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

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

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

Neutrino mass-mixing: an overview

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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

δ

mass ordering

α_1, α_2

m_0

Precision era
(< 5%)

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
- 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

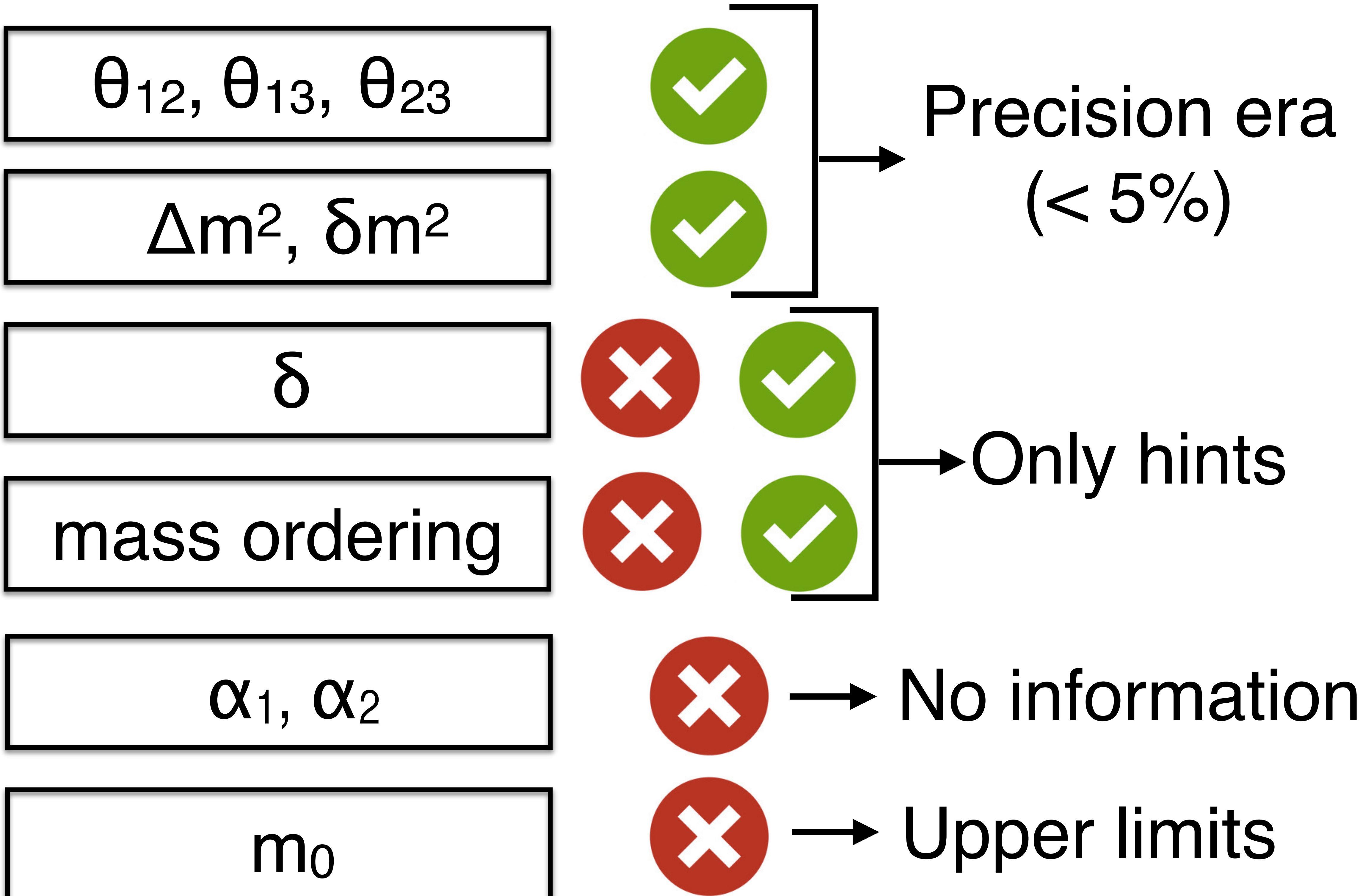
- α_1, α_2

→ No information

- m_0

Neutrino mass-mixing: an overview

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



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

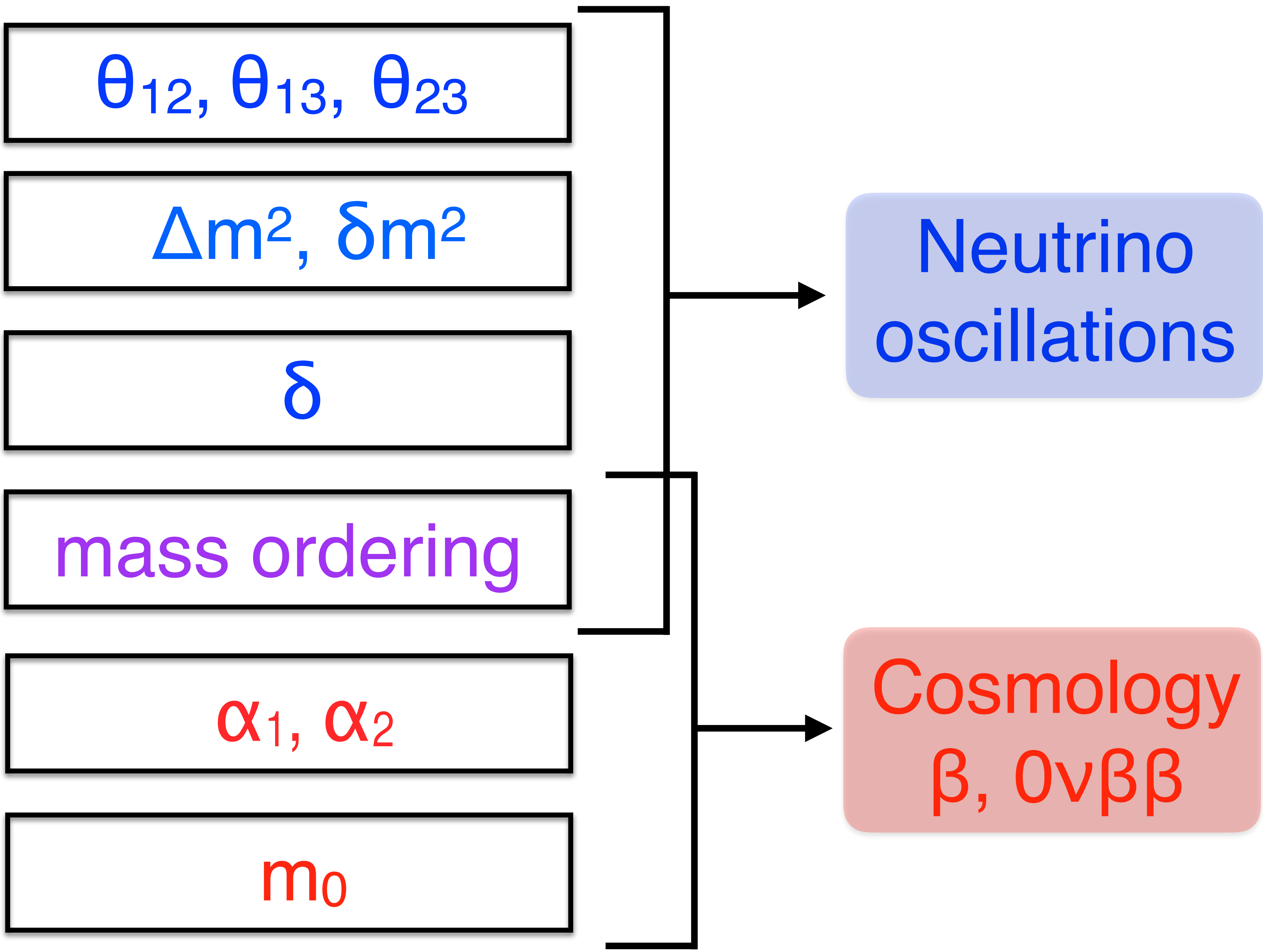
α_1, α_2

m_0

→ Neutrino oscillations

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

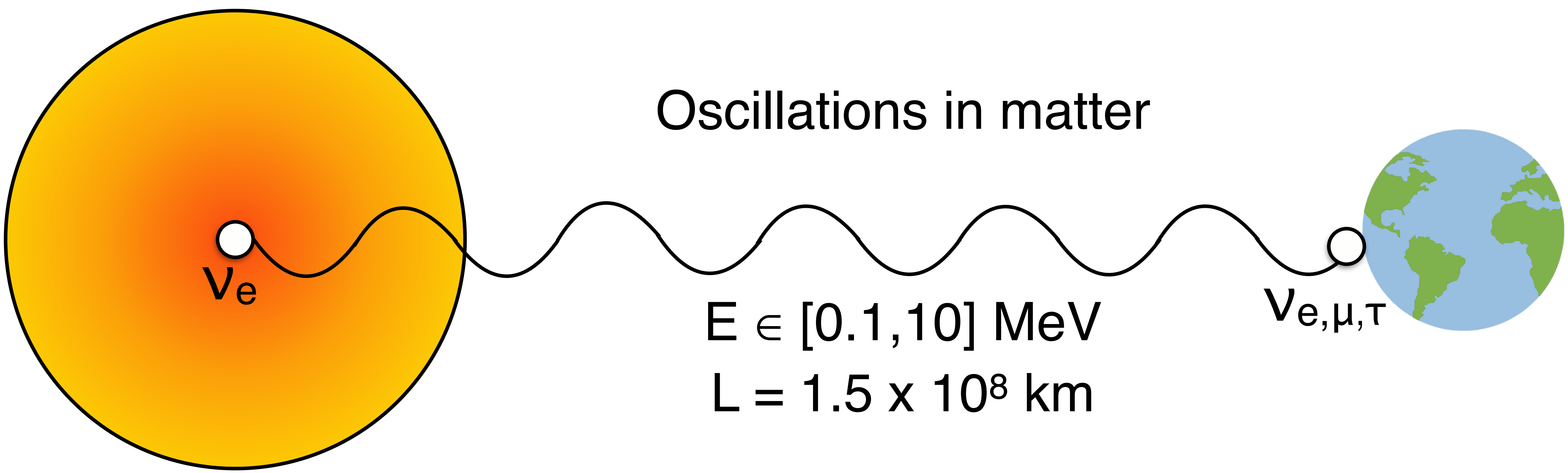
→ **GLOBAL ANALYSIS**

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

Oscillation datasets

Solar (Homestake,Gallex,GNO, Borexino,SNO,SK)	⟷	$(\theta_{12}, \delta m^2, \theta_{13})$

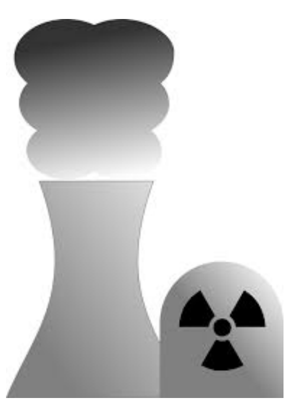


K. Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D 94 (2016) no.5, 052010
B. Aharmim *et al.* [SNO Collaboration], Phys. Rev. C 88 (2013) 025501
B. T. Cleveland, *et al.*, Astrophys. J. 496 (1998) 505
J. N. Abdurashitov *et al.* [SAGE Collaboration], Phys. Rev. C 80 (2009)
F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, Phys. Lett. B 685 (2010) 47
M. Agostini *et al.* [BOREXINO Collaboration], Nature 562 (2018) no.7728, 505

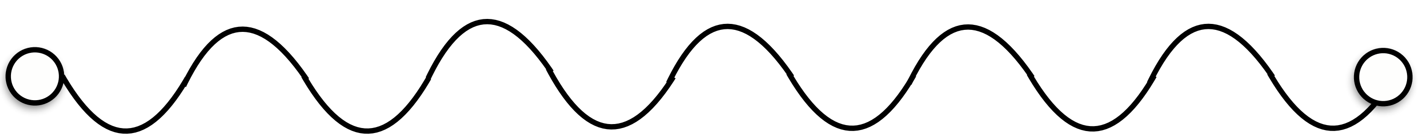
Oscillation datasets

Solar ⟷ $(\theta_{12}, \delta m^2, \theta_{13})$
(Homestake,Gallex,GNO, Borexino,SNO,SK)

KamLAND ⟷ $(\theta_{12}, \delta m^2, \theta_{13})$



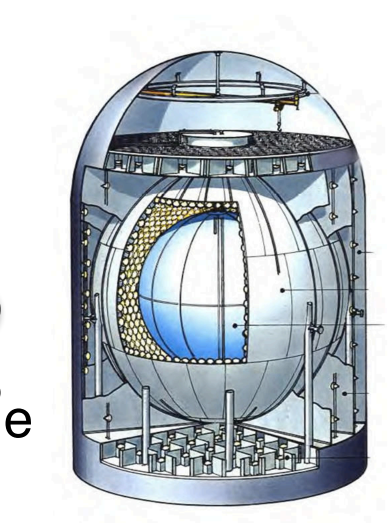
Oscillations in matter



$\bar{\nu}_e$ $\bar{\nu}_e$

$E \in [0,10]$ MeV

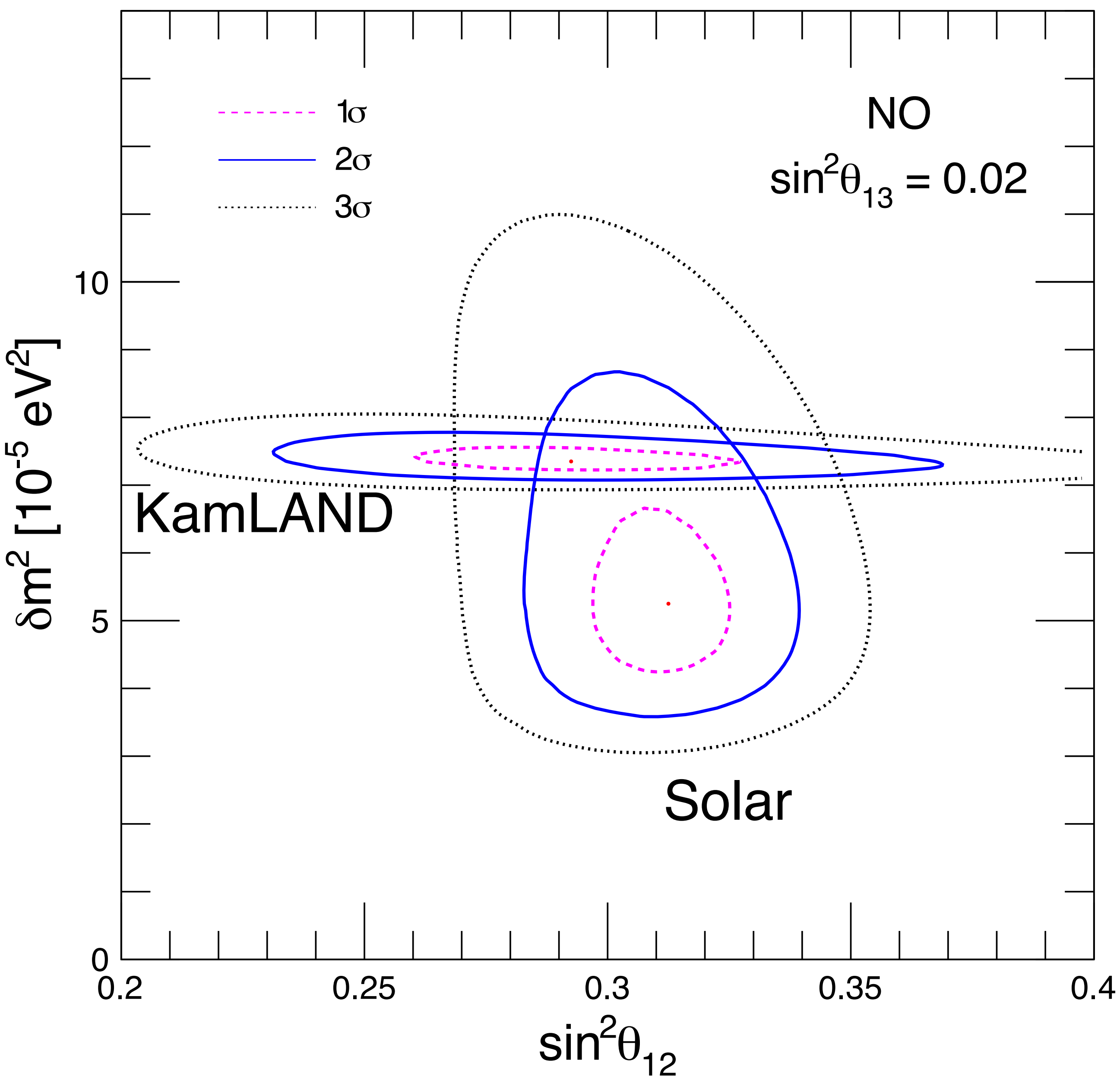
$L \sim 180$ km



A. Gando *et al.* [KamLAND Collaboration], Phys. Rev. D83 (2011) 052002

Solar and KamLAND

Comparison between Solar and KamLAND



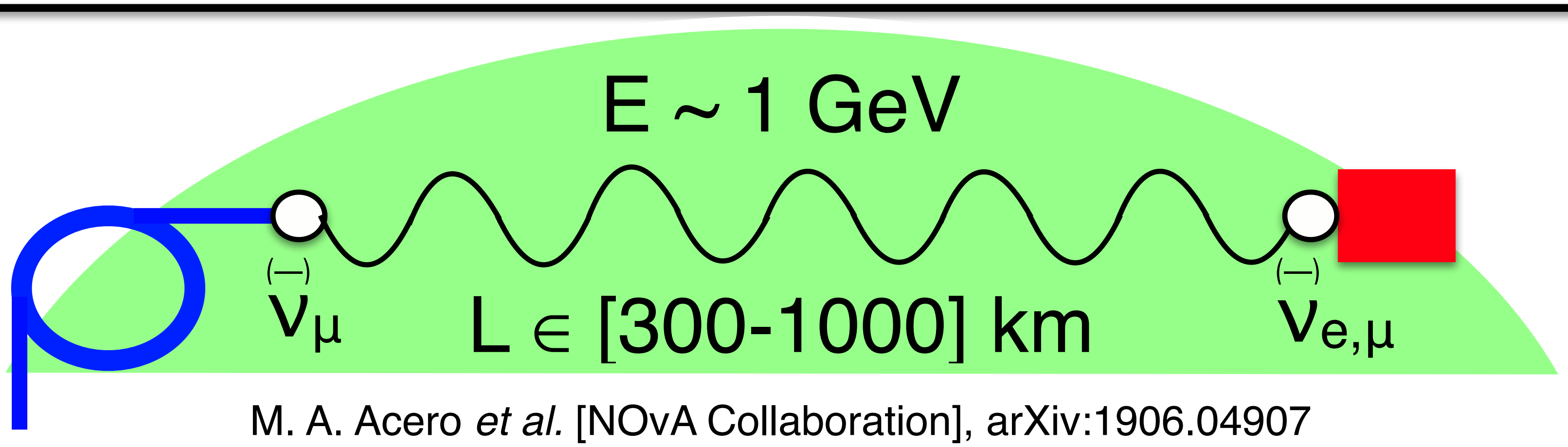
Long standing weak tension in terms of δm^2

Oscillation datasets

Solar (Homestake,Gallex,GNO, Borexino,SNO,SK) ⟷ $(\theta_{12}, \delta m^2, \theta_{13})$

KamLAND ⟷ $(\theta_{12}, \delta m^2, \theta_{13})$

Long baseline acc. (T2K, NOvA, MINOS) ⟷ $(\theta_{23}, \Delta m^2, \delta, \text{MO}, \theta_{13})$

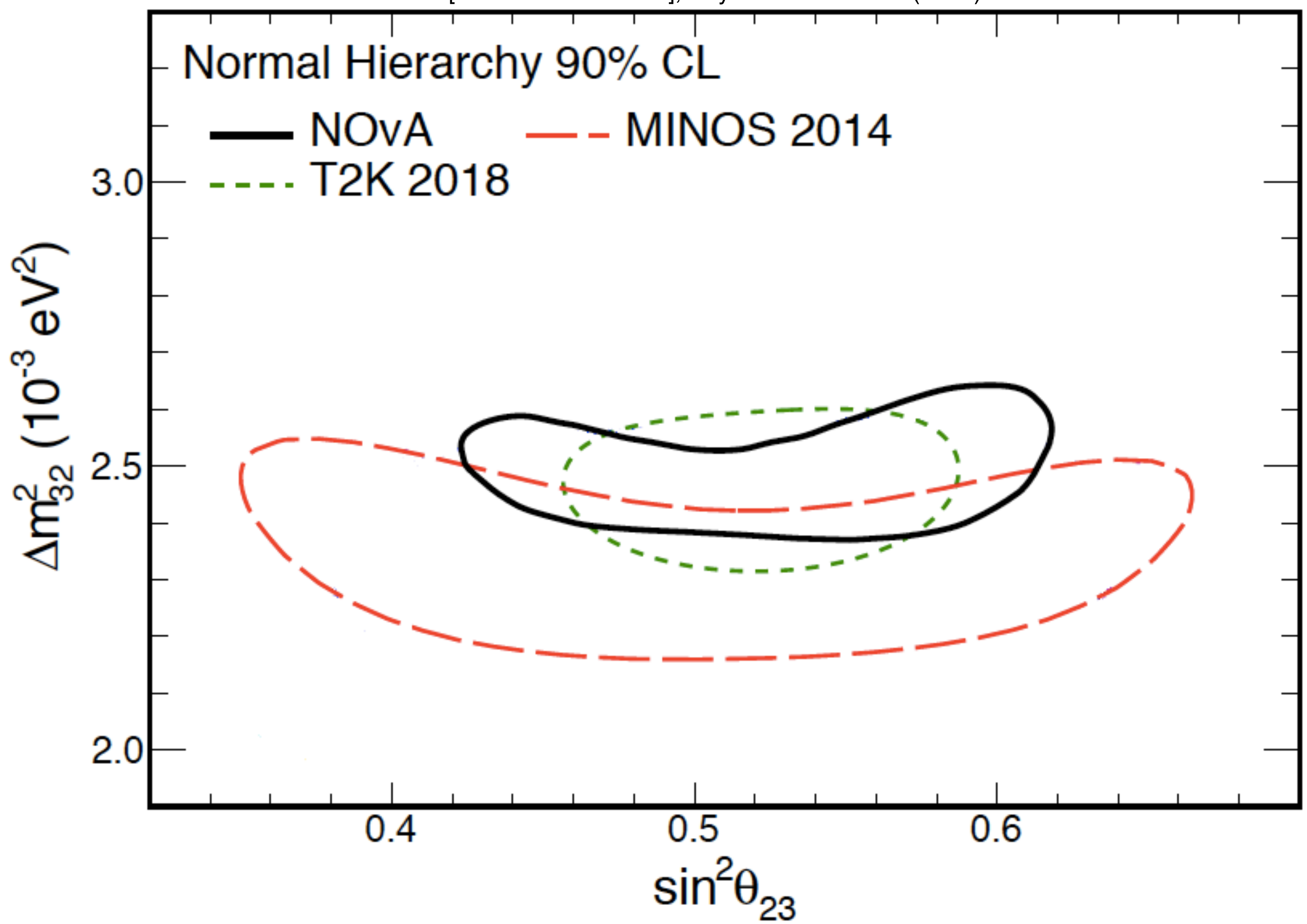


M. A. Acero *et al.* [NOvA Collaboration], arXiv:1906.04907
M. Friend, “Updated Results from the T2K Experiment with 3.13 × 1021 Protons on Target.” KEK seminar, January 10, 2019
P. Adamson et al. [MINOS Collaboration], Phys. Rev. Lett. 112 (2014) 191801

