The XIX International Conference on Topics in Astroparticle and Underground Physics - TAUP2025

Precision Neutrino Physics: Status and Outlook in the 3ν Paradigm

Antonio Marrone

Bari University

August 24 to August 30, 2025, Xichang, China

Precision era in neutrino oscillation phenomenology

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

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%)

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

$\Delta m^2 \sim 2.495 \times 10^{-3}\ \mathrm{eV}^2$ (0.8%)

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

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

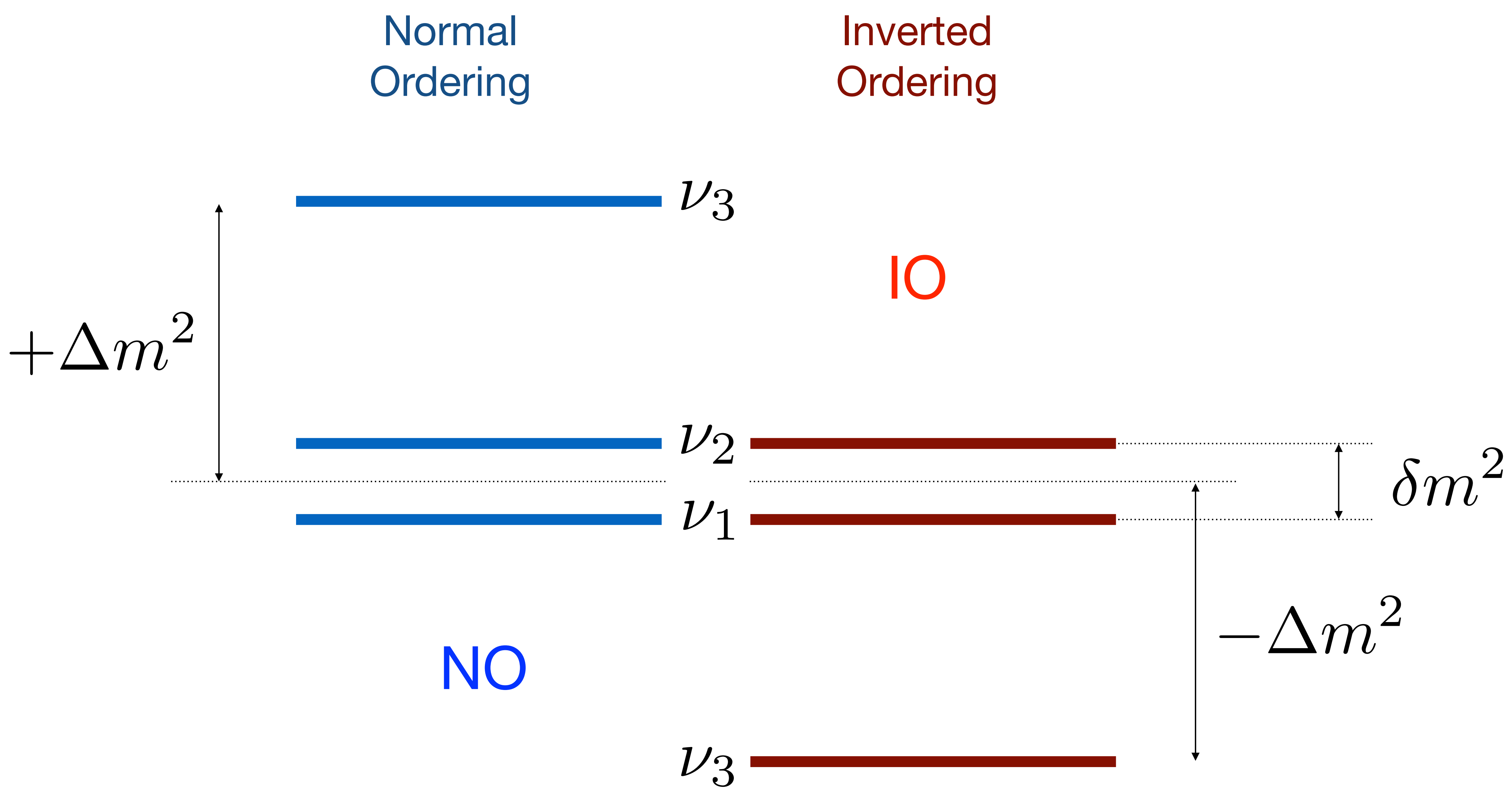
$\Delta m^2 \sim 2.495 \times 10^{-3}\ \text{eV}^2$
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \text{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

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

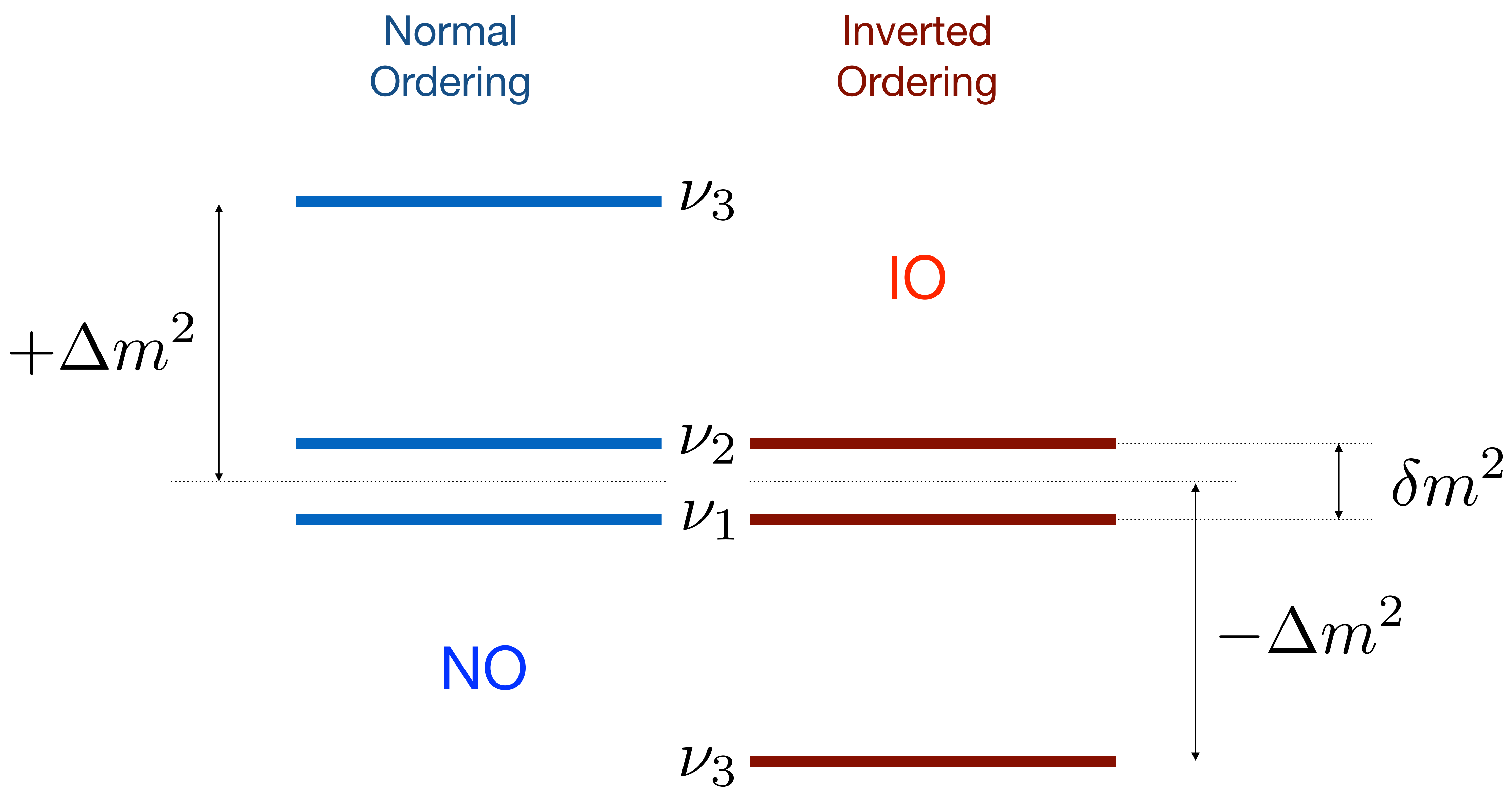
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \mathrm{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

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

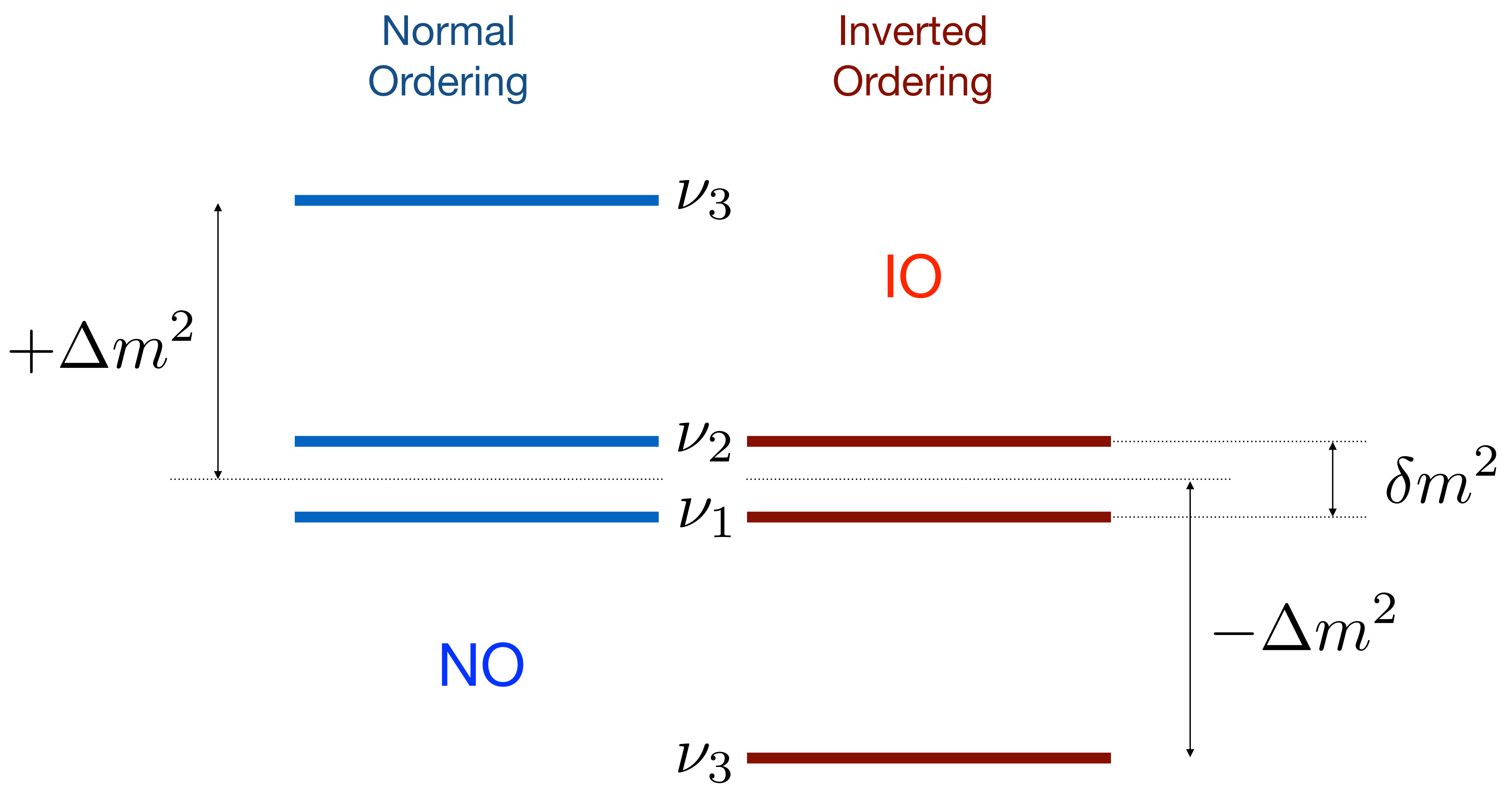
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \mathrm{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

Mass Ordering

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

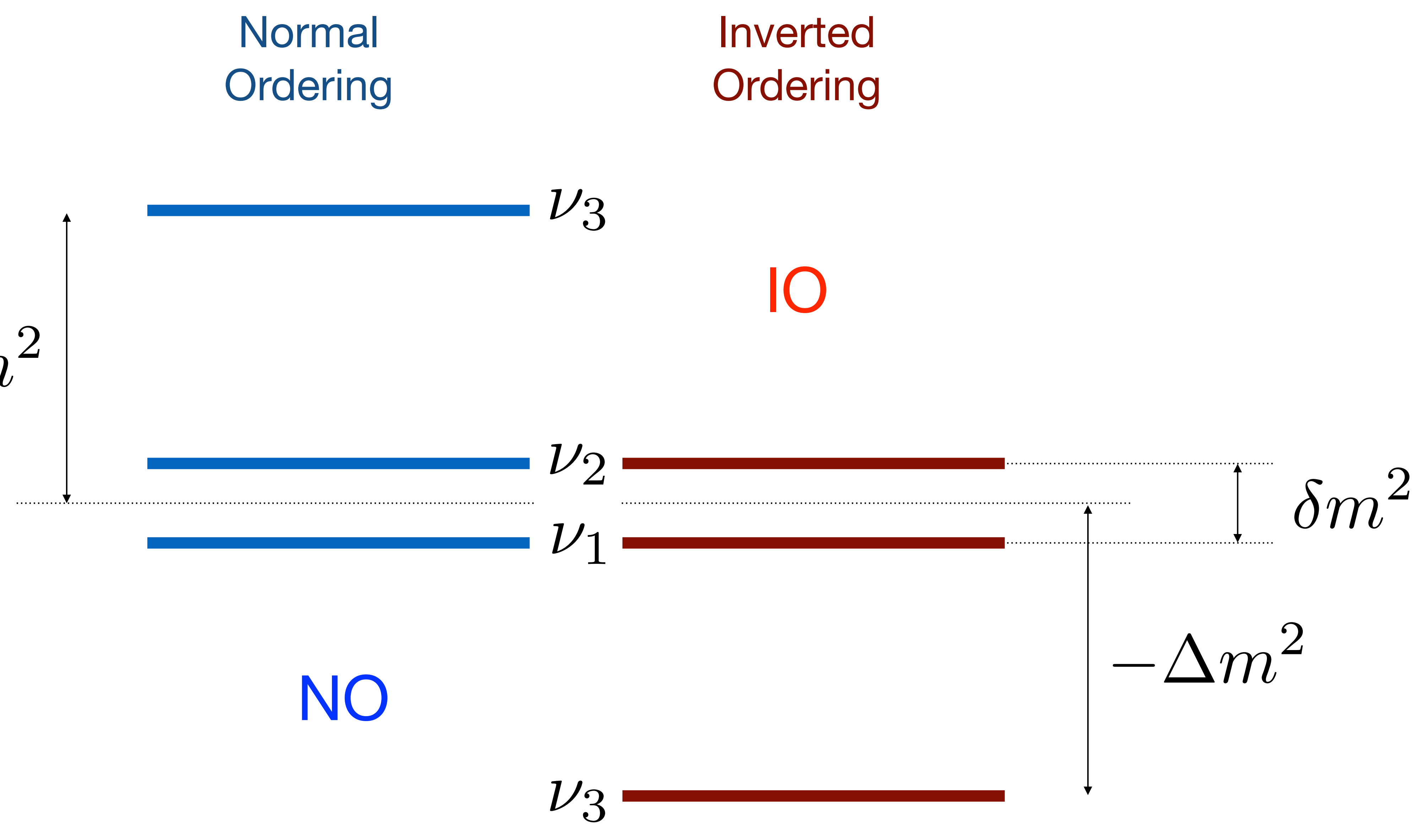
$\Delta m^2 \sim 2.495 \times 10^{-3}$ eV^2
$\Delta m^2 \sim 2.465 \times 10^{-3}$ eV^2 (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

Mass Ordering

CP-violating phase δ_{CP}

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

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

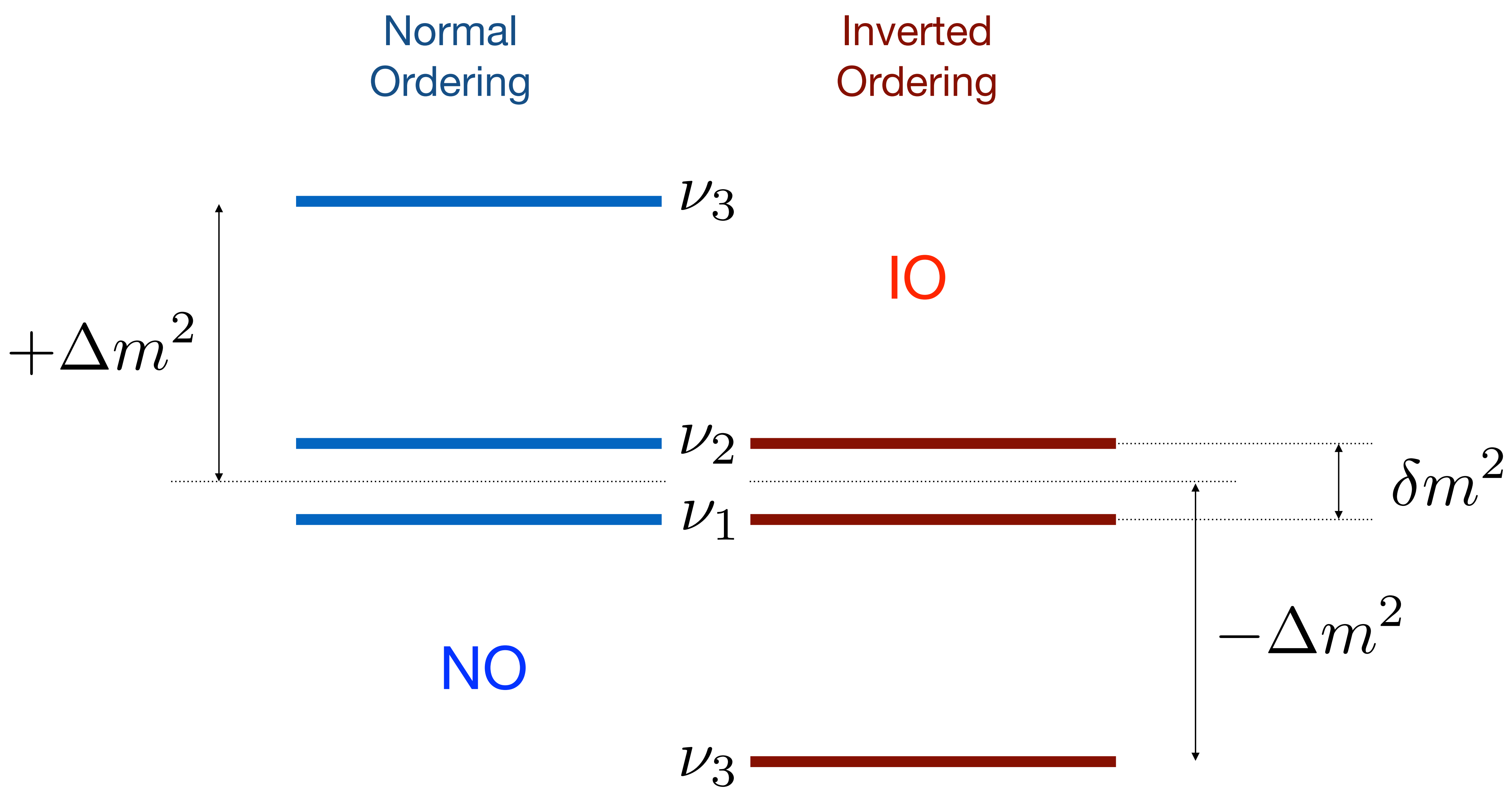
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \text{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

Mass Ordering

CP-violating phase δ_{CP}

Octant of θ_{23}

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

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

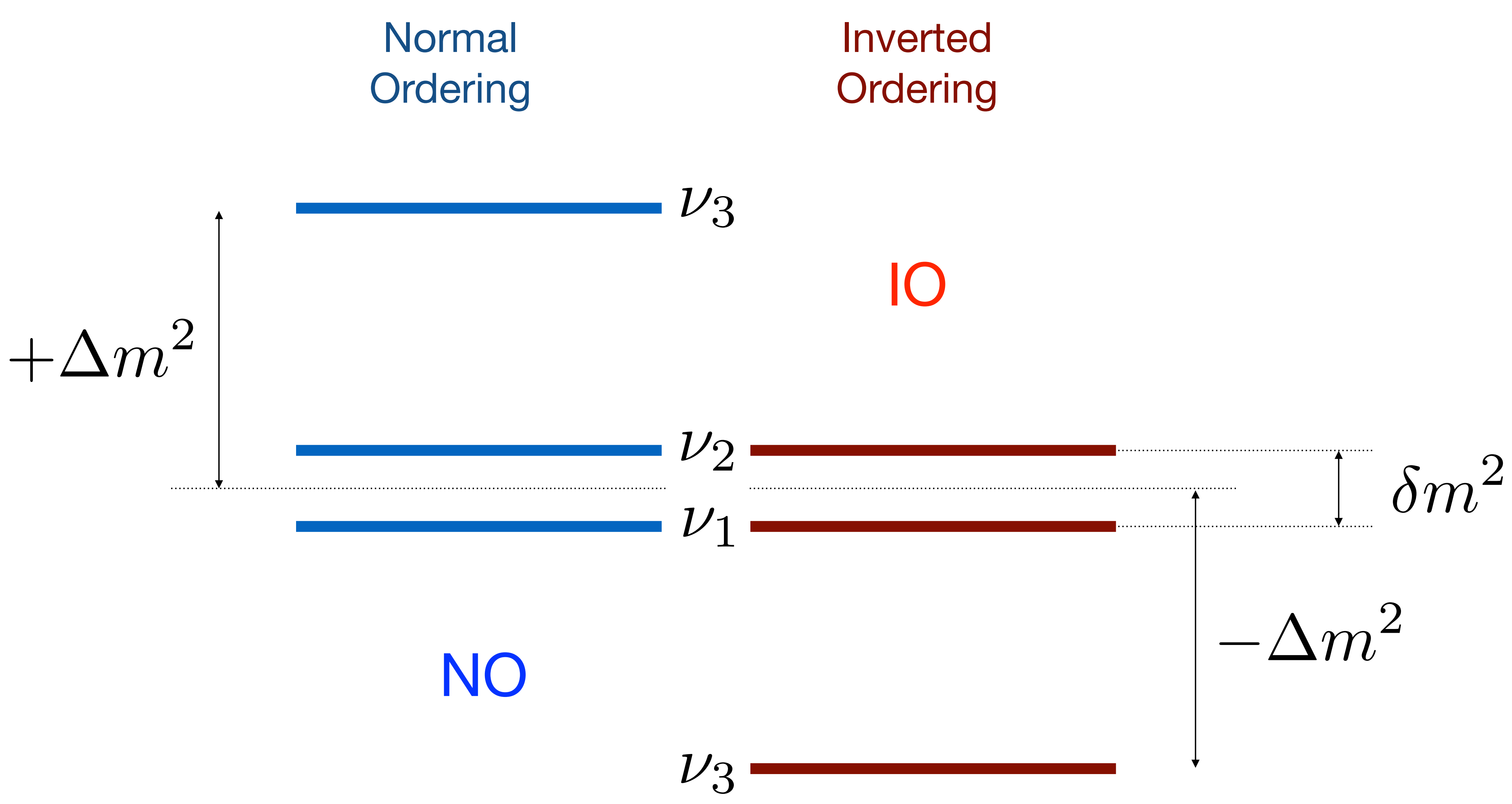
$\Delta m^2 \sim 2.465 \times 10^{-3}$ eV^2 (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \frac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

Mass Ordering

CP-violating phase δ_{CP}

Octant of θ_{23}

Absolute mass scale

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

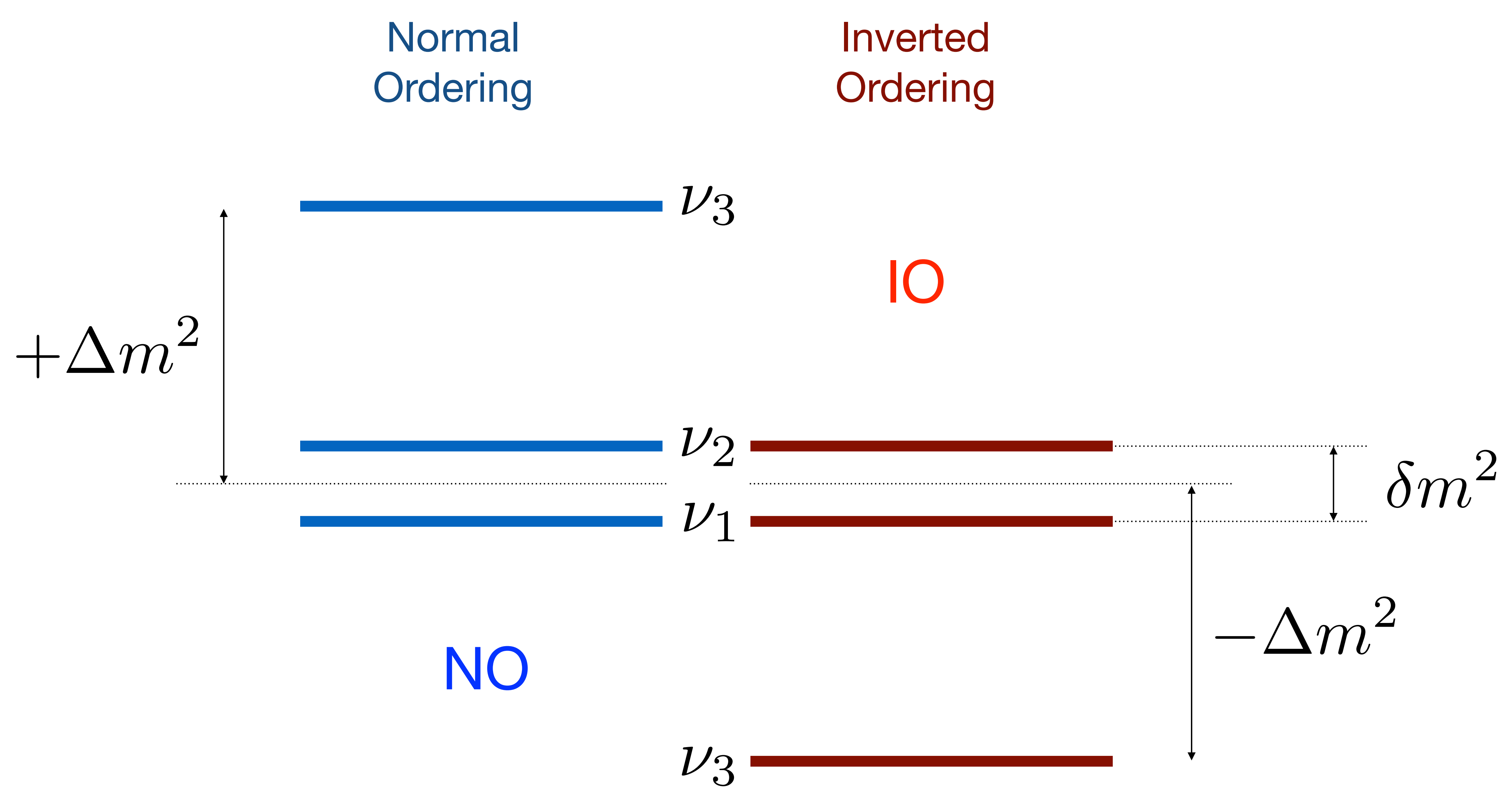
$\Delta m^2 \sim 2.495 \times 10^{-3}\ \mathrm{eV}^2$
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \mathrm{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

- Mass Ordering
- CP-violating phase δ_{CP}
- Octant of θ_{23}
- Absolute mass scale
- Nature of ν (Dirac/Majorana)

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

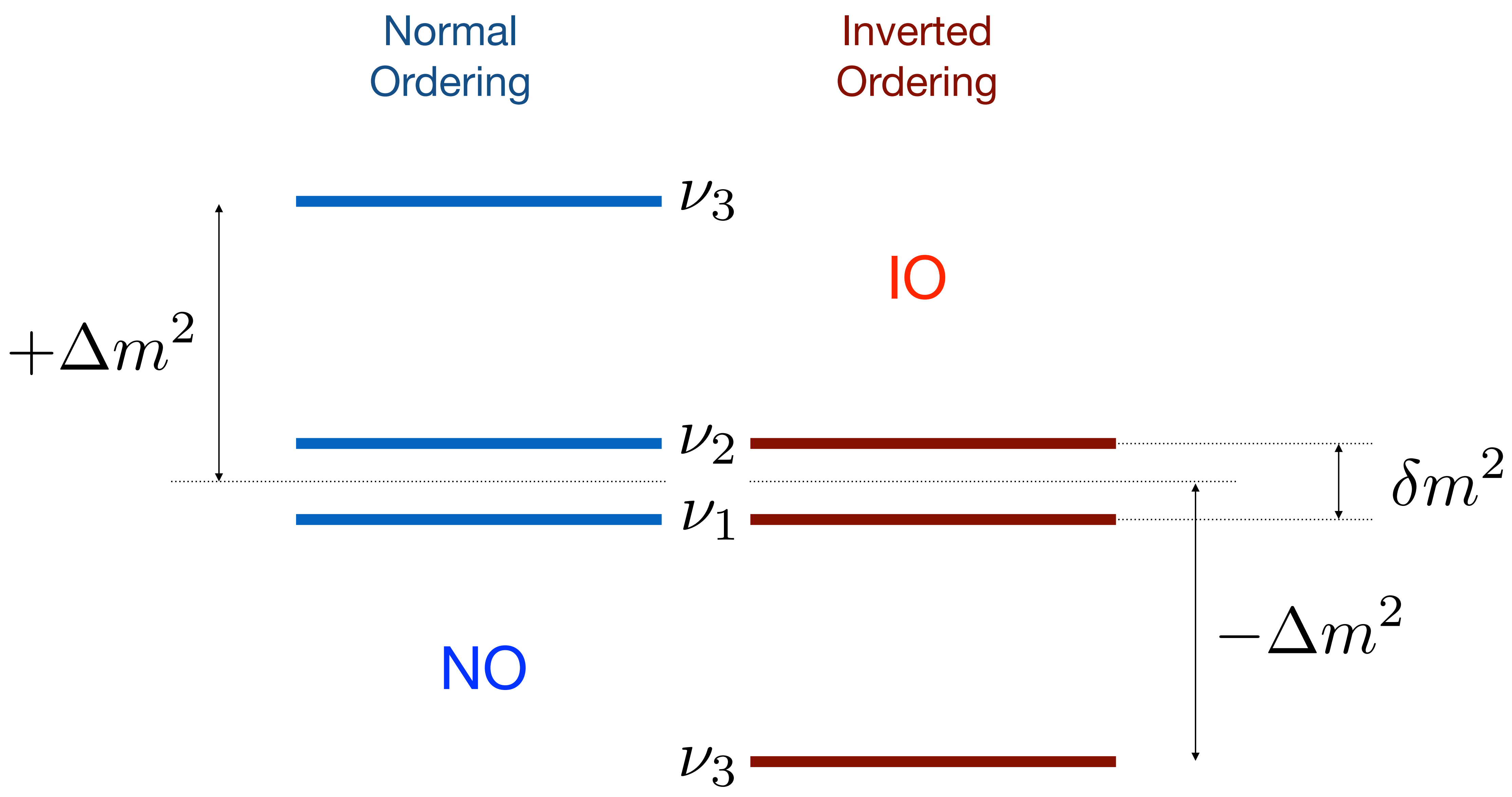
$\Delta m^2 \sim 2.495 \times 10^{-3}\ \mathrm{eV}^2$
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \mathrm{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

