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# GLOBAL ANALYSIS OF NEUTRINO OSCILLATIONS AND MASS ORDERING IN THE LIGHT OF JUNO

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Bari group global analysis (F. Capozzi, E. Lisi, F. Marcone, A. M.)

release 2026.a (paper in preparation) · **www.global-nu.org**



FRAMEWORK

# THREE MASSIVE AND MIXED NEUTRINOS

See also: M. C. Gonzalez-Garcia,
"Lessons from Global Analysis of Neutrino Oscillation Results"
(this conference, yesterday)

$$U = U(\theta_{12}, \theta_{13}, \theta_{23}, \delta) \qquad \delta m^2 = m_2^2 - m_1^2$$

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$$\Delta m^2 = m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)$$

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Other groups use $\Delta m^2_{31}$ and $\Delta m^2_{32}$:

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- Every new percent on $\theta_{ij}$ sharpens the tests of flavour symmetries

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**Abbreviations used in this talk**

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**SolRea** Solar + LBrea + SBrea: ordering-blind starting point

**ACdis, ACapp, AC** accelerator $\nu_\mu$ disappearance, $\nu_e$ appearance, both
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JUNO has a twofold impact: (i) it dominates $\delta m^2$ and $\theta_{12}$; (ii) its $|\Delta m^2|$ measured with $\bar{\nu}_e$, compared with that measured with $\nu_\mu$ (accelerators, atmospherics), **is sensitive to the mass ordering**

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$\alpha$ ($+1$: NO, $-1$: IO) emerges when $|\Delta m^2|$ is measured in two ways that must agree:

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**Guiding question:** **where does the global preference for normal ordering come from**, and what does JUNO add to it?

# SEVEN DATA SETS, SIX PARAMETERS AND $\alpha$

| | $\sin^2\theta_{12}$ | $\delta m^2$ | $\sin^2\theta_{13}$ | $\lvert\Delta m^2\rvert$ | $\alpha$ | $\sin^2\theta_{23}$ | $\delta$ |
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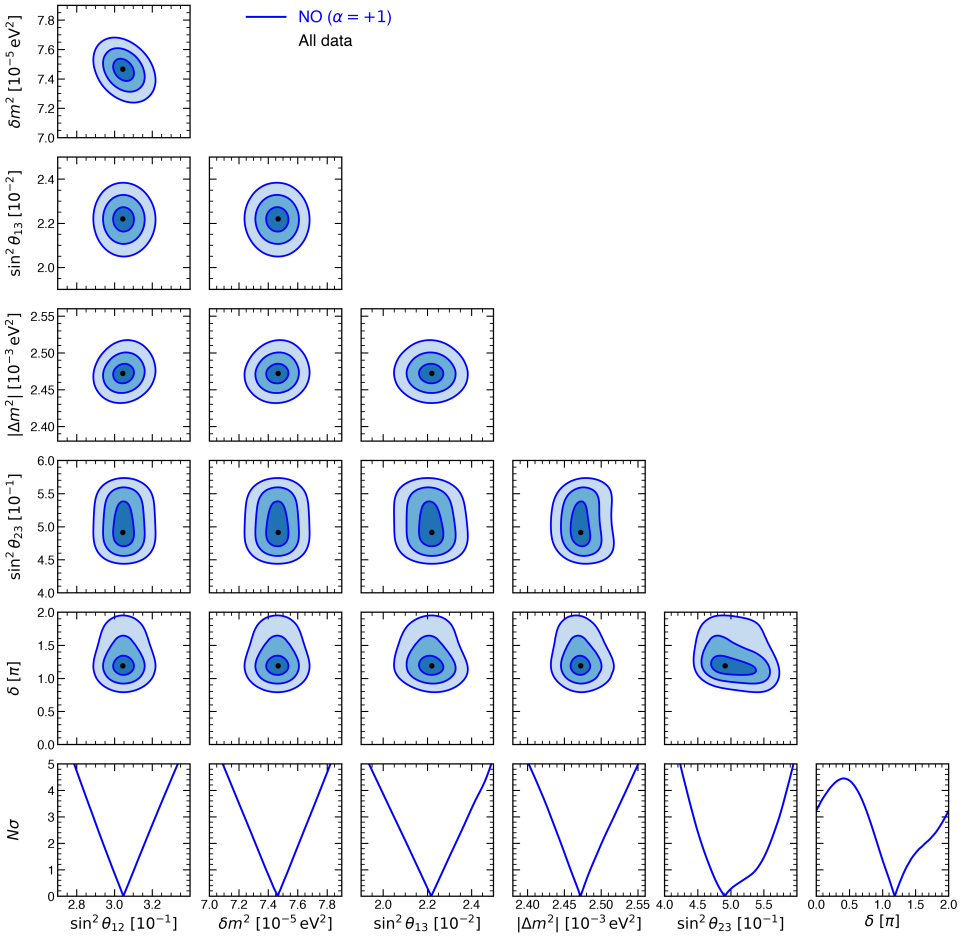
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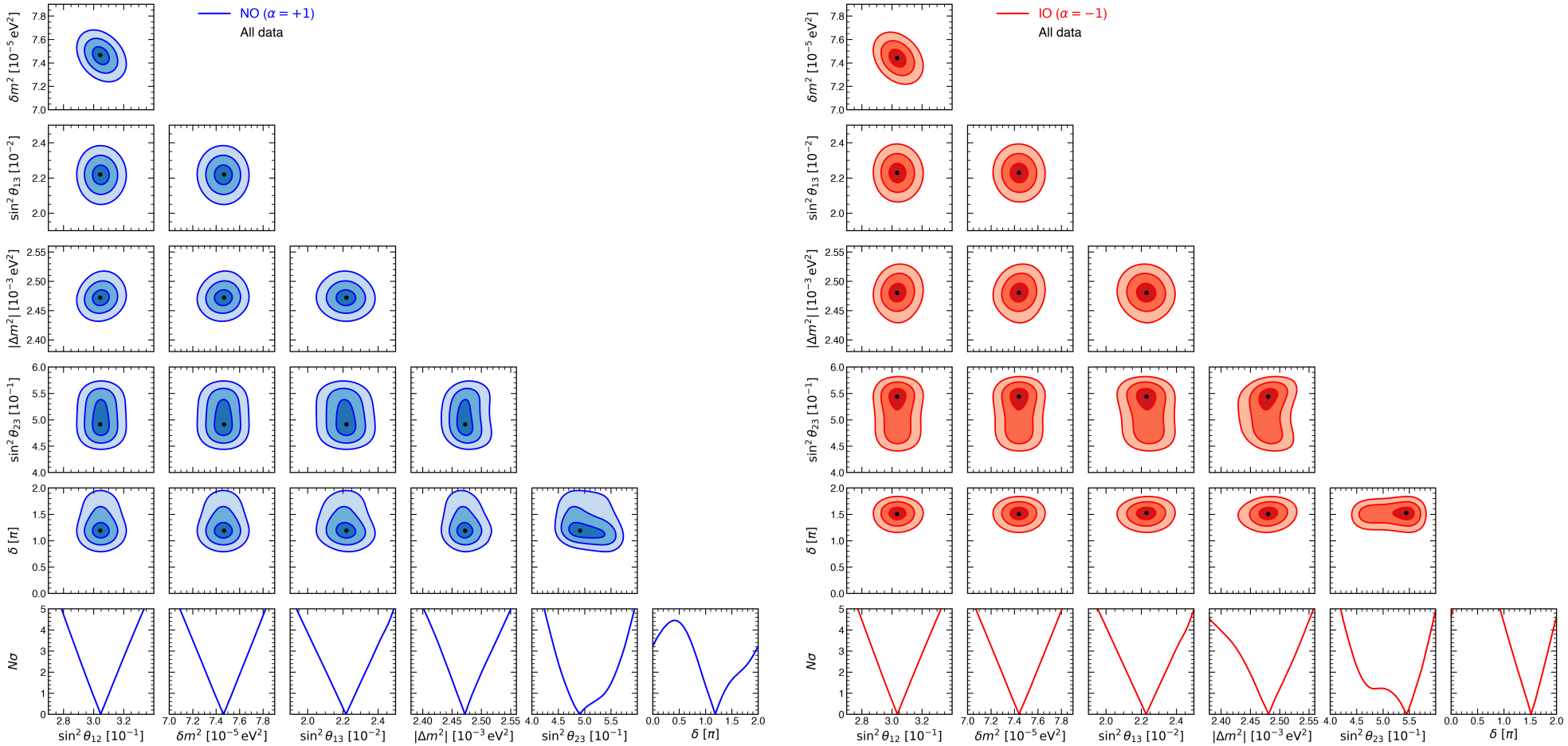
**SYNERGIES AND TENSIONS**

Comparing the orders shows which data sets reinforce each other and which are in tension

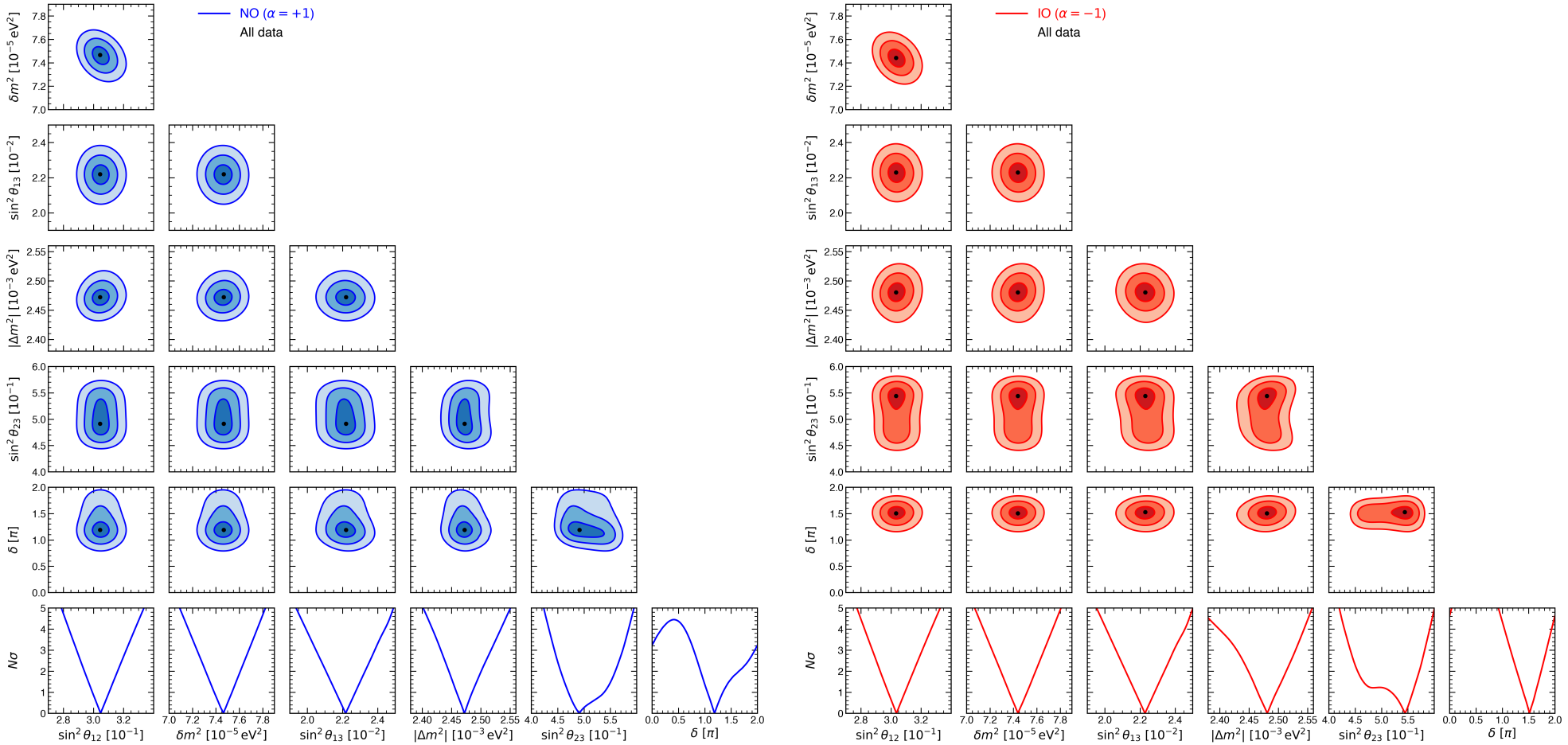
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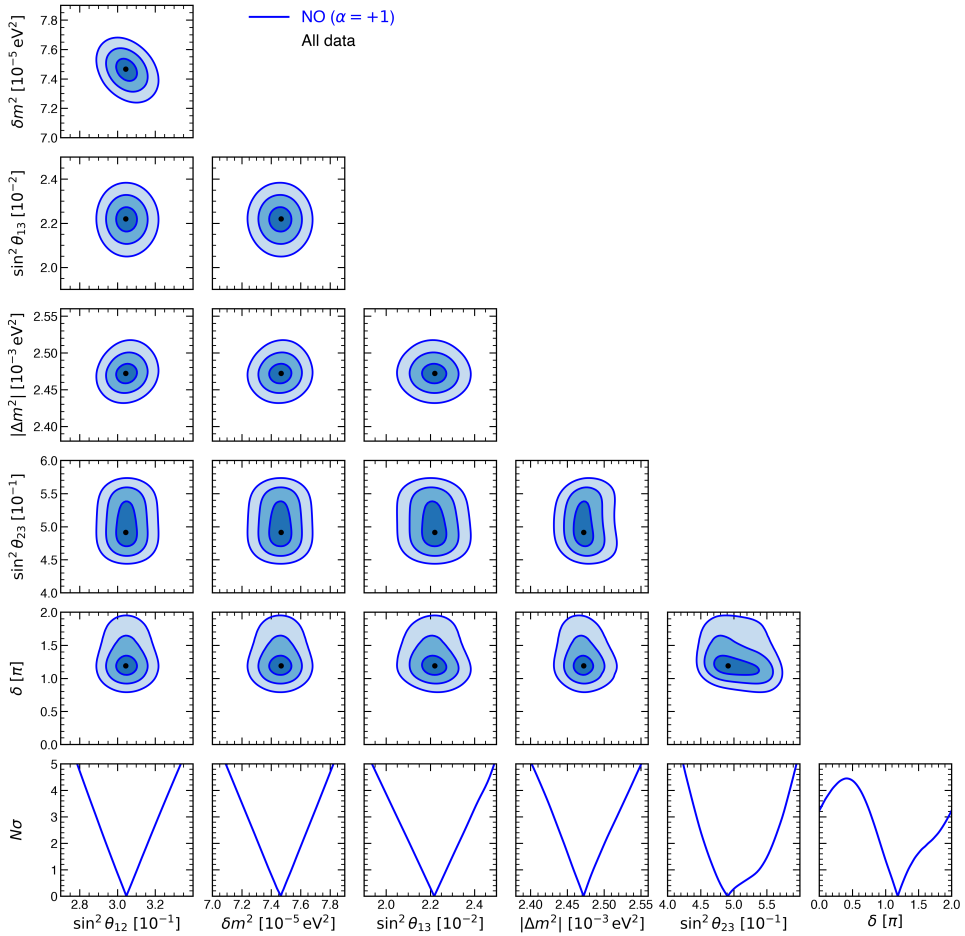

