INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS 39th Course

Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics

Constraints on neutrino oscillation parameters from global fits

A. Marrone - Univ. of Bari & INFN

Erice, September 16-24, 2017

Outline

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- Neutrino Oscillation parameters: knowns and unknowns

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- Constraints on absolute masses and their ordering from $0\nu\beta\beta$ and Cosmology

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- Constraints on absolute masses and their ordering from $0\nu\beta\beta$ and Cosmology
- Mass Ordering from MBL experiments and ATM neutrinos
- Conclusions

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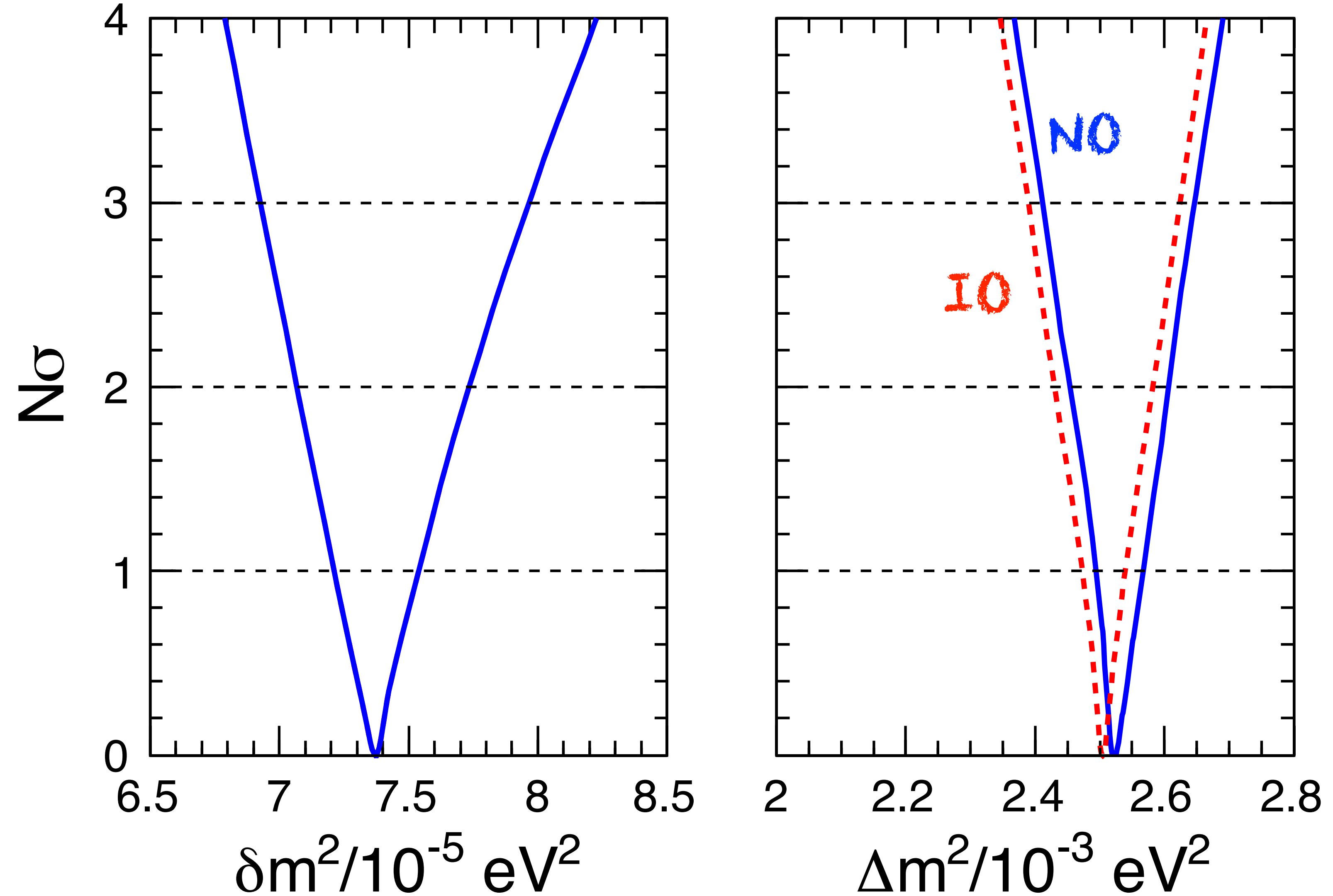

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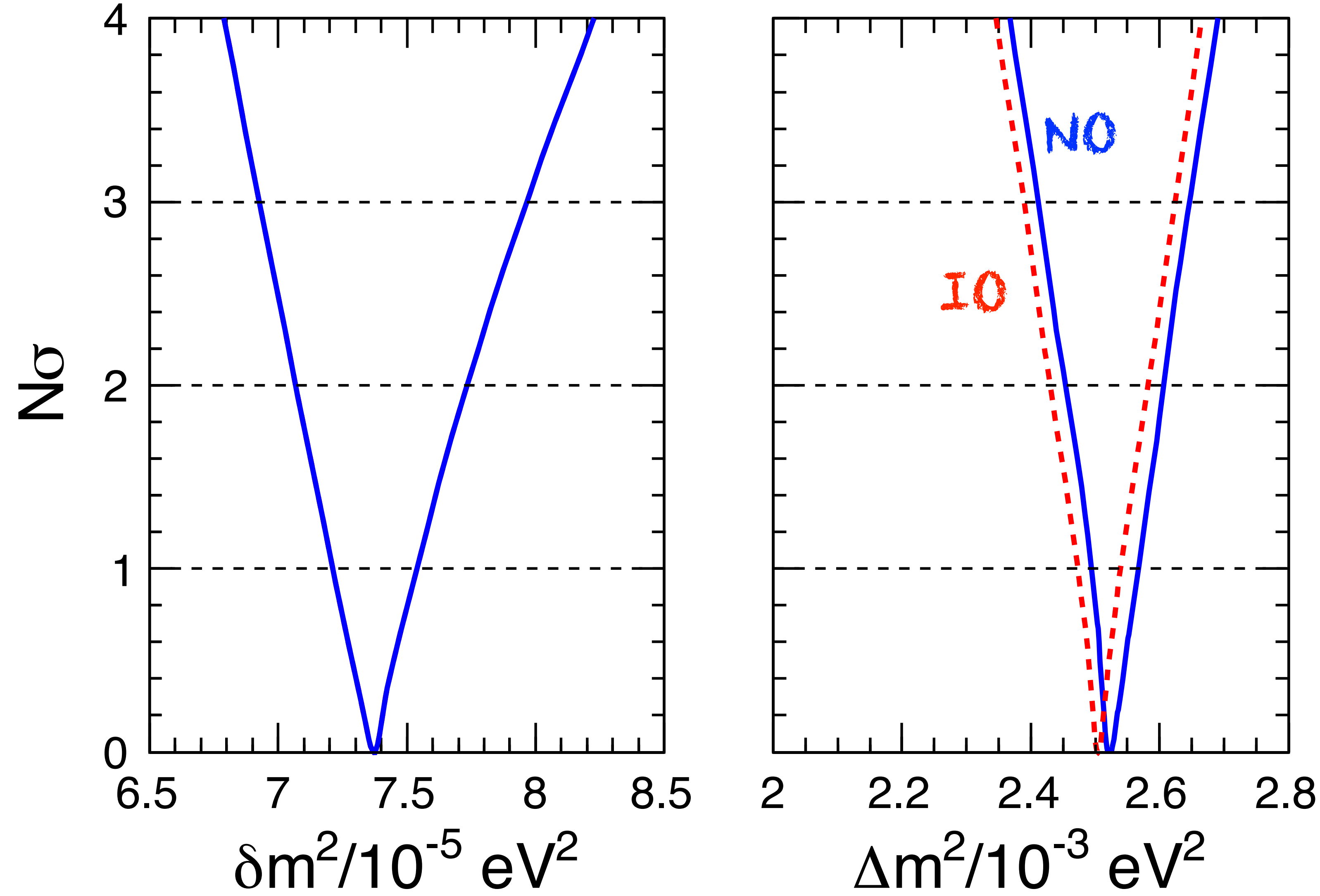

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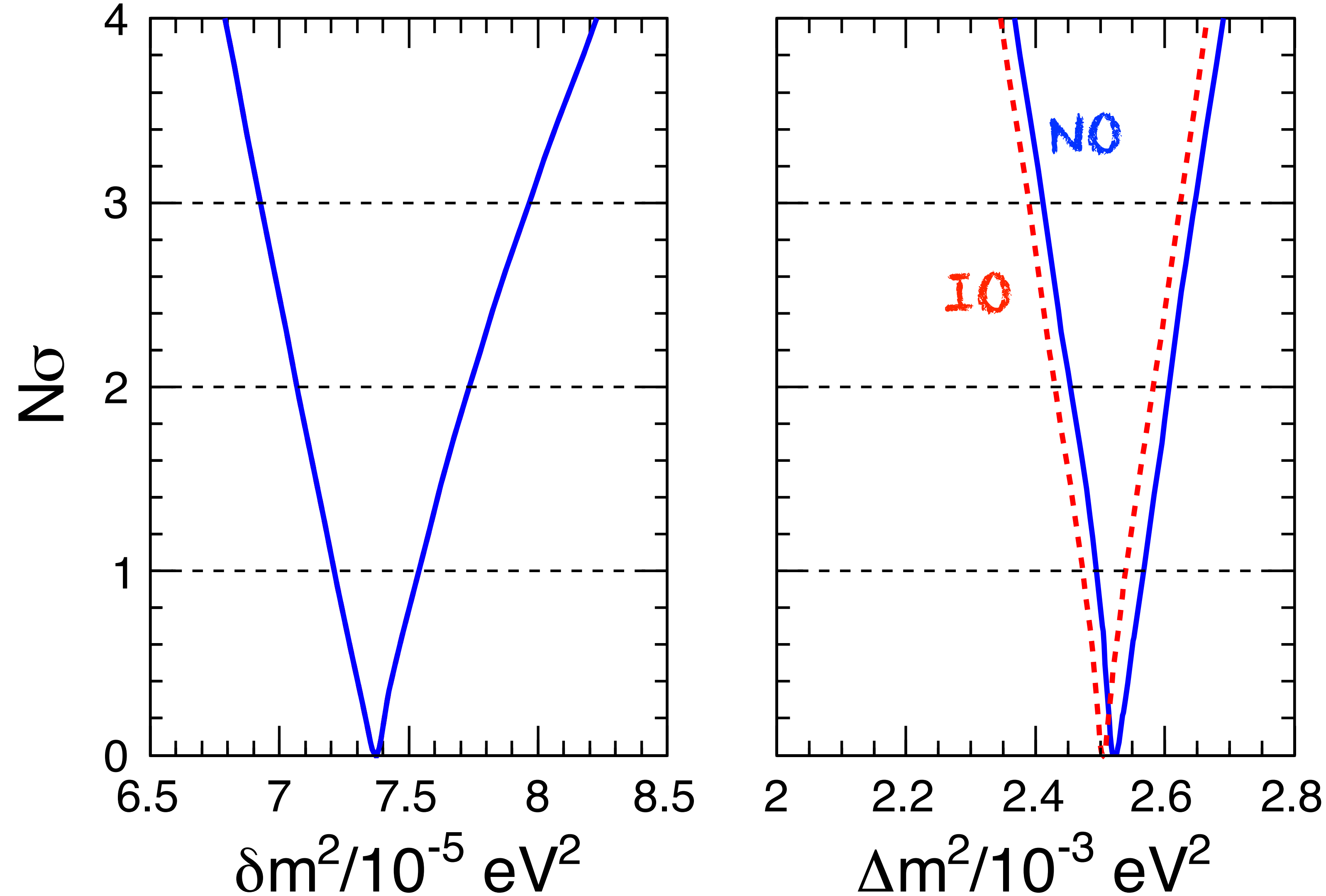

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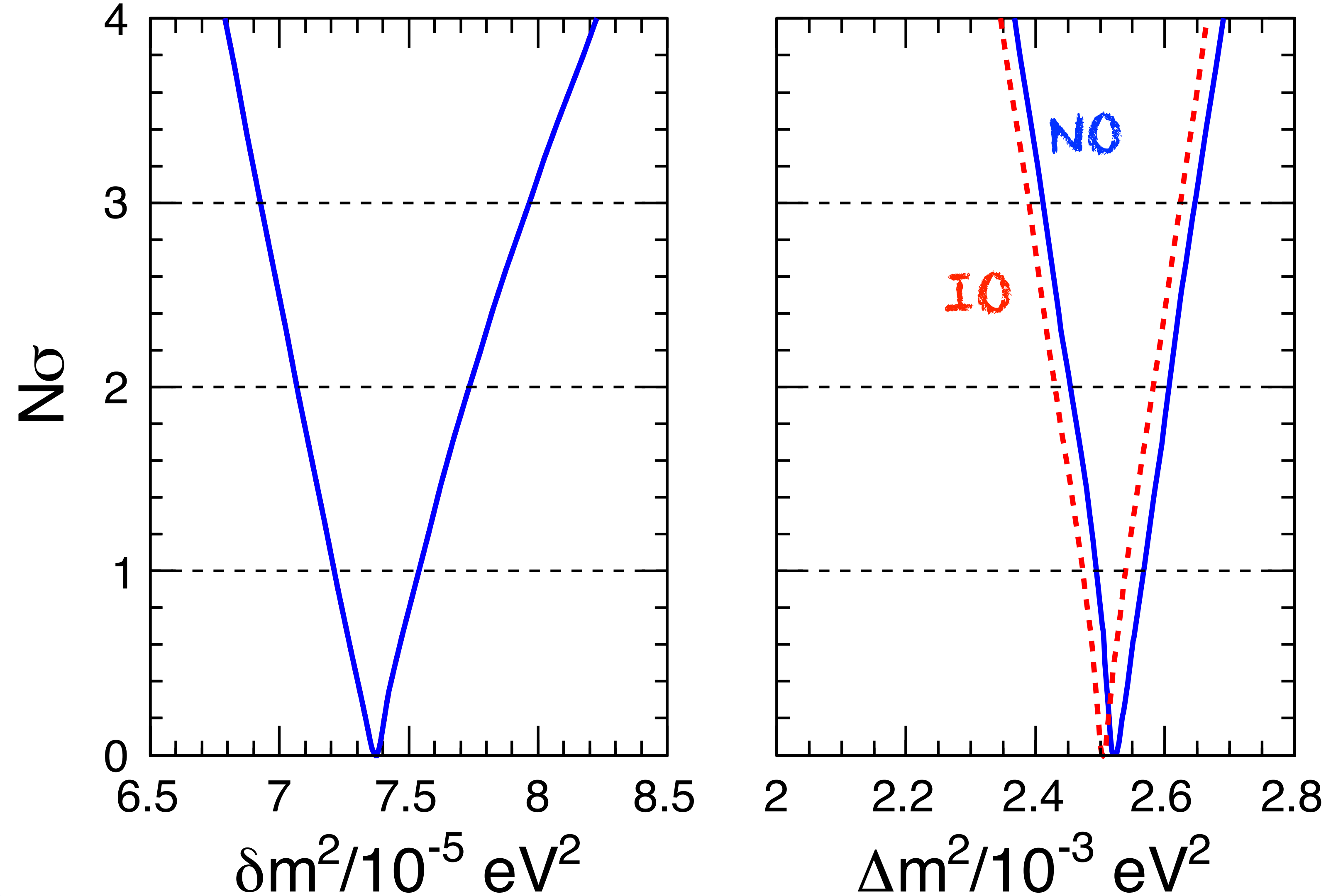

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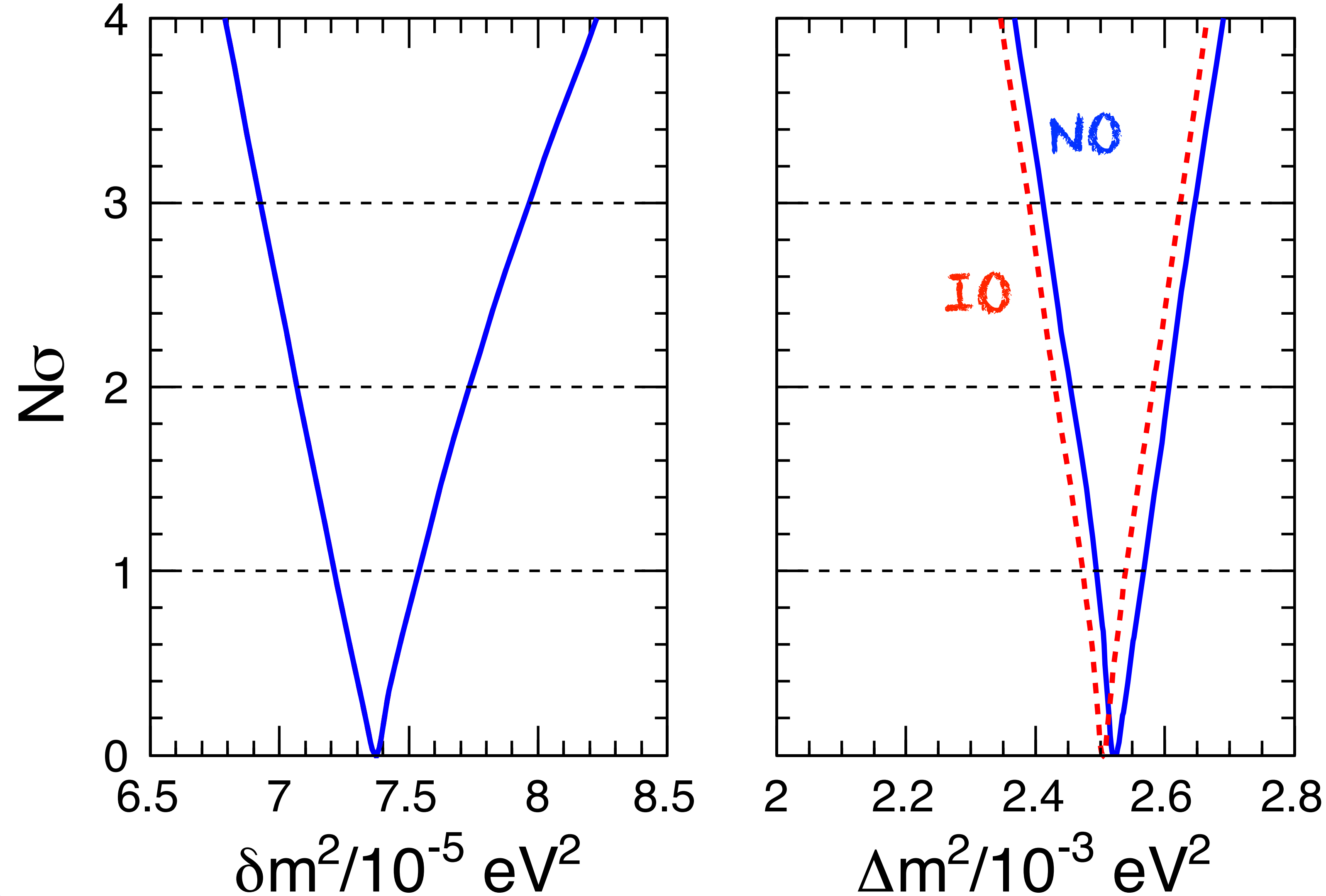

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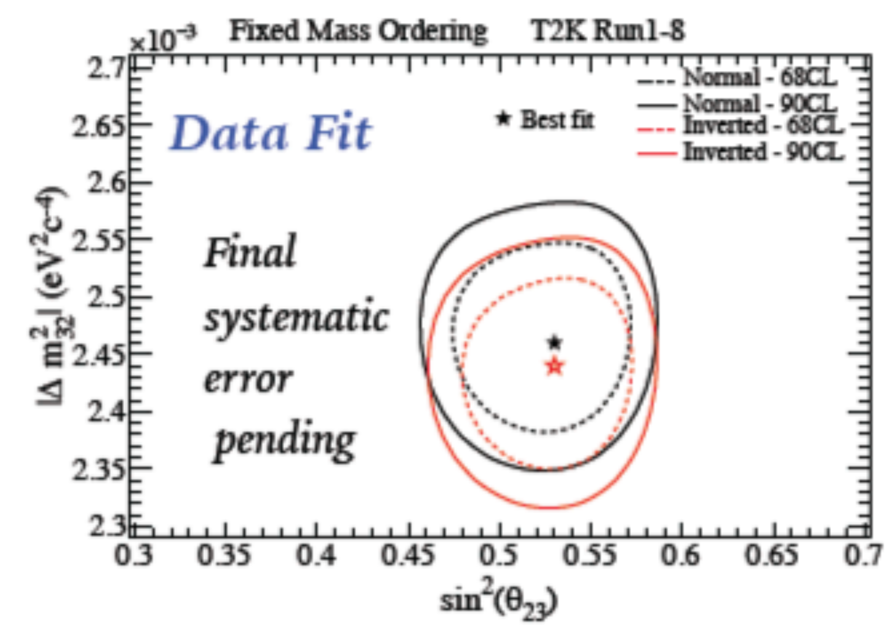
T2K update

$$\Delta m^2_{32} = (2.45 \pm 0.05) \times 10^{-3}\,\mathrm{eV}^2$$
or
$$\Delta m^2_{32} = (-2.52 \pm 0.05) \times 10^{-3}\,\mathrm{eV}^2$$

→



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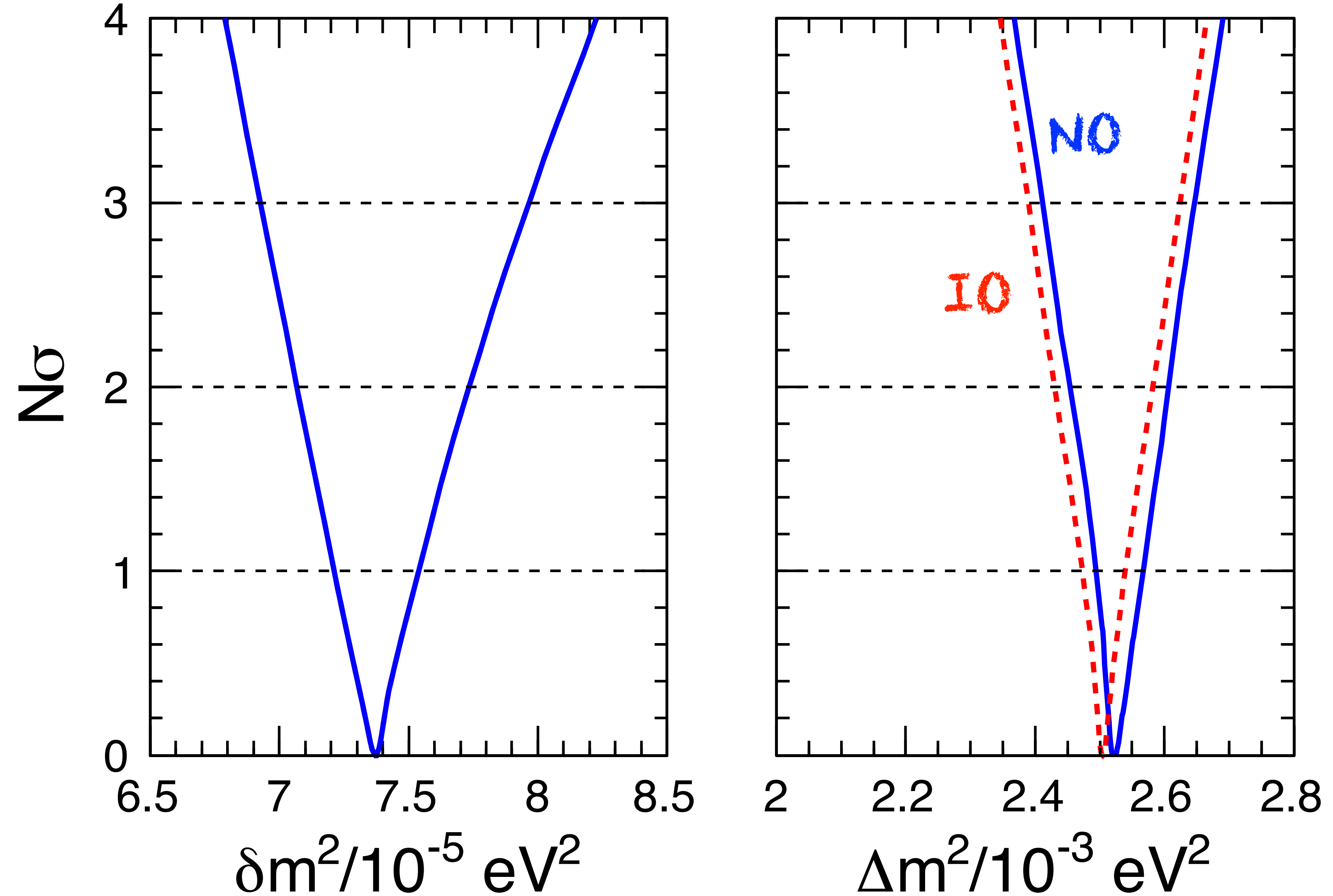

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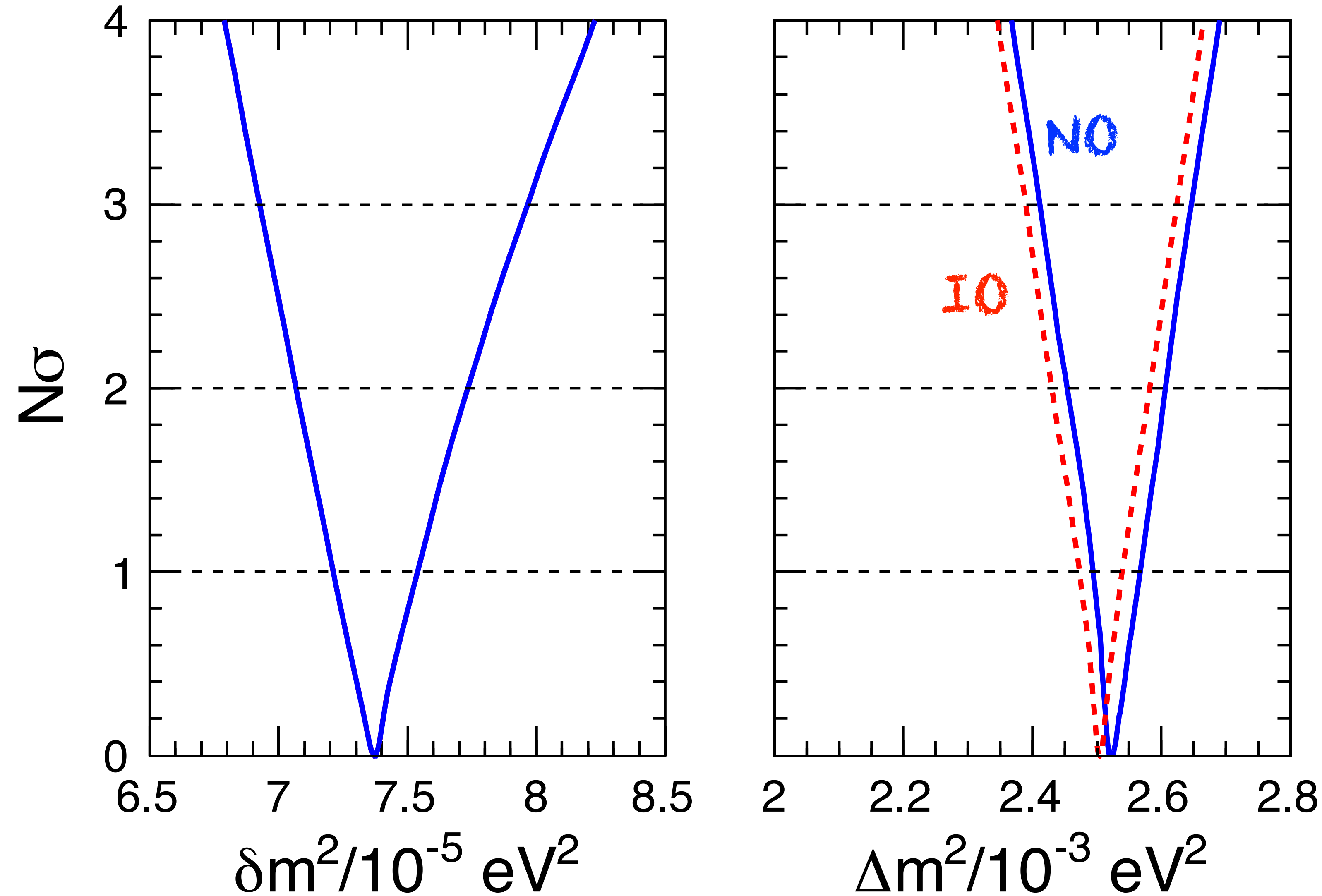

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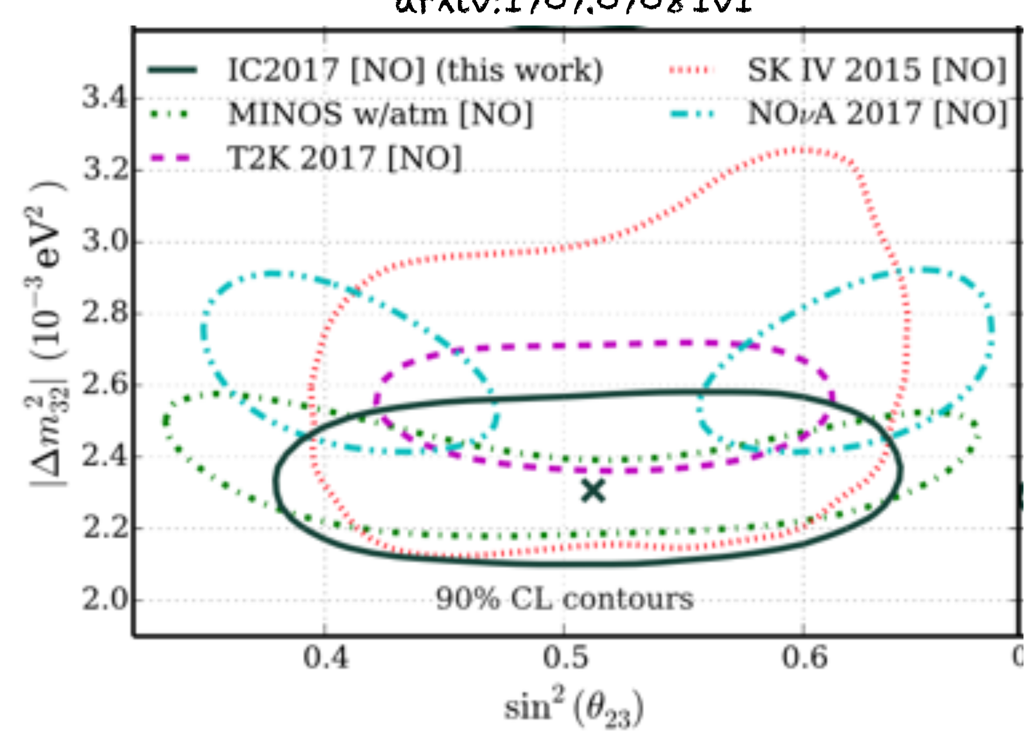

