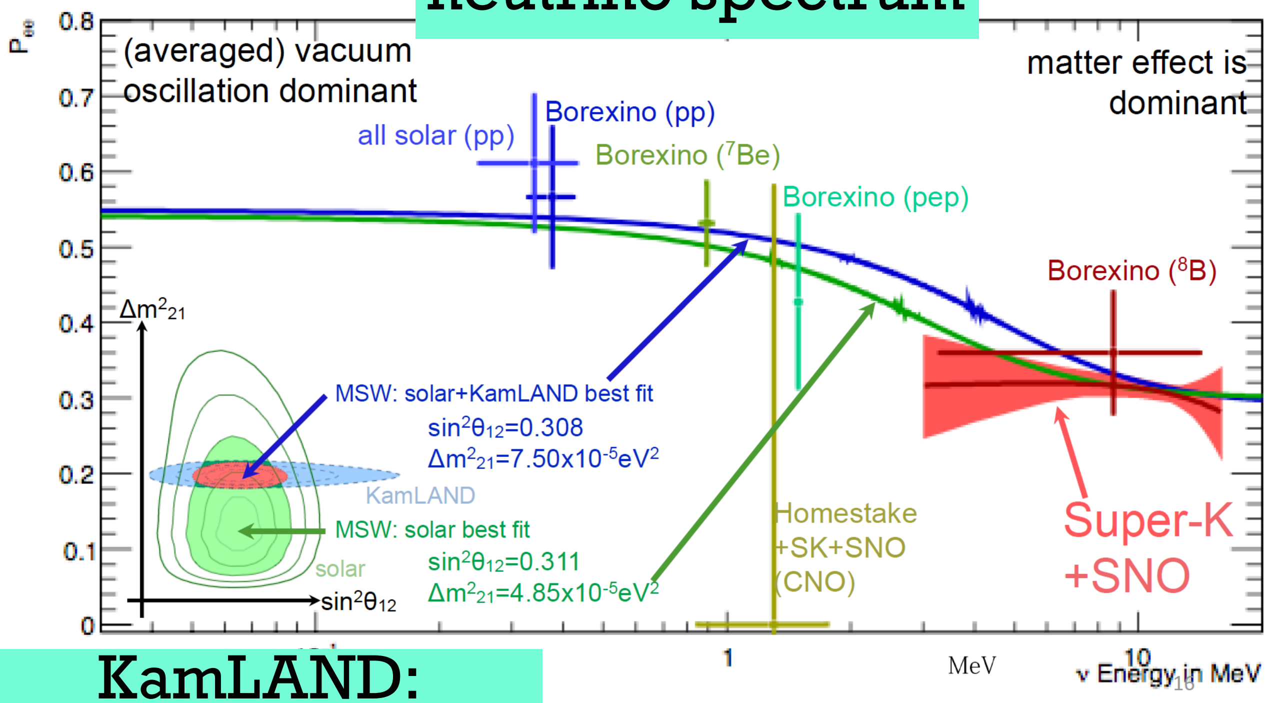
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

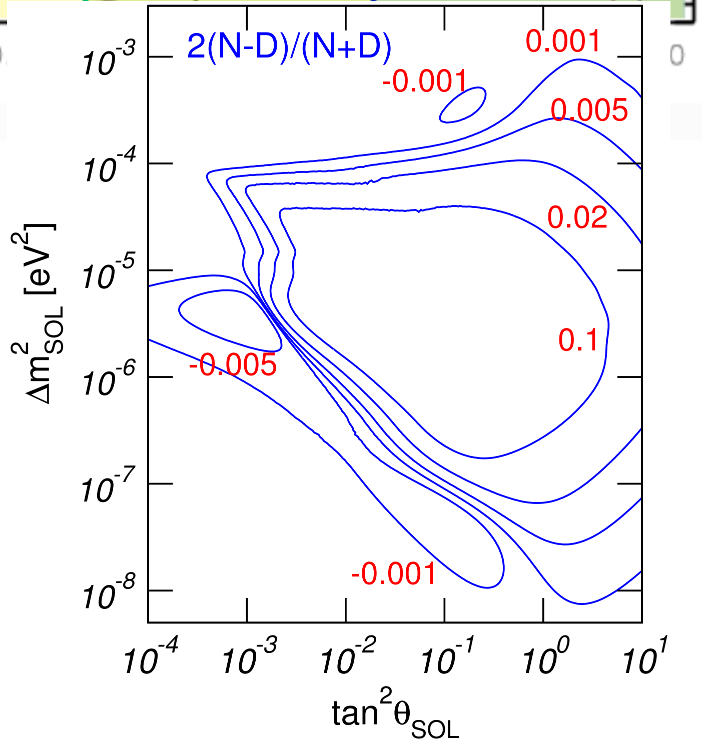
different experimental techniques



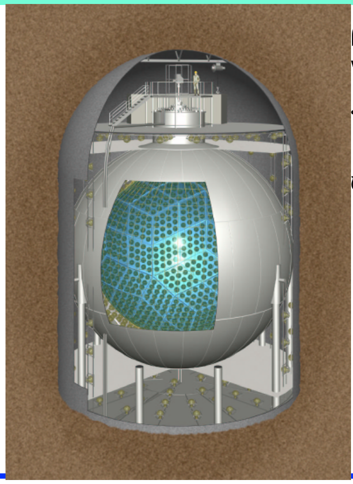
neutrino spectrum

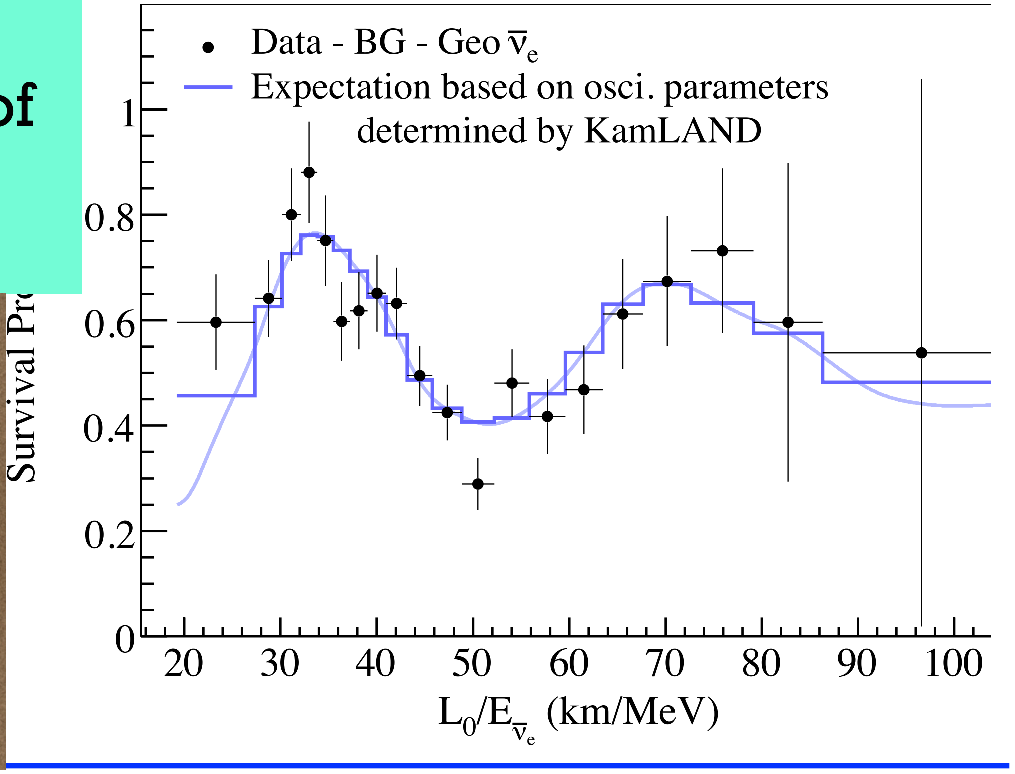


day/night asymmetry



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

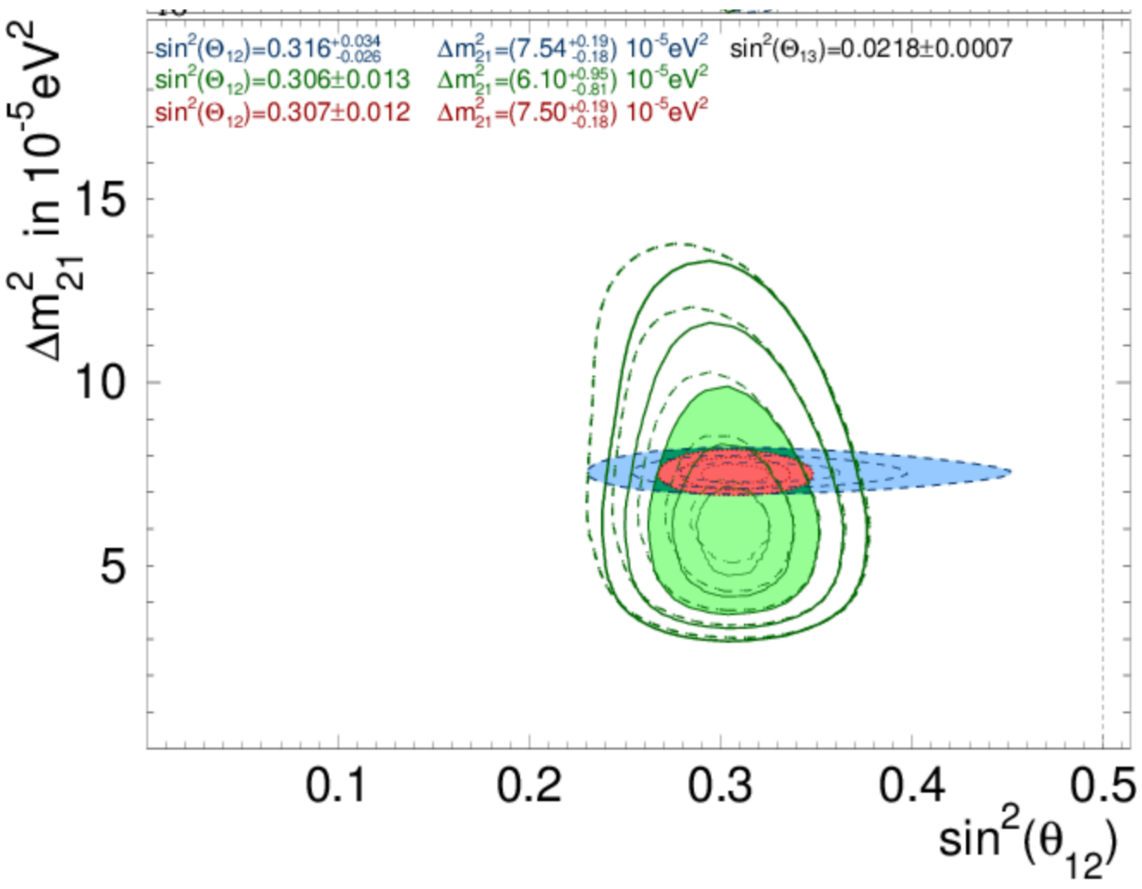
- "GS98" :: Grevesse & Sauval (1998), Space Sci. Rev., 85, 161.
- "AGSS09" :: Asplund et al. (2009), ARA&A, 47, 481.
- "C11" :: Caffau et al. (2011), Sol. Phys., 268, 255.
- "AAG21" :: Asplund et al. (2021), A&A 653, A141.
- "MB22m" :: Magg et al. (2022), A&A 661, A140. (Meteoritic)
- "MB22p" :: Magg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