Long baseline accelerator experiments

Comparison of constraints for (θ_{23},Δm^2)

M. A. Acero *et al.* [NOvA Collaboration], Phys. Rev. Lett. 123 (2019) 151803

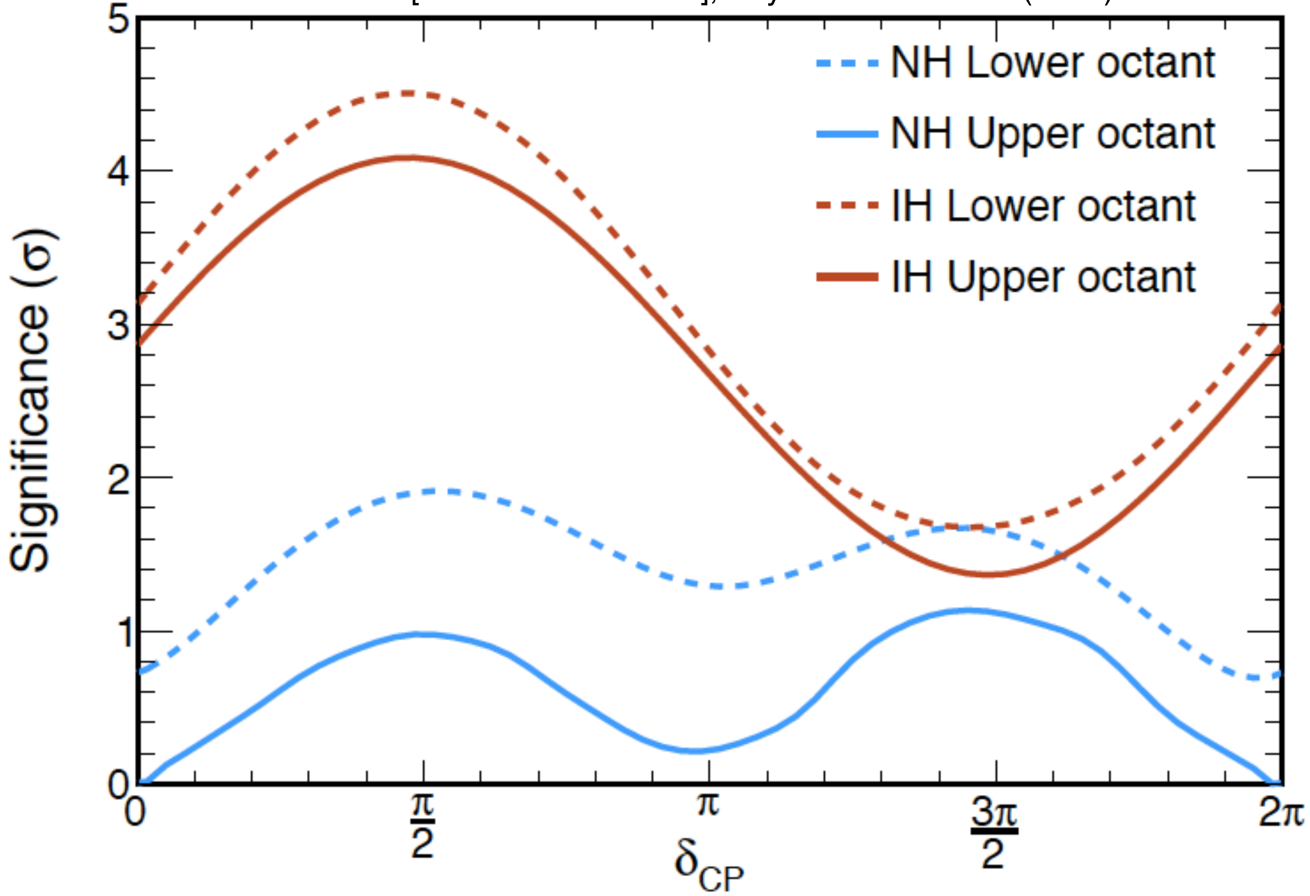


Slight preference for non maximal θ_{23}. Good agreement!

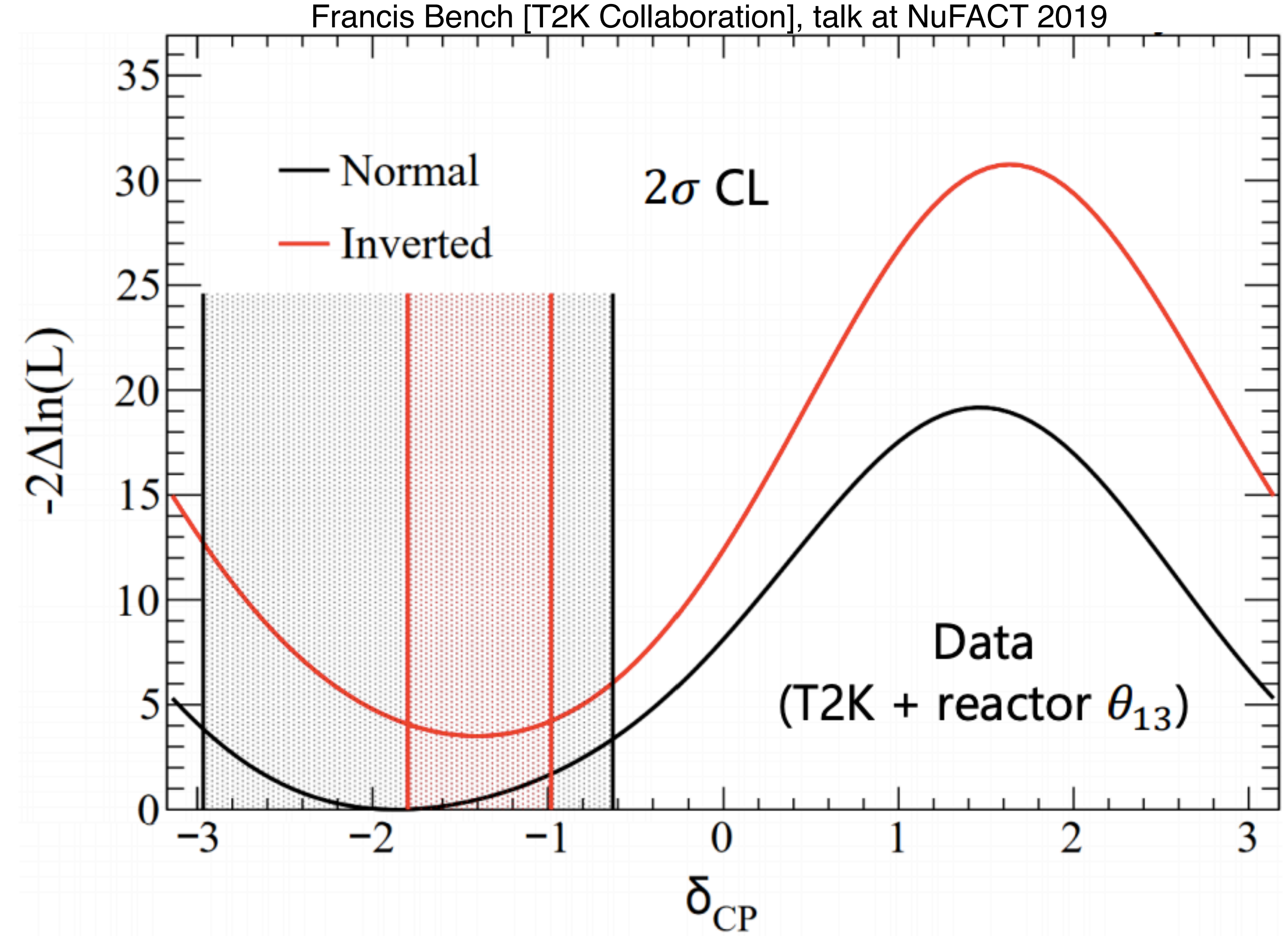
Long baseline accelerator experiments

Comparison of constraints for δ

M. A. Acero *et al.* [NOvA Collaboration], Phys. Rev. Lett. 123 (2019) 151803



Francis Bench [T2K Collaboration], talk at NuFACT 2019



Small tension in terms of δ. Preference for normal ordering

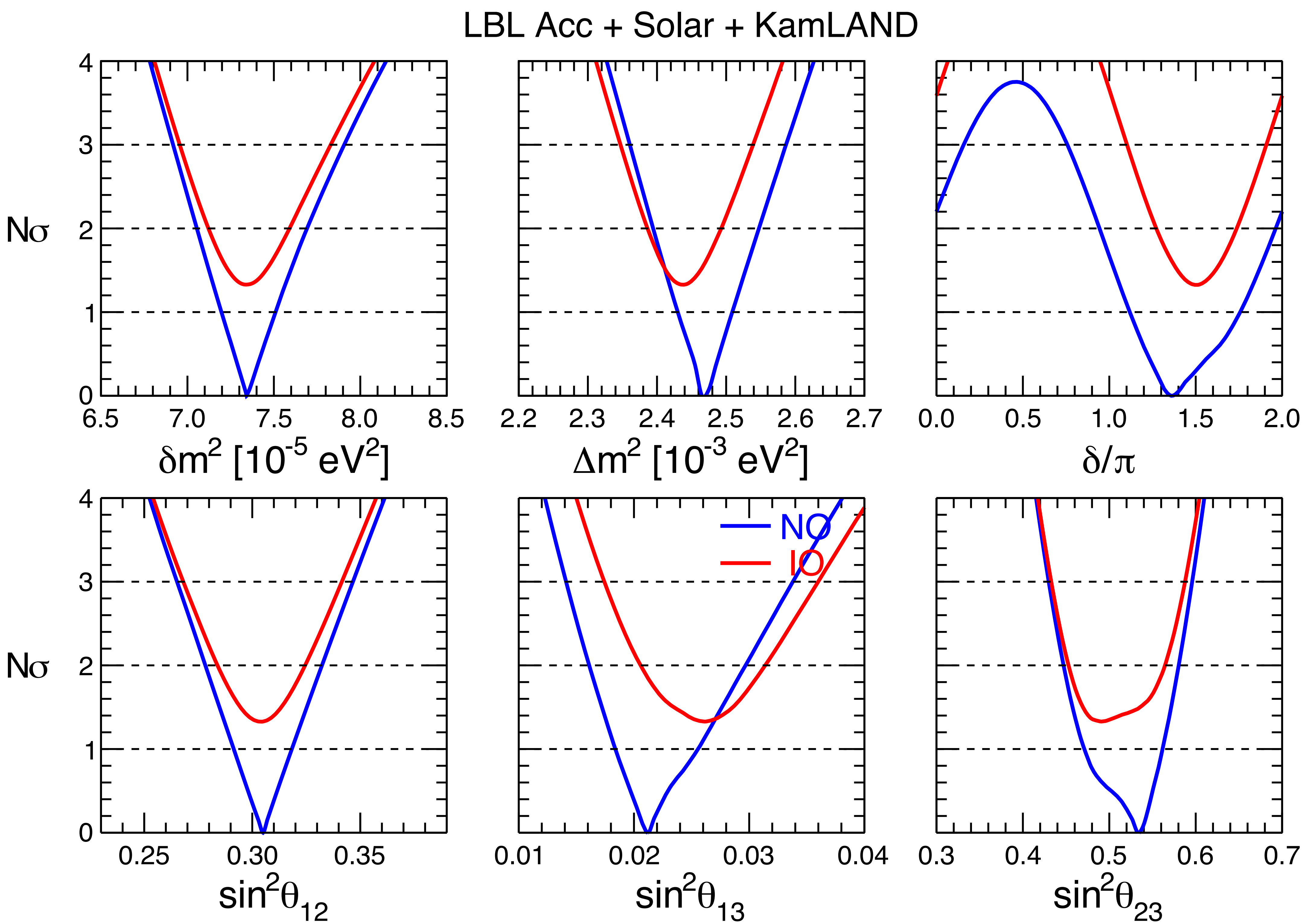
Oscillation datasets

Solar (Homestake,Gallex,GNO, Borexino,SNO,SK)	⟷	$(\theta_{12}, \delta m^2, \theta_{13})$
KamLAND	⟷	$(\theta_{12}, \delta m^2, \theta_{13})$
Long baseline acc. (T2K, NOvA, MINOS)	⟷	$(\theta_{23}, \Delta m^2, \delta, MO, \theta_{13})$

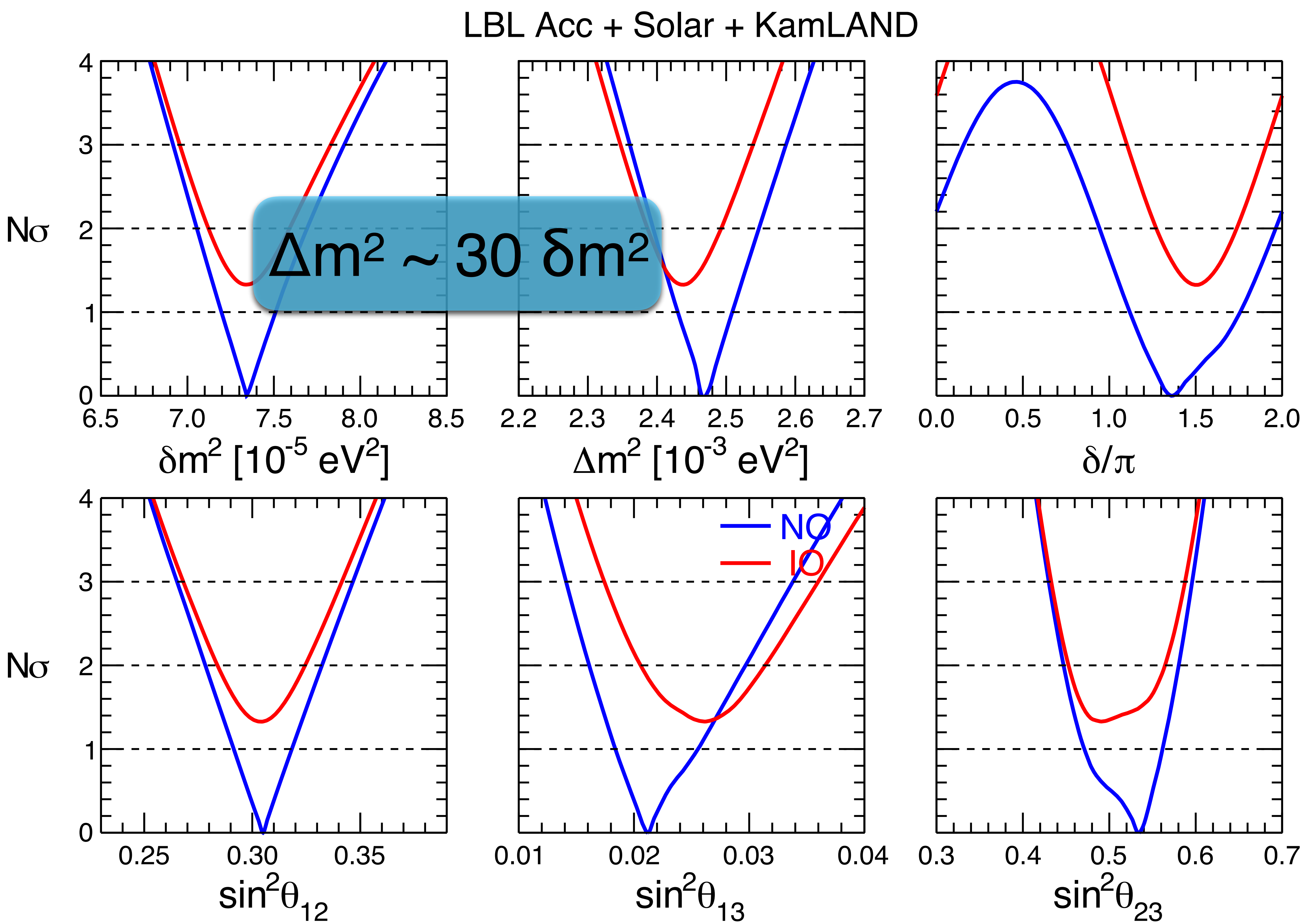
Combined they are sensitive to **all parameters**

