Global Analysis of Neutrino Oscillations and Mass Constraints in the Era of Subpercent Precision

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Neutrino oscillation phenomenology: entering the precision era

Based on Capozzi+, arXiv:2503.07752, PRD 111 (2025) 9, 093006

Neutrino oscillation phenomenology: entering the precision era

Solar parameters

$$\delta m^2 \sim 7.37 \times 10^{-5}\ \mathrm{eV}^2 \qquad (2.3\%)$$

$$\sin^2\theta_{12} \sim 0.303 \qquad (4.5\%)$$

Reactor mixing angle

$$\sin^2\theta_{13} \sim 2.23 \times 10^{-2} \qquad (2.4\%)$$

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Atmospheric parameters

$\Delta m^2 \sim 2.495 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2 \sim 2.465 \times 10^{-3}\ \mathrm{eV}^2$

(0.8%)

$\sin^2\theta_{23} \sim 0.473 \times 10^{-2}$ (5.1%)

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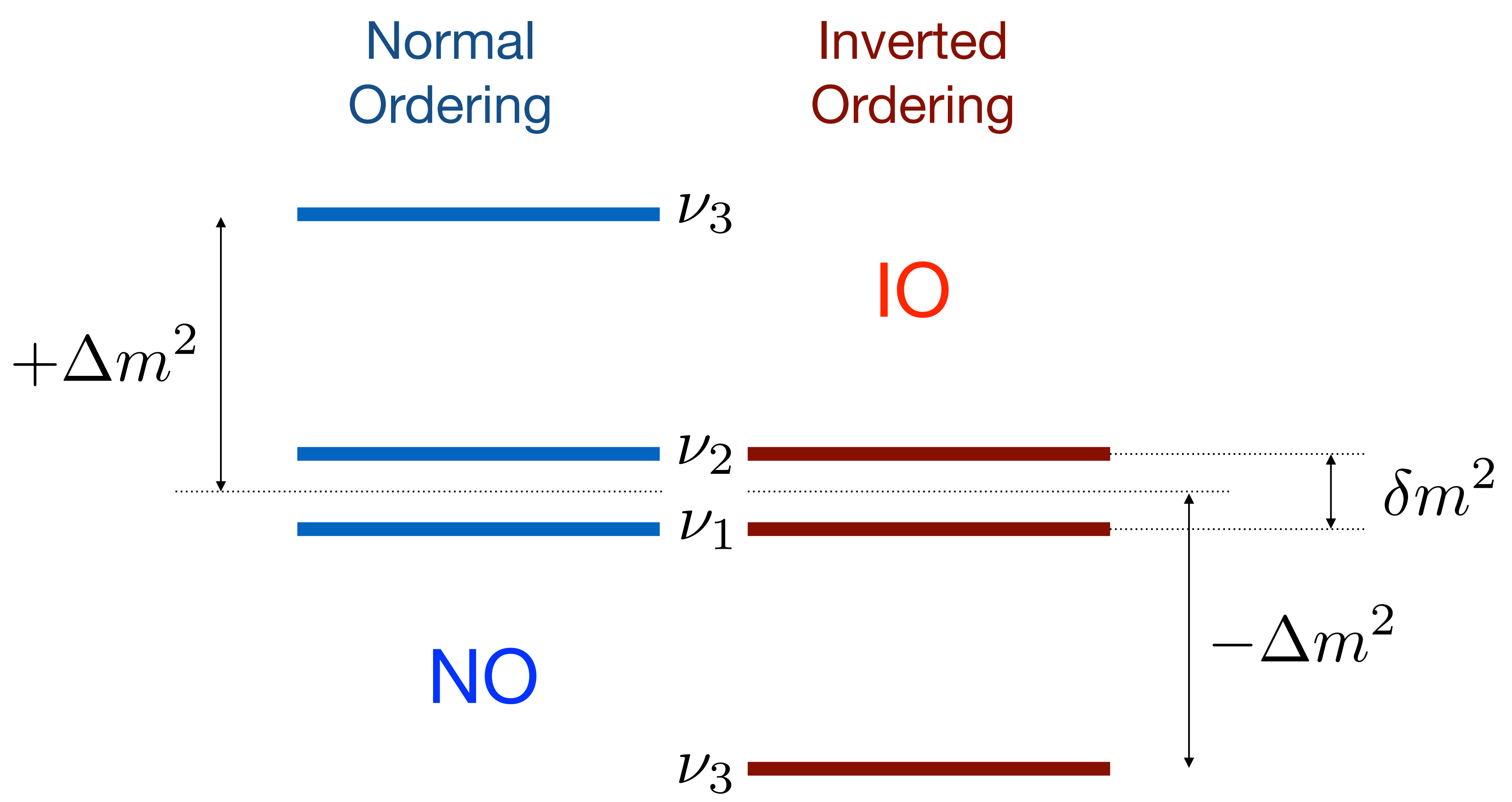

$$\Delta m^2 = \frac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$$

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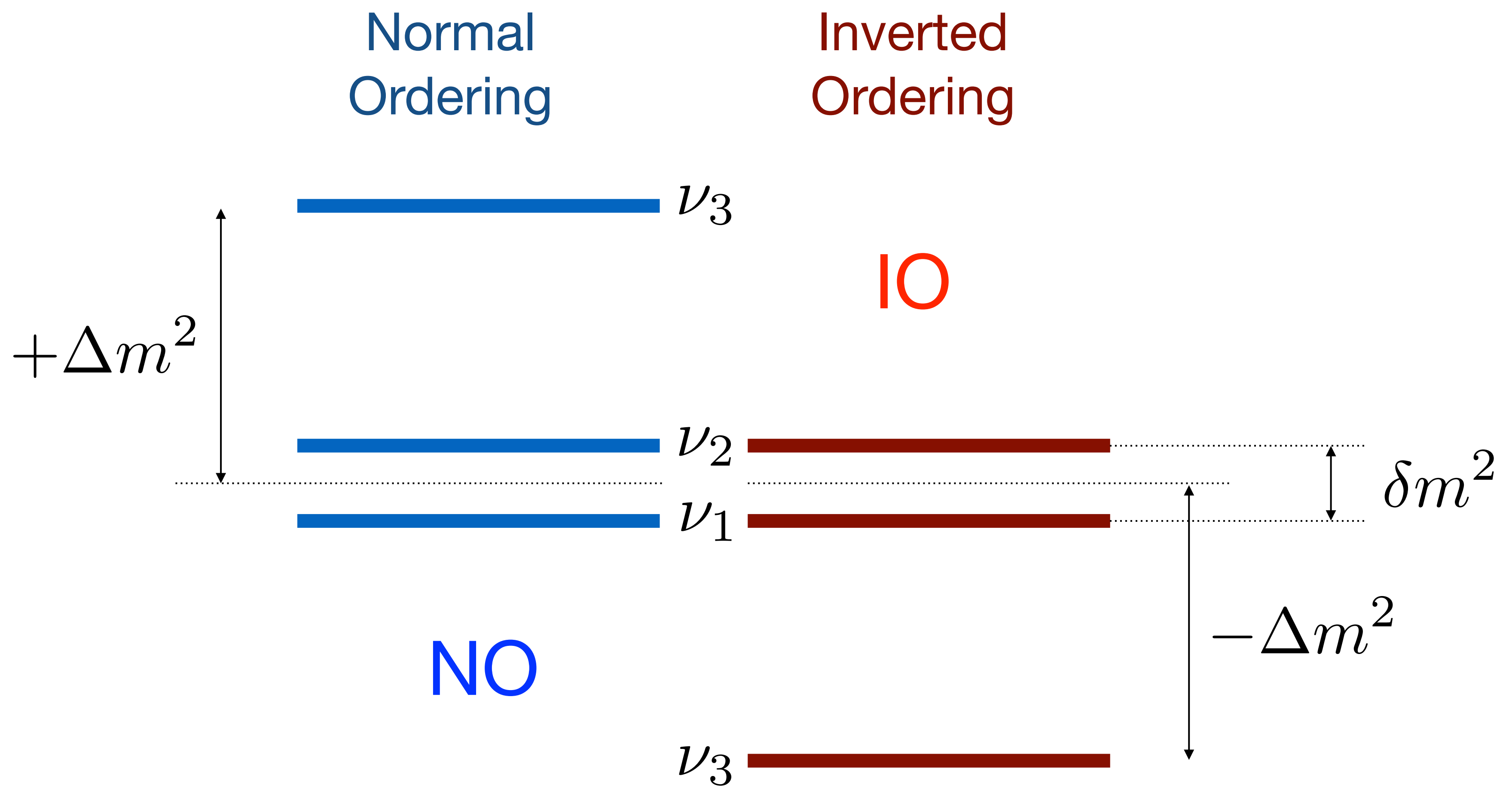

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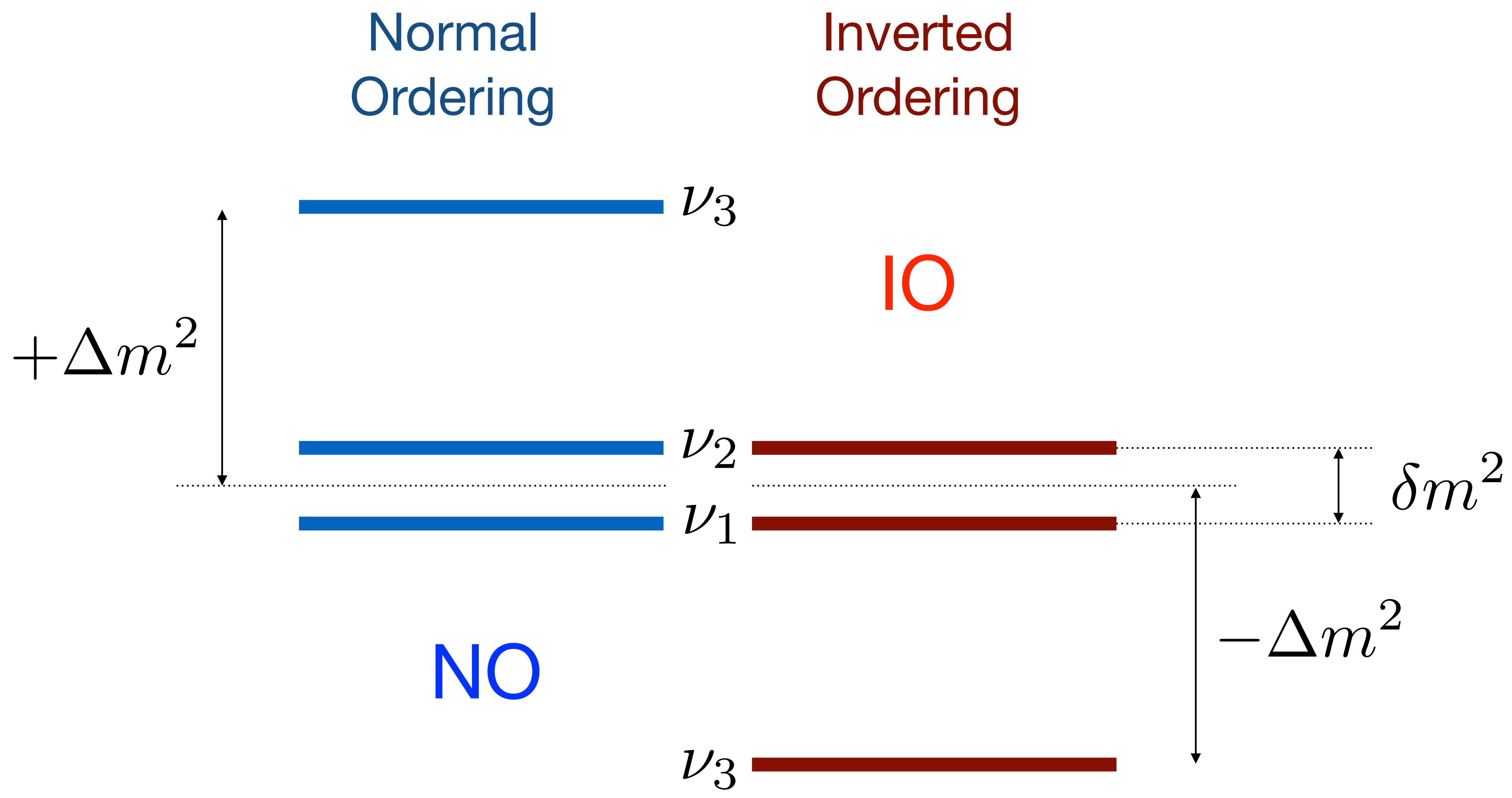

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Mass Ordering

CP-violating phase δ_{CP}

Octant of θ_{23}

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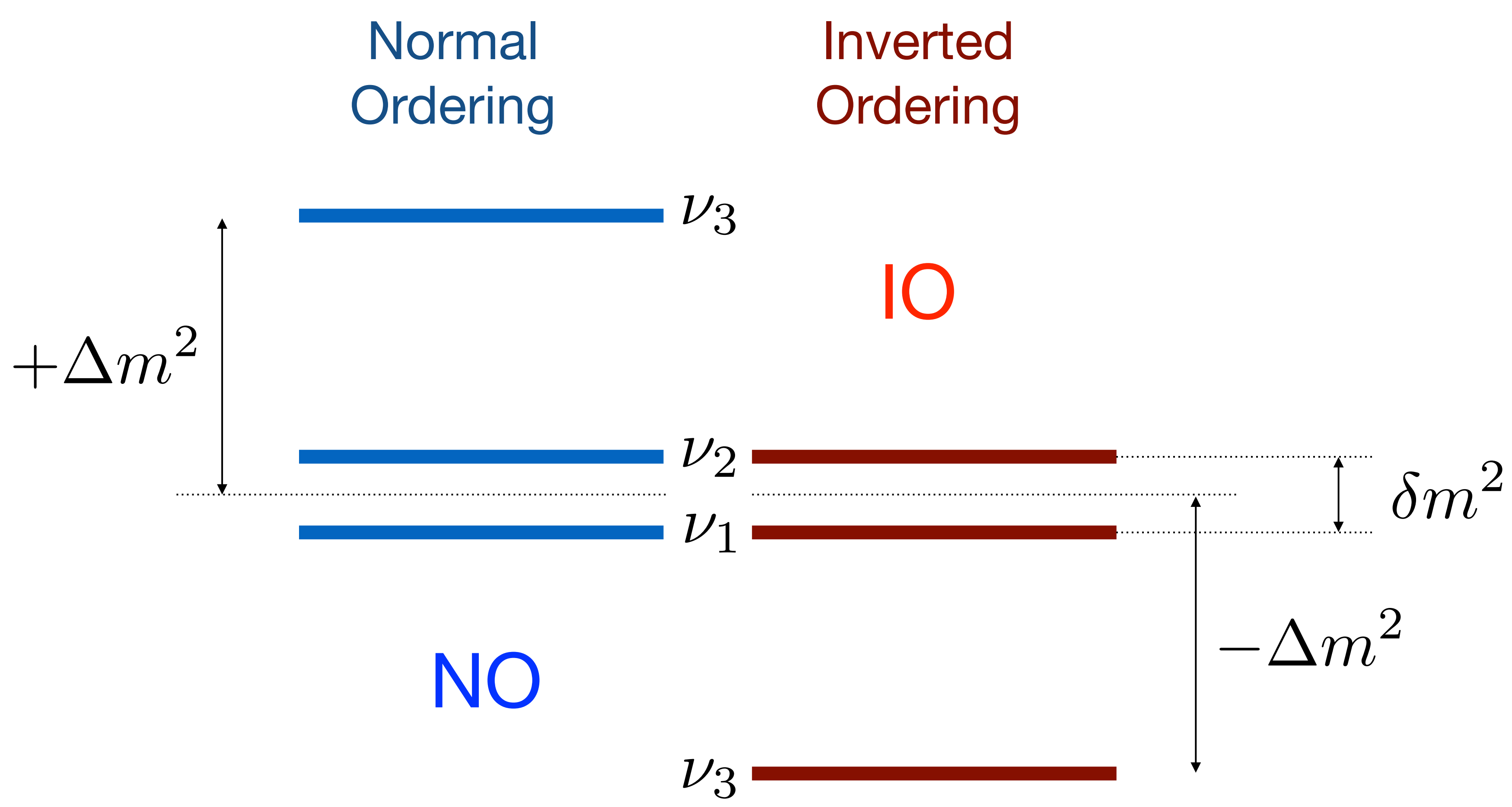

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Absolute mass scale

Nature of ν (Dirac/Majorana)

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Methodological sequence for global oscillation analysis

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Long Baseline Accelerator + Solar + KamLAND

minimal set sensitive to all oscillation parameters $(\delta m^2, \Delta m^2, \theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$ and to mass ordering

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Long Baseline Acc. + Solar + KamLAND + Short Baseline Reactor + Atmospheric

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Bounds on sigle parameters, after marginalisation over all other parameter, shown in terms of $N\sigma = \sqrt{\Delta\chi^2}$

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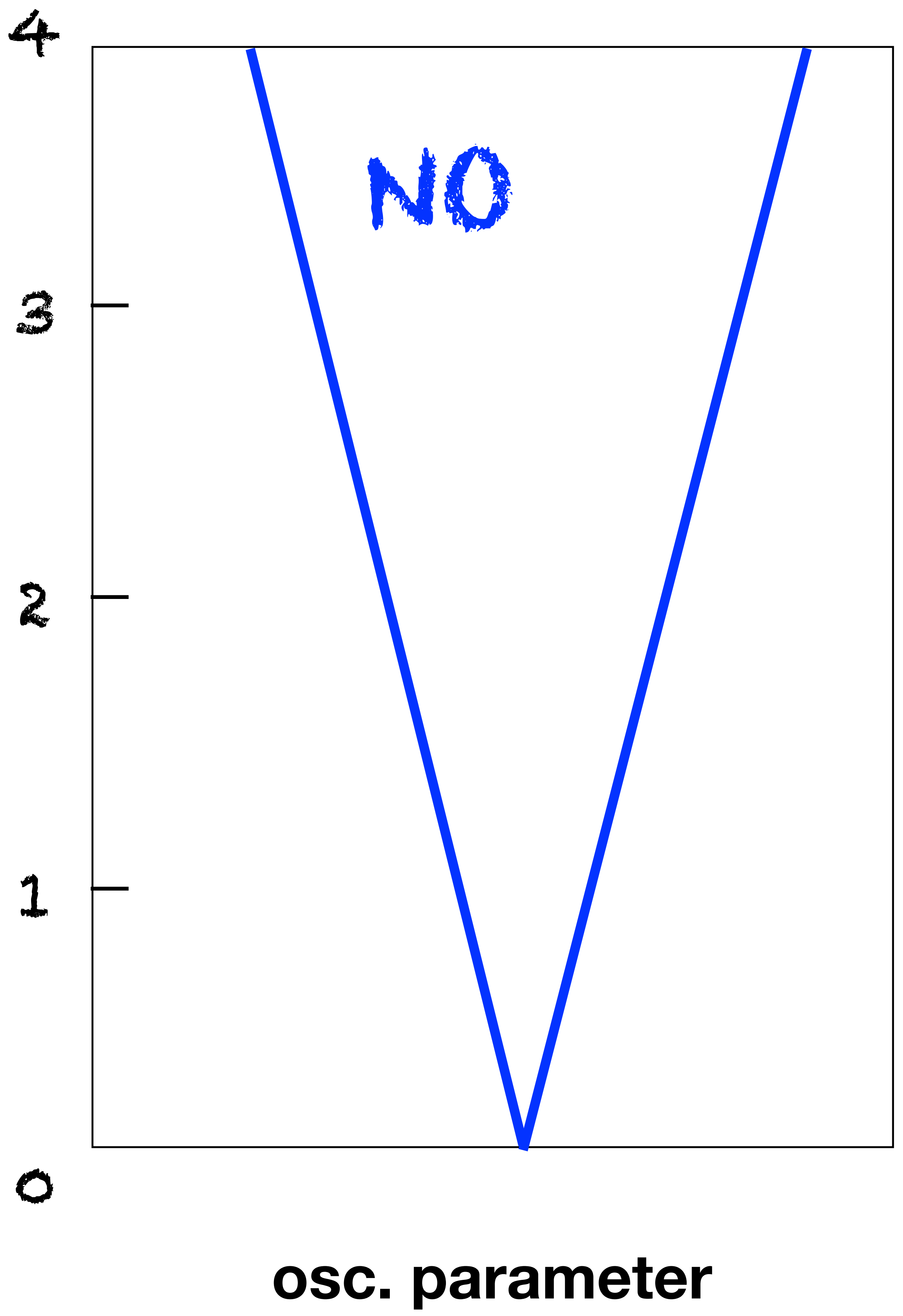
Bounds linear and symmetric for gaussian errors



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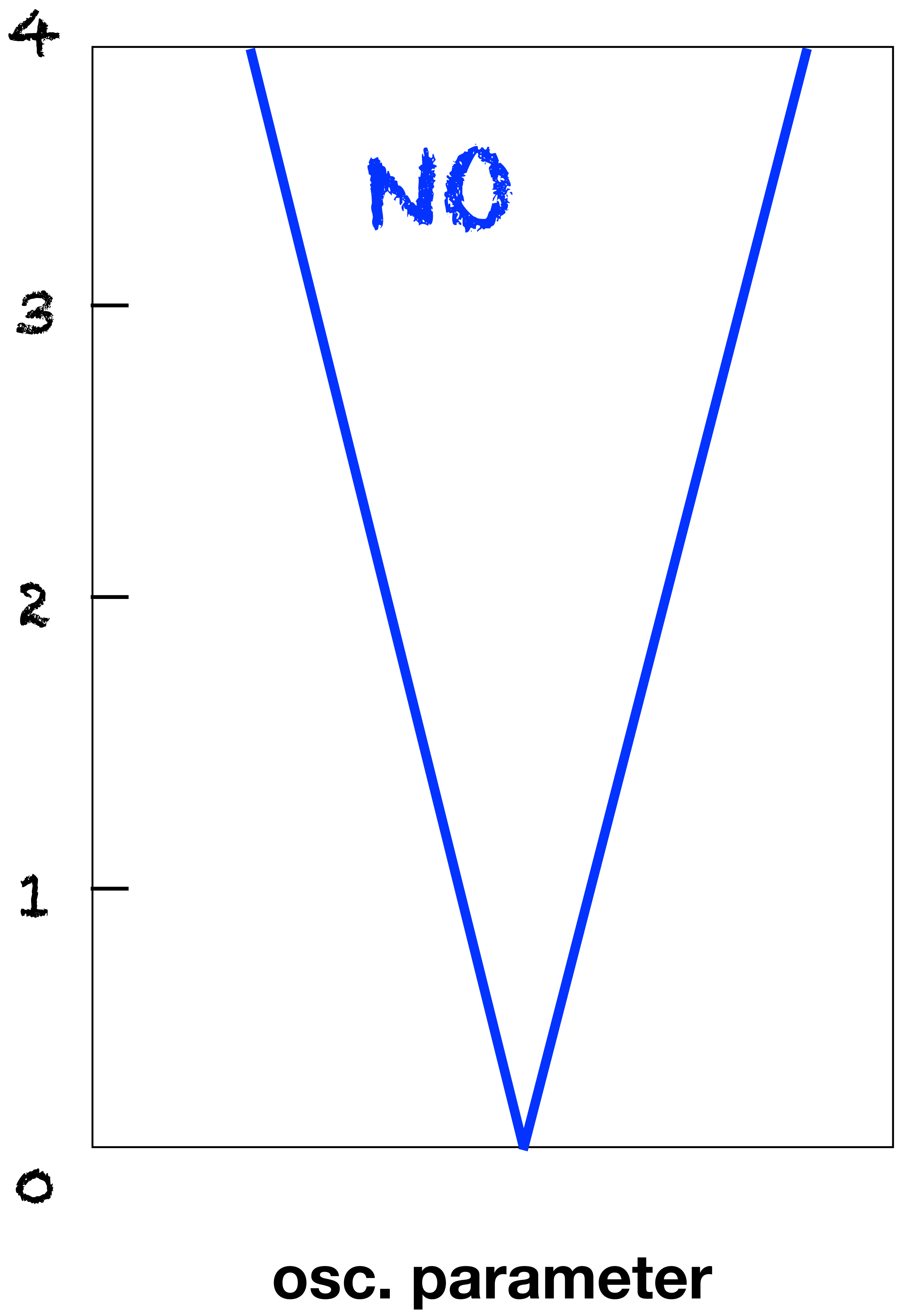
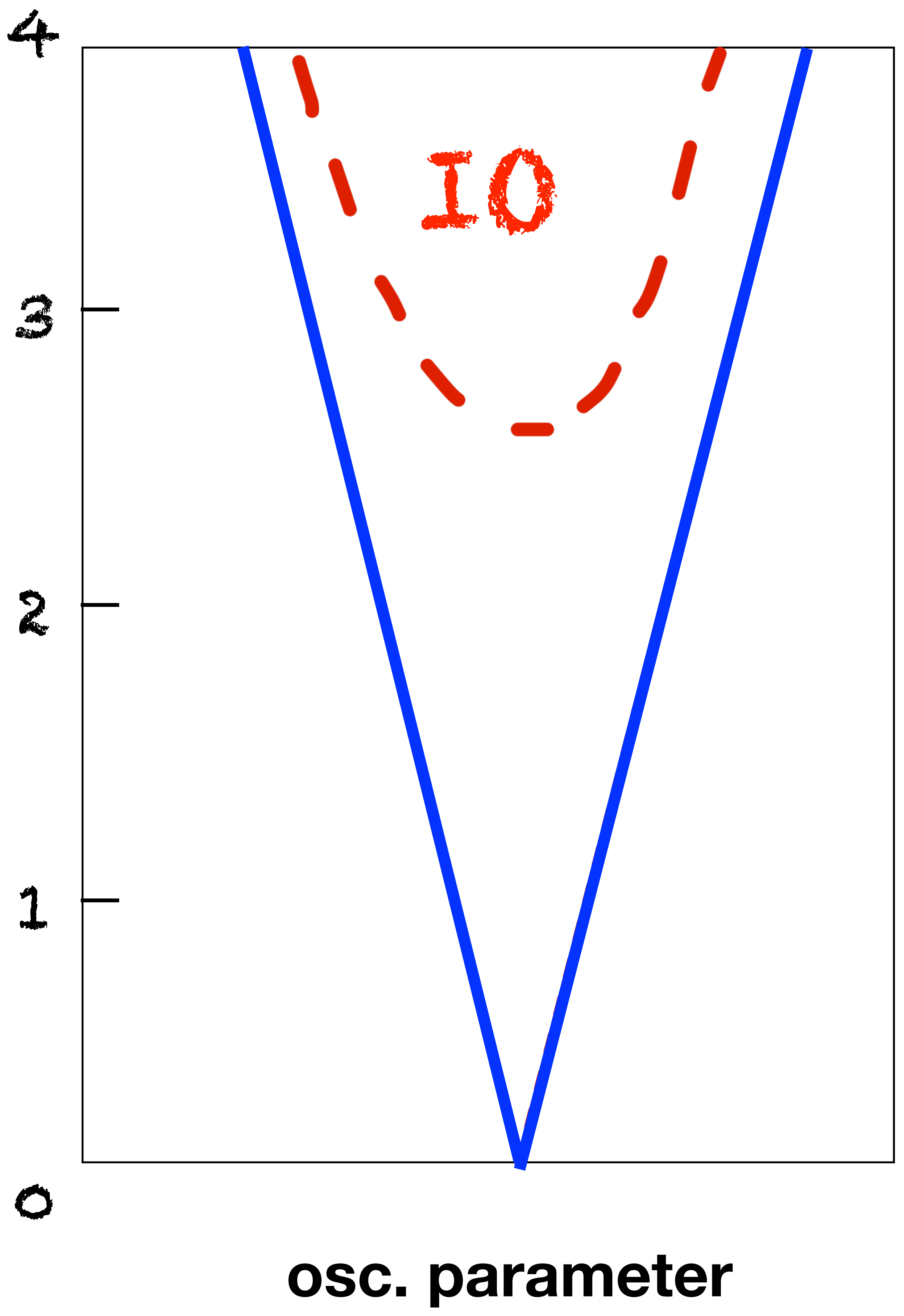
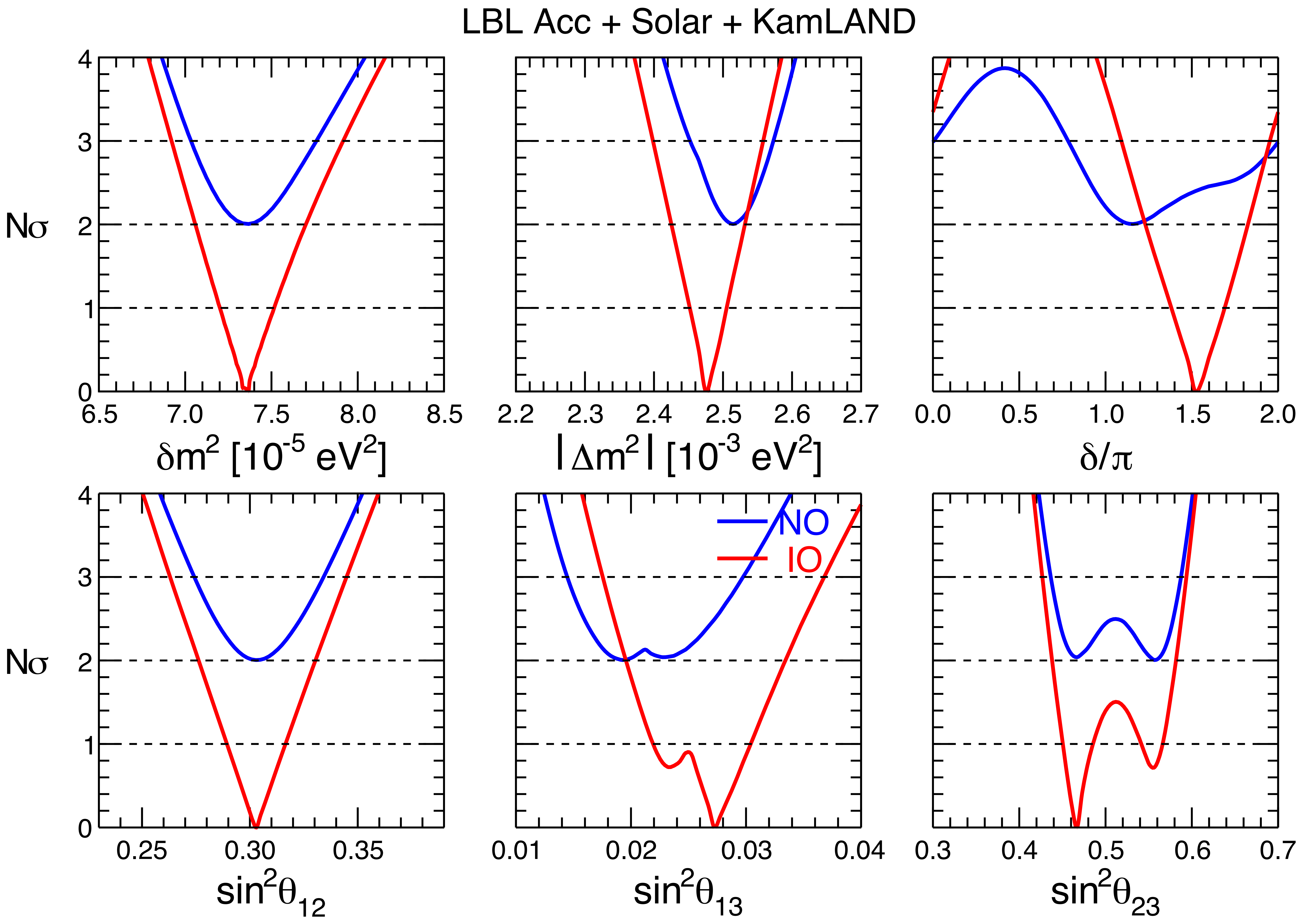


