Status of 3-neutrino mass-mixing parameters

based on (Prog. Part. Nucl. Phys. 102 (2018) 48, Phys. Rev. D 95 (2017) no.9, 096014) + **oscillation update 2019**
in collaboration with E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo

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Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

$$\theta_{12}, \theta_{13}, \theta_{23}$$

3 mixing angles

Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

$\theta_{12}, \theta_{13}, \theta_{23}$	3 mixing angles
$\boldsymbol{\delta}$	**1 Dirac phase**

CP violation if $\boldsymbol{\delta \neq 0,\pi}$

Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

θ_{12}, θ_{13}, θ_{23}	3 mixing angles
δ	**1 Dirac phase**

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij} \qquad c_{ij} = \cos\theta_{ij}$$

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha,i}|\nu_i\rangle$$

Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

$\theta_{12}, \theta_{13}, \theta_{23}$	3 mixing angles
δ	1 Dirac phase
$\Delta m^2, \delta m^2$	**2 mass differences**

$$\Delta m^2 = m^2_3 - (m^2_2 + m^2_1)/2$$

atmospheric
mass difference

$$\delta m^2 = m^2_2 - m^2_1 > 0$$

solar
mass difference

Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

θ_{12}, θ_{13}, θ_{23}	3 mixing angles
δ	1 Dirac phase
Δm^2, δm^2	2 mass differences
mass ordering	

Normal mass ordering (**NO**): $m_3 > m_2 > m_1$ and $\Delta m^2 > 0$

Inverted mass ordering (**IO**): $m_2 > m_1 > m_3$ and $\Delta m^2 < 0$

Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

$\theta_{12}, \theta_{13}, \theta_{23}$	3 mixing angles
δ	1 Dirac phase
$\Delta m^2, \delta m^2$	2 mass differences
mass ordering	
α_1, α_2	**2 Majorana phases**

Neutrino mass-mixing: an overview

In a 3-neutrino framework we have 10 mass and mixing parameters

$\theta_{12}, \theta_{13}, \theta_{23}$	3 mixing angles
δ	1 Dirac phase
$\Delta m^2, \delta m^2$	2 mass differences
mass ordering	
α_1, α_2	2 Majorana phases
$\mathbf{m_0}$	**absolute mass scale**

Neutrino mass-mixing: an overview

What **we know** and what **we do not know**

θ_{12}, θ_{13}, θ_{23}

Δm^2, δm^2

Precision era ($< 5\%$)

δ

mass ordering

α_1, α_2

m_0

Neutrino mass-mixing: an overview

What **we know** and what **we do not know**

- θ_{12}, θ_{13}, θ_{23} ✓
- Δm^2, δm^2 ✓

→ Precision era (< 5%)

- δ ✗ ✓
- mass ordering ✗ ✓

→ Only hints

- α_1, α_2
- m_0

Neutrino mass-mixing: an overview

What **we know** and what **we do not know**

- θ_{12}, θ_{13}, θ_{23}
- Δm^2, δm^2

→ Precision era (< 5%)

- δ
- mass ordering

→ Only hints

- α_1, α_2

→ No information

- m_0

Neutrino mass-mixing: an overview

What **we know** and what **we do not know**

- $\theta_{12}, \theta_{13}, \theta_{23}$ ✓
- $\Delta m^2, \delta m^2$ ✓

→ Precision era (< 5%)

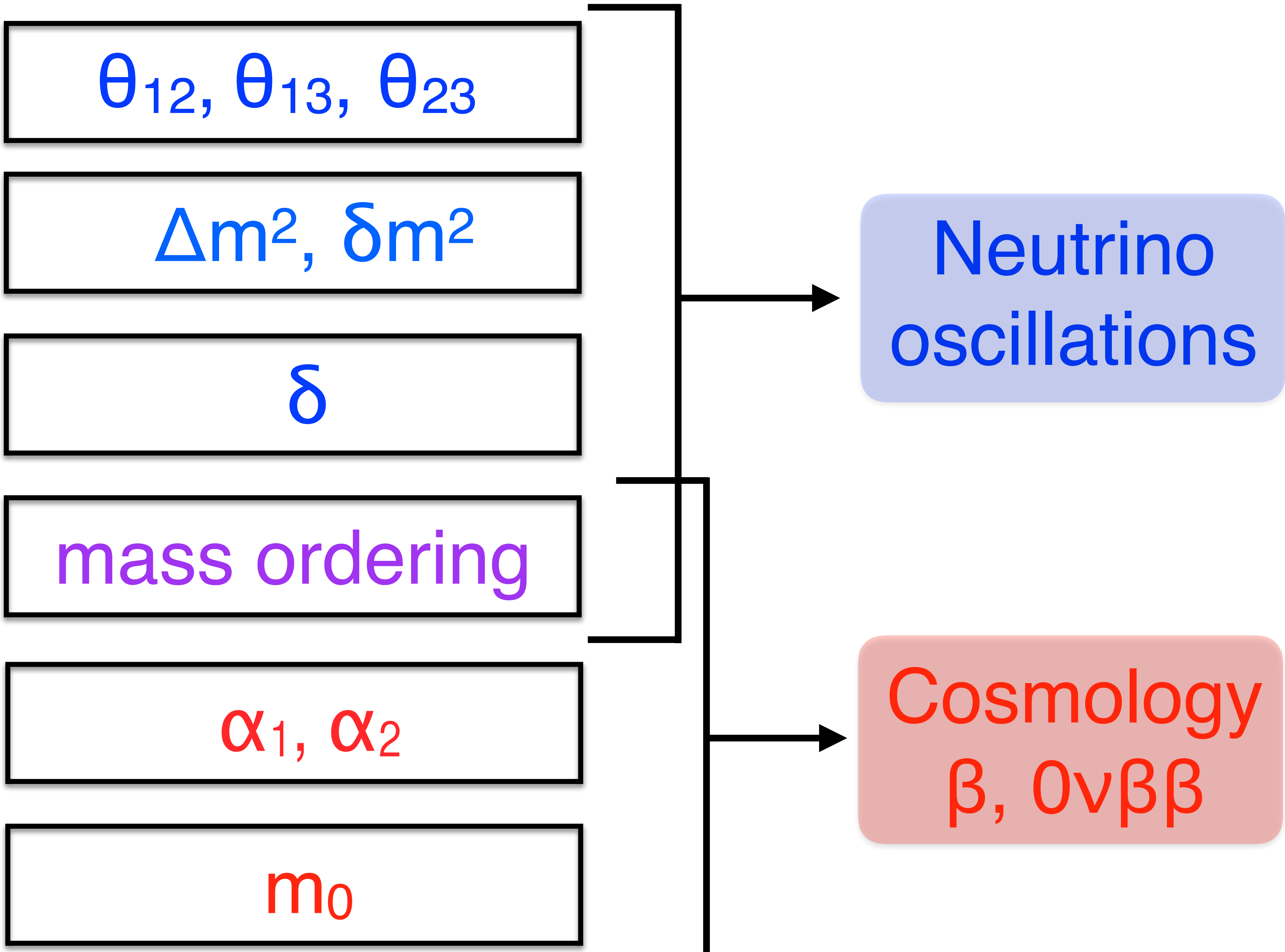
- δ ✗ ✓
- mass ordering ✗ ✓

→ Only hints

- α_1, α_2 ✗ → No information
- m_0 ✗ → Upper limits

Neutrino mass-mixing: an overview

How do we measure the mass-mixing parameters?



Neutrino mass-mixing: an overview

How do we measure the mass-mixing parameters?

- θ_{12}, θ_{13}, θ_{23}
- Δm^2, δm^2
- δ
- mass ordering
- α_1, α_2
- m_0

→ **GLOBAL ANALYSIS**

Global analysis of oscillation data

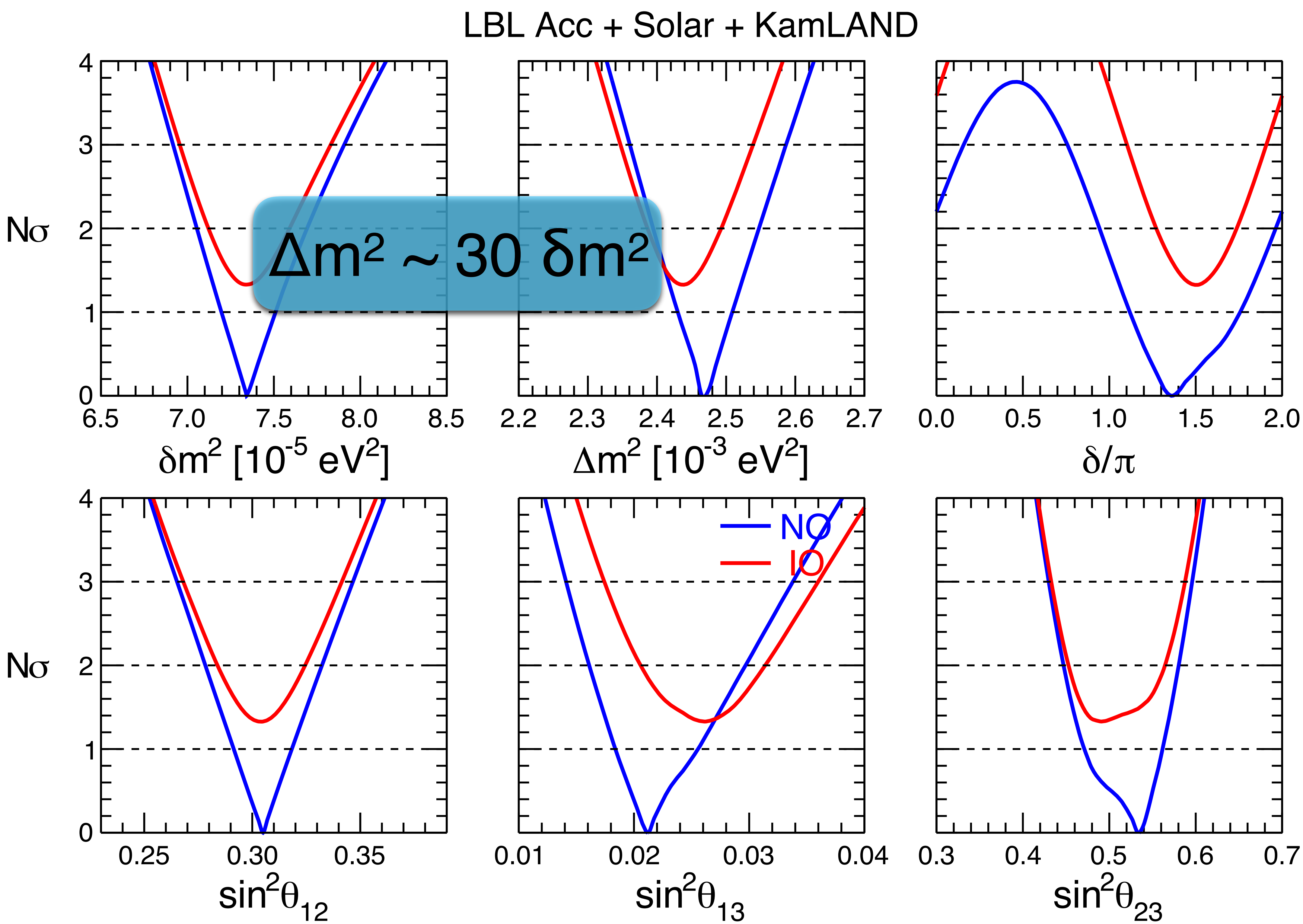
Prog. Part. Nucl. Phys. 102 (2018) 48 + **OSCILLATION UPDATE 2019**
in collaboration with E. Lisi, A. Marrone and A. Palazzo

Global analysis of oscillation data

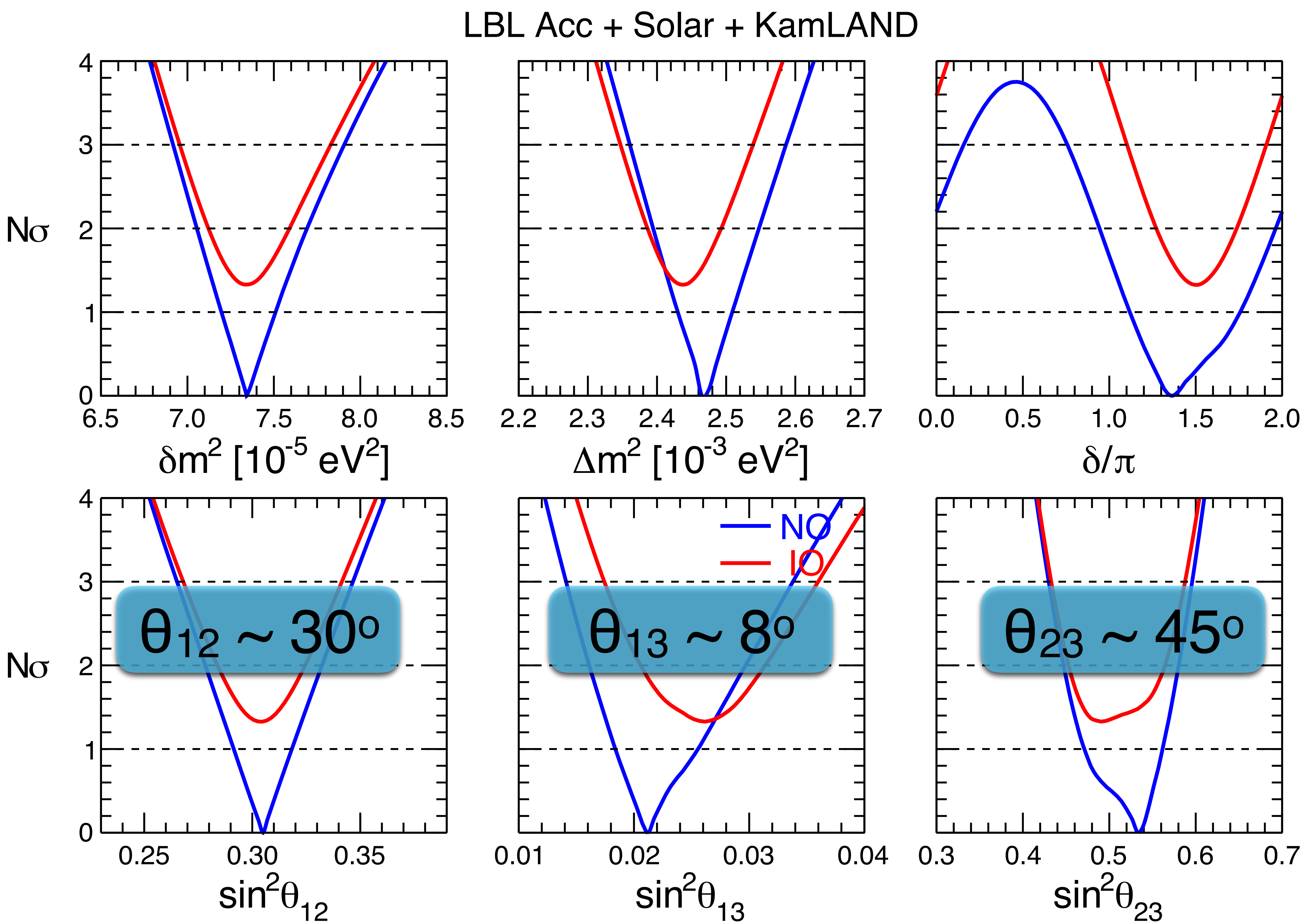
We start from:

Experiment Type	Oscillation Channel(s)	Sensitive to
Solar (Homestake,Gallex,GNO, Borexino,SNO,SK)	$\nu_e \longrightarrow \nu_e$	$(\theta_{12}, \delta m^2, \theta_{13})$
Long baseline reactors (KamLAND)	$\bar{\nu}_e \longrightarrow \bar{\nu}_e$	$(\theta_{12}, \delta m^2, \theta_{13})$
Long baseline accelerator (T2K, NOvA, MINOS)	$\bar{\nu}_\mu \longrightarrow \bar{\nu}_{\mu,e}$ $\nu_\mu \longrightarrow \nu_{\mu,e}$	$(\theta_{23}, \Delta m^2, \delta, \text{MO}, \theta_{13})$