- Mass Ordering
- CP-violating phase δ_{CP}
- Octant of θ_{23}
- Absolute mass scale
- Nature of ν (Dirac/Majorana)

Based on Capozzi+, arXiv:2503.07752, PRD 111 (2025) 9, 093006, Contains various new oscillation and nonoscillation inputs after our previous global analysis 2107.00532

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

Solar parameters

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

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

Atmospheric parameters

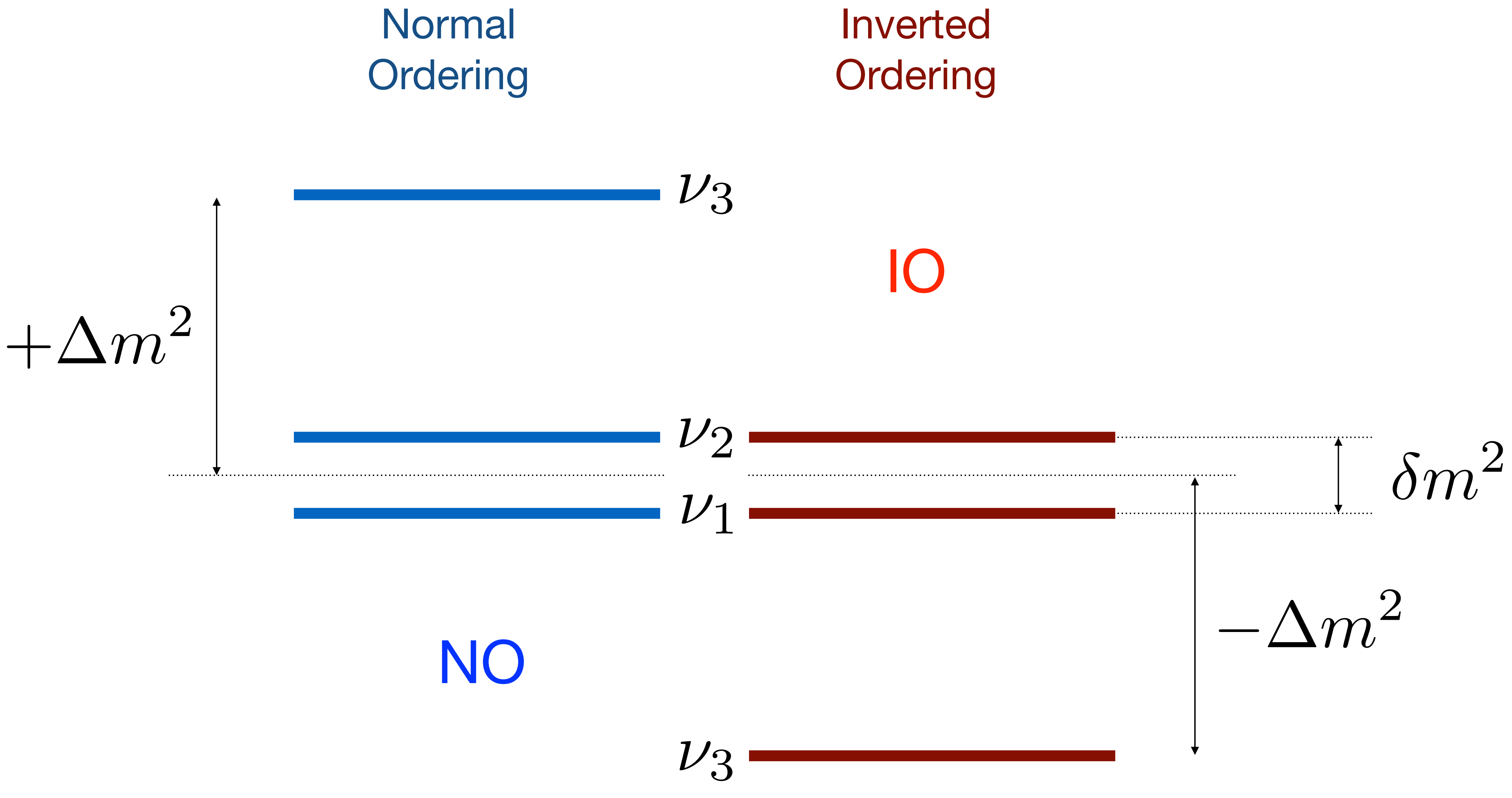
$\Delta m^2 \sim 2.495 \times 10^{-3}\ \mathrm{eV}^2$
$\Delta m^2 \sim 2.465 \times 10^{-3}\ \mathrm{eV}^2$ (0.8%)

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

$\sin^2\theta_{23} \sim 0.545 \times 10^{-2}$ (4.3%)

Reactor mixing angle

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



Note that in our notation $\Delta m^2 = \dfrac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$

What we still do not know

Mass Ordering

CP-violating phase δ_{CP}

Octant of θ_{23}

Absolute mass scale

Nature of ν (Dirac/Majorana)

Based on Capozzi+, arXiv:2503.07752, PRD 111 (2025) 9, 093006, Contains various new oscillation and nonoscillation inputs after our previous global analysis 2107.00532

Mass ordering can be determined by exploiting interference between oscillations driven by Δm^2 and those driven by a second term Q whose sign is known

Mass ordering can be determined by exploiting interference between oscillations driven by Δm^2 and those driven by a second term Q whose sign is known

$Q \propto \delta m^2$ medium-baseline reactors

Mass ordering can be determined by exploiting interference between oscillations driven by Δm^2 and those driven by a second term Q whose sign is known

$Q \propto \delta m^2$ medium-baseline reactors

$Q \propto G_F E N_e$ matter effects in accelerator/atmospheric ν

Mass ordering can be determined by exploiting interference between oscillations driven by Δm^2 and those driven by a second term Q whose sign is known

$Q \propto \delta m^2$	medium-baseline reactors
$Q \propto G_F E N_e$	matter effects in accelerator/atmospheric ν
$Q \propto G_F E N_\nu$	self-interaction effects in supernovae

Mass ordering can be determined by exploiting interference between oscillations driven by Δm^2 and those driven by a second term Q whose sign is known

$Q \propto \delta m^2$ medium-baseline reactors

$Q \propto G_F E N_e$ matter effects in accelerator/atmospheric ν

$Q \propto G_F E N_\nu$ self-interaction effects in supernovae

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

Mass ordering can be determined by exploiting interference between oscillations driven by Δm^2 and those driven by a second term Q whose sign is known

$Q \propto \delta m^2$ — medium-baseline reactors

$Q \propto G_F E N_e$ — matter effects in accelerator/atmospheric ν

$Q \propto G_F E N_\nu$ — self-interaction effects in supernovae

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: $\alpha = -1$

Useful analysis sequence in the global analysis of oscillation data

Useful analysis sequence in the global analysis of oscillation data

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

Useful analysis sequence in the global analysis of oscillation data

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

Long Baseline Accelerator + Solar + KamLAND + Short Baseline Reactor

Add sensitivity to $\Delta m^2, \theta_{13}$ + correlations

Useful analysis sequence in the global analysis of oscillation data

Long Baseline Accelerator + Solar + KamLAND

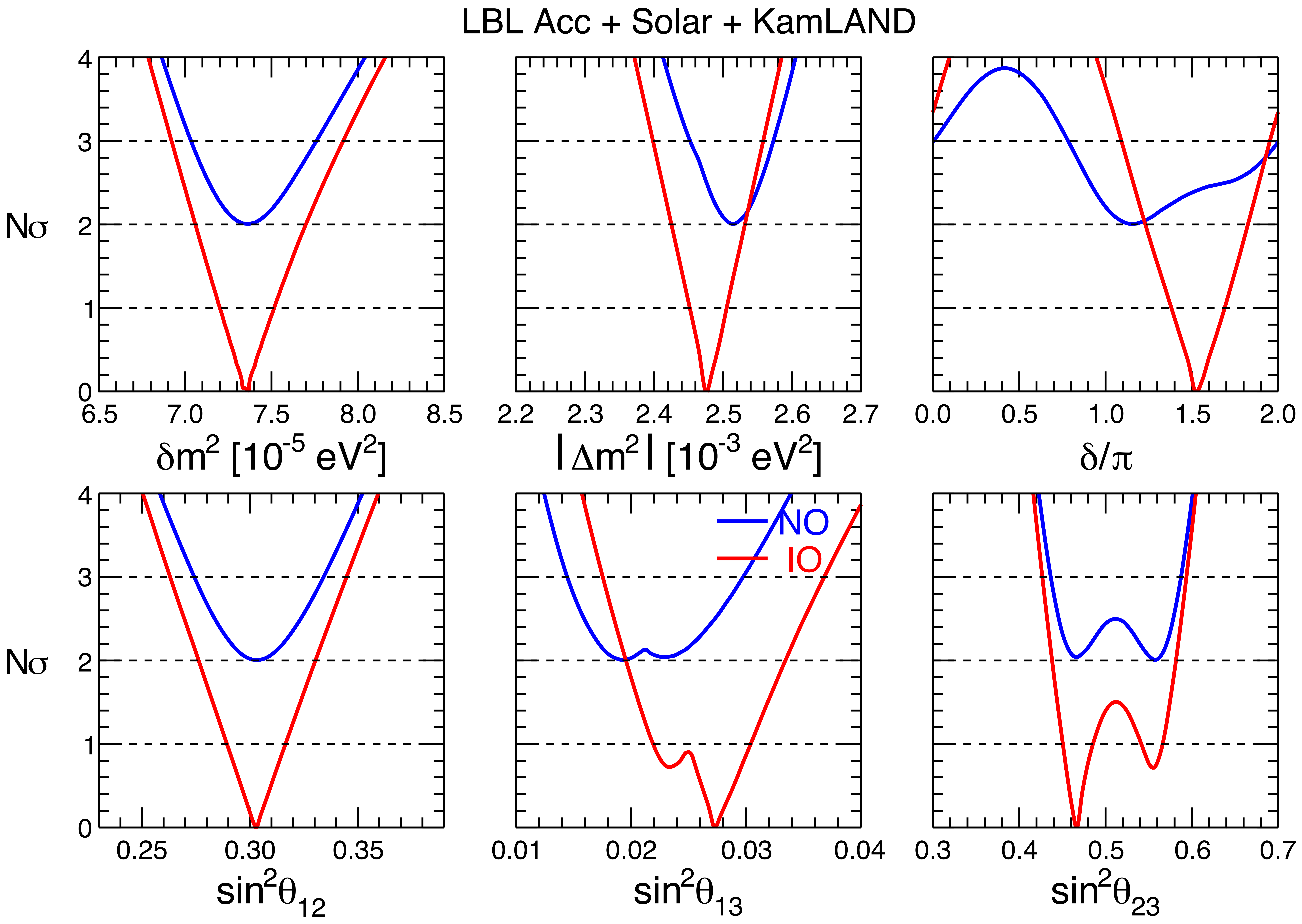
minimal set sensitive to all oscillation parameters $(\delta m^2, \Delta m^2, \theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$ and to mass ordering

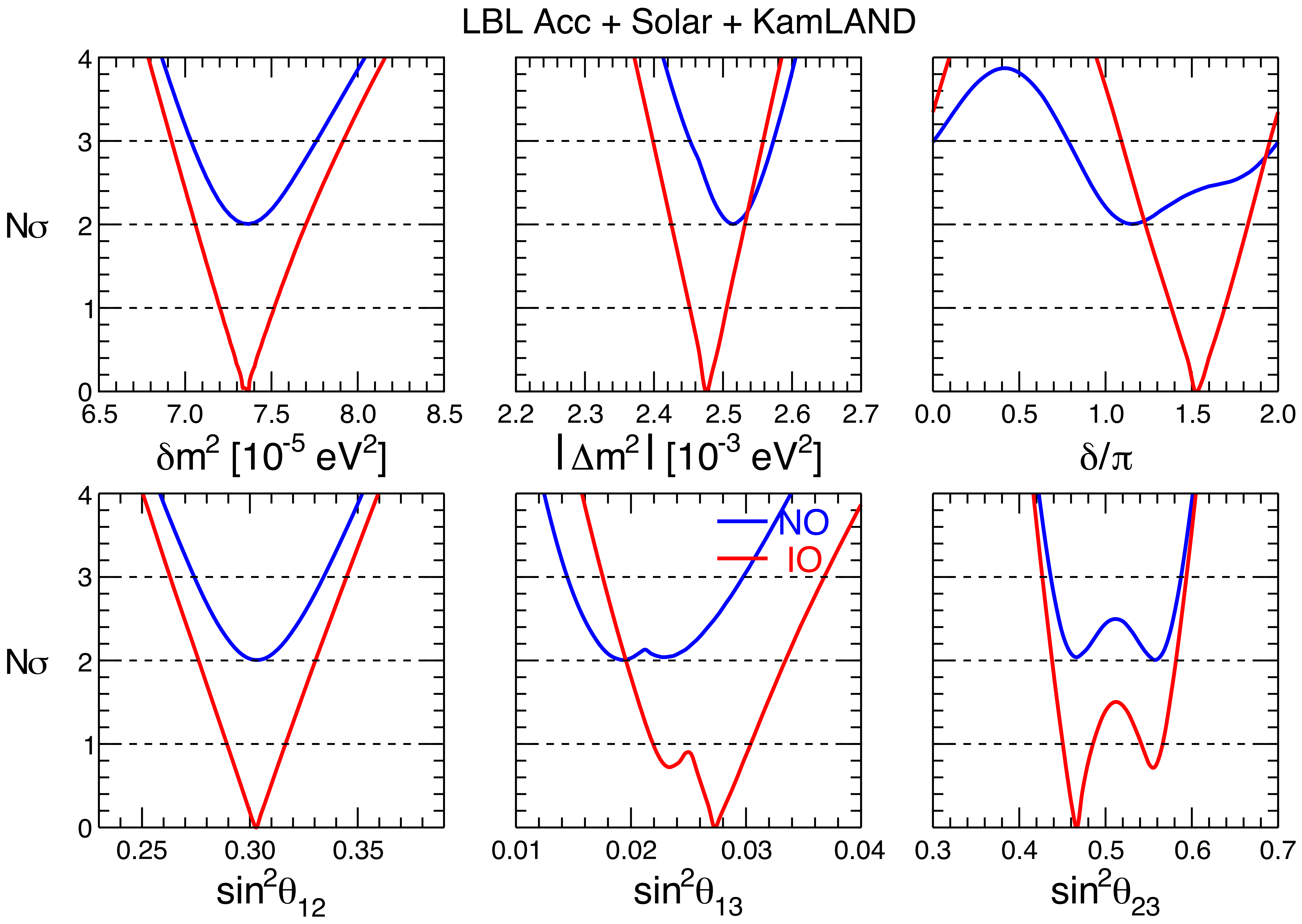
Long Baseline Accelerator + Solar + KamLAND + Short Baseline Reactor

Add sensitivity to $\Delta m^2, \theta_{13}$ + correlations

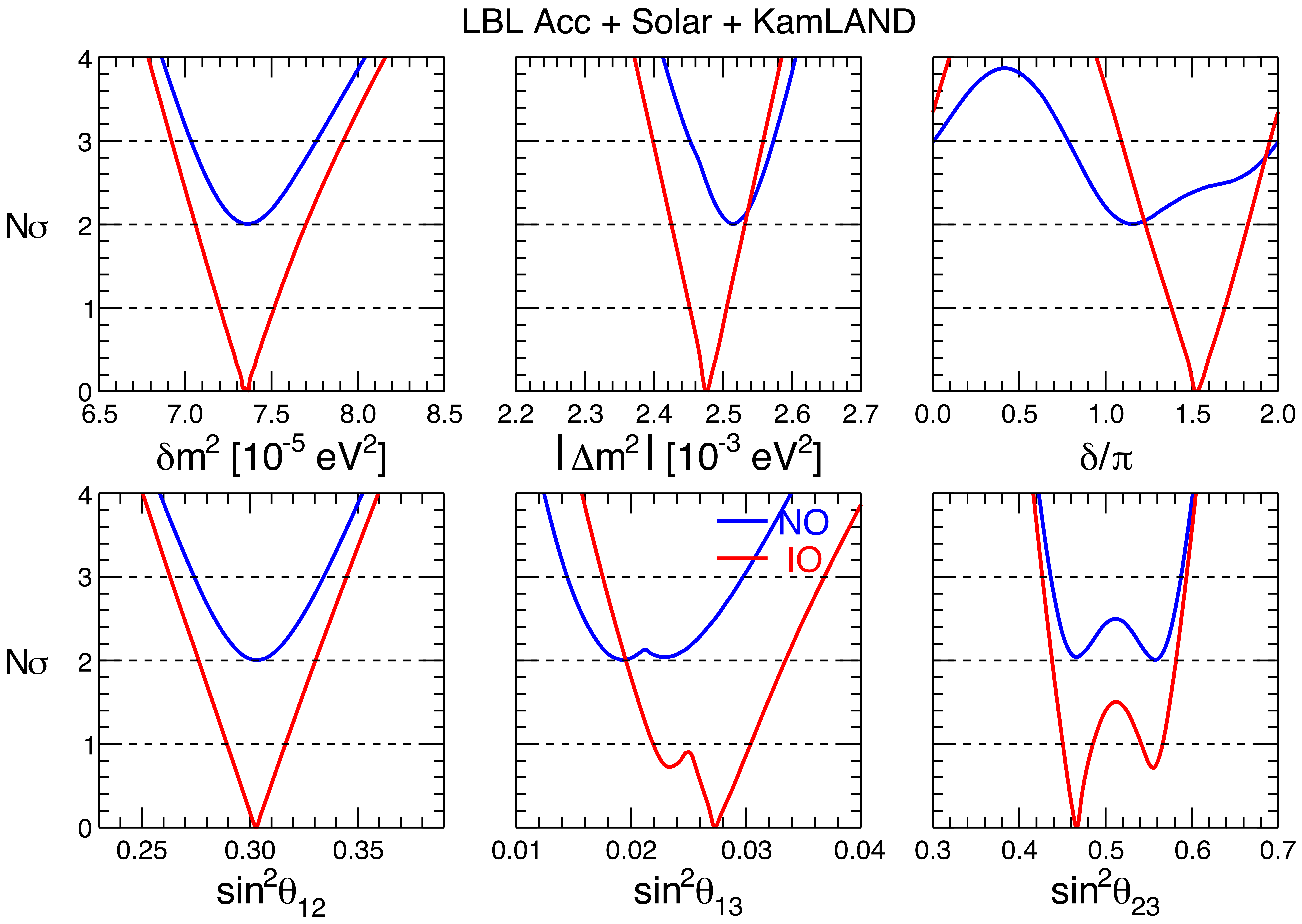
Long Baseline Acc. + Solar + KamLAND + Short Baseline Reactor + Atmospheric

Add sensitivity to $\Delta m^2, \theta_{23}, \delta_{CP}$ and mass ordering


LBL Acc + Solar + KamLAND
Nσ
δm² [10⁻⁵ eV²]
|Δm²| [10⁻³ eV²]
δ/π
sin²θ₁₂
sin²θ₁₃
sin²θ₂₃
NO
IO
0
1
2
3
4
6.5
7.0
7.5
8.0
8.5
2.2
2.3
2.4
2.5
2.6
2.7
0.0
0.5
1.0
1.5
2.0
0.25
0.30
0.35
0.01
0.02
0.03
0.04
0.3
0.4
0.5
0.6
0.7

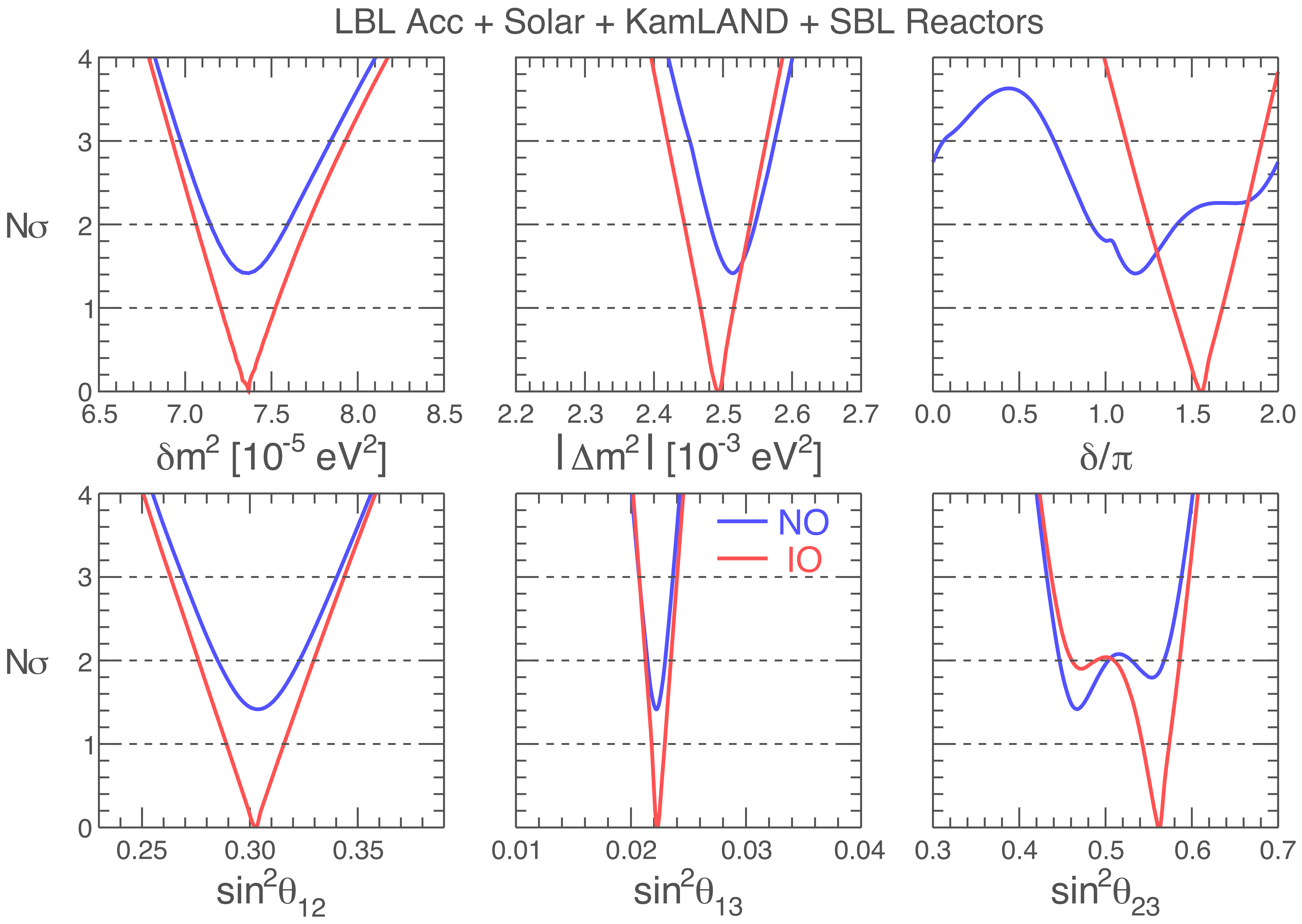


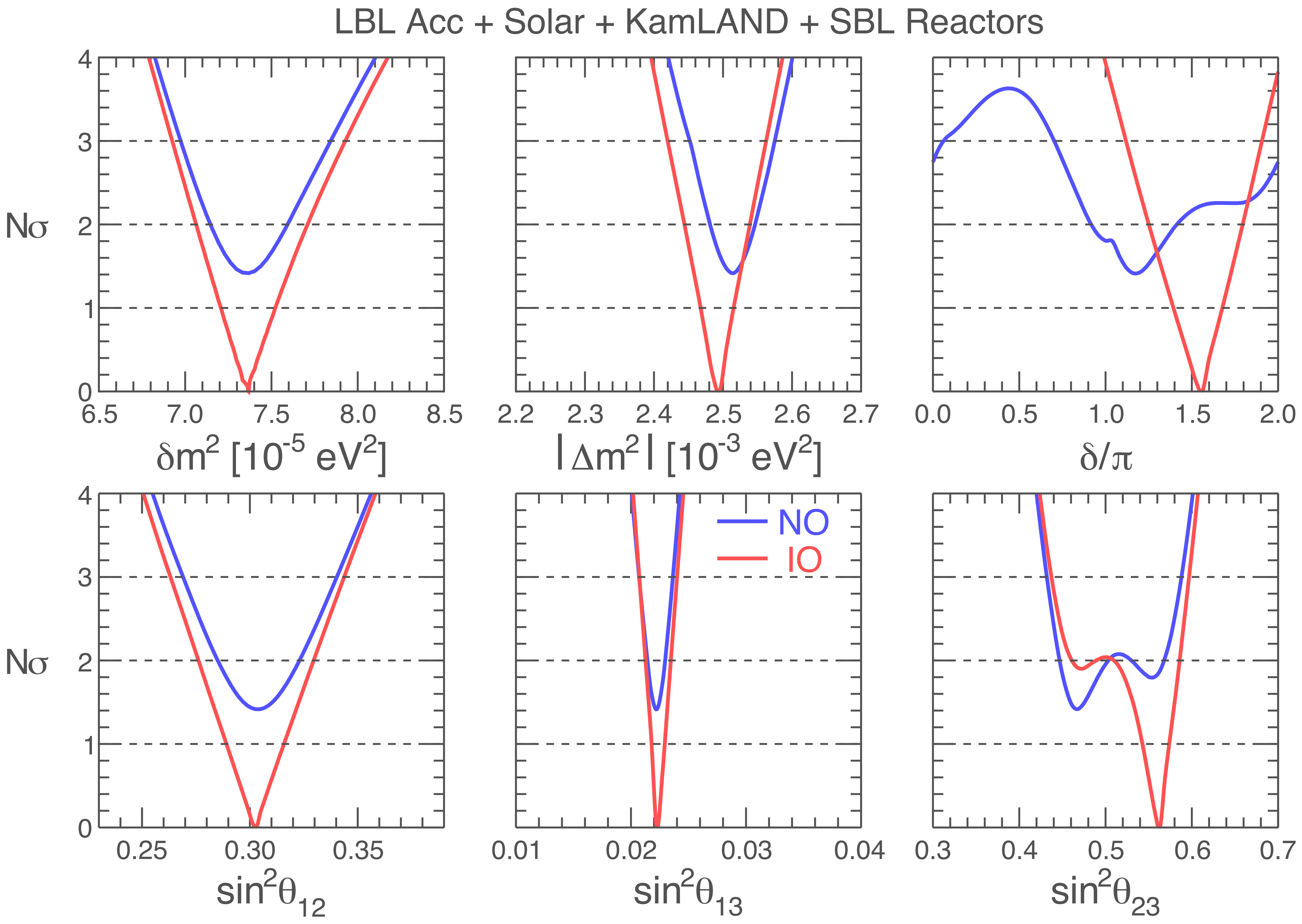
T2K and NOvA prefer NO separately, and IO in combination (at 2σ).



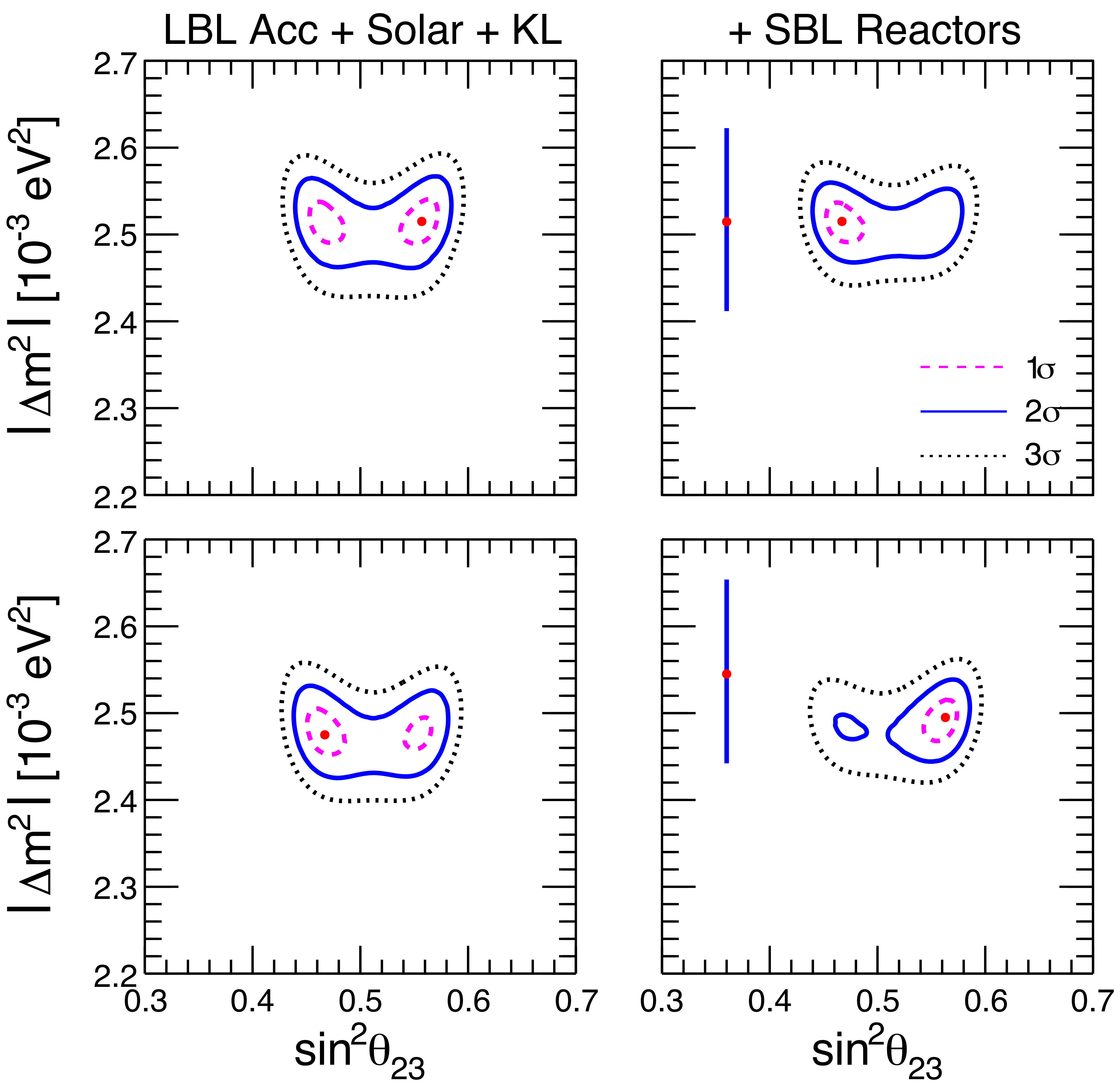
T2K and NOvA prefer NO separately, and IO in combination (at 2σ).