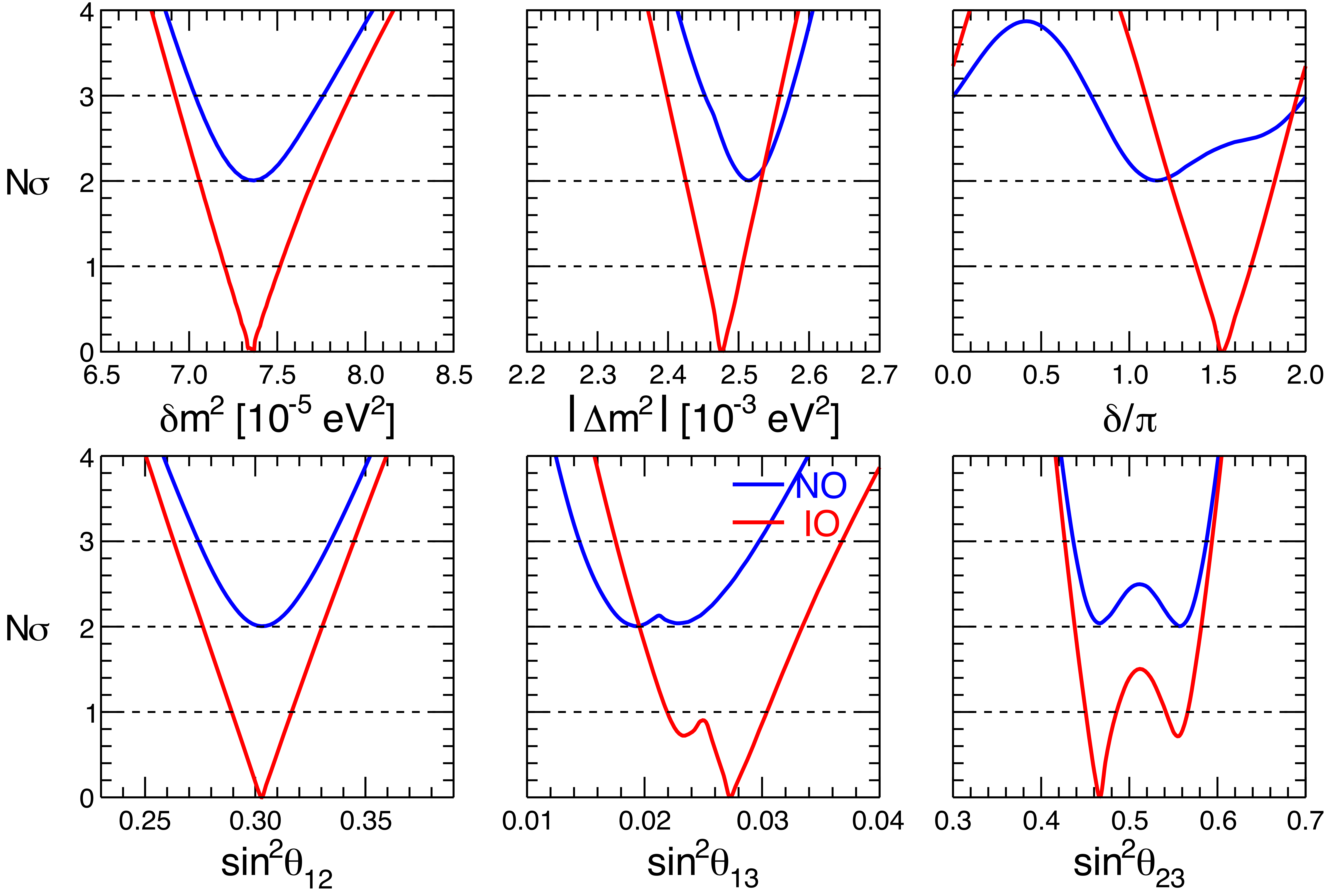
Bounds for IO move upwards
(currently bes fit in NO)



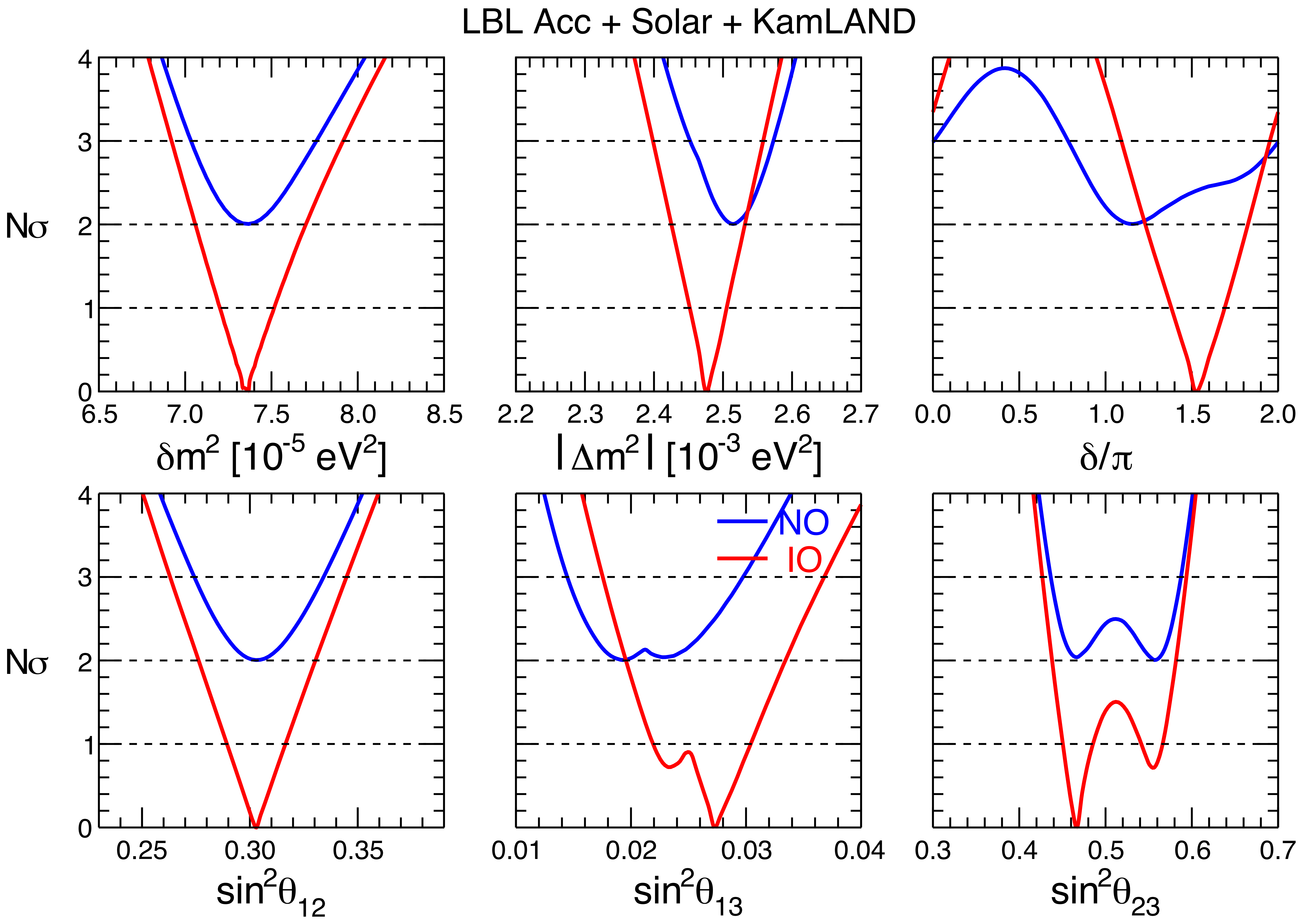


LBL Acc + Solar + KamLAND
Nσ
δm² [10⁻⁵ eV²]
|Δm²| [10⁻³ eV²]
δ/π
sin²θ12
sin²θ13
sin²θ23
NO
IO

LBL Acc + Solar + KamLAND



Gaussian errors for
$(\delta m^2, |\Delta m^2|, \sin^2\theta_{12})$



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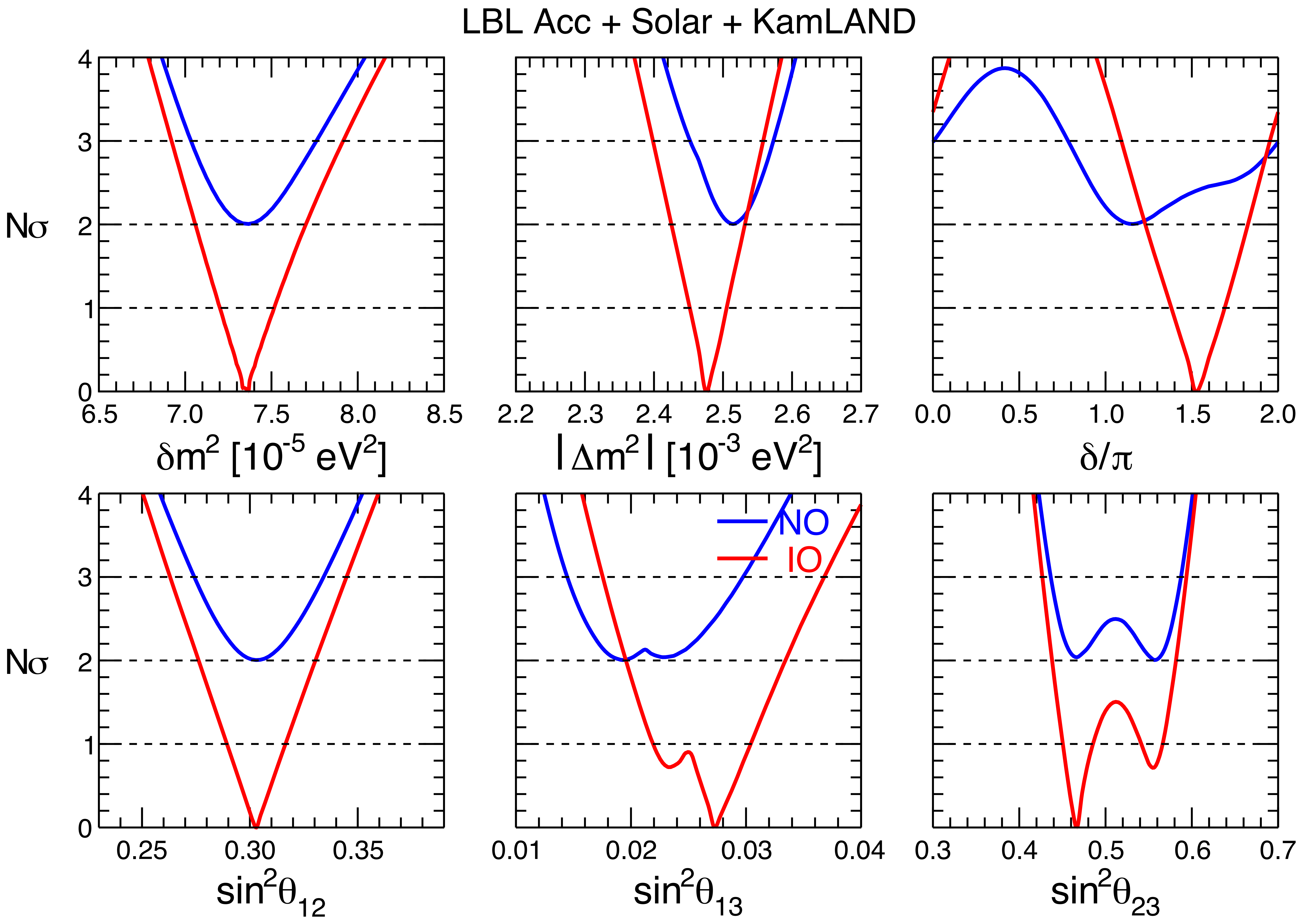
Two minima for θ_{13} from some residual degeneracy



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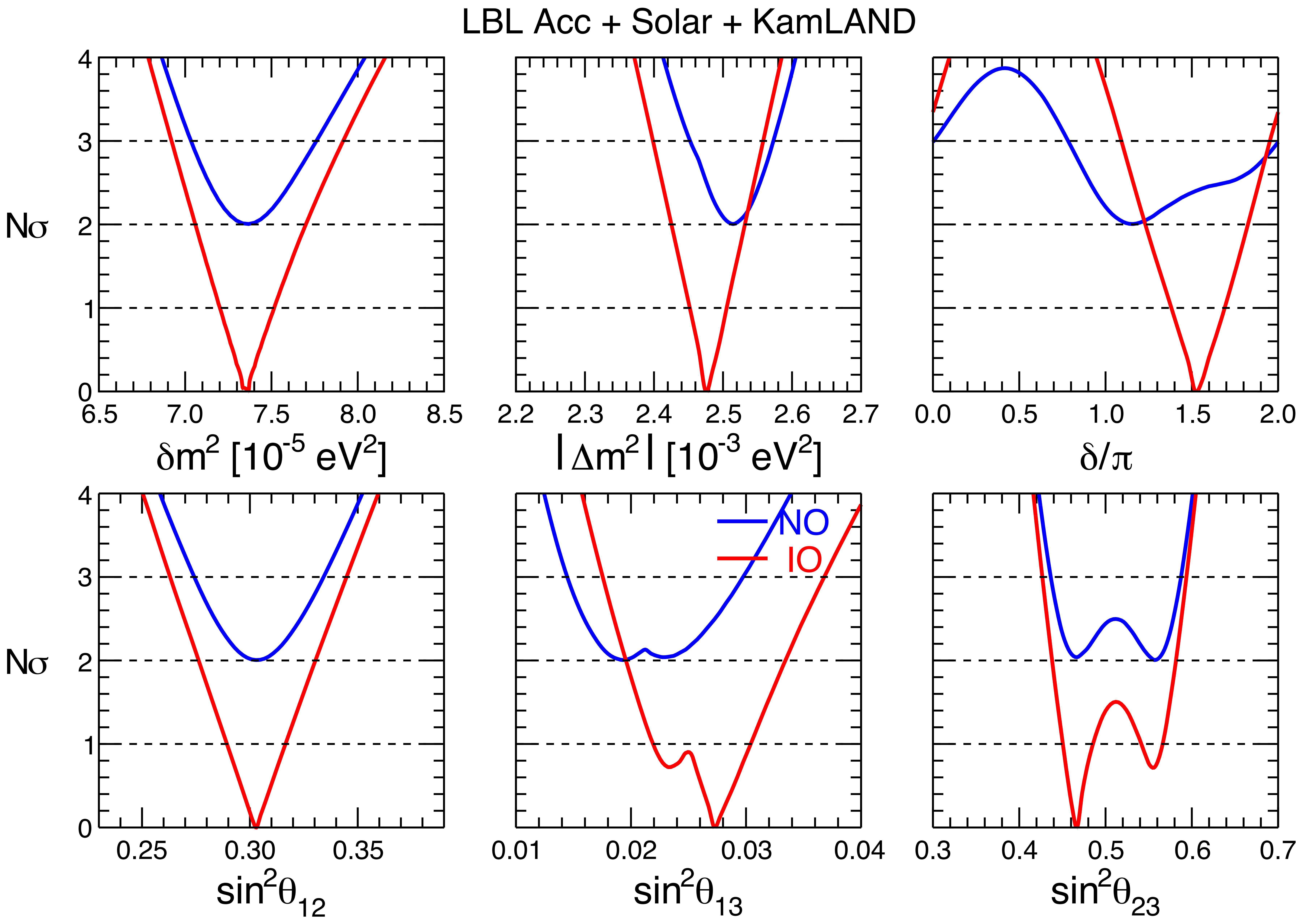

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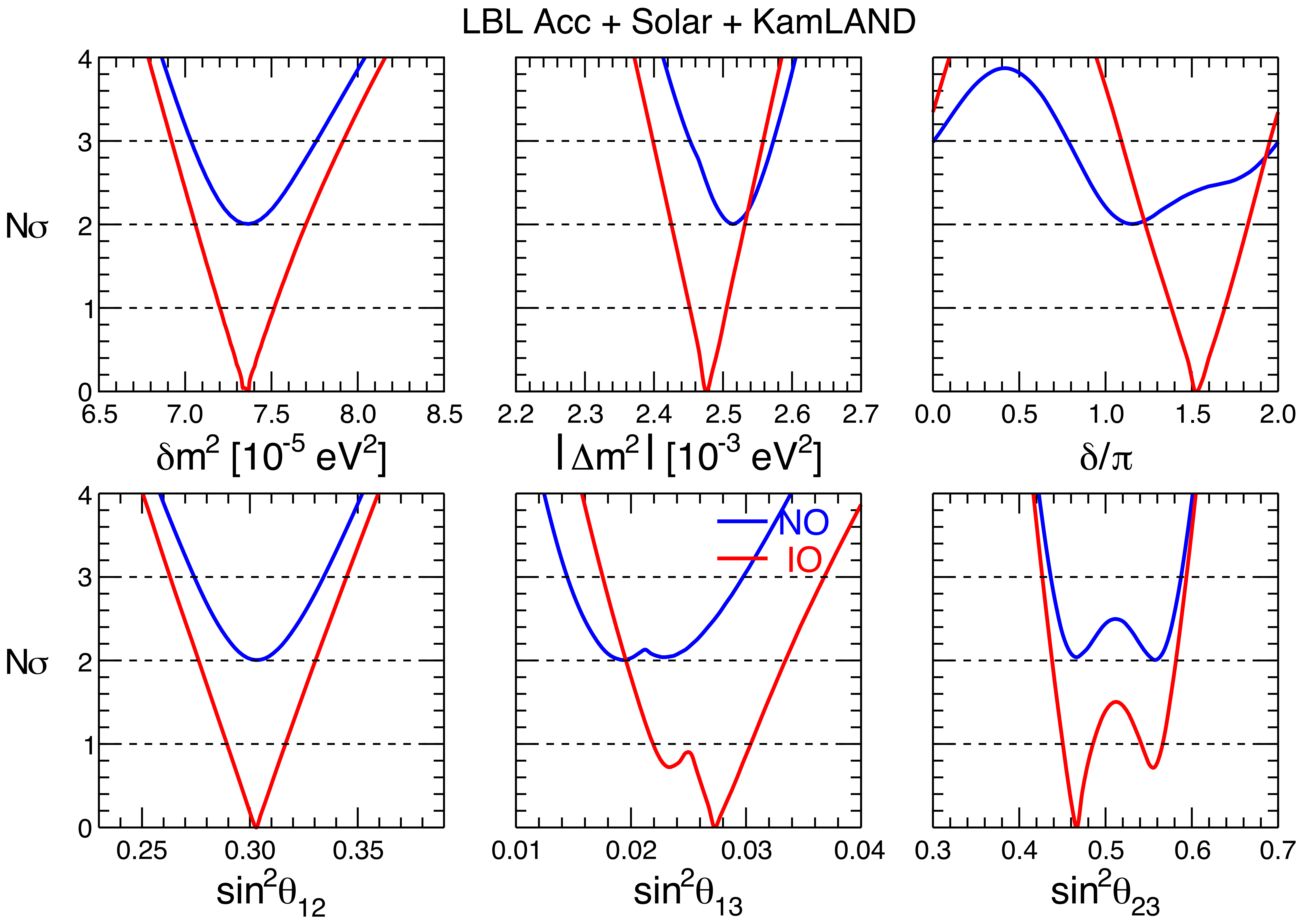

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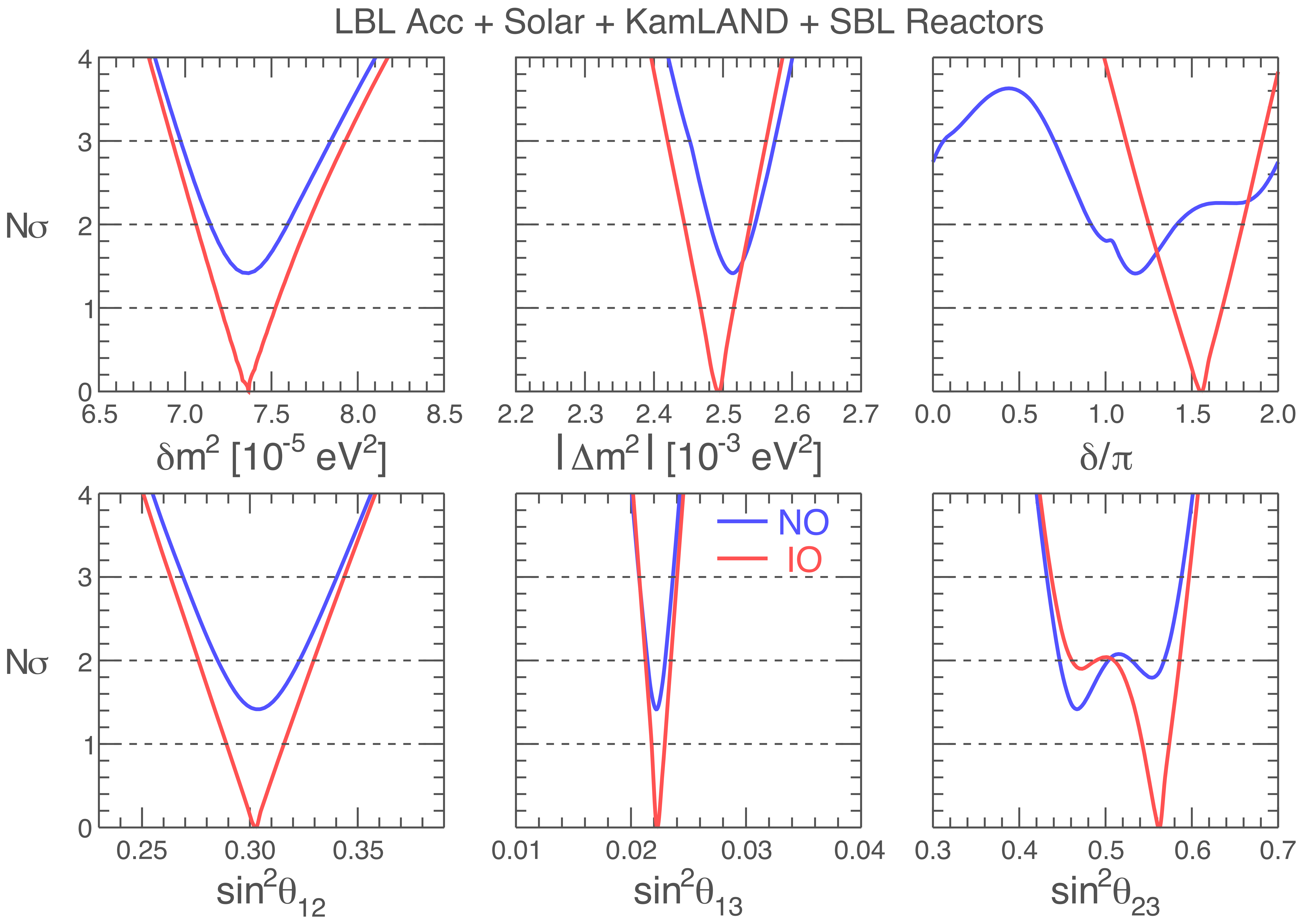
Due to some tension, in IO, indications for CP violation $> 3\sigma$



LBL Acc + Solar + KamLAND + SBL Reactors
Nσ
δm² [10⁻⁵ eV²]
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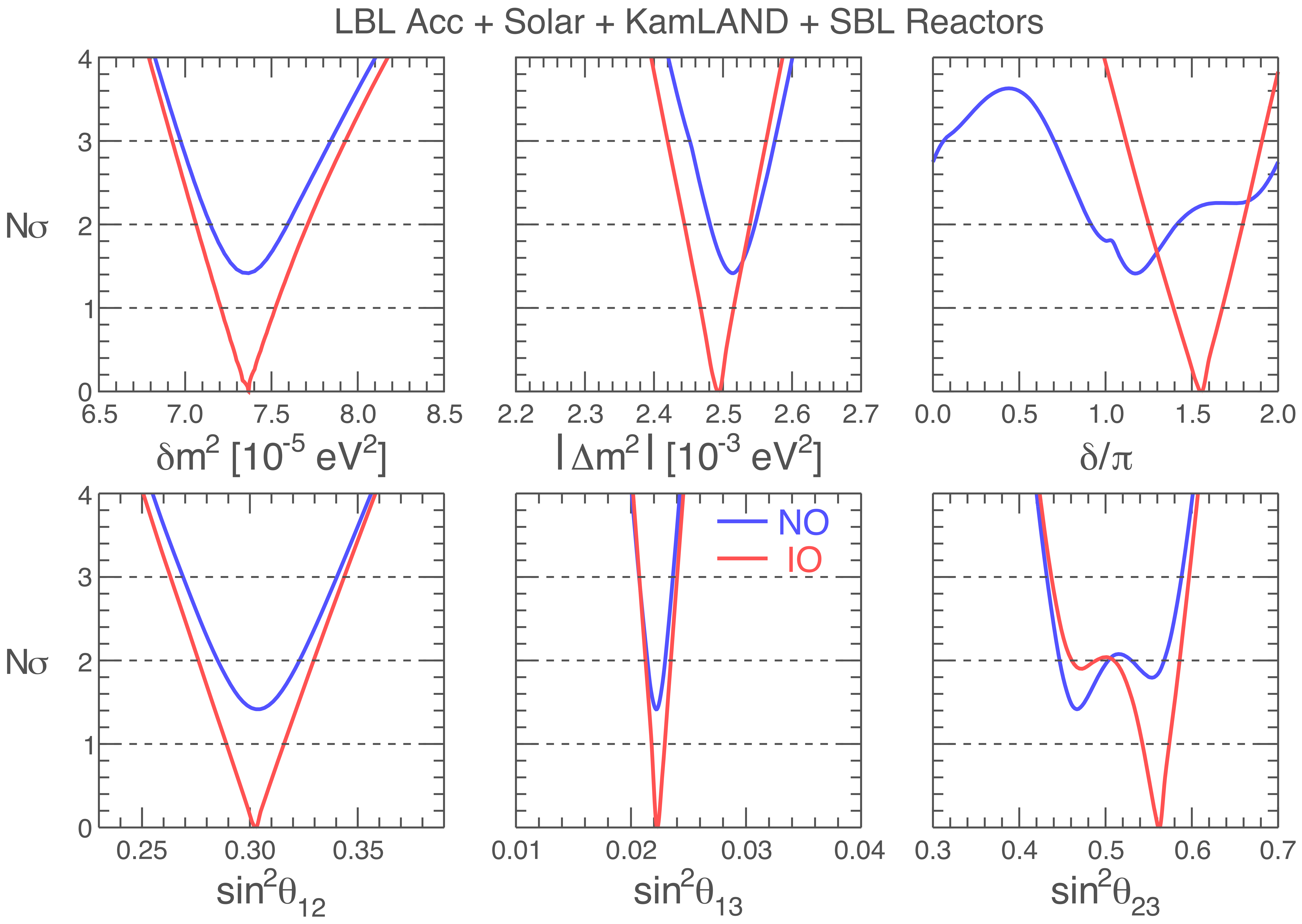

Adding SBL reactors:

