

Global analysis of neutrino oscillation data

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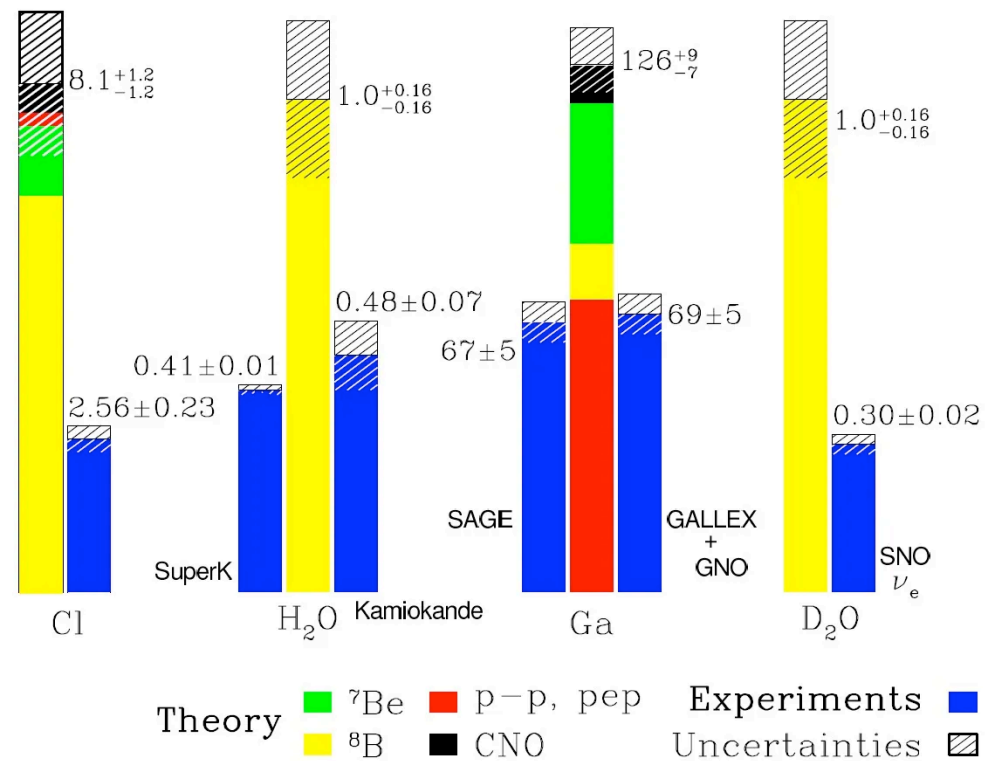
EXCELENCIA
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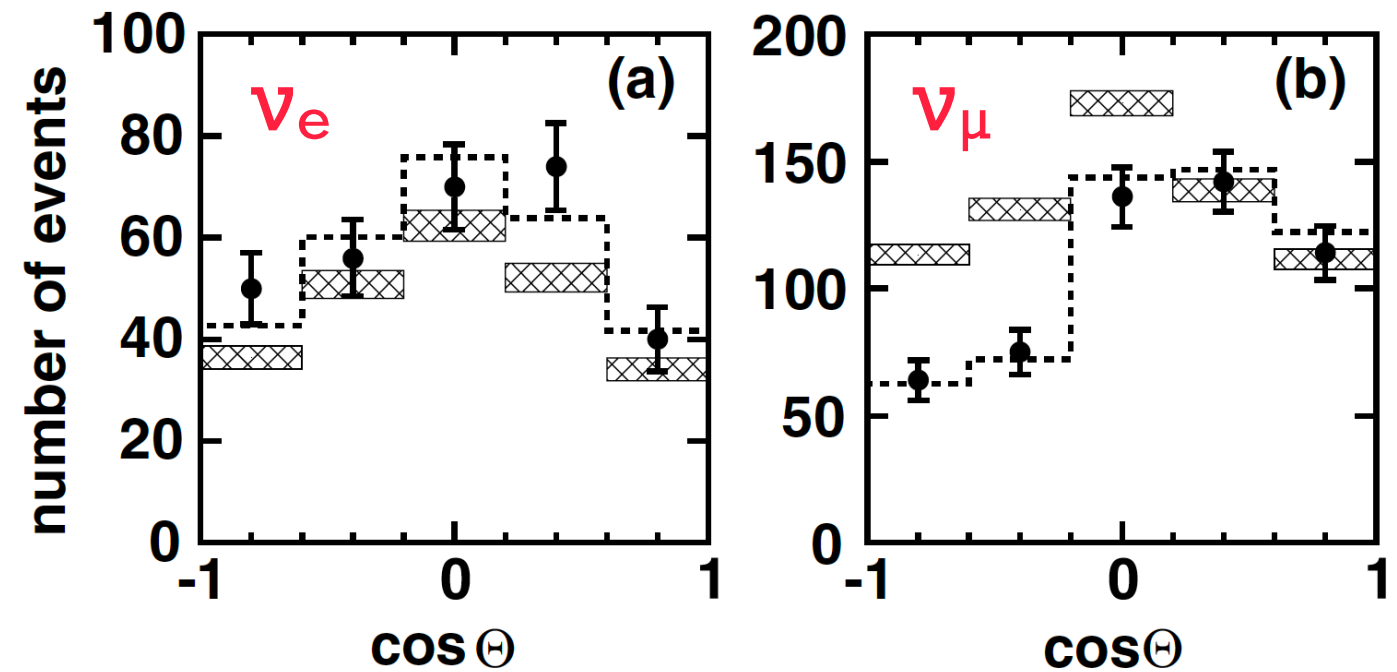
GENERALITAT
VALENCIANA
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Universitats i Ocupació

Neutrino anomalies

Solar neutrino problem (60's)



Atmospheric neutrino anomaly (80's)



$$\nu_e \rightarrow \nu_\mu, \nu_\tau$$



$$\nu_\mu \rightarrow \nu_\tau$$

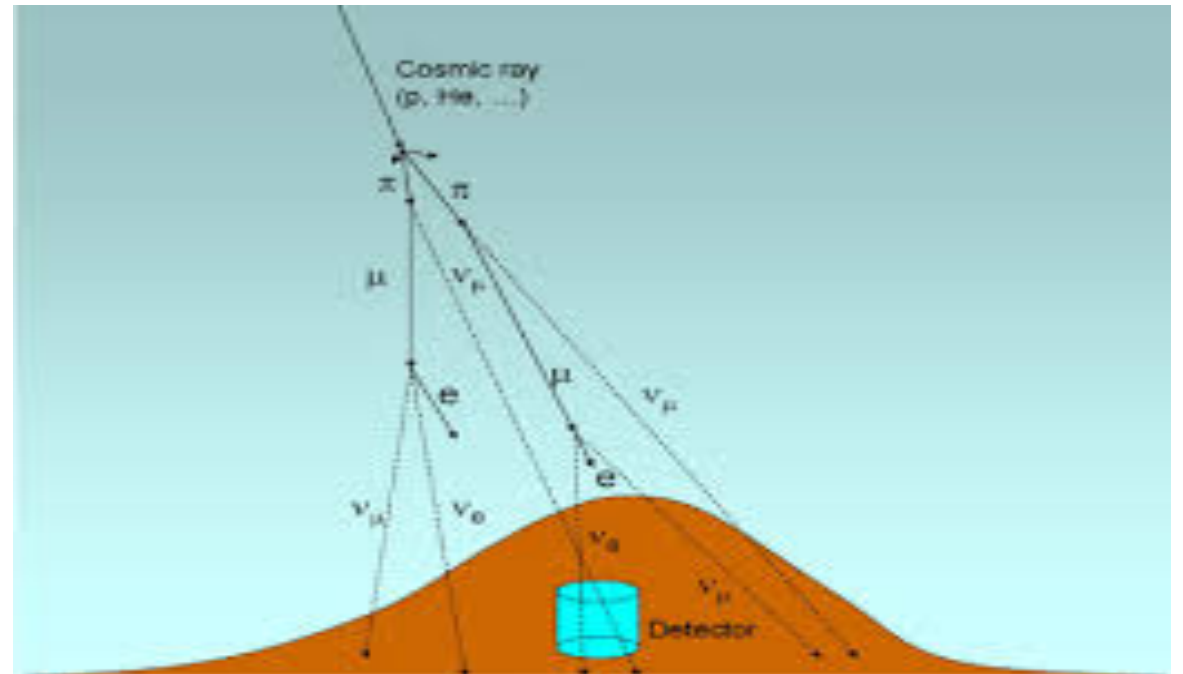
2015: Nobel Prize

Neutrino oscillations

Solar neutrinos



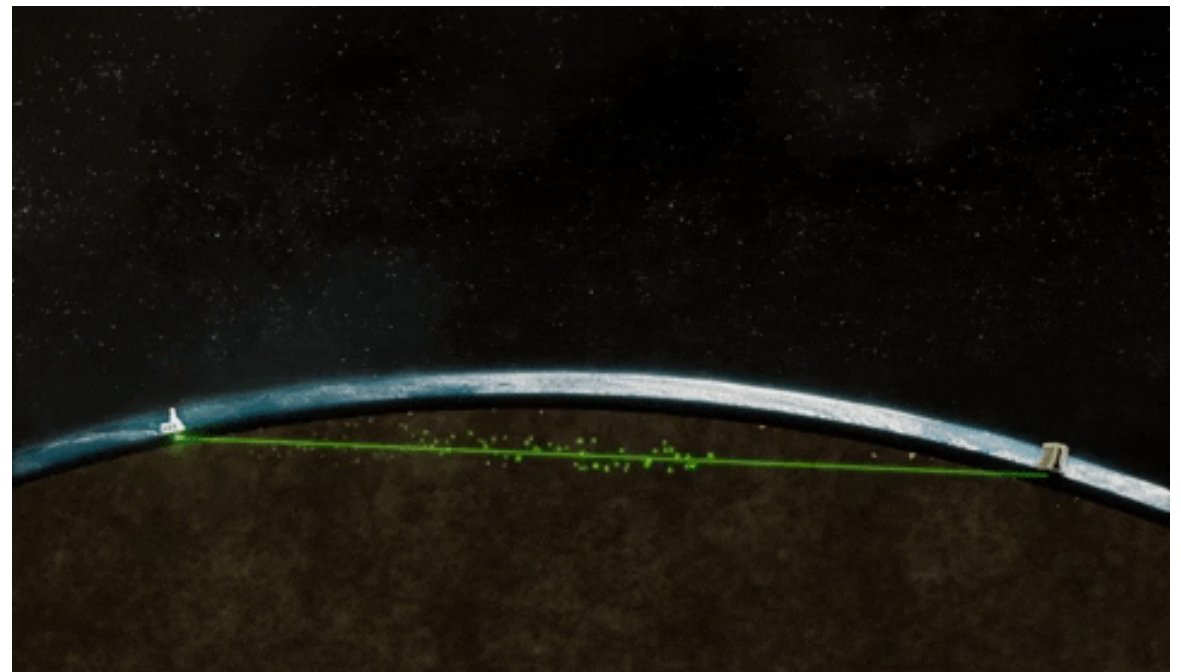
Atmospheric neutrinos



Reactor neutrinos



Accelerator neutrinos



The three-flavour ν picture

neutrino mixing

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

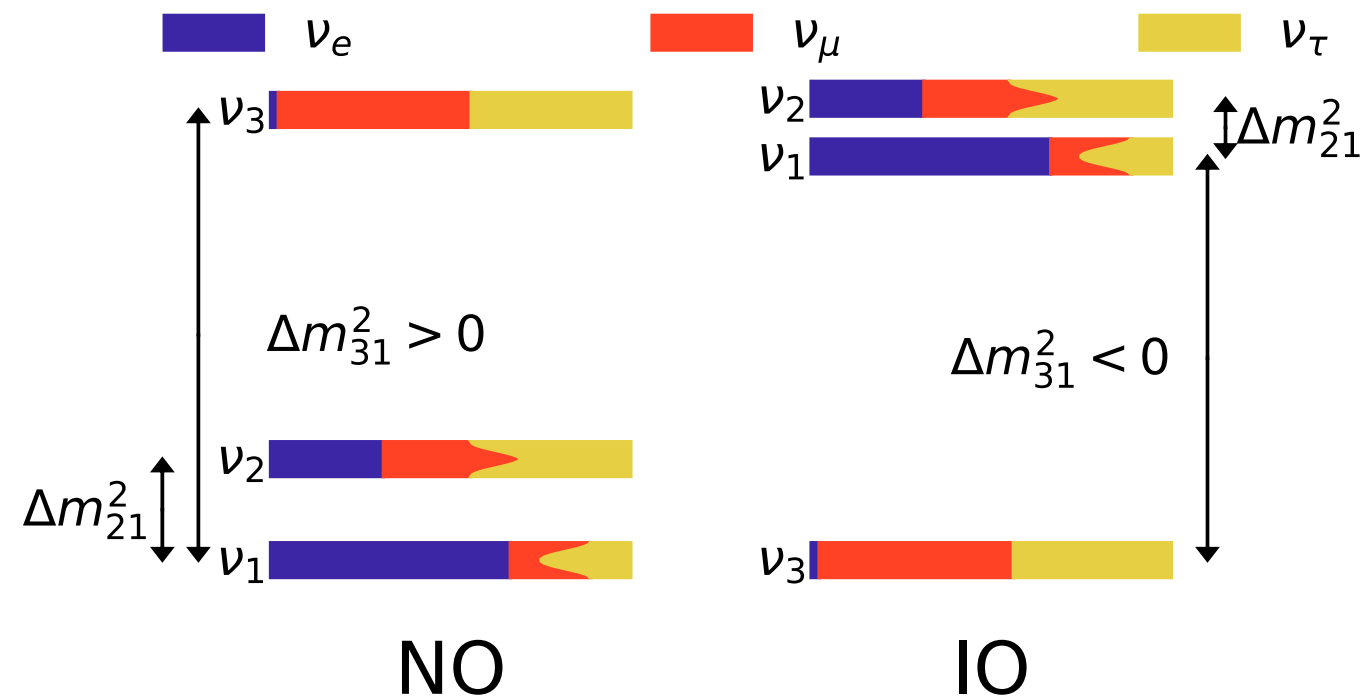
neutrino mass spectrum

- ✓ 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:

$$\Delta m_{21}^2, \Delta m_{31}^2$$



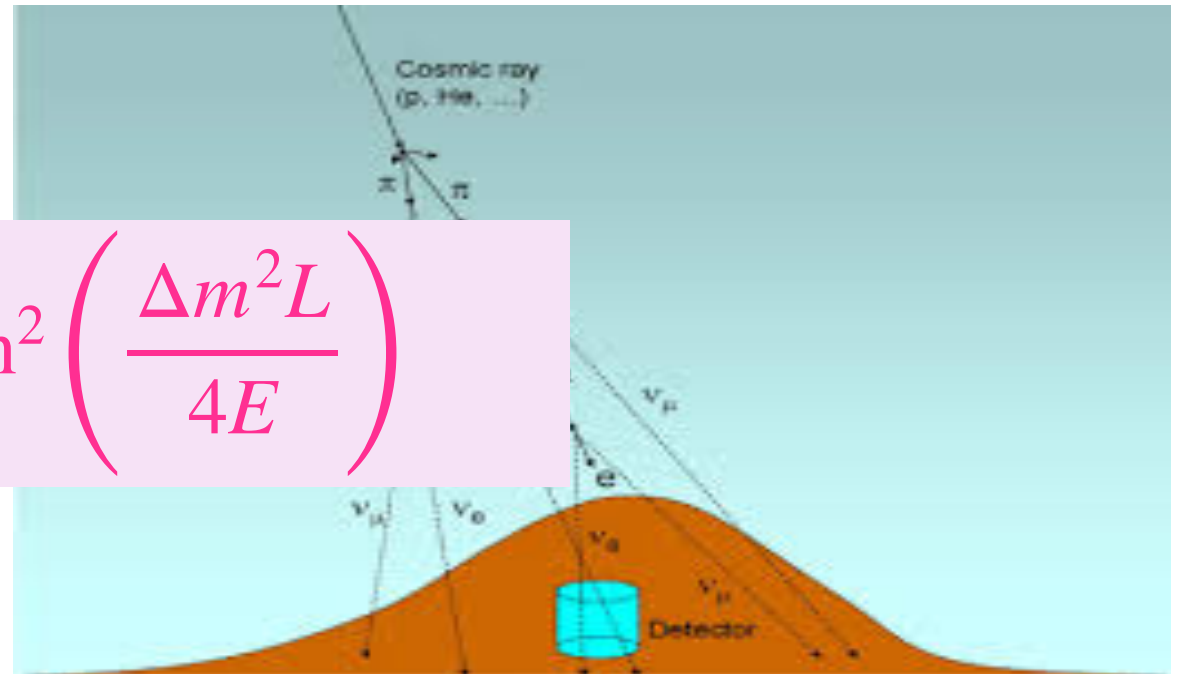
Neutrino oscillations

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



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

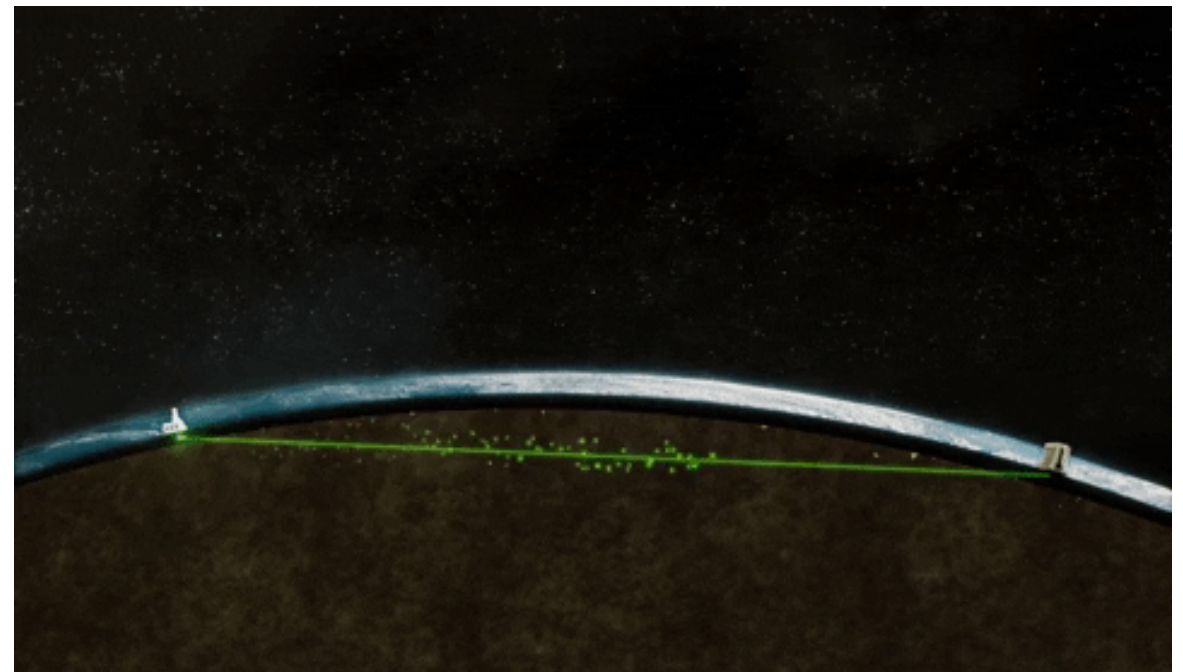
Atmospheric sector: $\theta_{23}, \Delta m^2_{31}$



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



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



Three-neutrino oscillations

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\alpha j} U_{\beta i} U_{\beta j}^*) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right)$$