LBL Acc + Solar + KamLAND

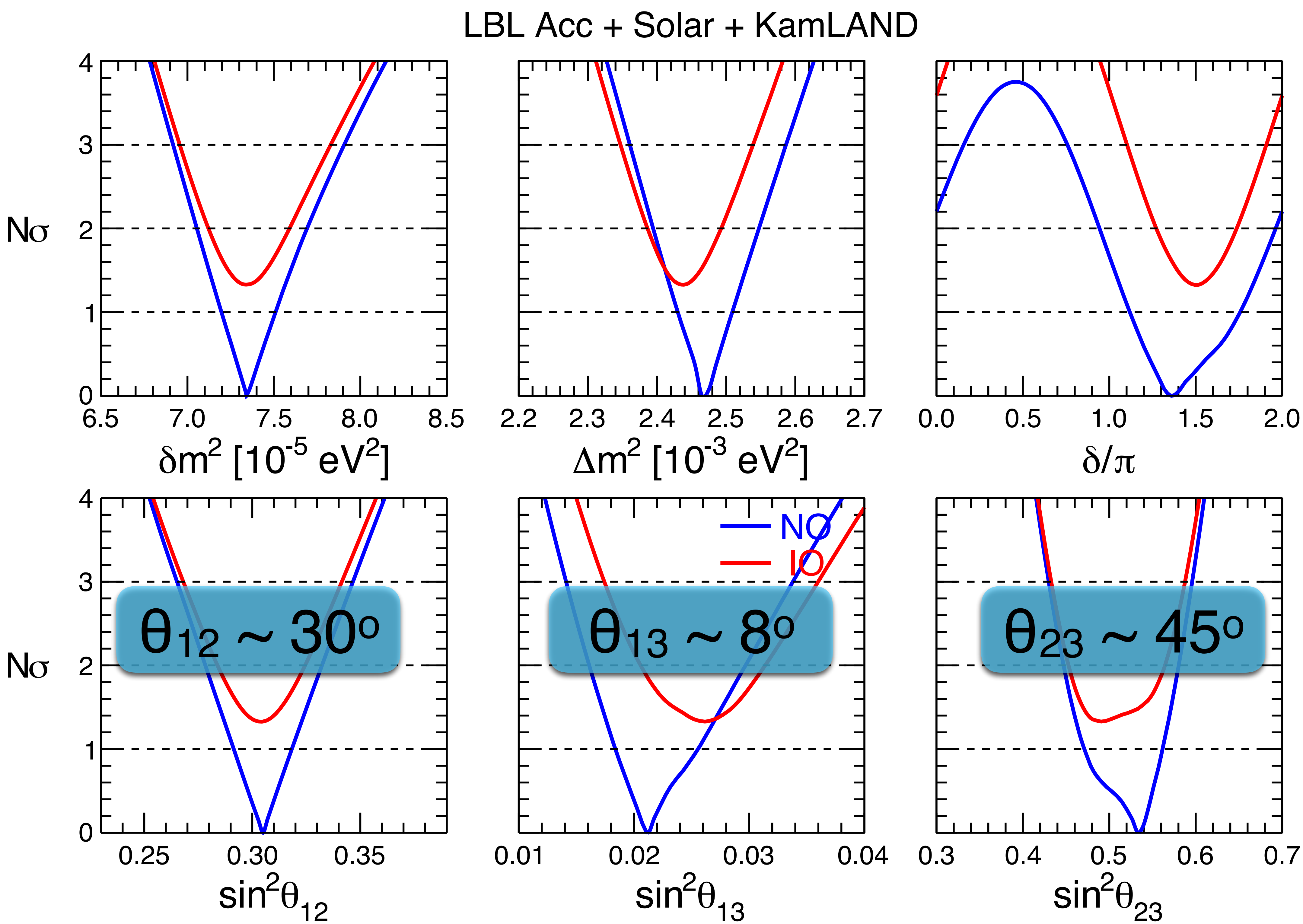
Analysis results



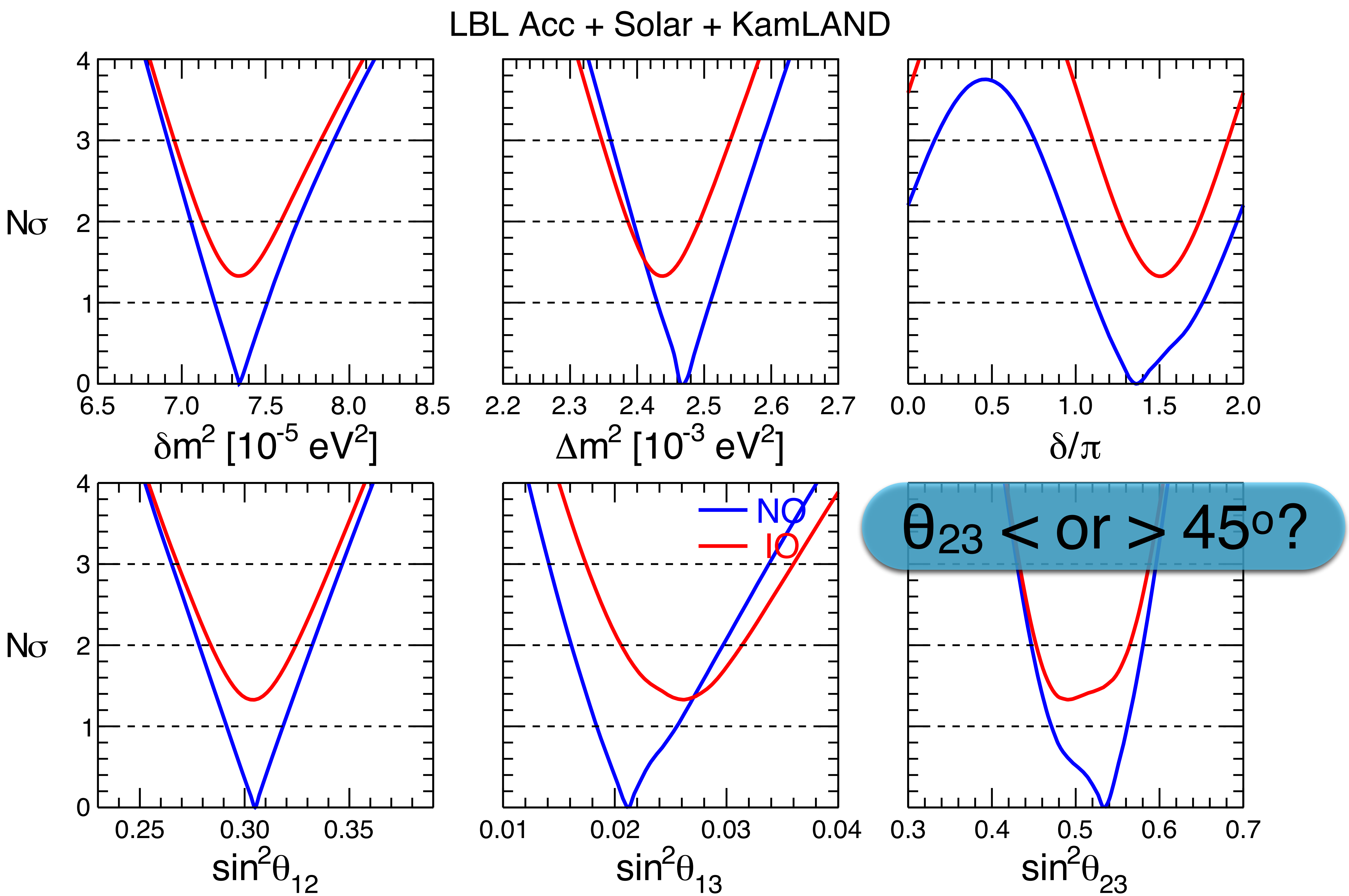
Analysis results



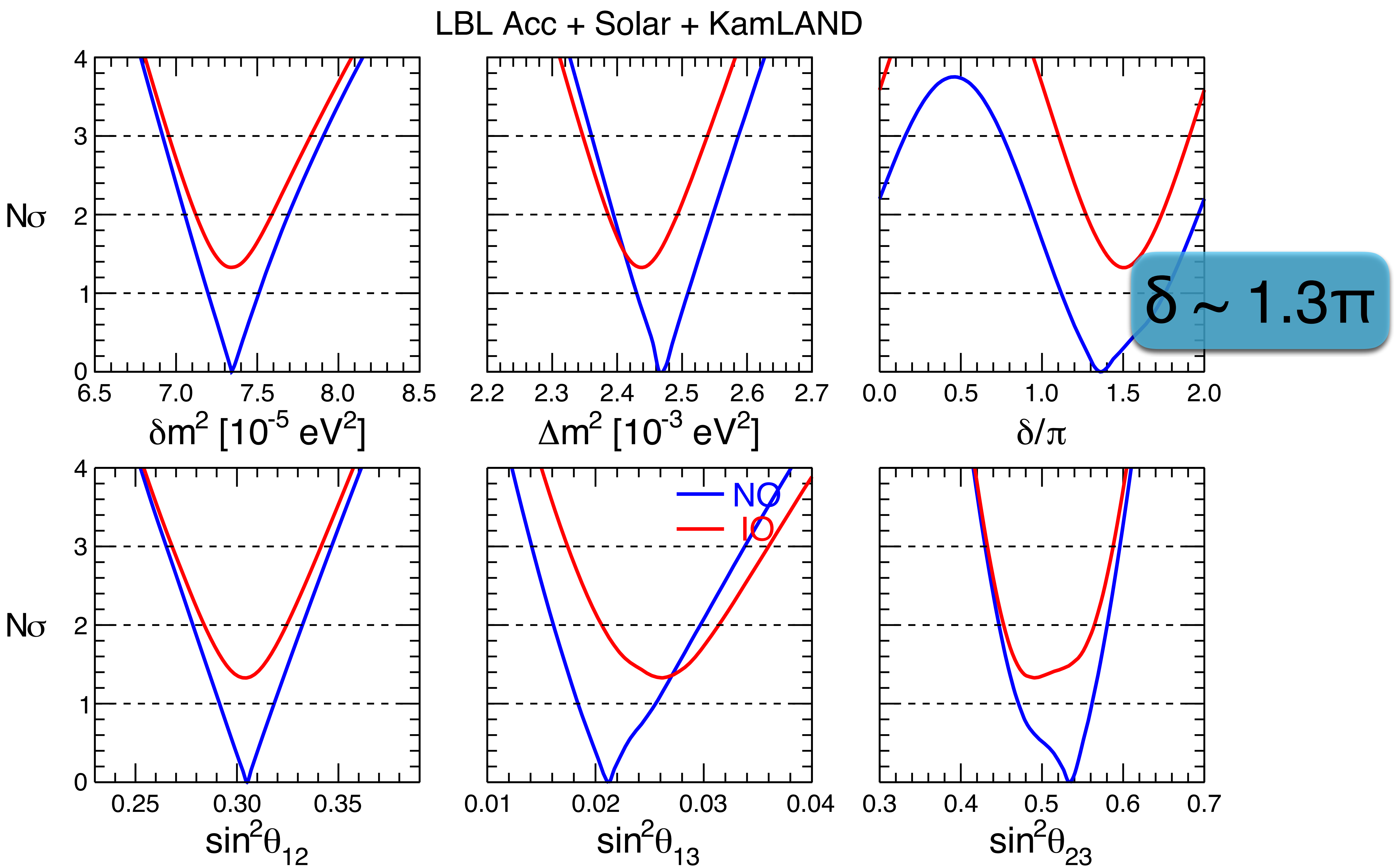
Analysis results



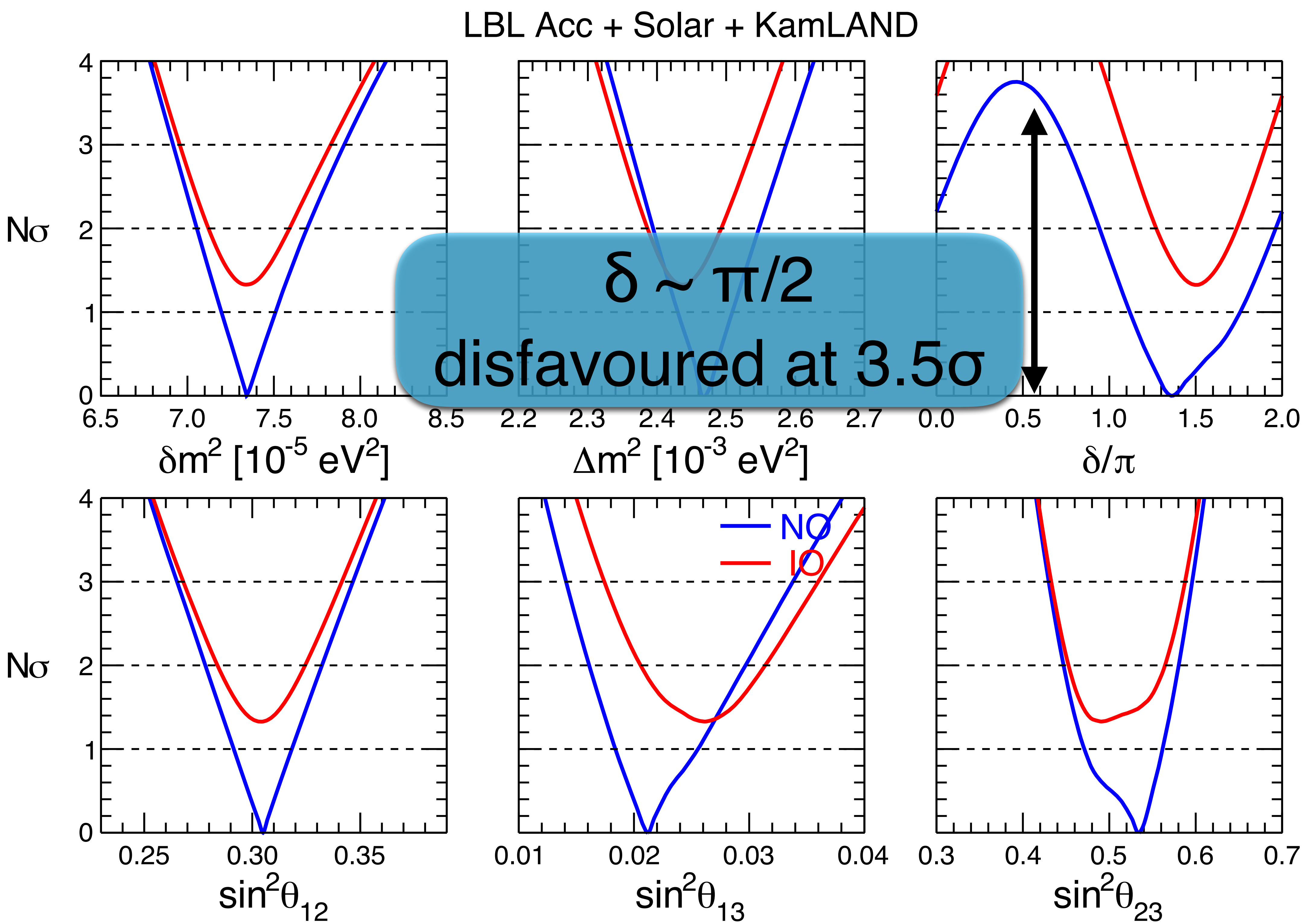
Analysis results



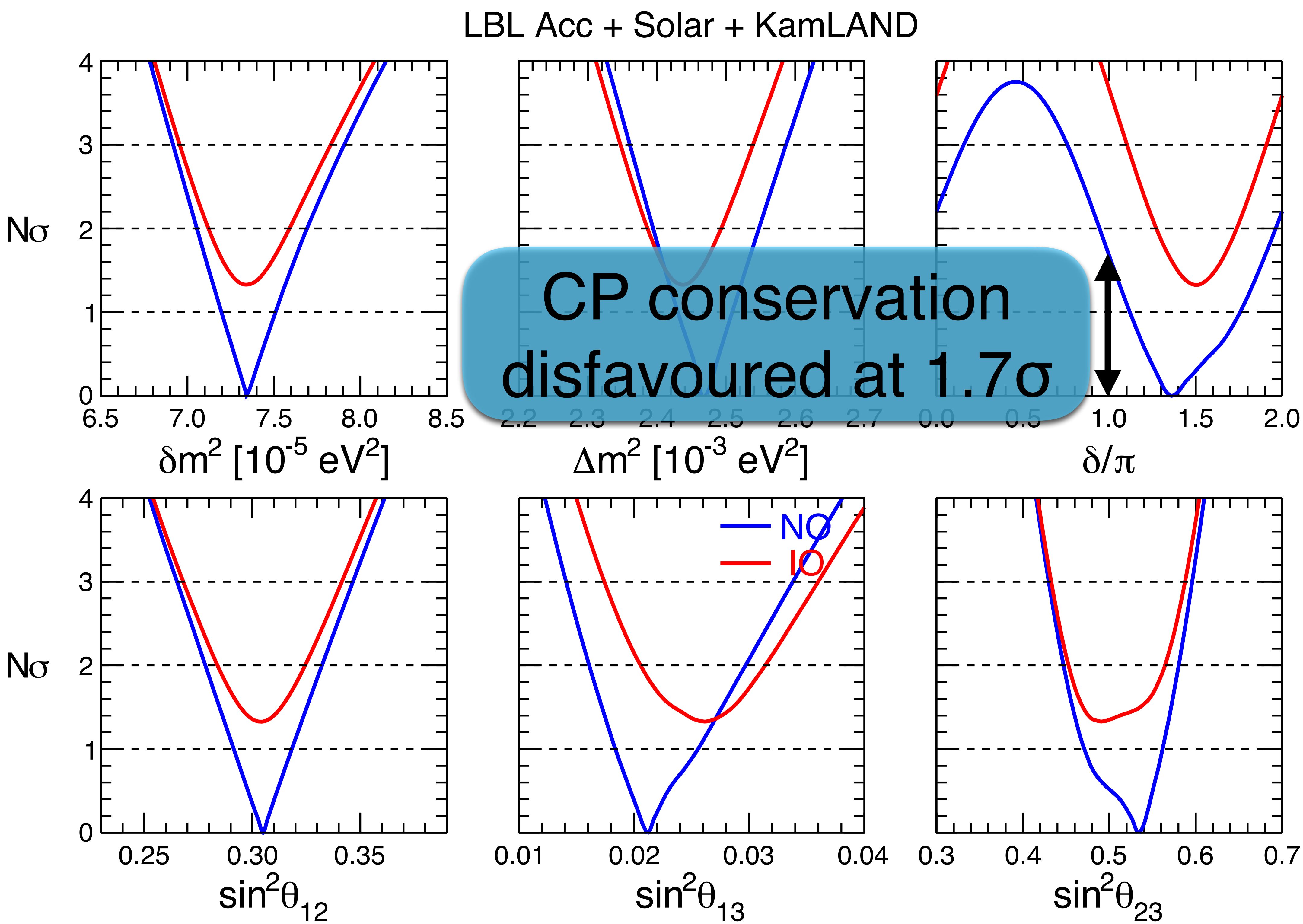
Analysis results



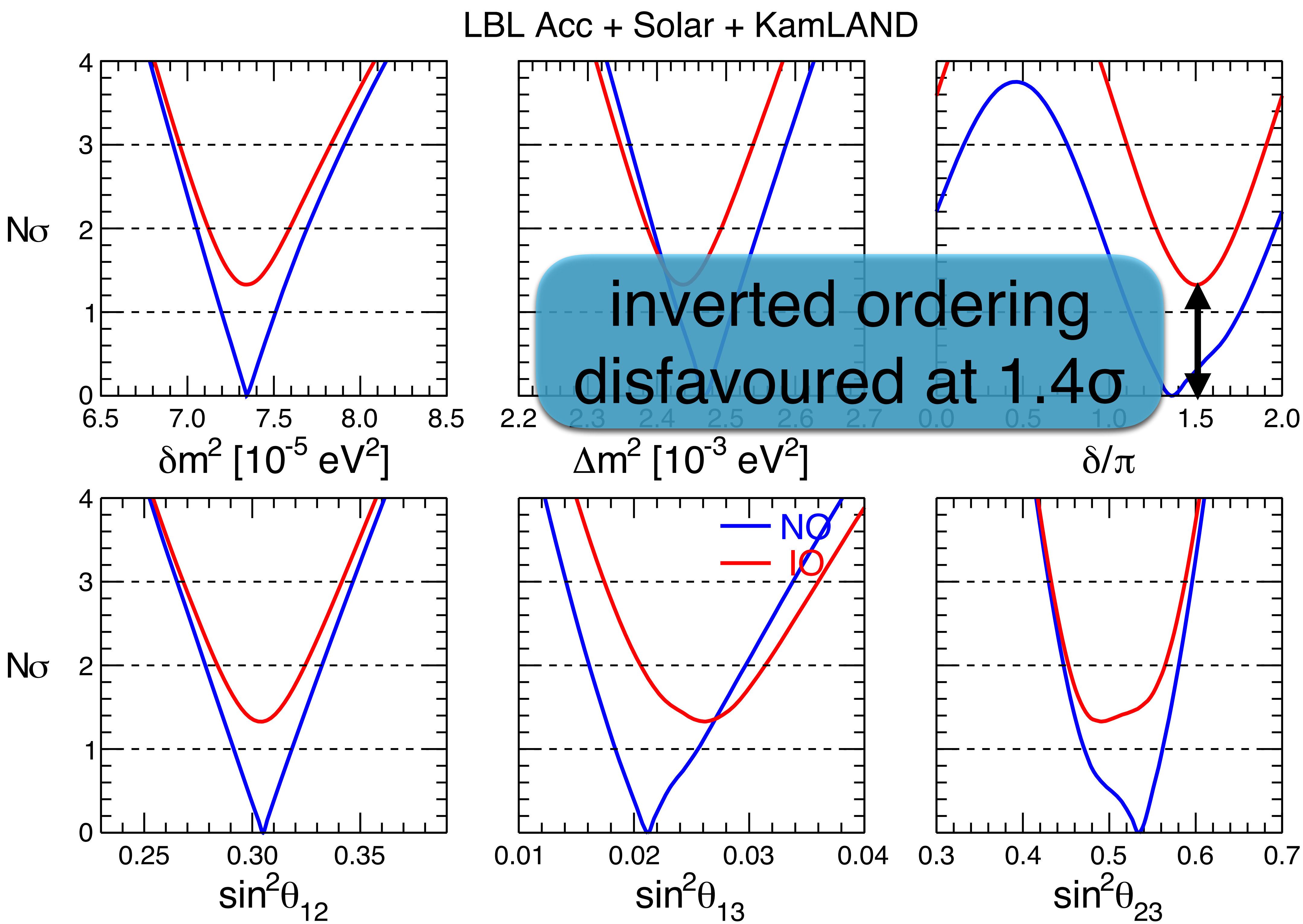
Analysis results



Analysis results



Analysis results

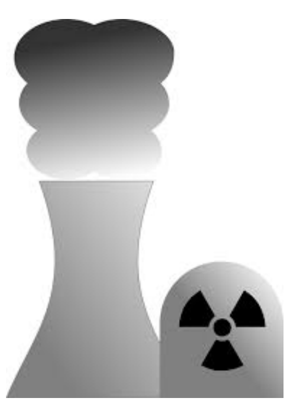


Oscillation datasets

We then strongly constrain θ_{13} with:

SBL reactors ⟷ **(θ_{13}, Δm^2)**

(Daya Bay, Double Chooz, RENO)

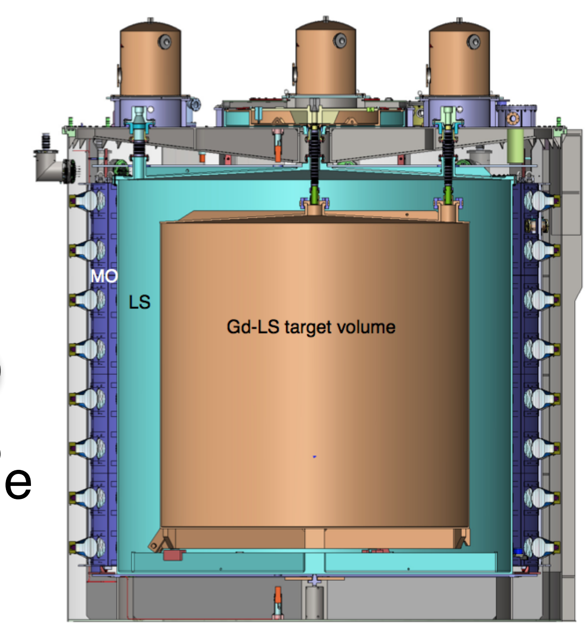


Oscillations in vacuum

$\bar{\nu}_e$ $\bar{\nu}_e$

$L \sim 1$ km

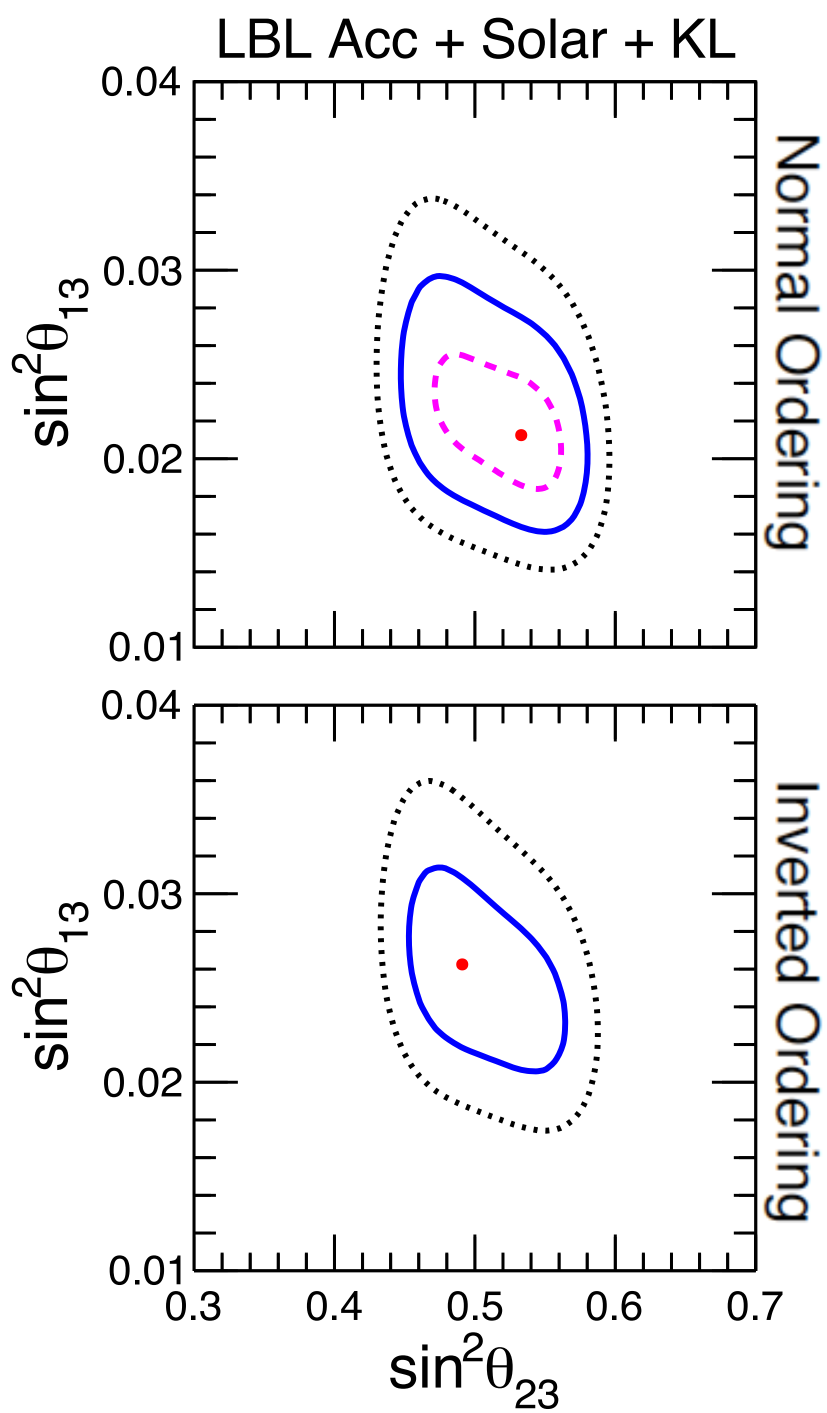
$E \in [0,10]$ MeV



Phys. Rev. D 87 (2013) no.9, 093002

Daya Bay collaboration, D. Adey *et al.*, arXiv:1809.02261
RENO collaboration, G. Bak et al., arXiv:1806.00248
A. Cabrera Serra, Talk given at the CERN EP colloquium, CERN, Switzerland, September 20, 2016.