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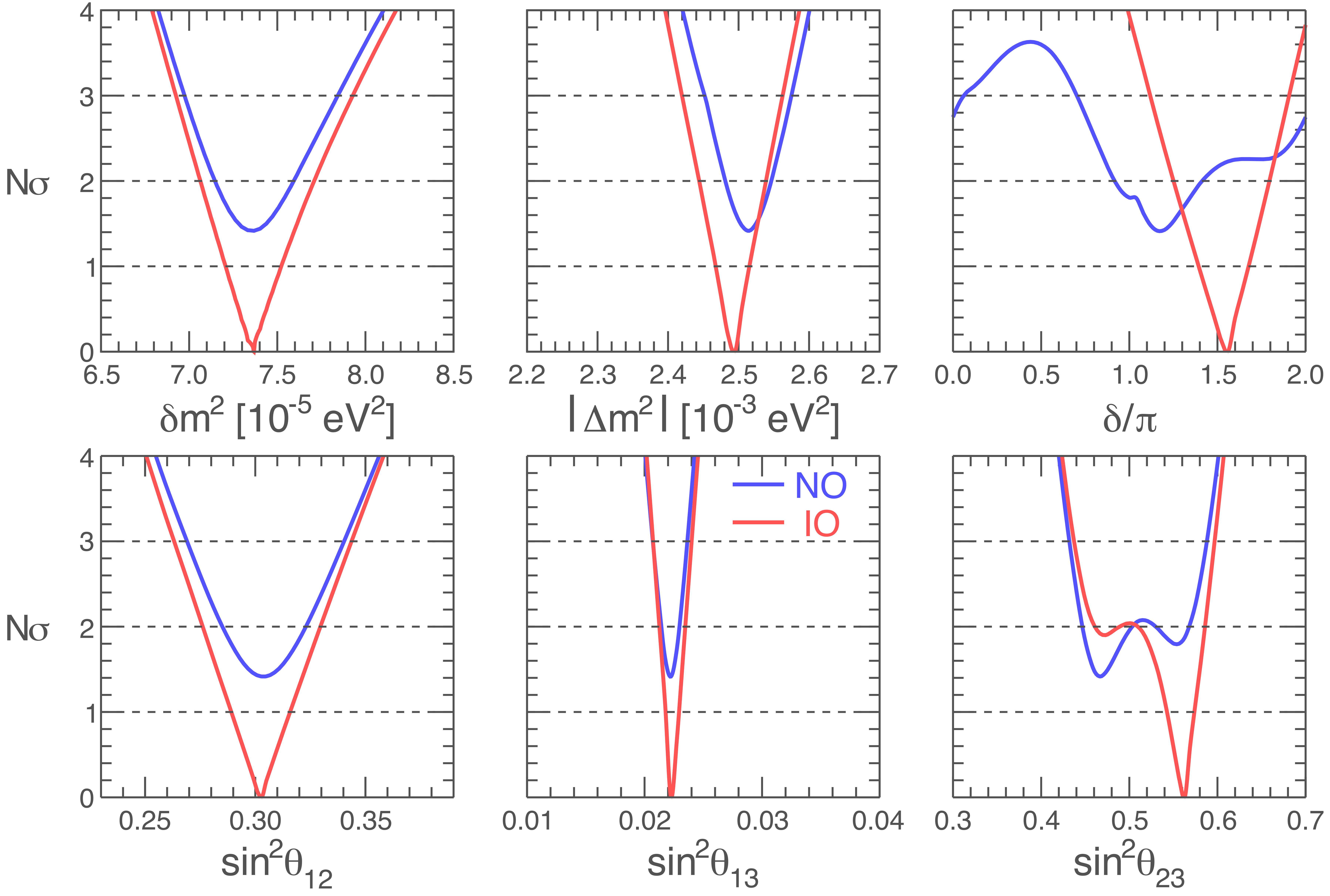
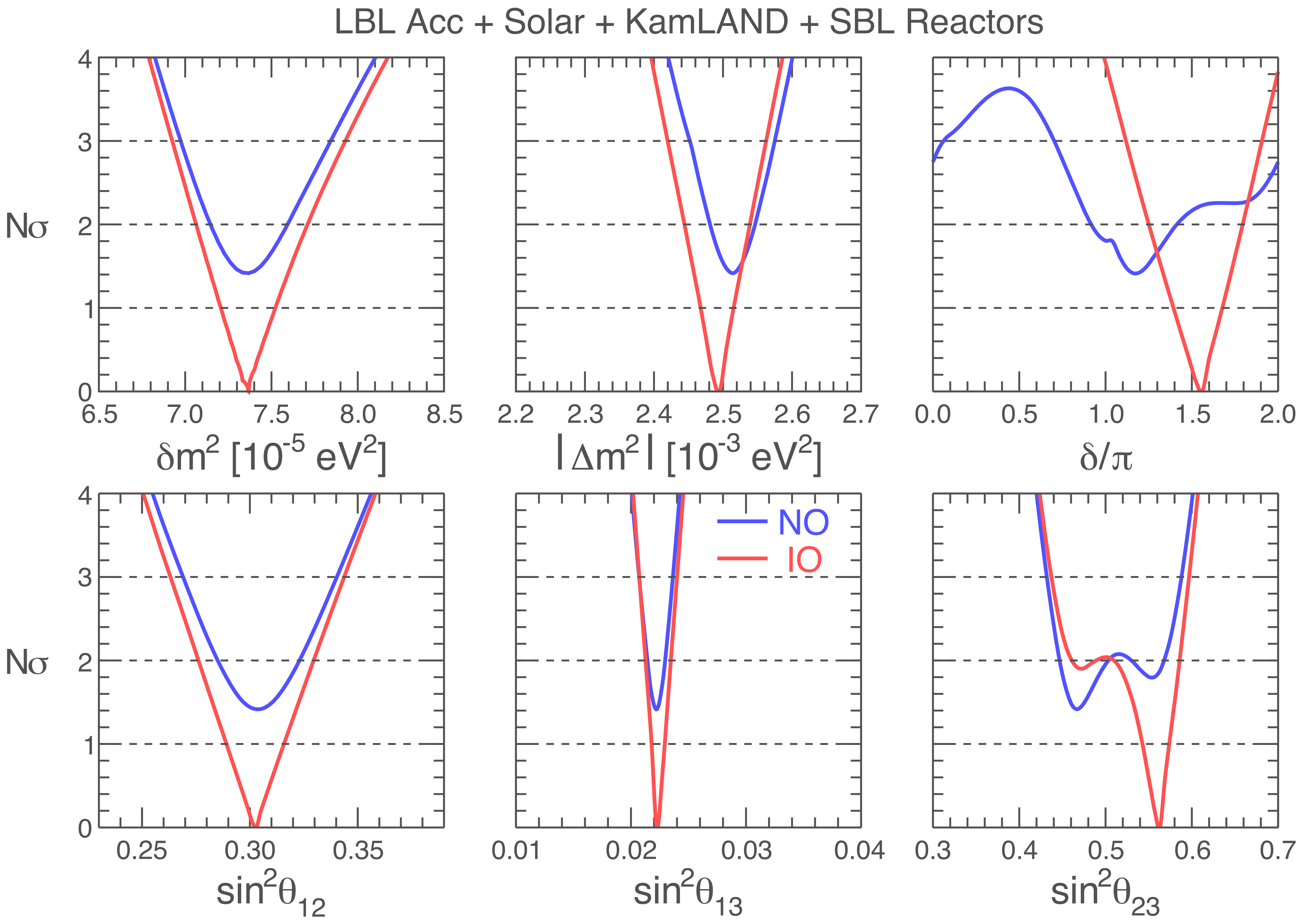


Adding SBL reactors:

Lower value of θ_{13} preferred



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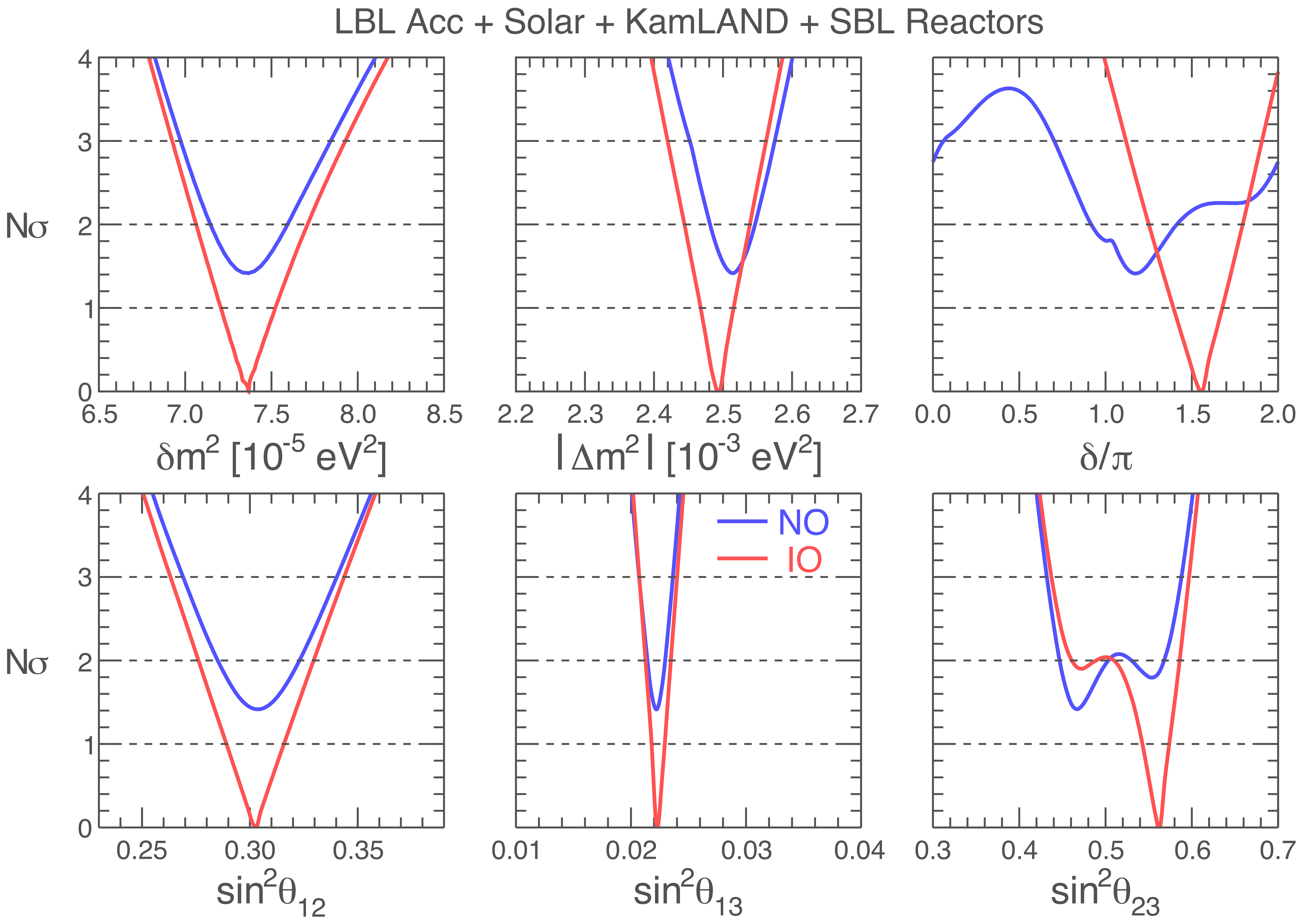
Octant amiguity for θ_{23} decreased, but still at $\sim 2\sigma$ for IO



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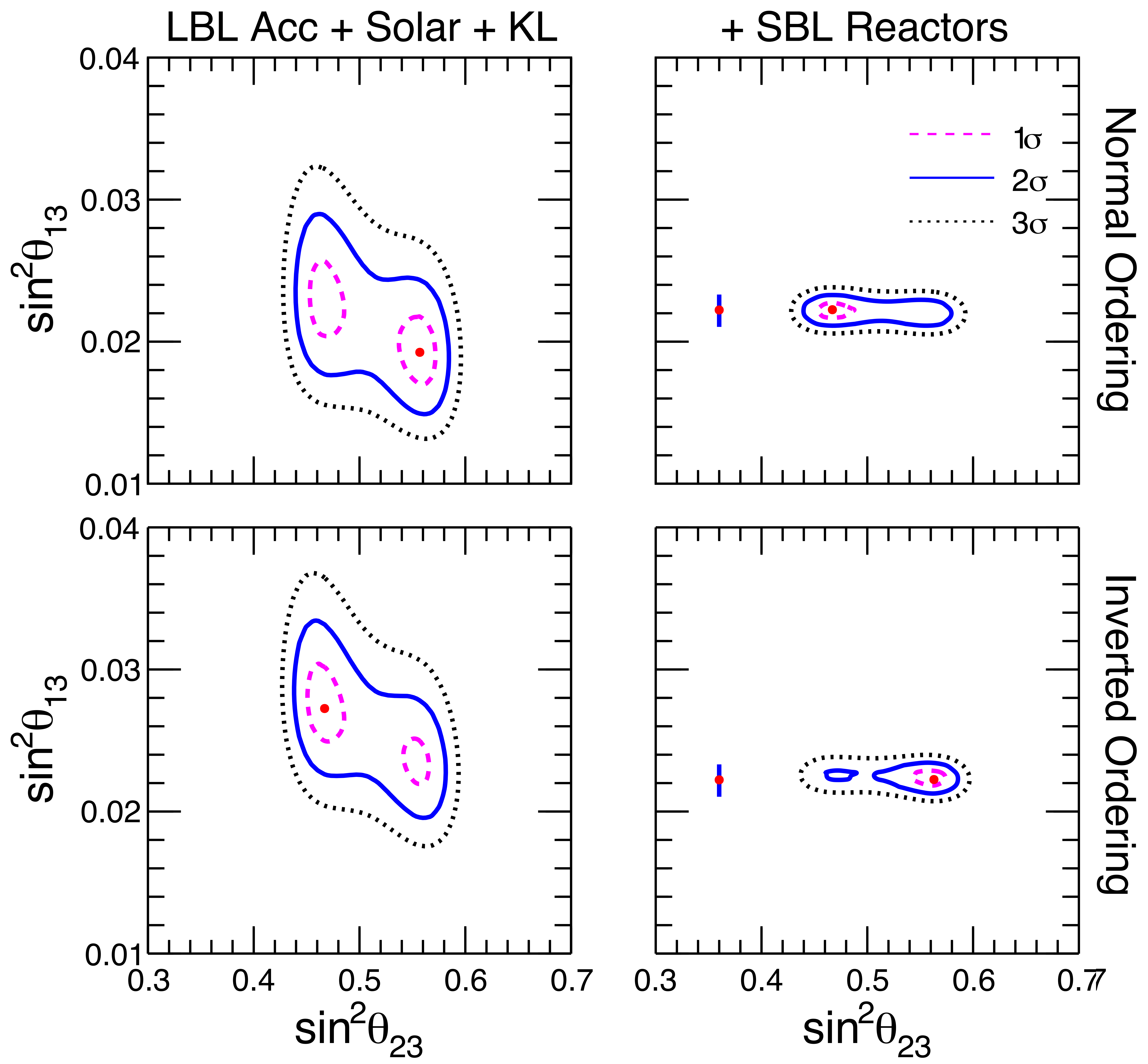
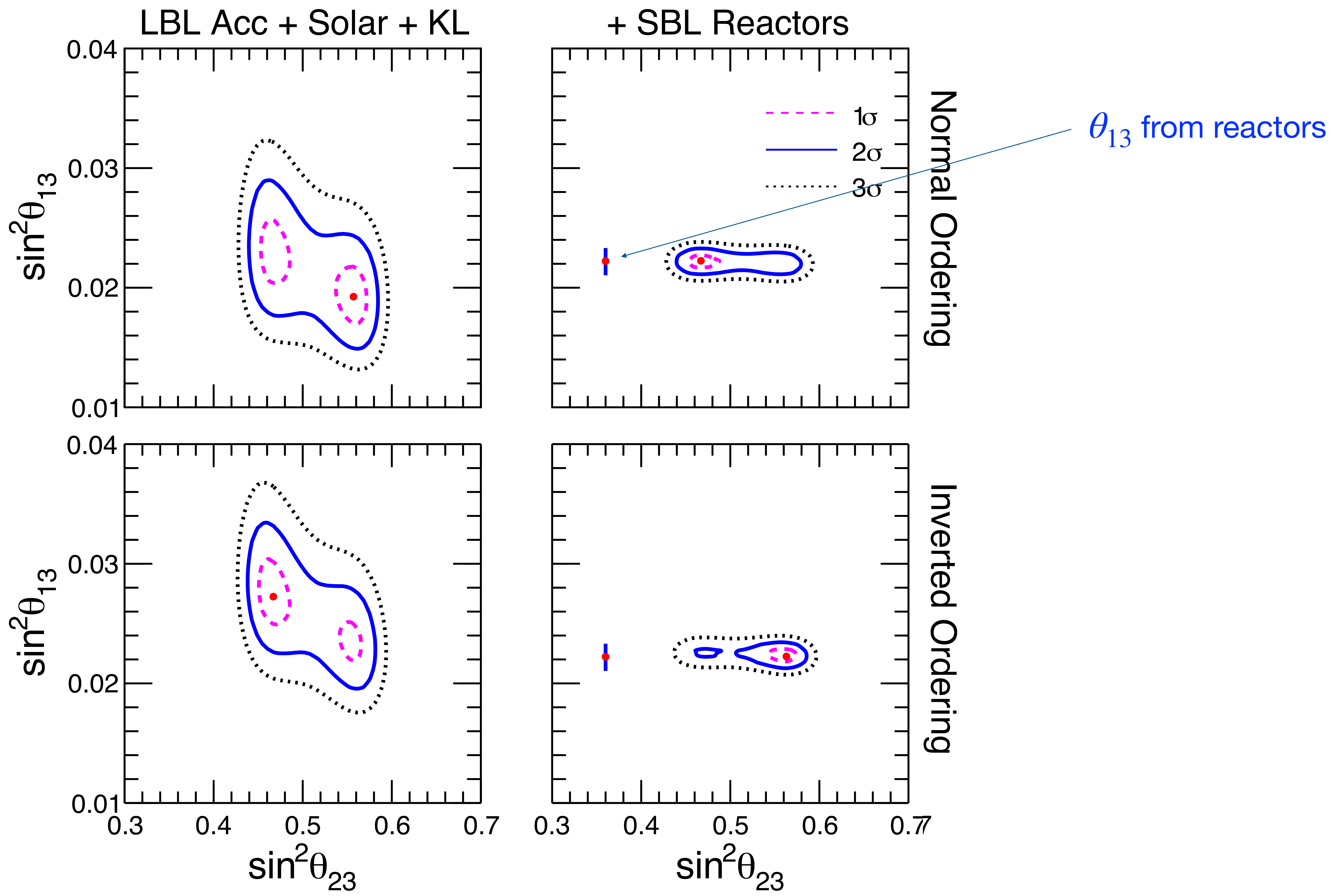
Adding SBL reactors: Still preference for IO, but at lower CL ($\sim 1.4\sigma$)



LBL Acc + Solar + KL
+ SBL Reactors
Normal Ordering
Inverted Ordering
1σ
2σ
3σ
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
0.01
0.02
0.03
0.04
0.3
0.4
0.5
0.6
0.7



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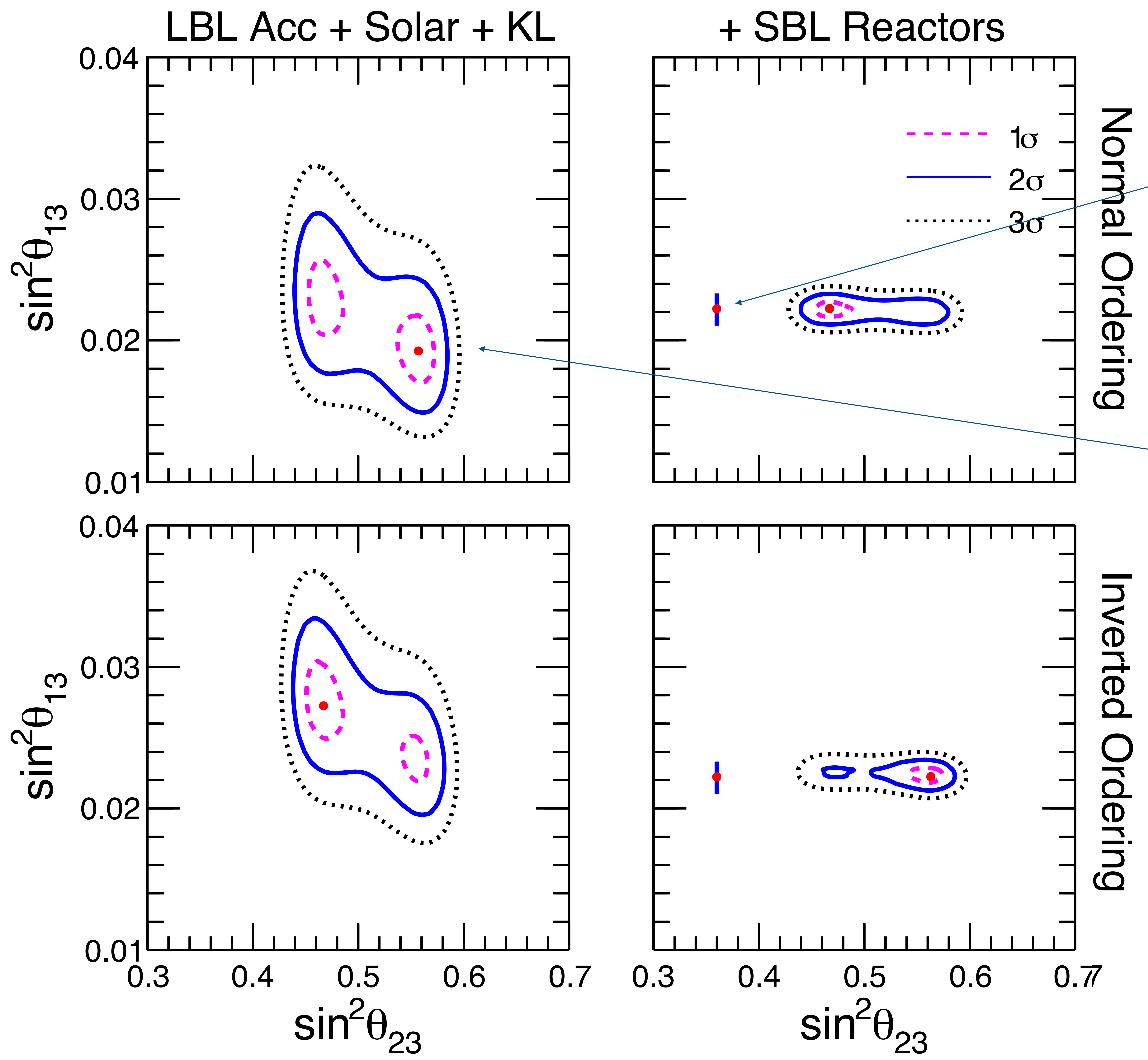
θ_{13} from reactors



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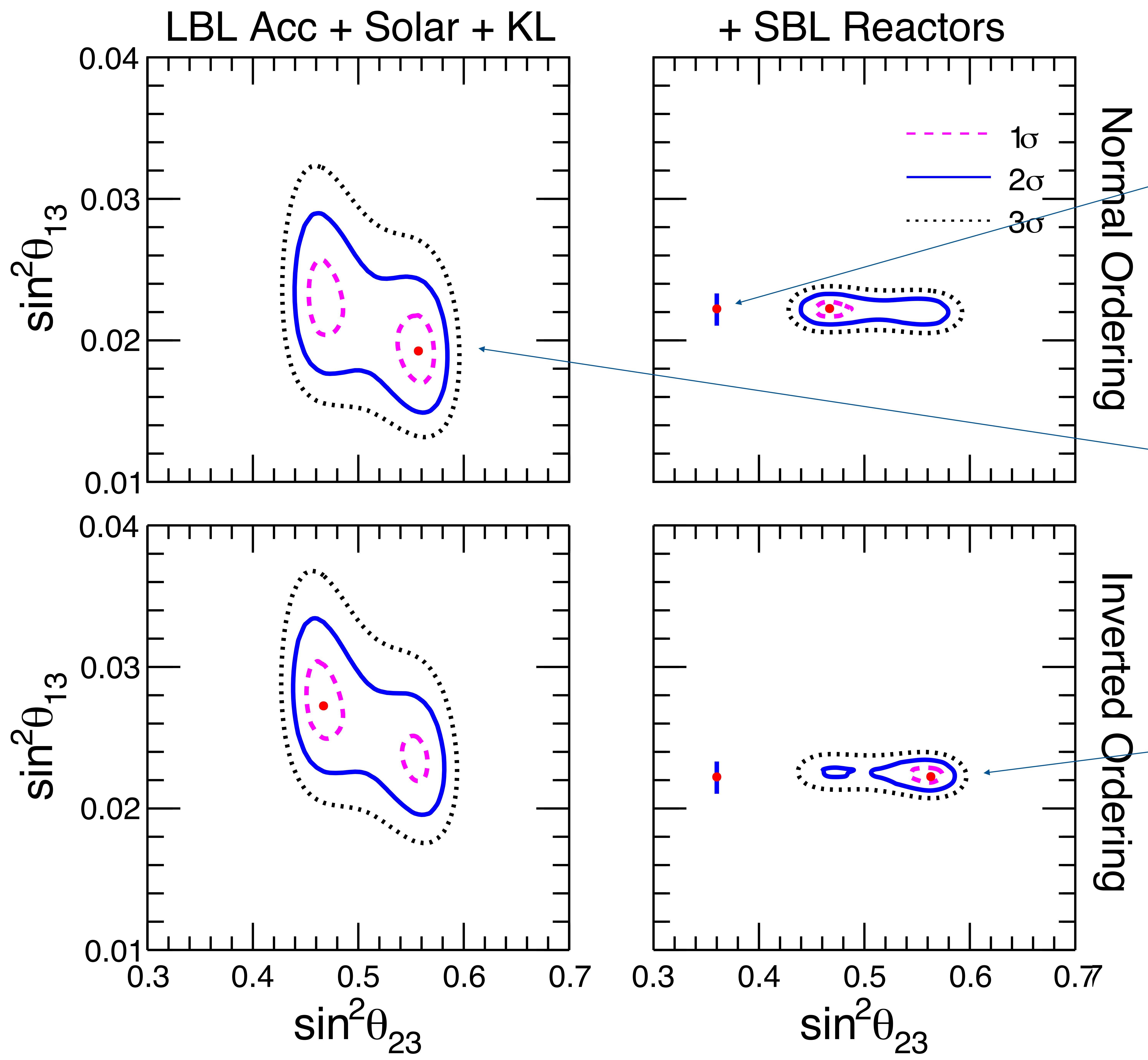
Anticorrelation between (ϑ_{23},ϑ_{13}) due to leading term in the appearance channel probability at accelerators



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lower ϑ_{13} value preferred by reactors data favours second octant for ϑ_{23}

SBL reactor measurement of Δm^2 more in agreement with LBL accel. in NO than in IO

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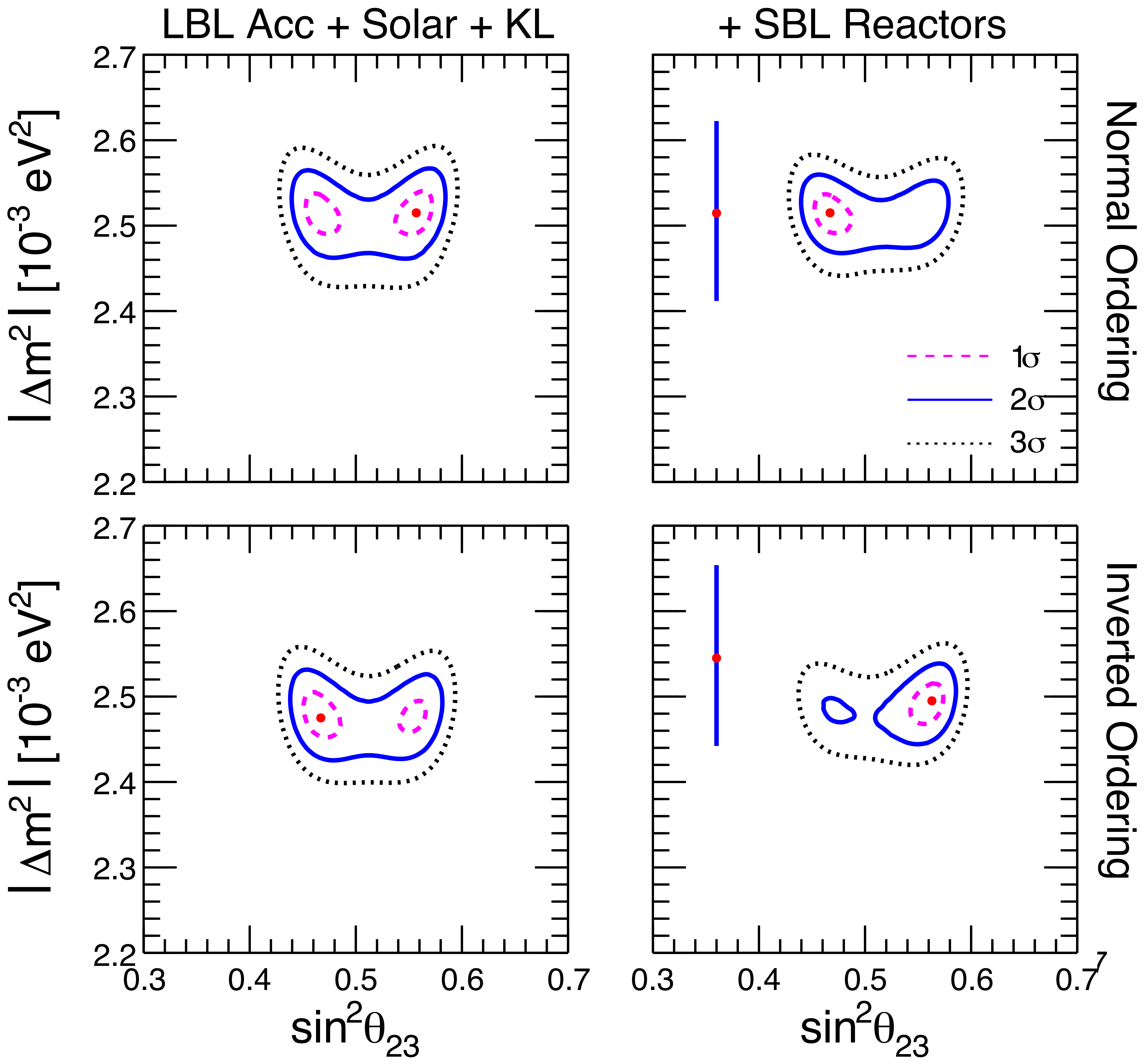

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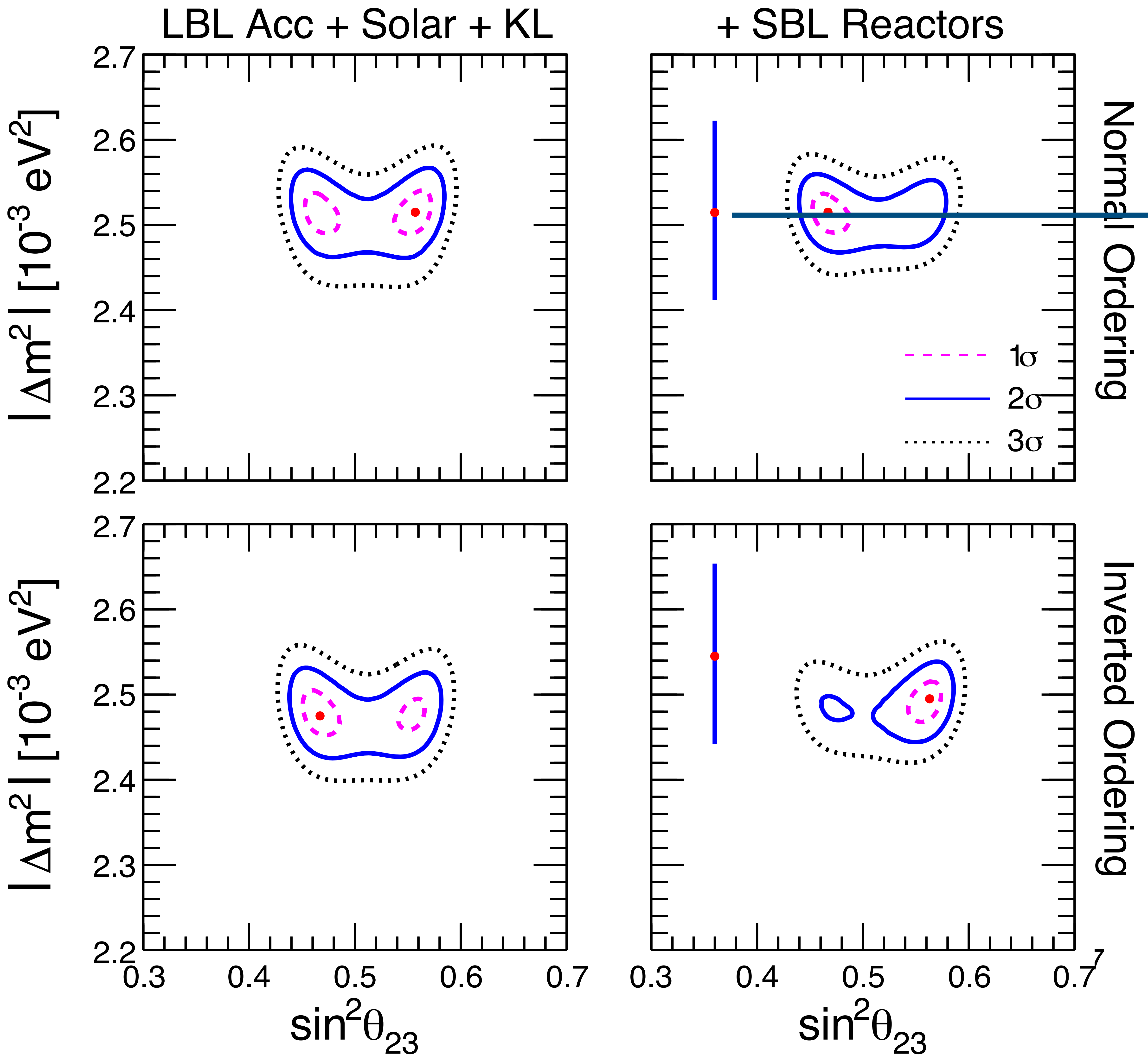