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

atmos + accel

$(\nu_\mu \rightarrow \nu_\tau)$

SBL reac + accel

$(\nu_e \rightarrow \nu_e \text{ and } \nu_\mu \rightarrow \nu_e)$

solar + LBL reac

$(\nu_e \rightarrow \nu_e)$

Maximal
sensitivity at

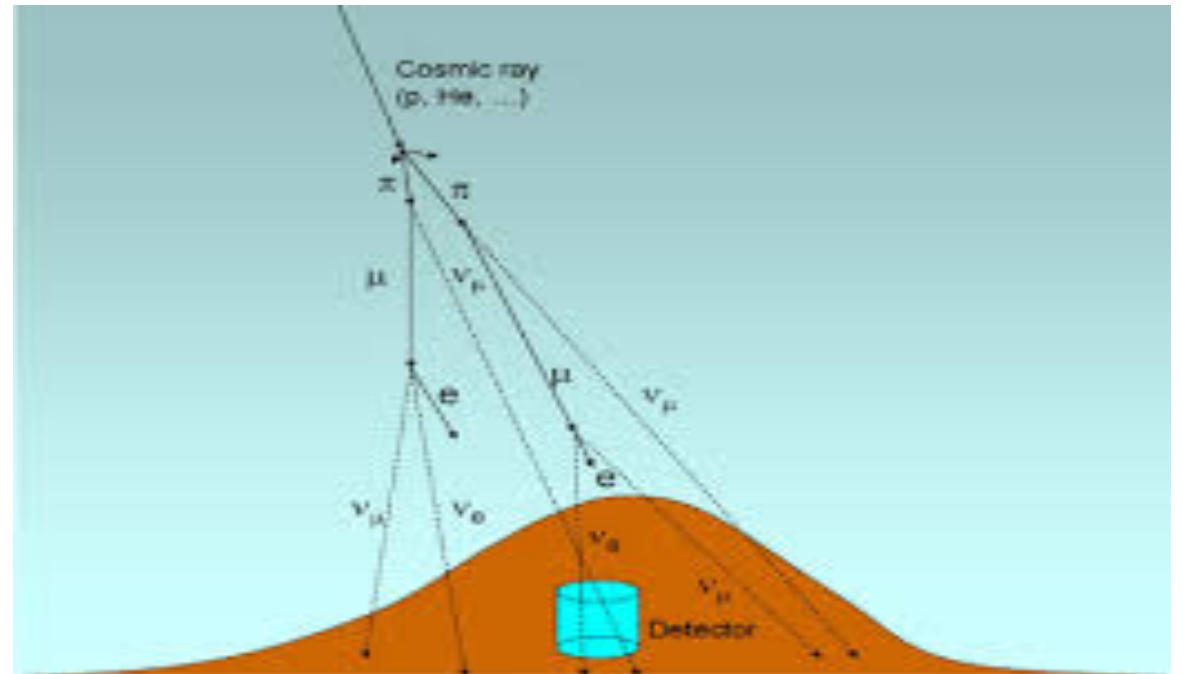
$$\frac{\Delta m_{ij}^2 L}{4E} \sim \frac{\pi}{2} = 1.27 \frac{\Delta m_{ij}^2 [eV^2] L [km]}{E [GeV]}$$

Neutrino oscillations

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



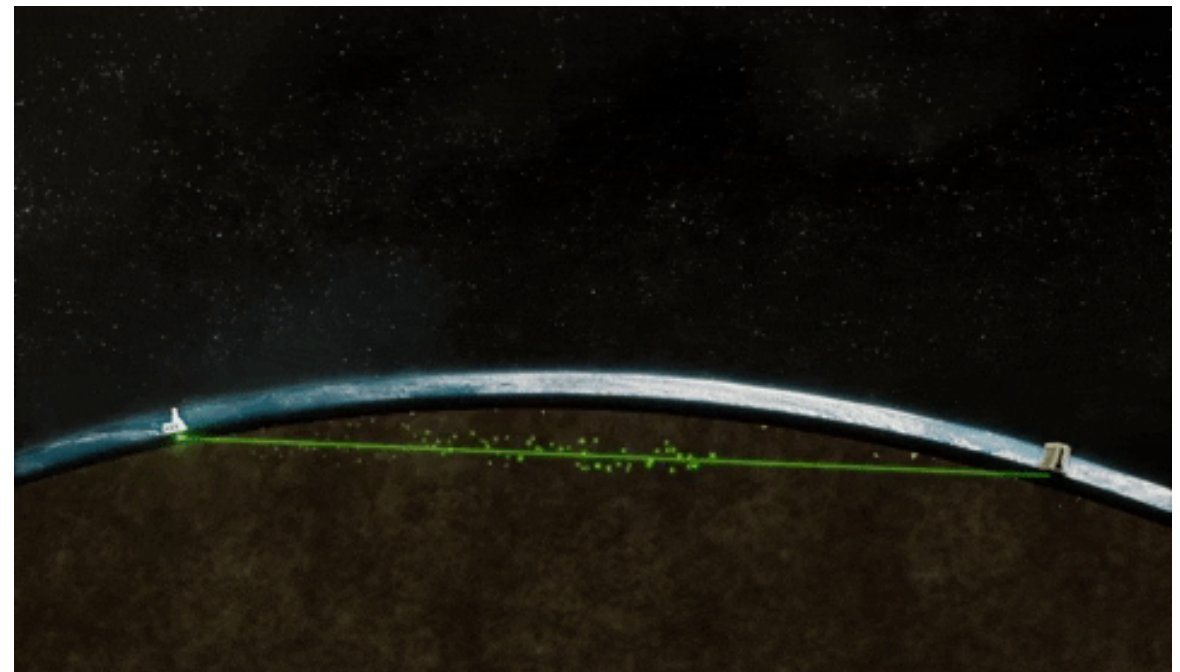
Atmospheric sector: θ_{23} , θ_{13} , Δm^2_{31} , δ



Reactor sector (SBL): θ_{13} , Δm^2_{31}



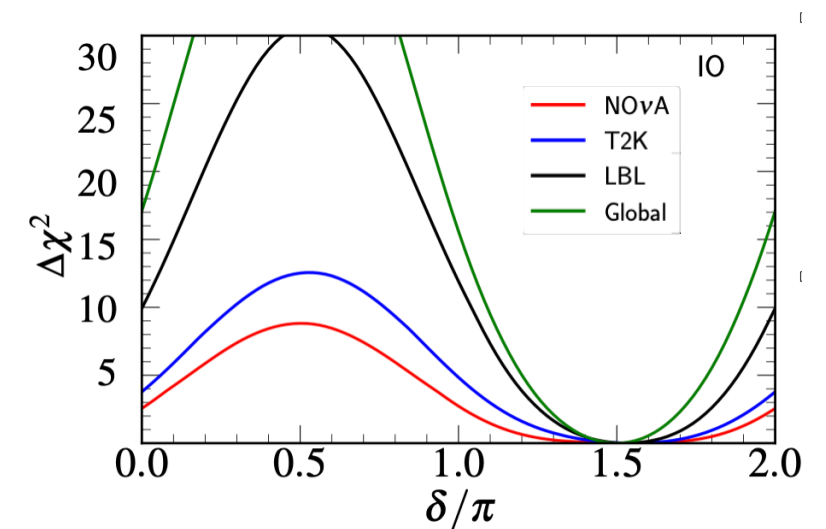
Accelerator sector: θ_{23} , θ_{13} , Δm^2_{31} , δ



Global analysis to ν oscillations

1

Compensate low statistics in
subleading oscillation effects
searches



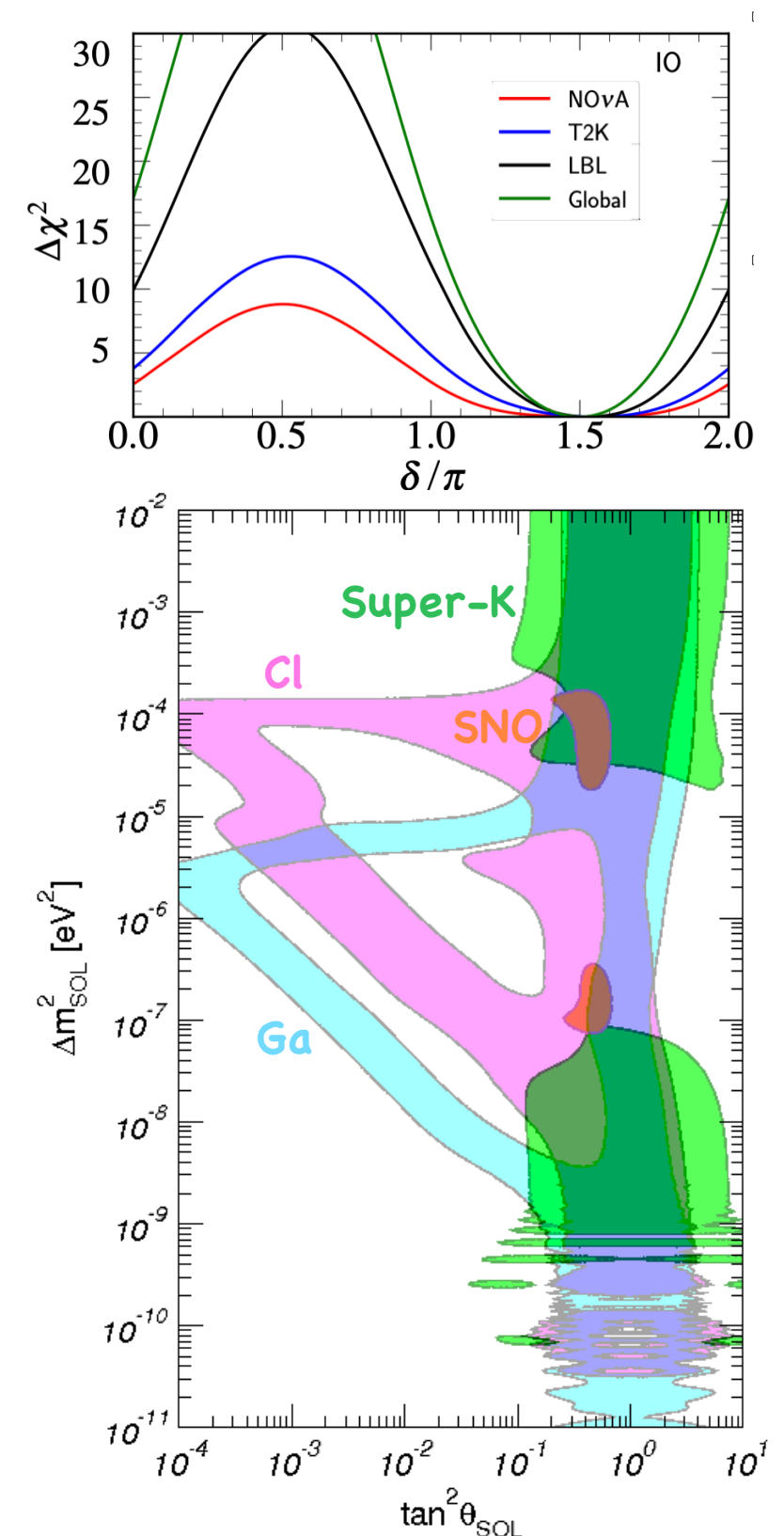
Global analysis to ν oscillations

1

Compensate low statistics in
subleading oscillation effects
searches

2

Exploit synergies among
experiments



Global analysis to ν oscillations

1

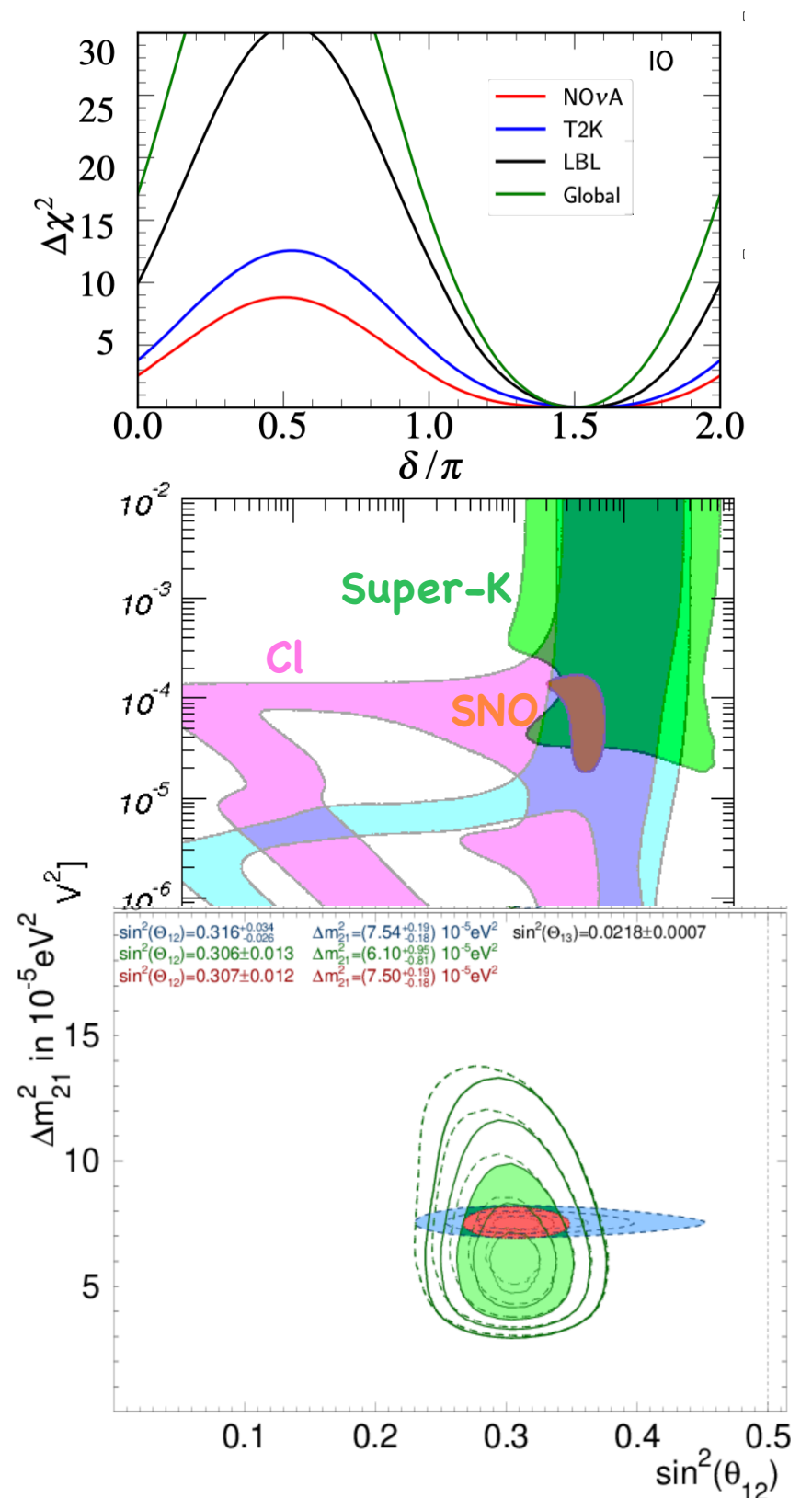
Compensate low statistics in subleading oscillation effects searches

2

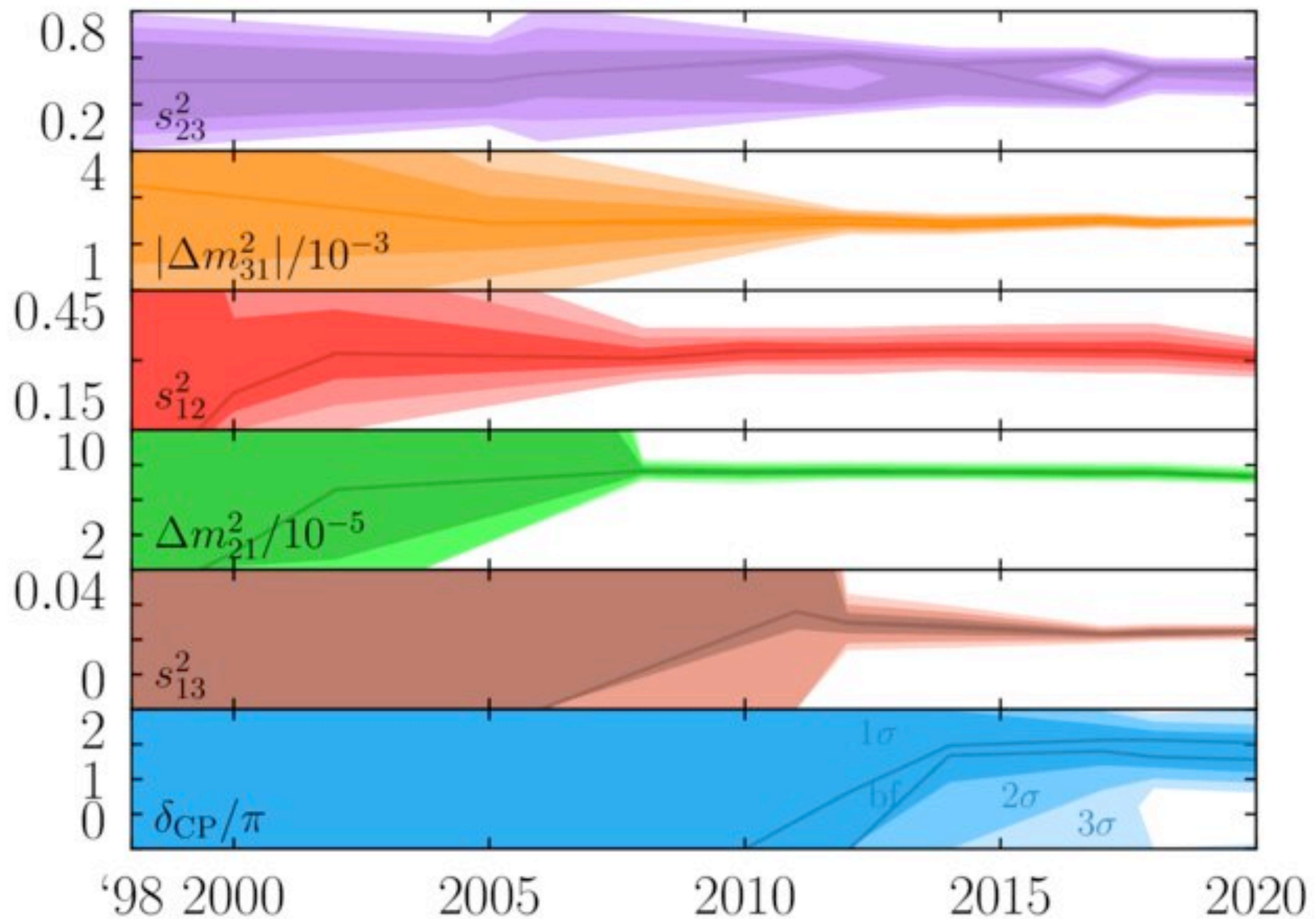
Exploit synergies among experiments

3

Reveal tensions among data



Three-neutrino oscillation parameters

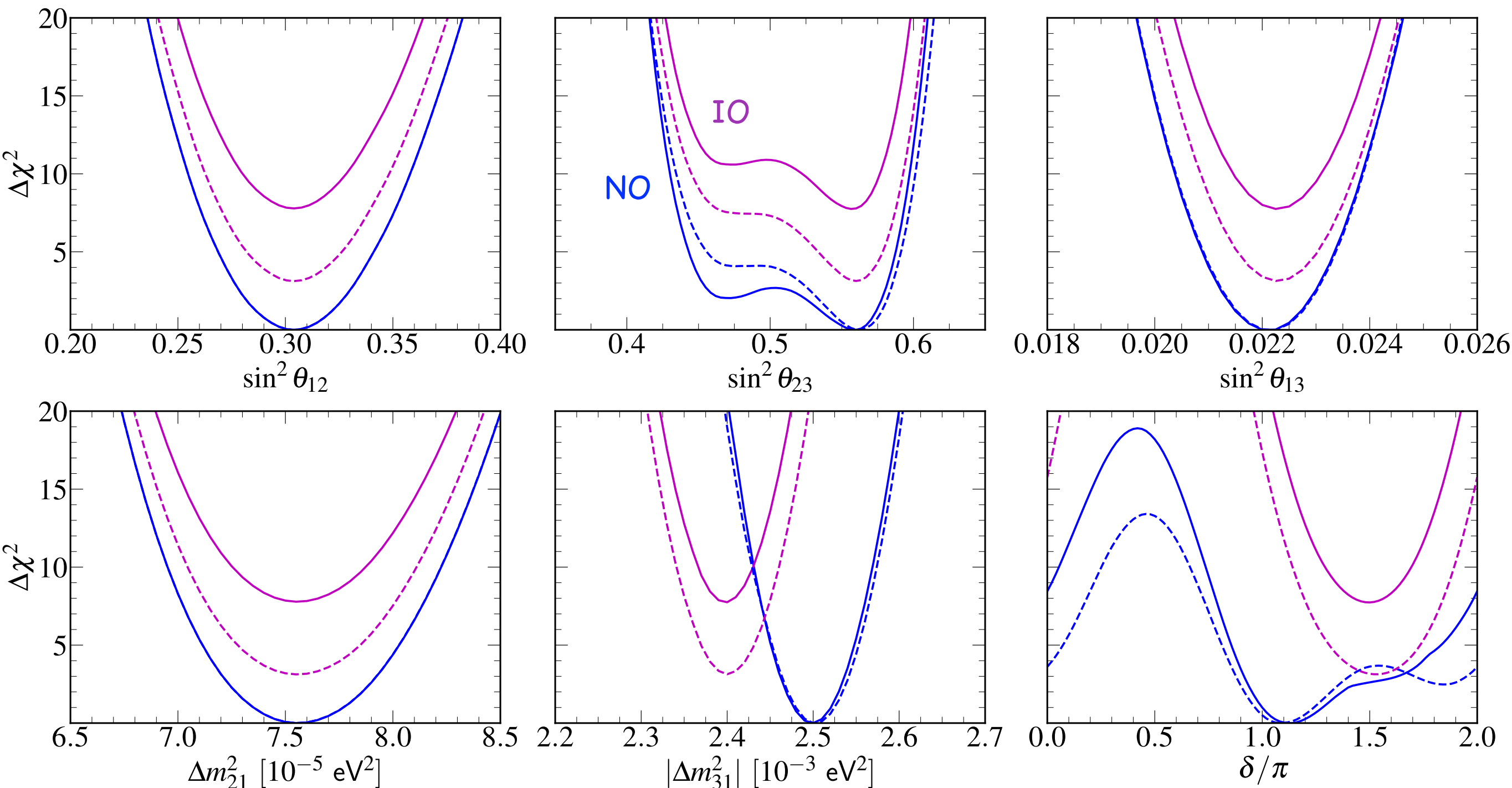


Denton et al, Snowmass Neutrino Frontier: NF01 Report [arXiv:2212.00809]