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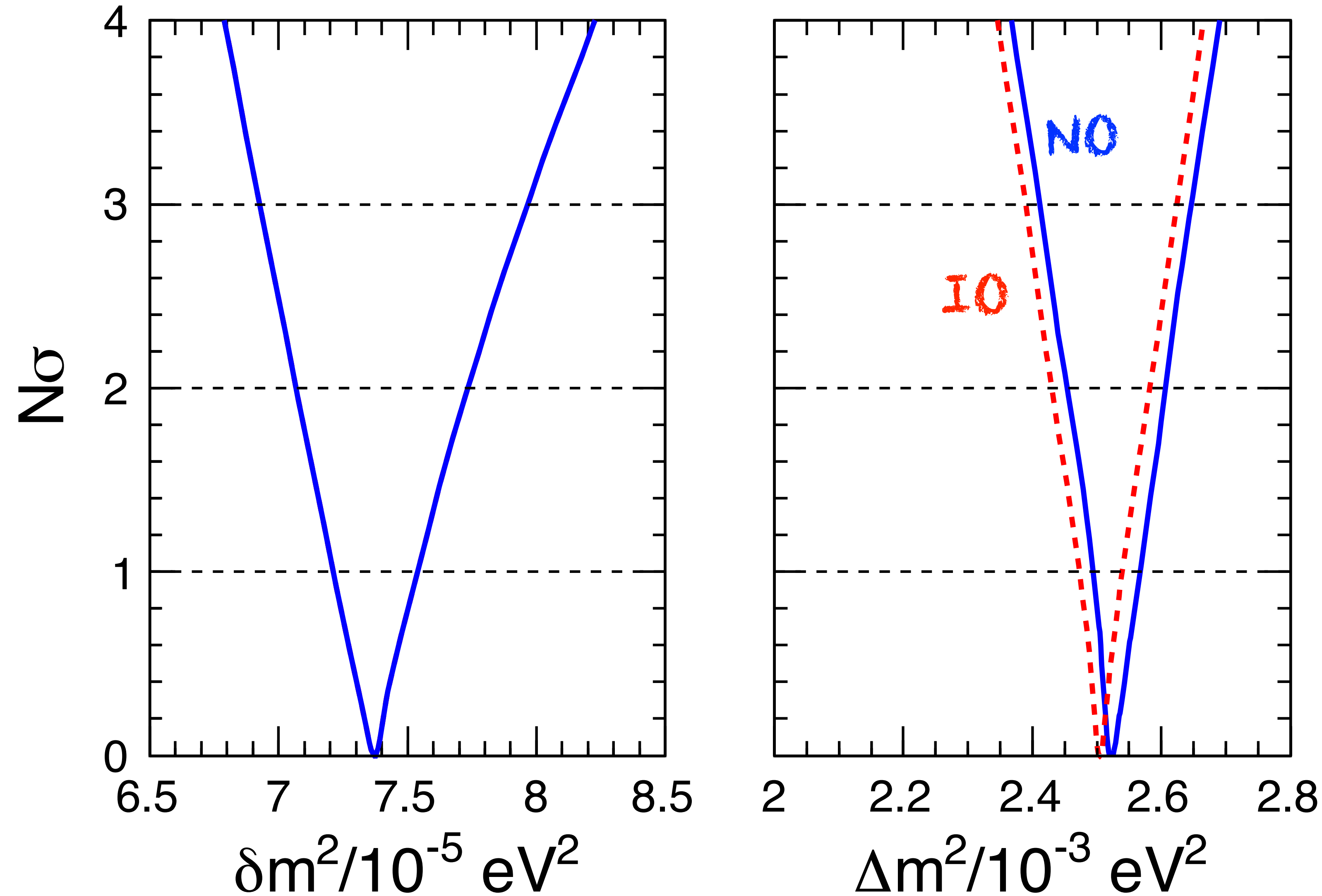

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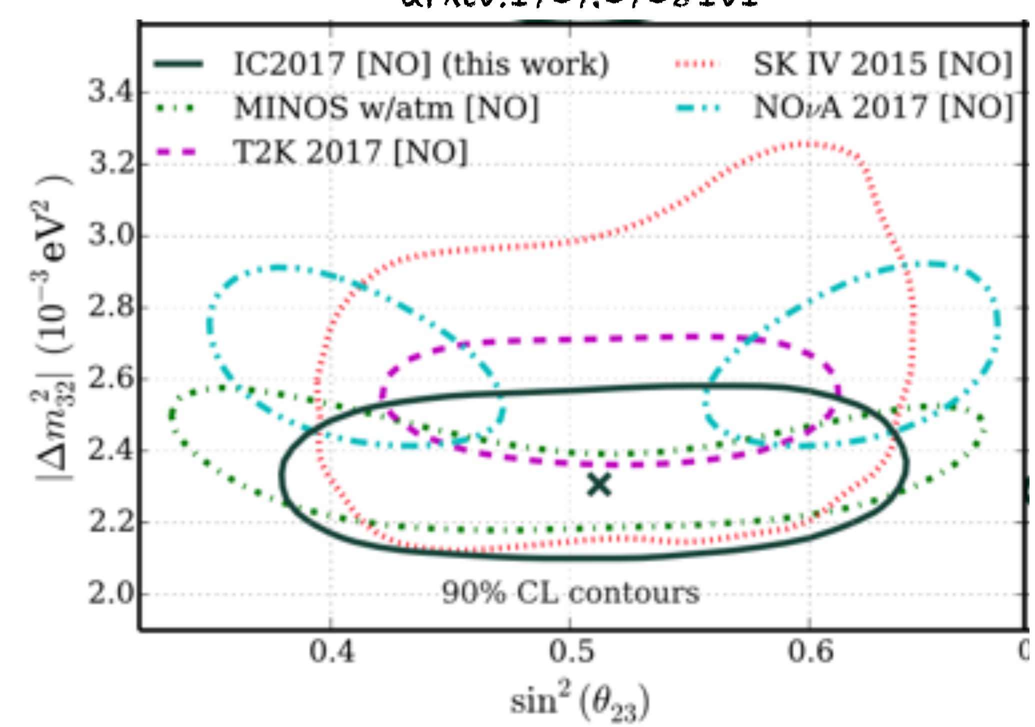
IceCube DeepCore update →

Daya Bay result

arXiv:1707.07081v1



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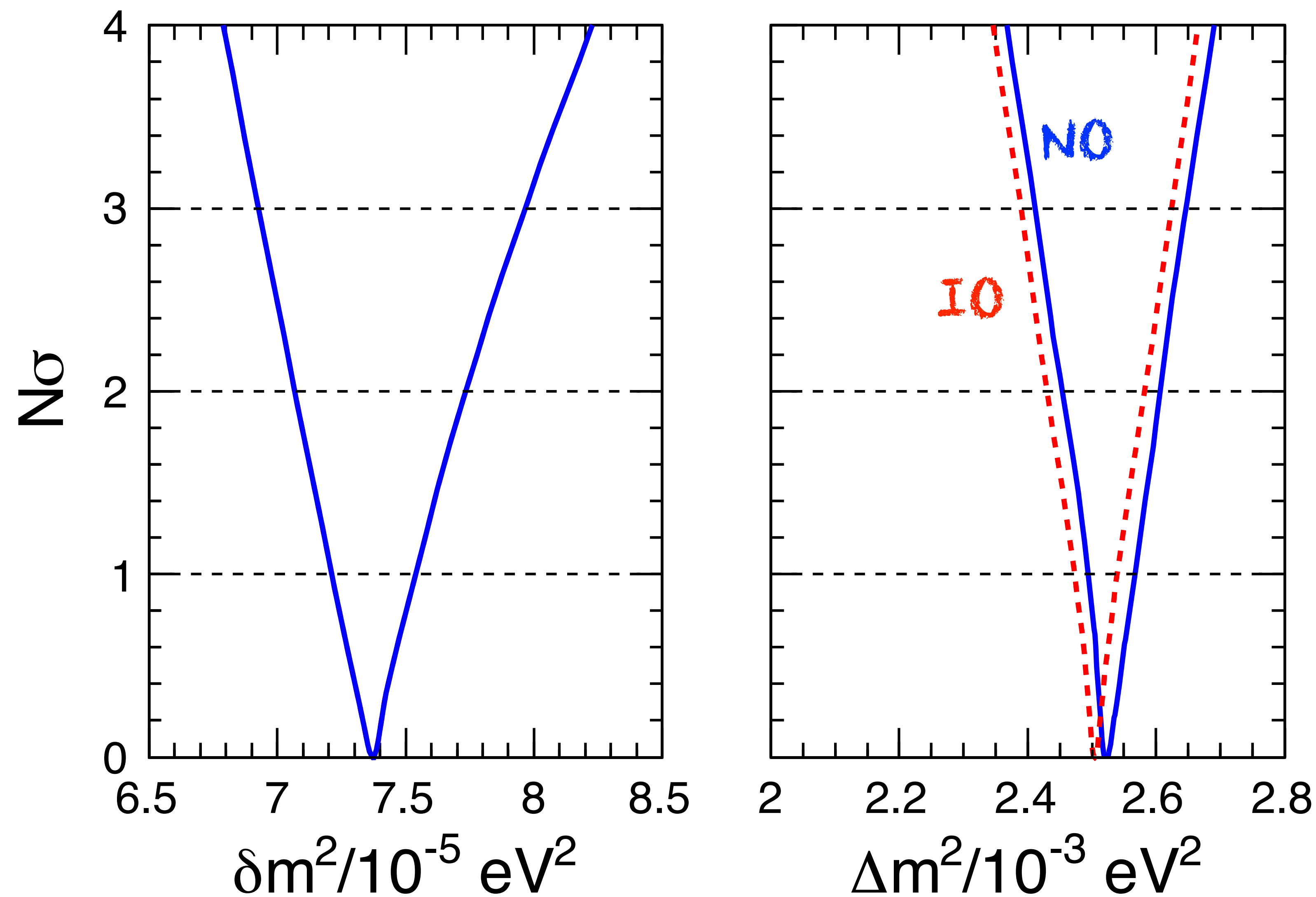

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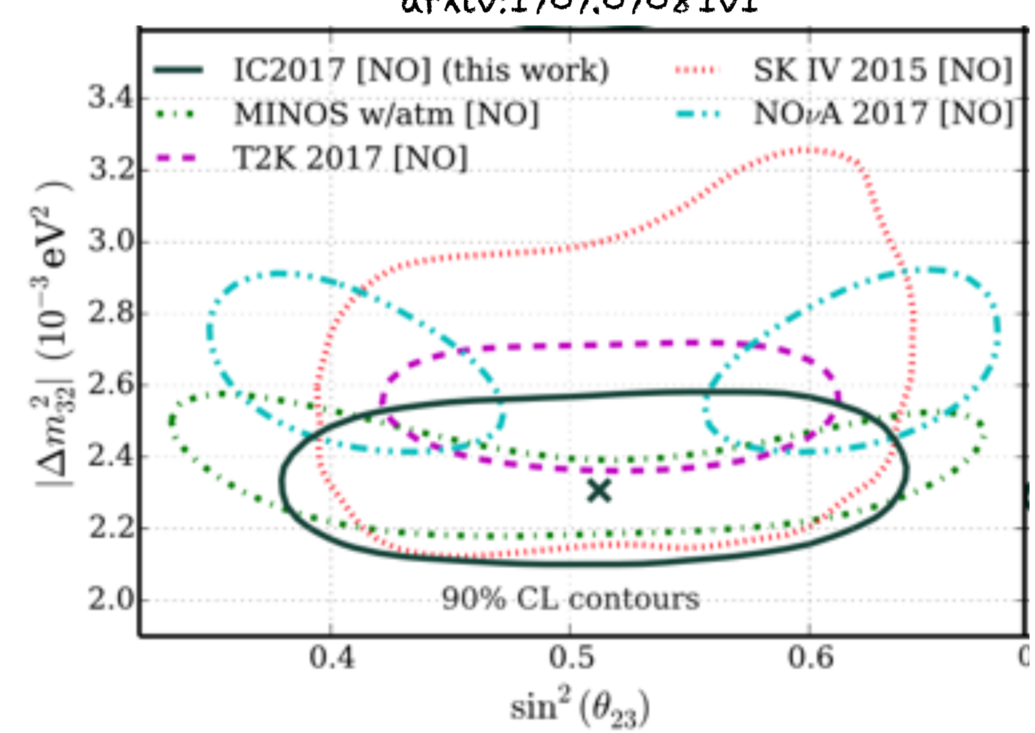

Daya Bay result

Δm^2_{32} (NH)=[2.45±0.06(stat.)±0.06(syst.)]×10⁻³eV²

Δm^2_{32} (IH)=[−2.55±0.06(stat.)±0.06(syst.)]×10⁻³eV²

Mixing Angles

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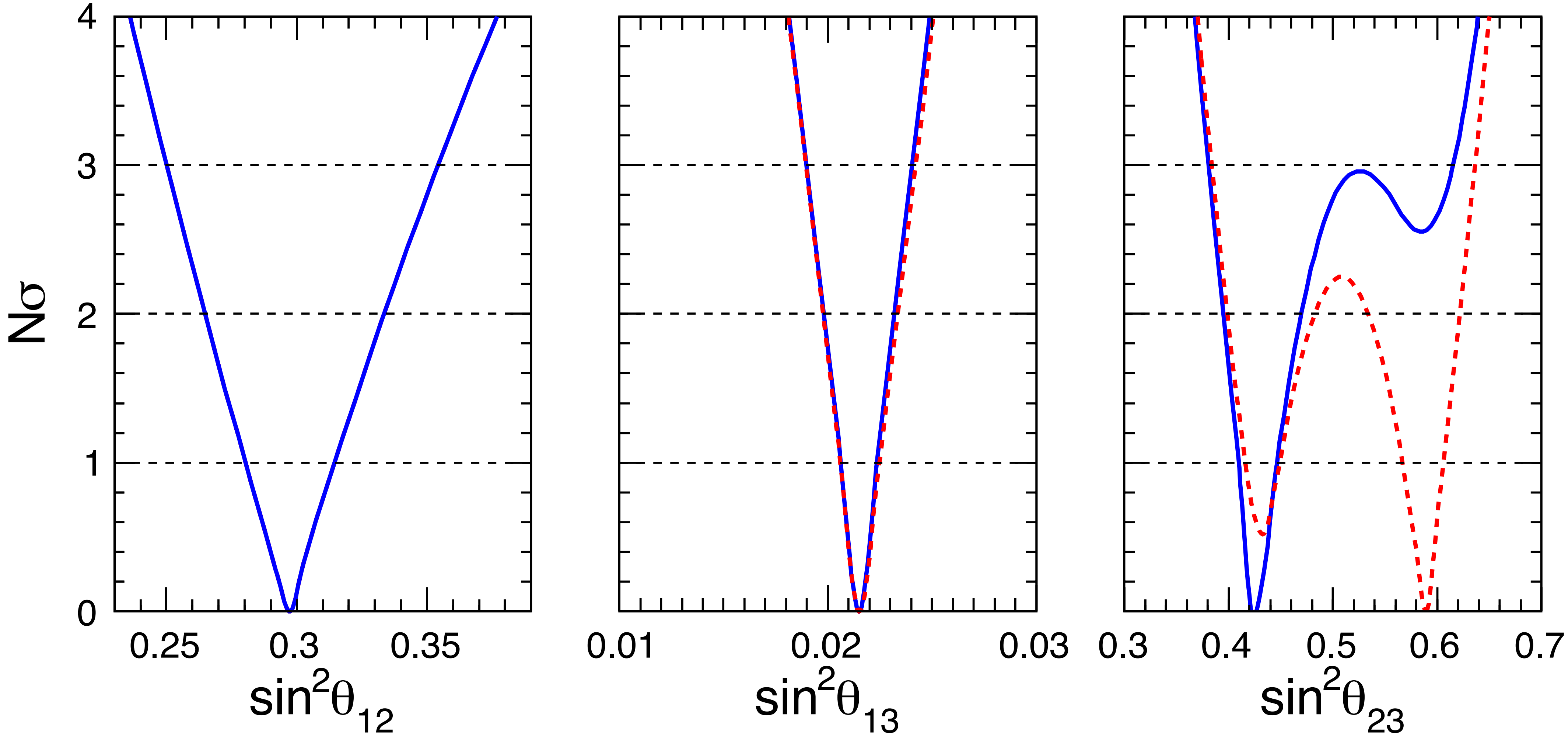

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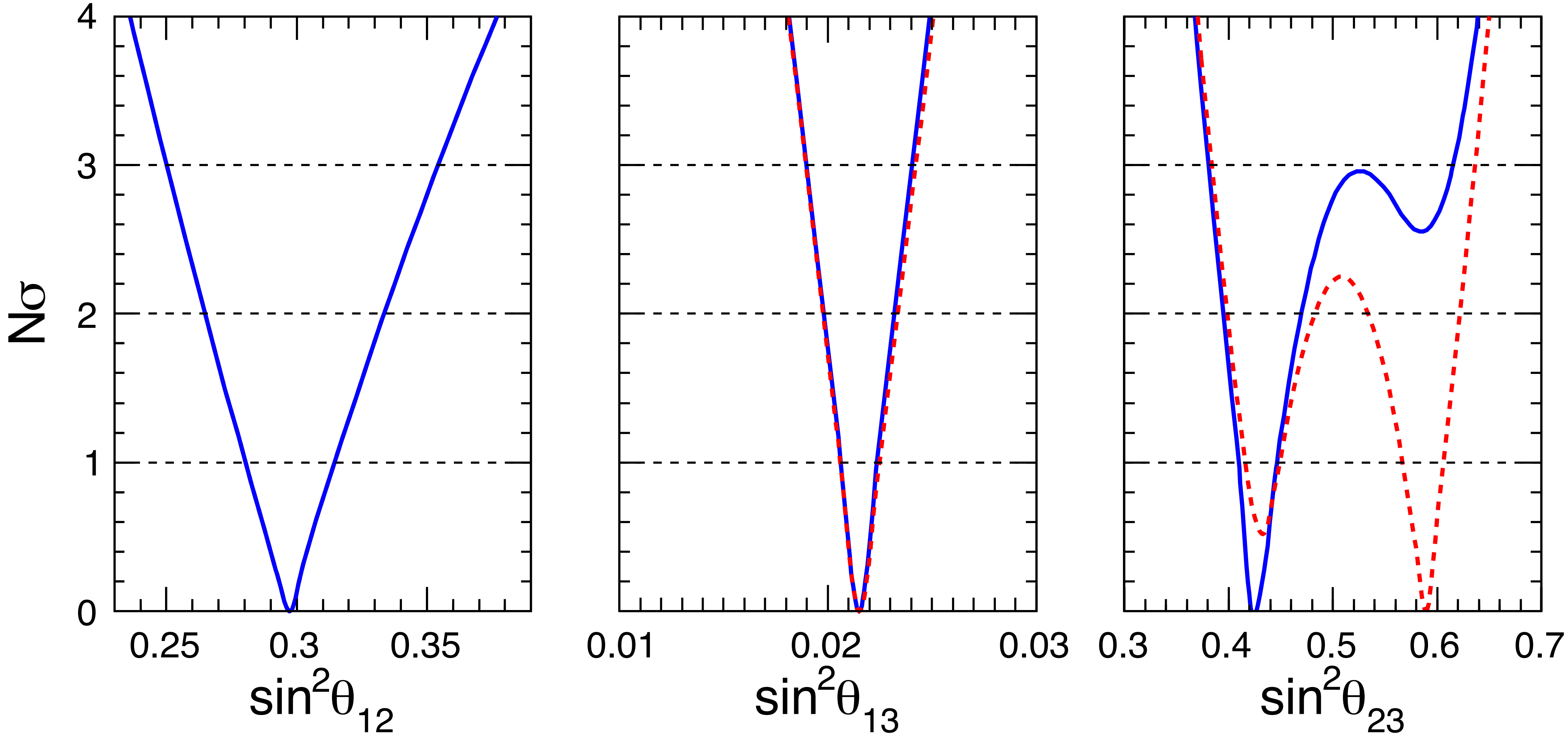

Mixing angles (θ_{23},θ_{12}) have both lower and upper bounds at more than 3σ

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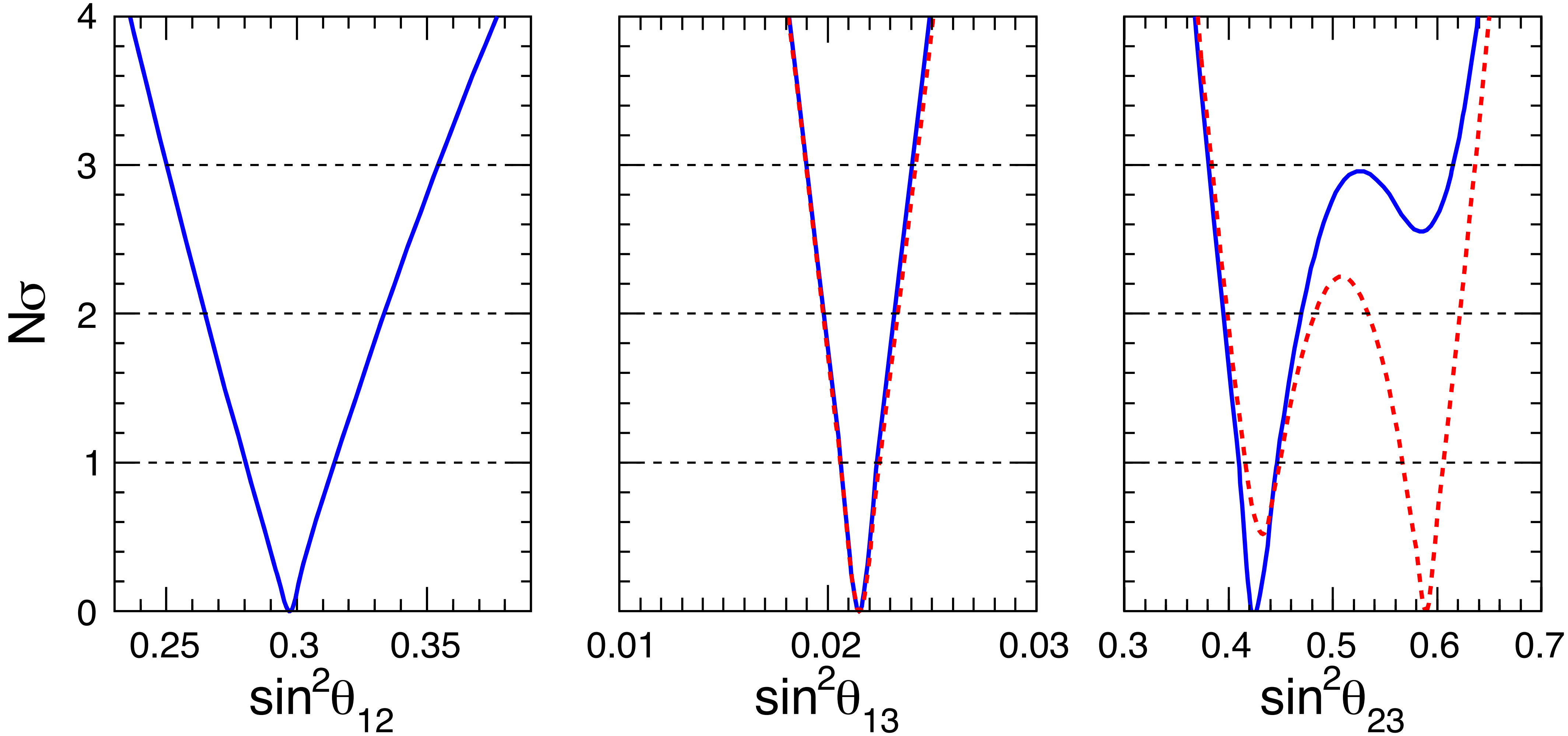

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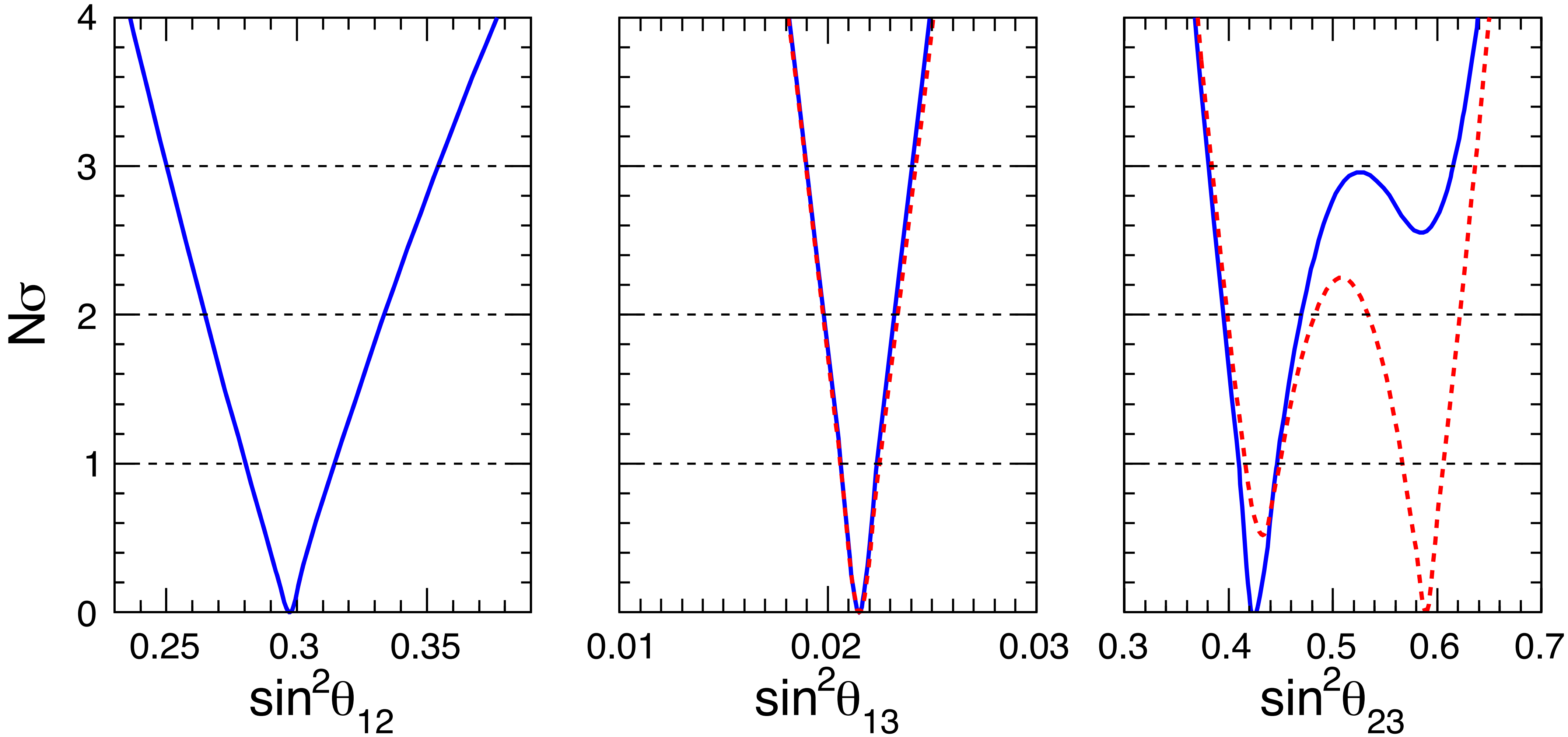