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

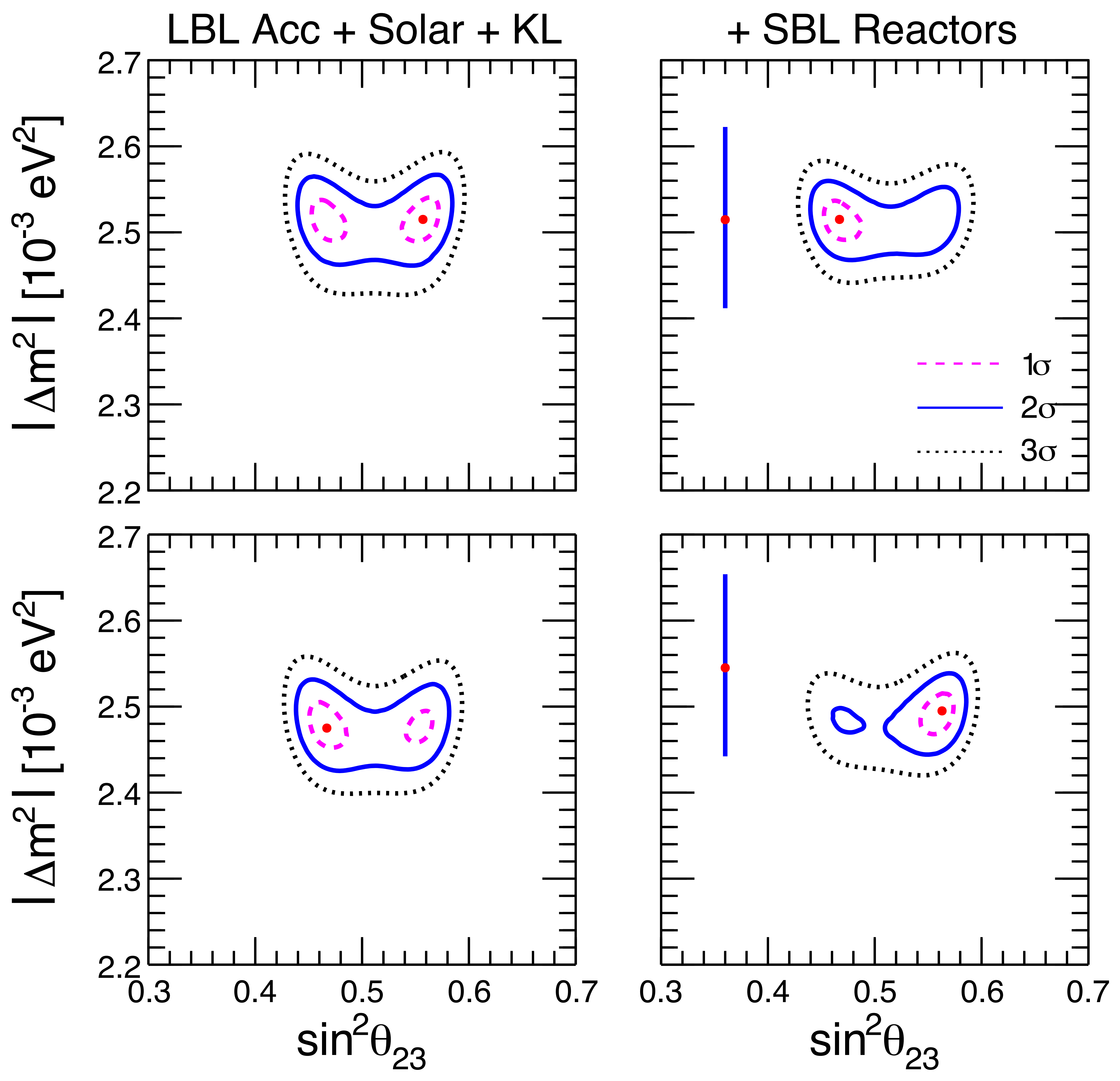

LBL Acc + Solar + KamLAND + SBL Reactors
Nσ
δm² [10⁻⁵ eV²]
|Δm²| [10⁻³ eV²]
δ/π
sin²θ12
sin²θ13
sin²θ23
NO
IO
0
1
2
3
4
6.5
7.0
7.5
8.0
8.5
2.2
2.3
2.4
2.5
2.6
2.7
0.0
0.5
1.0
1.5
2.0
0.25
0.30
0.35
0.01
0.02
0.03
0.04
0.3
0.4
0.5
0.6
0.7



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

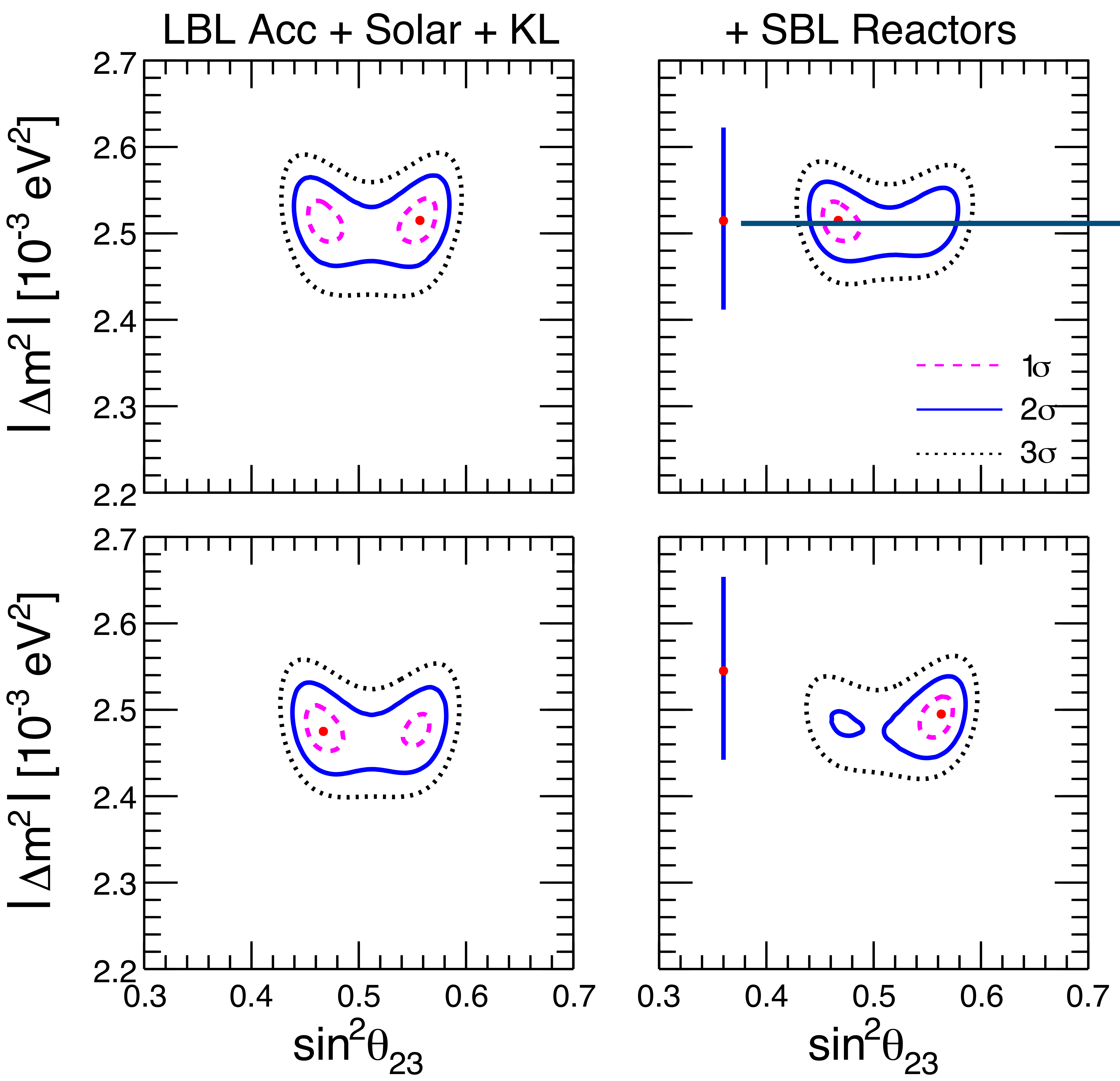


LBL Acc + Solar + KL
+ SBL Reactors
|Δm²| [10⁻³ eV²]
sin²θ23
1σ
2σ
3σ
2.7
2.6
2.5
2.4
2.3
2.2
0.3
0.4
0.5
0.6
0.7



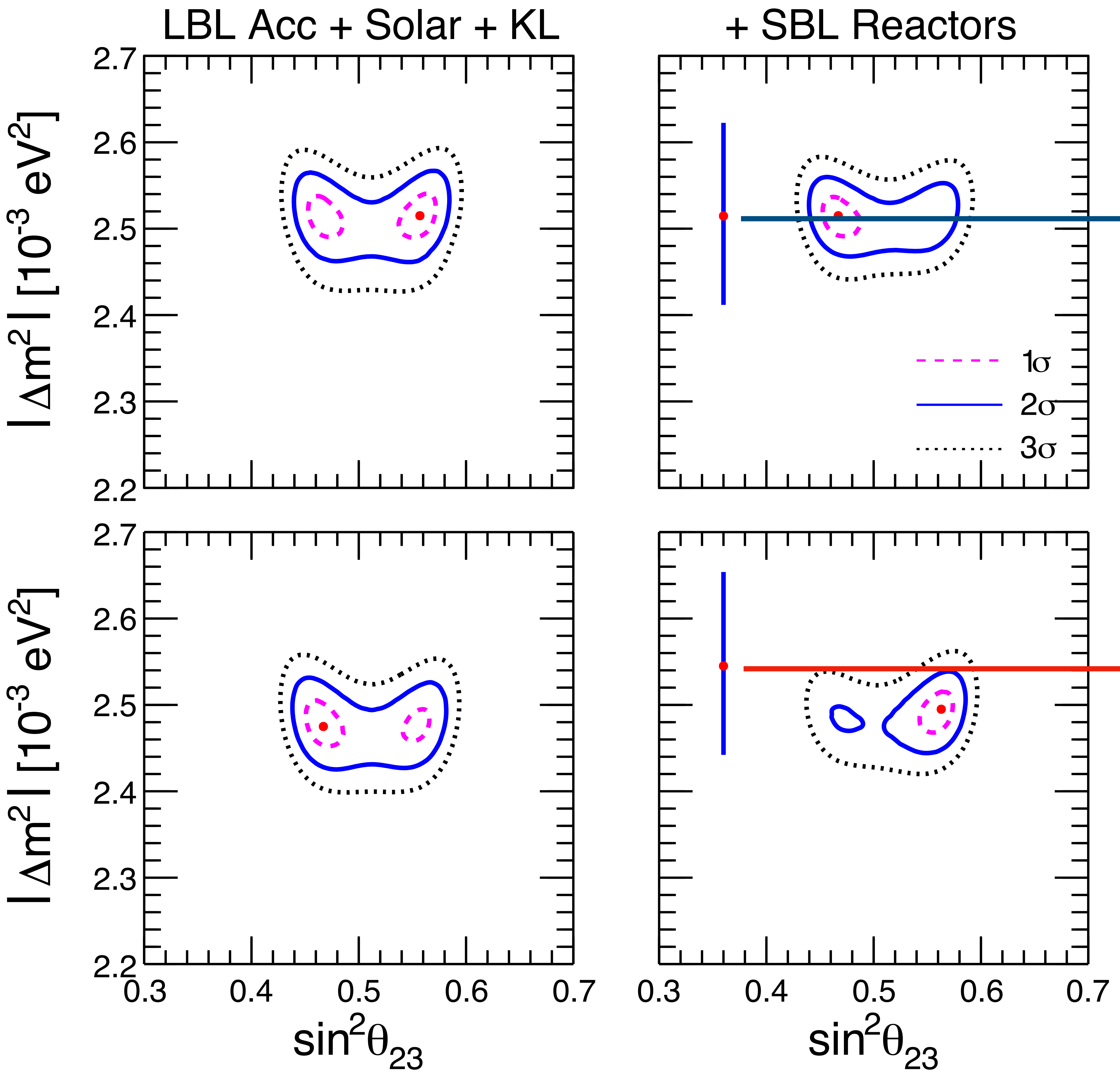
SBL reactor measurement of Δm^2 more in agreement with LBL accel. in NO than in IO

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



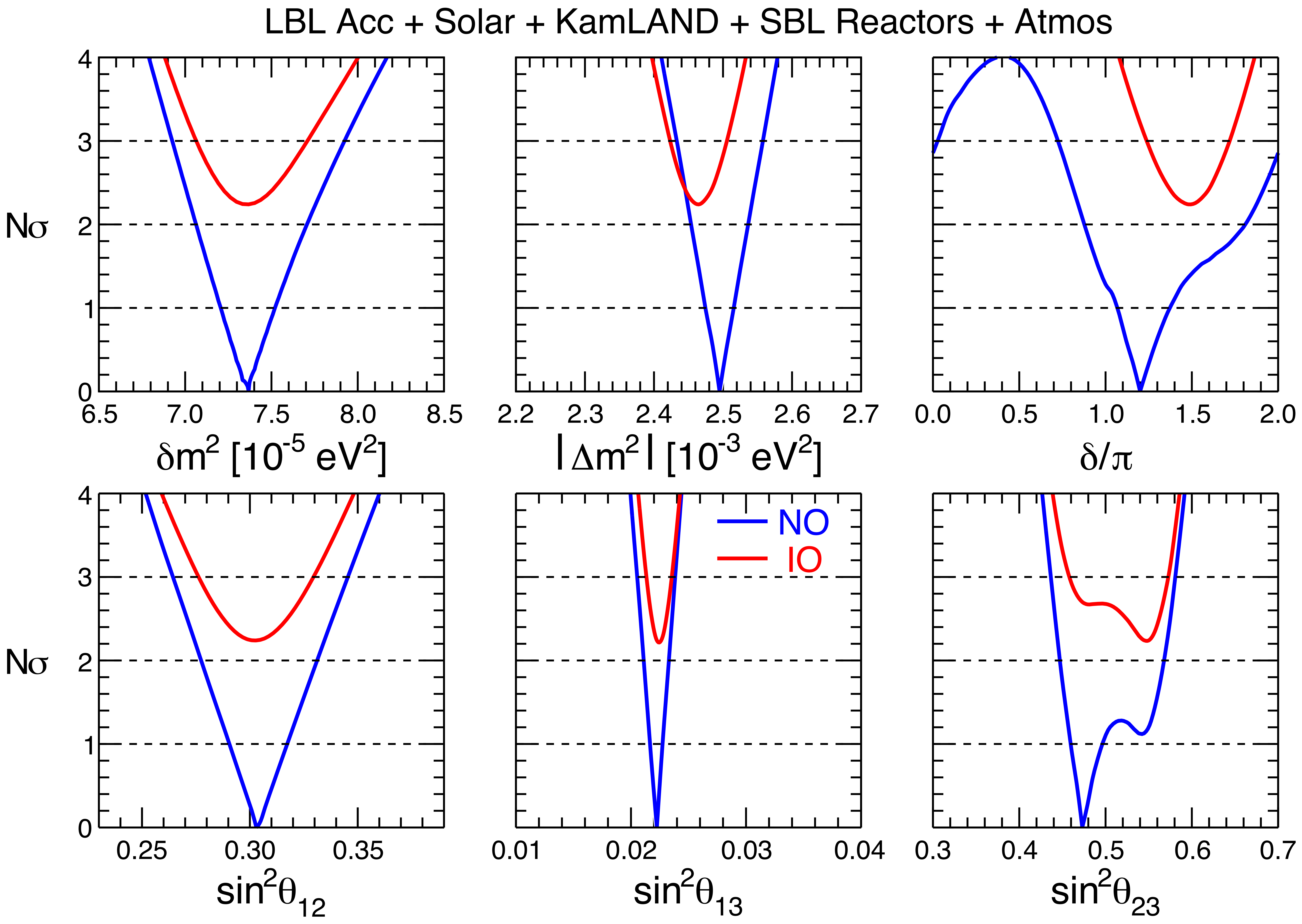
Good agreement in NO

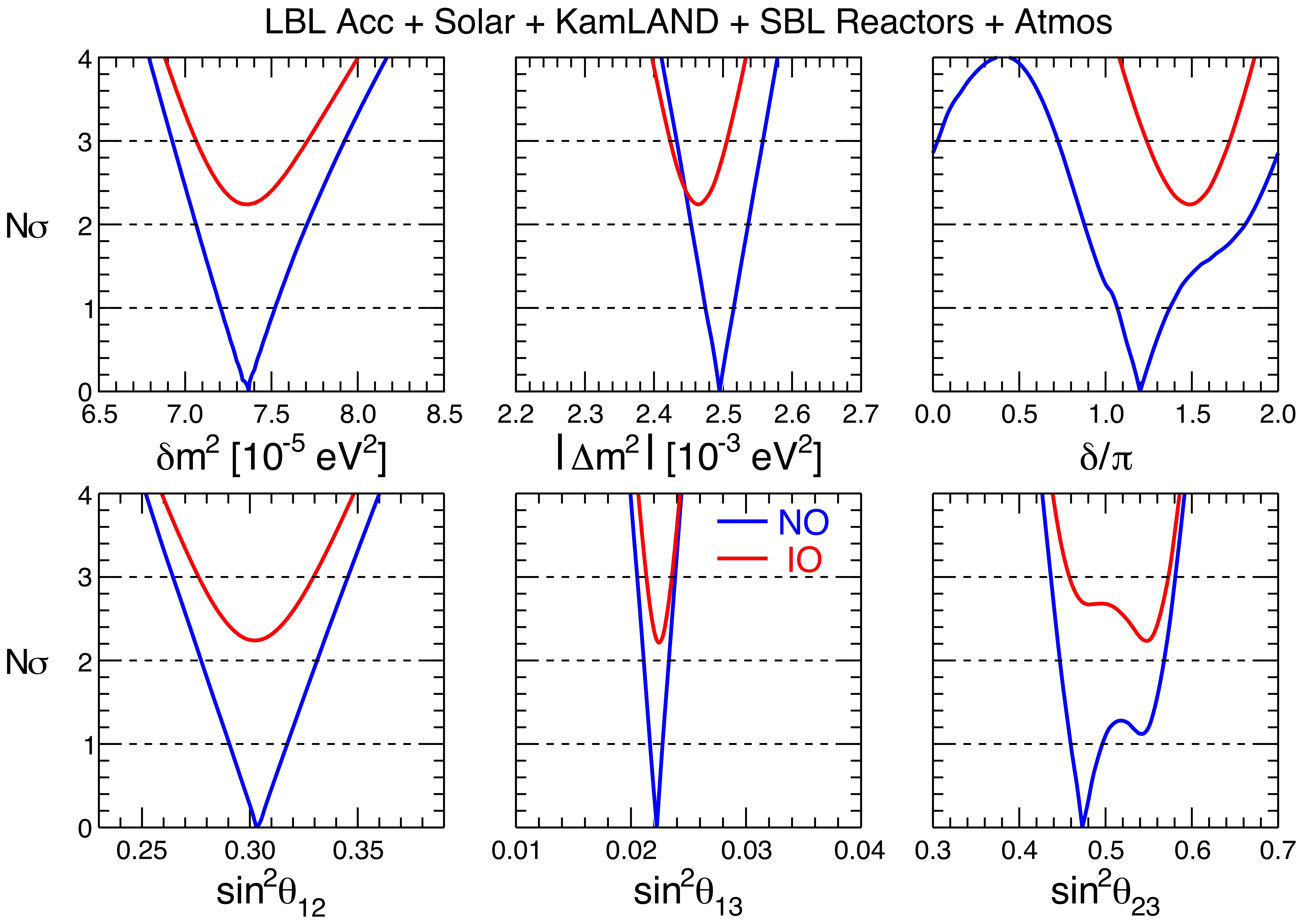
SBL reactor measurement of Δm^2 more in agreement with LBL accel. in NO than in IO



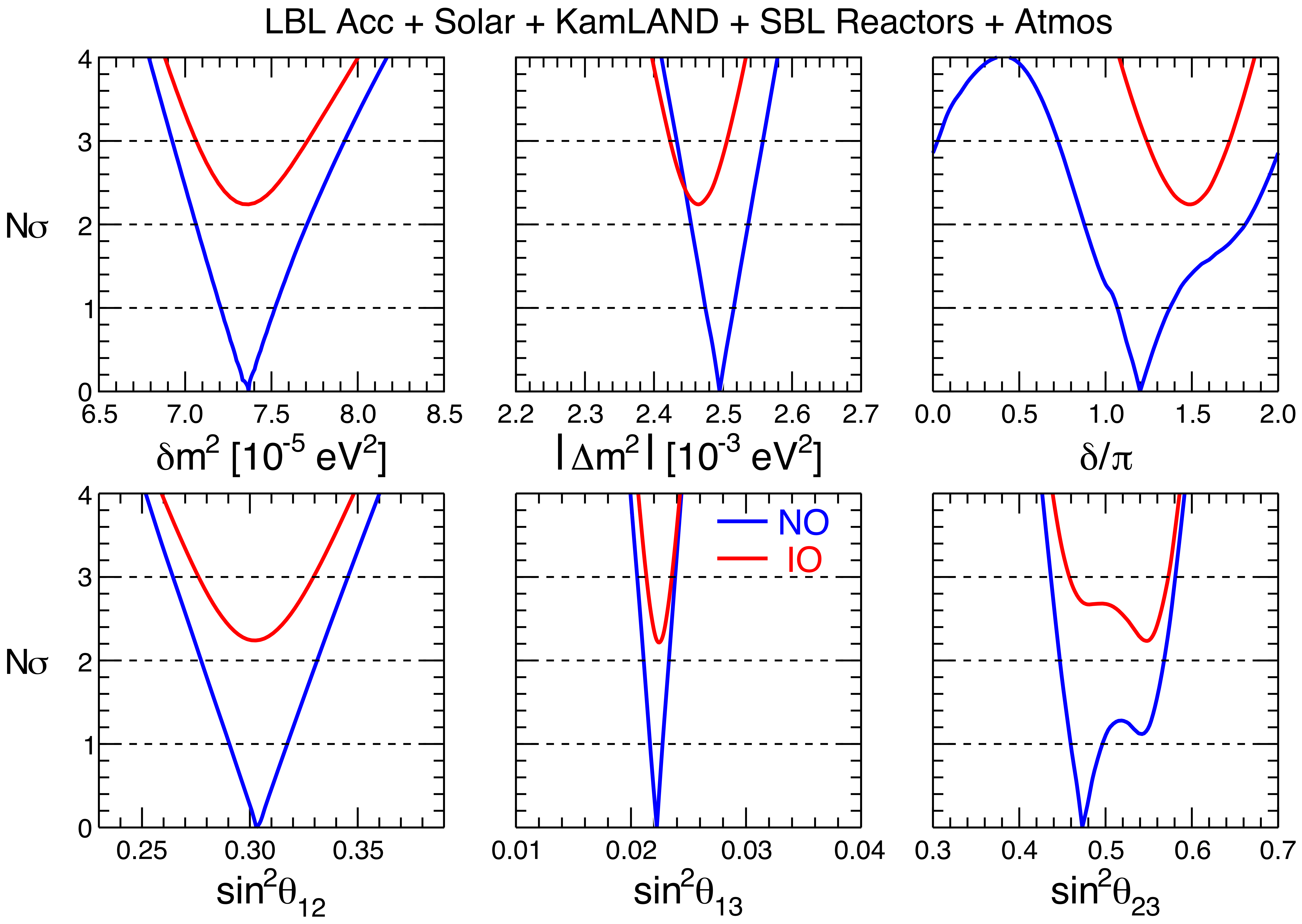
Good agreement in NO

Slightly higher value in IO


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

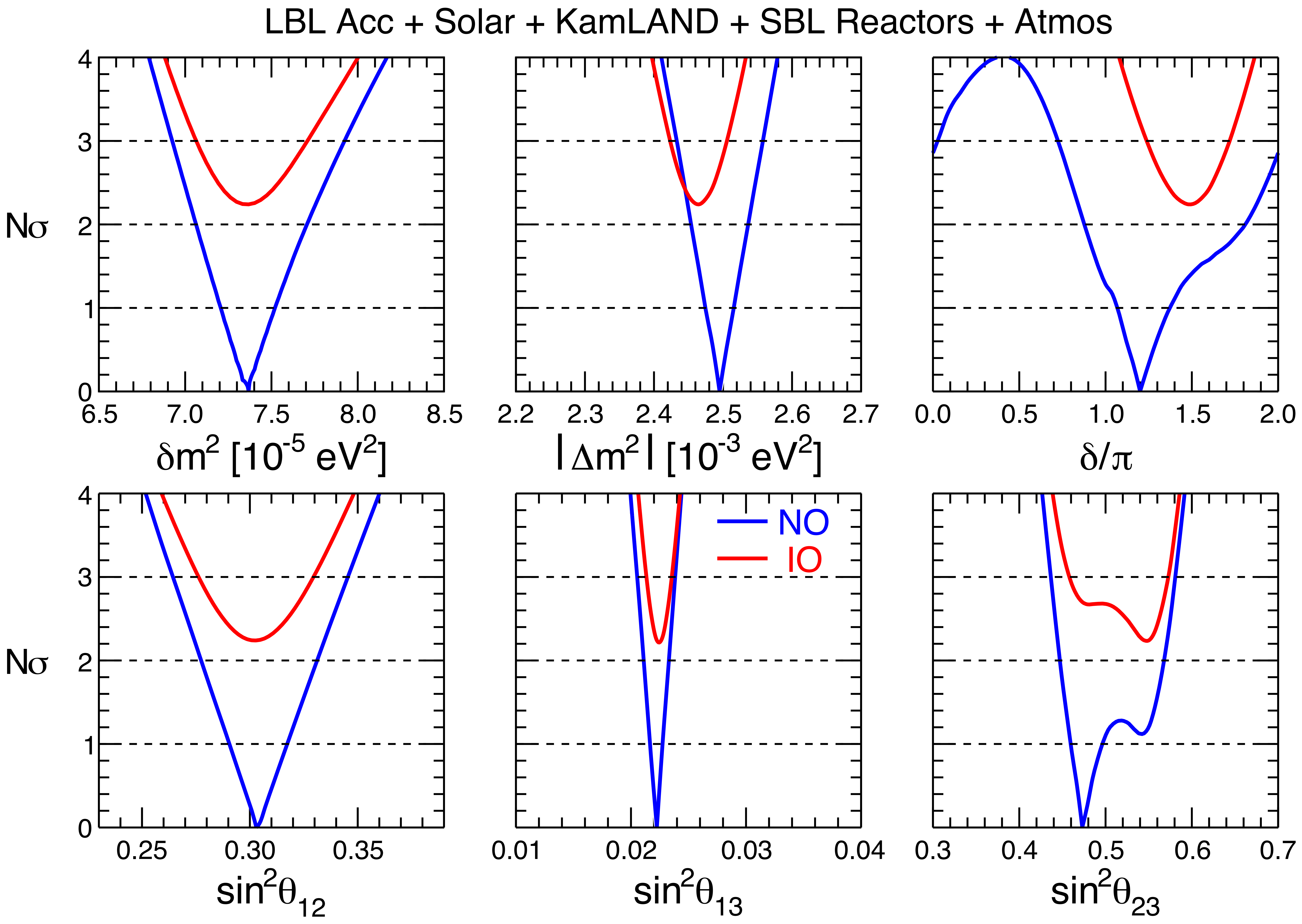


In addition, reac+acc more in agreement with atmospheric data in NO than in IO



In addition, reac+acc more in agreement with atmospheric data in NO than in IO

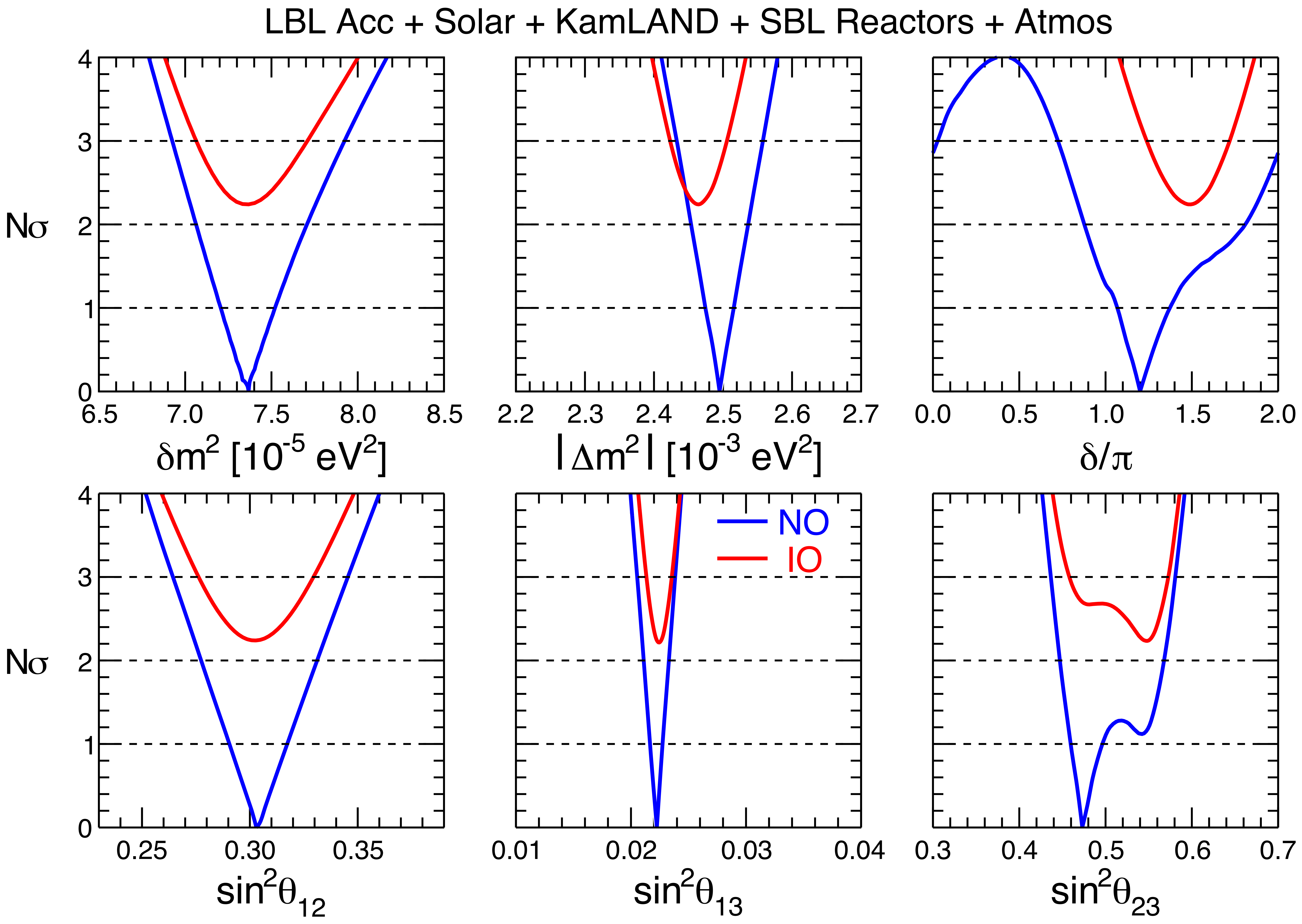
Global combination prefers NO at ~2.2σ



In addition, reac+acc more in agreement with atmospheric data in NO than in IO

Global combination prefers NO at ~2.2σ

Weak hint for CP violation (~1.3σ) and first octant (~1.1σ)