✦MB22m: high Z

✦ AAG21: low Z

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

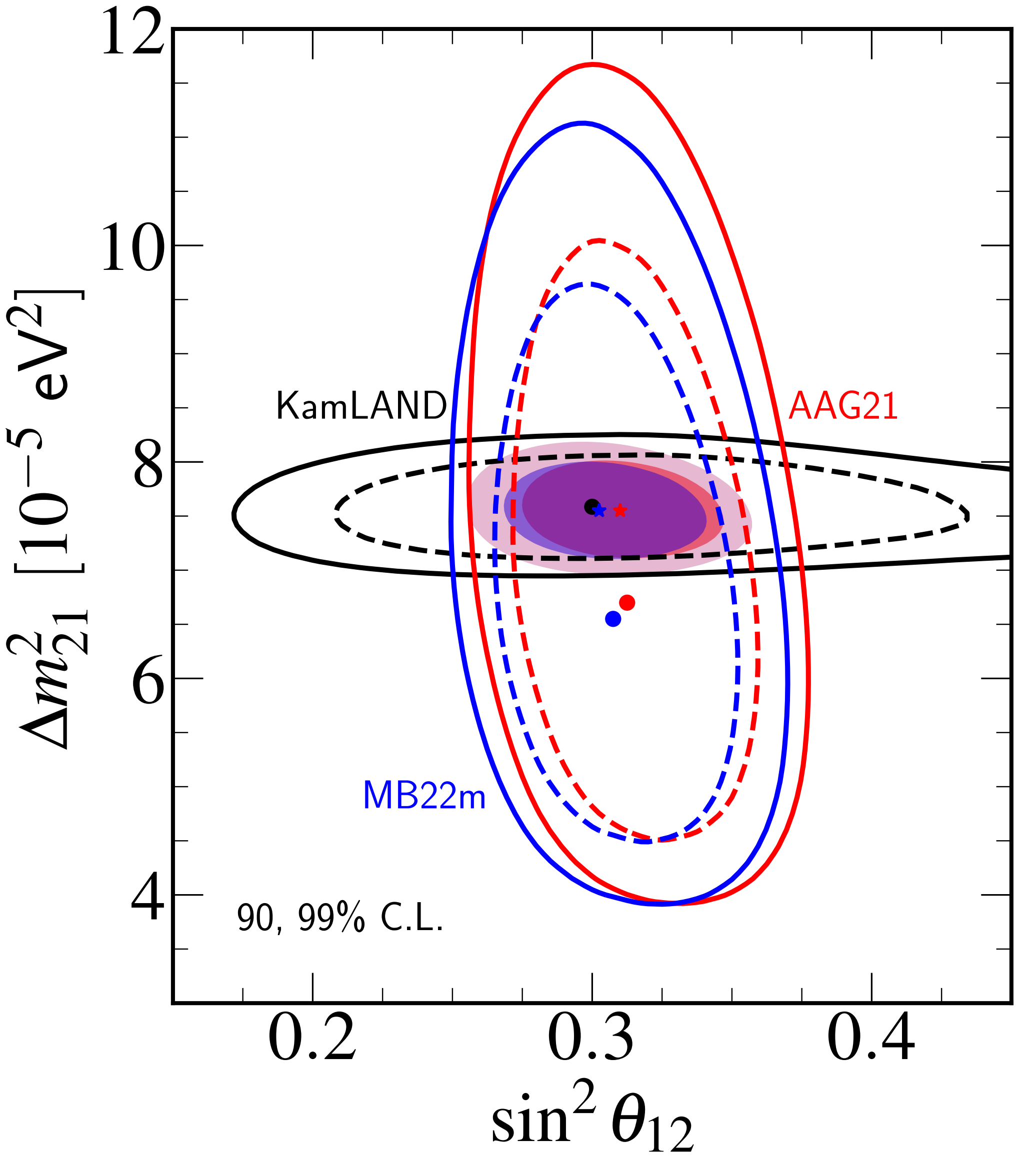
SK Collab, PRD 109 (2024) 092001



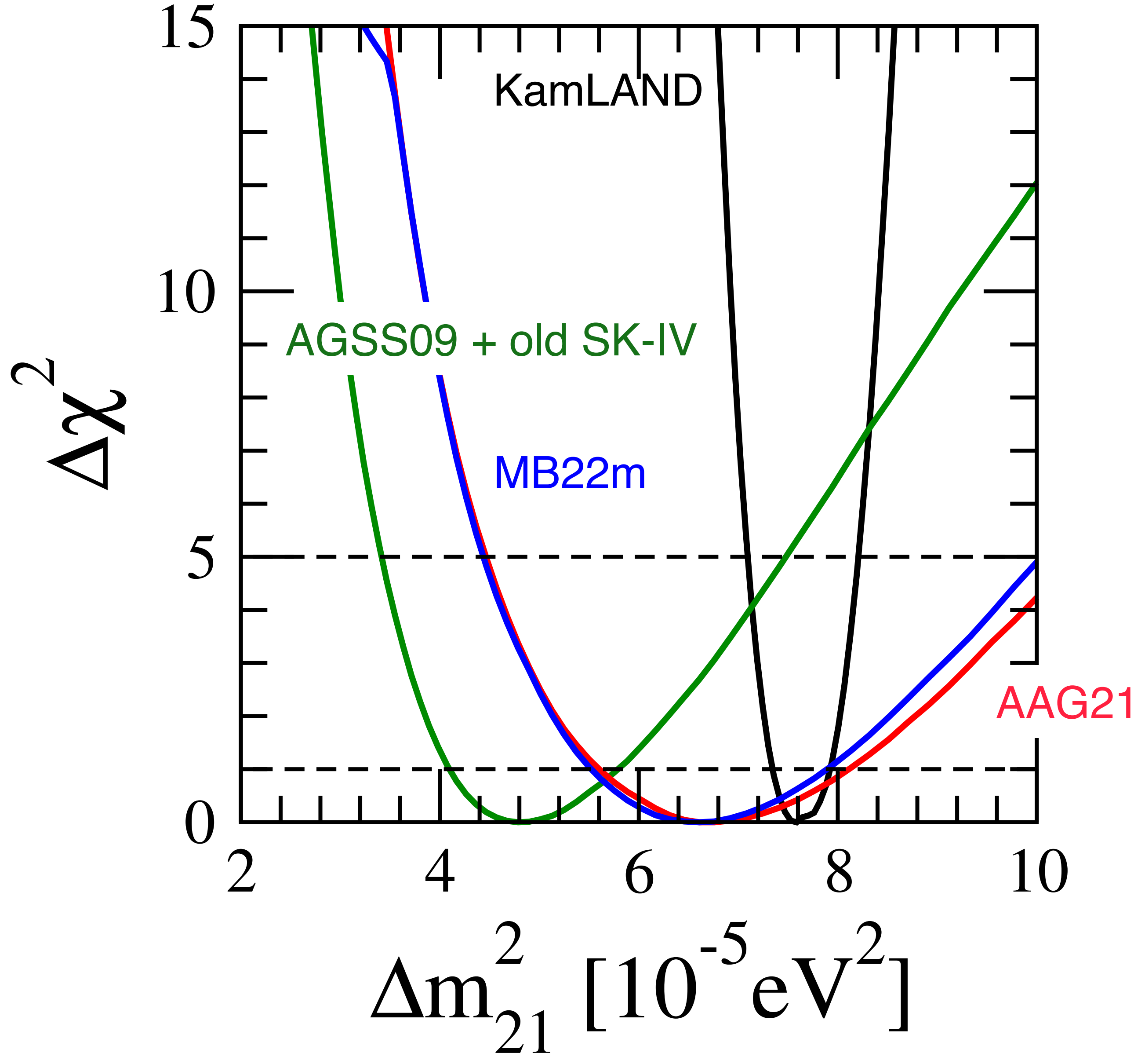
~1.5σ deviation wrt Δm^2_{21} measured in KamLAND (fixed θ_{13})

The solar sector

free θ13



free θ13

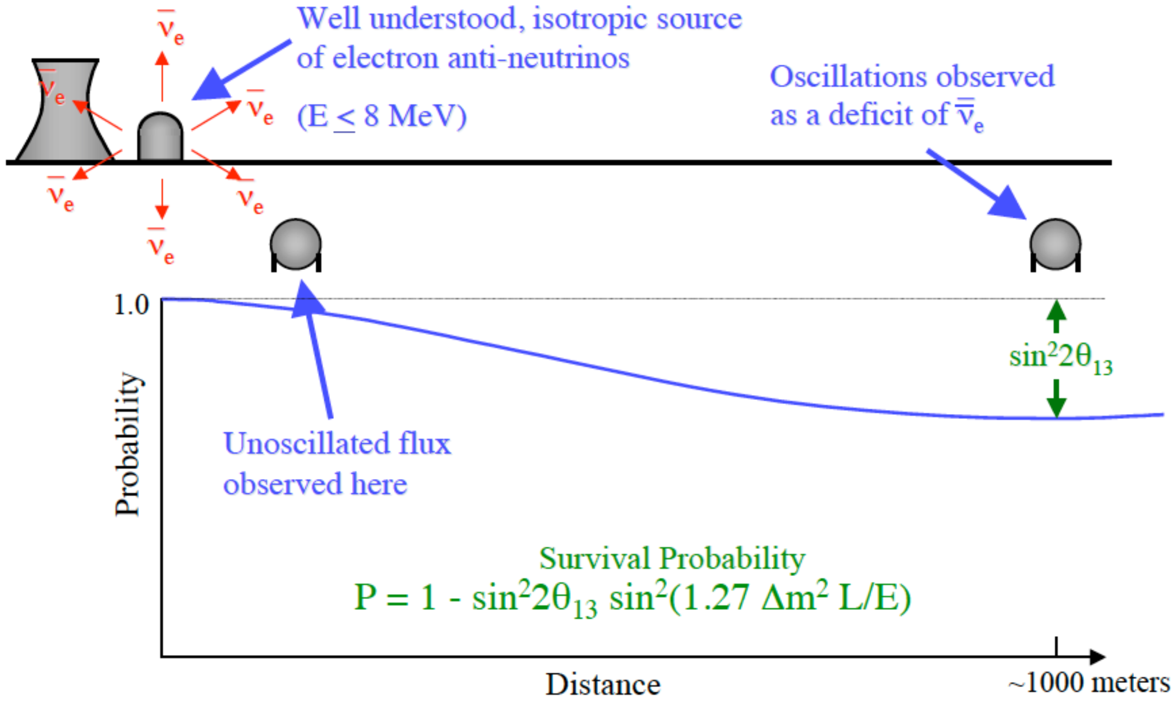


- θ_{12} measurement dominated by solar data
- Δm^2_{21} better measured by KamLAND.
- new SK-IV data reduce the tension in Δm^2_{21} measurement (~2σ → ~1σ deviation)

The reactor sector

km-baseline reactor experiments:

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



Well understood, isotropic source of electron anti-neutrinos ($E \lesssim 8$ MeV)

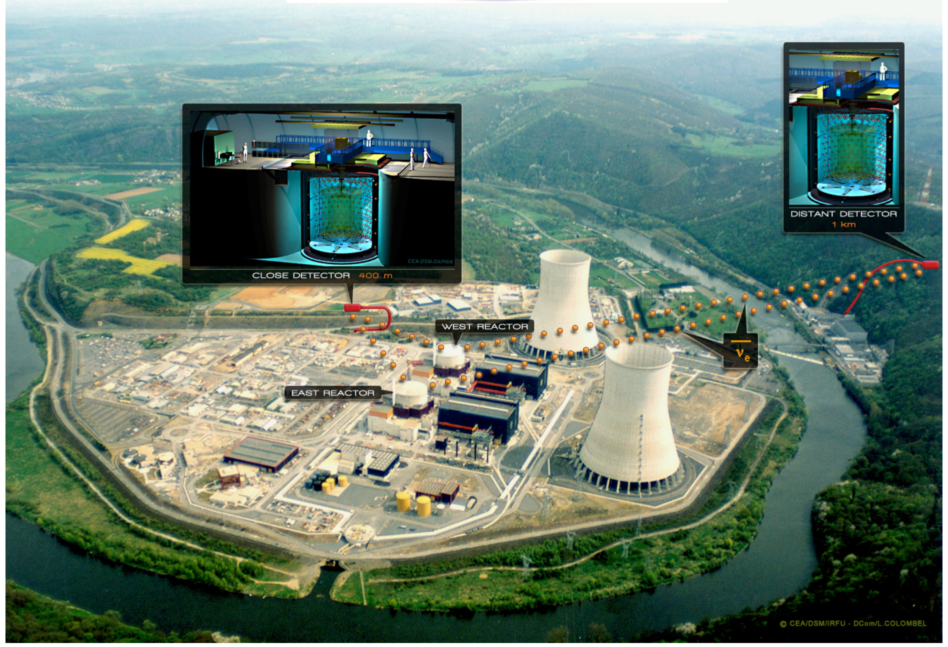
Oscillations observed as a deficit of $\bar{\nu}_e$