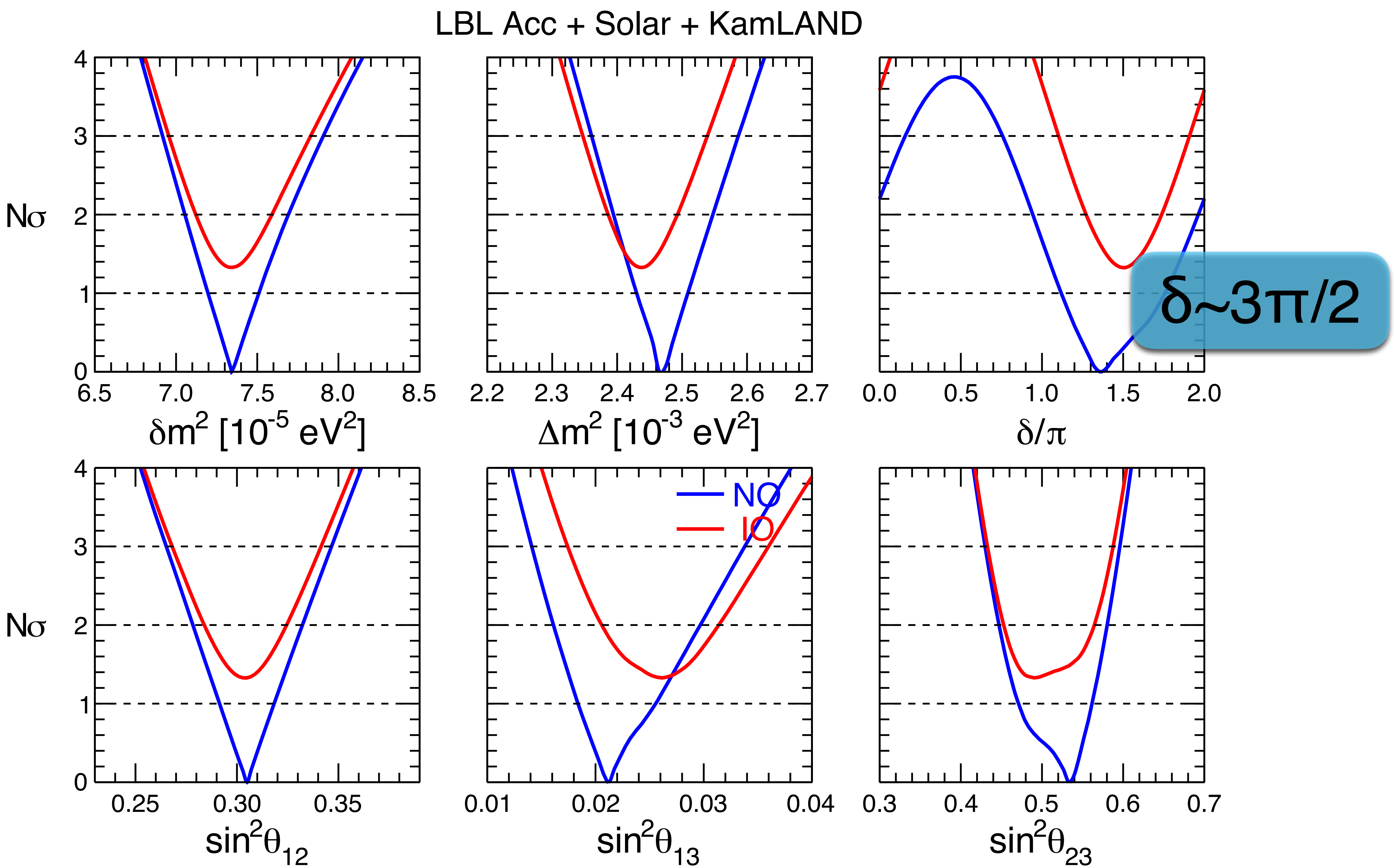
Analysis results: mass differences



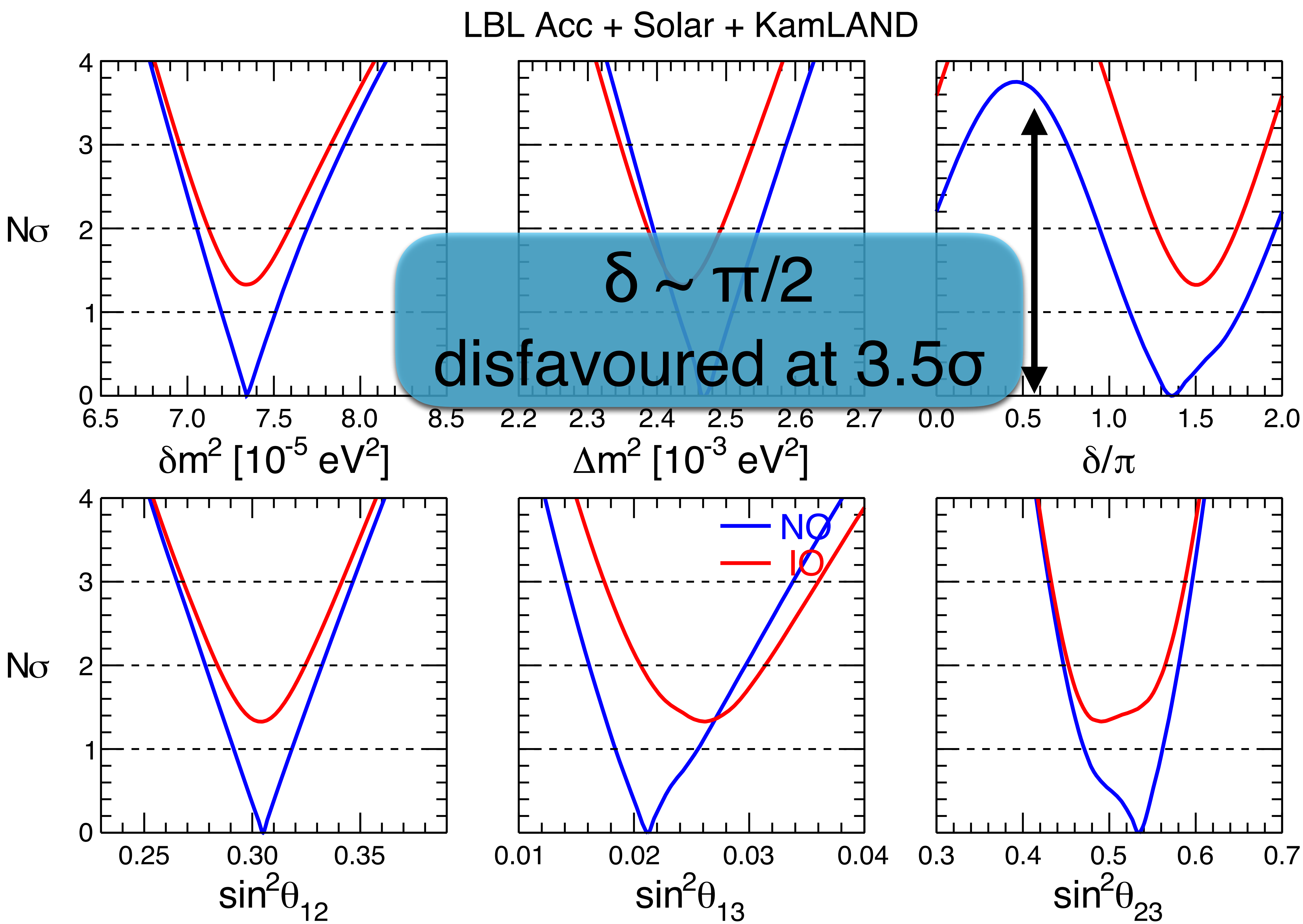
Analysis results: mixing angles



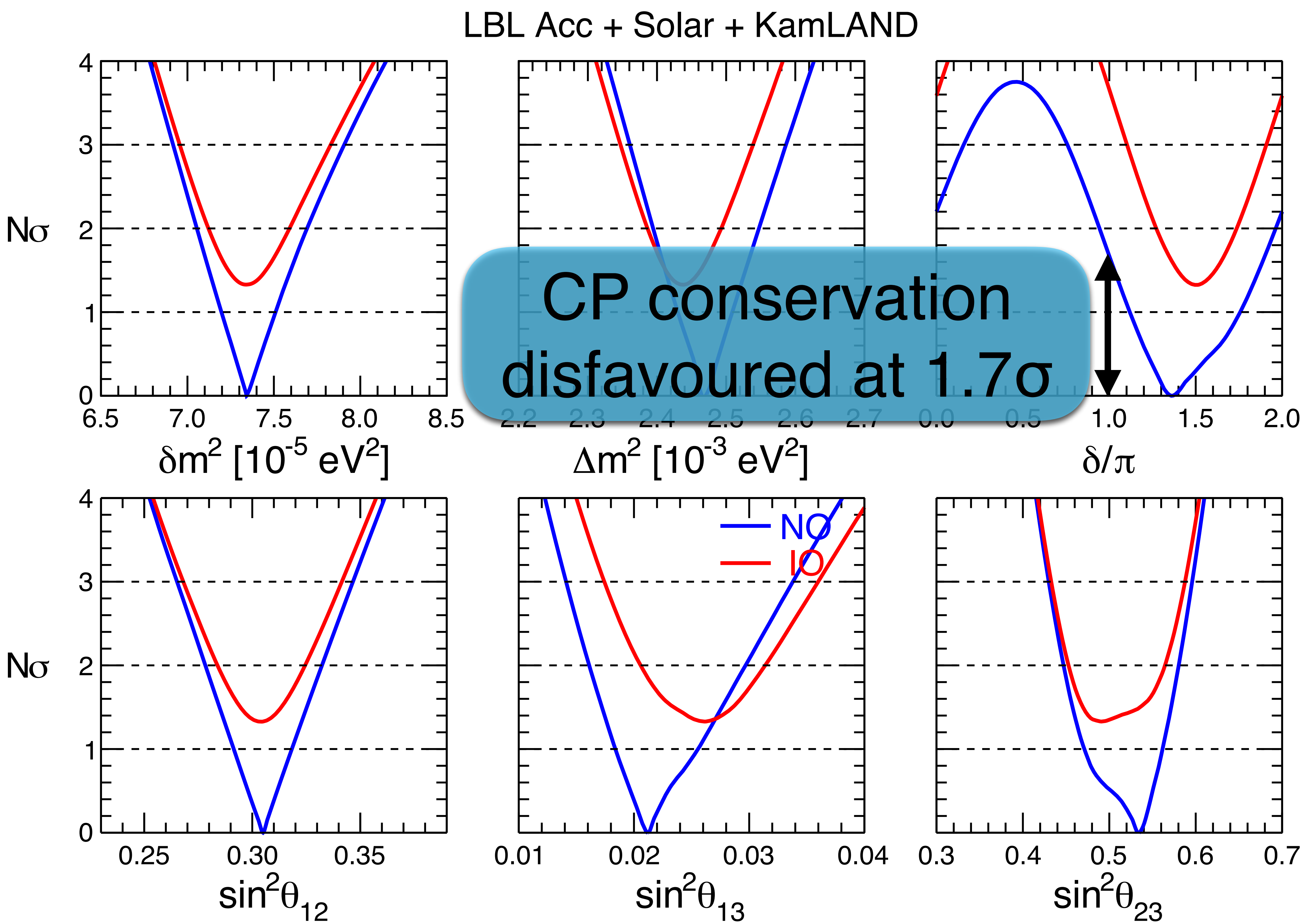
Analysis results: CP violation



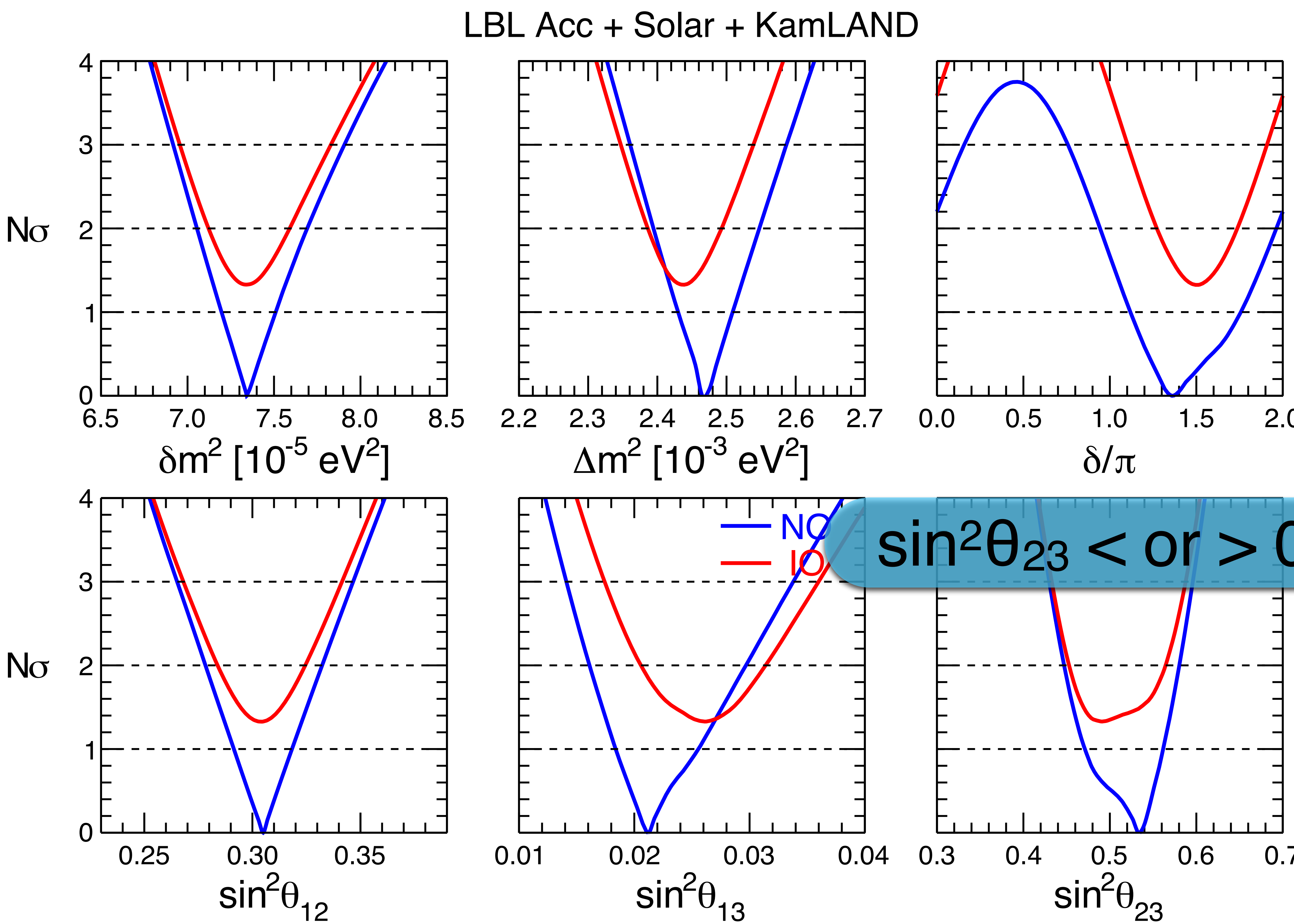
Analysis results: CP violation



Analysis results: CP violation

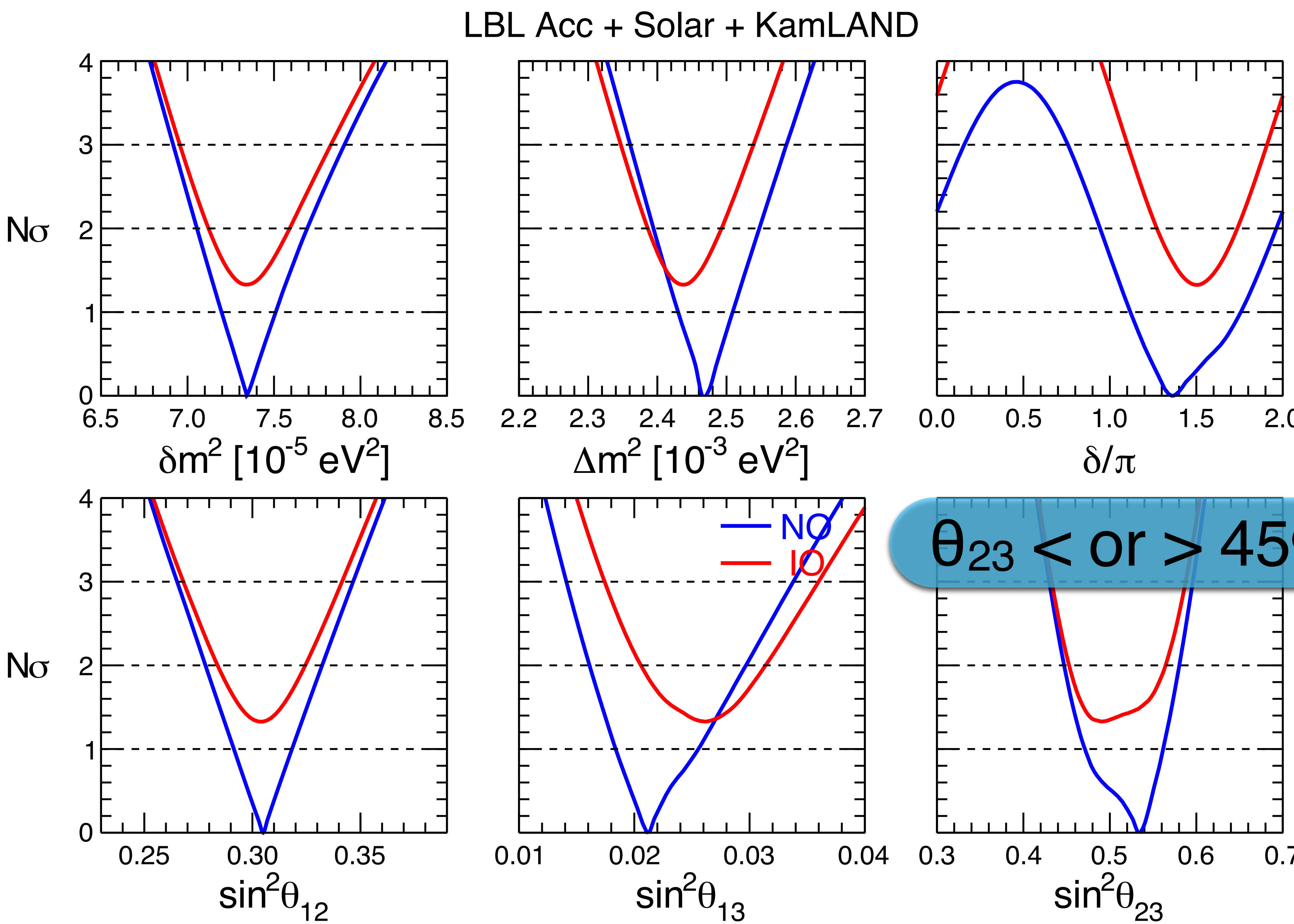


Analysis results: θ_{23}



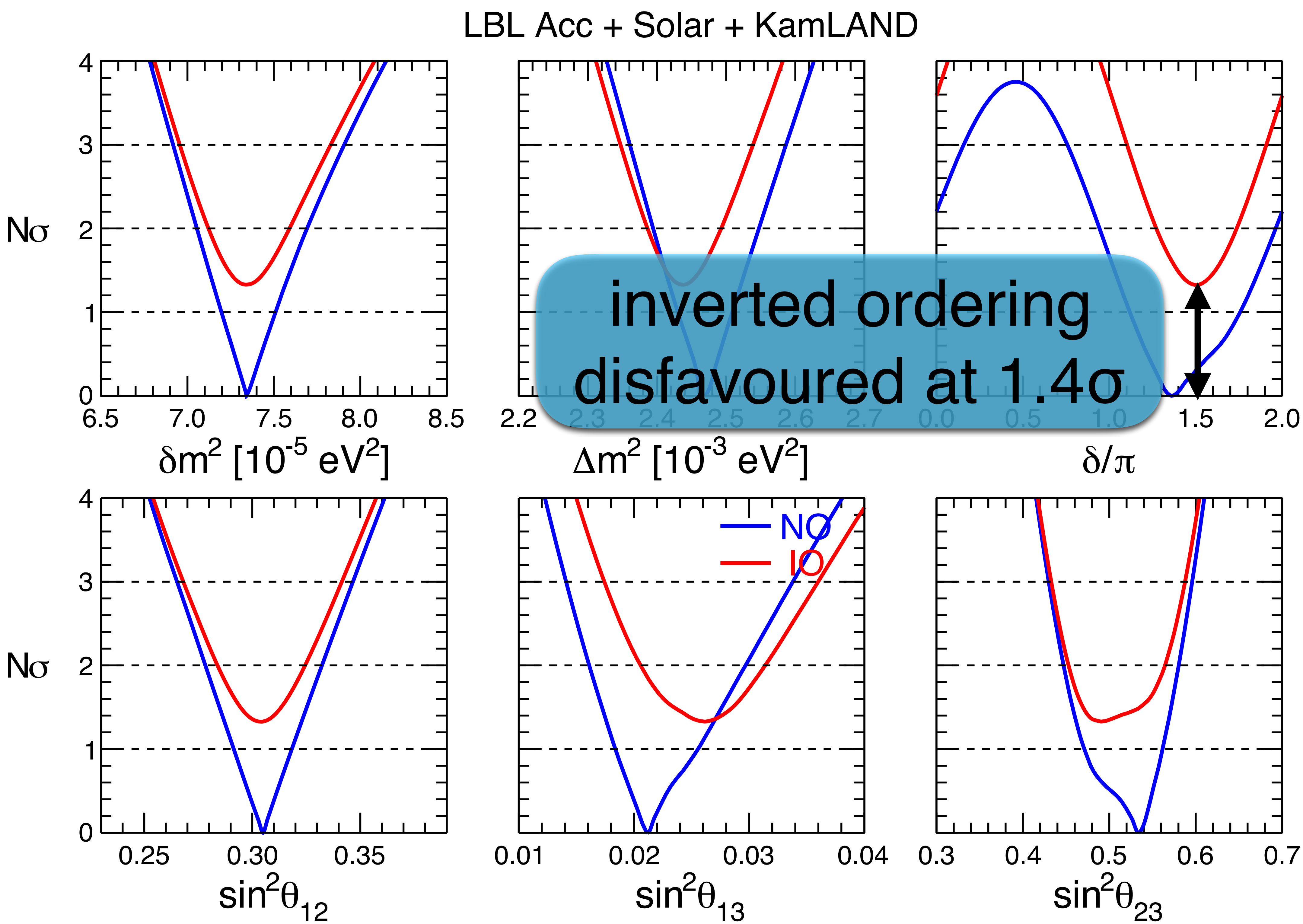
sin²θ23 < or > 0.5?

Analysis results: θ_{23}



θ_{23} < or > 45°?