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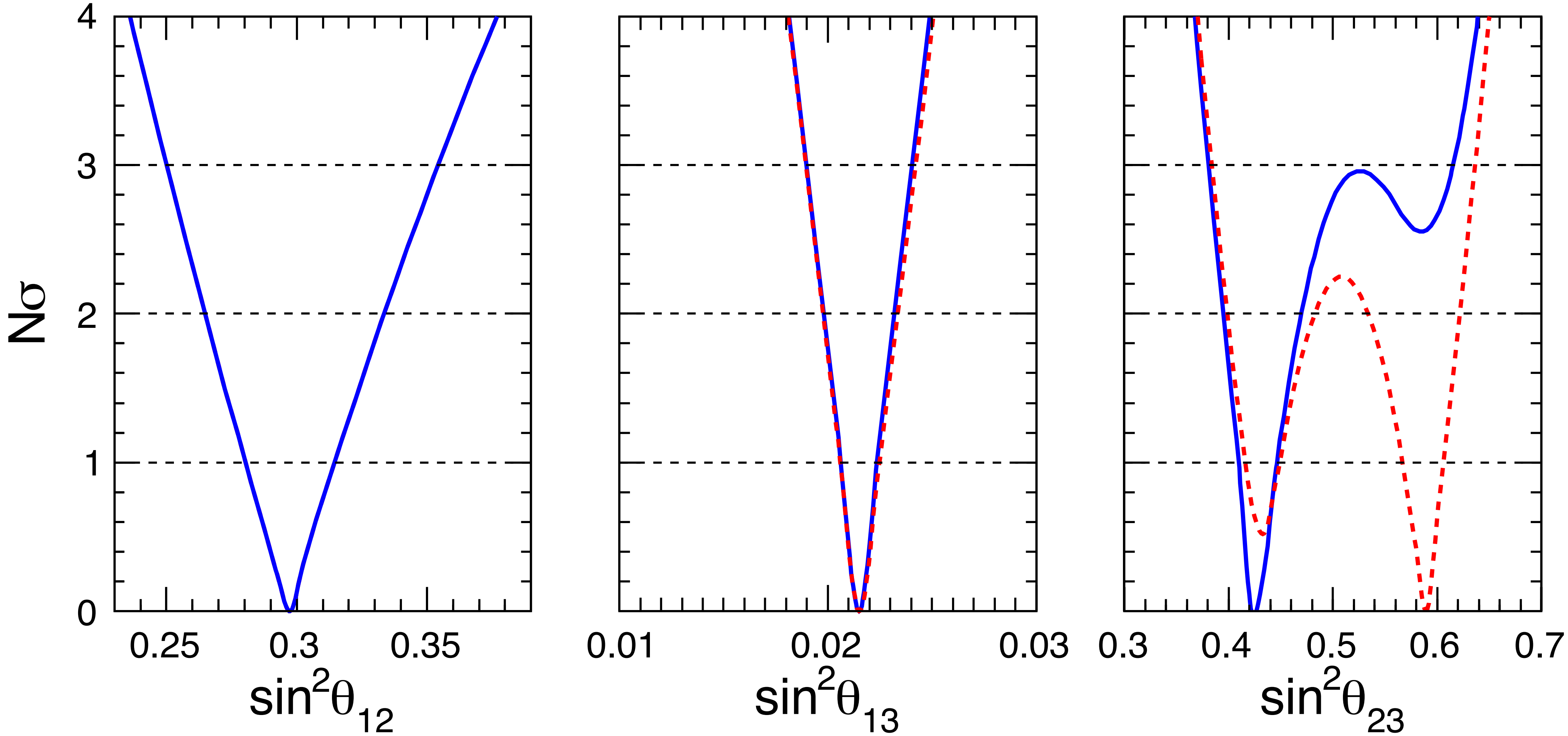
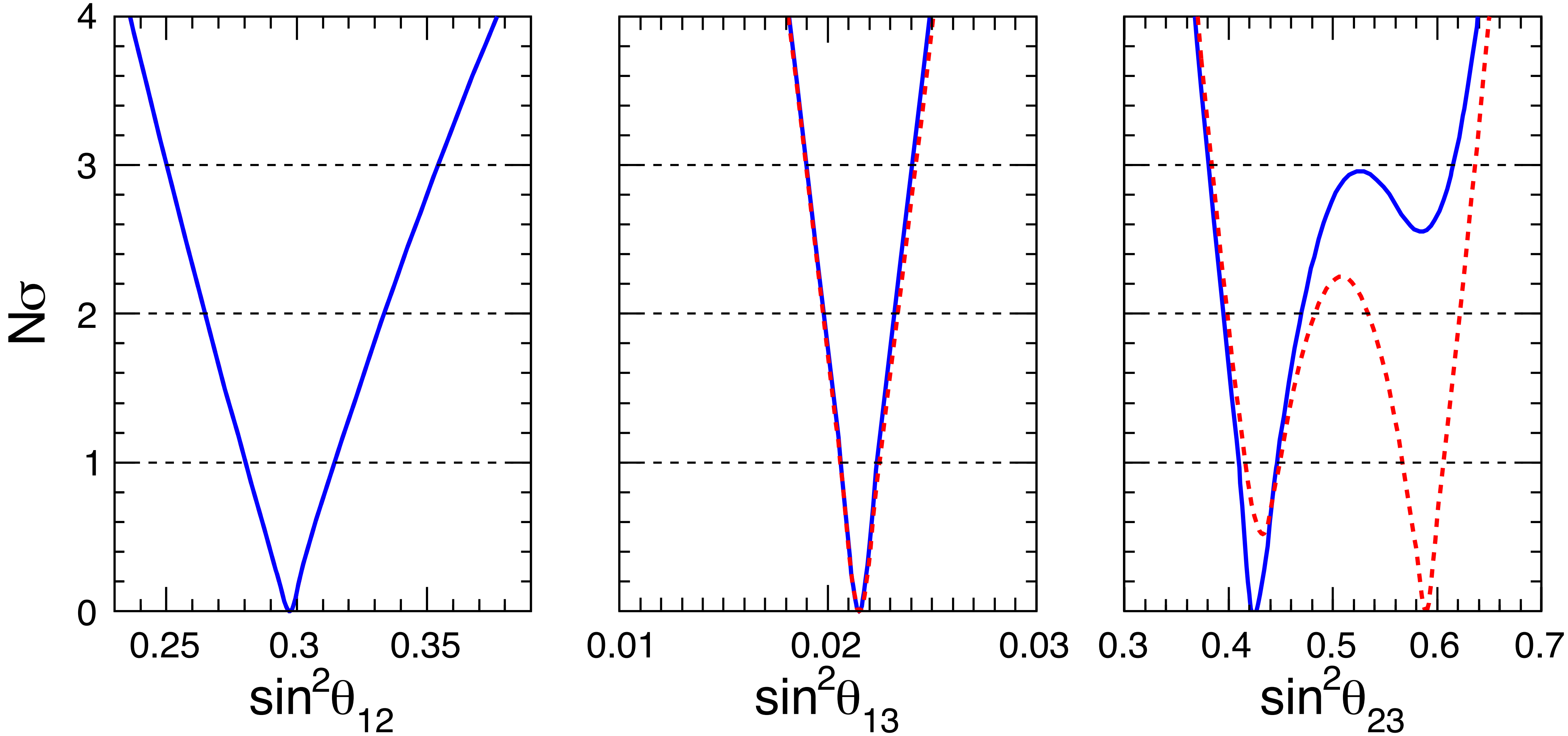


θ_{23} maximal mixing disfavored at about more than 2σ level

best-fit octant flips with mass ordering

Mixing Angles



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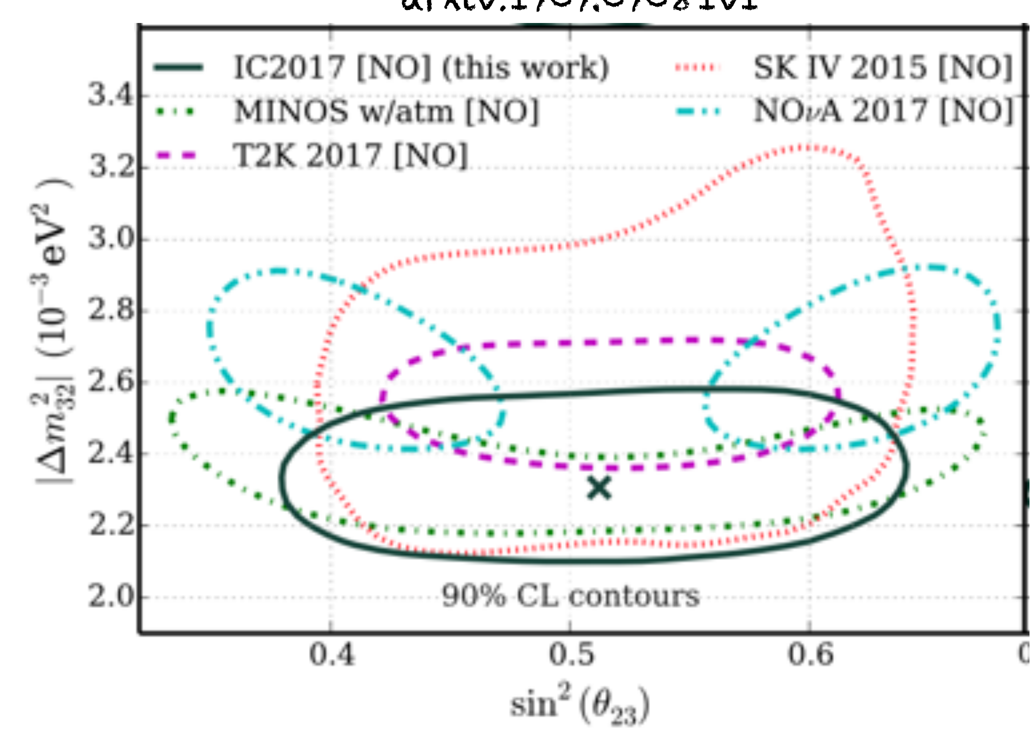

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NOvA and MINOS prefer nonmaximal mixing

CP phase δ

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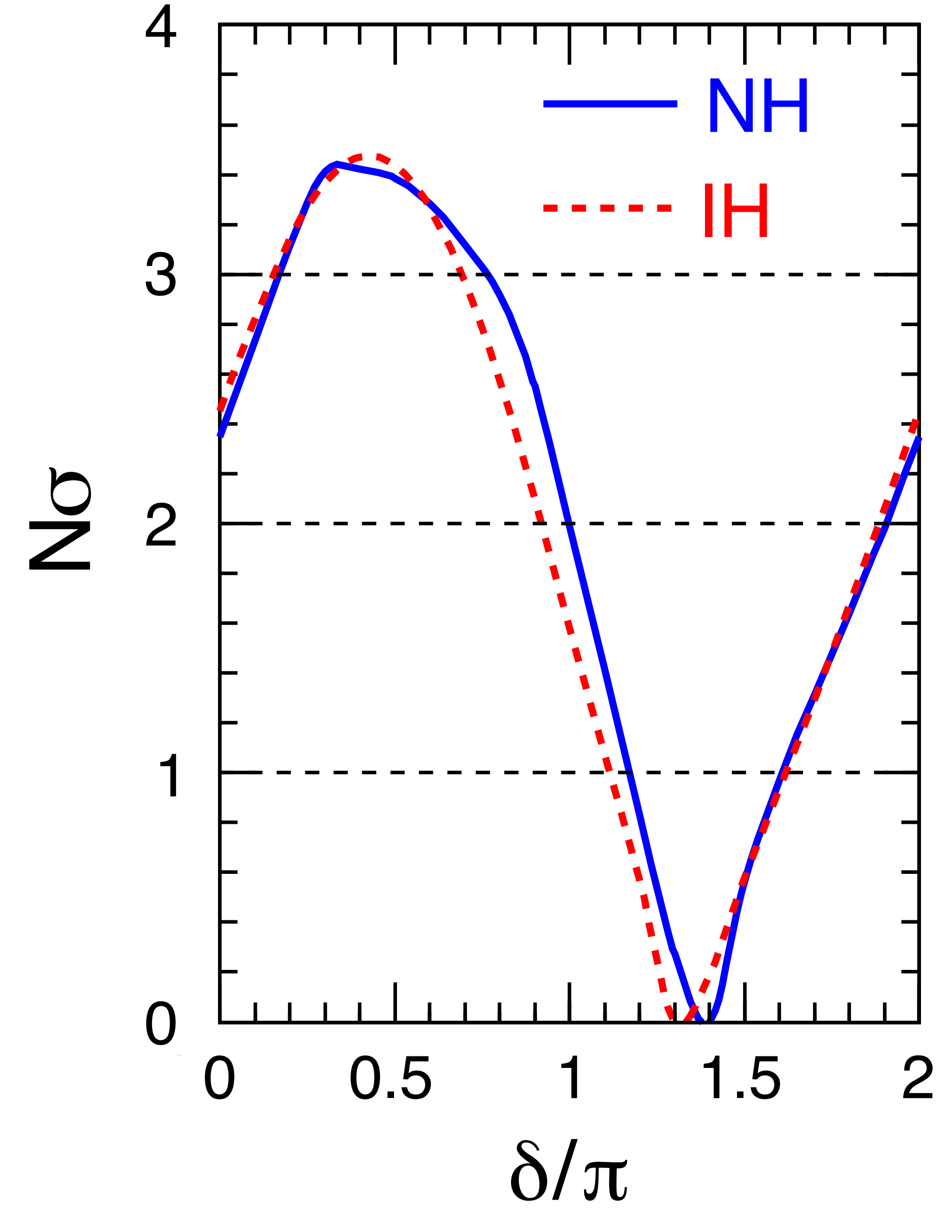
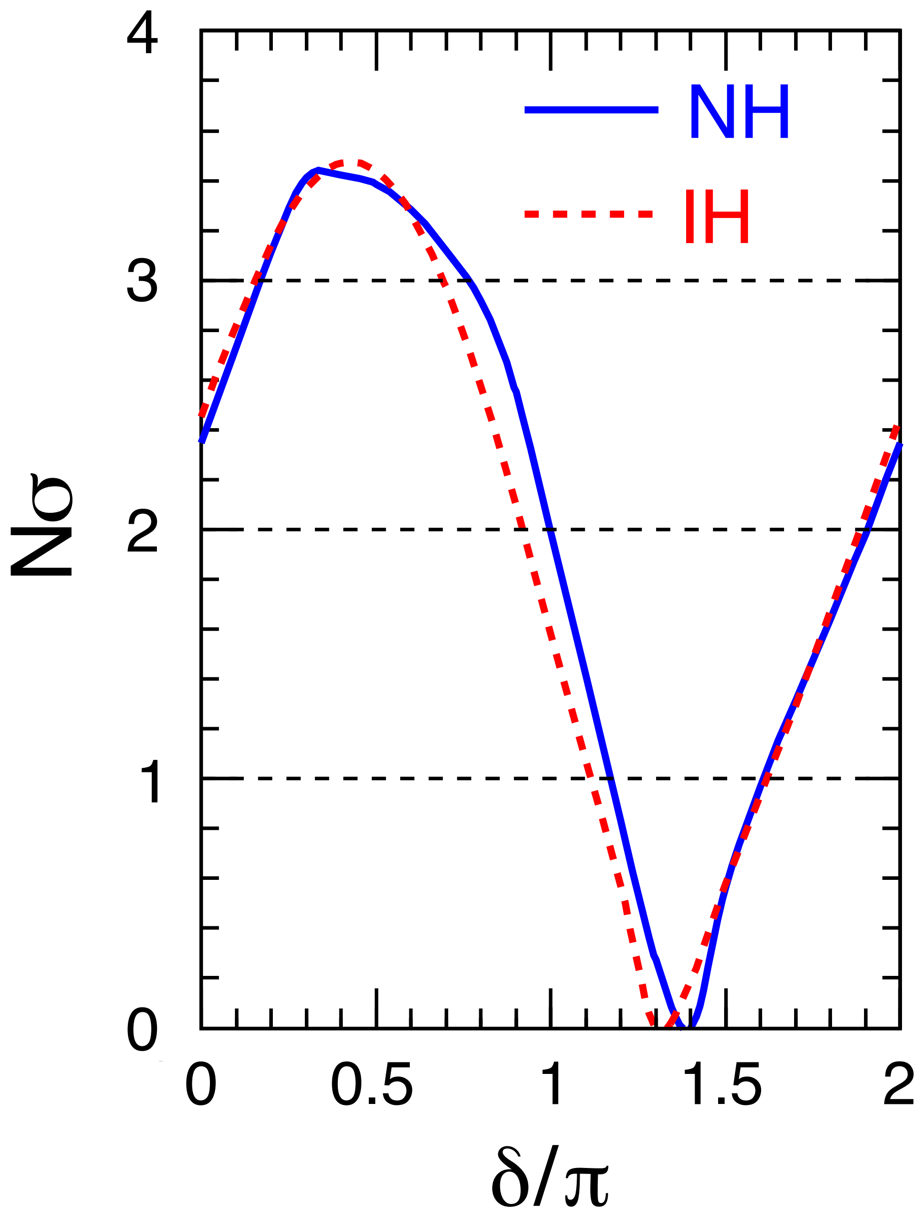


CP phase δ

- CP phase: $\delta \sim 1.4\,\pi$ at best fit
- CP-conserving cases ($\delta = 0, \pi$) disfavored at $\sim 2\sigma$ level or more
- Significant fraction of the $[0,\pi]$ range disfavored at $>3\sigma$



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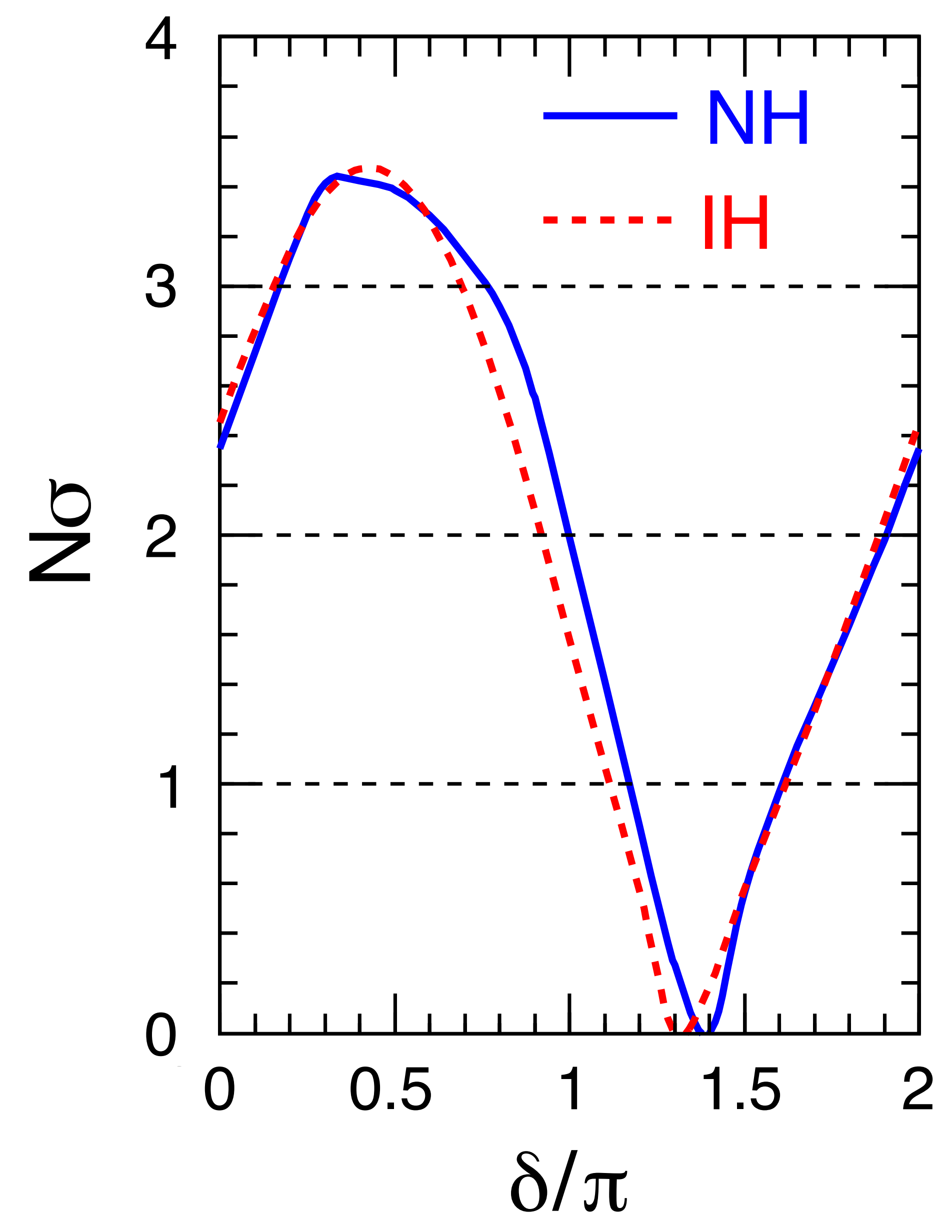
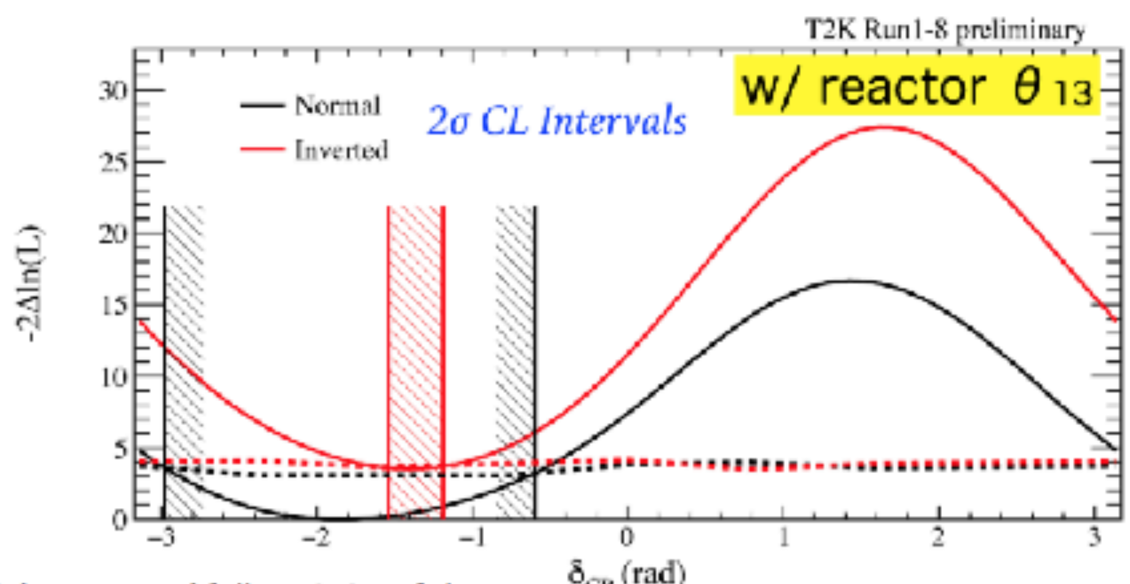


New T2K results: KEK seminar on 4 August 2017

Based on 89 ν_e and 7 $\overline{\nu}_e$ events



- 30% of the expected full statistics of the experiment
- 30% improvement in efficiency x acceptance
- Important improvements in neutrino interactions modelling

- δ_{CP} determination is very important for future searches of MH in long baseline experiments

Precision era in neutrino oscillation phenomenology

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Standard 3ν mass-mixing framework parameters

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Standard 3ν mass-mixing framework parameters

Known

δm^2	2.3%
Δm^2	1.6%
$\sin^2\theta_{12}$	5.8%
$\sin^2\theta_{13}$	4.0%
$\sin^2\theta_{23}$	$\sim 9.6\%$

Bari group, Nucl.Phys. B908 (2016) 218-234

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CP-violating phase δ

Octant of θ_{23}

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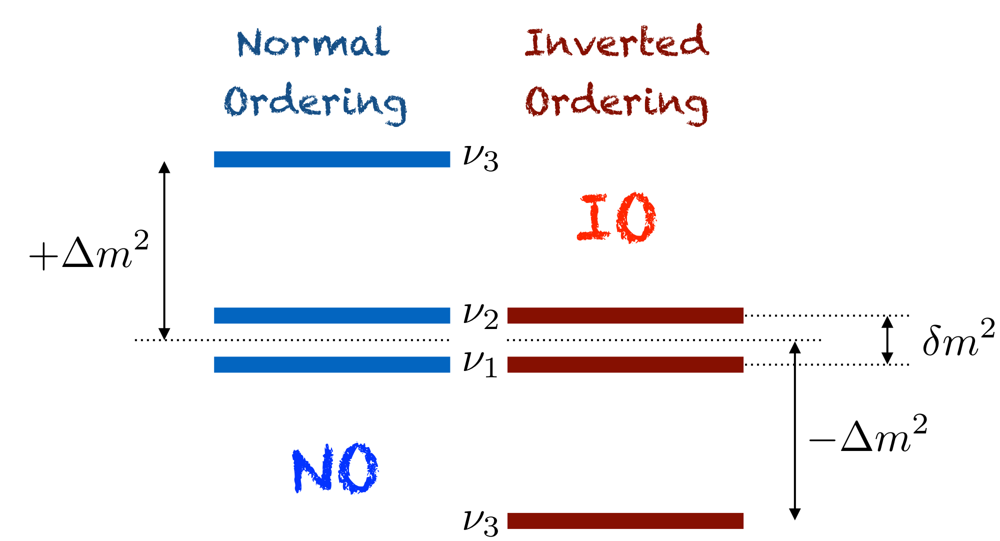
[Dirac/Majorana neutrinos, Majorana phases, absolute mass scale]

Next part of the talk on Mass Ordering →



Mass Ordering: present situation

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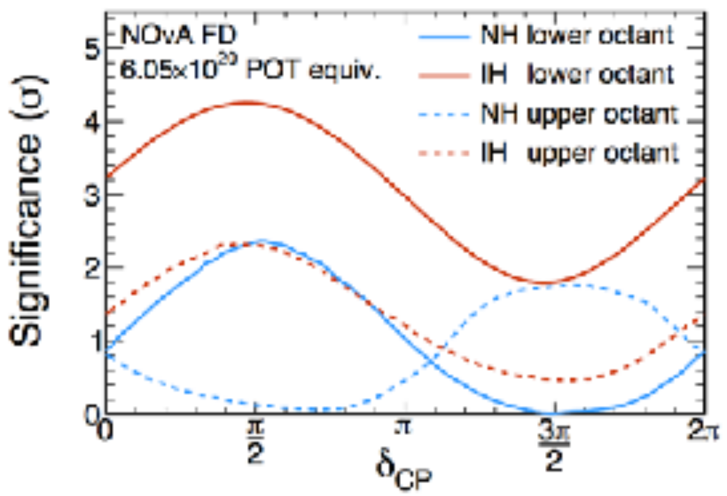
NOvA - slight preference for NO



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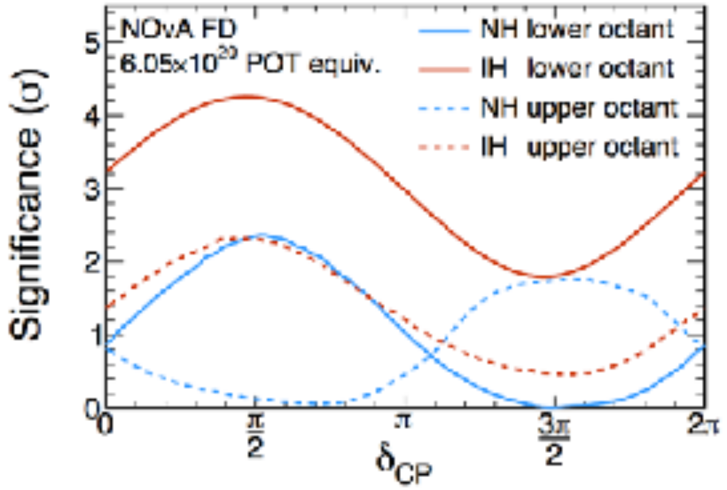

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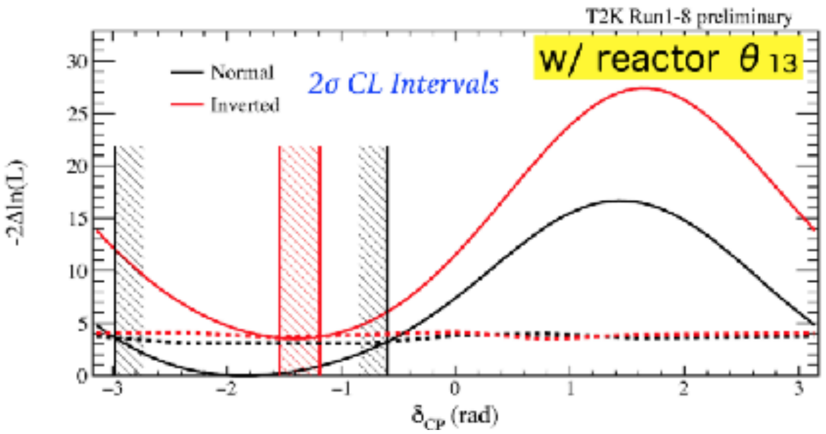

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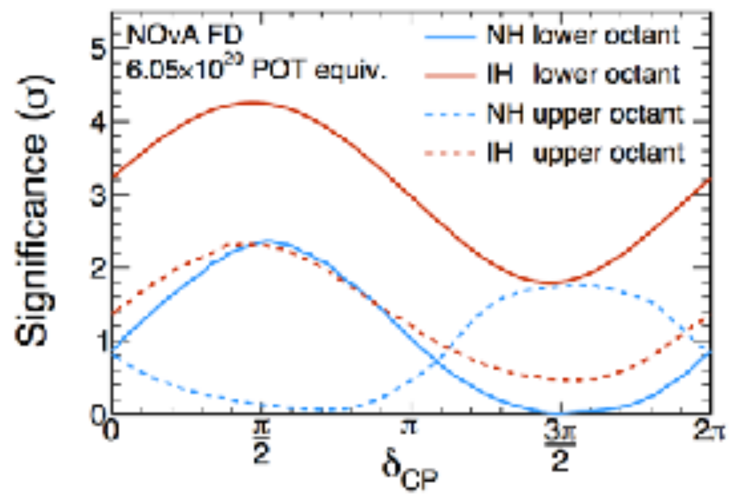

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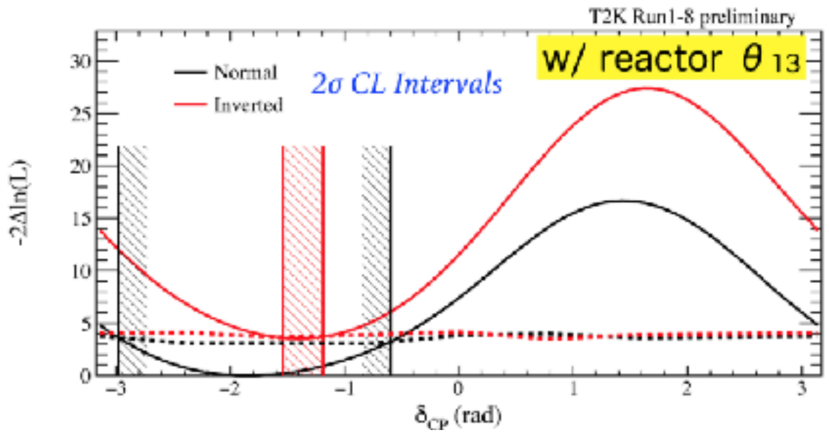