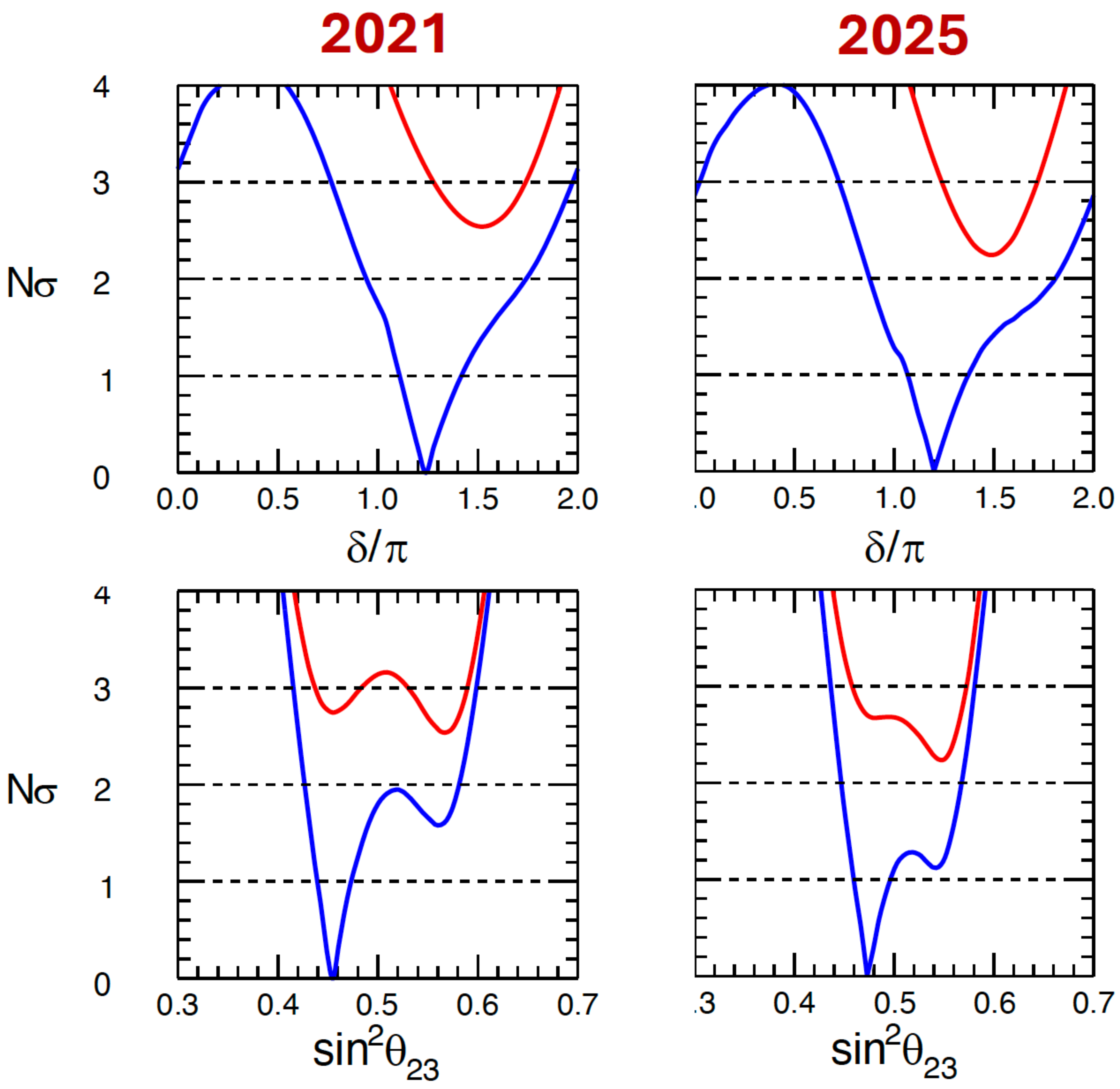


In addition, reac+acc more in agreement with atmospheric data in NO than in IO

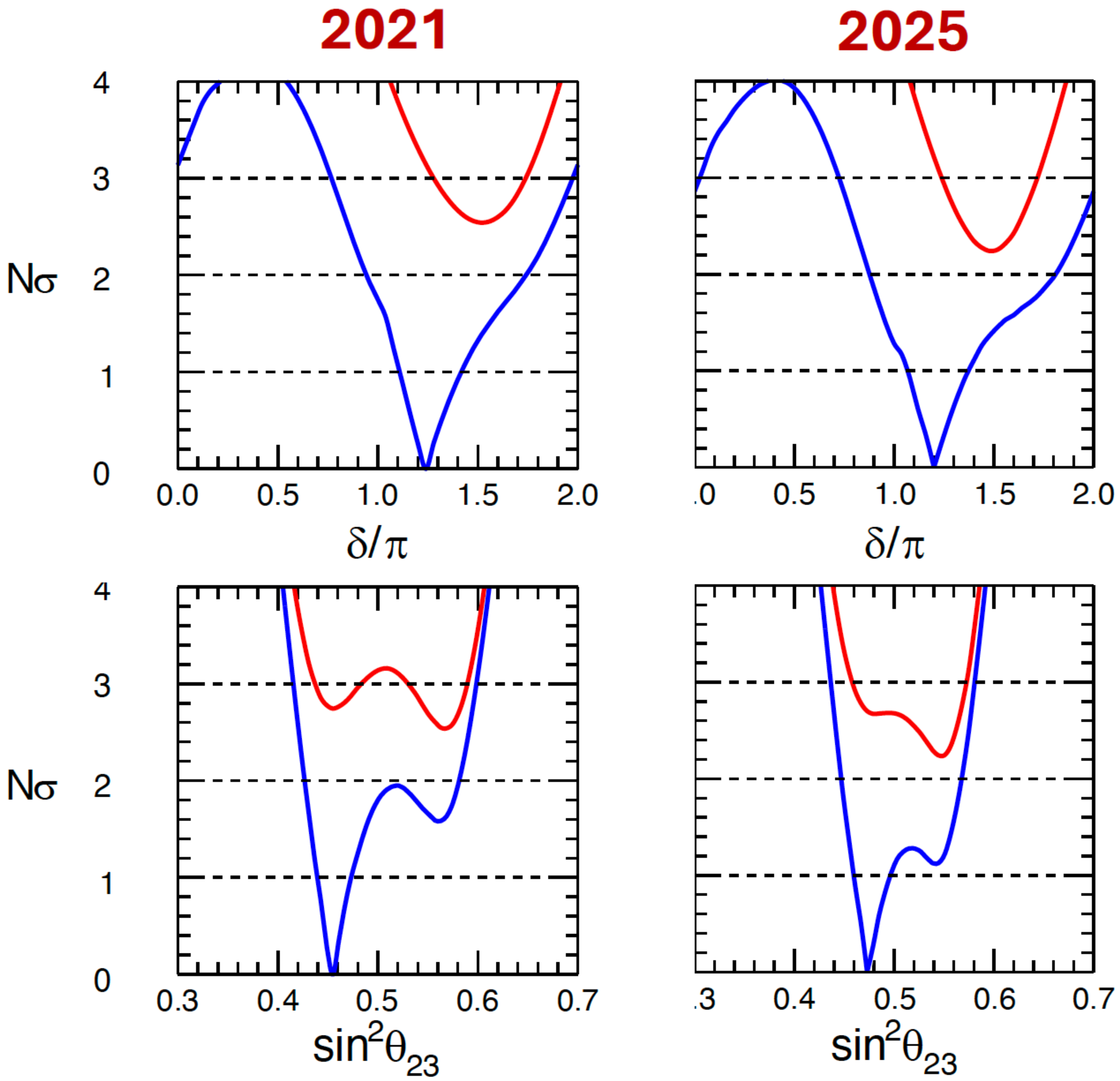
Global combination prefers NO at ~2.2σ

Weak hint for CP violation (~1.3σ) and first octant (~1.1σ)

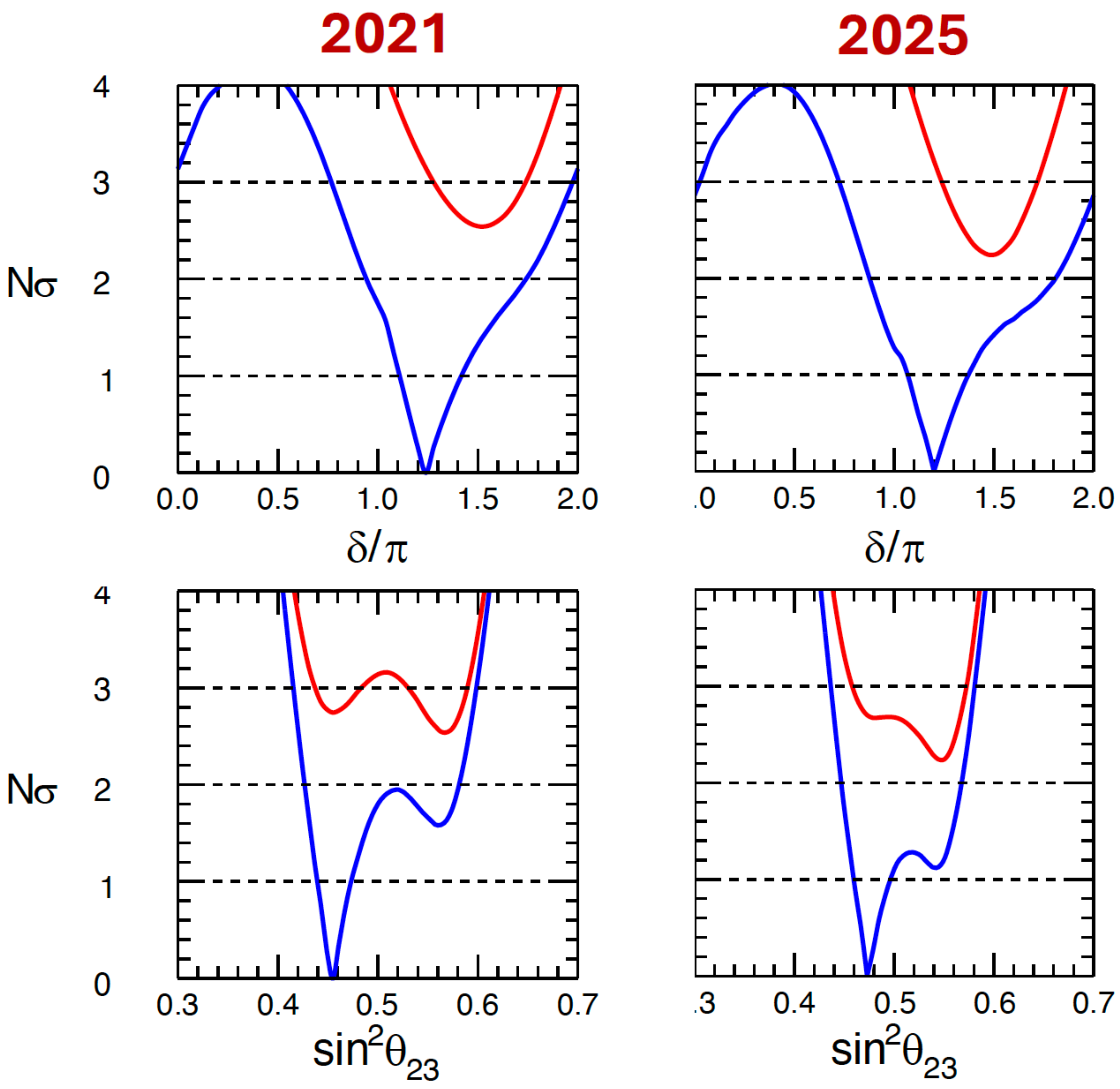
Overall status of oscillation unknowns is more uncertain than in older analyses


2021
2025
Nσ
Nσ
0
1
2
3
4
0.0
0.5
1.0
1.5
2.0
δ/π
δ/π
0.3
0.4
0.5
0.6
0.7
sin²θ₂₃
sin²θ₂₃

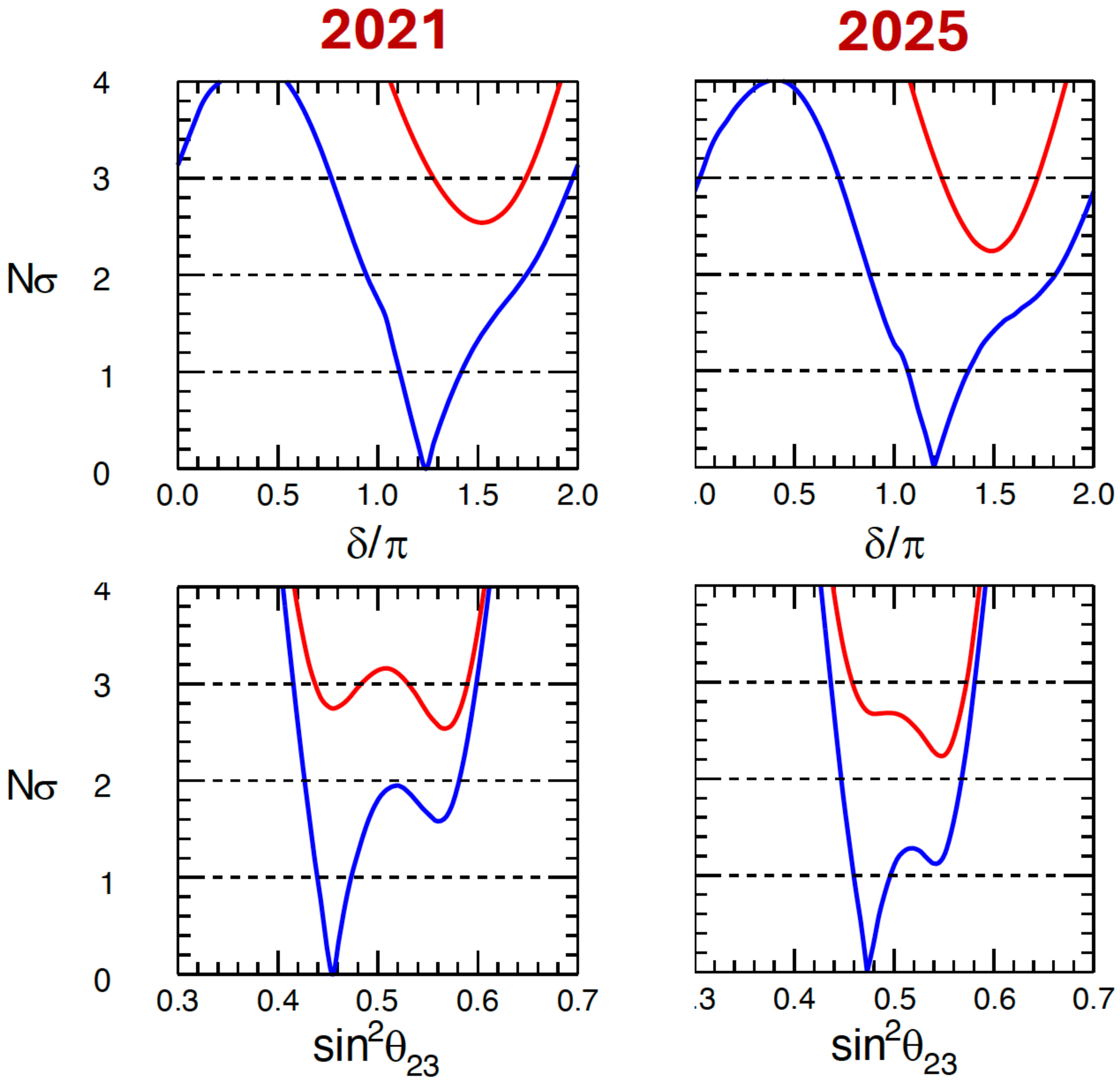
Updated results on oscillation unknowns (octant of θ_{23} and δ_{CP})



Updated results on oscillation unknowns (octant of θ_{23} and δ_{CP})



Weaker hint for NO and CP violation



Updated results on oscillation unknowns (octant of θ_{23} and δ_{CP})

Weaker hint for NO and CP violation

Closer and more degenerate octants

TABLE I. Global 3ν oscillation analysis: best-fit values and allowed ranges at $N_\sigma = 1, 2, 3$, for either NO or IO. The last column shows the formal "1σ parameter accuracy," defined as $1/6$ of the 3σ range, divided by the best-fit value (in percent). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that δ/π is cyclic (mod 2). Last row: $\Delta\chi^2$ offset between IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21–7.52	7.06–7.71	6.93–7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91–3.17	2.77–3.31	2.64–3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475–2.515	2.454–2.536	2.433–2.558	0.8
	IO	2.465	2.444–2.485	2.423–2.506	2.403–2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17–2.27	2.11–2.33	2.06–2.38	2.4
	IO	2.23	2.19–2.30	2.14–2.35	2.08–2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60–4.96	4.47–5.68	4.37–5.81	5.1
	IO	5.45	5.28–5.60	4.58–5.73	4.43–5.83	4.3
δ/π	NO	1.20	1.07–1.37	0.88–1.81	0.73–2.03	18
	IO	1.48	1.36–1.61	1.24–1.72	1.12–1.83	8
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+5.0				

Percent accuracy on “known” parameters

TABLE I. Global 3ν oscillation analysis: best-fit values and allowed ranges at $N_\sigma = 1, 2, 3$, for either NO or IO. The last column shows the formal “1σ parameter accuracy,” defined as $1/6$ of the 3σ range, divided by the best-fit value (in percent). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that δ/π is cyclic (mod 2). Last row: $\Delta\chi^2$ offset between IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	“1σ” (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21–7.52	7.06–7.71	6.93–7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91–3.17	2.77–3.31	2.64–3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475–2.515	2.454–2.536	2.433–2.558	0.8
	IO	2.465	2.444–2.485	2.423–2.506	2.403–2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17–2.27	2.11–2.33	2.06–2.38	2.4
	IO	2.23	2.19–2.30	2.14–2.35	2.08–2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60–4.96	4.47–5.68	4.37–5.81	5.1
	IO	5.45	5.28–5.60	4.58–5.73	4.43–5.83	4.3
δ/π	NO	1.20	1.07–1.37	0.88–1.81	0.73–2.03	18
	IO	1.48	1.36–1.61	1.24–1.72	1.12–1.83	8
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+5.0				

Percent accuracy on “known” parameters

In particular, Δm^2 formally determined at the subpercent level, 1σ = 0.8%

TABLE I. Global 3ν oscillation analysis: best-fit values and allowed ranges at $N_\sigma = 1, 2, 3$, for either NO or IO. The last column shows the formal “1σ parameter accuracy,” defined as 1/6 of the 3σ range, divided by the best-fit value (in percent). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that δ/π is cyclic (mod 2). Last row: $\Delta\chi^2$ offset between IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	“1σ” (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21–7.52	7.06–7.71	6.93–7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91–3.17	2.77–3.31	2.64–3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475–2.515	2.454–2.536	2.433–2.558	0.8
	IO	2.465	2.444–2.485	2.423–2.506	2.403–2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17–2.27	2.11–2.33	2.06–2.38	2.4
	IO	2.23	2.19–2.30	2.14–2.35	2.08–2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60–4.96	4.47–5.68	4.37–5.81	5.1
	IO	5.45	5.28–5.60	4.58–5.73	4.43–5.83	4.3
δ/π	NO	1.20	1.07–1.37	0.88–1.81	0.73–2.03	18
	IO	1.48	1.36–1.61	1.24–1.72	1.12–1.83	8
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+5.0				

Percent accuracy on “known” parameters

In particular, Δm^2 formally determined at the subpercent level, 1σ = 0.8%

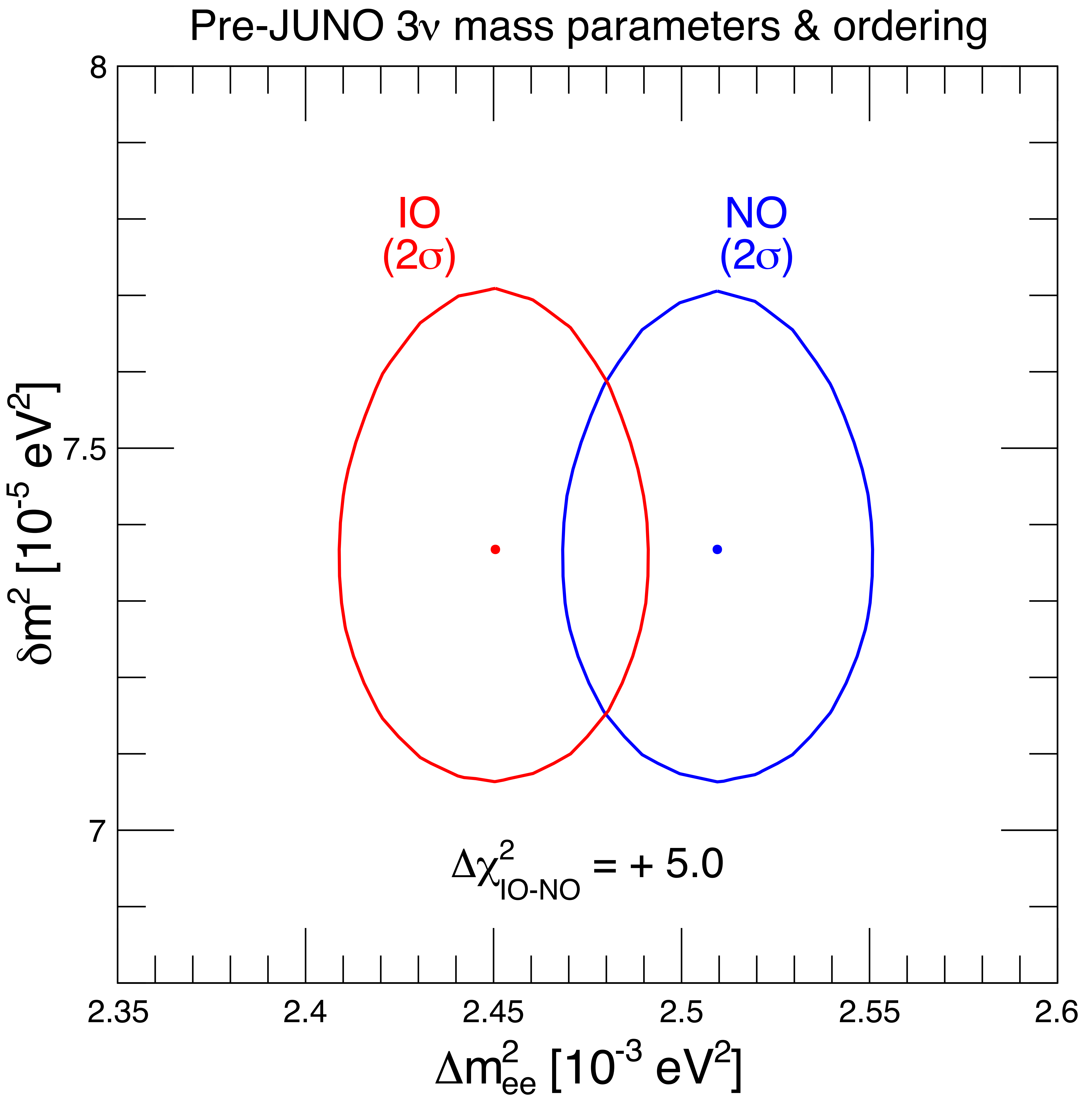
TABLE I. Global 3ν oscillation analysis: best-fit values and allowed ranges at $N_\sigma = 1, 2, 3$, for either NO or IO. The last column shows the formal “1σ parameter accuracy,” defined as 1/6 of the 3σ range, divided by the best-fit value (in percent). We recall that $\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$ and that δ/π is cyclic (mod 2). Last row: $\Delta\chi^2$ offset between IO and NO.

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	“1σ” (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21–7.52	7.06–7.71	6.93–7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91–3.17	2.77–3.31	2.64–3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475–2.515	2.454–2.536	2.433–2.558	0.8
	IO	2.465	2.444–2.485	2.423–2.506	2.403–2.527	0.8
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17–2.27	2.11–2.33	2.06–2.38	2.4
	IO	2.23	2.19–2.30	2.14–2.35	2.08–2.41	2.4
$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60–4.96	4.47–5.68	4.37–5.81	5.1
	IO	5.45	5.28–5.60	4.58–5.73	4.43–5.83	4.3
δ/π	NO	1.20	1.07–1.37	0.88–1.81	0.73–2.03	18
	IO	1.48	1.36–1.61	1.24–1.72	1.12–1.83	8
$\Delta\chi^2_{\text{IO-NO}}$	IO-NO	+5.0				

However, one should be cautious about interpreting subpercent-level accuracies, since correlated effects from neutrino energy reconstruction, interaction models, and systematic uncertainties across accelerator and atmospheric experiments still require significant improvement

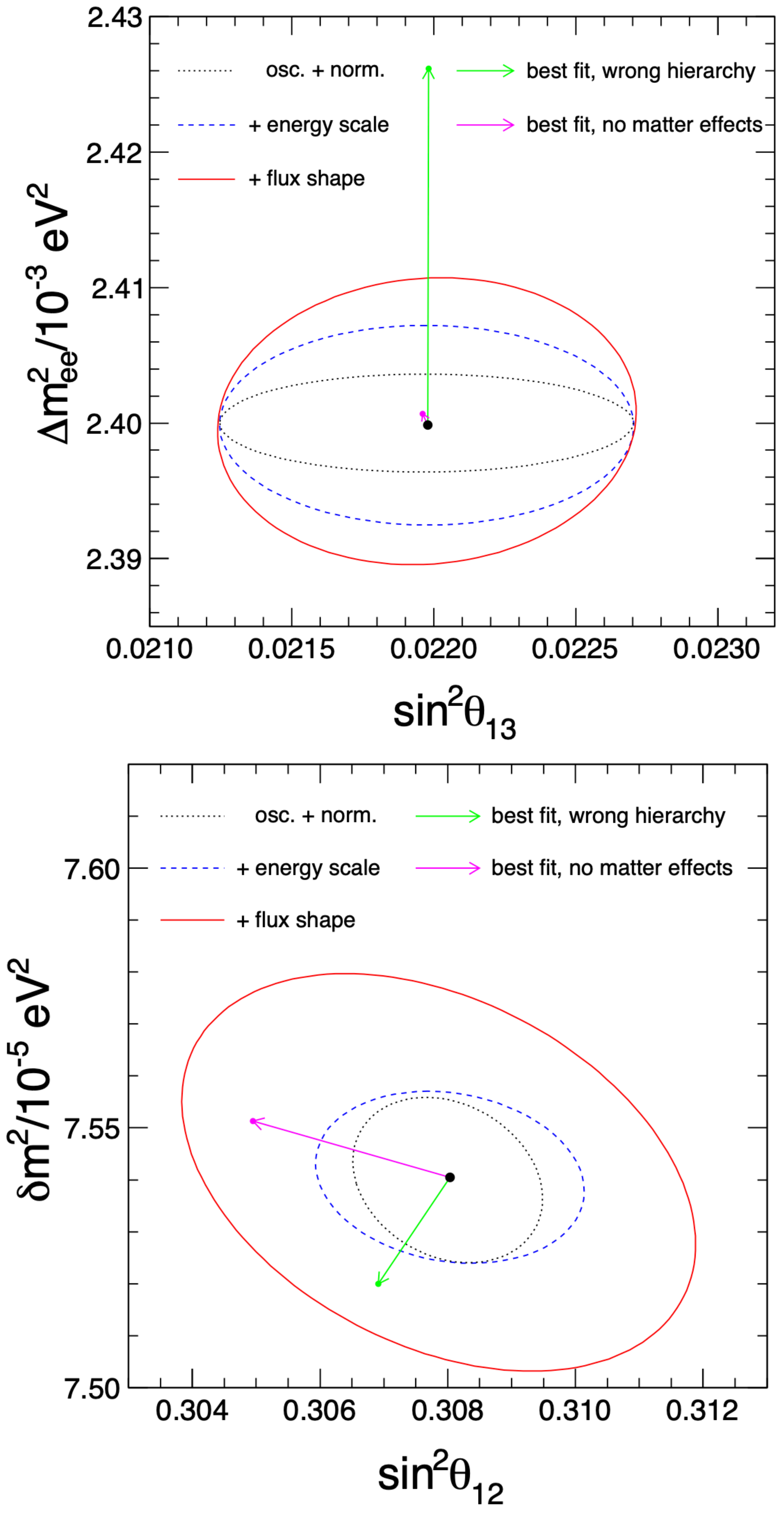
Present knowledge about the two JUNO oscillation frequencies

Present knowledge about the two JUNO oscillation frequencies



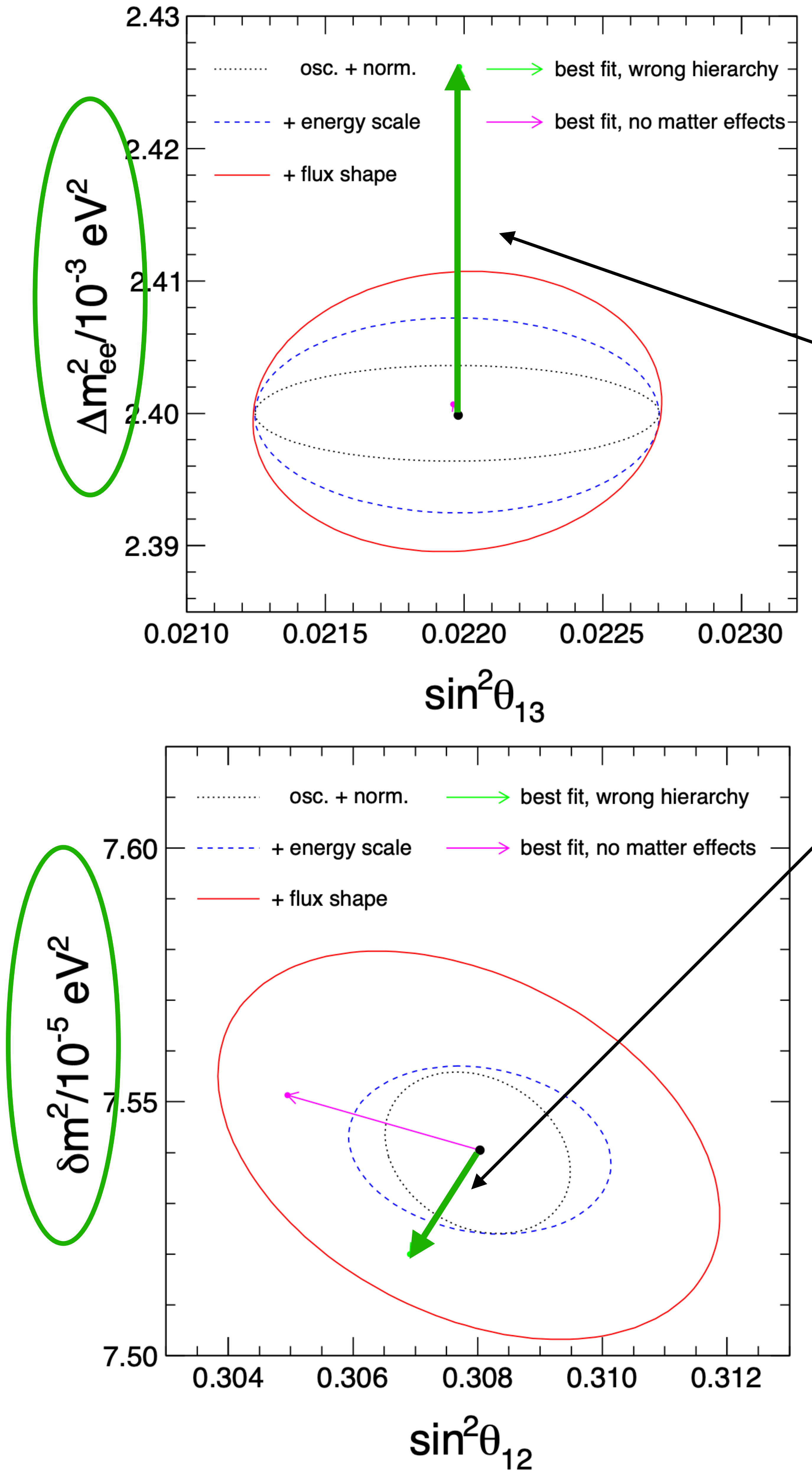
JUNO measurements will lead to slightly displaced best fits for the two frequencies in NO and IO