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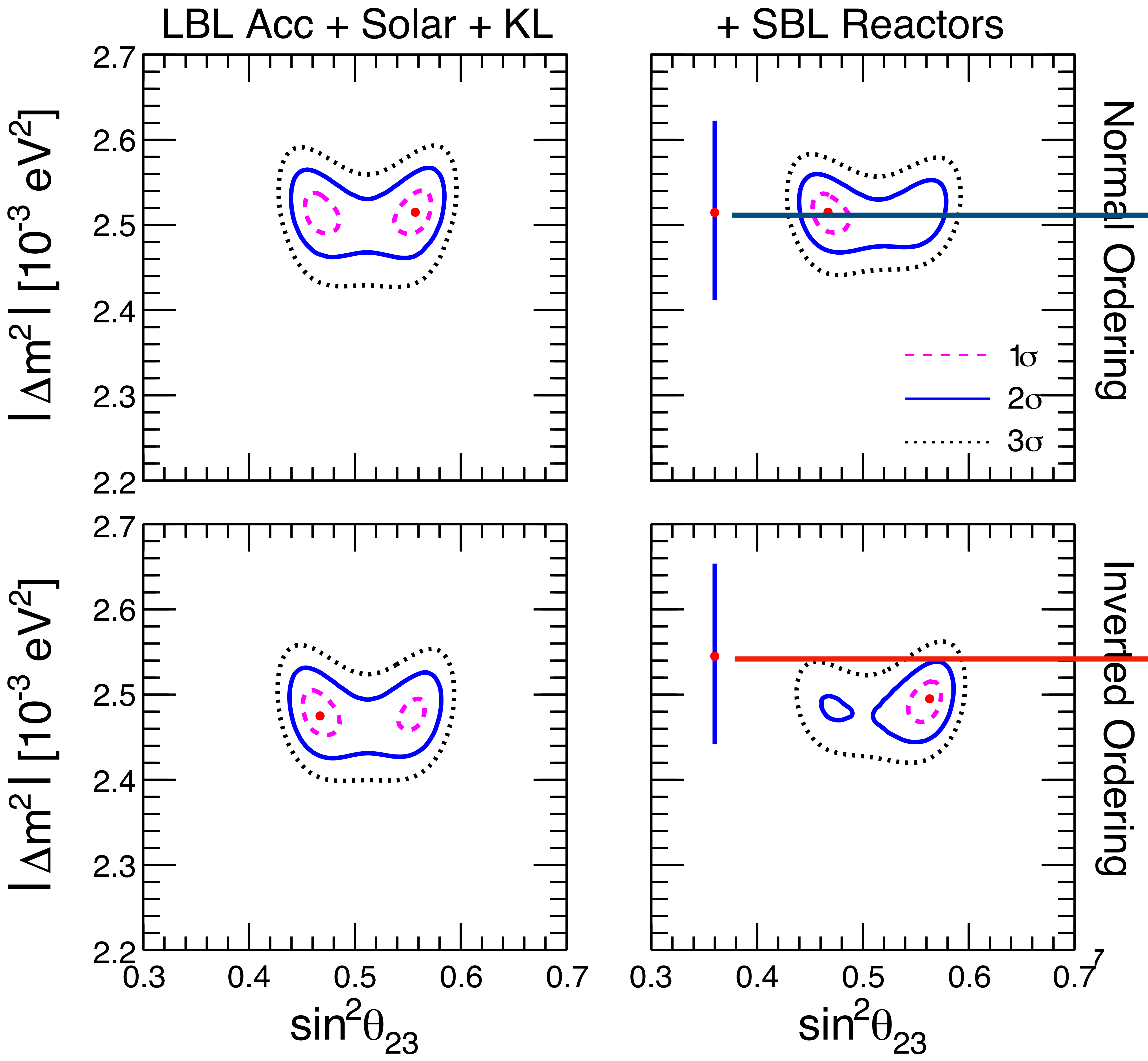

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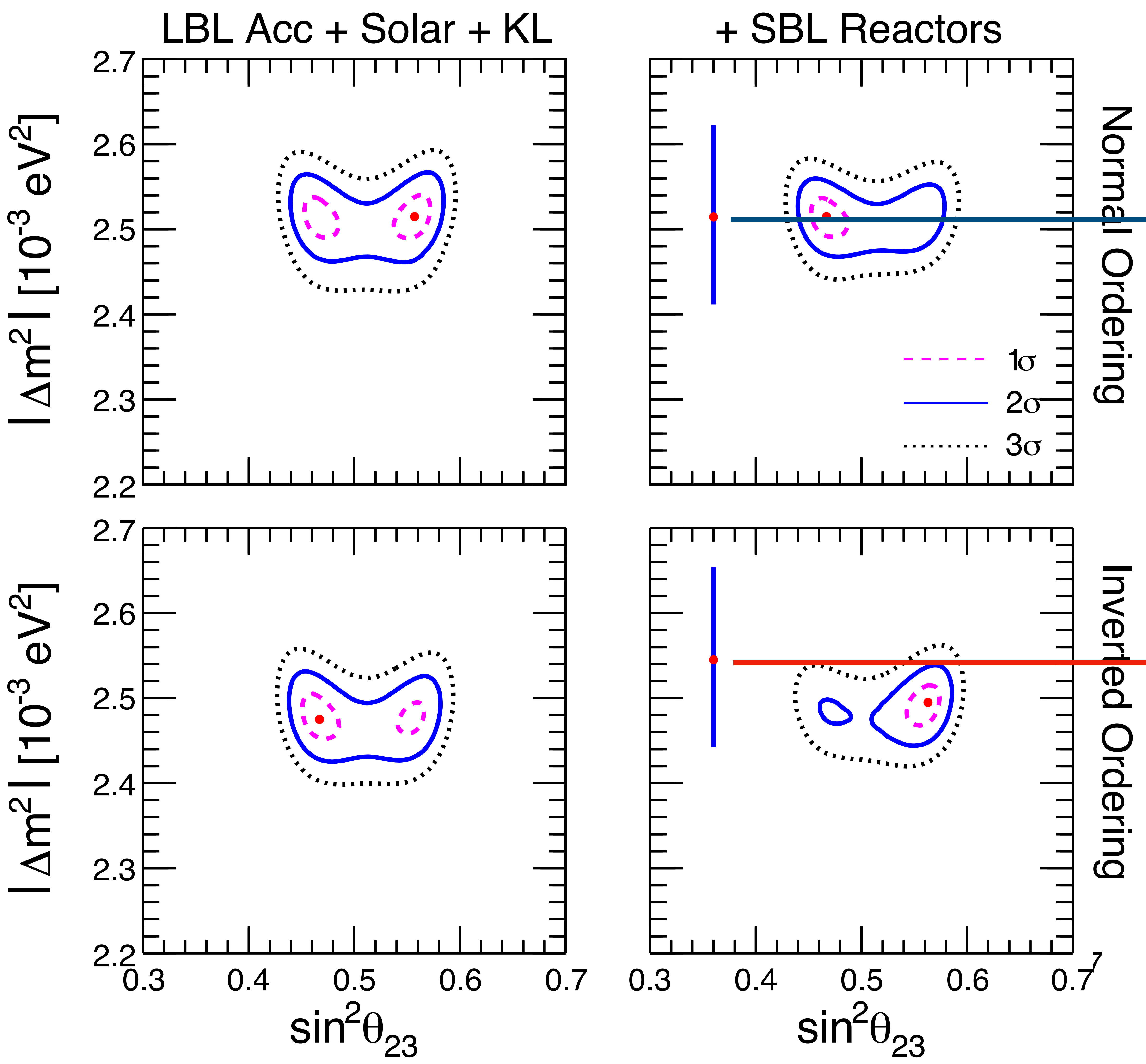

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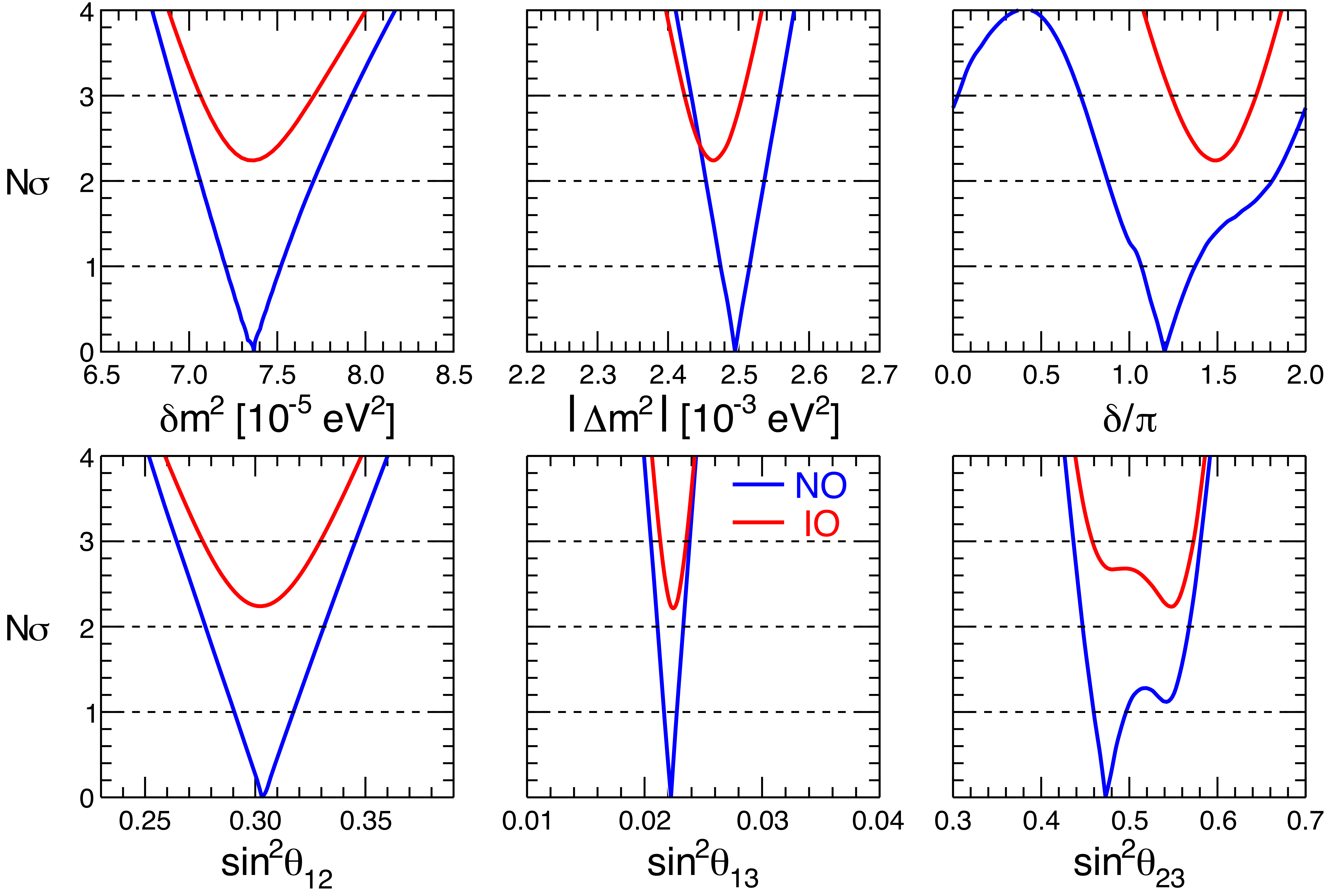
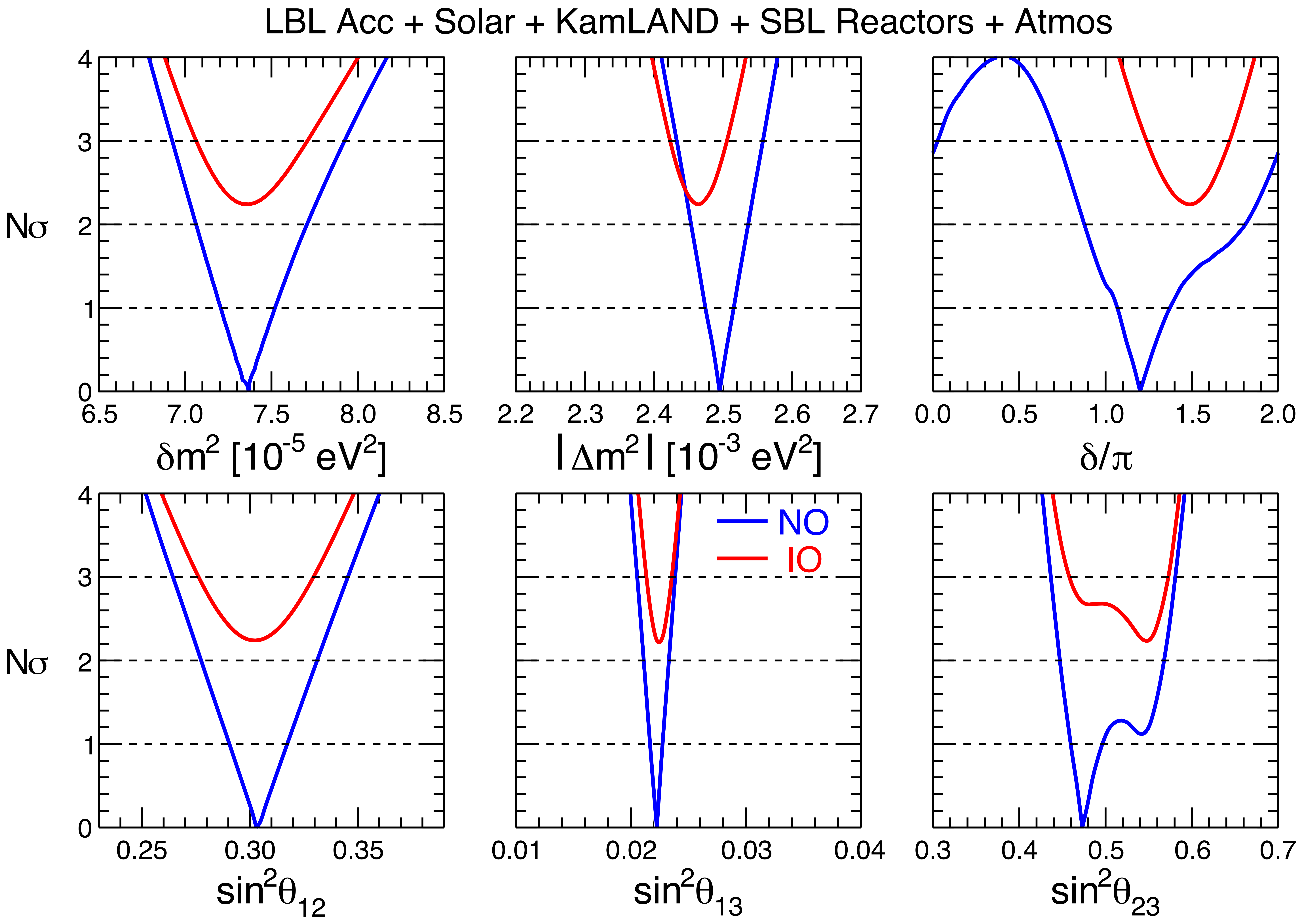
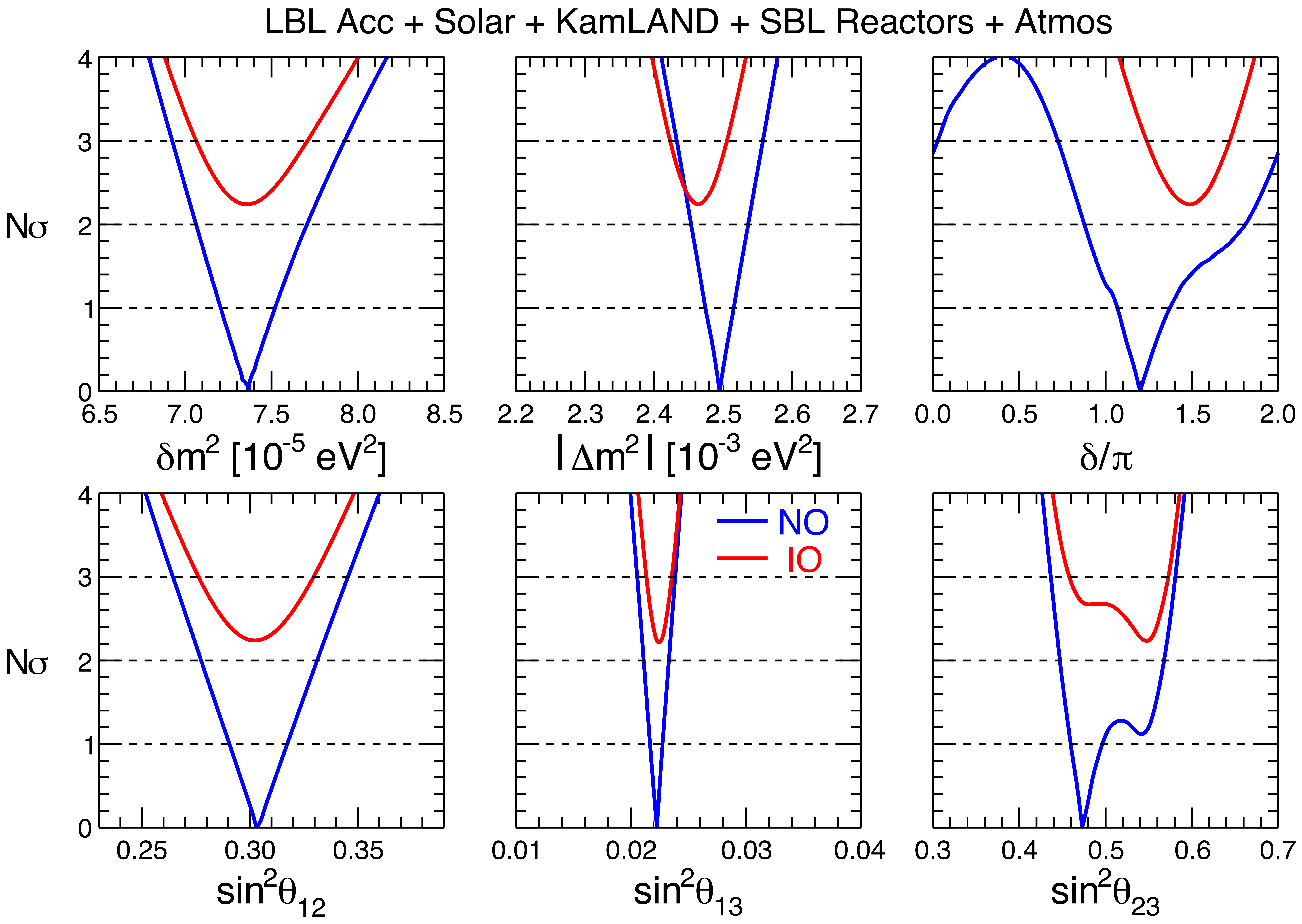
SBL reactor measurements favor NO and prefer first (second) octant of θ_{23} in NO (IO)

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos





Including atmospheric data favors NO over IO at ~2.2σ



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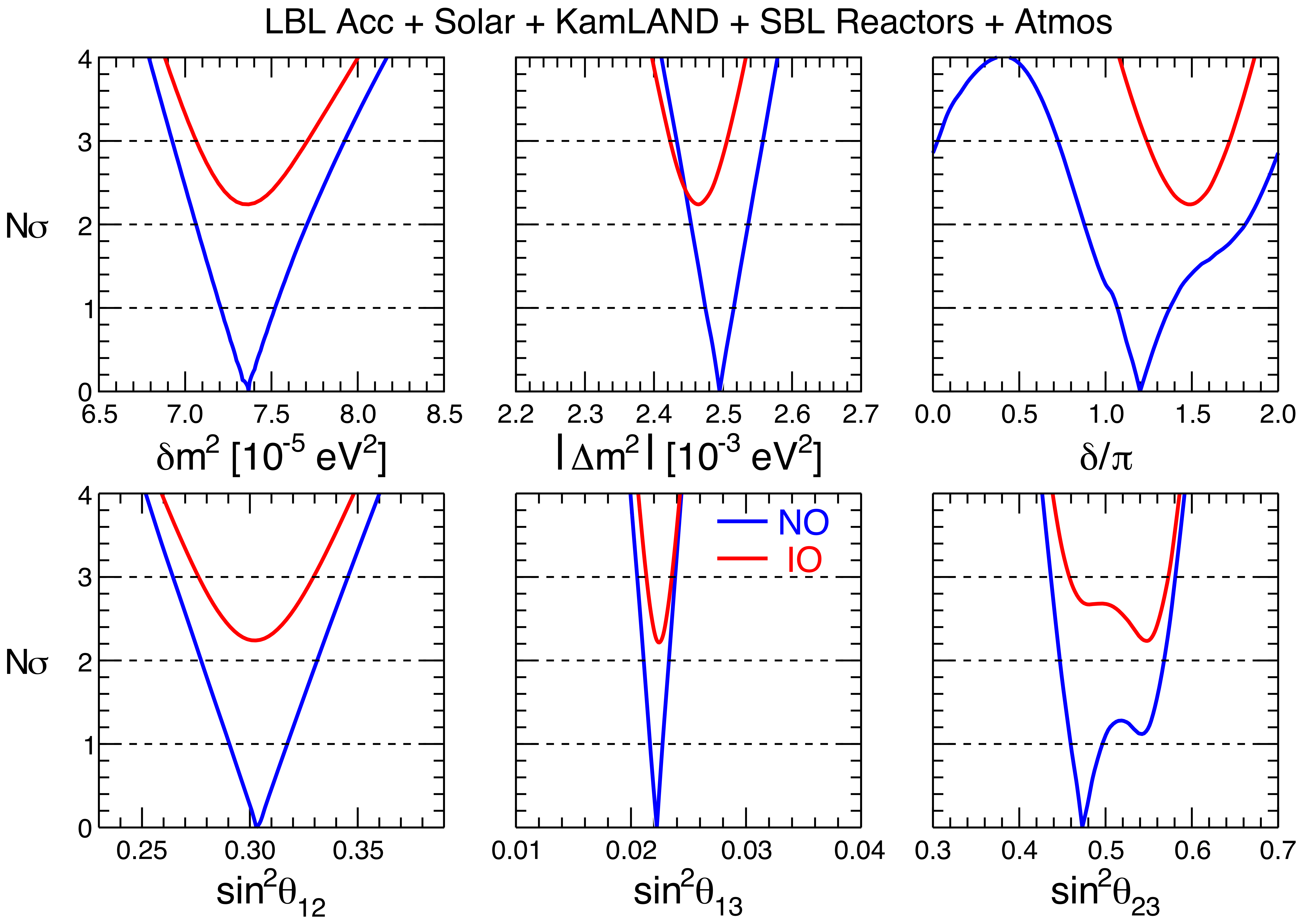

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Overall status of oscillation unknowns is more uncertain than in older analyses

Absolute ν masses $\Rightarrow (m_\beta, m_{\beta\beta}, \Sigma)$

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β decay experiments, sensitive to the "effective electron neutrino mass"

$$m_\beta = [c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2]^{1/2}$$

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$$\Sigma = m_1 + m_2 + m_3$$

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Note that the three observables are correlated by oscillation data

Neutrinoless Double Beta Decay results

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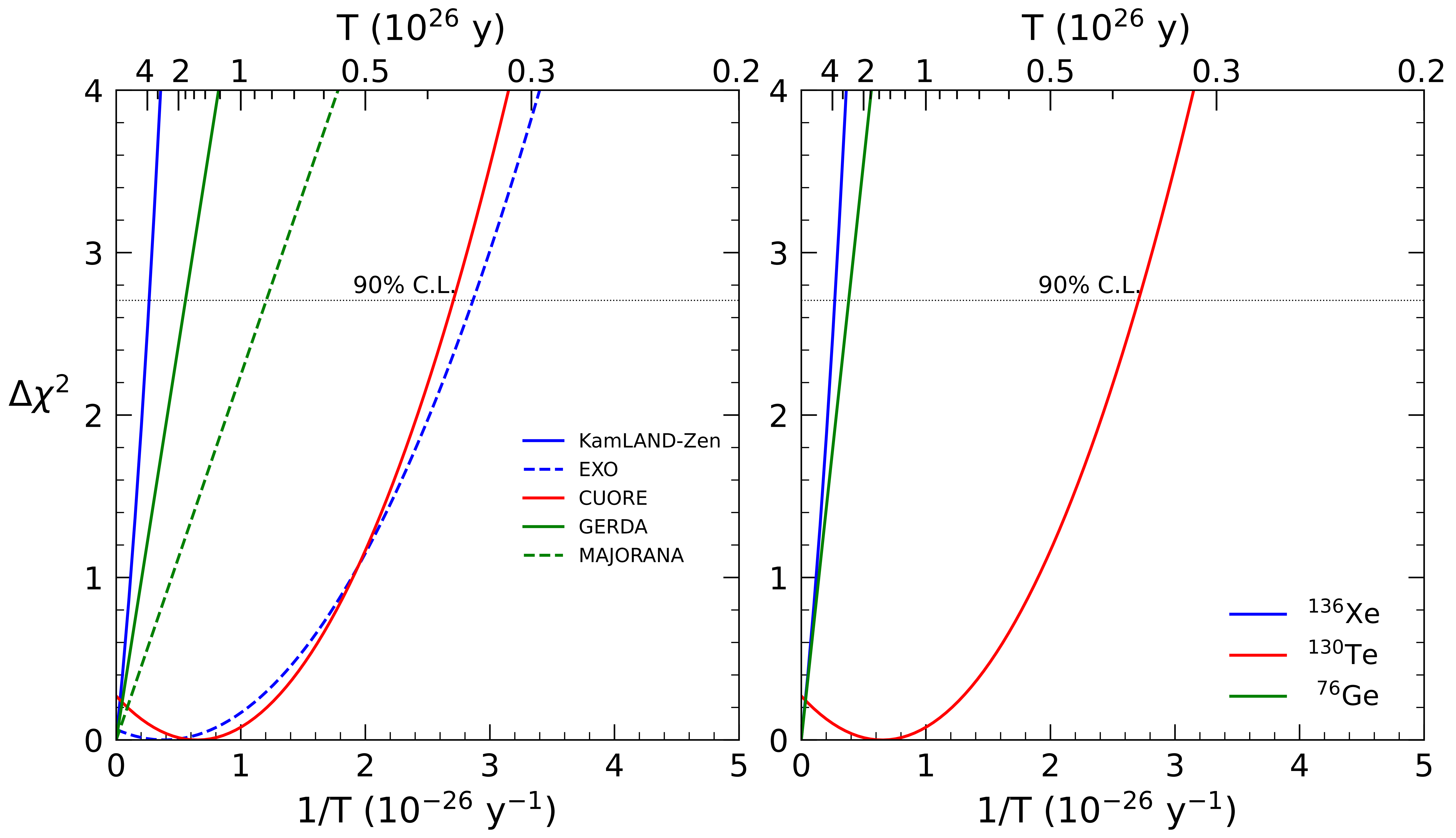