SK preference for NO $\Delta\chi^2_{IH-NH} = 5.2$

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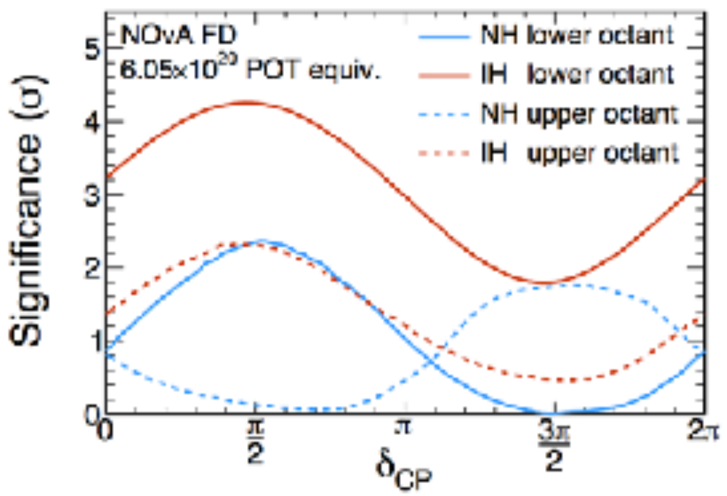

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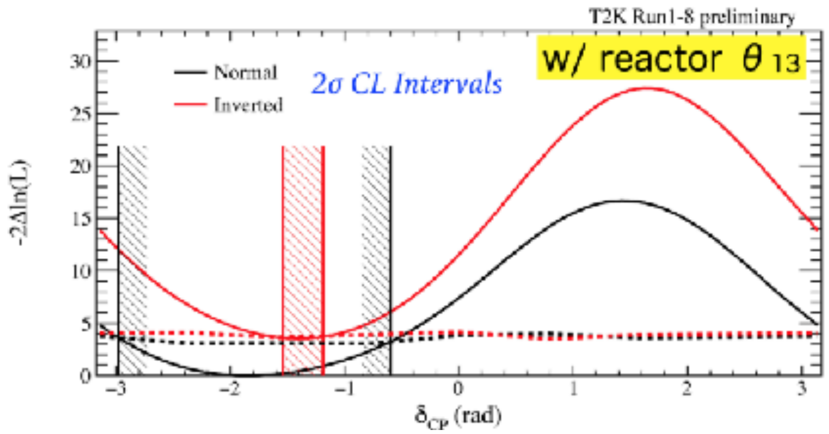

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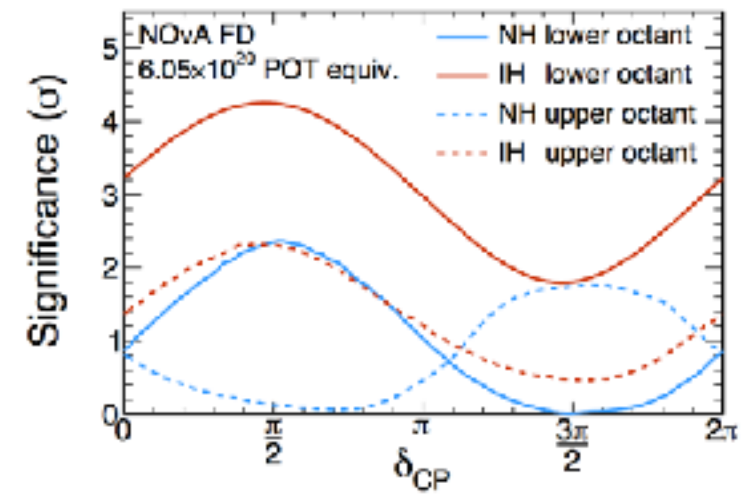

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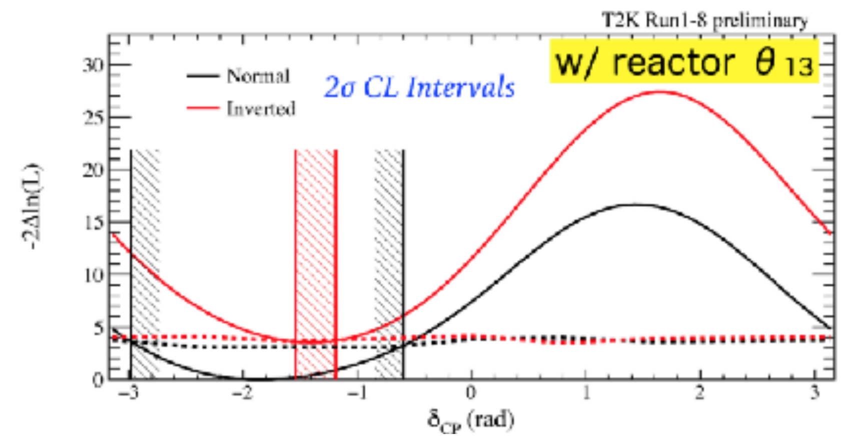

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Nu-Fit sept. 2017 (very preliminary, see talk of C.Gonzalez-Garcia) $\Delta\chi^2_{IH-NH} \sim 3$

de Salas et al. (arXiv:1708.01186) $\Delta\chi^2_{IH-NH} = 2.7$

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Info on absolute masses and ordering from non oscillation data from the following observables

- β Decay $m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$
- $0\beta\beta\nu$ $m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$

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- Cosmology & Astrophysics $$\Sigma = m_1 + m_2 + m_3$$

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Normal Ordering

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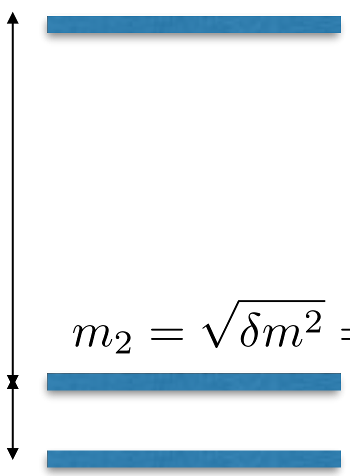
Normal Ordering

$$m_3 = \sqrt{\Delta m^2 + \delta m^2/2} = 5.06 \times 10^{-2}\ \text{eV}$$

$$m_2 = \sqrt{\delta m^2} = 0.86 \times 10^{-2}\ \text{eV}$$

$$m_1 = 0$$



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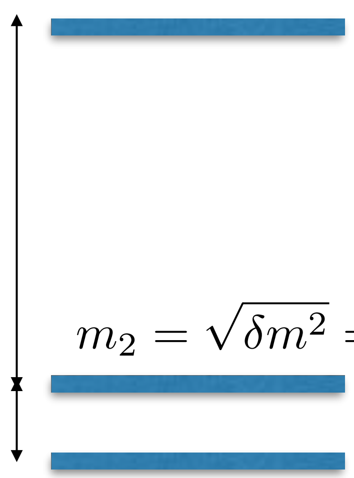


$$m_2 = \sqrt{\delta m^2} = 0.86 \times 10^{-2}\ \text{eV}$$

$$m_1 = 0$$

$$\Sigma \gtrsim 6.5 \times 10^{-2}\ \text{eV}$$

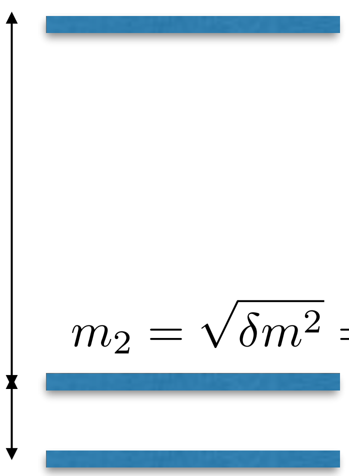
Cosmology is dominantly sensitive to the sum of neutrino masses Σ

Oscillations independent on the absolute mass scale but give rise to a lower bound on Σ when the lightest mass is zero

Normal Ordering

Inverted Ordering

$m_3 = \sqrt{\Delta m^2 + \delta m^2/2} = 5.06 \times 10^{-2}\ \mathrm{eV}$



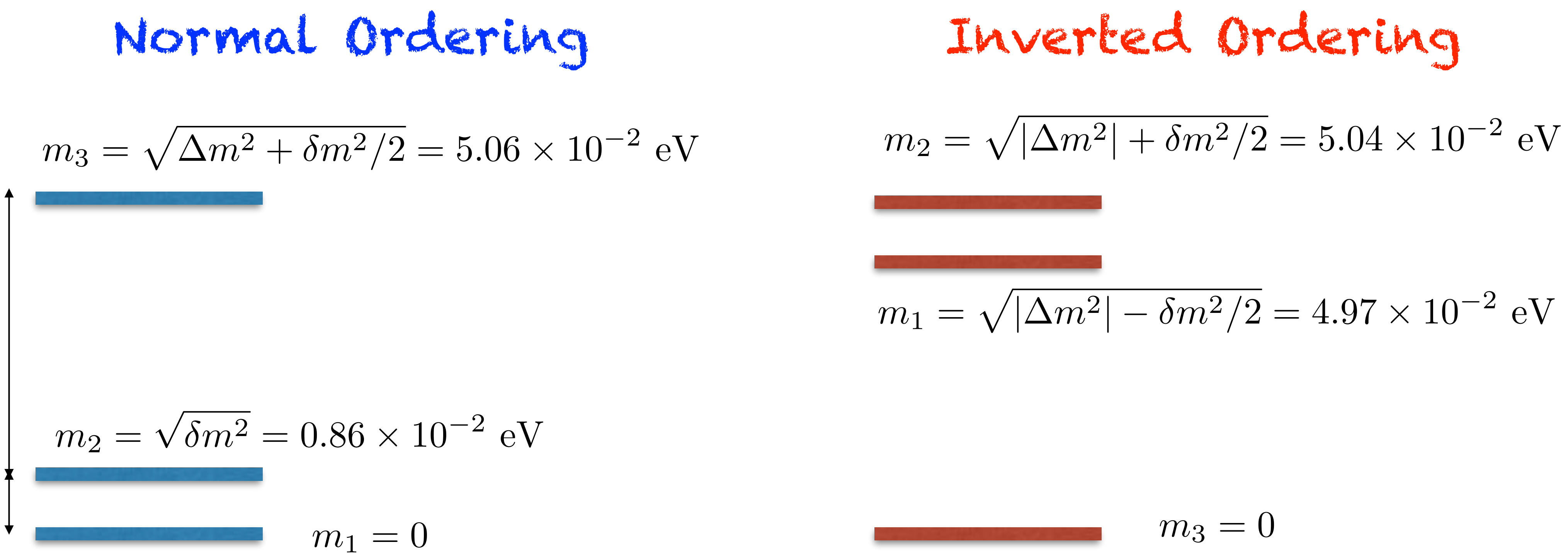
$m_2 = \sqrt{\delta m^2} = 0.86 \times 10^{-2}\ \mathrm{eV}$

$m_1 = 0$

$$\Sigma \gtrsim 6.5 \times 10^{-2}\ \mathrm{eV}$$

Cosmology is dominantly sensitive to the sum of neutrino masses Σ

Oscillations independent on the absolute mass scale but give rise to a lower bound on Σ when the lightest mass is zero



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Inverted Ordering

$$m_2 = \sqrt{|\Delta m^2| + \delta m^2/2} = 5.04 \times 10^{-2}\ \mathrm{eV}$$

$$m_1 = \sqrt{|\Delta m^2| - \delta m^2/2} = 4.97 \times 10^{-2}\ \mathrm{eV}$$

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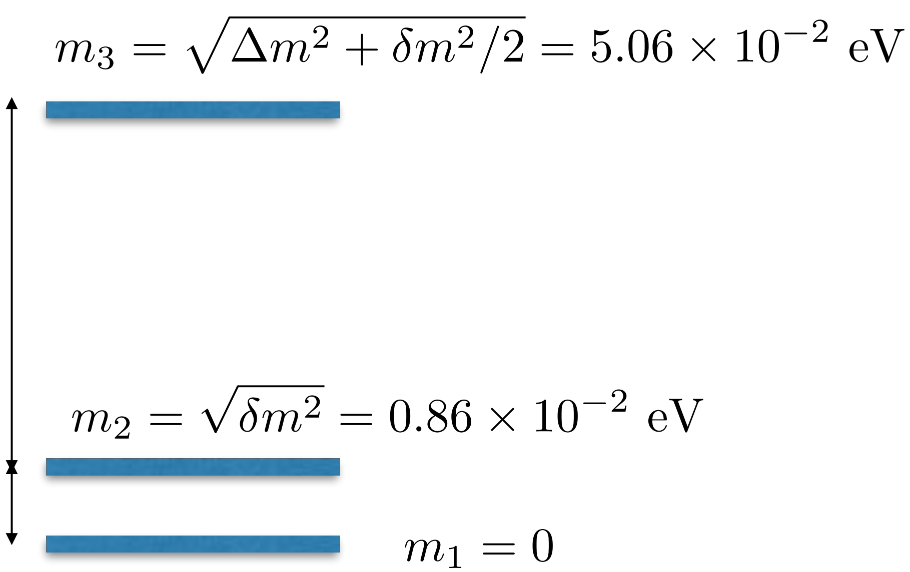

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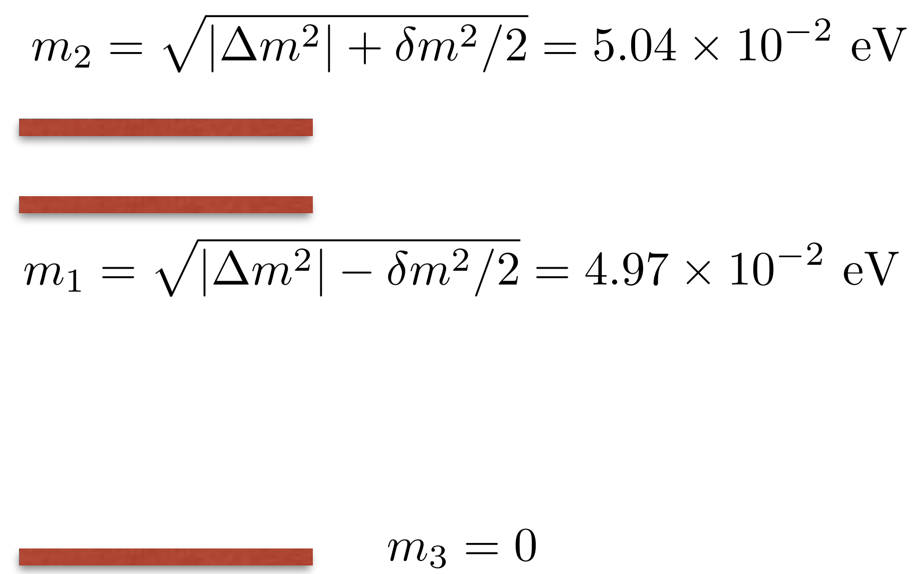

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The lower bound on Σ for IO only a factor ~2 smaller than the strongest limit set at present by cosmological data

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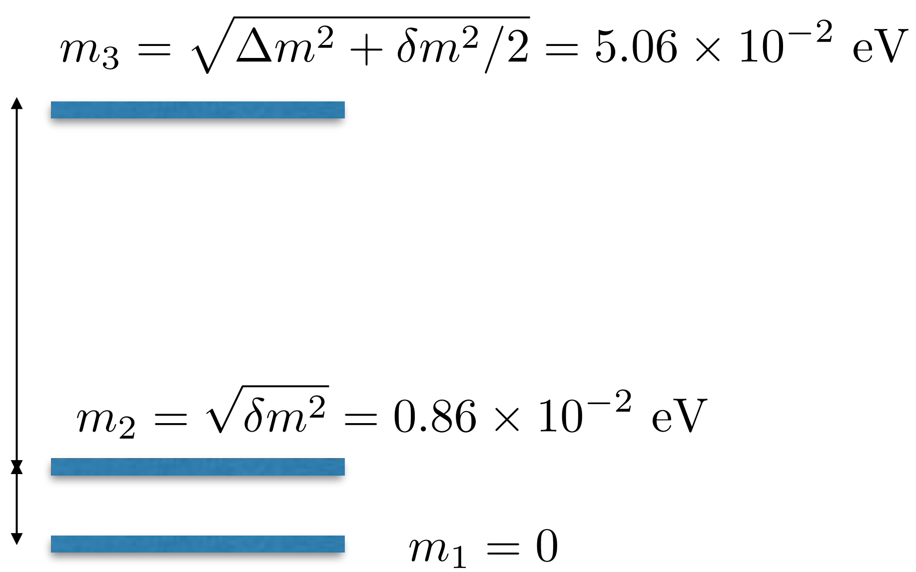

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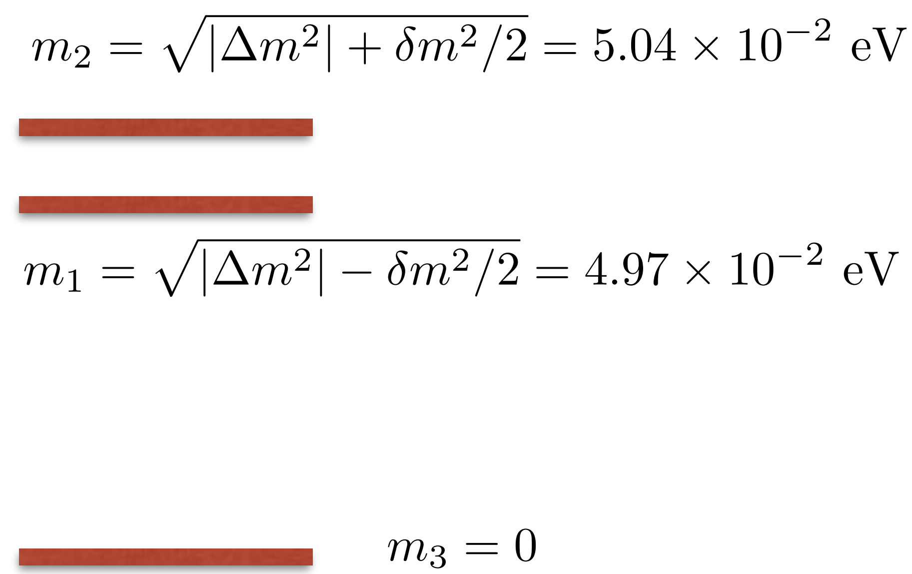

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($m_{\beta\beta}$,Σ) are correlated by oscillation data →

When deriving parameter bounds, two possible strategies

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Take NO and IO as two
alternative hypotheses

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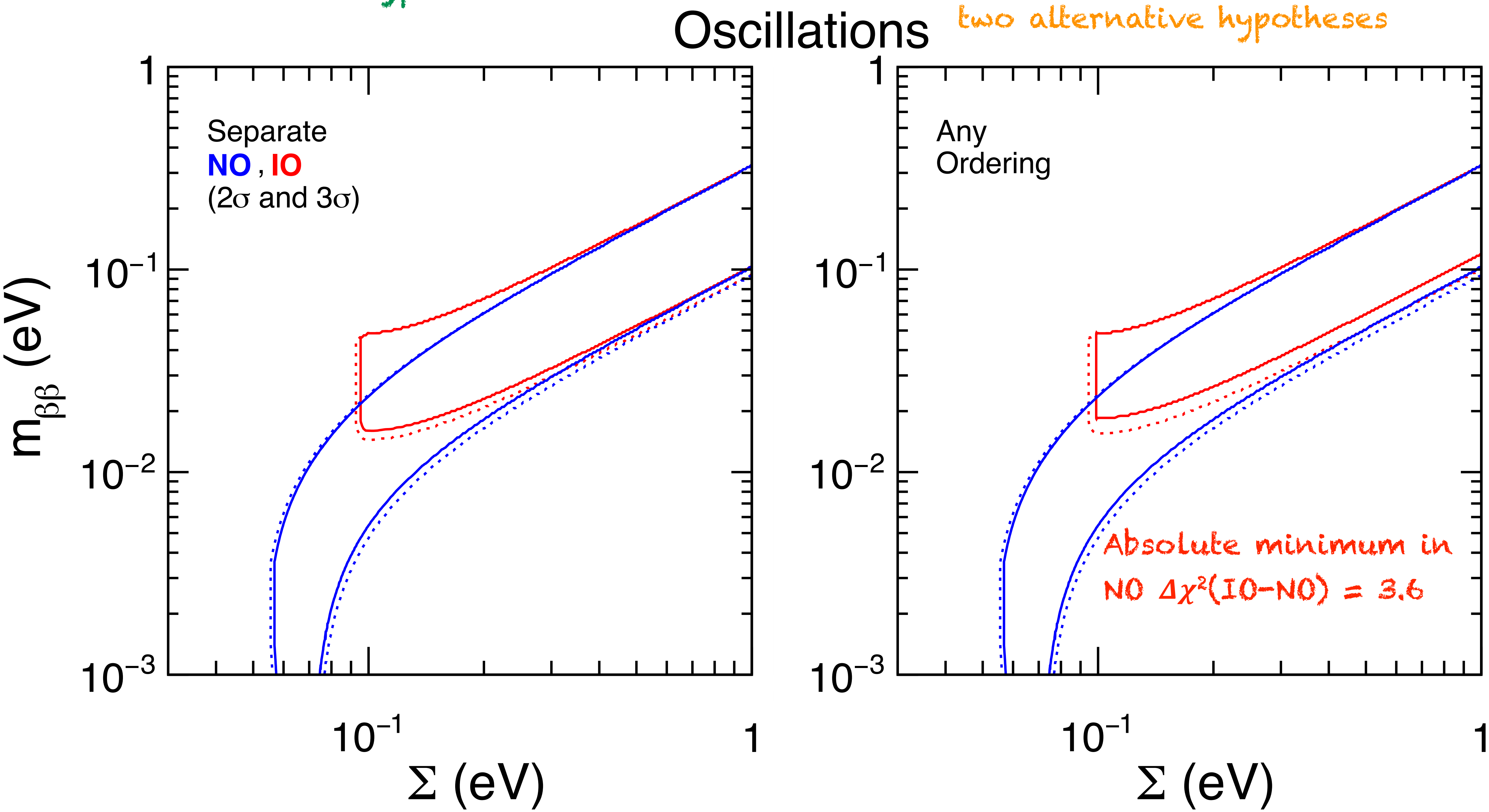

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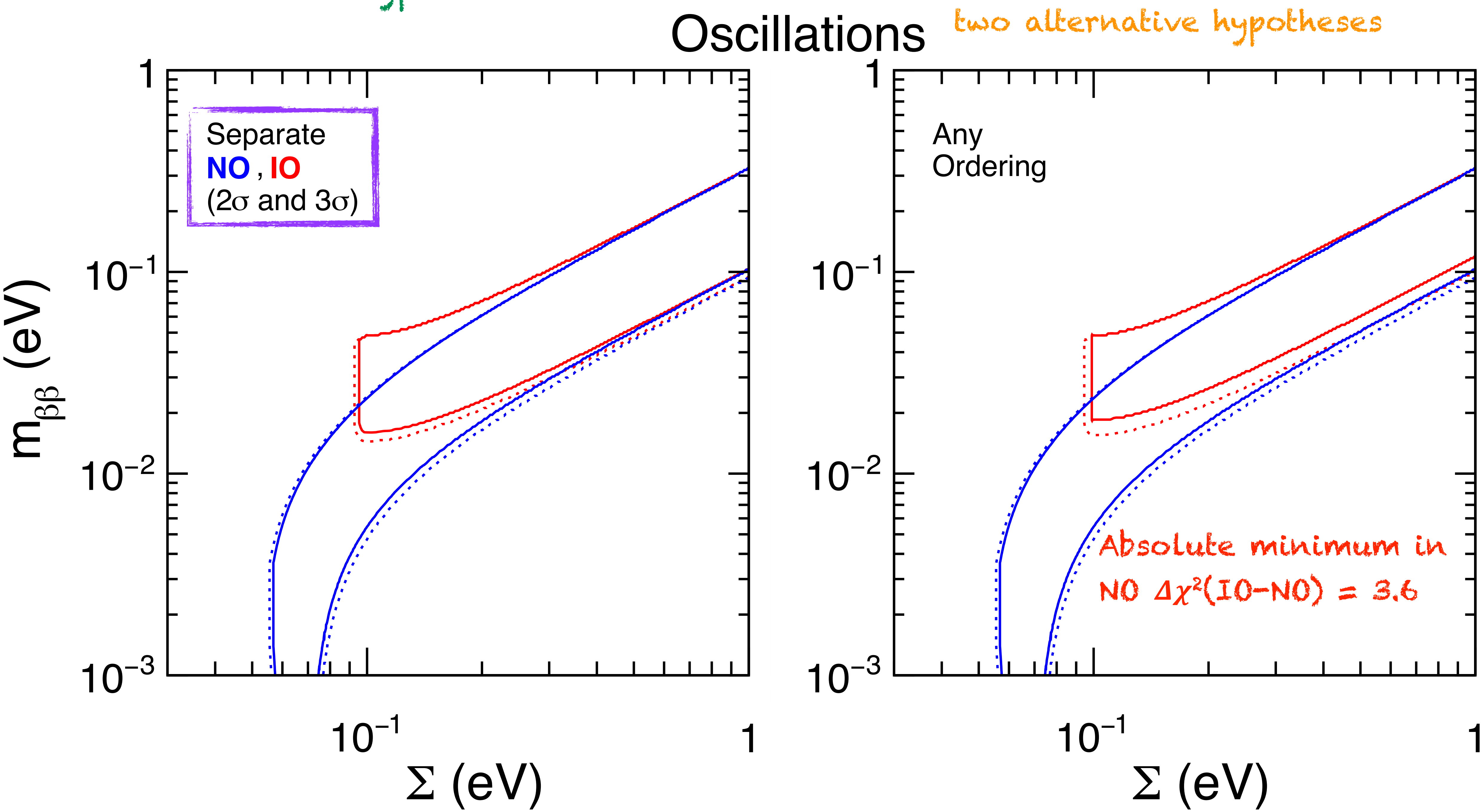

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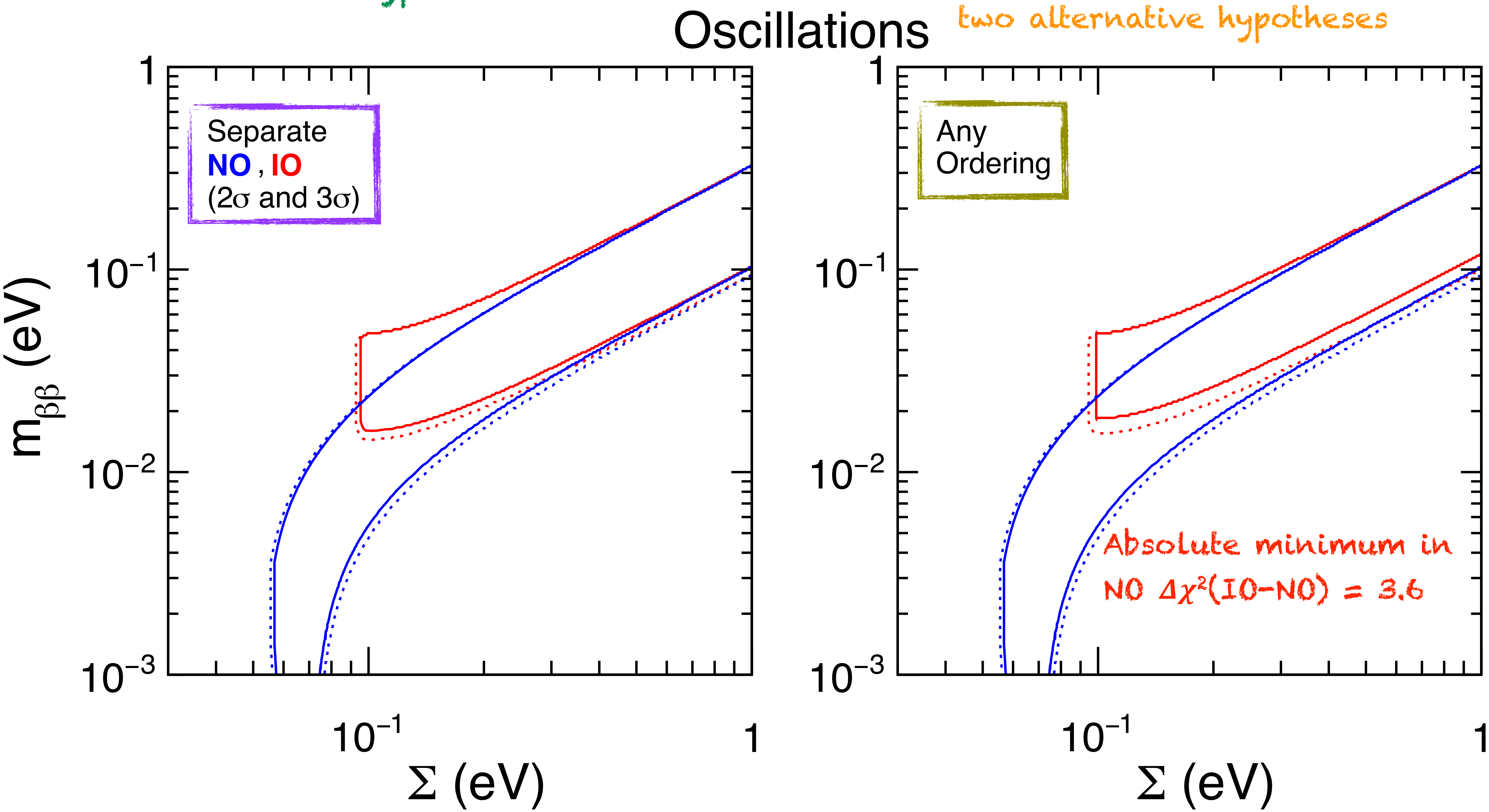