$\Delta\chi^2(\mathrm{IO} - \mathrm{NO})$

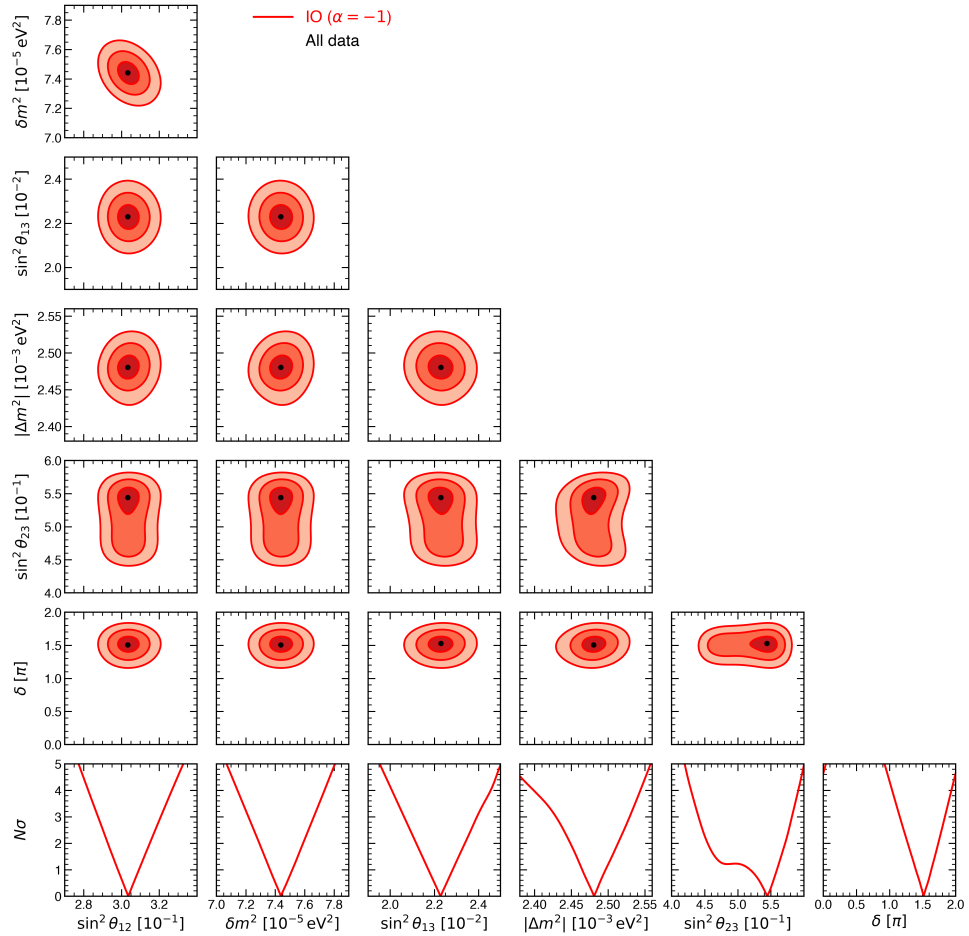
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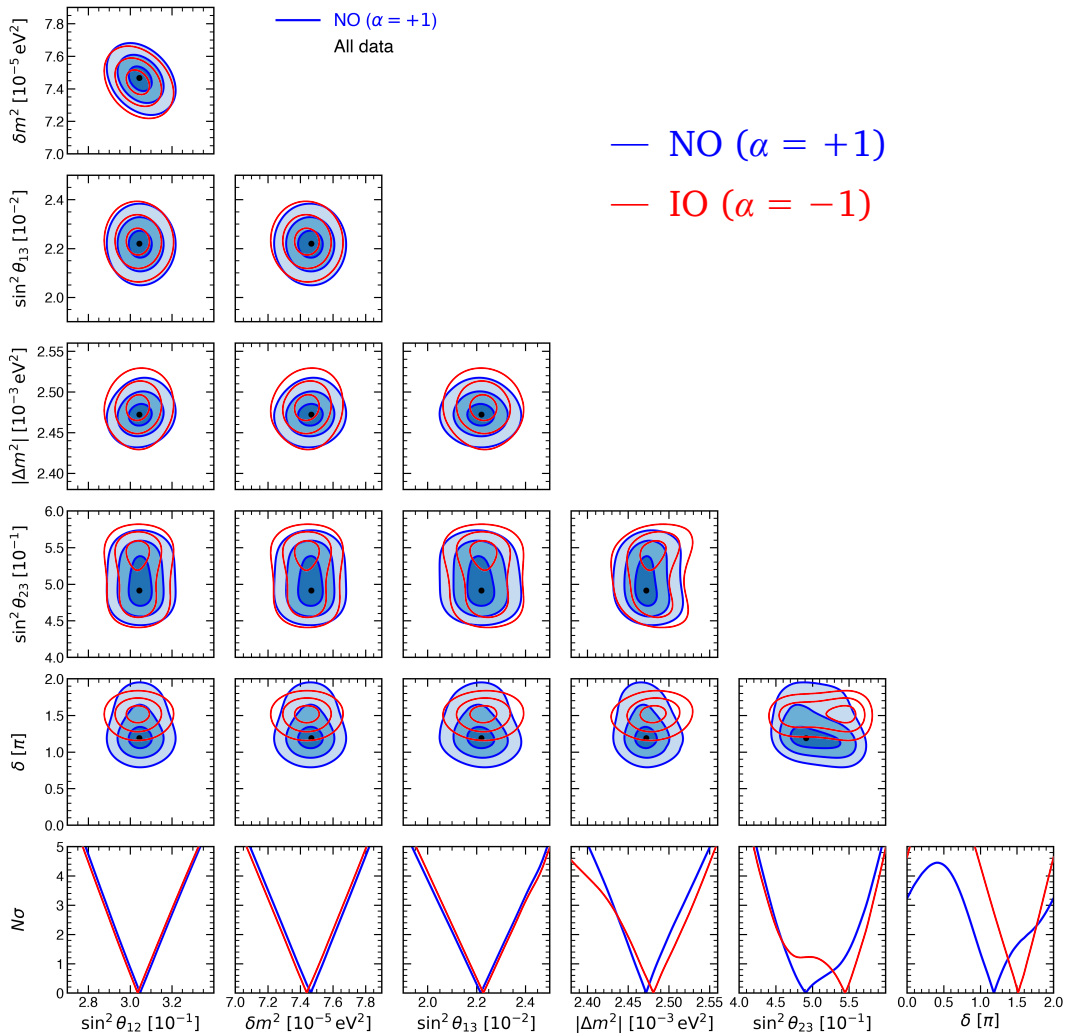
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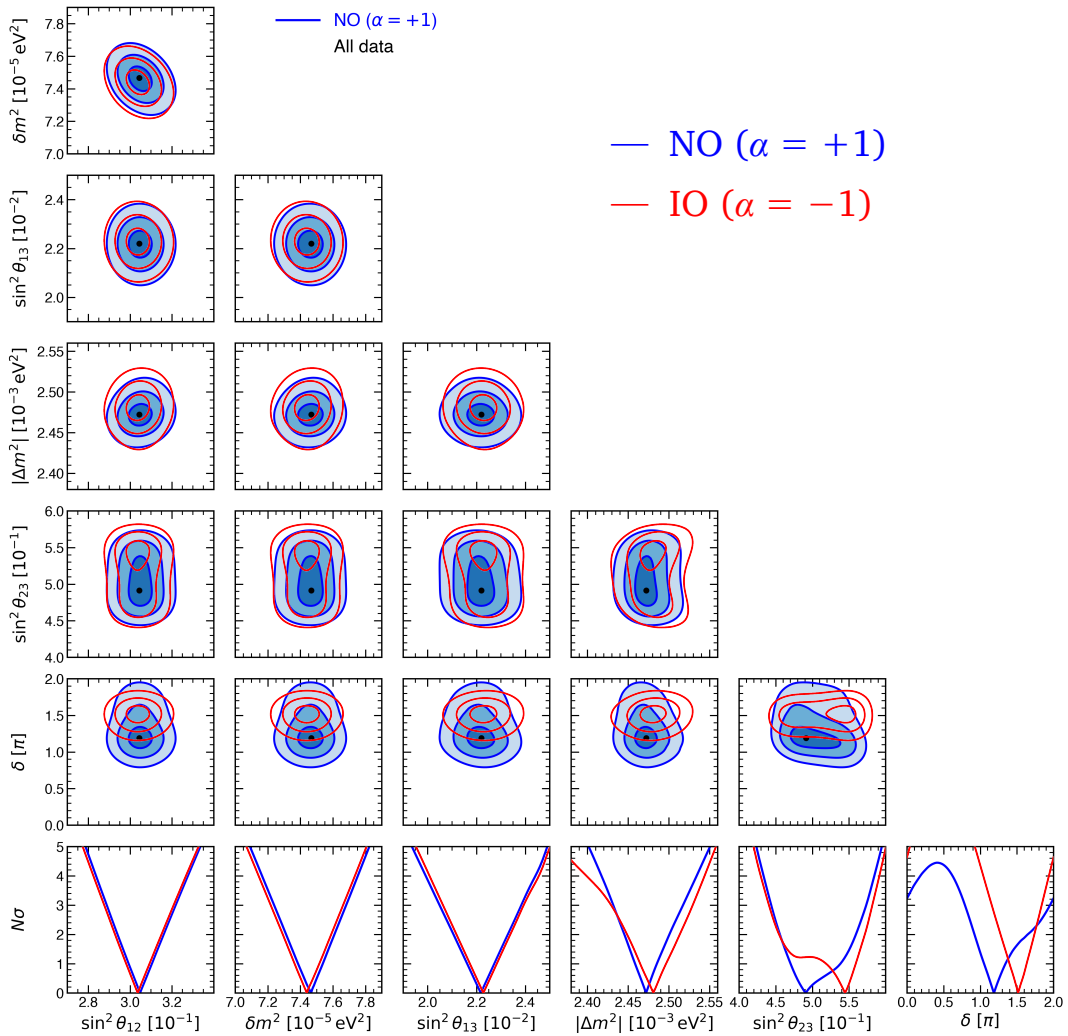
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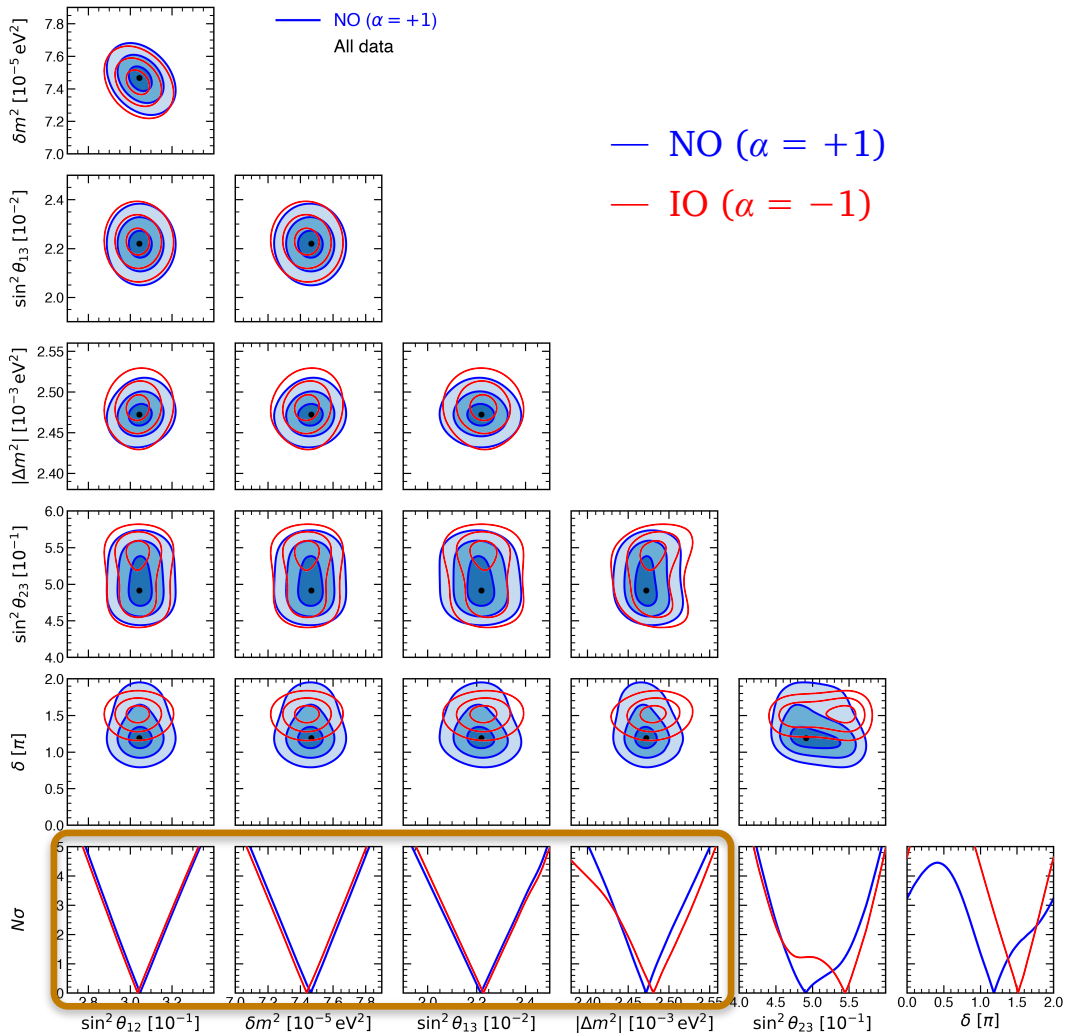
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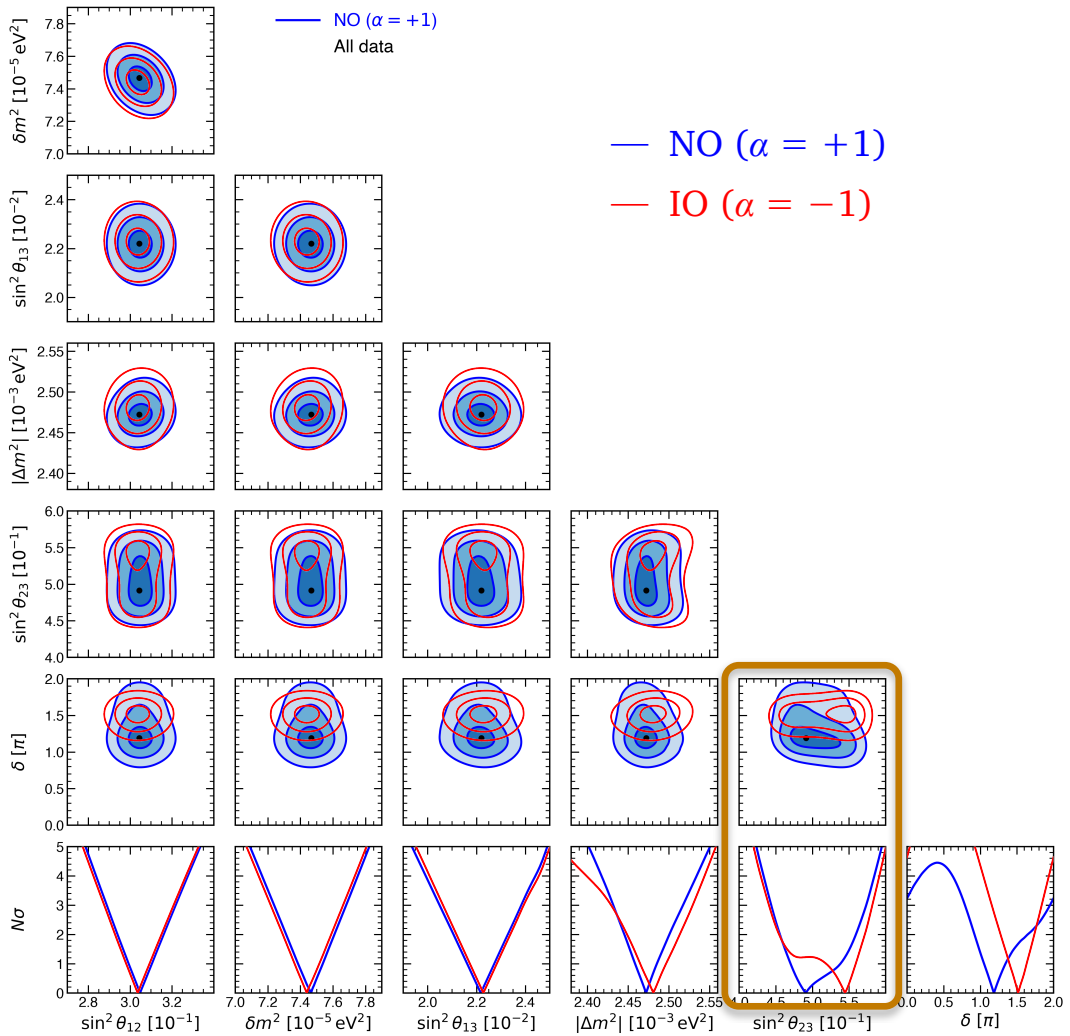
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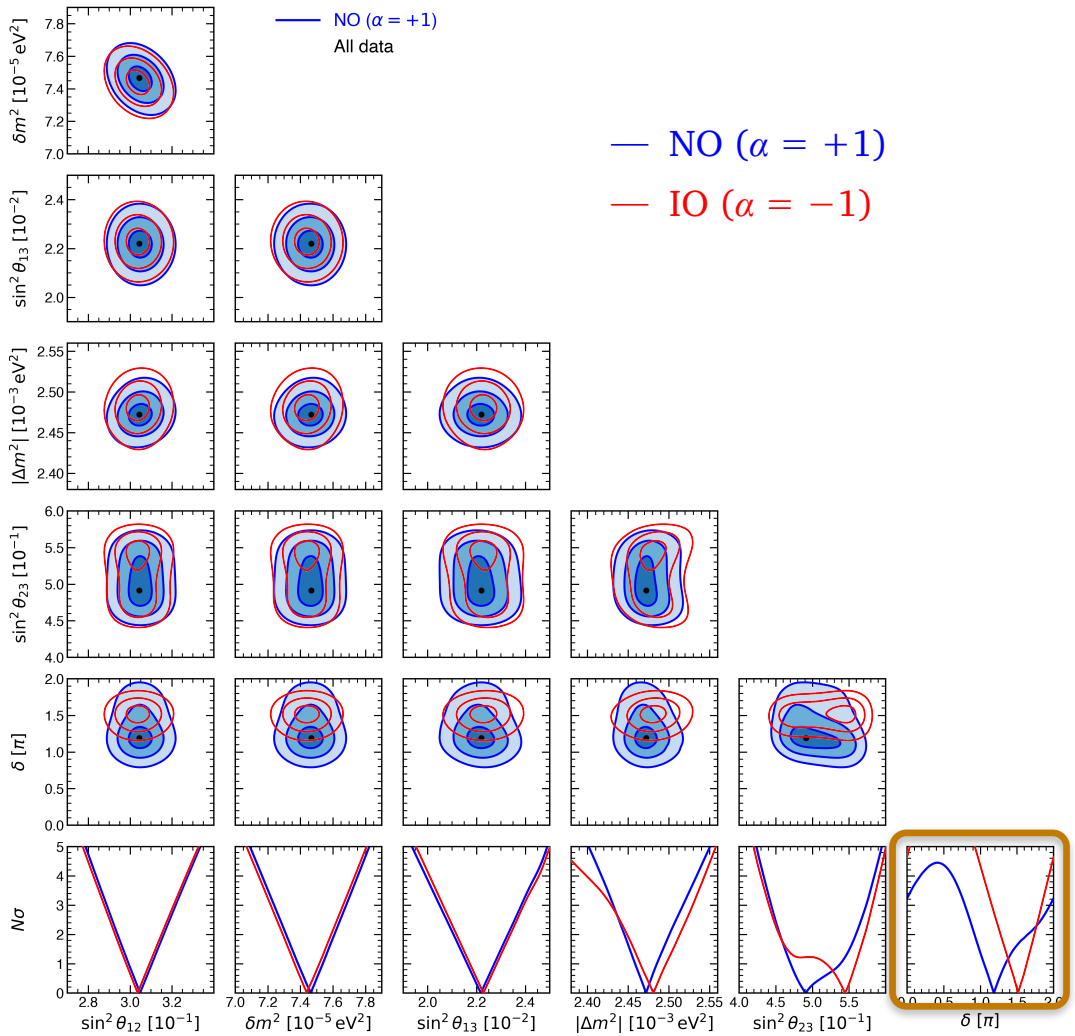
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NO favoured
**3.92σ**

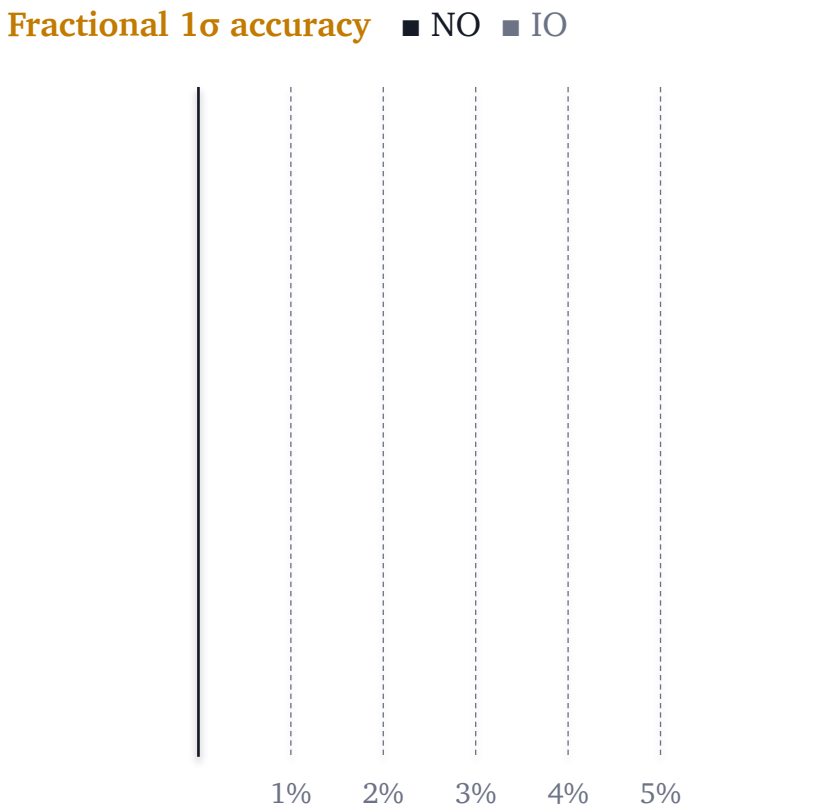
δ / π (NO | IO)
**1.19 | 1.52**

$\sin^2\theta_{23}$ (NO | IO)
**0.49 | 0.54**

# BEST FIT, RANGES AND PRECISION

| Parameter | NO | 3σ range | IO | 3σ range |
|---|---|---|---|---|

3σ: $\Delta\chi^2 = 9$ from the minimum of each ordering. $\Delta\chi^2(\mathrm{IO} - \mathrm{NO}) = +15.34$

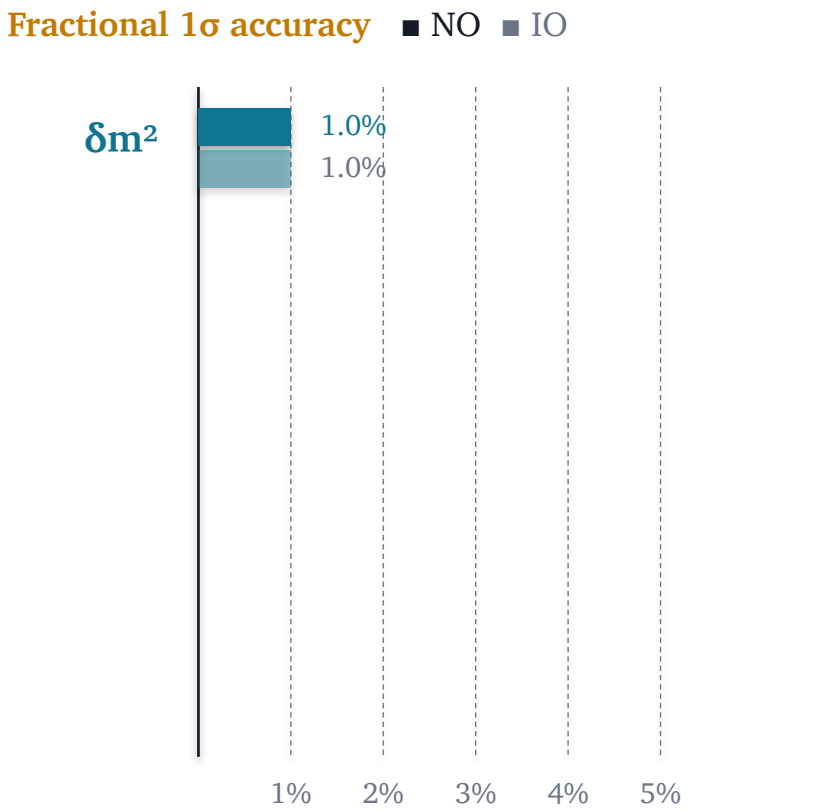



**Other global fits:** NuFIT, JHEP 12 (2024) 216, www.nu-fit.org
Valencia, JHEP 02 (2021) 071

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| Parameter | NO | 3σ range | IO | 3σ range |
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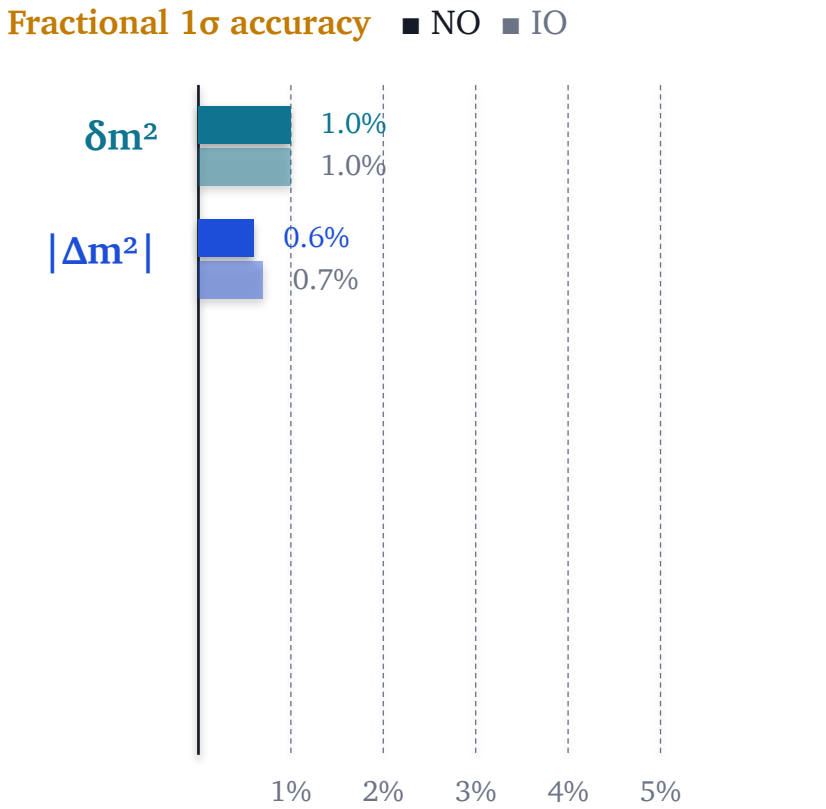



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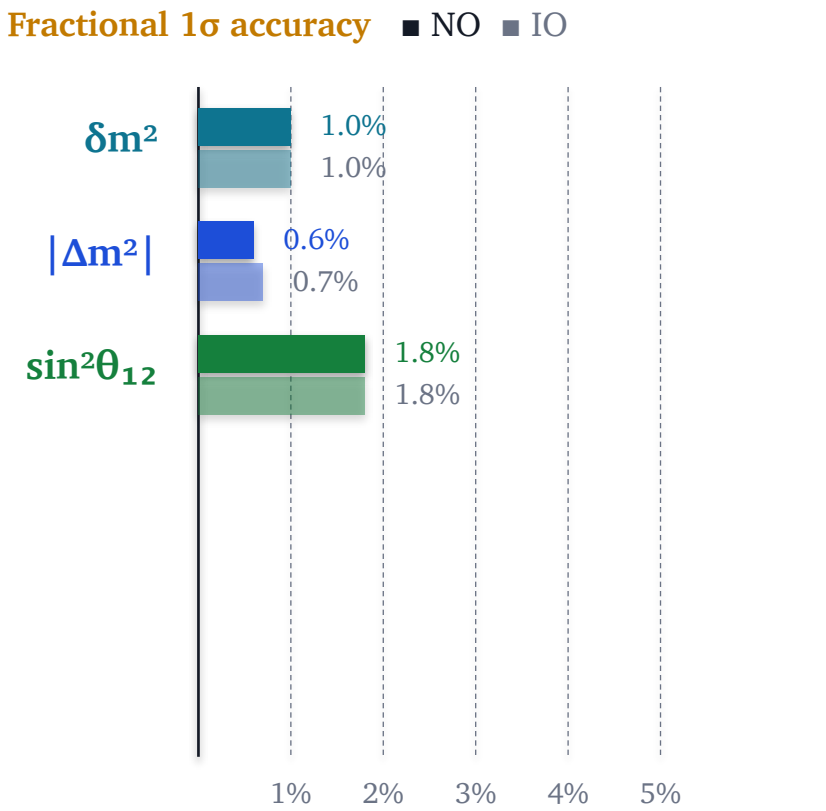



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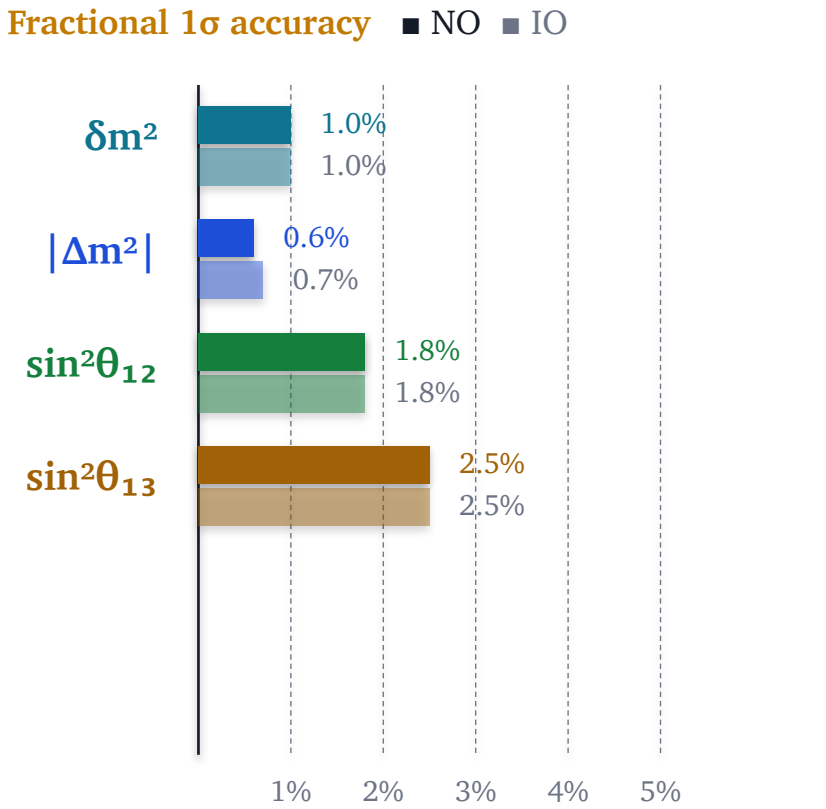



