Synthesizing Data: Global Fit (3-Neutrinos)

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Outline

- Neutrino oscillation parameters: knowns and unknowns
- Mass ordering from oscillation and non-oscillation data
- Combined analysis of oscillation and non-oscillation data
- Conclusions

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Based on
F. Capozzi, E. Di Valentino, E. Lisi, A.M., A. Melchiorri and A. Palazzo Phys.Rev. D95 (2017) no.9, 096014

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

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What we known

δm^2	2.3%
Δm^2	1.6%
$\sin^2\theta_{12}$	5.8%
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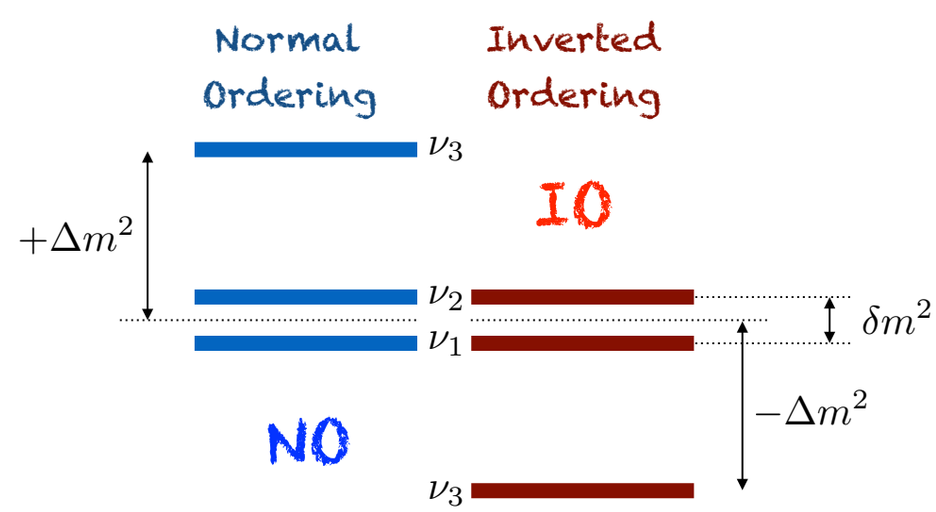
What we still do not know

CP-violating phase δ

Octant of θ_{23}

Mass Ordering → $\mathrm{sign}(\Delta m^2)$

$$\Delta m^2 = (\Delta m^2_{13} + \Delta m^2_{23})/2$$



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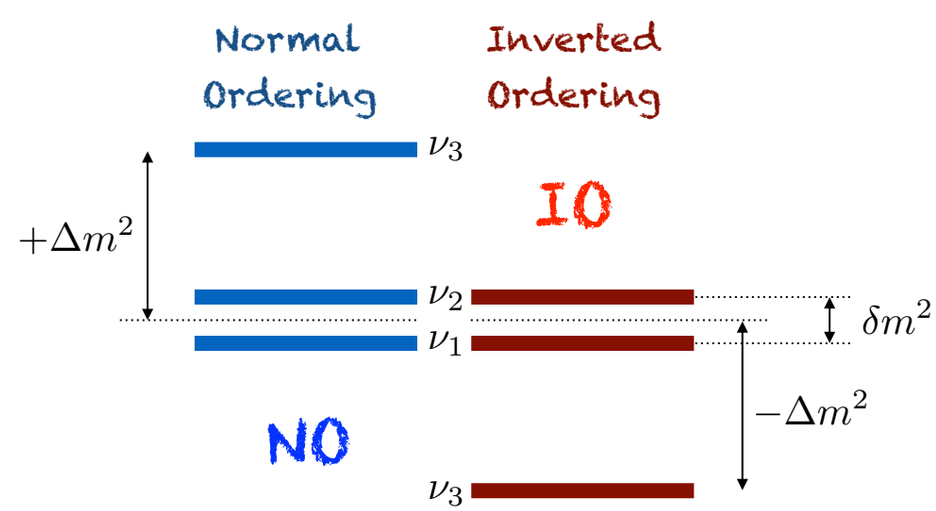

[We also don't know Dirac/Majorana neutrinos, Majorana phases, absolute mass scale]

Bounds on single oscillation parameters

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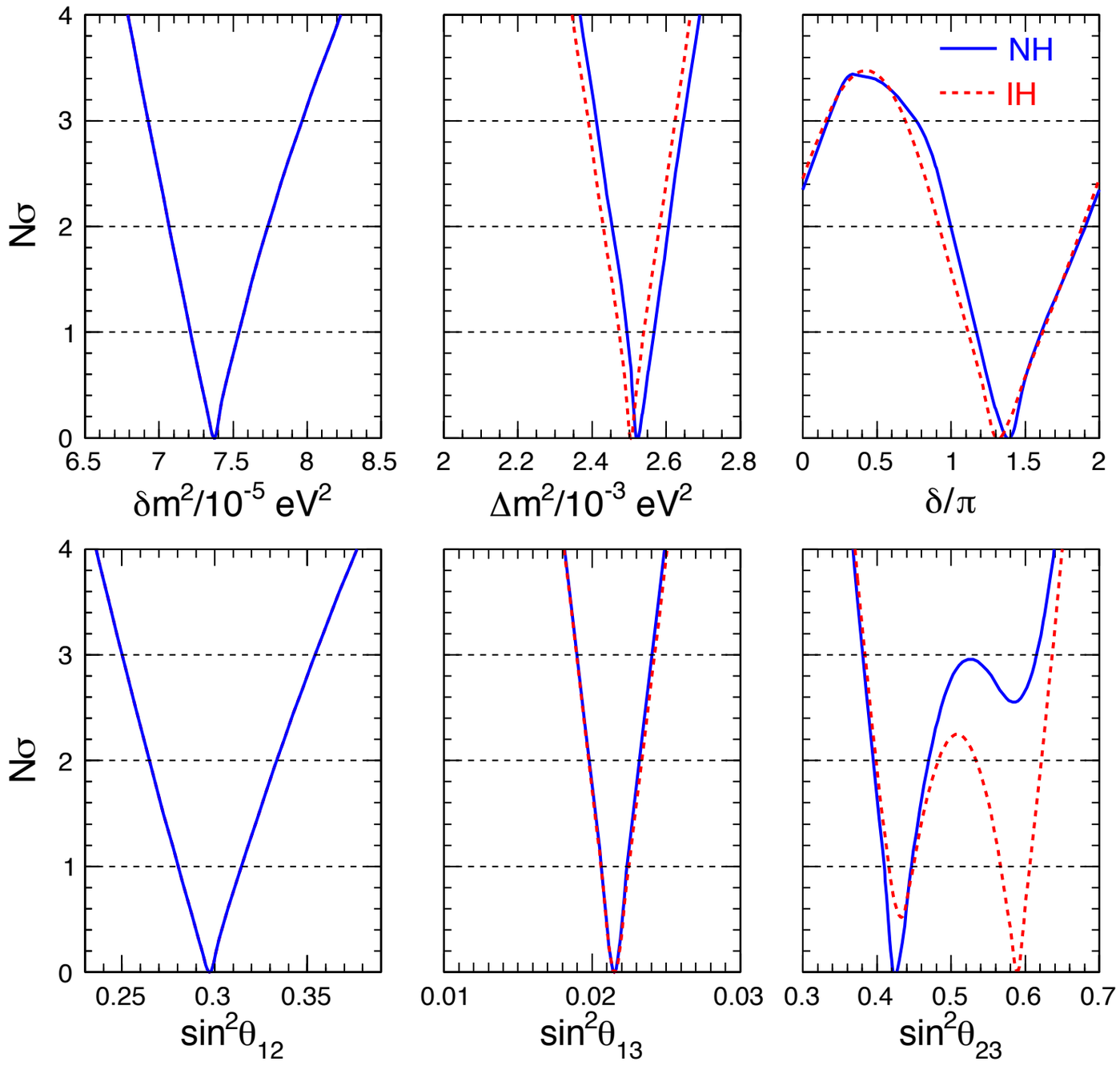

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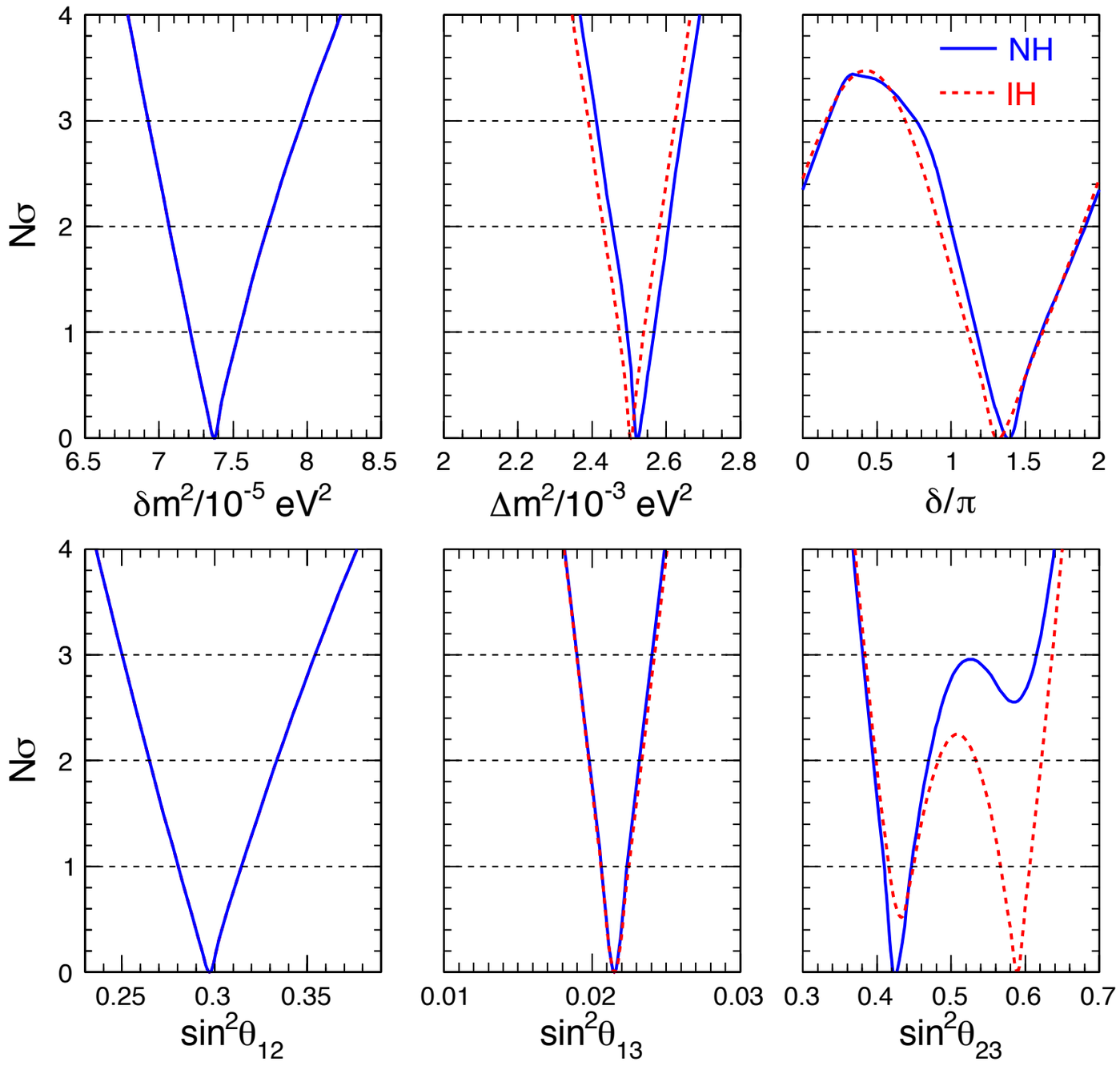

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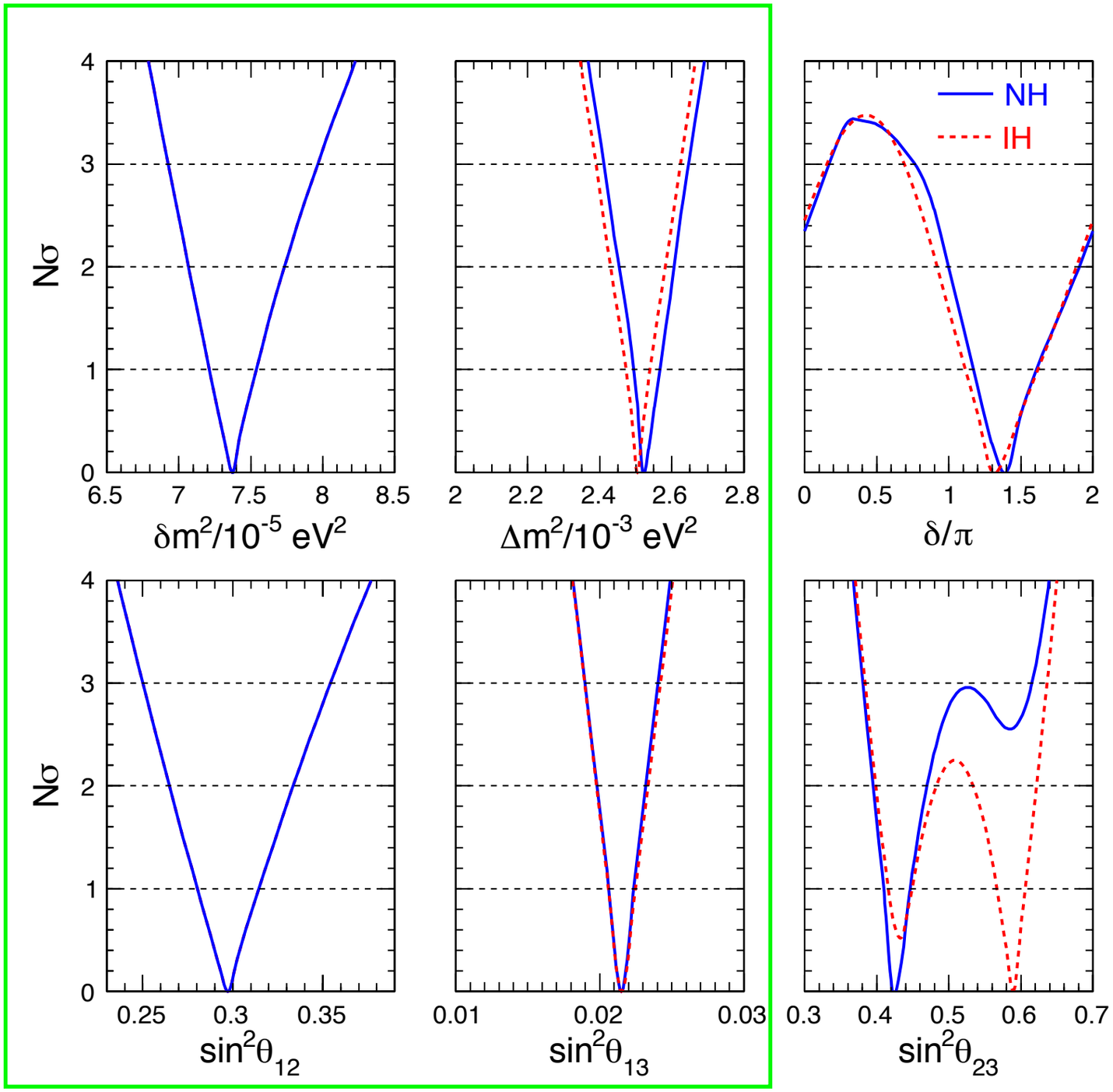

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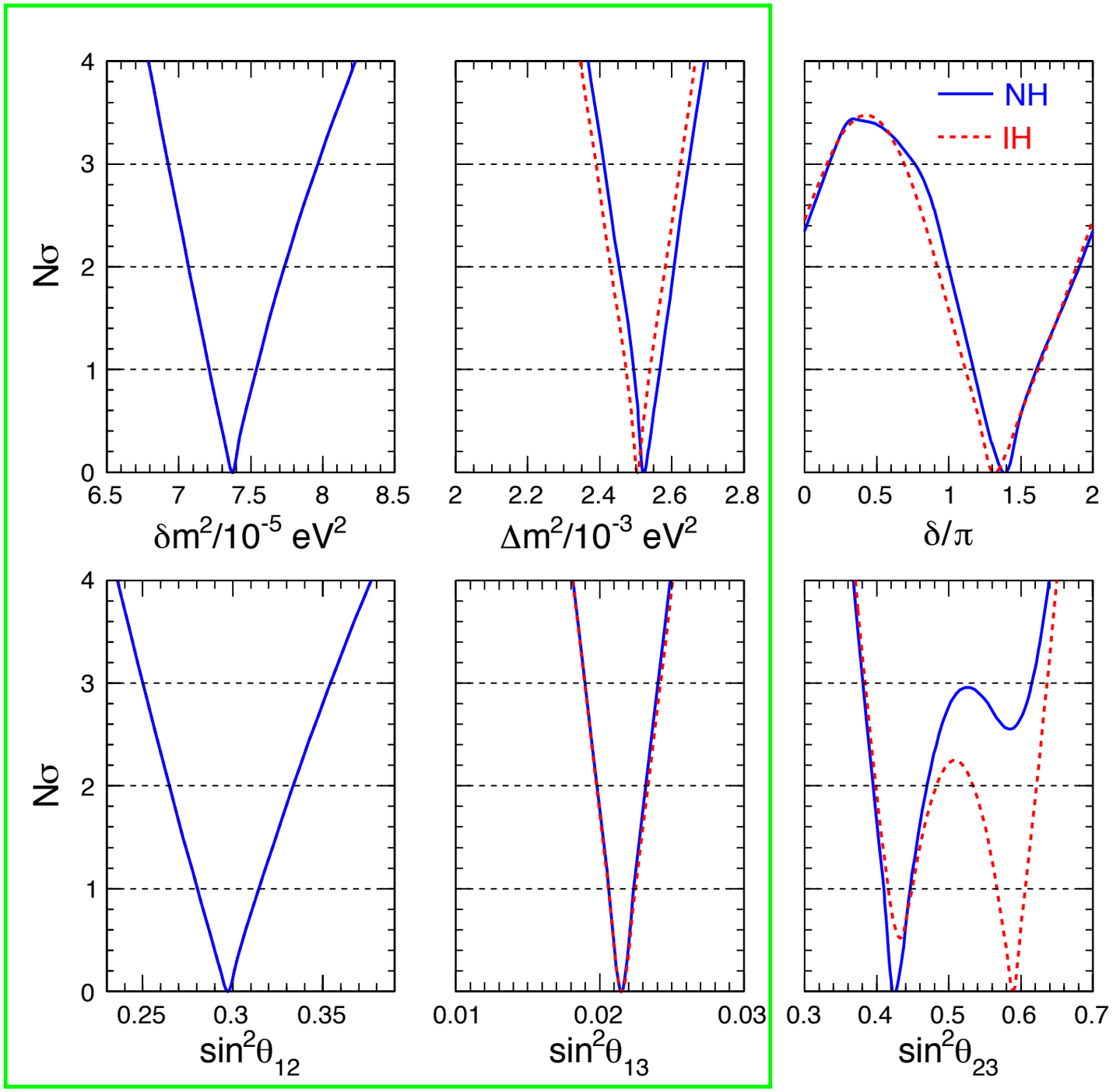

Squared mass differences and mixing angles have both lower & upper bounds at more than 3σ

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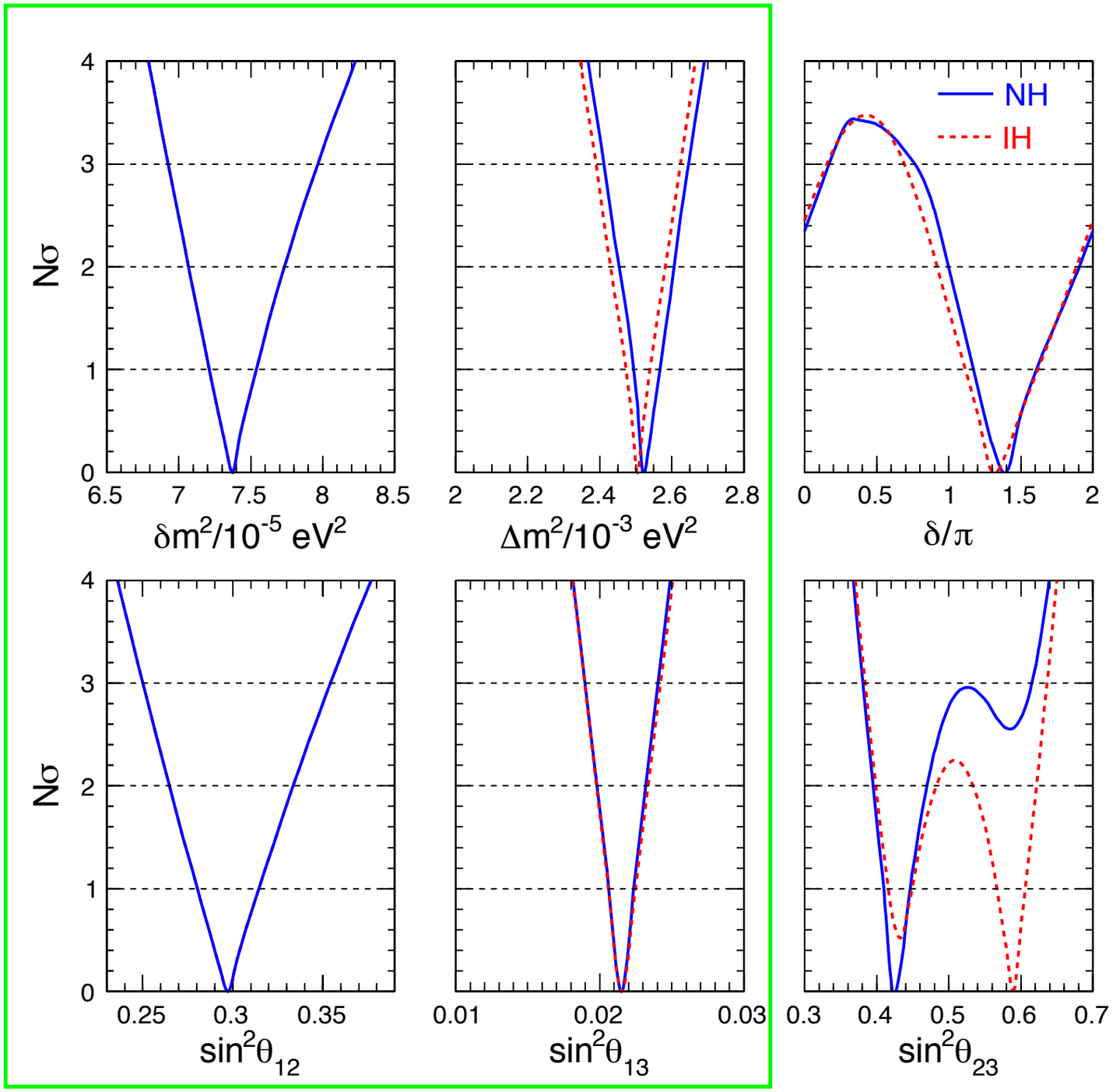

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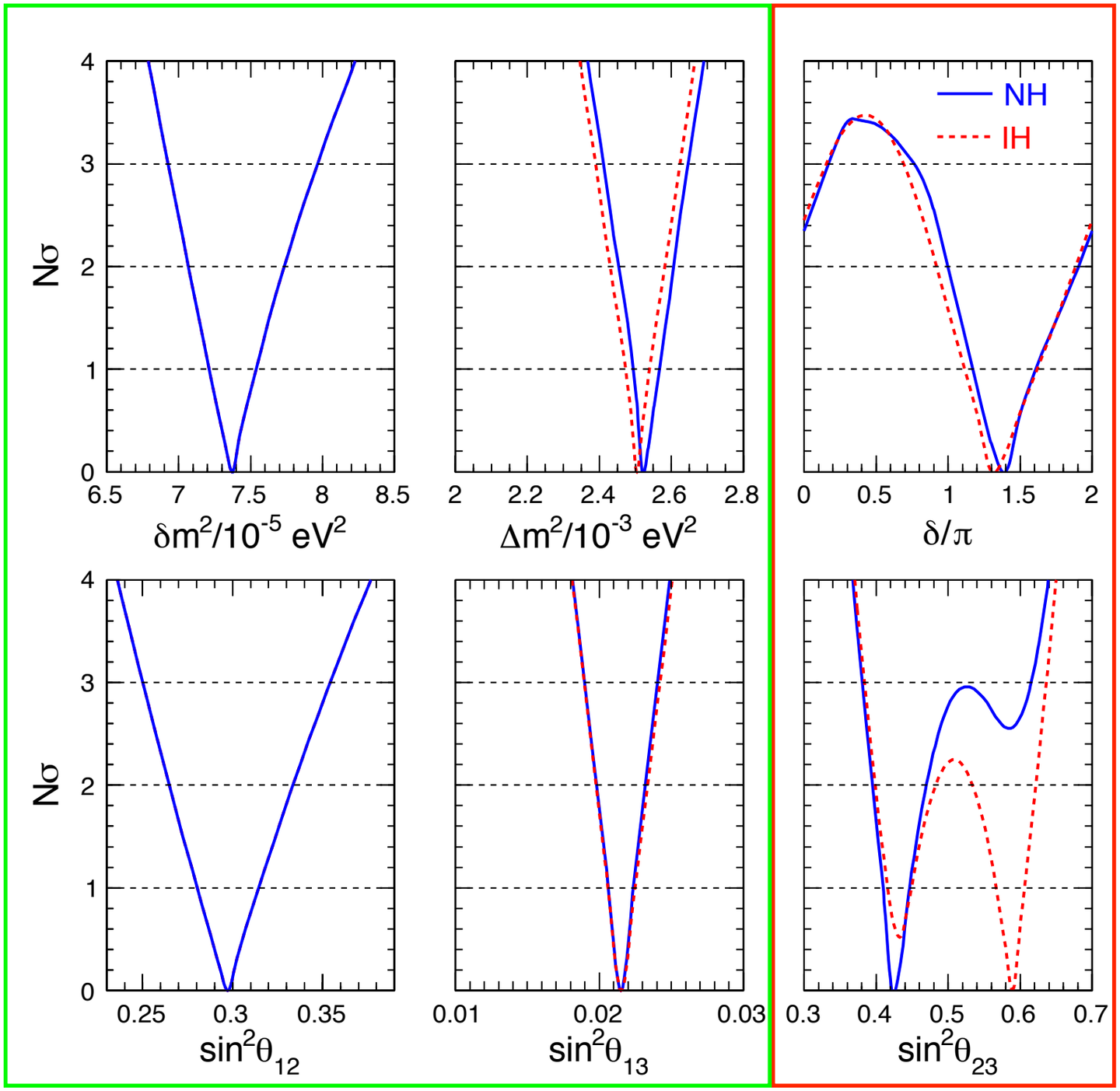