Unoscillated flux observed here

Survival Probability

$$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\,\Delta m^2\,L/E)$$

DOUBLE CHOOZ

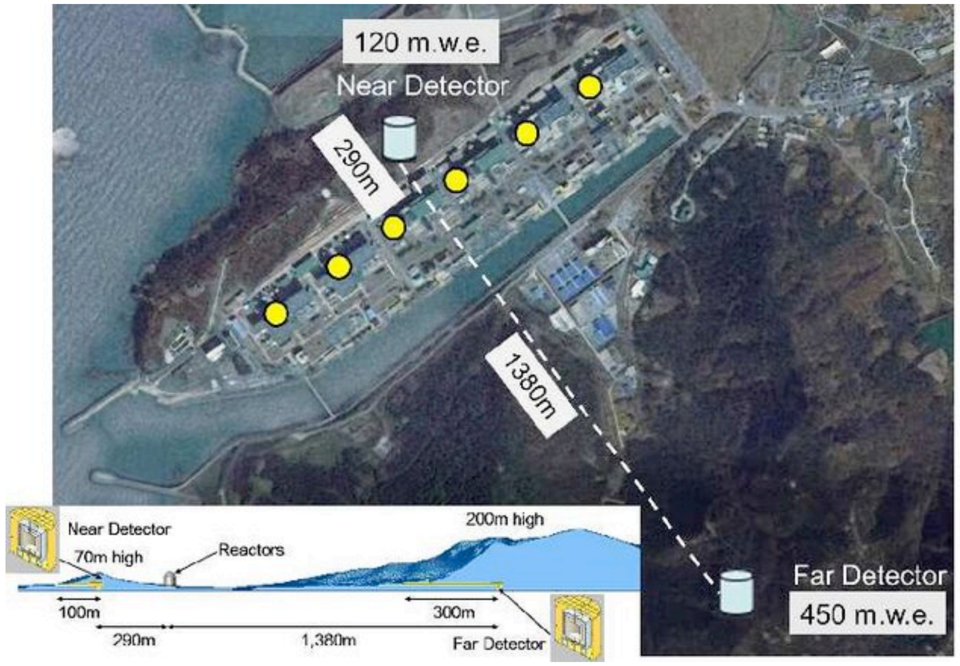


2 cores + 1 ND + 1 FD

Daya Bay θ_{13}

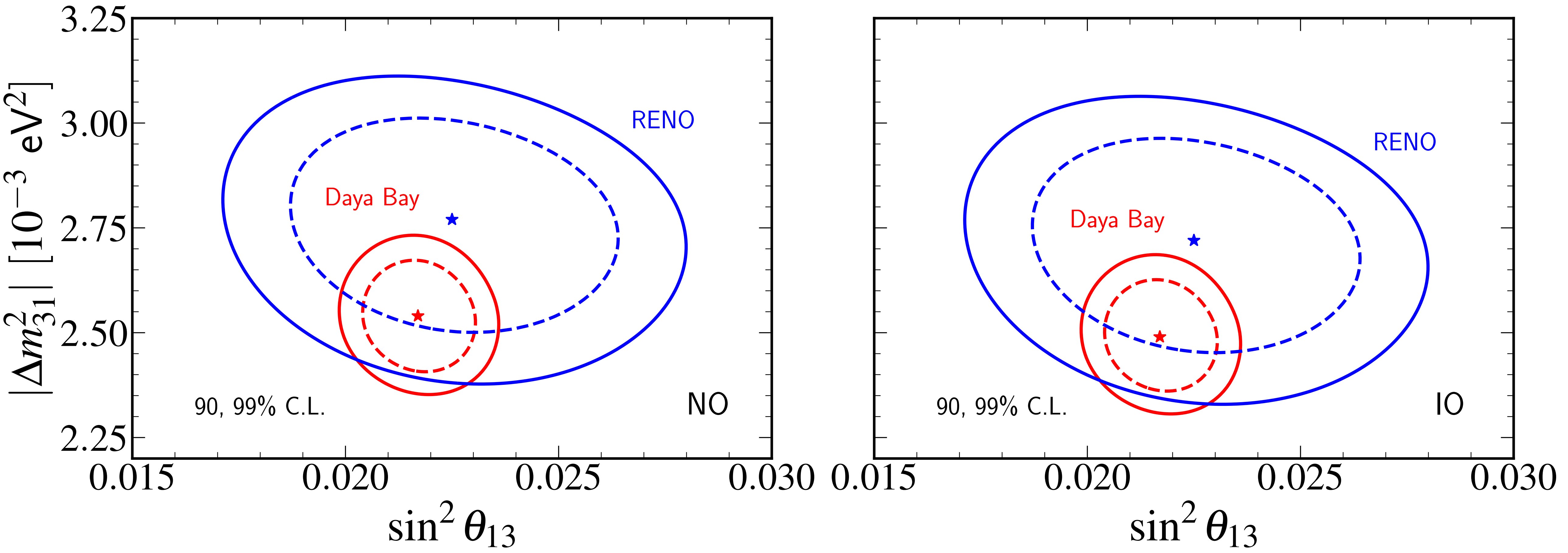
6 cores + 4 ND + 4FD

RENO ν θ_{13}



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

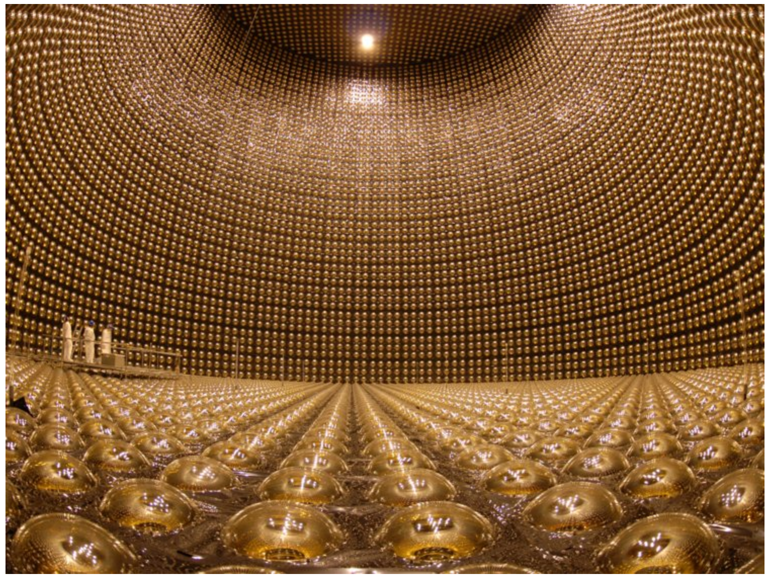
- **RENO**: 2900-day data: $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ (7%)

J. Yoo [RENO Collaboration] @ Neutrino-2020

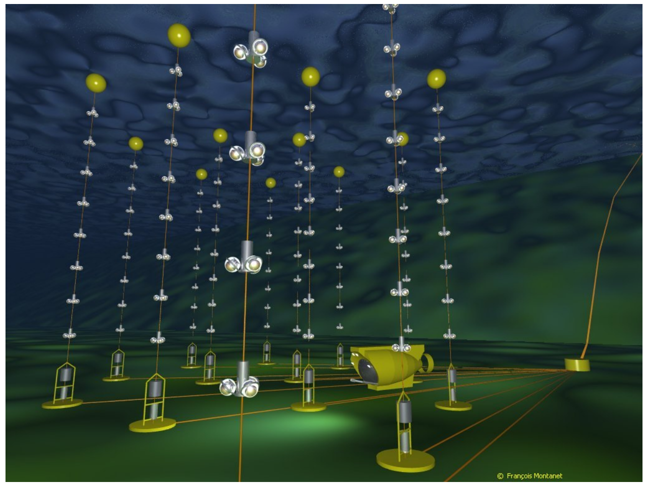
The atmospheric sector

Atmospheric experiments

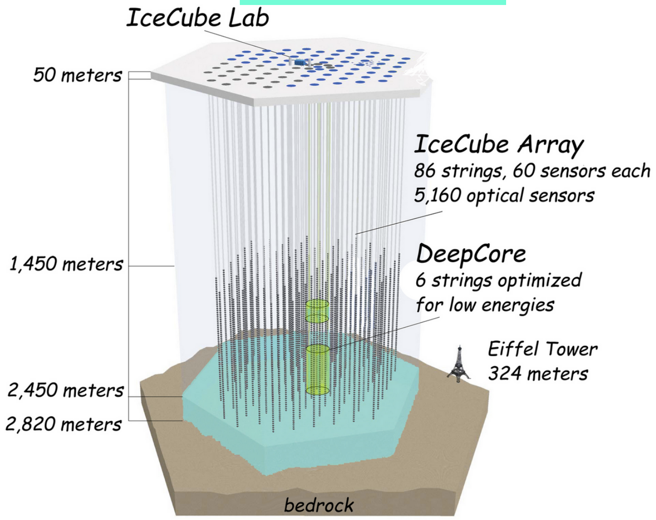
Super-Kamiokande



ANTARES & KM3NeT

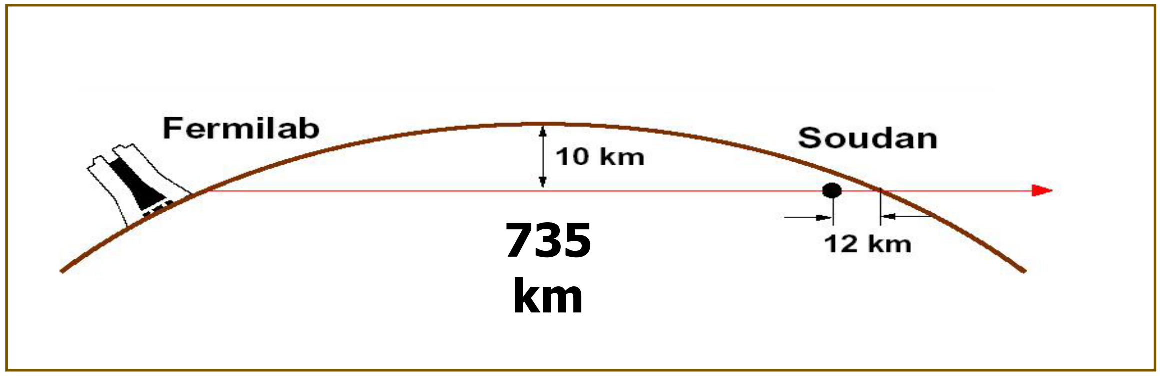


IceCube

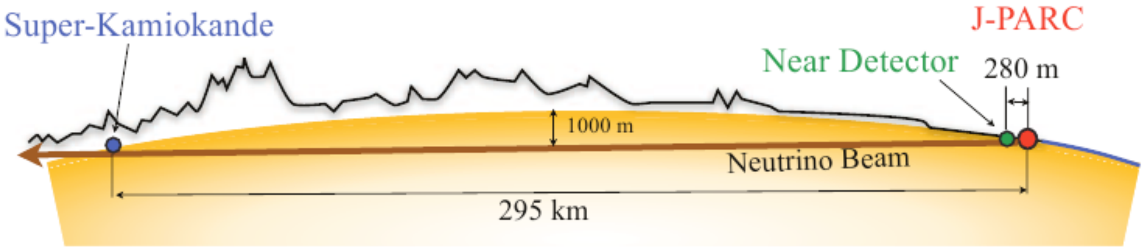


Accelerator long-baseline experiments

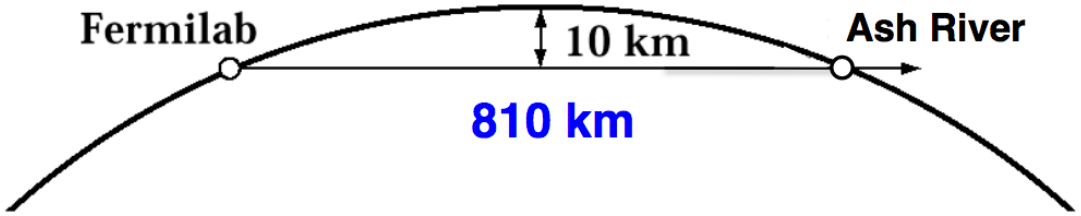
MINOS



T2K



NOvA



→ consistent with atmospheric data

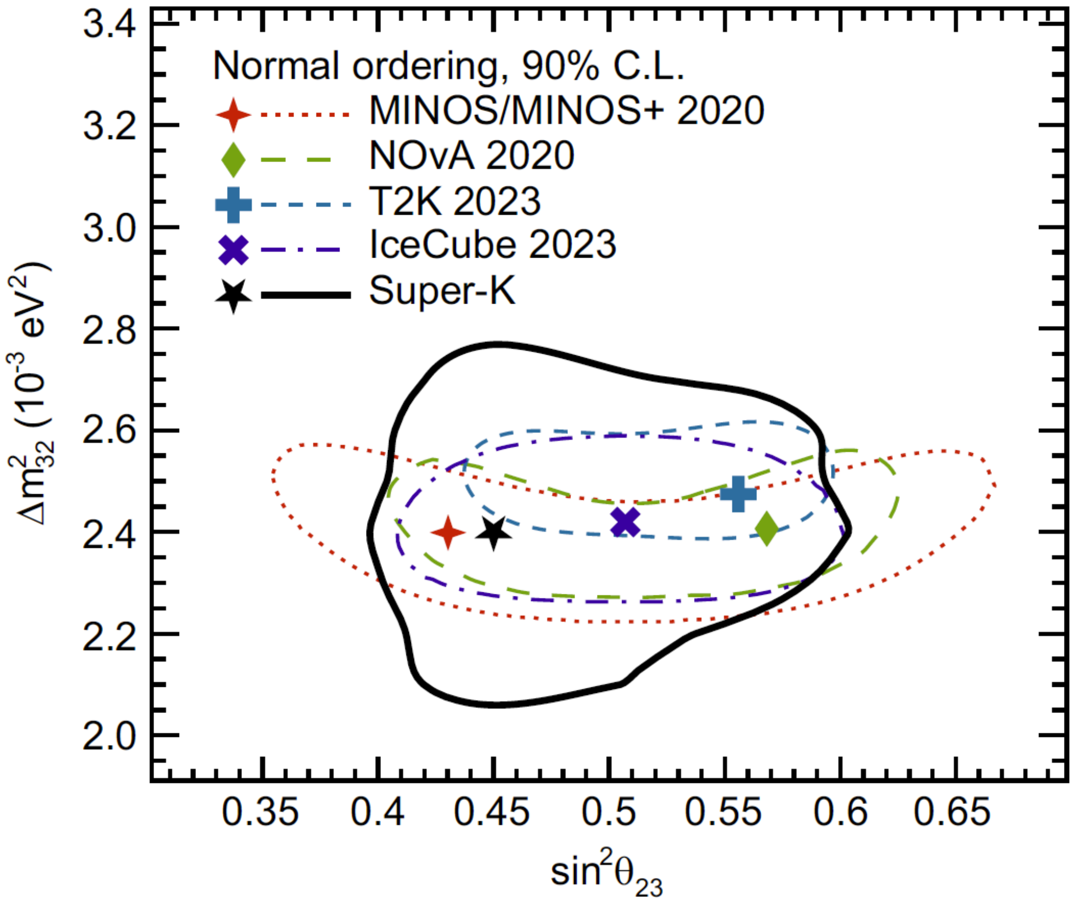
→ atm ν oscillations confirmed by lab exps

The atmospheric sector

New Results

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

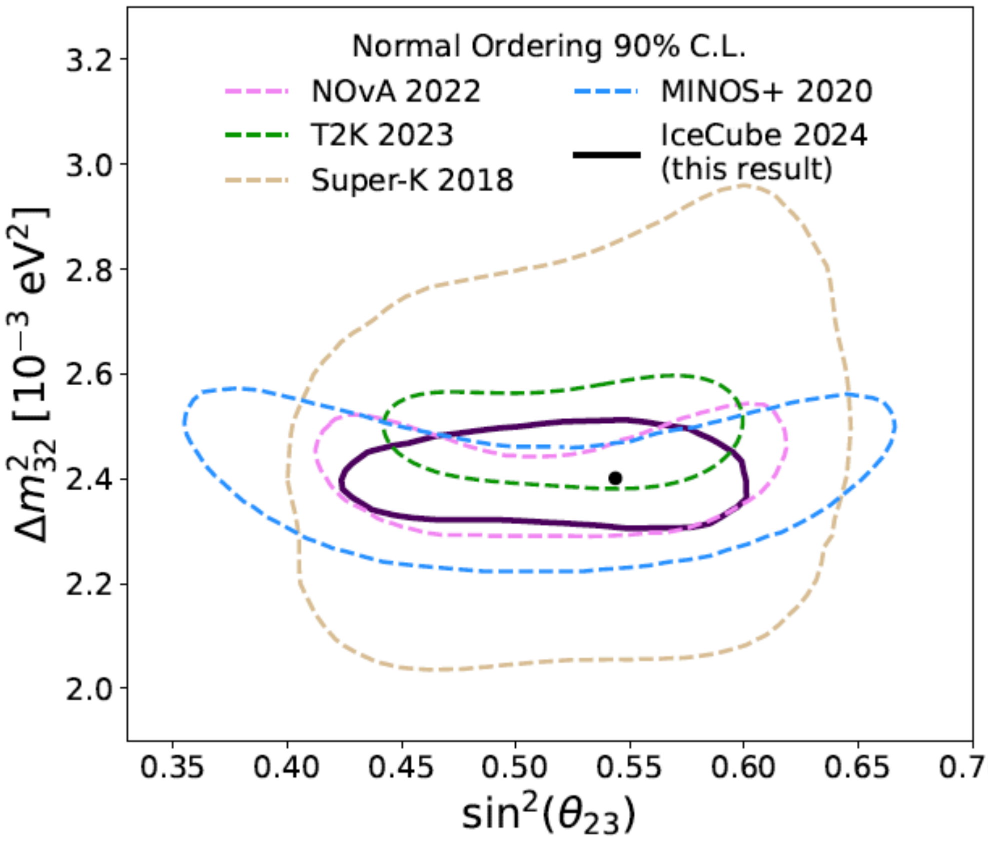
SK Collab, PRD 109 (2024) 072014



$\Delta\chi^2$(IO-NO) = 5.69 (θ_{13} constrained)