Global fit to ν oscillation parameters

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

<https://globalfit.astroparticles.es/>

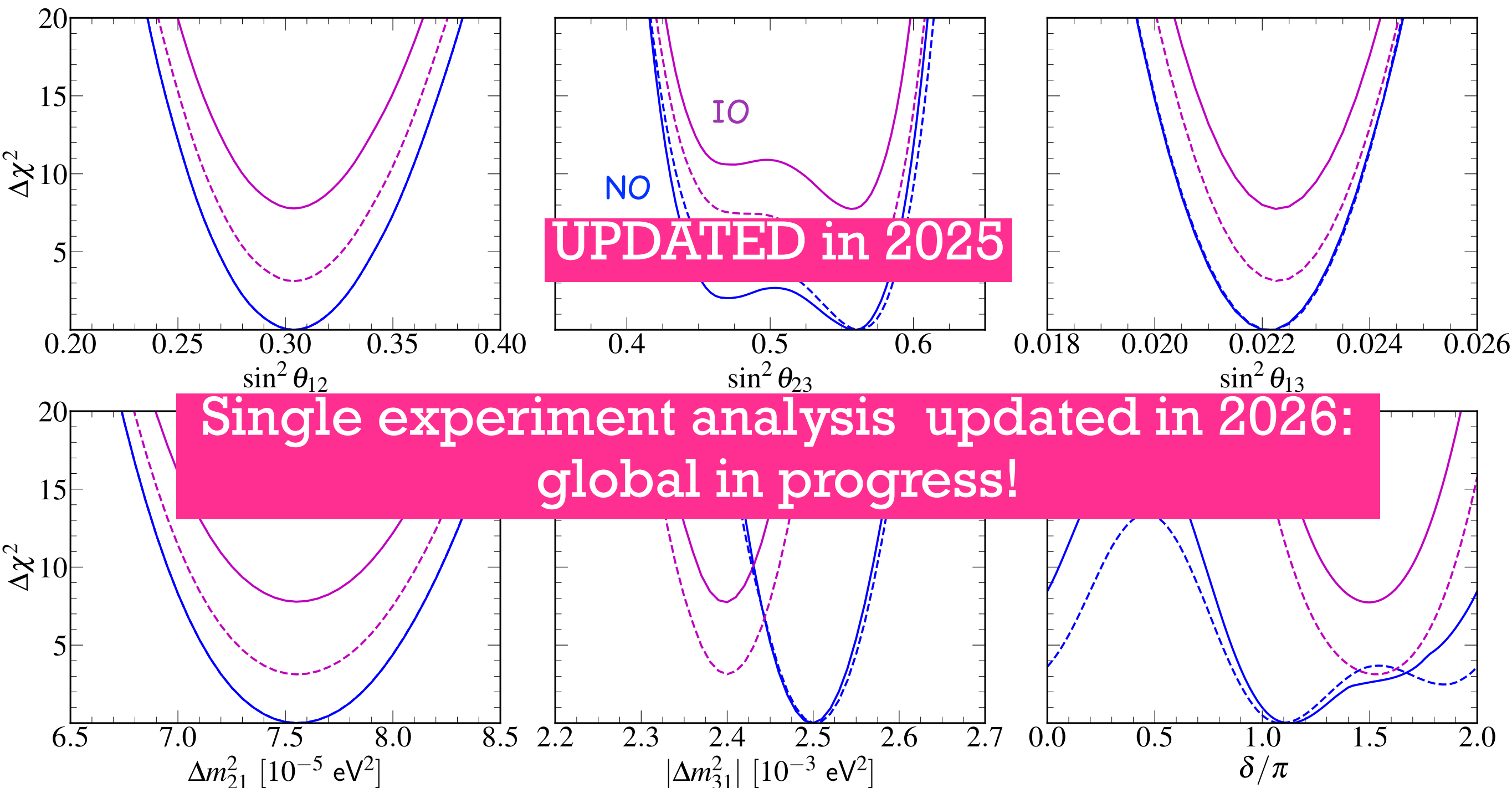


See also NuFIT and Bari Group

Global fit to ν oscillation parameters

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

<https://globalfit.astroparticles.es/>



See also NuFIT and Bari Group

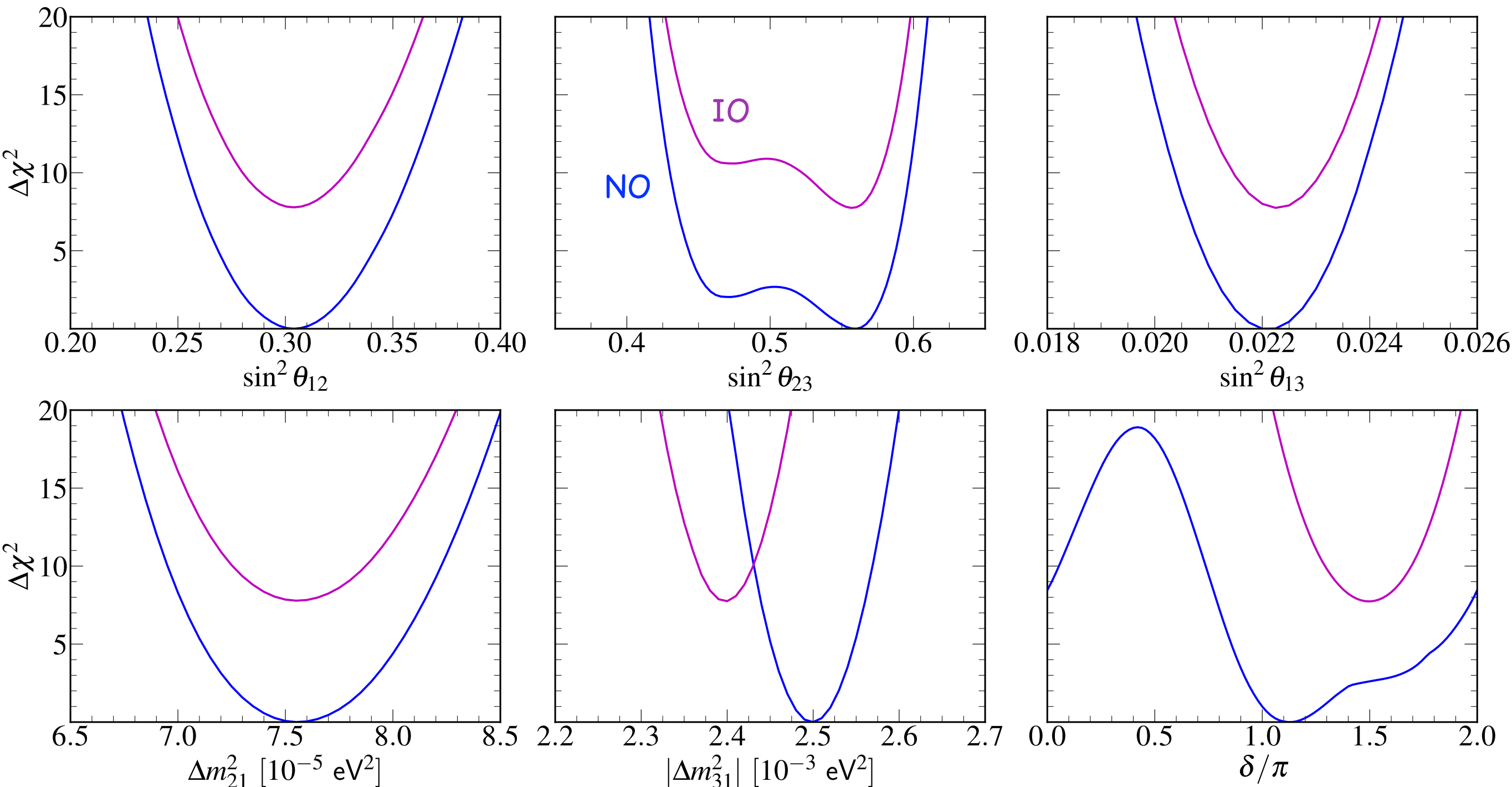
— w SK-atm - - - w/o SK.atm

Global fit to ν oscillation parameters

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

<https://globalfit.astroparticles.es/>

UPDATED!



with SK atmospheric

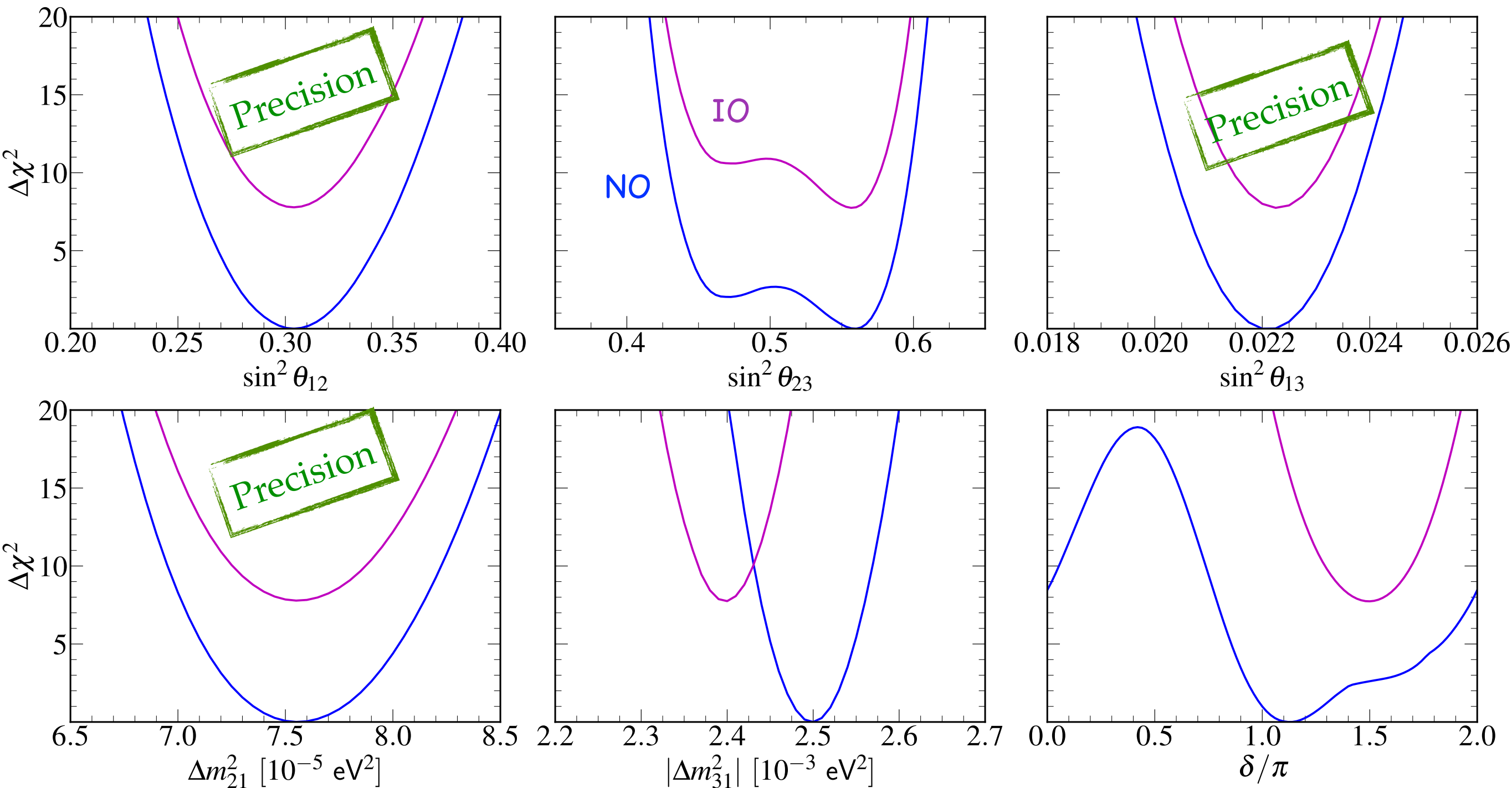
$\Delta\chi^2(\text{IO-NO}) = 7.7$

Global fit to ν oscillation parameters

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UPDATED!



with SK atmospheric

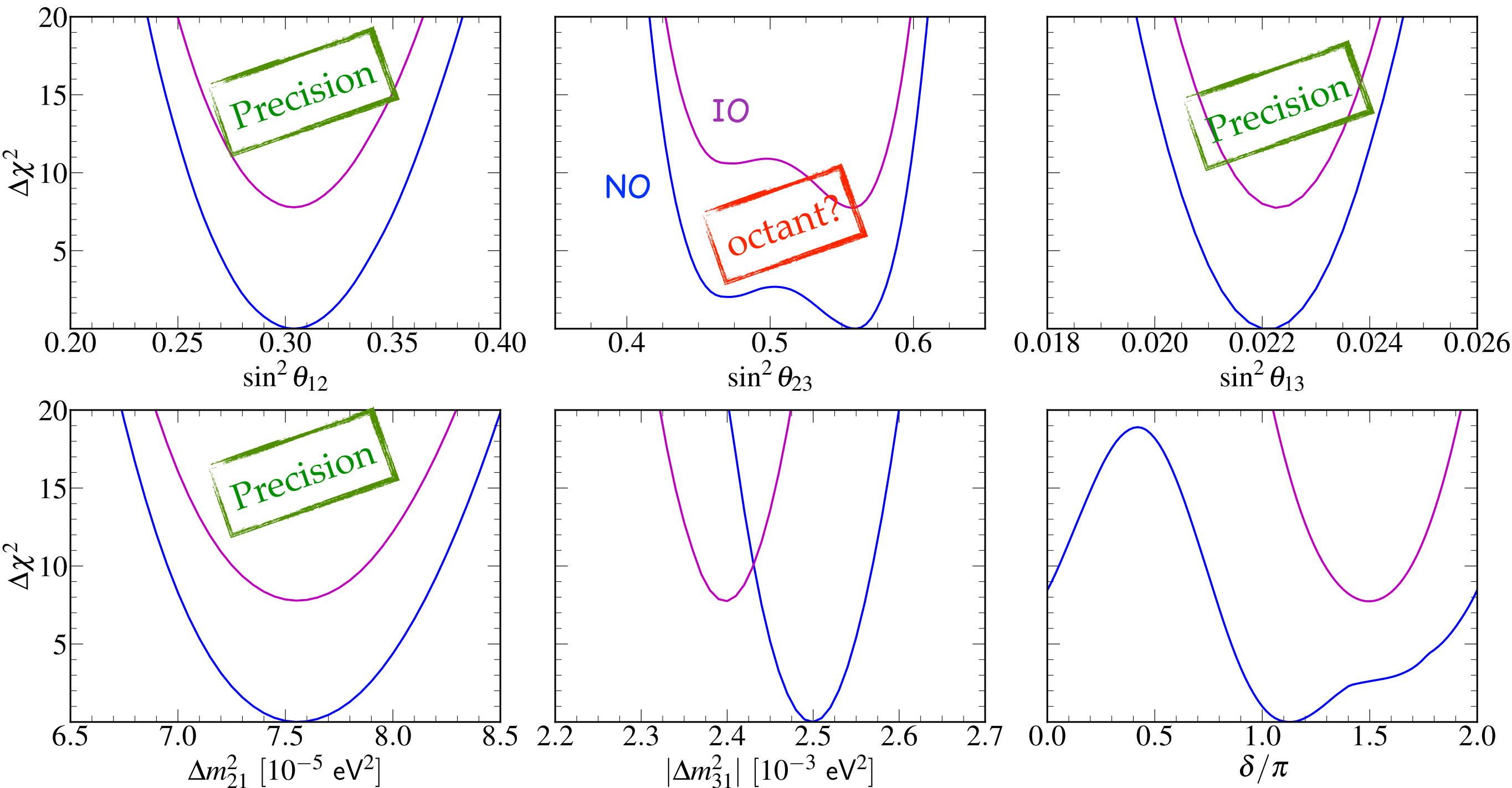
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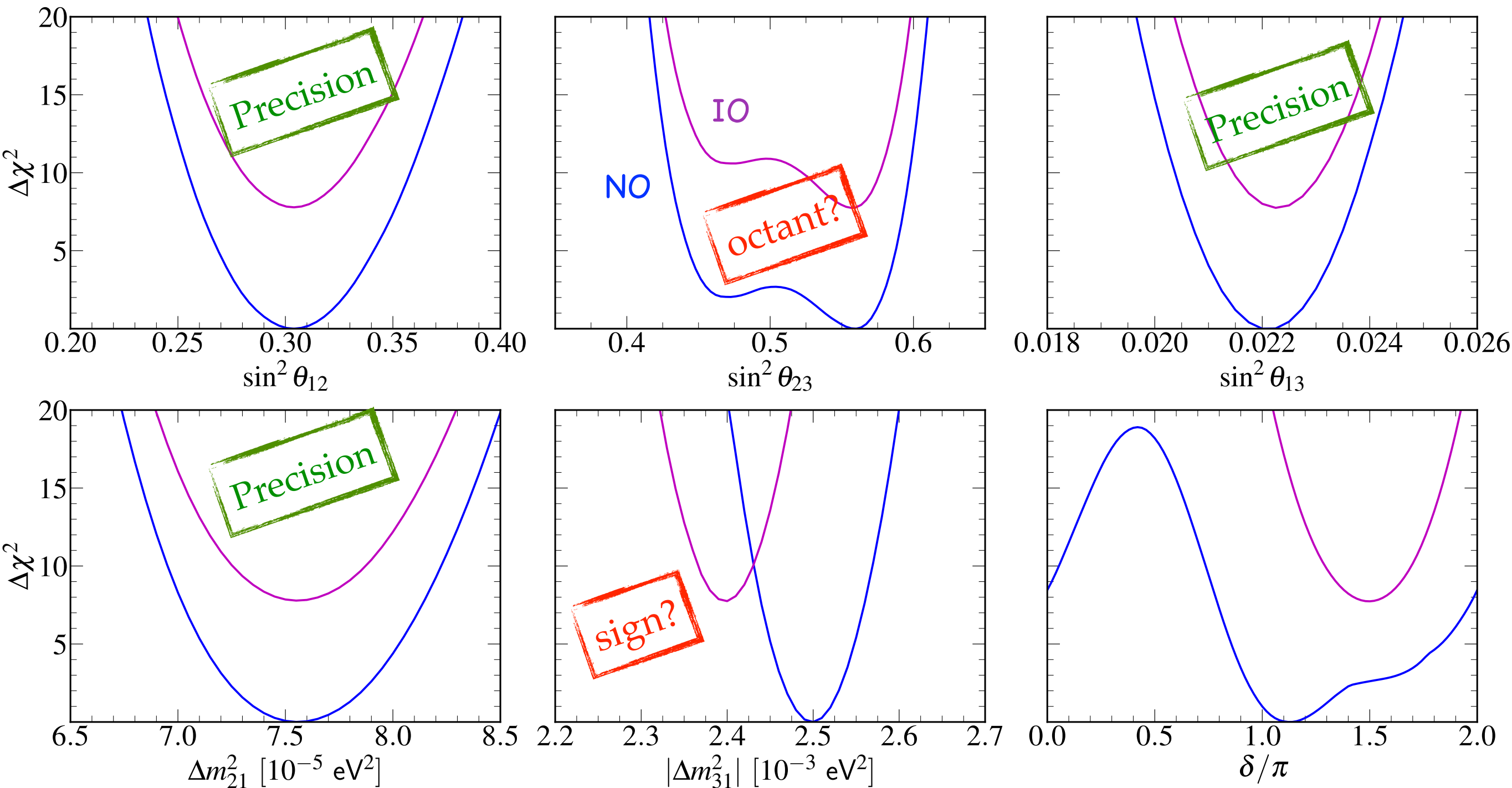
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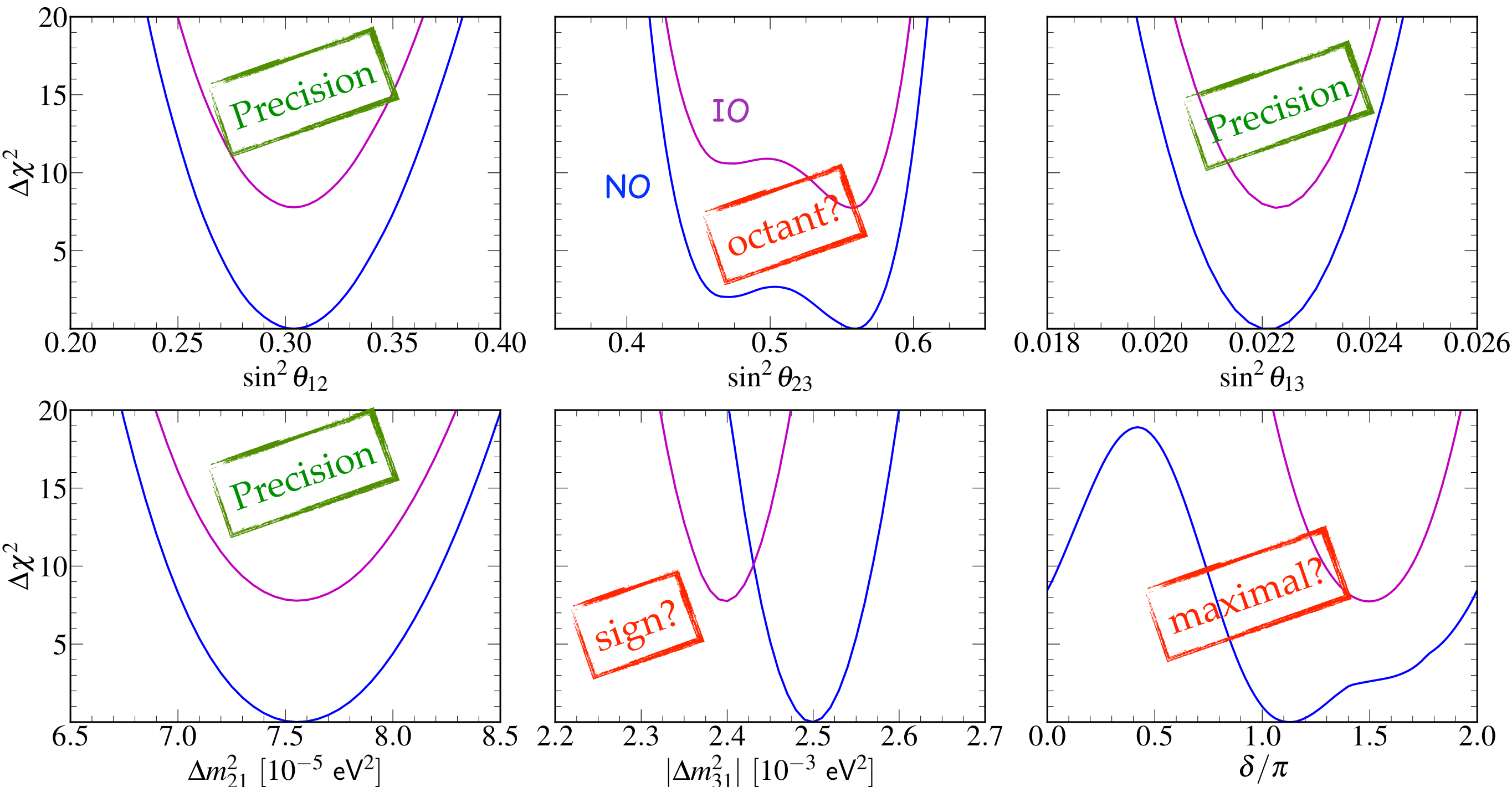
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UPDATED!