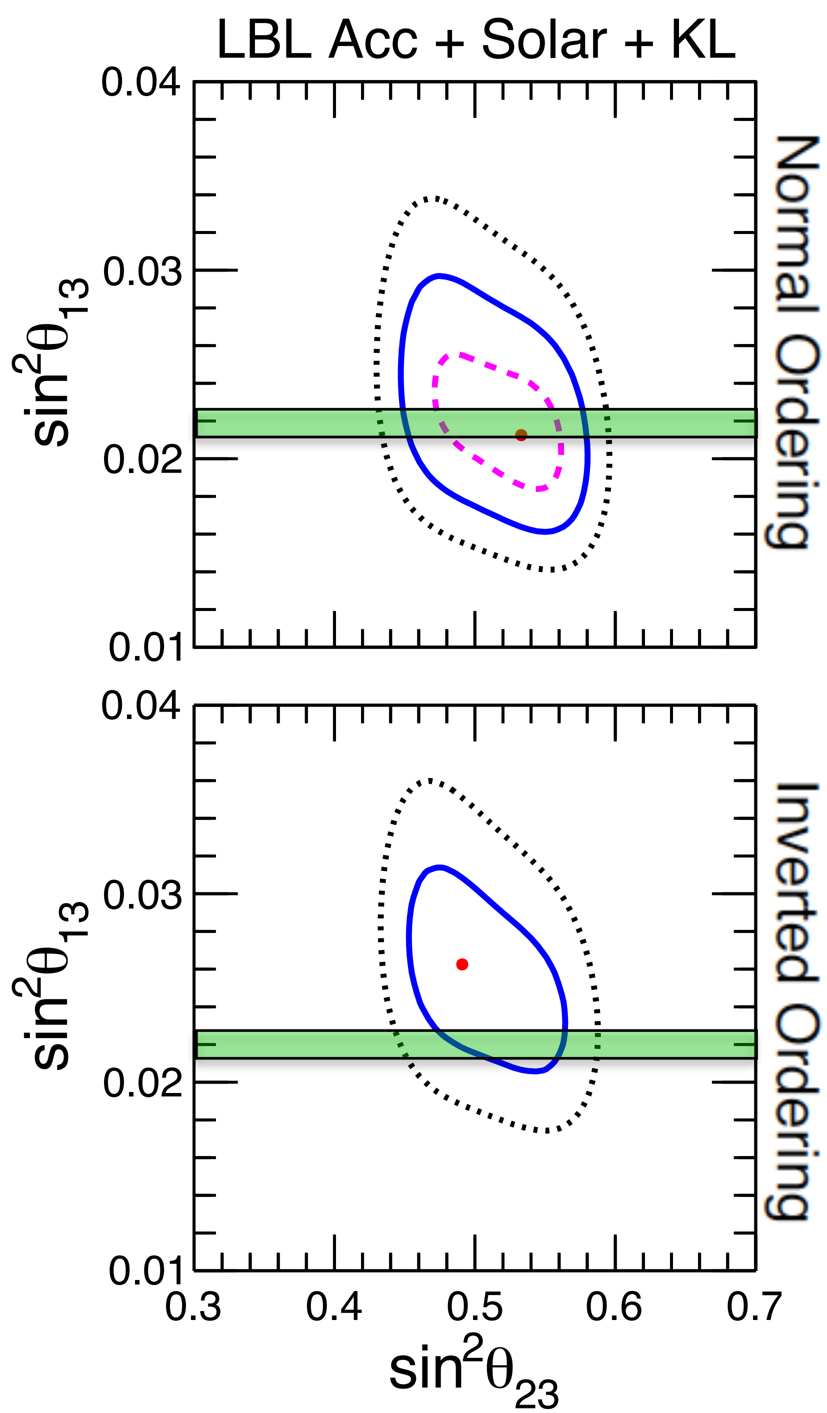
Analysis results: covariance (θ_{23},θ_{13})



θ_{23} and θ_{13} are anti-correlated

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

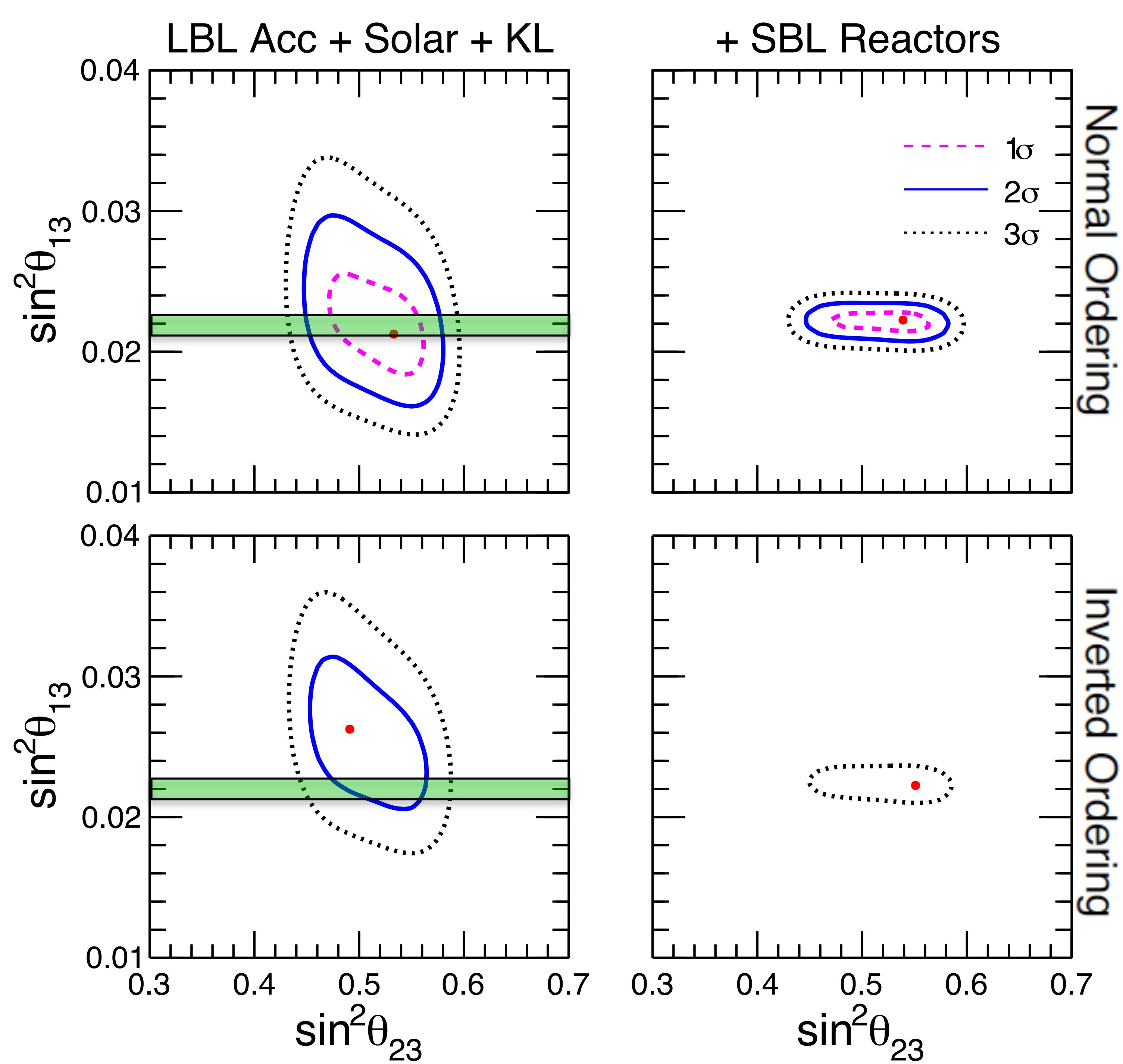
Analysis results: covariance (θ_{23},θ_{13})



1σ SBL reactor constraint

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

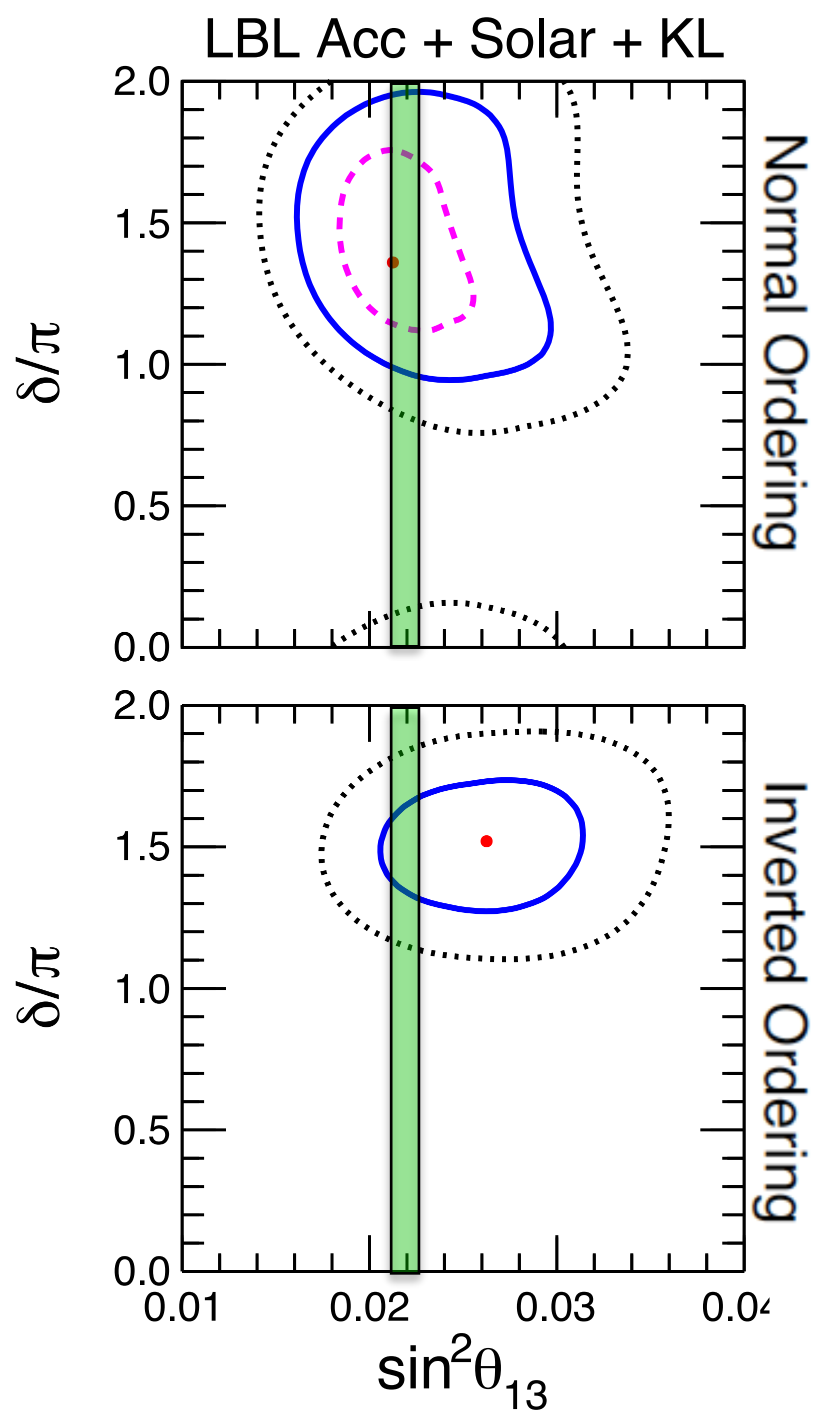
Analysis results: covariance (θ_{23},θ_{13})



1σ SBL reactor constraint

IO disfavored at 2σ

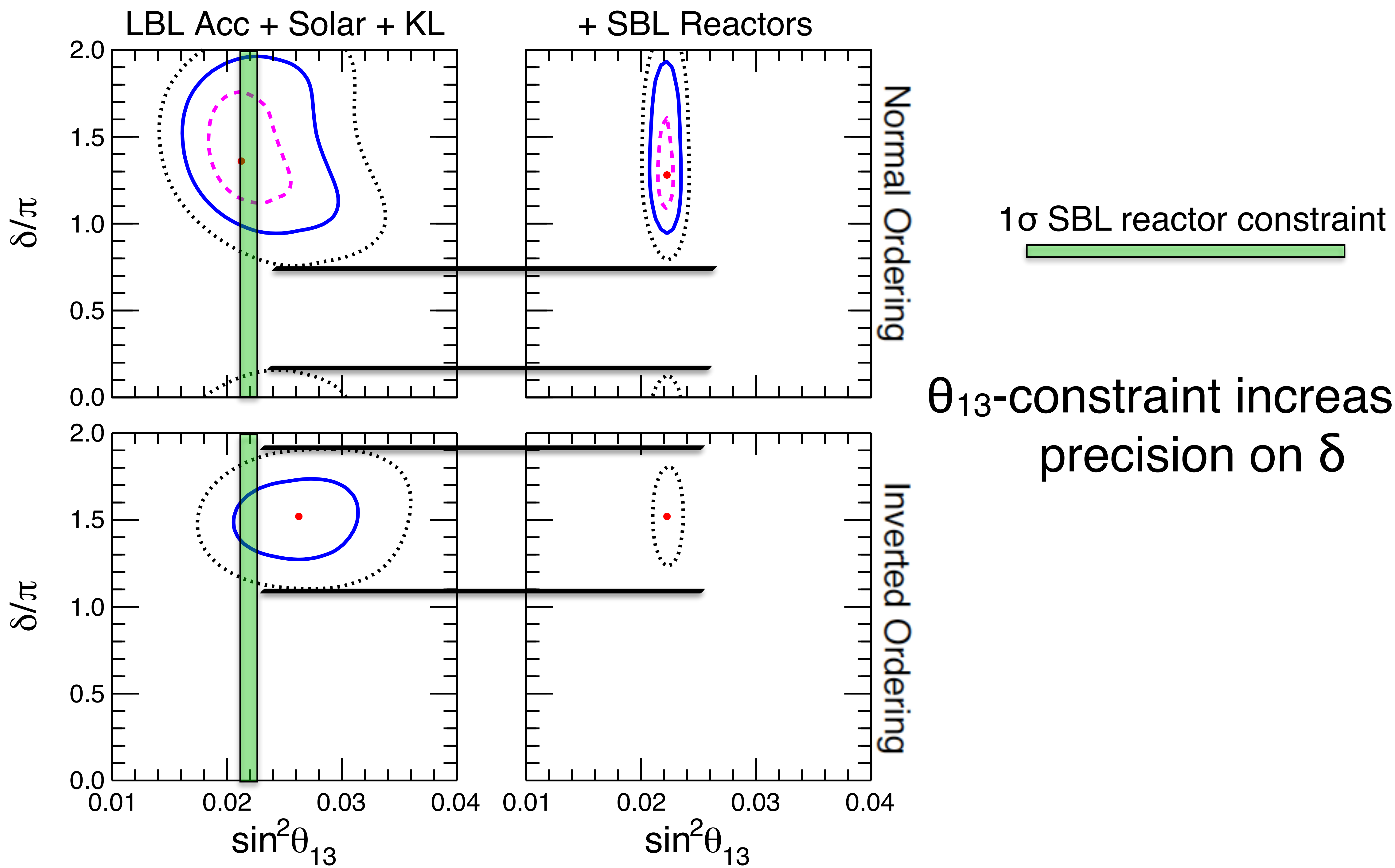
Analysis results: covariance (θ_{13},δ)



1σ SBL reactor constraint

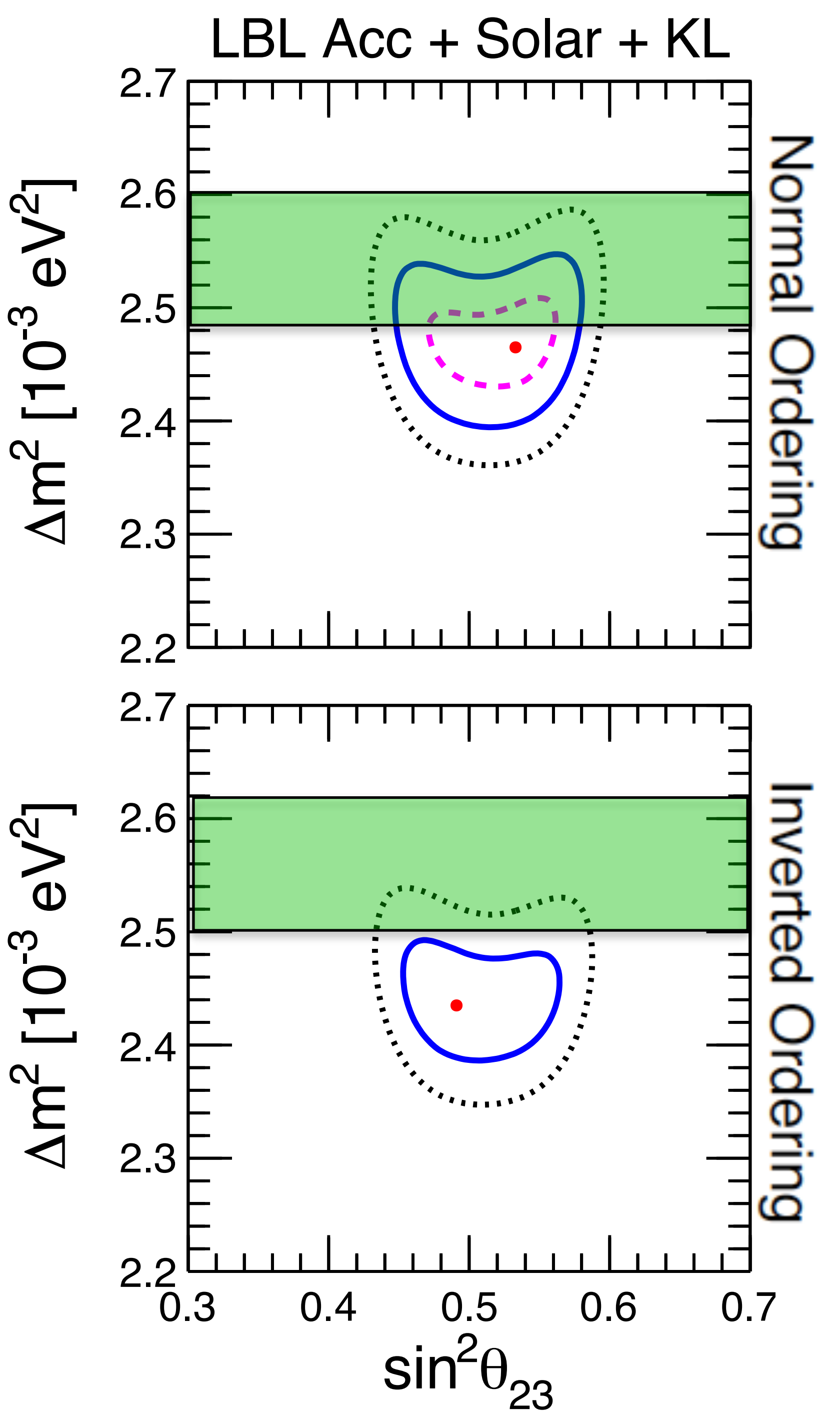
θ_{13}-constraint increases precision on δ