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



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

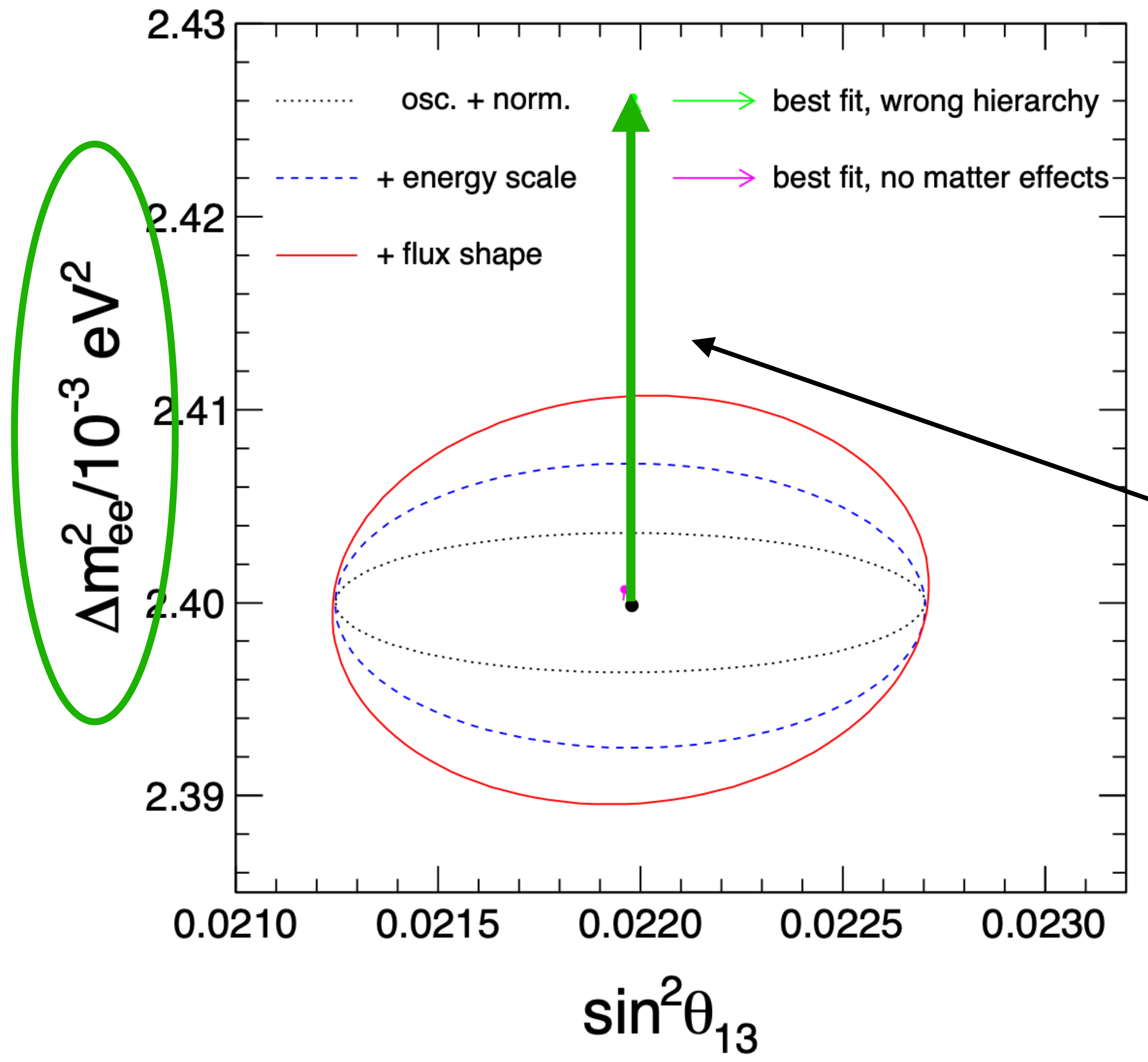
Phys.Rev.D 92 (2015) 9, 093011

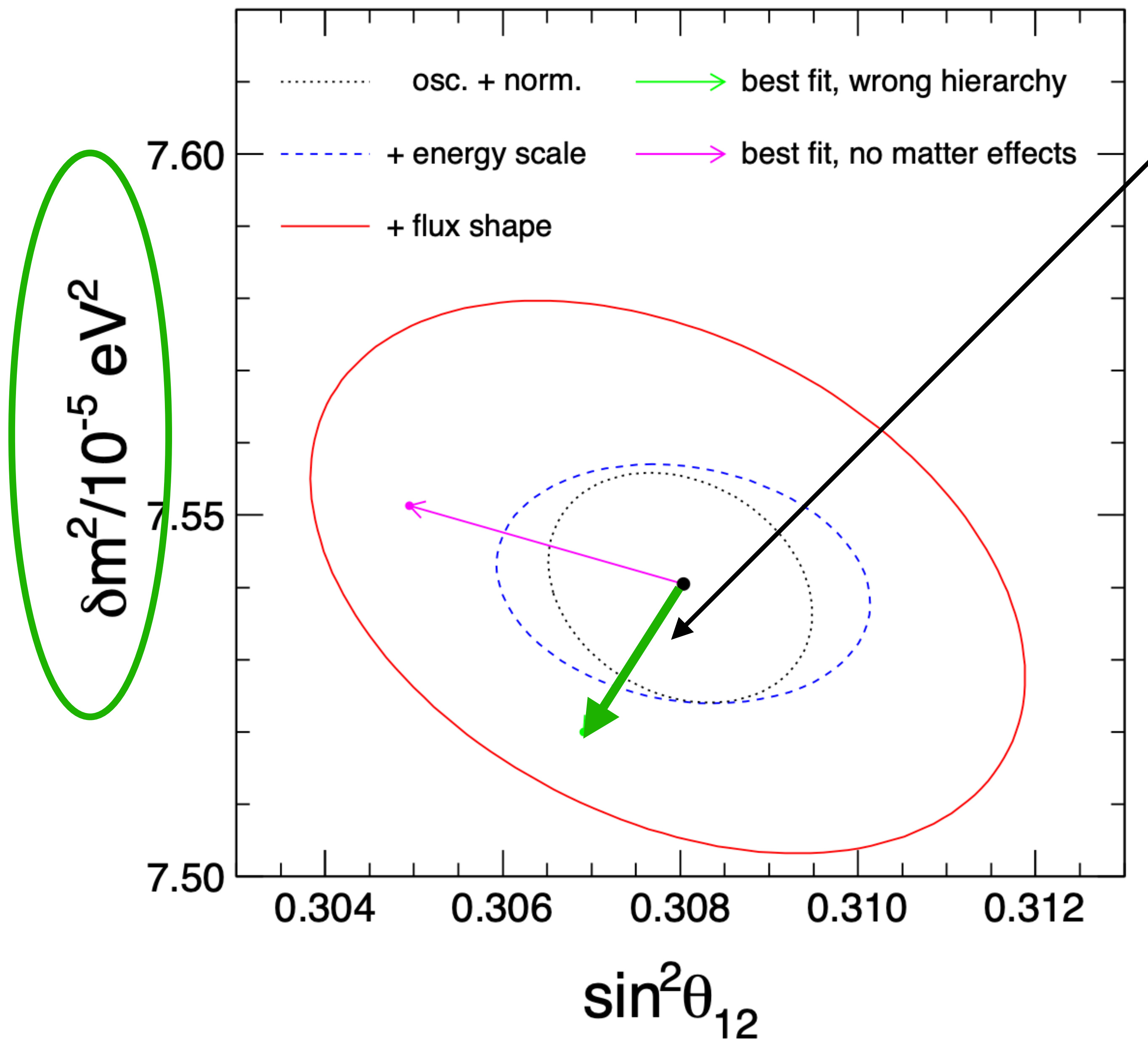


Green arrows: shifts of best fits when passing from NO to IO assumption

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

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

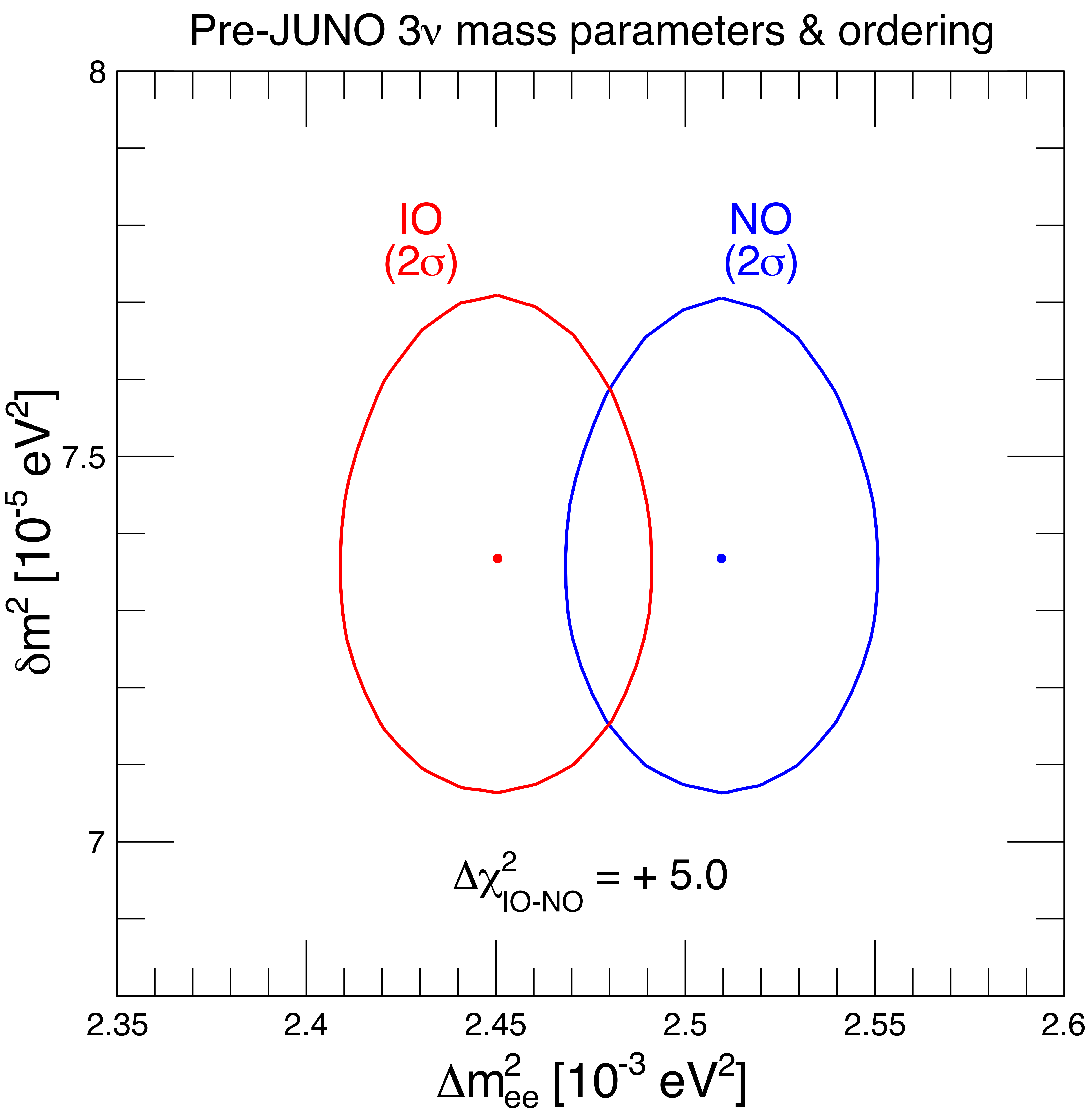




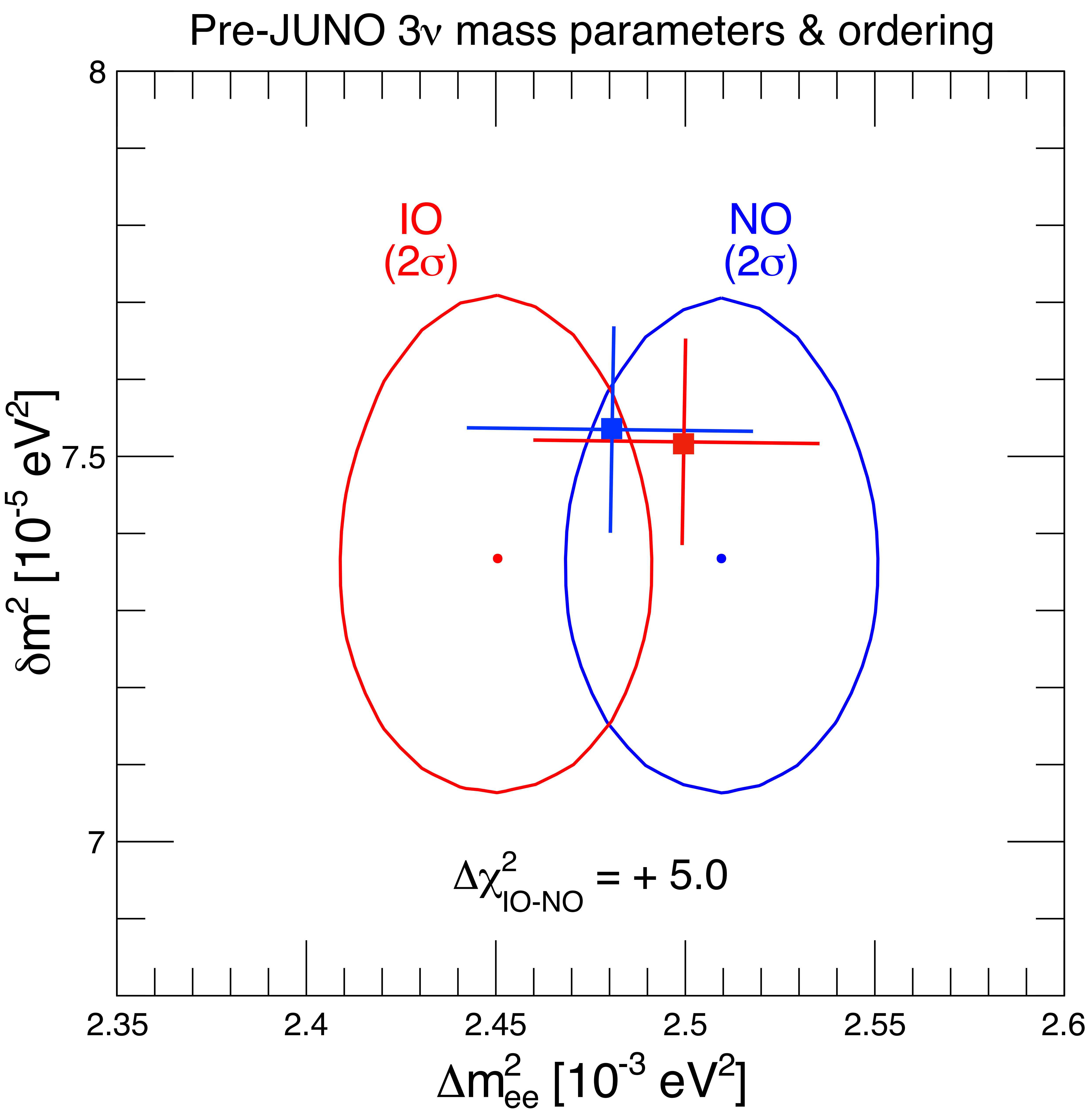
Green arrows: shifts of best fits when passing from NO to IO assumption

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



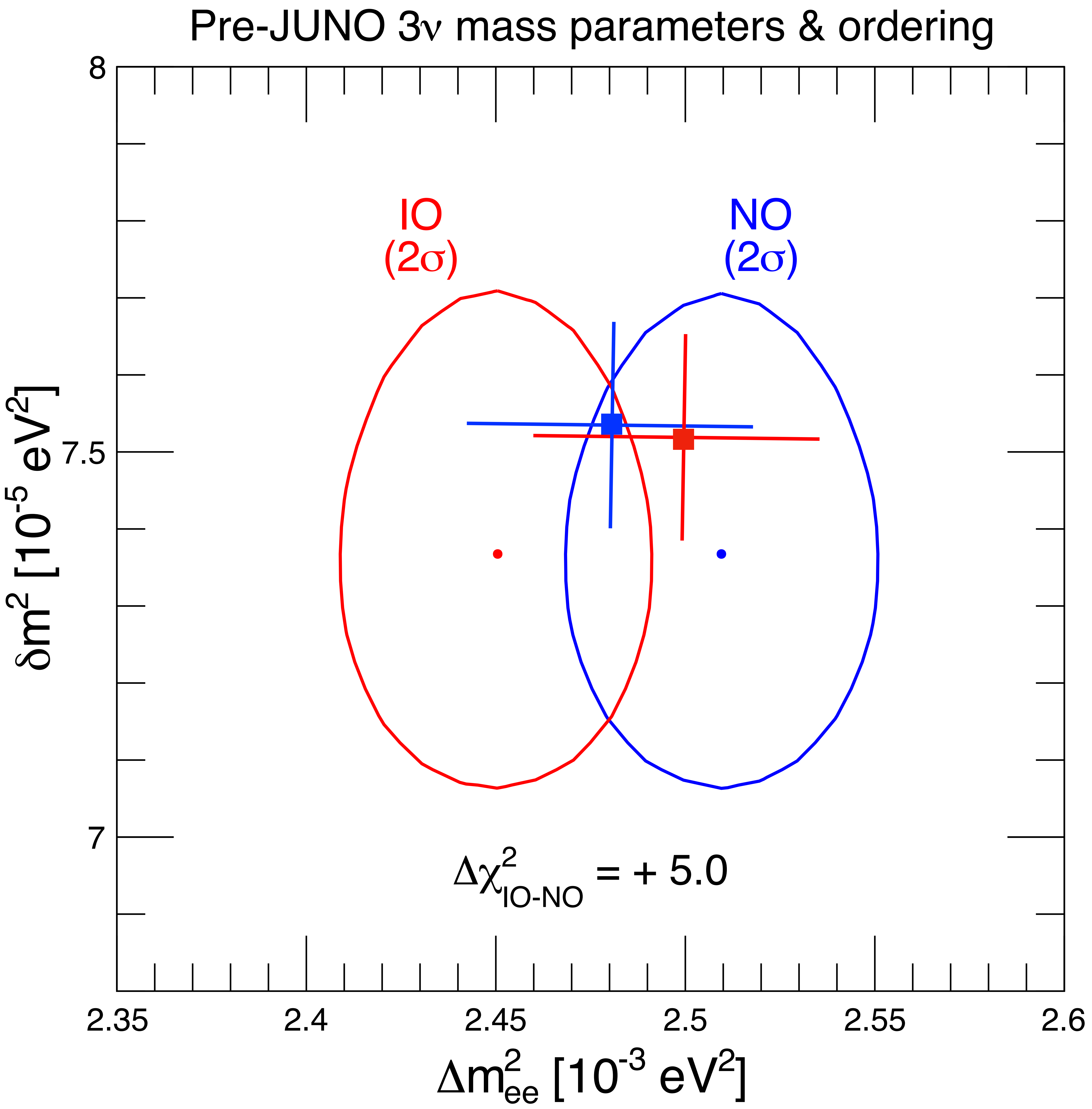
Typical relative displacement between JUNO bestfit point in NO and IO

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

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

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

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



Typical relative displacement between JUNO bestfit point in NO and IO

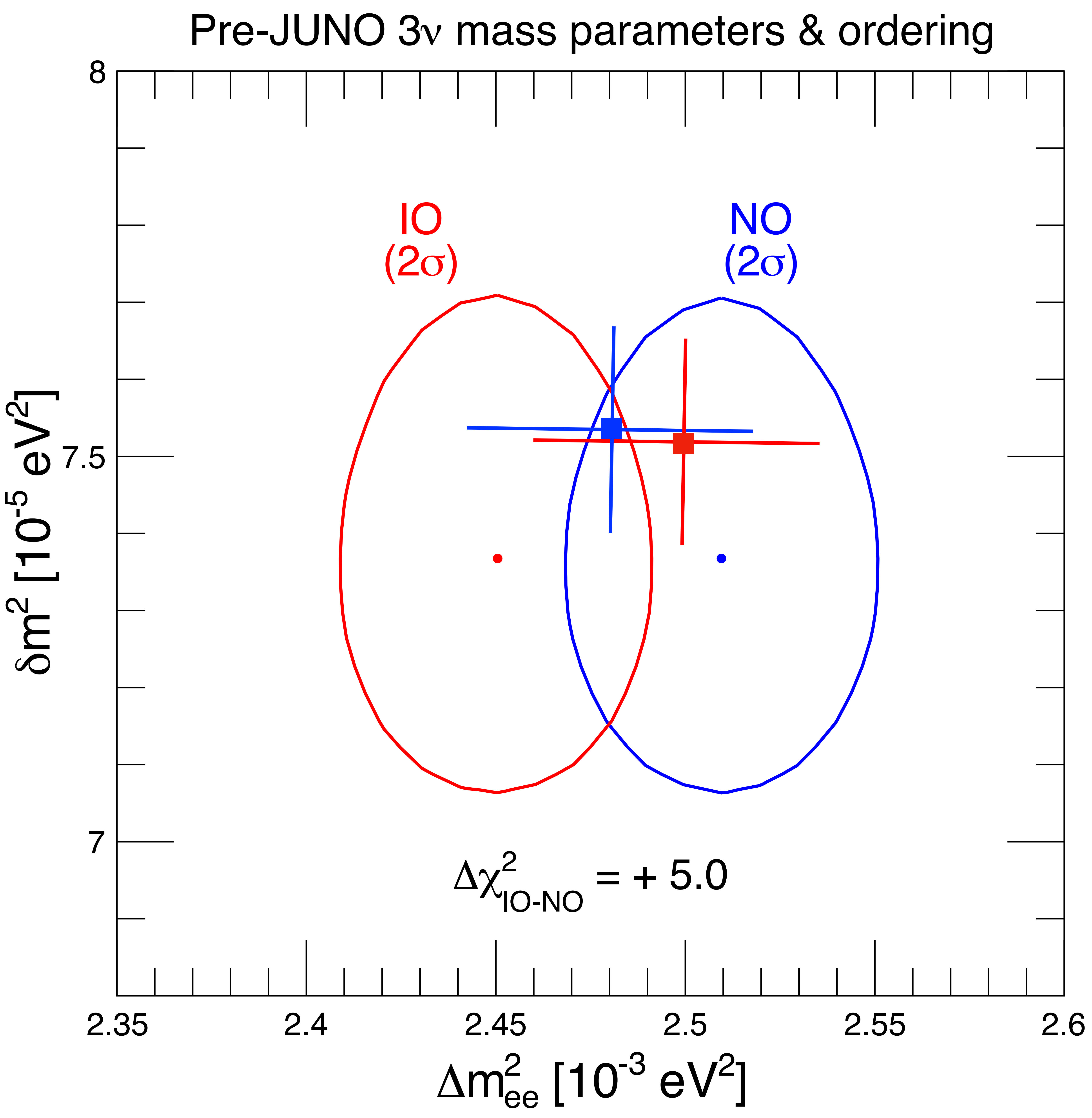
$$\delta m^2\ (2\sigma)\ \sim 0.15 \times 10^{-5}\ \text{eV}^2$$

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

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

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

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



Typical relative displacement between JUNO bestfit point in NO and IO

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

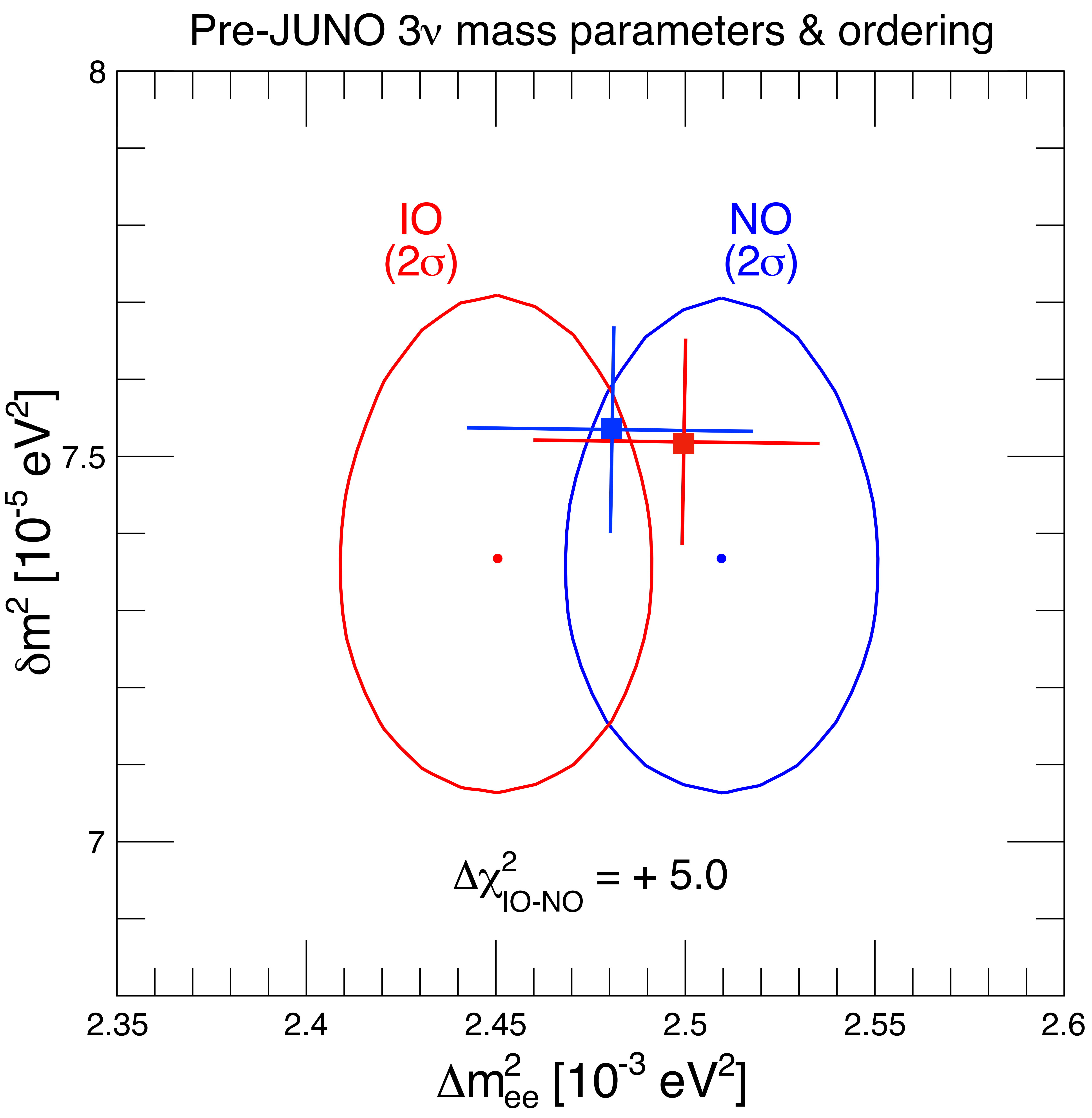
$$\Delta m^2_{ee}\ (2\sigma)\ \sim 0.04 \times 10^{-3}\ \text{eV}^2$$

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

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

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

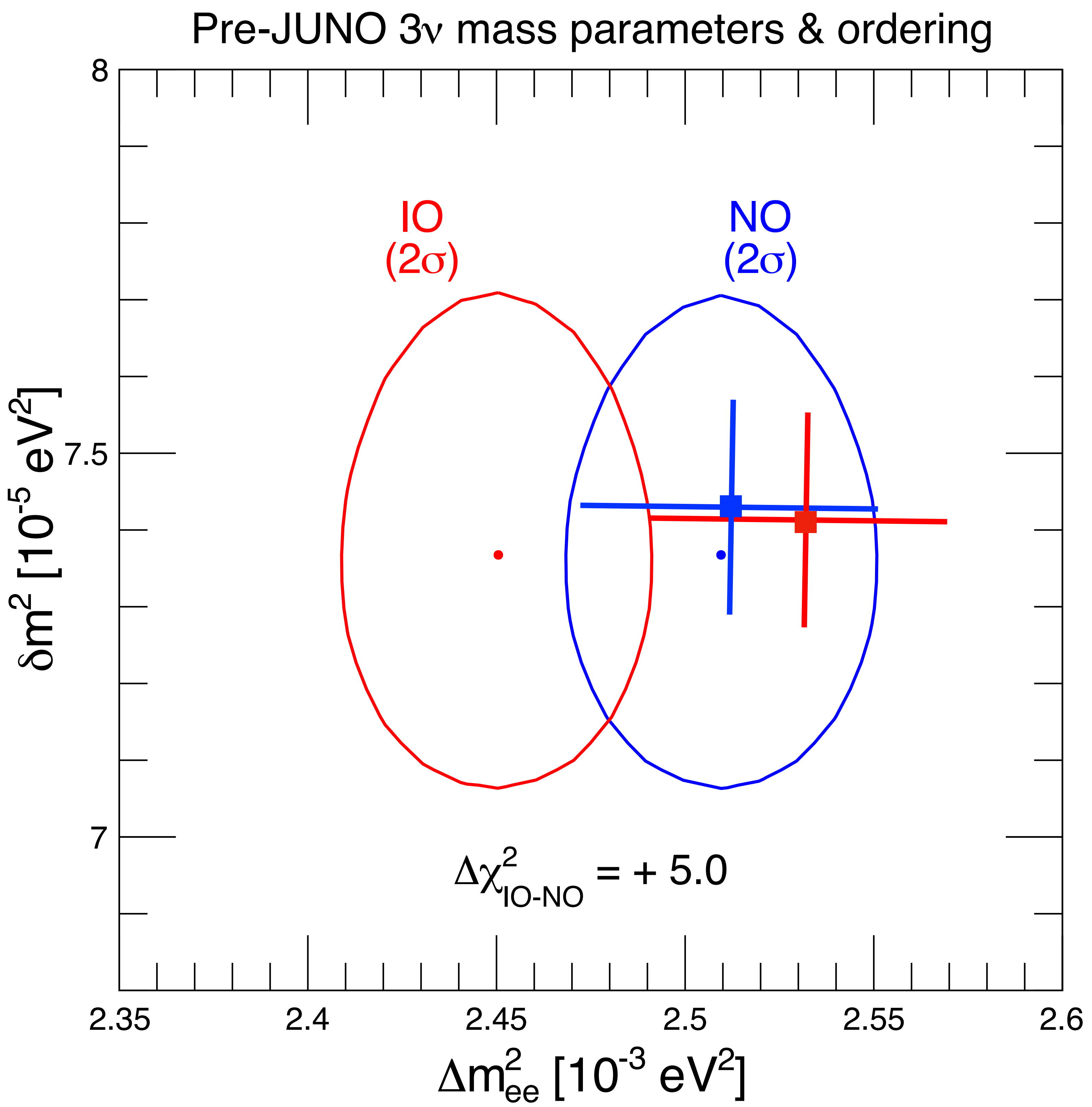
While statistical fluctuations can initially mask the distinction between NO and IO, with higher exposure the true difference is expected to become evident