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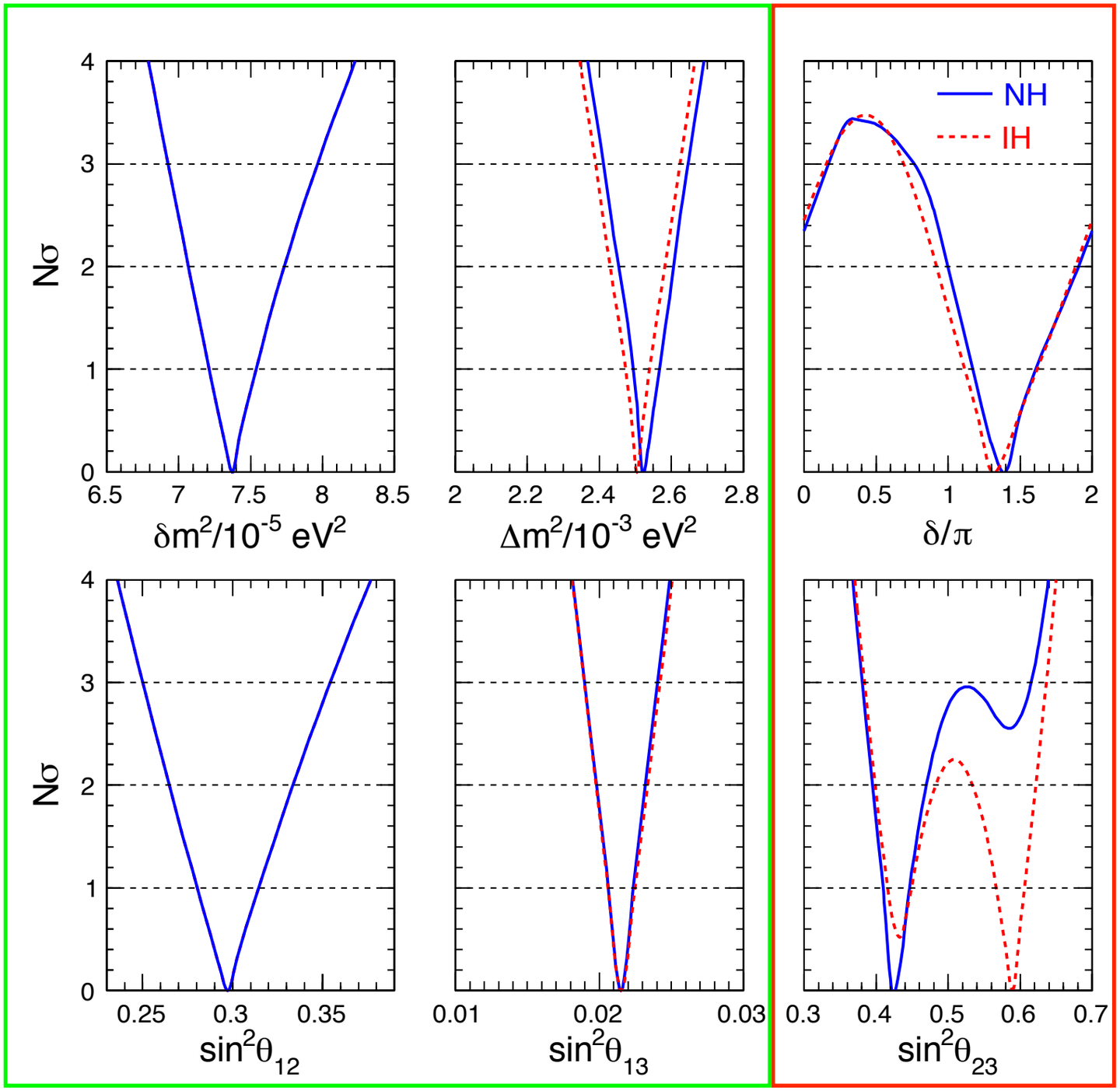

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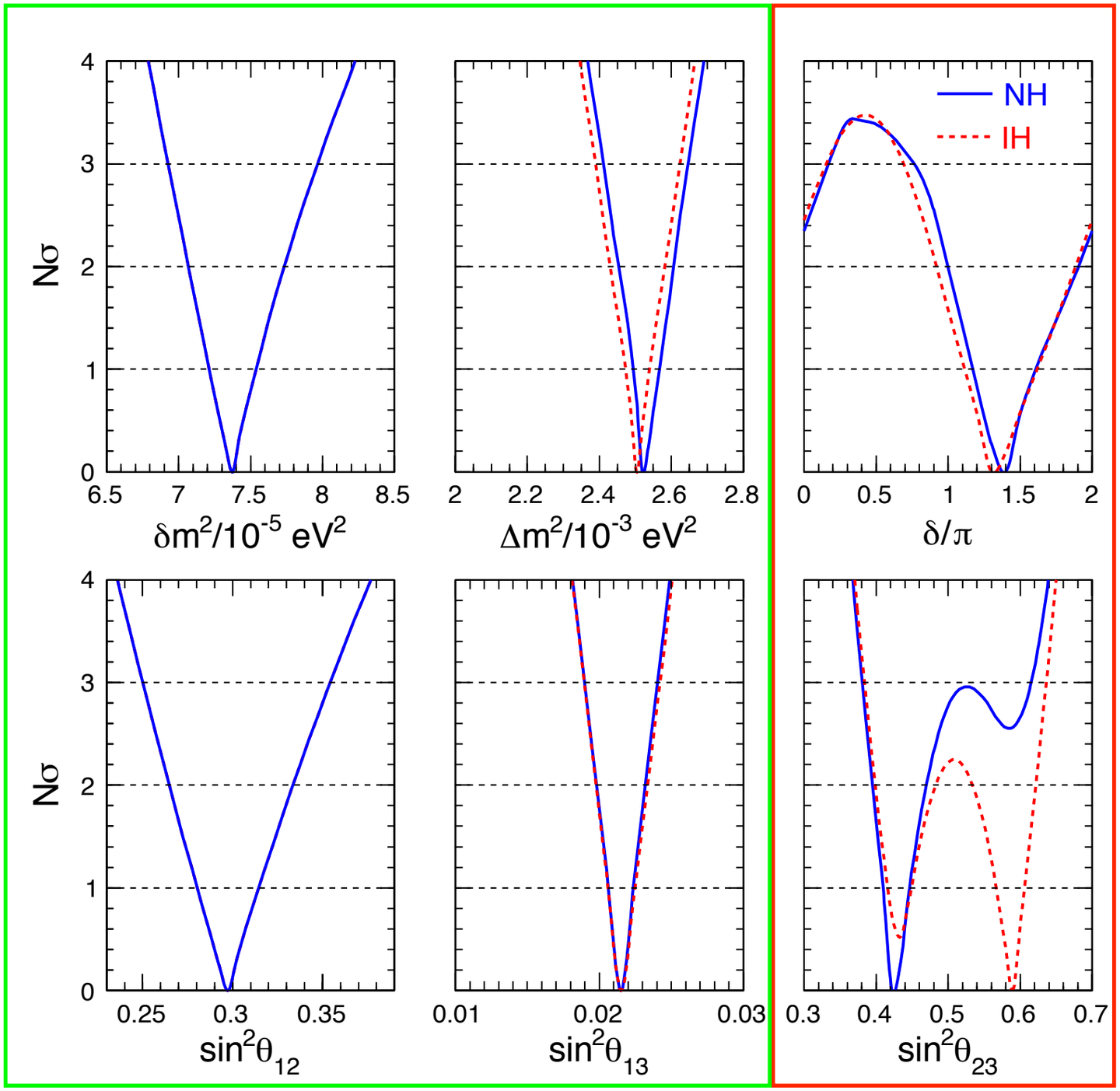

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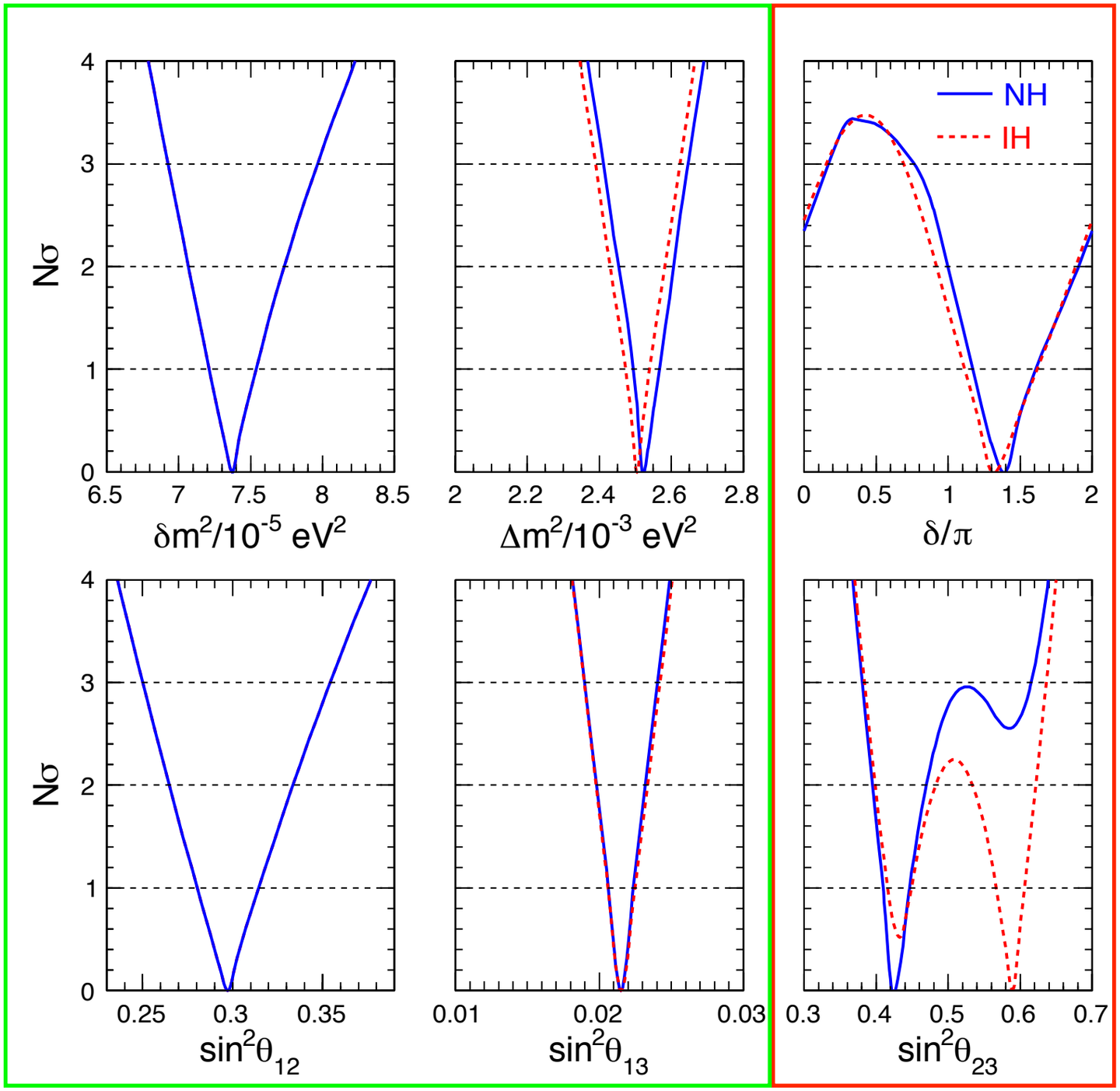

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$$\Delta\chi^2_{\mathrm{IO-NO}} = 3.6$$

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Herein: Atmospheric = SK + DeepCore

Knowns: $(\sin^2\theta_{13}, \Delta m^2)$

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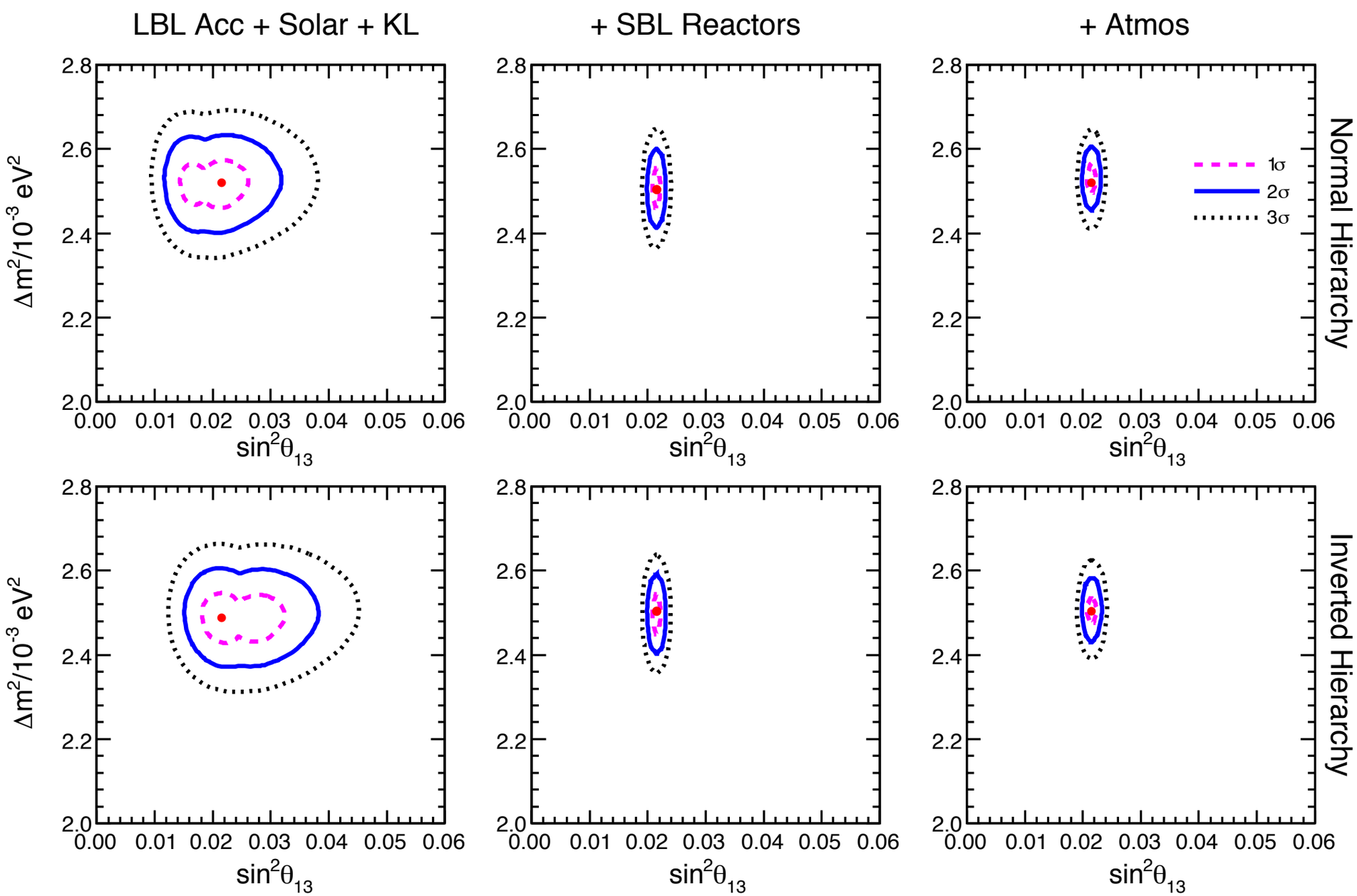

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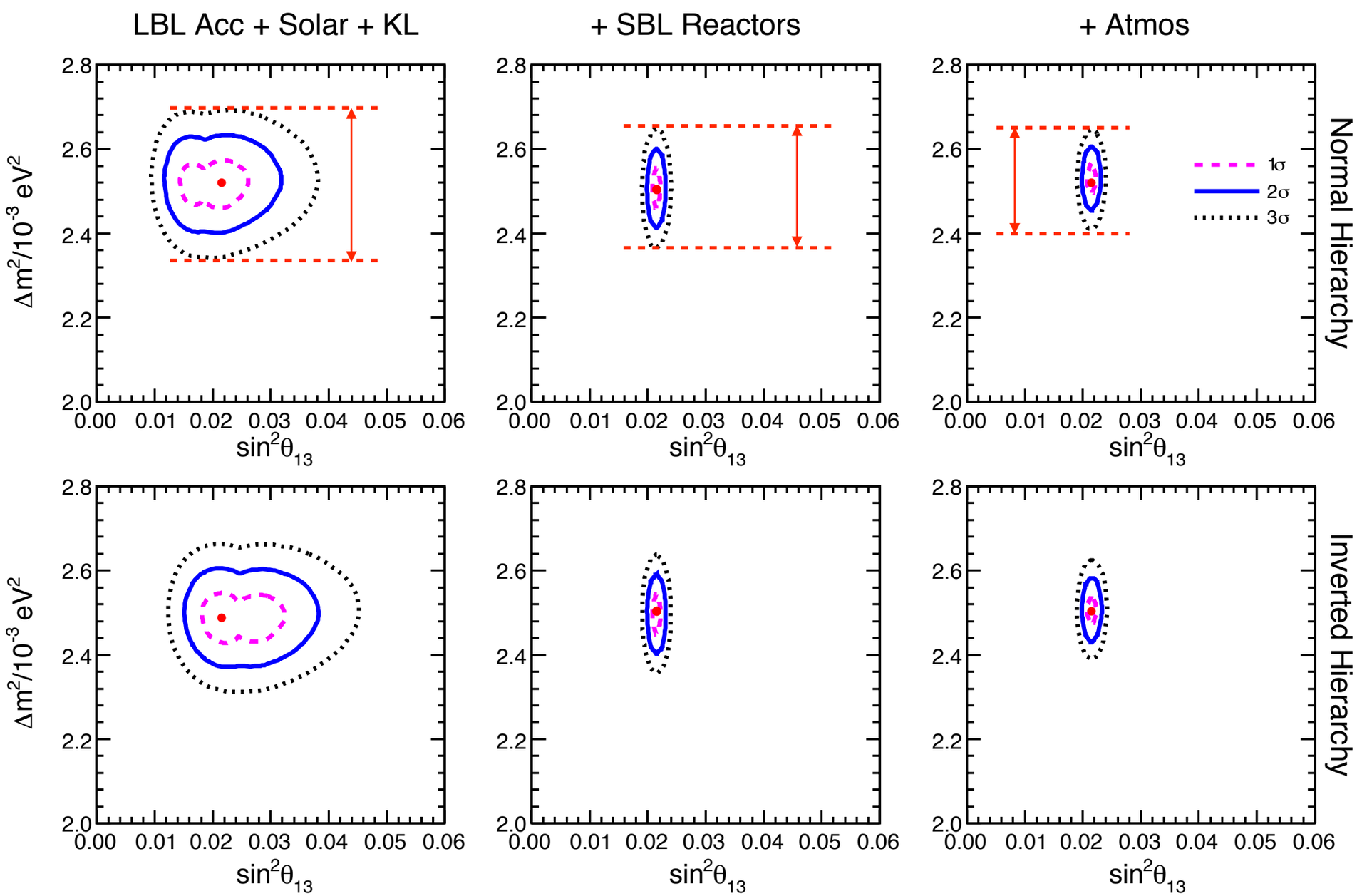

Progressive reduction of the allowed Δm^2 range by adding new data sets

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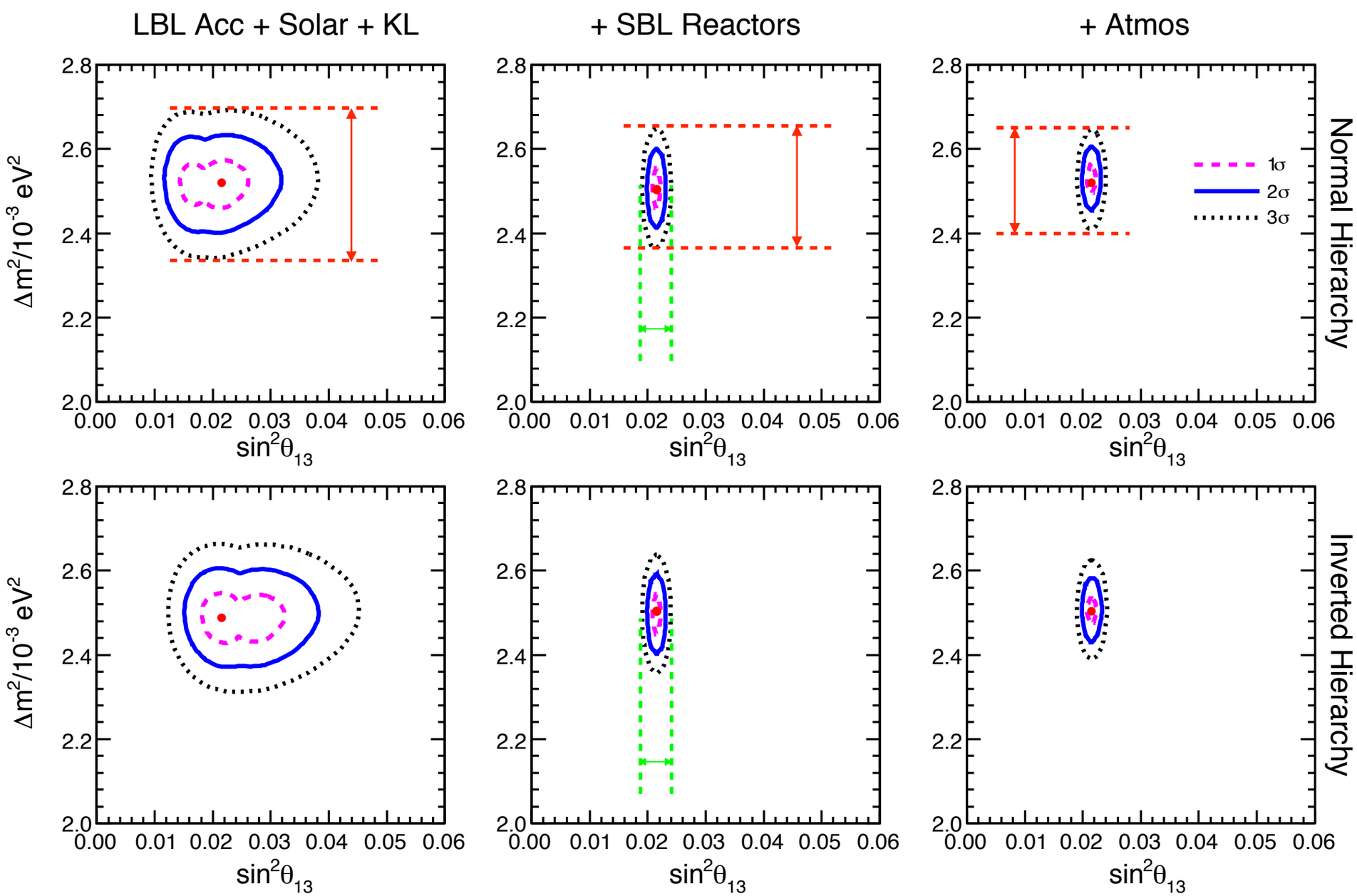

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$\sin^2\theta_{13}$ best measured by reactors

Unknowns: δ, the octant of θ_{23} and Mass Ordering

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δ

θ_{23}

octant

$\Delta\chi^2_{IO-NO}$

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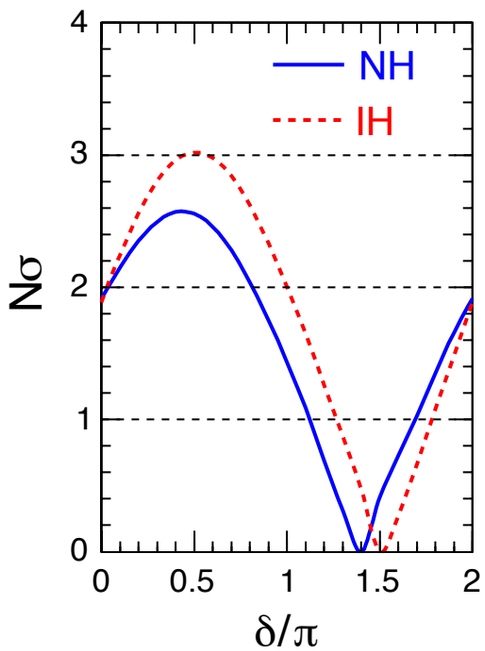
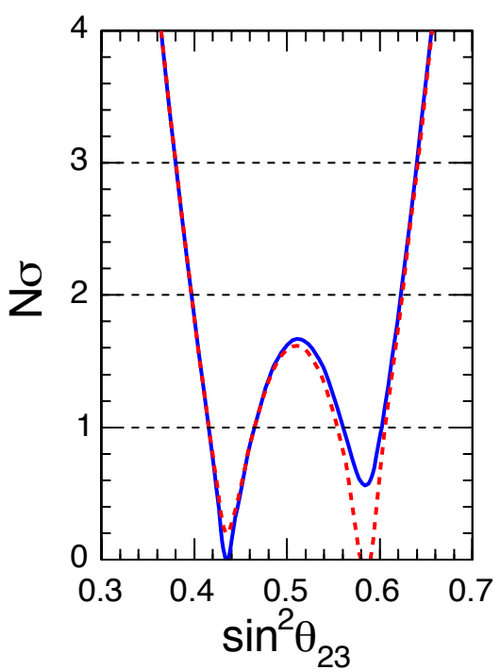
LBL+Sol+KL

δ



θ_{23}

octant



$\Delta\chi^2_{IO-NO}$ +1.1

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LBL+Sol+KL

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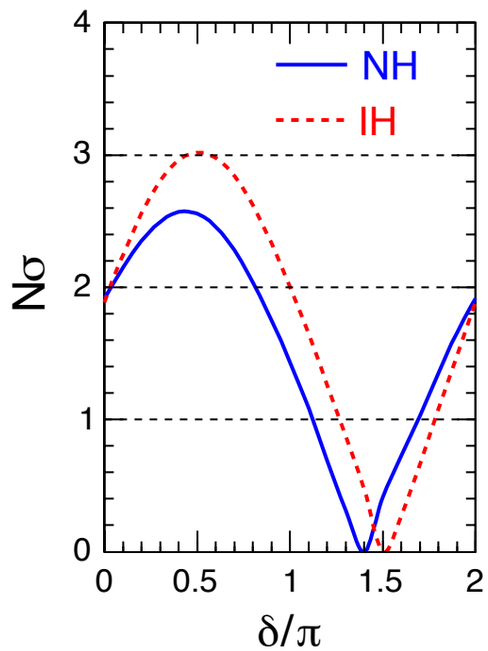
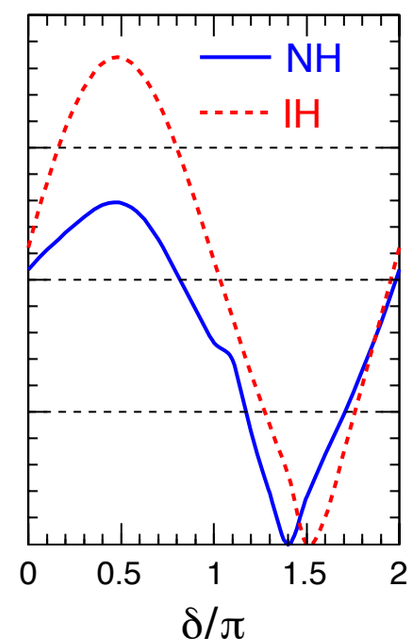
δ





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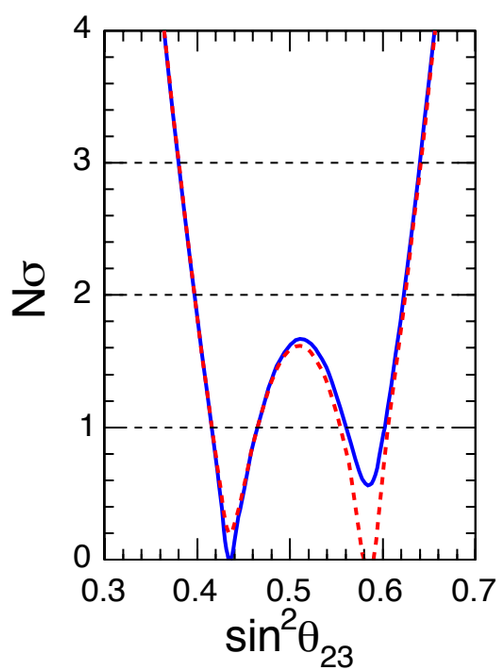