with SK atmospheric

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

Global fit to ν oscillation parameters

			relative 1σ uncert	
parameter	best fit $\pm 1\sigma$	3σ range		
Δm_{21}^2 [10^{-5}eV^2]	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %	
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	2.50 ± 0.02	2.43–2.57	0.9 %	mass ordering?
$ \Delta m_{31}^2 $ [10^{-3}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		

Neutrino oscillations

Reactor sector: θ_{13} , Δm^2_{31}



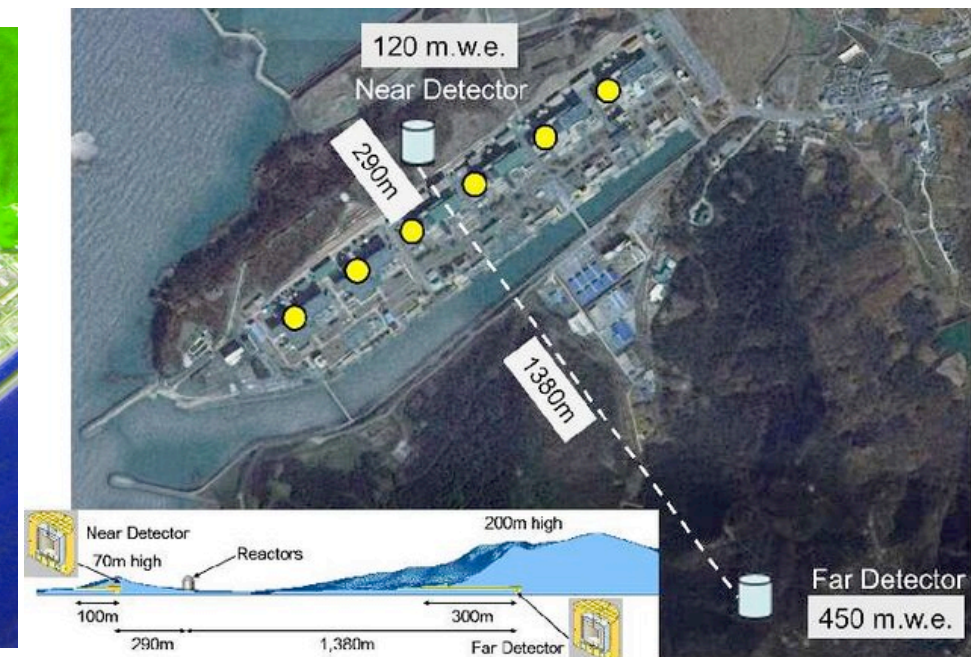
SBL reactor experiments



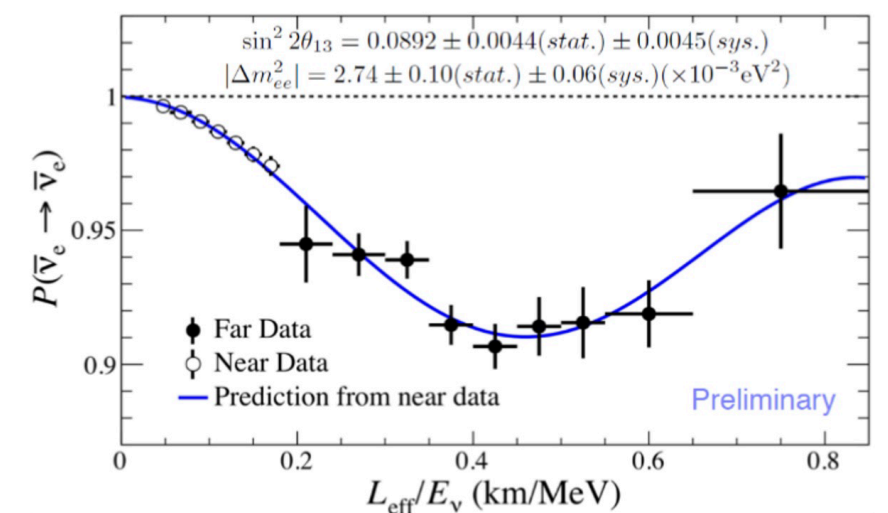
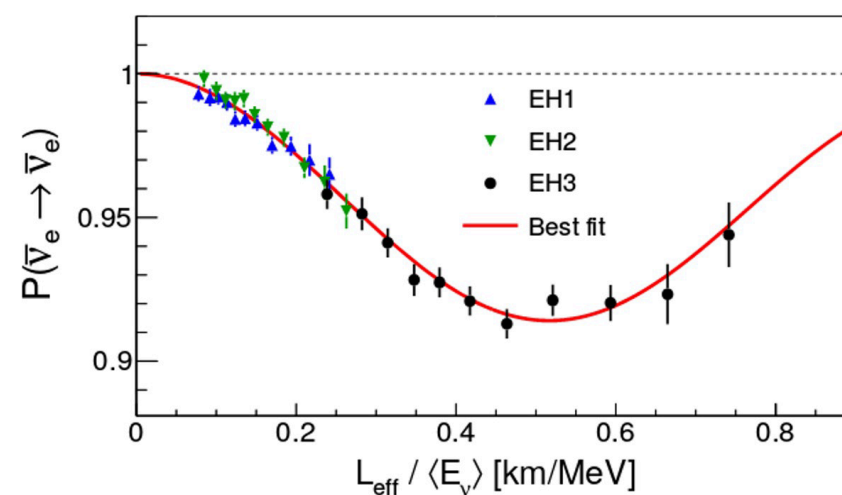
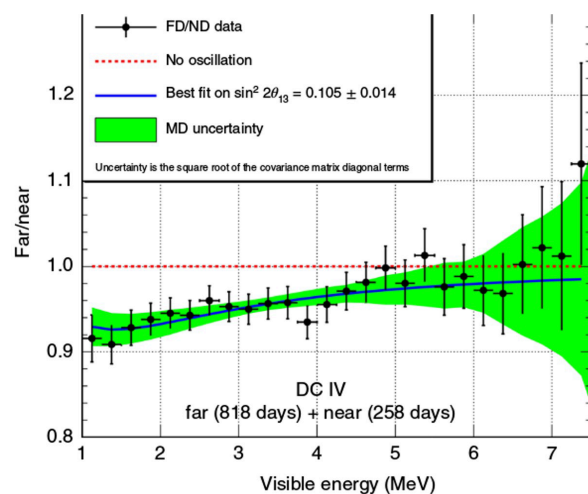
2 reactors + 1 ND + 1 FD (10 ton)



6 reactors + 4 ND + 4FD (20 ton)

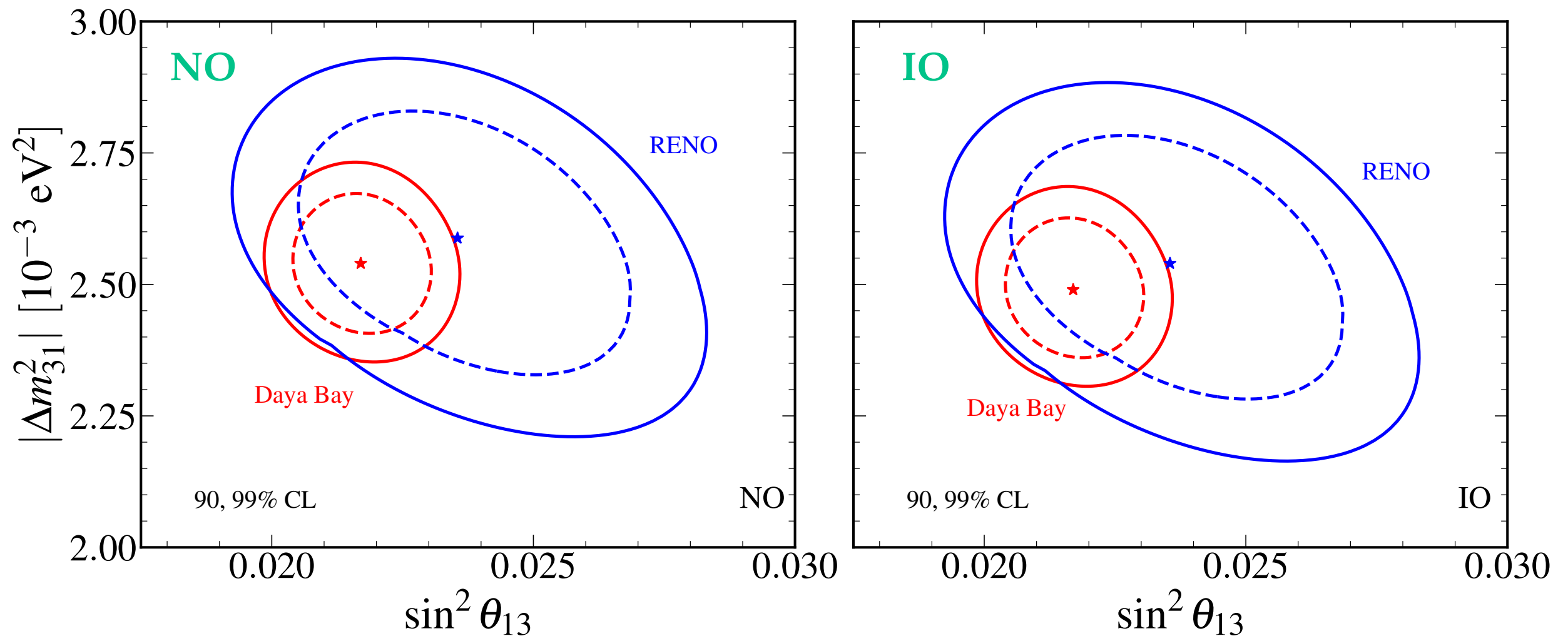


6 reactors + 1 ND + 1 FD (16 ton)



The reactor sector

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E} \right)$$

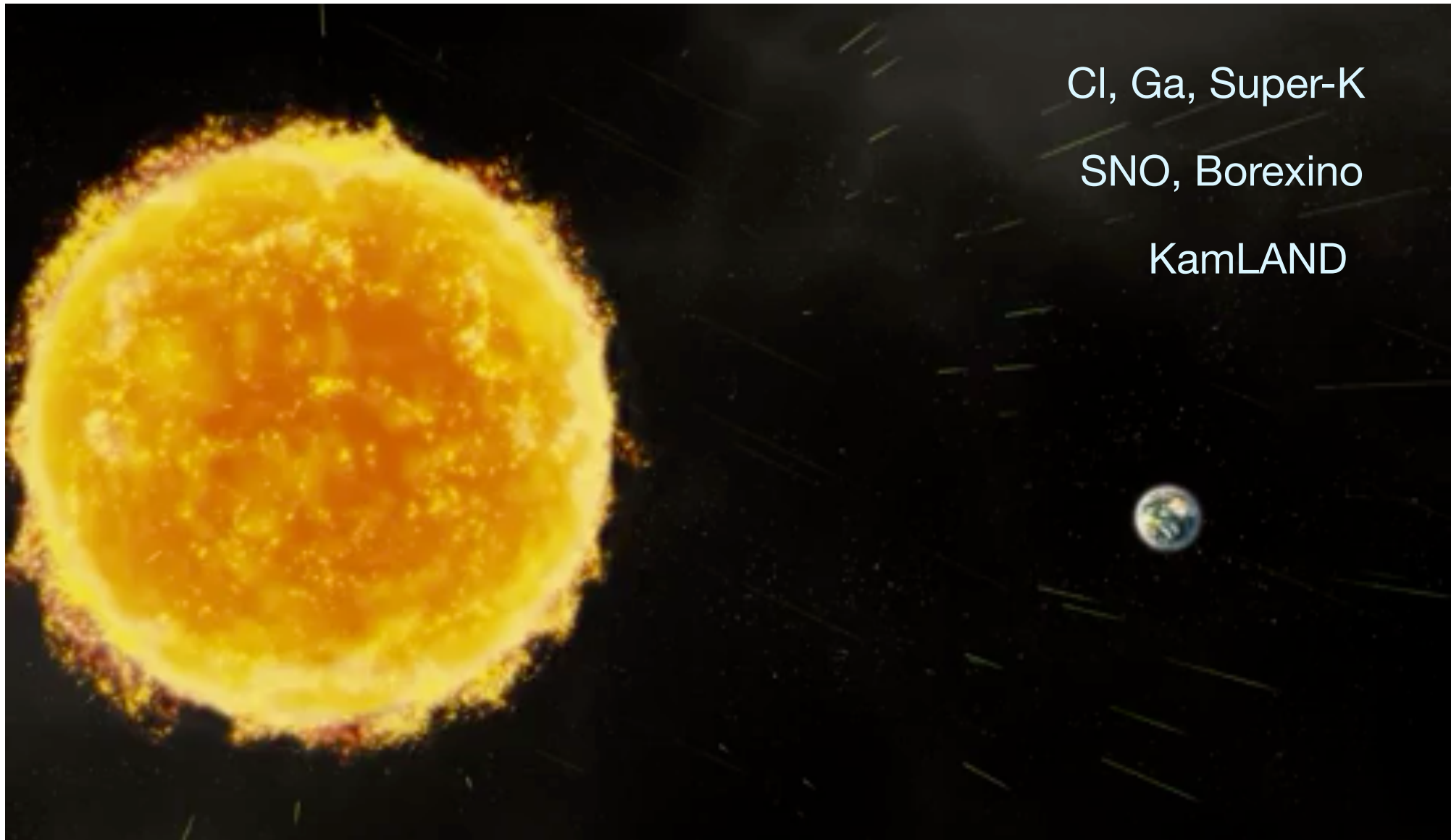


$$\sin^2 \theta_{13} = (2.20^{+0.07}_{-0.04}) \cdot 10^{-2}$$

$$\sin^2 \theta_{13} = (2.23^{+0.05}_{-0.06}) \cdot 10^{-2}$$

Neutrino oscillations

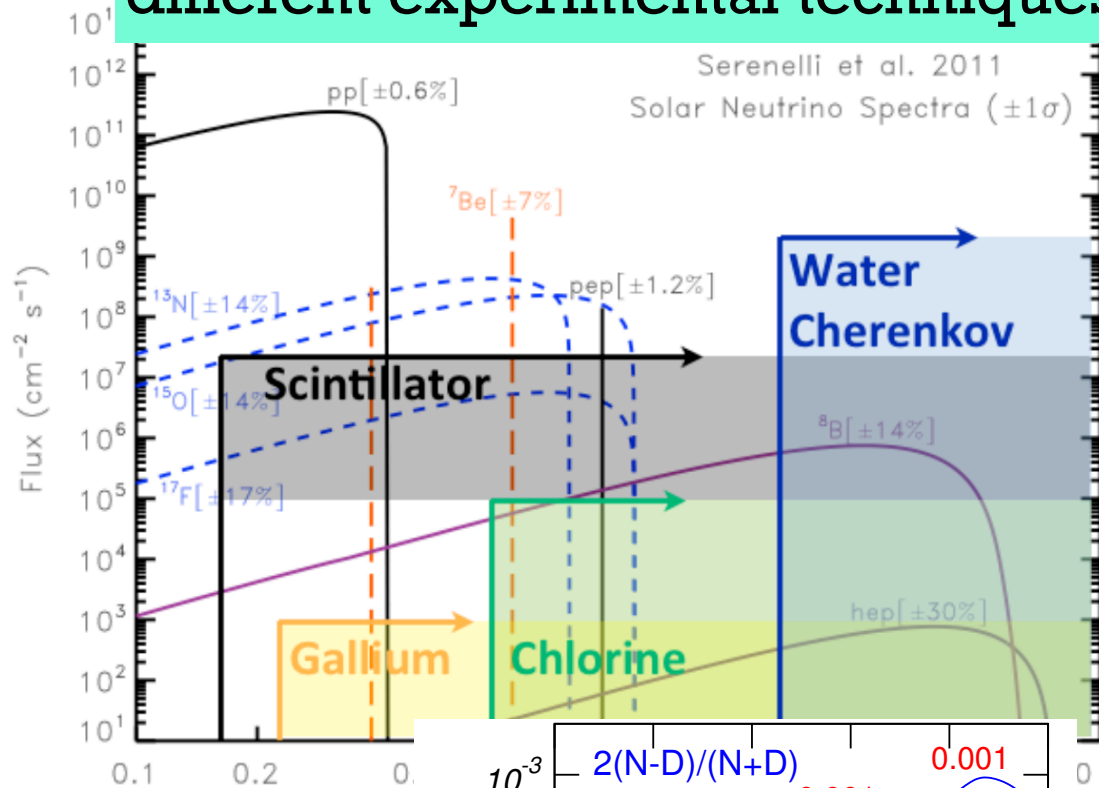
Solar sector: θ_{12} , θ_{13} , Δm^2_{21}



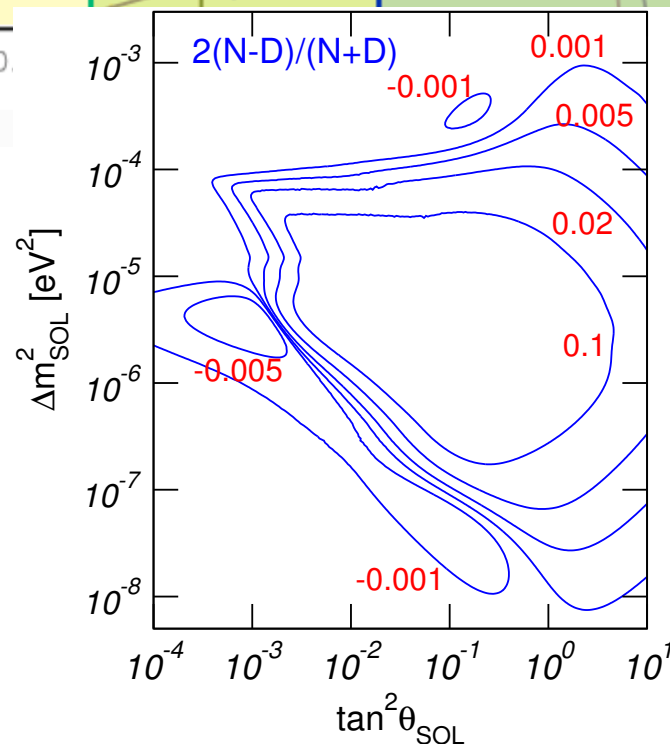
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