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



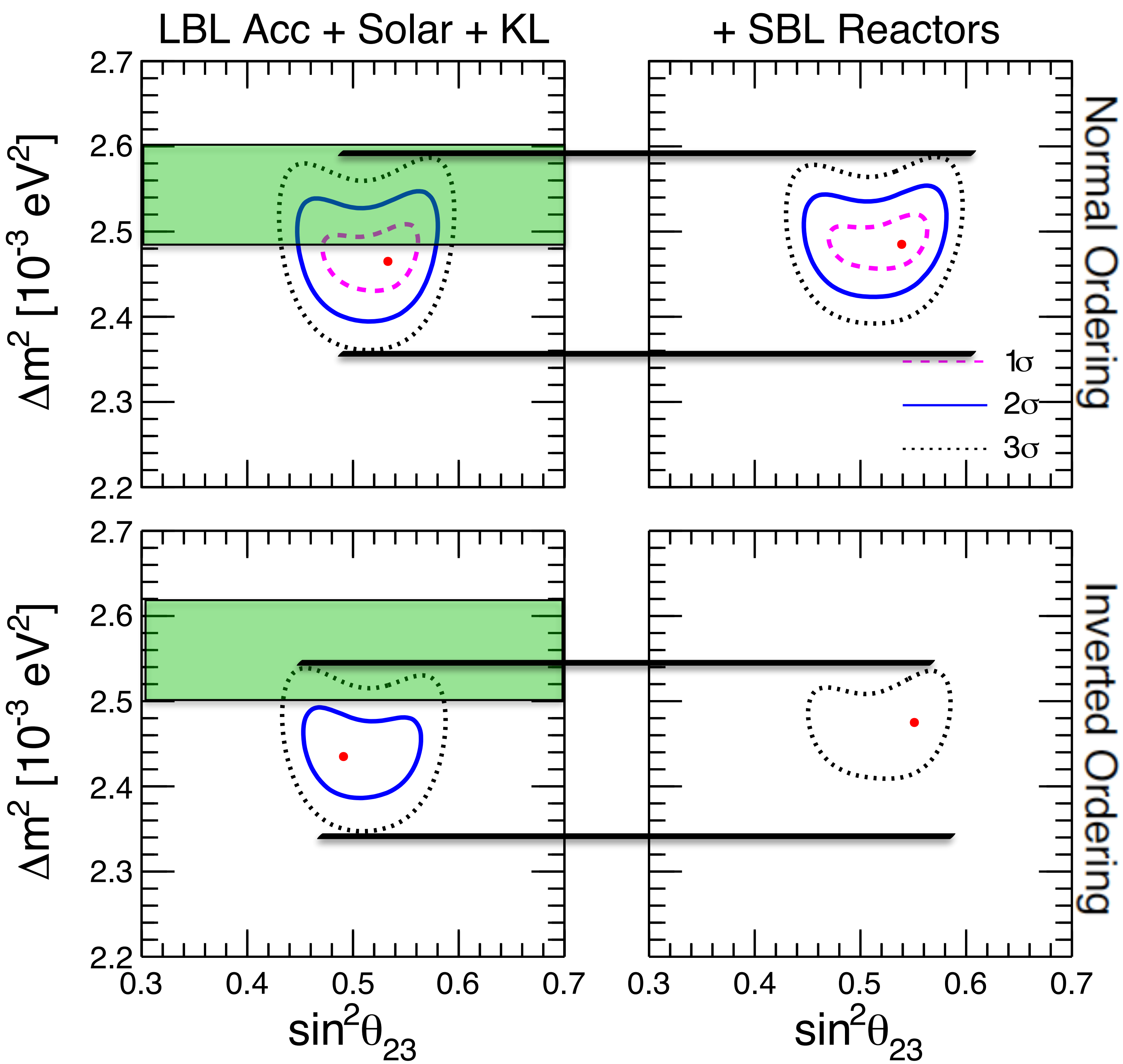
θ_{13}-constraint increases precision on δ

Analysis results: covariance (θ_{23},Δm^2)



Δm^2 more compatible in NO

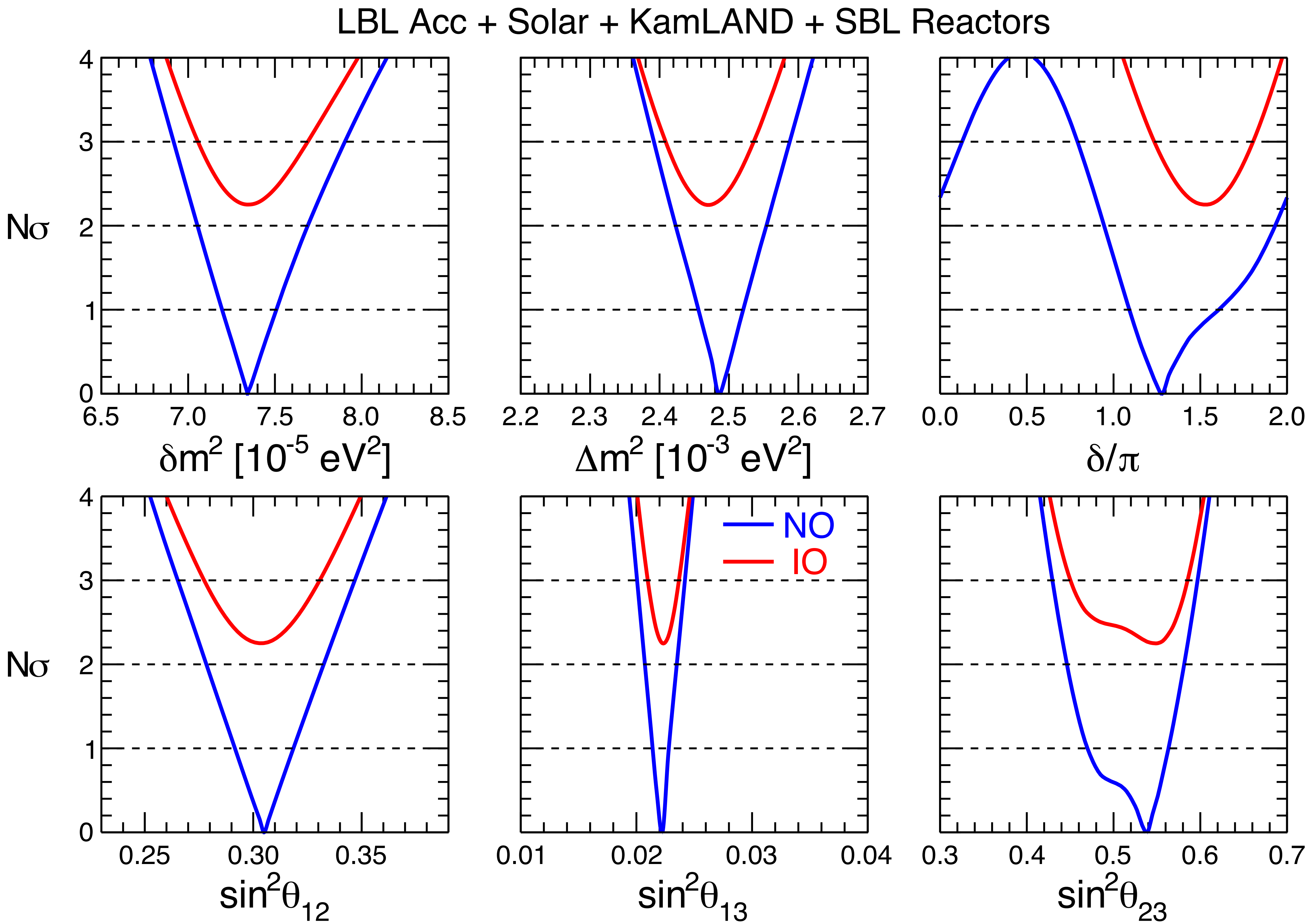
Analysis results: covariance (θ_{23},Δm^2)



1σ SBL reactor constraint

Improved Δm^2 precision
IO disfavoured at 2σ

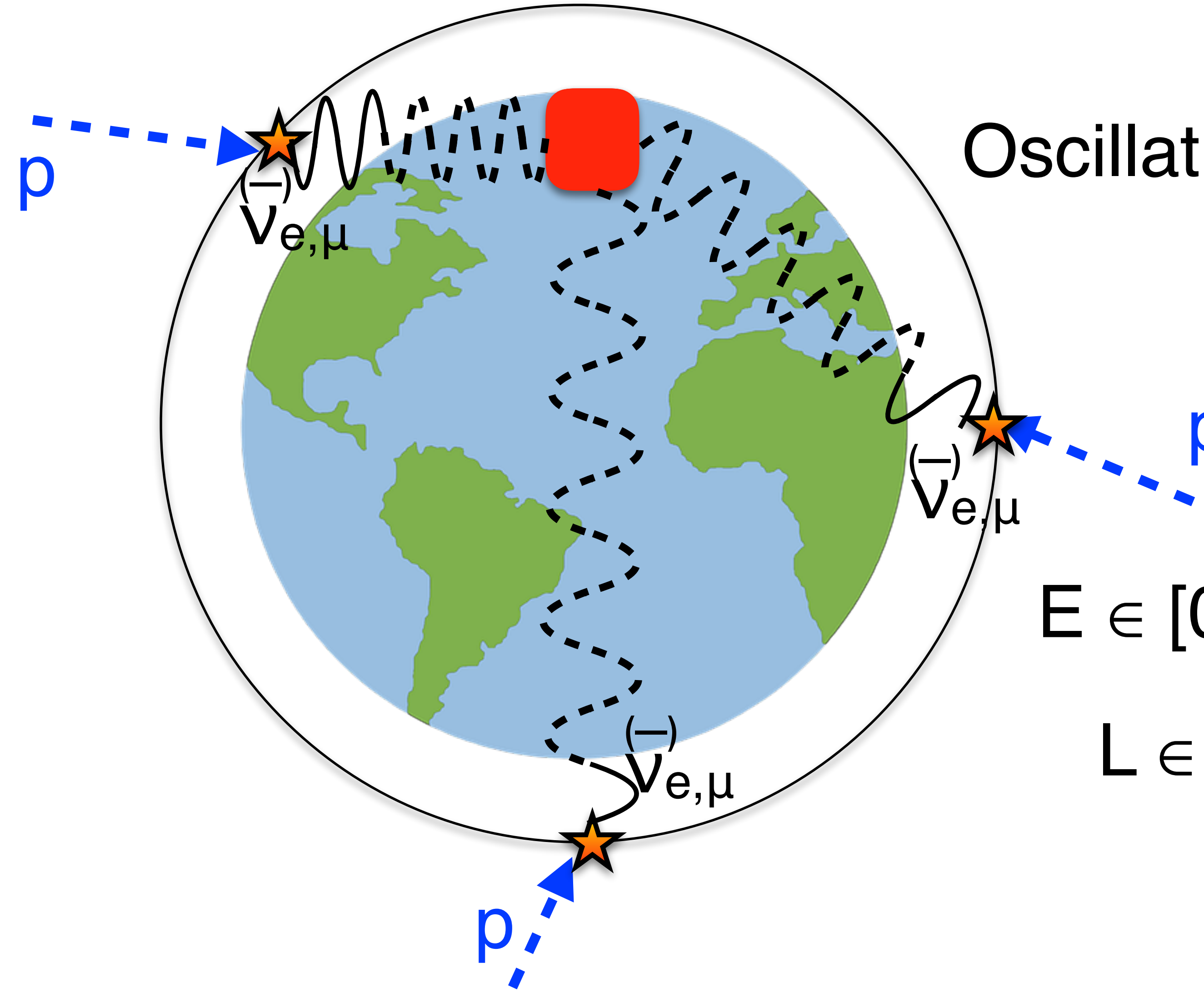
Analysis results



Oscillation datasets

We finally add the rich phenomenology of atmospheric neutrinos

Atmospheric (Super-Kamiokande, IceCube-Deepcore)	$\longleftrightarrow$	$(\theta_{23}, \Delta m^2, \text{MO}, \delta, \theta_{13})$



Oscillations in matter

$E \in [0.1, 10^4]$ GeV

$L \in [0, 10^4]$ km

K. Abe *et al.*, [Super-Kamiokande Collaboration] Phys. Rev. D97 (2018) 072001
M. G. Aartsen et al. [IceCube Collaboration], Phys. Rev. Lett. 120 (2018) no.7, 071801

Oscillation datasets

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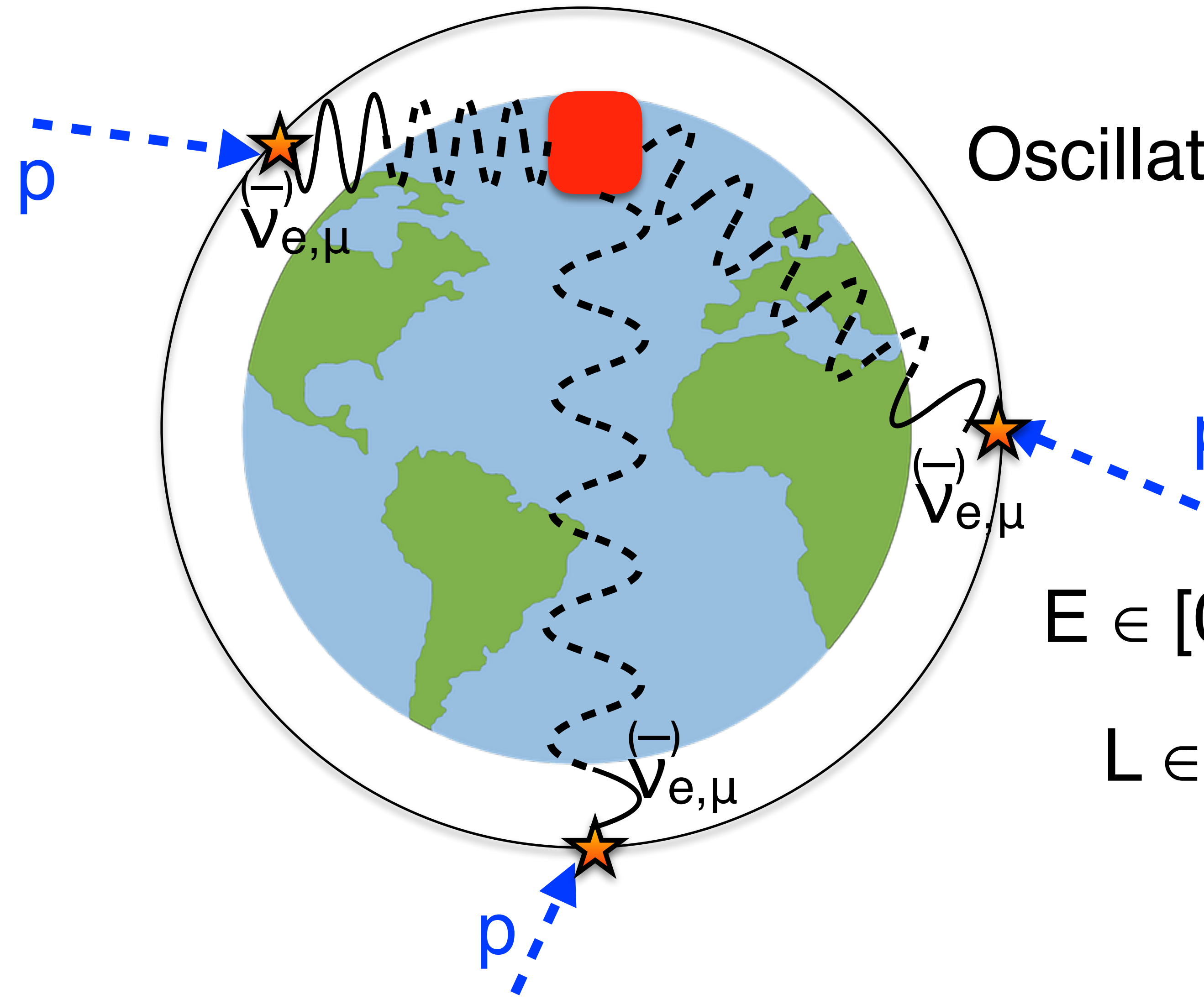
Atmospheric (Super-Kamiokande, IceCube-Deepcore) ⟷ **$(\theta_{23}, \Delta m^2, \mathrm{MO}, \delta, \theta_{13})$**



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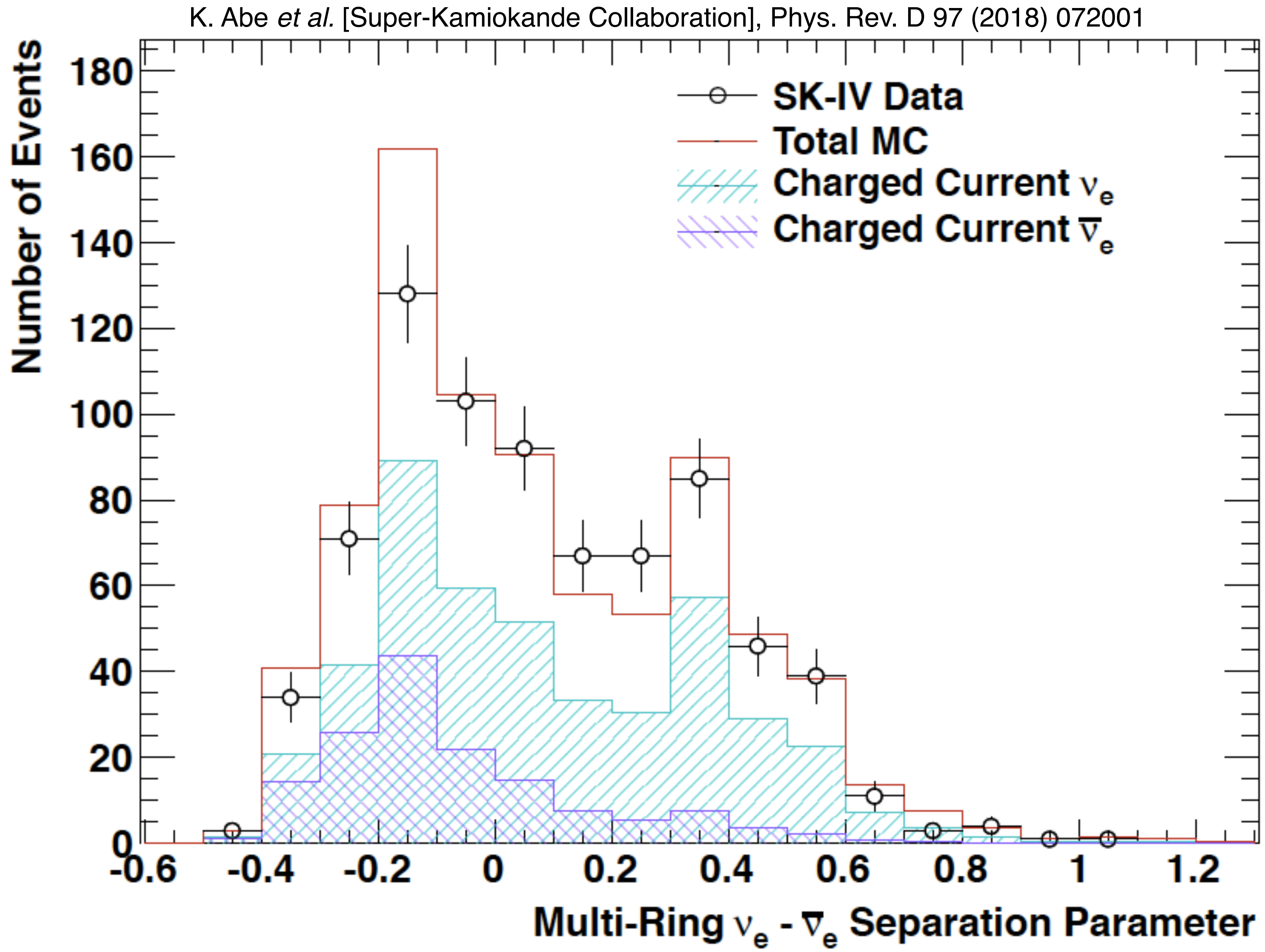
UPDATE IN PROGRESS