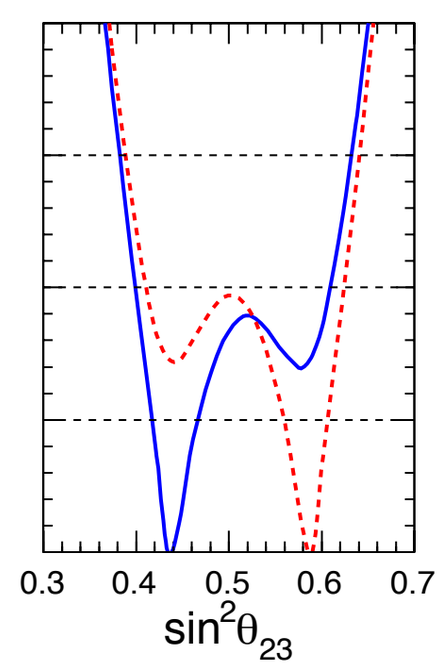

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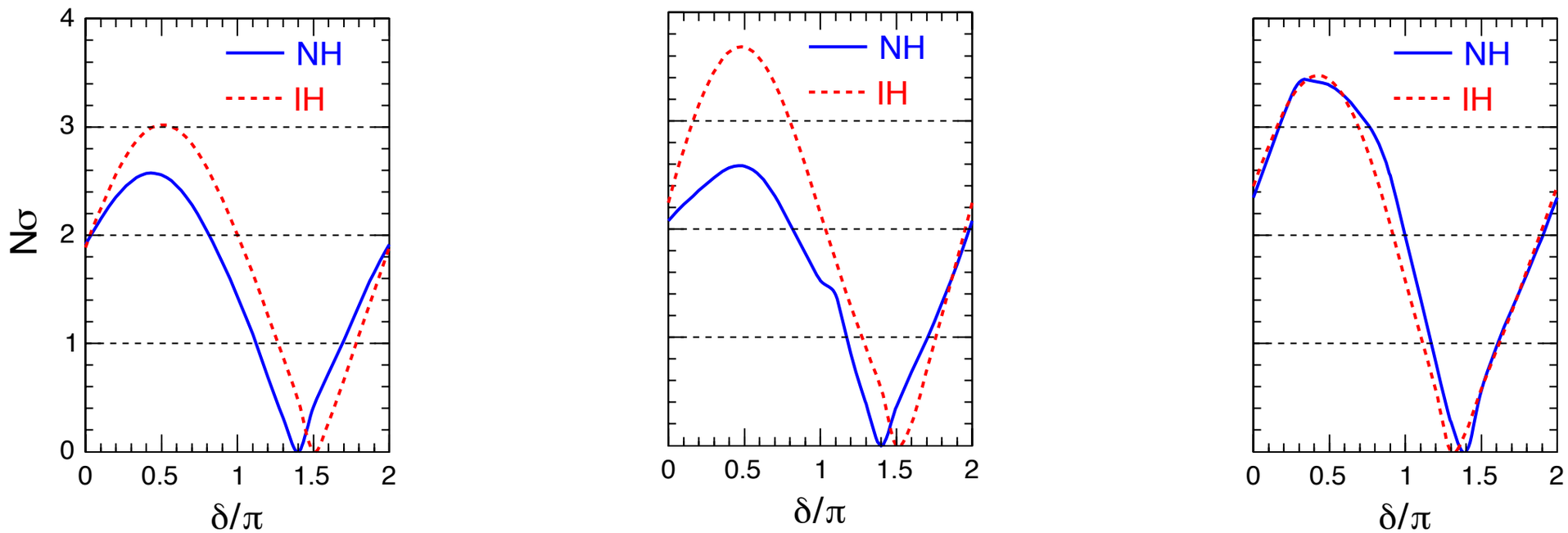
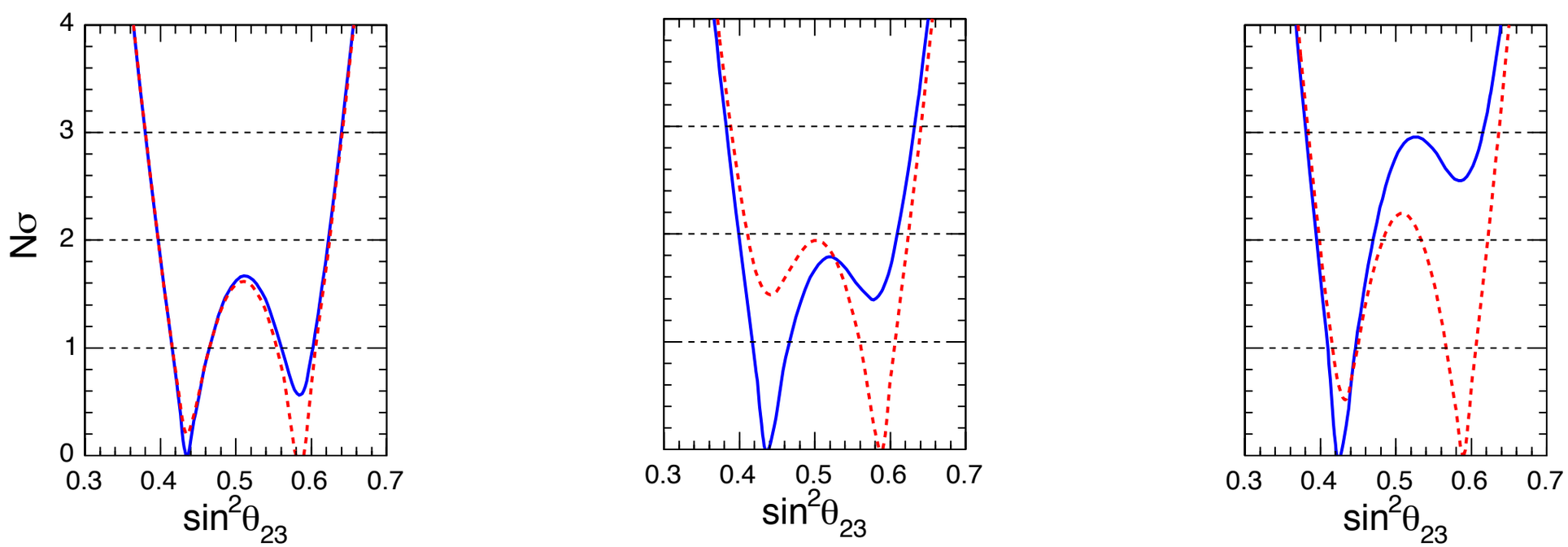
Unknowns: δ, the octant of θ_{23} and Mass Ordering

LBL+Sol+KL | +SBL | +Atm

δ



θ_{23} octant



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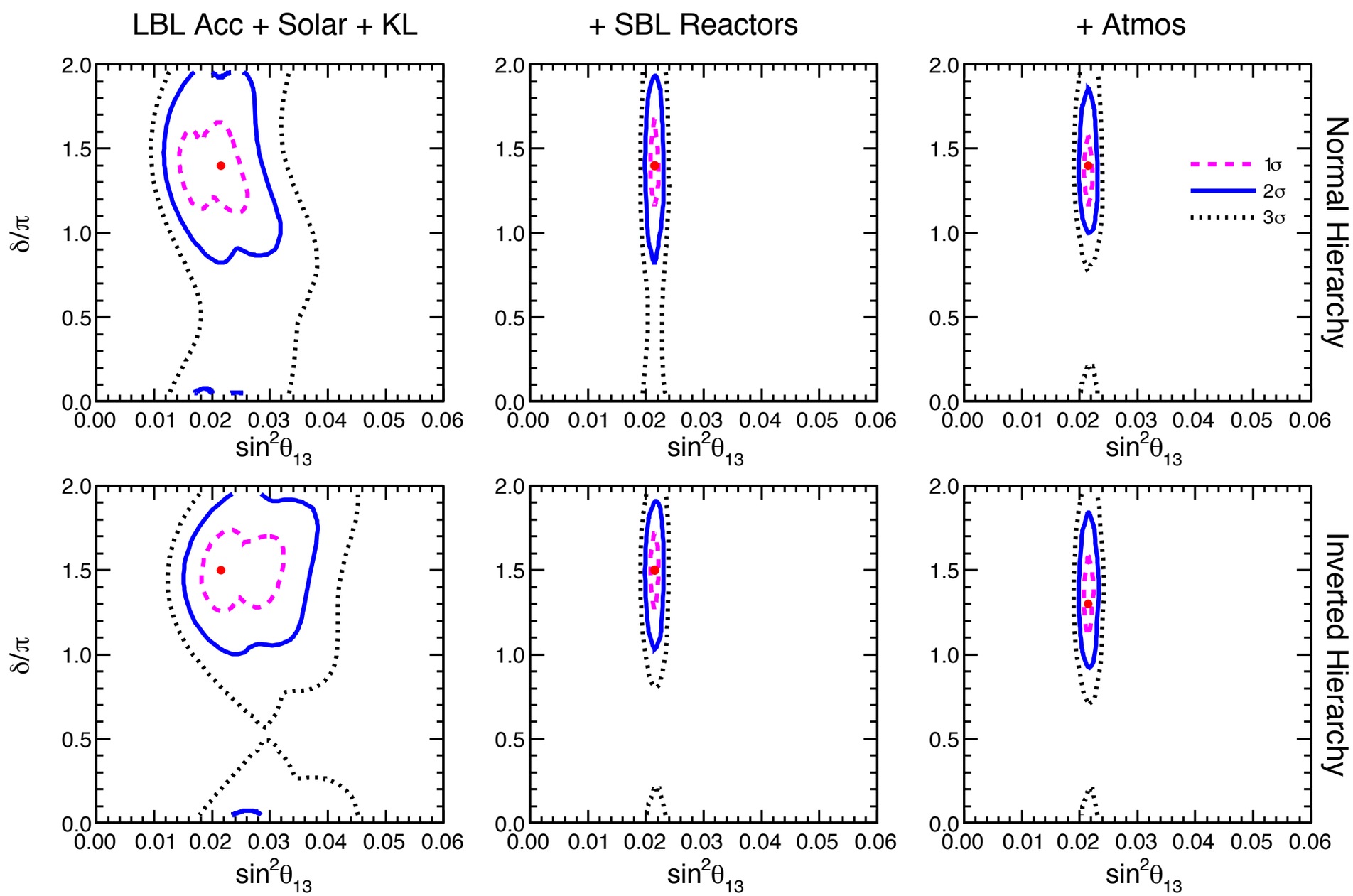

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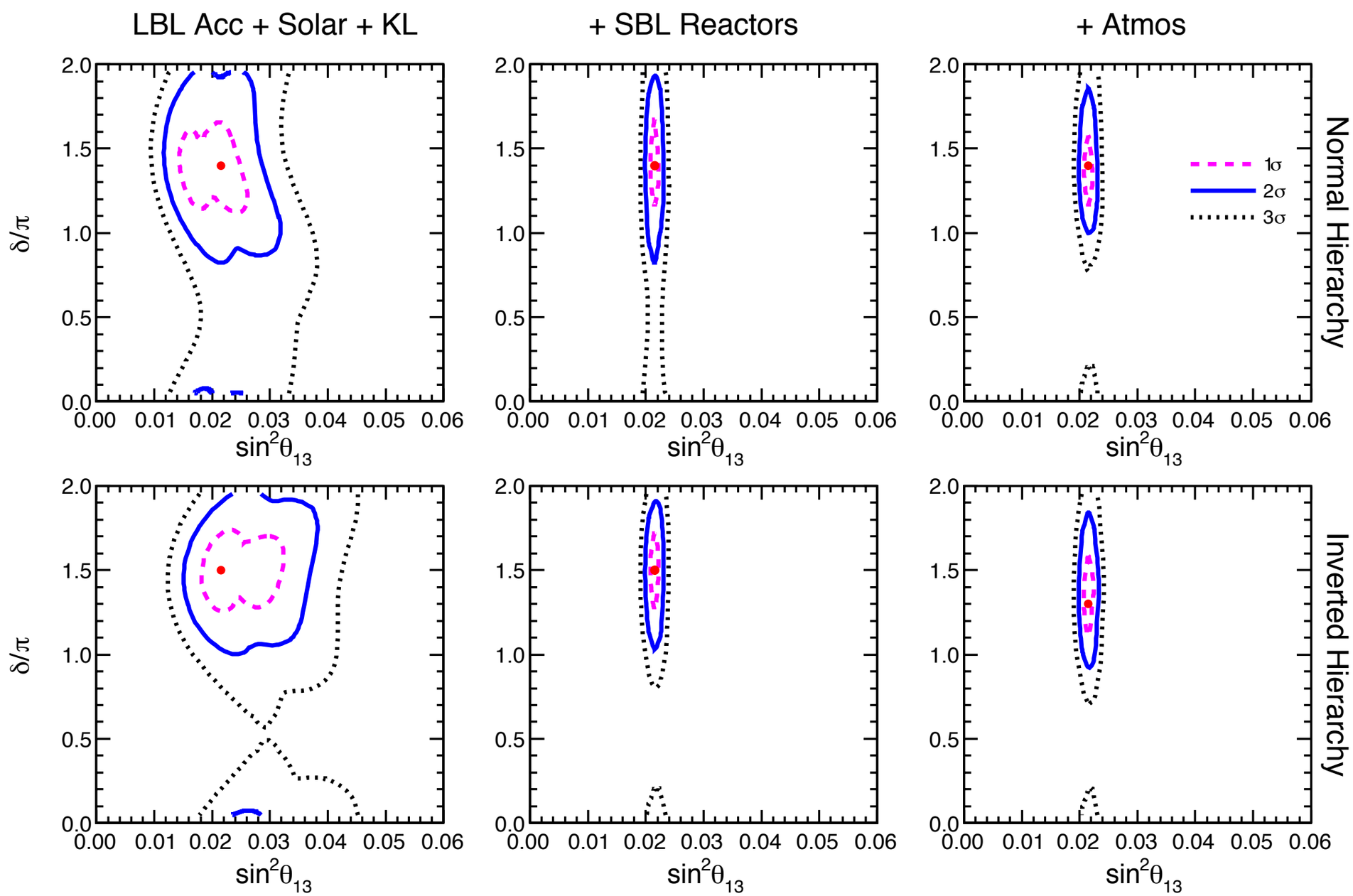

θ_{23} octant degeneracy effect on "wavy bands" in the (δ,θ_{13}) plane

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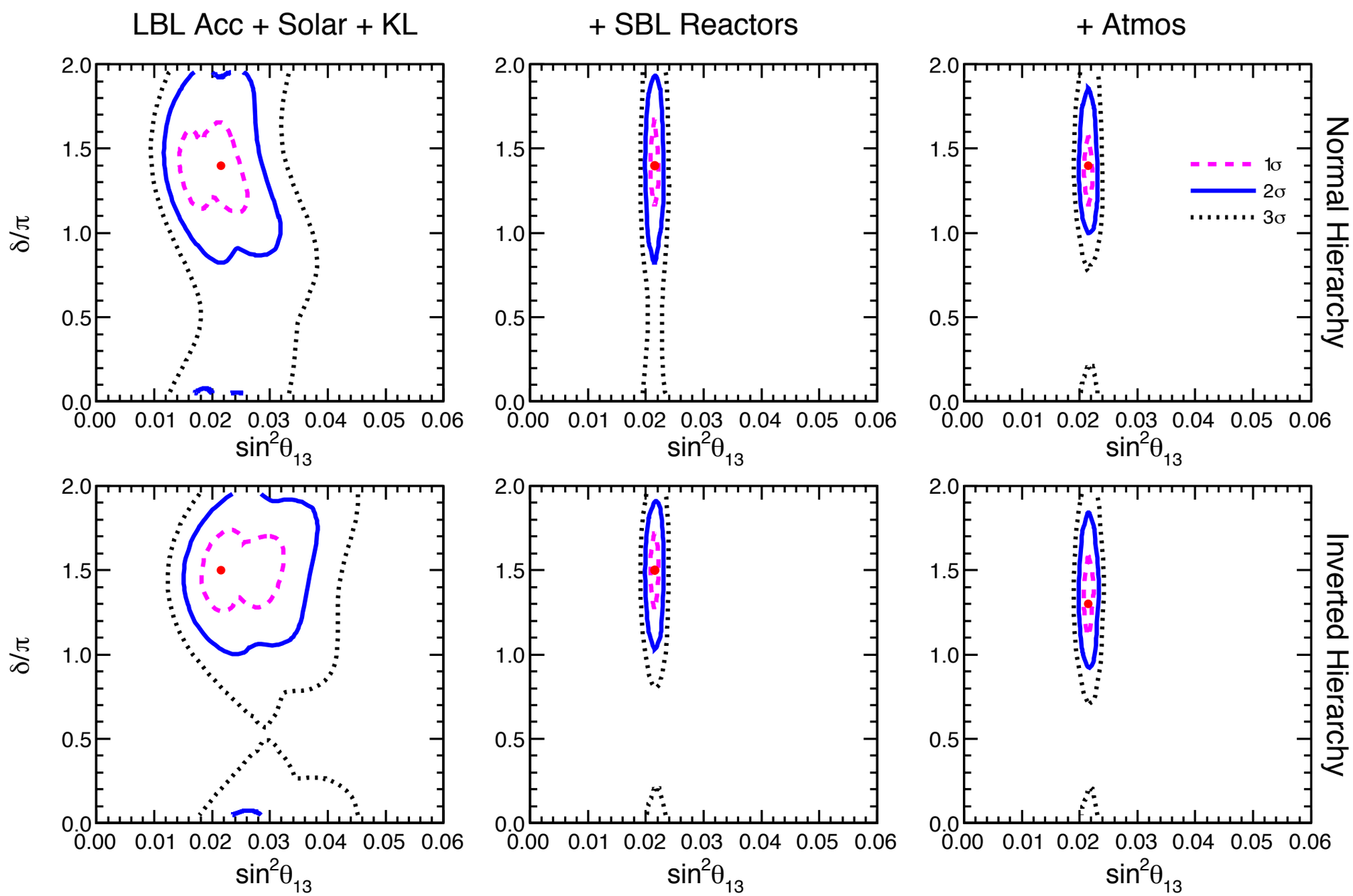

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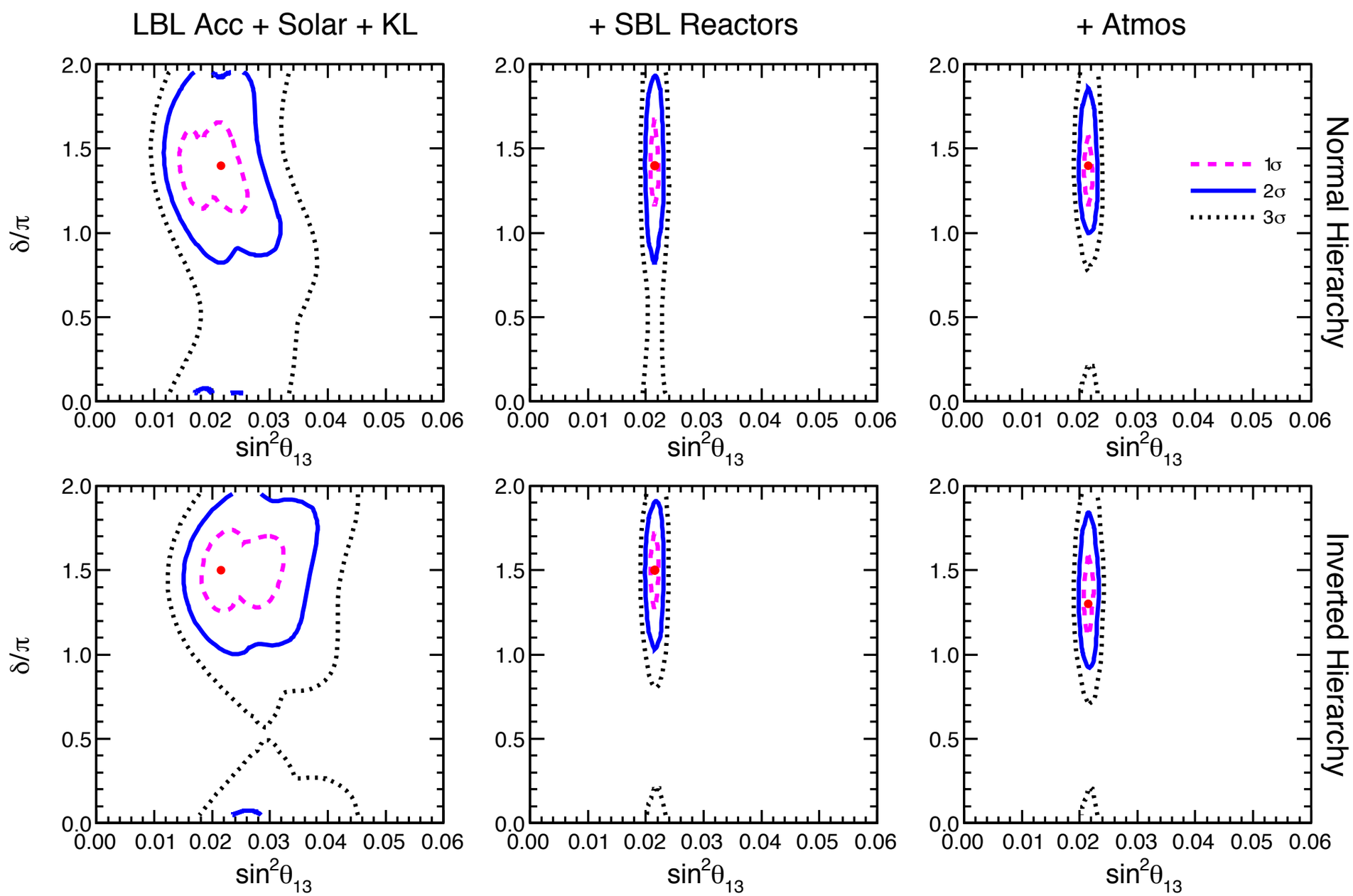

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Results in the (δ,θ_{13}) plane corroborated by atmospheric data

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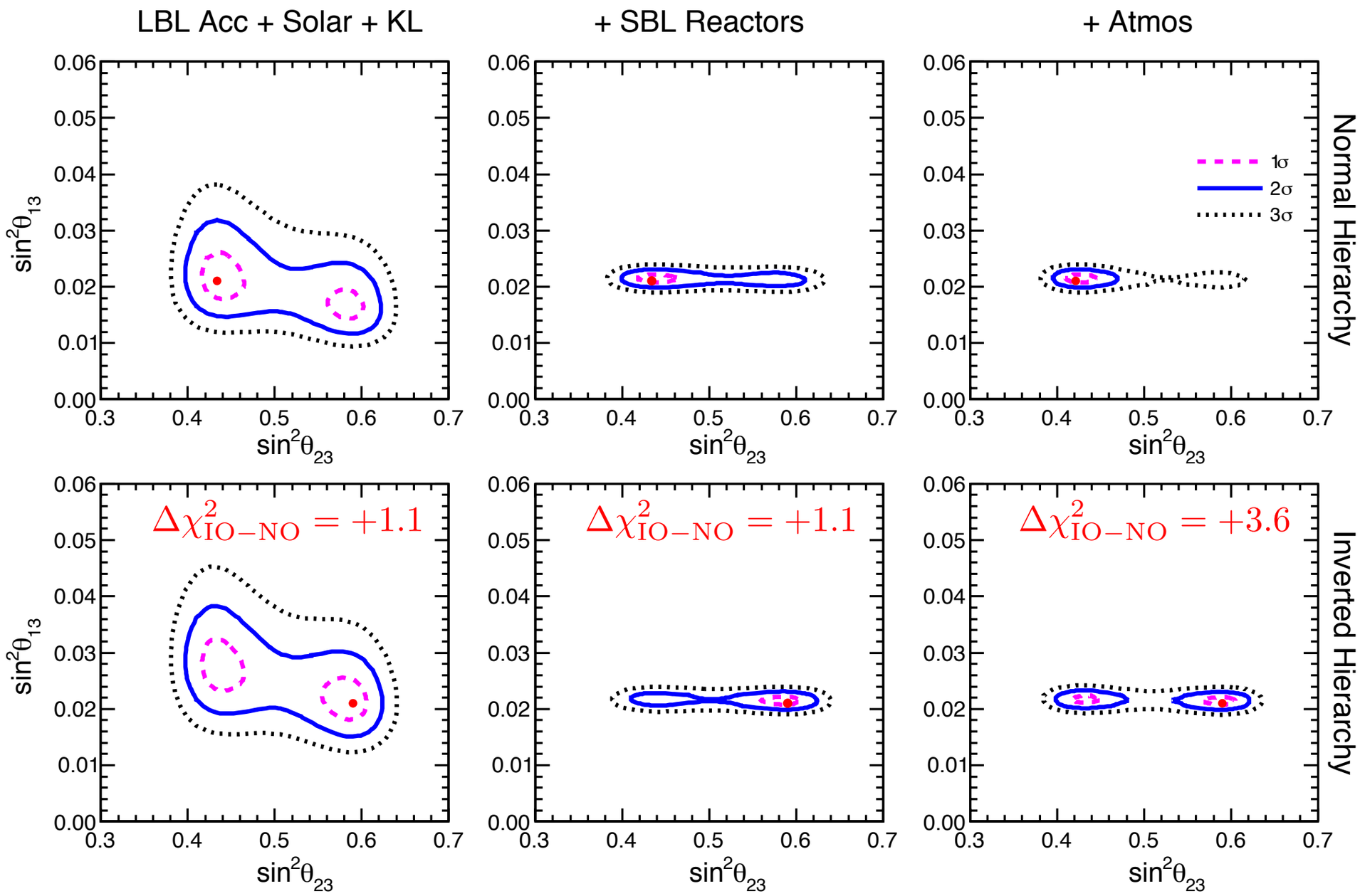

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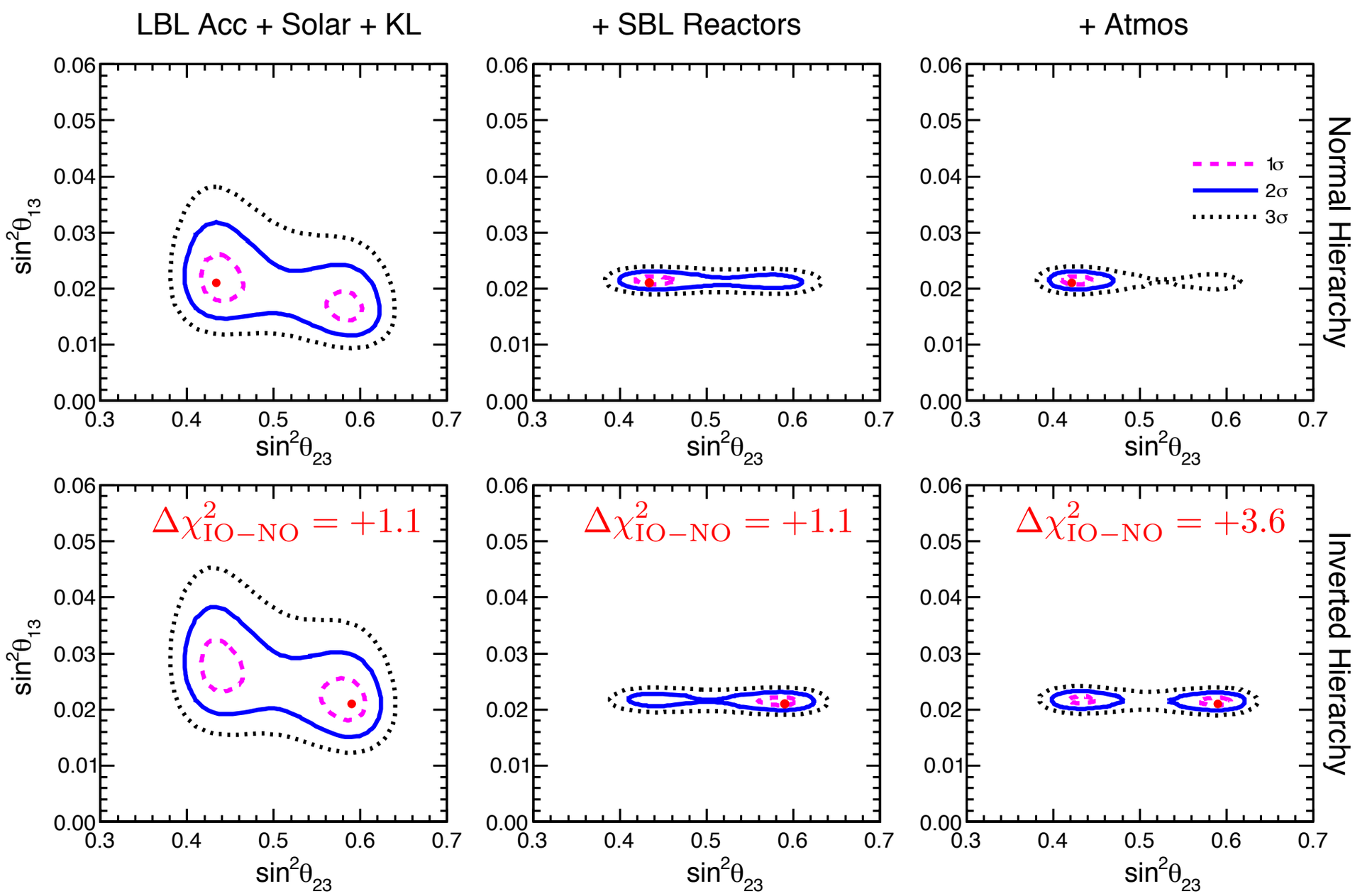