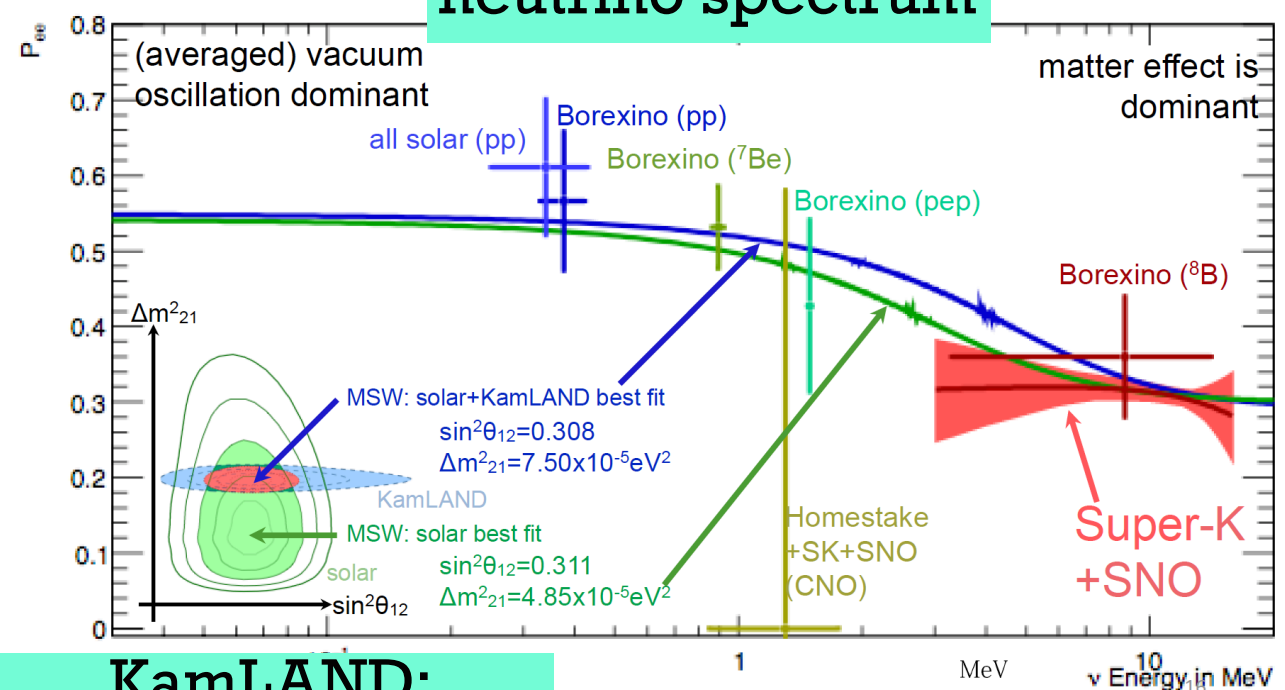
different experimental techniques



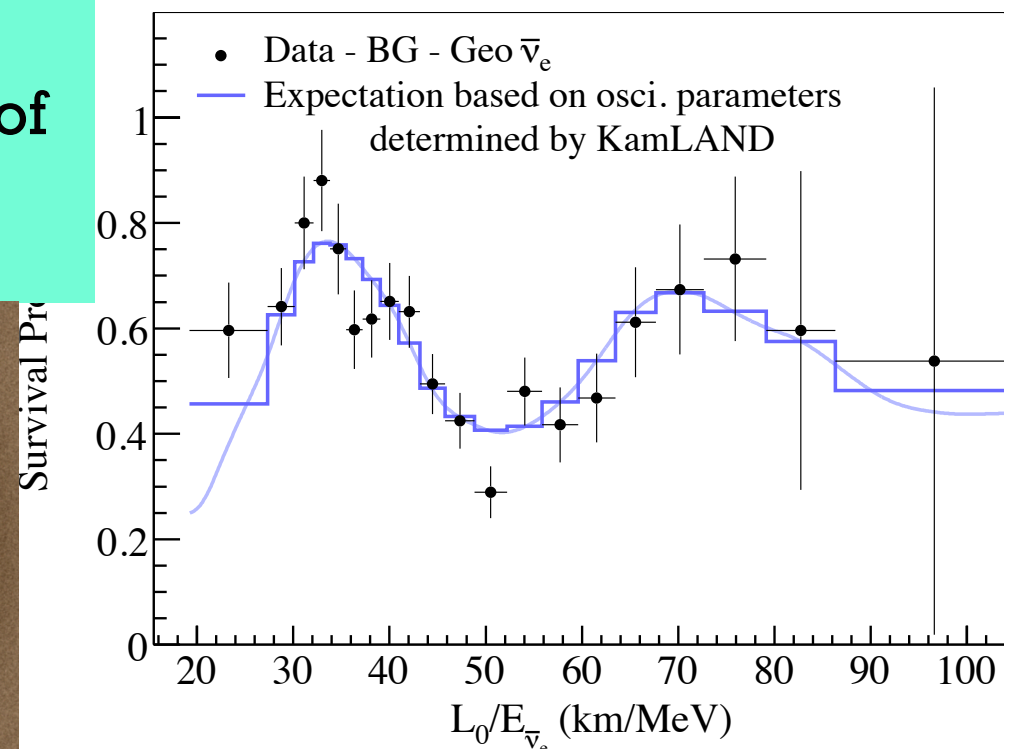
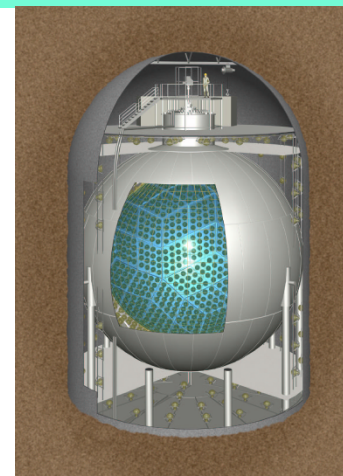
day/night asymmetry



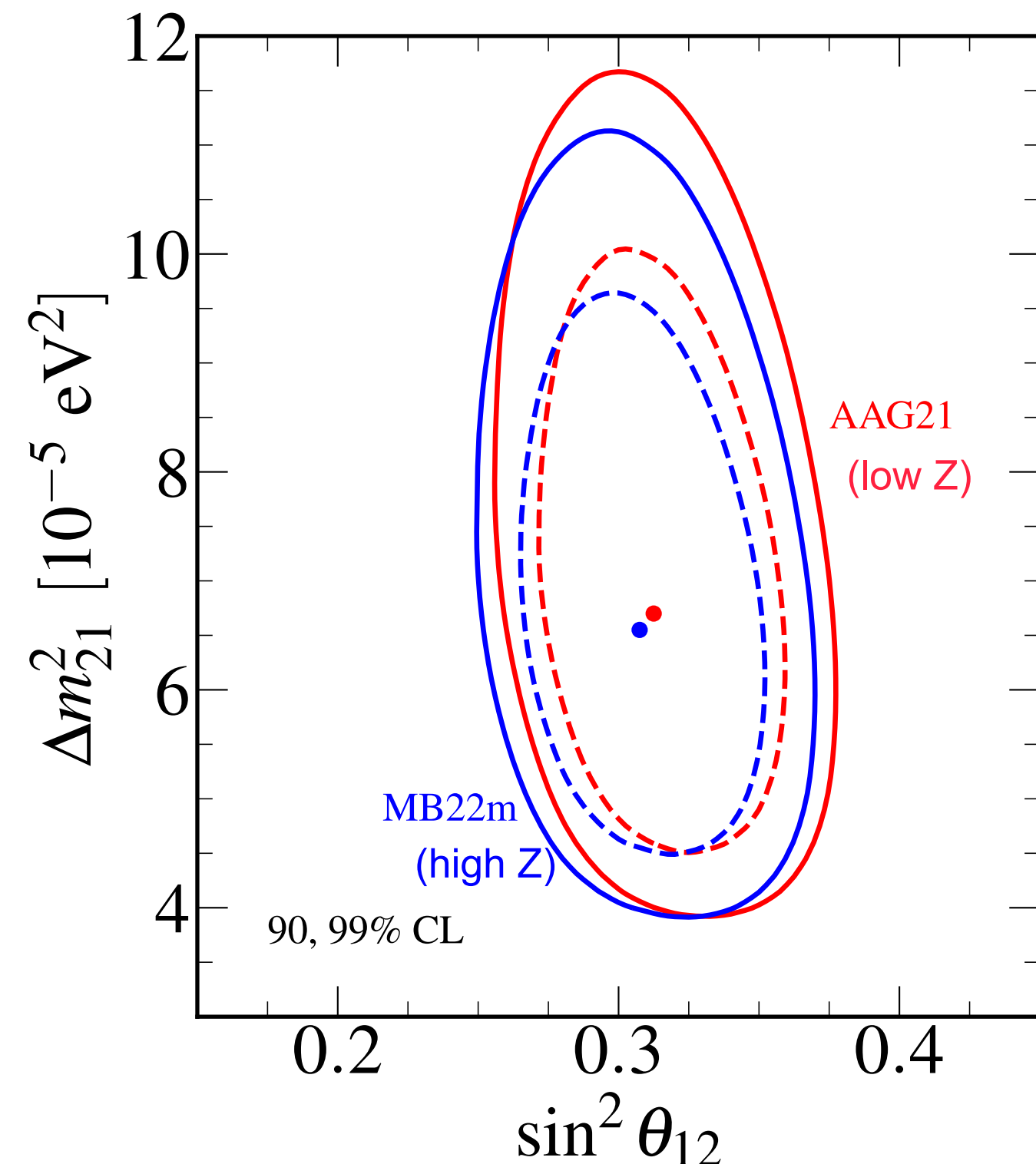
neutrino spectrum



KamLAND:
precise
measurement of
oscillation
frequency



The solar sector

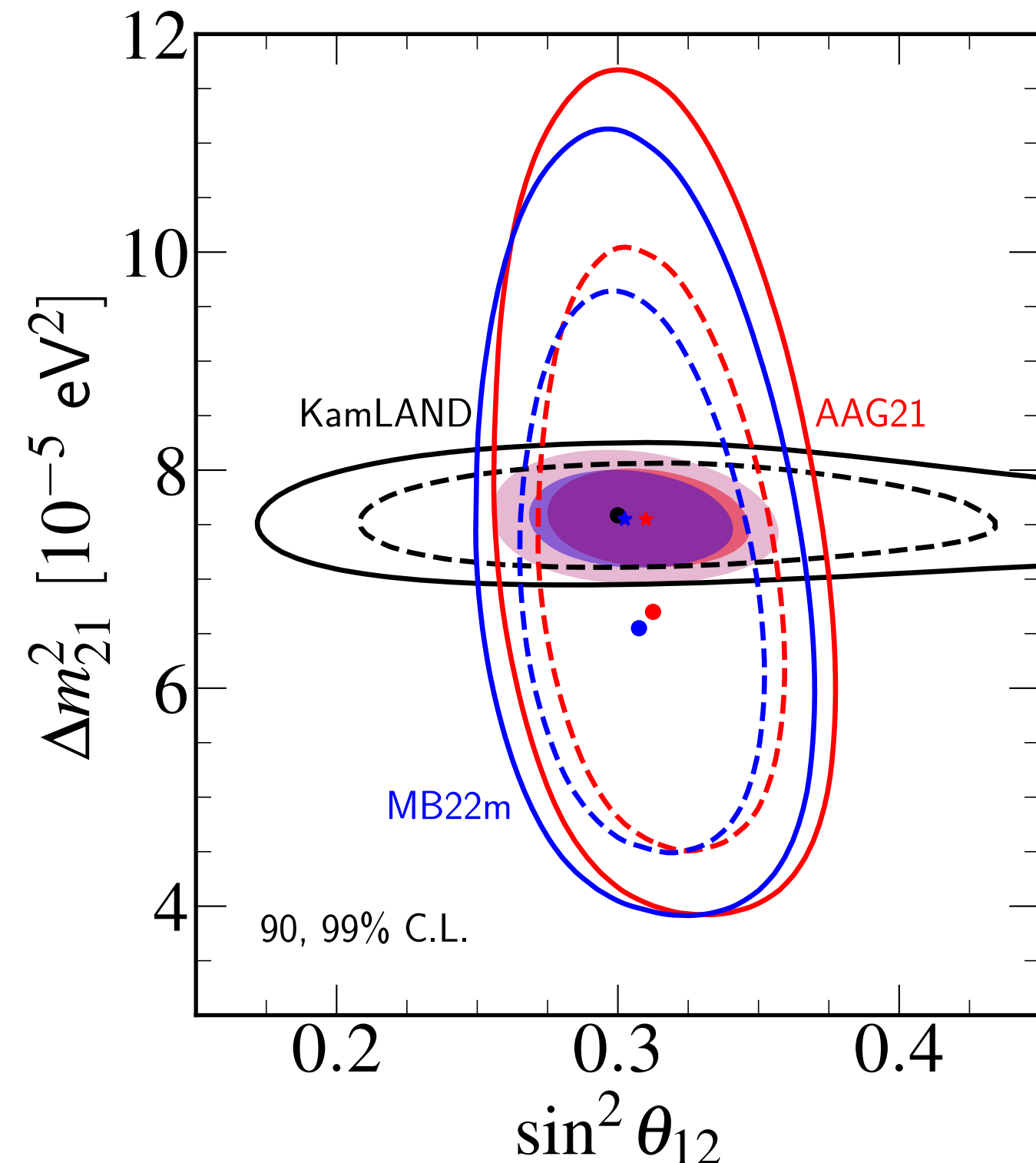


- ♦ θ_{12} measurement dominated by solar neutrino data
- ♦ Δm^2_{21} is better measured by KamLAND.
- ♦ **1.5 σ mismatch** between the values of Δm^2_{21} measured by solar and KamLAND

$$\sin^2 \theta_{12} = 0.304 \pm 0.016$$

$$\Delta m^2_{21} = (7.55 \pm 0.21) \times 10^{-5} \text{ eV}^2$$

The solar sector



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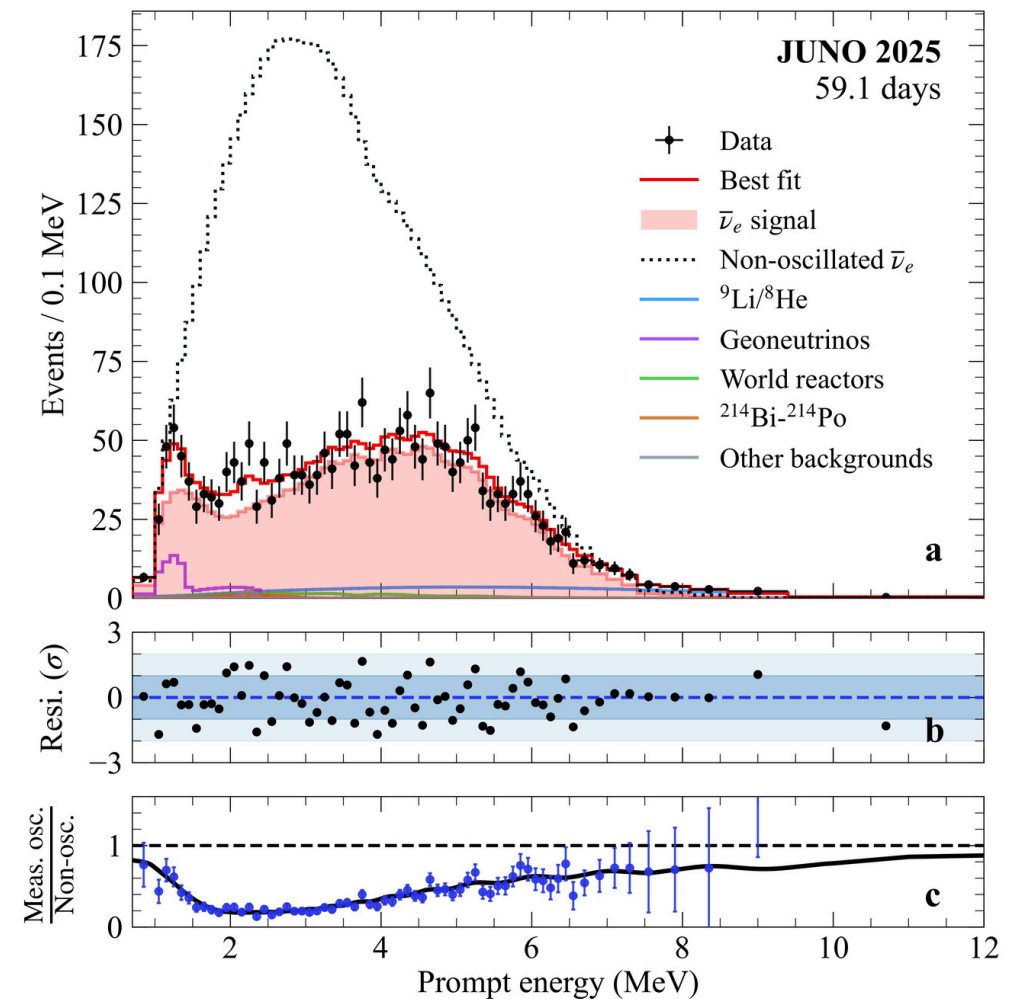
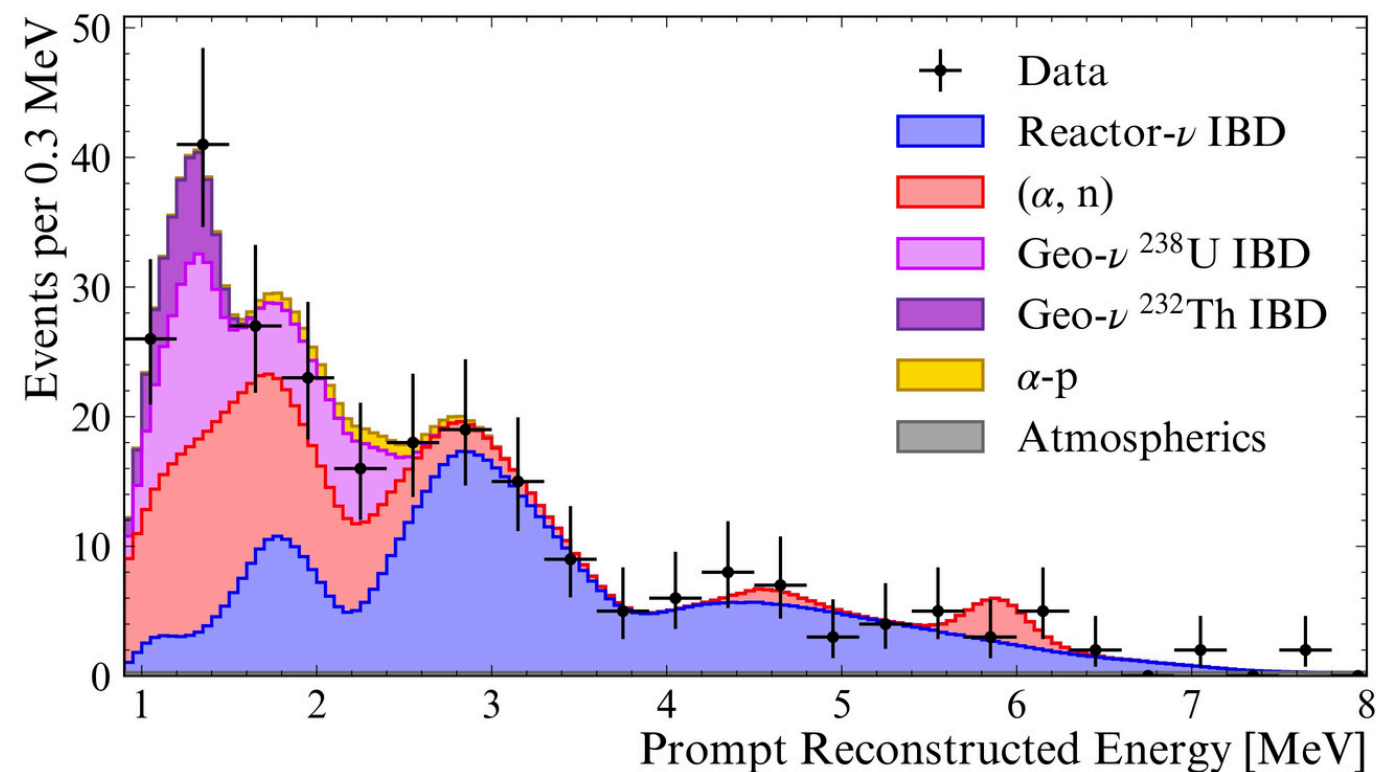
$$\sin^2 \theta_{12} = 0.304 \pm 0.016$$

$$\Delta m^2_{21} = (7.55 \pm 0.21) \times 10^{-5} \text{ eV}^2$$

New reactor data for solar sector

JUNO [arXiv:2511.14593]

SNO+ [arXiv:2511.11856]