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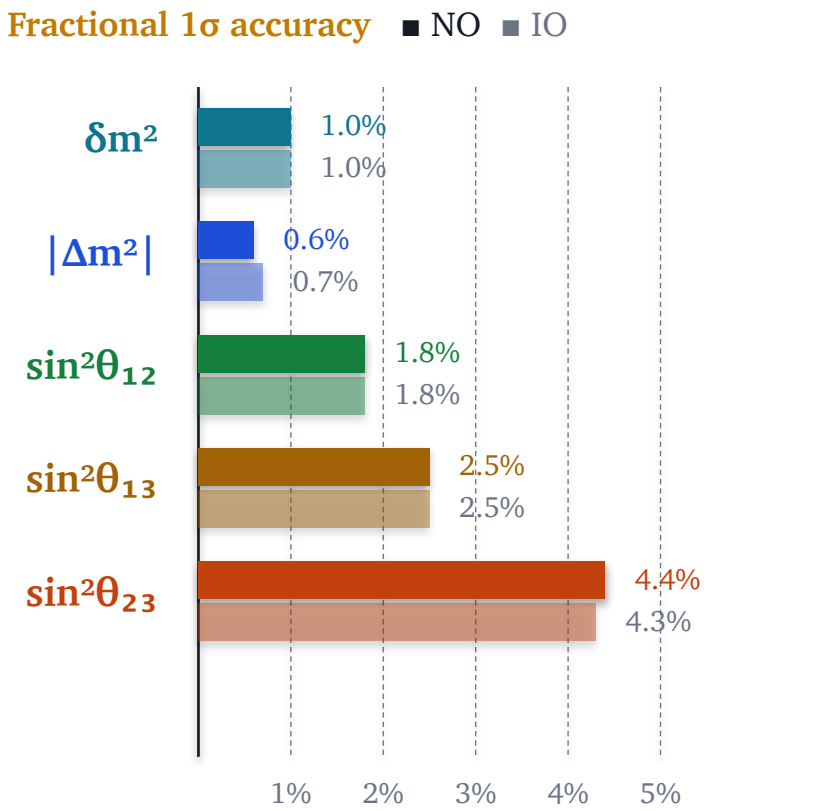



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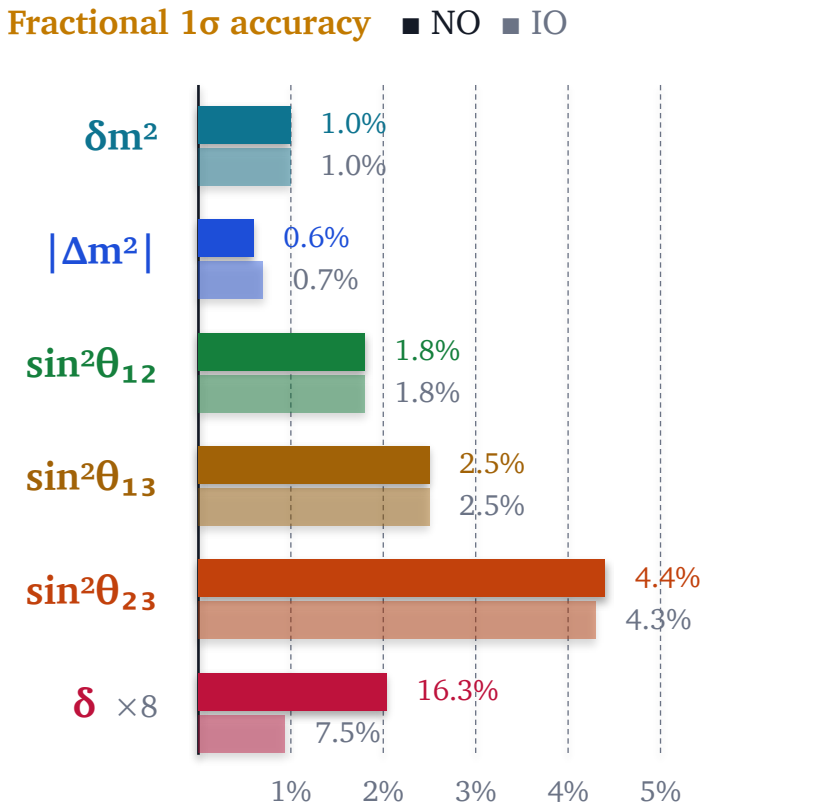



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| $\delta / \pi$ | 1.186 | 0.790 – 1.951 | 1.517 | 1.157 – 1.838 |

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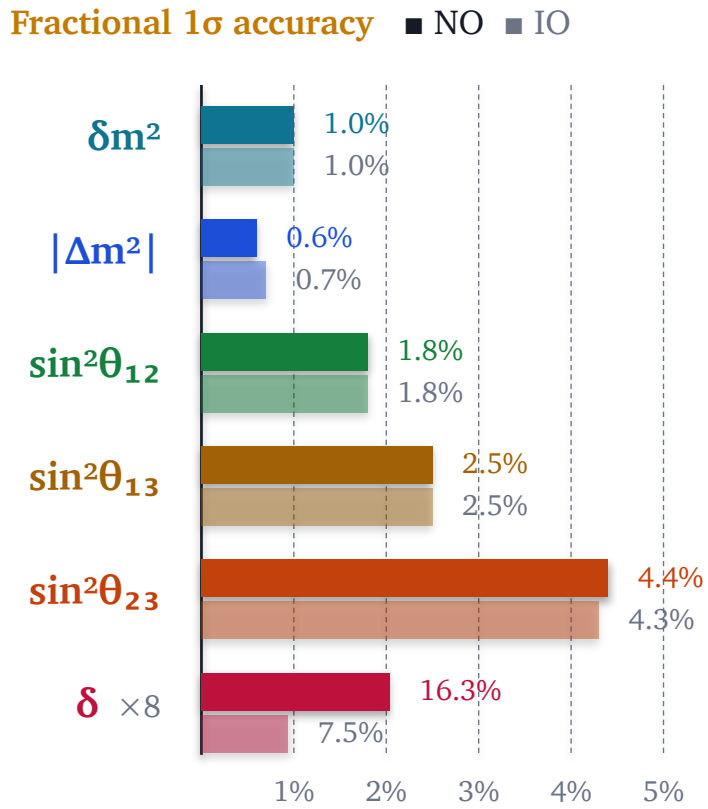



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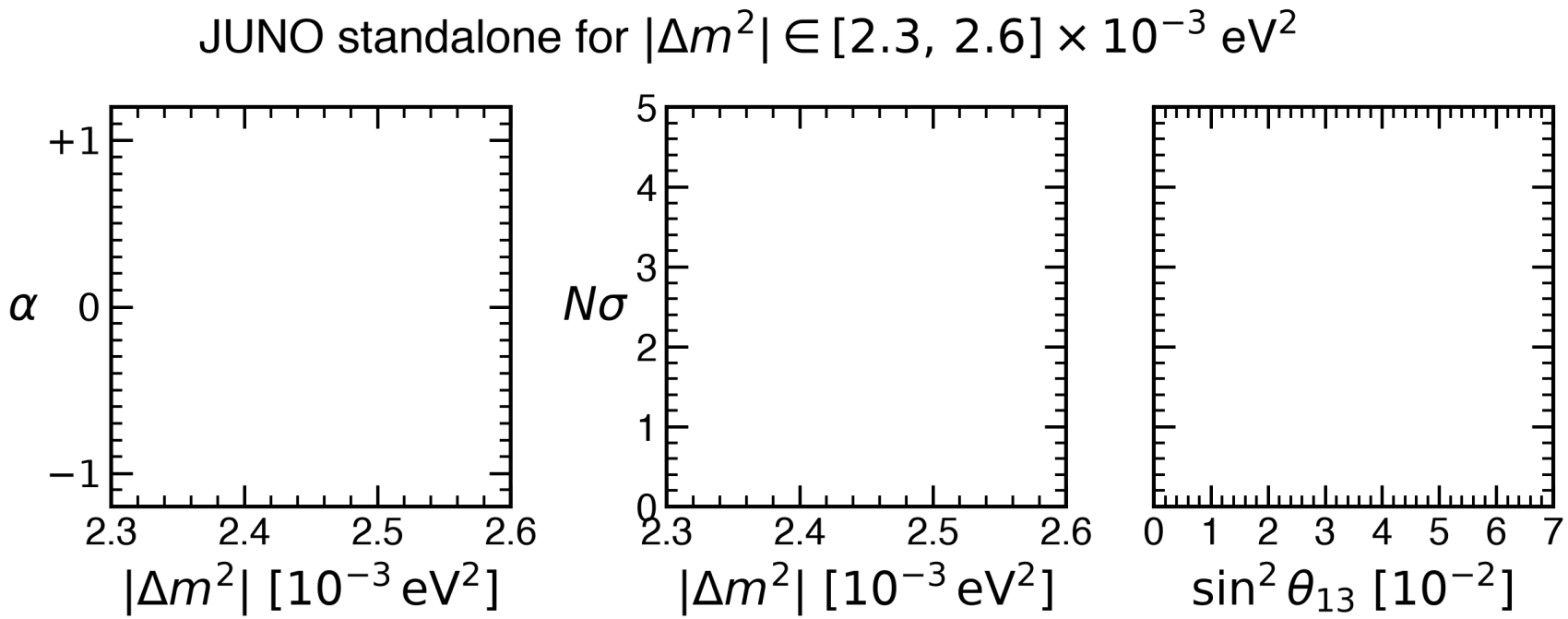
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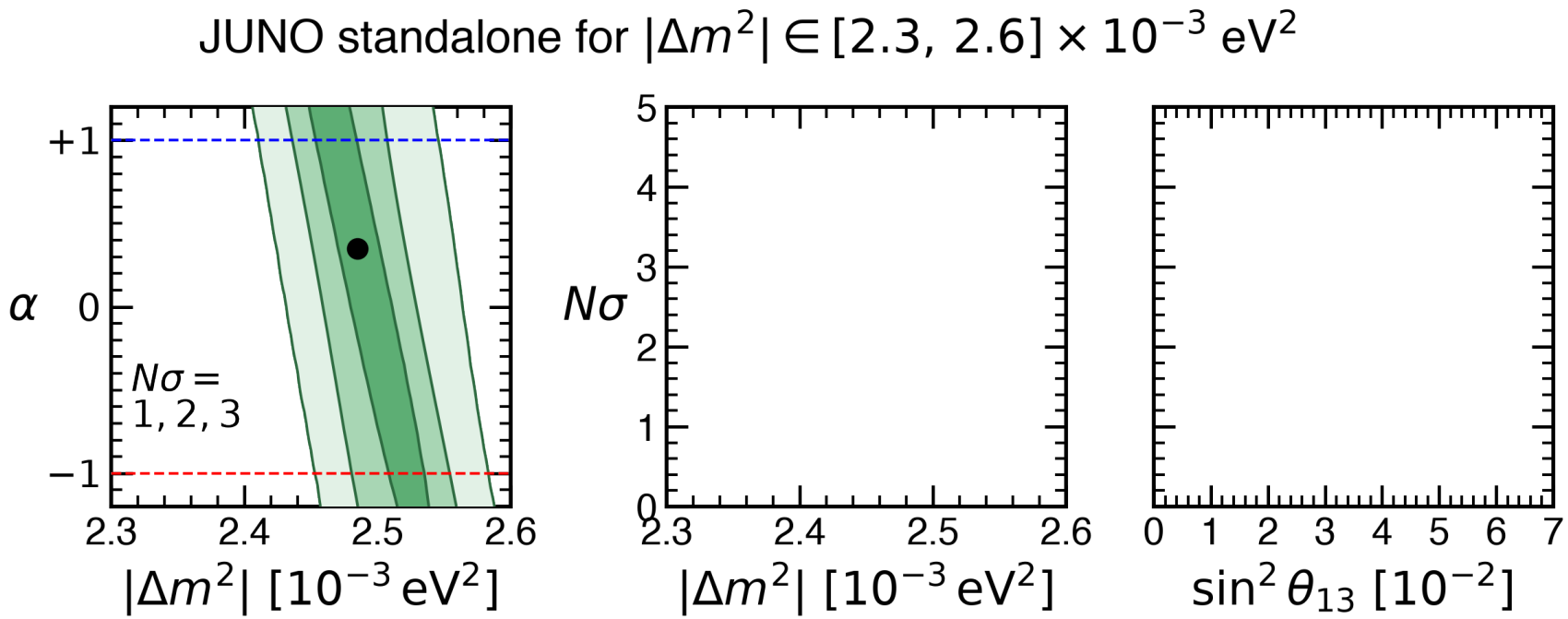

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Four of six parameters below 2.5%; **$\theta_{23}$ and $\delta$ are still poorly determined**

# JUNO STANDALONE



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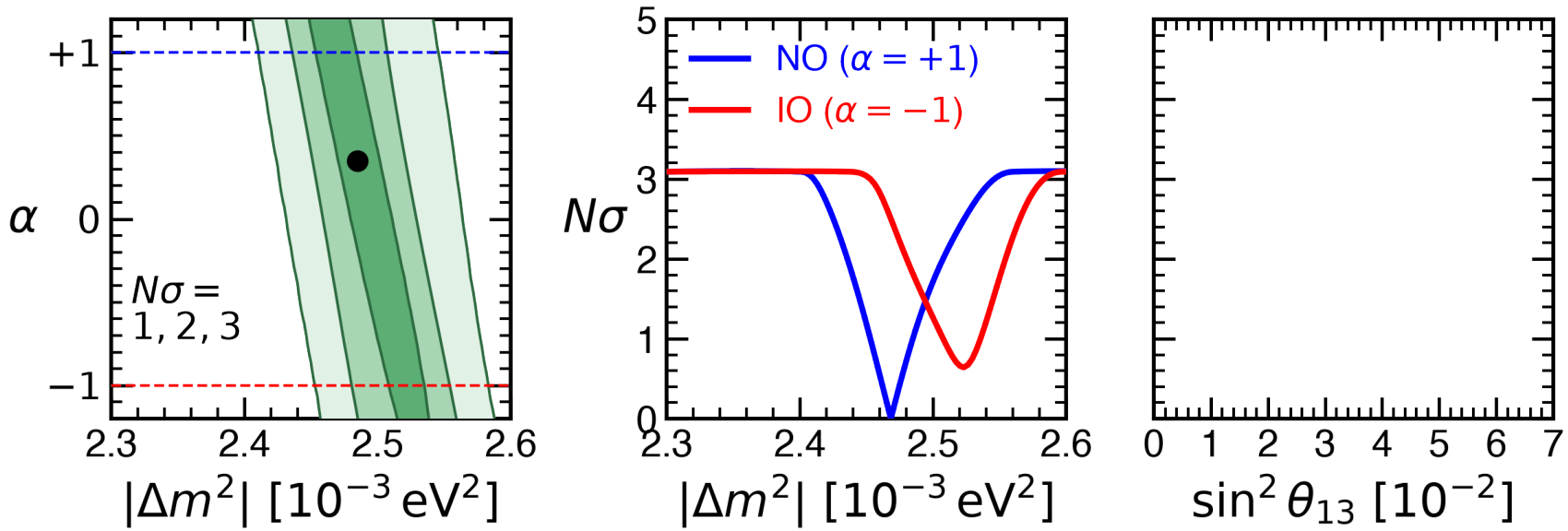



**$\alpha$ left free:** JUNO selects a tilted band in ($|\Delta m^2|$, $\alpha$), best fit $\alpha \approx +0.35$

Each value of $\alpha$ gives a different $|\Delta m^2|$

# JUNO STANDALONE

JUNO standalone for $|\Delta m^2| \in [2.3, 2.6] \times 10^{-3}$ eV$^2$




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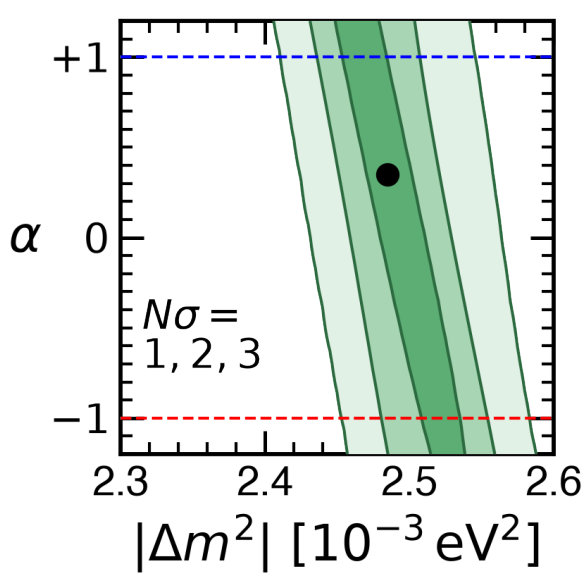
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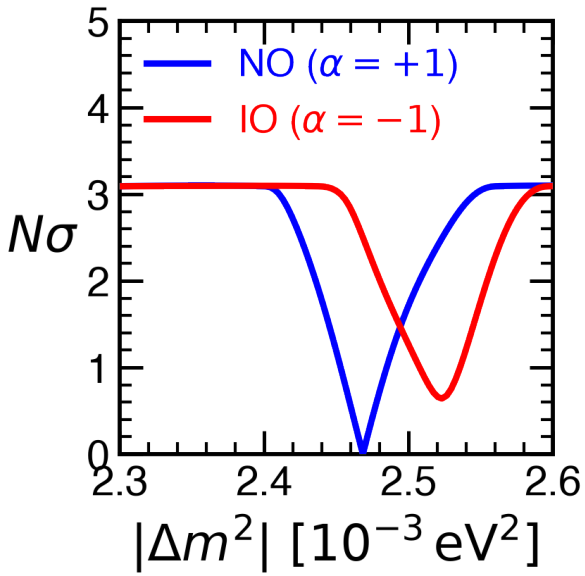
$\alpha = +1, -1$: $|\Delta m^2| =$ **2.468** (NO), **2.523** (IO)

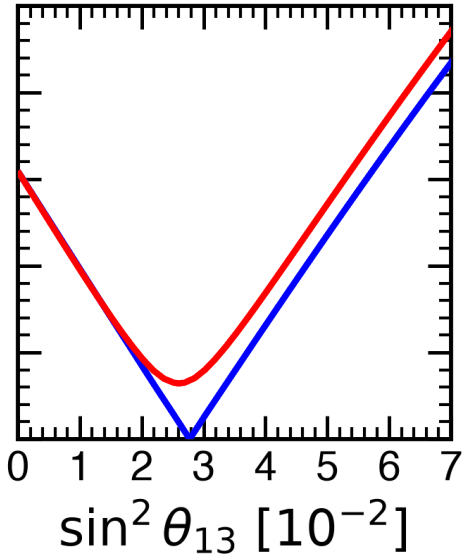
$\Delta\chi^2$(IO − NO) = **+0.41** only: **the sign of $\alpha$ must come from the other data**

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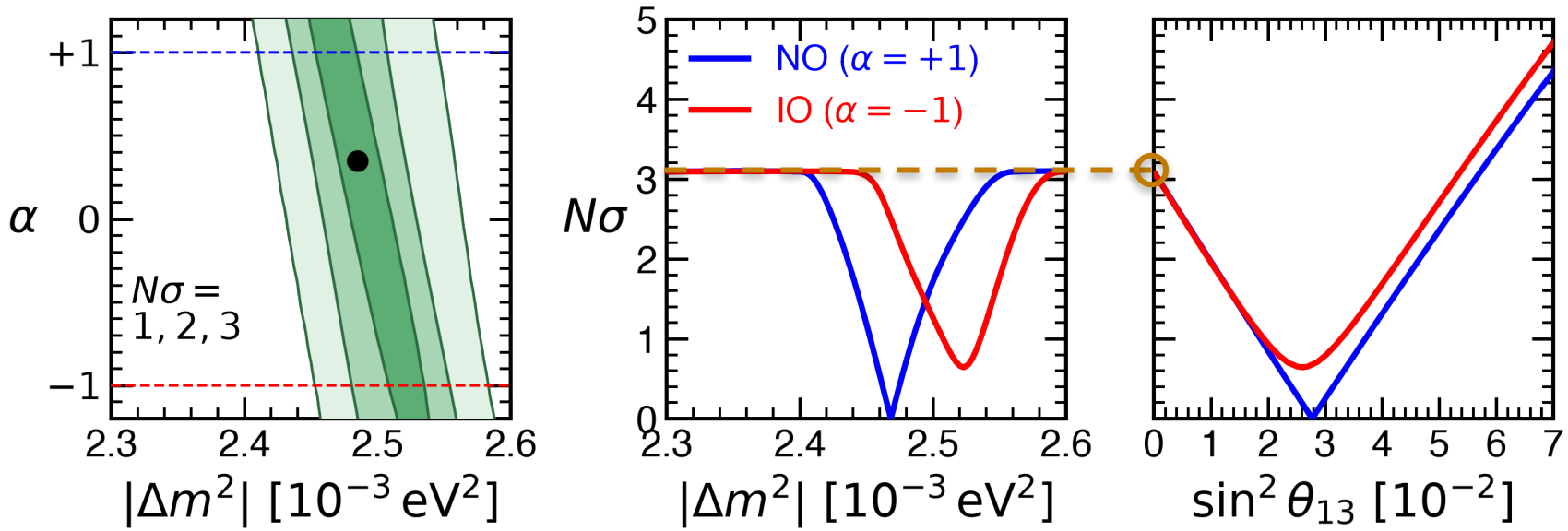
$\sin^2\theta_{13} =$ **2.78**$\times 10^{-2}$ (NO), **2.60**$\times 10^{-2}$ (IO), known to about 30%

$\theta_{13}$ comes from SBrea

# JUNO STANDALONE

**Plateau at Nσ ≈ 3.1:** away from the minimum the best fit has $\theta_{13} \to 0$ (no fast oscillations), and $\chi^2$ no longer depends on $|\Delta m^2|$ or $\alpha$

JUNO standalone for $|\Delta m^2| \in [2.3, 2.6] \times 10^{-3}$ eV$^2$




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# THE WHOLE IS MORE THAN THE SUM OF THE PARTS

$\Delta\chi^2$(IO − NO) when each data set is added alone to SolRea (ordering-blind)

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| JUNO | AC | Atmos |
|---|---|---|
| **−0.48** | **+0.90** | **+9.06** |
| −0.69σ | +0.95σ | +3.01σ |

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| JUNO | AC | Atmos | naive sum |
|---|---|---|---|
| **−0.48** | **+0.90** | **+9.06** | **9.48** |
| −0.69σ | +0.95σ | +3.01σ | 3.08σ |

**Wrong:** $-0.48 + 0.90 + 9.06 = 9.48$, but $\Delta\chi^2$ values do not add up

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| JUNO | AC | Atmos | naive sum | all data |
|---|---|---|---|---|
| **−0.48** | **+0.90** | **+9.06** | **9.48** | **15.34** |
| −0.69σ | +0.95σ | +3.01σ | 3.08σ | 3.92σ |

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Why does the combination give **5.86** more than the naive sum?