IceCube DeeCore 9.3 yrs

IceCube Collab, arXiv:2405.02163



The atmospheric sector

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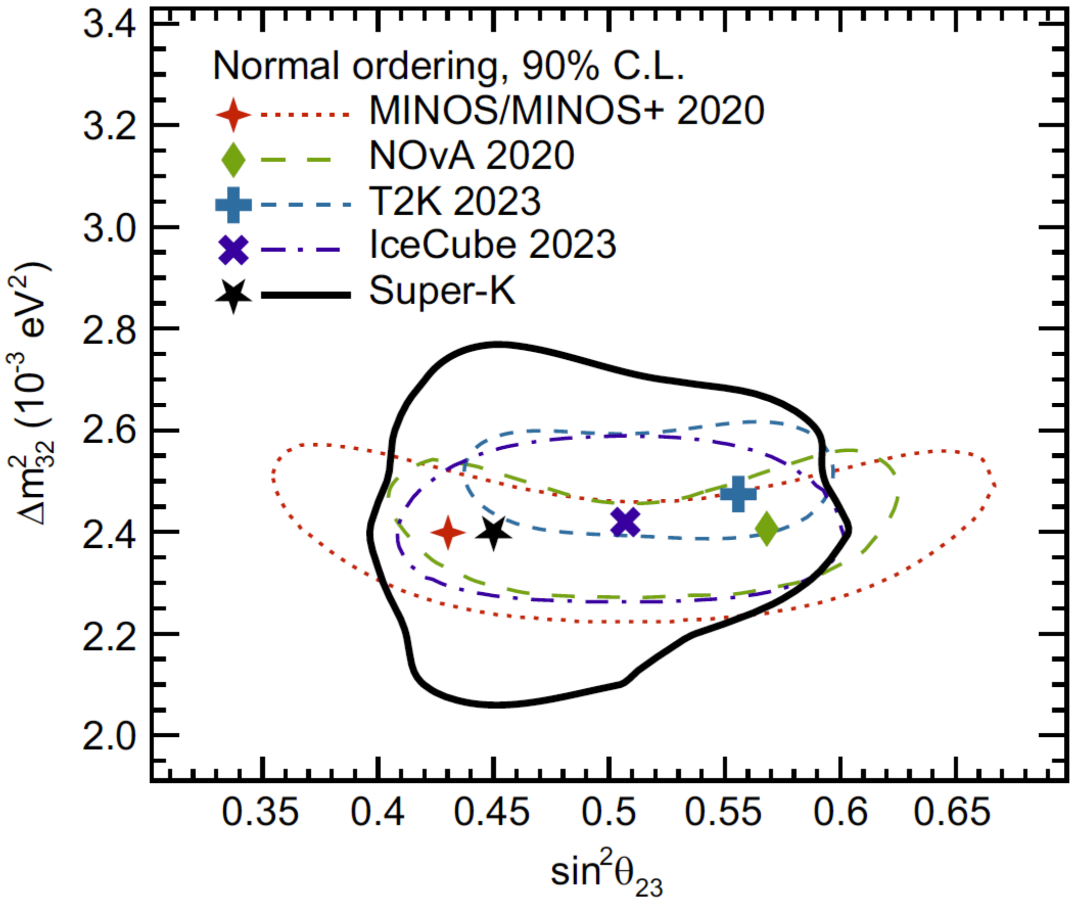
SK Collab, PRD 109 (2024) 072014

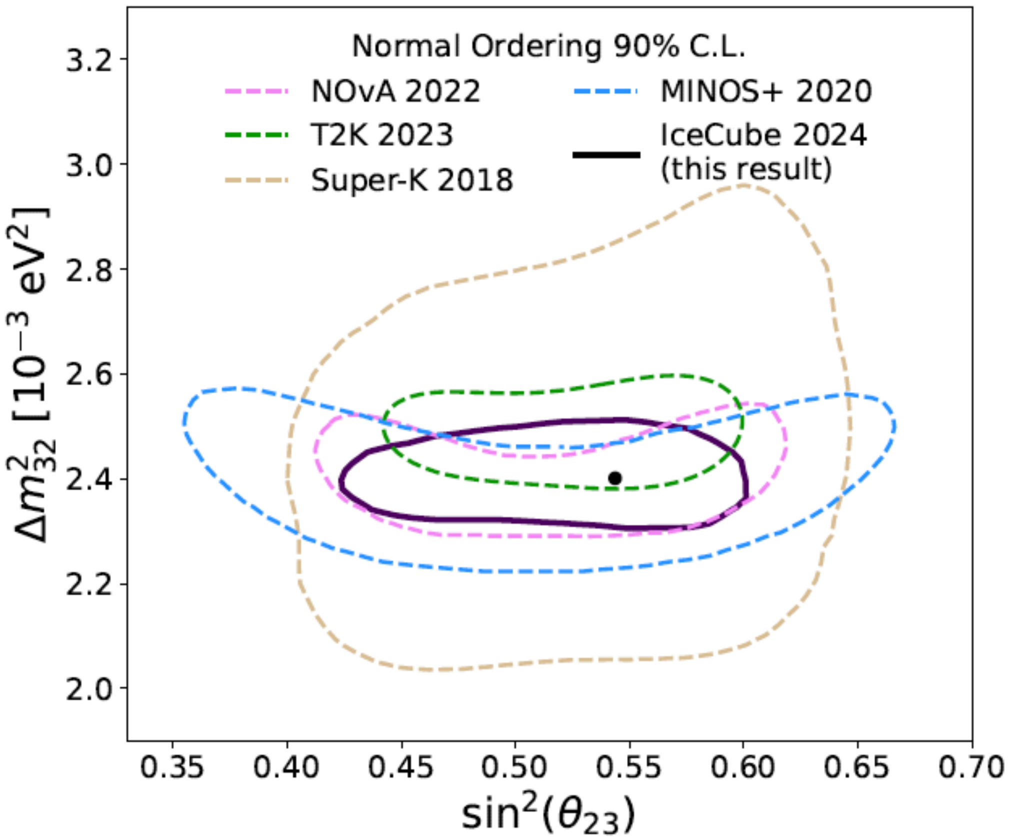


$\Delta\chi^2$(IO-NO) = 5.69 (θ_{13} constrained)

χ^2 tables

IceCube DeeCore 9.3 yrs

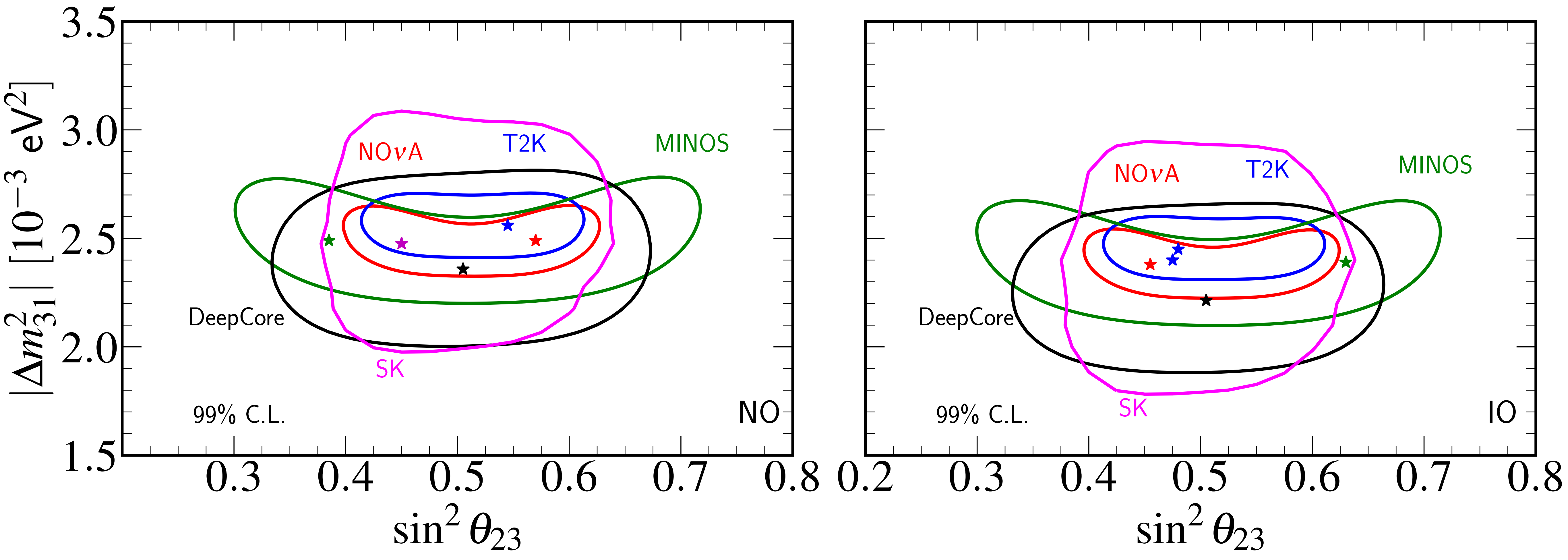
IceCube Collab, arXiv:2405.02163



Not included

The atmospheric sector

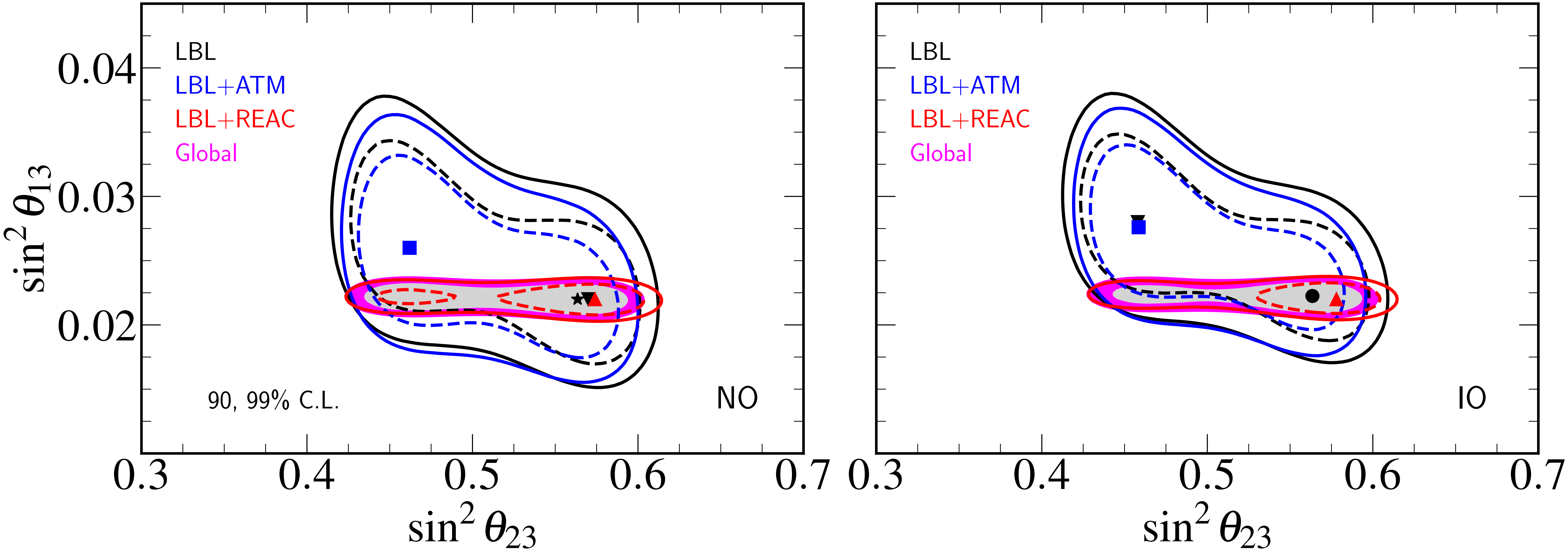
Valencia Global Fit (Pre-Nu2024)