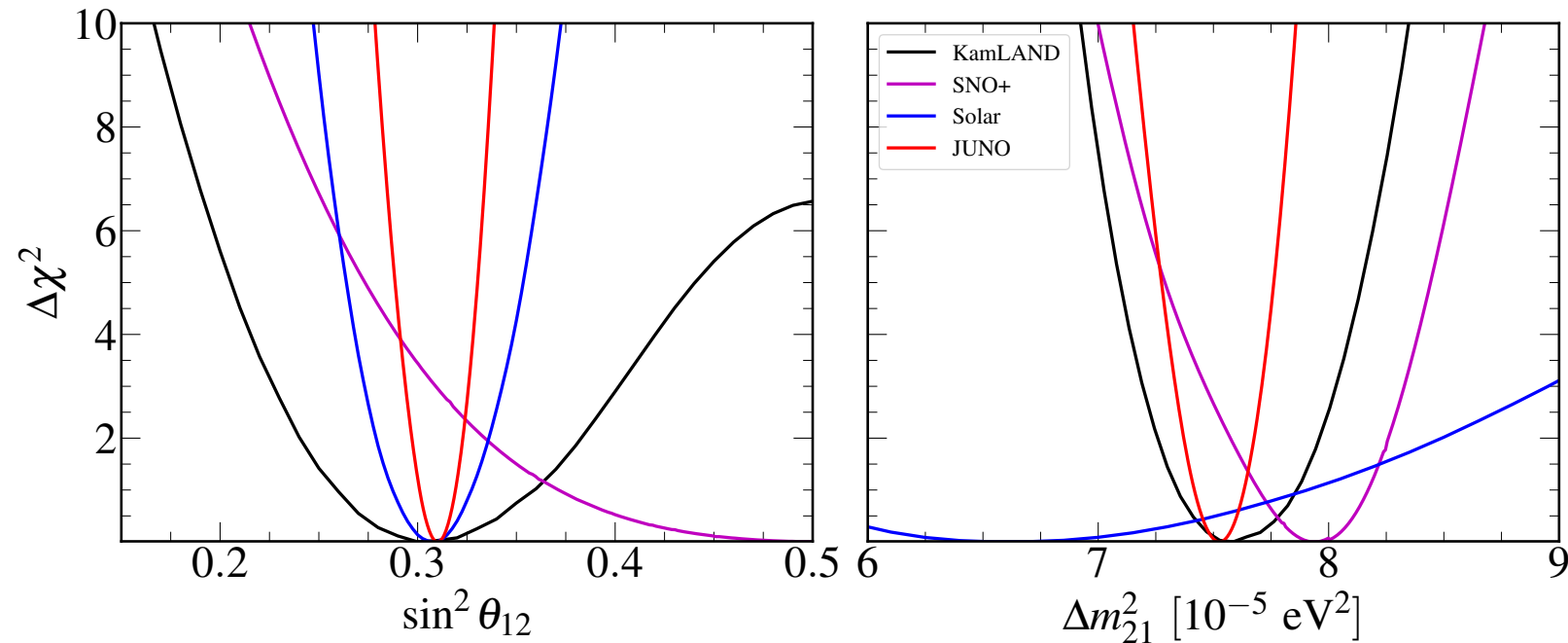
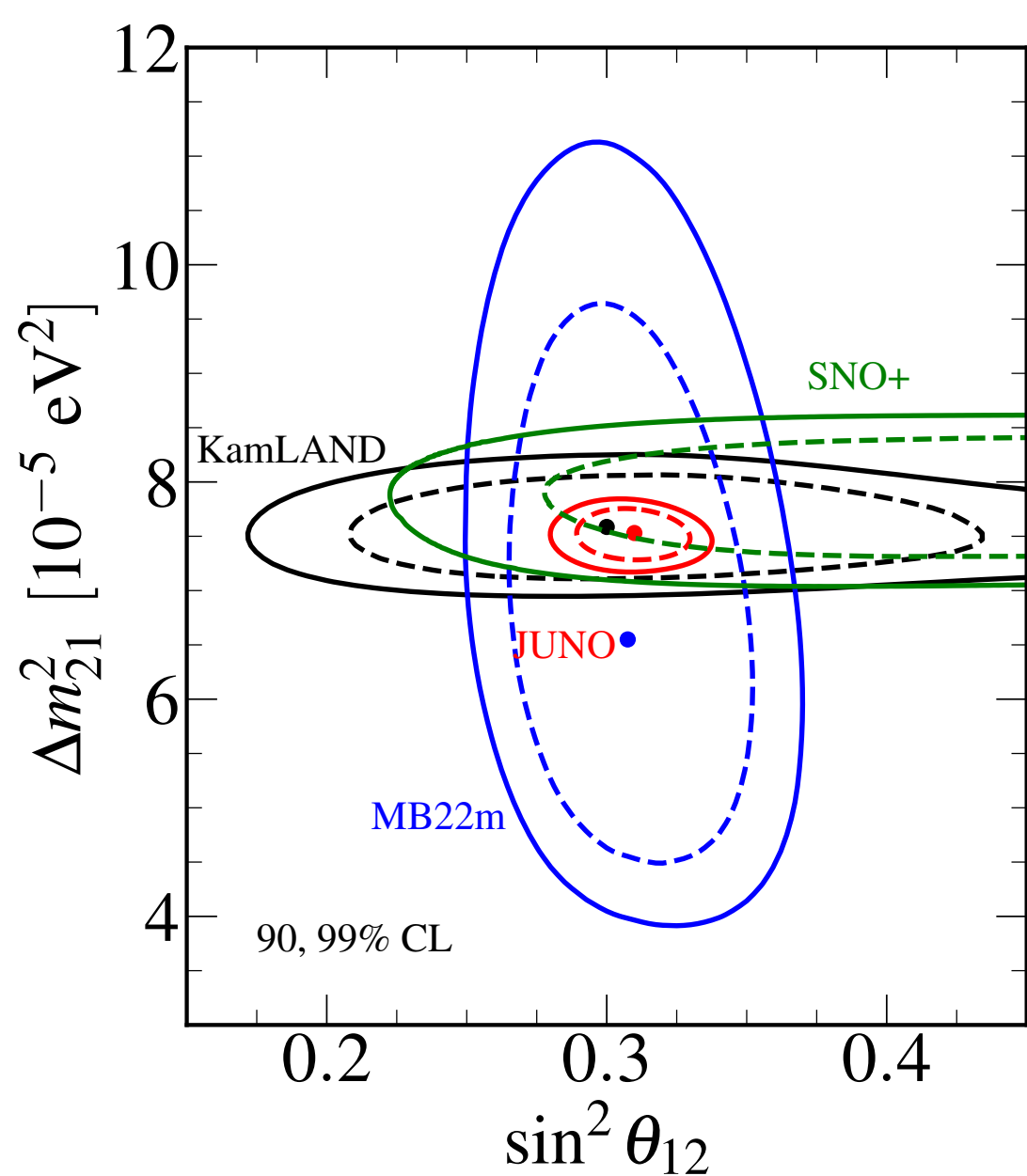
◆ LBL reactor exp (240-350km)

◆ 1.46 kton-years (May 2022-July 2025)

◆ Medium baseline reactor exp (50 km)

◆ 59.1 days of exposure

The solar sector after JUNO



Best precision ever reached for
 Δm_{21}^2 and θ_{12} thanks to JUNO

$$\frac{\sigma_{\Delta m_{21}^2}}{\Delta m_{21}^2} = 1.55 \%$$

$$\frac{\sigma_{\sin^2 \theta_{12}}}{\sin^2 \theta_{12}} = 2.81 \%$$

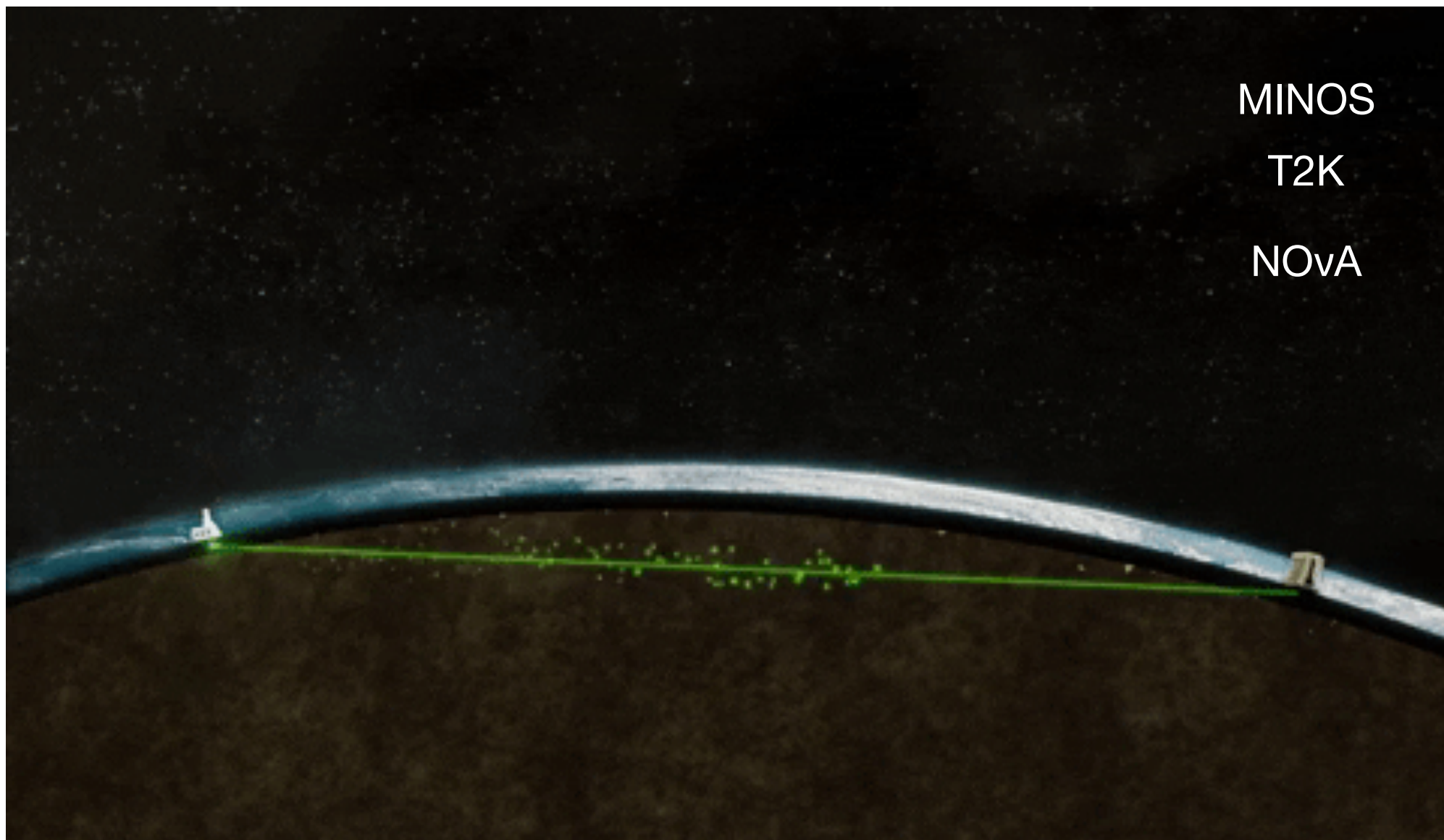
Neutrino oscillations

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



Neutrino oscillations

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



Atmospheric & accelerator sector

ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2 \left(1.27 \frac{\Delta m_{32}^2 L}{E} \right)$$

→ only sensitive to $\sin^2 2\theta_{23}$ and $|\Delta m_{32}^2|$

ν_e and $\bar{\nu}_e$ appearance (in matter)

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}]$$

$$(\mp) \alpha \frac{J_0 \sin \delta_{CP}}{A(1-A)} \sin \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$

$$+ \alpha \frac{J_0 \cos \delta_{CP}}{A(1-A)} \cos \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

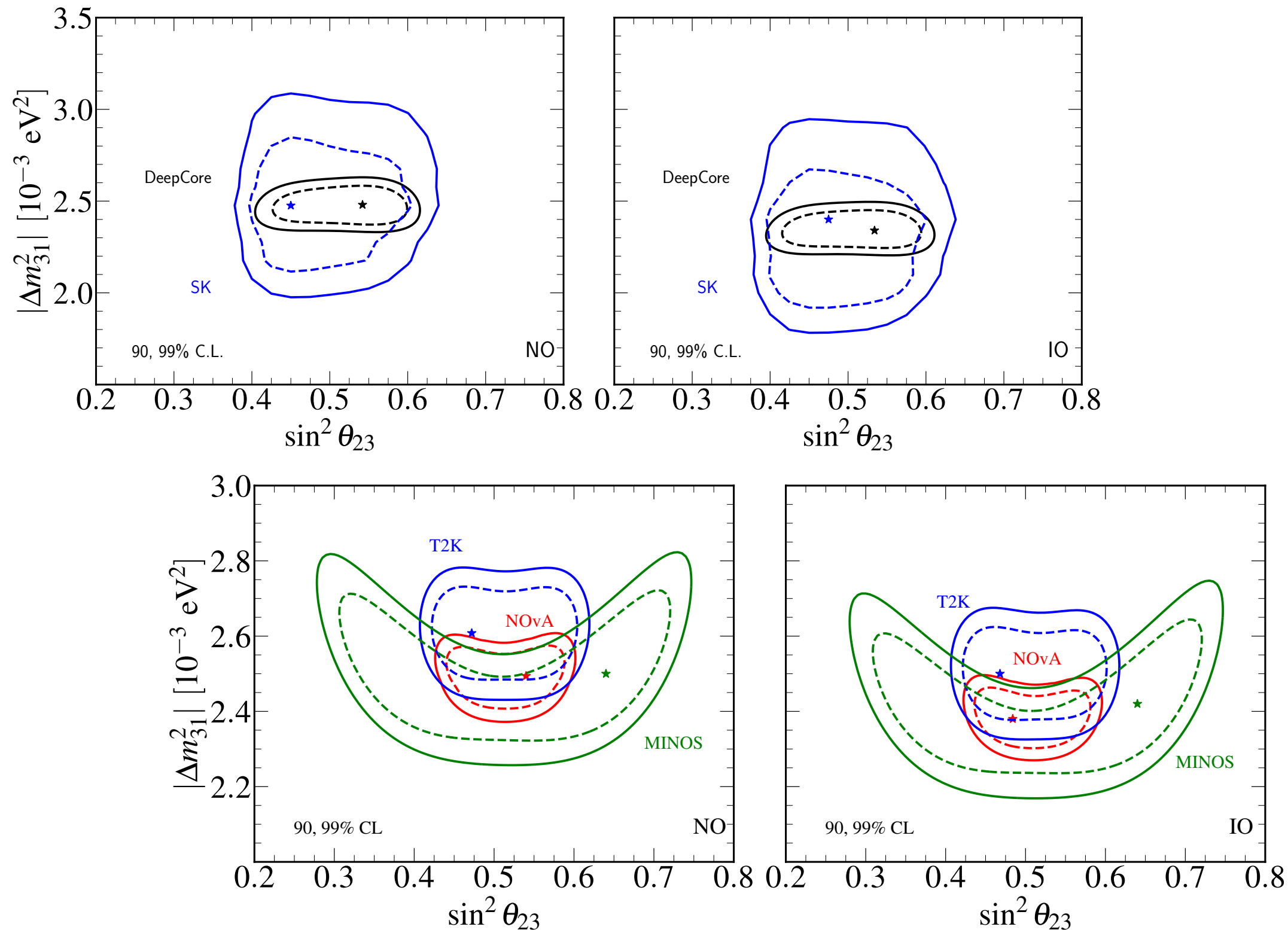
$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2 \sim 1/30$$

$$J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13}$$

$$A = (\mp) 2\sqrt{2} G_F n_e E / \Delta m_{31}^2$$

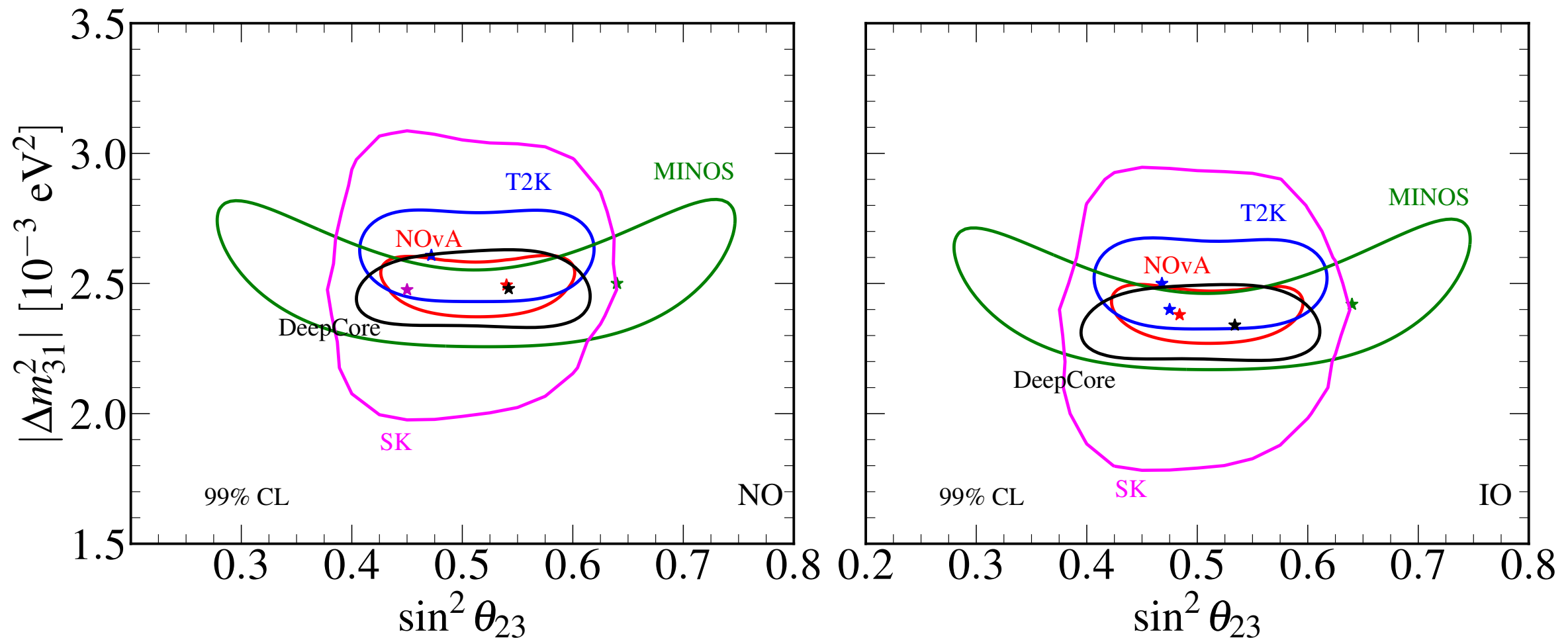
→ Sensitivity to δ_{CP} , the mass ordering (sign A) and the octant of θ_{23}

Atmospheric & accelerator sector



2026
update

Atmospheric & accelerator sector

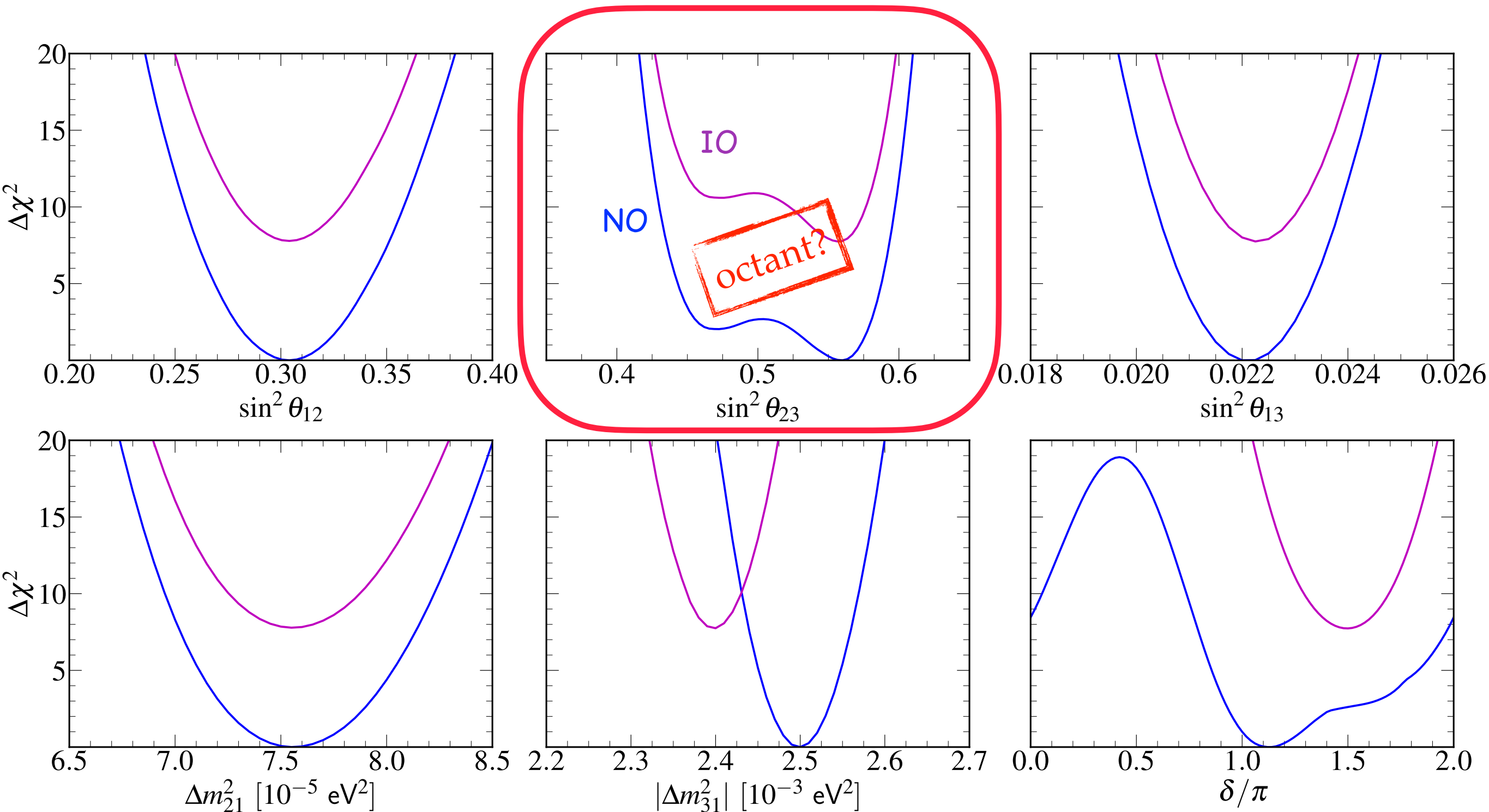


$$|\Delta m_{31}^2| = (2.50 \pm 0.02) \cdot 10^{-3} \text{ eV}^2$$

$$|\Delta m_{31}^2| = (2.40 \pm 0.02) \cdot 10^{-3} \text{ eV}^2$$

- ◆ Great agreement among all the experiments
- ◆ Best sensitivity obtained by T2K, NOvA and DeepCore.
- ◆ IC-DeepCore starts being competitive with LBL accelerator experiments
- ◆ Not possible to resolve the octant of the atmospheric angle.