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**Wrong:** $-0.48 + 0.90 + 9.06 = 9.48$, but $\Delta\chi^2$ values do not add up

Why does the combination give **5.86** more than the naive sum?

Method: add the data sets to SolRea one at a time, in four different orders, and look where the preference for NO jumps

# FOUR PATHS TO THE SAME ANSWER

Four orders of adding the data to SolRea: after each step, $\Delta\chi^2(\mathrm{IO}-\mathrm{NO})$ and, below it, $N\sigma$

| | JUNO first | $\Delta\chi^2$ ($N\sigma$) | JUNO first | $\Delta\chi^2$ ($N\sigma$) | JUNO last | $\Delta\chi^2$ ($N\sigma$) | JUNO last | $\Delta\chi^2$ ($N\sigma$) | Why |
|---|---|---|---|---|---|---|---|---|---|

$N\sigma = \pm\sqrt{|\Delta\chi^2(\mathrm{IO}-\mathrm{NO})|}$; negative: IO preferred

III · WHERE DOES 3.92σ COME FROM?

# FOUR PATHS TO THE SAME ANSWER

Four orders of adding the data to SolRea: after each step, $\Delta\chi^2(\mathrm{IO}-\mathrm{NO})$ and, below it, $N\sigma$

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|---|---|---|---|---|---|---|---|---|---|
| start | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | Reactors and the Sun are blind to $\alpha$ |

$N\sigma = \pm\sqrt{|\Delta\chi^2(\mathrm{IO}-\mathrm{NO})|}$; negative: IO preferred

# FOUR PATHS TO THE SAME ANSWER

Four orders of adding the data to SolRea: after each step, $\Delta\chi^2$(IO − NO) and, below it, Nσ

| | JUNO first | $\Delta\chi^2$ (Nσ) | JUNO first | $\Delta\chi^2$ (Nσ) | JUNO last | $\Delta\chi^2$ (Nσ) | JUNO last | $\Delta\chi^2$ (Nσ) | Why |
|---|---|---|---|---|---|---|---|---|---|
| start | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | Reactors and the Sun are blind to $\alpha$ |
| step 1 | + JUNO | −0.48<br>−0.69σ | + JUNO | −0.48<br>−0.69σ | + ACdis | +2.04<br>+1.43σ | + Atmos | +9.06<br>+3.01σ | Alone, each data set gives little, except Atmos; JUNO even prefers IO slightly |

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|---|---|---|---|---|---|---|---|---|---|
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| step 2 | + ACdis | +3.97<br>+1.99σ | + Atmos | +13.42<br>+3.66σ | + ACapp | +0.90<br>+0.95σ | + ACdis | +8.87<br>+2.98σ | AC or Atmos meet JUNO: the two $\lvert\Delta m^2\rvert$ agree only in NO → big jumps |

$N\sigma = \pm\sqrt{|\Delta\chi^2(\mathrm{IO}-\mathrm{NO})|}$; negative: IO preferred

# FOUR PATHS TO THE SAME ANSWER

Four orders of adding the data to SolRea: after each step, $\Delta\chi^2$(IO − NO) and, below it, N$\sigma$

| | JUNO first | $\Delta\chi^2$ (N$\sigma$) | JUNO first | $\Delta\chi^2$ (N$\sigma$) | JUNO last | $\Delta\chi^2$ (N$\sigma$) | JUNO last | $\Delta\chi^2$ (N$\sigma$) | Why |
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| step 2 | + ACdis | +3.97<br>+1.99σ | + Atmos | +13.42<br>+3.66σ | + ACapp | +0.90<br>+0.95σ | + ACdis | +8.87<br>+2.98σ | AC or Atmos meet JUNO: the two $\lvert\Delta m^2\rvert$ agree only in NO → big jumps |
| step 3 | + ACapp | +3.99<br>+2.00σ | + ACdis | +16.52<br>+4.06σ | + Atmos | +7.37<br>+2.71σ | + ACapp | +7.37<br>+2.71σ | ACapp never helps, in any path: T2K and NOνA prefer different δ in NO |

N$\sigma = \pm\sqrt{|\Delta\chi^2(\text{IO} - \text{NO})|}$; negative: IO preferred

III · WHERE DOES 3.92σ COME FROM?

# FOUR PATHS TO THE SAME ANSWER

Four orders of adding the data to SolRea: after each step, $\Delta\chi^2$(IO − NO) and, below it, Nσ

| | JUNO first | $\Delta\chi^2$ (Nσ) | JUNO first | $\Delta\chi^2$ (Nσ) | JUNO last | $\Delta\chi^2$ (Nσ) | JUNO last | $\Delta\chi^2$ (Nσ) | Why |
|---|---|---|---|---|---|---|---|---|---|
| start | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | SolRea | 0.00<br>0.00σ | Reactors and the Sun are blind to $\alpha$ |
| step 1 | + JUNO | −0.48<br>−0.69σ | + JUNO | −0.48<br>−0.69σ | + ACdis | +2.04<br>+1.43σ | + Atmos | +9.06<br>+3.01σ | Alone, each data set gives little, except Atmos; JUNO even prefers IO slightly |
| step 2 | + ACdis | +3.97<br>+1.99σ | + Atmos | +13.42<br>+3.66σ | + ACapp | +0.90<br>+0.95σ | + ACdis | +8.87<br>+2.98σ | AC or Atmos meet JUNO: the two $\lvert\Delta m^2\rvert$ agree only in NO → big jumps |
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| step 4 | + Atmos | **+15.34**<br>+3.92σ | + ACapp | **+15.34**<br>+3.92σ | + JUNO | **+15.34**<br>+3.92σ | + JUNO | **+15.34**<br>+3.92σ | JUNO last meets a precise $\nu_\mu$ $\lvert\Delta m^2\rvert$: $\Delta\chi^2$ +7.97. Same end point for every order |

Nσ = $\pm\sqrt{\lvert\Delta\chi^2(\text{IO} - \text{NO})\rvert}$; negative: IO preferred

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$N\sigma = \pm\sqrt{|\Delta\chi^2(\text{IO} - \text{NO})|}$; negative: IO preferred

The preference for NO jumps when **$\nu_\mu$ data** (AC, Atmos) meet **$\bar{\nu}_e$ data** (SBrea, JUNO)

# WHAT JUNO ADDS, STEP BY STEP

JUNO's $|\Delta m^2|$ ($\bar{\nu}_e$) is compared with more and more $\nu_\mu$ information

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$\Delta\chi^2$(IO − NO) added by JUNO

**STEP 1** **JUNO on SolRea** only $\bar{\nu}_e$ data: no lever on $\alpha$ **−0.48**

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# WHAT JUNO ADDS, STEP BY STEP

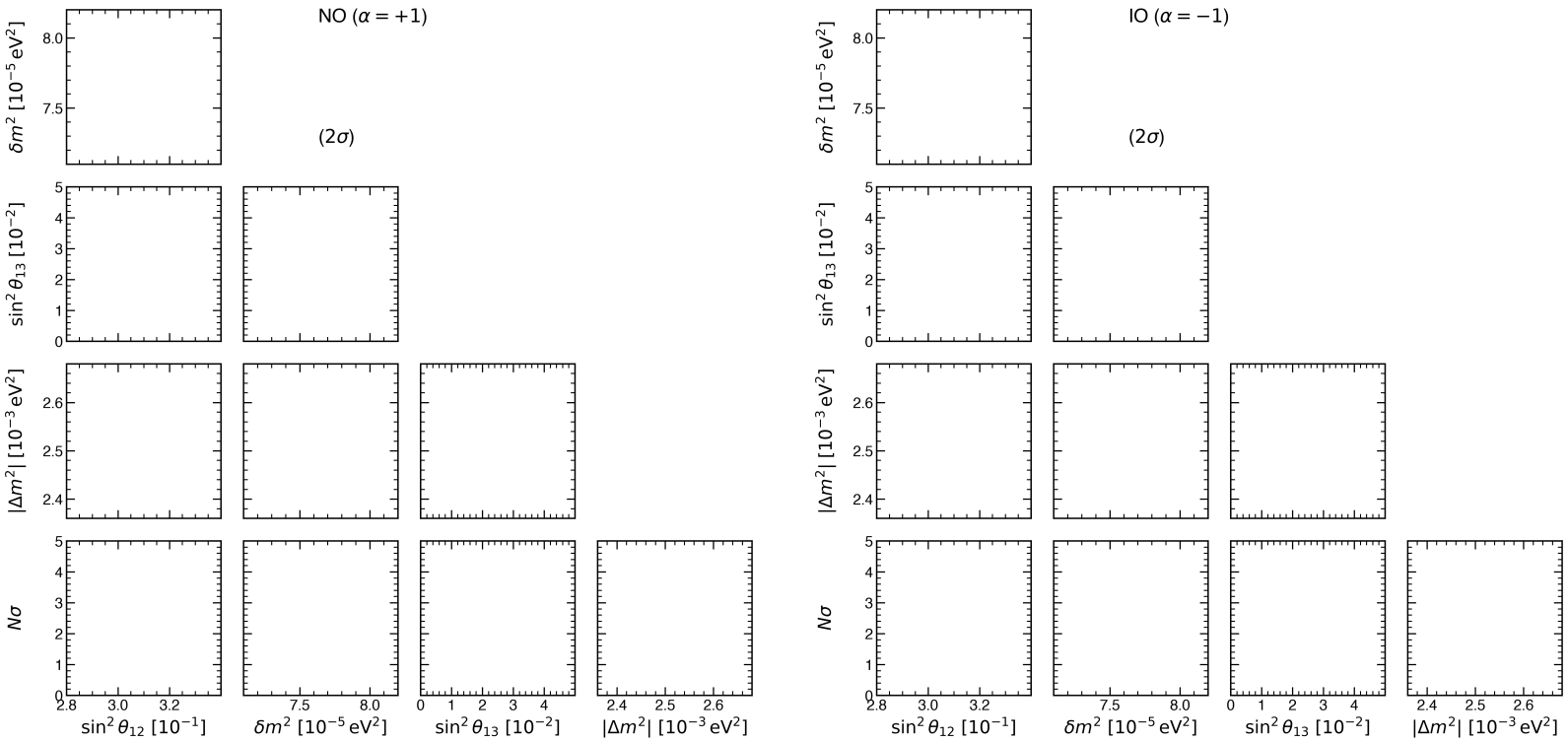
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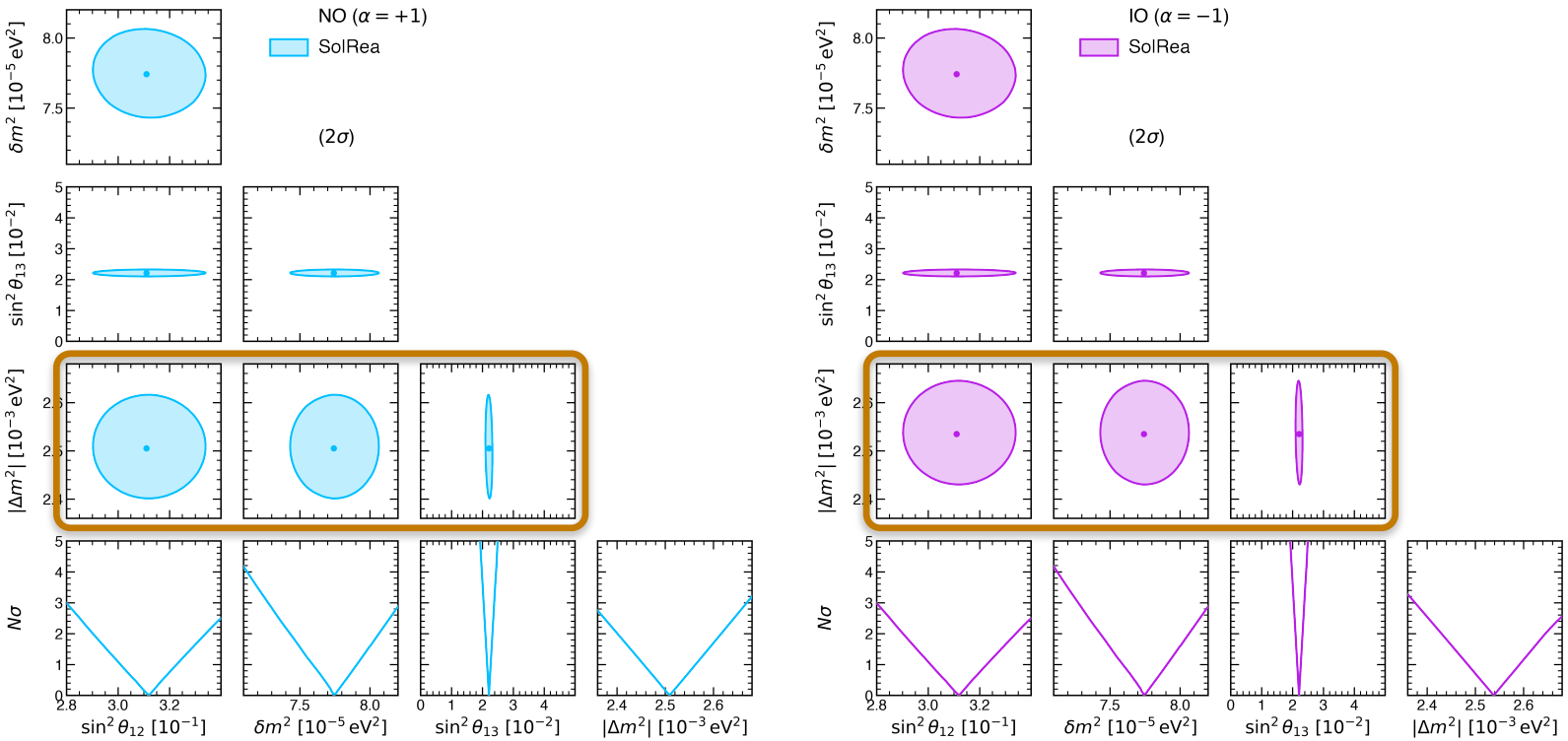
Figures: 2σ regions, NO left, IO right.

What matters: do the $|\Delta m^2|$ regions of JUNO and of the $\nu_\mu$ data **overlap?**

# STEP 1: JUNO ON SolRea

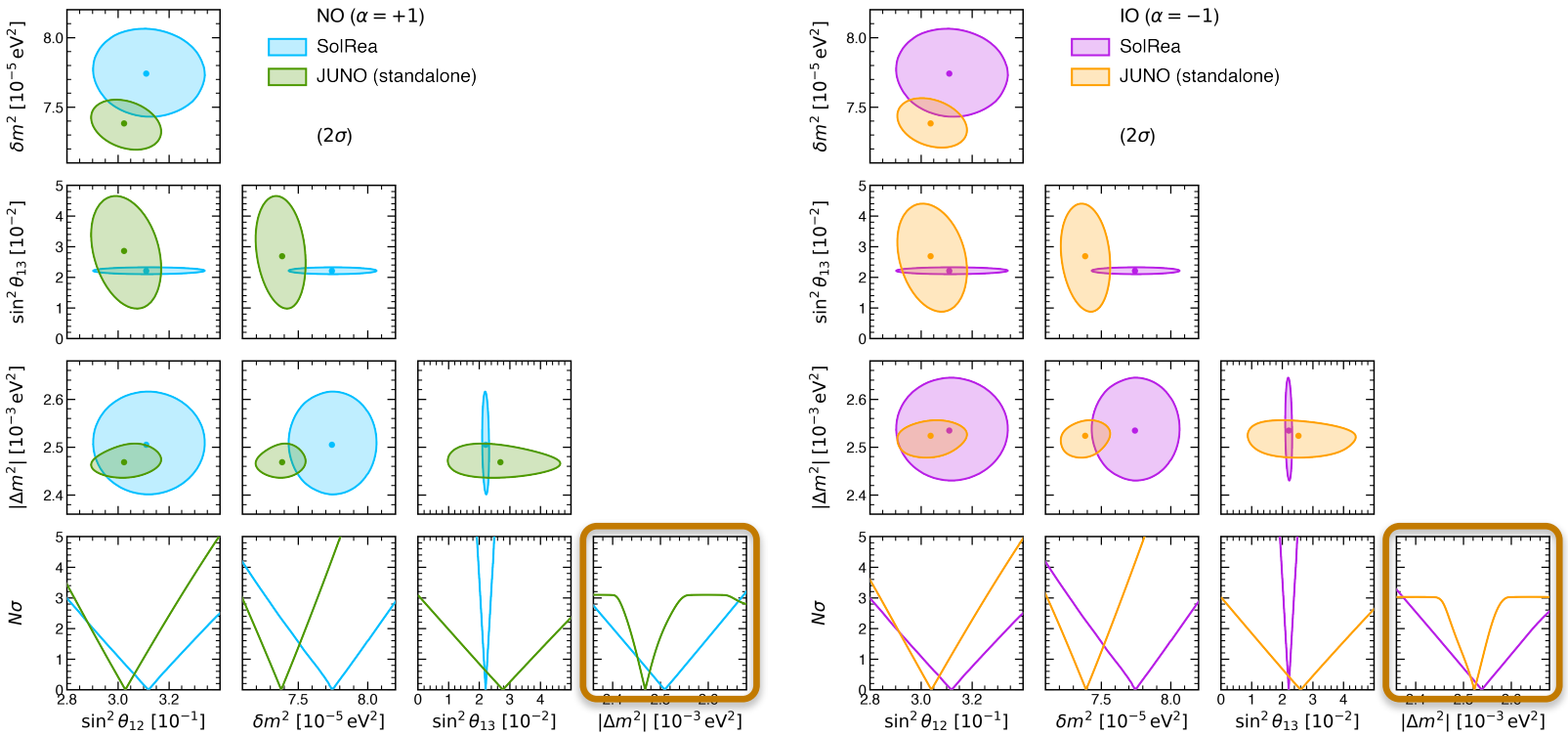


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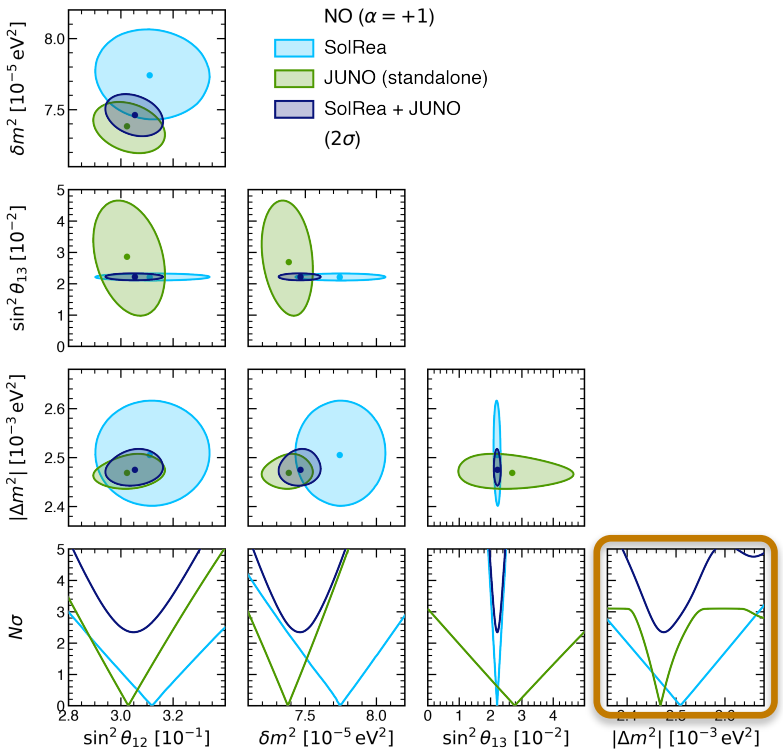

- **SolRea:** same regions in NO and IO, except $|\Delta m^2|$, shifted by $\alpha$; $\Delta\chi^2(\mathrm{IO} - \mathrm{NO}) = 0$