90% CL regions from individual experiments

The octant of θ_{23}

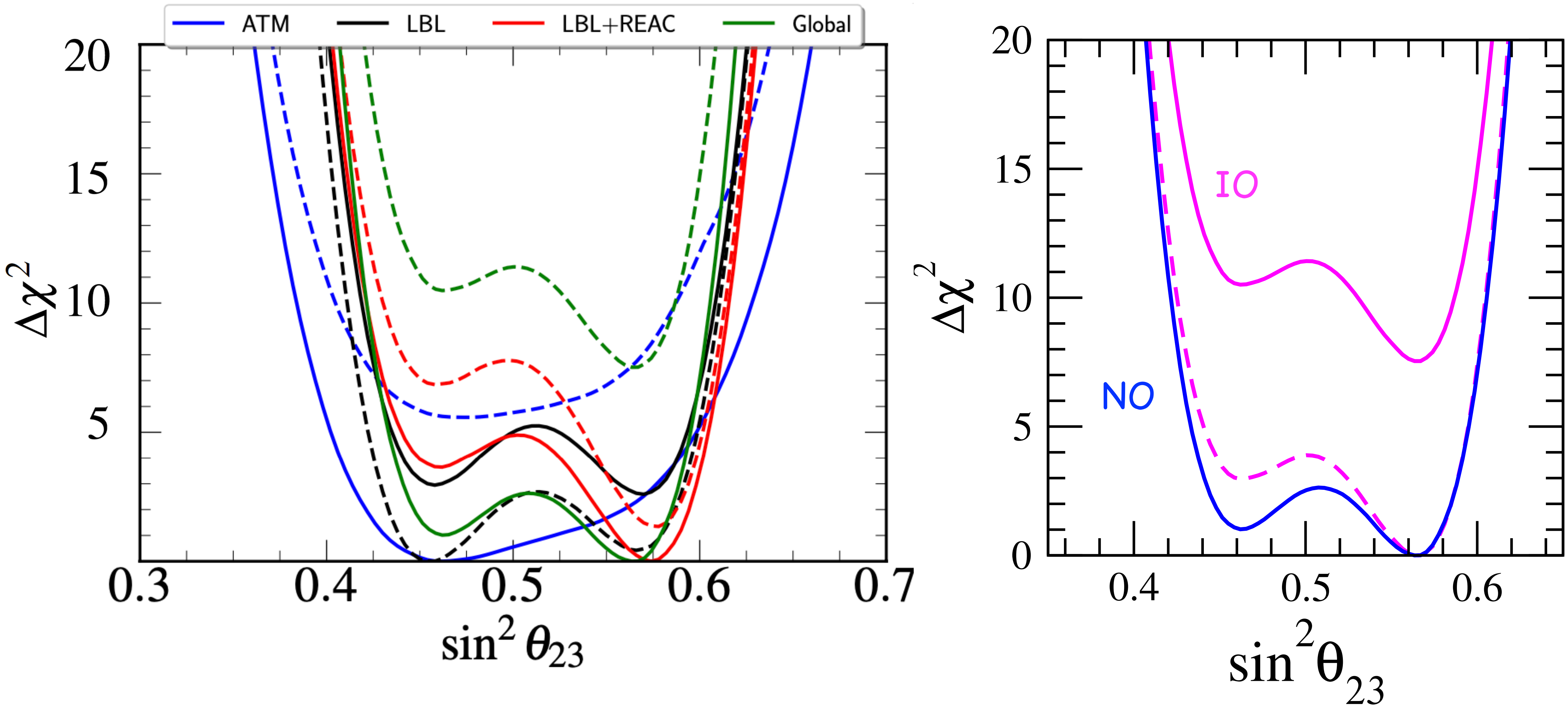
Valencia Global Fit (Pre-Nu2024)



- **LBL** combination slightly prefer UO (NO) and LO(IO) with $\Delta\chi^2 = 0.3\text{-}0.4$
- **ATM** data show a slight preference for LO (NO and IO) with $\Delta\chi^2 > 1.4(0.2)$ for $\theta_{23} > 45°$
- LBL + ATM prefers LO (NO and IO) with $\Delta\chi^2 \sim 1.0\text{-}2.0$ over UO
- REAC breaks the degeneracy in favor of UO (NO and IO) with $\Delta\chi^2 \sim 3.5\text{-}4.5$ over LO
- Global analysis show a milder preference for UO with $\Delta\chi^2 \sim 1.0\text{-}3.0$ over LO

The octant of θ_{23}

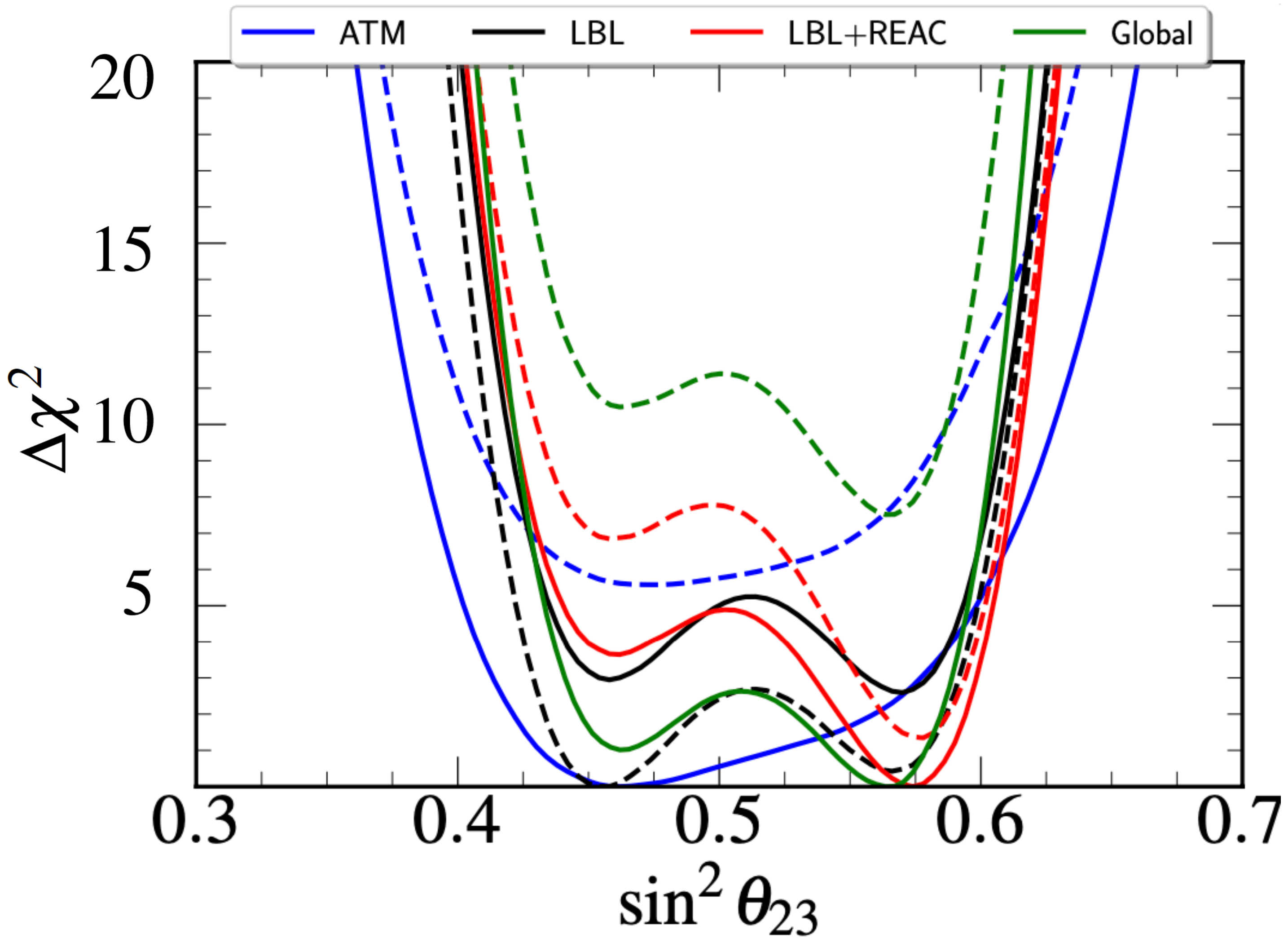
Valencia Global Fit (Pre-Nu2024)

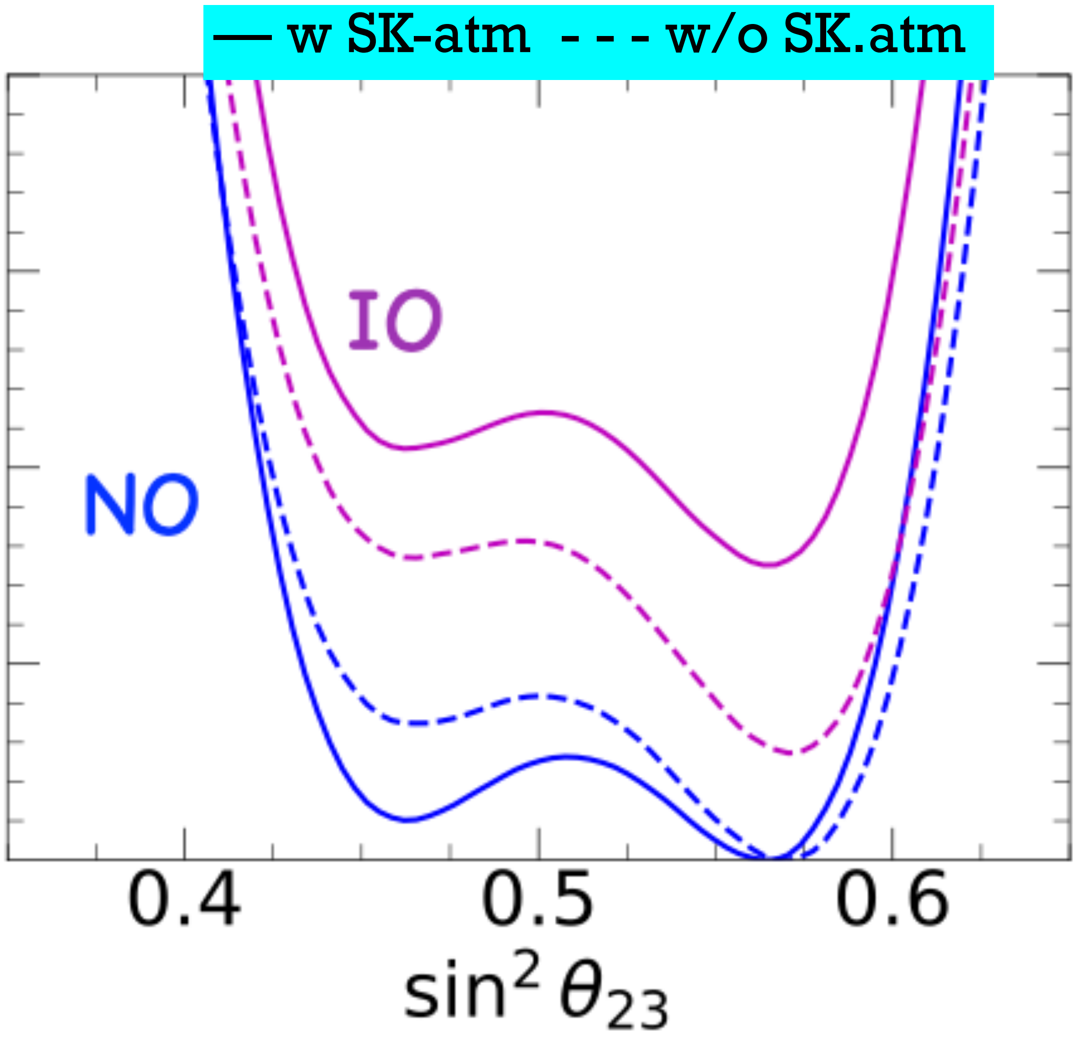


- ✦ Lower-octant slightly disfavoured with $\Delta\chi^2 \geq 1.0$ (3.0) for NO (IO)
- ✦ Maximal mixing disfavoured with $\Delta\chi^2 = 2.5$ (3.9) for NO (IO)

The octant of θ_{23}

Valencia Global Fit (Pre-Nu2024)

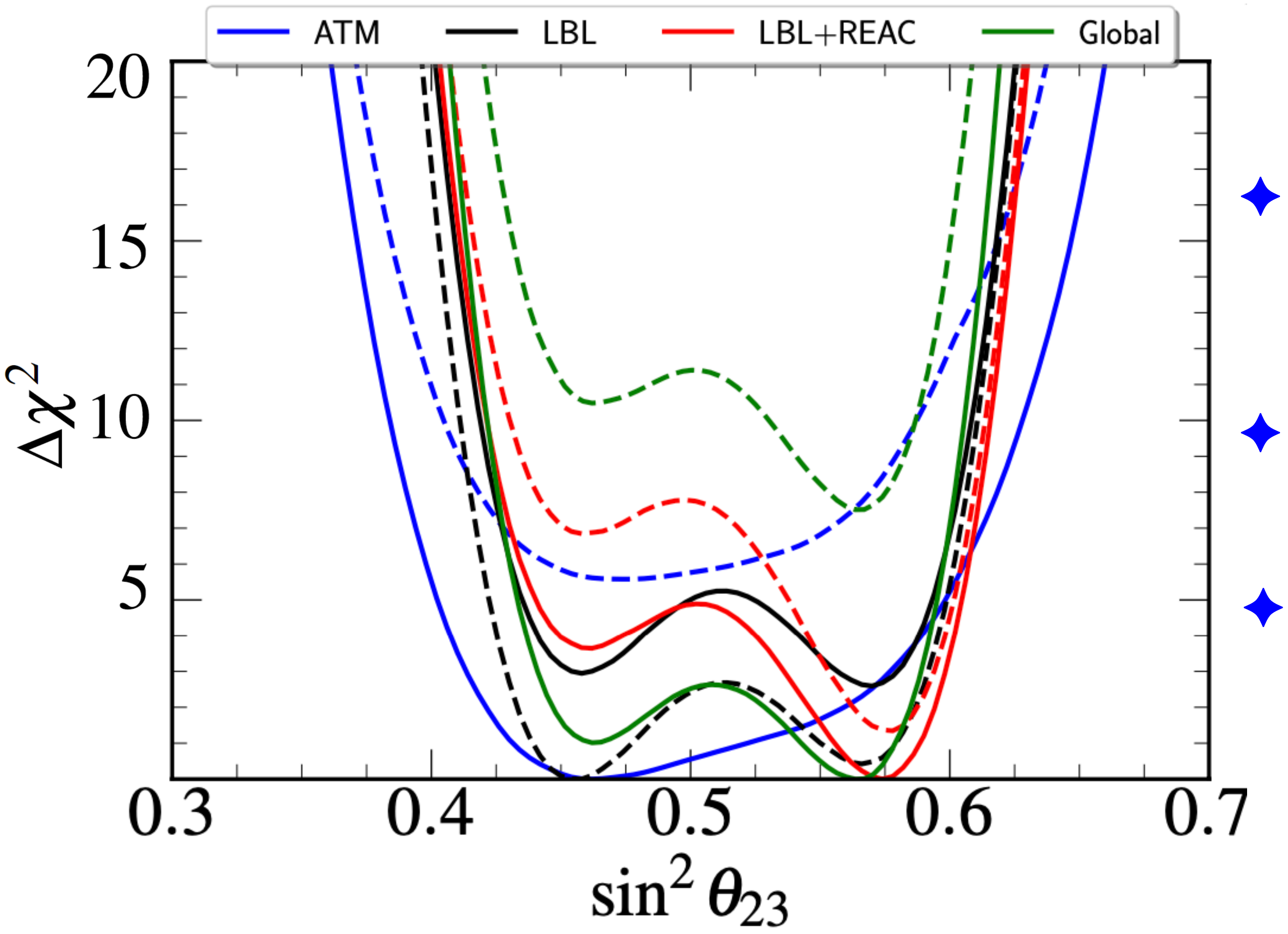




- ✦ Lower-octant slightly disfavoured with $\Delta\chi^2 \geq 1.0$ (3.0) for NO (IO)
  - ⇒ w/o SK: LO more disfavoured, with $\Delta\chi^2 \sim 3.5$
- ✦ Maximal mixing disfavoured with $\Delta\chi^2 =$ 2.5 (3.9) for NO (IO)