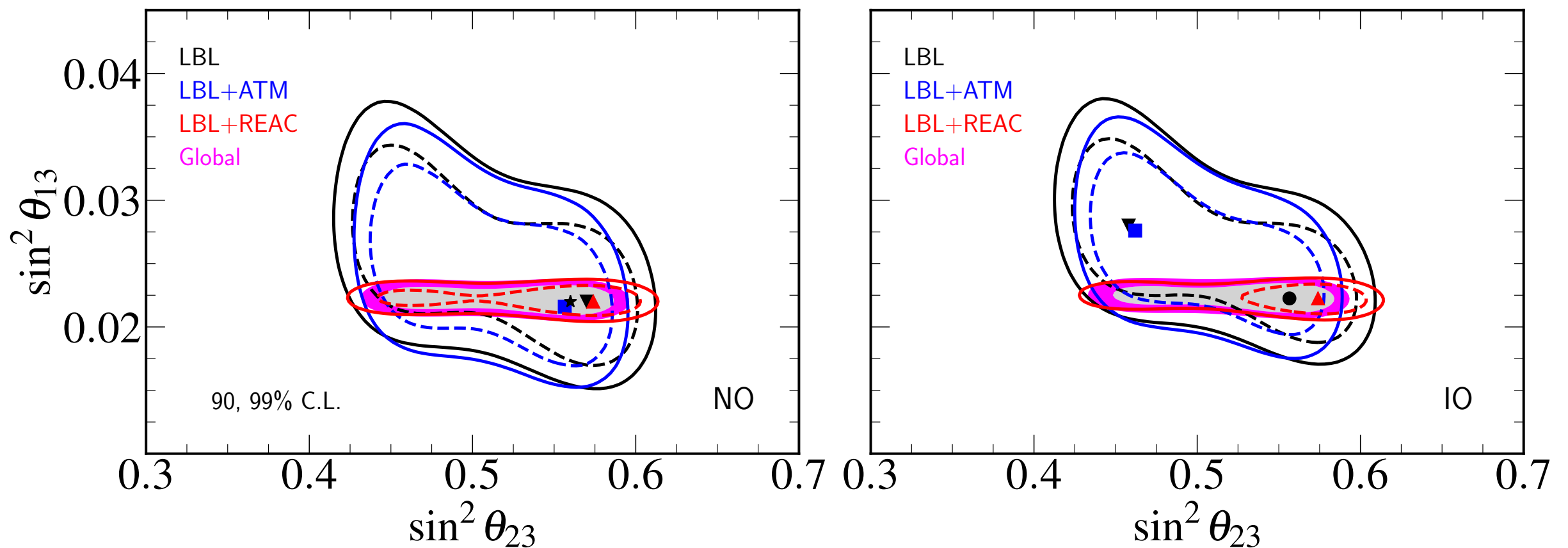
Global fit to ν oscillation parameters



with SK atmospheric

The octant of θ_{23}

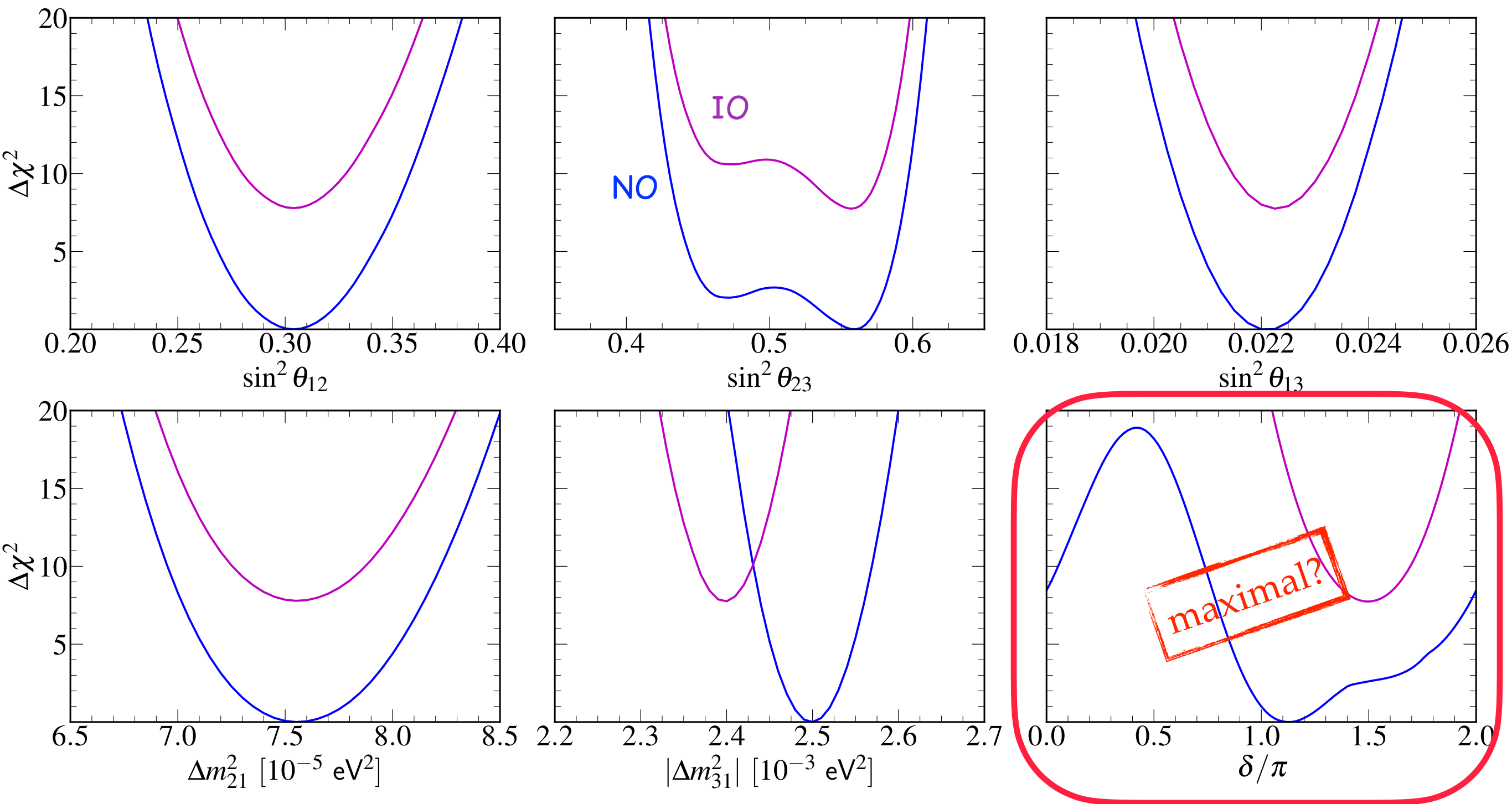
- ♦ **LBL** combination slightly prefer UO (NO) and LO(IO) with $\Delta\chi^2 = 0.3-0.4$
- ♦ **LBL + ATM** prefers UO (NO) and LO(IO) with $\Delta\chi^2 \sim 0.3-1$
- ♦ **REAC** breaks the degeneracy in favor of UO (NO and IO) with $\Delta\chi^2 \sim 3.5-5.2$ over LO
- ♦ **Global** analysis show a milder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



$$\sin^2 \theta_{23} = (5.60^{+0.13}_{-0.22}) \cdot 10^{-1}$$

$$\sin^2 \theta_{23} = (5.57^{+0.14}_{-0.20}) \cdot 10^{-1}$$

Global fit to ν oscillation parameters

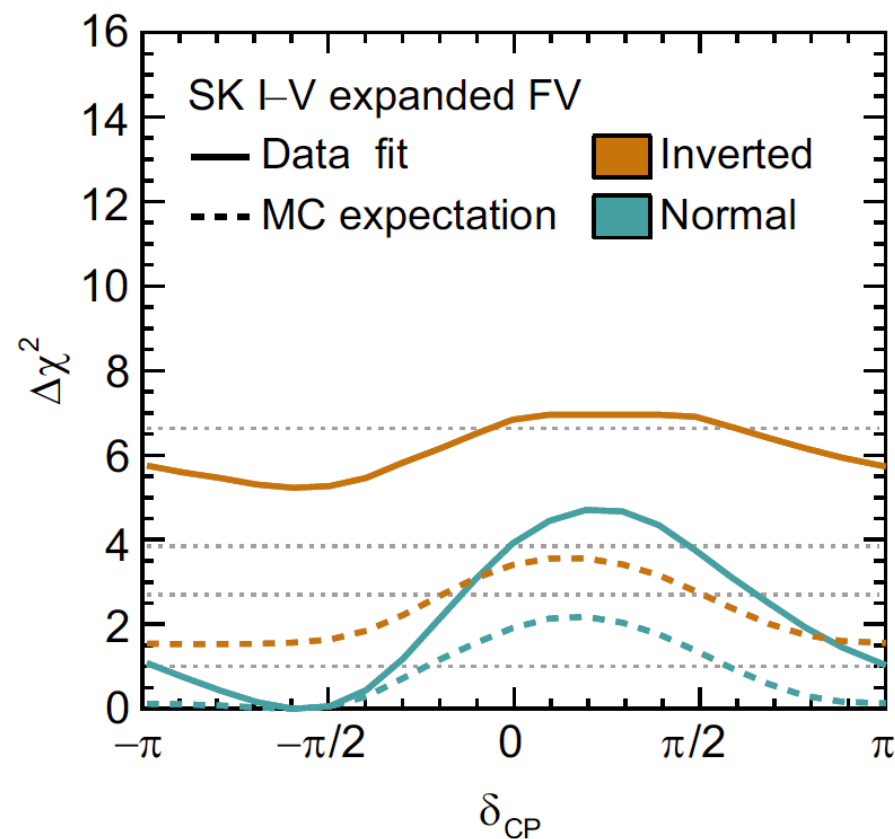


with SK atmospheric

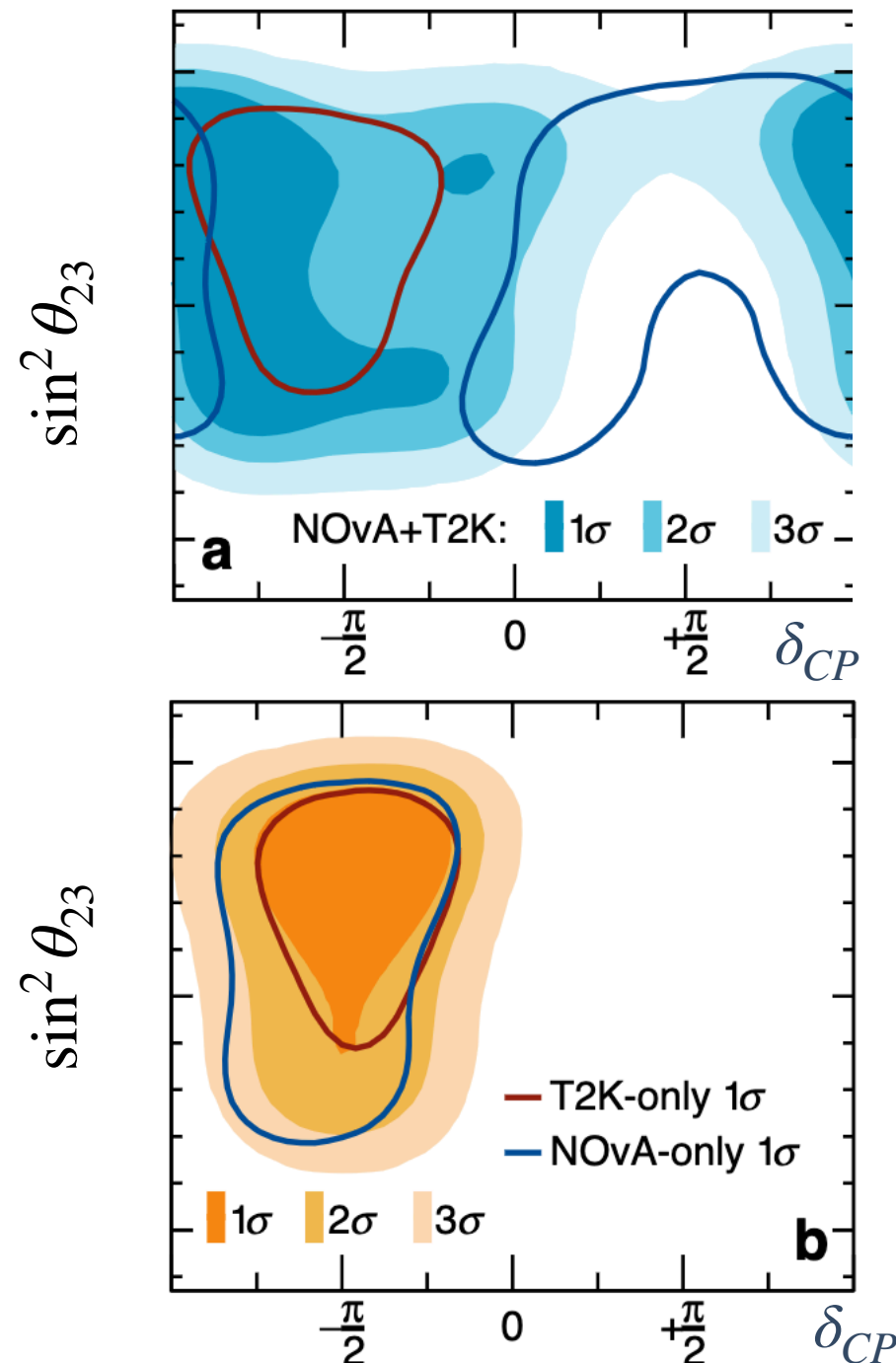
The CP phase

Observation of the appearance channels $\nu_\mu \rightarrow \nu_e$ in atmospheric and accelerator experiments allows to measure δ_{CP}

SK Collab, PRD 109 (2024) 072014



Super-Kamiokande observes a ν_e excess in agreement with maximal CP phase $\delta_{CP} \sim 3\pi/2$

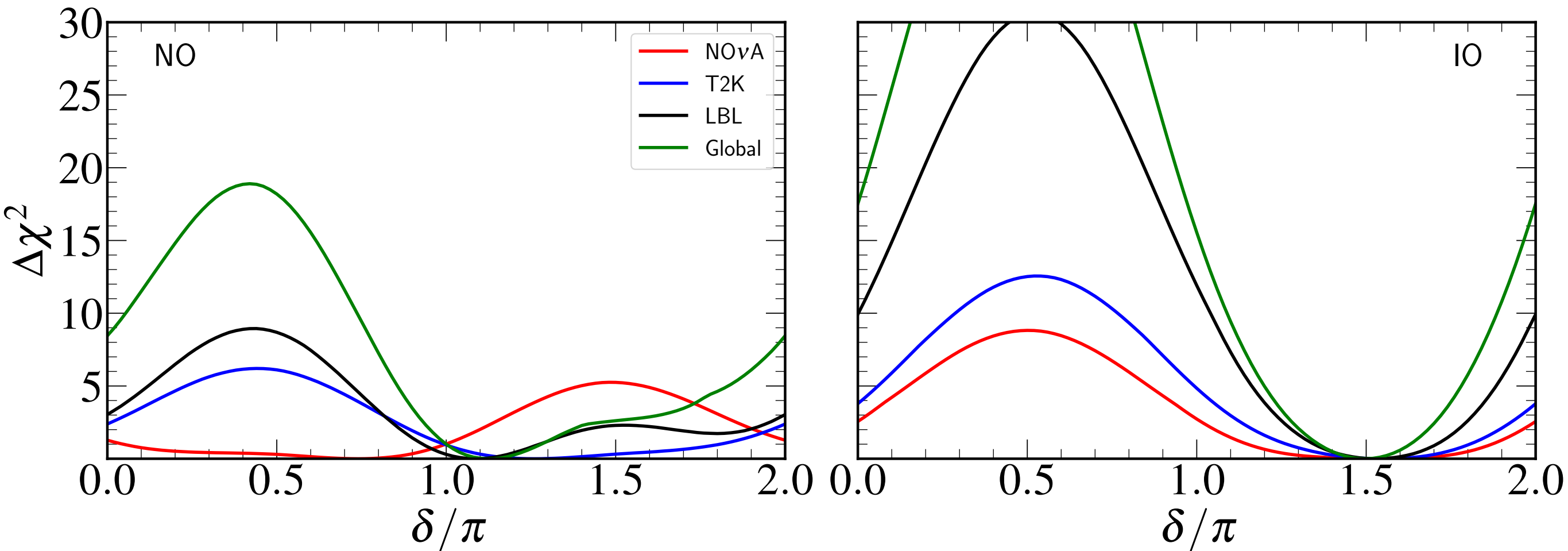


Joint T2K & NOvA analysis
2510.19888

T2K prefers also
 $\delta_{CP} \sim 3\pi/2$

NOvA results
depend on mass
ordering

The CP phase



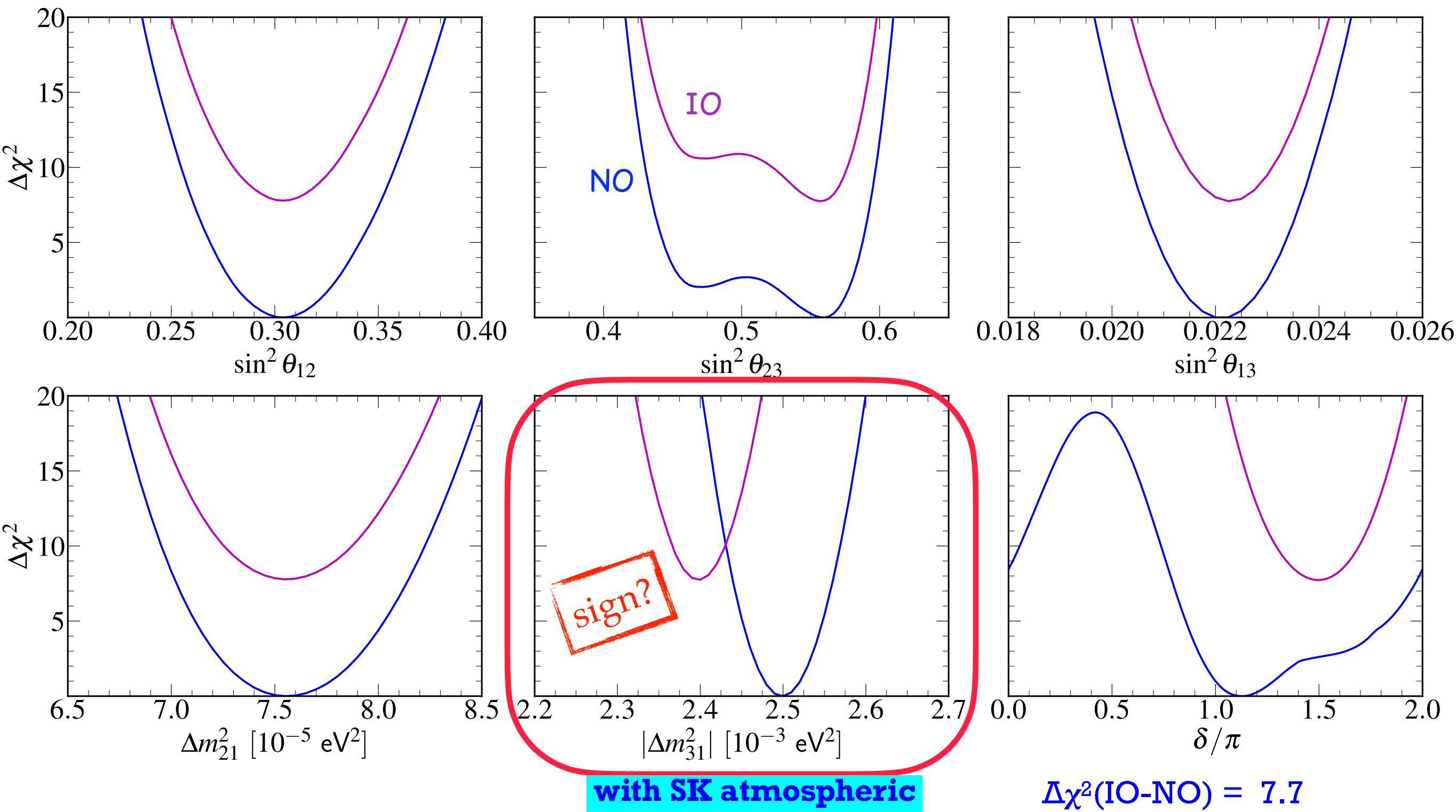
◆ NO: mismatch between NOvA and T2K and SK atmospheric results