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

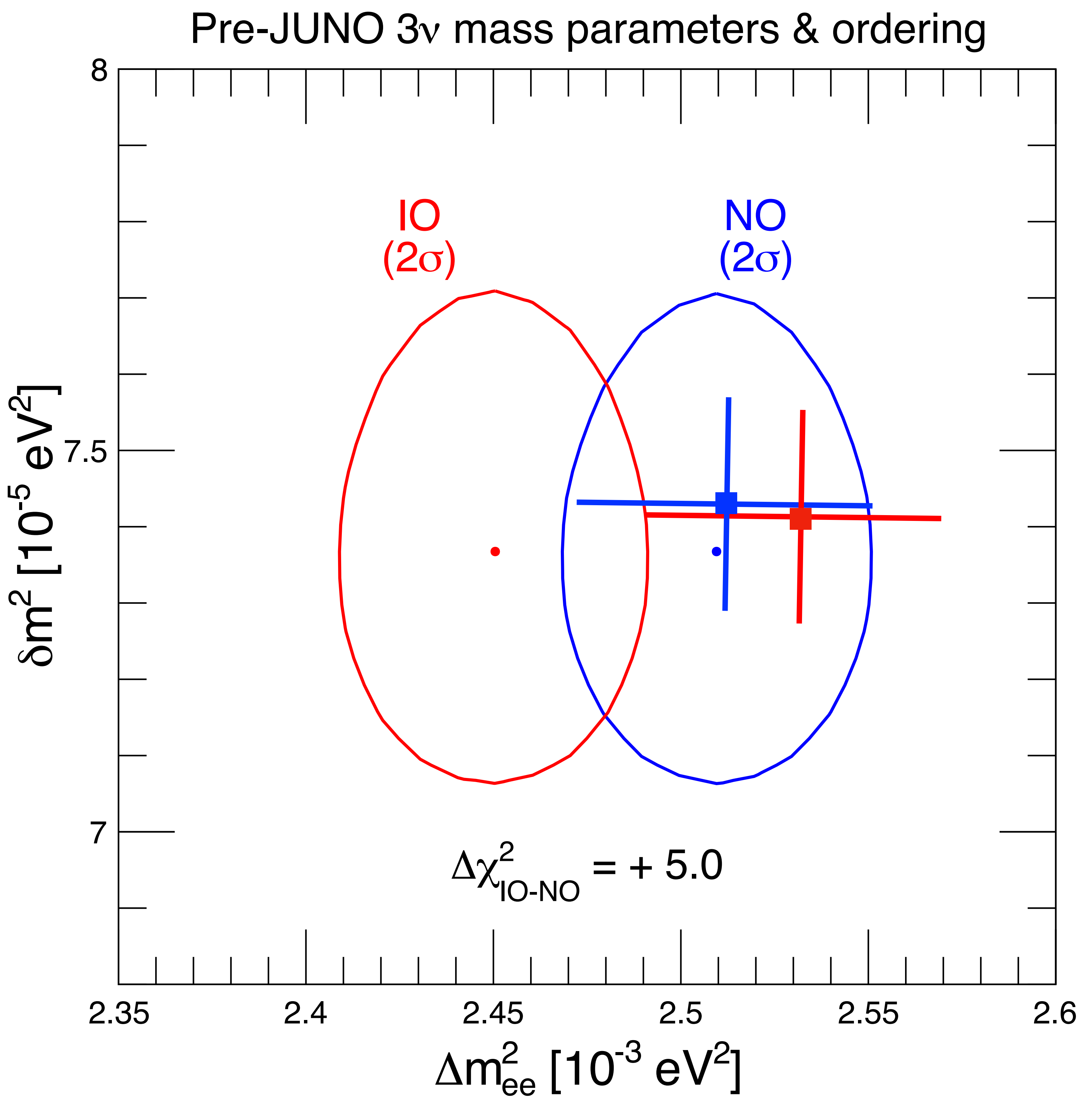
Examples of possible JUNO first data compared with pre-JUNO data

A synergy favoring NO

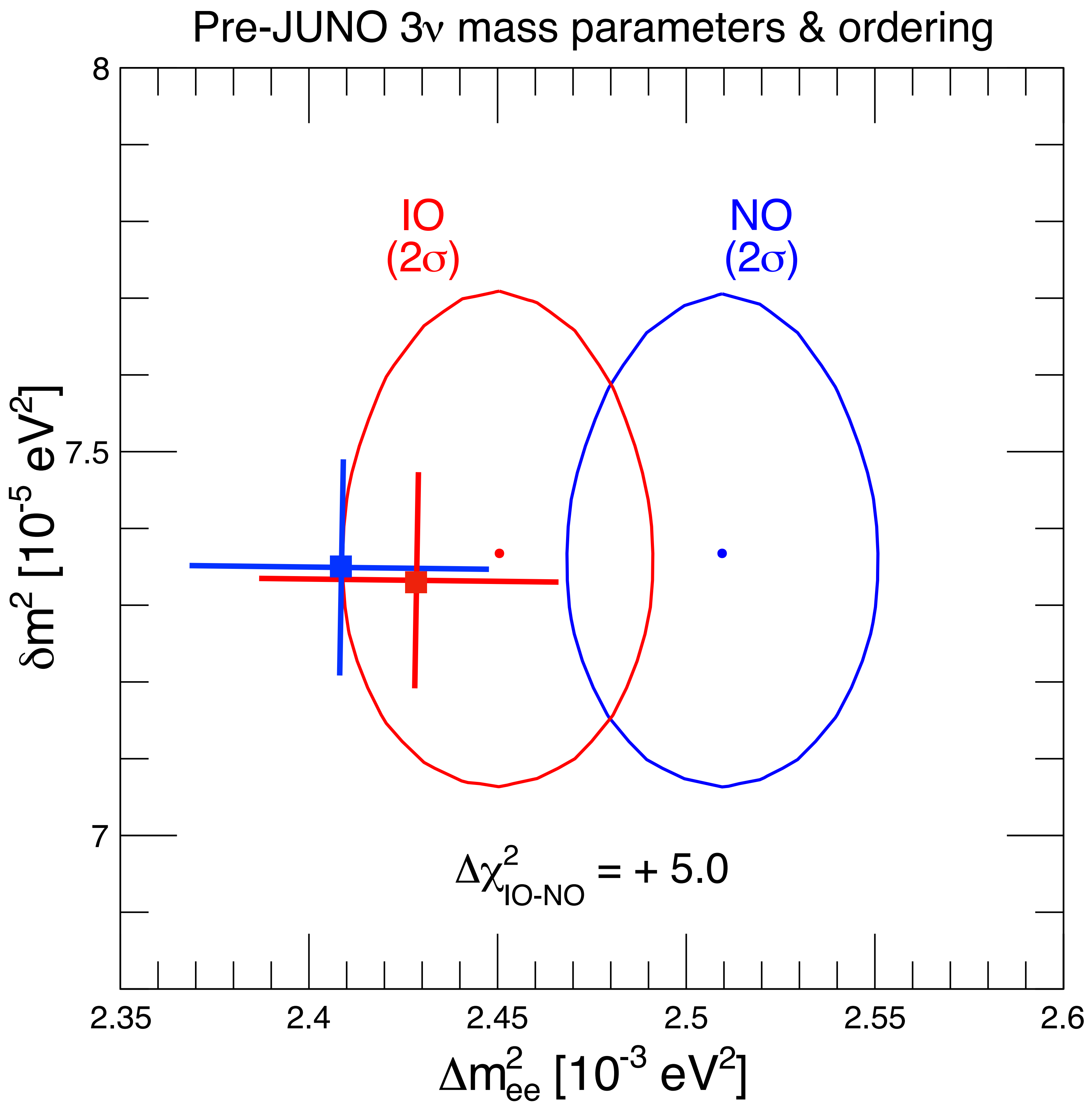


Examples of possible JUNO first data compared with pre-JUNO data

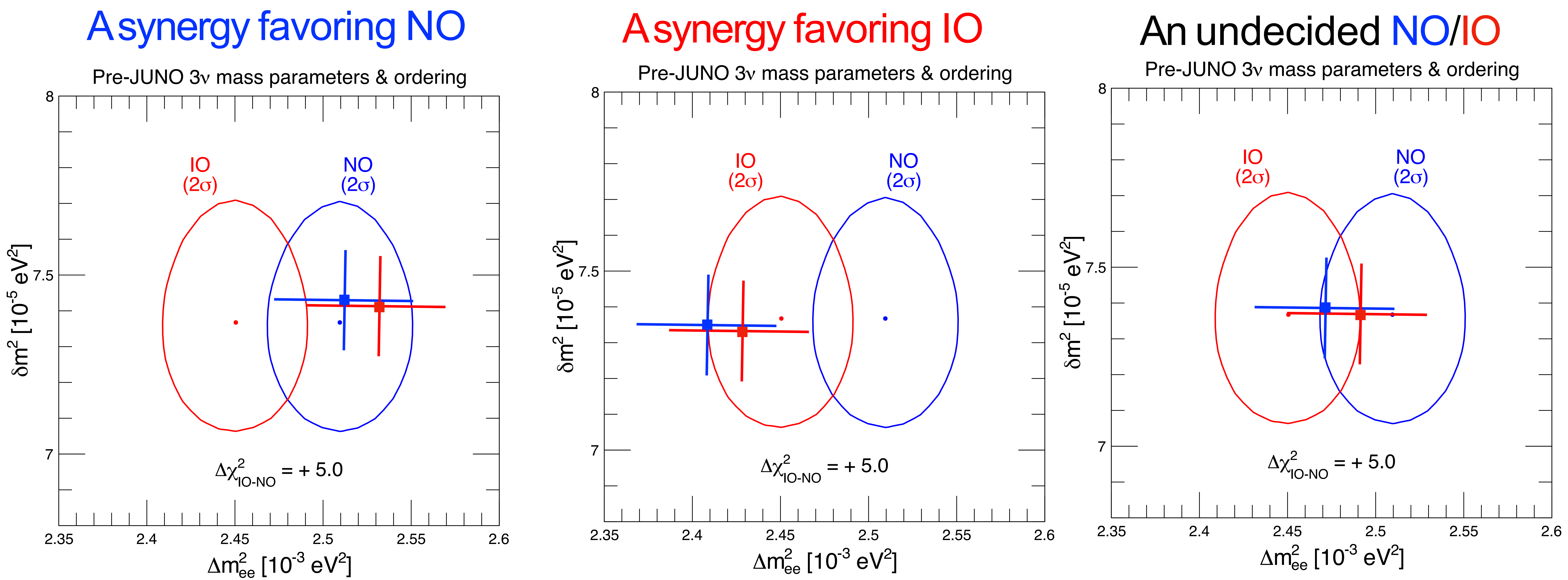
A synergy favoring NO



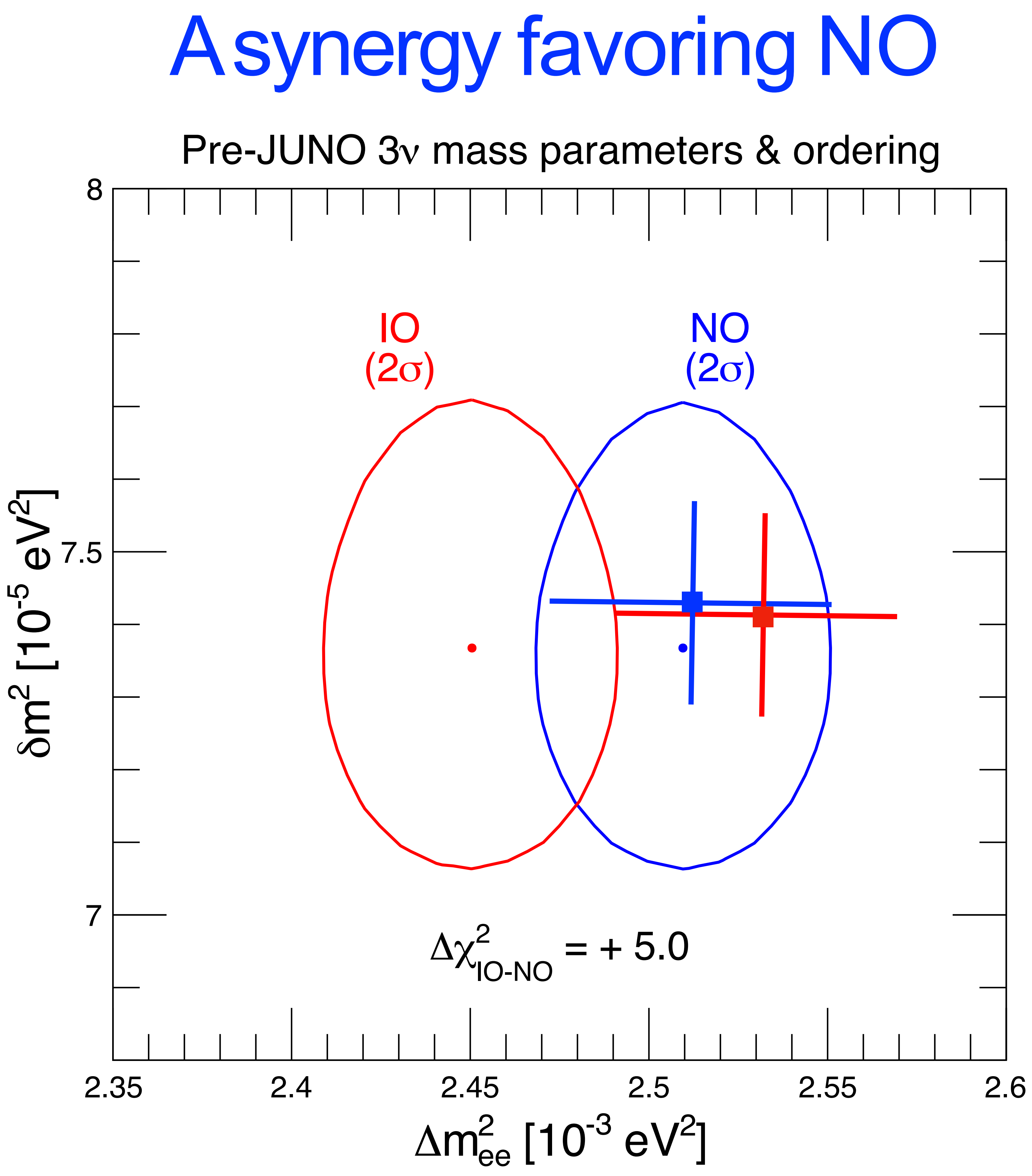
A synergy favoring IO

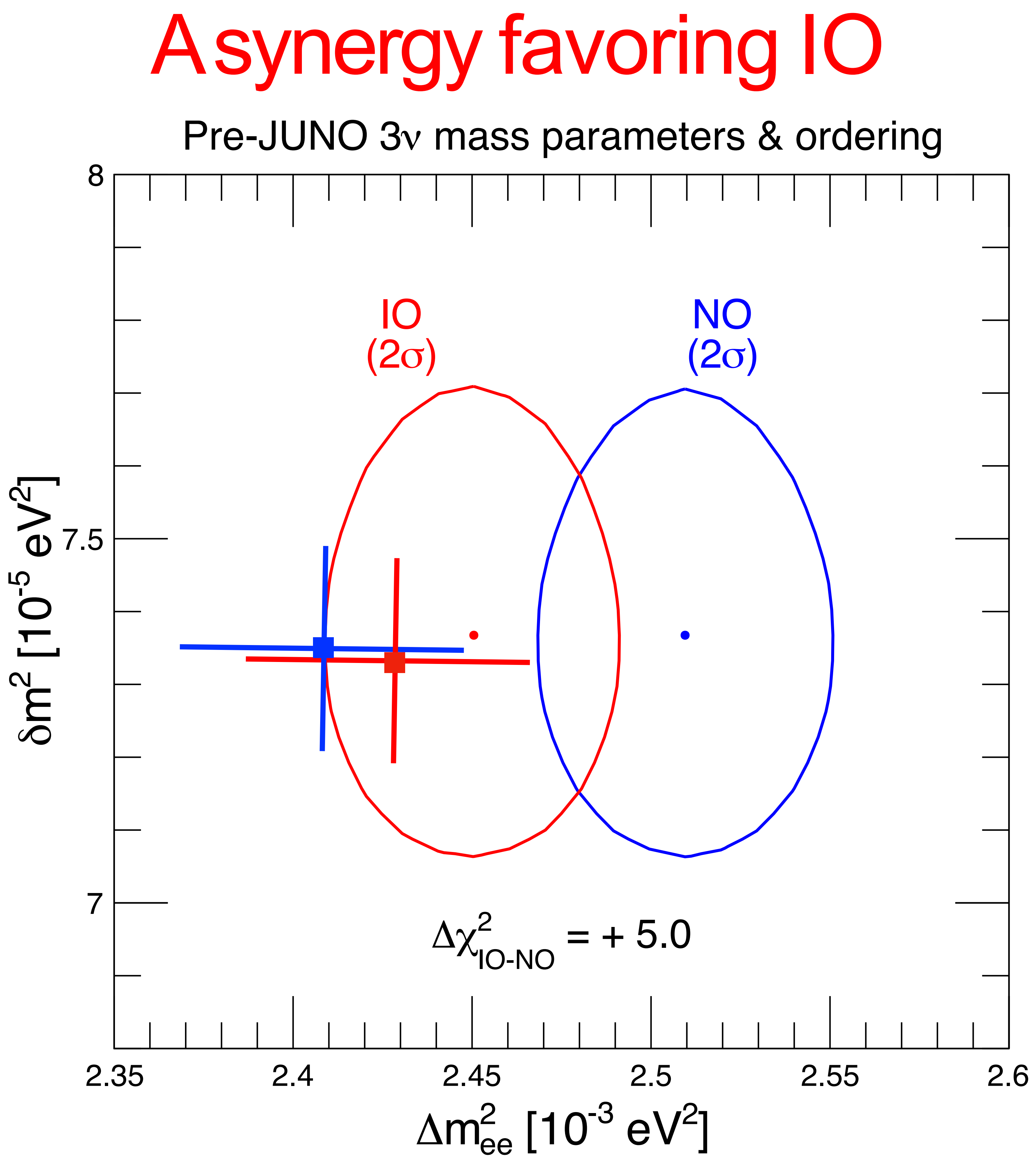


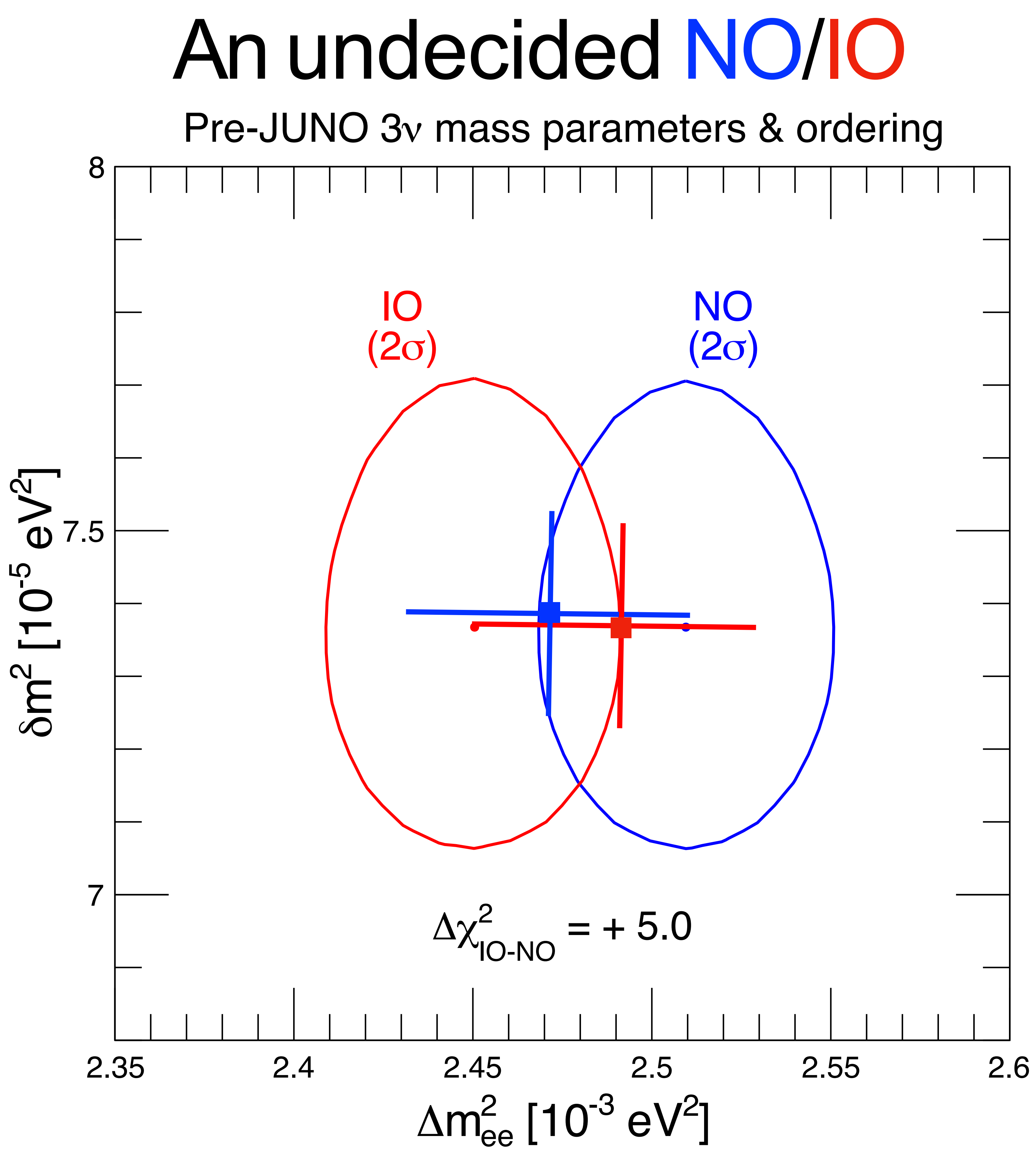
Examples of possible JUNO first data compared with pre-JUNO data



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



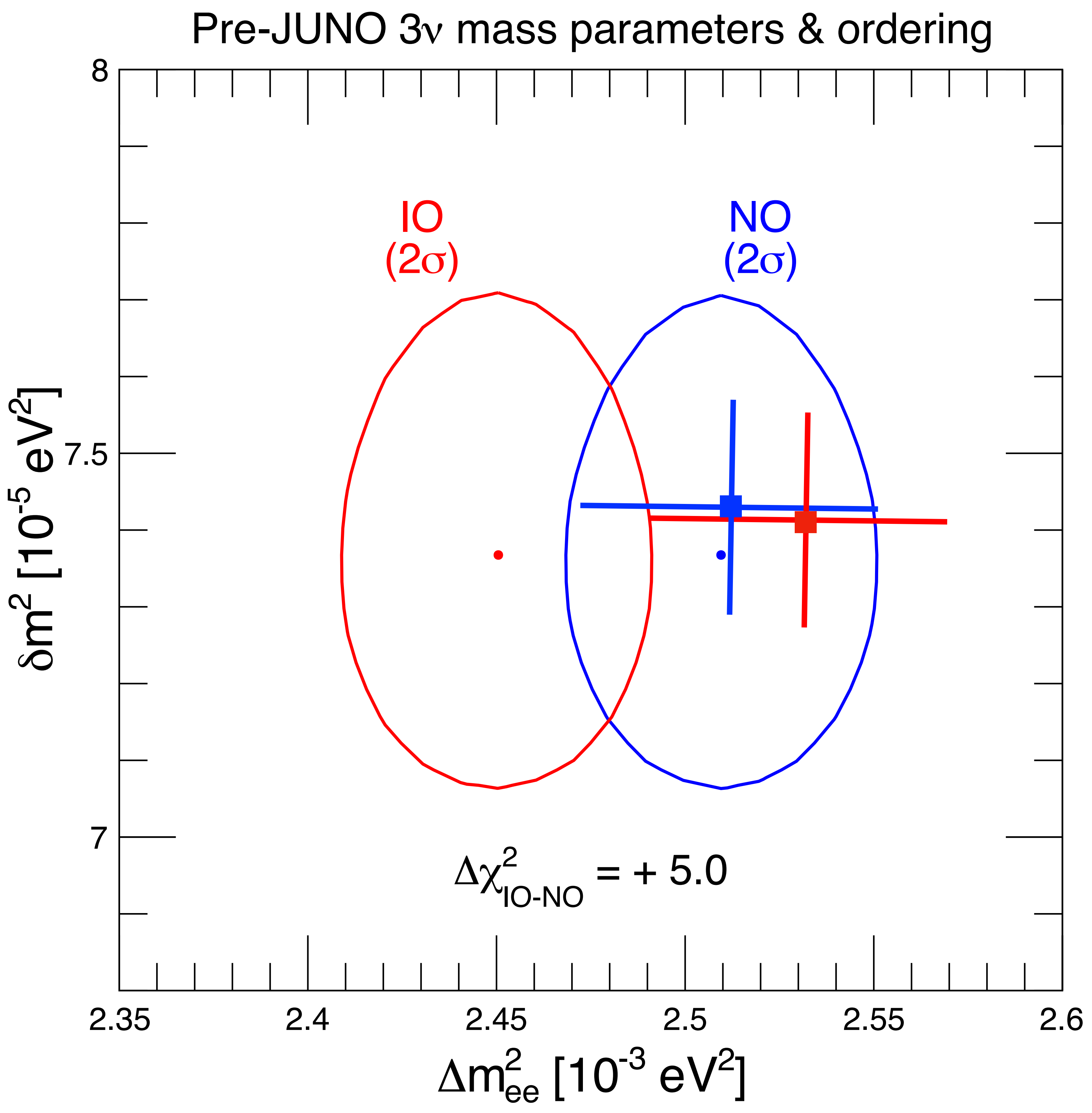




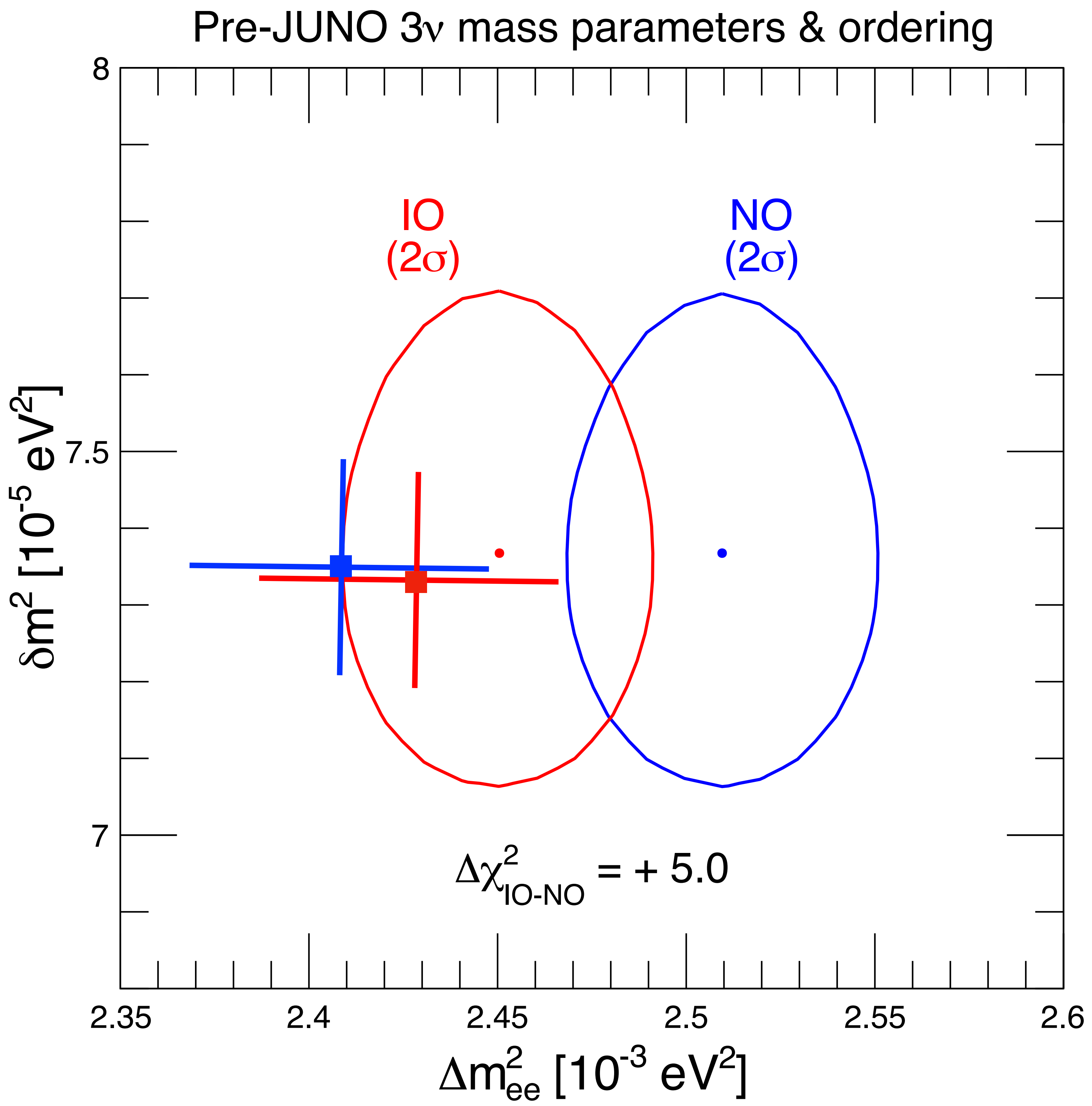
Global analyses helpful to understand correlated impact on other parameters

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

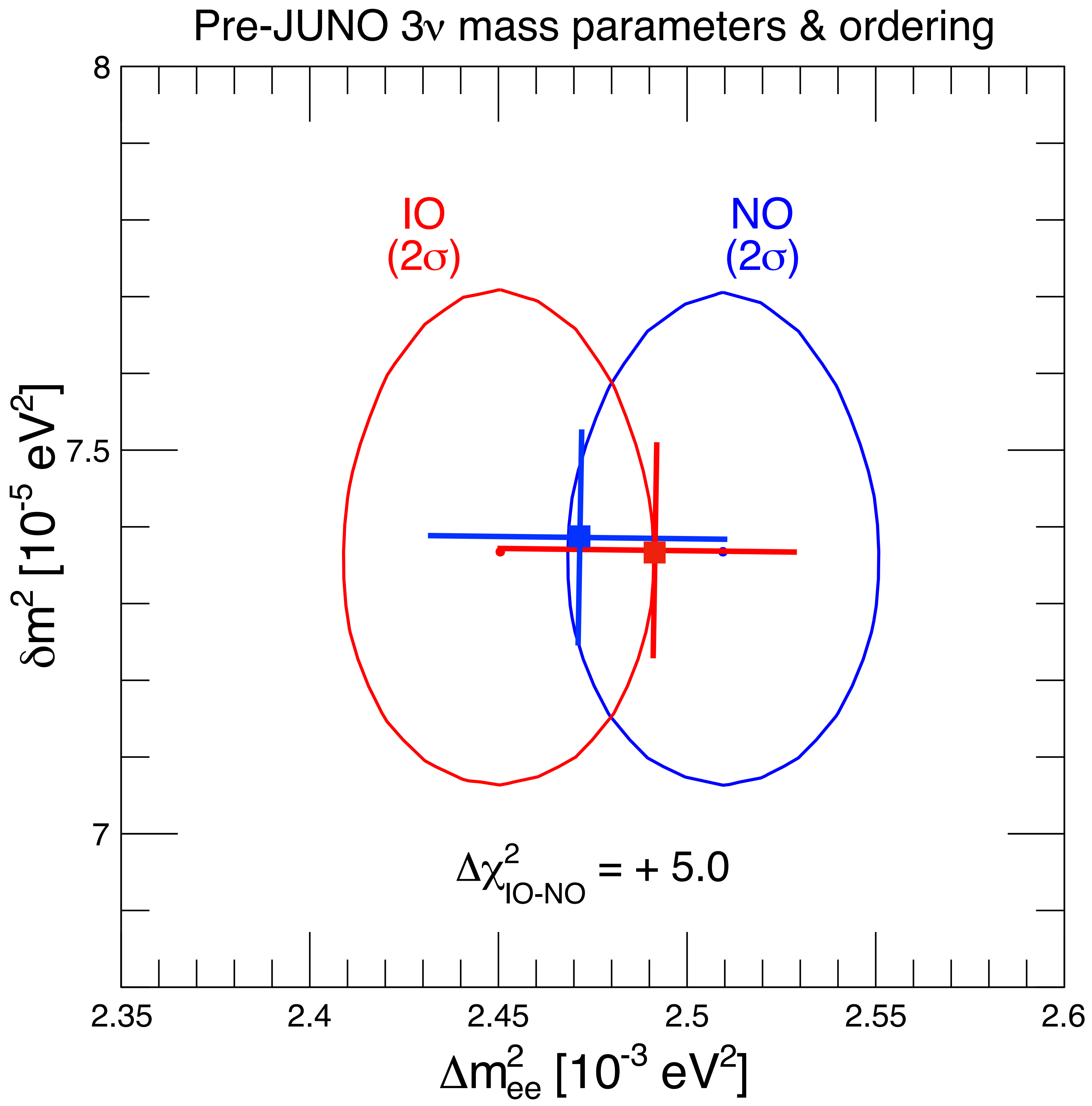
A synergy favoring NO



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.