The mass ordering

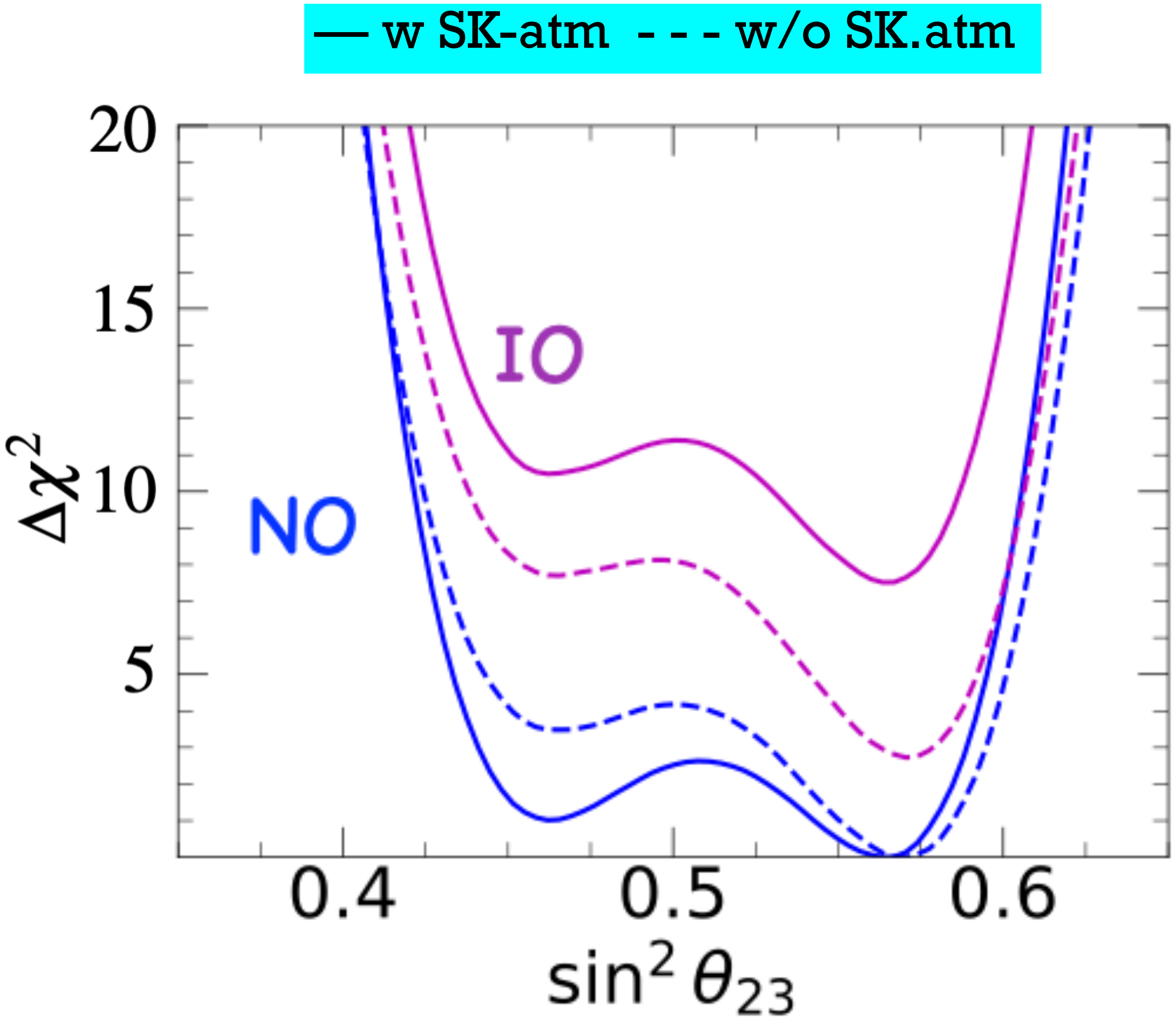
Valencia Global Fit (Pre-Nu2024)



- ✦ T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.2$-0.4
- ✦ **LBL** prefer IO with $\Delta\chi^2 \approx 2.4$ (tension NO)
- ✦ LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.3$ (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)

The mass ordering

Valencia Global Fit (Pre-Nu2024)



- ✦ T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.2$-0.4
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- ✦ 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)= 7.5 (2.7) w SK-atm (w/o SK-atm)

  assuming Wilk's theorem: 2.7σ (1.6σ) preference for NO w SK-atm (w/o SK-atm)

The mass ordering

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

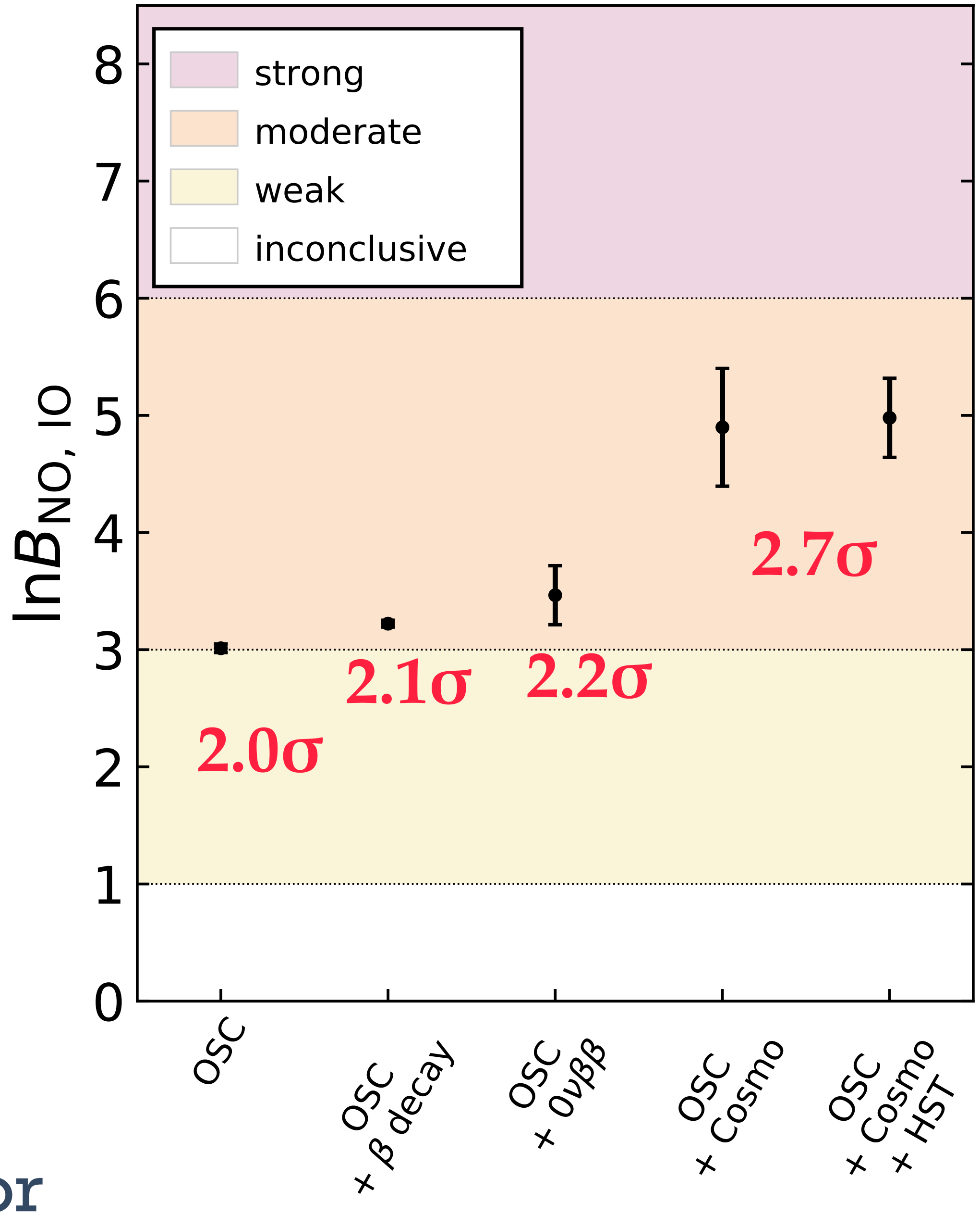
Results from the combined bayesian analysis:

⇒ 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

de Salas et al, JHEP 02 (2021) 071



The mass ordering

Experimental sensitivity to neutrino masses:

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

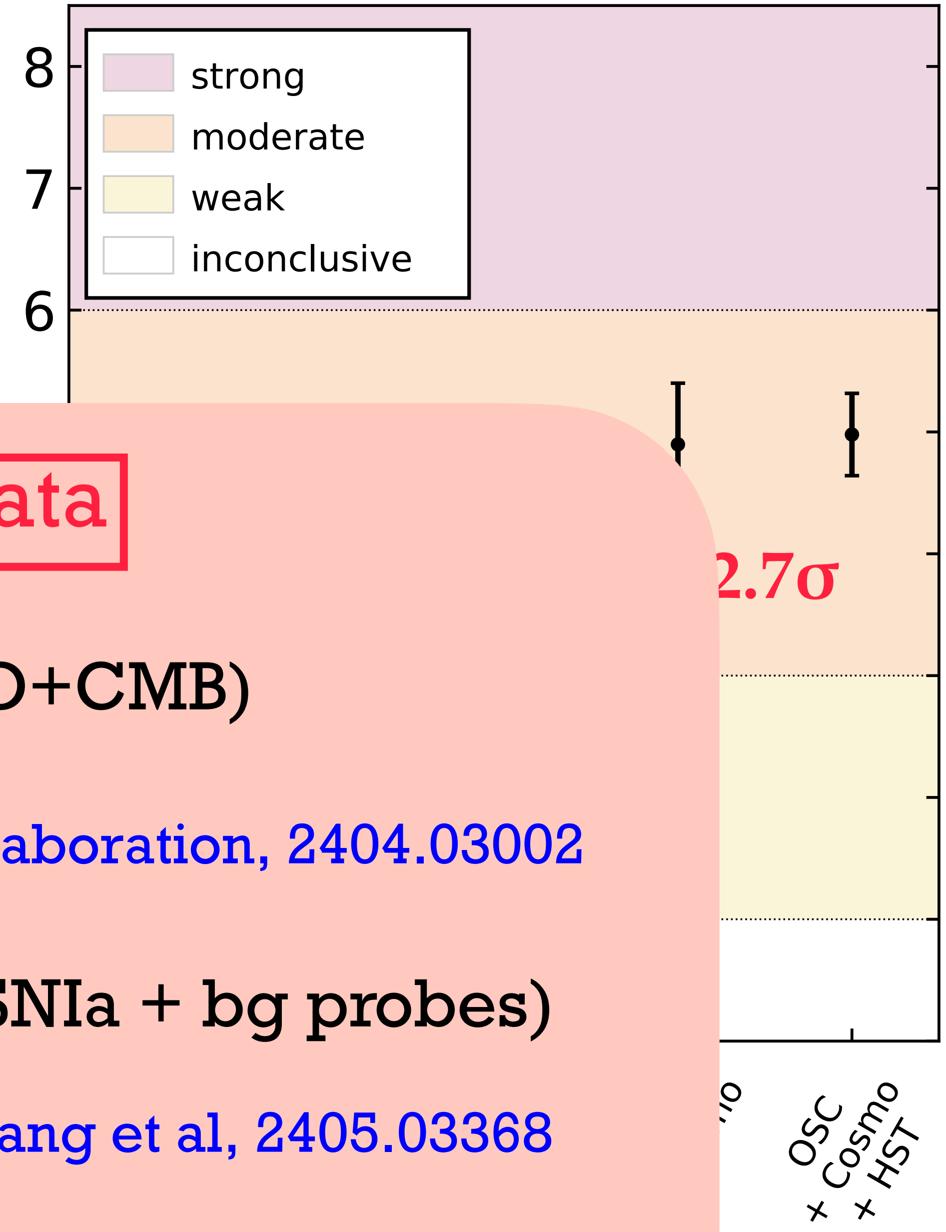
Results

⇒ weal
oscil

⇒ β-de

⇒ cosn
NO fron

de Salas et al, JHEP 02 (2021) 071



New cosmological data

$\Sigma m_\nu < 0.072$ eV (95%, DESI BAO+CMB)