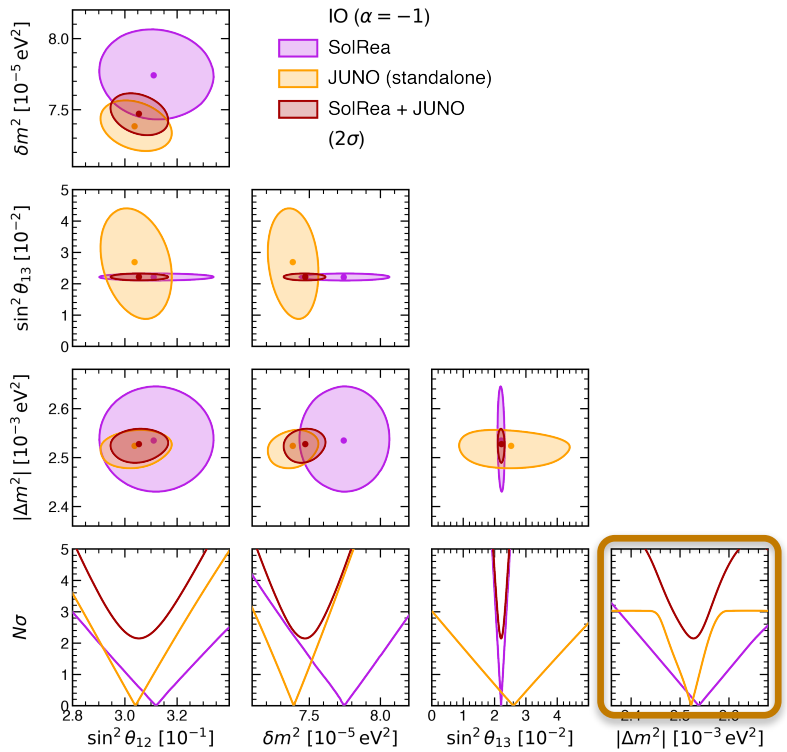
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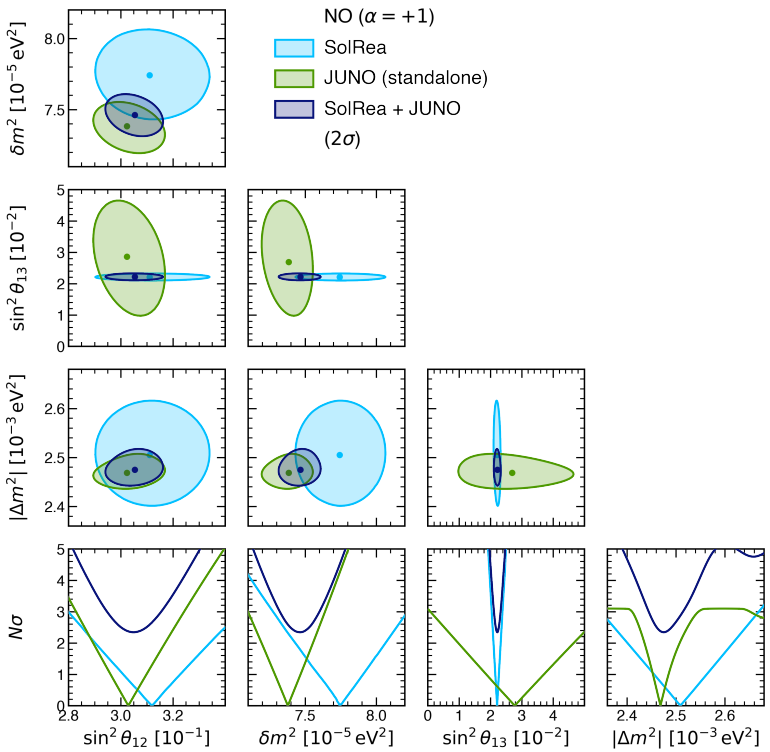
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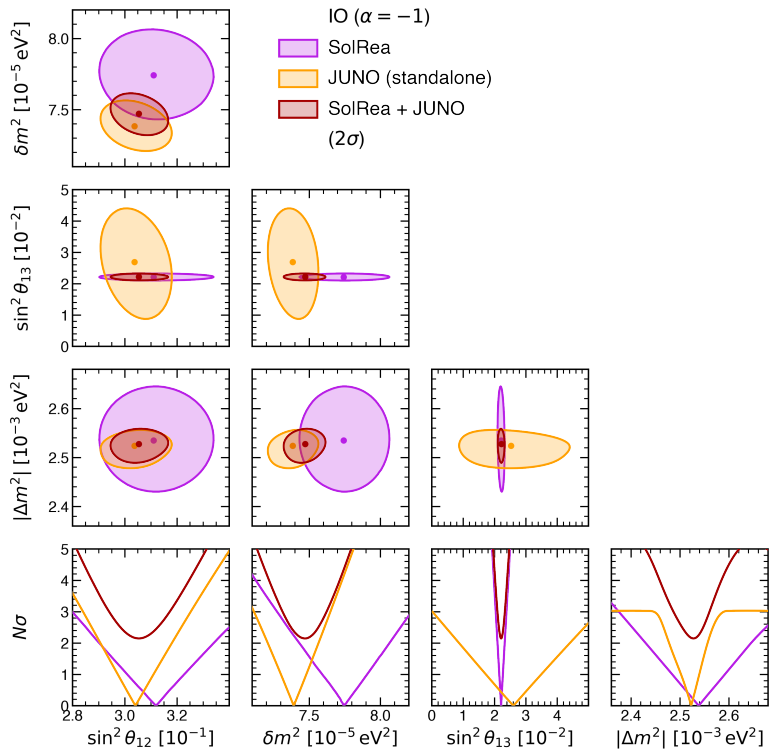



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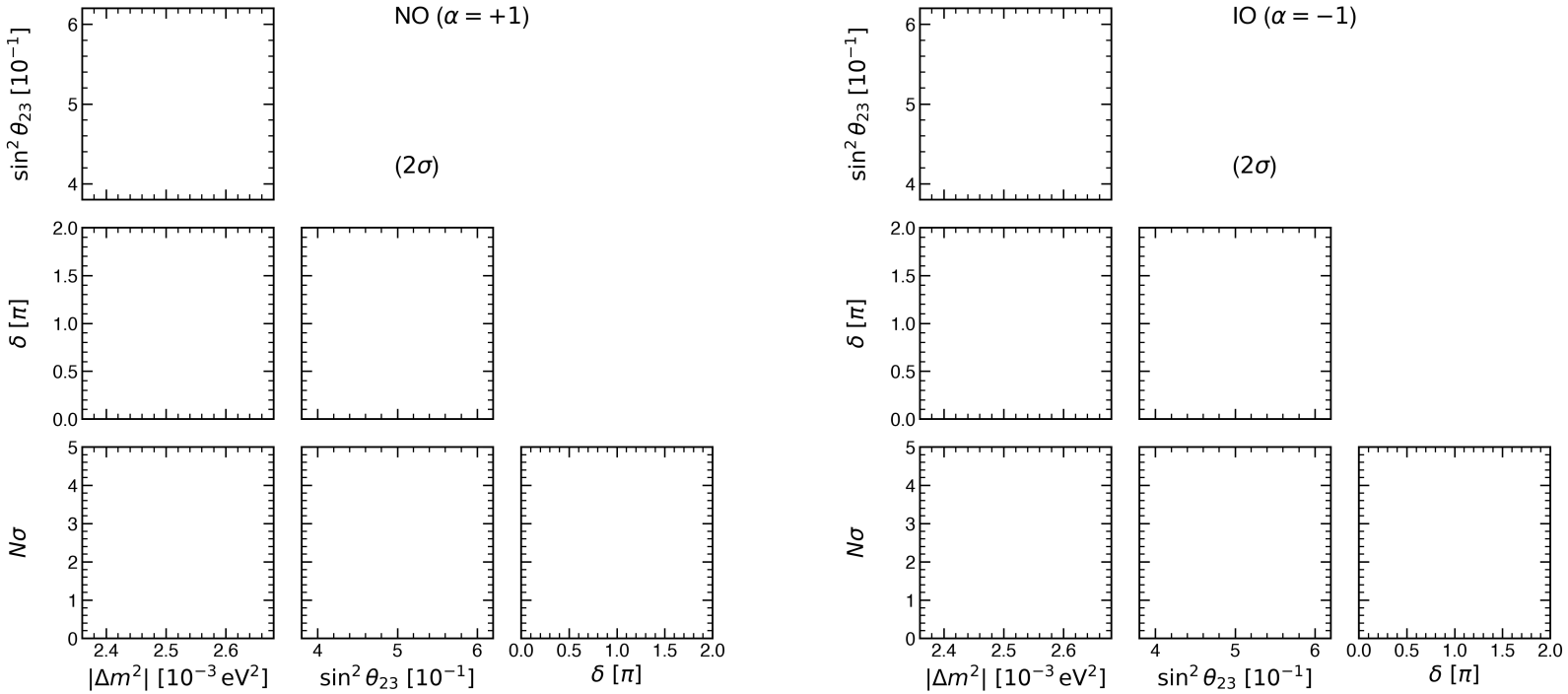


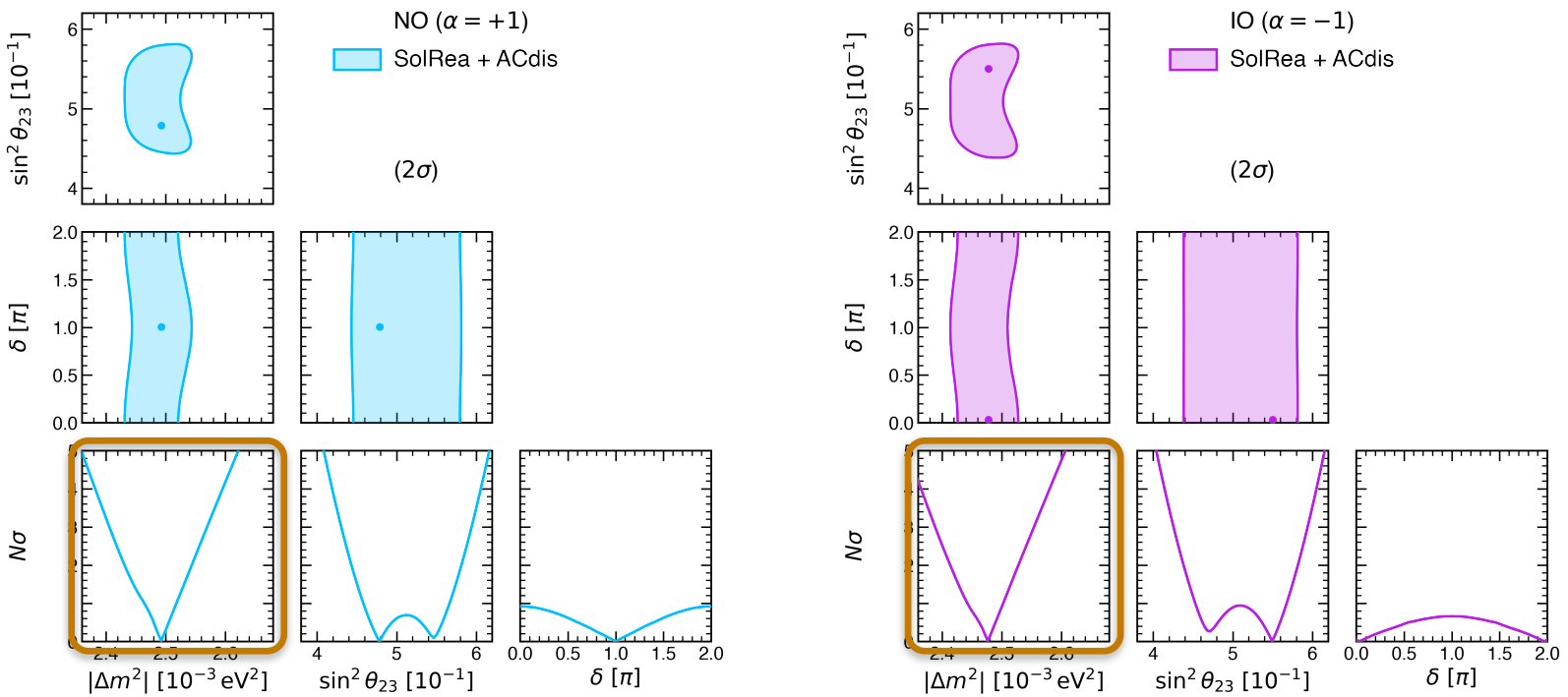

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SBrea and JUNO measure $|\Delta m^2|$ with the same flavour, $\bar{\nu}_e$: no lever on $\alpha$, only a small shift

# STEP 2: JUNO ON SolRea + AC

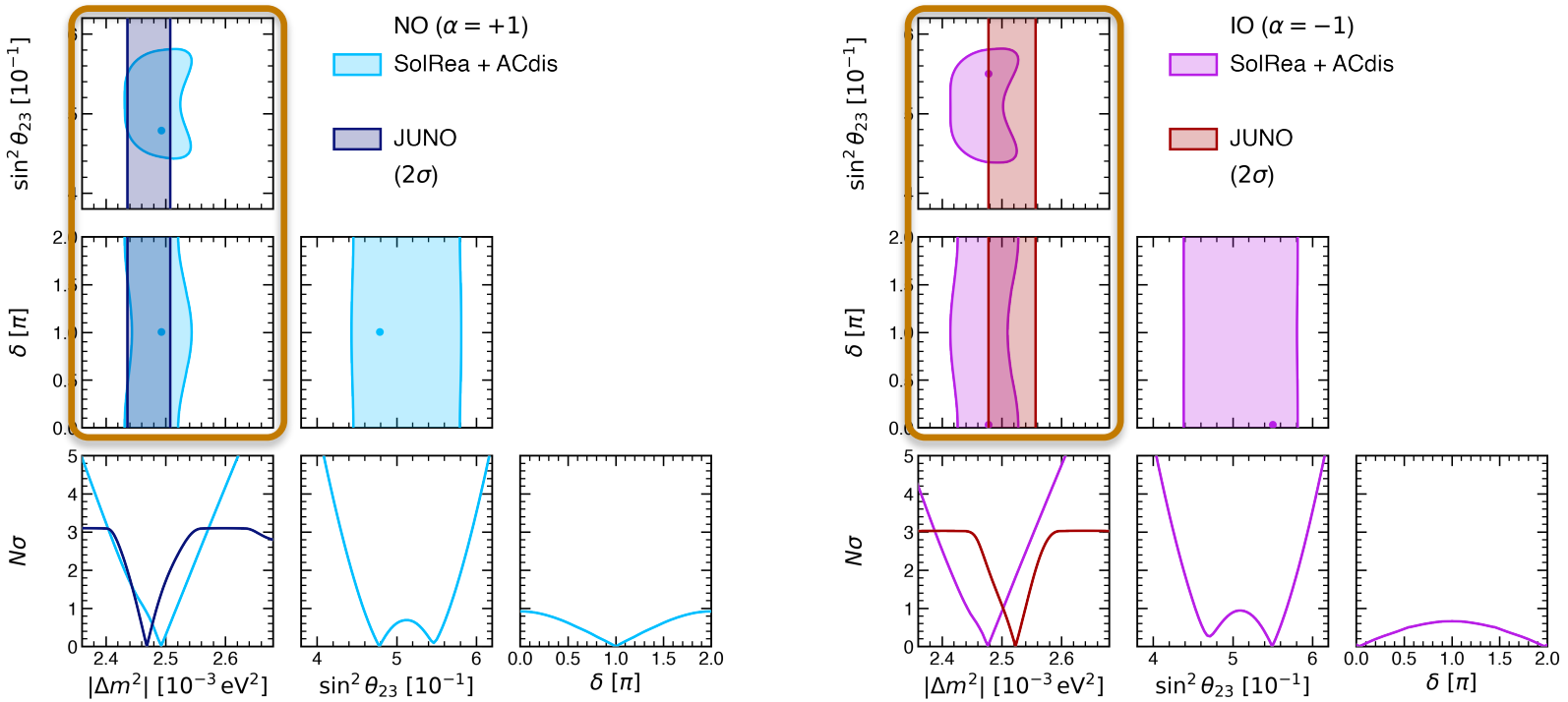


# STEP 2: JUNO ON SolRea + AC




- **AC ($\nu_\mu$):** $|\Delta m^2| = 2.488$ (NO), 2.467 (IO)

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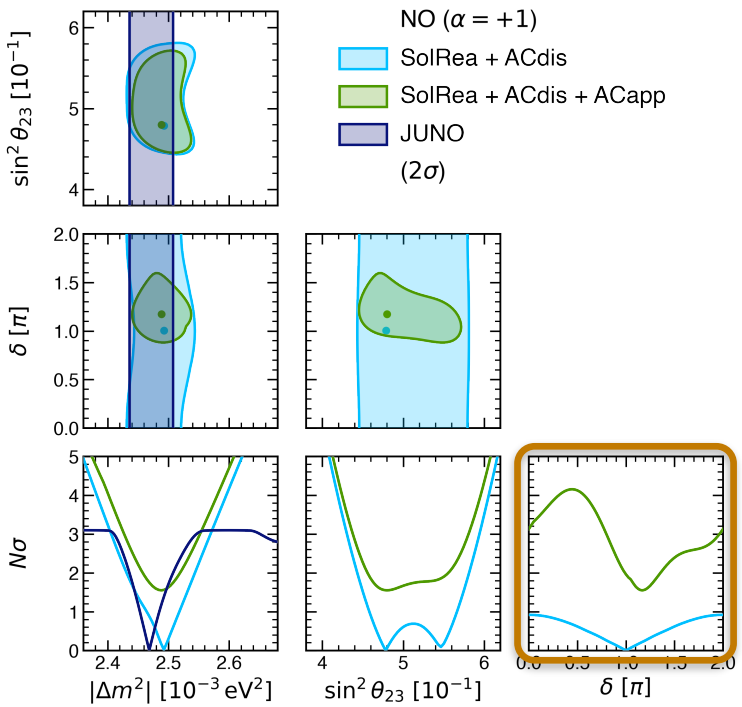


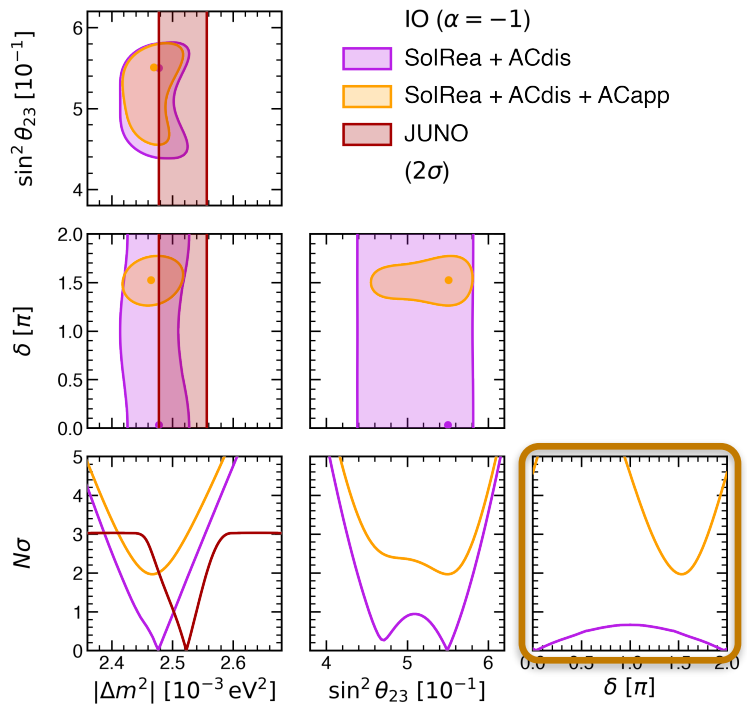




- **AC ($\nu_\mu$):** $|\Delta m^2| = 2.488$ (NO), 2.467 (IO)
- **JUNO ($\bar{\nu}_e$):** $|\Delta m^2| = 2.468$ (NO), 2.523 (IO). NO: AC inside the band; IO: at its edge

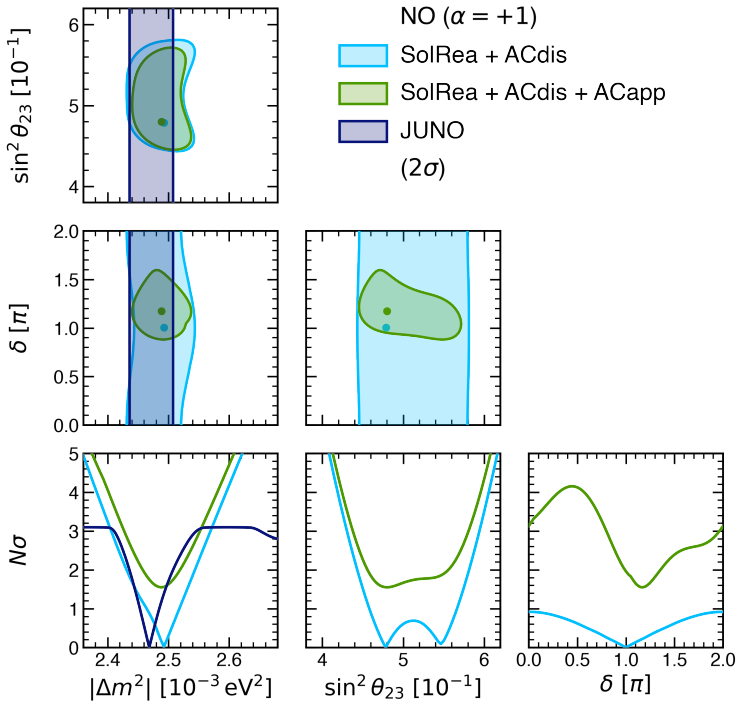
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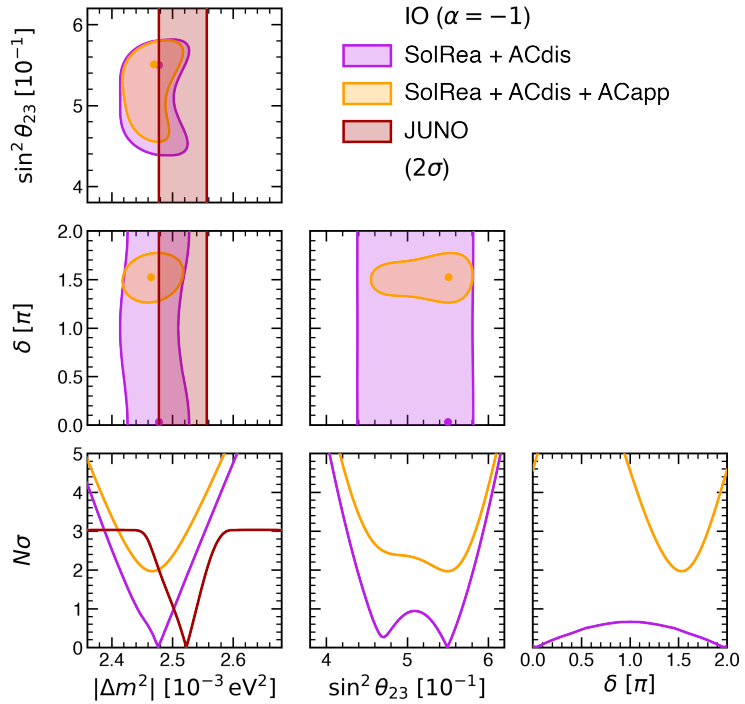



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- **+ AC appearance:** fixes δ (1.17π in NO, 1.53π in IO) at a cost of 1.55σ (NO), 1.97σ (IO): T2K vs NOνA

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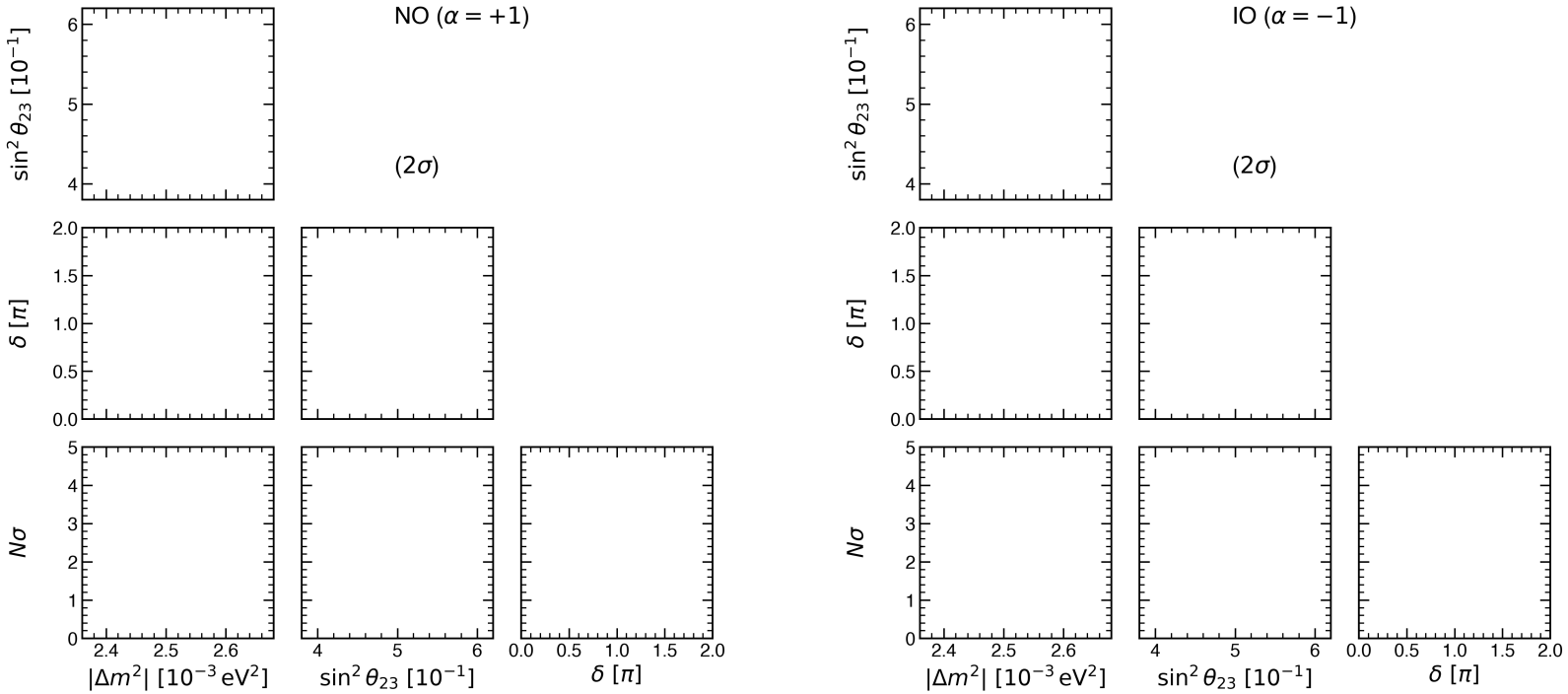