Analysis results: mass ordering



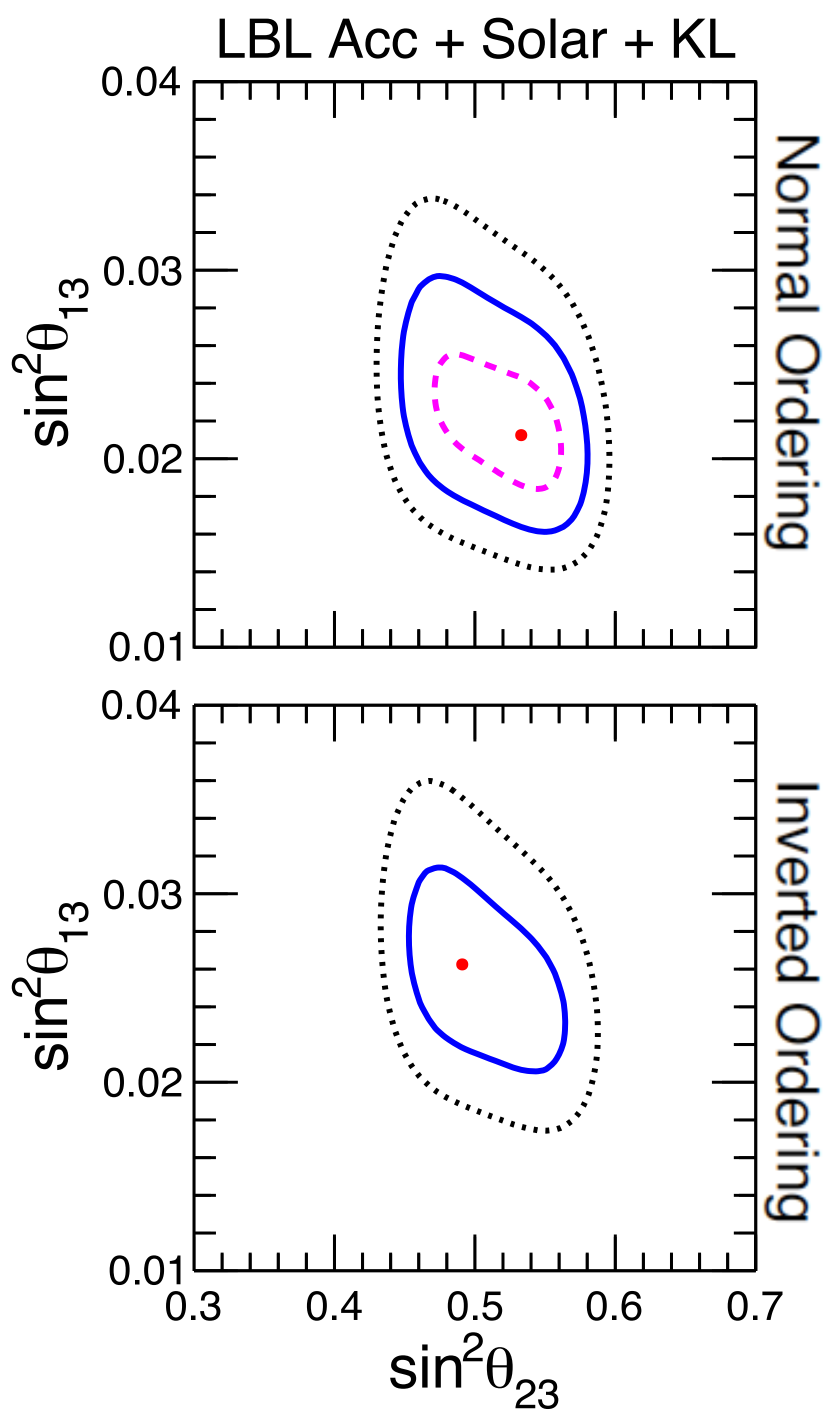
Global analysis of oscillation data

… Then we strongly constrain θ_{13} with …

Short baseline reactors $\bar{\nu}_e \longrightarrow \bar{\nu}_e$ $(\theta_{13}, \Delta m^2)$

(Daya Bay, Double Chooz, RENO)

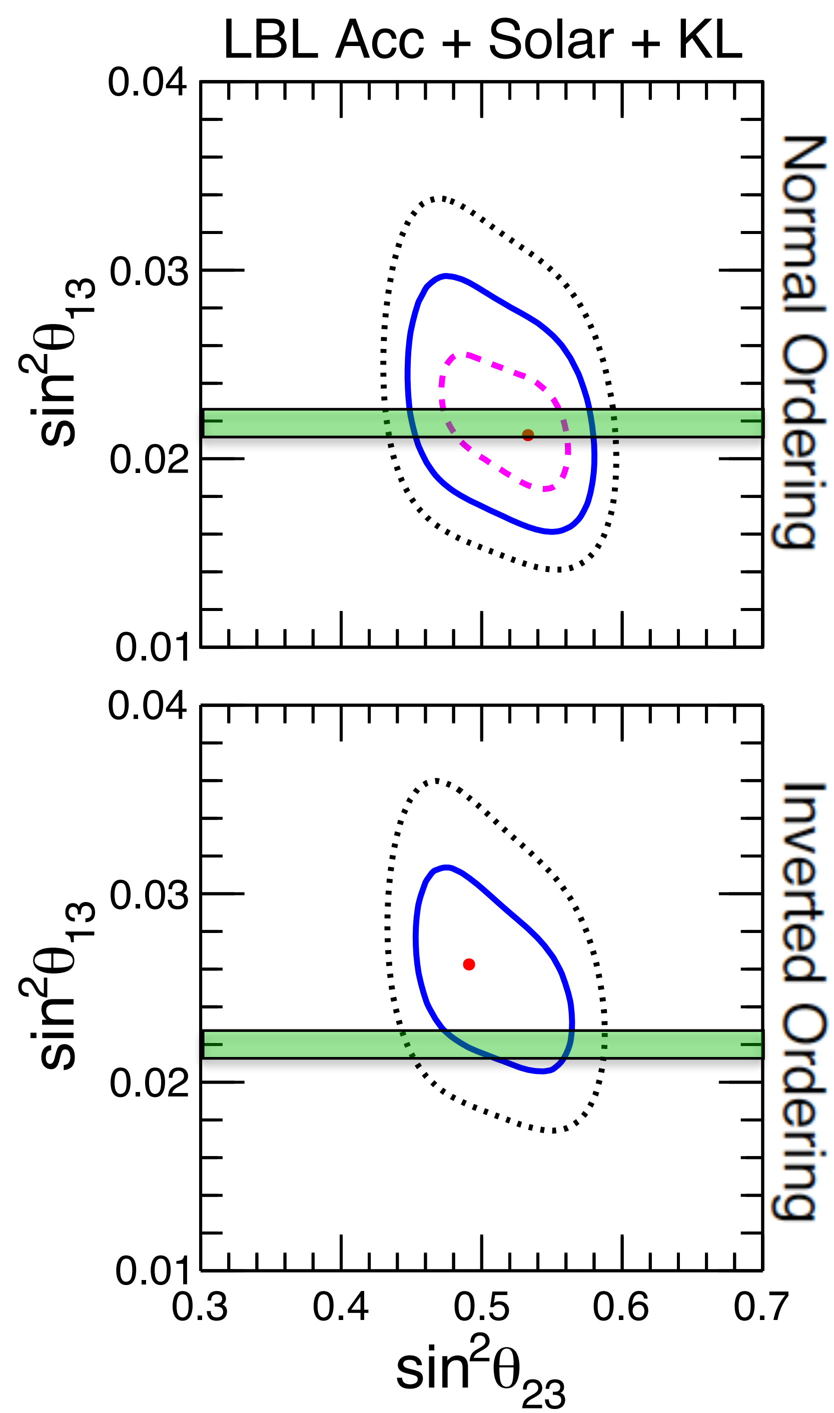
Analysis results: covariance (θ_{23},θ_{13})



θ_{23} and θ_{13} are anti-correlated

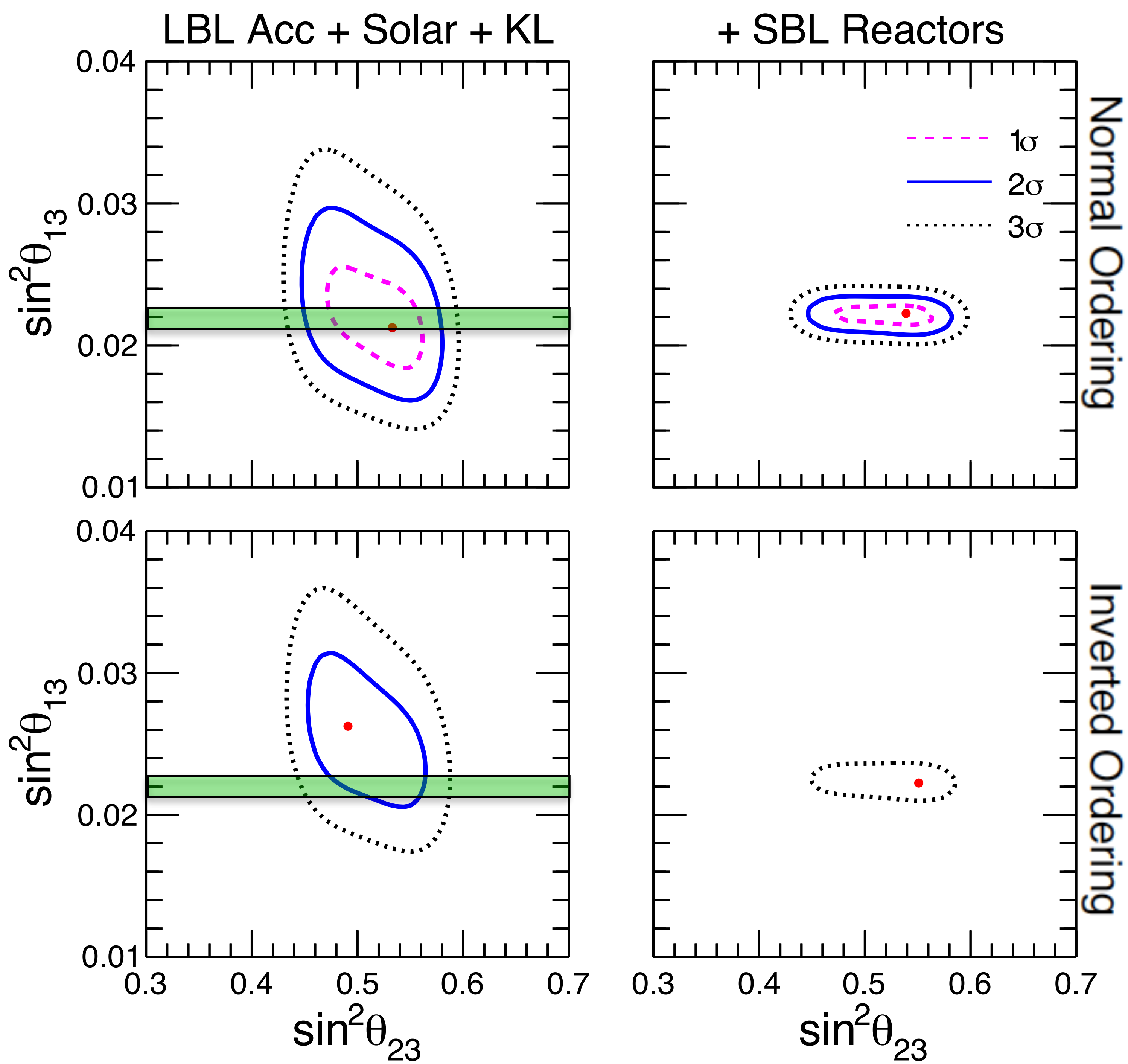
$$P_{\nu_\mu \to \nu_e}(\mathrm{LBL}) \propto \sin^2\theta_{13} \sin^2\theta_{23}$$

Analysis results: covariance (θ_{23},θ_{13})



SBL reactors favor NO and θ_{23} 2nd octant

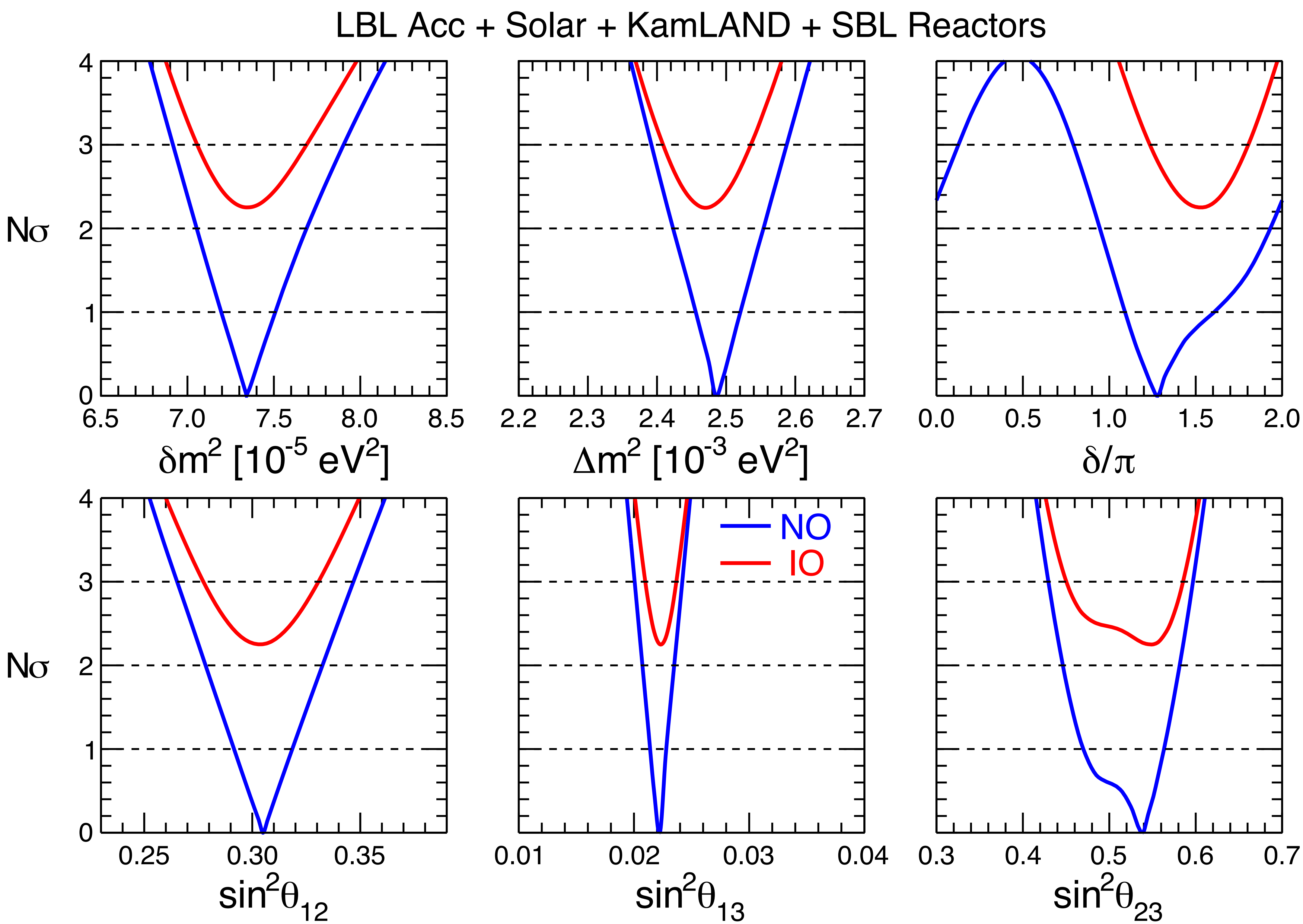
Analysis results: covariance (θ_{23},θ_{13})



1σ SBL reactor constraint

IO disfavored at 2σ

Analysis results



Global analysis of oscillation data

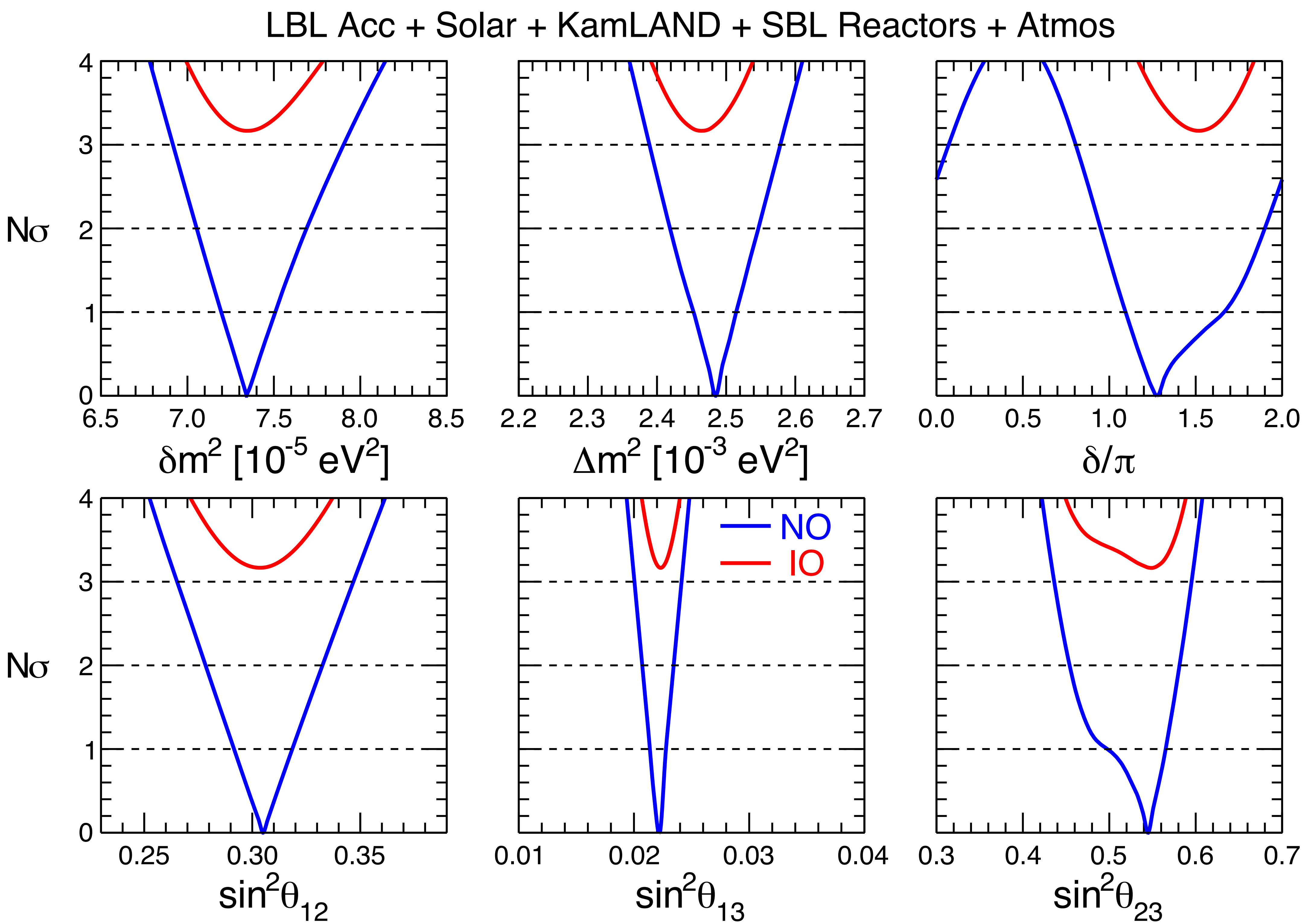
… Then we strongly constrain θ_{13} with …