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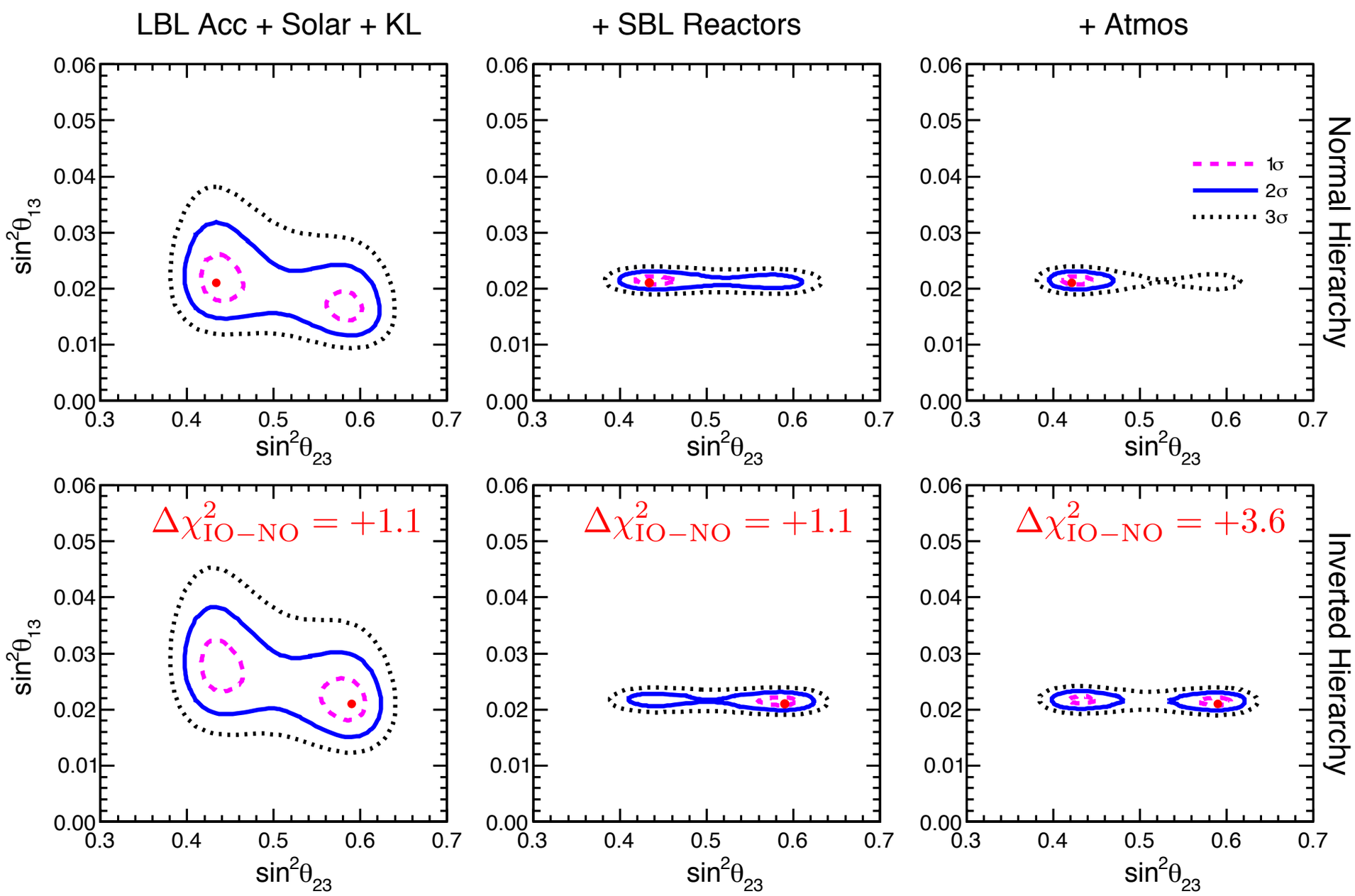

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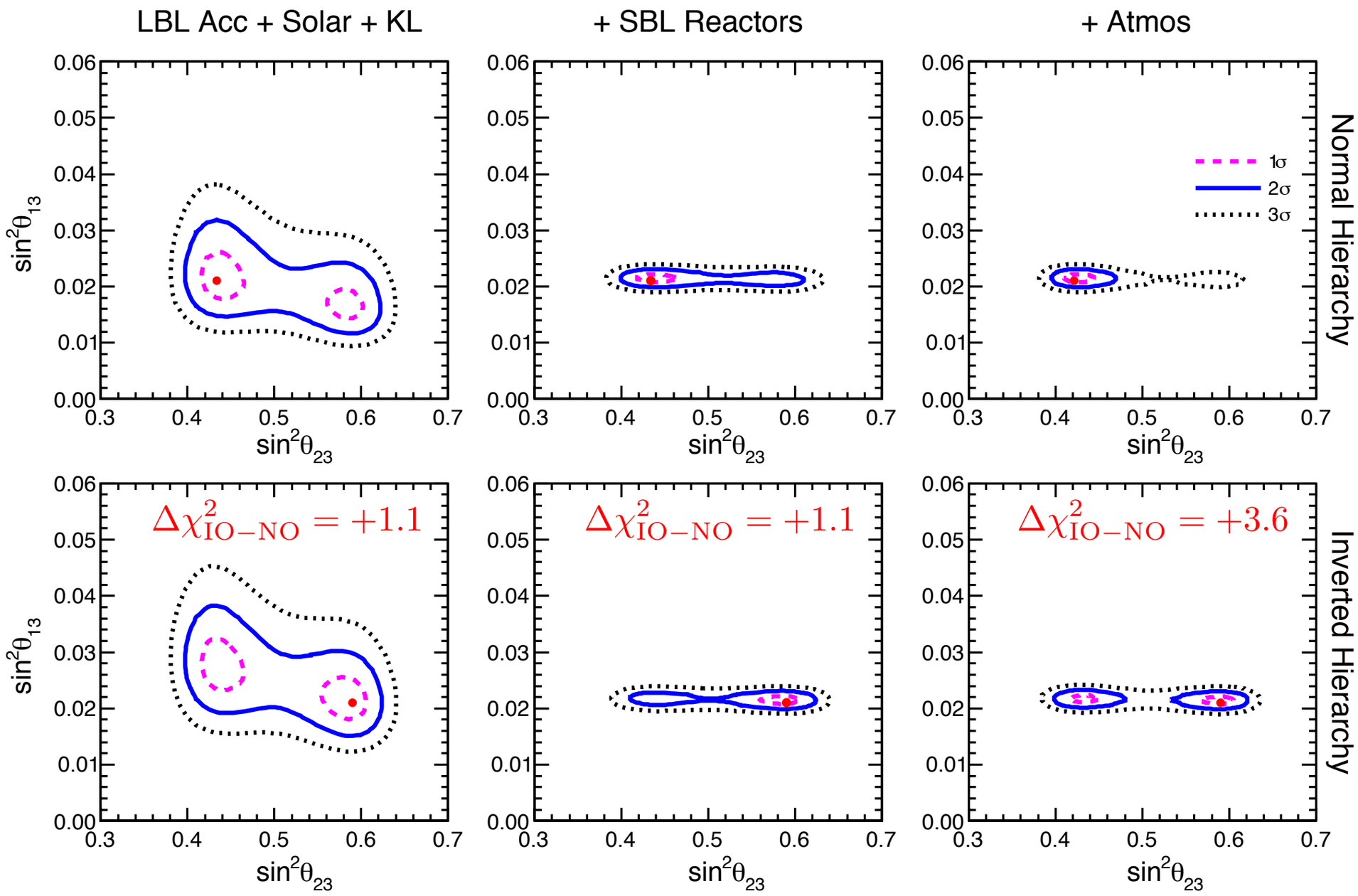

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Atmospheric data introduce some differences in the relative likelihood of the two octants in NO and IO

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Info from oscillation experiments

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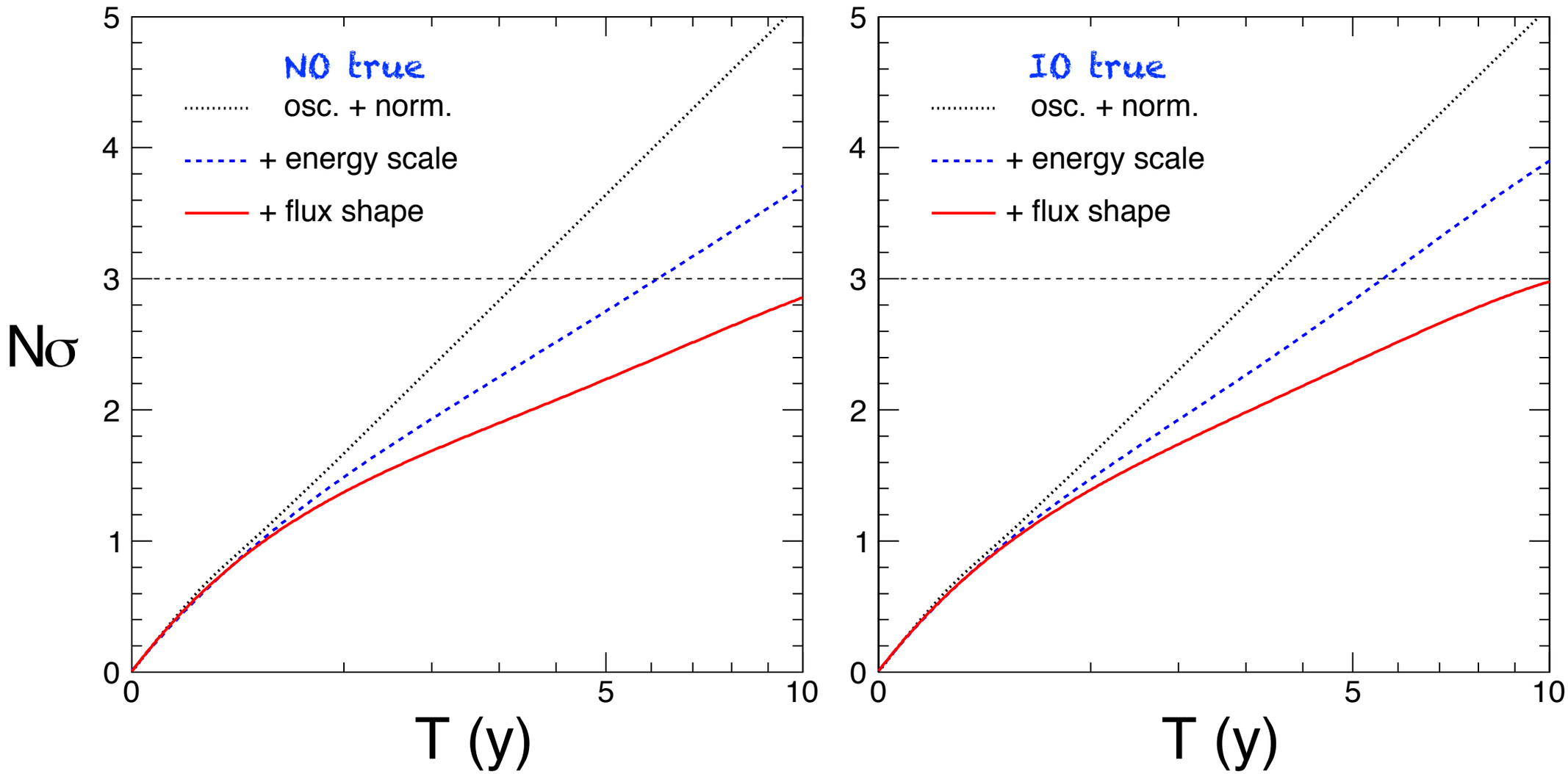
- Cosmology & Atrophysics

JUNO-like prospective sensitivity to mass ordering (*)

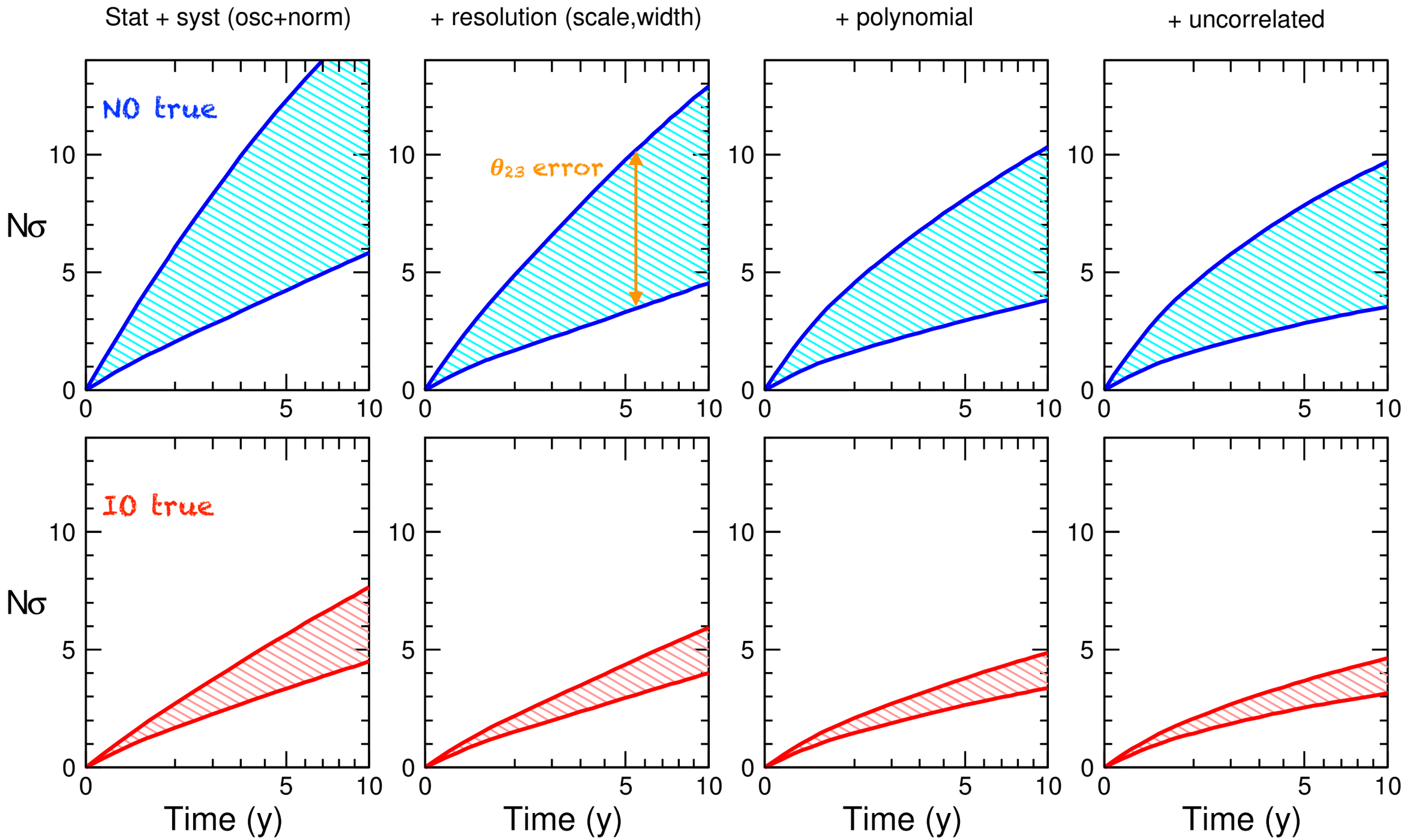
Abscissa scales as $T^{1/2}$ -> linear behaviour for pure statistical errors



Inclusion of energy-scale uncertainties bends the linear rise, but still allows 3σ discrimination after ~6 years of data taking. With the inclusion of flux-shape uncertainties: 3σ sensitivity in ~10 years

Phys.Rev. D92 (2015) no.9, 093011

PINGU sensitivity to mass ordering (similarly for ORCA)



Mass ordering discrimination reduced by 2D spectral shape systematics due to atmospheric fluxes, cross sections, detector response, ...

Phys.Rev. D91 (2015) 073011

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Add up $\chi^2_{\rm osc} + \chi^2_\Sigma + \chi^2_{\beta\beta}$ in the $(\Sigma, m_{\beta\beta})$ plane

When deriving parameter bounds, two possible strategies

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(1) Take NO and IO as two alternative hypotheses

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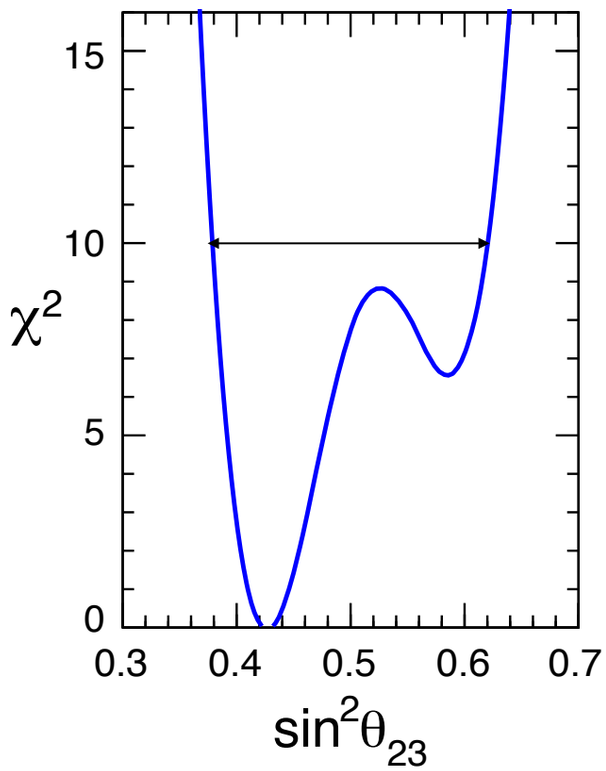

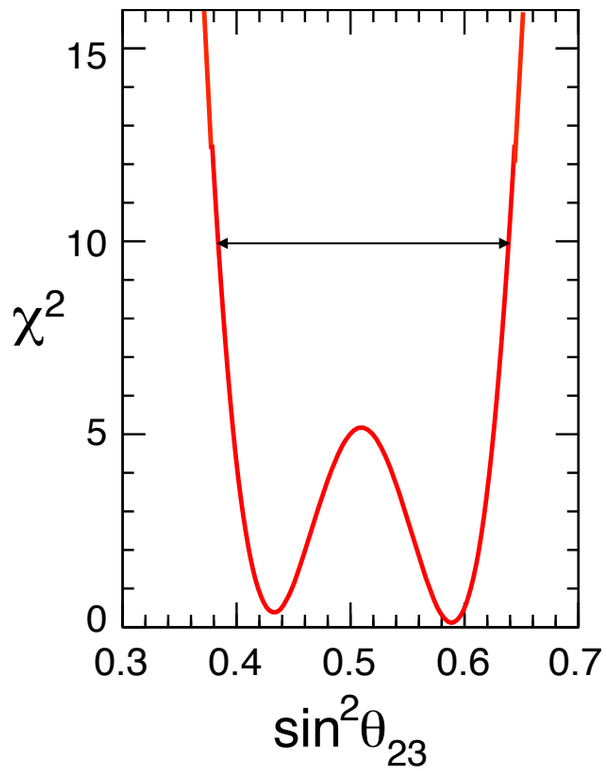

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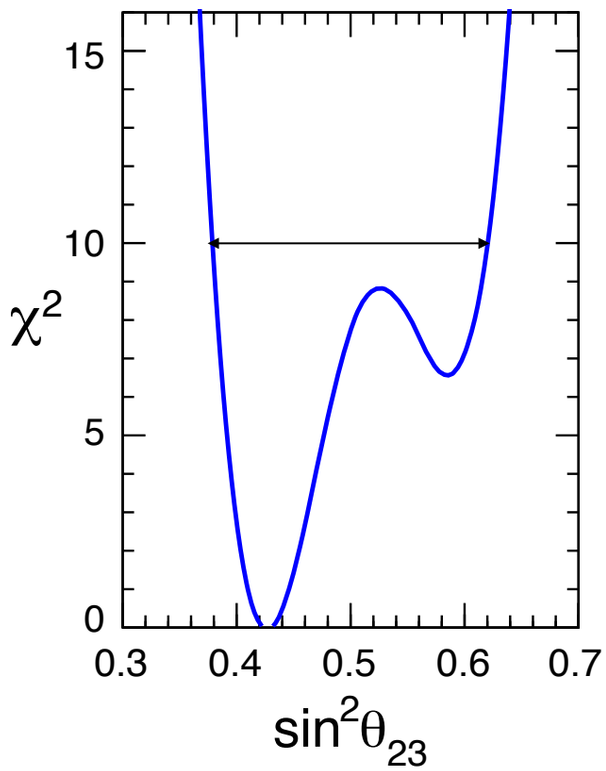

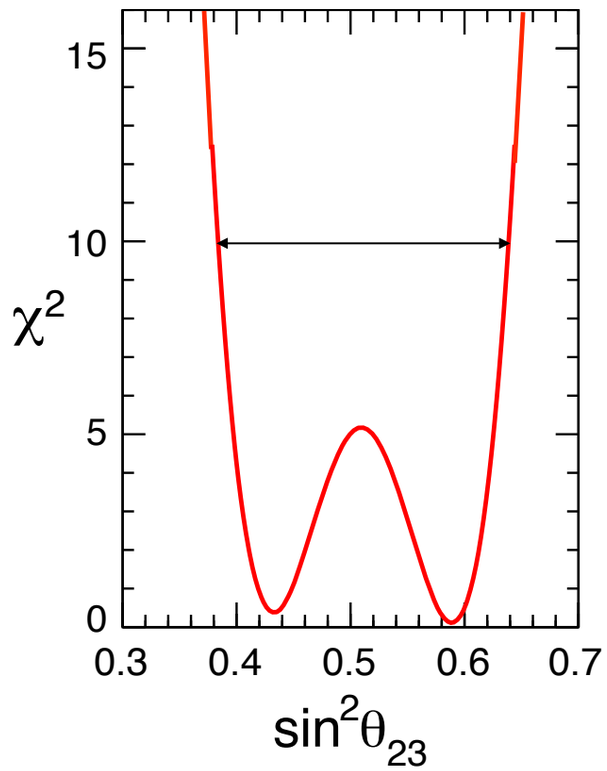

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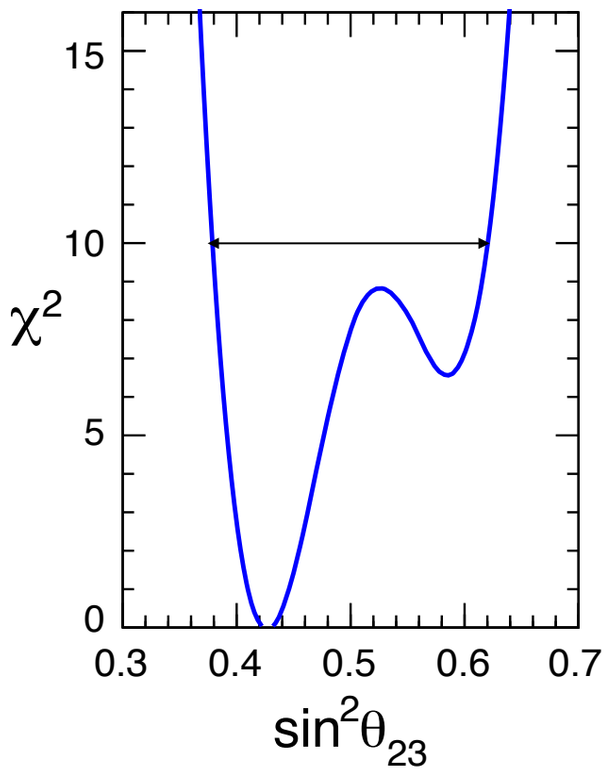

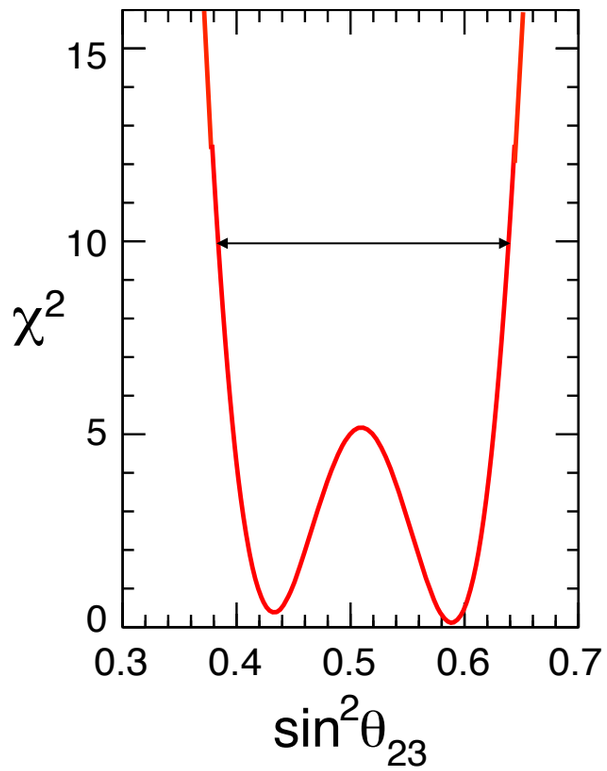

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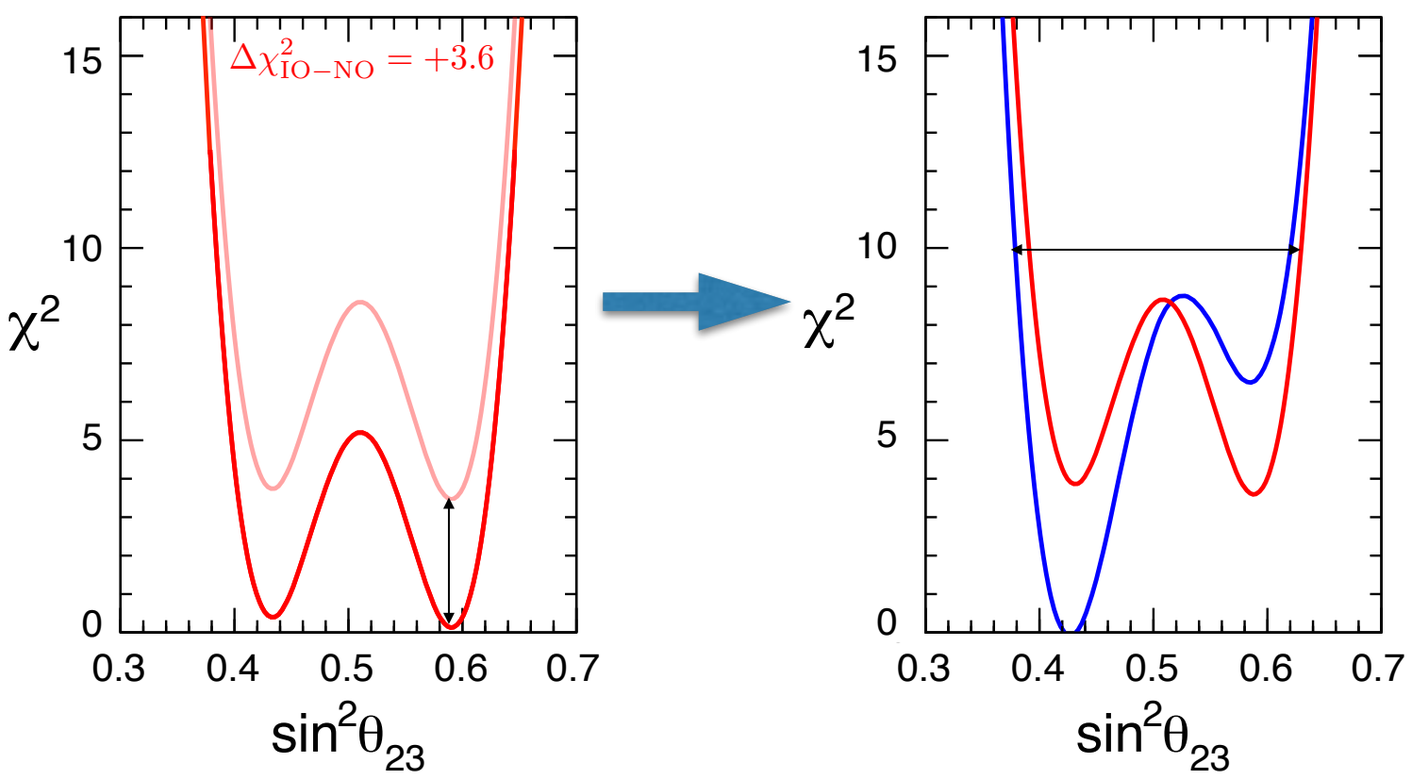