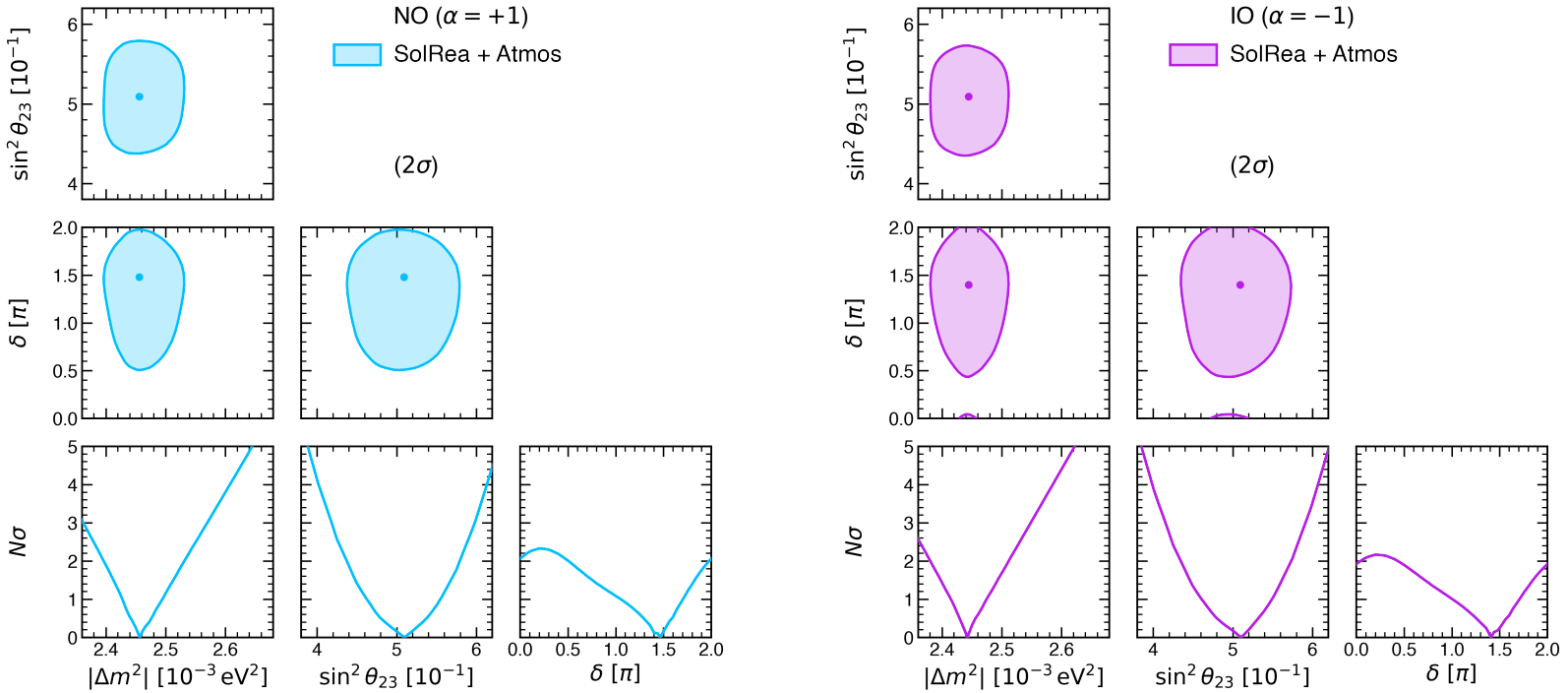

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The $\nu_\mu$ and $\bar{\nu}_e$ values of $|\Delta m^2|$ agree better in NO → JUNO adds **+3.09**

# STEP 3: JUNO ON SolRea + AC + Atmos



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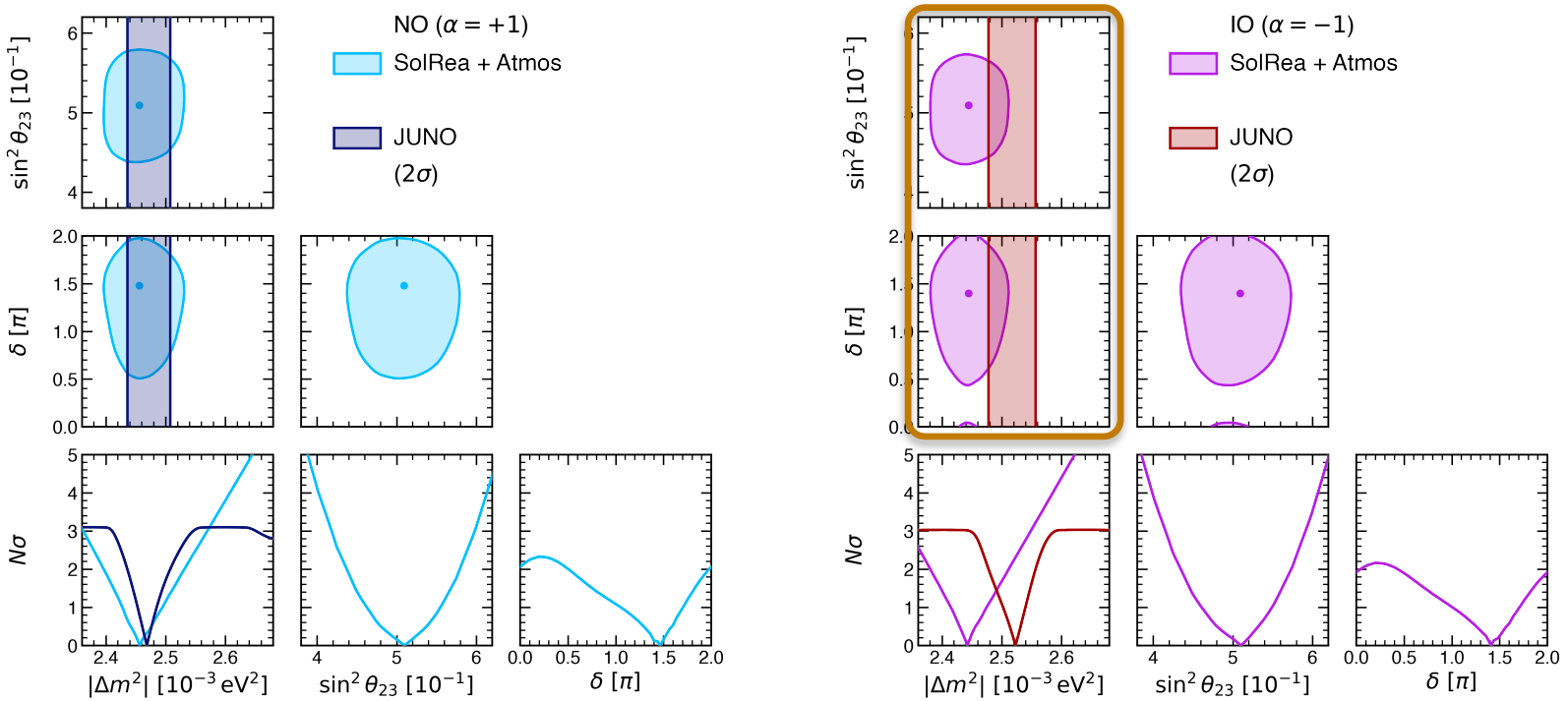






- **Atmos ($\nu_\mu$):** prefers NO already by itself ($\Delta\chi^2 = 9.06$ on SolRea)

# STEP 3: JUNO ON SolRea + AC + Atmos

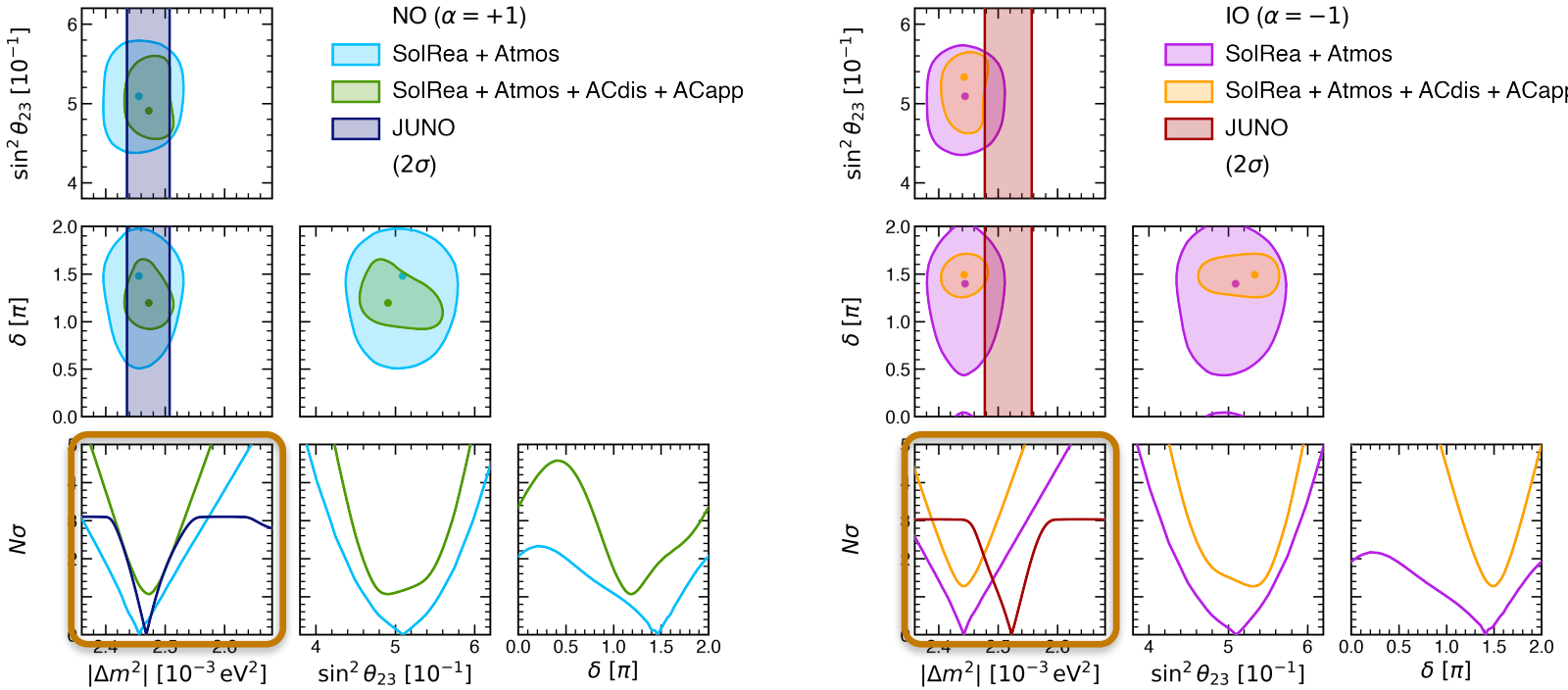






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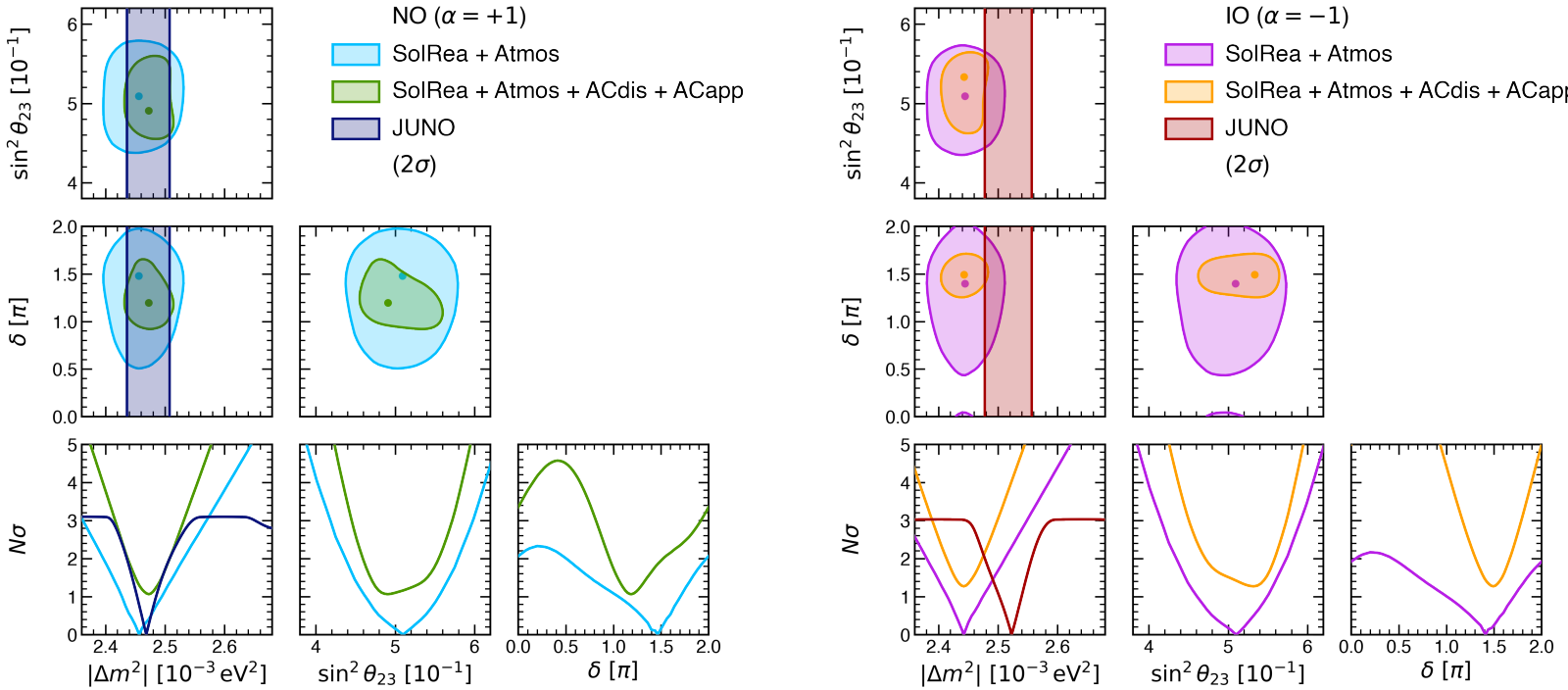






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NO: all regions overlap within JUNO's band. IO: they barely touch → JUNO adds **+7.97**

# ANATOMY OF 3.92σ

$\Delta\chi^2$(IO − NO) of all data, split into three parts

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all data except JUNO

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**+7.37**
all data except JUNO

**+0.41**
JUNO alone

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$\Delta\chi^2$(IO − NO) of all data, split into three parts



**+7.37**
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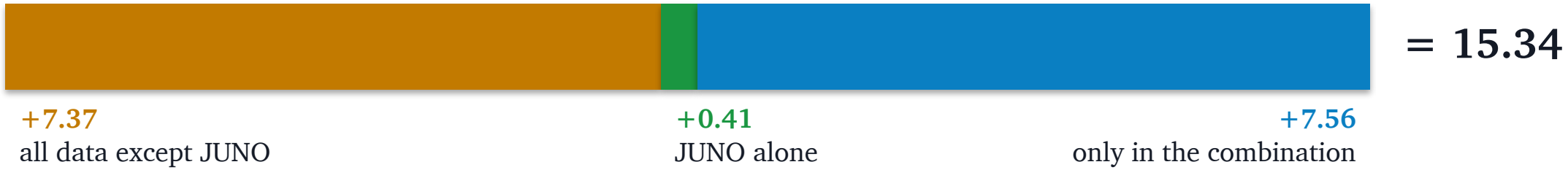
**+0.41**
JUNO alone

**+7.56**
only in the combination

- +7.56 exists only in the combination:
**the $\bar{\nu}_e$–$\nu_\mu$ $|\Delta m^2|$ mismatch in IO**

# ANATOMY OF 3.92σ

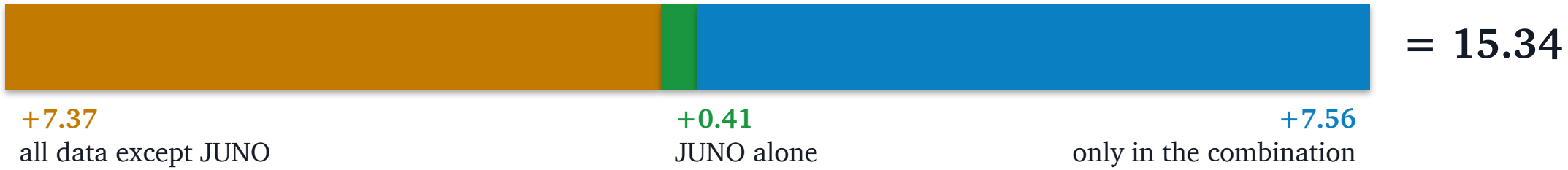
$\Delta\chi^2$(IO − NO) of all data, split into three parts




- +7.56 exists only in the combination: **the $\bar{\nu}_e$–$\nu_\mu$ $|\Delta m^2|$ mismatch in IO**
- Without JUNO: 2.71σ. **With JUNO: 3.92σ**

# ANATOMY OF 3.92σ

$\Delta\chi^2$(IO − NO) of all data, split into three parts

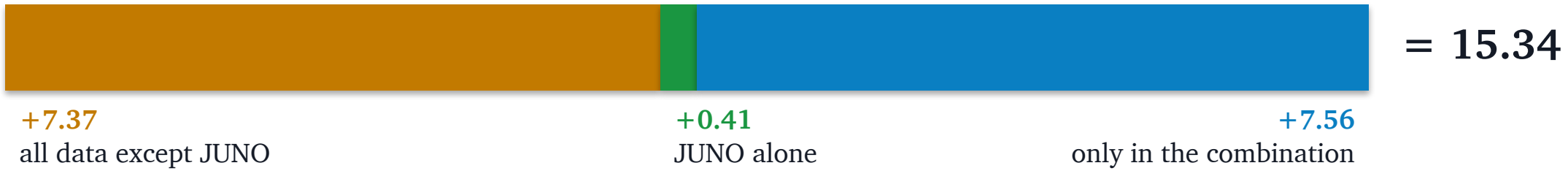



What JUNO adds, $\Delta\chi^2$(IO − NO), depending on the data already in the fit

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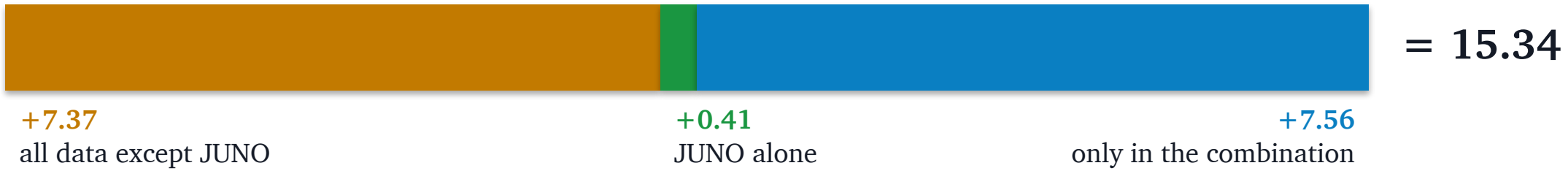

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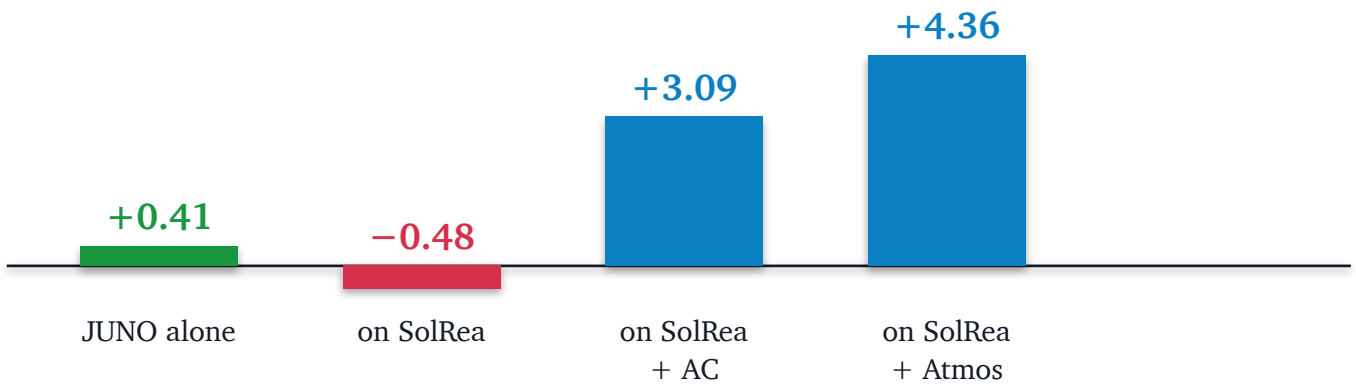


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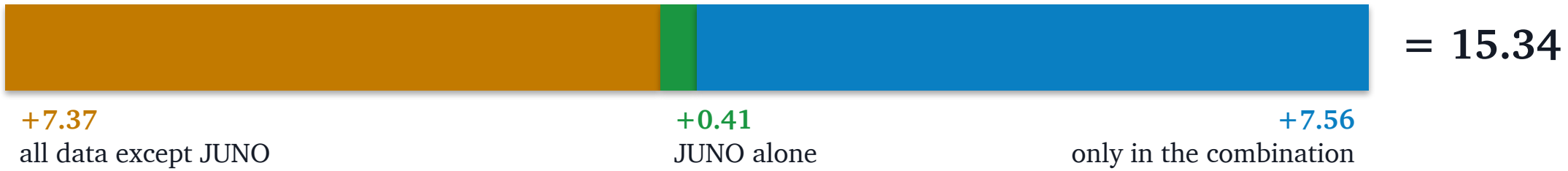