Short baseline reactors (Daya Bay, Double Chooz, RENO)	$\bar{\nu}_e \longrightarrow \bar{\nu}_e$	(θ_{13}, Δm^2)

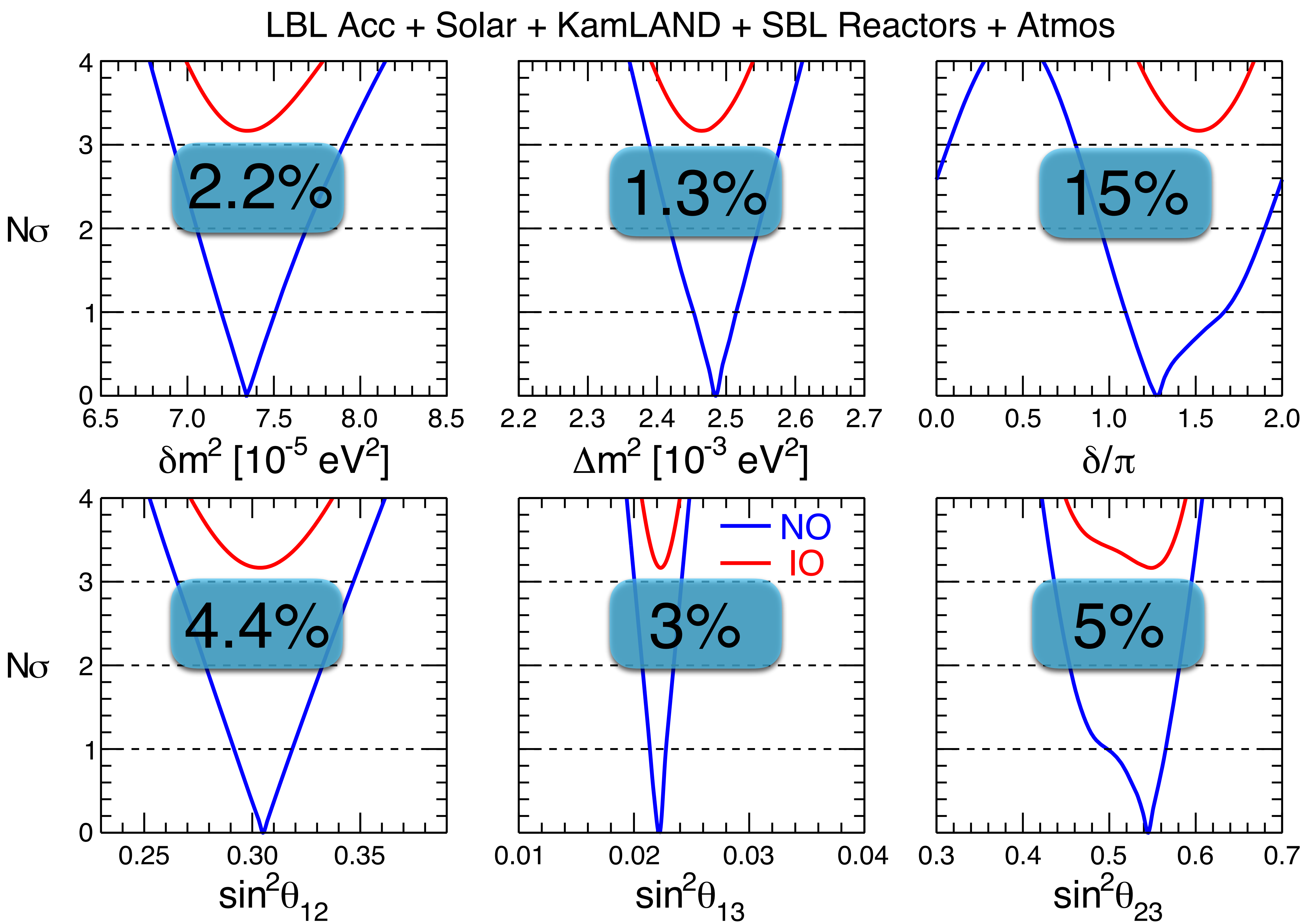
… And we finally add the rich phenomenology of atmospheric neutrinos

Atmospheric (Super-Kamiokande, IceCube-Deepcore)	$\bar{\nu}_\mu \longrightarrow \bar{\nu}_{\mu,e}$ $\nu_\mu \longrightarrow \nu_{\mu,e}$	(θ_{23}, Δm^2, MO, δ, θ_{13})

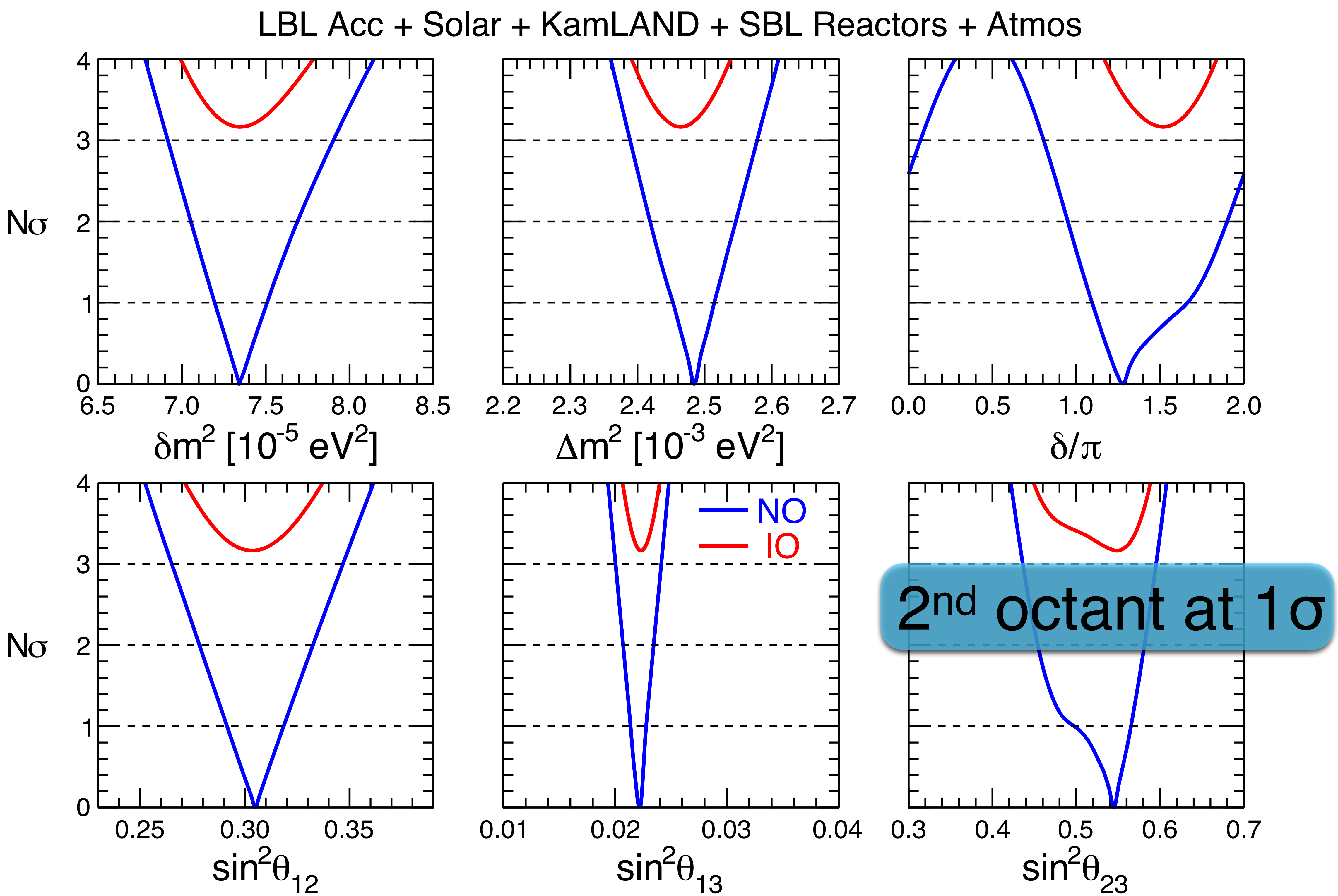
Analysis results



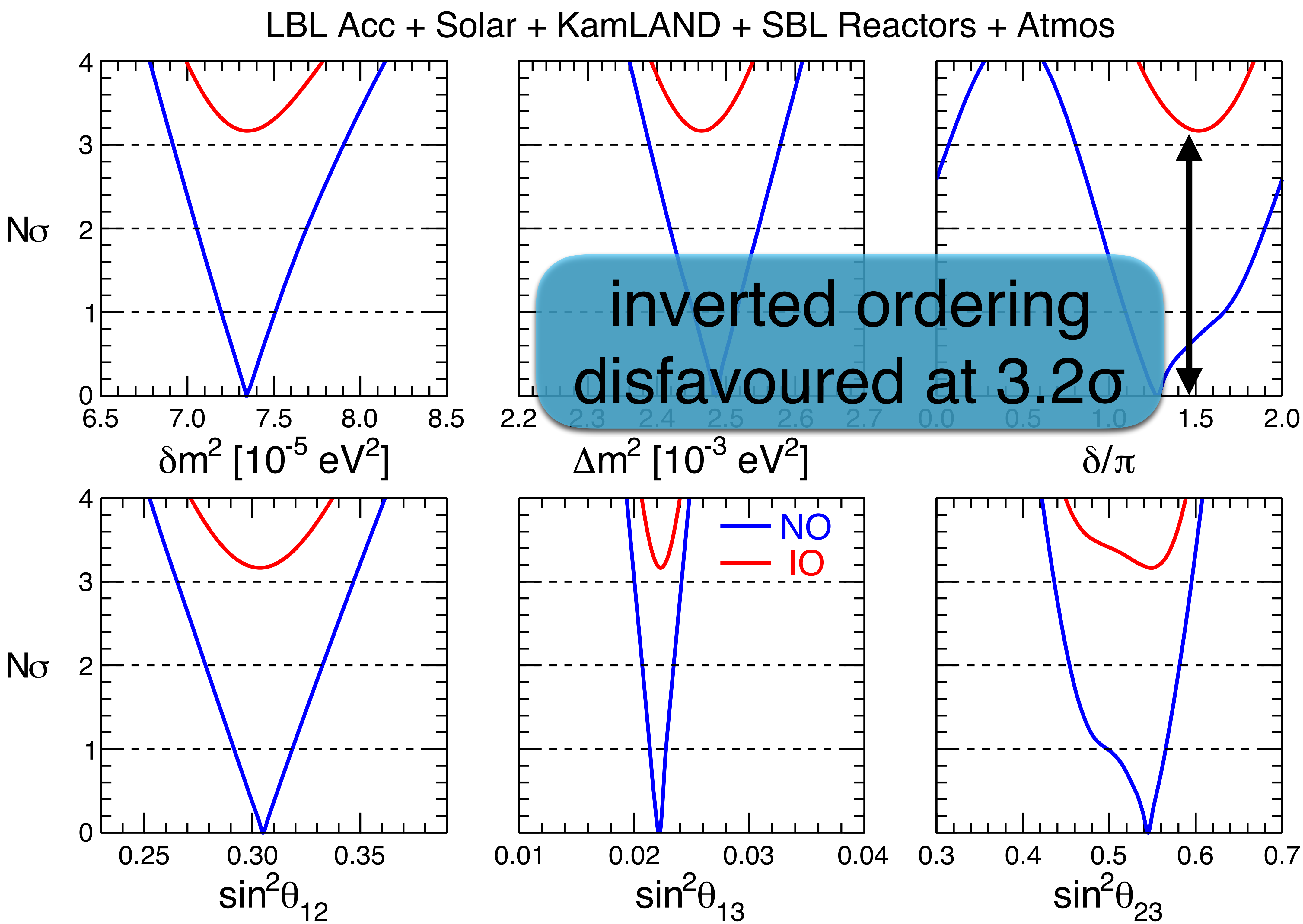
Analysis results



Analysis results



Analysis results

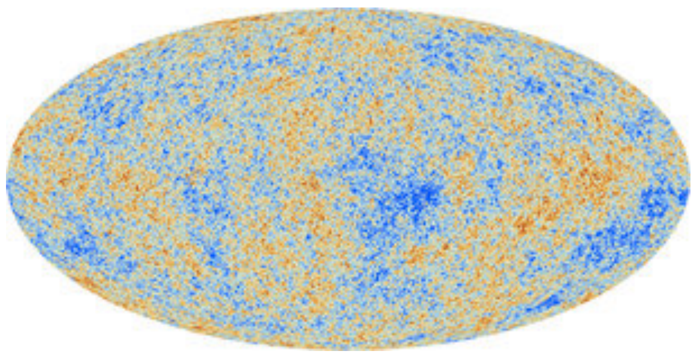


Non-oscillation data

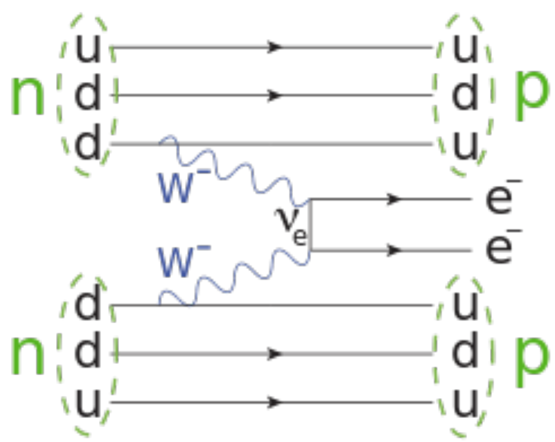
Phys. Rev. D 95 (2017) no.9, 096014)
in collaboration with E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo

Non oscillation data: variables

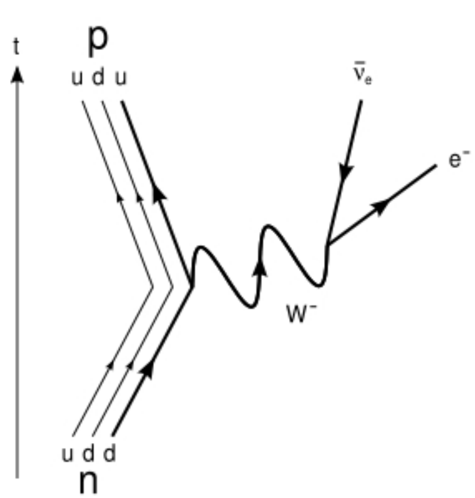
Cosmology, β and 0νββ decays can probe:



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



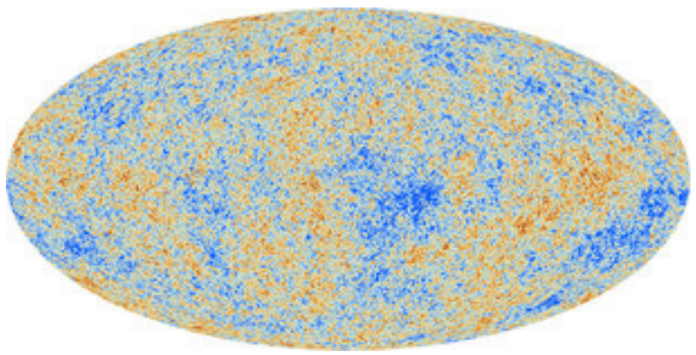
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



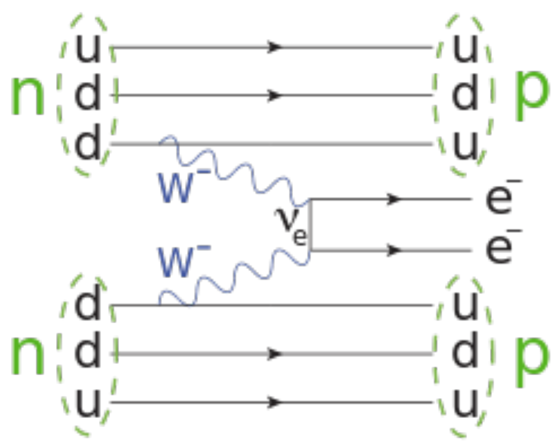
$$m_\beta^2 = \sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i^2$$

Non oscillation data: variables

Here we focus on Σ and $m_{\beta\beta}$



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

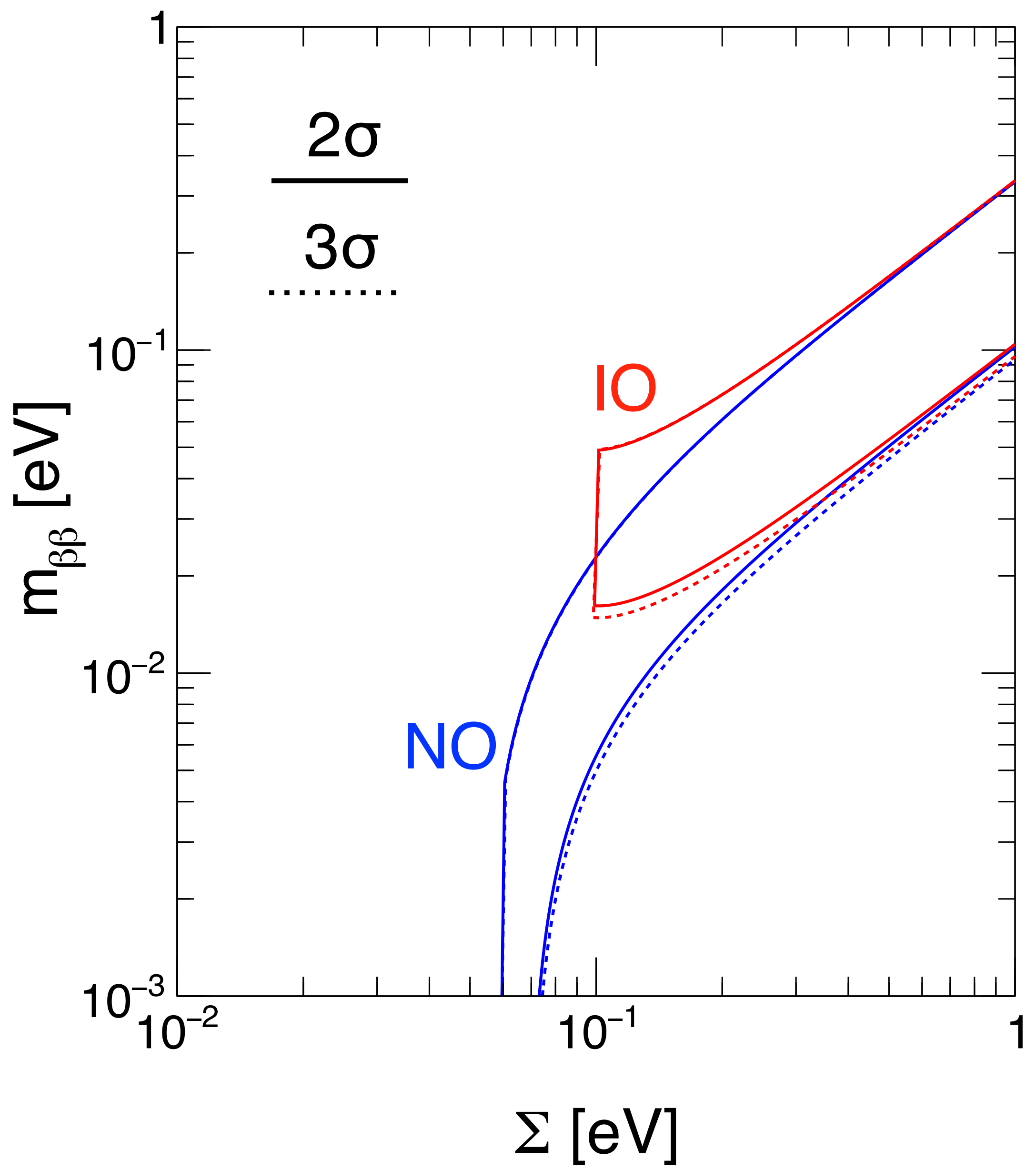


$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

$$m_\beta^2 = \sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i^2$$

Constraints on (Σ, $m_{\beta\beta}$)