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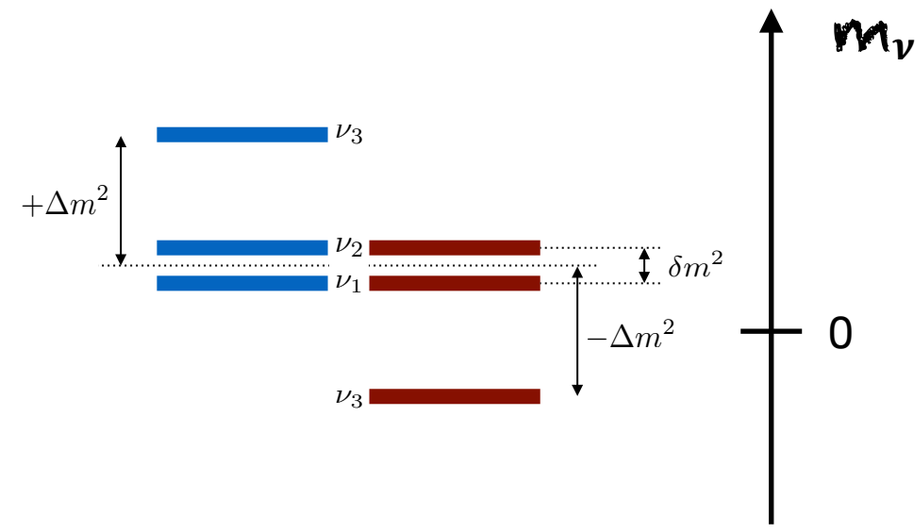
Oscillations independent on the absolute mass scale but give rise to a lower bound on Σ to wich cosmological data are sensitive



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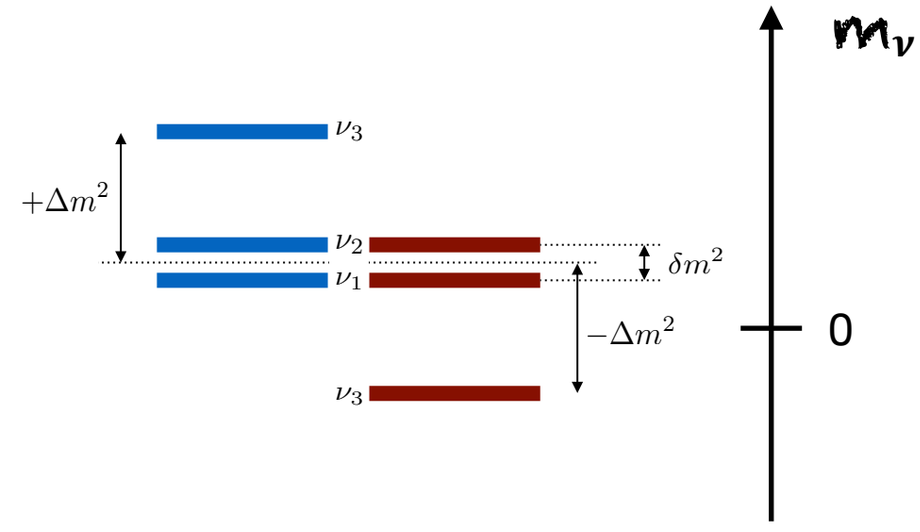
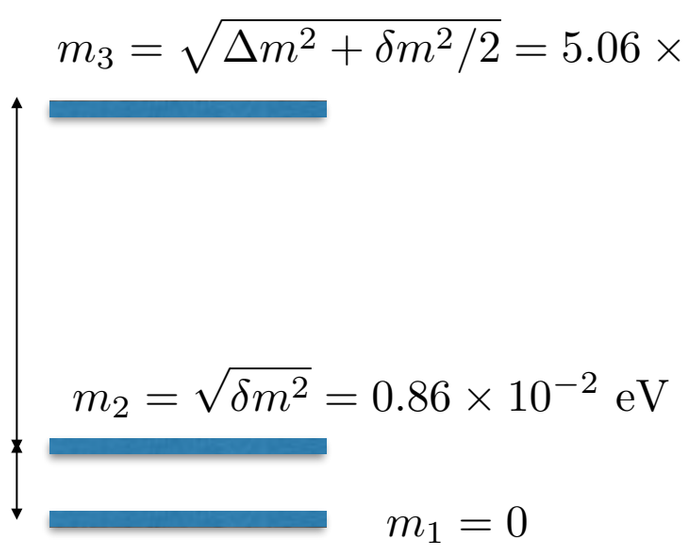


Normal Ordering



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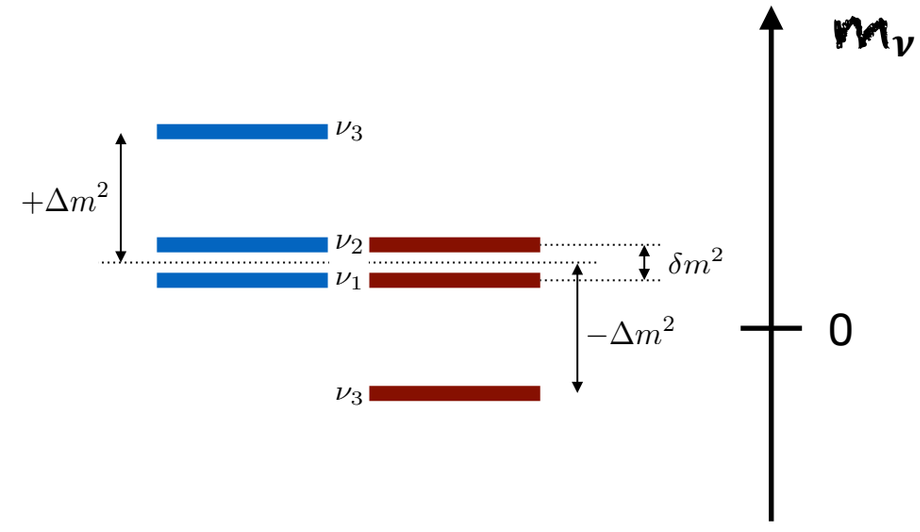

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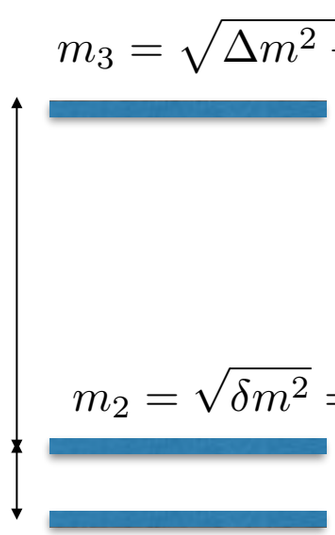

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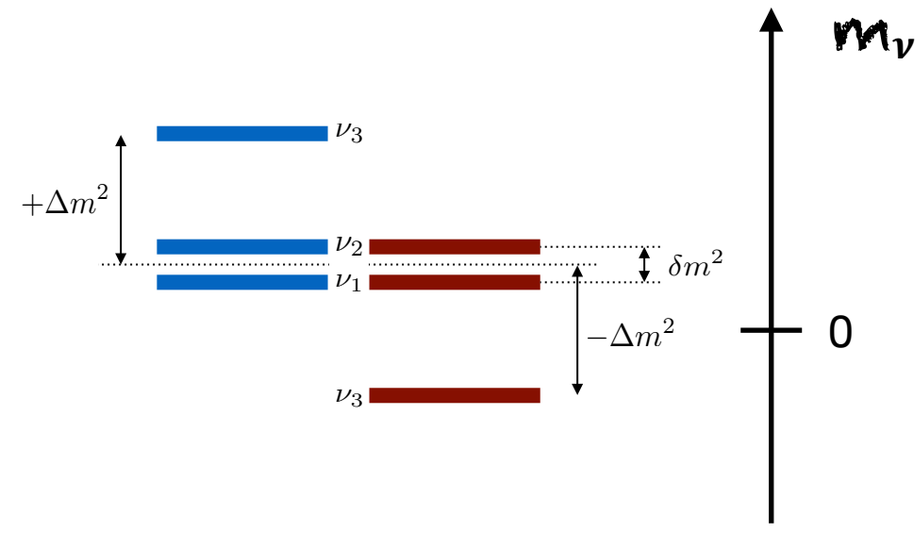

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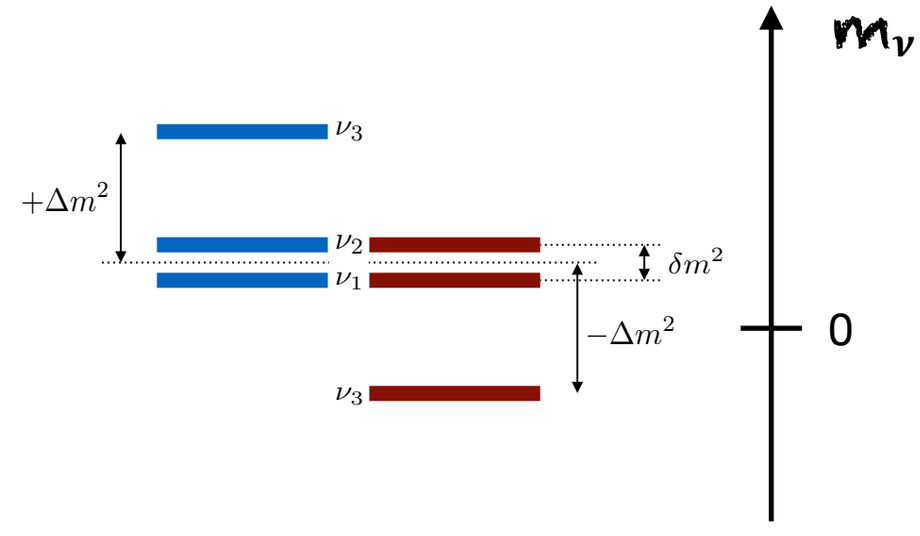

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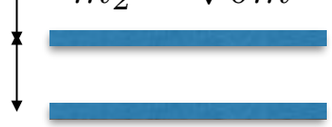

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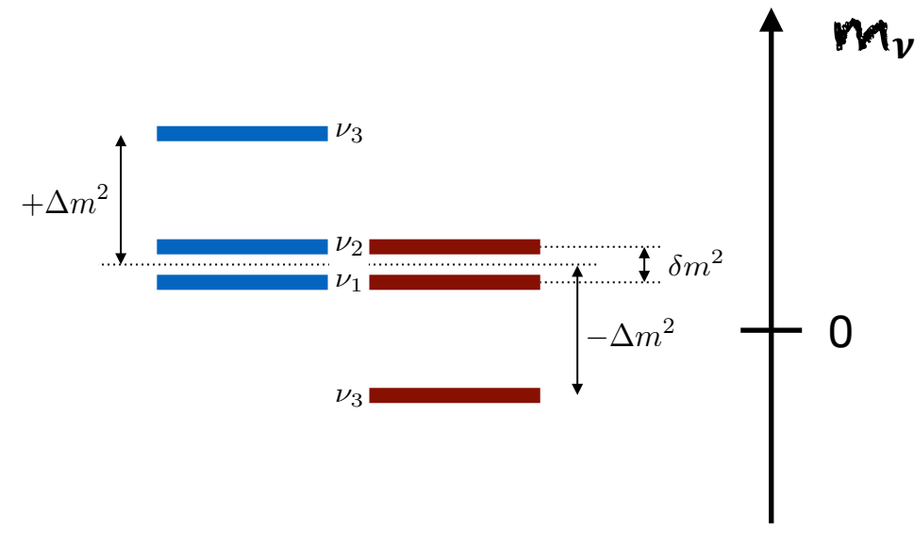

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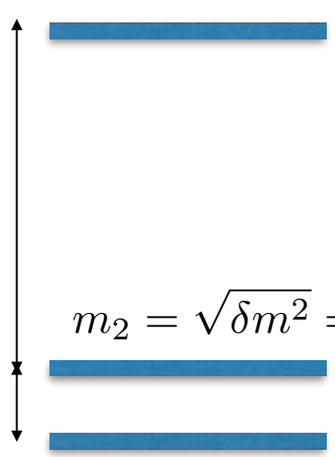

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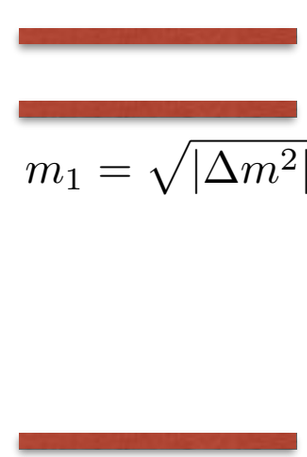

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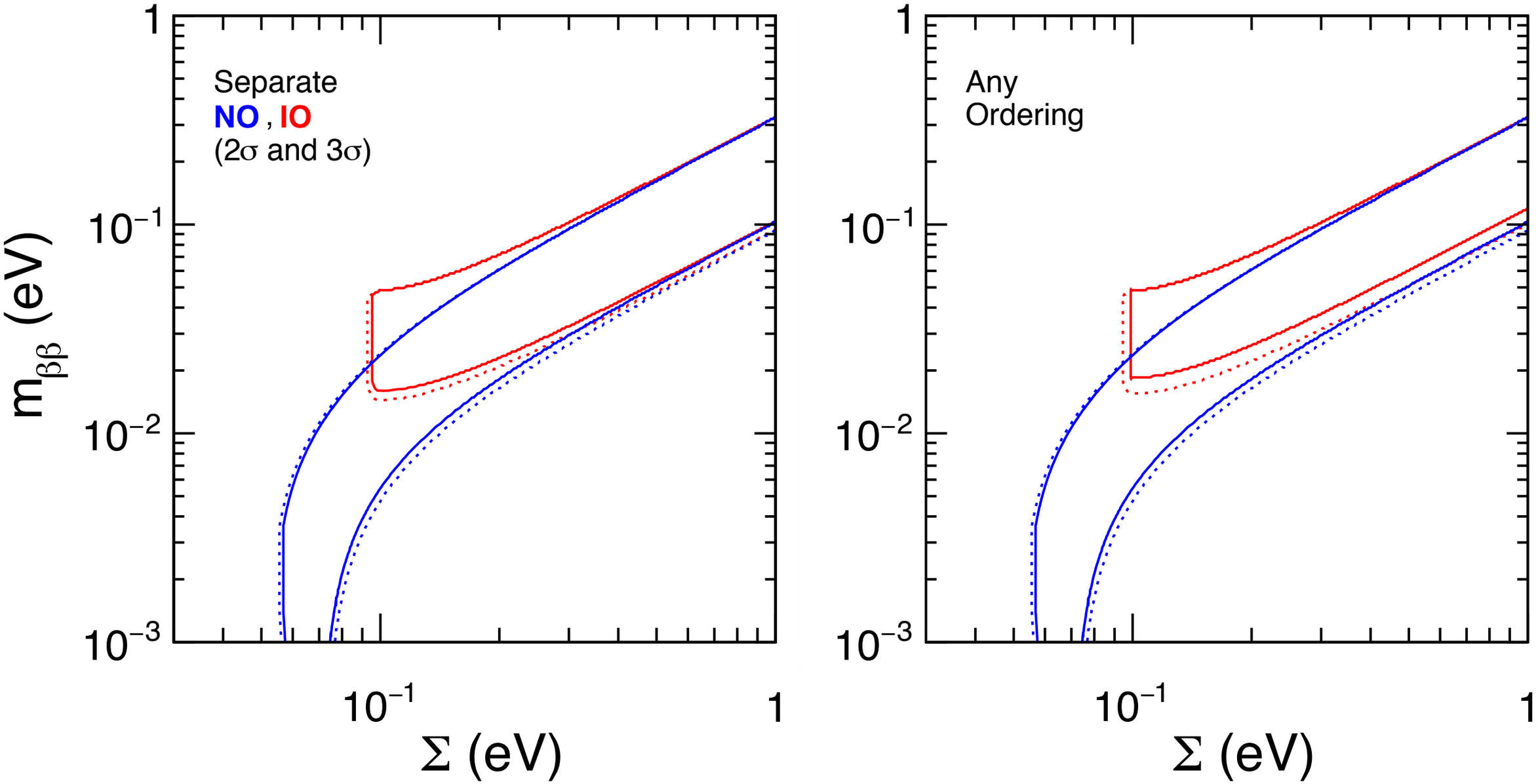
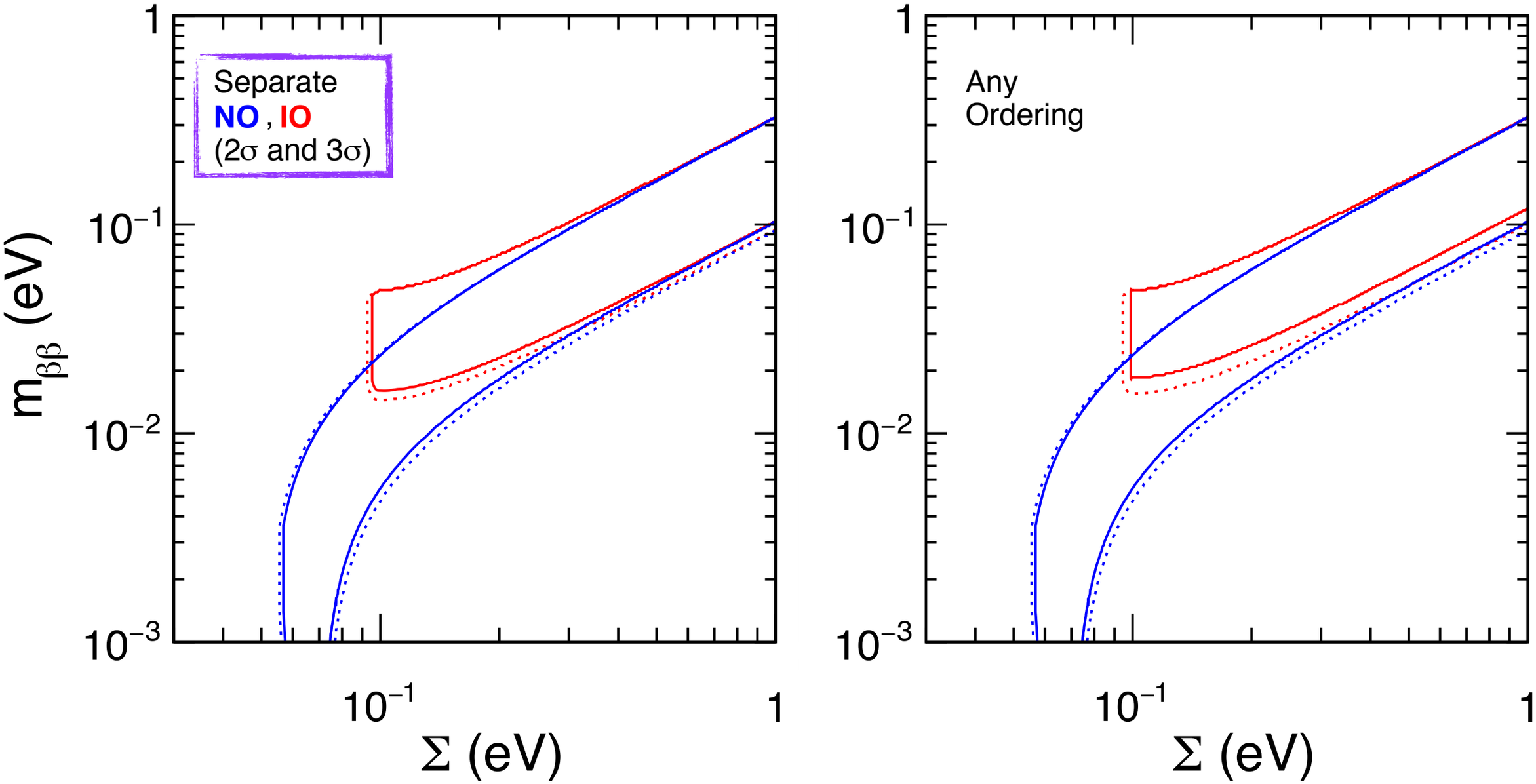
The lower bound on Σ for IO only a factor ~2 smaller than the strongest limit set at present by cosmological data

Oscillations



Absolute minimum in NO, $\Delta\chi^2$(IO−NO) = 3.6

Oscillations



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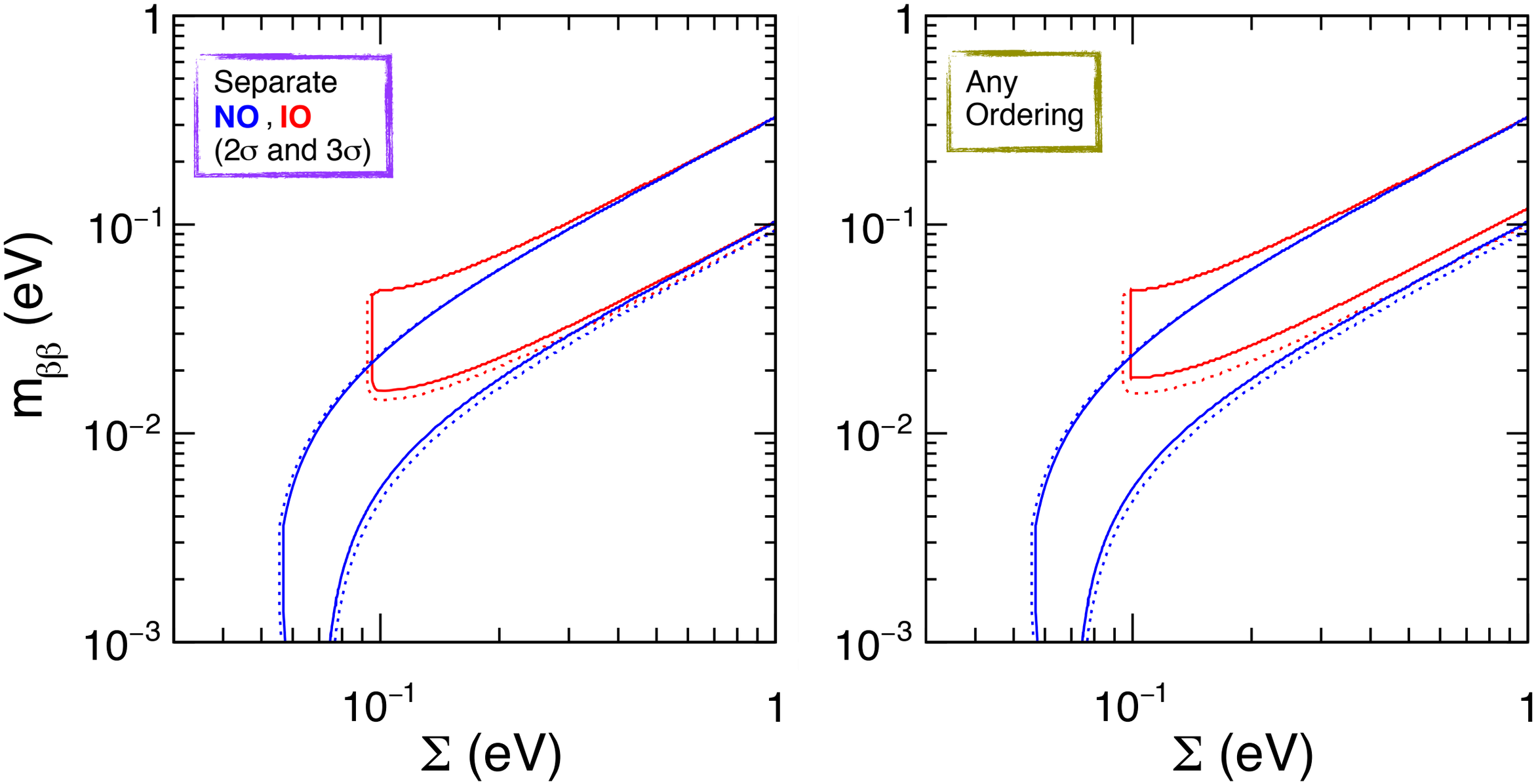

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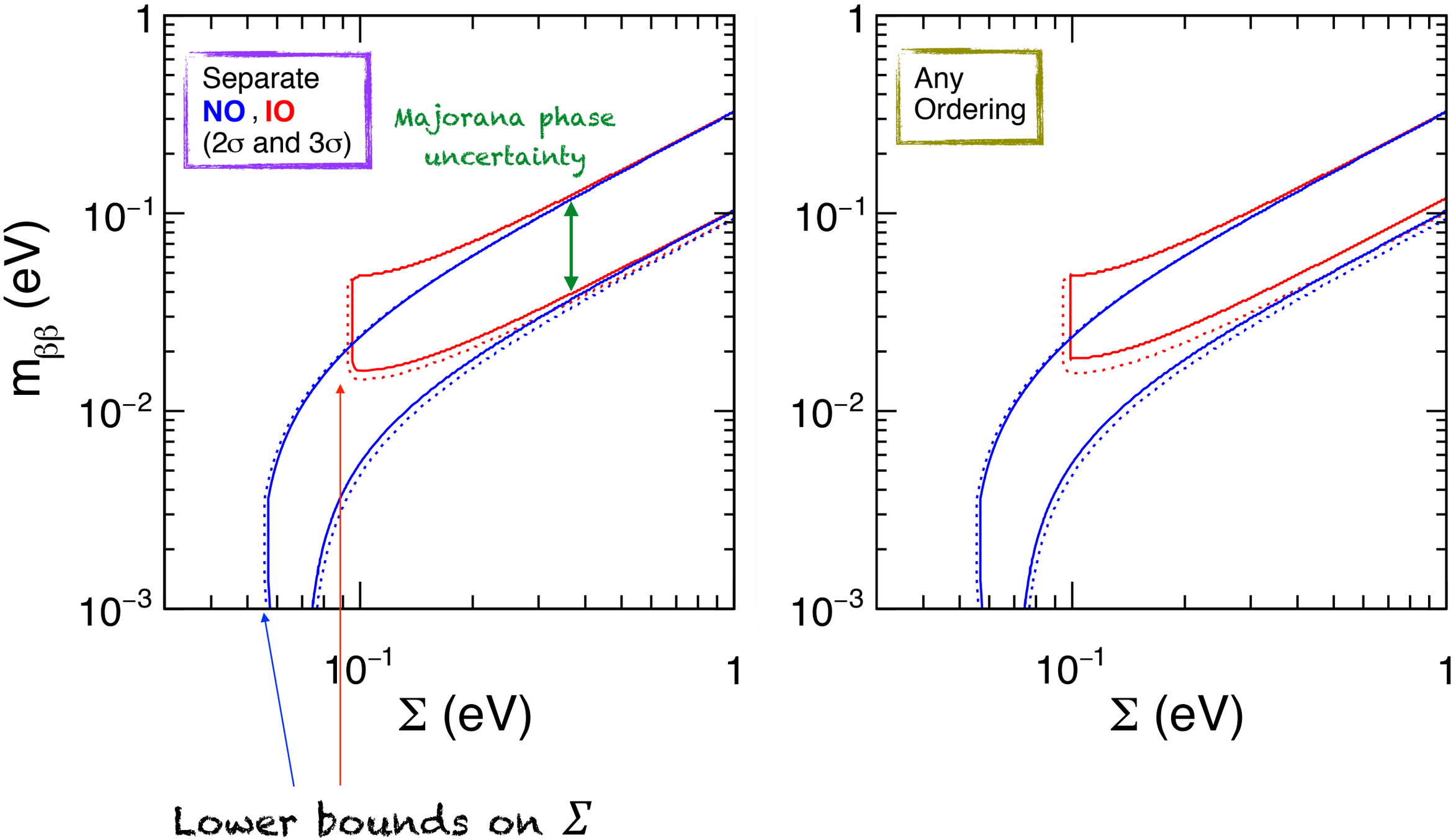