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

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

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

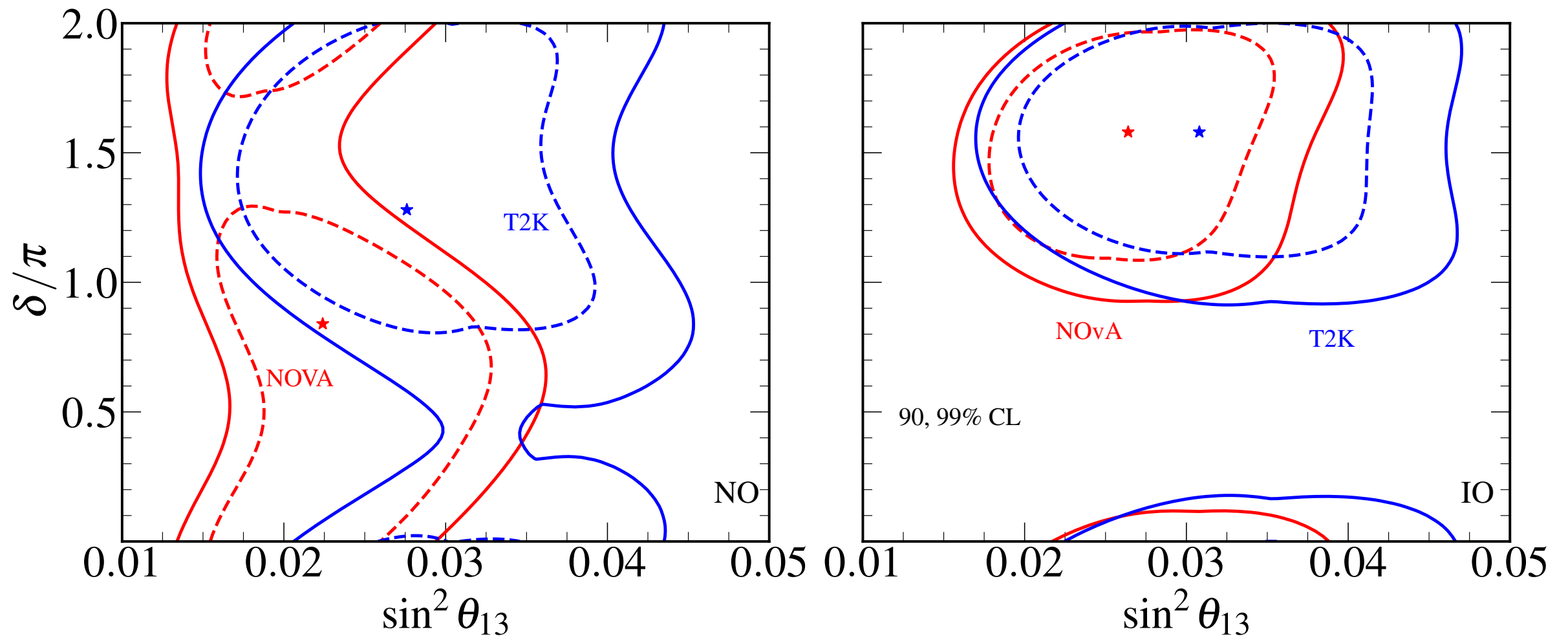
Global fit to ν oscillation parameters



The mass ordering

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

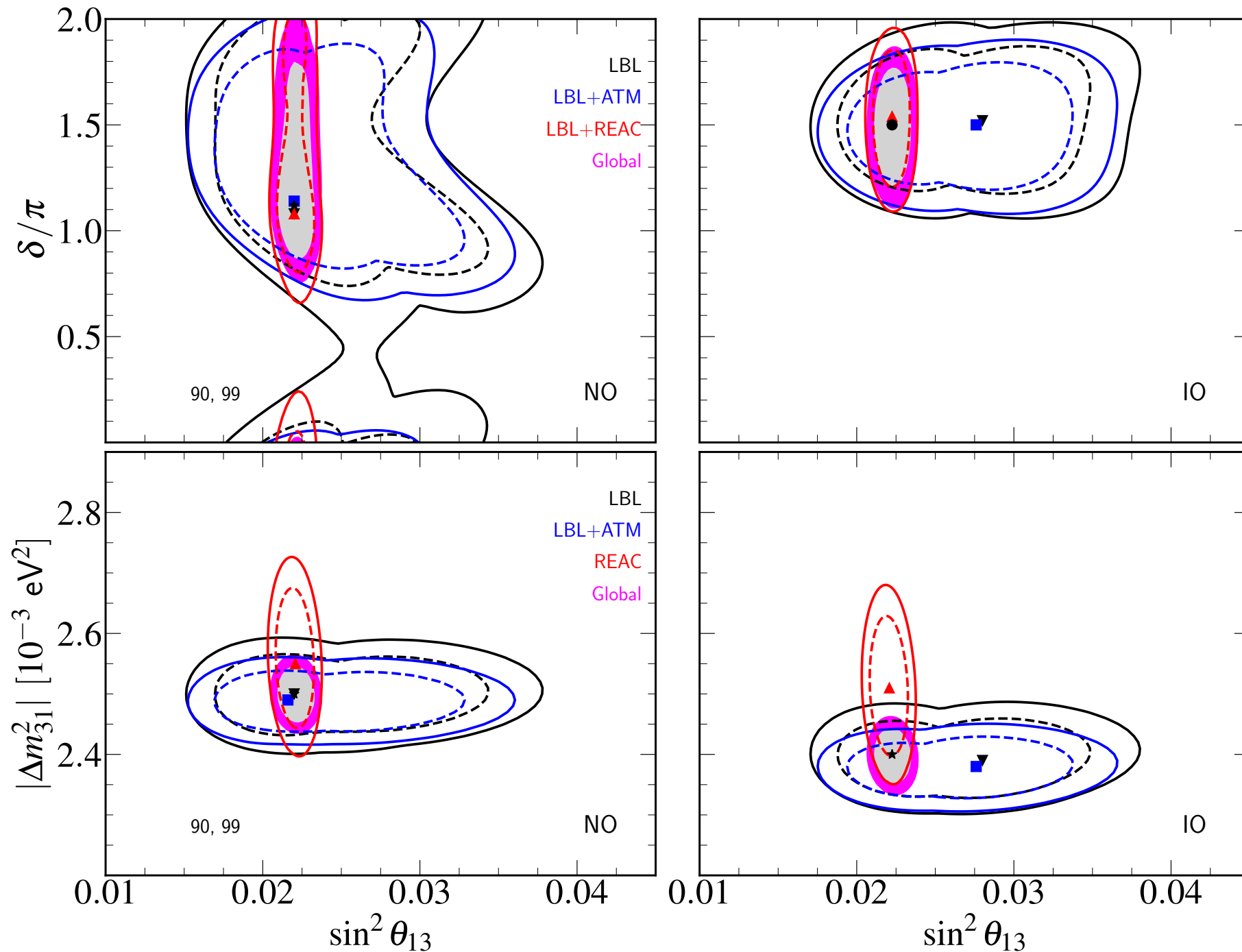
Tension between T2K and NOvA δ preference in NO



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

The mass ordering

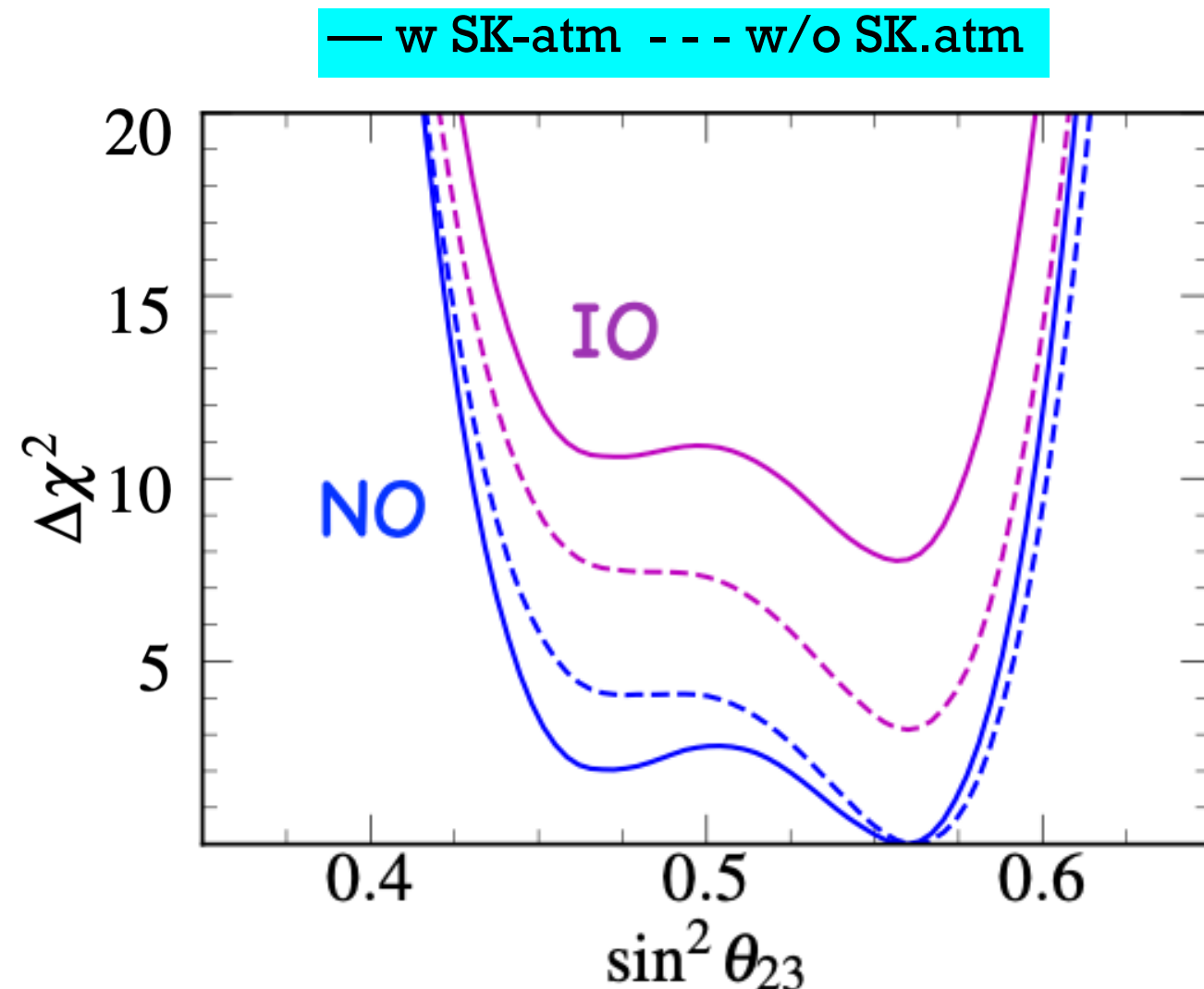
Tension between LBL and REAC Δm^2_{31} preference in IO



◆ 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)

The mass ordering

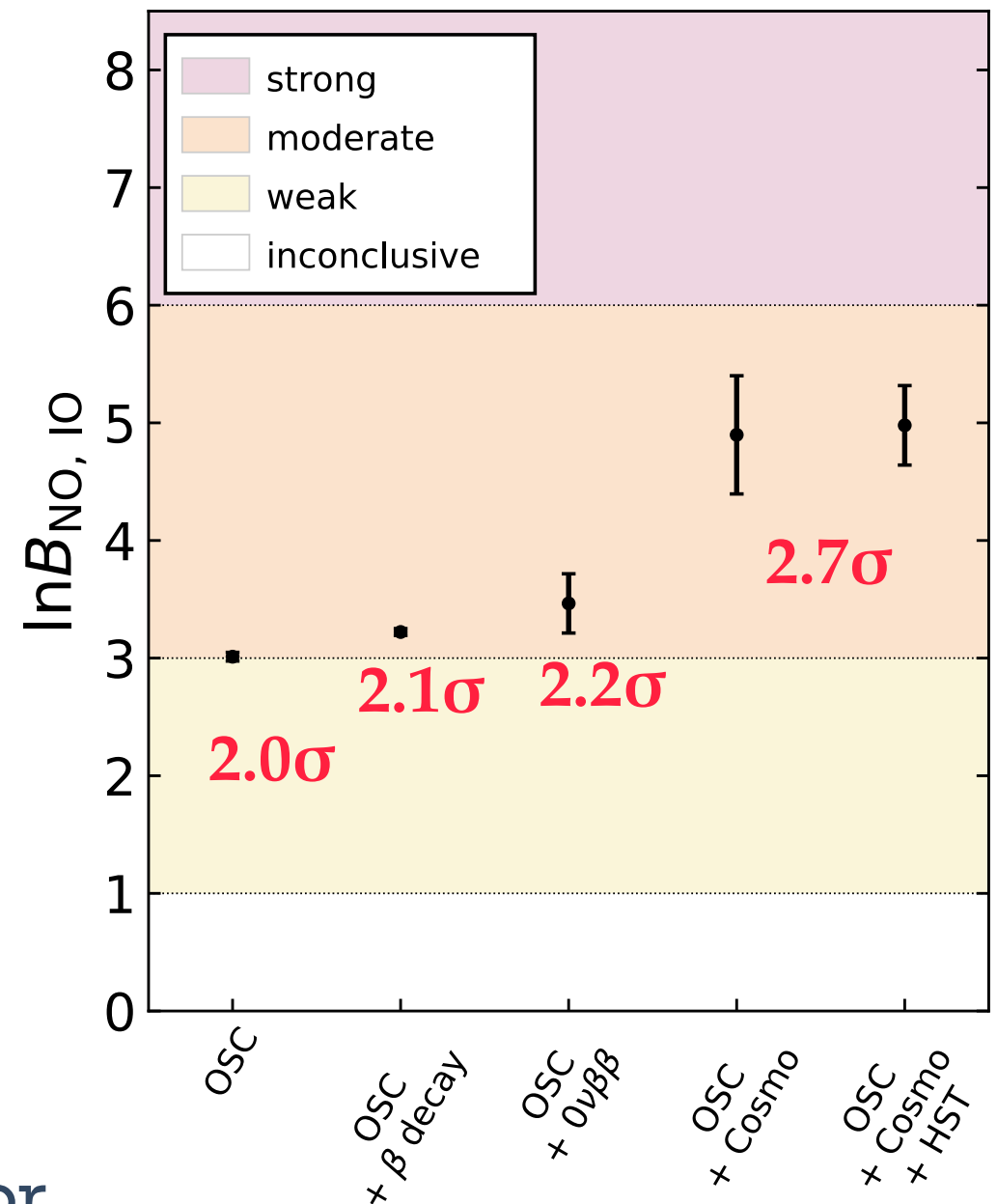
Experimental sensitivity to neutrino masses:

- ♦ ν -oscillations: Δm^2_{ij}
- ♦ β -decay: $m_\beta = f(m_i, \theta_{ij})$ **$m_\beta < 1.1$ eV (90% CL)**
- ♦ $0\nu\beta\beta$: $m_{\beta\beta} = f(m_i, \theta_{ij}, \phi_i)$
- ♦ 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 $0\nu\beta\beta$ have little impact on MO.
- ⇒ cosmological data enhances the preference for NO from 2.0σ to 2.7σ

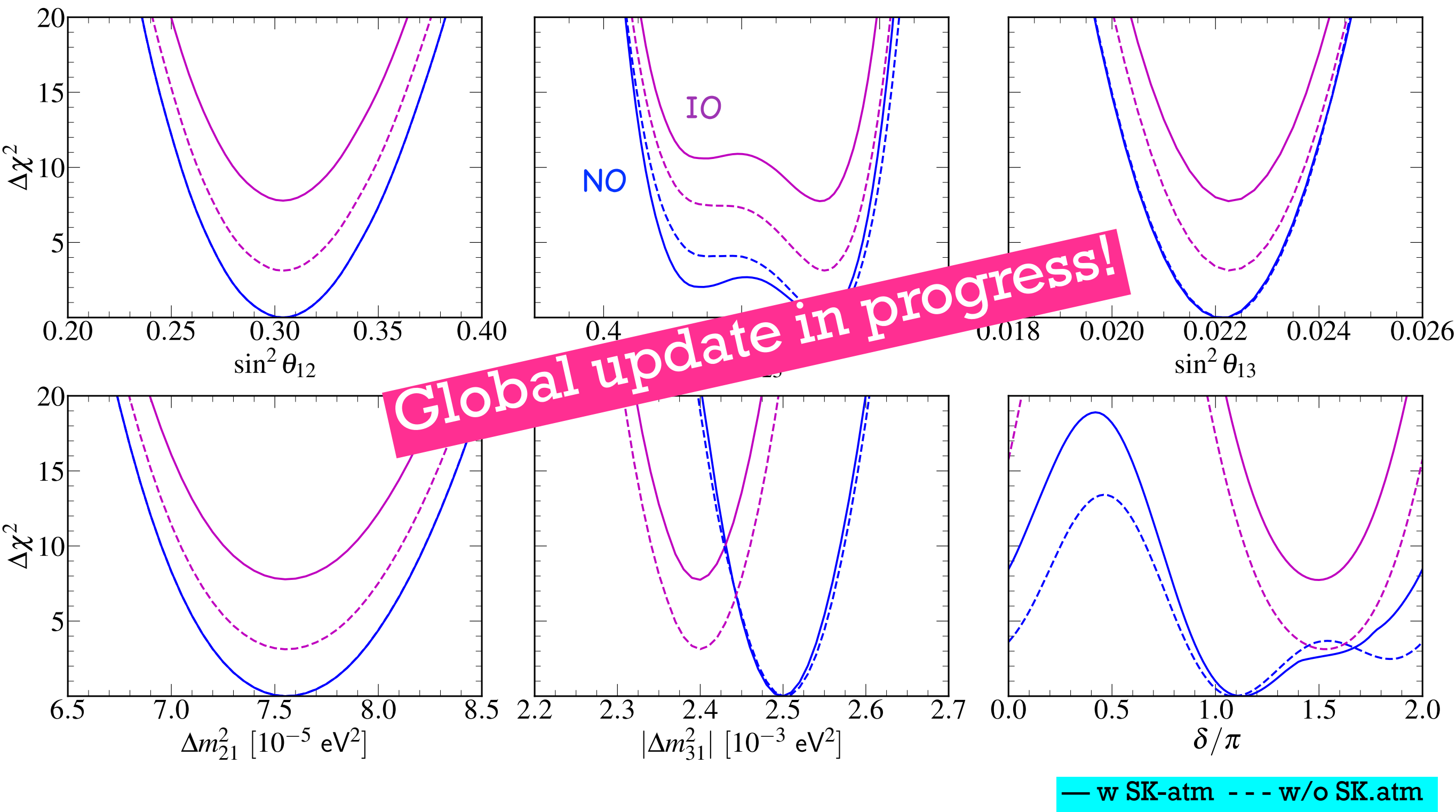
de Salas et al, JHEP 02 (2021) 071



Global fit to ν oscillation parameters

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

<https://globalfit.astroparticles.es/>



Summary

- ◆ **Global fits to neutrino oscillations** exploit complementarities of data sets to enhance the sensitivity of individual experiments.
- ◆ From the **updated three-neutrino global fit**:
 - ✓ precise determinations for most parameters ($\sim 1 - 5\%$)
 - ✓ slight preference for $\theta_{23} > 45^\circ$ - 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)
 - ✓ $\delta_{\text{BF}} = 1.12\pi$ (1.5π) for NO (IO) ; $\delta = \pi/2$ **disfavored** at 4.3σ (6.8σ) for NO (IO)
- ◆ First **JUNO** data established leading precision in solar parameters.
- ◆ The tension between **T2K** and NOvA impacts the determination of the mass ordering and CP violation.

Thank you

Hvala