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

β decay experiments, sensitive to the “effective electron neutrino mass”

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

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

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

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

$0\nu\beta\beta$ decay experiments sensitive to the "Effective Majorana mass":

$$m_{\beta\beta} = |\, c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \,|$$

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

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

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

$0\nu\beta\beta$ decay experiments sensitive to the "Effective Majorana mass":

$$m_{\beta\beta} = |\, c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \,|$$

Cosmology and Astrophysics observations, dominantly sensitive to the sum of neutrino masses:

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

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

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

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

$0\nu\beta\beta$ decay experiments sensitive to the "Effective Majorana mass":

$$m_{\beta\beta} = |\, c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \,|$$

Cosmology and Astrophysics observations, dominantly sensitive to the sum of neutrino masses:

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

These observables may provide handles to distinguish NO/IO

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

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

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

$0\nu\beta\beta$ decay experiments sensitive to the "Effective Majorana mass":

$$m_{\beta\beta} = | c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} |$$

Cosmology and Astrophysics observations, dominantly sensitive to the sum of neutrino masses:

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

These observables may provide handles to distinguish NO/IO

Majorana phases give a new source of CP violation

Three observables $(m_\beta, m_{\beta\beta}, \Sigma)$ sensitive to the absolute ν masses

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

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

$0\nu\beta\beta$ decay experiments sensitive to the "Effective Majorana mass":

$$m_{\beta\beta} = |\, c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3} \,|$$

Cosmology and Astrophysics observations, dominantly sensitive to the sum of neutrino masses:

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

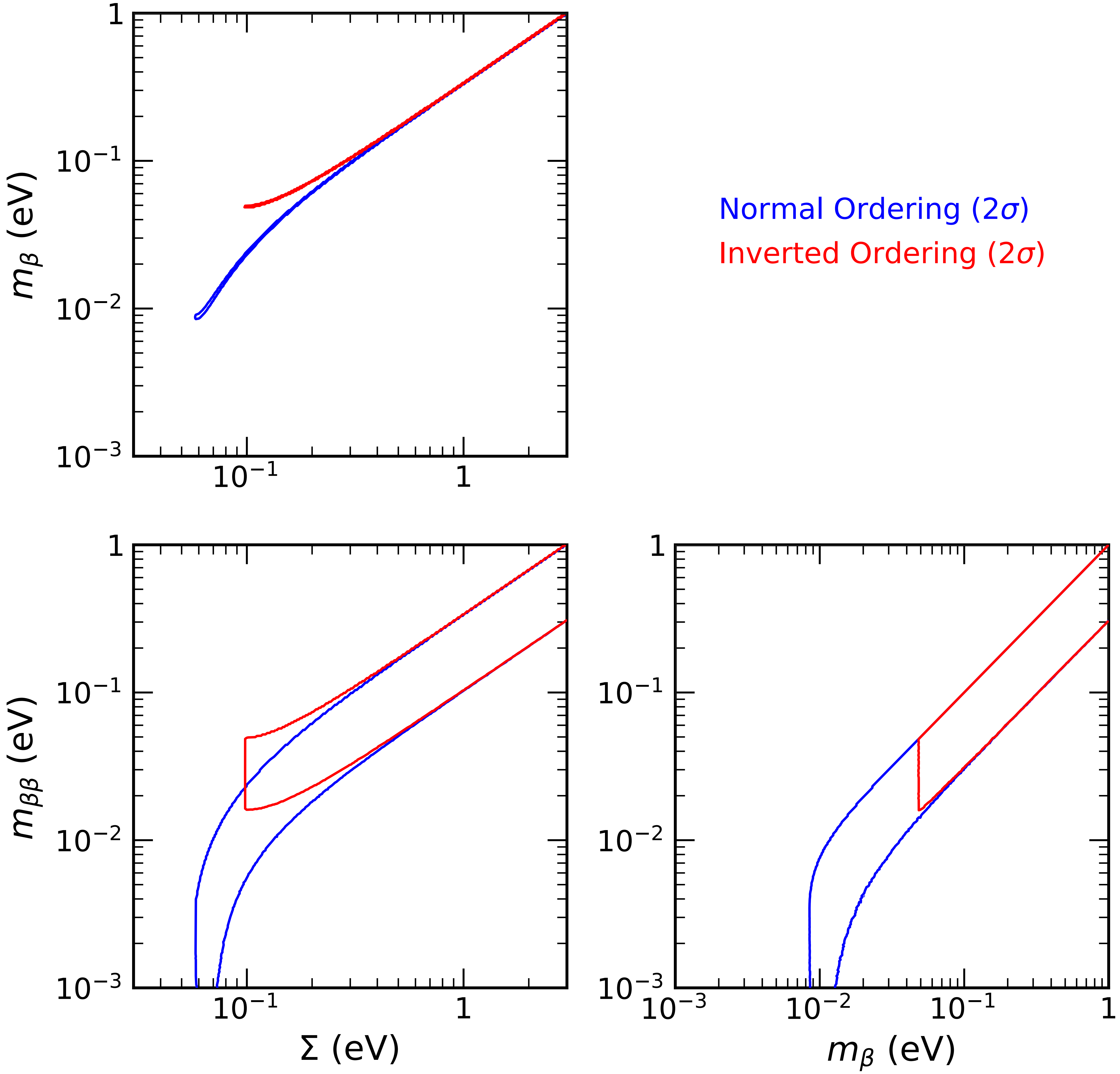
These observables may provide handles to distinguish NO/IO

Majorana phases give a new source of CP violation

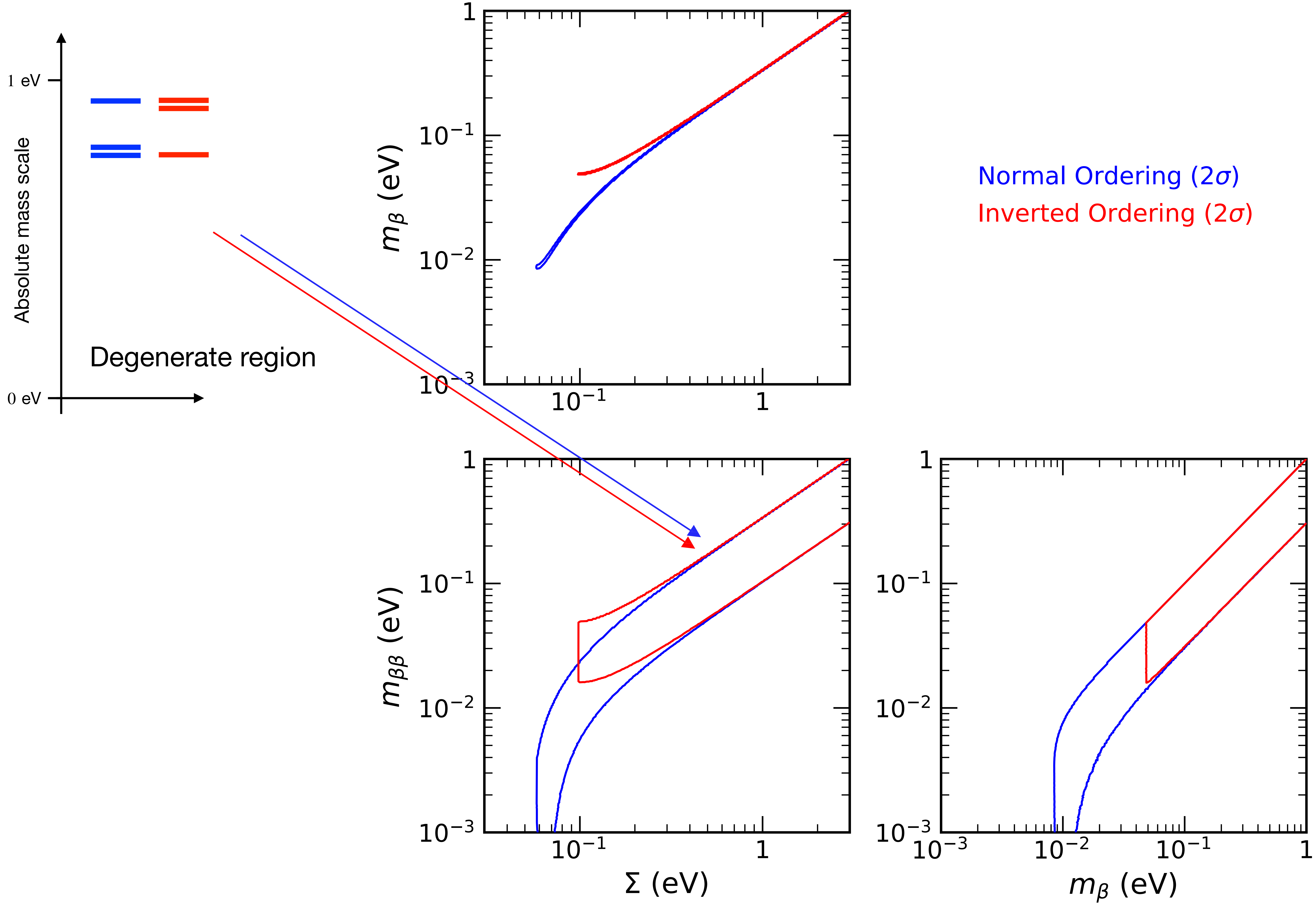
The three observables are correlated by oscillation data →

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

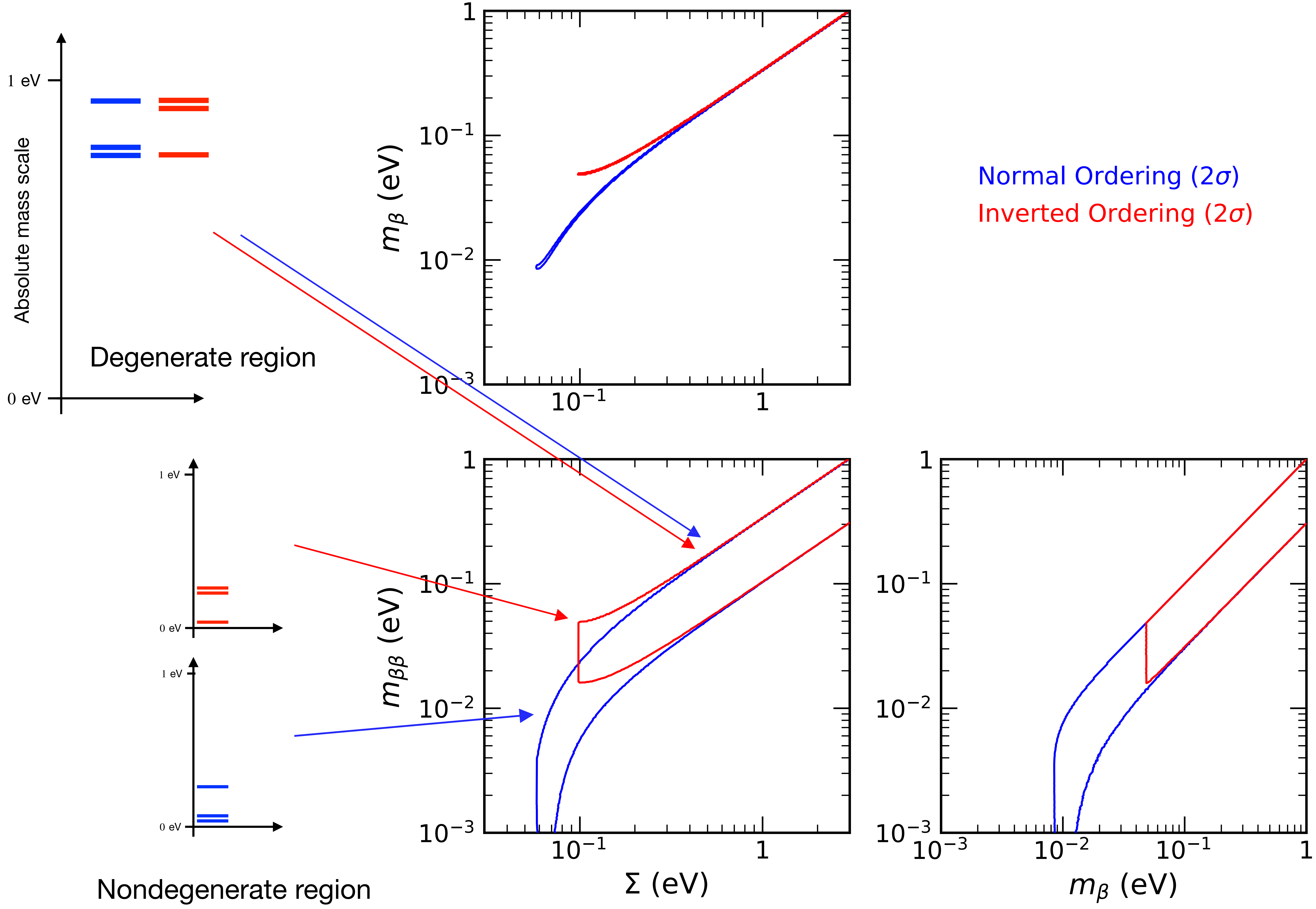
Regions allowed by oscillations on $(\Sigma, m_\beta, m_{\beta\beta})$



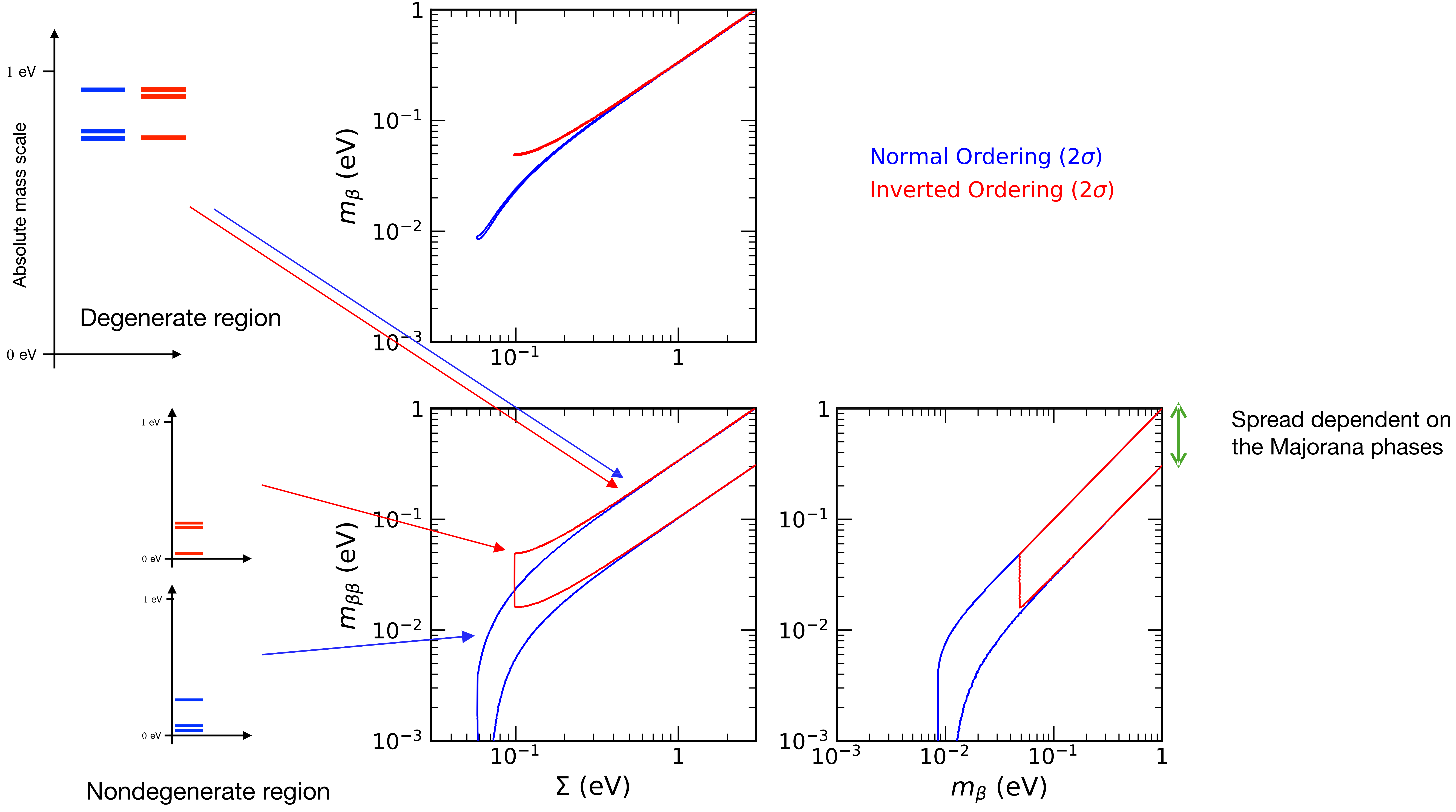
Regions allowed by oscillations on $(\Sigma, m_\beta, m_{\beta\beta})$



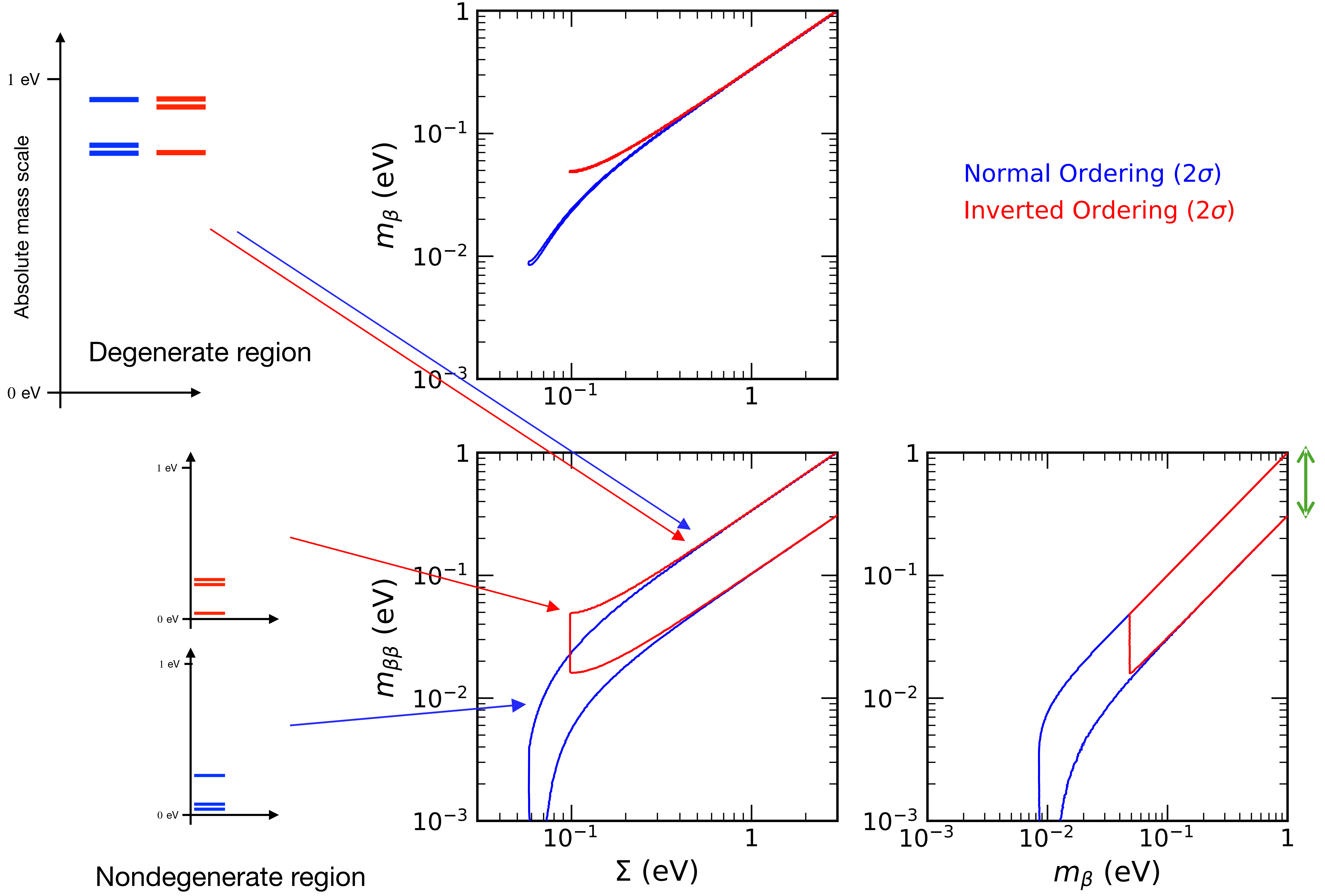
Regions allowed by oscillations on $(\Sigma, m_\beta, m_{\beta\beta})$