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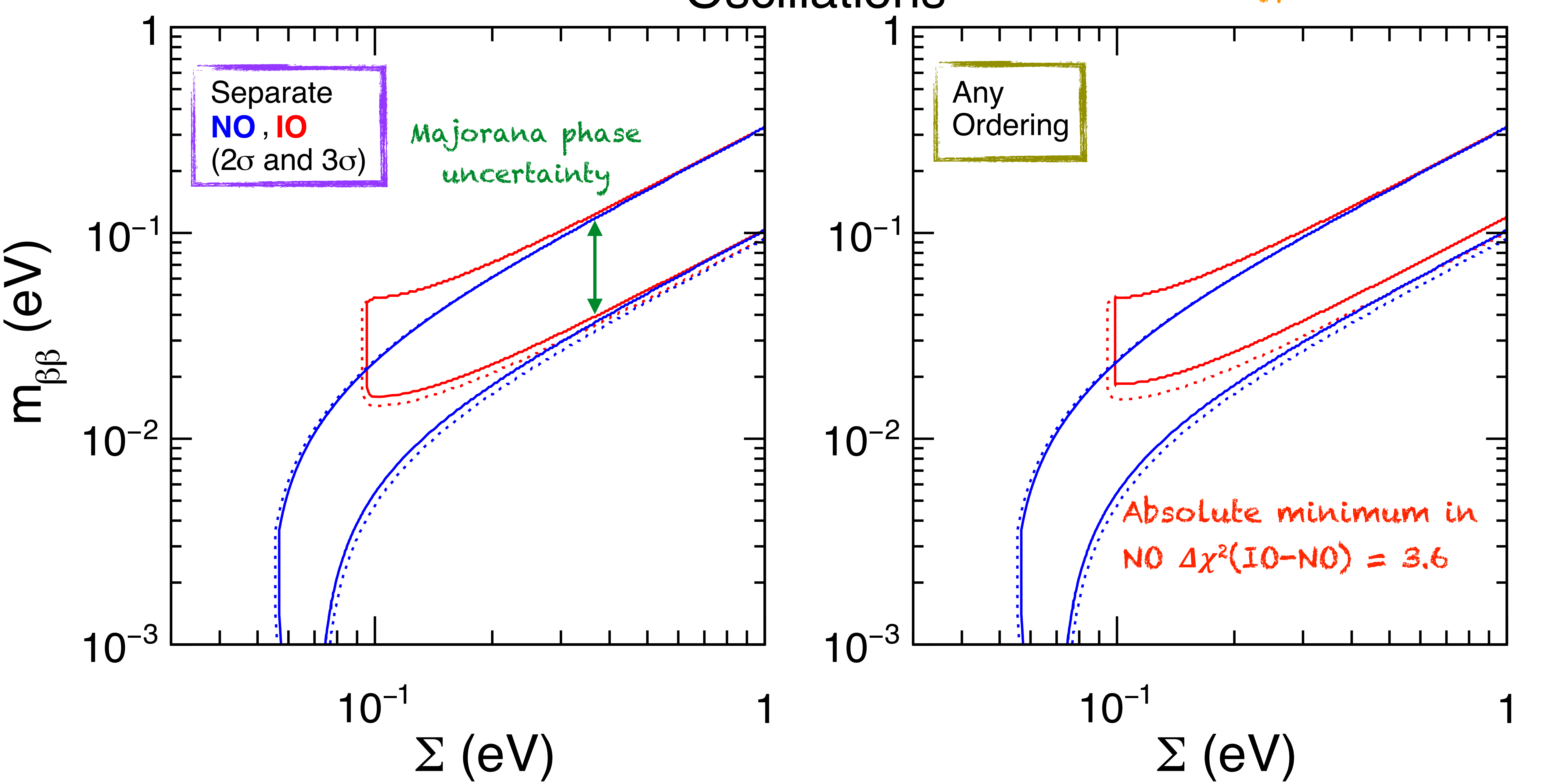

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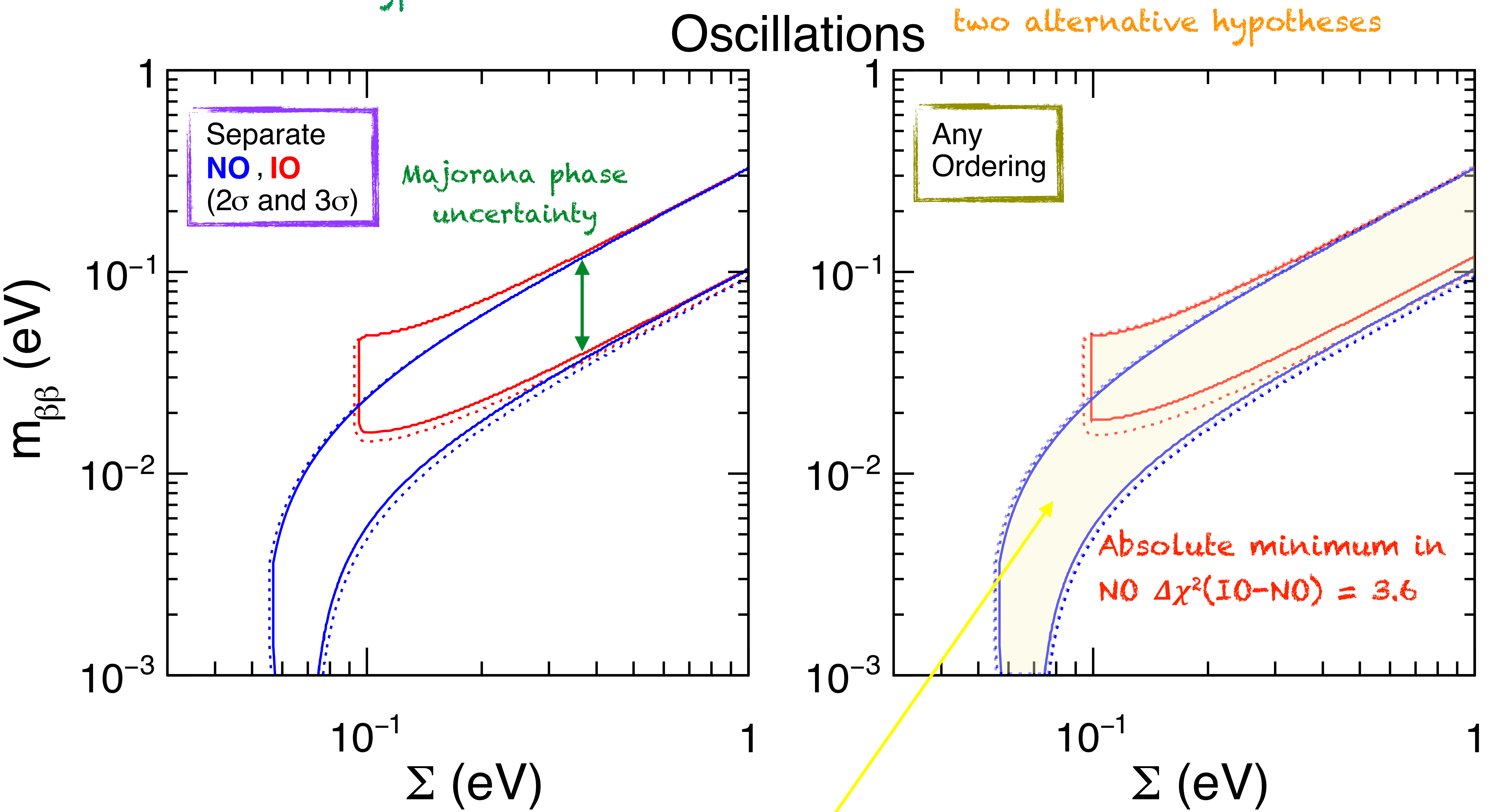

When minimising also with respect to the mass ordering the allowed parameter space is the union of the contours

Including $0\beta\beta\nu$ data

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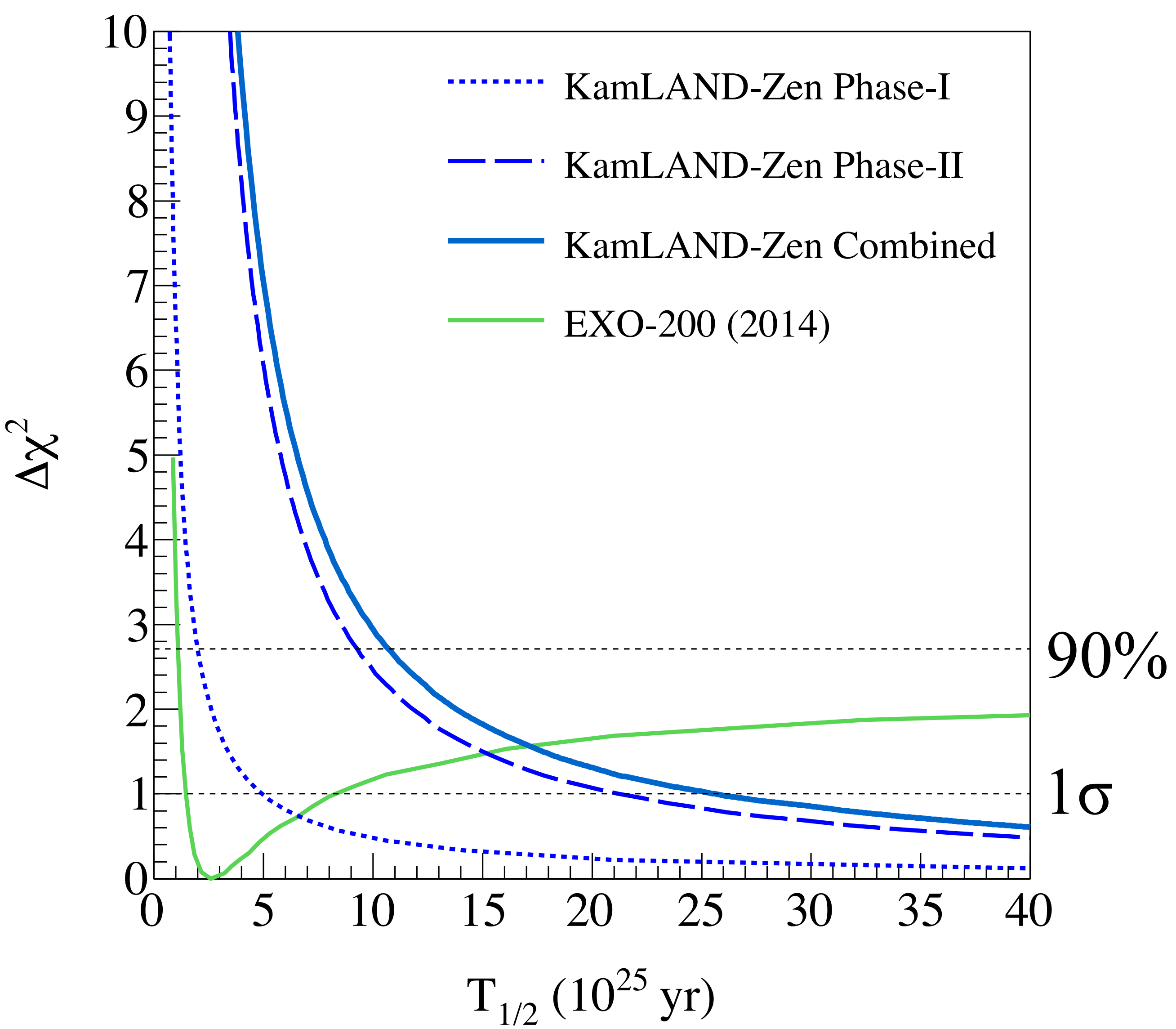
KamLAND-Zen ^{136}Xe Limits (90% C.L.)	
Phase 1	$T_{1/2}(0\nu) > 1.9 \times 10^{25}$ yr
Phase 2	$T_{1/2}(0\nu) > 9.2 \times 10^{25}$ yr
Combined	$\mathbf{T_{1/2}(0\nu) > 1.07 \times 10^{26}}$ **yr**



J. Ouellet, talk at ICHEP2016

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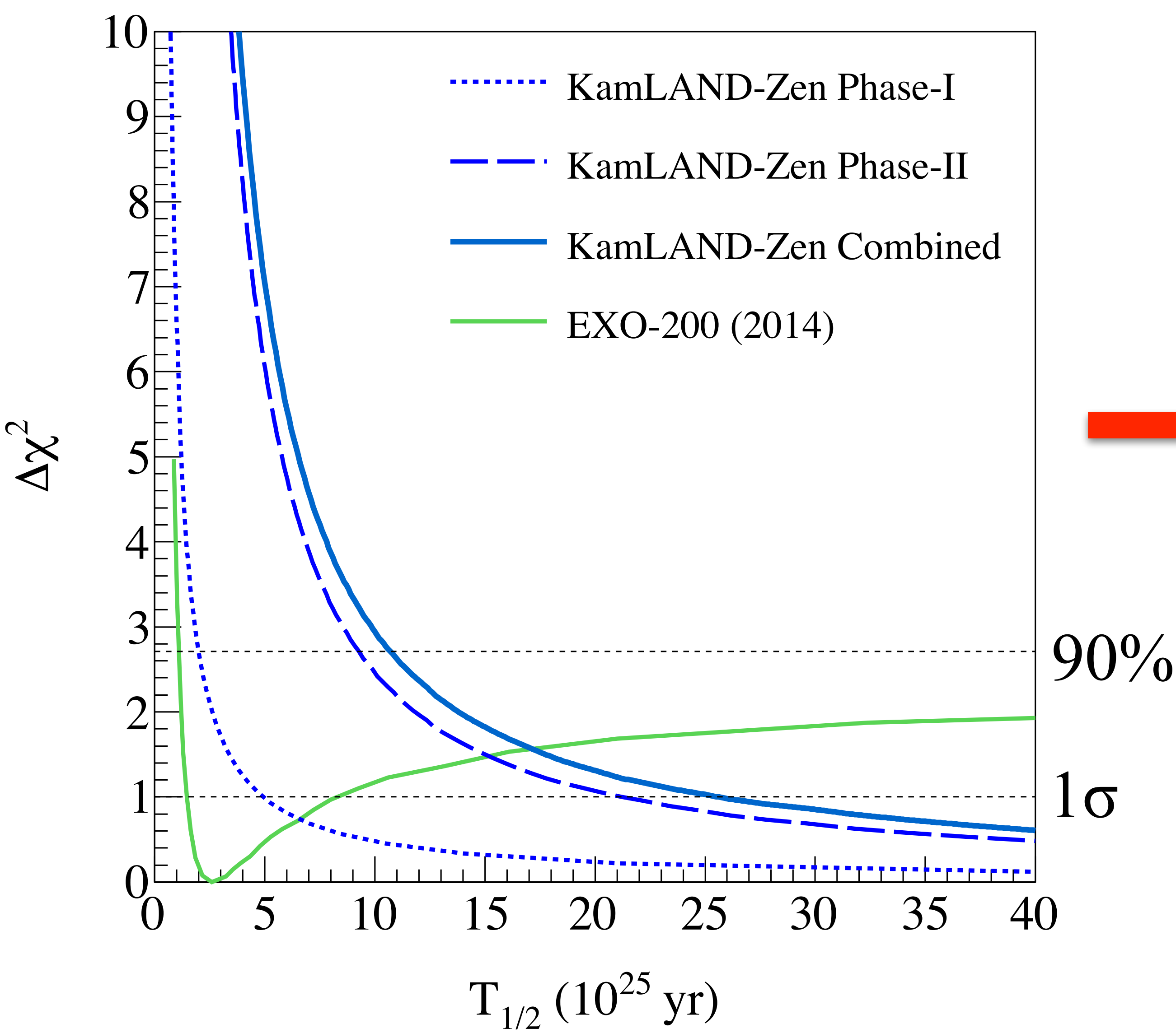

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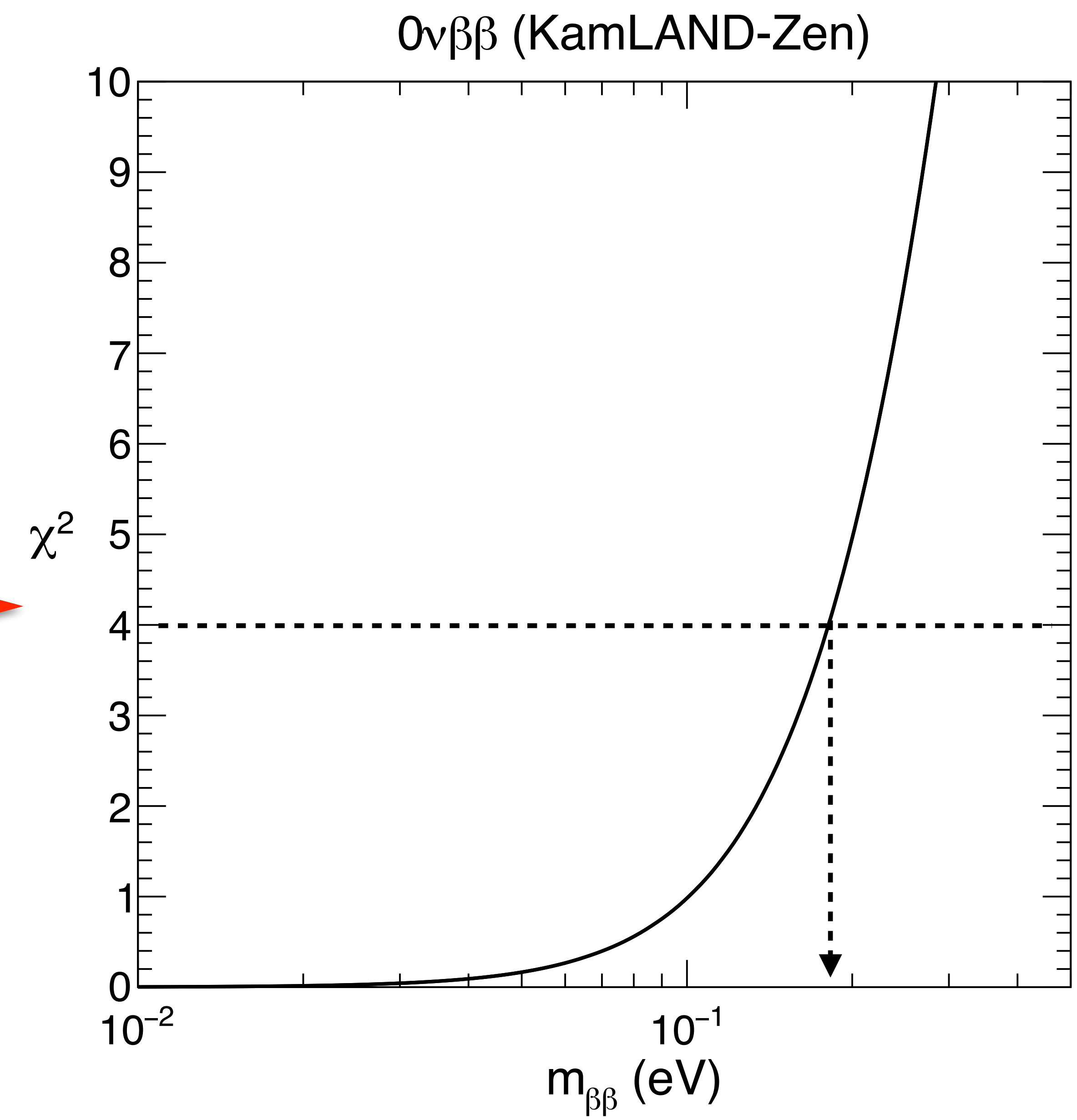
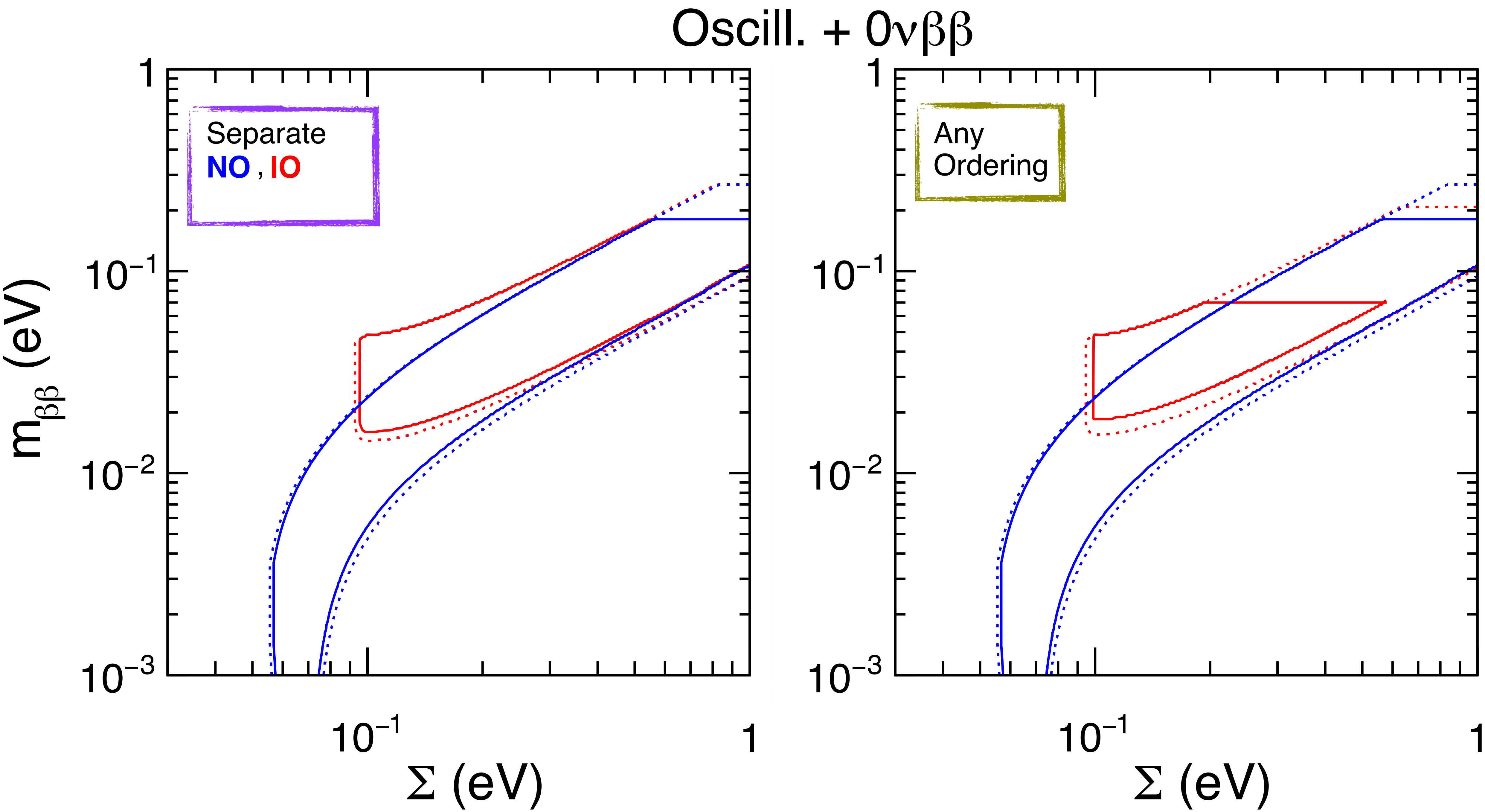
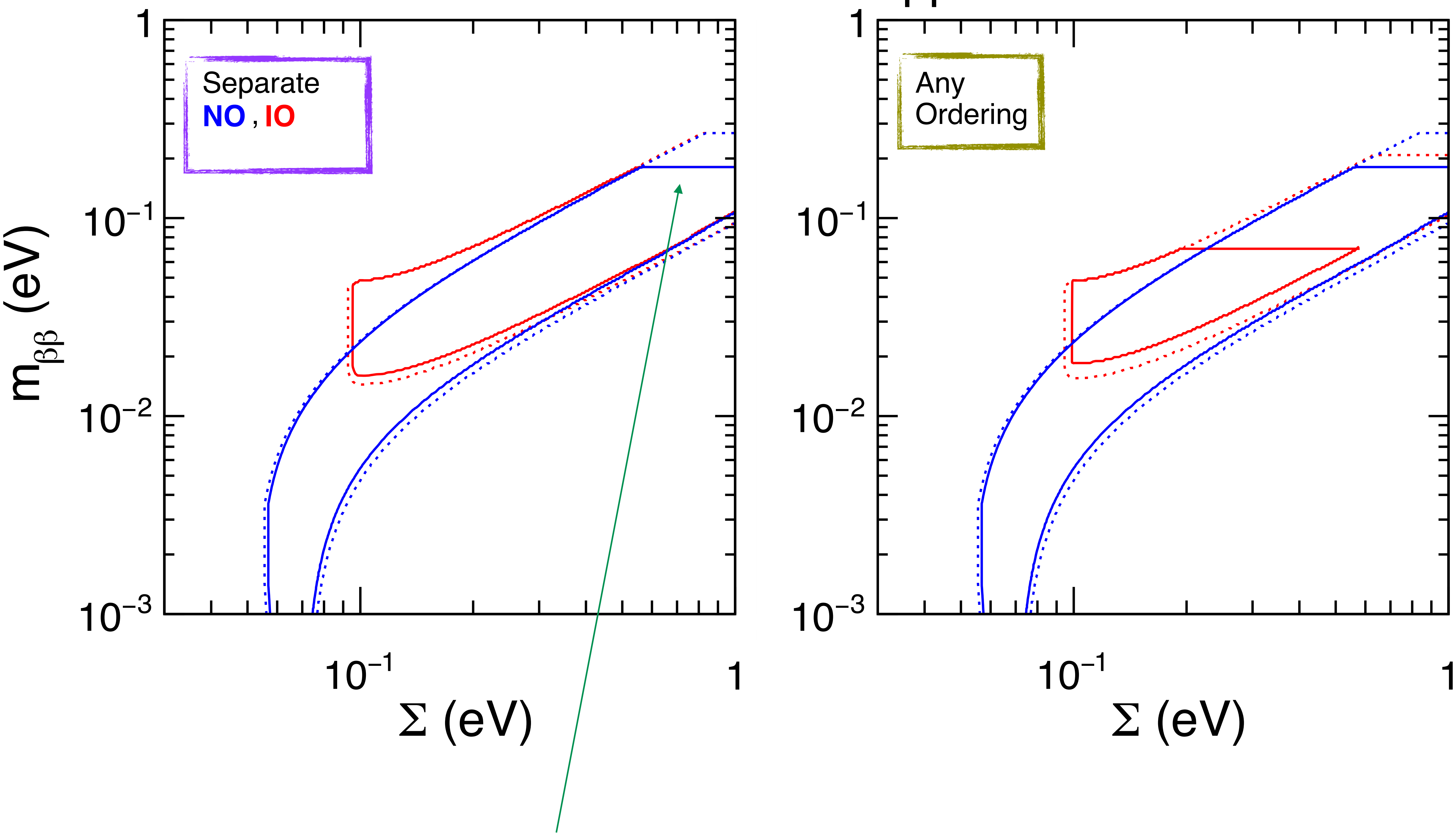
+NME Likelihood based on:
E.Lisi, A.Rotunno, F.Simkovic,
arXiv:1506.04058



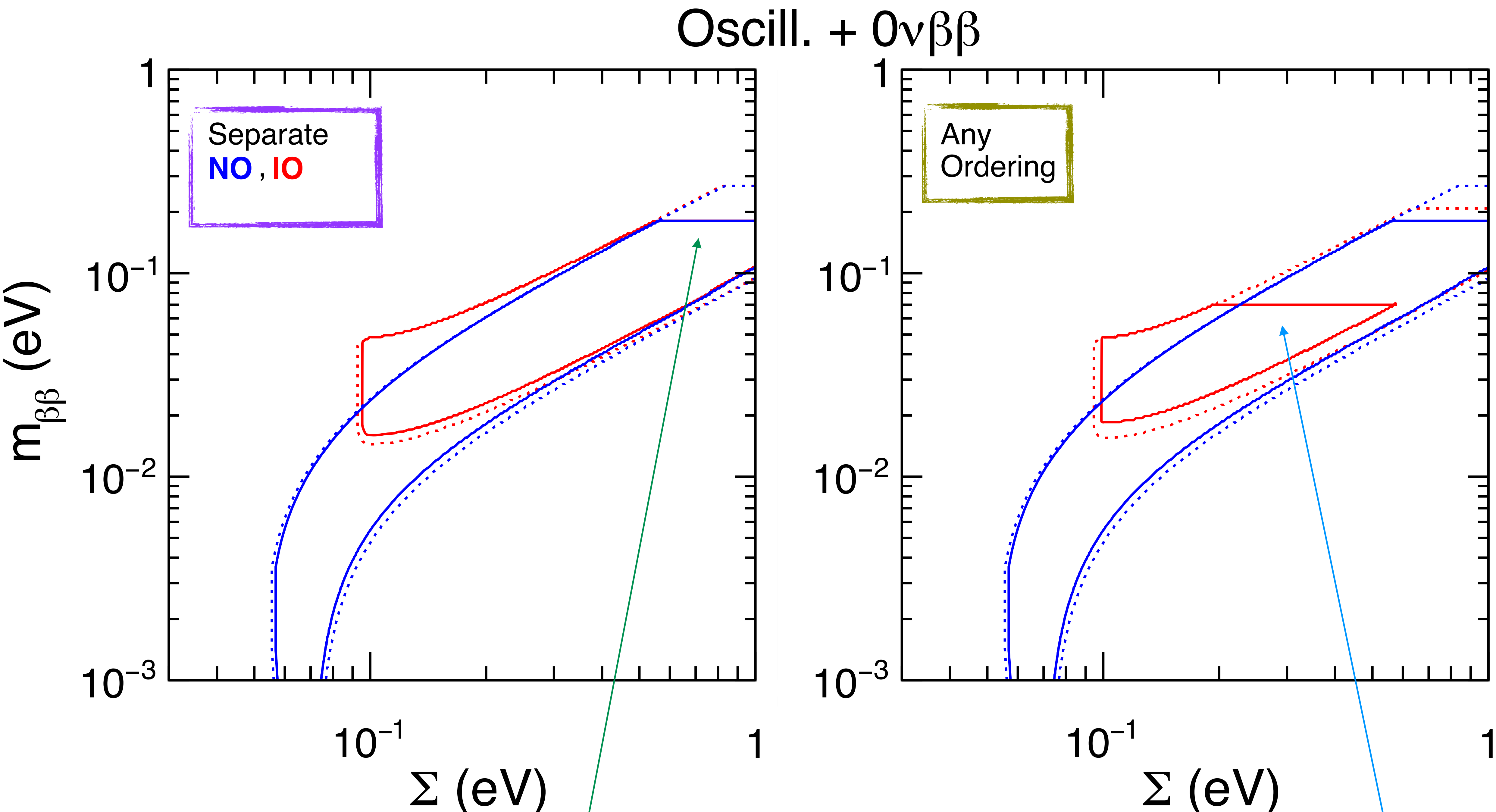
$m_{\beta\beta} \lesssim 0.2$ eV at 2σ


Oscill. + 0νββ
Separate
NO , IO
Any
Ordering
1
10^{-1}
10^{-2}
10^{-3}
$m_{\beta\beta}$ (eV)
10^{-1}
1
Σ (eV)
10^{-1}
1
Σ (eV)