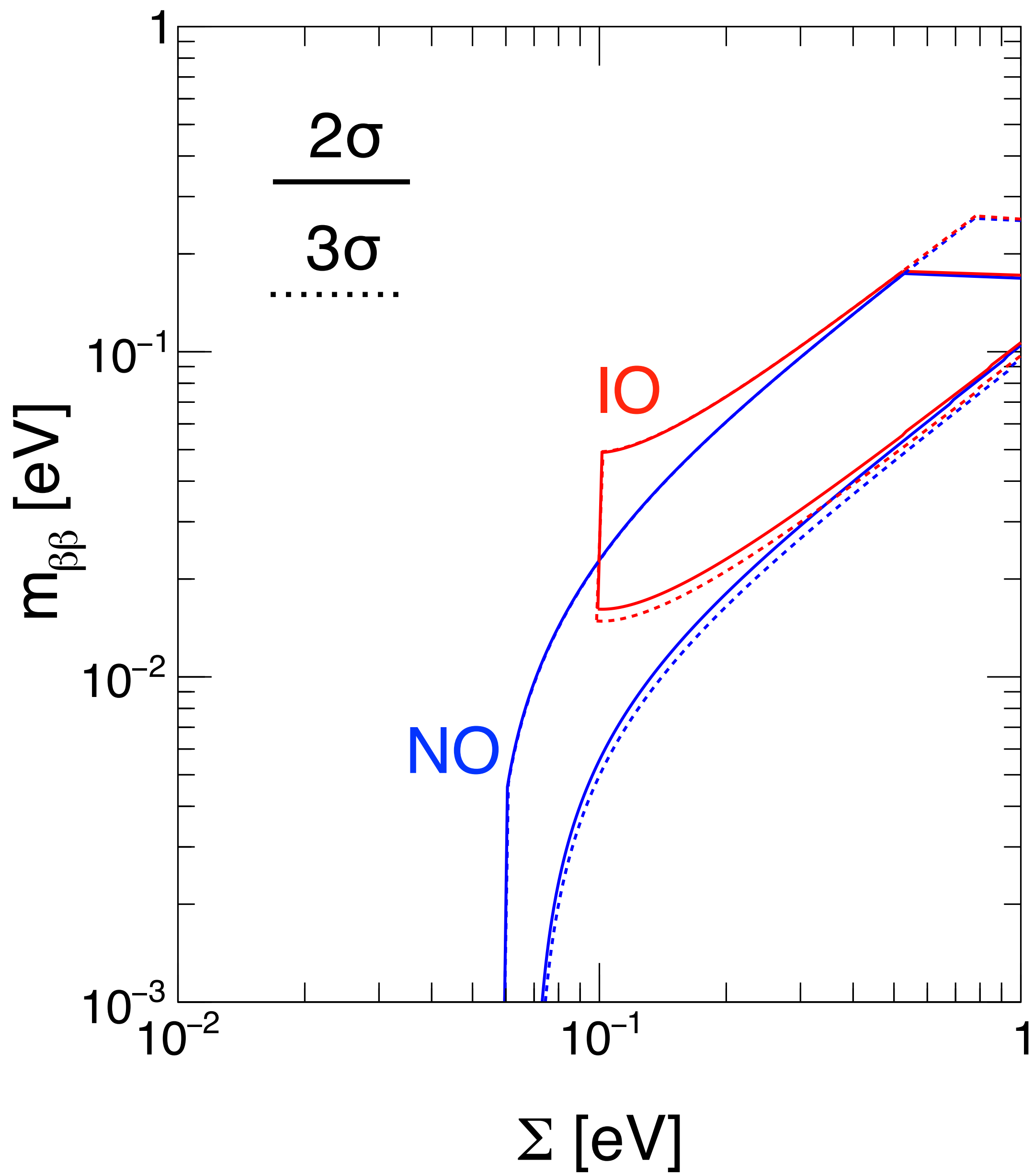
Only oscillation constraints, with $\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(IO)$



$\Sigma(NO) > 0.06$ eV and $\Sigma(IO) > 0.1$ eV

Constraints on (Σ,$m_{\beta\beta}$)

Oscillation + 0νββ constraints, with $\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(IO)$



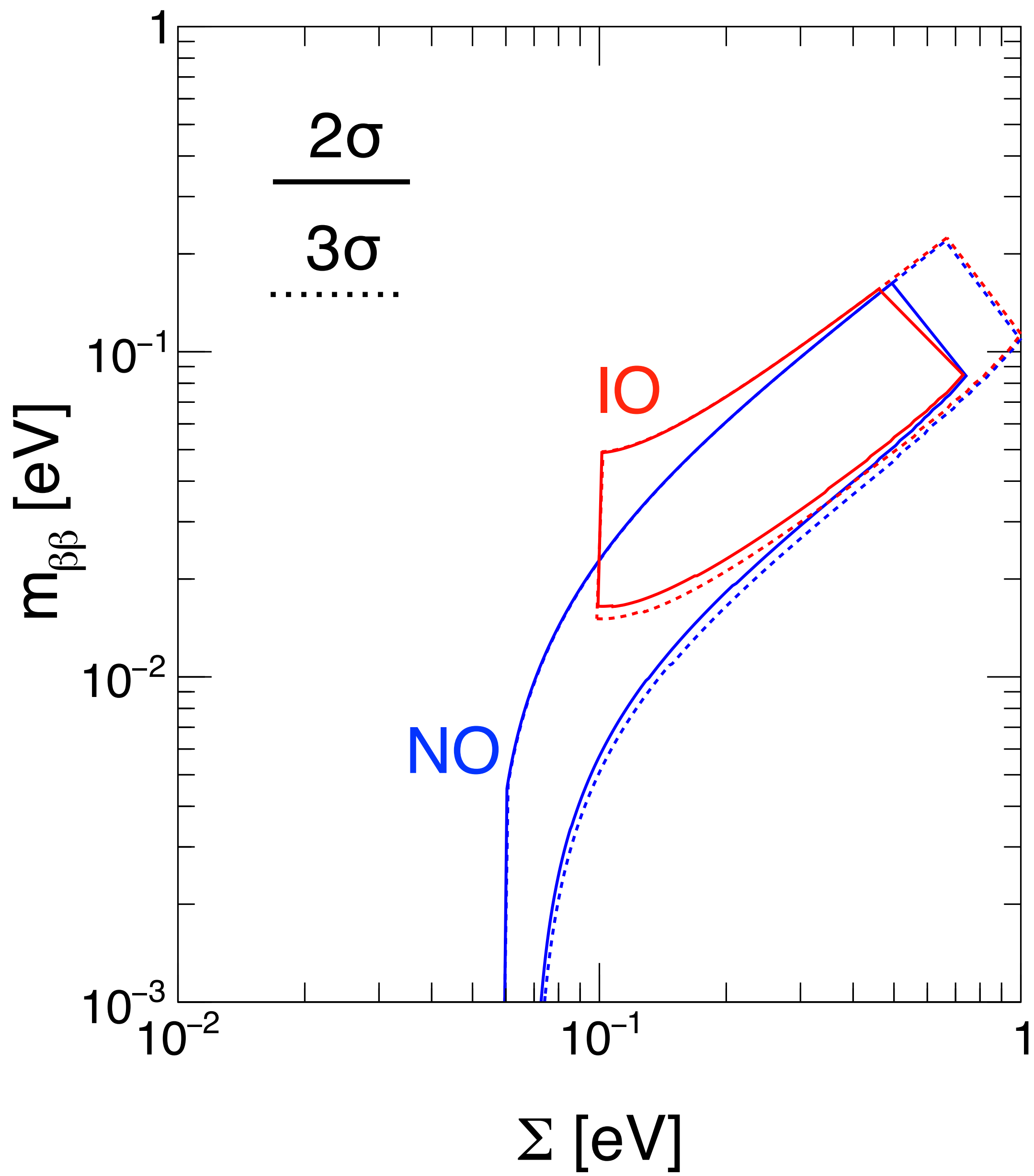
KamLAND-Zen data from
Phys. Rev. Lett. 117, no. 8, 082503 (2016)
(update in progress)

$m_{\beta\beta} < 0.2$ eV (2σ)

Constraints on (Σ,$m_{\beta\beta}$)

Oscillation + $0\nu\beta\beta$ + cosmology (conservative) constraints

$\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(IO)$



Capozzi, Di Valentino, Lisi, Marrone, Melchiorri and Palazzo, Phys. Rev. D 95 (2017) no.9, 096014

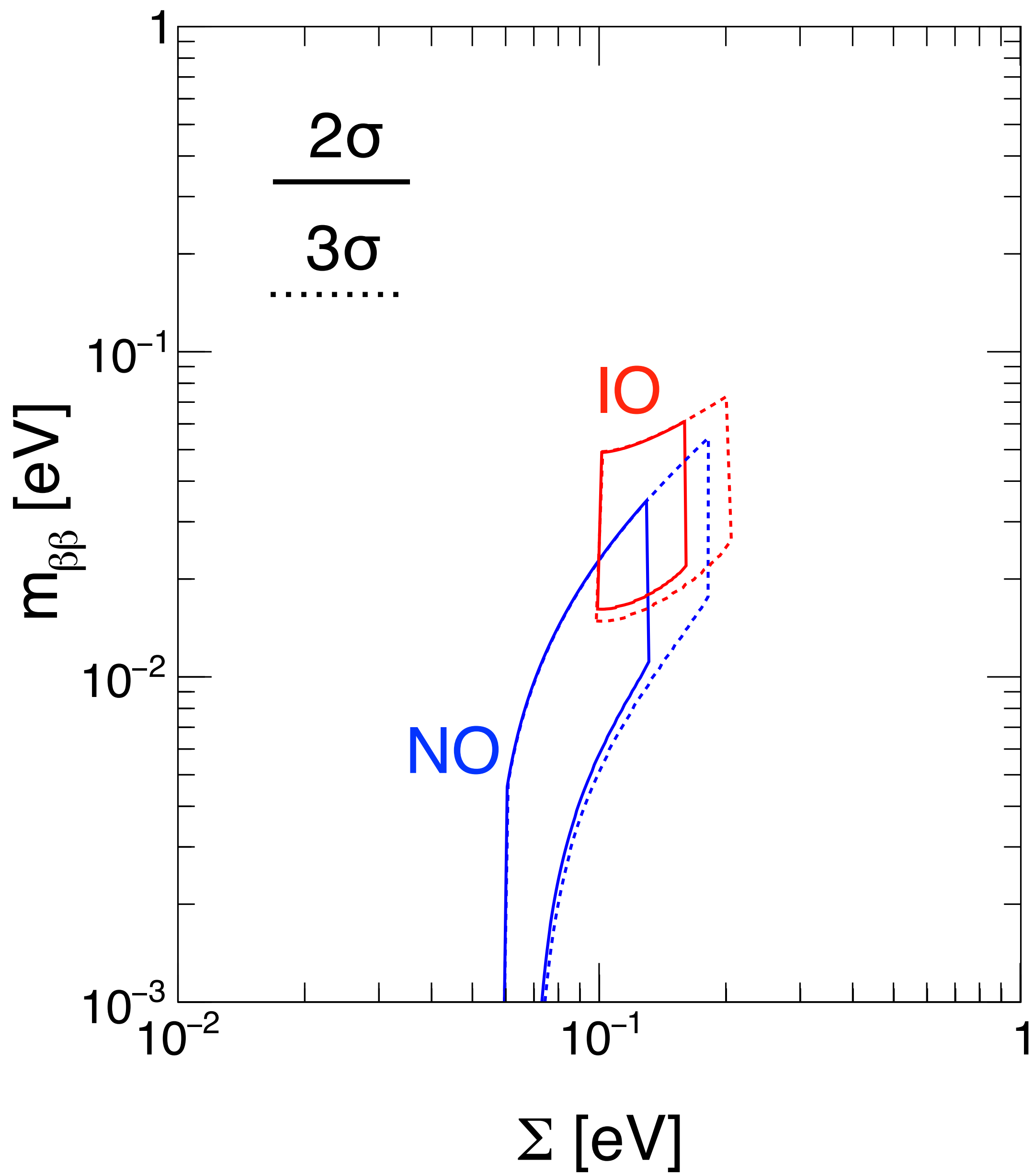
Update in Progress

$\Sigma < 0.7$ eV (2σ)

Constraints on (Σ,$m_{\beta\beta}$)

Oscillation + 0νββ + cosmology (aggressive) constraints

$\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(IO)$



Capozzi, Di Valentino, Lisi, Marrone, Melchiorri and Palazzo, Phys. Rev. D 95 (2017) no.9, 096014

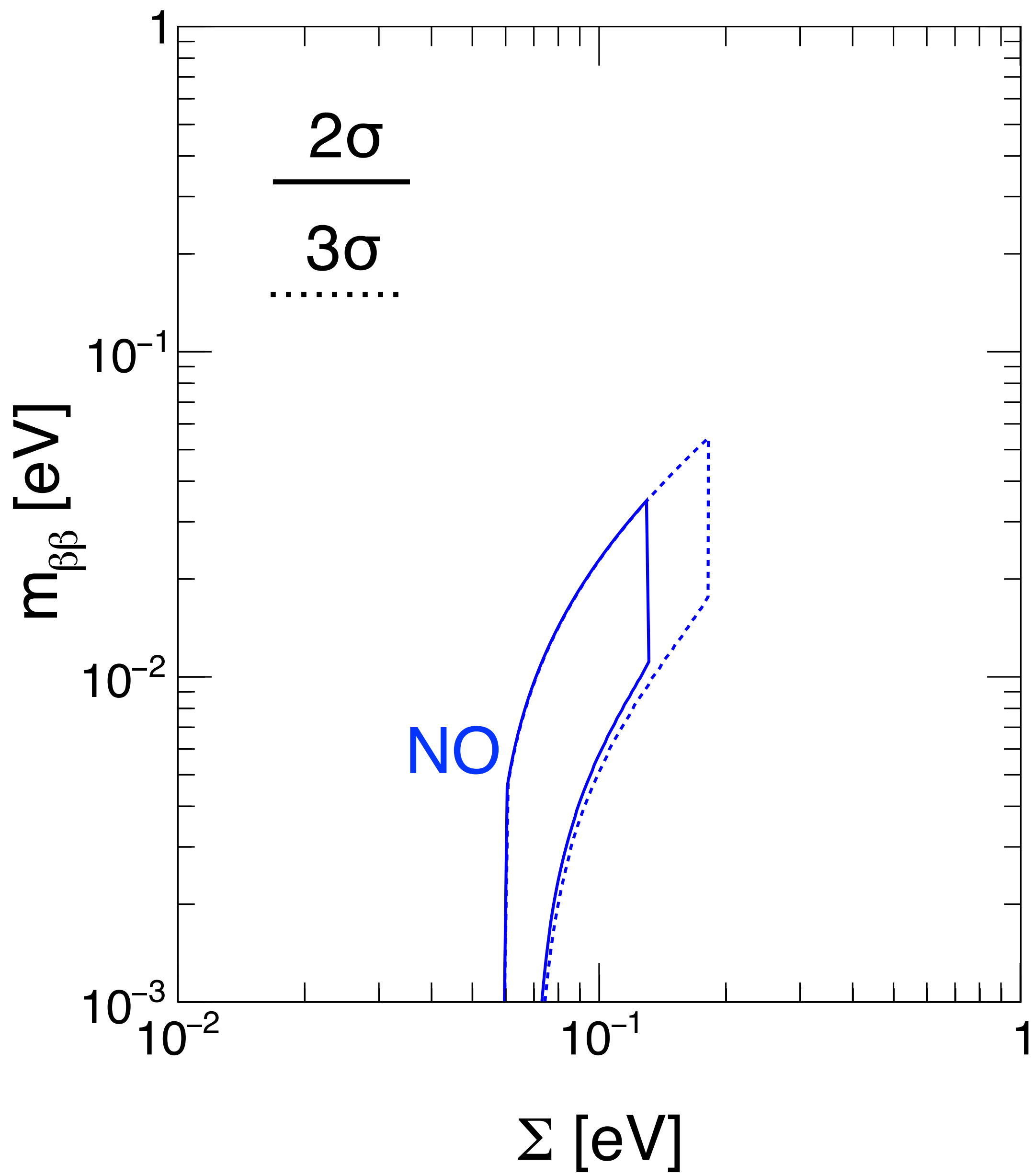
Update in Progress

$\Sigma < 0.2$ eV (2σ)

Constraints on $(\Sigma, m_{\beta\beta})$

Oscillation + 0νββ + cosmology (aggressive) constraints

$\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(NO)$



$\Delta\chi^2(IO - NO) = 11.7 > 10.2$ from oscillations

Conclusions

Intense research activity in neutrino mass-mixing parameters

We have entered the **precision era**

Hint for **CP violation (2σ)** and for **normal ordering (3σ)**

Small hint in favour of the **second octant of θ_{23}**

Non oscillation data **corroborates preference for normal ordering**

Thank you

Notation

The χ^2 depends on 7 parameters

$$\chi^2_{\rm osc} = \chi^2_{\rm osc}(\theta_{12}, \theta_{13}, \theta_{23}, \delta, \delta m^2, \Delta m^2, {\rm sign}(\Delta m^2))$$

We define the $\Delta\chi^2$

$$\Delta\chi^2({\rm NO}) = \chi^2_{\rm osc}(\Delta m^2 > 0) - \min[\chi^2_{\rm osc}(\Delta m^2 > 0)]$$