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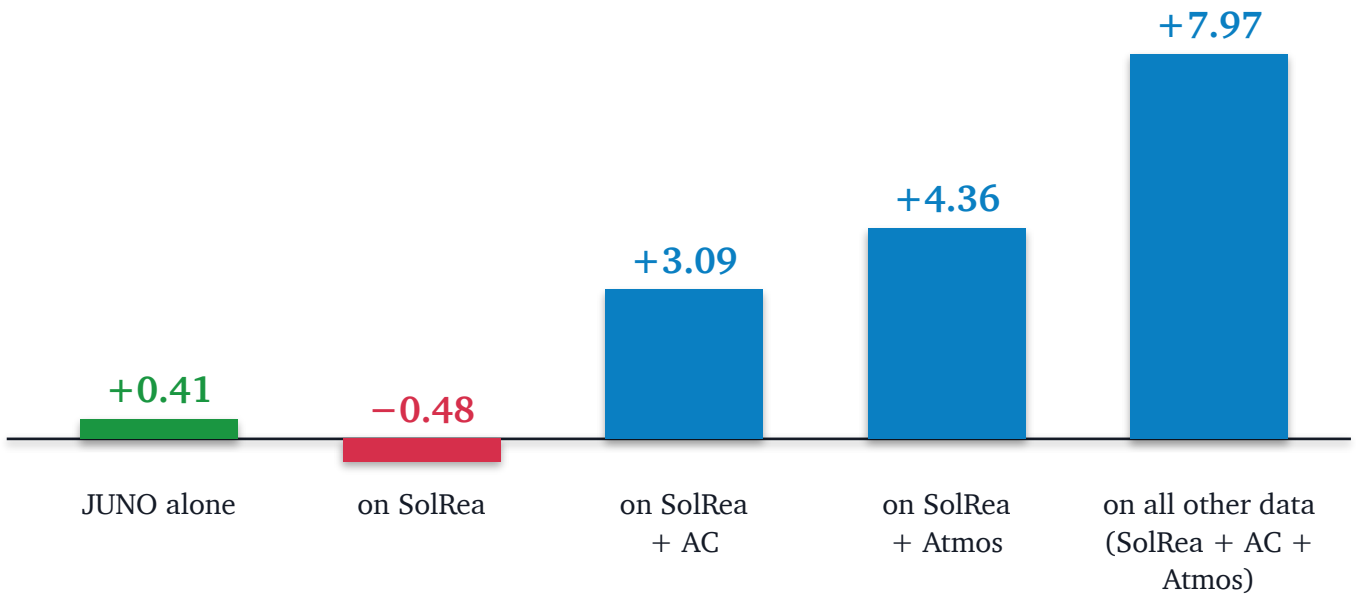

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# ANATOMY OF 3.92σ

$\Delta\chi^2$(IO − NO) of all data, split into three parts



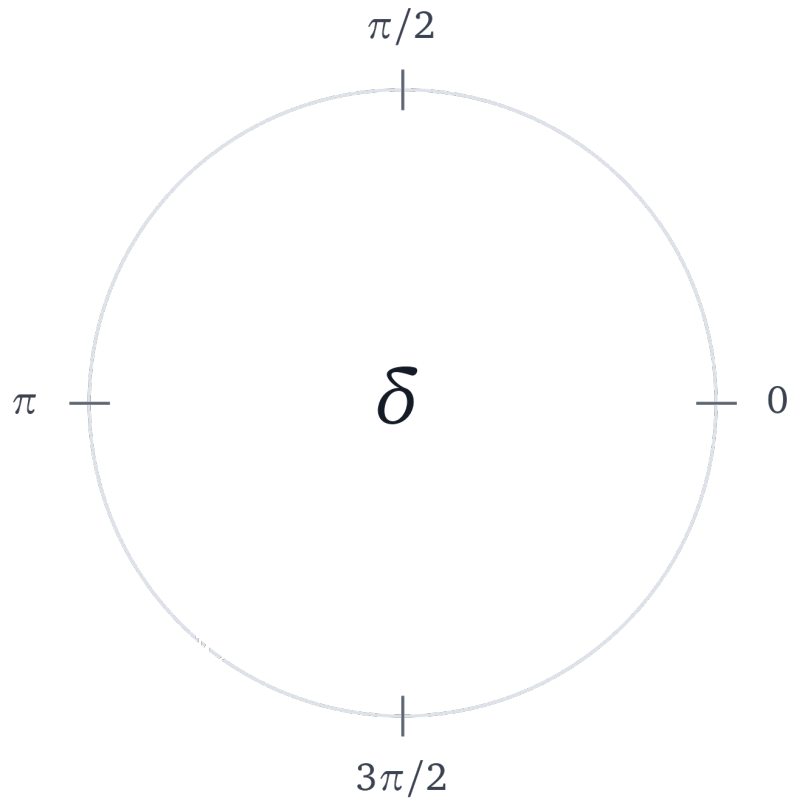

What JUNO adds, $\Delta\chi^2$(IO − NO), depending on the data already in the fit




- +7.56 exists only in the combination: **the $\bar{\nu}_e$–$\nu_\mu$ $|\Delta m^2|$ mismatch in IO**
- Without JUNO: 2.71σ. **With JUNO: 3.92σ**
- Last bar = green + blue parts above: 0.41 + 7.56 = 7.97

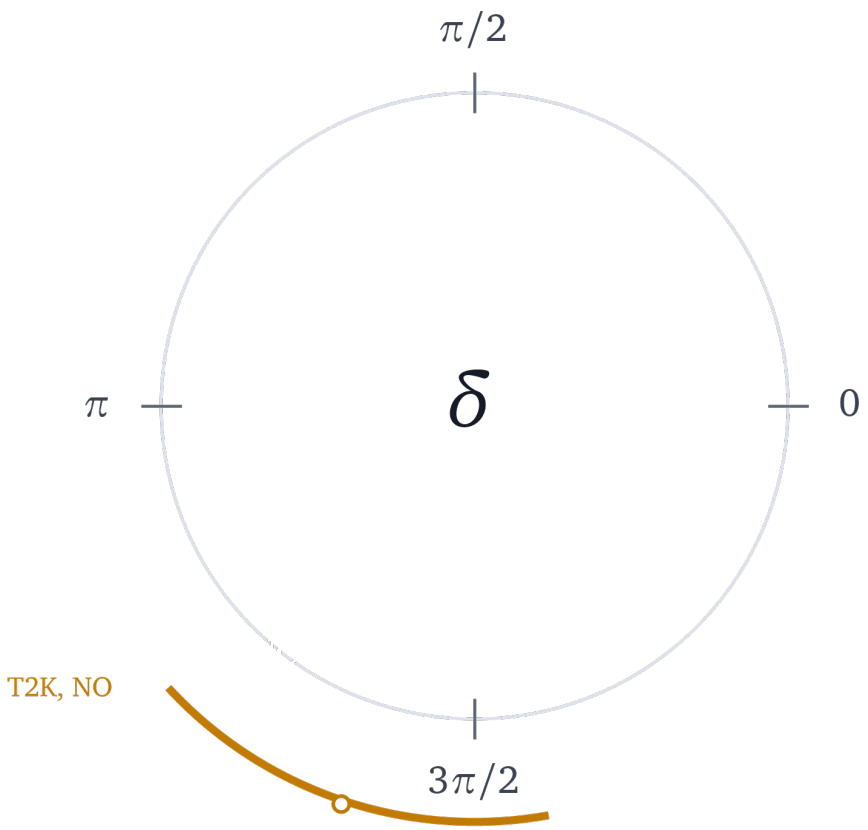
# THE CP PHASE AND THE T2K – NOνA INTERPLAY

Outer arcs: T2K or NOνA with all other data except the other one




inner arcs: all data, 1σ (thick), 2σ (thin);  outer arcs: 1σ

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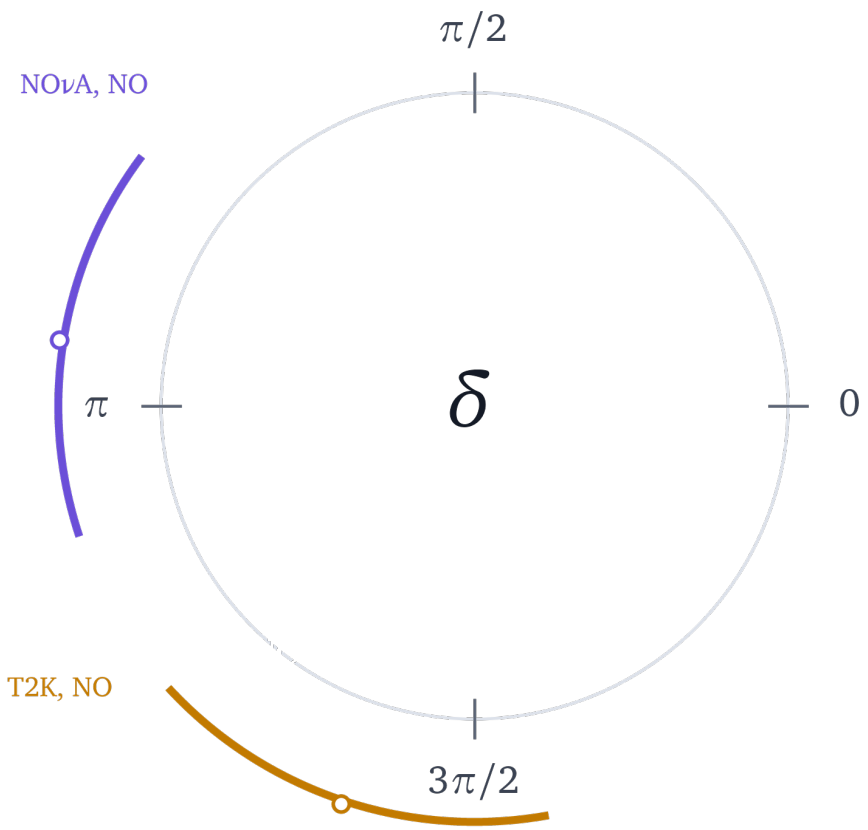



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**T2K, NO:** $\delta = 1.40\pi$

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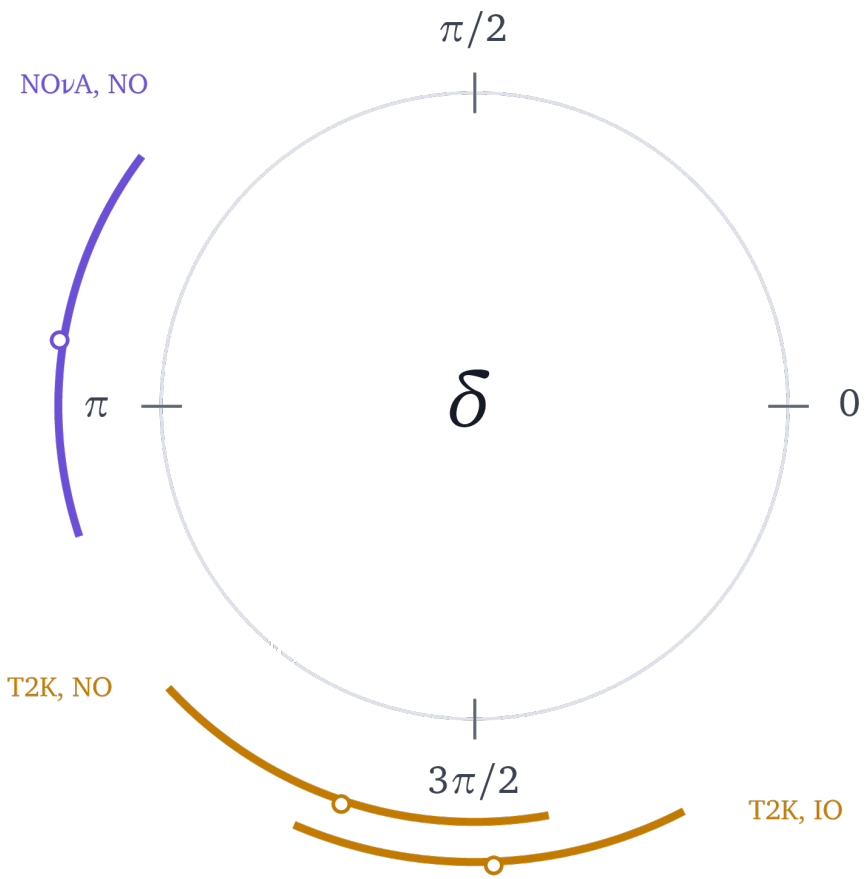

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**NOνA, NO:** $\delta = 0.95\pi \rightarrow$ **T2K and NOνA prefer different δ**

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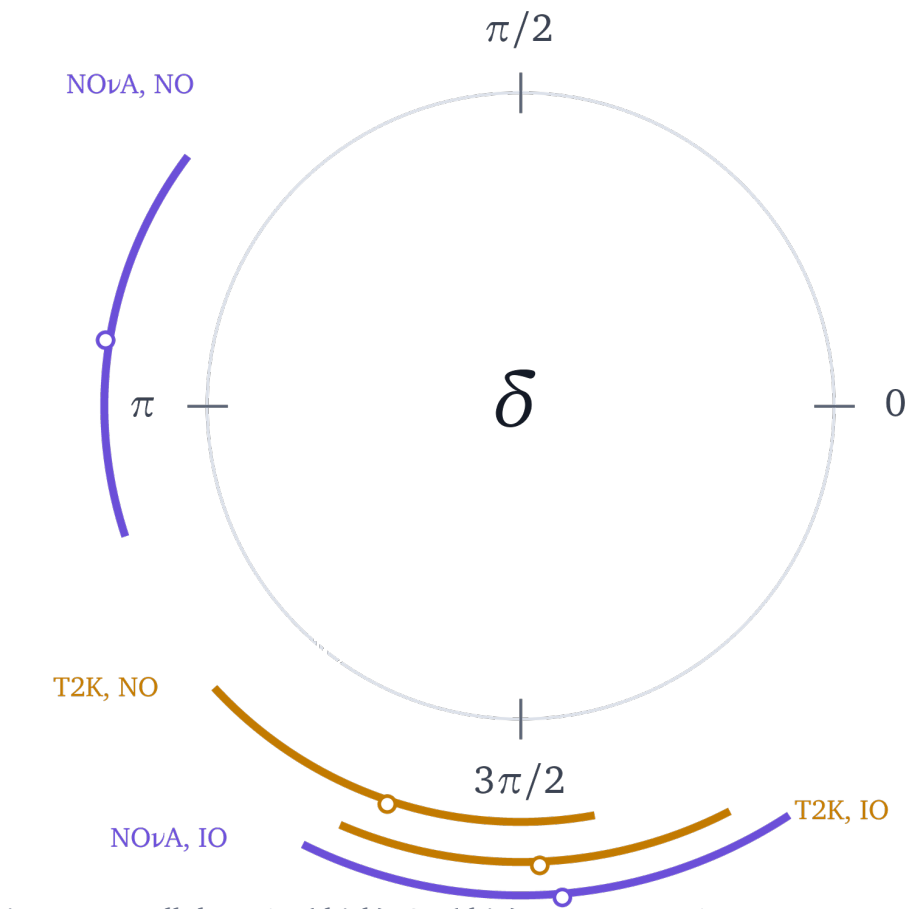
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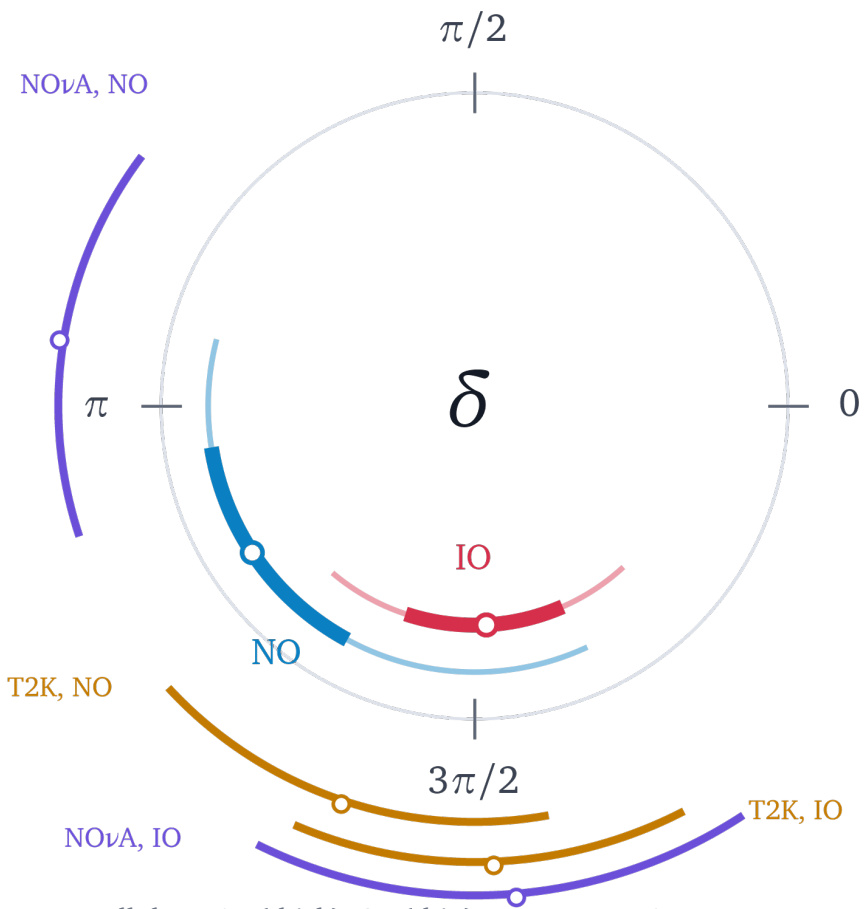
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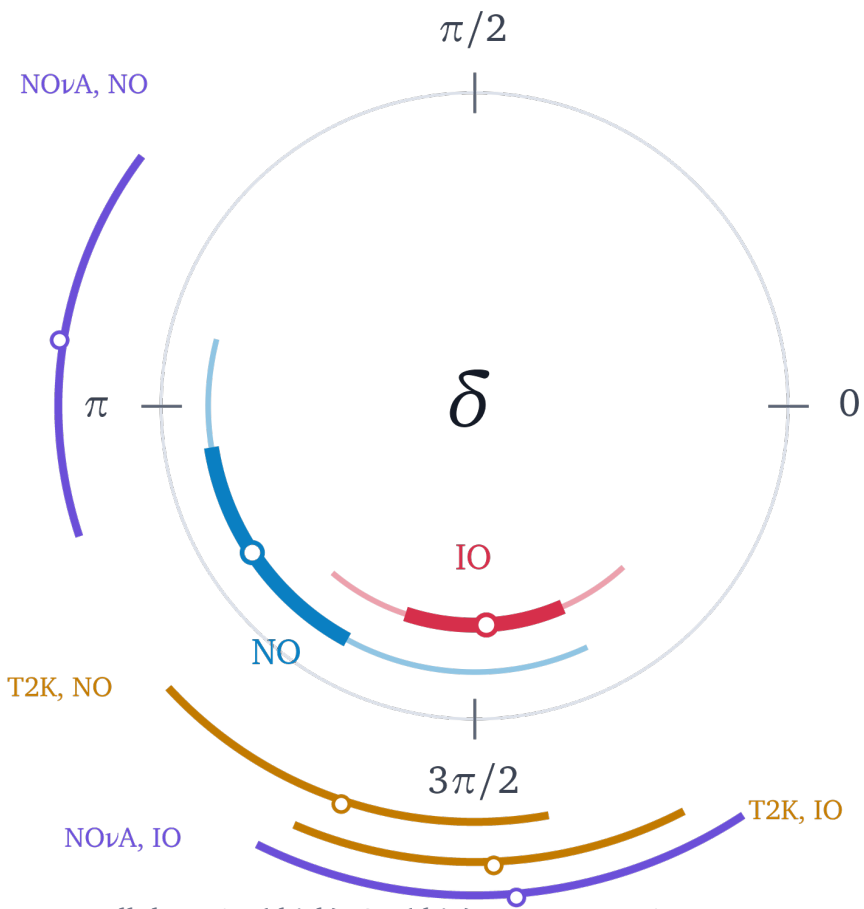
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**All data (inner arcs):**

**NO:** $\delta/\pi = 1.19 \pm 0.15$; $\delta = \pi$ at 1.4σ, $\delta = \pi/2$ at 4.4σ

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**Compatibility test ($\chi^2_{PG}$):** increase of $\chi^2$ when the two data sets are fitted with common $\theta_{23}$, $\delta$, $|\Delta m^2|$, $\theta_{13}$ instead of separately; 4 dof, converted to σ

| Tension | NO | IO |
|---|---|---|
| T2K vs all other data | 1.73σ | 0.35σ |
| NOνA vs all other data | 0.95σ | 0.62σ |
| T2K vs NOνA | **1.59σ** | 0.41σ |

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## Thank you for your attention

Tables, figures and $\chi^2$ profiles: **www.global-nu.org**

# Backup

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# WHY: TWO EFFECTIVE SPLITTINGS FOR ONE $\Delta m^2$

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

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\,\Delta m^2_{31} + \cos^2\theta_{12}\,\Delta m^2_{32} + \cos\delta\,\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\,\delta m^2$$

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| \simeq \pm\delta m^2\left(\cos 2\theta_{12} - \cos\delta\,\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\right)$$

\+ for NO, − for IO: $|\Delta m^2_{ee}| > |\Delta m^2_{\mu\mu}|$ in NO, $|\Delta m^2_{ee}| < |\Delta m^2_{\mu\mu}|$ in IO (Nunokawa et al. 2005)

| $\lvert\Delta m^2\rvert$ best fit / $10^{-3}$ eV$^2$ | NO | IO |
|---|---|---|
| $\bar{\nu}_e$ disappearance: JUNO | 2.468 | 2.523 |
| $\nu_\mu$ disappearance: SolRea + Atmos + AC | 2.473 | 2.442 |
| difference | **−0.005** | **+0.081** |

- NO: the two flavours **agree within 0.005**
- IO: **0.081 apart**, ≈ 4× JUNO's own 1σ

Only one sign of $\alpha$ makes the $\bar{\nu}_e$ and $\nu_\mu$ measurements of $|\Delta m^2|$ consistent: $\alpha = +1$ **(NO)**

BACKUP

# THE JUNO ANALYSIS

- We rebuild the JUNO fit from the published data: spectrum, backgrounds and uncertainties
- Same statistical treatment as in the JUNO paper
- Checked first on the spectrum without oscillations