Oscill. + 0νββ



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



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

Cosmological Data

Bari group, E. Di Valentino, A. Melchiorri,
Phys.Rev. D95 (2017) no.9, 096014)

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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
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TT	Temperature anisotropy
TE,EE	Polarization
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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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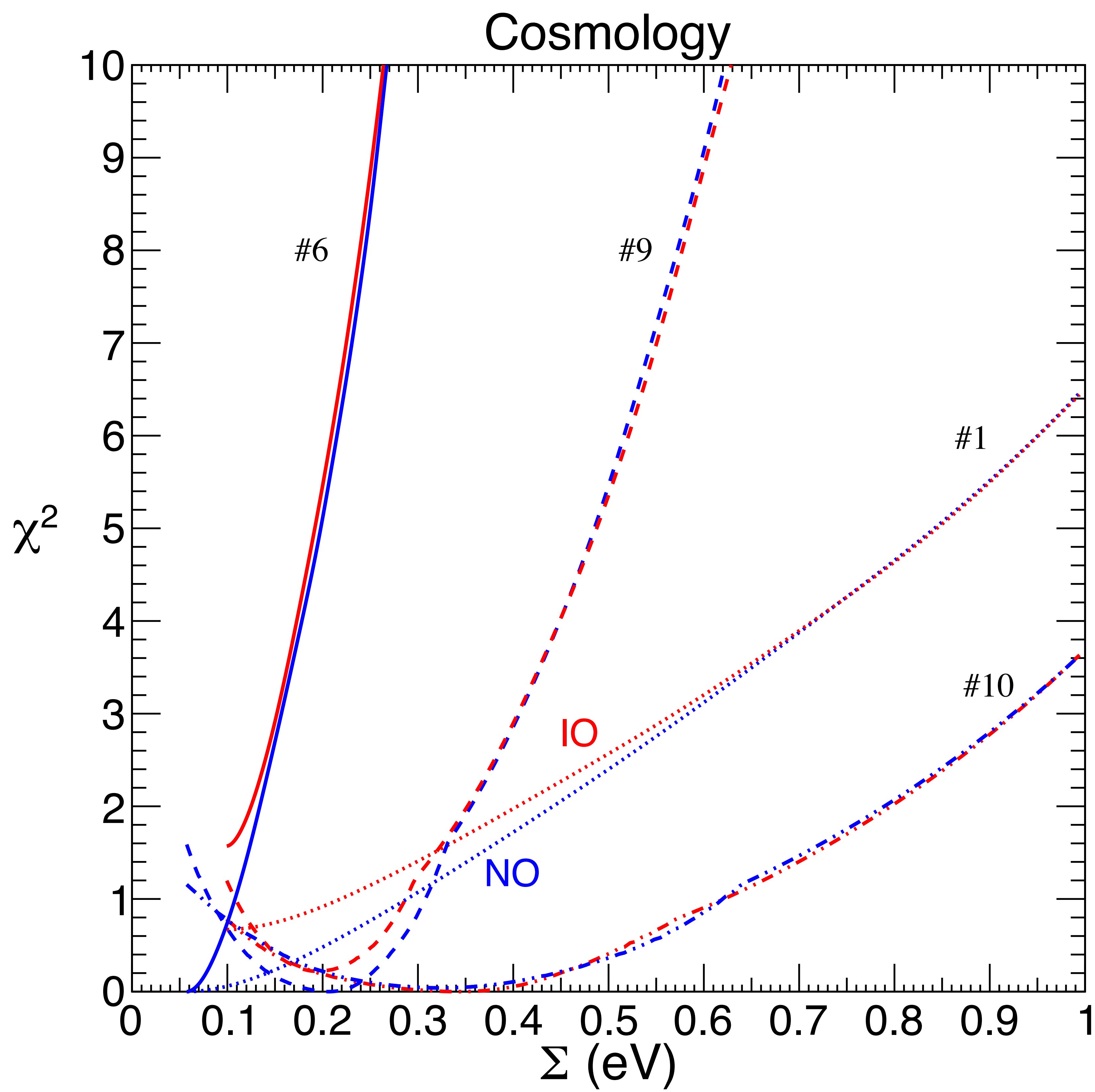

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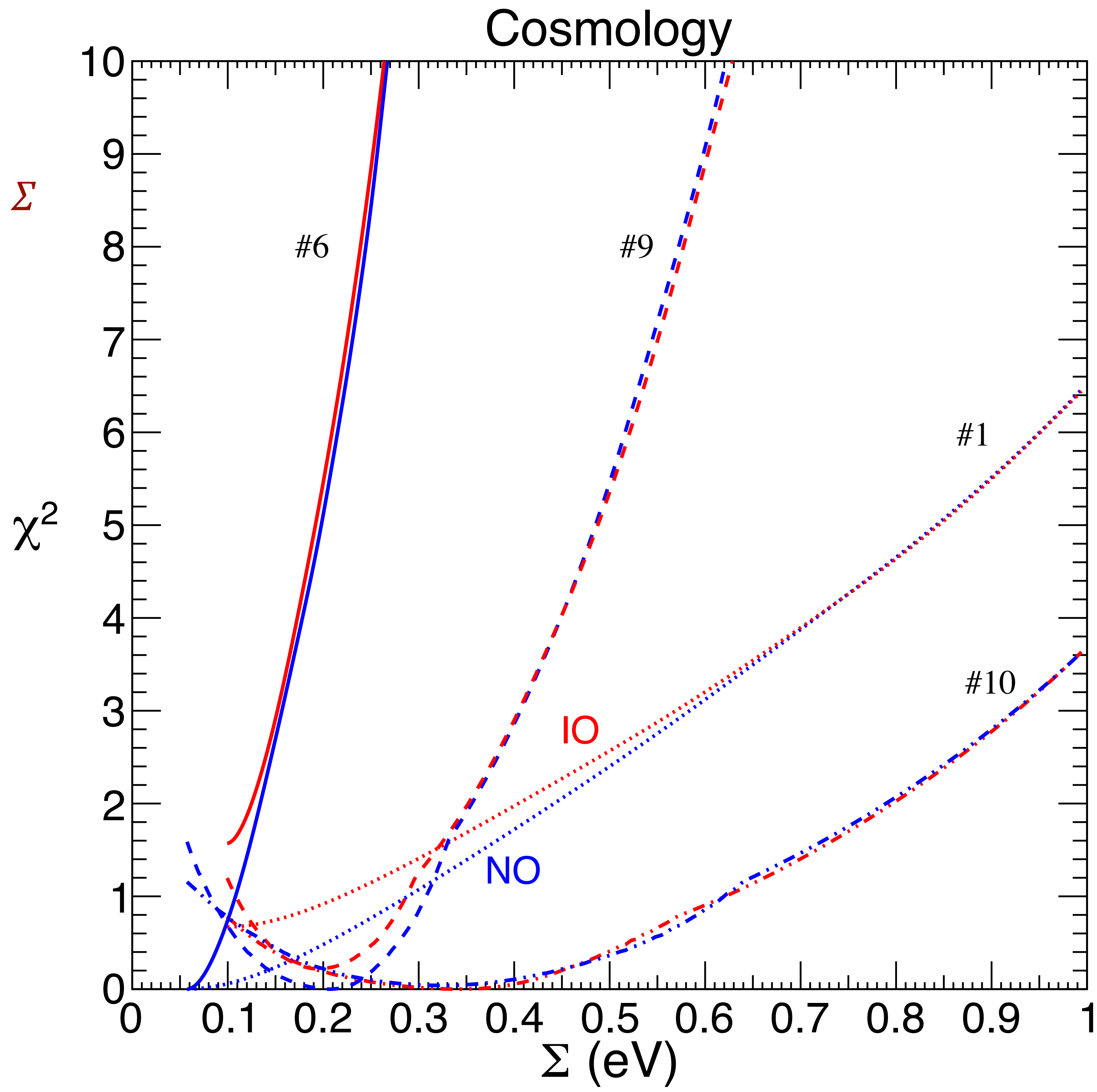
- χ^2 curves for NO and IO converge for large Σ



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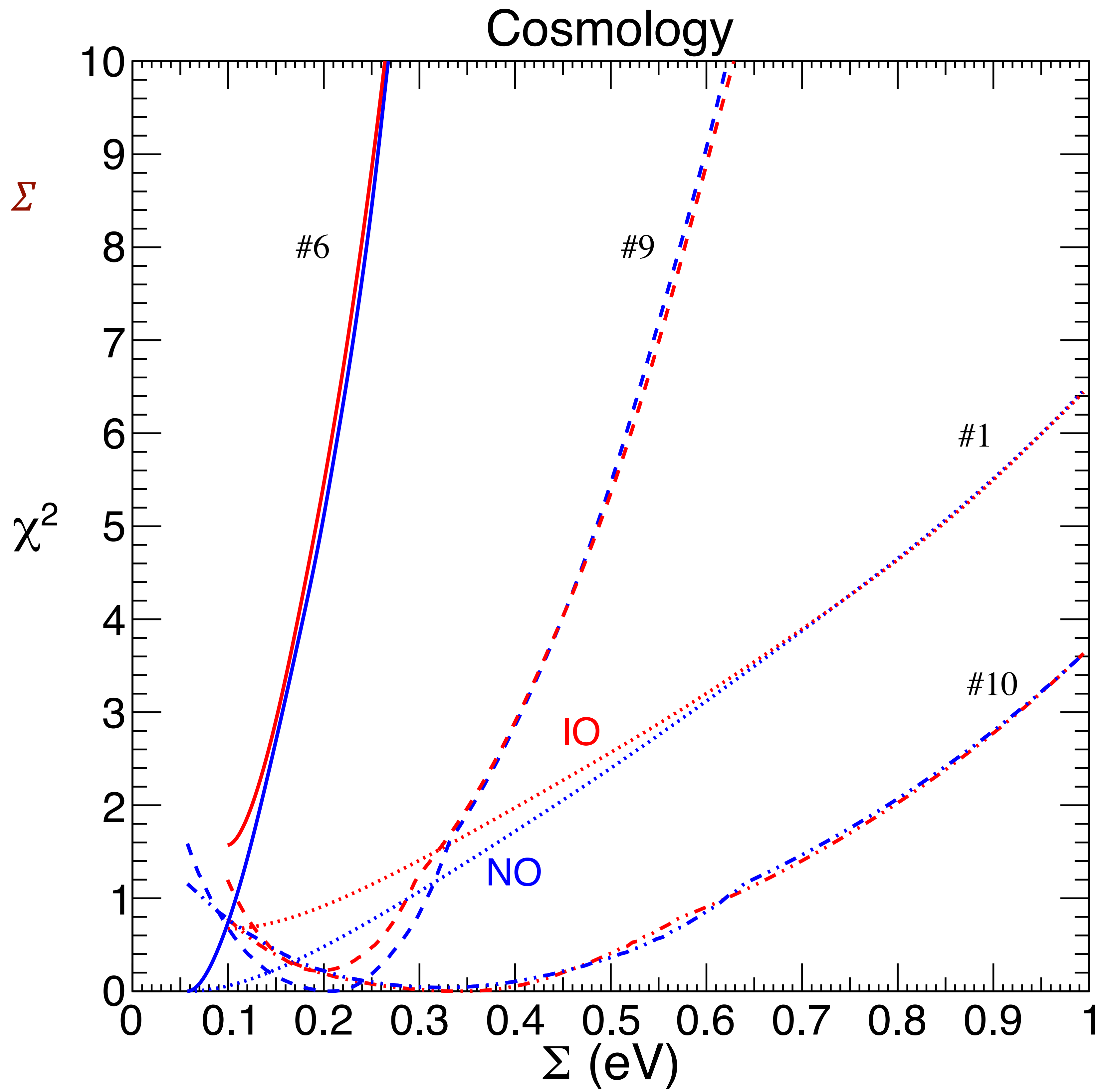

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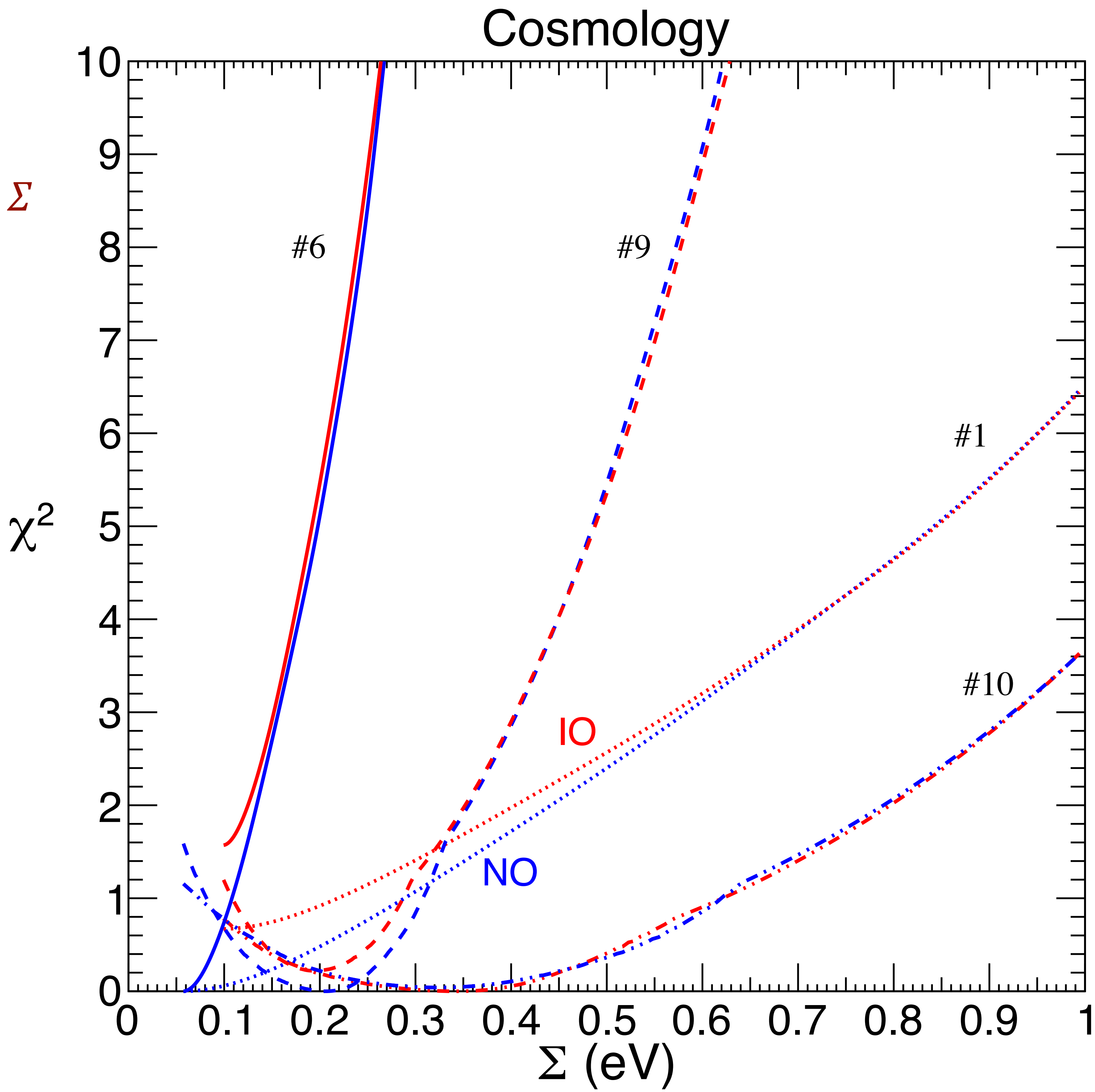

4 selected cases with increasingly strong bounds on Σ

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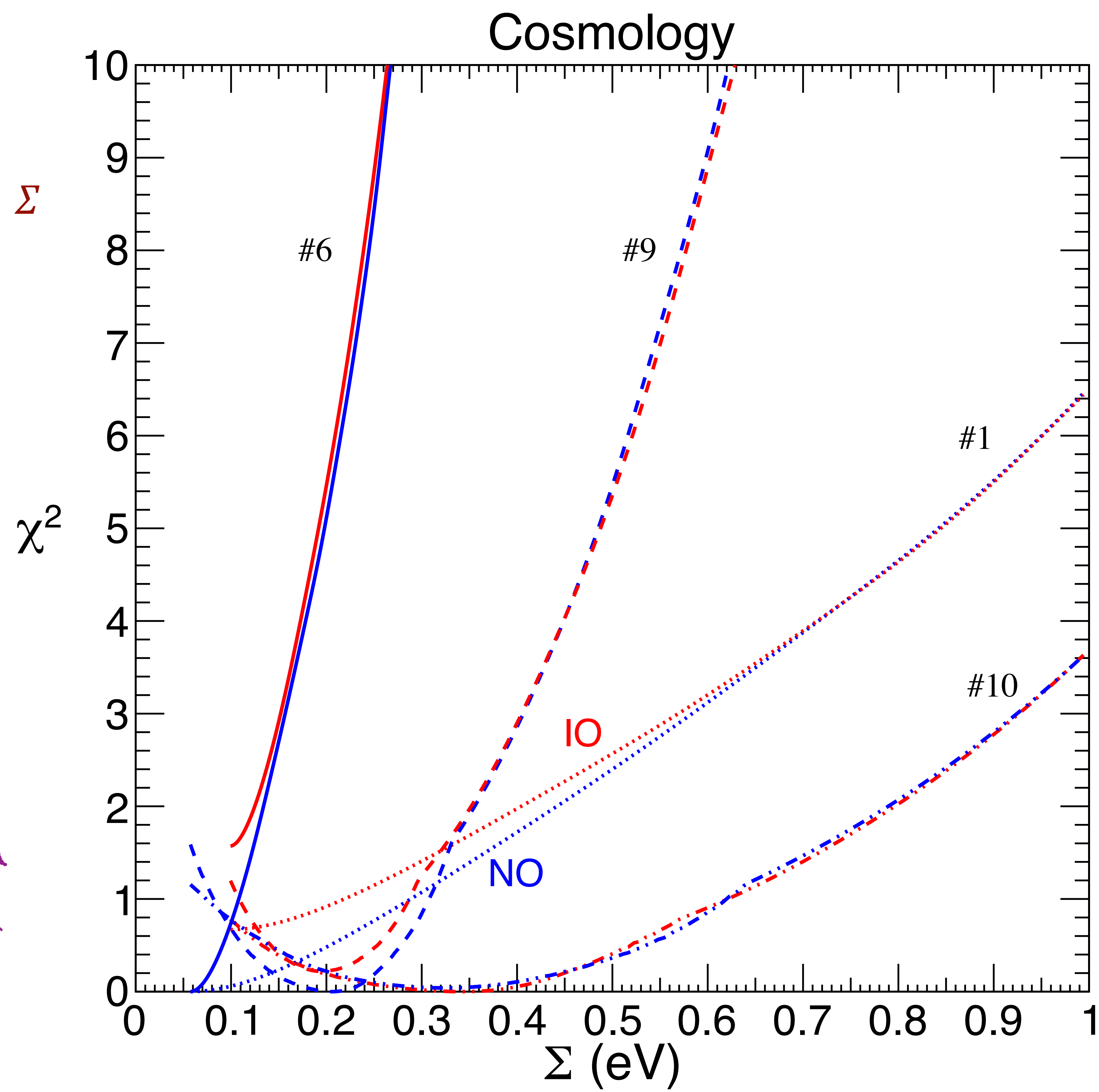
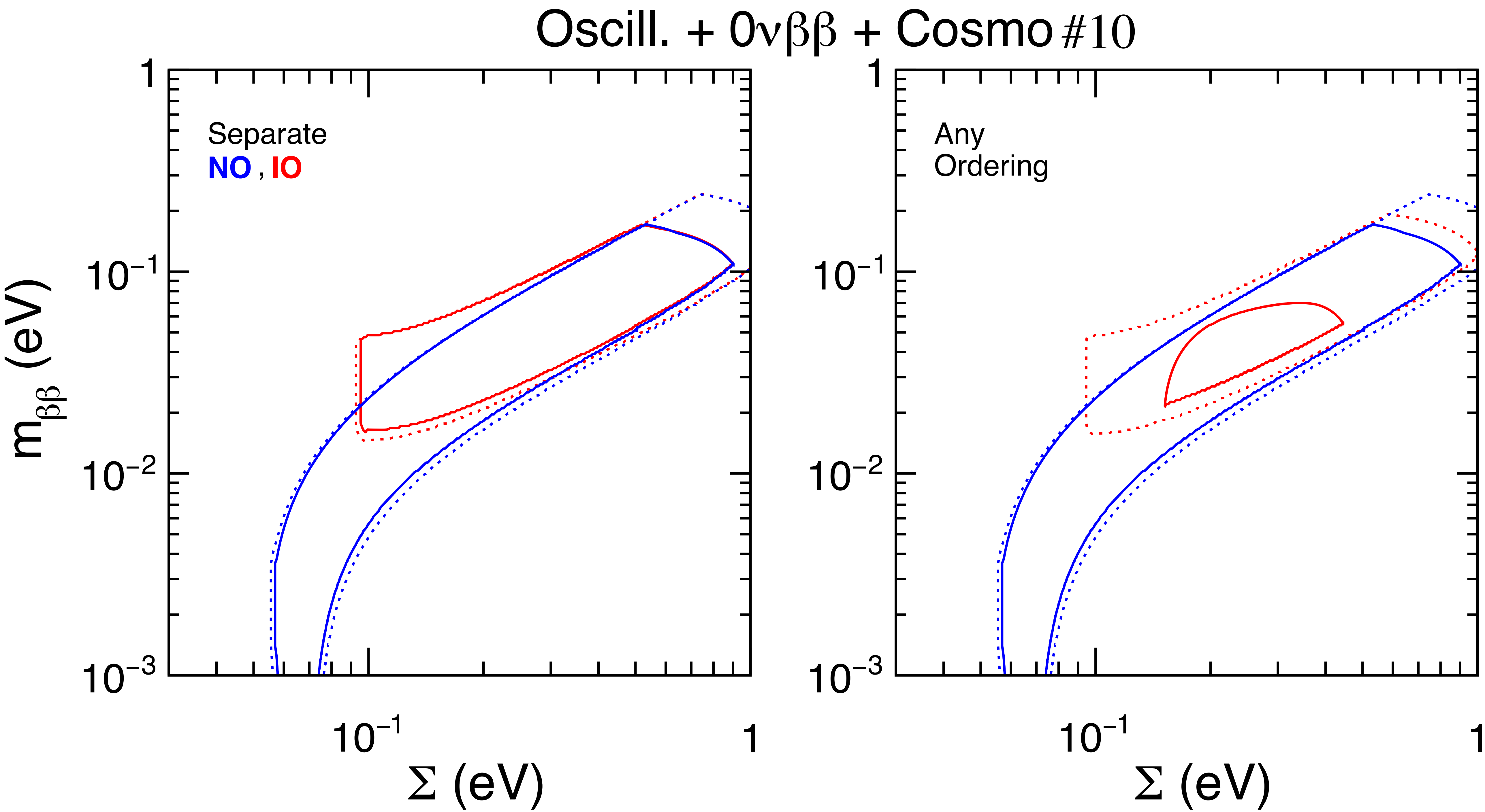
- $\Sigma = 0$ not allowed
- For cases #10 and #9 the minimum of the χ^2 is reached for a value of Σ higher than the minimum allowed



Combination of oscillation and non-osculation data



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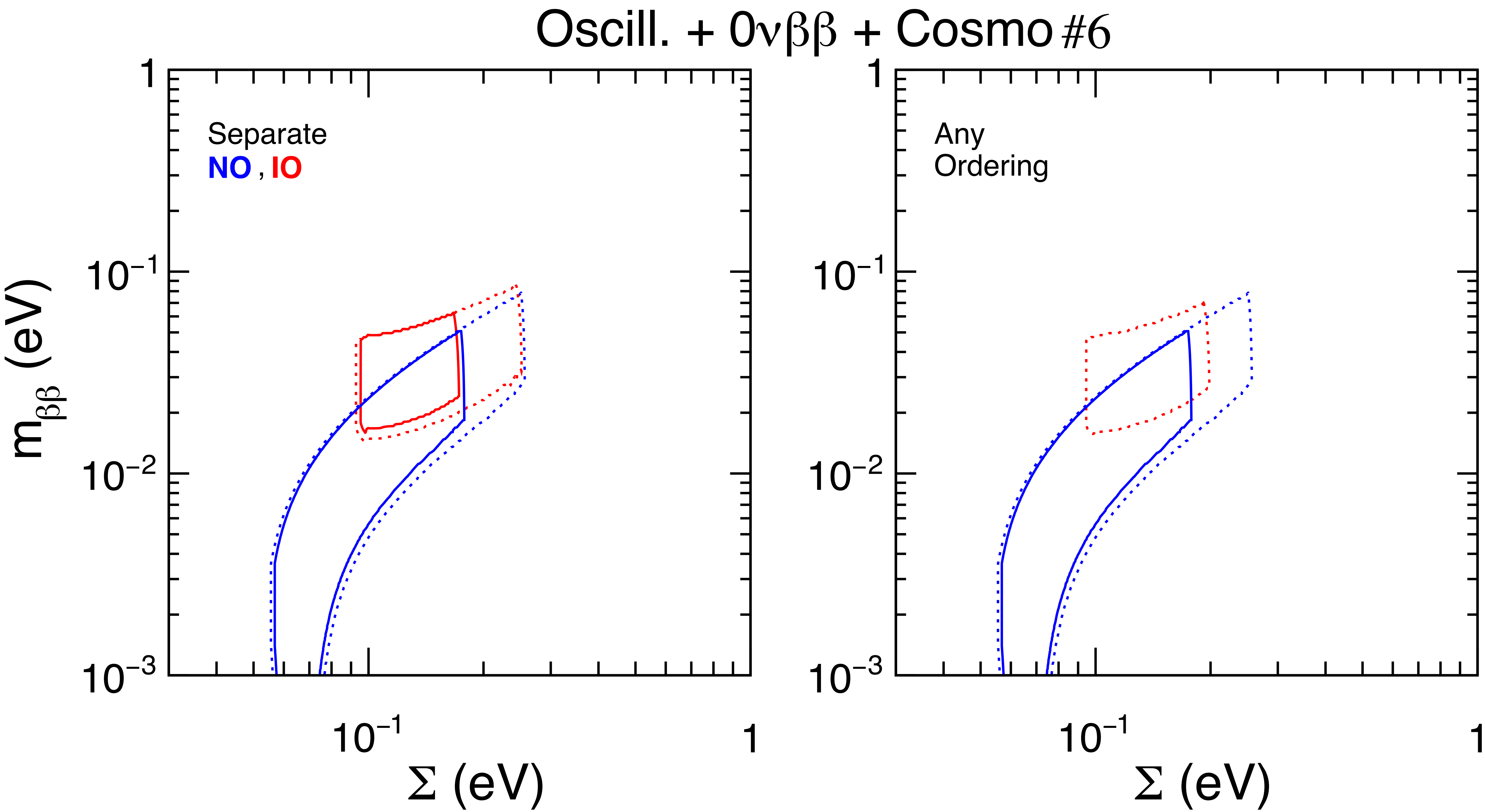

MBL reactor exp. (JUNO, RENO-50)

Mass ordering discrimination through interference between long-wavelength oscillations driven by $(\delta m^2, \theta_{12})$ and short-wavelength ones driven by $(\Delta m^2, \theta_{13})$