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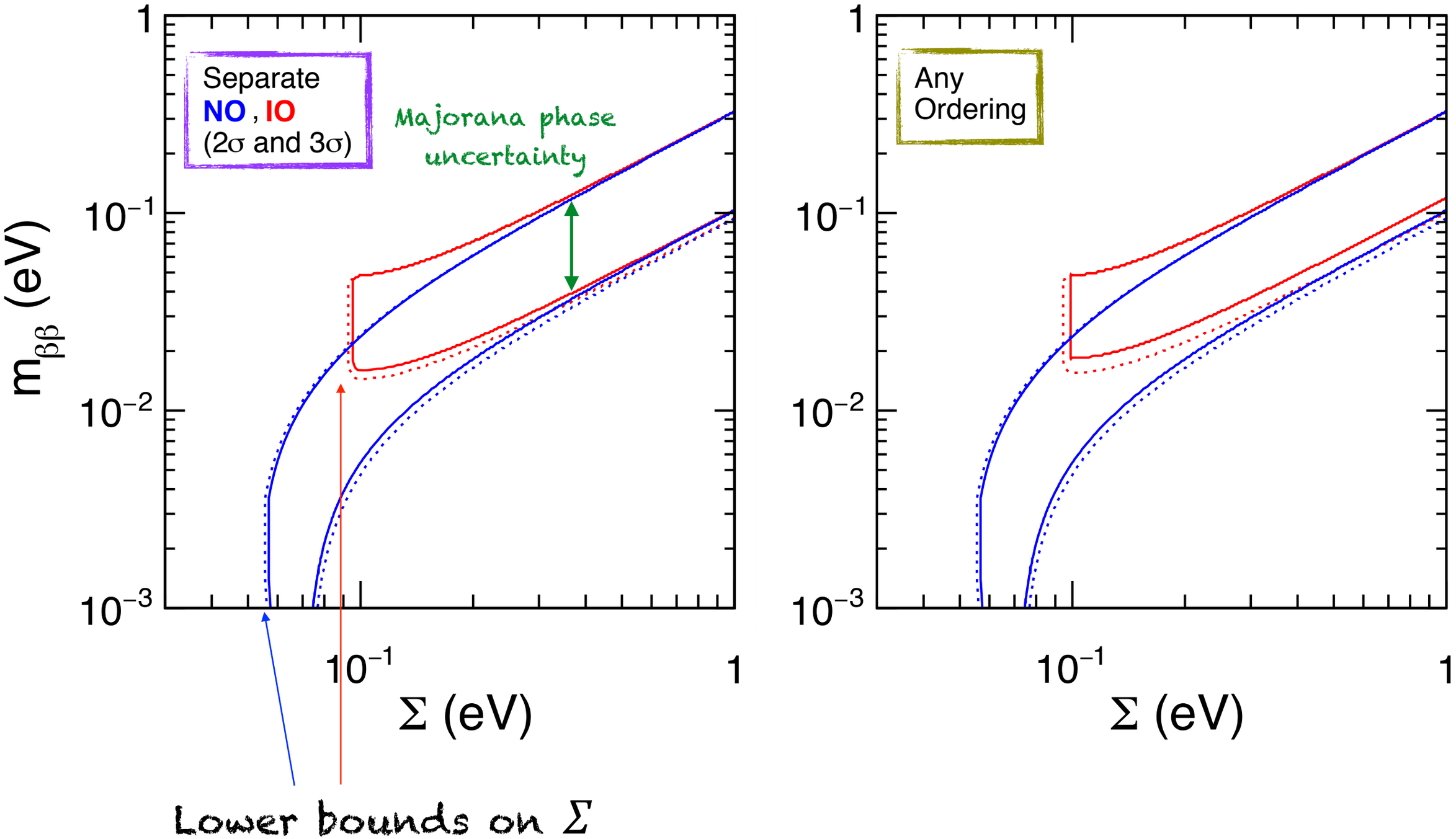

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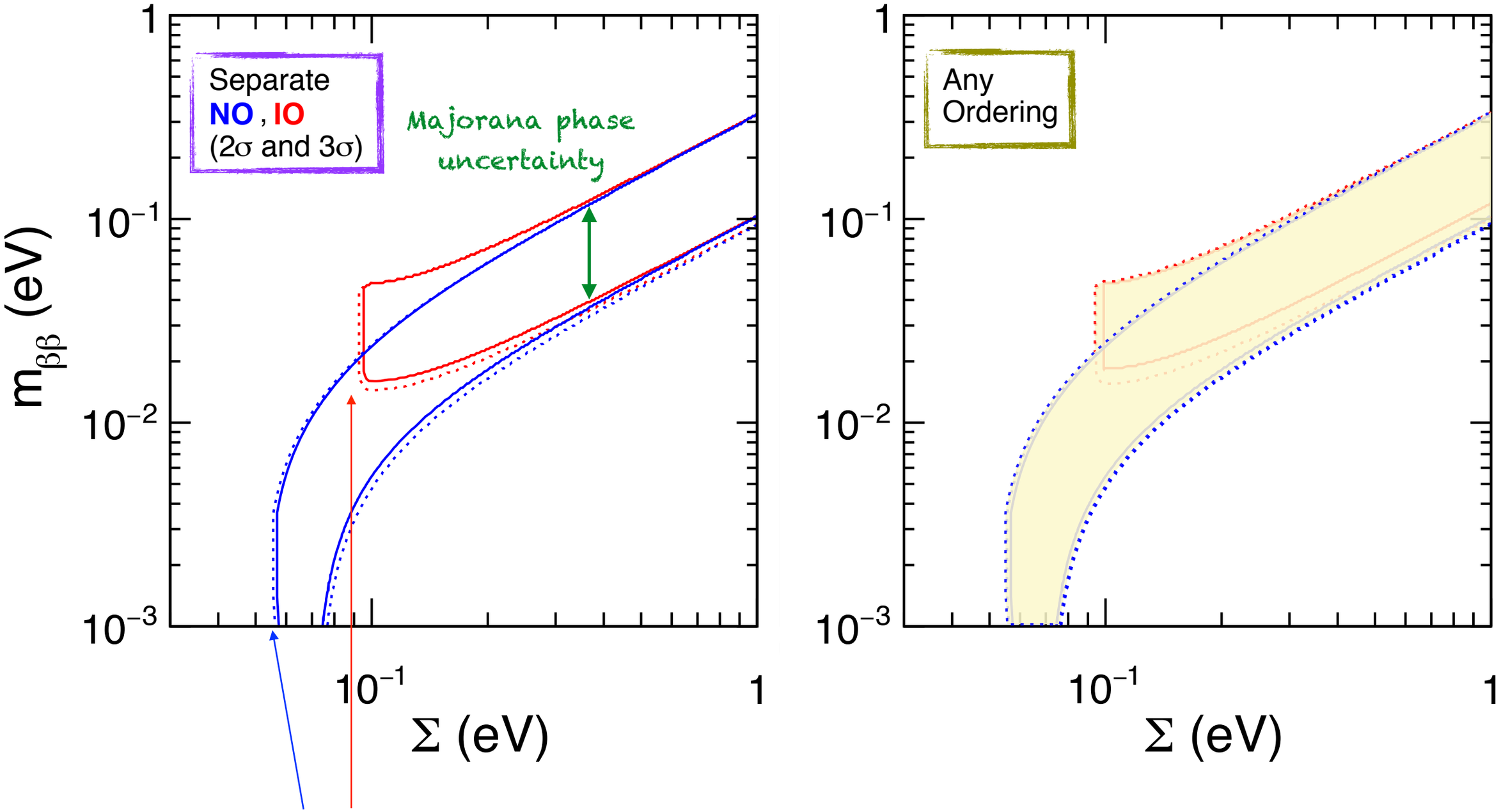

Lower bounds on Σ

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Including $0\nu\beta\beta$ data

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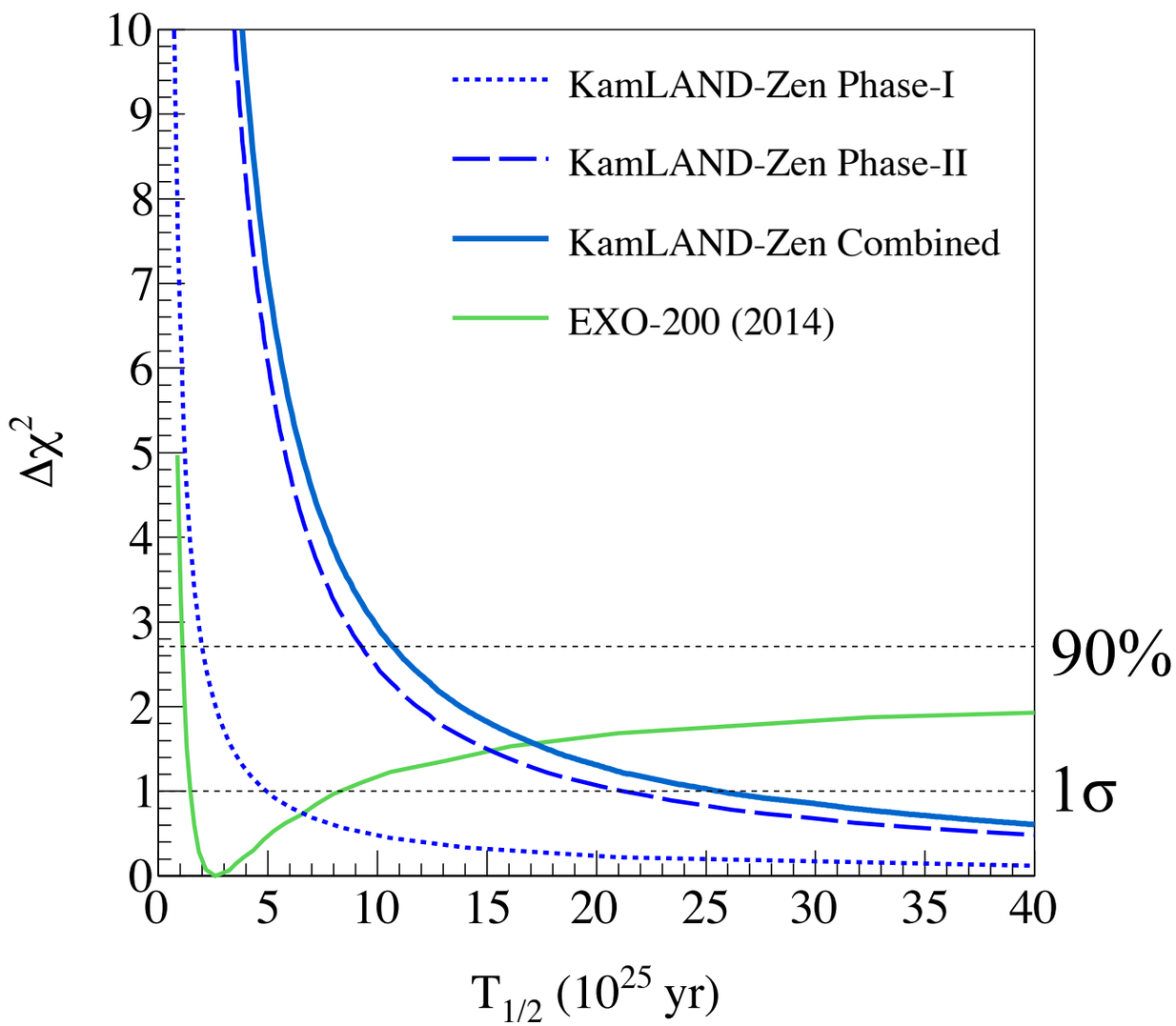
KamLAND-Zen ^{136}Xe Limits (90% C.L.)	
Phase 1	$T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr
Phase 2	$T_{1/2}(0\nu) > 9.2 \times 10^{25}$ yr
Combined	**$T_{1/2}(0\nu) > 1.07 \times 10^{26}$ yr**



J. Ouellet, talk at ICHEP2016

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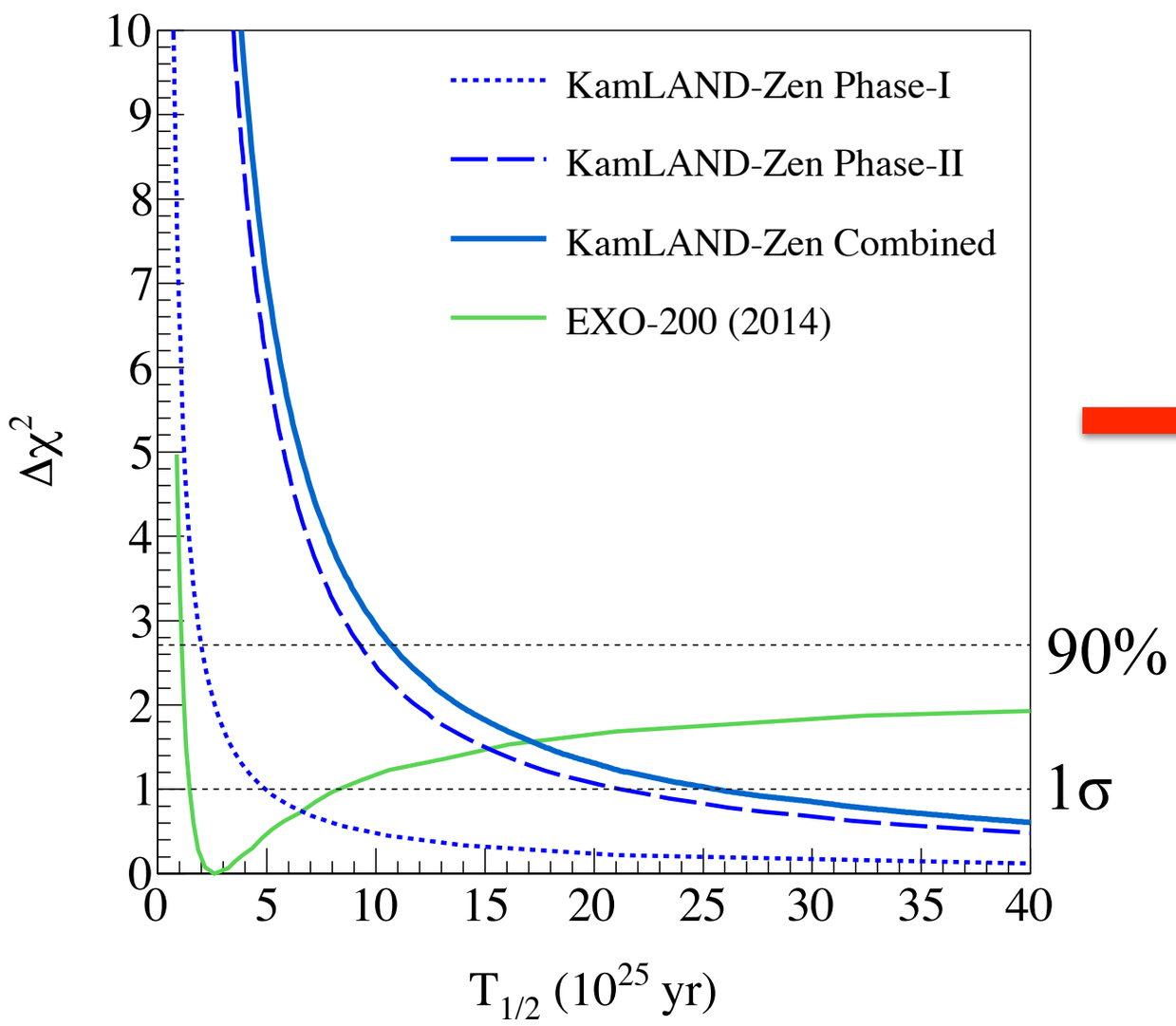

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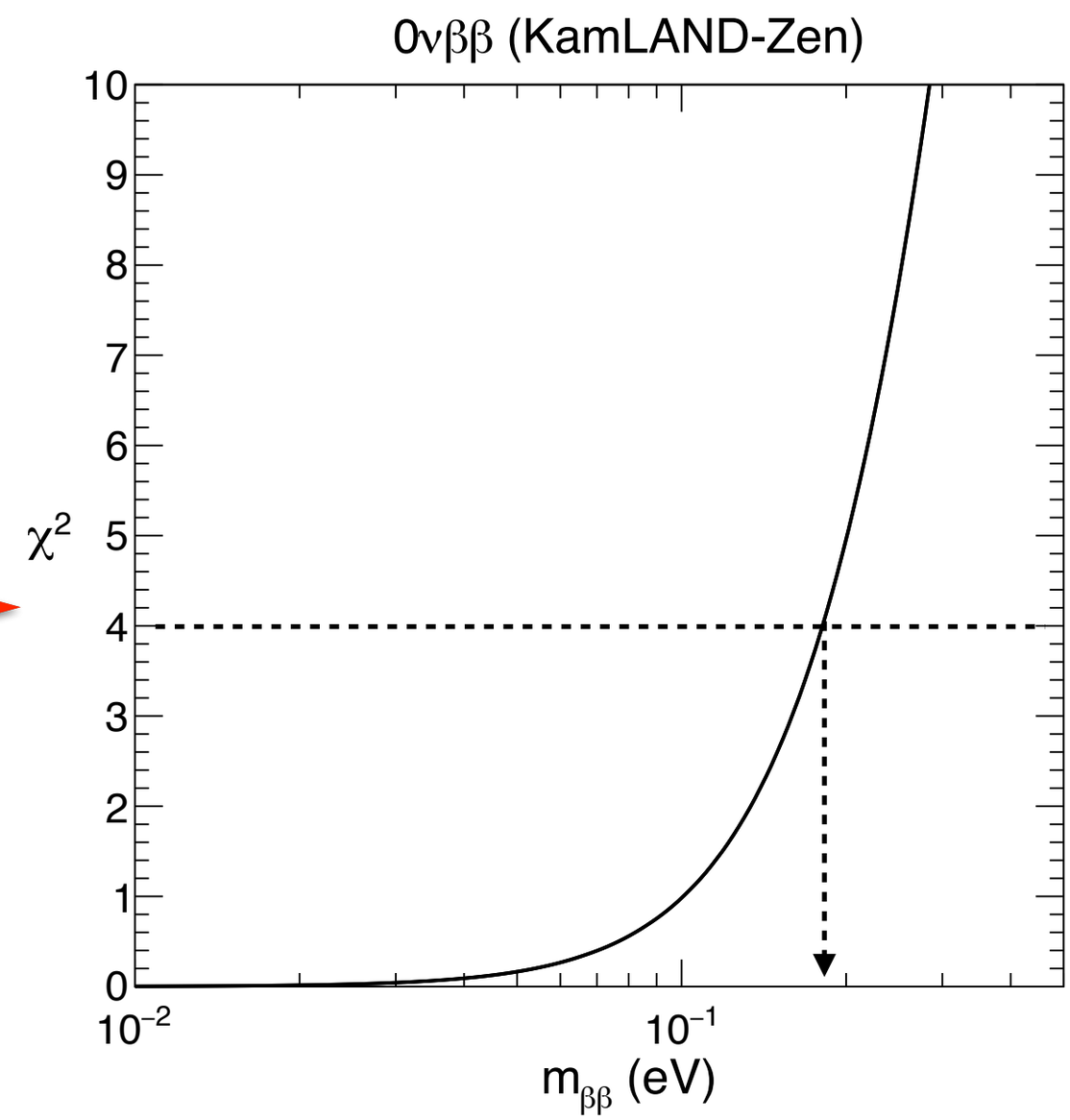
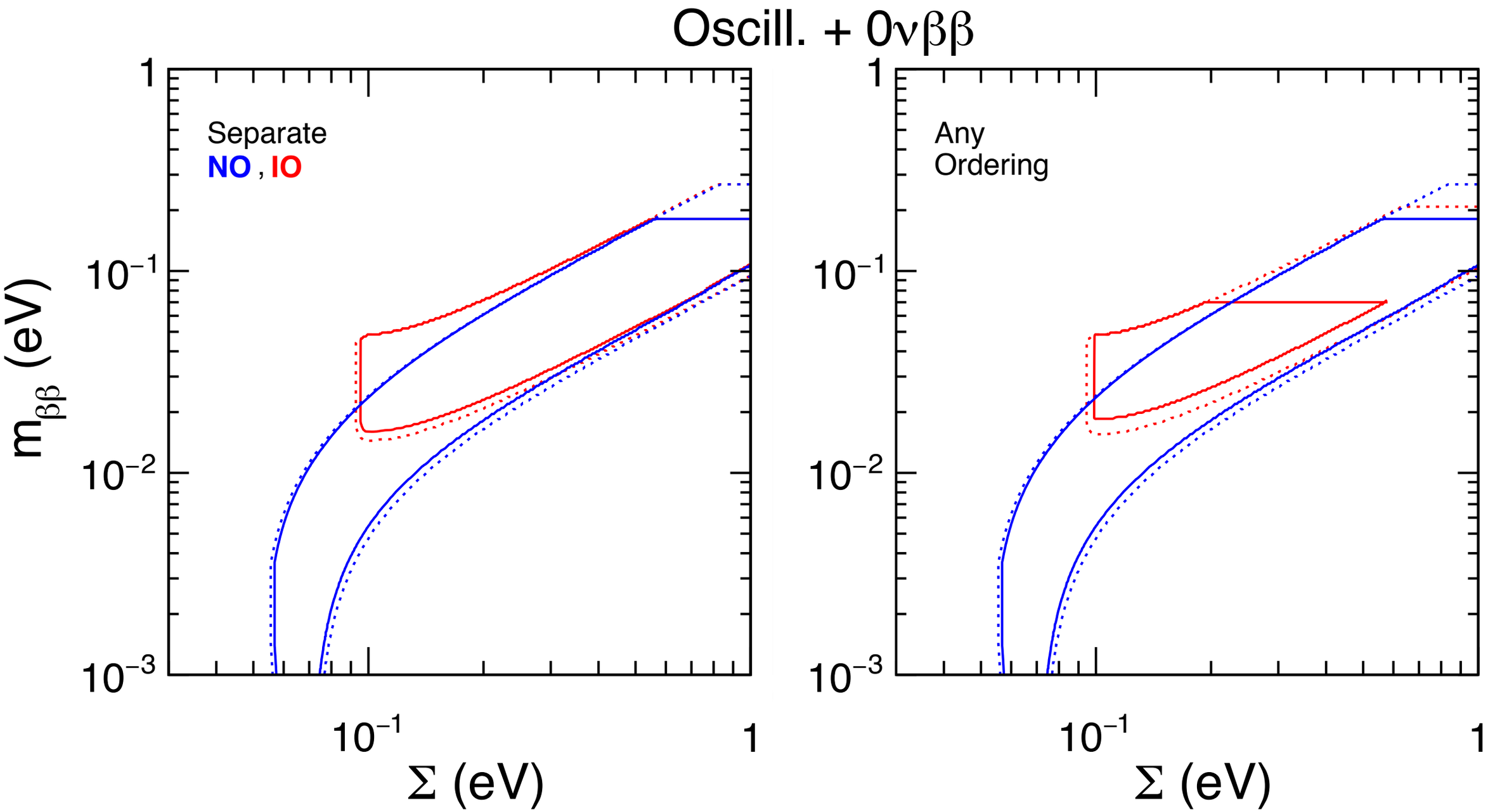
+NME Likelihood based on:
E.Lisi, A.Rotunno, F.Simkovic,
arXiv:1506.04058