Agreement well below 1σ on all observables

| | JUNO paper | this work |
|---|---|---|
| $\lvert\Delta m^2_{31}\rvert$ NO [$10^{-3}$ eV$^2$] | 2.509 | 2.508 |
| $\lvert\Delta m^2_{31}\rvert$ IO [$10^{-3}$ eV$^2$] | 2.482 | 2.486 |
| $\Delta\chi^2$(IO−NO), JUNO + DB | +0.05 | −0.08 |
| $\Delta\chi^2$(IO−NO), JUNO, phys. tooth* | +0.31 | +0.23 |
| $\sin^2\theta_{12}$, 68% C.L. (NO) | 0.294–0.313 | 0.295–0.314 |
| $\delta m^2$, 68% C.L. (NO) [$10^{-5}$ eV$^2$] | 7.27–7.50 | 7.26–7.52 |

* $\lvert\Delta m^2_{31}\rvert$ in $[2.40, 2.62]\times10^{-3}$ eV$^2$, $\sin^2\theta_{13} = 0.0223$. With Daya Bay we use its official 2022 $\chi^2$ (the paper: Gaussian pull on $\Delta m^2_{31}$)

BACKUP

# SURVIVAL PROBABILITIES AND EFFECTIVE SPLITTINGS

**Disappearance in vacuum, flavour $\ell = e, \mu$** ($\Delta_{31} = \Delta m^2_{31}\, L / 4E$, and similarly $\Delta_{32}$, $\Delta_{21}$)

$$P_{\ell\ell} = 1 - 4\,|U_{\ell 3}|^2 \left(|U_{\ell 1}|^2 \sin^2 \Delta_{31} + |U_{\ell 2}|^2 \sin^2 \Delta_{32}\right) - 4\,|U_{\ell 1}|^2 |U_{\ell 2}|^2 \sin^2 \Delta_{21}$$

**For $\Delta_{21} \ll 1$: one effective splitting for each flavour**

$$P_{\ell\ell} \simeq 1 - 4\,|U_{\ell 3}|^2 \left(1 - |U_{\ell 3}|^2\right) \sin^2\left(\frac{\Delta m^2_{\ell\ell} L}{4E}\right) \qquad \Delta m^2_{\ell\ell} = \frac{|U_{\ell 1}|^2\, \Delta m^2_{31} + |U_{\ell 2}|^2\, \Delta m^2_{32}}{|U_{\ell 1}|^2 + |U_{\ell 2}|^2}$$

$\bar{\nu}_e \to \bar{\nu}_e$ SBrea, JUNO

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

$\nu_\mu \to \nu_\mu$ AC, Atmos

$$\Delta m^2_{\mu\mu} \simeq \sin^2\theta_{12}\, \Delta m^2_{31} + \cos^2\theta_{12}\, \Delta m^2_{32} + \cos\delta\, \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}\, \delta m^2$$

**In terms of $|\Delta m^2|$ and $\alpha = \pm 1$**

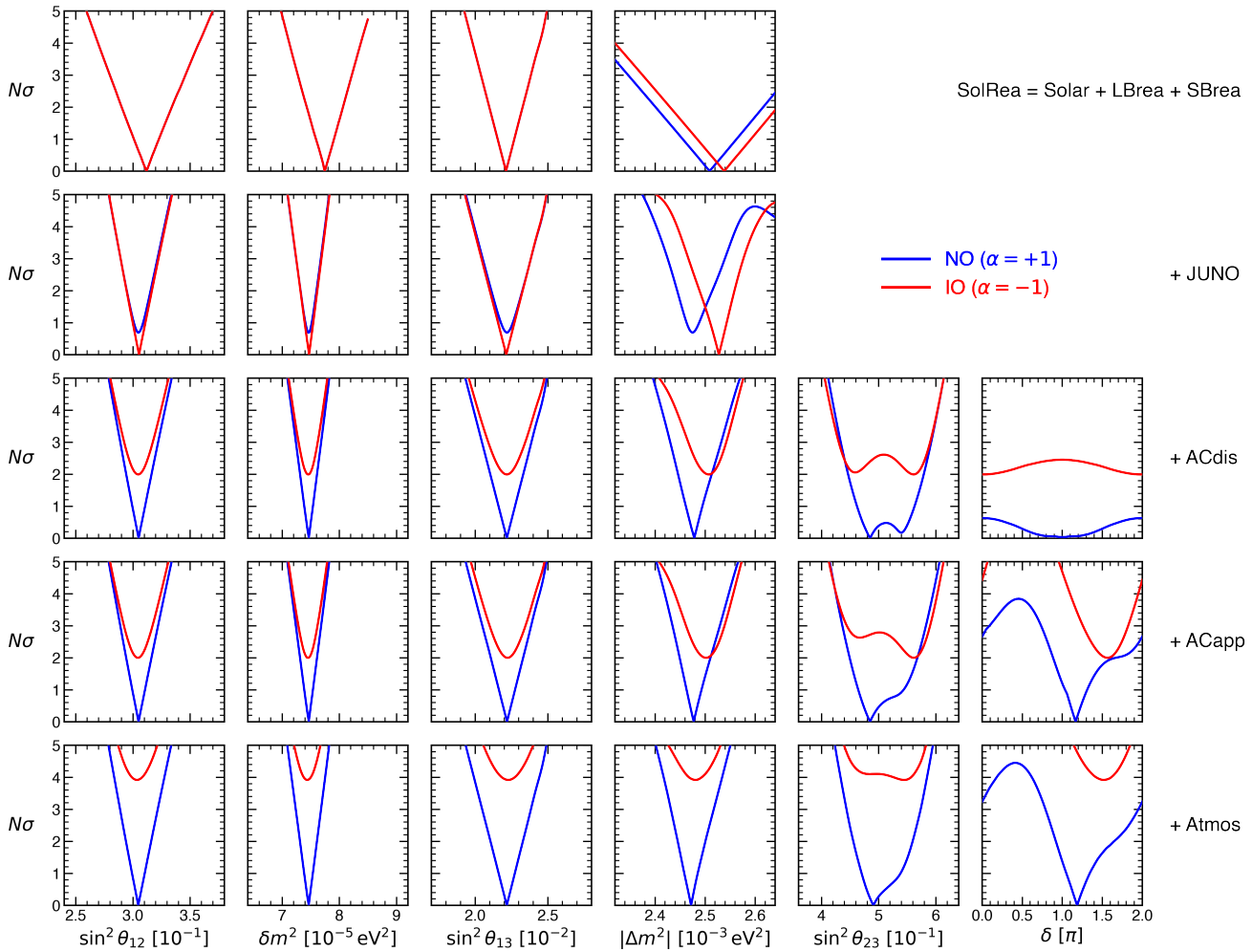
$$|\Delta m^2_{ee}| = |\Delta m^2| + \frac{\alpha}{2} \cos 2\theta_{12}\, \delta m^2 \qquad |\Delta m^2_{\mu\mu}| \simeq |\Delta m^2| - \frac{\alpha}{2} \left(\cos 2\theta_{12} - 2\cos\delta\, \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23}\right) \delta m^2$$

**Opposite shifts: the $\bar{\nu}_e$ and $\nu_\mu$ measurements give the same $|\Delta m^2|$ only for the true $\alpha$**

Leading order in $\delta m^2\, L / 4E$ (Nunokawa et al. 2005). At JUNO ($L \approx 52.5$ km) $\Delta_{21} \sim 1$: the full expression is needed

BACKUP

# THE DEFAULT PATH, STEP BY STEP




- SolRea: NO and IO curves coincide, except $|\Delta m^2|$ shifted by $\alpha$
- + JUNO: precise $|\Delta m^2|$ in both orderings, IO ahead by 0.7σ
- + ACdis: $|\Delta m^2_{\mu\mu}|$ matches JUNO only in NO → +2.0σ
- + ACapp: δ appears, ordering unchanged (2.0σ)
- + Atmos: **+3.9σ**; δ and the octant now differ between NO and IO

BACKUP

# BEST FIT AND ALLOWED RANGES

| Parameter | NO best fit | 1σ range | 3σ range | "1σ" | IO best fit | 1σ range | 3σ range | "1σ" |
|---|---|---|---|---|---|---|---|---|
| $\delta m^2 / 10^{-5}$ eV$^2$ | **7.465** | 7.386 – 7.538 | 7.239 – 7.681 | 1.0% | **7.439** | 7.364 – 7.516 | 7.218 – 7.662 | 1.0% |
| $\lvert\Delta m^2\rvert / 10^{-3}$ eV$^2$ | **2.472** | 2.459 – 2.485 | 2.432 – 2.517 | 0.6% | **2.481** | 2.465 – 2.497 | 2.429 – 2.529 | 0.7% |
| $\lvert\Delta m^2_{31}\rvert / 10^{-3}$ eV$^2$ | **2.509** | 2.496 – 2.523 | 2.469 – 2.555 | 0.6% | **2.444** | 2.428 – 2.459 | 2.392 – 2.492 | 0.7% |
| $\lvert\Delta m^2_{32}\rvert / 10^{-3}$ eV$^2$ | **2.435** | 2.421 – 2.448 | 2.394 – 2.480 | 0.6% | **2.518** | 2.502 – 2.534 | 2.466 – 2.567 | 0.7% |
| $\sin^2\theta_{12} / 10^{-1}$ | **3.047** | 2.993 – 3.104 | 2.888 – 3.217 | 1.8% | **3.036** | 2.981 – 3.092 | 2.876 – 3.208 | 1.8% |
| $\sin^2\theta_{13} / 10^{-2}$ | **2.218** | 2.162 – 2.273 | 2.049 – 2.384 | 2.5% | **2.228** | 2.173 – 2.283 | 2.063 – 2.393 | 2.5% |
| $\sin^2\theta_{23} / 10^{-1}$ | **4.908** | 4.703 – 5.383 | 4.439 – 5.735 | 4.4% | **5.446** | 5.188 – 5.592 | 4.408 – 5.819 | 4.3% |
| $\delta / \pi$ | **1.186** | 1.052 – 1.343 | 0.790 – 1.951 | 16.3% | **1.517** | 1.399 – 1.632 | 1.157 – 1.838 | 7.5% |

Intervals at $\Delta\chi^2 = 1, 9$ from the minimum of each ordering. "1σ" = (3σ range)/6, relative to the best fit. $\Delta\chi^2(\mathrm{IO} - \mathrm{NO}) = +15.34$

Tables, figures and $\chi^2$ profiles: **www.global-nu.org**

BACKUP

# ROBUSTNESS OF THE ORDERING RESULT

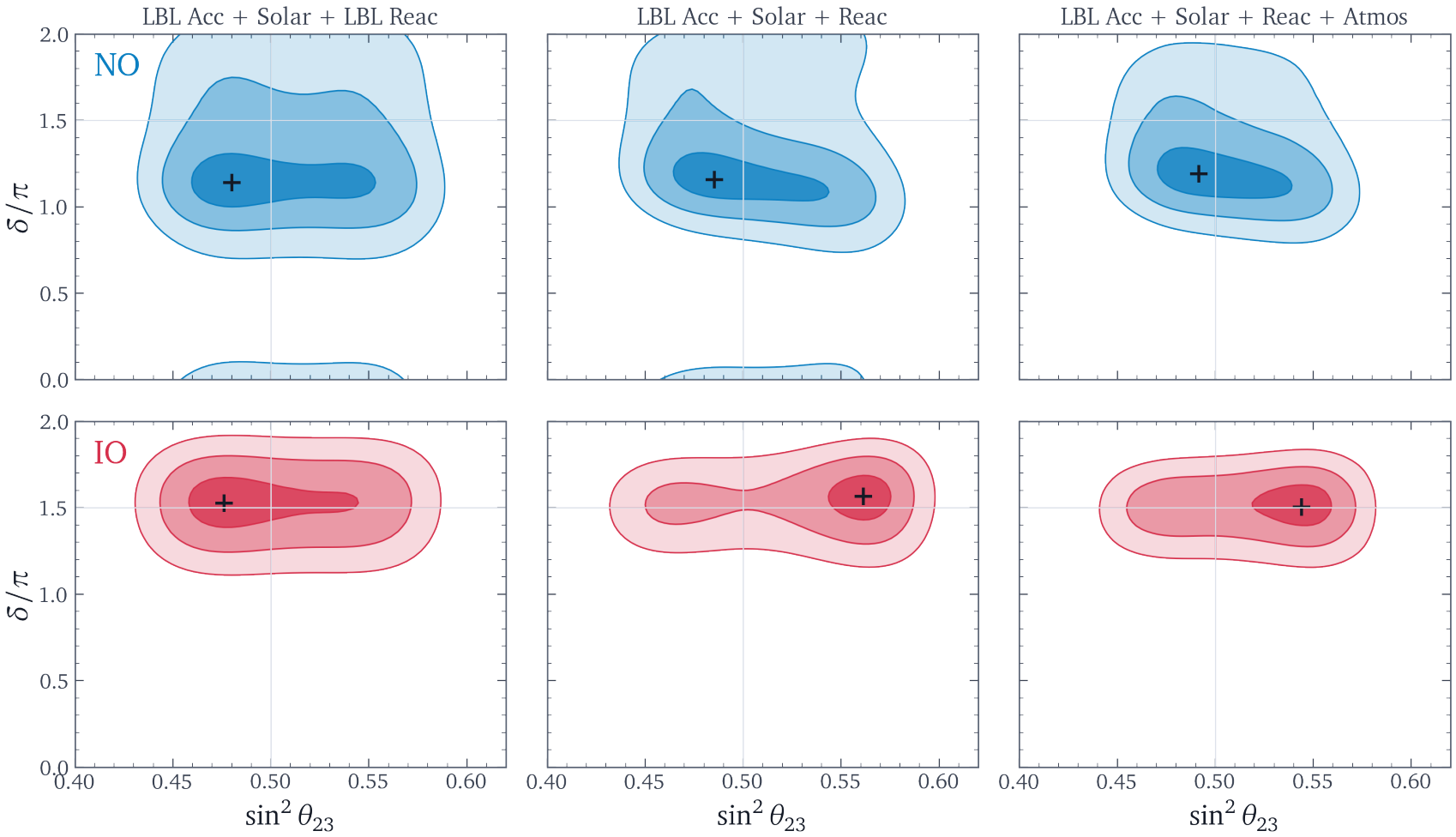
| Data set | $\Delta\chi^2$(IO−NO) | Nσ |
|---|---|---|
| All data (SolRea + JUNO + AC + Atmos) | +15.34 | 3.92 |
| All data except KM3NeT/ORCA6 | +14.49 | 3.81 |
| All data except SK-Gd reactors | +15.00 | 3.87 |
| All data except JUNO | +7.37 | 2.71 |

Each row is the complete data set with only the indicated sample removed (rows are not cumulative).

Removing JUNO halves the ordering $\Delta\chi^2$; removing ORCA6 or SK-Gd changes it by less than 1.

BACKUP

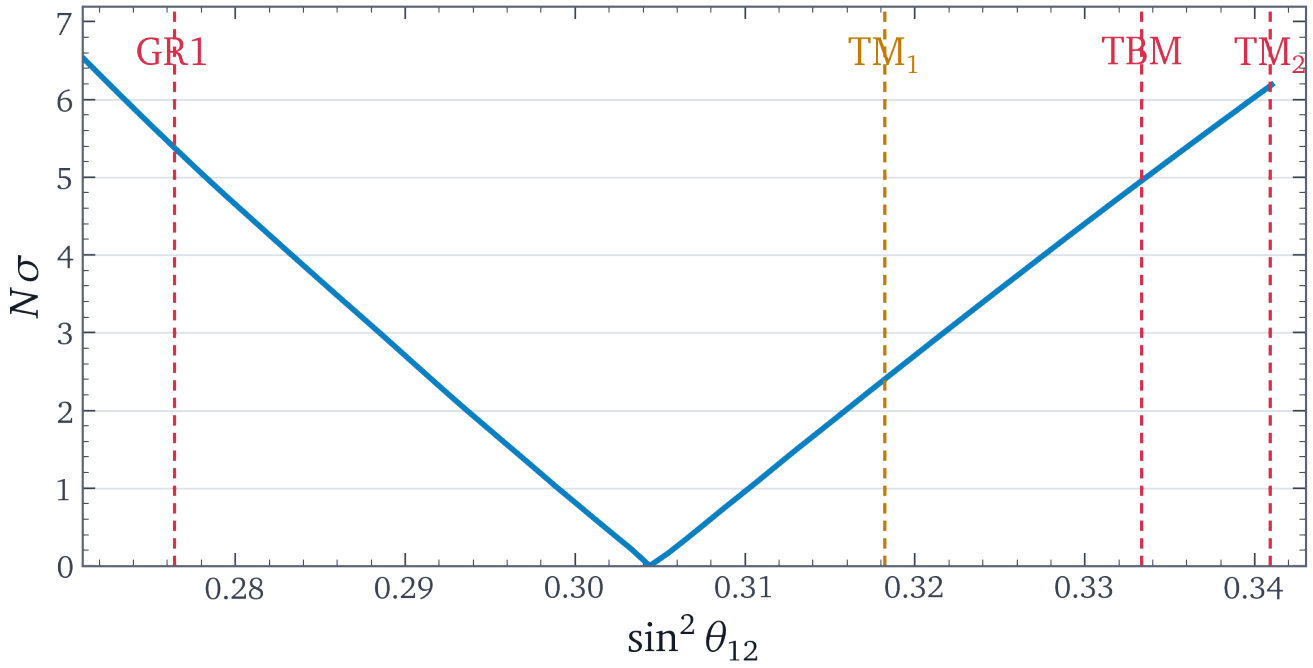
# CORRELATED BOUNDS ON $(\sin^2\theta_{23}, \delta)$




| $\Delta\chi^2$(lower−upper) | NO | IO |
|---|---|---|
| LBL Acc + Solar + LBL Reac | −0.45 | −0.56 |
| LBL Acc + Solar + Reac | −0.25 | +2.91 |
| LBL Acc + Solar + Reac + Atmos | −0.07 | +1.50 |

- contours: $\Delta\chi^2 = 1, 4, 9$ w.r.t. each ordering minimum
- octant open in NO; mild upper-octant preference in IO
- NO: $\delta \approx 1.2\pi$; IO: $\delta \approx 1.5\pi$

# $\theta_{12}$ AT 1.8%: TESTS OF MIXING PATTERNS




TBM : $\sin^2\theta_{12} = \frac{1}{3}$, GR1 : $\tan\theta_{12} = 1/\varphi \Rightarrow \sin^2\theta_{12} \simeq 0.276$

$\mathrm{TM}_1$ : $|U_{e1}|^2 = \frac{2}{3} \Rightarrow \sin^2\theta_{12} = 1 - \dfrac{2}{3\cos^2\theta_{13}} \simeq 0.318$

$\mathrm{TM}_2$ : $|U_{e2}|^2 = \frac{1}{3} \Rightarrow \sin^2\theta_{12} = \dfrac{1}{3\cos^2\theta_{13}} \simeq 0.341$

| Pattern | $\sin^2\theta_{12}$ | $\Delta\chi^2$ | Nσ |
|---|---|---|---|
| TBM | 1/3 | 24.5 | 5.0 |
| $\mathrm{TM}_1$ | 0.318 | 5.8 | 2.4 |
| $\mathrm{TM}_2$ | 0.341 | 38 | 6.2 |
| GR1 | 0.276 | 29 | 5.4 |

all data, NO, 1D profile; $\mathrm{TM}_{1,2}$ at $\sin^2\theta_{13} = 0.0222$ (correlations neglected)

**TBM, $\mathrm{TM}_2$, GR1: ≥ 5σ**

excluded by the $\theta_{12}$ measurement alone

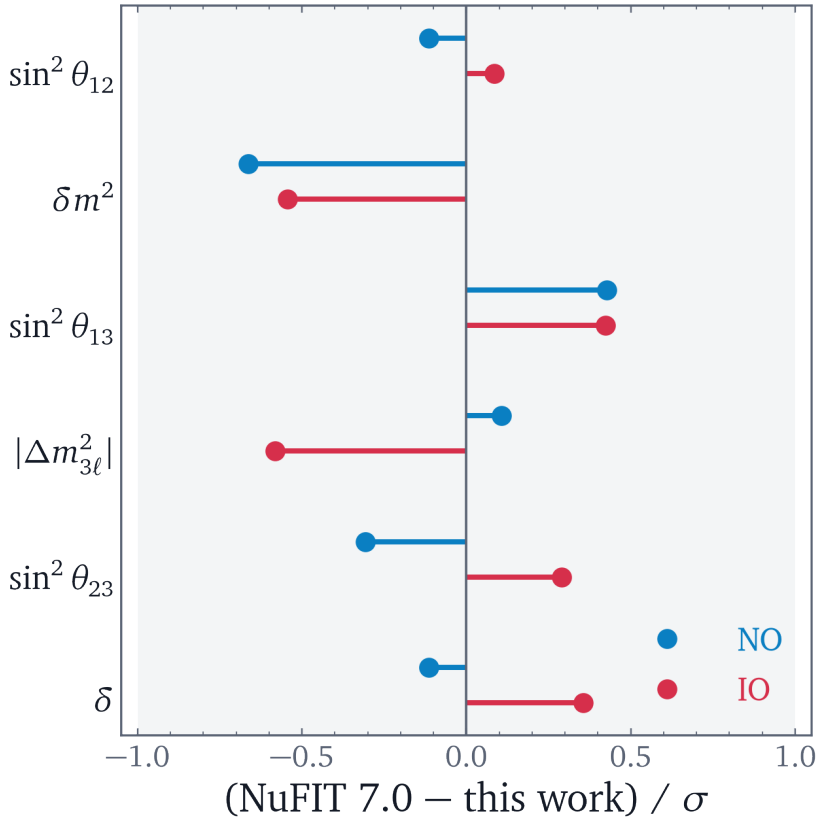
**$\mathrm{TM}_1$: 2.4σ**

still allowed by current data

BACKUP

# COMPARISON WITH NUFIT 7.0 (PRELIMINARY)

| NO | this work (all data) | NuFIT 7.0 (SK-atm) | diff. |
|---|---|---|---|
| $\sin^2\theta_{12}$ | $0.3047 \pm 0.0055$ | $0.3041 \pm 0.0056$ | $-0.1\sigma$ |
| $\delta m^2$ [$10^{-5}$ eV$^2$] | $7.465 \pm 0.076$ | $7.415 \pm 0.070$ | $-0.7\sigma$ |
| $\sin^2\theta_{13}$ | $0.0222 \pm 0.0006$ | $0.0224 \pm 0.0006$ | $+0.4\sigma$ |
| $\lvert\Delta m^2_{31}\rvert$ [$10^{-3}$ eV$^2$] | $2.509 \pm 0.013$ | $2.511 \pm 0.015$ | $+0.1\sigma$ |
| $\sin^2\theta_{23}$ | $0.491^{+0.048}_{-0.021}$ | $0.480^{+0.021}_{-0.016}$ | $-0.3\sigma$ |
| $\delta_{CP}$ [°] | $213 \pm 26$ | $210^{+25}_{-37}$ | $-0.1\sigma$ |
| $\Delta\chi^2$(IO−NO) | +15.3 | +11.6 (+5.0 w/o SK-atm) | |




NuFIT values read off the preliminary curves shown at NOW 2026 (no tables available); IO pulls shown in the plot.