DESI Collaboration, 2404.03002

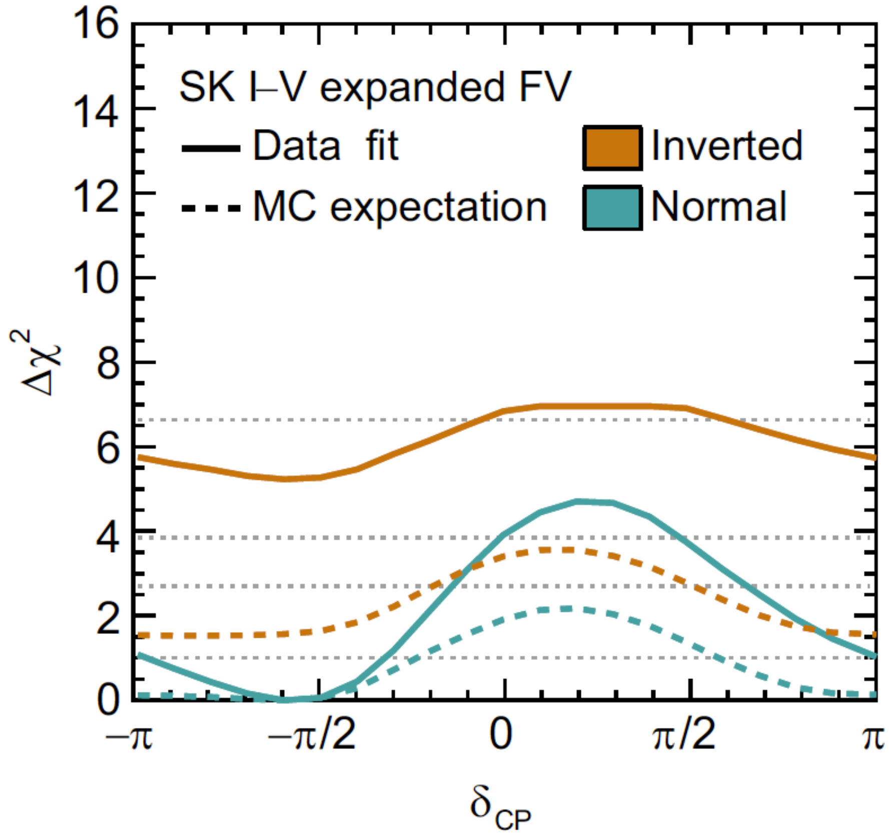
$\Sigma m_\nu < 0.043$ eV (95%, DESI BAO+CMB+SNIa + bg probes)

Wang et al, 2405.03368

Cosmo session on Thursday

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

T2K

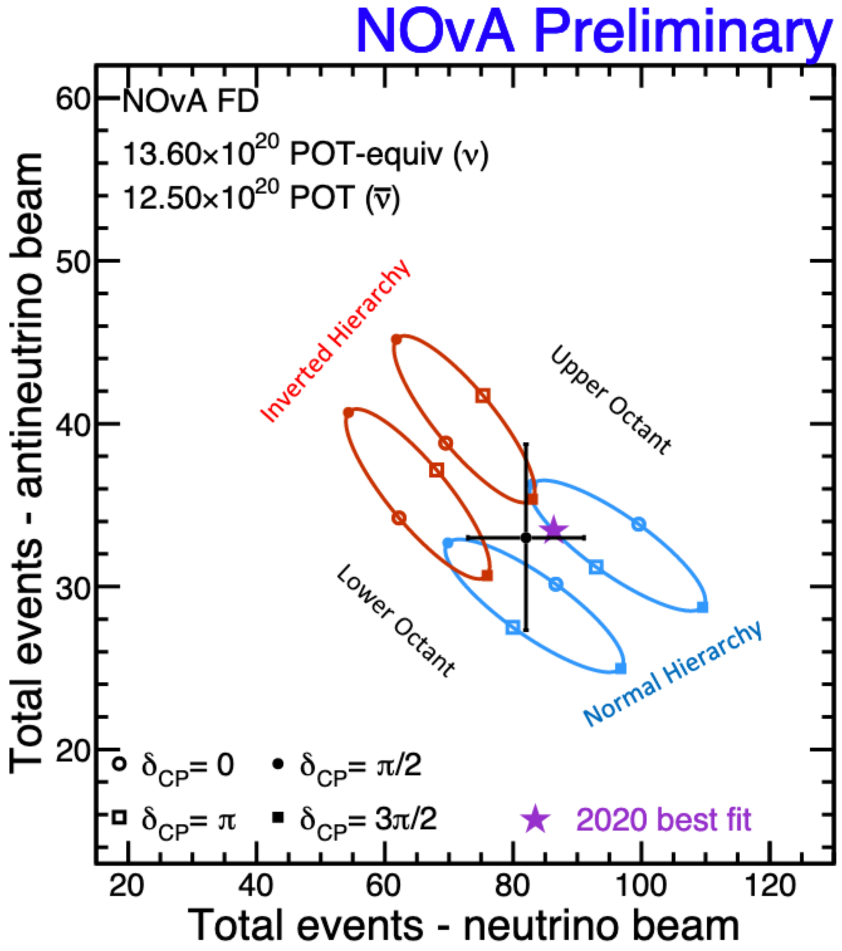
H. Tanaka, TAUP 2019

$\delta_{BF} \simeq 3\pi/2$ 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

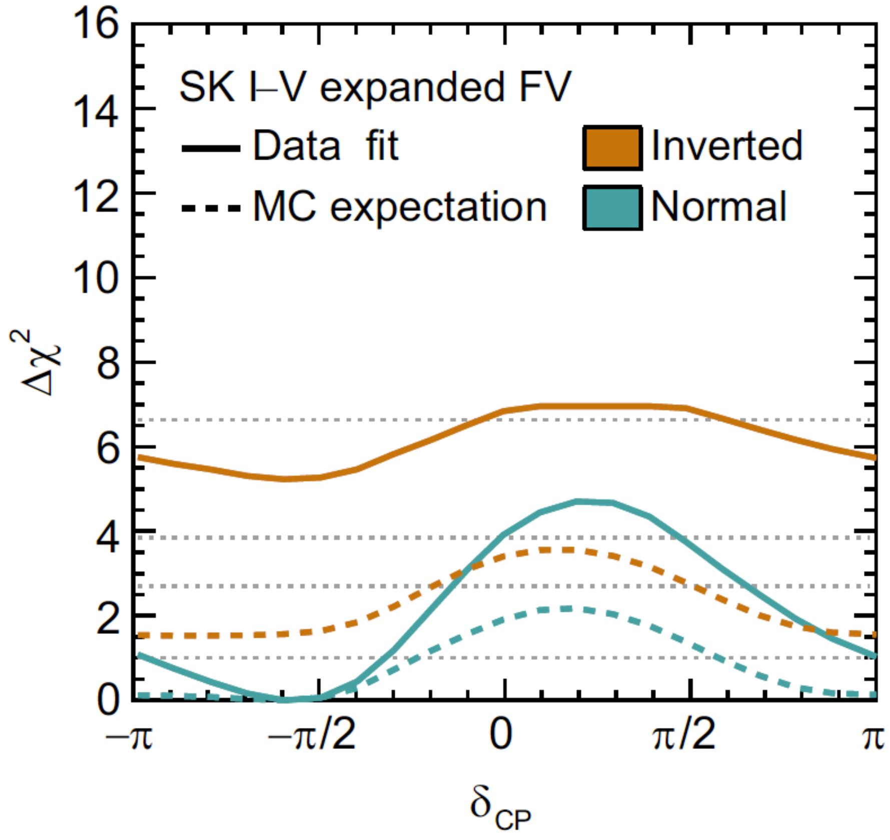
No strong asymmetry in the ν_e / $\bar{\nu}_e$ app rates



P Vahle, TAUP 2021

The CP phase

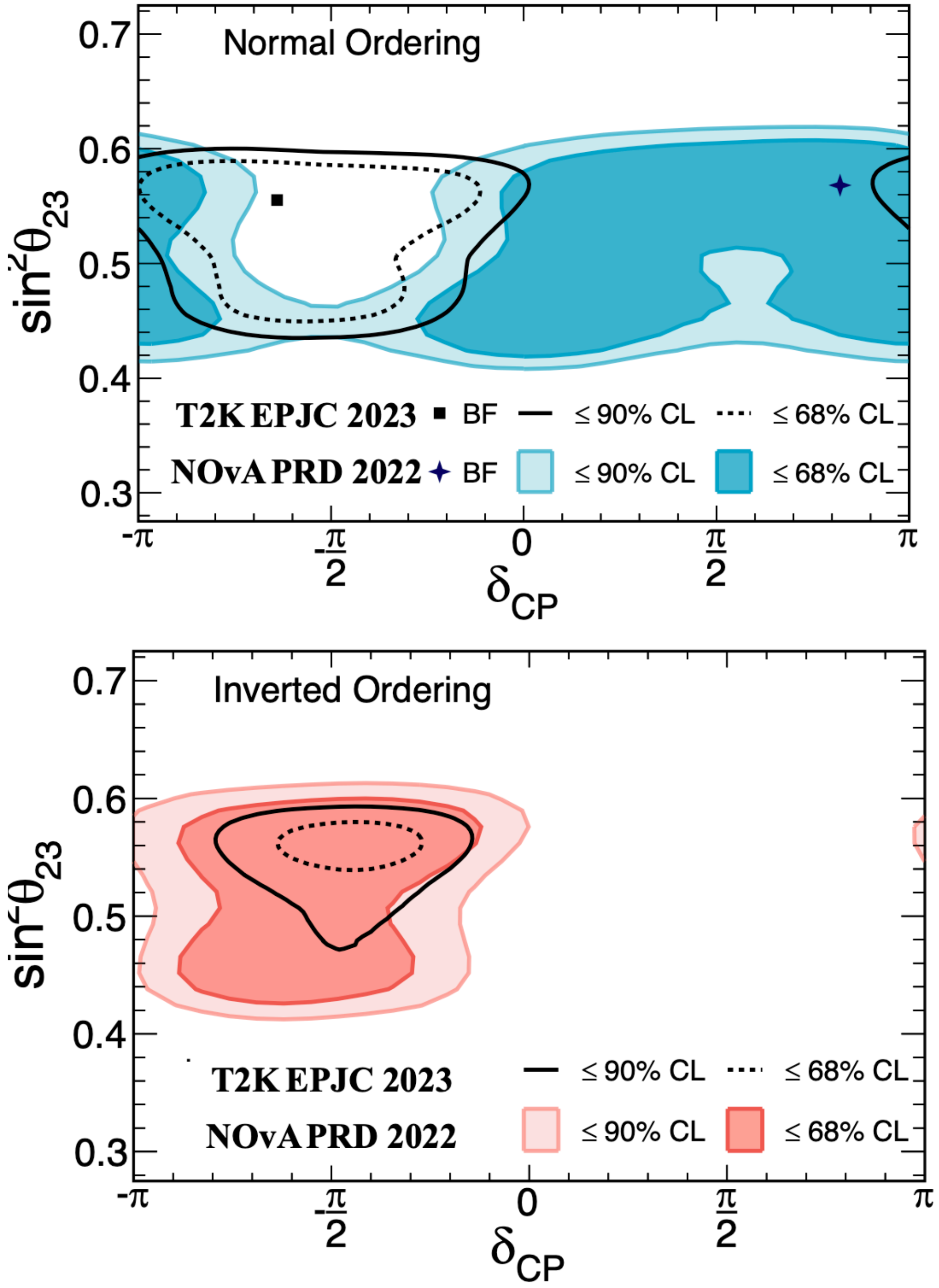
Super-Kamiokande (atm)



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

SK Collab, PRD 109 (2024) 072014

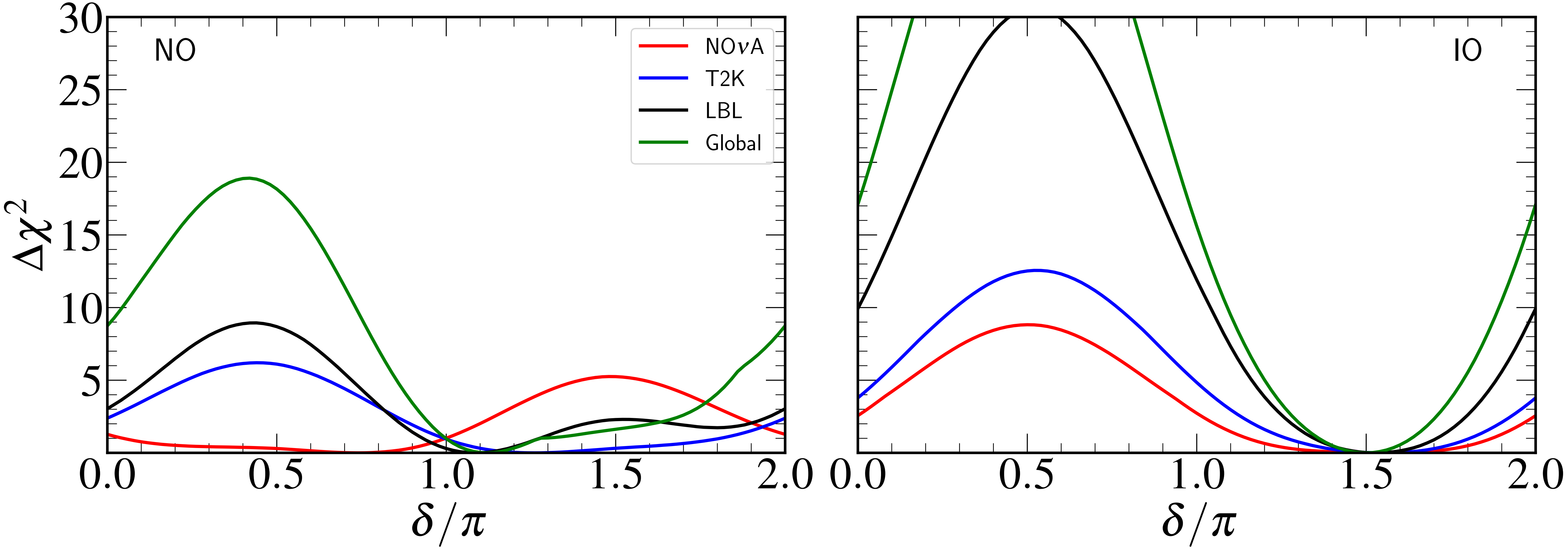
Slight tension T2K & NOvA for NO



A. Booth, 2024

The CP phase

Valencia Global Fit (Pre-Nu2024)