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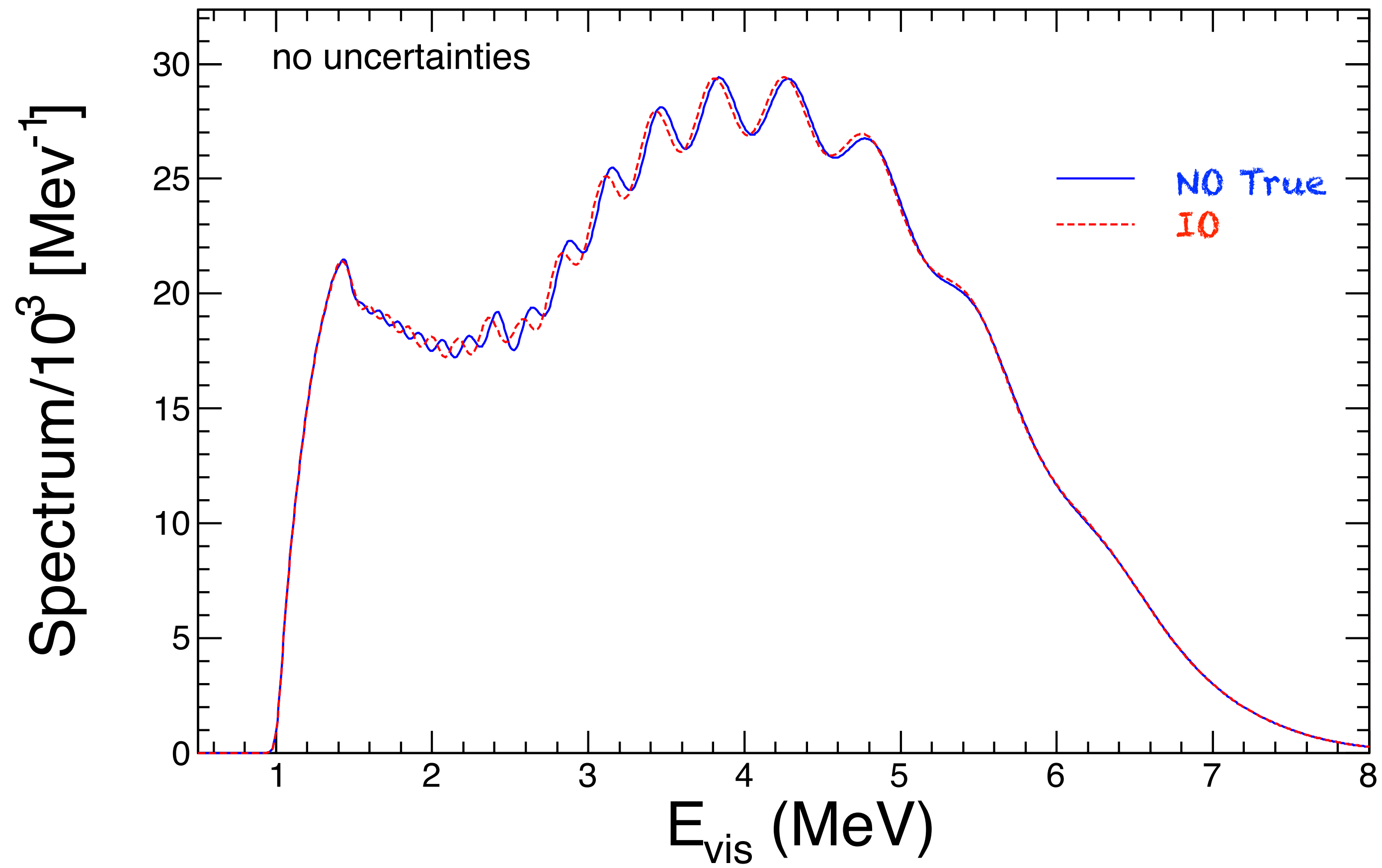

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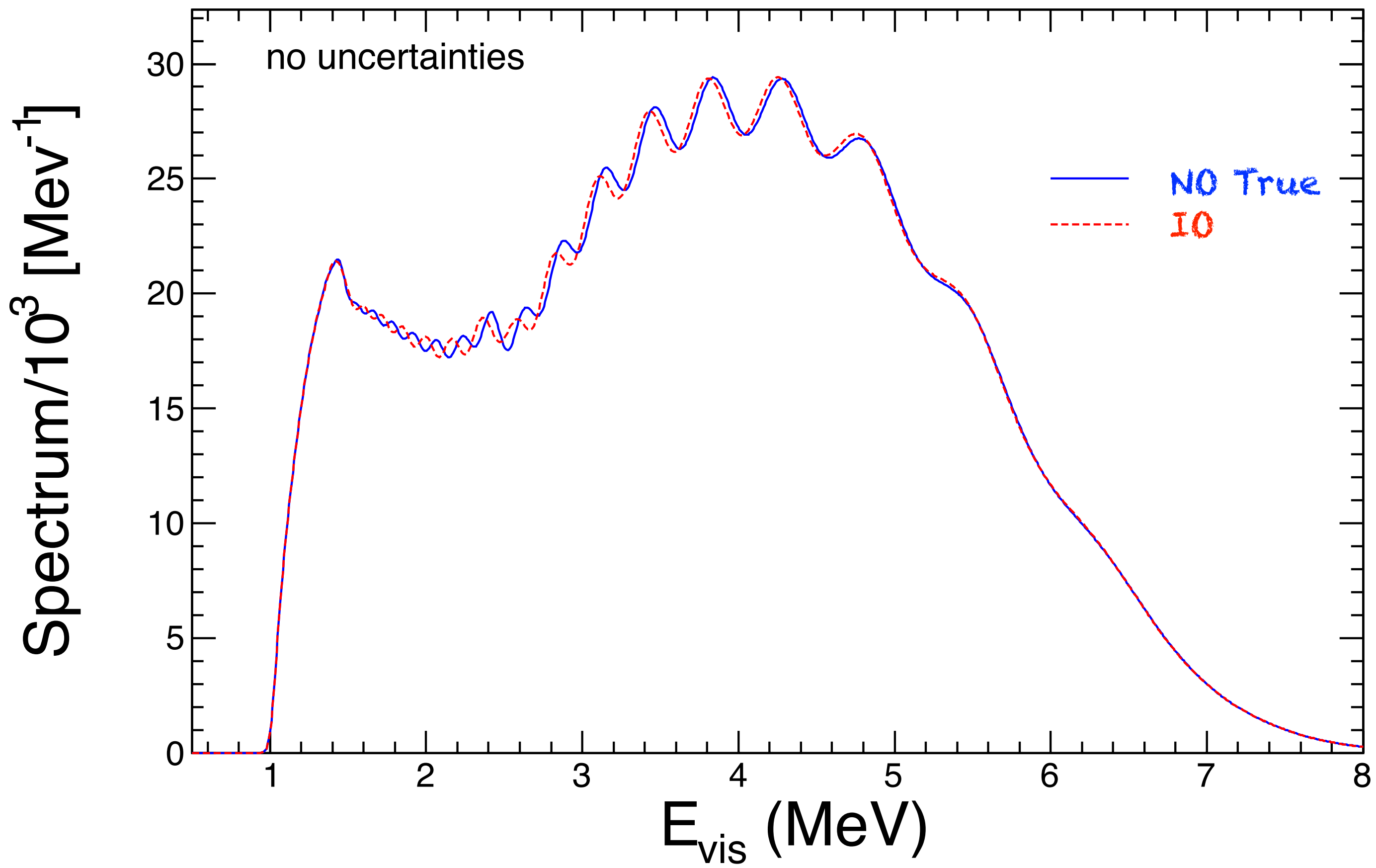

Expect O(10^5) events in a few years

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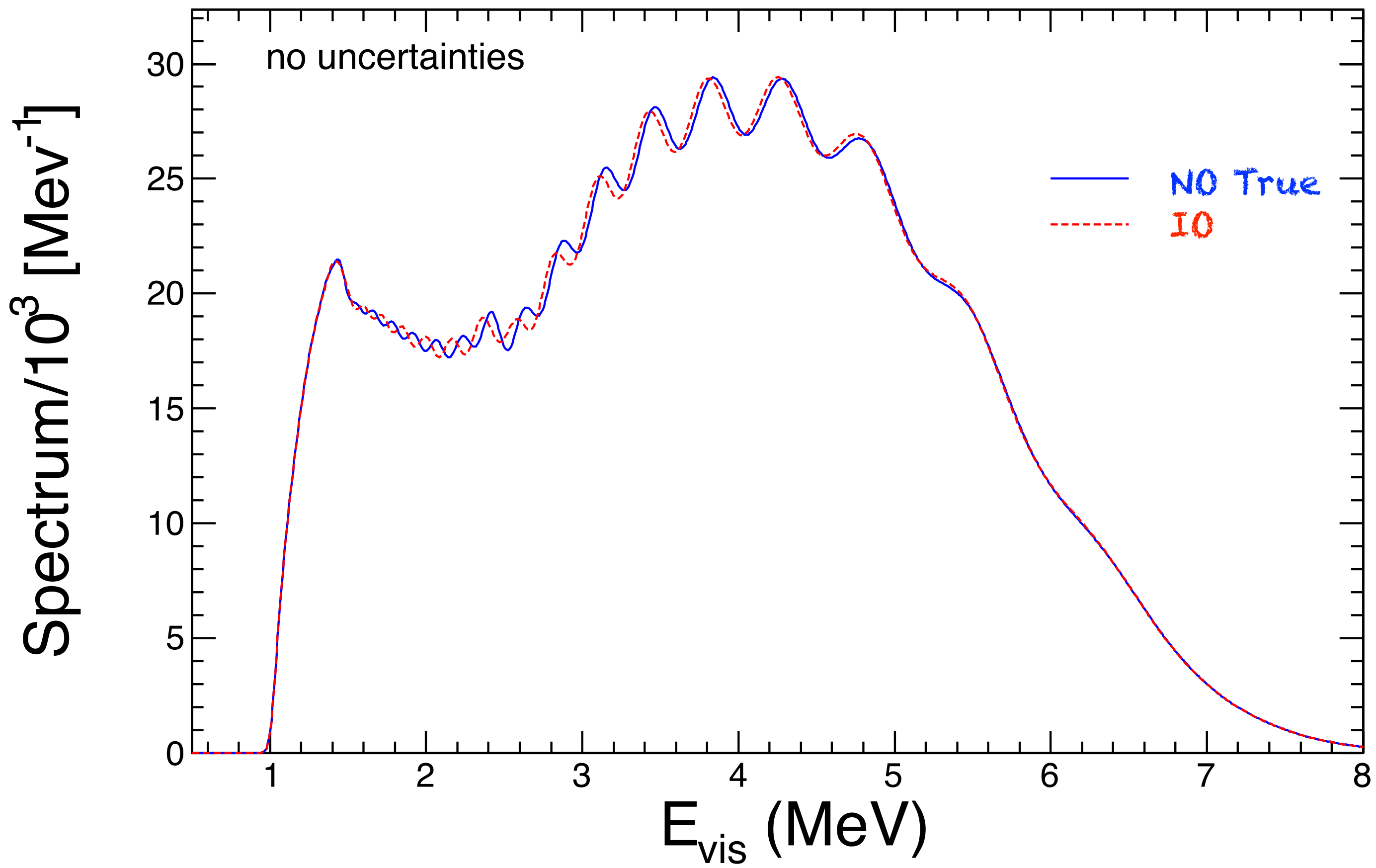

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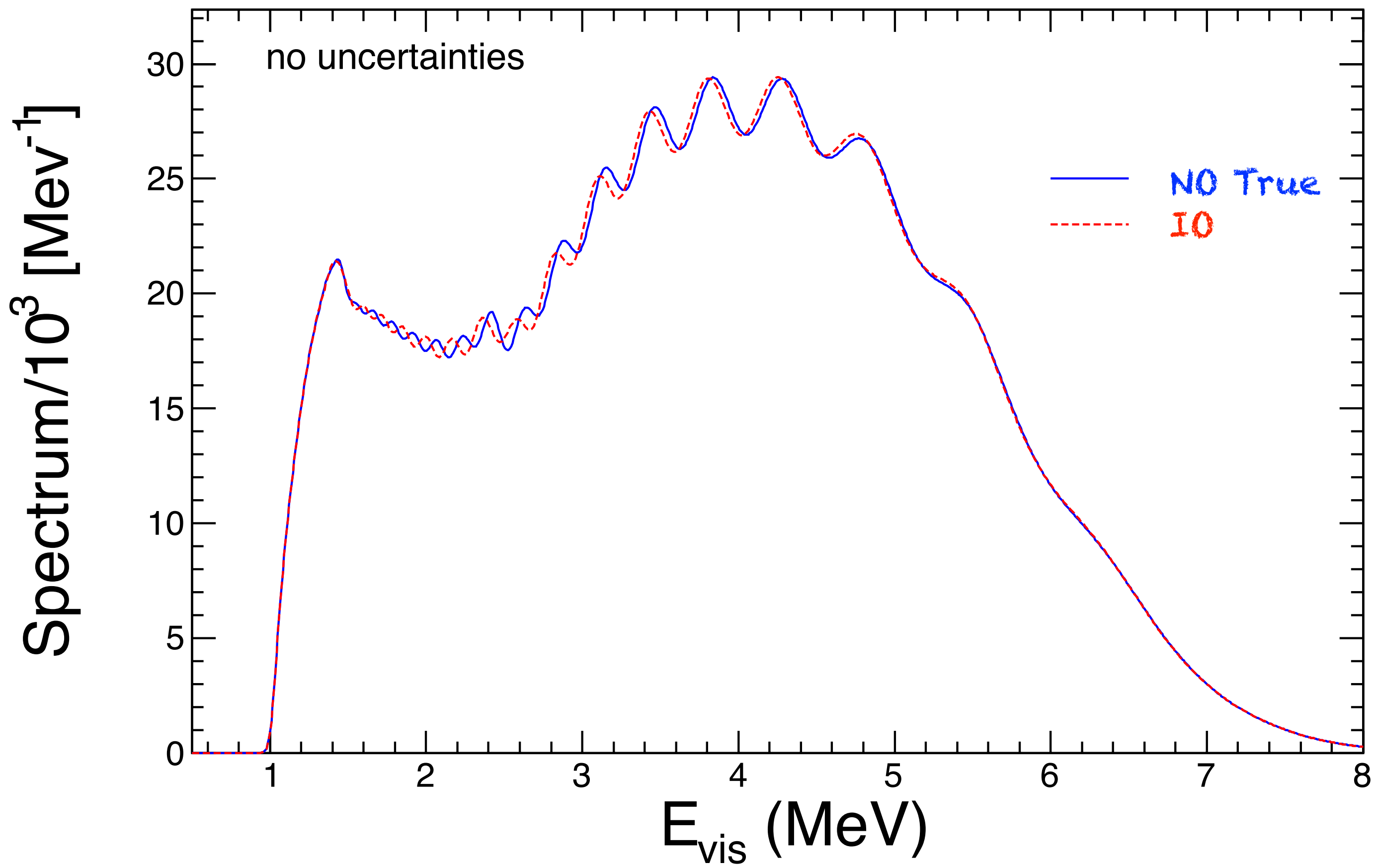

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Most important systematic errors

- energy resolution
- energy scale
- flux shape

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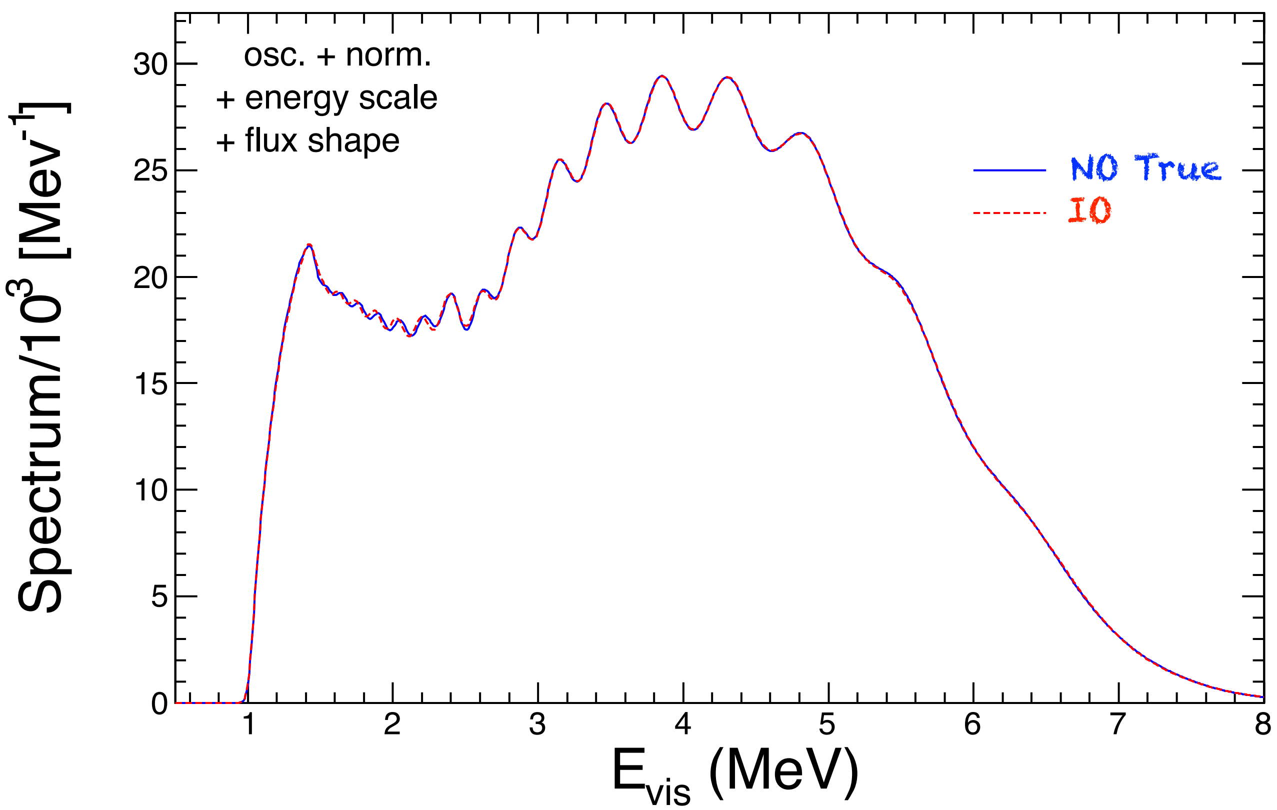
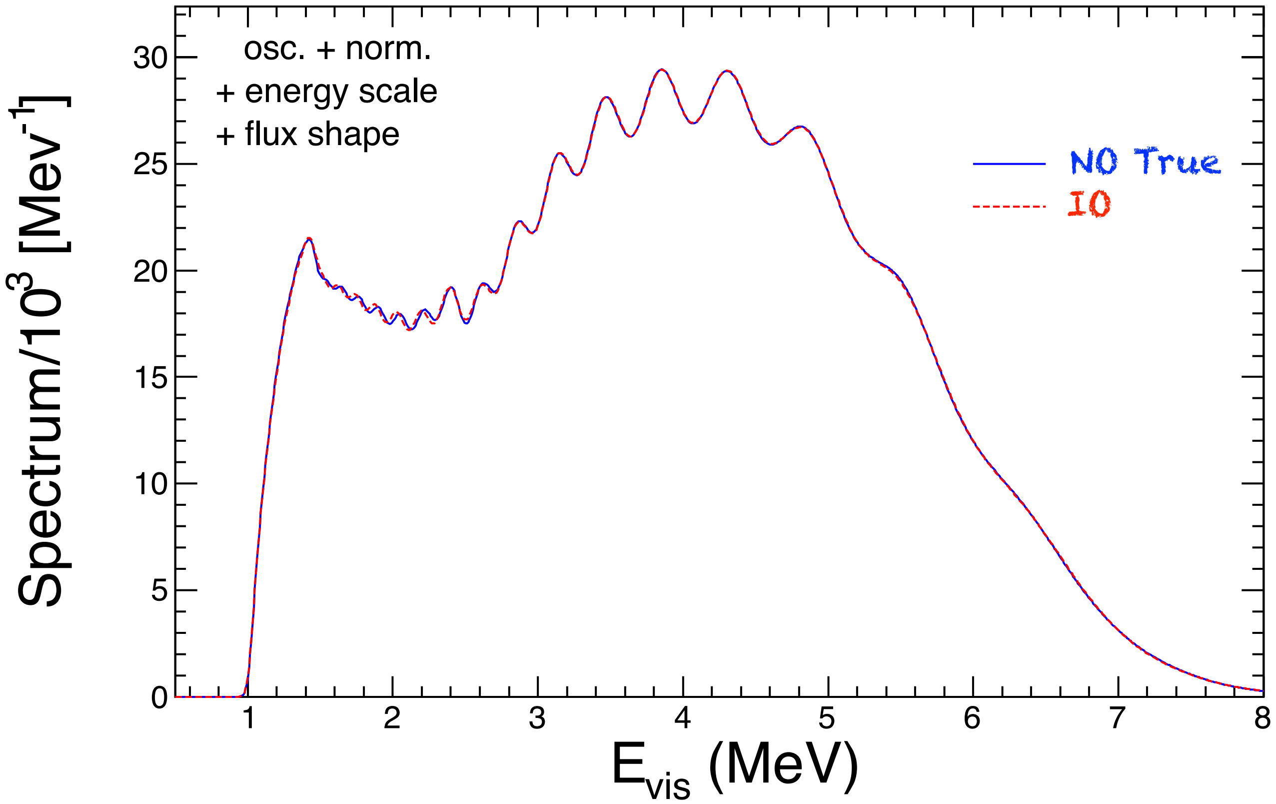


After the inclusion of energy scale and flux shape uncertainties, NO (true) and IO (fit) spectra become less distinguishable → some loss of sensitivity to mass ordering

Energy scale uncertainties
E->E'(E) stretch the "x-axis"



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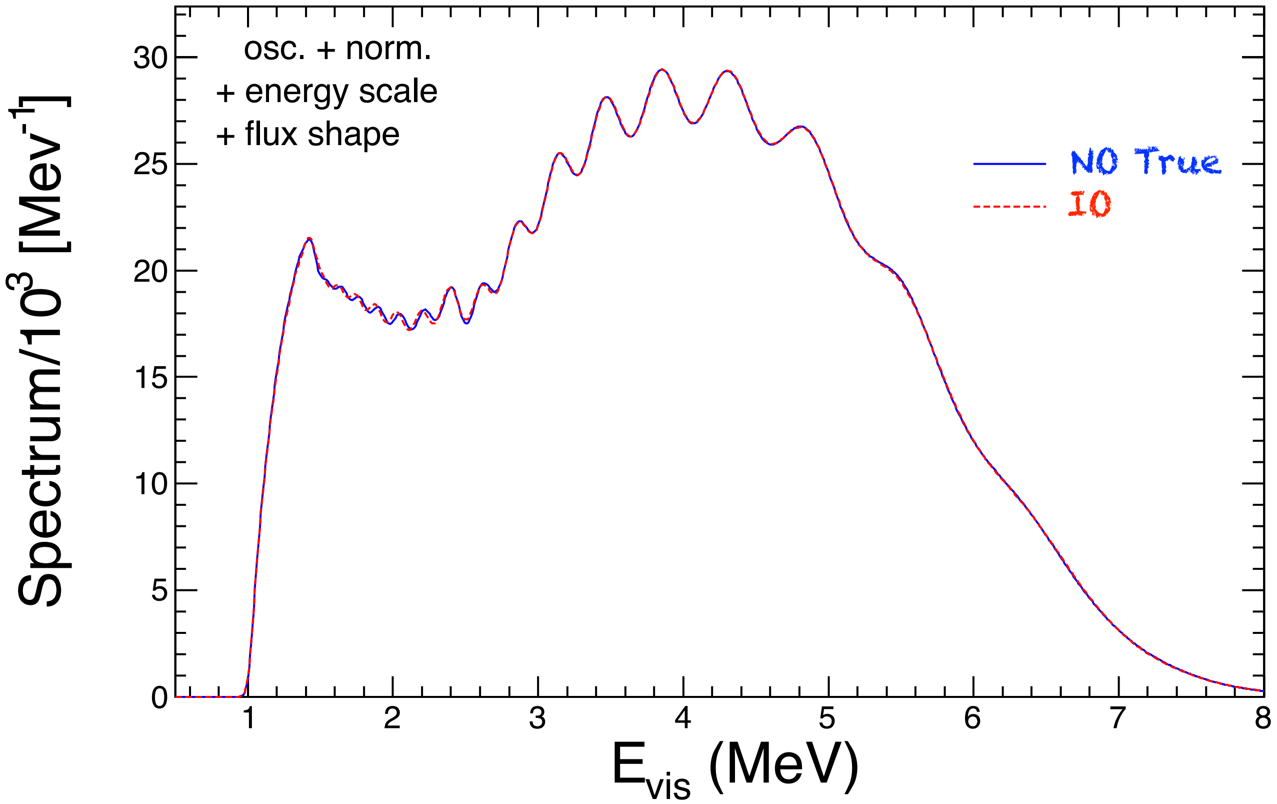
Flux shape uncertainties
Φ(E)->Φ′(E) stretch the "y-axis"



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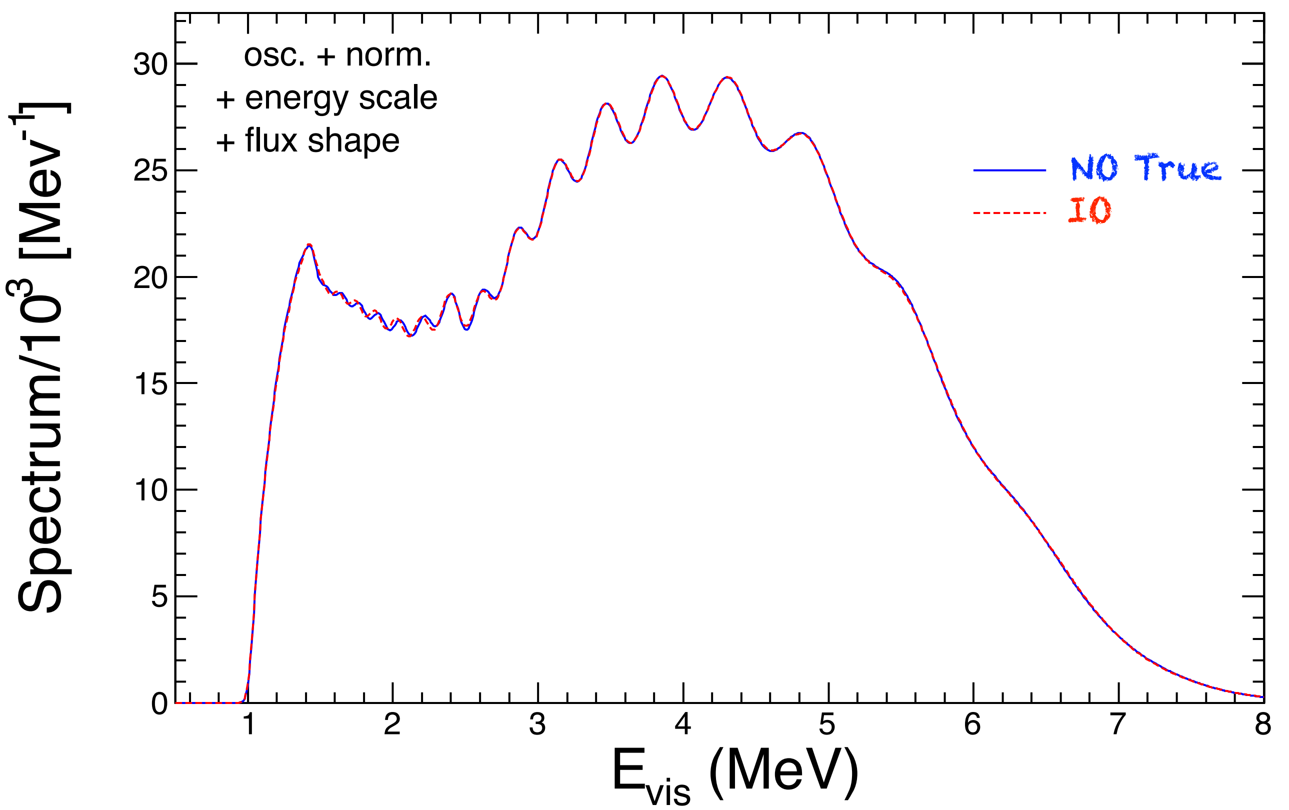

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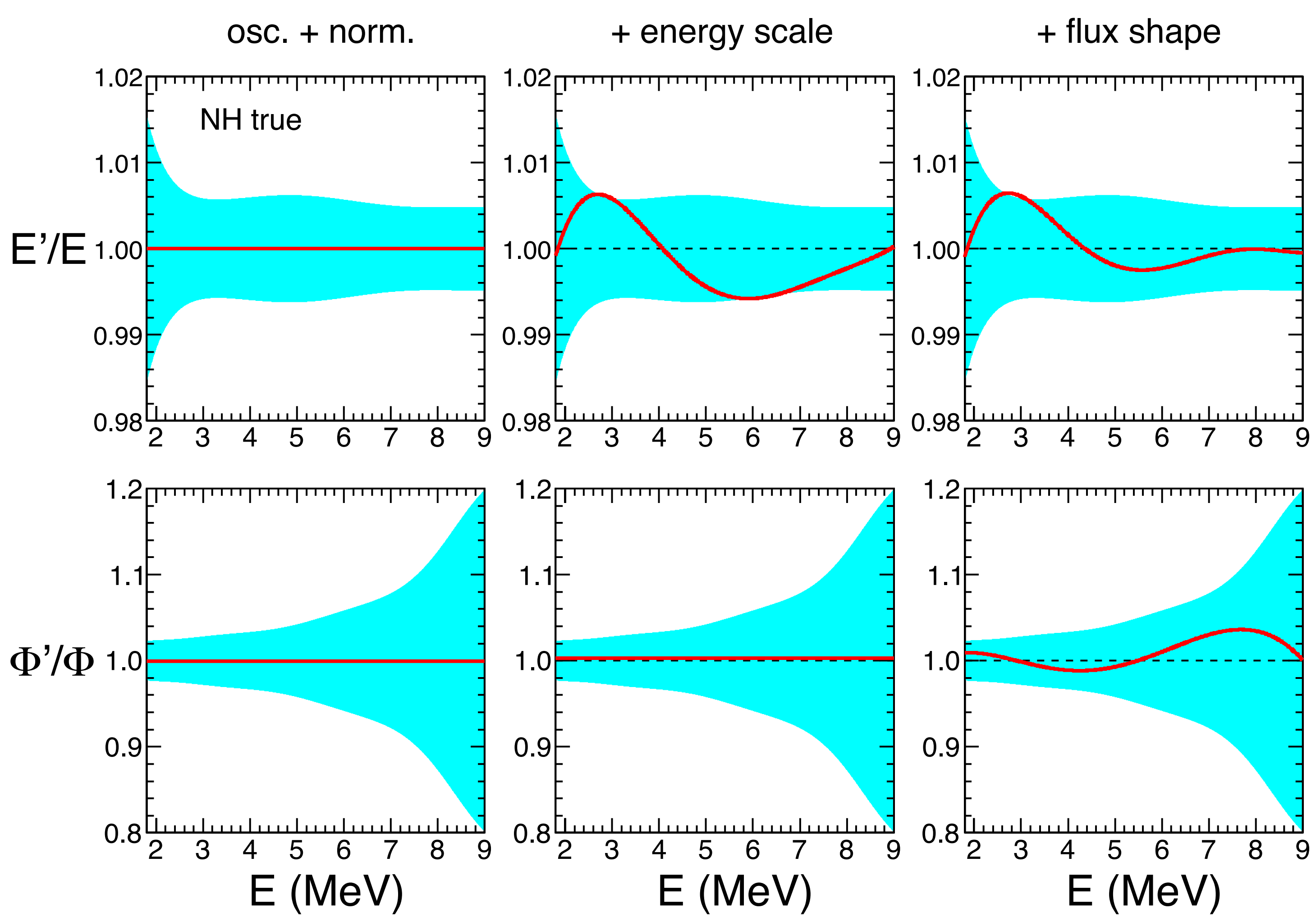