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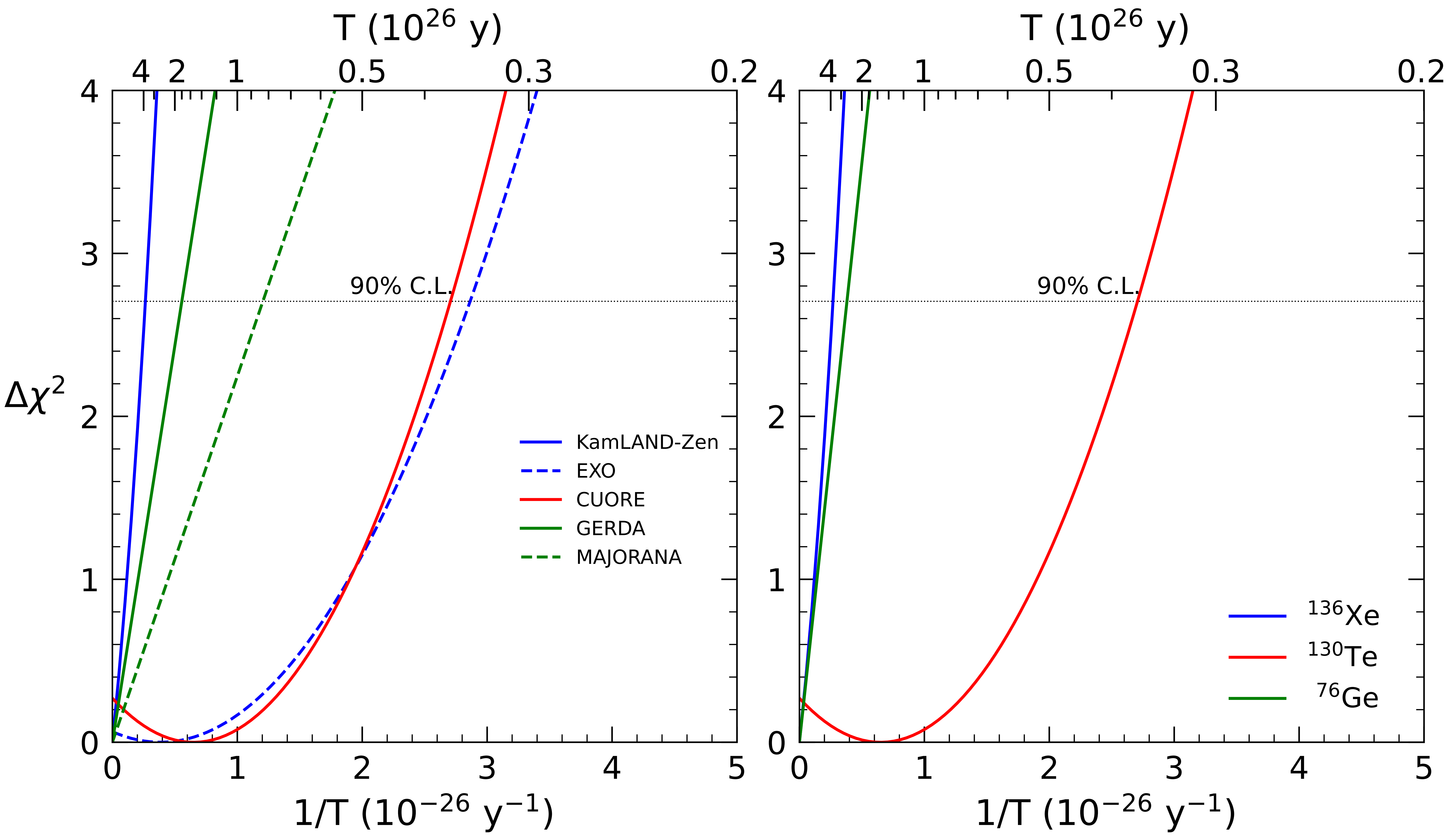
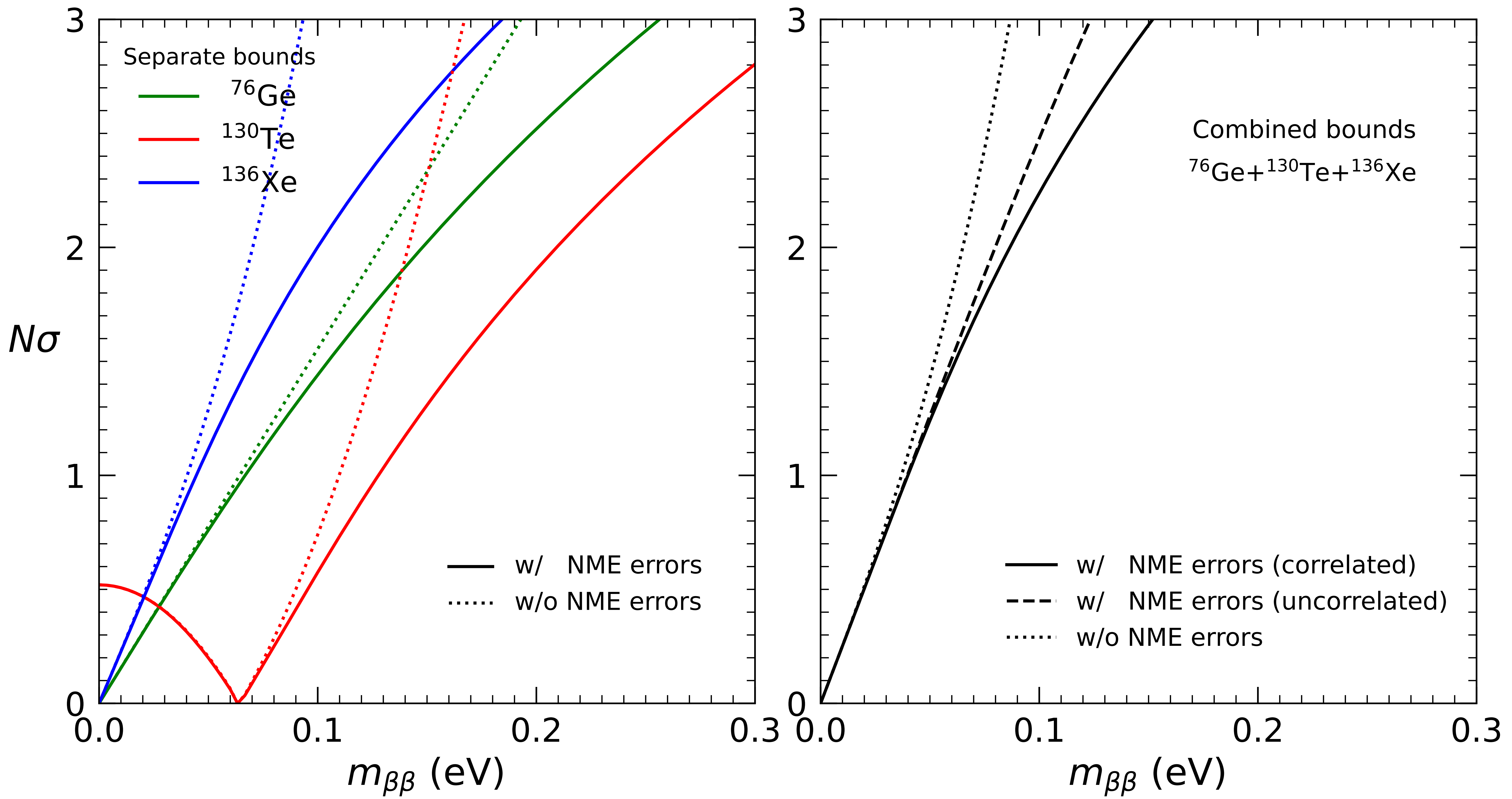


Translating bounds on the half-life T to bounds on $m_{\beta\beta}$ requires the knowledge of the nuclear matrix element M (NME) for the decay at issue since

$$\frac{1}{T} = \text{phase space} \times |M|^2 \times m_{\beta\beta}^2$$

Neutrinoless Double Beta Decay results



Translating bounds on the half-life T to bounds on $m_{\beta\beta}$ requires the knowledge of the nuclear matrix element M (NME) for the decay at issue since

$$\frac{1}{T} = \text{phase space} \times |M|^2 \times m_{\beta\beta}^2$$

Regions allowed by oscillations on $(\Sigma, m_\beta, m_{\beta\beta})$

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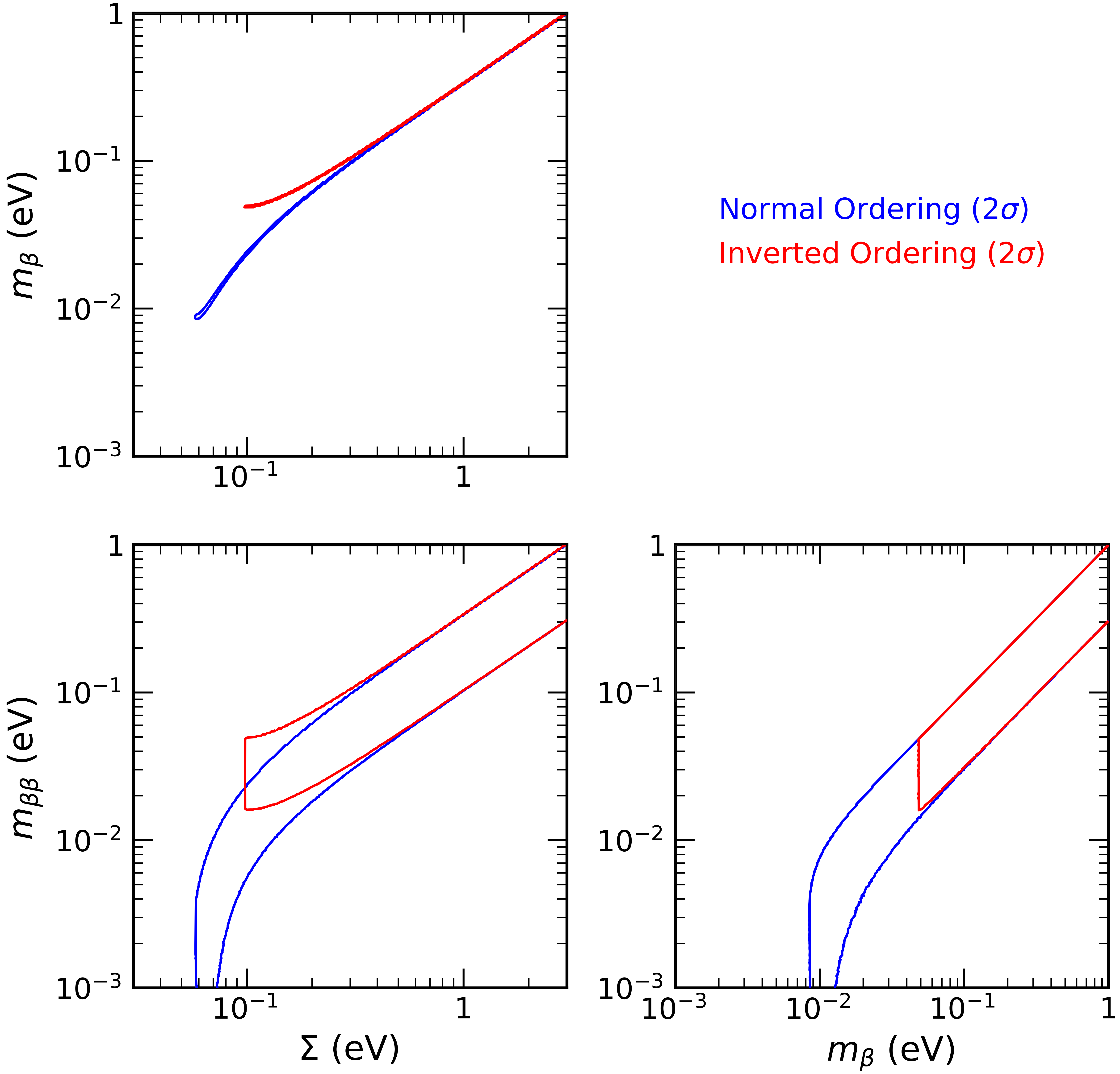

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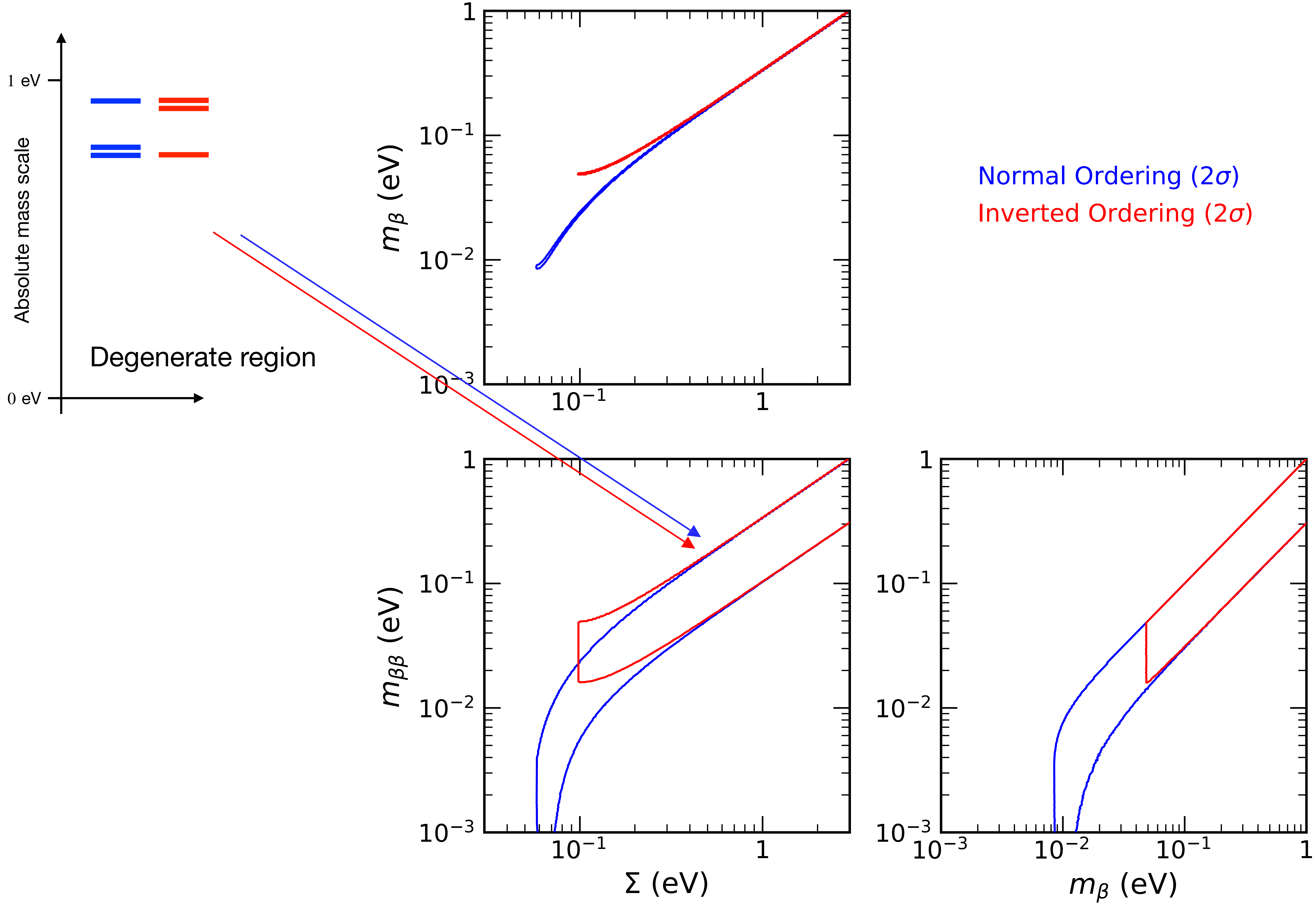

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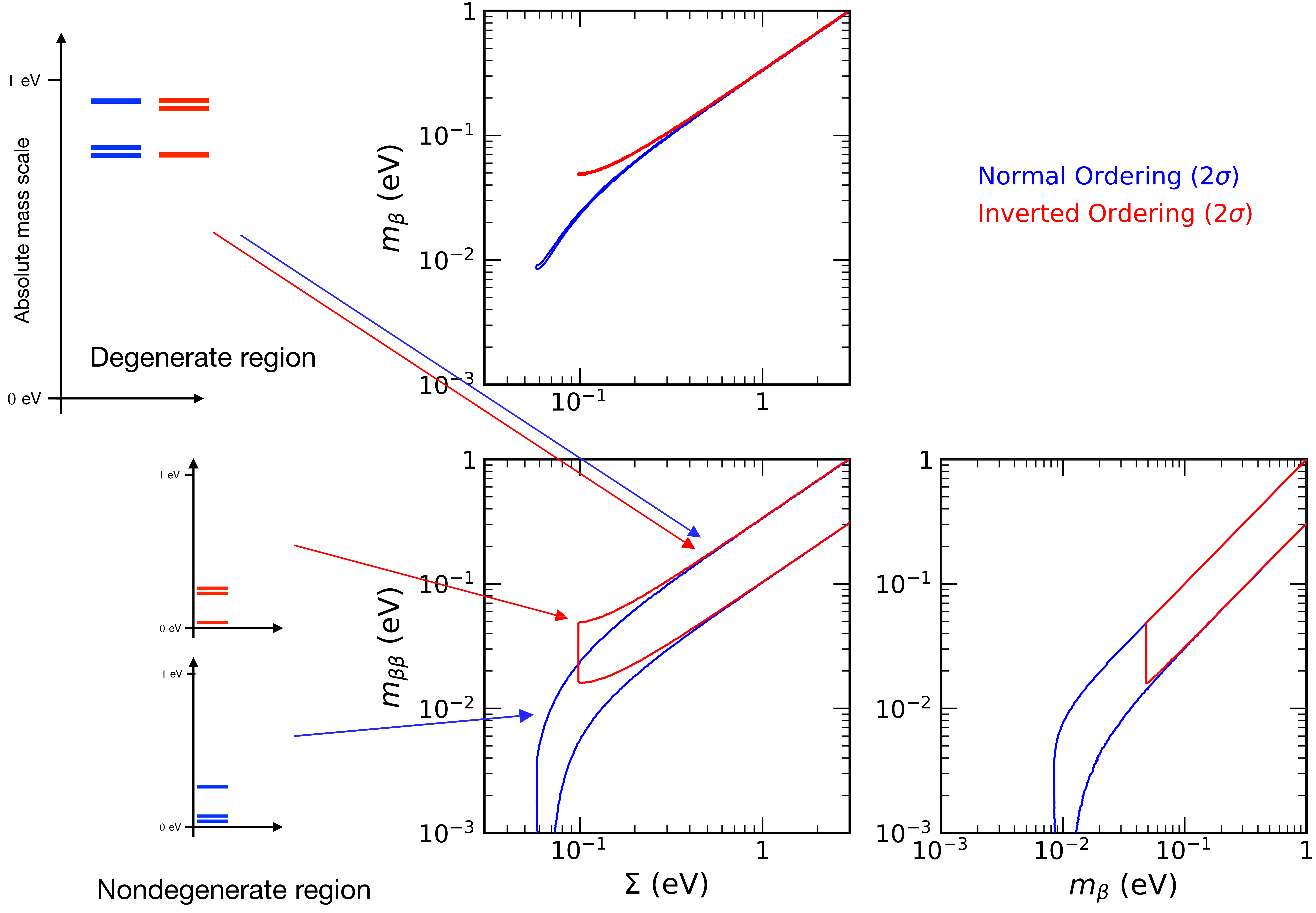

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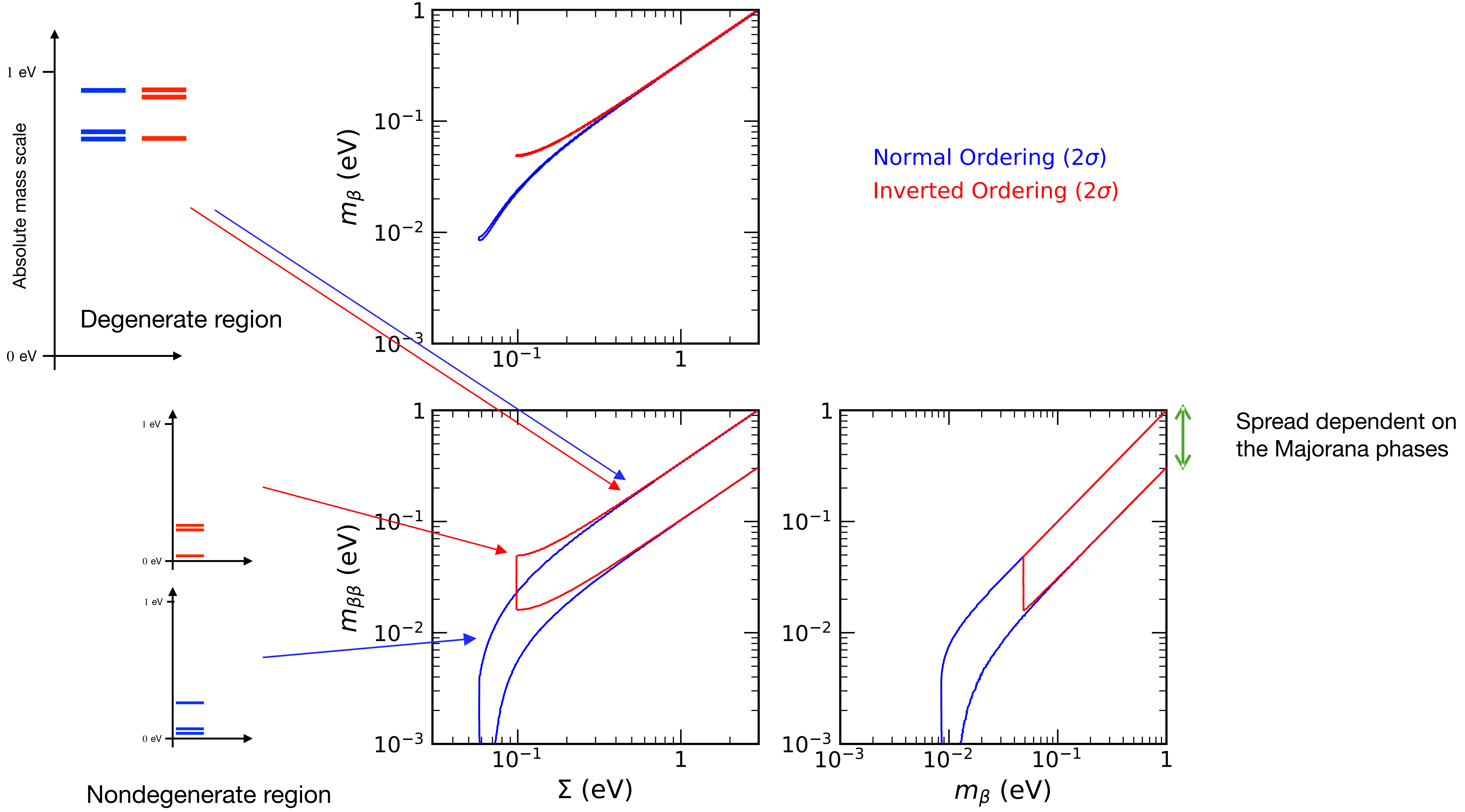

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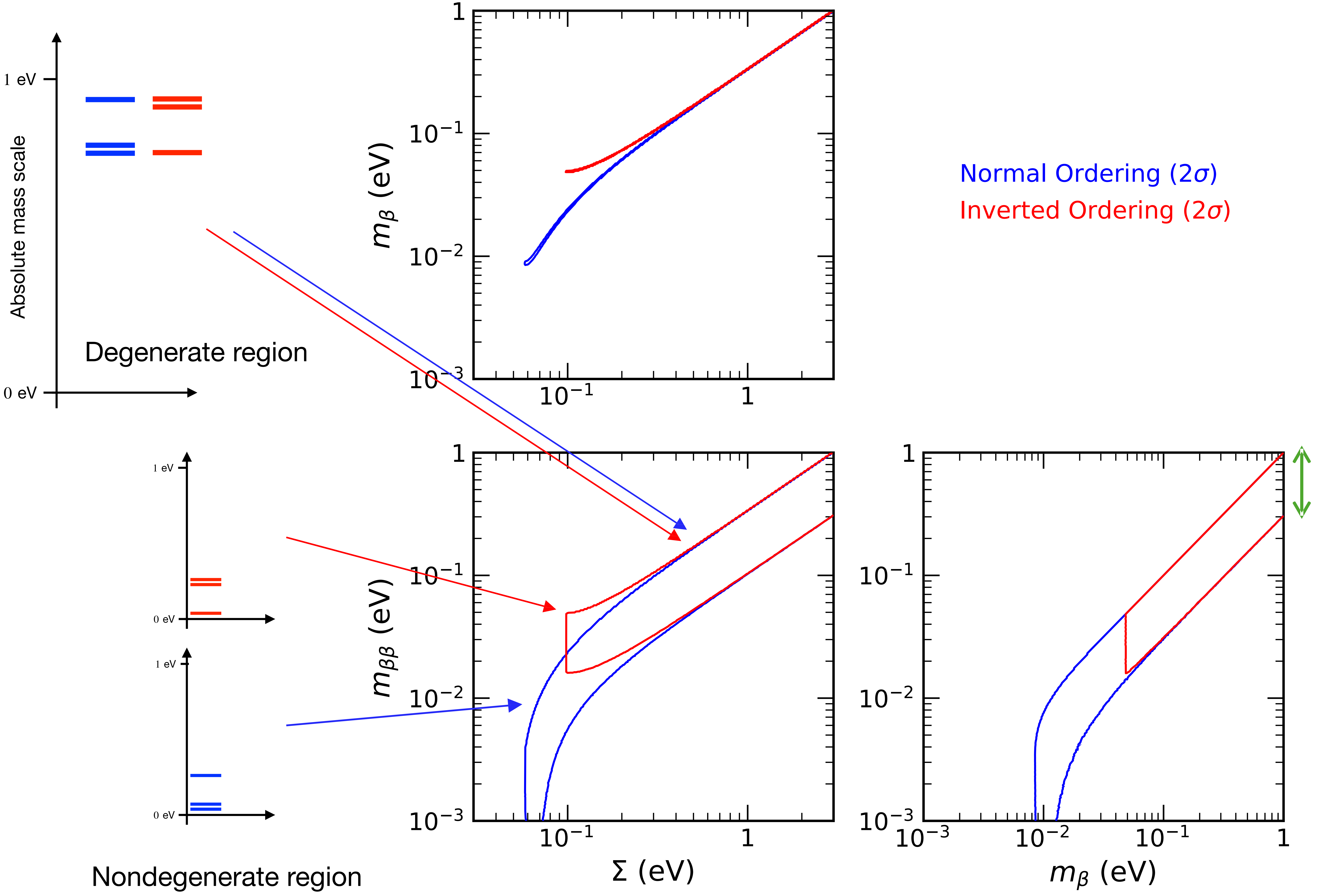
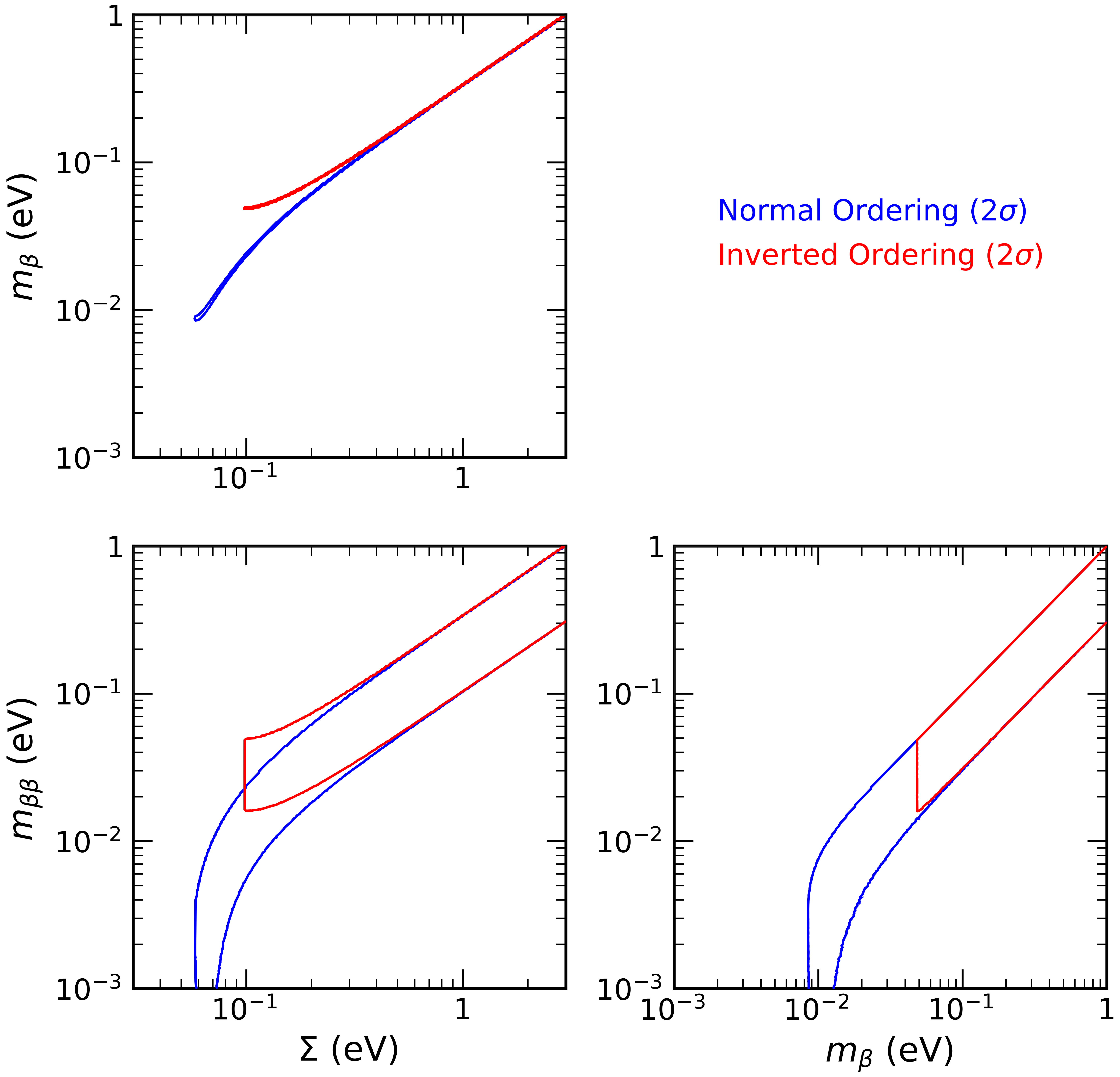


Normal Ordering (2σ)

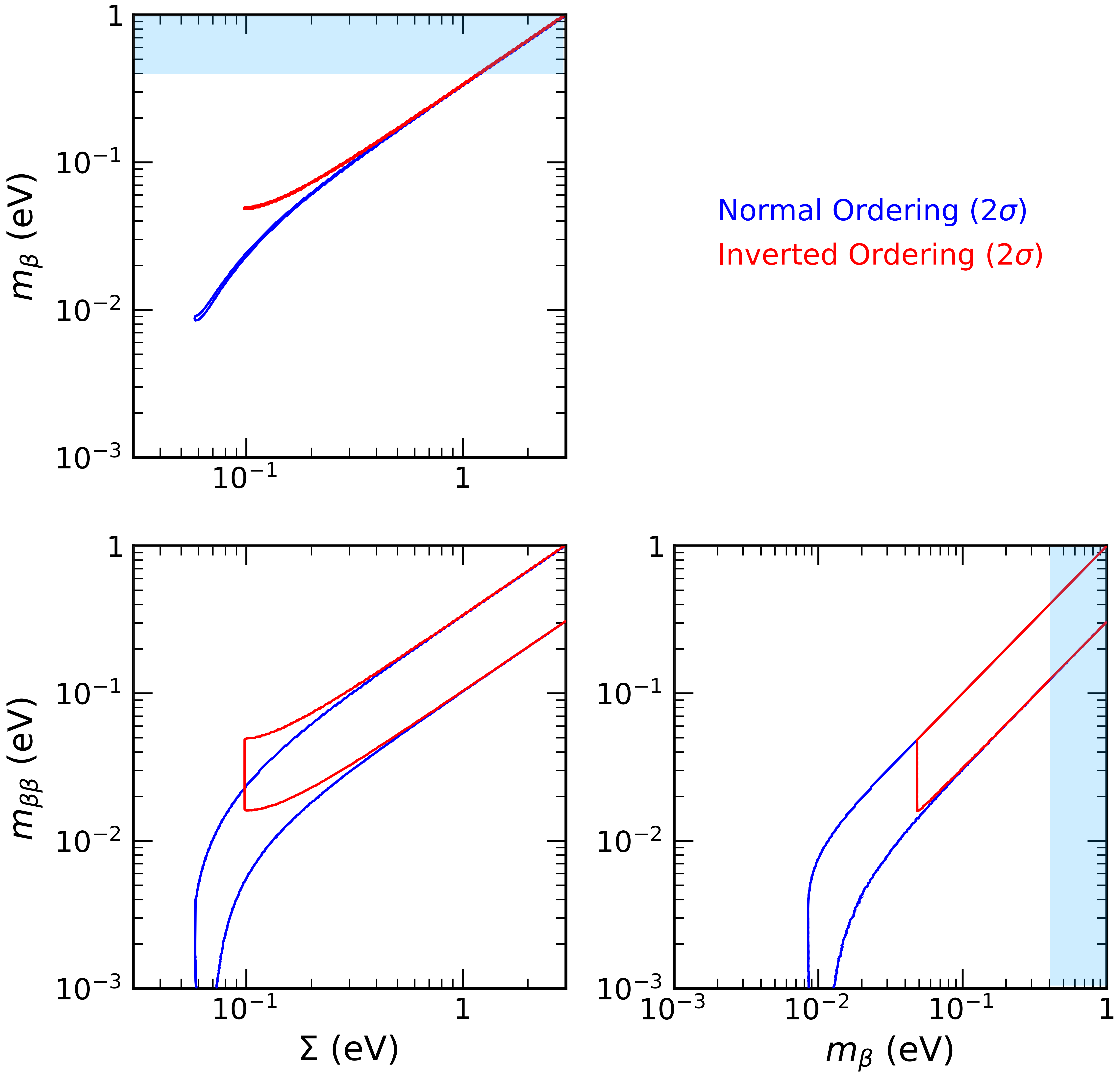
Inverted Ordering (2σ)