Super-K constraints

Mass ordering sensitivity depends on distinguishing ν_e from $\bar{\nu}_e$

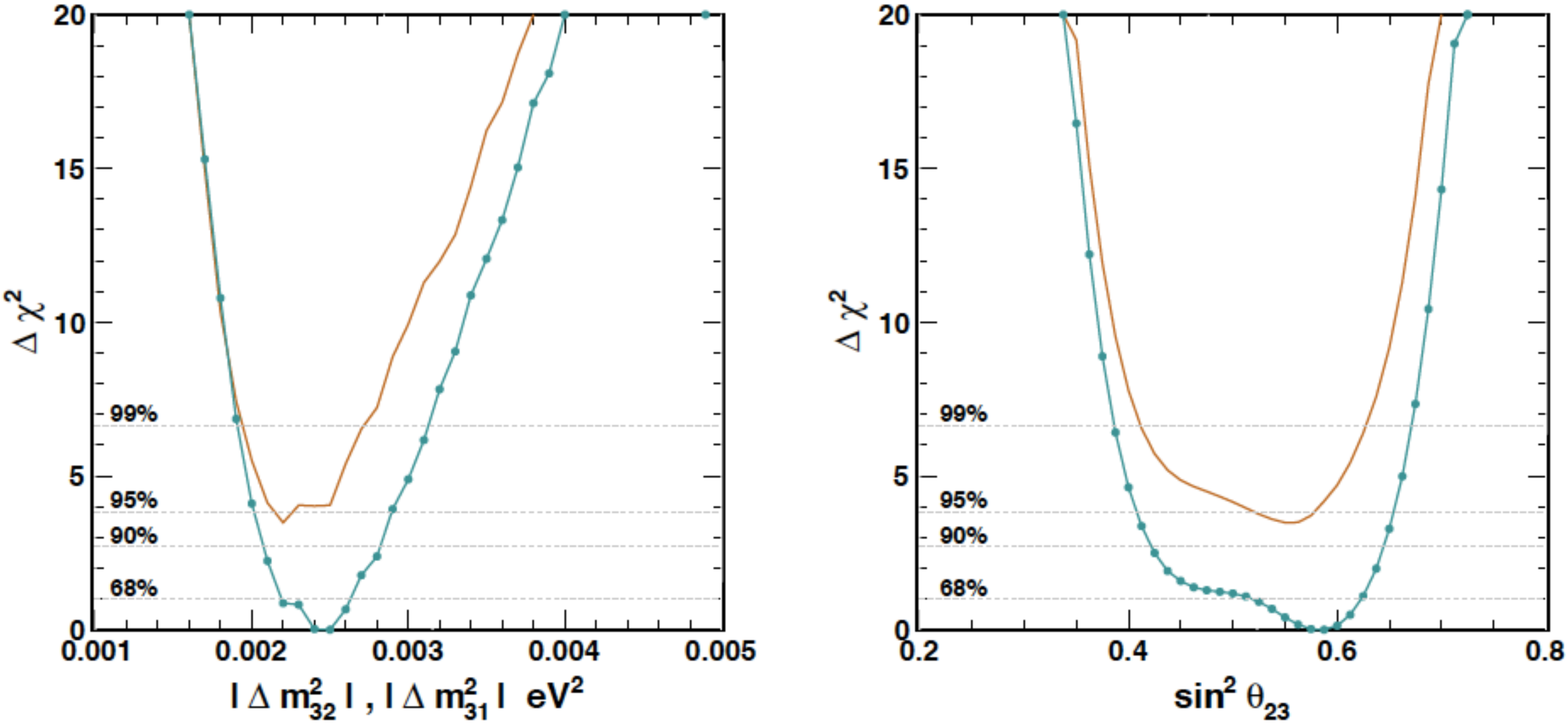


Separation is performed on a statistical basis in Super-K

Super-K constraints

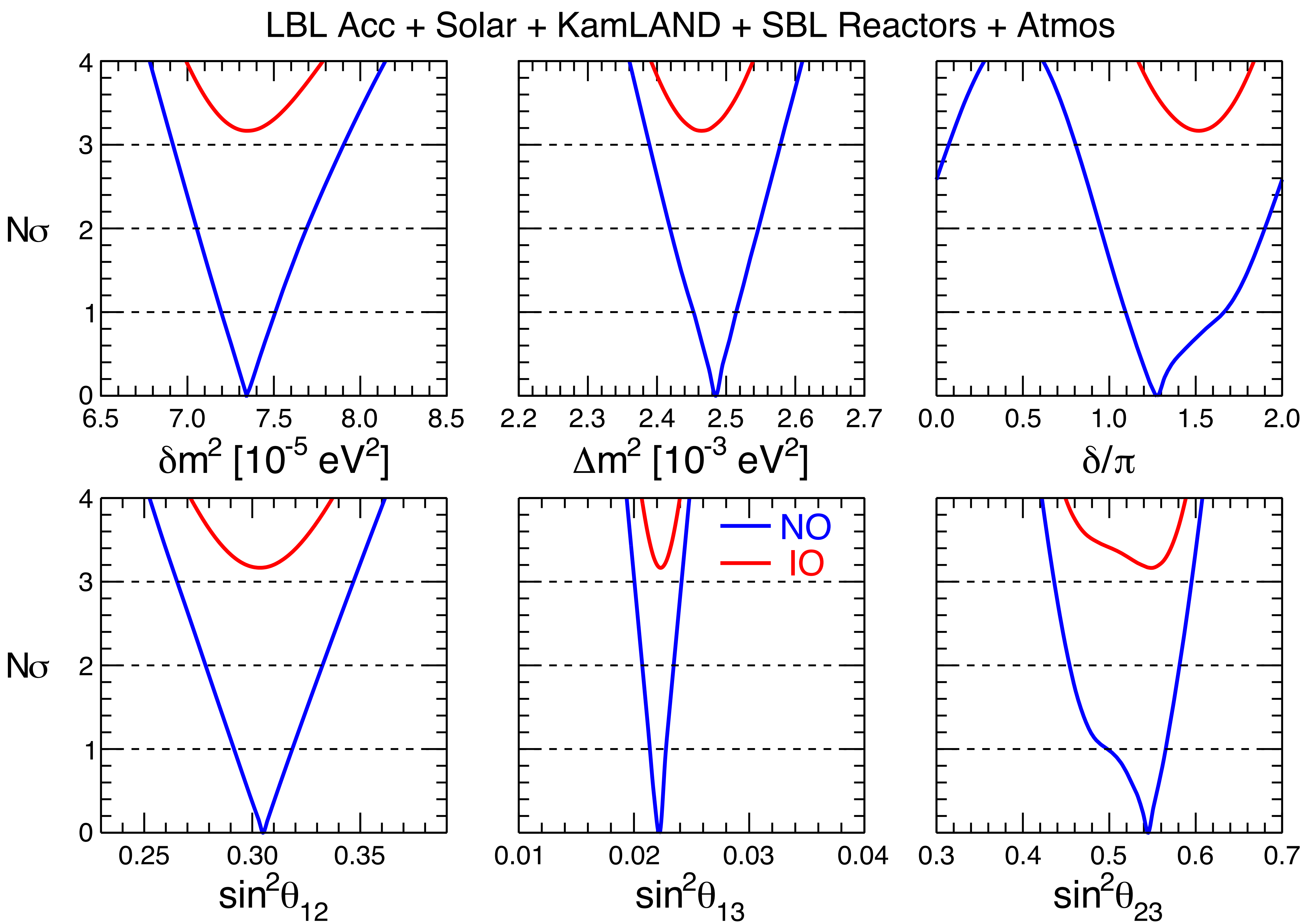
Mass ordering sensitivity depends on distinguishing ν_e from $\bar{\nu}_e$

K. Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D 97 (2018) 072001

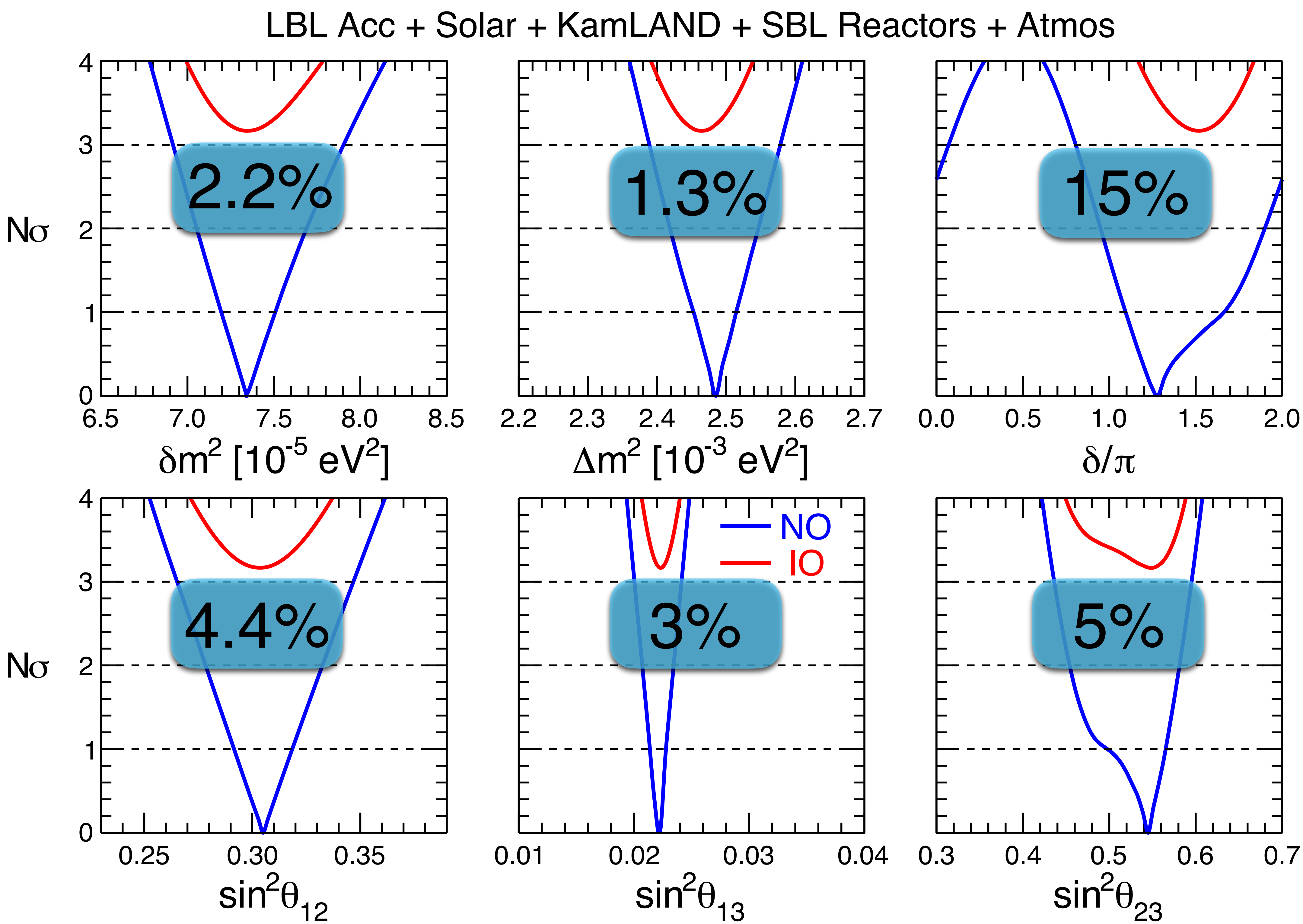


Preference for normal ordering (~2σ) and second octant (~1σ)

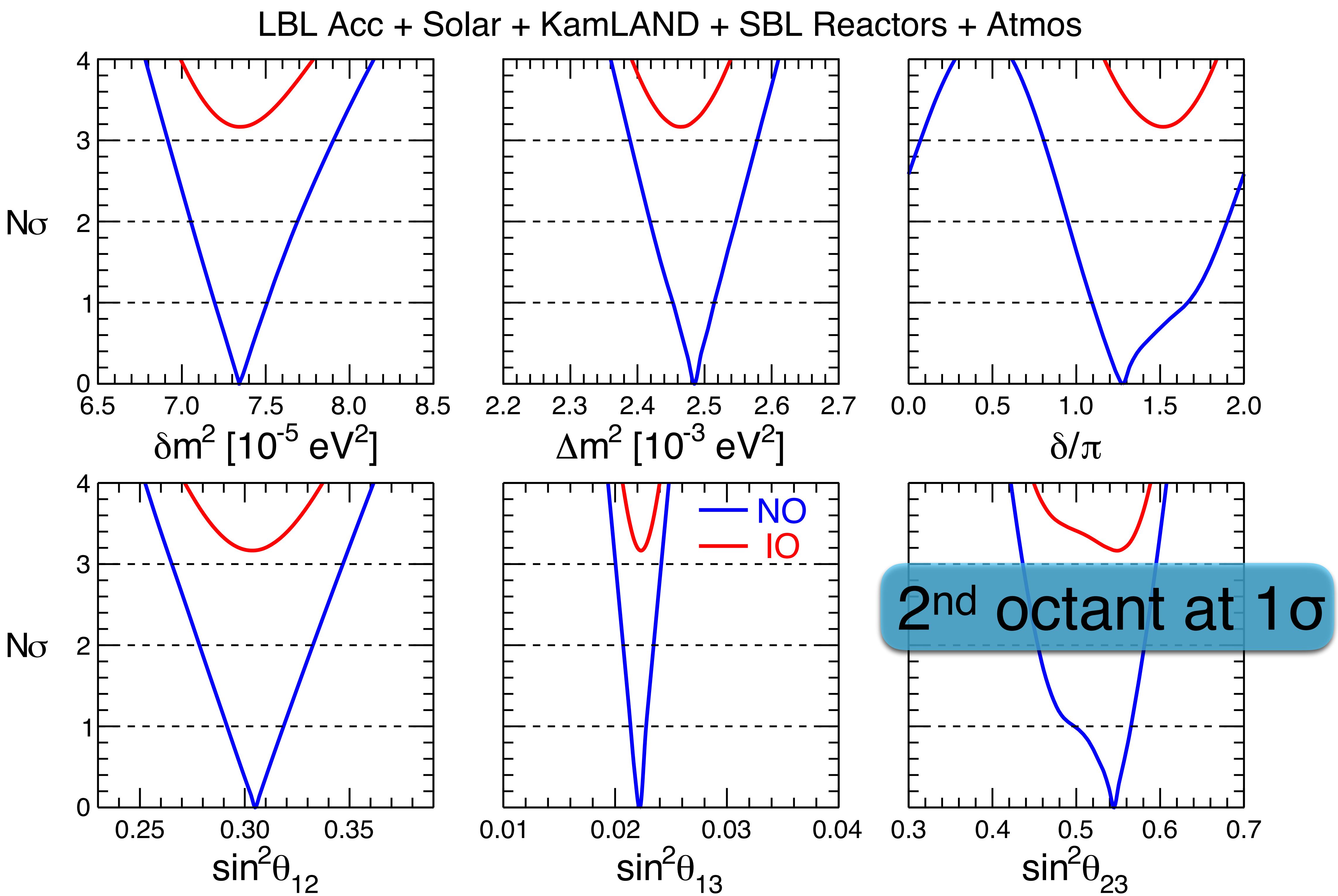
Analysis results



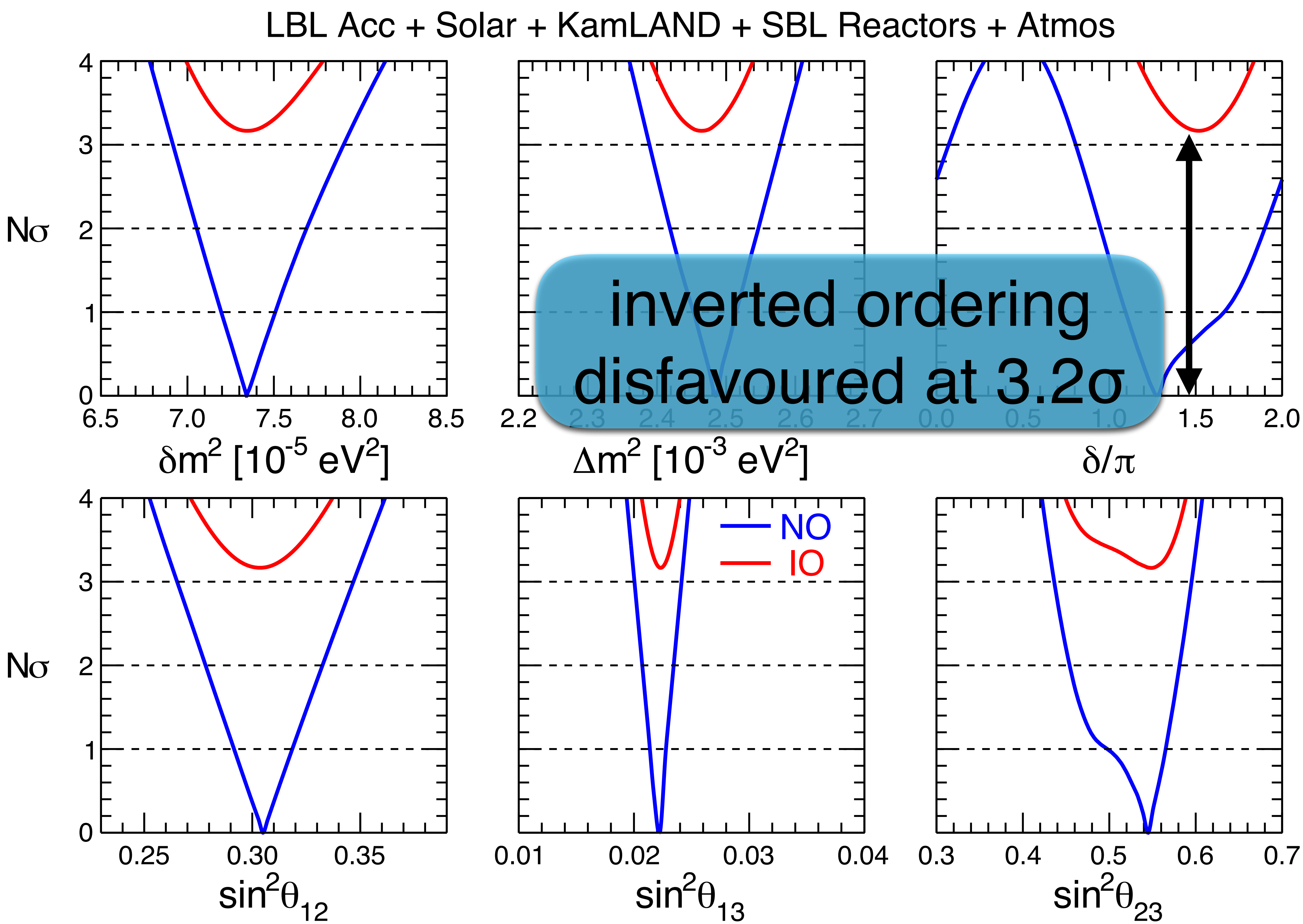
Analysis results



Analysis results



Analysis results



Future challenges

Current and future level precision creates unprecedented challenges:

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- analysis details are becoming too complicated for external pheno groups (systematics, A.I. tools, …)

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- common ingredients must be treated in the context of a global analysis (models for cross sections, fluxes, …)

Future challenges

Current and future level precision creates unprecedented challenges:

- analysis details are becoming too complicated for external pheno groups (systematics, A.I. tools, …)

- common ingredients must be treated in the context of a global analysis (models for cross sections, fluxes, …)

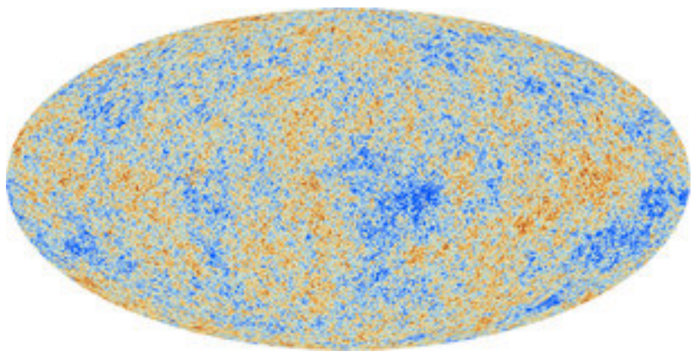
Global analyses will require joint experimental effort

Non-oscillation data

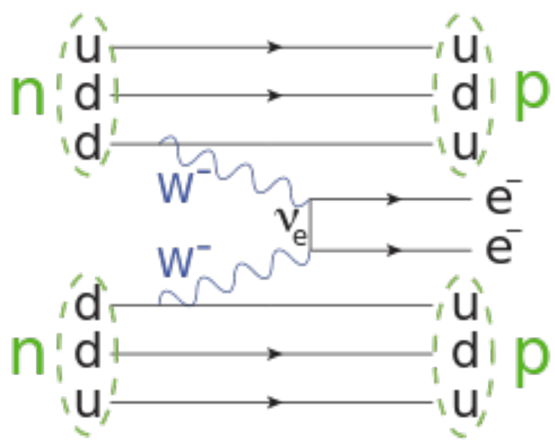
Phys. Rev. D 95 (2017) no.9, 096014)
in collaboration with E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo

Non oscillation data

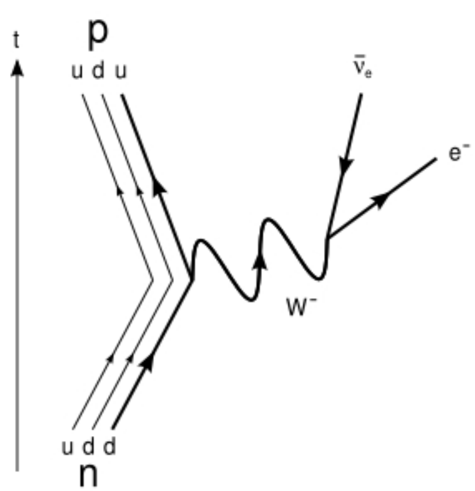
Cosmology, β and 0νββ decays can probe:



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



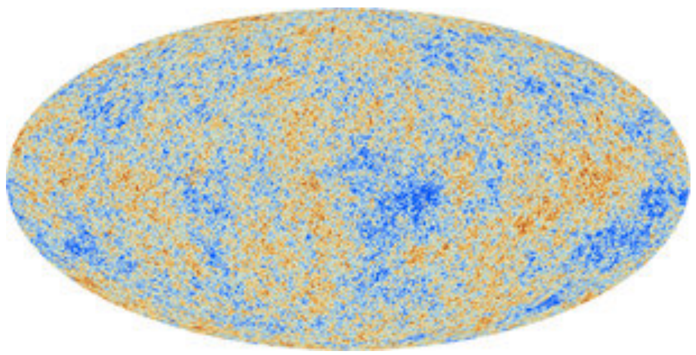
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



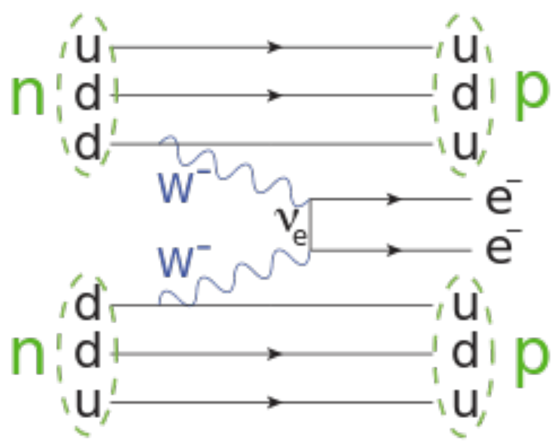
$$m_\beta^2 = \sum_{i=1}^{3} |U_{ei}|^2 \, m_i^2$$