$m_{\beta\beta} \lesssim 0.2$ eV at 2σ


Oscill. + 0νββ
Separate
NO , IO
Any
Ordering
$m_{\beta\beta}$ (eV)
Σ (eV)
1
10^{-1}
10^{-2}
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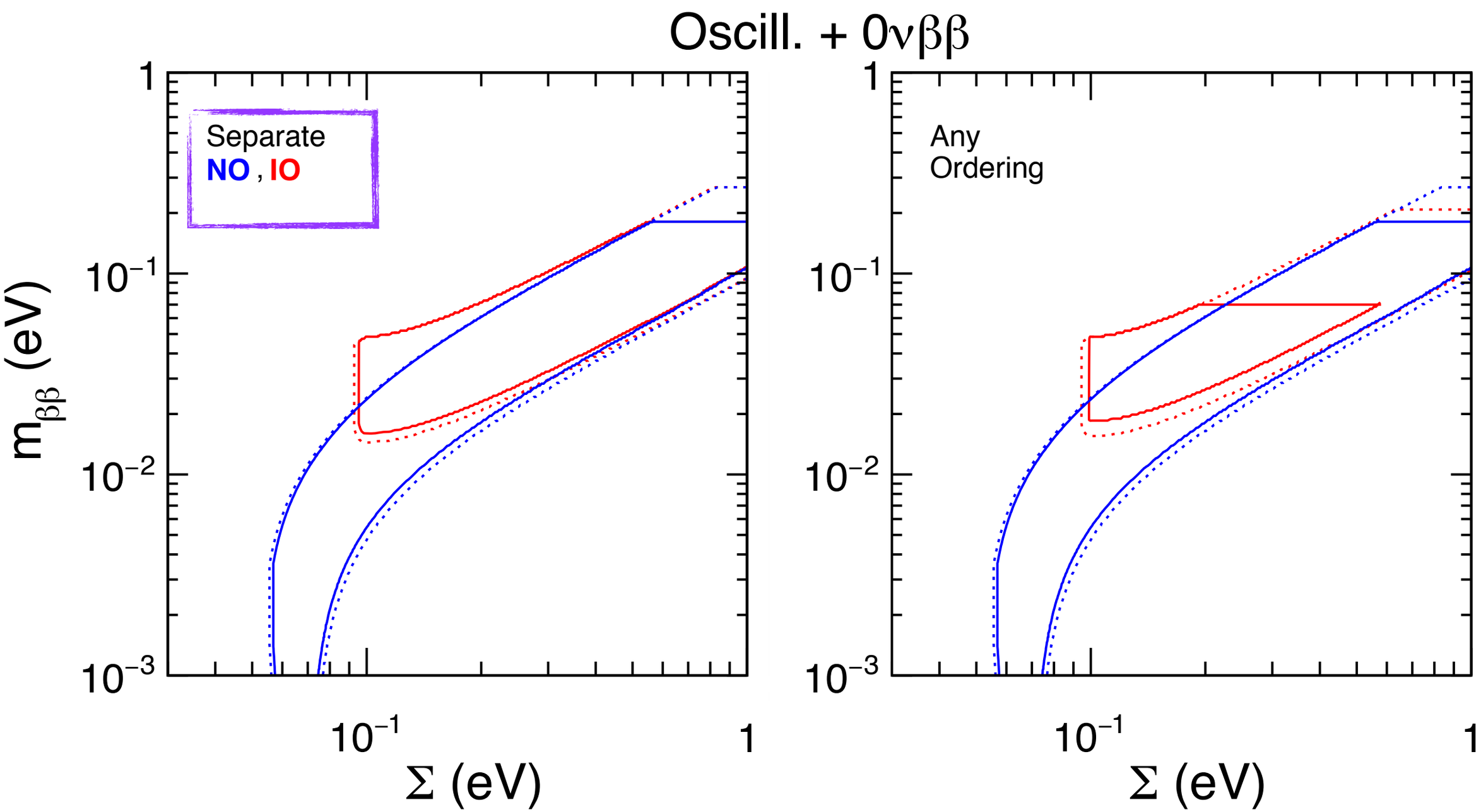
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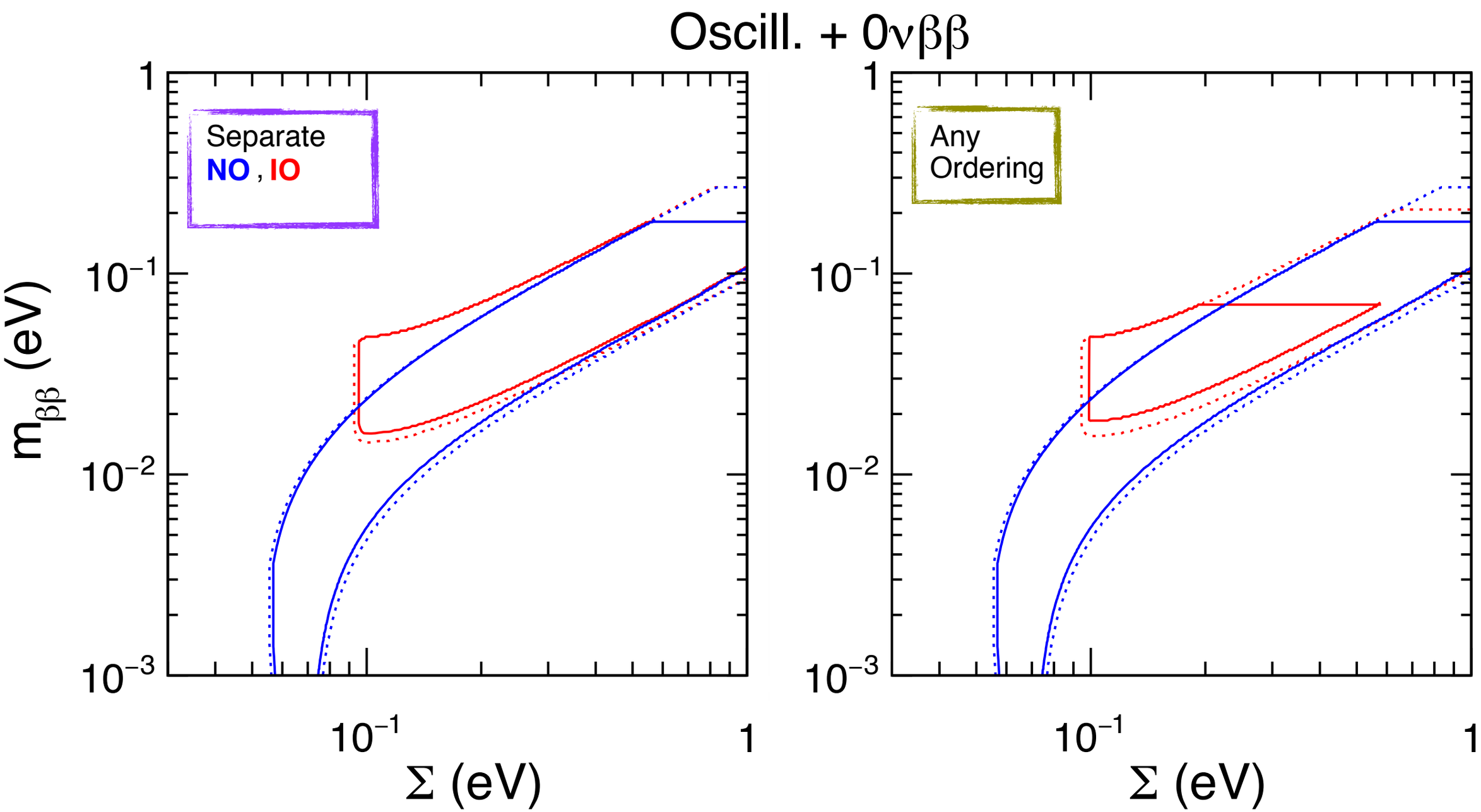
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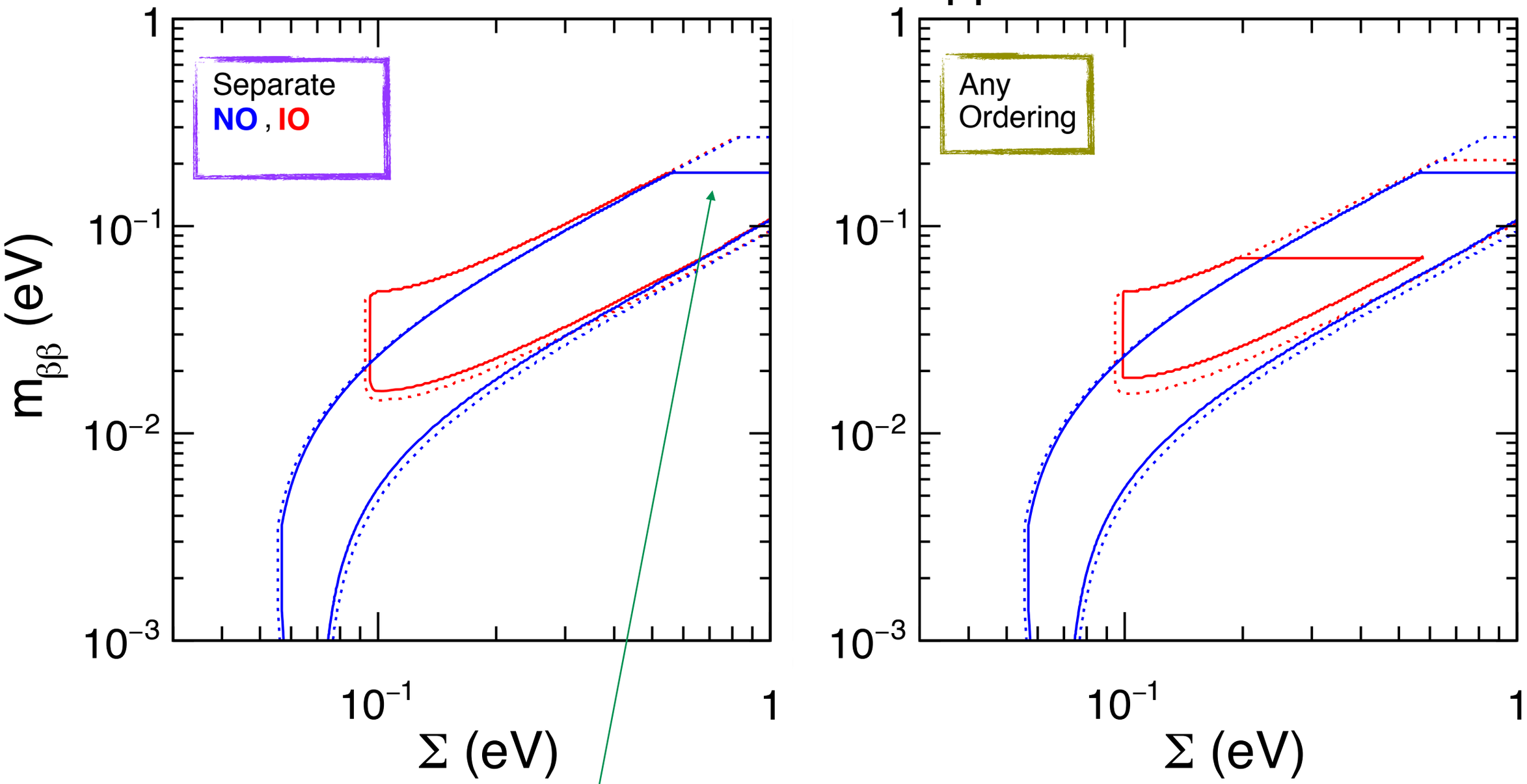
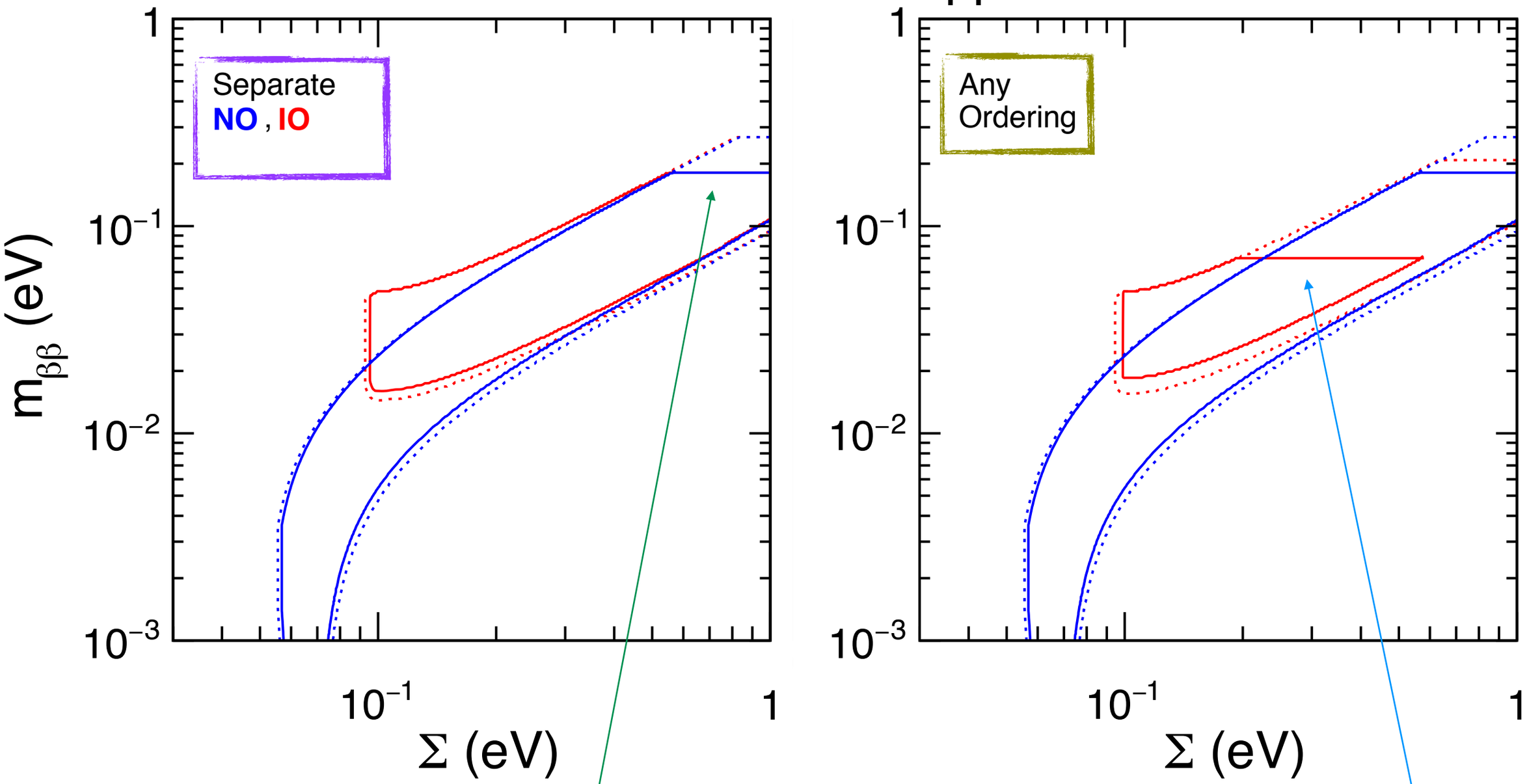


On the left: 2σ bound from KL-Zen when $m_{\beta\beta} \lesssim 0.2$ eV

Oscill. + 0νββ



On the left: 2σ bound from KL-Zen when $m_{\beta\beta} \lesssim 0.2$ eV

On the right: constraint from KL-Zen added to the $\Delta\chi^2$=3.6 offset from oscillations —> stronger bound on $m_{\beta\beta}$ for IO

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All in all 12 = 6 x 2 data set combinations
6 cases with A_{lens}=1 and 6 with A_{lens} free

Planck TT + τ_{HFI}
Planck TT + τ_{HFI} + lensing
Planck TT + τ_{HFI} + BAO
Planck TT, TE, EE + τ_{HFI}
Planck TT, TE, EE + τ_{HFI} + lensing
Planck TT, TE, EE + τ_{HFI} + BAO

TT	Temperature anisotropy
TE,EE	Polarization
τ_{HFI}	Reionization prior on optical depth
BAO	Baryon acoustic oscillation

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	ΛCDM + Σ	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	ΛCDM + Σ	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	ΛCDM + Σ	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	ΛCDM + Σ	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	ΛCDM + Σ	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	ΛCDM + Σ	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	ΛCDM + Σ + A_{lens}	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	ΛCDM + Σ + A_{lens}	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	ΛCDM + Σ + A_{lens}	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
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4	ΛCDM + Σ	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	ΛCDM + Σ	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	ΛCDM + Σ	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
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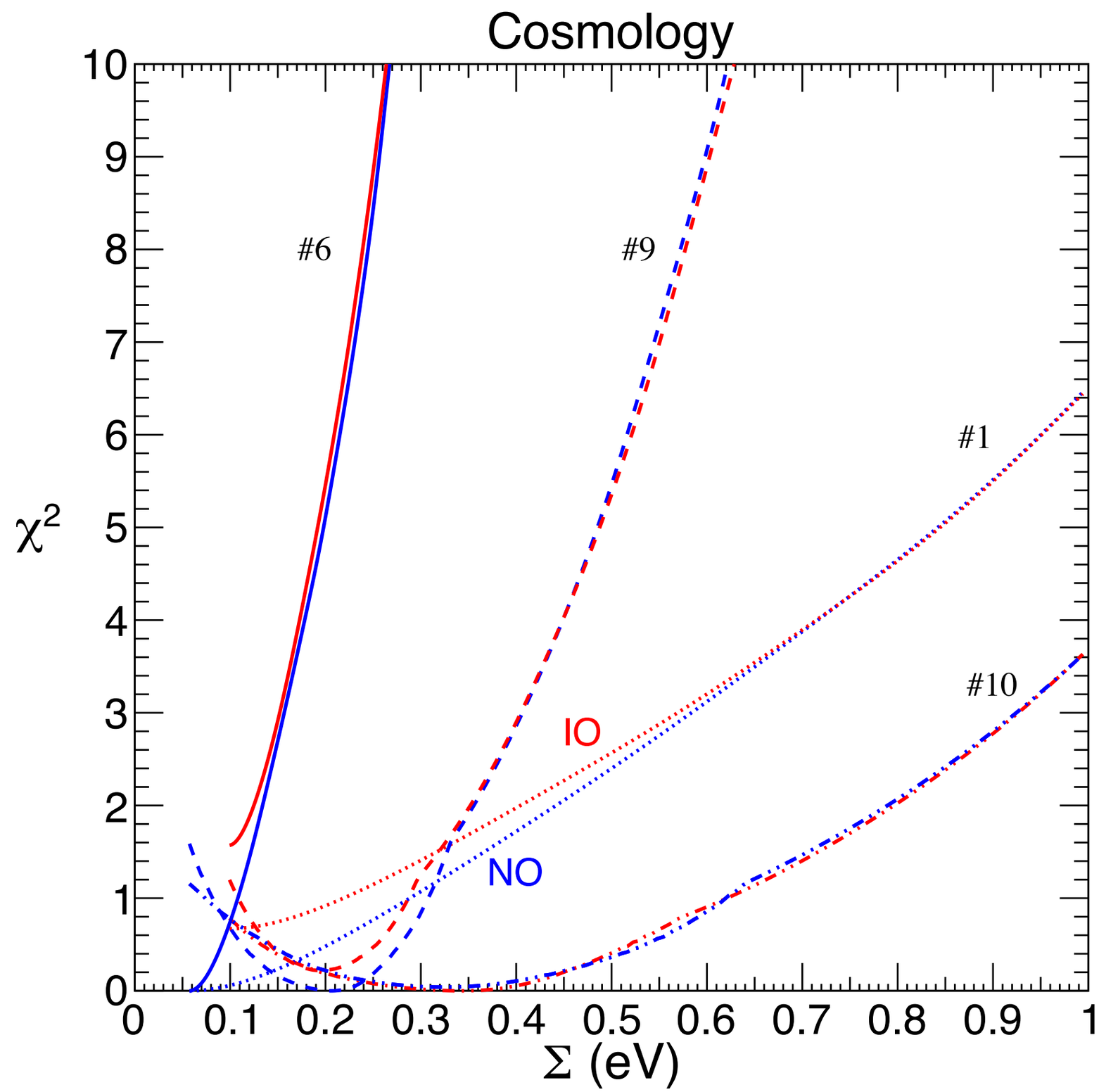
Focus on 4 representative cases → (#10,#1,#9,#6)

4 selected cases with increasingly strong bounds on Σ



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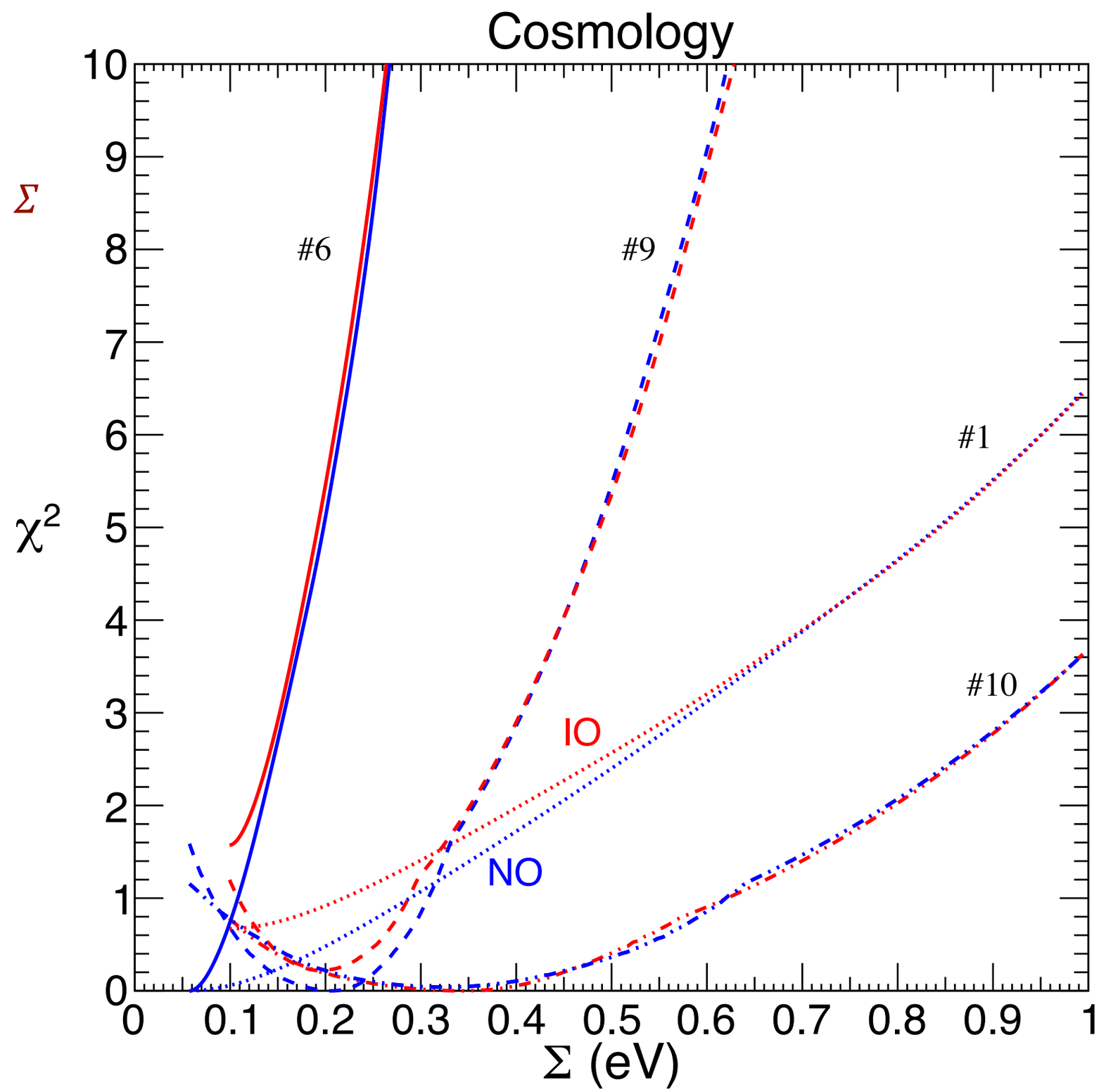
- χ^2 curves for NO and IO converge for large Σ



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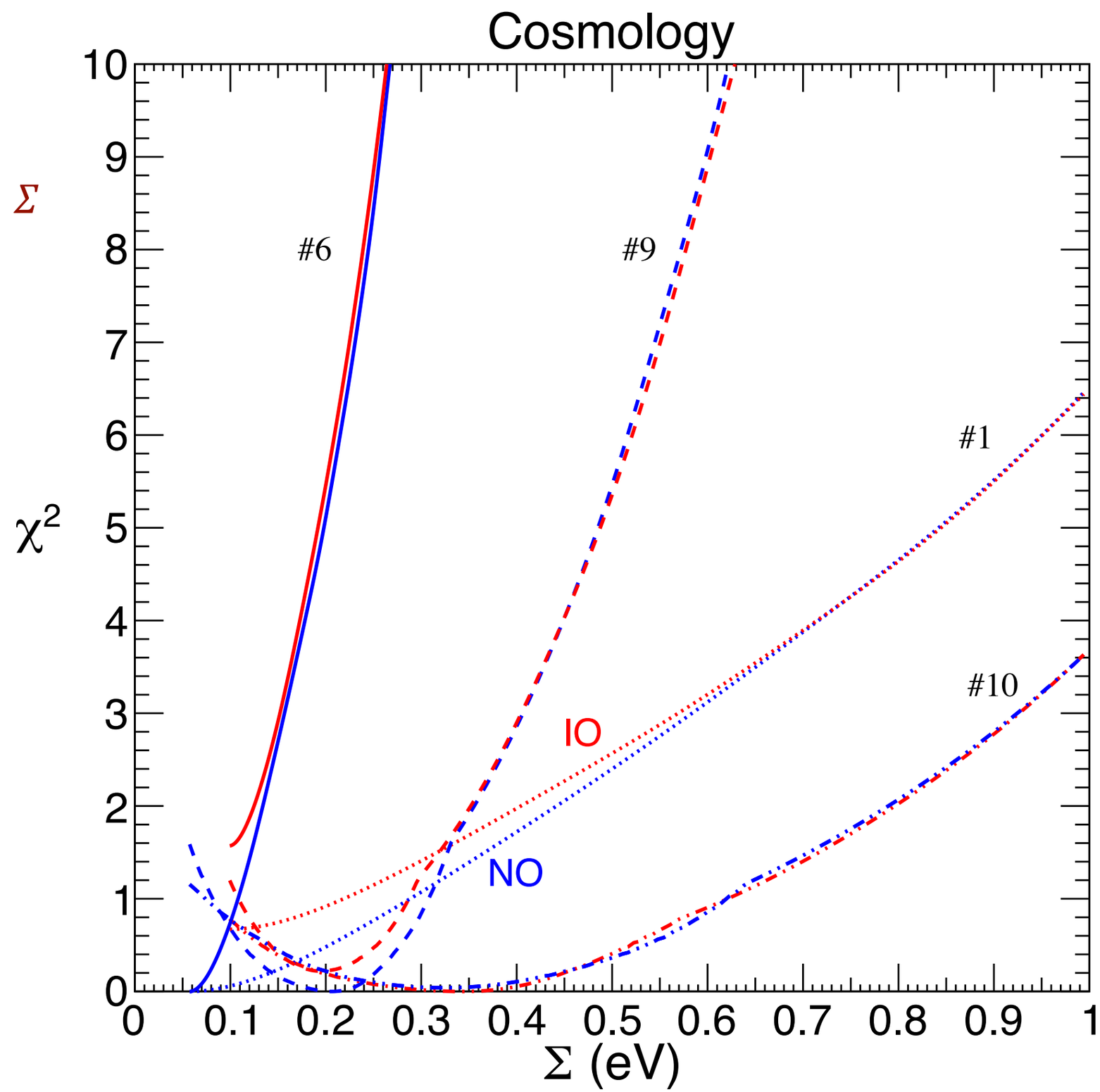

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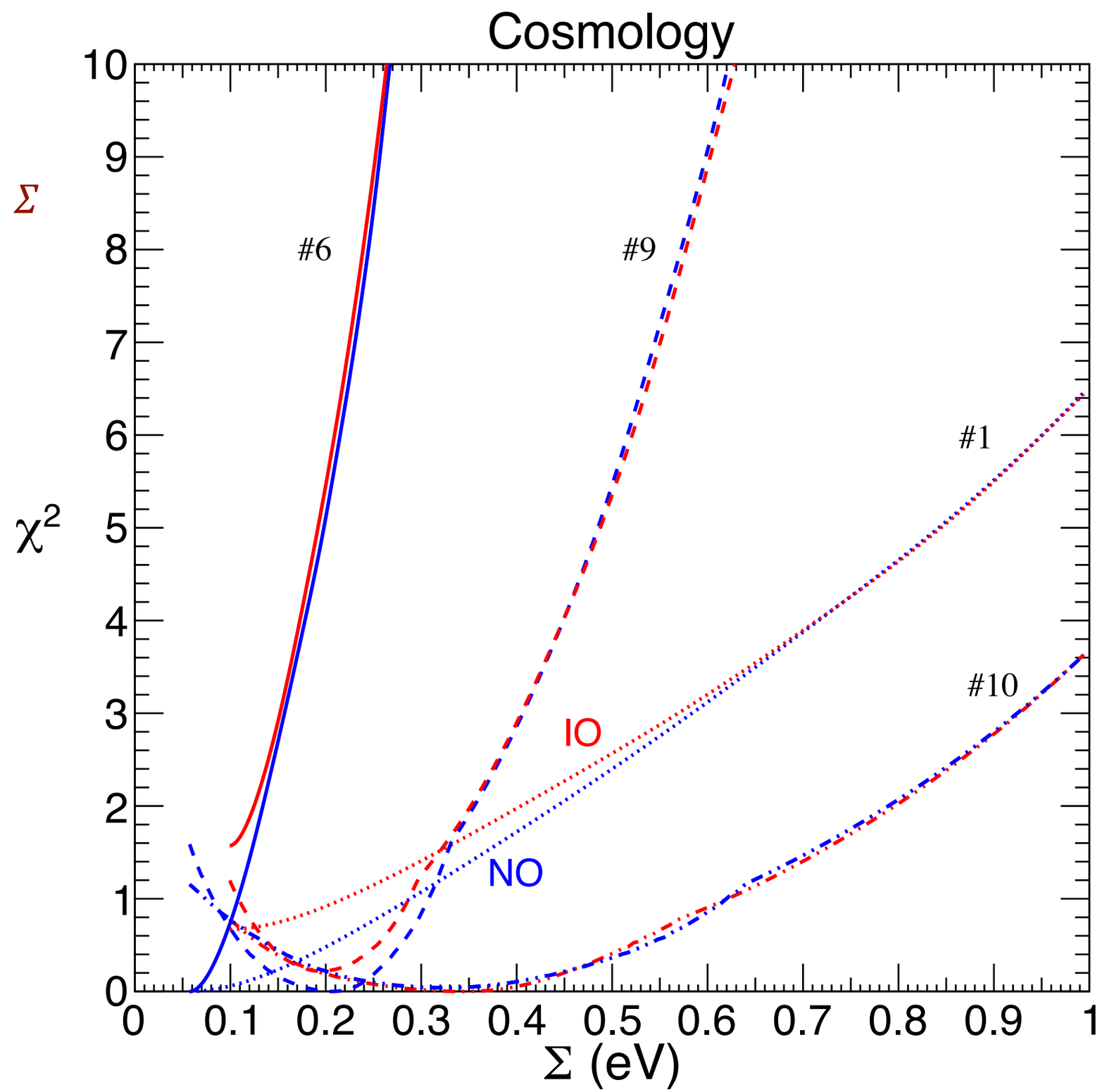