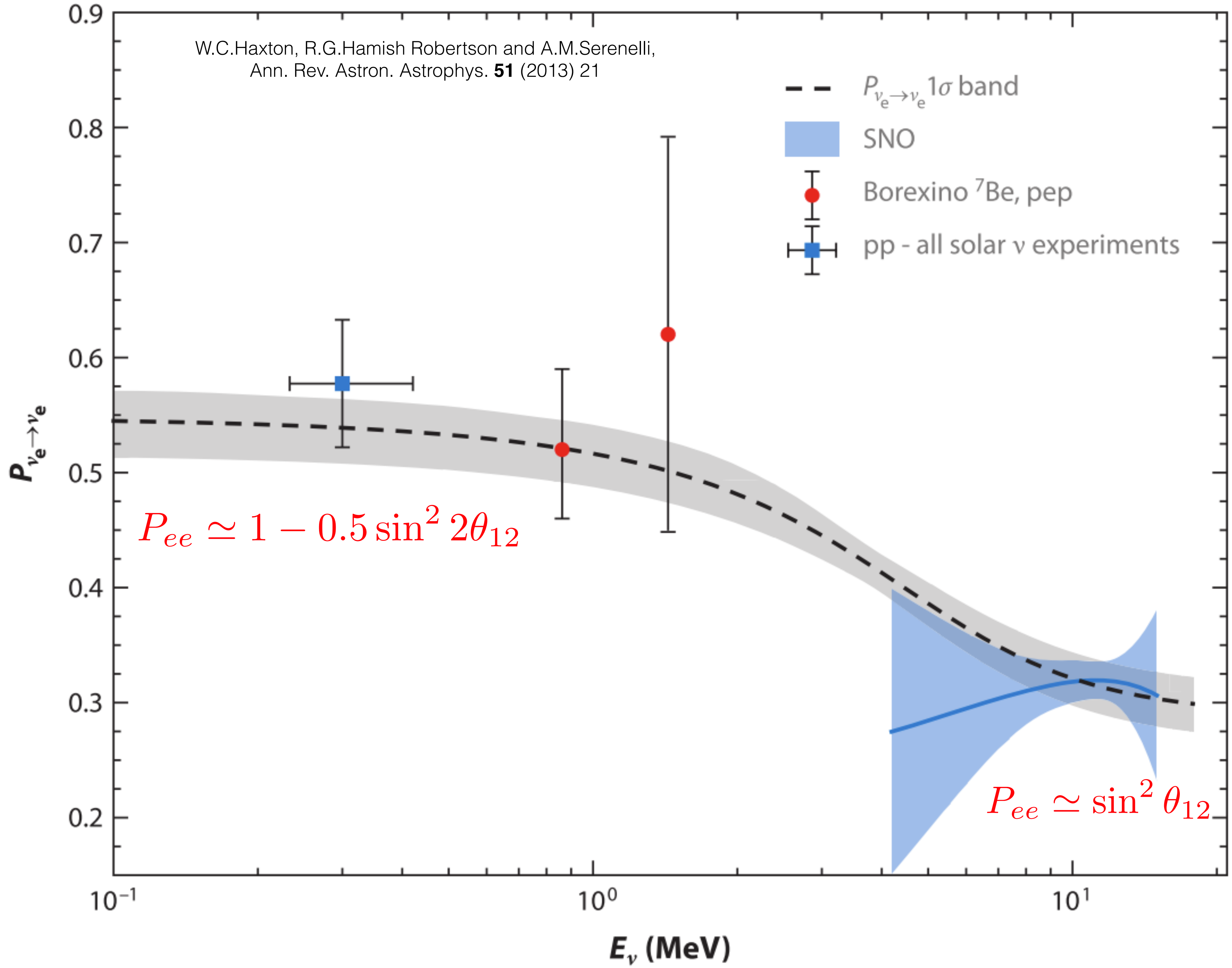
$$\Delta\chi^2({\rm IO}) = \chi^2_{\rm osc}(\Delta m^2 < 0) - \min[\chi^2_{\rm osc}(\Delta m^2 < 0)]$$

We report the results in terms of

$$N\sigma = \sqrt{\Delta\chi^2}$$

Solar sector (θ_{12},δm^2)

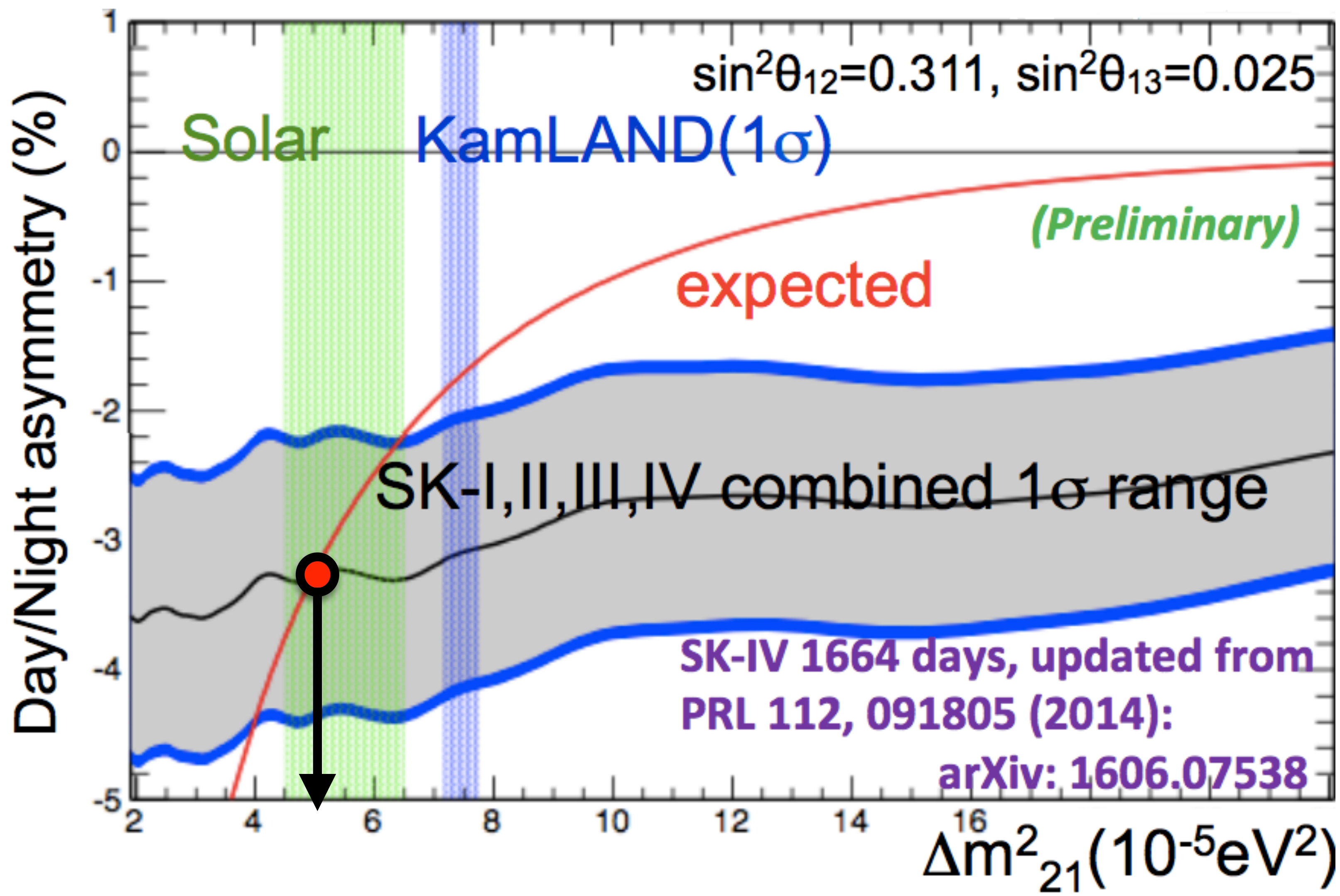
Daytime survival probability of ν_e as a function of energy



Solar sector (θ_{12},δm^2)

Day/Night asymmetry $\propto 1/\Delta m^2_{21}$

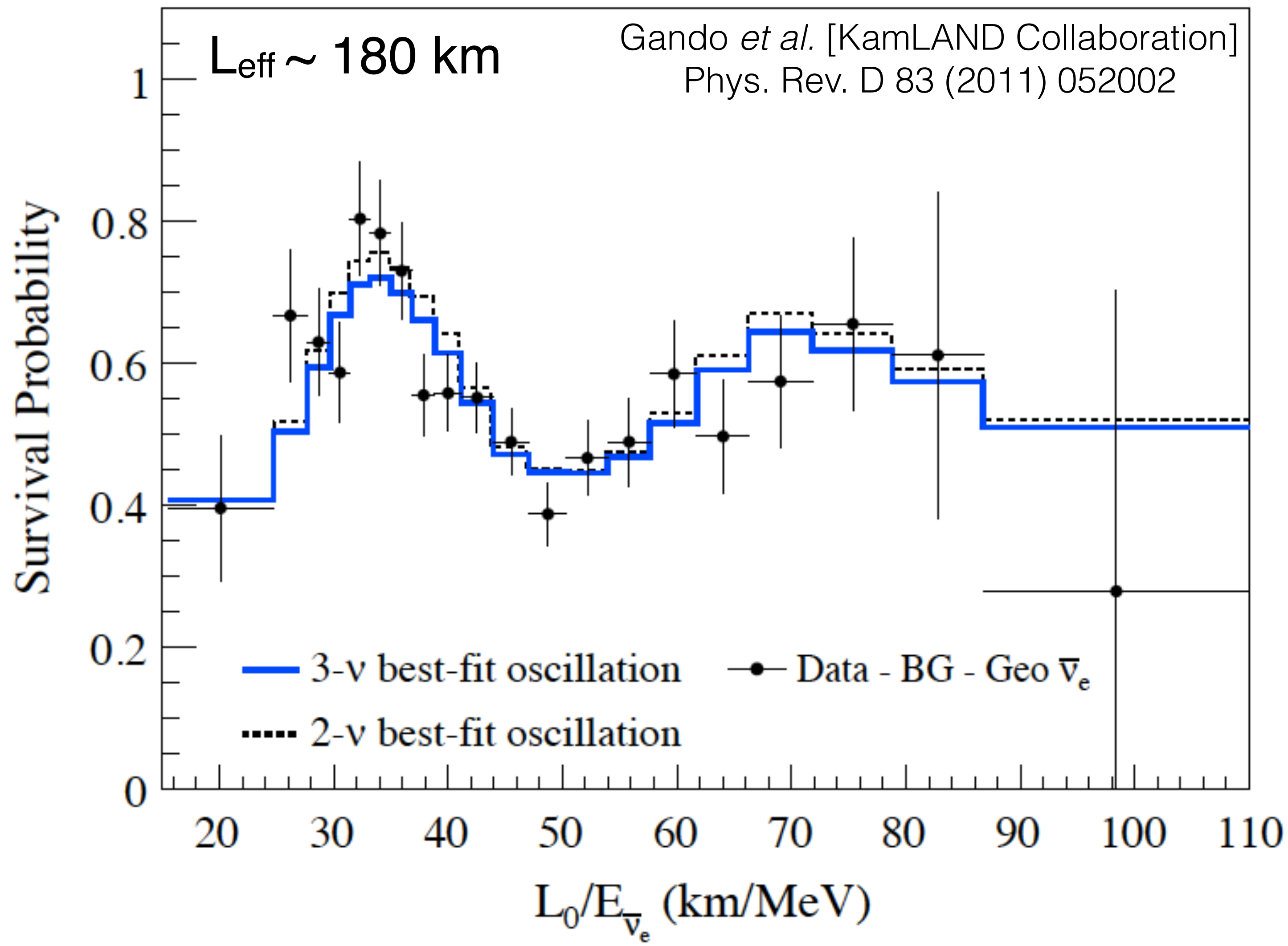
Super-Kamiokande Collaboration, Neutrino 2016



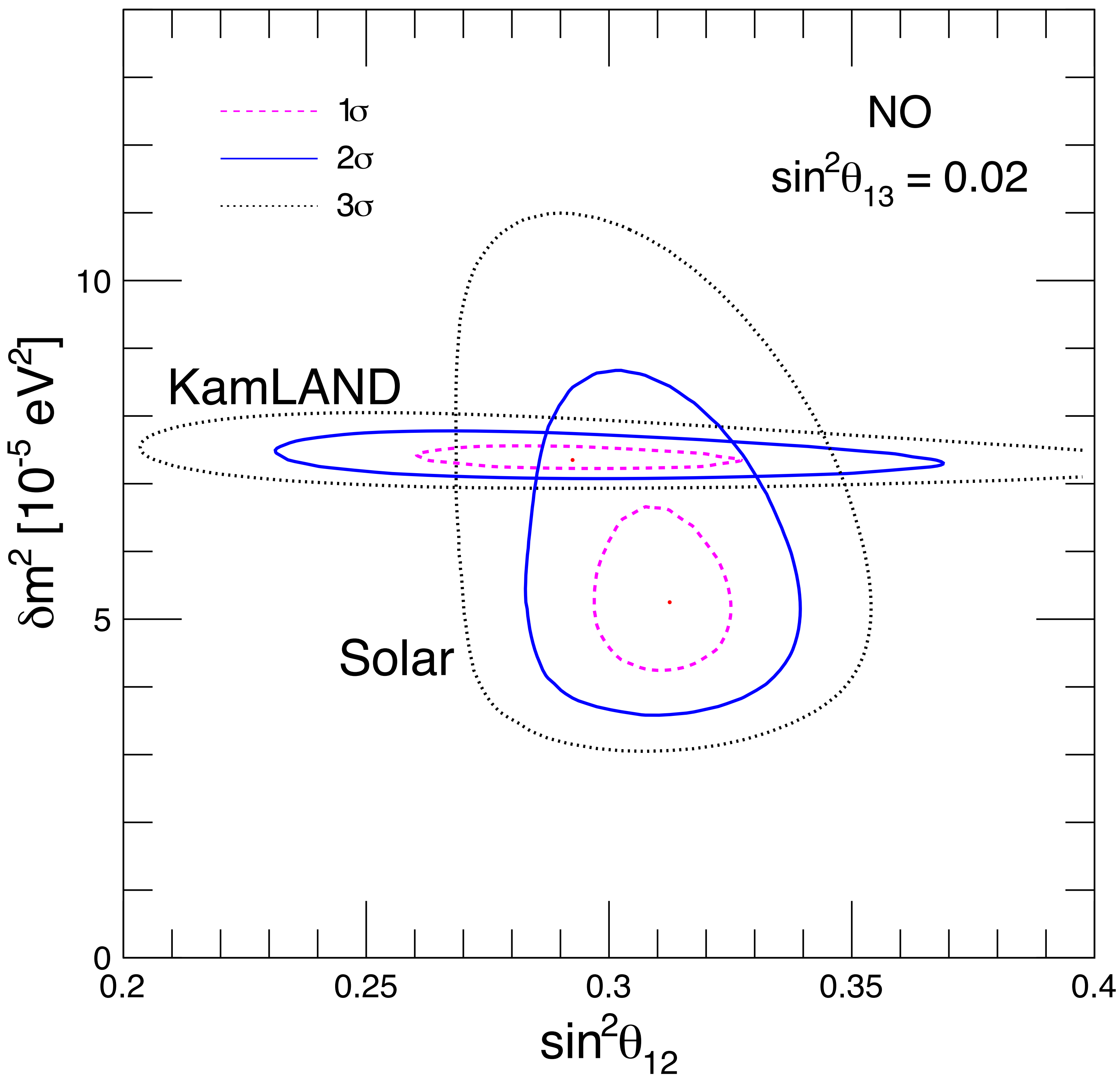
$\Delta m^2_{21} \sim 5 \times 10^{-5}$ eV^2

Solar sector (θ_{12},δm^2): KamLAND

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) \simeq 1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L_{\rm eff}}{4E}\right)$$



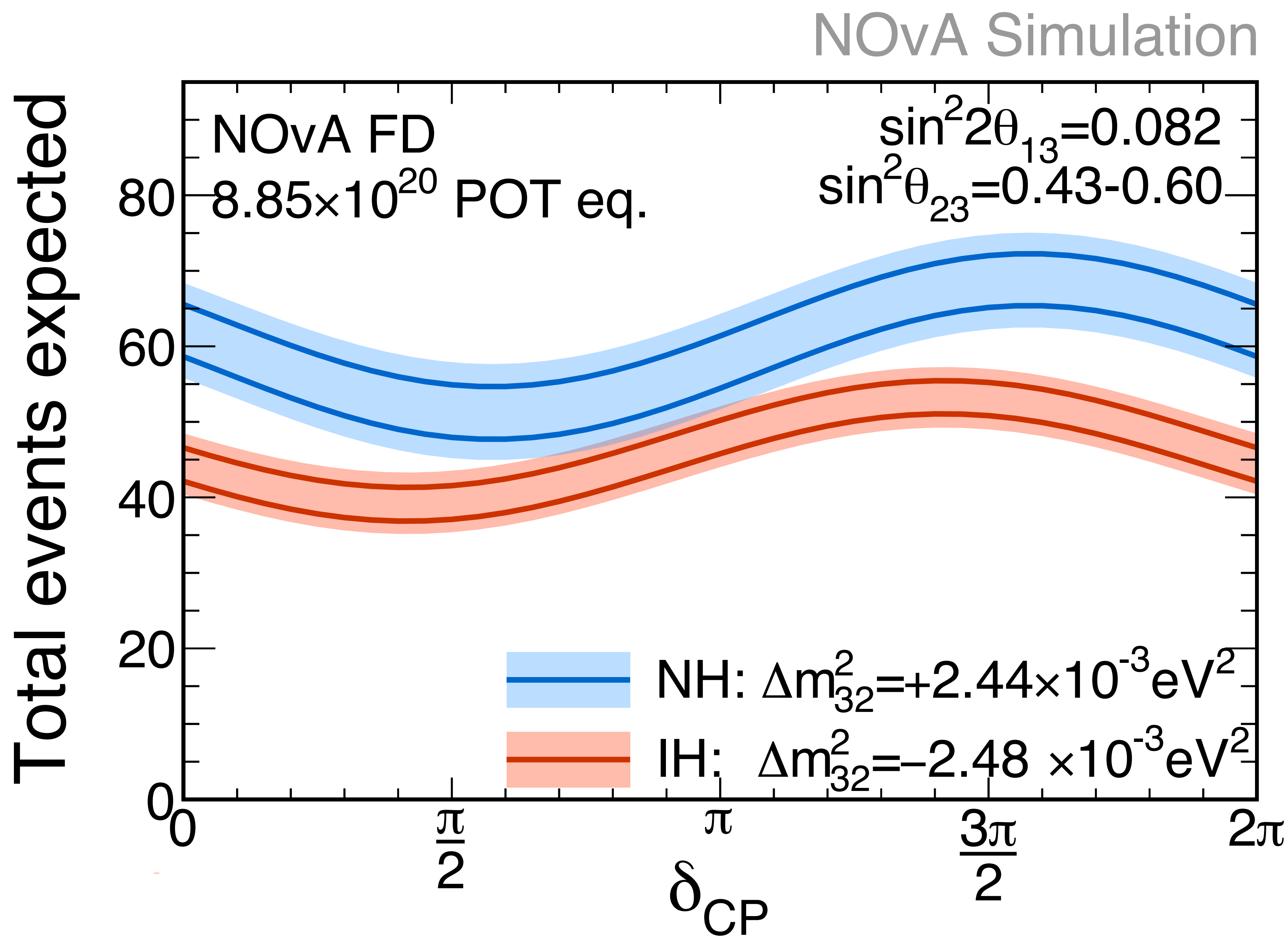
Covariance (θ_{12},δm^2)