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

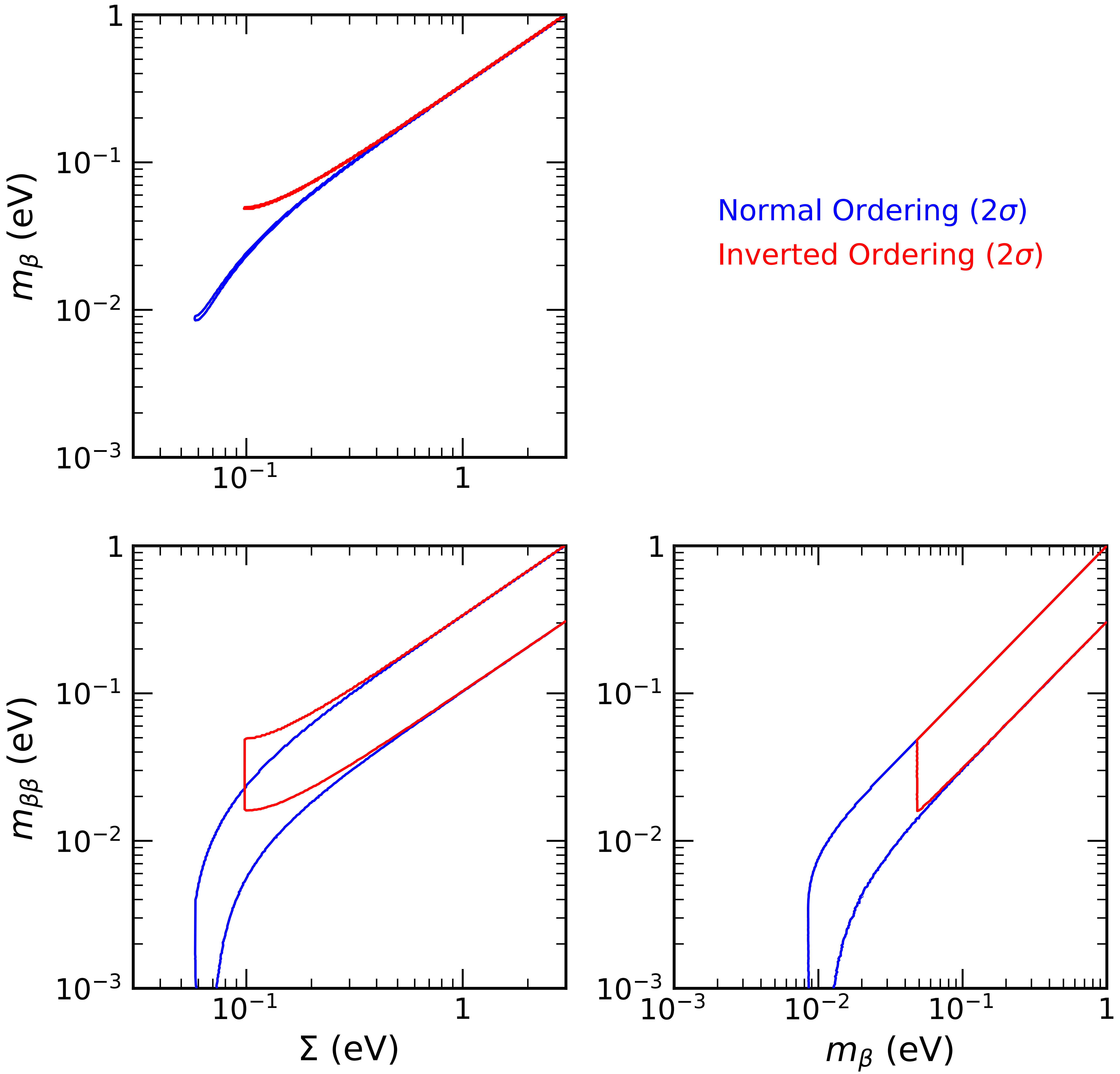


Regions allowed by oscillations on $(\Sigma, m_\beta, m_{\beta\beta})$

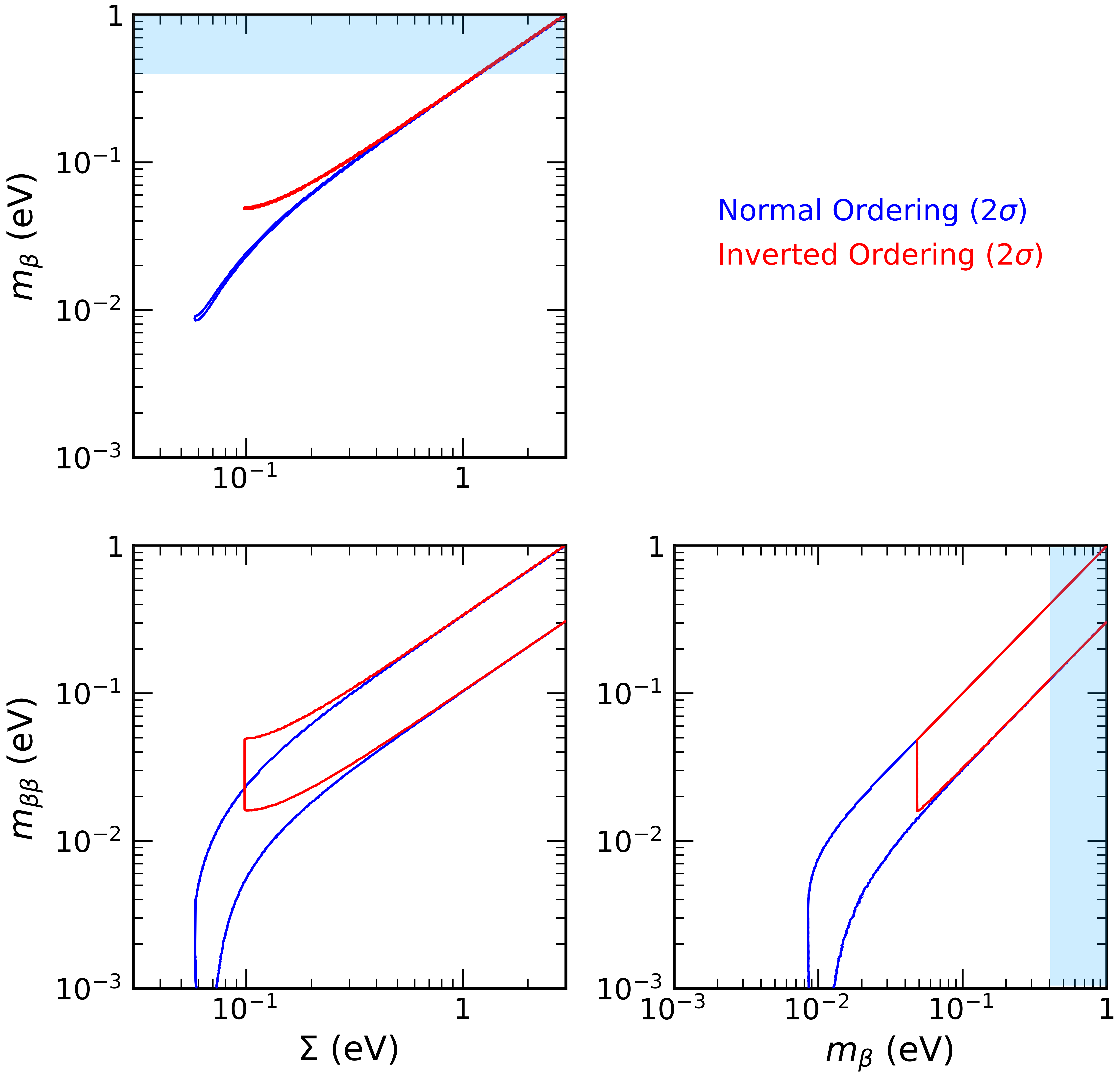


Spread dependent on the Majorana phases

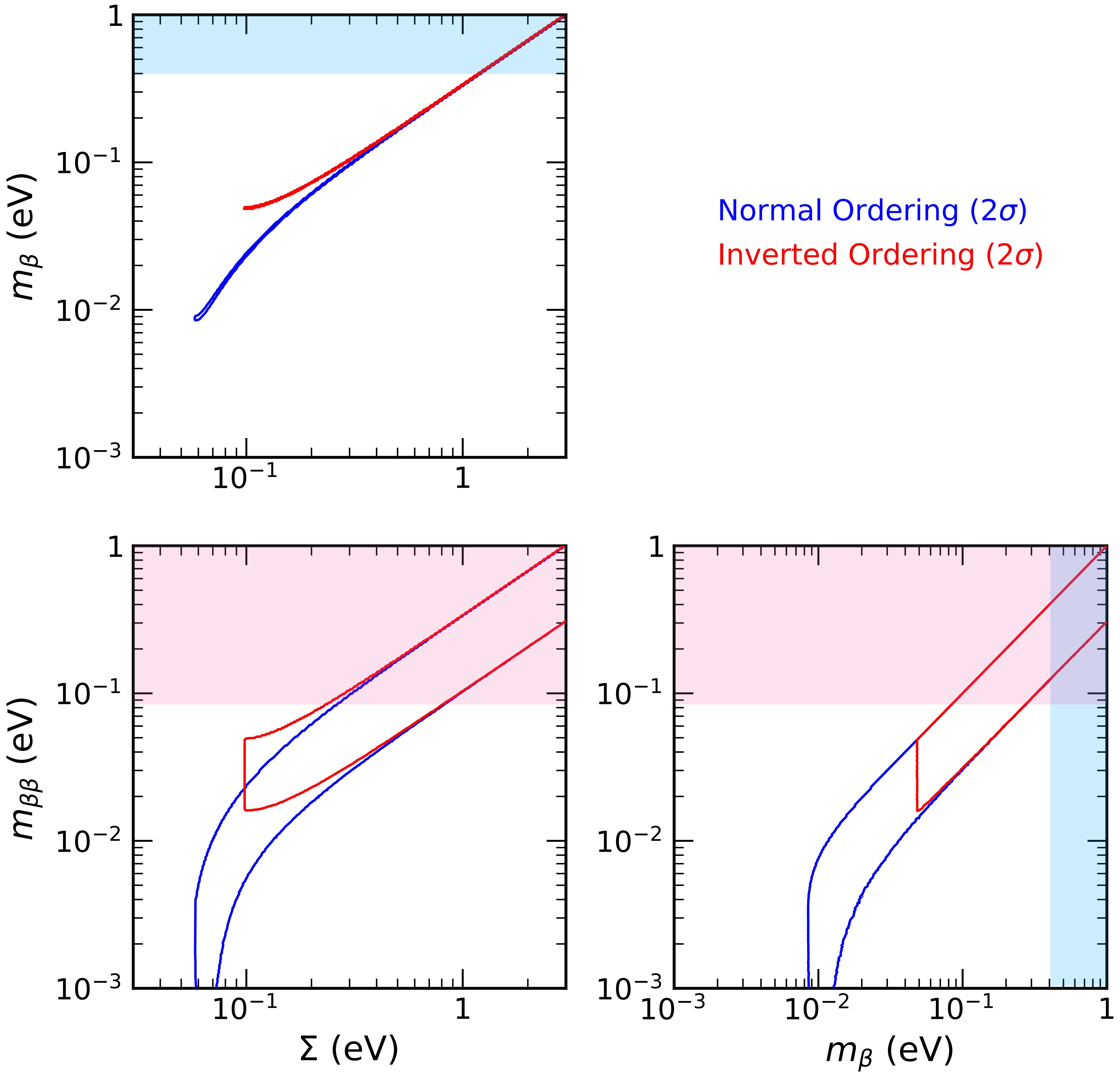
In principle can be measured if NME under control



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



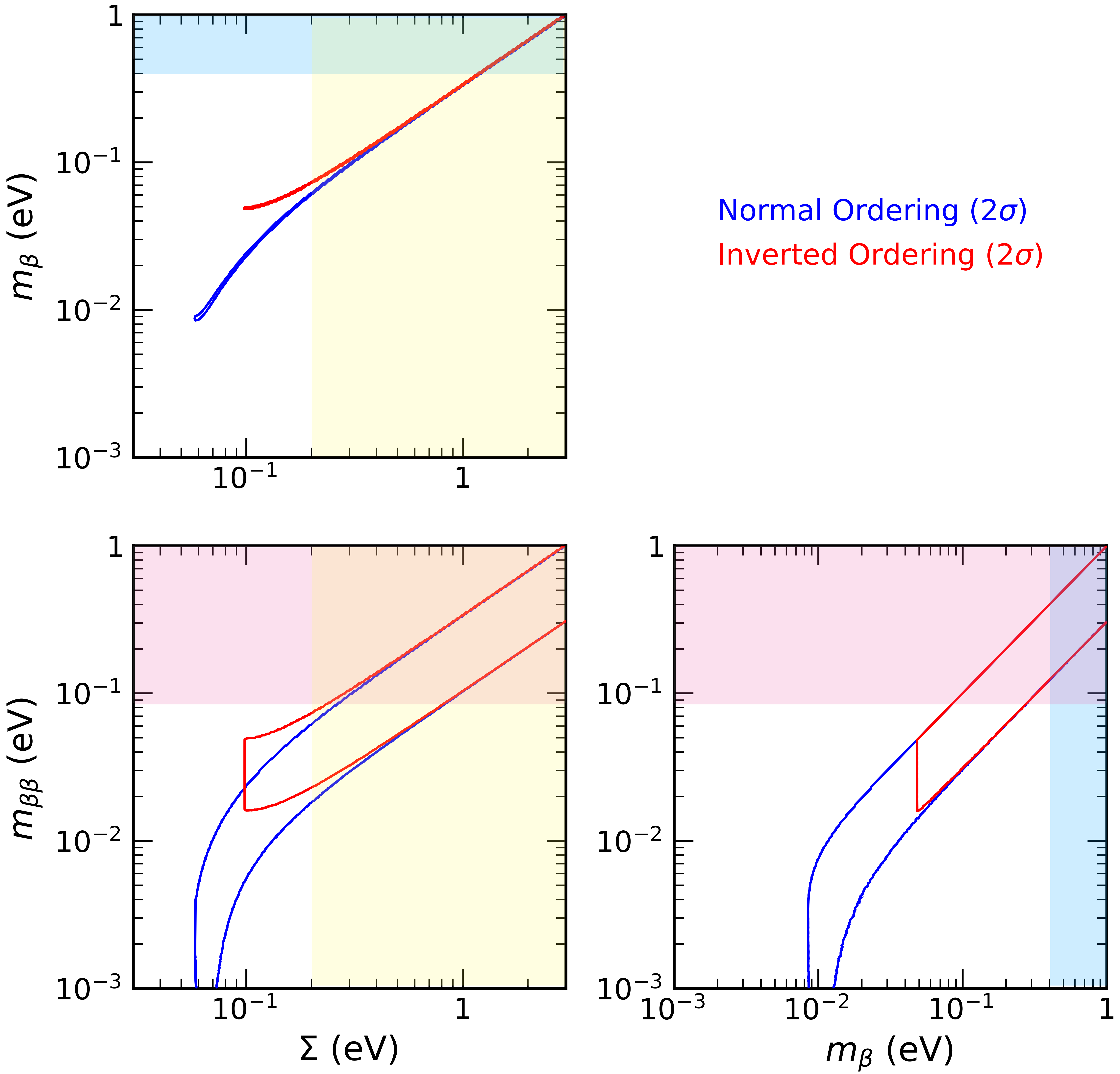
β decay - KATRIN



β decay - KATRIN

$0\nu\beta\beta$ decay

KamLAND-Zen, EXO, CUORE, GERDA



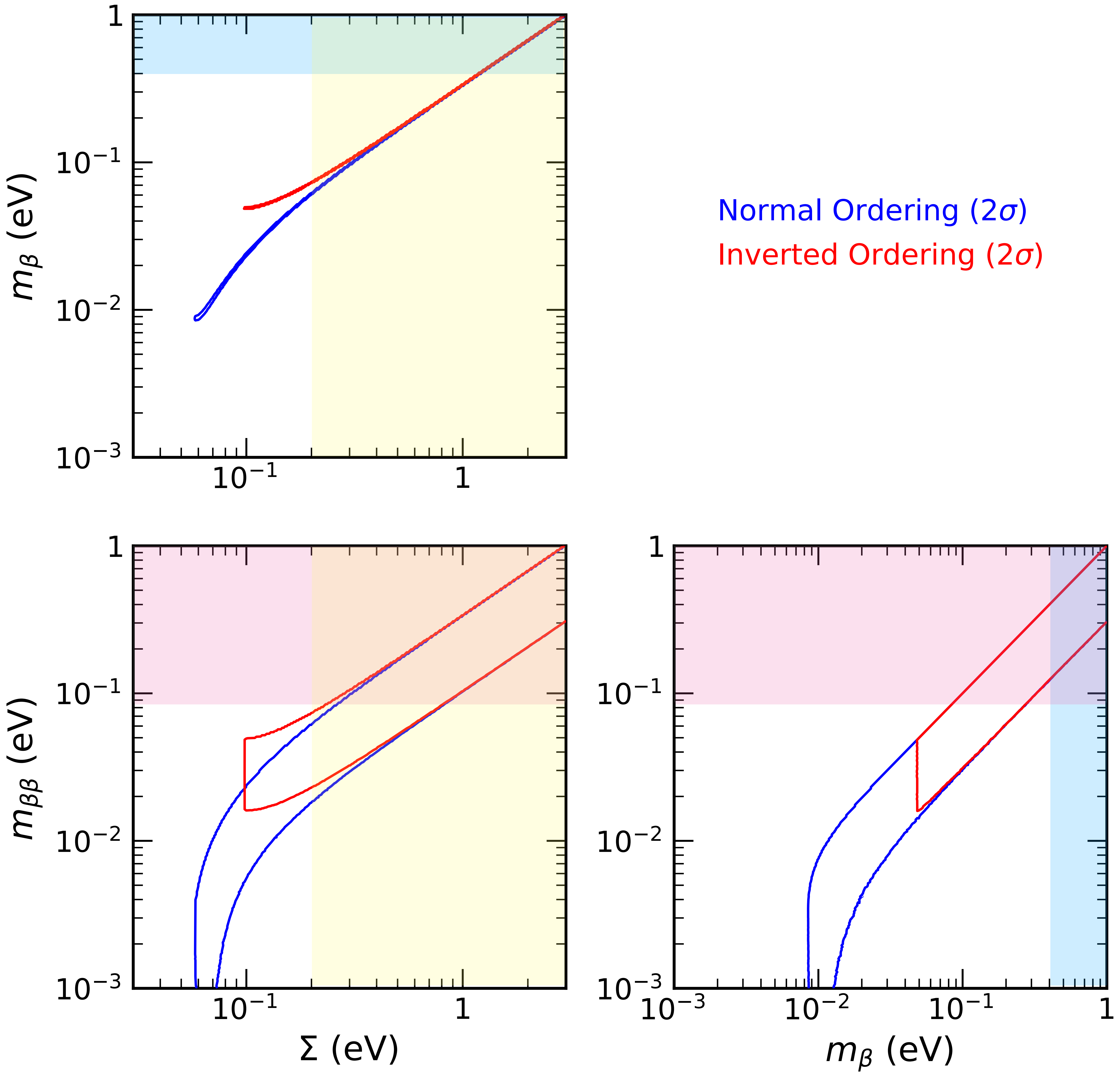
β decay - KATRIN

$0\nu\beta\beta$ decay

KamLAND-Zen, EXO, CUORE, GERDA

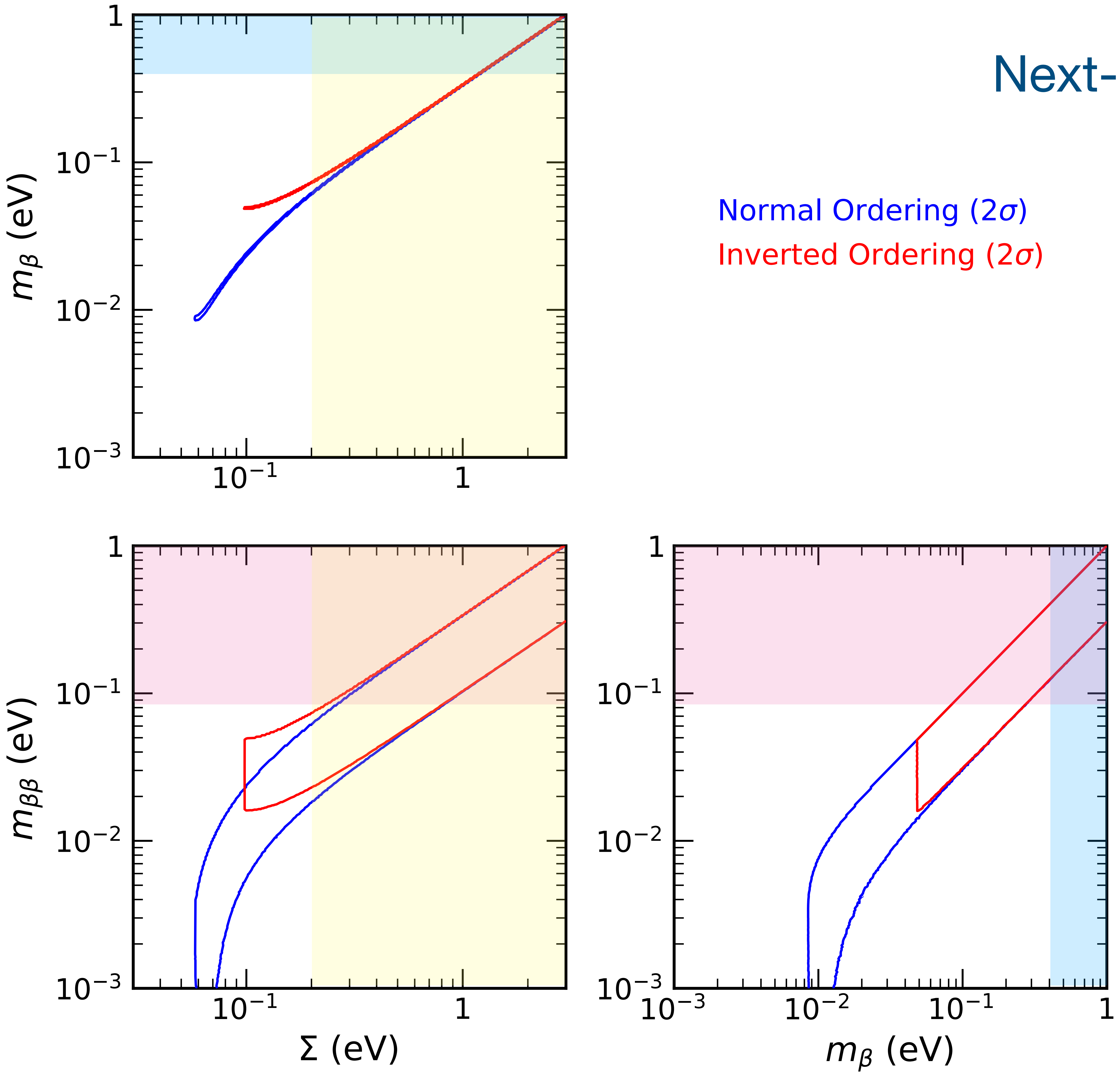
Astrophysics and Cosmology

CMB, BAO, lensing, …

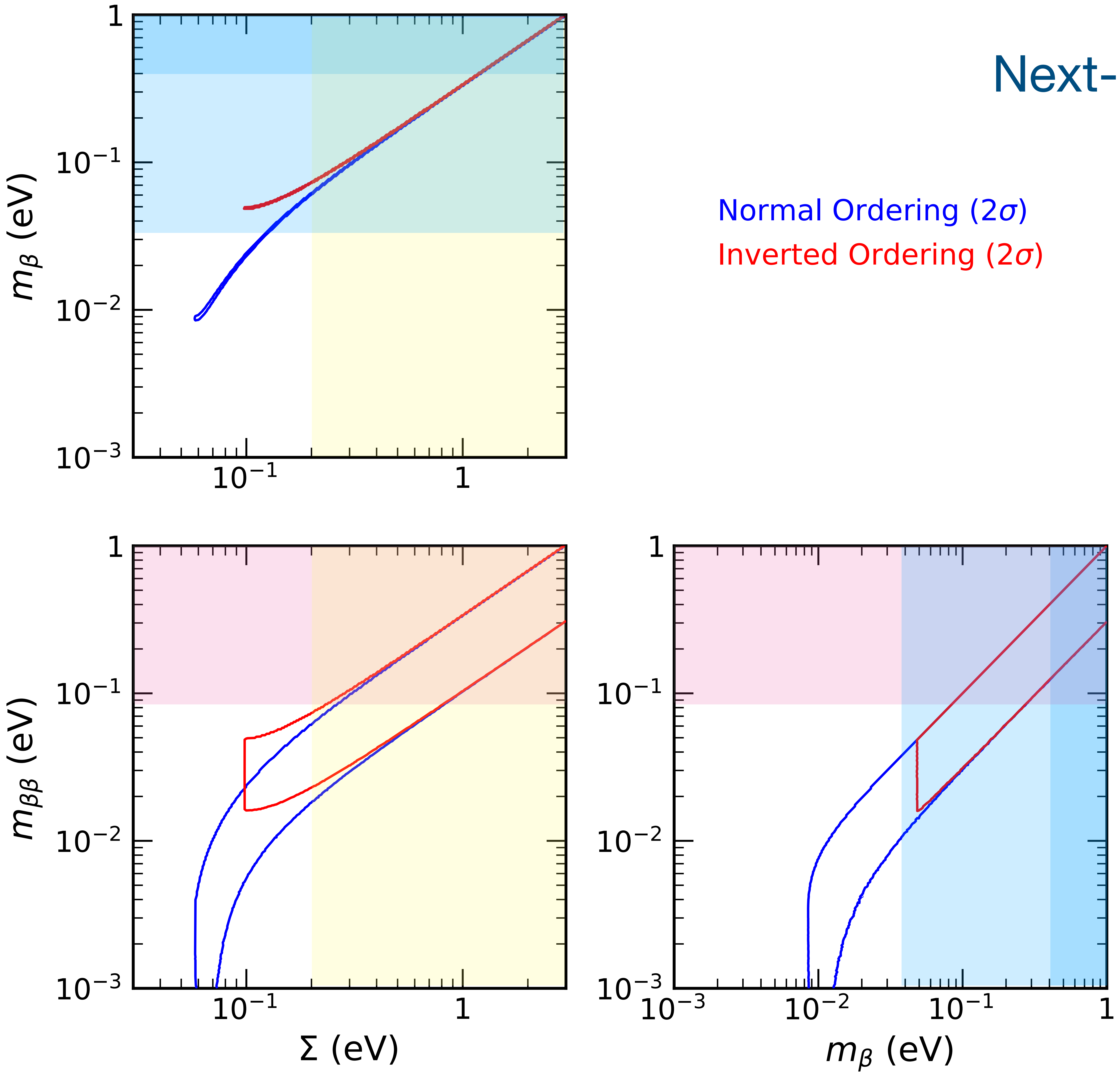


Normal Ordering (2σ)
Inverted Ordering (2σ)
m_β (eV)
$m_{\beta\beta}$ (eV)
Σ (eV)
m_β (eV)

Next-generation Projects ($\gtrsim$10 years)



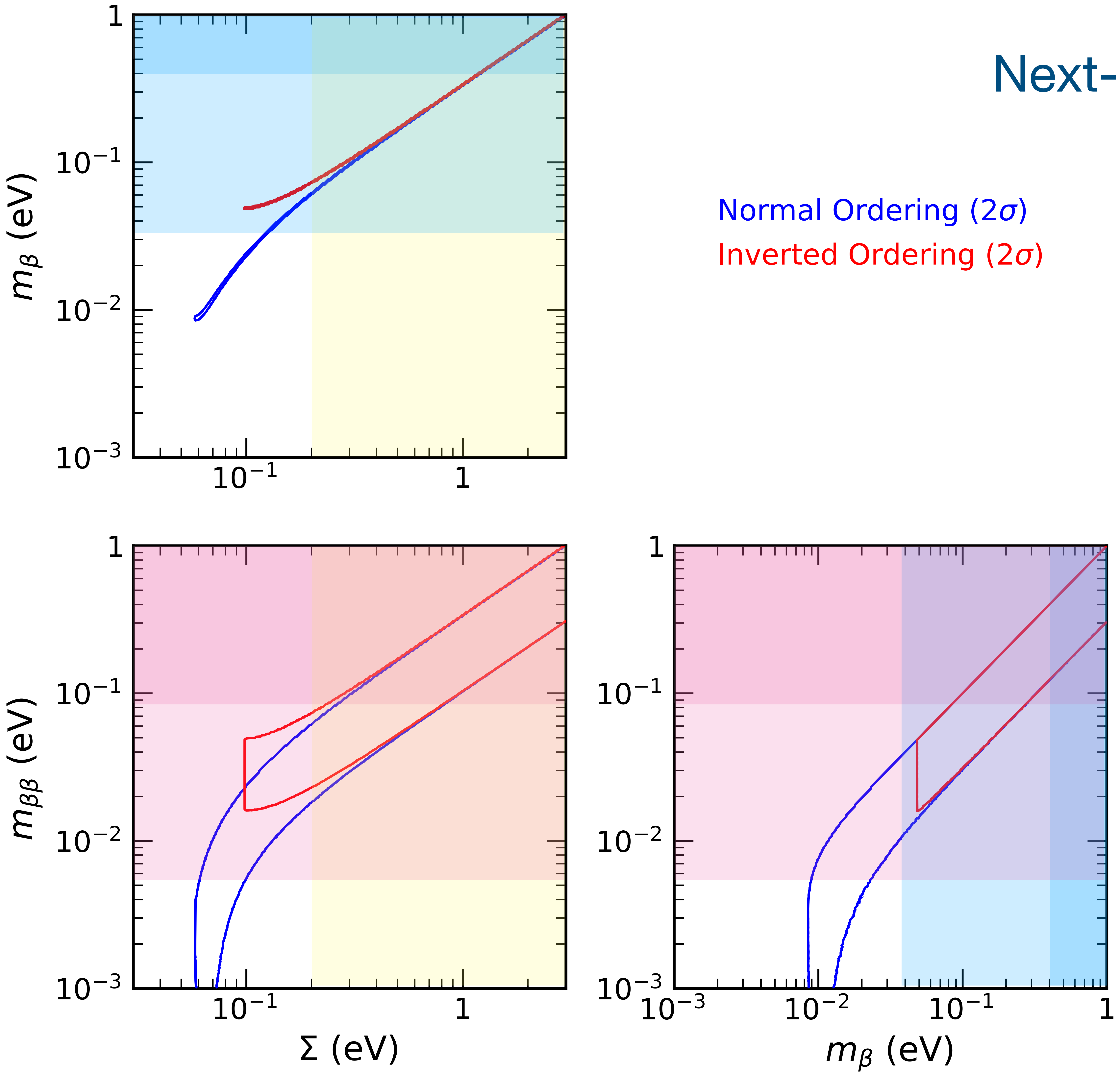
Next-generation Projects (≳10 years)



Normal Ordering (2σ)
Inverted Ordering (2σ)

β decay - Project-8, …

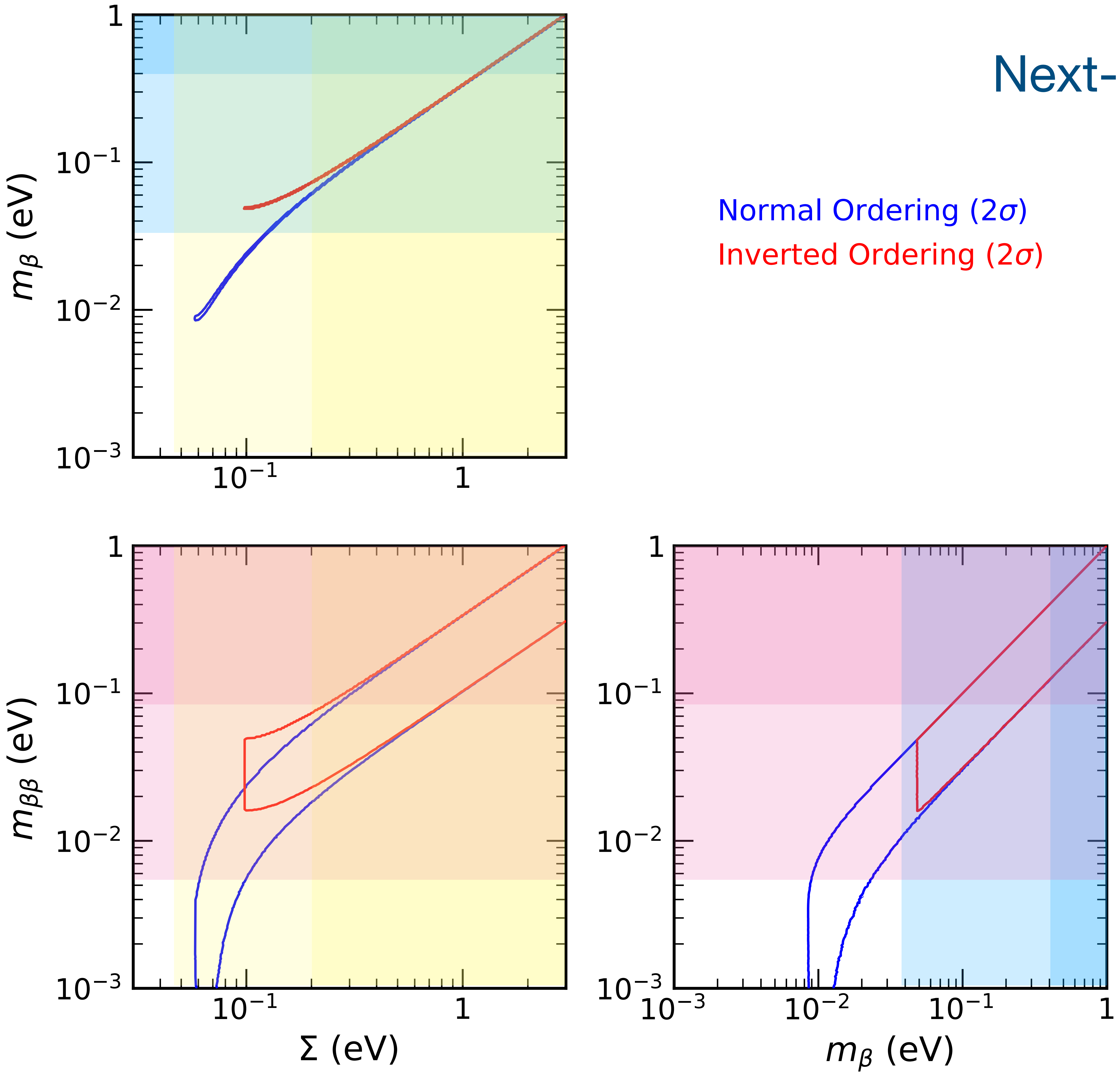
Next-generation Projects ($\gtrsim$10 years)



β decay - Project-8, …

$0\nu\beta\beta$ decay
LEGEND, NEXO, CUPID, …

Next-generation Projects (≳10 years)



Normal Ordering (2σ)

Inverted Ordering (2σ)

β decay - Project-8, …

$0\nu\beta\beta$ decay

LEGEND, NEXO, CUPID, …

Astrophysics and Cosmology

EUCLID, …

Summary and Perspectives

Summary and Perspectives

- **Precision reached**

Mixing angles and mass splittings well measured, with $|\Delta m^2|$ at **subpercent accuracy (0.8%)**

Summary and Perspectives

•**Precision reached**

Mixing angles and mass splittings well measured, with $|\Delta m^2|$ at **subpercent accuracy (0.8%)**

•**Oscillation unknowns**

Mass ordering, θ_{23} octant, CP phase δ_{CP} → still open, hints weak (≤ 2.2σ)

Summary and Perspectives

•Precision reached

Mixing angles and mass splittings well measured, with $|\Delta m^2|$ at **subpercent accuracy (0.8%)**

•Oscillation unknowns

Mass ordering, θ_{23} octant, CP phase δ_{CP} → still open, hints weak ($\leq 2.2\sigma$)

•Absolute masses

Current limits: $m_\beta \leq 0.50$ eV, $m_{\beta\beta} \leq 0.086$ eV, $\Sigma \leq 0.2$ eV (cosmology uncertain)

Summary and Perspectives

•Precision reached

Mixing angles and mass splittings well measured, with $|\Delta m^2|$ at **subpercent accuracy (0.8%)**

•Oscillation unknowns

Mass ordering, θ_{23} octant, CP phase δ_{CP} → still open, hints weak ($\leq 2.2\sigma$)

•Absolute masses

Current limits: $m_\beta \leq 0.50$ eV, $m_{\beta\beta} \leq 0.086$ eV, $\Sigma \leq 0.2$ eV (cosmology uncertain)

•Next steps

JUNO will sharpen $(\delta m^2, \Delta m^2_{ee})$, and test mass ordering with subpercent precision

Summary and Perspectives

- **Precision reached**

Mixing angles and mass splittings well measured, with $|\Delta m^2|$ at **subpercent accuracy (0.8%)**

- **Oscillation unknowns**

Mass ordering, θ_{23} octant, CP phase δ_{CP} → still open, hints weak (≤ 2.2σ)

- **Absolute masses**

Current limits: $m_\beta \leq 0.50$ eV, $m_{\beta\beta} \leq 0.086$ eV, $\Sigma \leq 0.2$ eV (cosmology uncertain)

- **Next steps**

JUNO will sharpen $(\delta m^2, \Delta m^2_{ee})$, and test mass ordering with subpercent precision

- **Outlook**

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