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

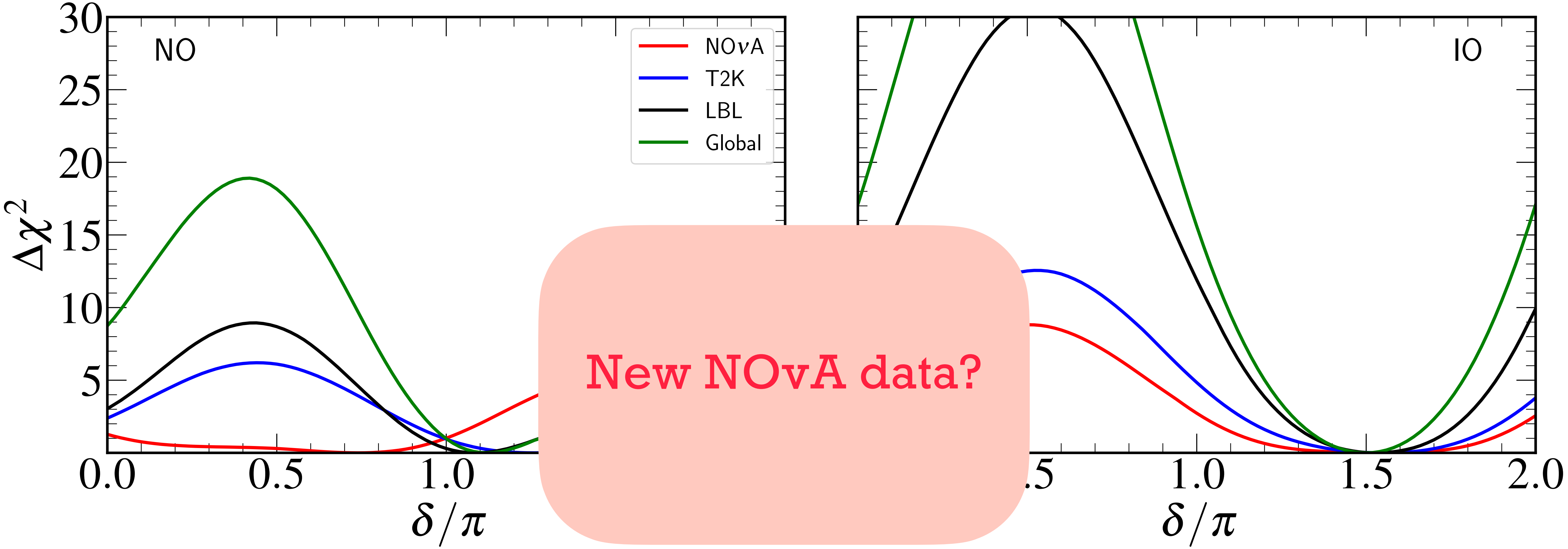
  δ_{BF} = 1.12π ; δ= π/2 (0) disfavored at 4.3σ (2.9σ)

- IO: all experiments prefer δ ≈ 3π/2

  δ_{BF} = 1.5π ; δ= π/2 (π) disfavored at 6.8σ (3.9σ)

The CP phase

Valencia Global Fit (Pre-Nu2024)



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

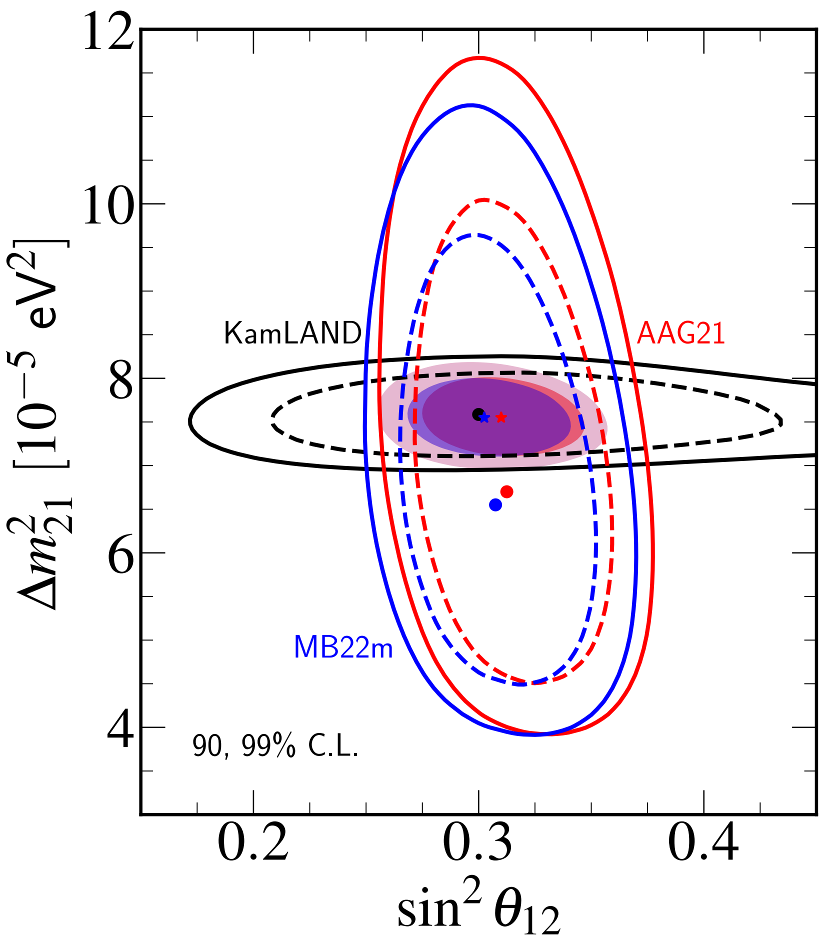
  $\delta_{BF} = 1.12\pi$; $\delta = \pi/2$ (0) disfavored at 4.3σ (2.9σ)

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

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

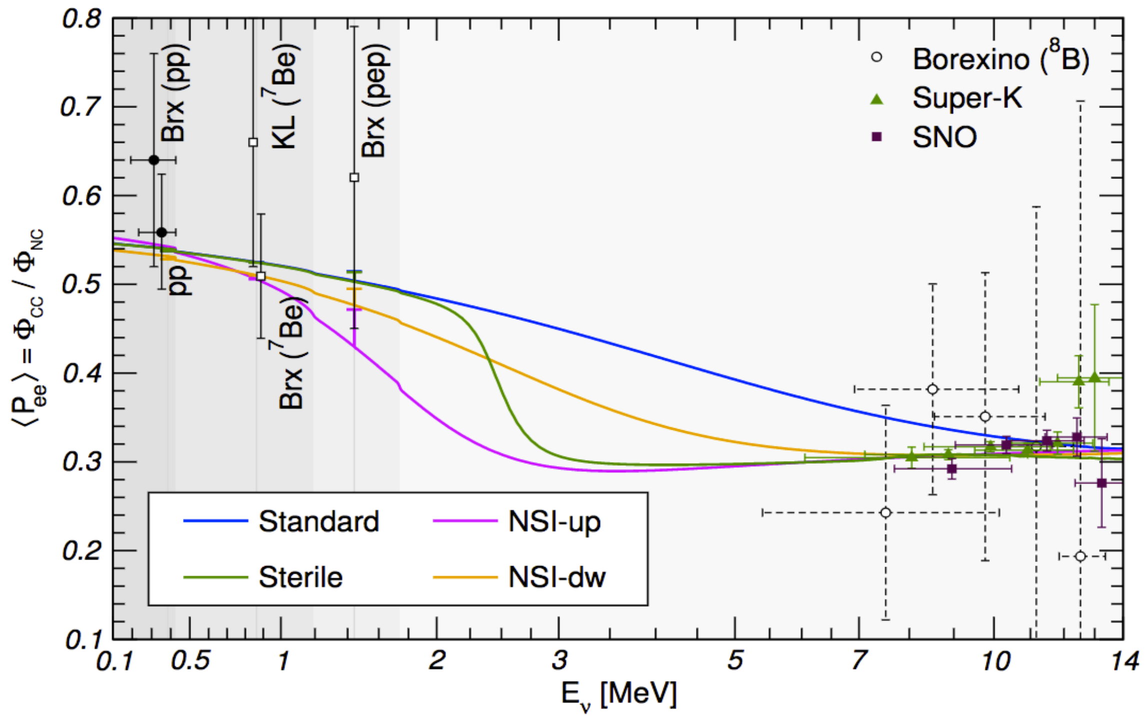
Tensions in global fits to 3ν oscillations ?

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

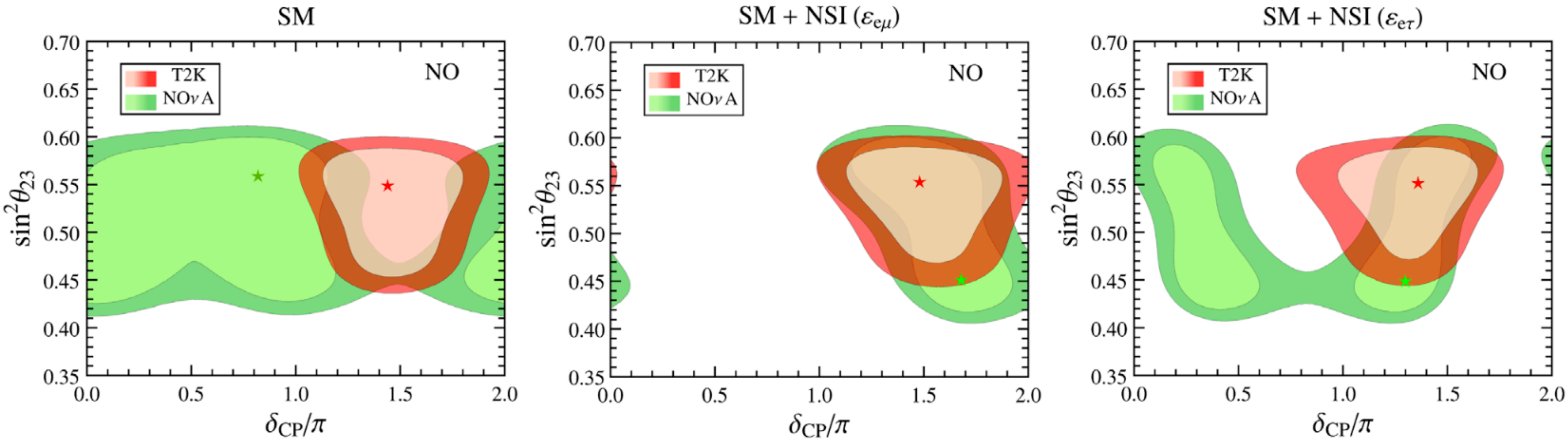
Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017)

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 ~ 0.2-0.3 may reconcile T2K and NOvA results.

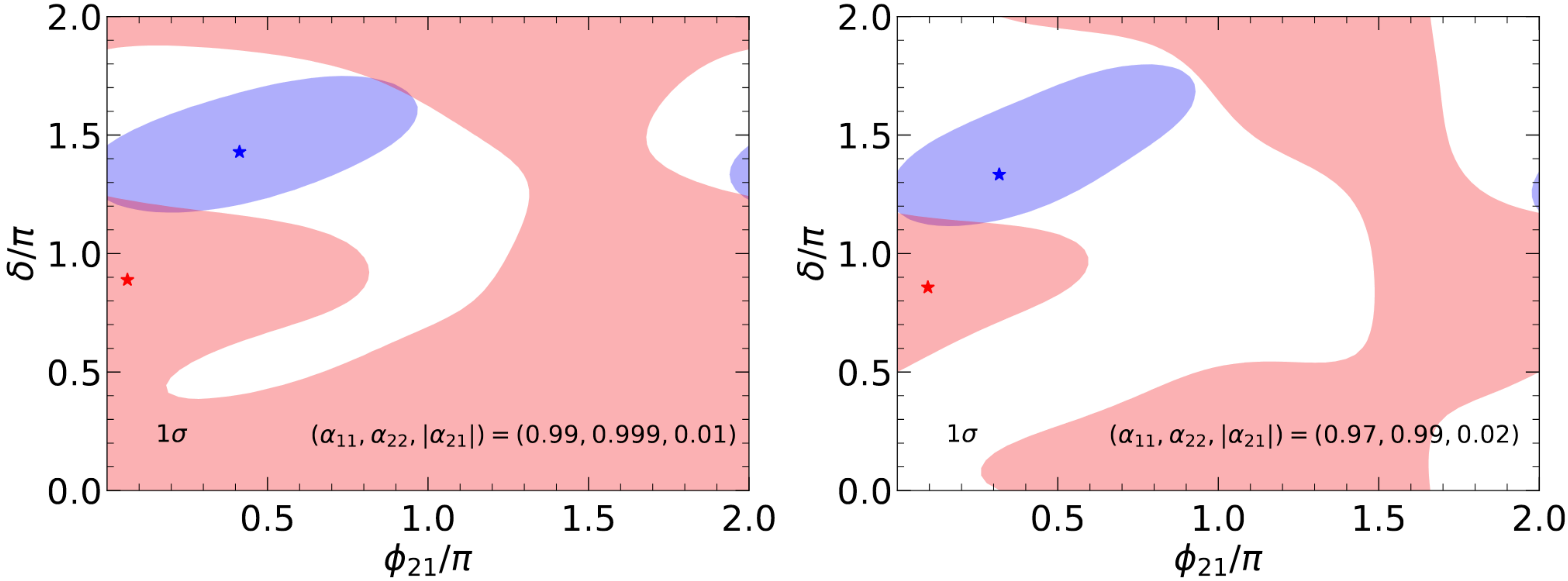


Chatterjee and Palazzo, PRL 2021

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.
- 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 pre-Nu24 global fit:
  - ✓ precise determinations for most parameters (~ 1 - 5%)
  - ✓ slight preference for $\theta_{23} > 45°$ - LO disfavoured by $\Delta\chi^2 \geq 1.0$ (3.0) for NO (IO)
  - ✓ normal ordering preferred over IO with $\Delta\chi^2 = 7.5$ (2.7) w SK (w/o SK)
    - ⇒ Some sensitivity from cosmology. New DESI data?
  - ✓ $\delta_{BF} = 1.12\pi$ (1.5π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.3σ (6.8σ) for NO (IO)
    - ⇒ New results from NOvA ?

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

Special thanks to Christoph A. Ternes and Pablo Martinez-Miravé

Thank you!