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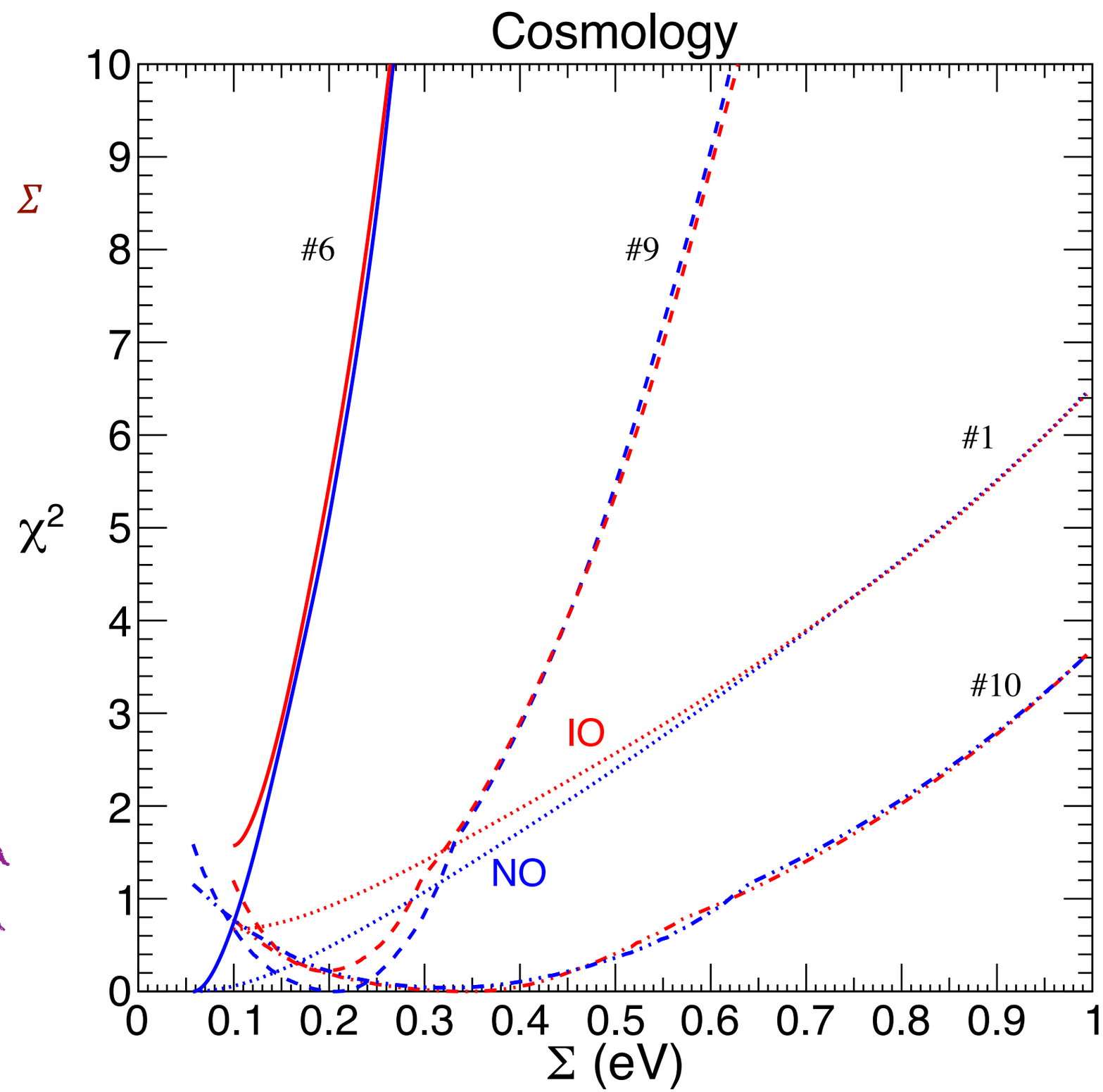
- For cases #10 and #9 the minimum of the χ^2 is reached for a value of Σ higher than the minimum allowed



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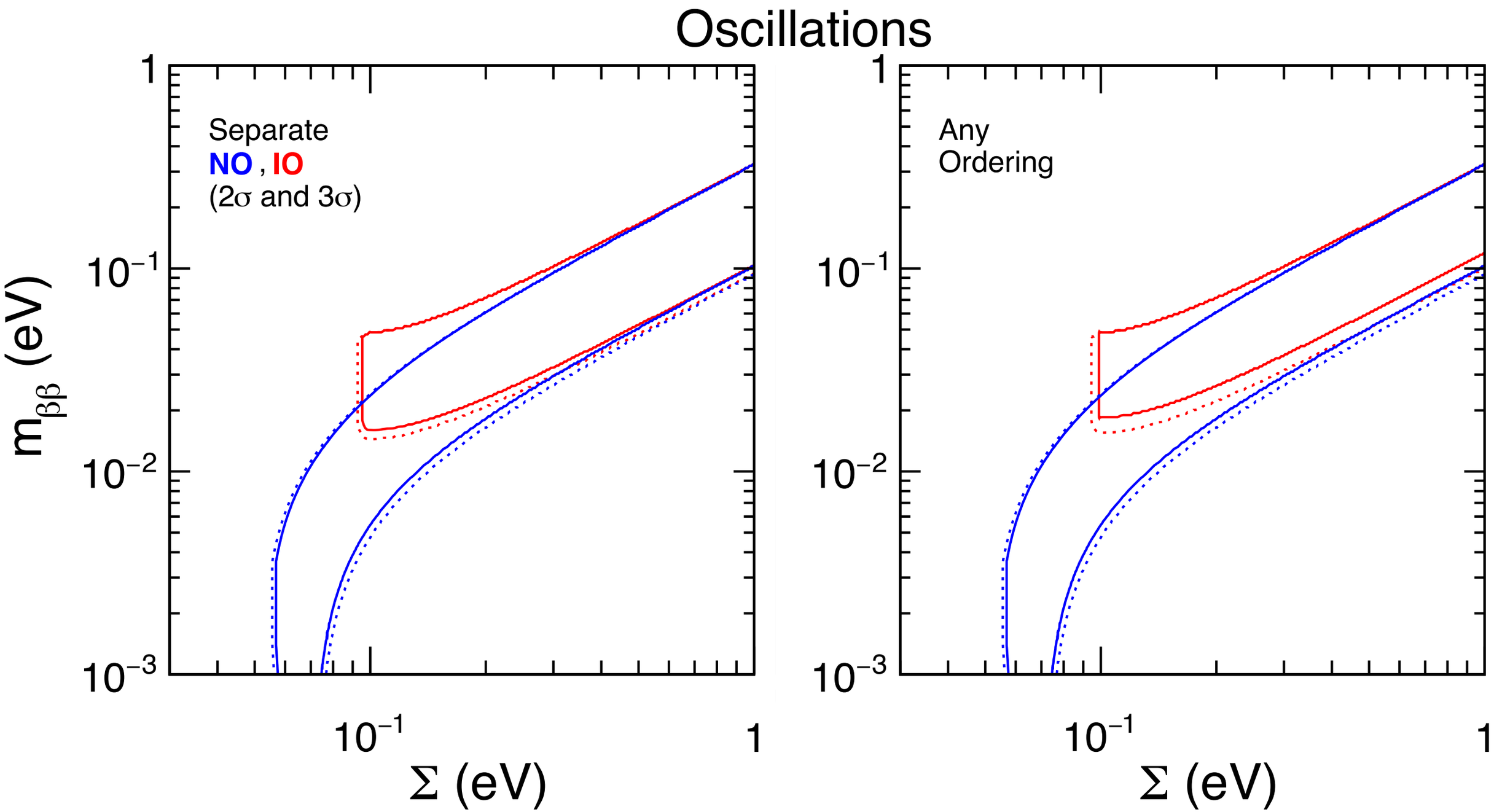

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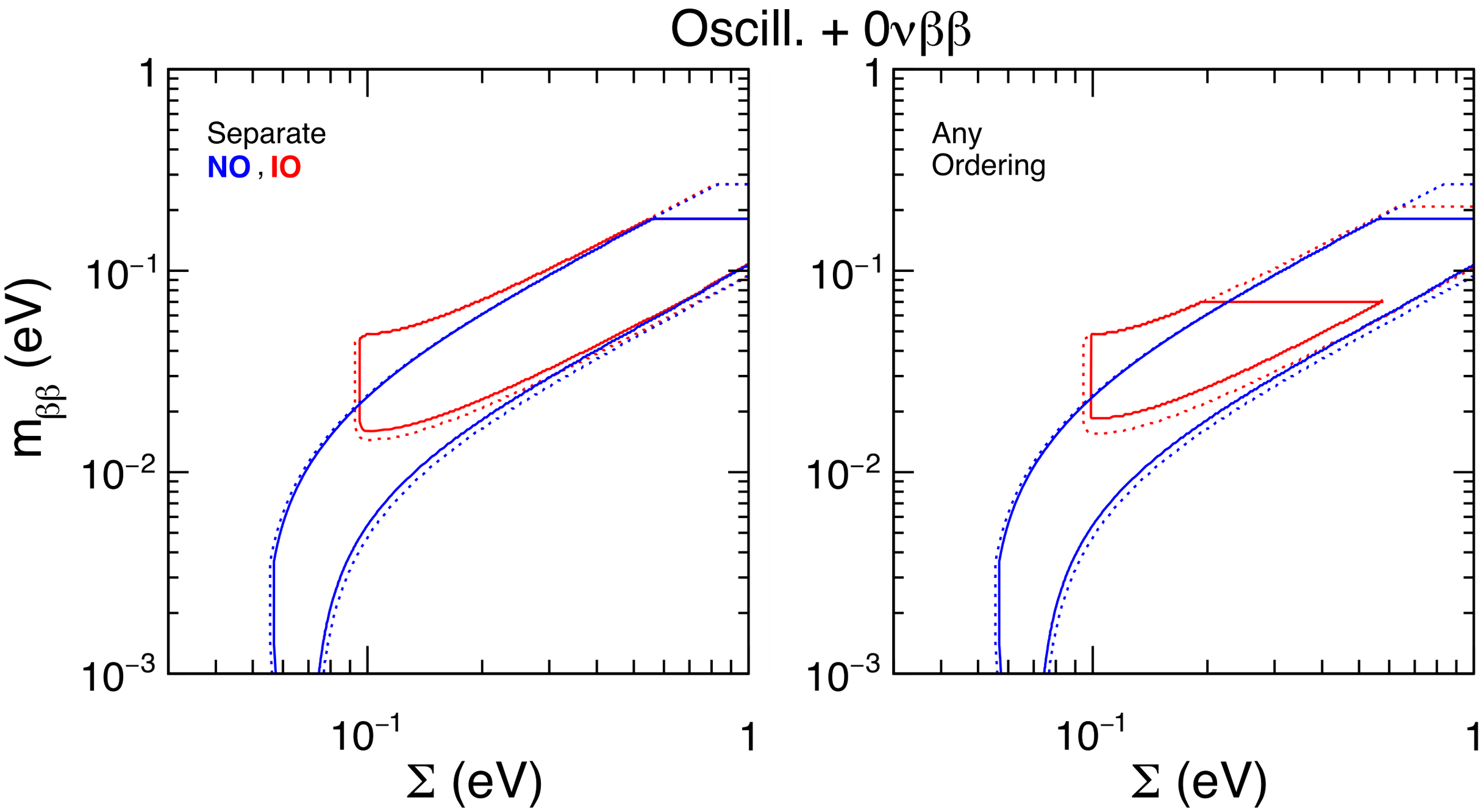

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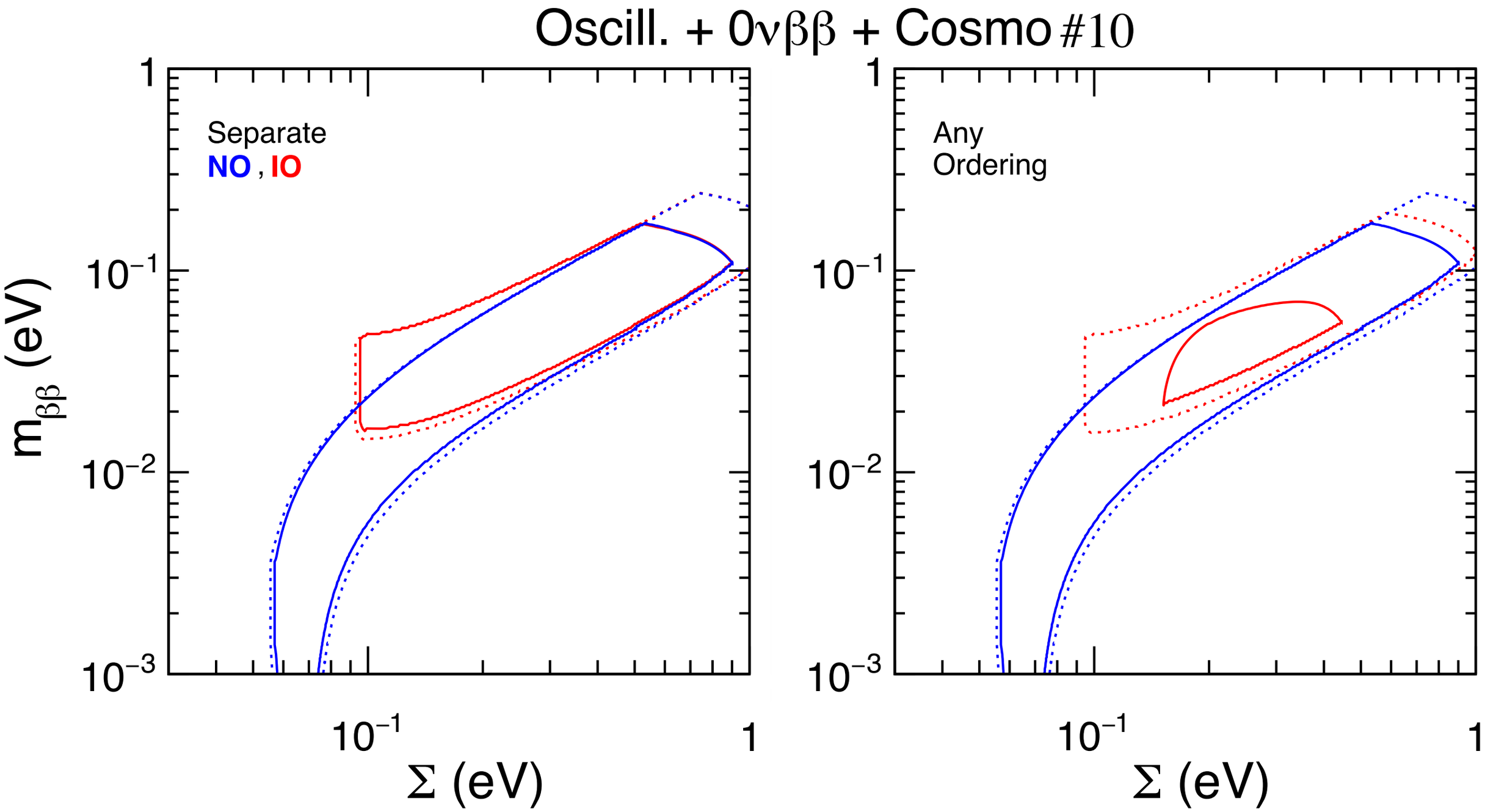

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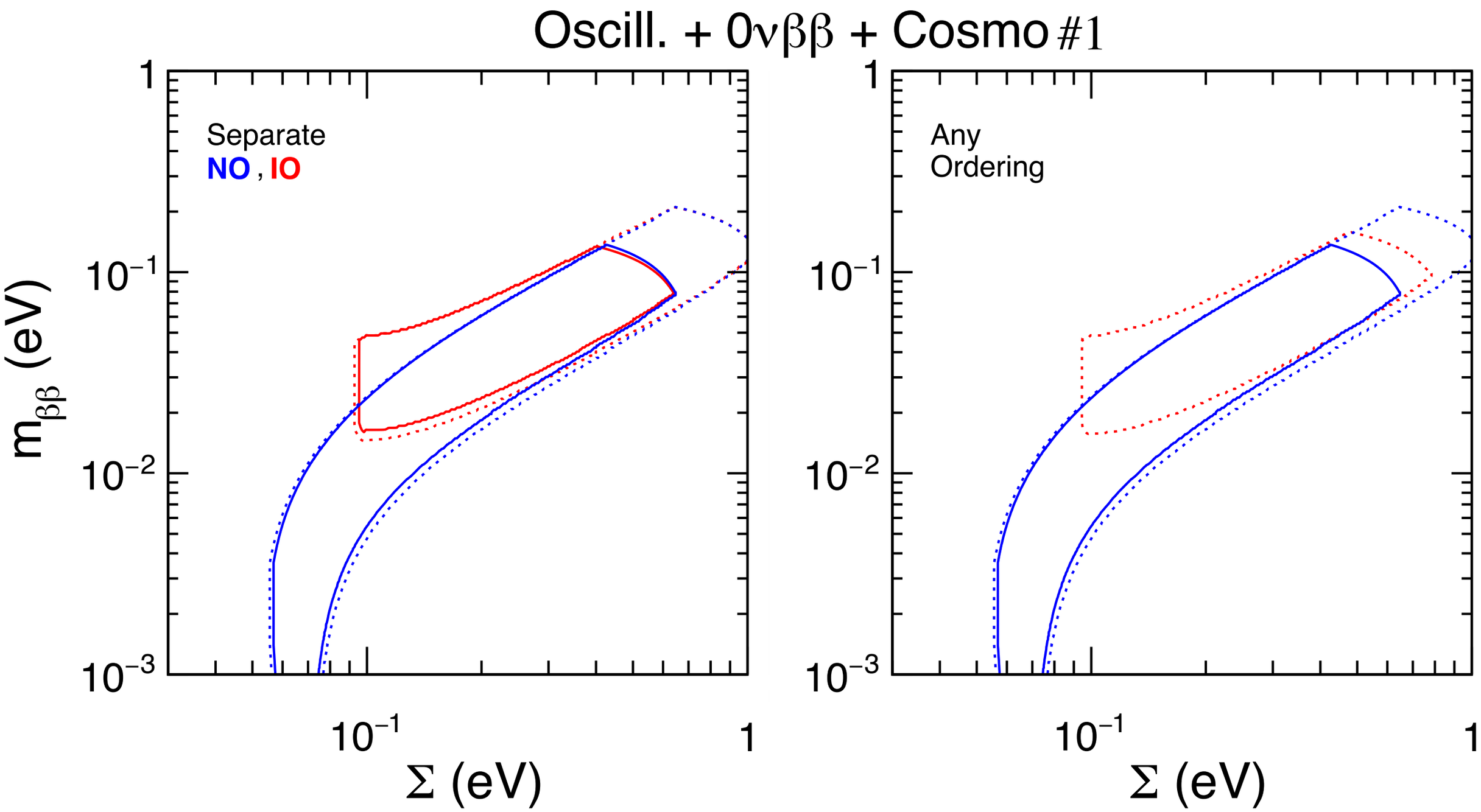

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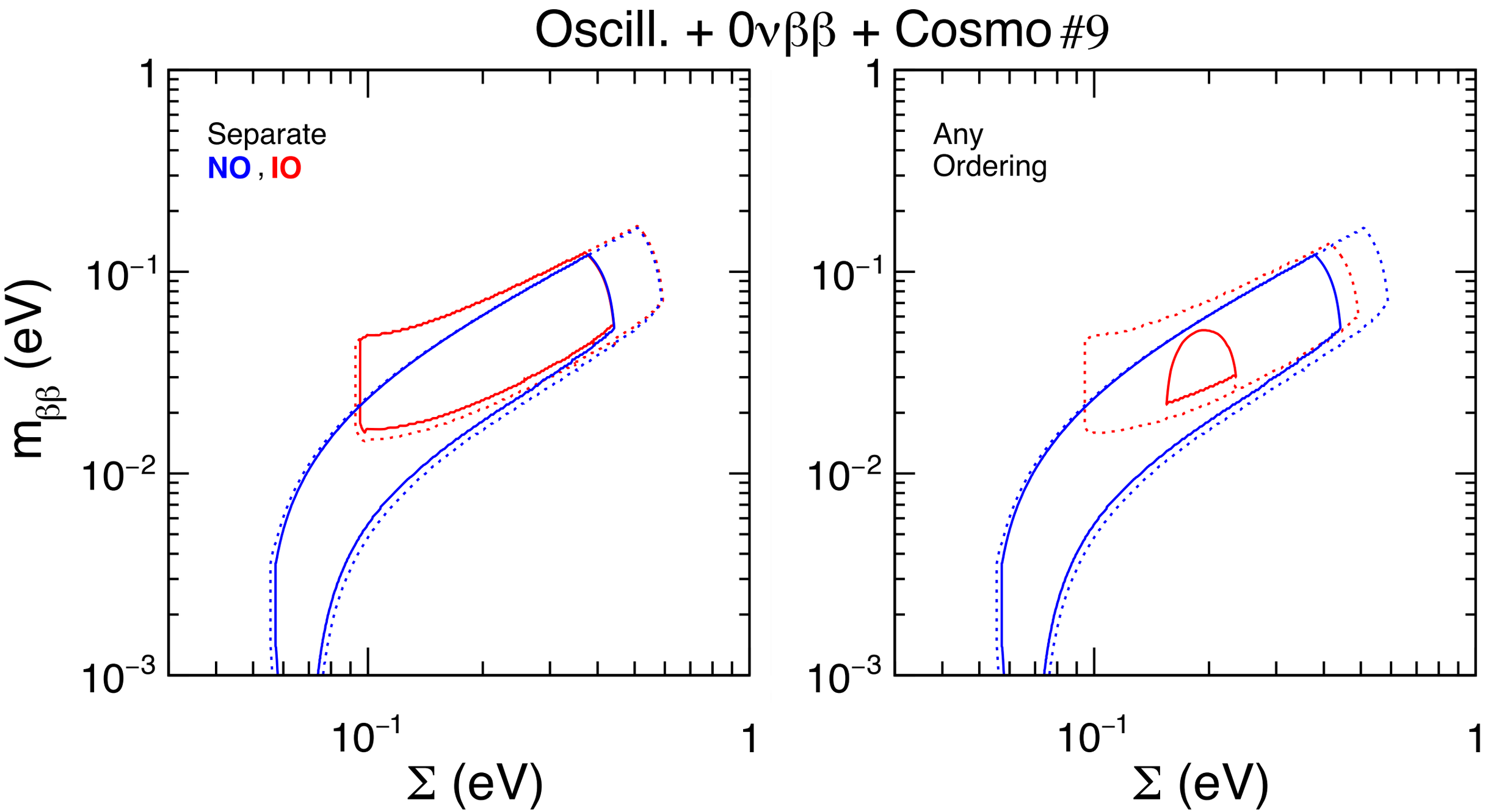

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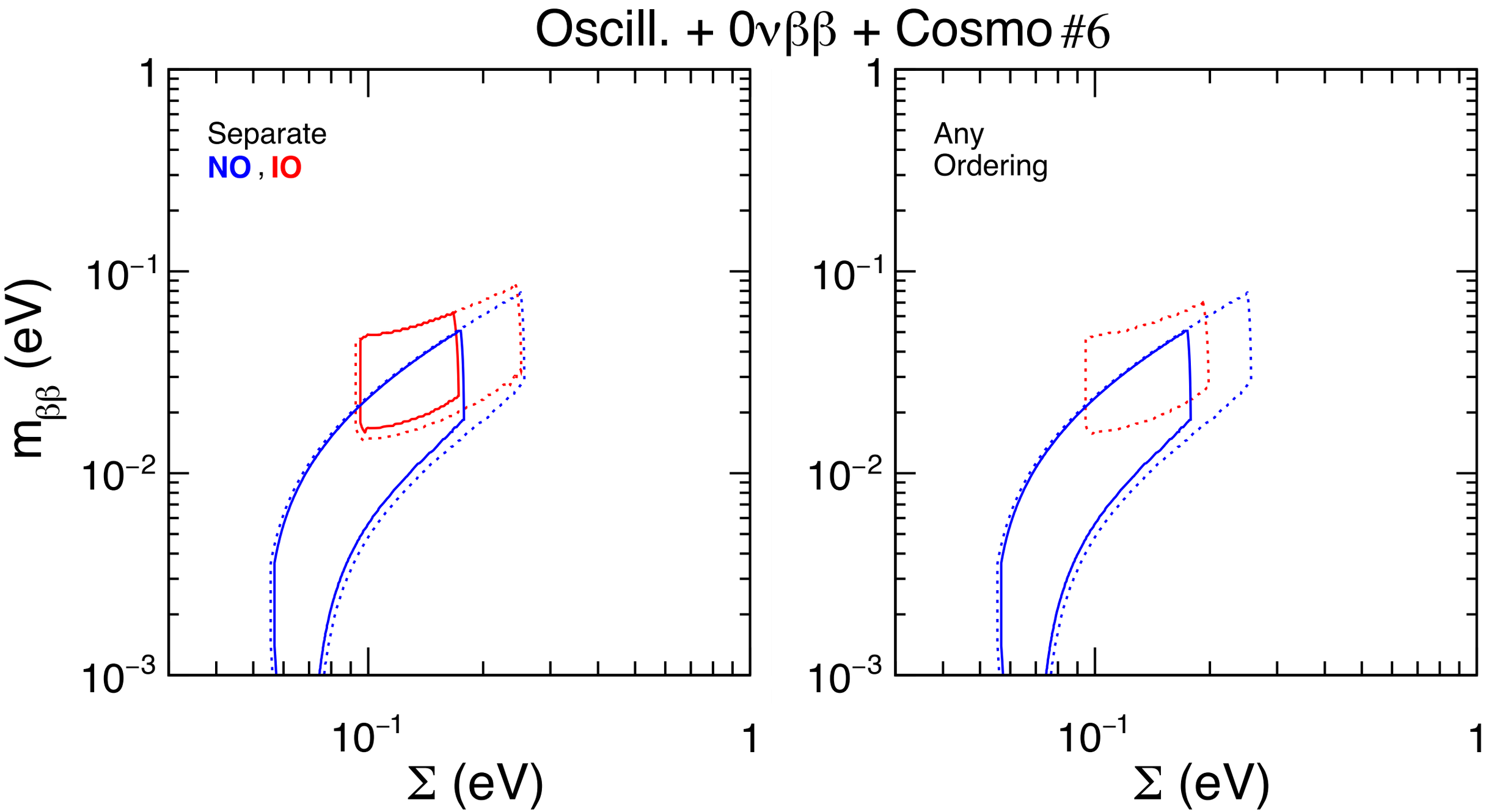

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