Spread dependent on the Majorana phases

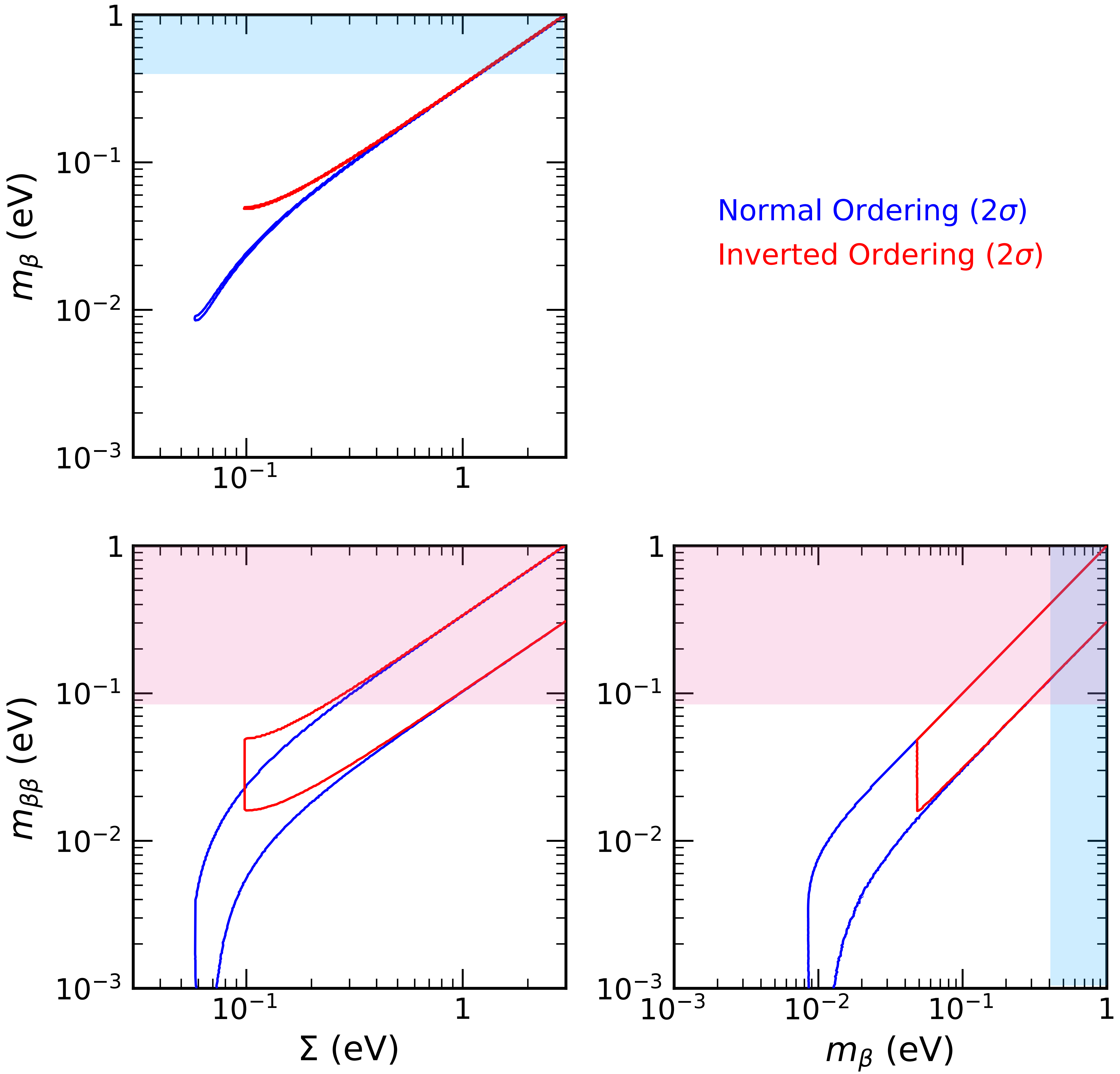
In principle can be measured if NME under control



Normal Ordering (2σ)
Inverted Ordering (2σ)
m_β (eV)
$m_{\beta\beta}$ (eV)
Σ (eV)
m_β (eV)
1
10^{-1}
10^{-2}
10^{-3}



β decay - KATRIN



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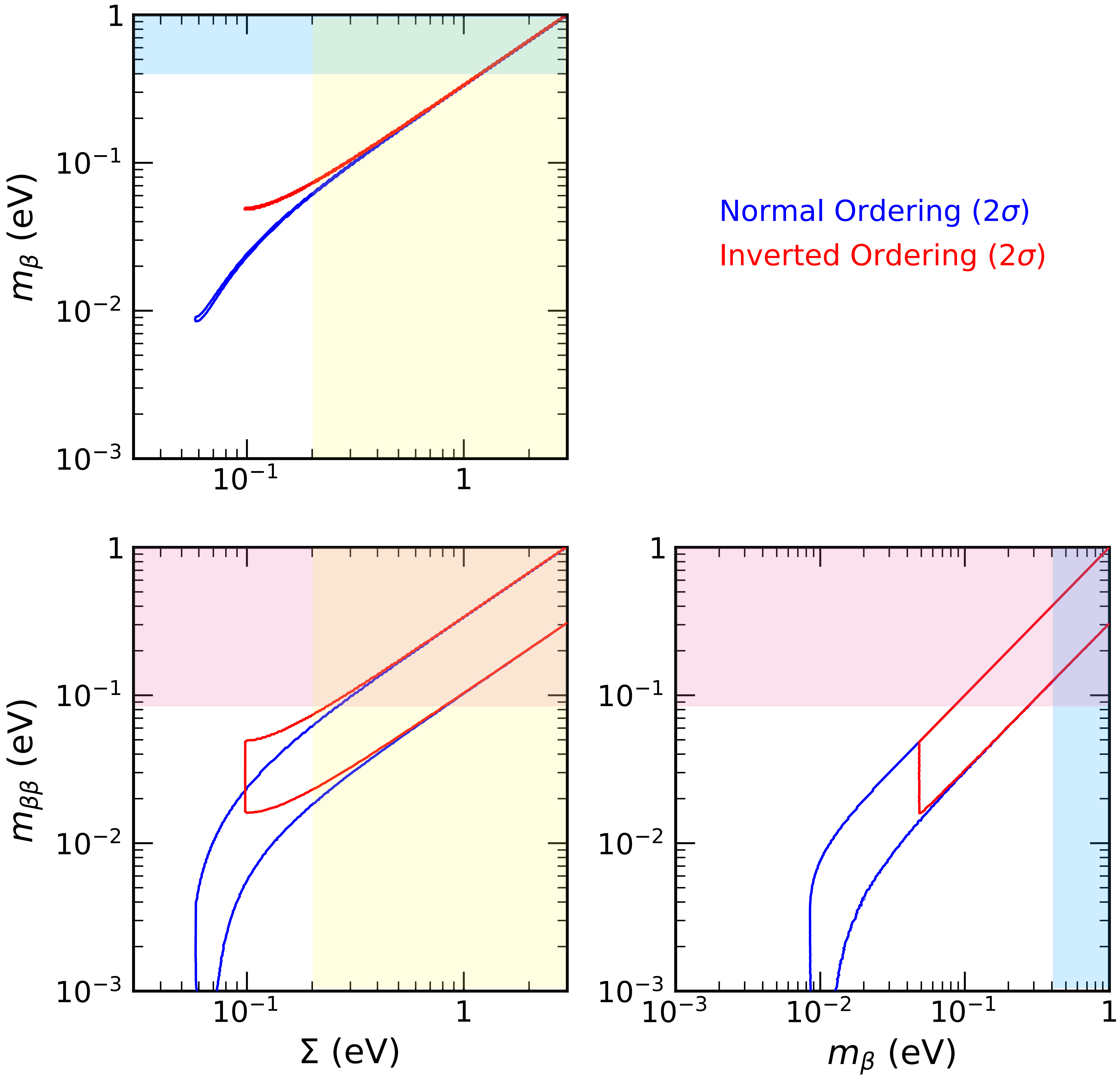
$0\nu\beta\beta$ decay

KamLAND-Zen, EXO, CUORE, GERDA



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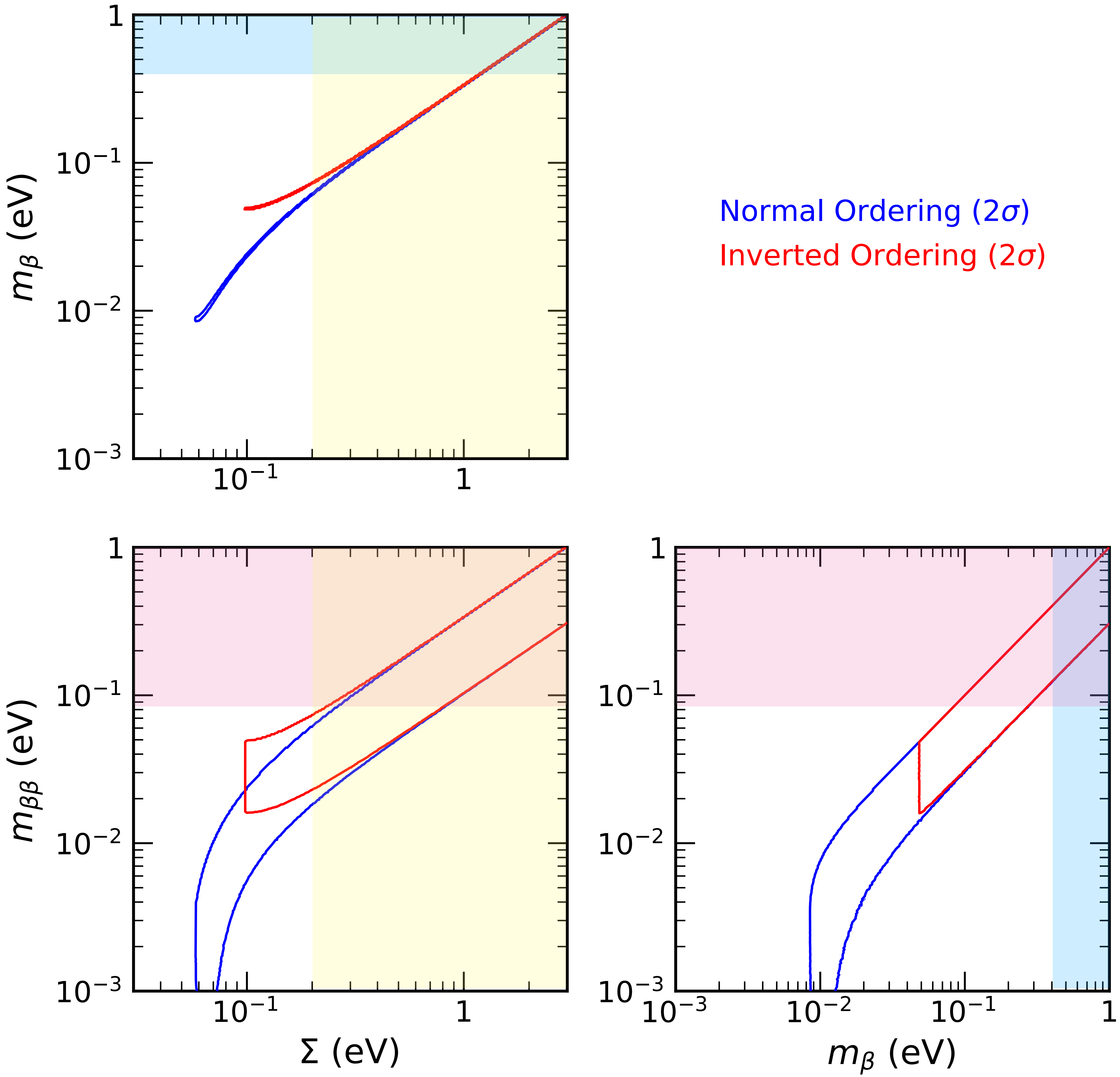
KamLAND-Zen, EXO, CUORE, GERDA

Astrophysics and Cosmology

CMB, BAO, lensing, …



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10^{-1}
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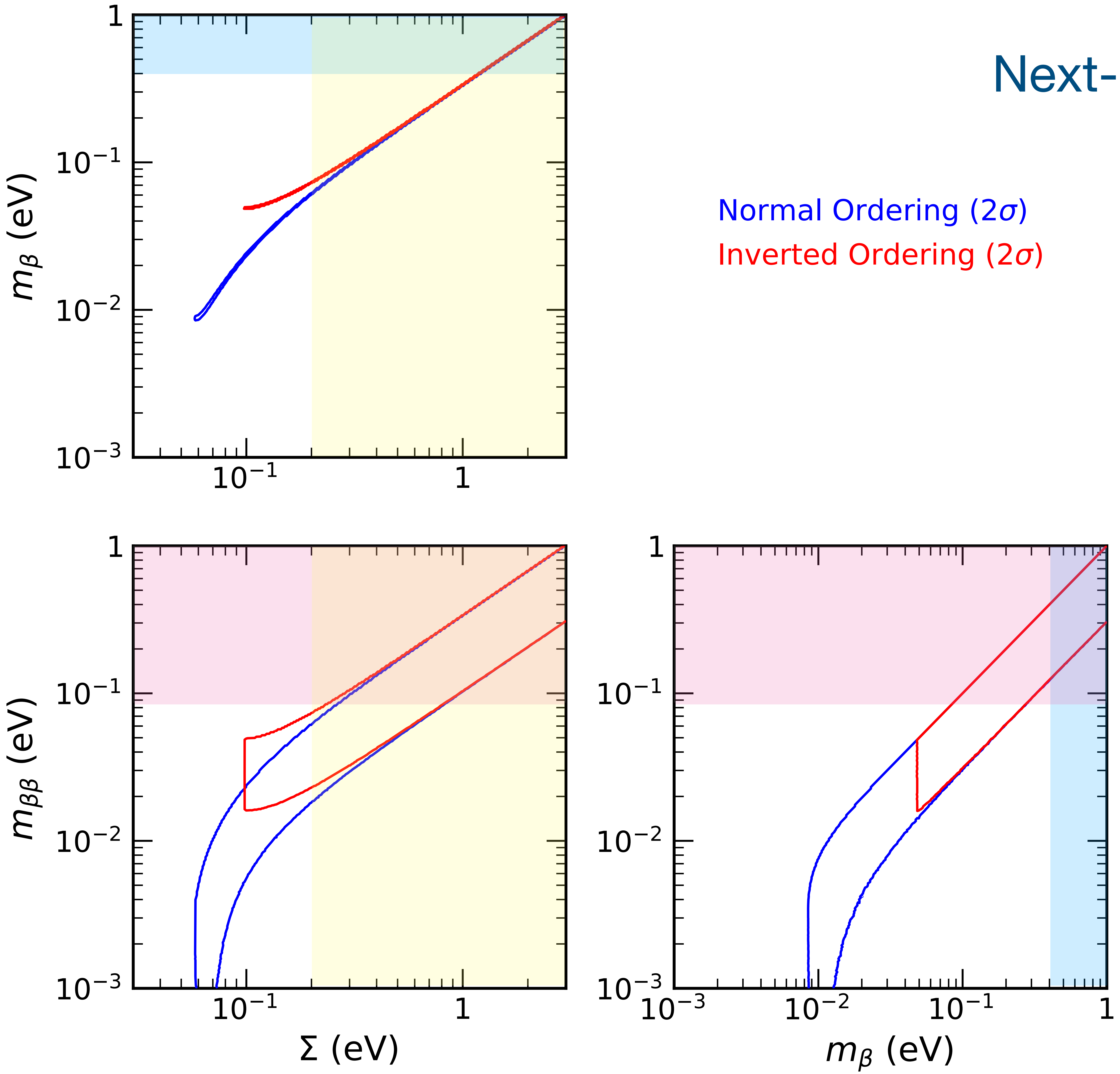
Next-generation Projects ($\gtrsim$10 years)



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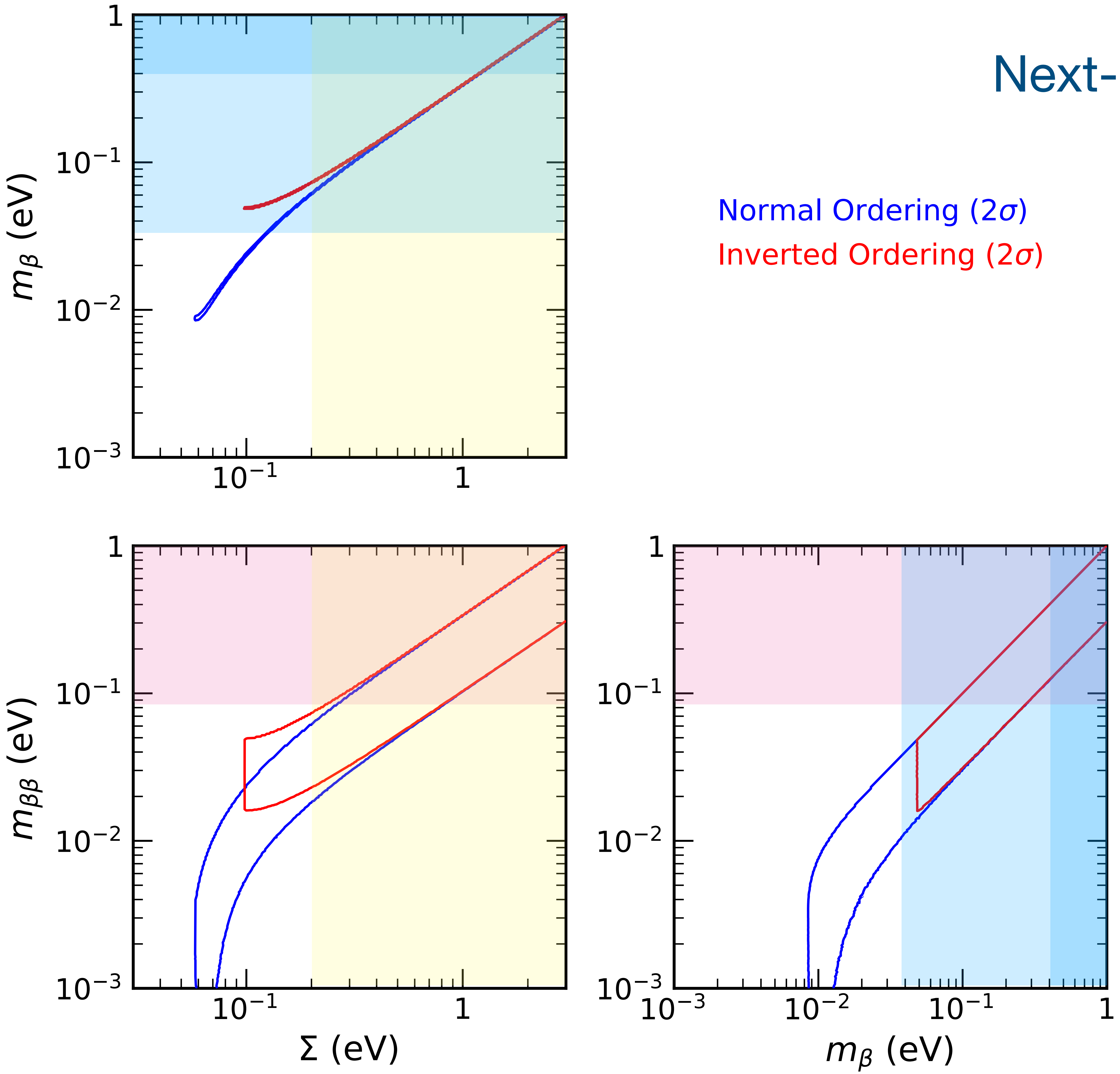

β decay - Project-8, …

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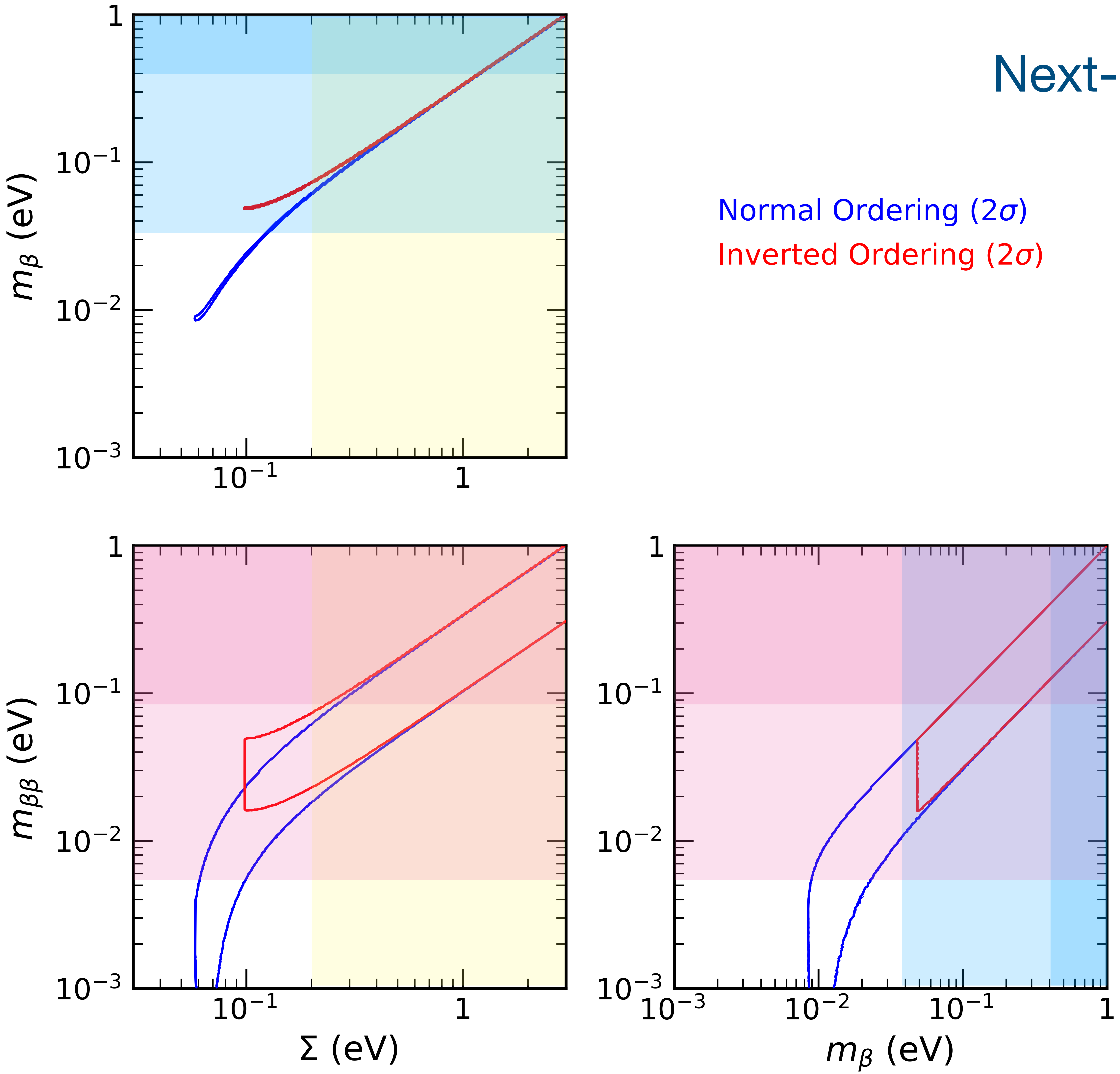

Normal Ordering (2σ)

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β decay - Project-8, …

$0\nu\beta\beta$ decay

LEGEND, NEXO, CUPID, …

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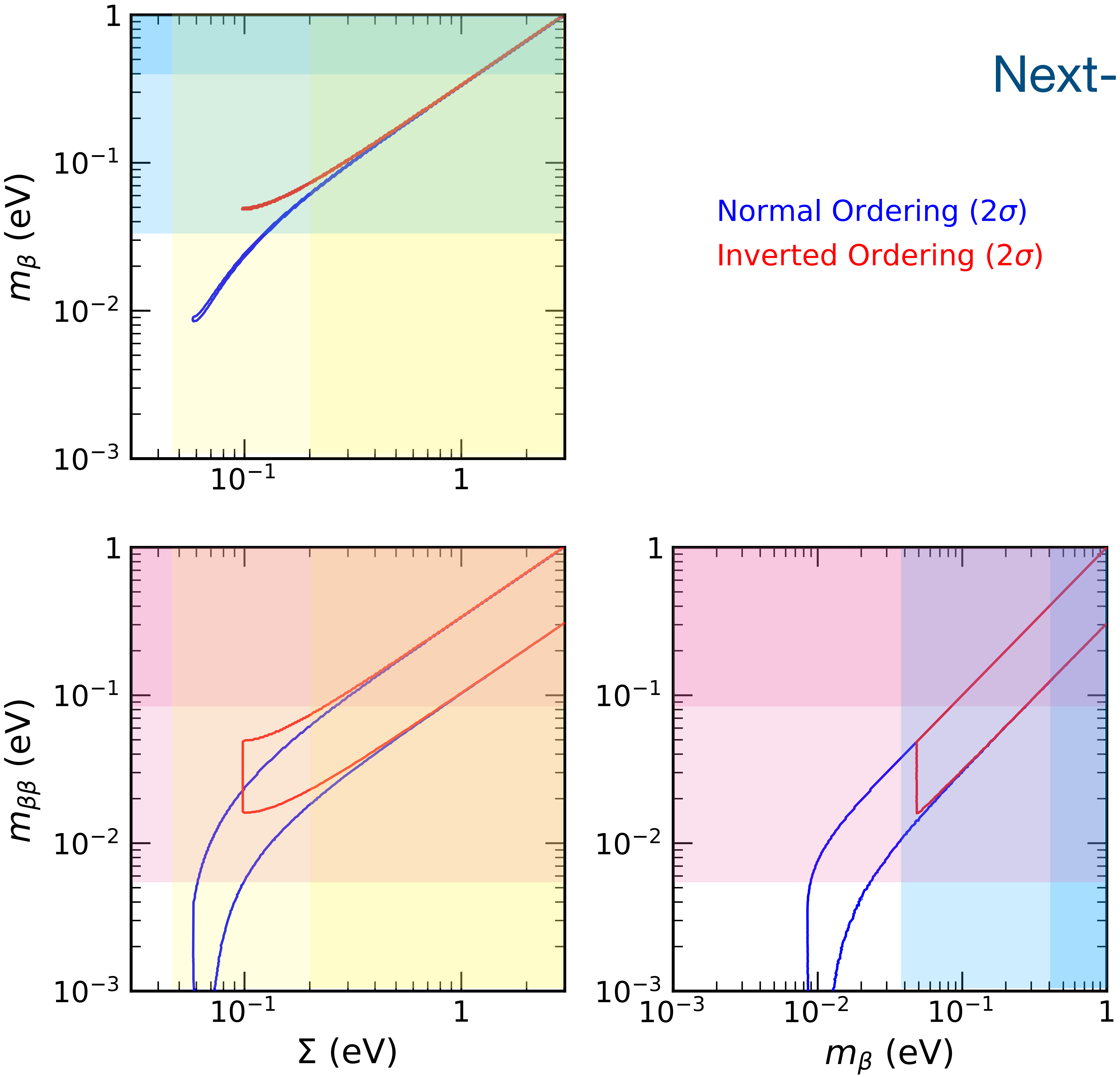

Normal Ordering (2σ)
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$0\nu\beta\beta$ decay
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Astrophysics and Cosmology
EUCLID, …

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Synergy across $|\Delta m^2|$ determinations from reactor, accelerator, and atmospheric data: measurements converge in the true ordering and separate in the wrong one

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Synergy across $|\Delta m^2|$ determinations from reactor, accelerator, and atmospheric data: measurements converge in the true ordering and separate in the wrong one

In particular, JUNO will be sensitive to

$$\Delta m^2_{ee} = |\Delta m^2| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$$