Non oscillation data

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



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

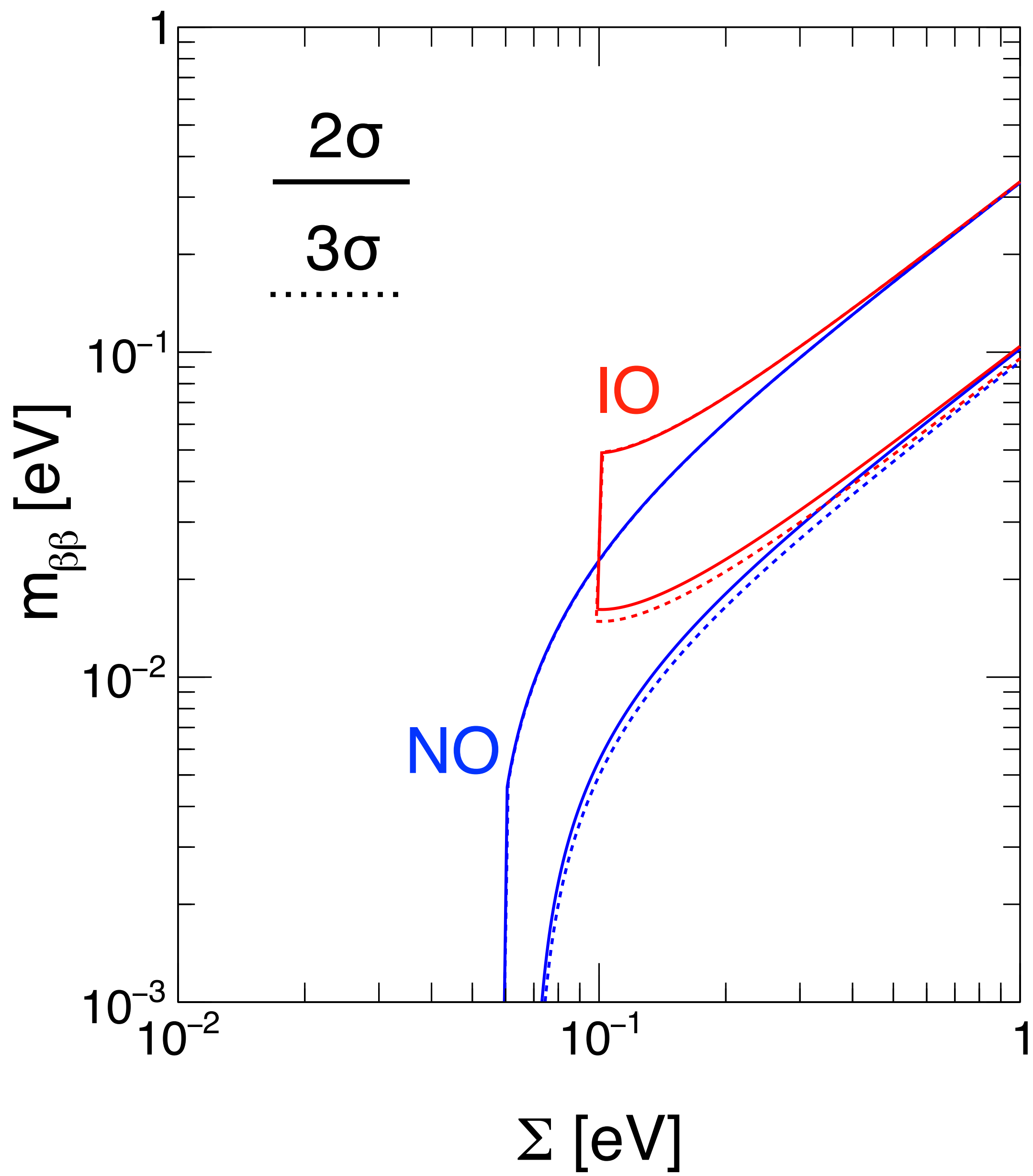


$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

ANALYSIS OF m_β CONSTRAINTS IN PROGRESS

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,$m_{\beta\beta}$)

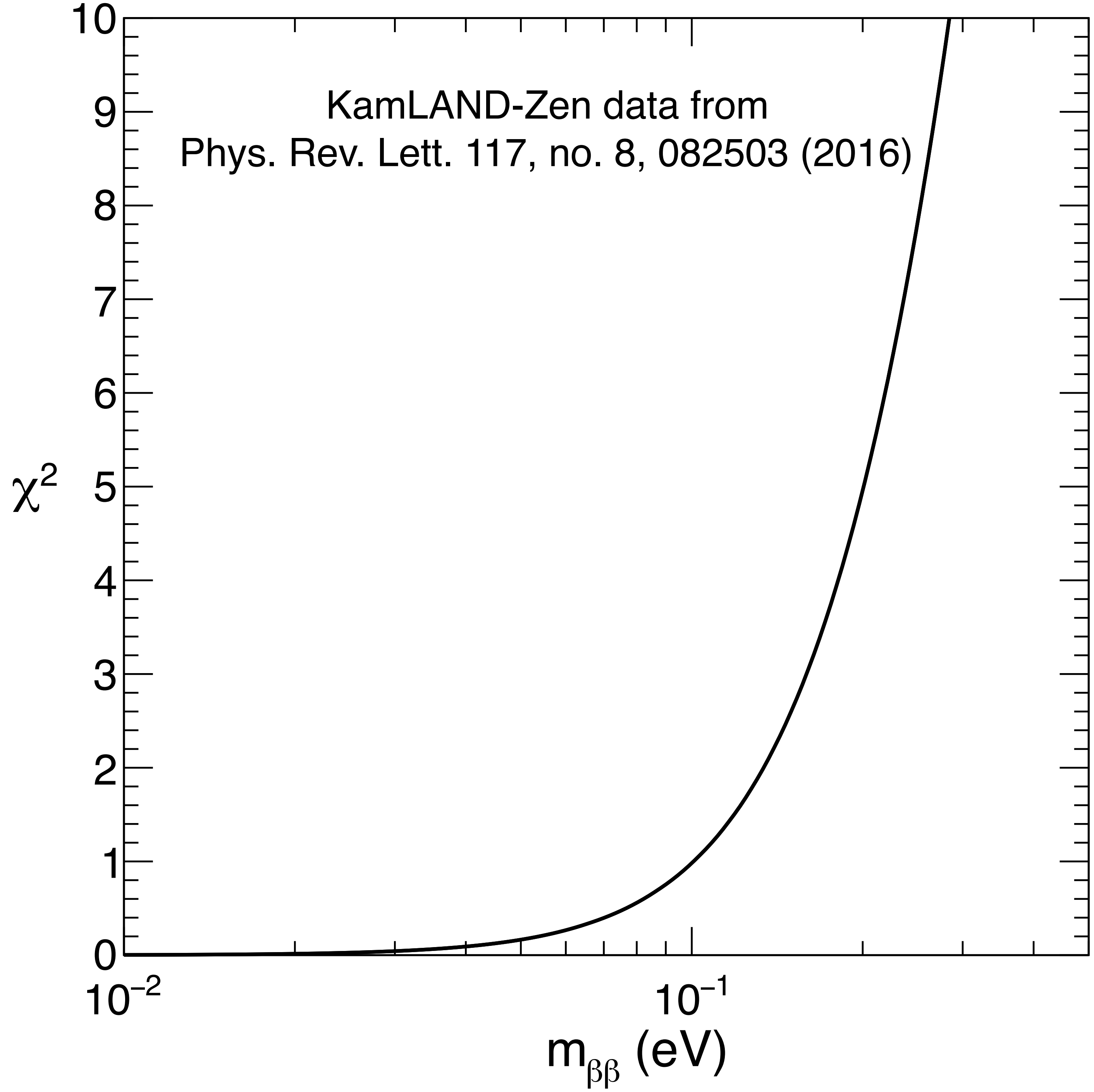
We convert the constraint on $T_{0\nu\beta\beta}$ from KamLAND-ZEN to $m_{\beta\beta}$

$$T_{0\nu\beta\beta}^{-1} = G\left|M^2\right|m_{\beta\beta}^2$$

0νββ constraints on $m_{\beta\beta}$

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

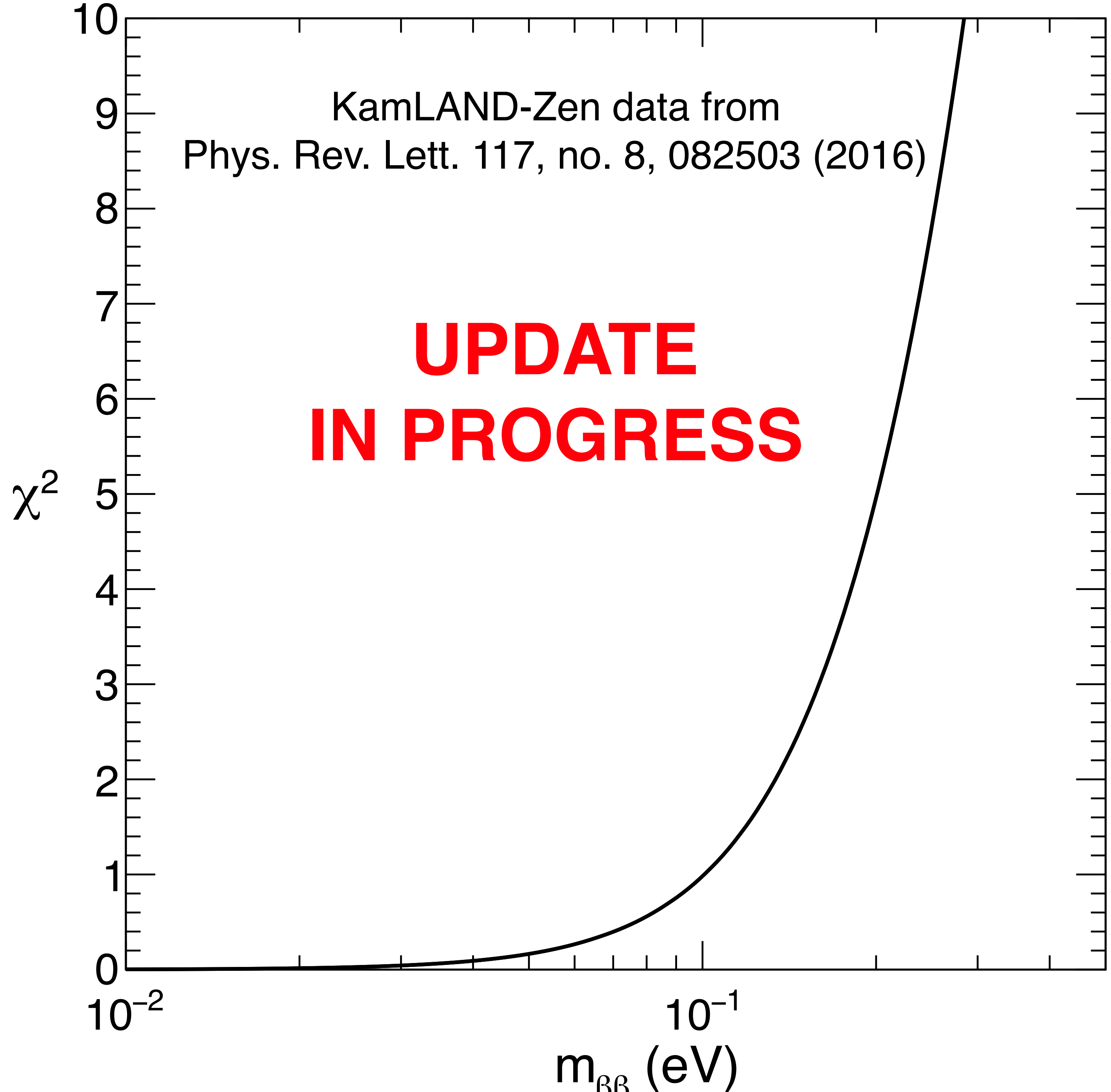
F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, Melchiorri and A. Palazzo, Phys. Rev. D 95 (2017) no.9, 096014



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

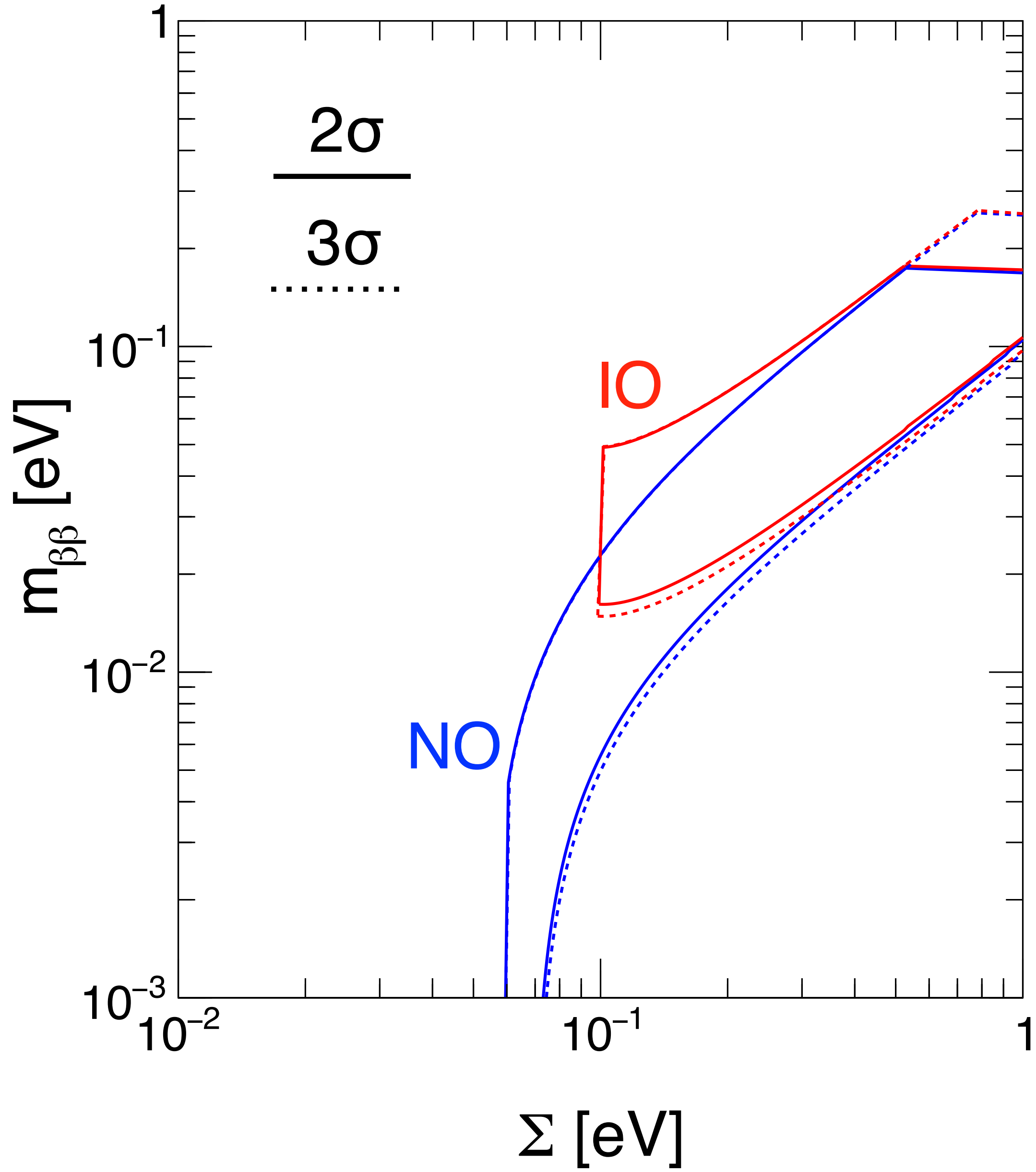
We convert the constraint on $T_{0\nu\beta\beta}$ from KamLAND-ZEN to $m_{\beta\beta}$

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



Constraints on (Σ,$m_{\beta\beta}$)

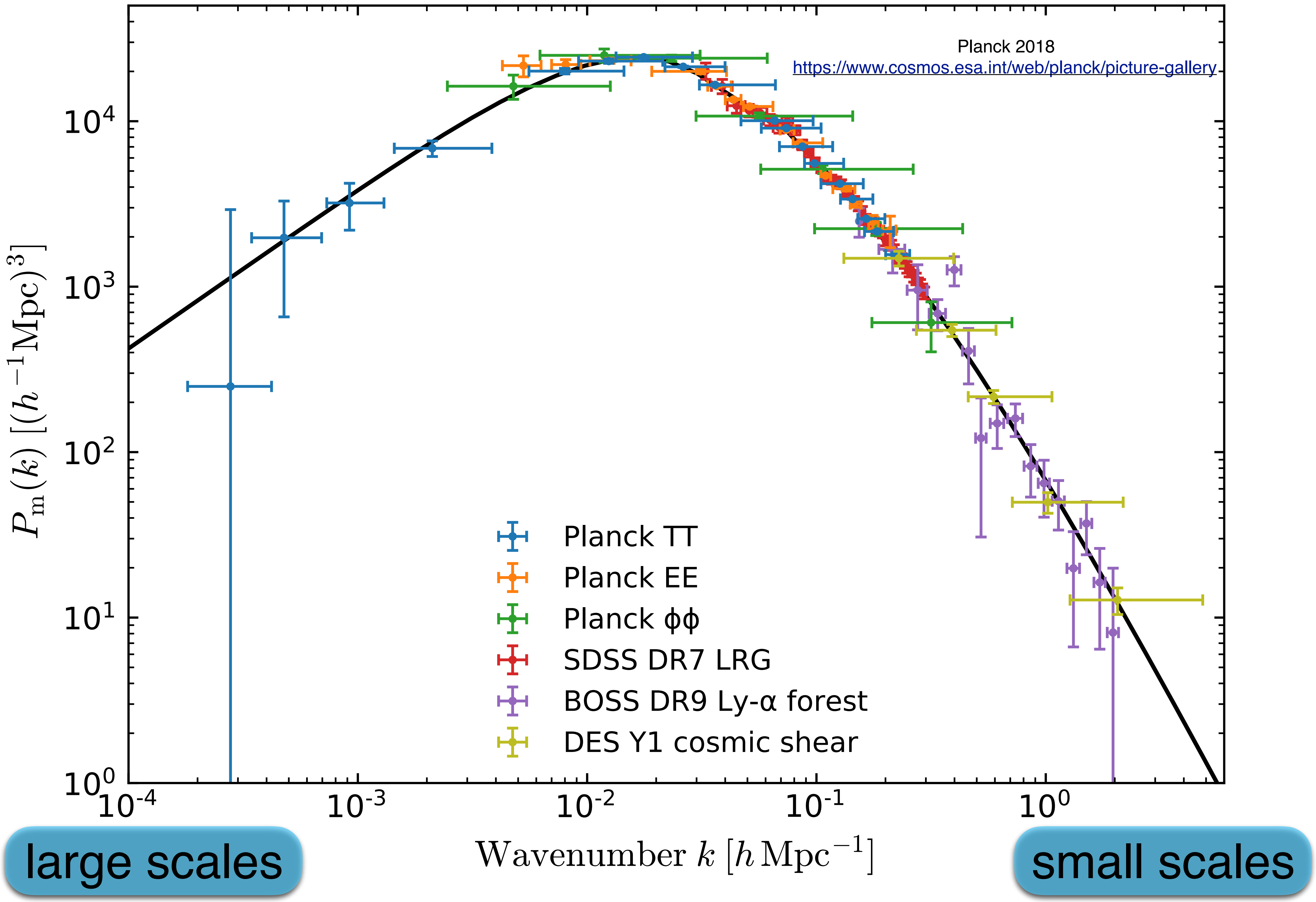
Oscillation + 0$\nu\beta\beta$ constraints, with $\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(IO)$



$m_{\beta\beta} < 0.2$ eV (2σ)