~ 2σ “tension” driven by the large day/night asymmetry from SK

Long baseline accelerator experiments

Comparison between data and predictions for NOvA ν_e-**appearance**

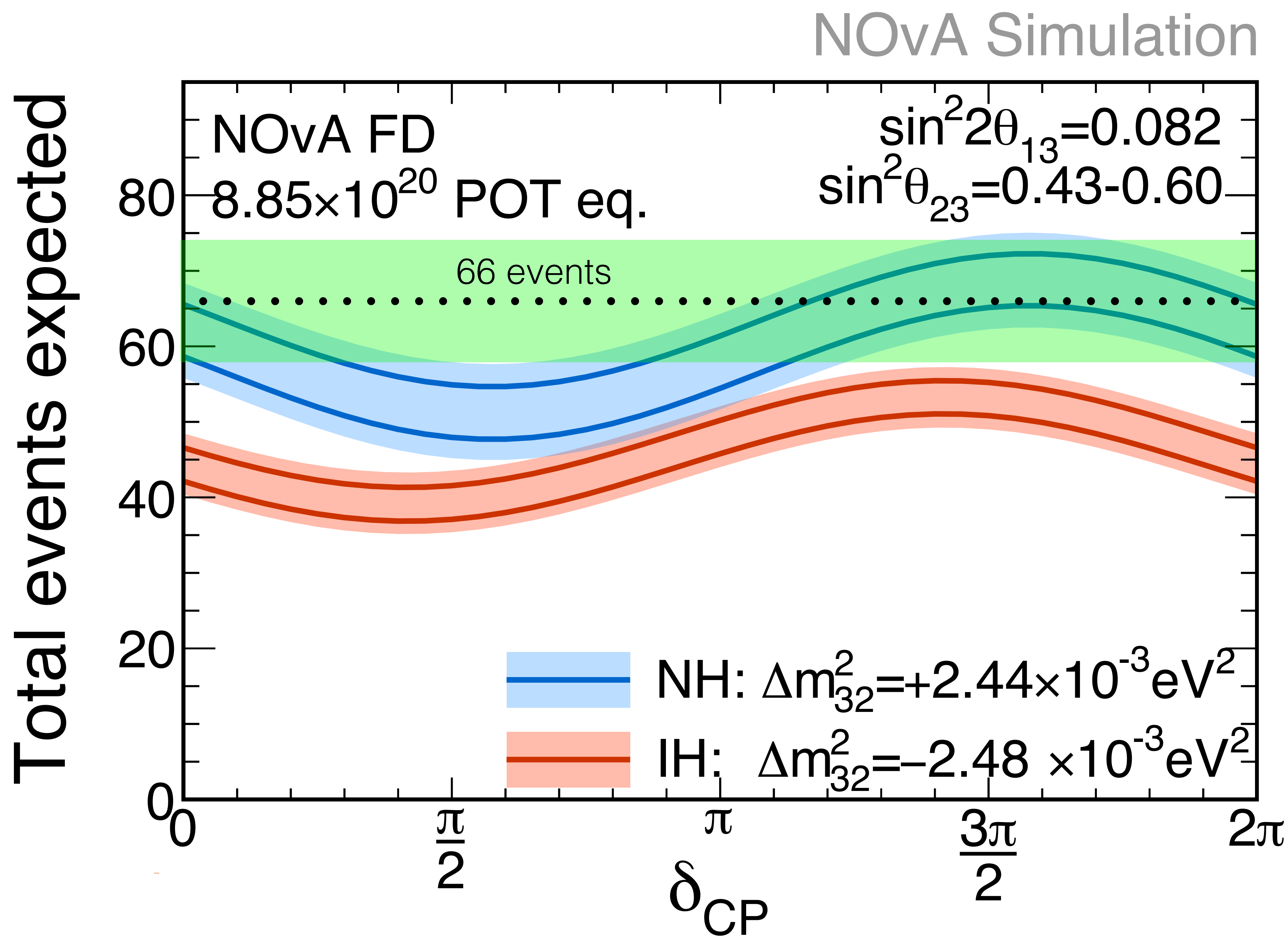


Alex Radovic, Fermilab Seminar, 12th January 2018

NO and **IO** predictions are **different** because of **matter effects**

Long baseline accelerator experiments

Comparison between data and predictions for NOvA ν_e-**appearance**



Alex Radovic, Fermilab Seminar, 12th January 2018

Preference for $\delta = 3\pi/2$ and NO

Long baseline accelerator experiments

Comparison between data and predictions (NO) for T2K ν_e-**appearance**

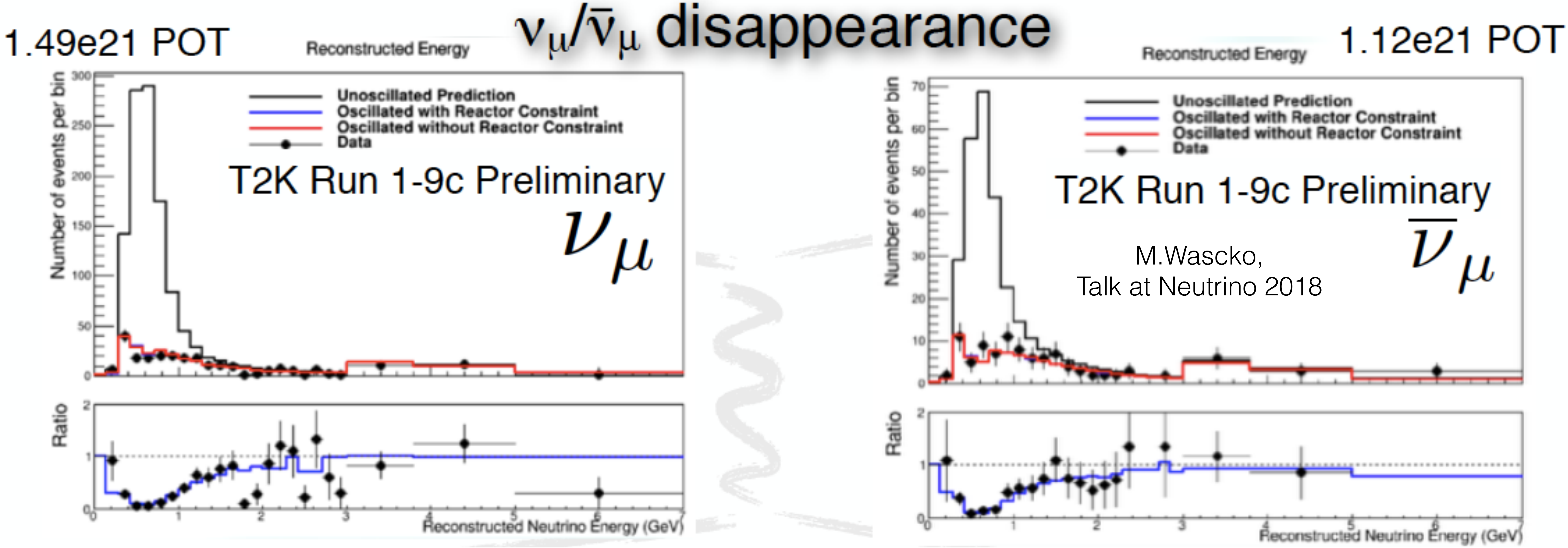
	Observed	$\delta = -\pi/2$	$\delta = 0$	$\delta = +\pi/2$	$\delta = \pi$
e-like ν mode	75	74.4	62.2	50.6	62.7
e-like+$1\pi^+$ ν mode	15	7.0	6.1	4.9	5.9
e-like $\bar{\nu}$ mode	15	17.1	19.4	21.7	19.3
μ-like ν mode	243	272.4	272.0	272.4	272.8
μ-like $\bar{\nu}$ mode	140	139.2	139.2	139.5	139.9

Preference for $\delta = 3\pi/2$ $(-\pi/2)$ and NO

Long baseline accelerator experiments

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

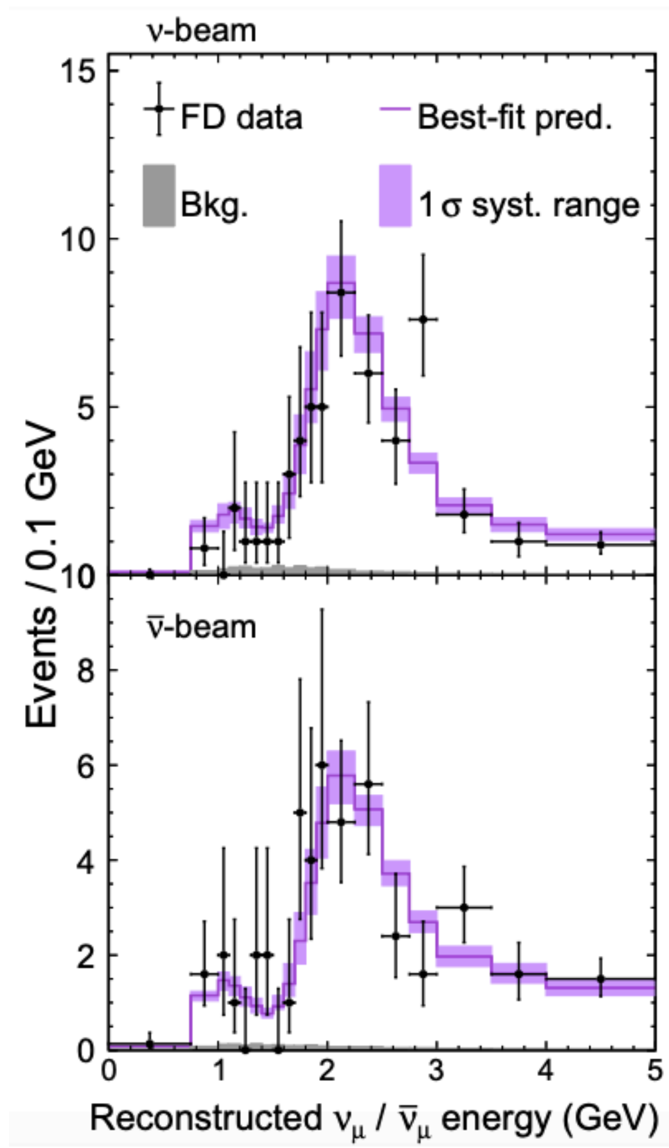
$\nu_\mu/\bar{\nu}_\mu$ disappearance



$P_{\mu\mu} \sim 0$ close oscillation minimum. T2K is compatible with $\theta_{23} = \pi/4$

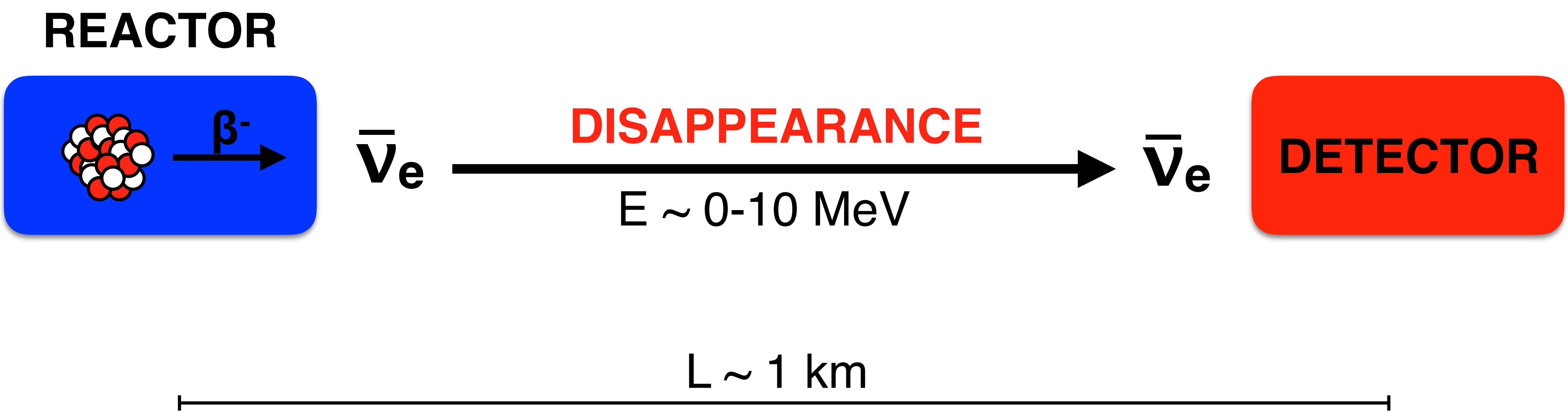
Long baseline accelerator experiments

$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$



NOvA is compatible with $\theta_{23} = \pi/4$

Short baseline reactor experiments

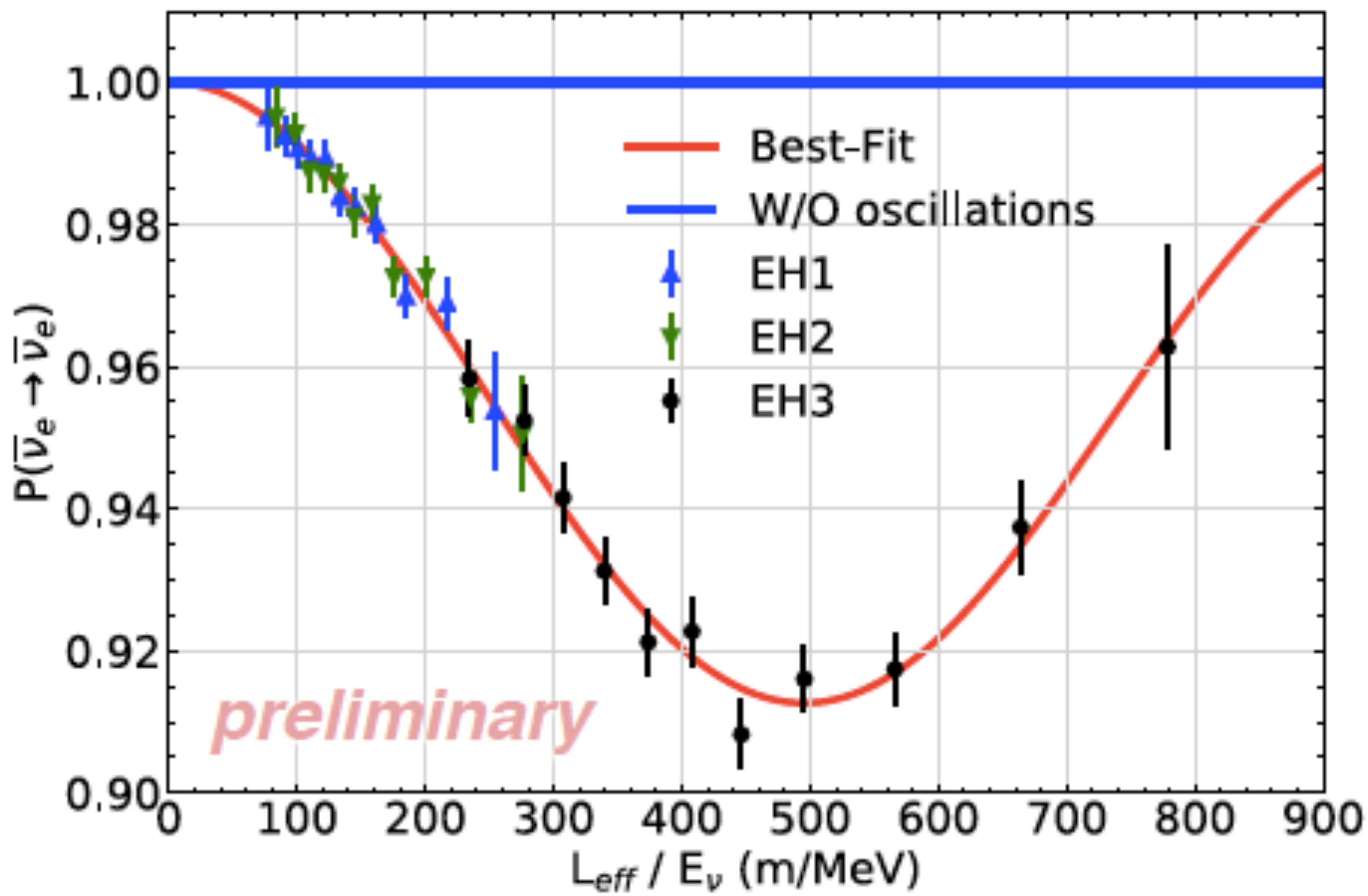


$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

Short baseline reactor experiments

Very large statistics accumulated: O(10^6) events

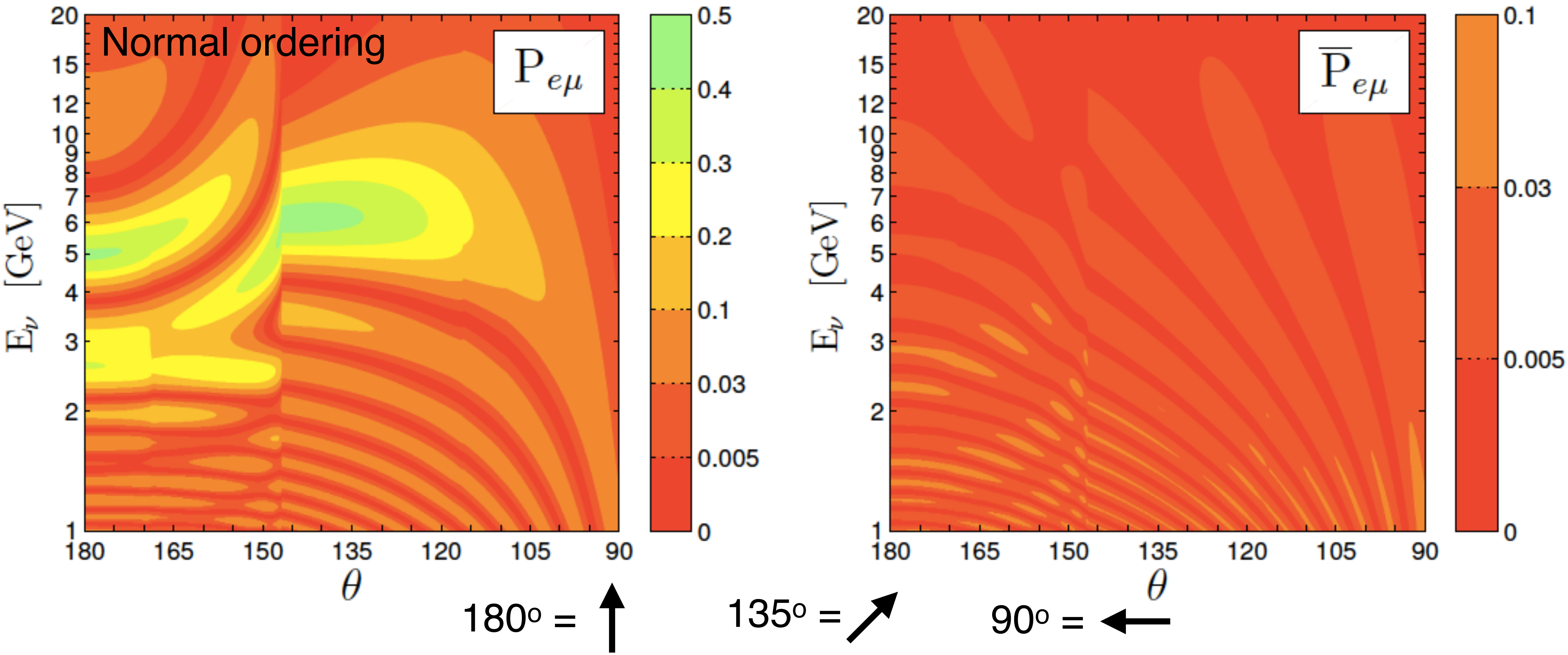
J. Pedro Ochoa-Ricoux, Talk at Neutrino 2018