NO: $\alpha = +1$ IO: $\alpha = -1$

Present knowledge about the two JUNO oscillation frequencies

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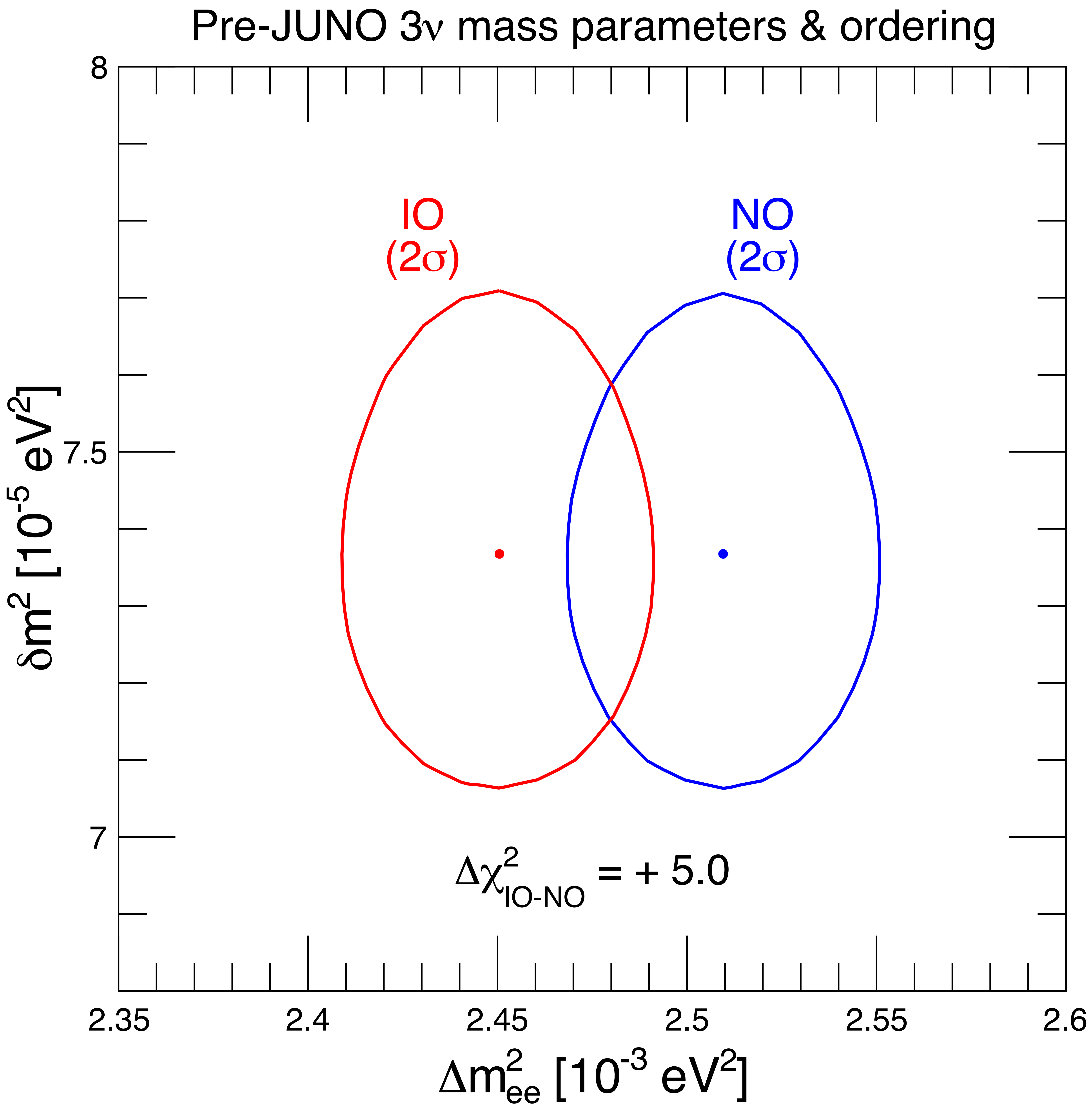
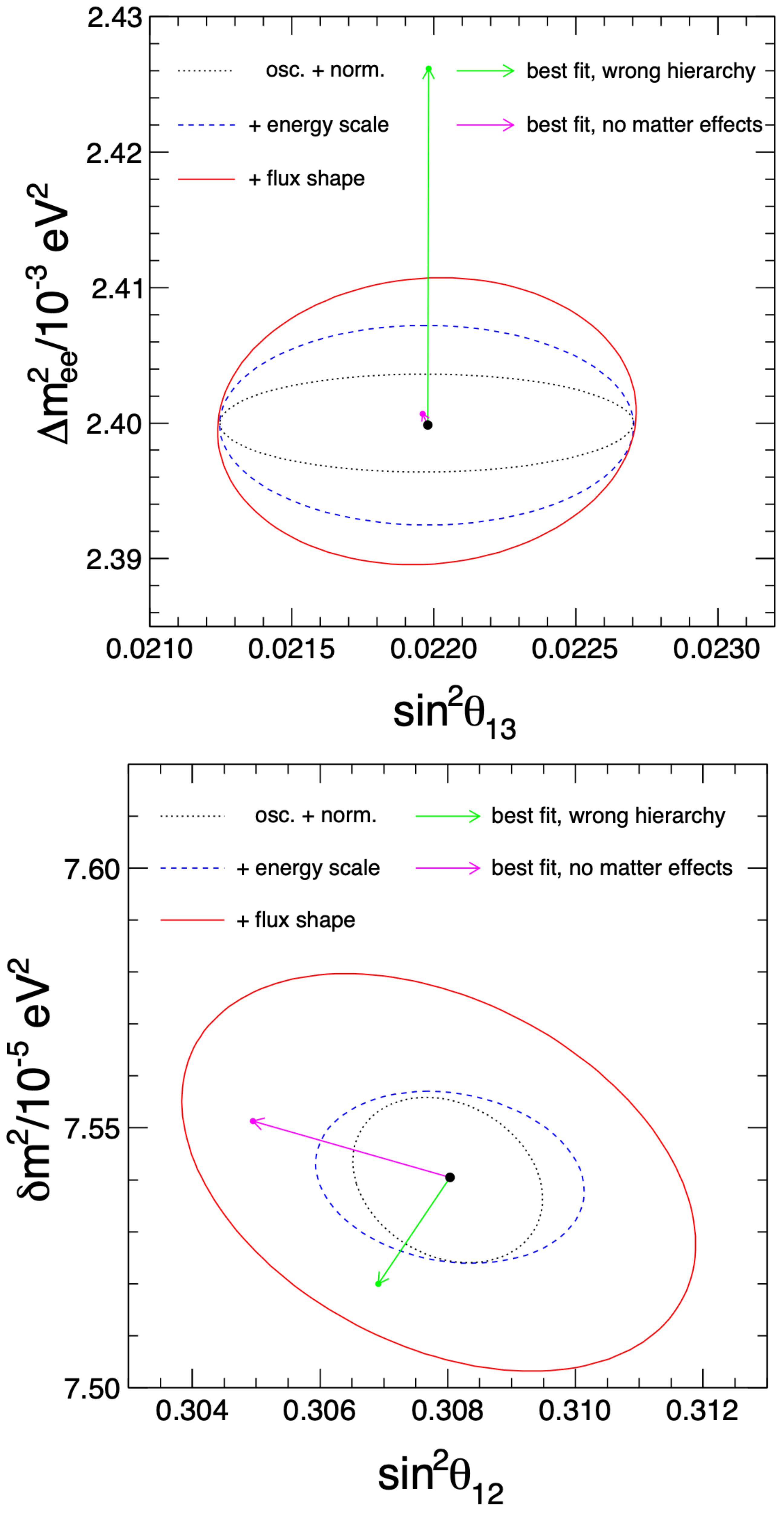


JUNO measurements will lead to slightly displaced best fits for the two frequencies in NO and IO

Phys.Rev.D 92 (2015) 9, 093011



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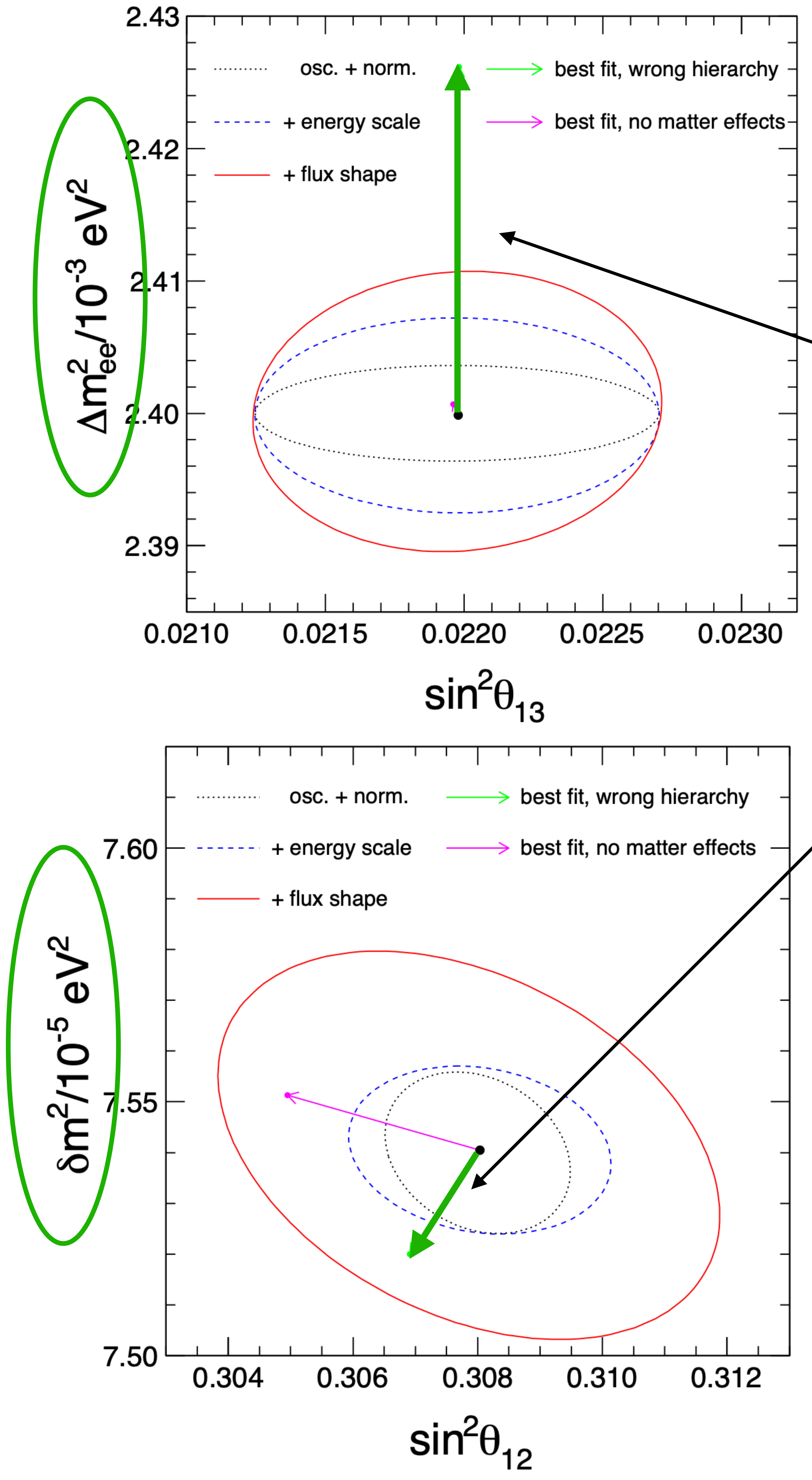

Green arrows: shifts of best fits when passing from NO to IO assumption

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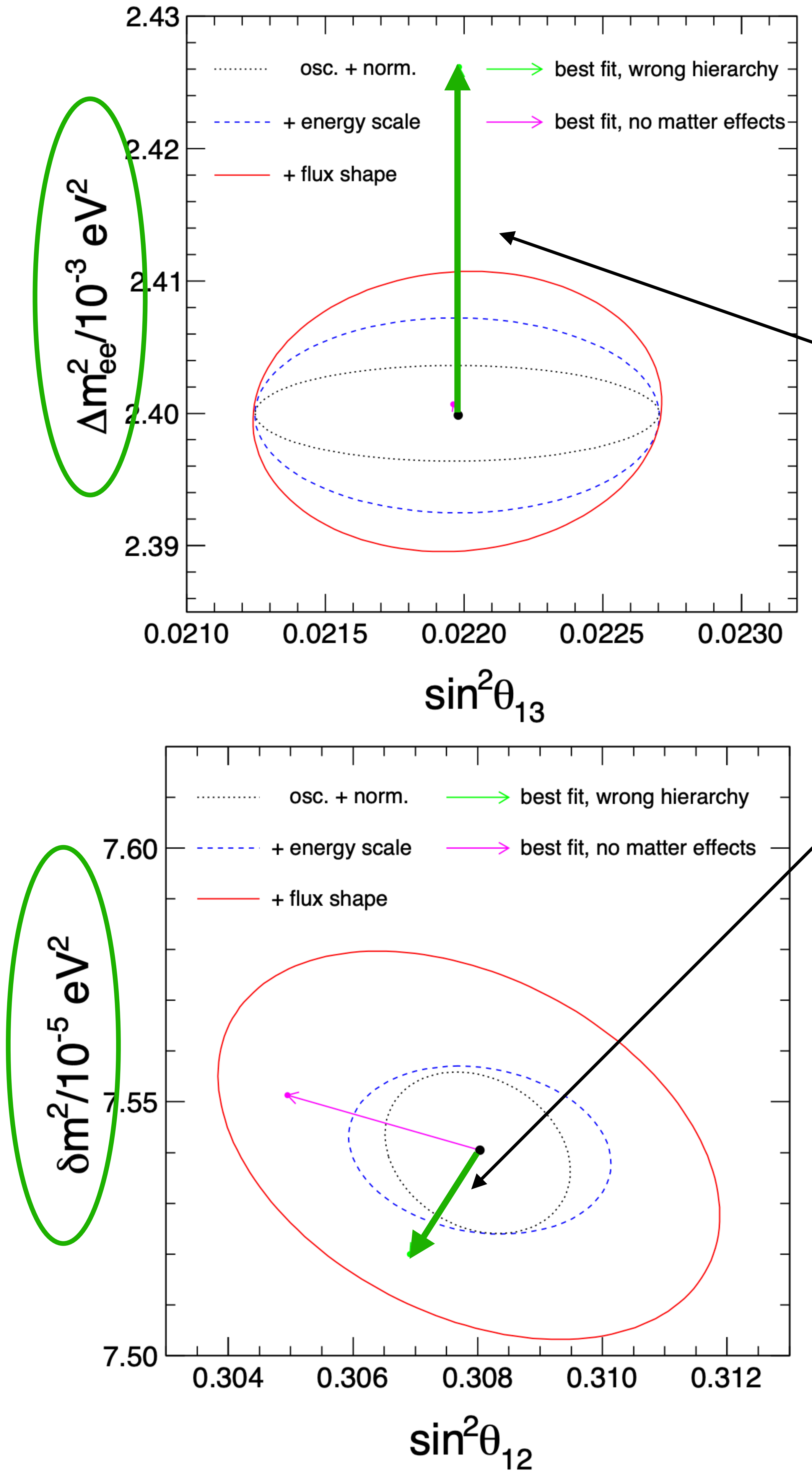
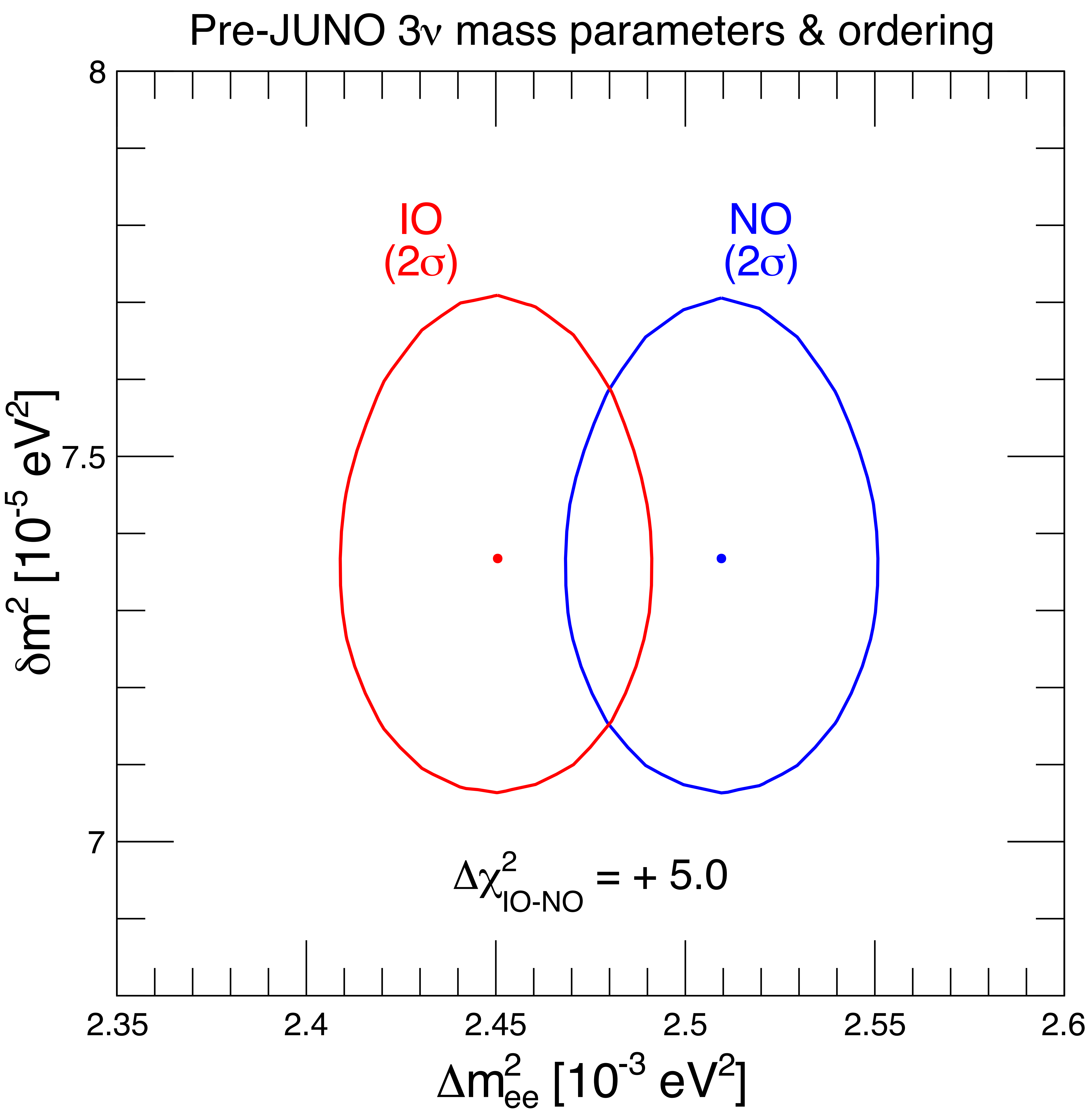


Green arrows: shifts of best fits when passing from NO to IO assumption

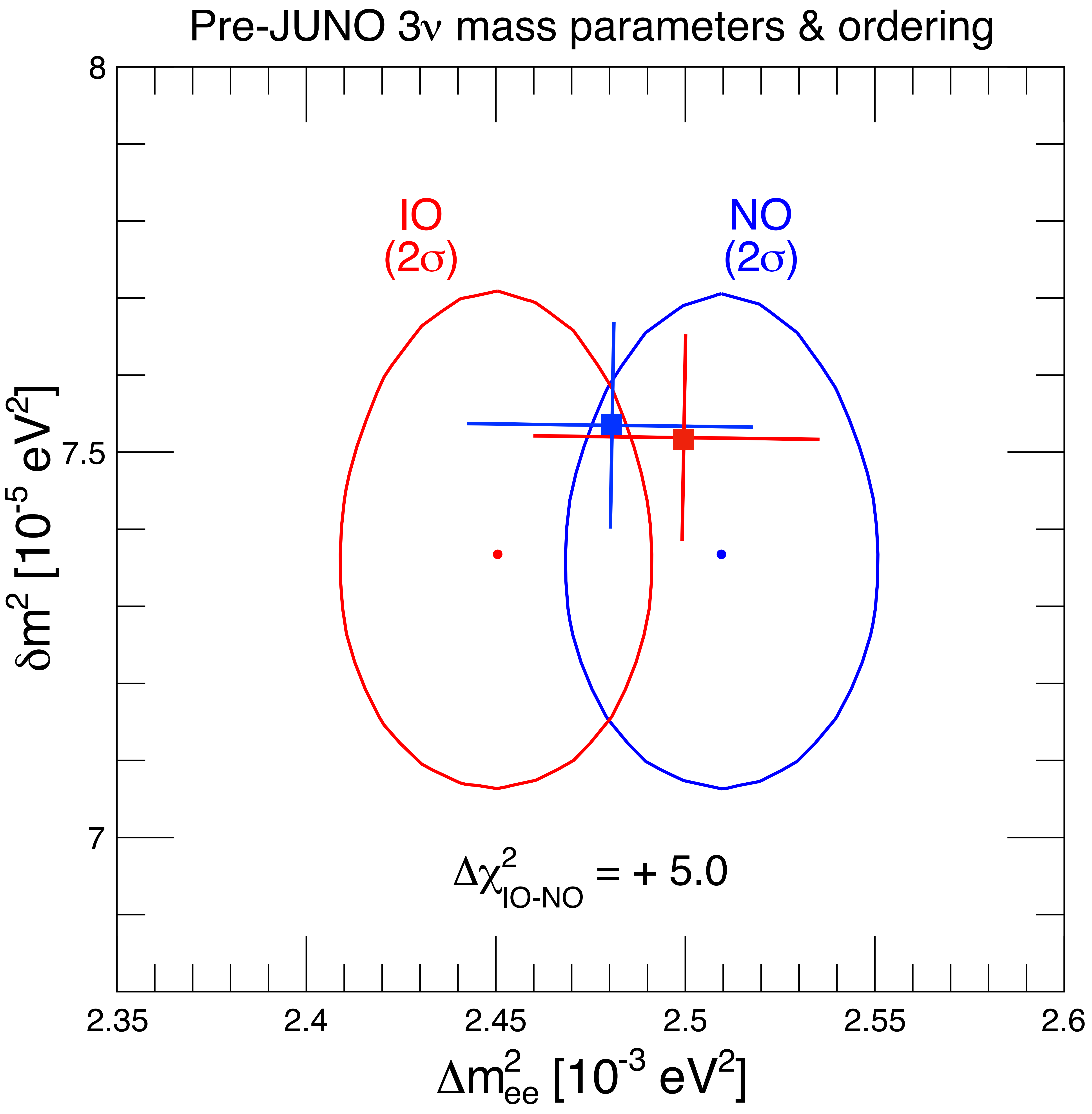
JUNO measurements will lead to slightly displaced best fits for the two frequencies in NO and IO

Shift of Δm^2 discussed in many papers (see Parke et al. for instance)
Specific values depend little on fit details.



Pre-JUNO 3ν mass parameters & ordering
IO
(2σ)
NO
(2σ)
$\Delta\chi^2_{IO-NO} = +5.0$
8
7.5
7
2.35
2.4
2.45
2.5
2.55
2.6
δm^2 [10^{-5} eV^2]
Δm^2_{ee} [10^{-3} eV^2]

Typical relative displacement between JUNO bestfit point in NO and IO



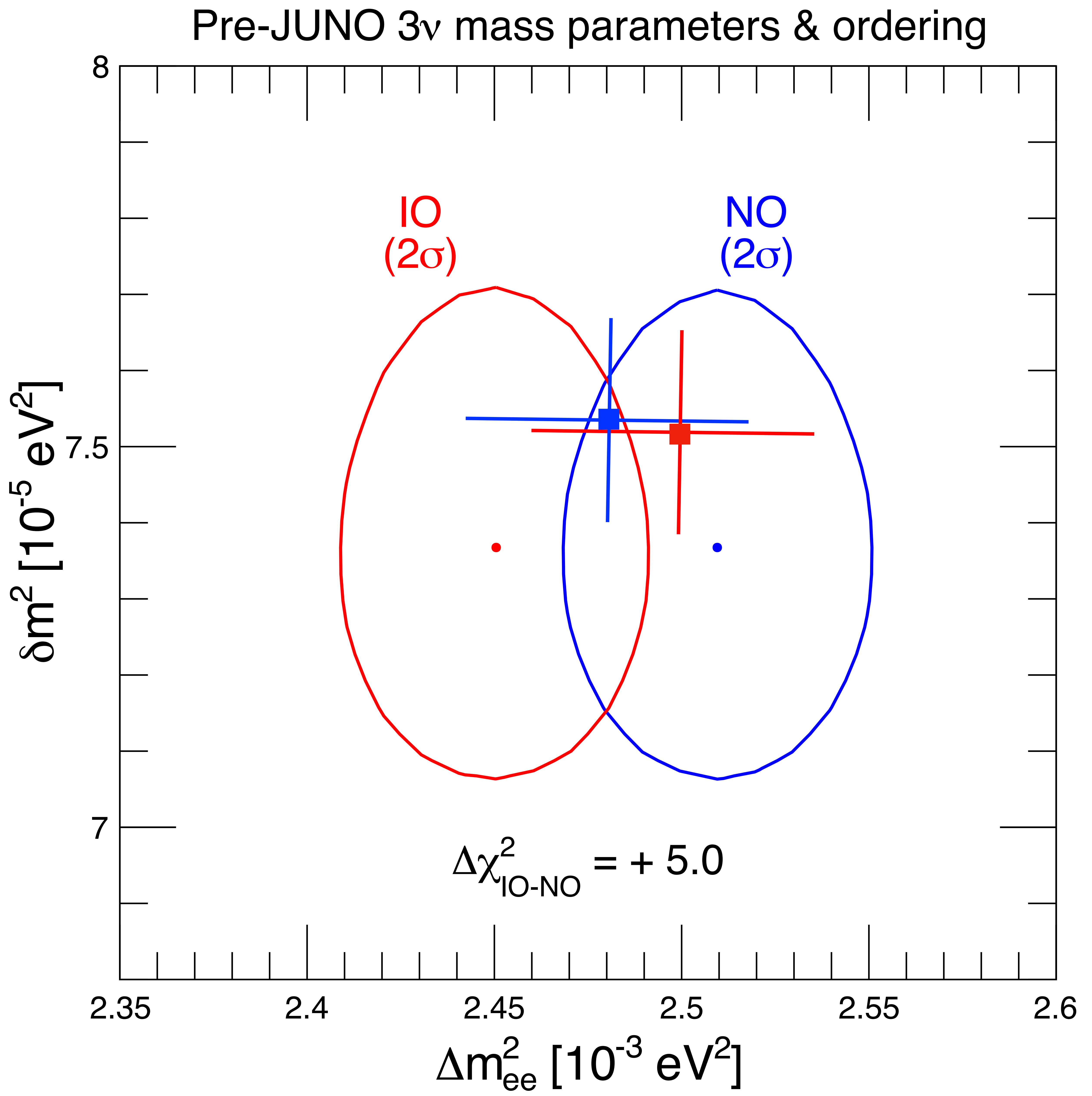
Typical relative displacement between JUNO bestfit point in NO and IO

$$\delta m^2 \ (2\sigma) \ \sim 0.15 \times 10^{-5} \text{ eV}^2$$

$$\Delta m^2_{ee} \ (2\sigma) \ \sim 0.04 \times 10^{-3} \text{ eV}^2$$

Sub-percent precision measurement of neutrino oscillation parameters with JUNO*

To cite this article: Angel Abusleme *et al* 2022 *Chinese Phys. C* **46** 123001



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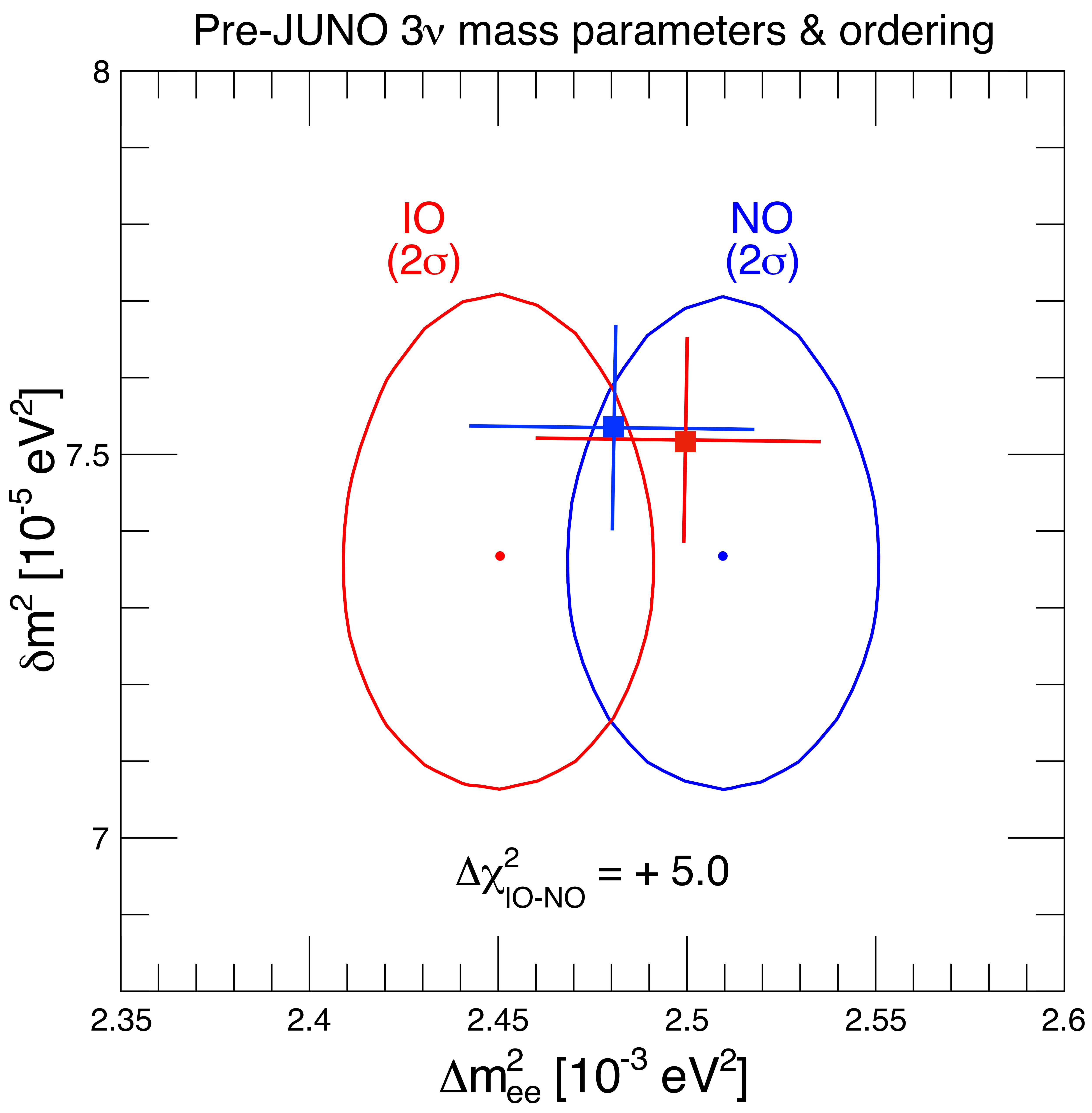
Relative shift between JUNO best-fit points is "opposite" to pre-JUNO best-fits → Adds to synergy



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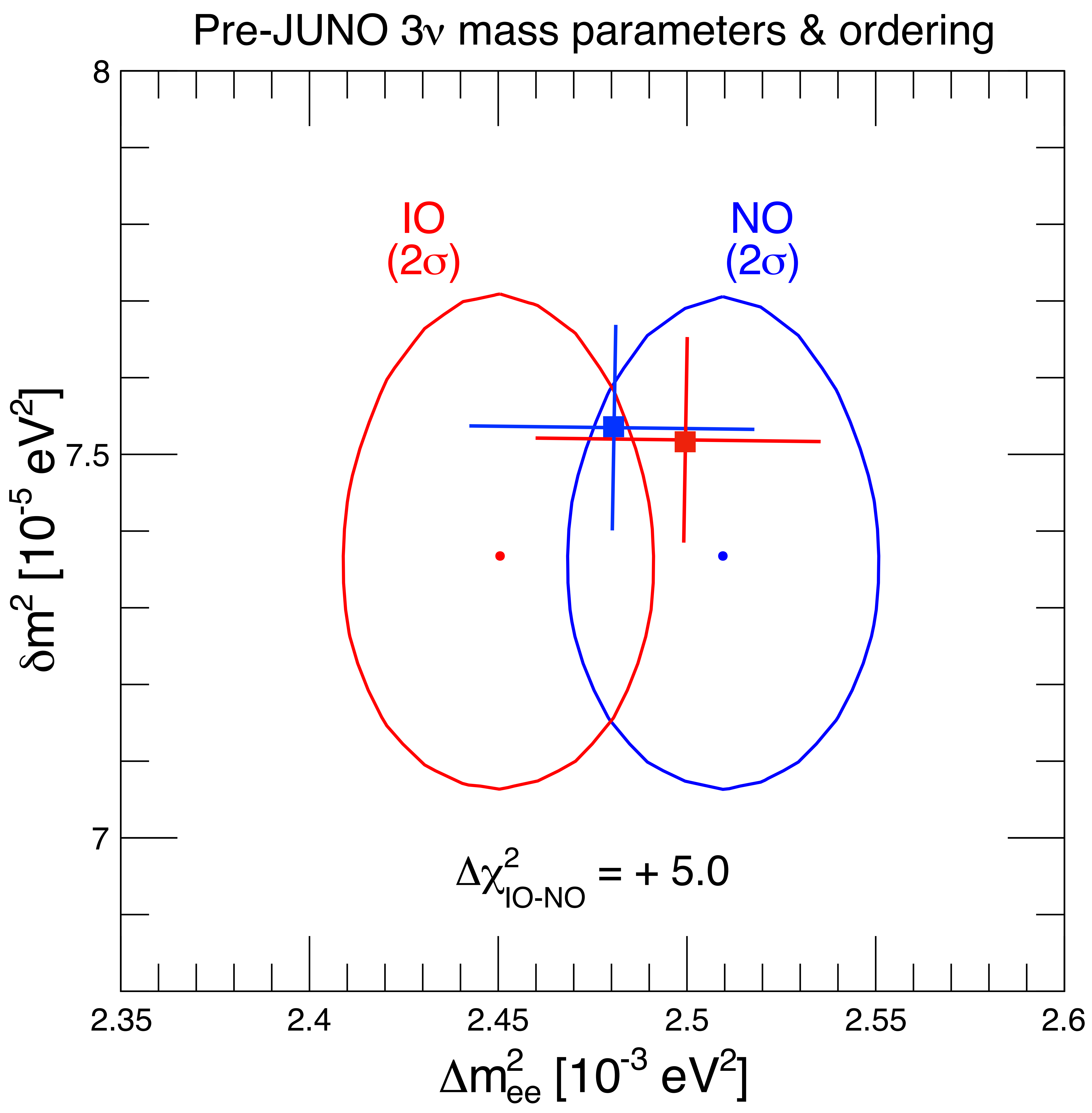
While statistical fluctuations can initially mask the distinction between NO and IO, with higher exposure the true difference is expected to become evident