In the context of MBL experiments we introduce smooth deformations of the detector energy scale and the reactor anti-neutrino flux (up to 5th-order polynomials, i.e. +12 systematic pulls) constrained by current error bands (in blue at ±1σ)

JUNO-like prospective sensitivity to mass ordering (our estimate*)

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

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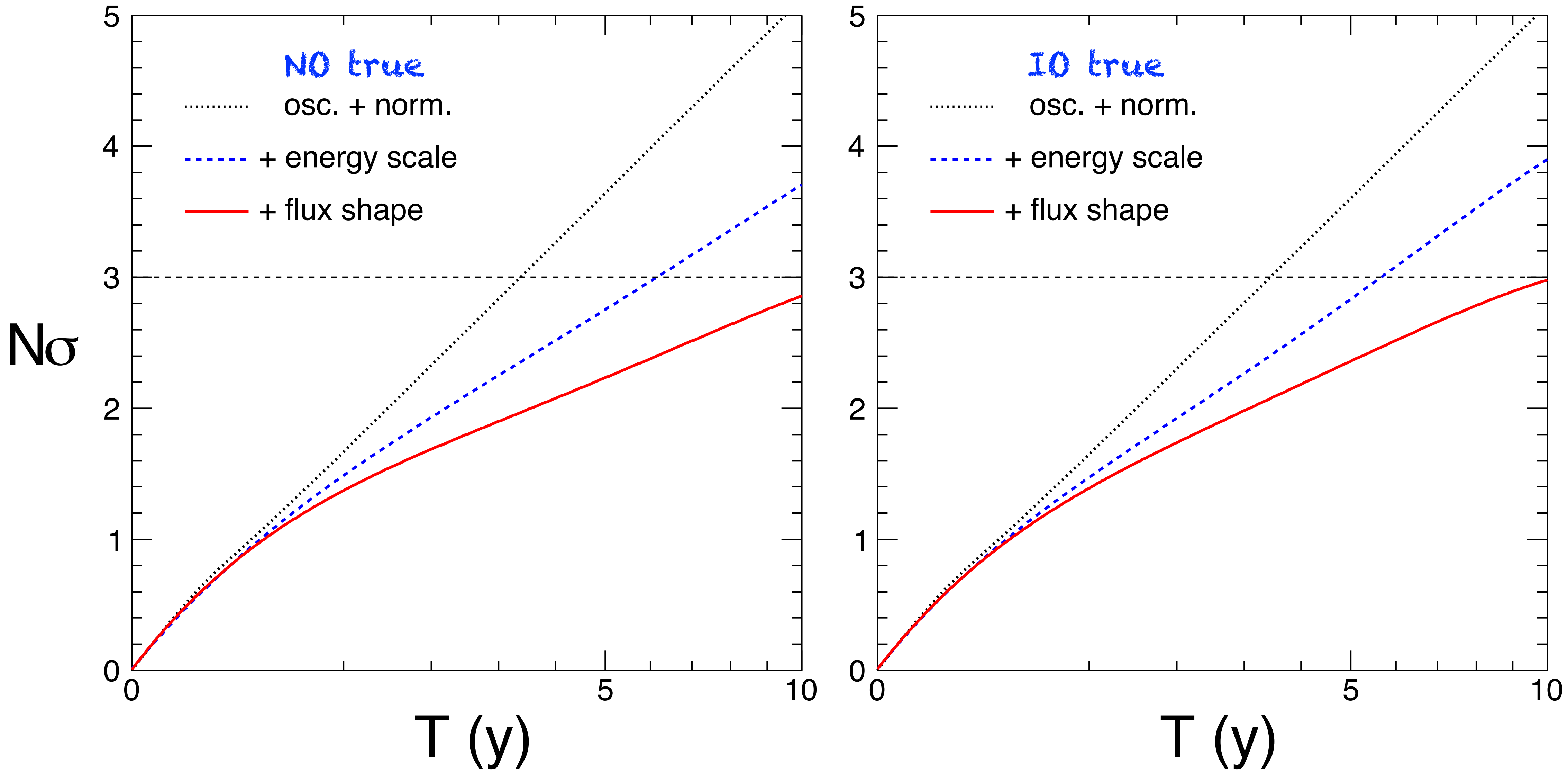

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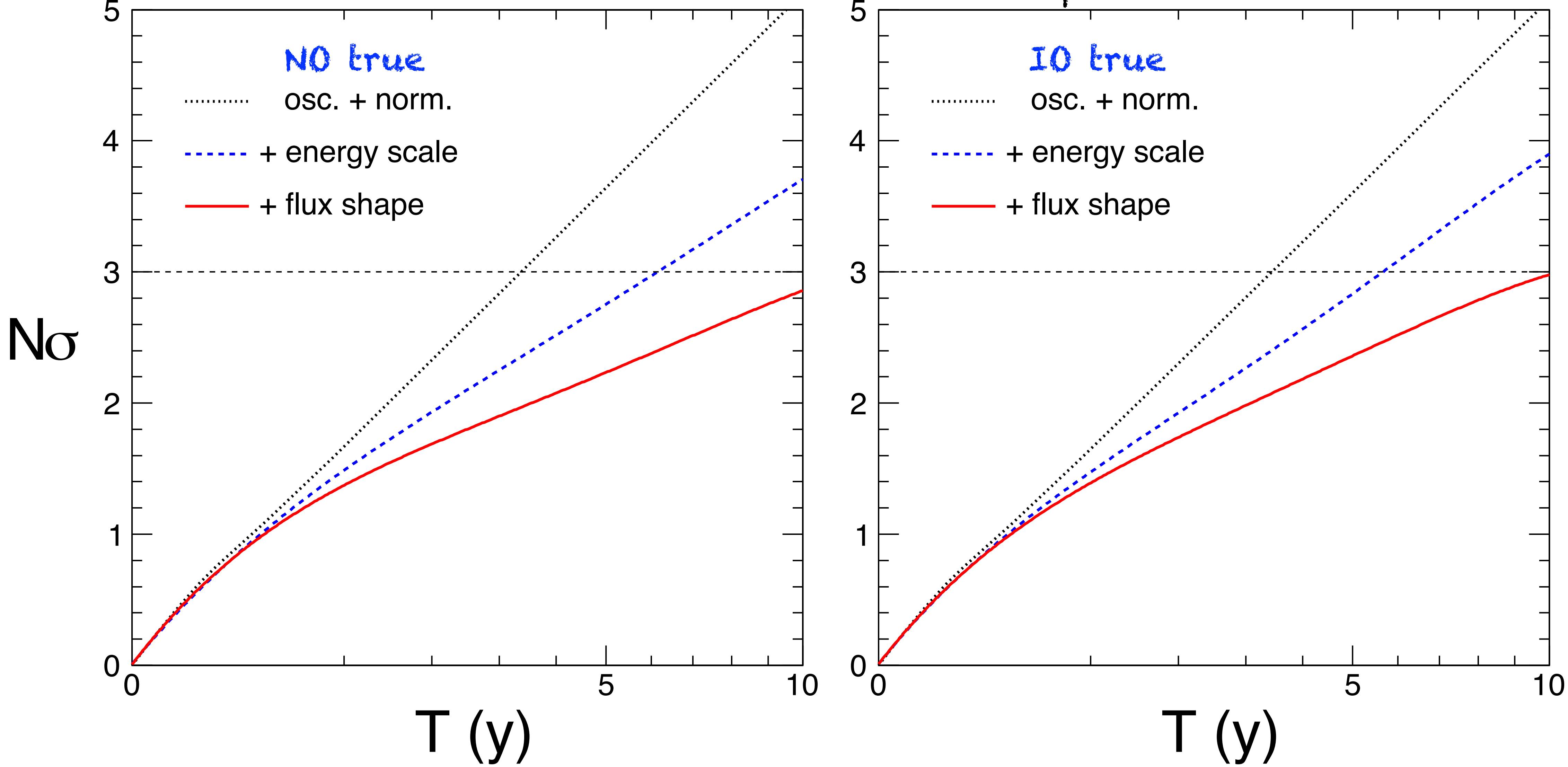
Abscissa scales as $T^{1/2}$ -> linear behaviour for pure statistical errors



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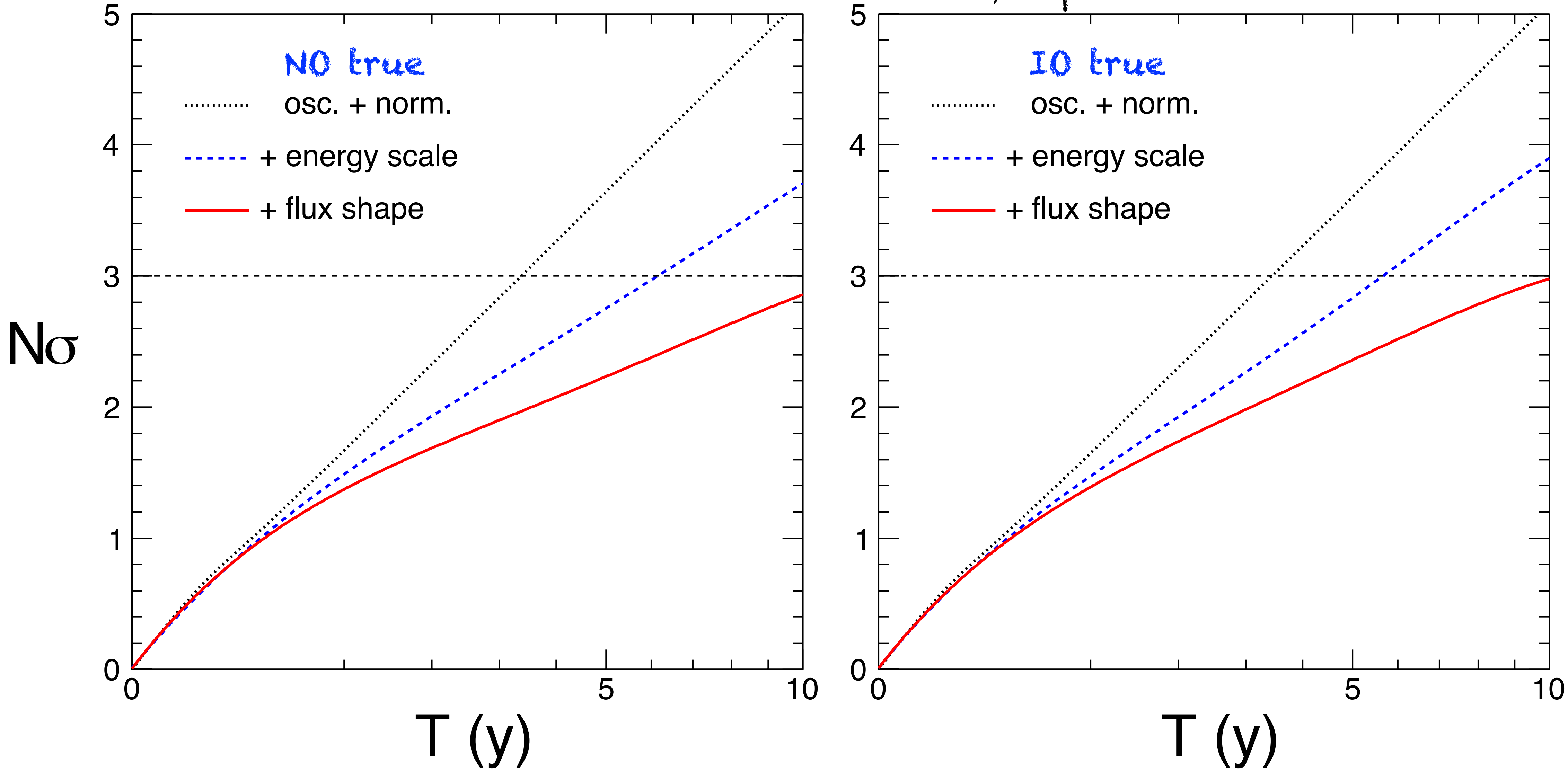

Inclusion of energy-scale uncertainties bends the linear rise, but still allows 3σ discrimination after ~6 years of data taking. With the inclusion of flux-shape uncertainties: 3σ sensitivity in ~10 years

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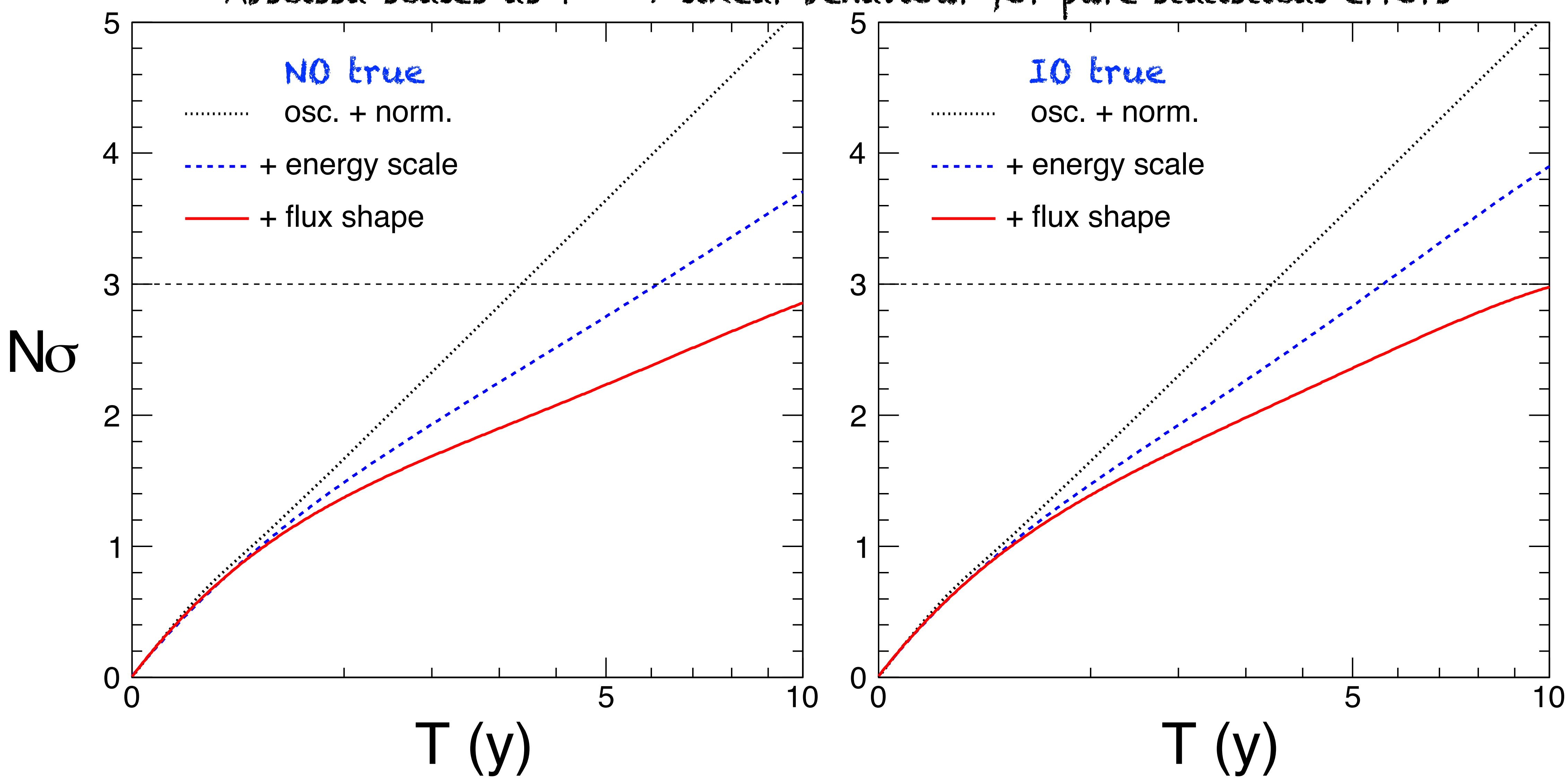

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Also the precise determination of $(\delta m^2, \theta_{12})$ affected: accuracy decreased by a factor of ~3, and the central values biased if wrong mass ordering is assumed

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PINGU (or ORCA) rate

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$$N_{ij}^{\alpha}(E_\nu,\theta) = \overbrace{V_{\text{eff}}^{\alpha}(E_\nu) \otimes \sigma(E_\nu) \otimes \Phi^{\alpha}(E_\nu,\theta)} \otimes P^{\alpha}(E_\nu,\theta) \otimes R^{\alpha}(E_\nu,\theta)$$

Volume — Cross Section — Flux — Probability — Resolution

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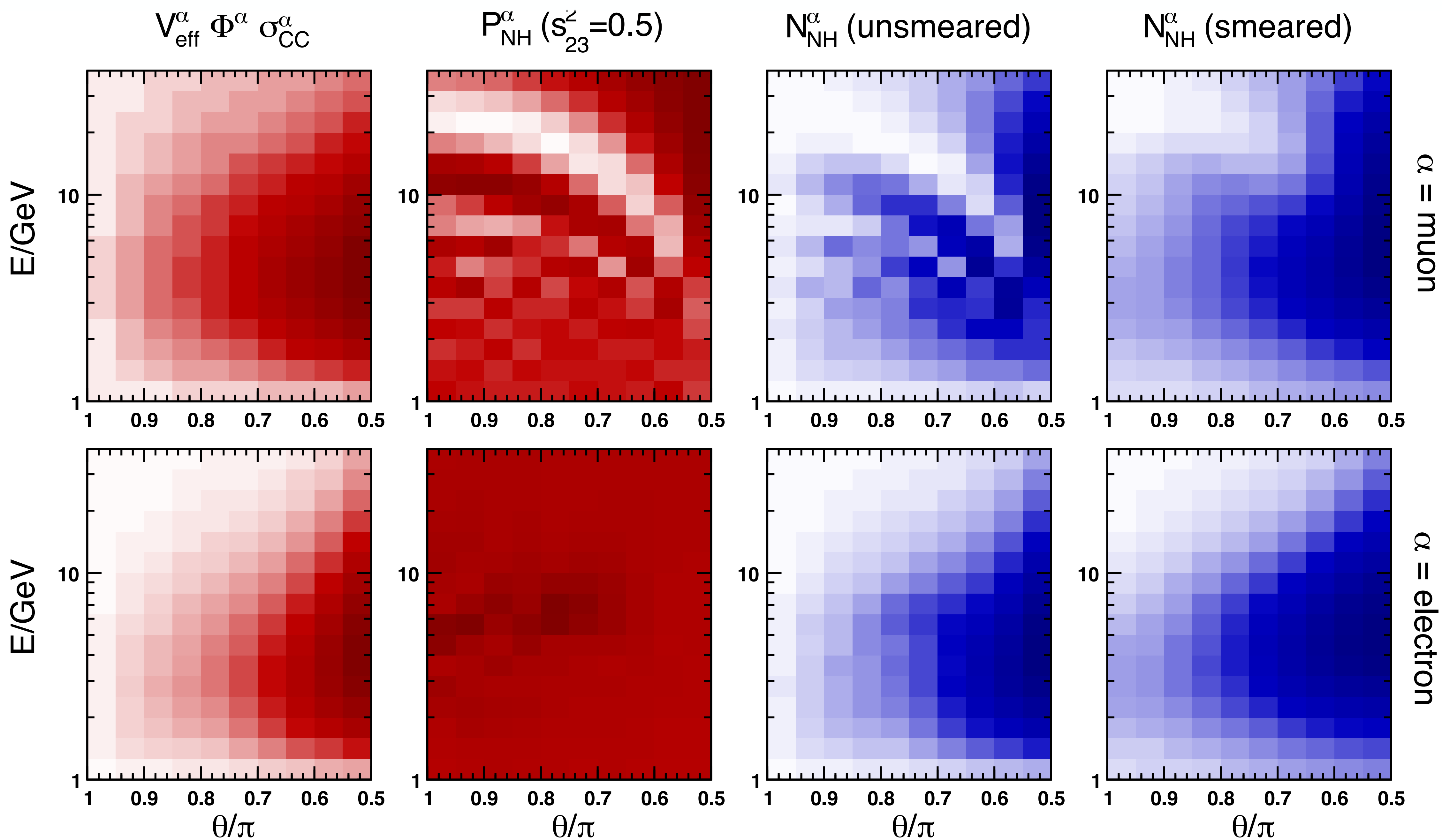
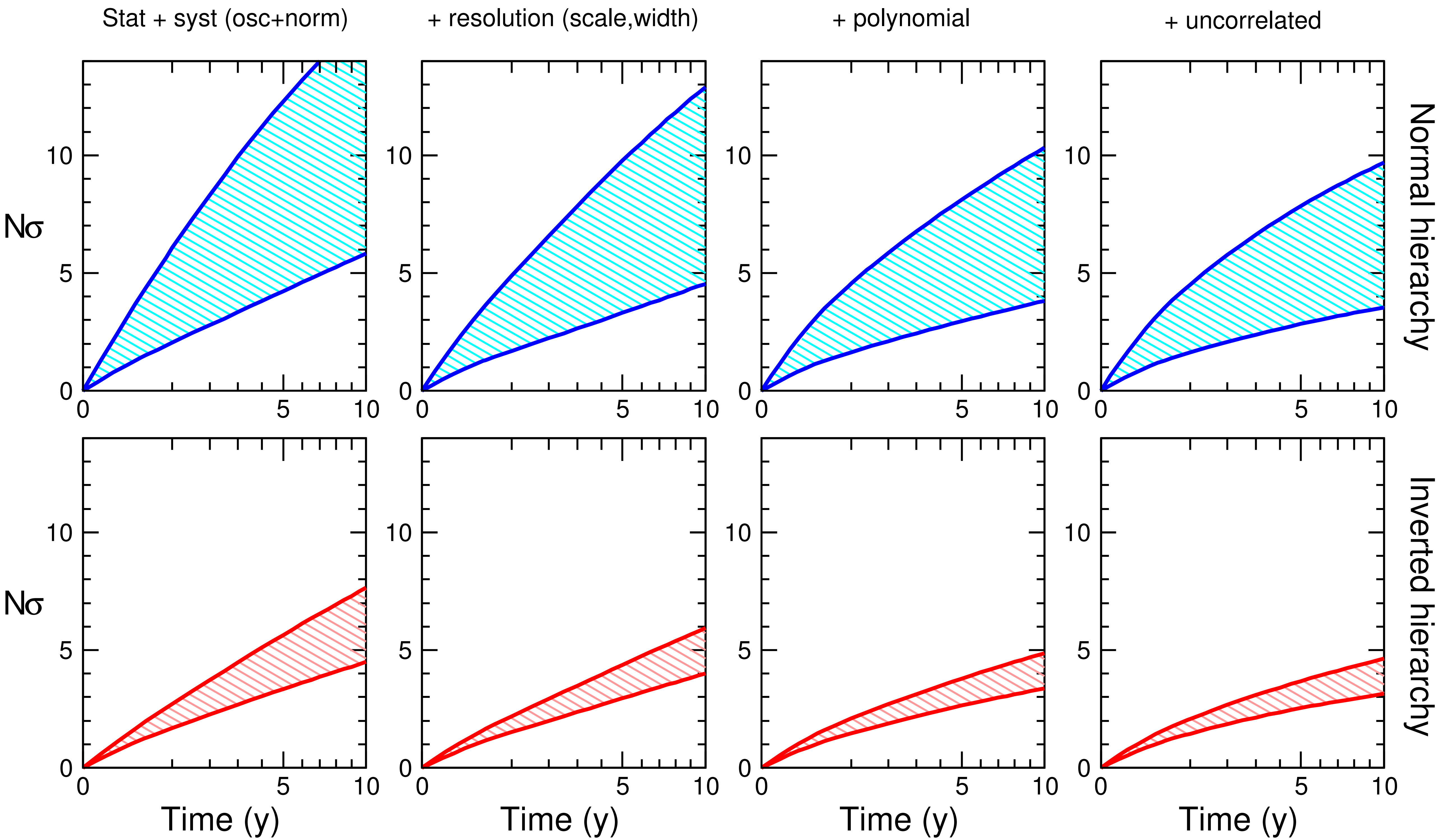
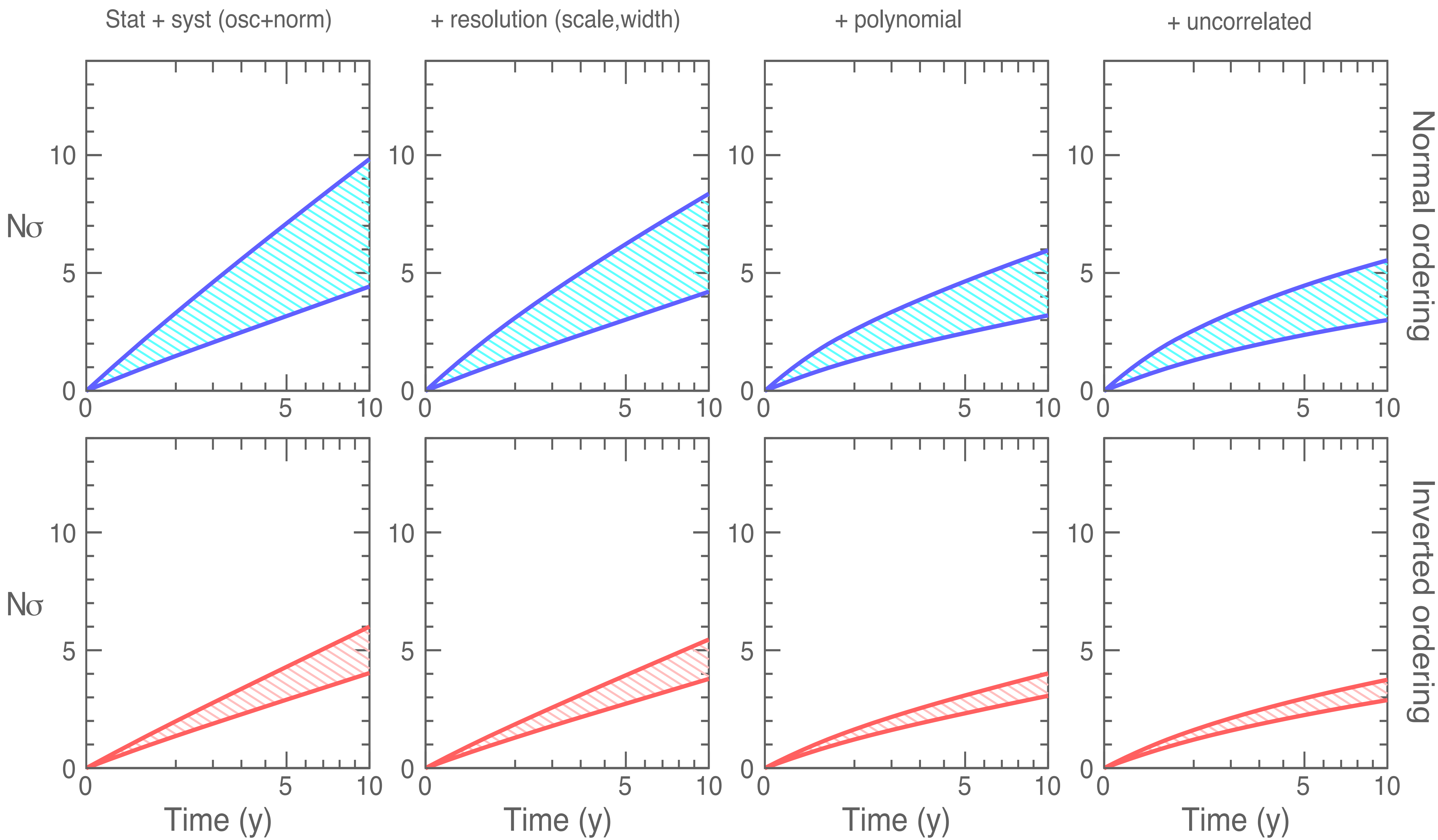


PINGU


Stat + syst (osc+norm)
+ resolution (scale,width)
+ polynomial
+ uncorrelated
Nσ
Nσ
Time (y)
Time (y)
Time (y)
Time (y)
Normal hierarchy
Inverted hierarchy
0
5
10

ORCA



Stat + syst (osc+norm)
+ resolution (scale,width)
+ polynomial
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Nσ
Nσ
Normal ordering
Inverted ordering
Time (y)
Time (y)
Time (y)
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10

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- Mass Ordering: IO disfavored by oscillation data:

	LBL+Sol+KL	+SBL	+ATM
$\Delta\chi^2$(IO−NO)	1.1	1.1	3.6

- Non oscillation data corroborate NO
- Info from ongoing - near future experiments