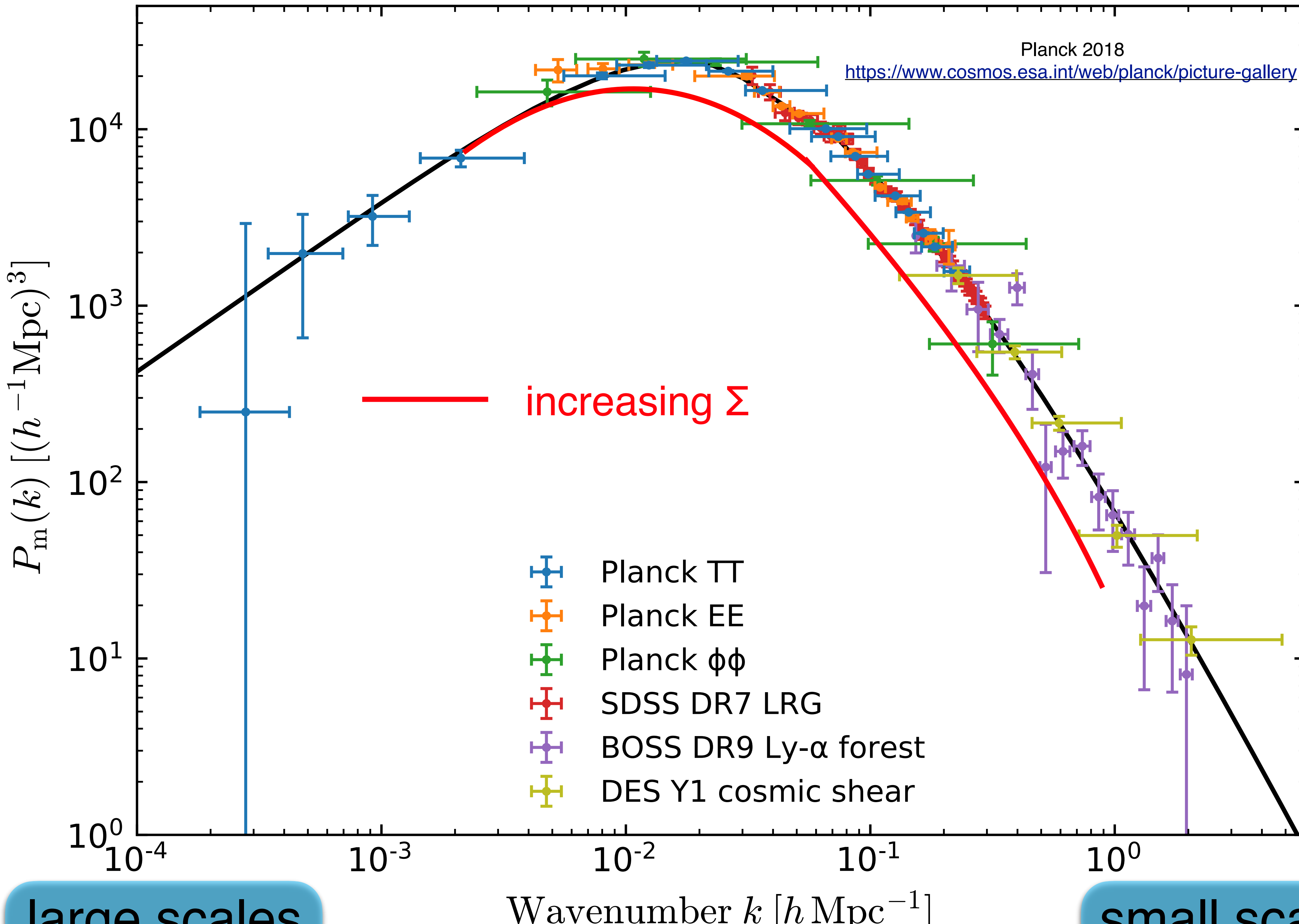
Cosmological constraints on Σ

The matter power spectrum represents the degree of clustering as a function of scales



Cosmological constraints on Σ

Neutrino masses (Σ) affect the matter power spectrum at small scales



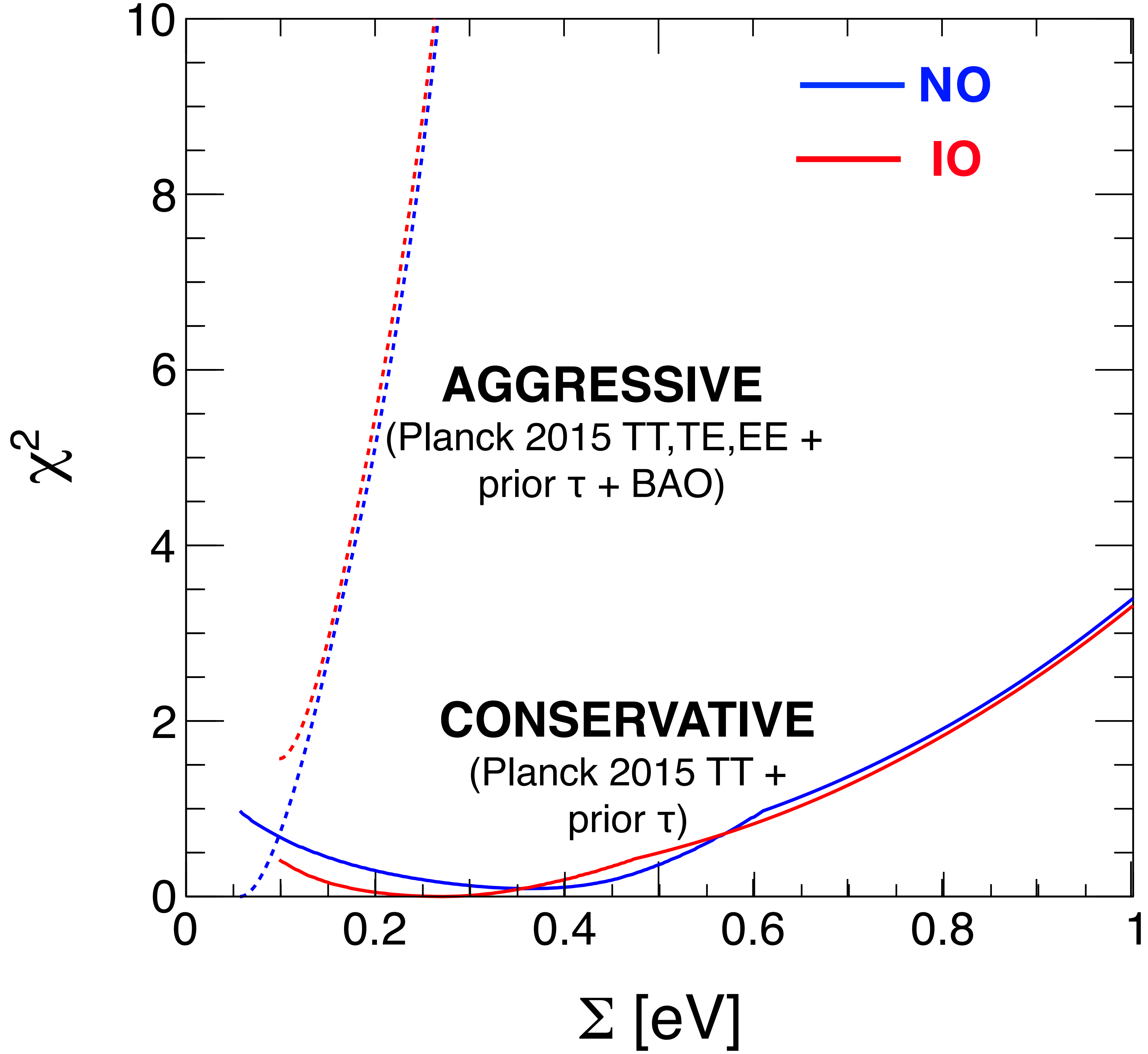
large scales

small scales

Cosmological constraints on Σ

We take the constraint from different cosmological observations

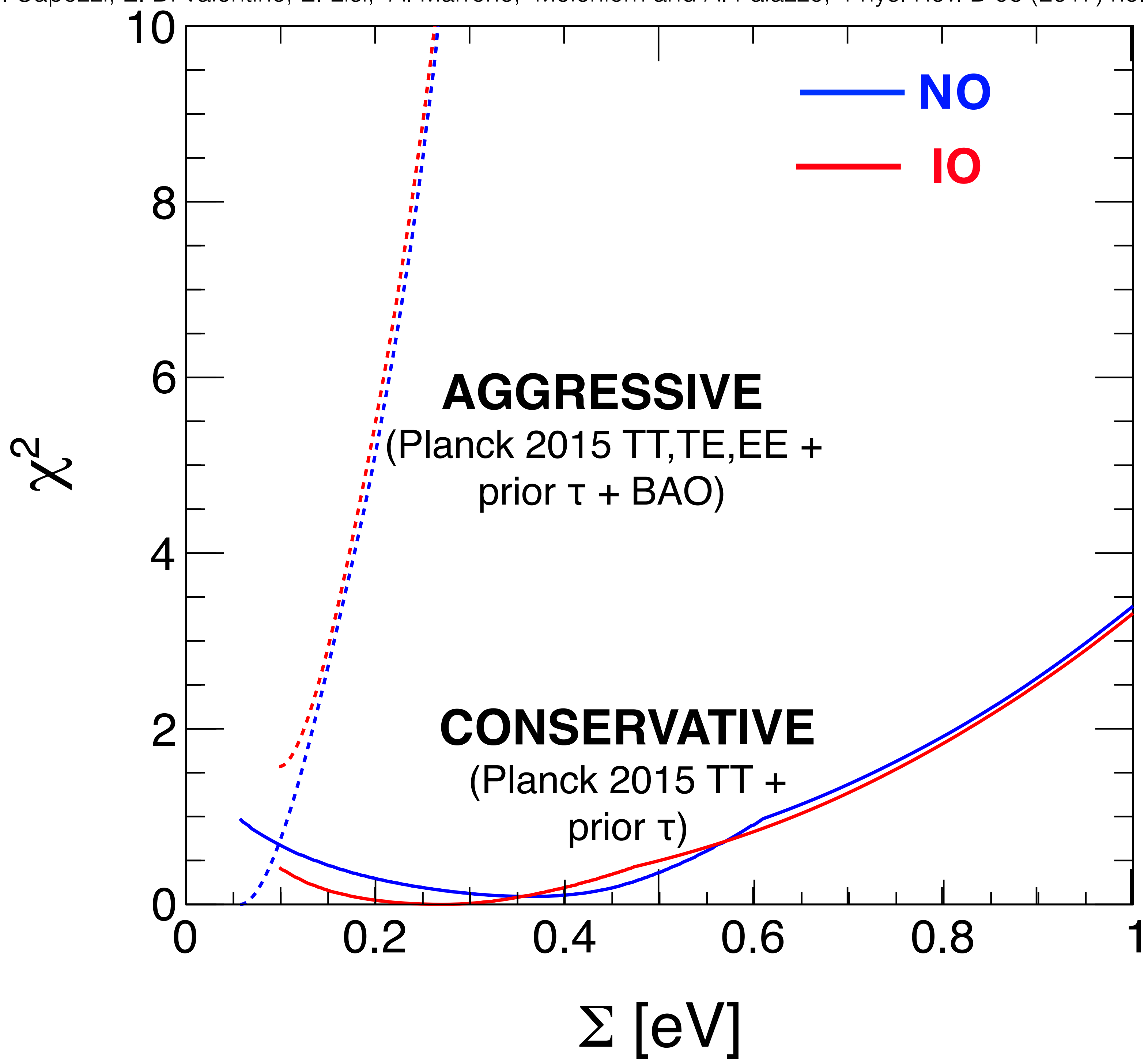
F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, Melchiorri and A. Palazzo, Phys. Rev. D 95 (2017) no.9, 096014



Cosmological constraints on Σ

We take the constraint from different cosmological observations

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

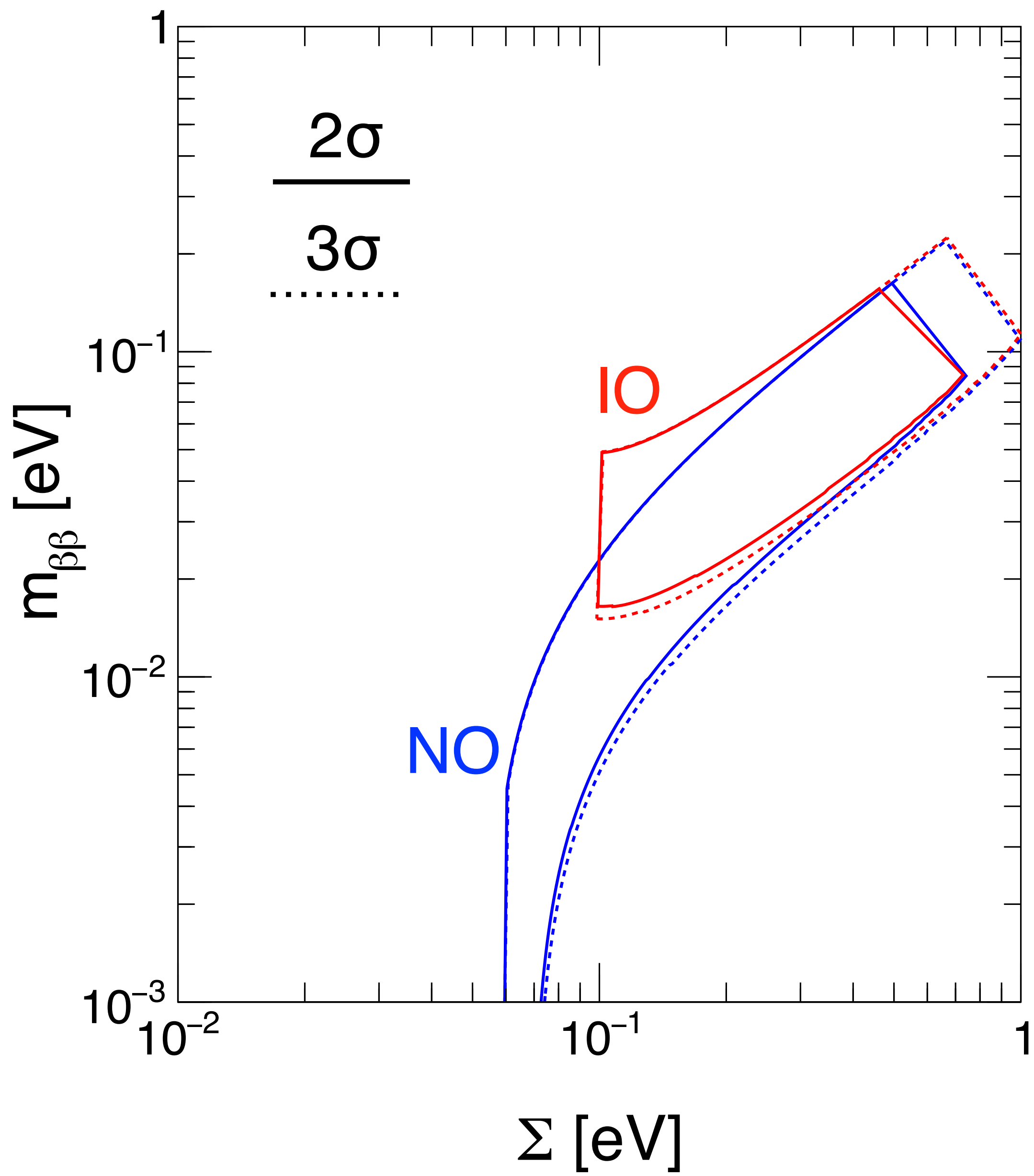


UPDATE IN PROGRESS

Constraints on (Σ,$m_{\beta\beta}$)

Oscillation + 0νββ + cosmology (conservative) constraints

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

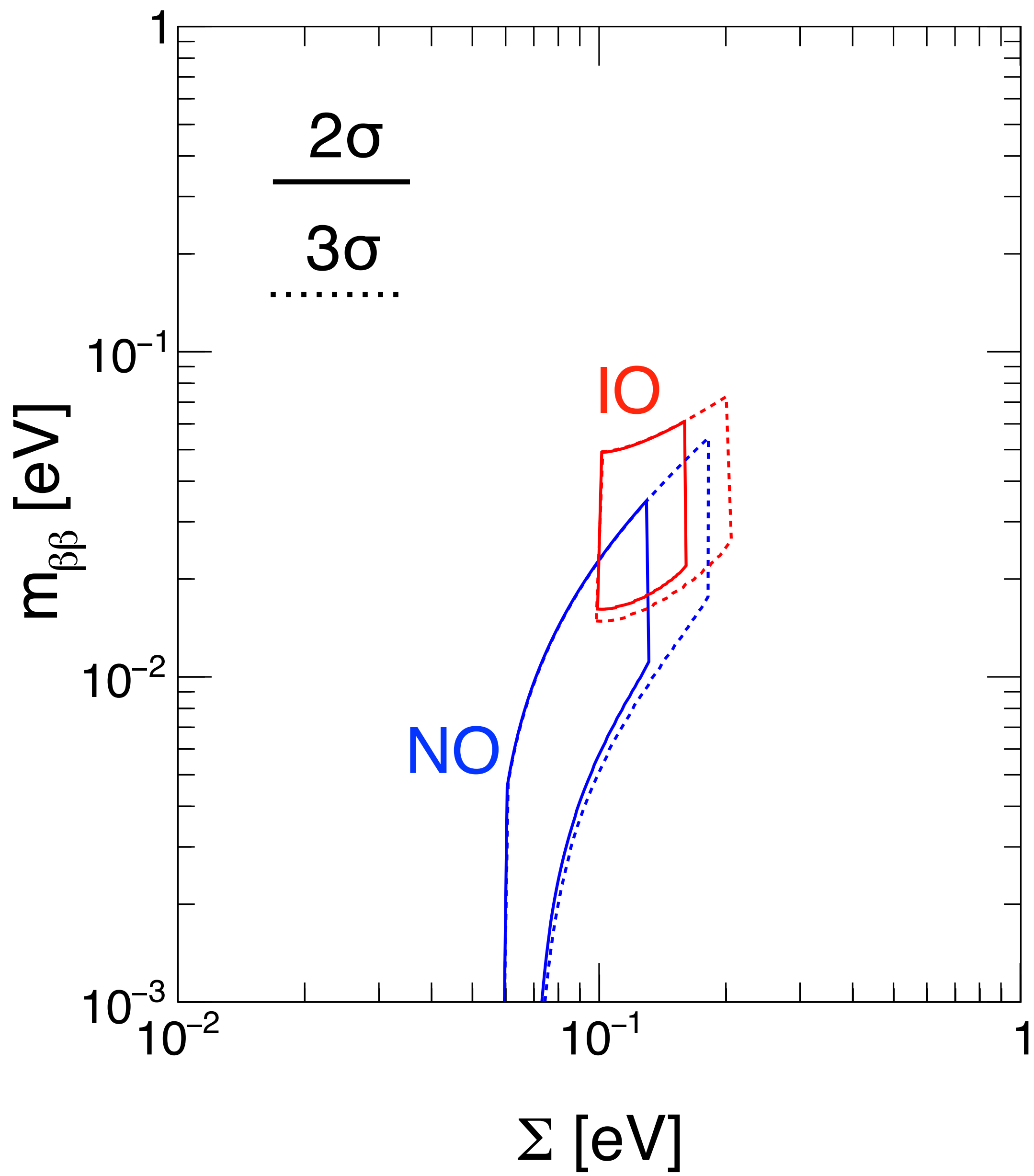


$\Sigma < 0.7$ eV (2σ)

Constraints on (Σ,$m_{\beta\beta}$)

Oscillation + 0νββ + cosmology (aggressive) constraints

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

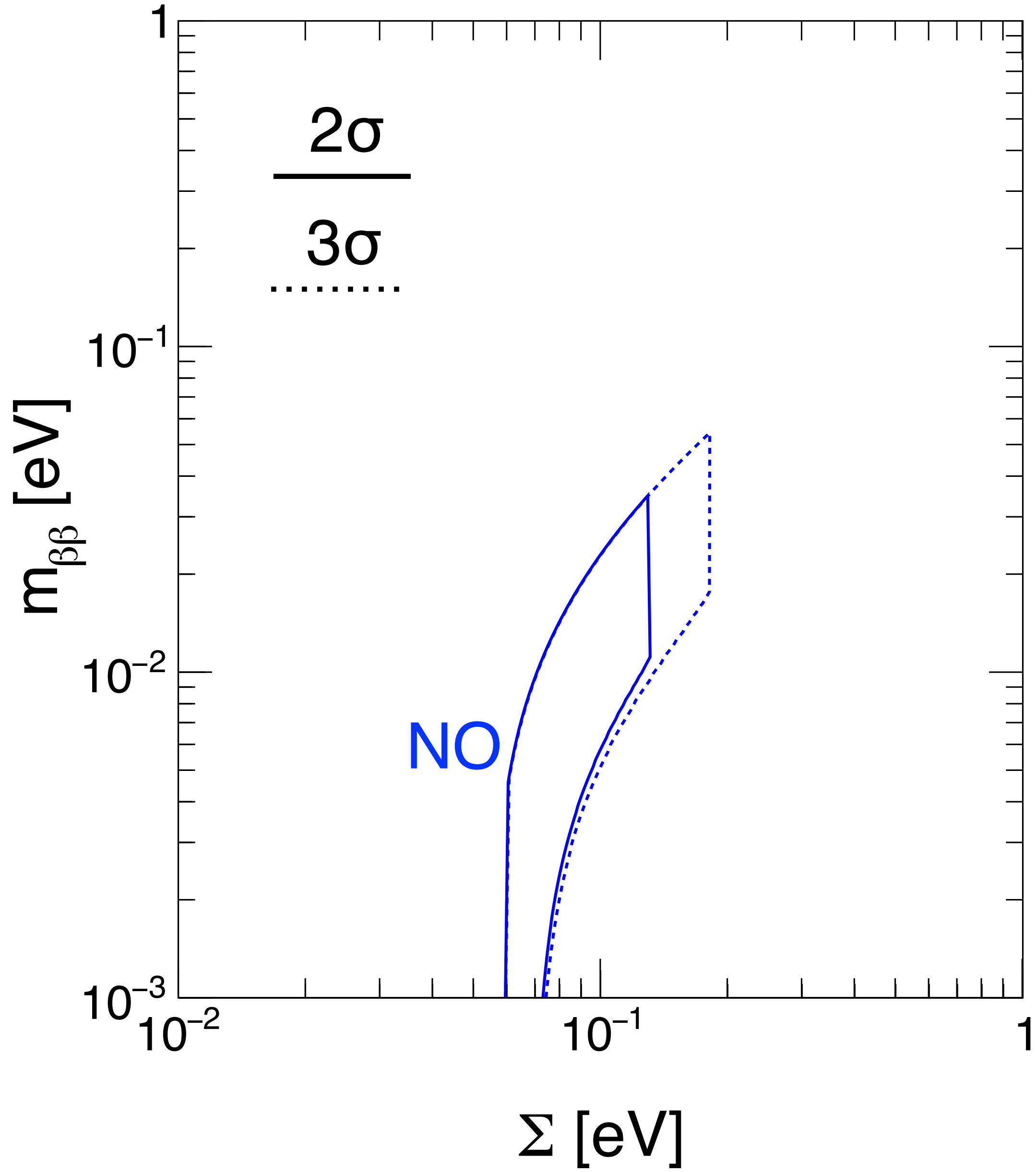


$\Sigma < 0.2$ eV (2σ)

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

Oscillation + $0\nu\beta\beta$ + 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

- Good **agreement** between different experiments
- We have entered the **precision era** for oscillation parameters
- 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**
- Global fit **new challenges**: required joint experimental (+ external) efforts

Thank you