Examples of possible JUNO first data compared with pre-JUNO data

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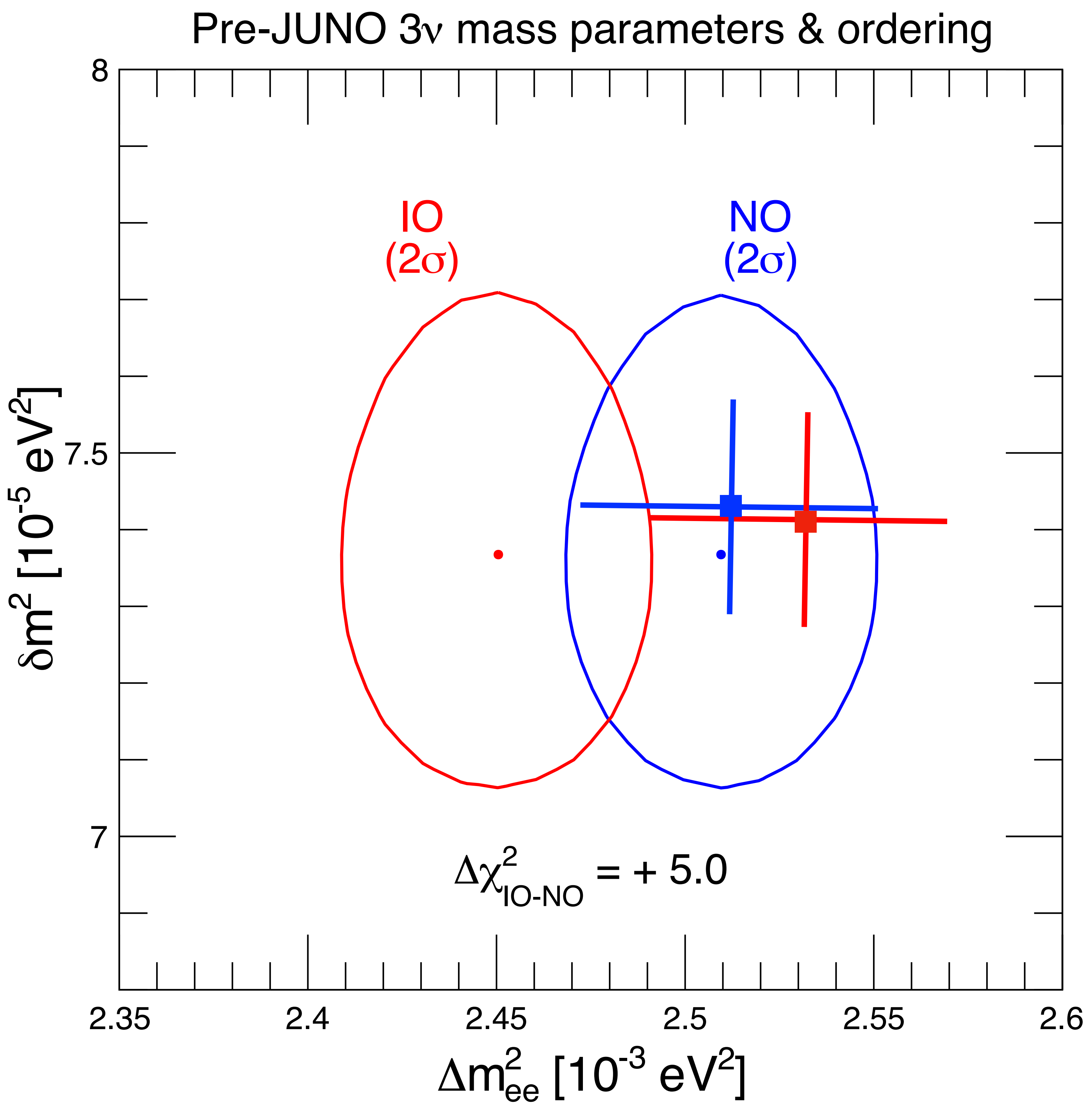
A synergy favoring NO



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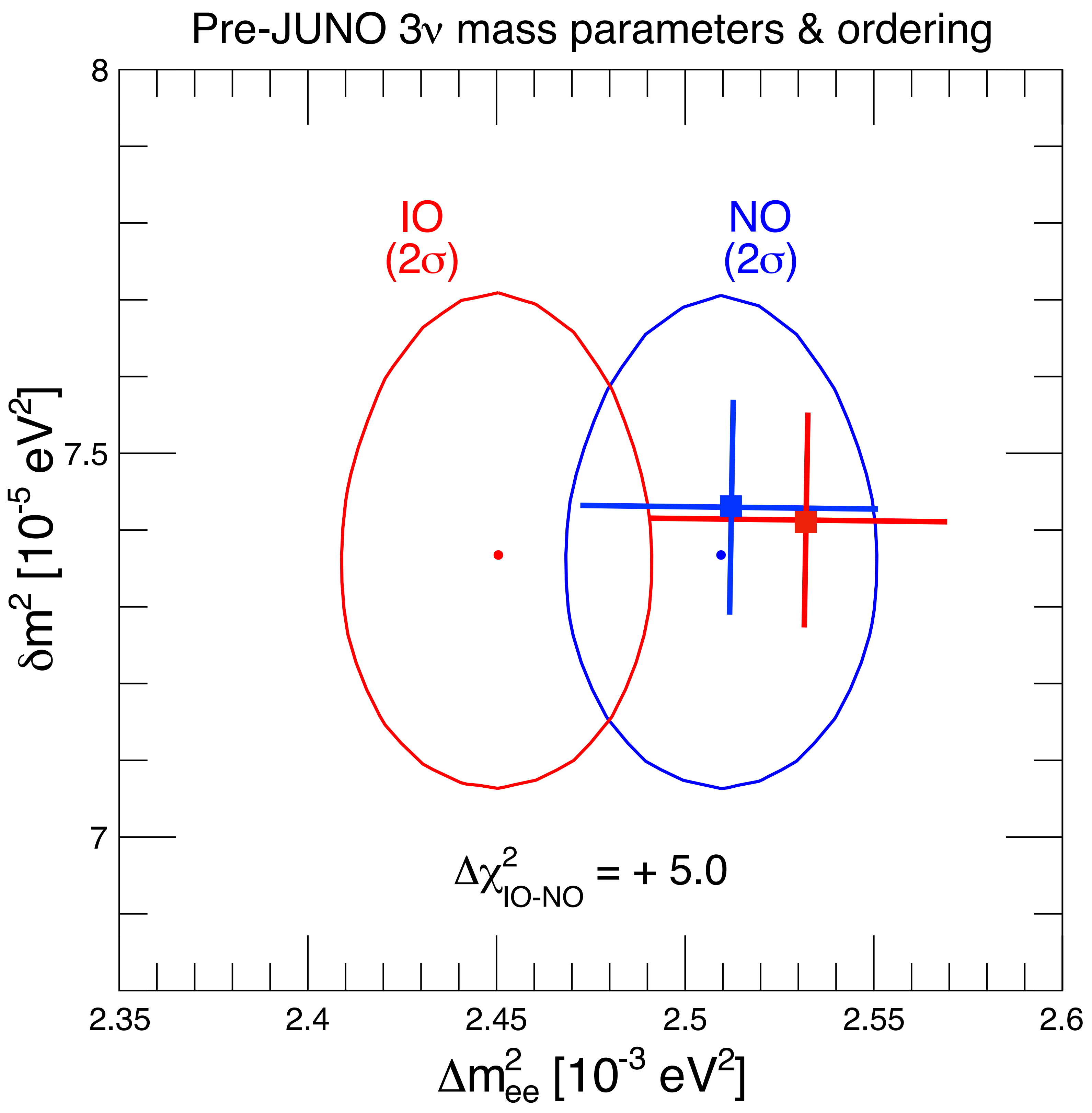
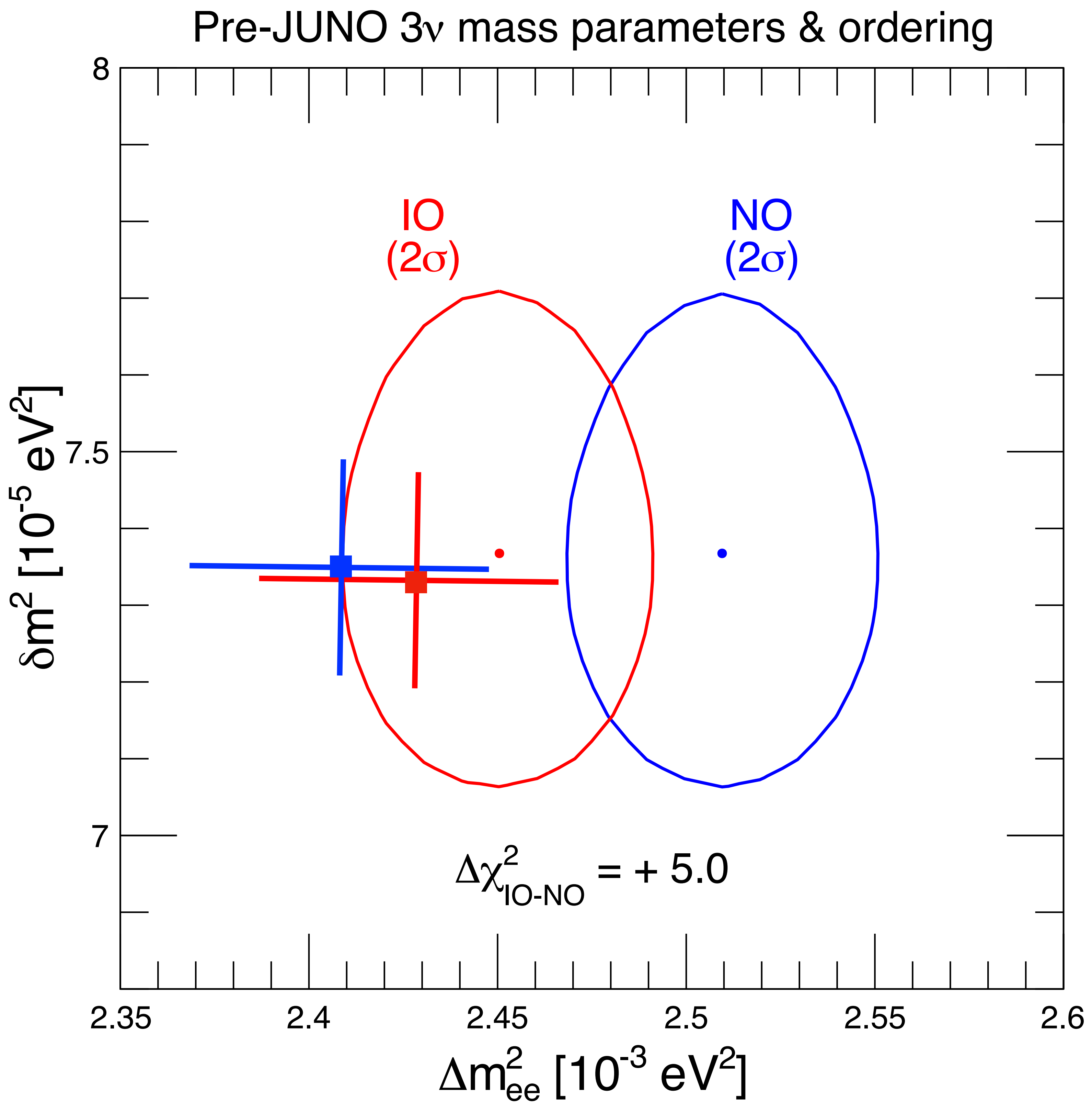


A synergy favoring IO



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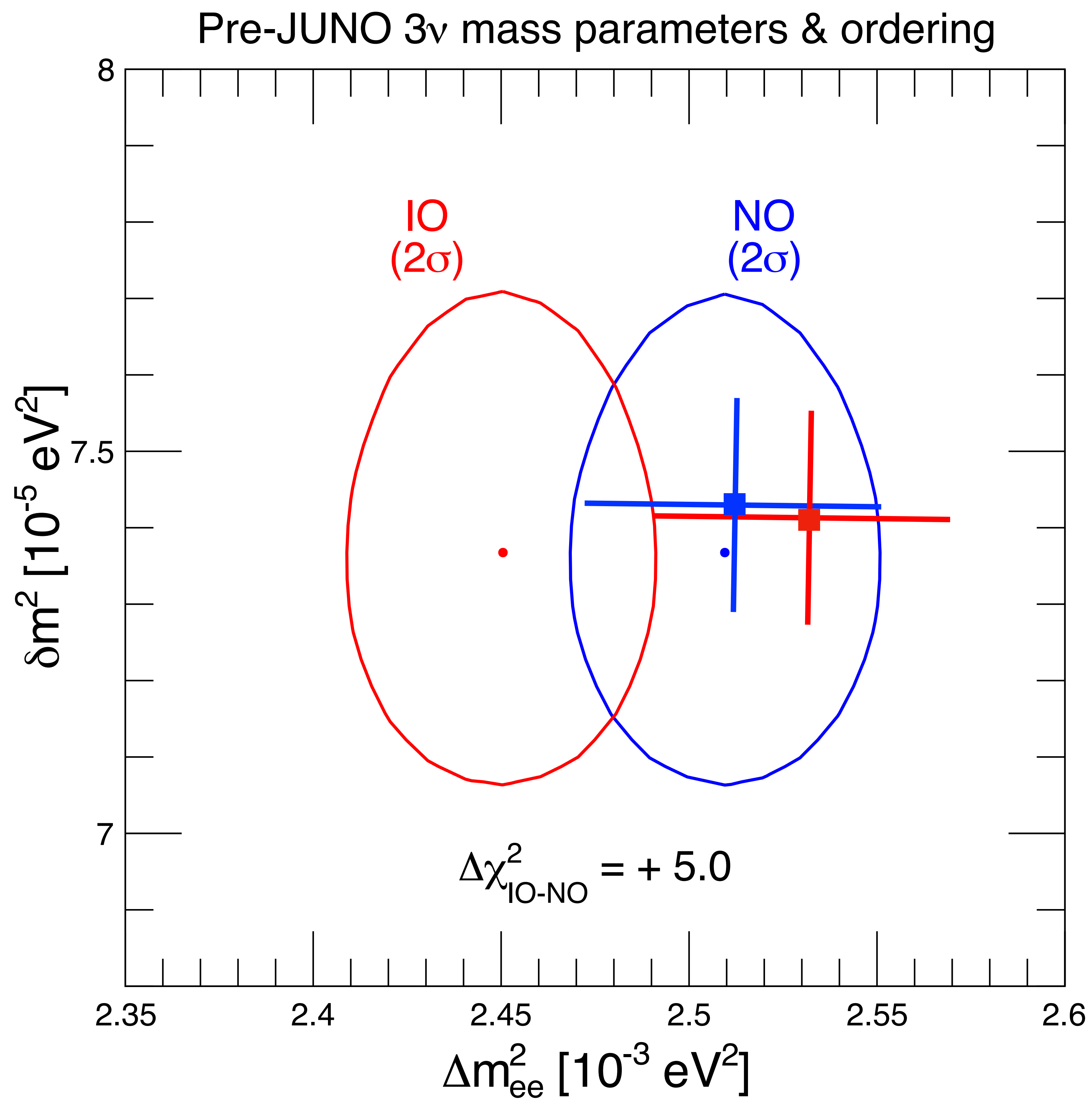
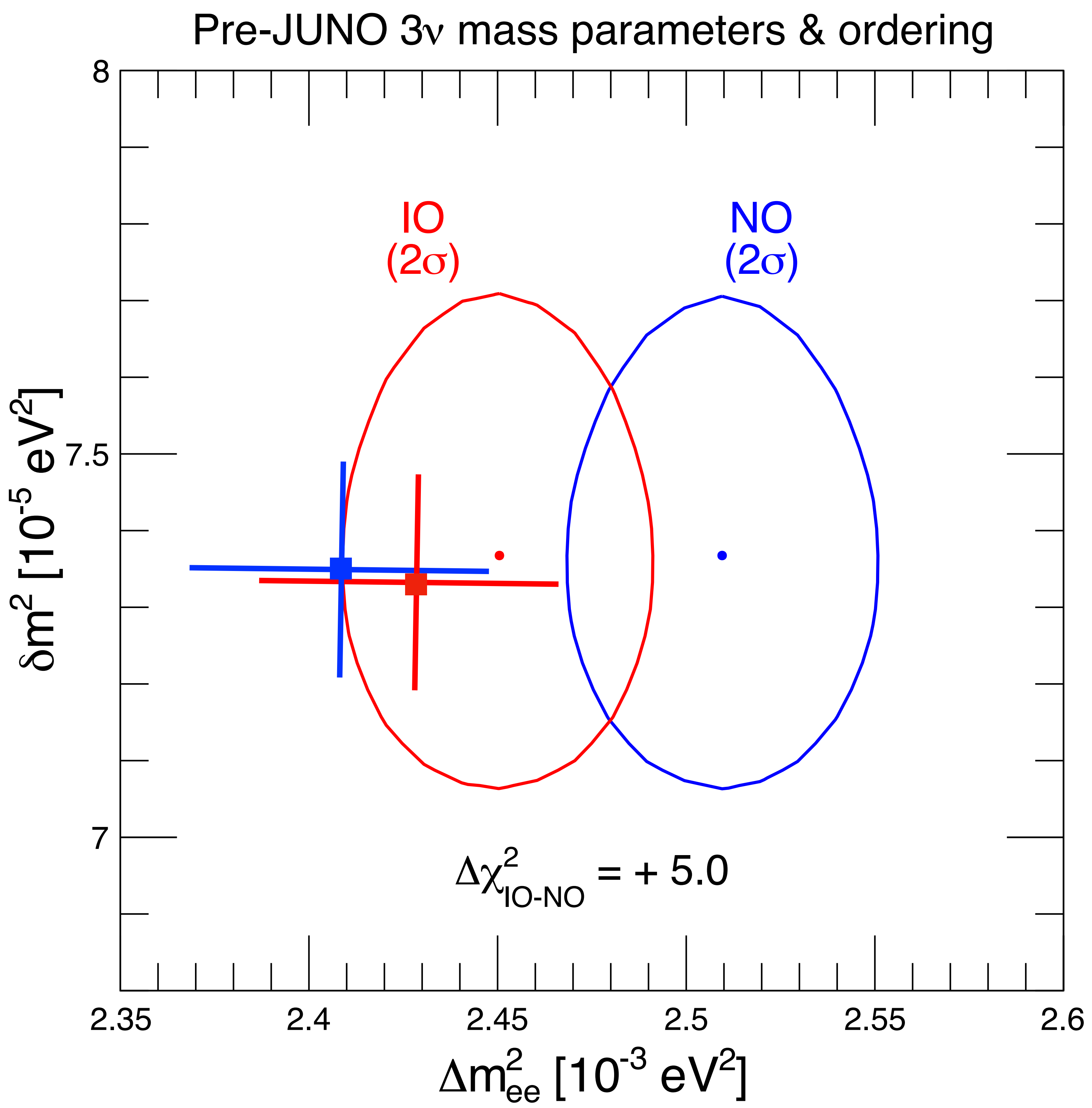
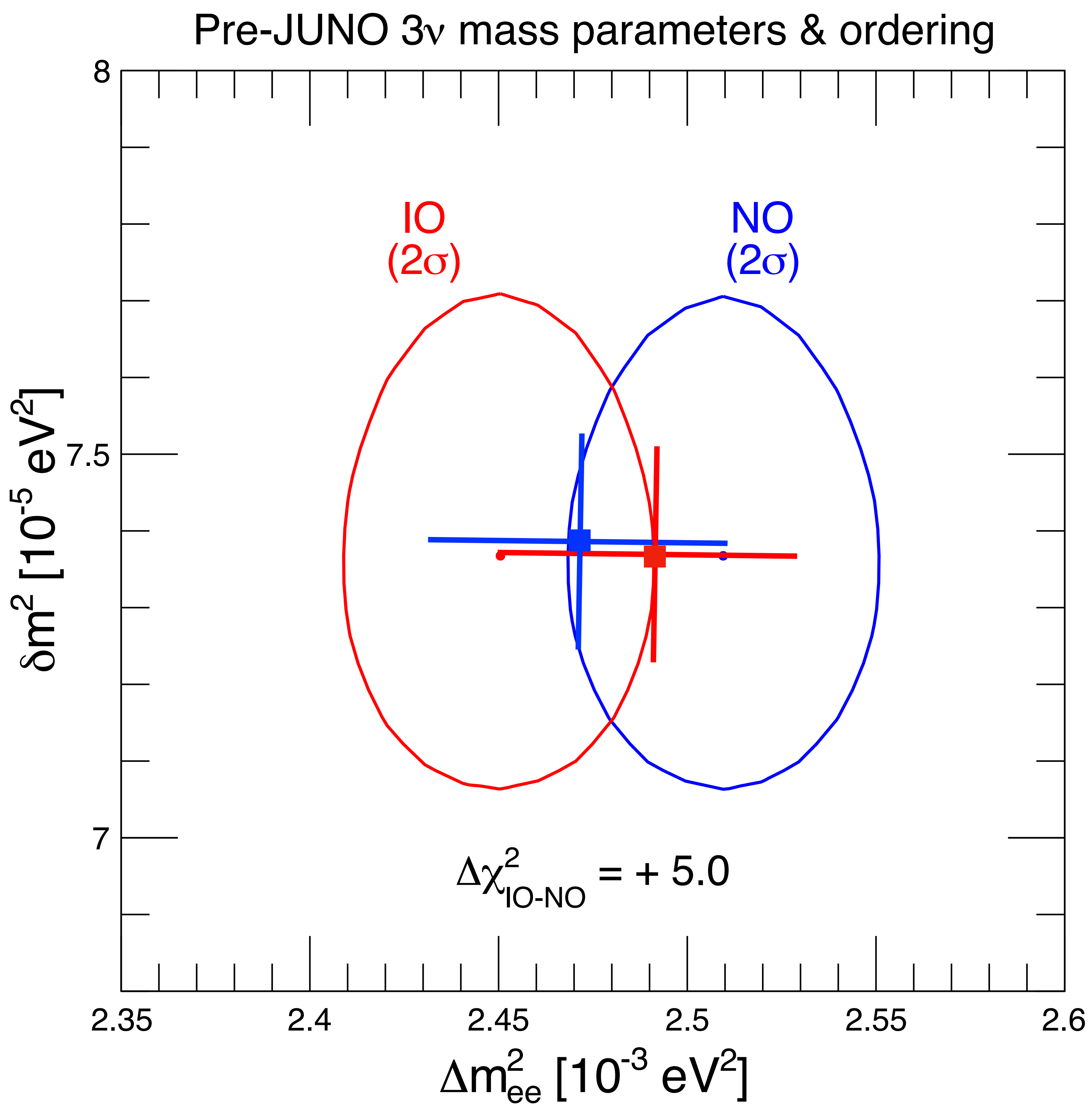


A synergy favoring IO



An undecided NO/IO



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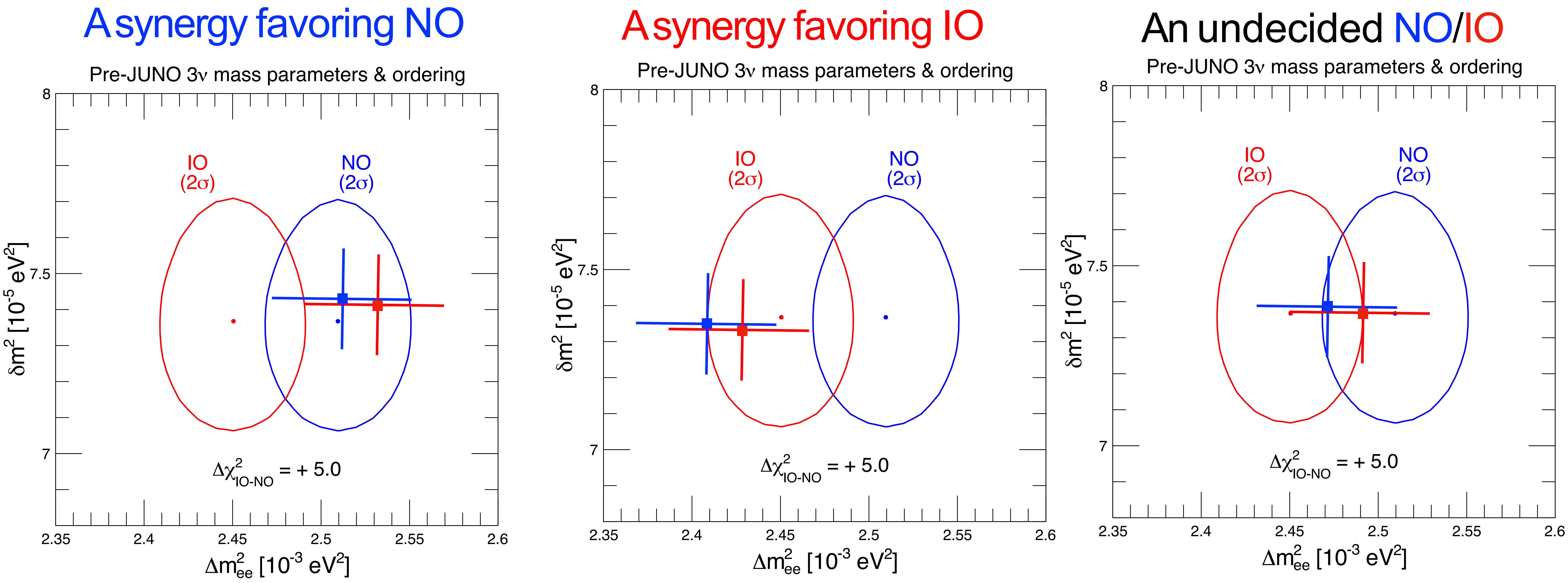
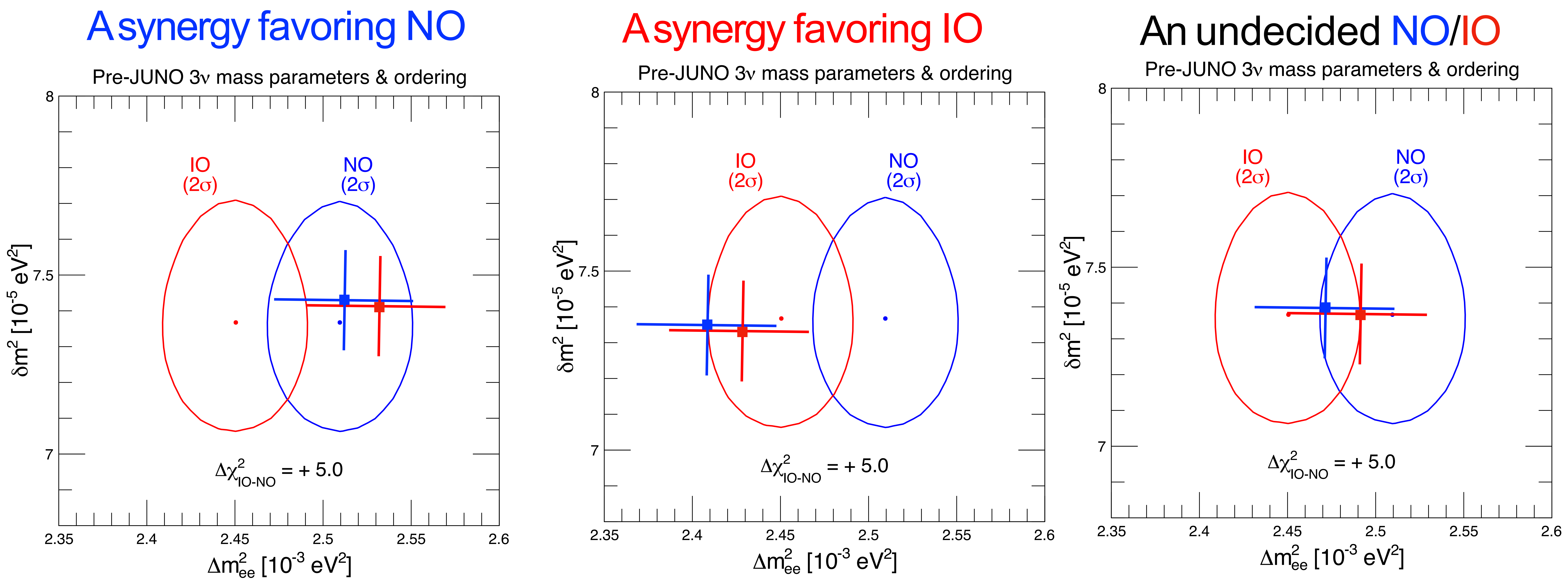


Global analyses helpful to understand correlated impact on other parameters

Examples of possible JUNO first data compared with pre-JUNO data

A synergy favoring NO · A synergy favoring IO · An undecided NO/IO



Global analyses helpful to understand correlated impact on other parameters

It will be instructive to locate the first JUNO data in this plane and eventually compare them with JUNO-alone NO/IO findings for convergence.

Summary and Perspectives

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Summary and Perspectives

- **Precision reached**

Percent accuracy on mixing angles and mass splittings - with $|\Delta m^2|$ at **subpercent accuracy (0.8%)**

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•Outlook

The 3ν framework is at a turning point: future synergies (or tensions) across oscillation, β-decay, 0νββ, cosmology will be decisive

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