$\sin^2 2\theta_{13} \sim 0.09$

$\Delta m^2_{31} \sim 2.5 \times 10^{-3}$ eV^2

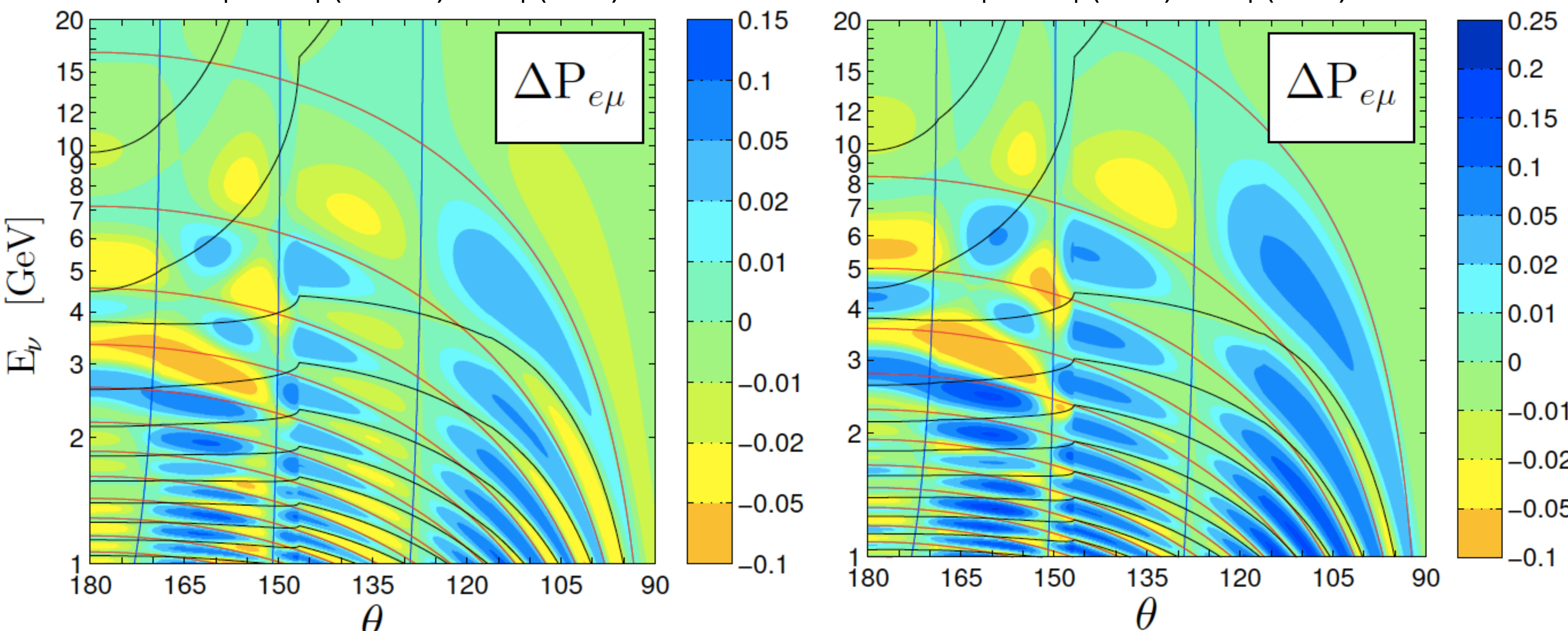
Atmospheric neutrino experiments



Matter effects make $P_{e\mu}$ very different from $\overline{P}_{e\mu}$

Atmospheric neutrino experiments

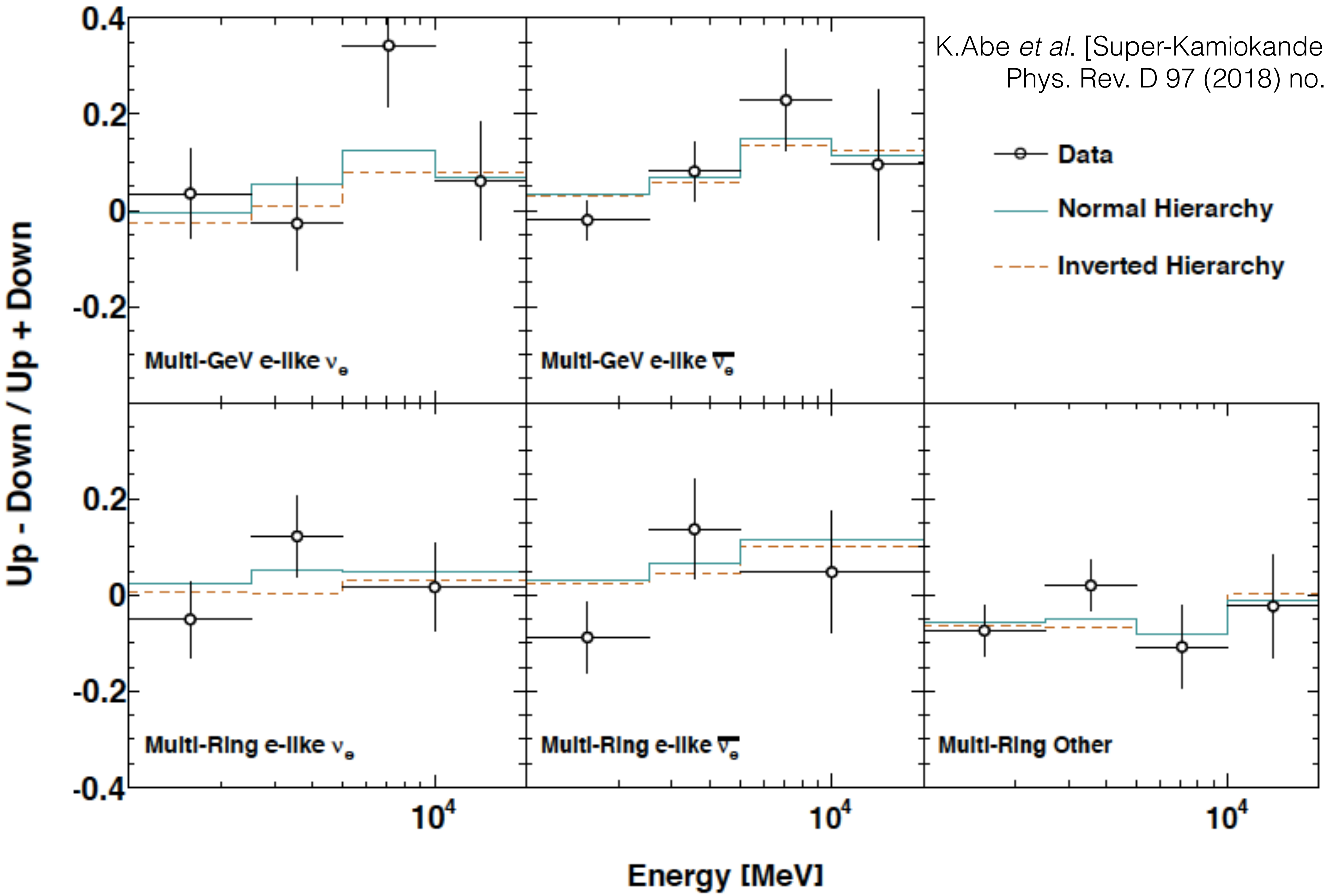
$\Delta P_{e\mu} = P_{e\mu}(\delta=\pi/2) - P_{e\mu}(\delta=0)$ $\Delta P_{e\mu} = P_{e\mu}(\delta=\pi) - P_{e\mu}(\delta=0)$



180° = ↑ 135° = ↗ 90° = ←

Atmospheric neutrinos are also sensitive to δ

Atmospheric neutrino experiments



K.Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D 97 (2018) no.7, 072001

SK prefers NO and 2nd octant because of excess of ν_e in e-like events

Long baseline accelerator experiments

$$P_{\mu e} \simeq P_{\rm atm} + P_{\rm sol} \underset{\text{IO}}{\overset{\text{NO}}{\pm}} 2\sqrt{P_{\rm atm}}\sqrt{P_{\rm sol}}\cos\left(\delta \underset{\text{IO}}{\overset{\text{NO}}{\pm}} \frac{\Delta m^2_{31} L}{4E}\right)$$

Experiment work near oscillation maximum: $\Delta m^2_{31} L/(4E) \sim \pi/2$

Ordering	δ	$\pm\cos(\delta \pm \Delta m^2_{31} L/(4E))$
normal	3π/2	+1
normal	π/2	-1
normal	0	0
normal	π	0

Long baseline accelerator experiments

$$\bar{P}_{\mu e} \simeq \bar{P}_{\rm atm} + \bar{P}_{\rm sol} \underset{\rm IO}{\overset{\rm NO}{\pm}} 2\sqrt{\bar{P}_{\rm atm}}\sqrt{\bar{P}_{\rm sol}} \cos\left(\delta \underset{\rm IO}{\overset{\rm NO}{\mp}} \frac{\Delta m^2_{31} L}{4E}\right)$$

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normal	π	0

Global analyses comparison

Bari Group

F. Capozzi, E. Lisi, A. Marrone, A. Palazzo

Prog. Part. Nucl. Phys. 102 (2018) 48

NUFIT Group

I. Esteban, M.C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni, T. Schwetz

JHEP 1901 (2019) 106

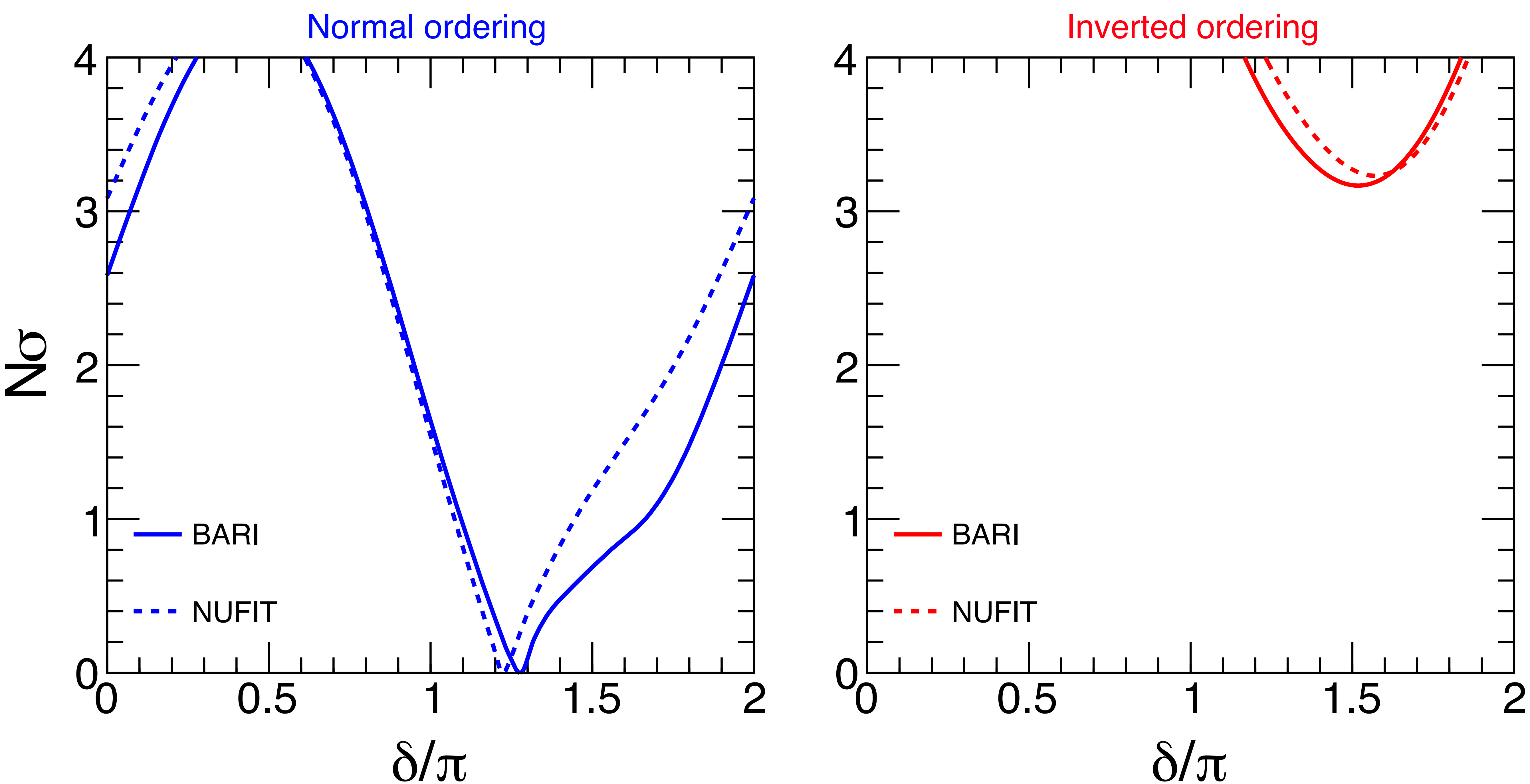
Valencia Group

P.F. de Salas, D.V. Forero, C.A. Ternes, M. Tortola and J.W.F. Valle

Phys. Lett. B 782, 633 (2018)

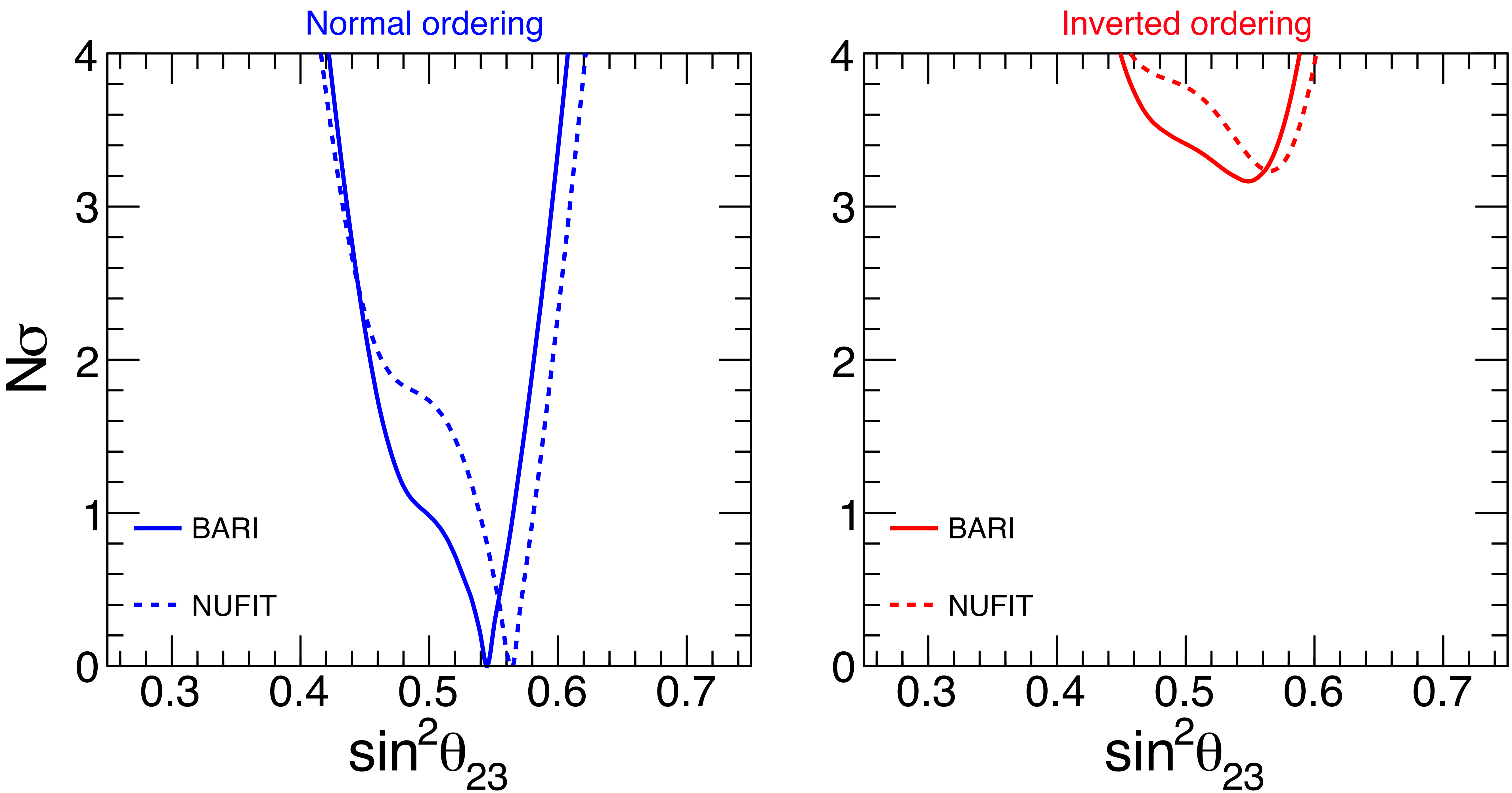
Global analyses comparison

Comparison in terms of δ



Global analyses comparison

Comparison in terms of θ_{23}



$0\nu\beta\beta$ constraints on $m_{\beta\beta}$

We convert the constraint on $T_{0\nu\beta\beta}$ from KamLAND-ZEN to $m_{\beta\beta}$

$$\chi^2(m_{\beta\beta}) = \min_{|M|}\left[\boxed{\chi^2(T_{0\nu\beta\beta}(m_{\beta\beta}, |M|))} + \boxed{\chi^2(|M|)}\right]$$

given by the collaboration
Phys. Rev. Lett. 117, no. 8, 082503 (2016)

our calculation

$$\boxed{\chi^2(|M|) = \frac{(\eta - \bar{\eta})^2}{\sigma_\eta^2}}$$

gA quenching uncertainty

residual uncertainty

$$\eta = \log_{10}(|M|) = \bar{\eta} + \boxed{\alpha(g_A - 1)} + \boxed{s\beta} \pm \boxed{\sigma}$$

short-range correlations

For ^{136}Xe we have α=0.458, β=0.021 σ=0.032

We assume σ_{gA}=0.15.

$$\sigma_\eta = \sqrt{(\alpha\sigma_{g_A})^2 + \beta^2 + \sigma^2} = 0.078$$

Constraint on Σ

We take the constraint from different cosmological observations

TABLE II: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\mathrm{CDM}+\Sigma$ and extended $\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$ models. The datasets refer to various combinations of the Planck power angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), reionization optical depth τ_{HFI}, lensing potential power spectrum (lensing), and BAO measurements. For each of the 12 cases we report the 2σ upper bounds on $\Sigma = m_1 + m_2 + m_3$ for NO and IO, together with the $\Delta\chi^2$ difference between the two mass orderings (with one digit after decimal point). For any Σ, the masses m_i are taken to obey the δm^2 and Δm^2 constraints coming from oscillation data. See the text for more details.

#	Model	Cosmological data set	Σ/eV (2σ), NO	Σ/eV (2σ), IO	$\Delta\chi^2_{\mathrm{IO-NO}}$
1	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI}	< 0.72	< 0.80	0.7
2	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\mathrm{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	−0.1
8	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\mathrm{CDM}+\Sigma+A_{\mathrm{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, Melchiorri and A. Palazzo, Phys. Rev. D 95 (2017) no.9, 096014

Constraint on Σ

We take the constraint from different cosmological observations

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conservative dataset

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, Melchiorri and A. Palazzo, Phys. Rev. D 95 (2017) no.9, 096014

Constraint on Σ

We take the constraint from different cosmological observations

TABLE II: Results of the global 3ν analysis of cosmological data within the standard $\Lambda\text{CDM} + \Sigma$ and extended $\Lambda\text{CDM} + \Sigma + A_{\text{lens}}$ models. The datasets refer to various combinations of the Planck power angular CMB temperature power spectrum (TT) plus polarization power spectra (TE, EE), reionization optical depth τ_{HFI}, lensing potential power spectrum (lensing), and BAO measurements. For each of the 12 cases we report the 2σ upper bounds on $\Sigma = m_1 + m_2 + m_3$ for NO and IO, together with the $\Delta\chi^2$ difference between the two mass orderings (with one digit after decimal point). For any Σ, the masses m_i are taken to obey the δm^2 and Δm^2 constraints coming from oscillation data. See the text for more details.

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aggressive dataset

F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, Melchiorri and A. Palazzo, Phys. Rev. D 95 (2017) no.9, 096014

Constraints on Σ

Free parameters in conservative approach:

$$\Omega_b, \Omega_{cm}, \tau, A_s, n_s, \Sigma, A_{lens}$$

Free parameters in aggressive approach:

$$\Omega_b, \Omega_{cm}, \tau, A_s, n_s, \Sigma$$
$$(A_{lens} = 1)$$