Physics in Collision 2019

XXXIX International Symposium on Physics in Collision

Department of Physics, National Taiwan University, Taipei, Taiwan | September 16-20, 2019

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

FRANCESCO CAPOZZI

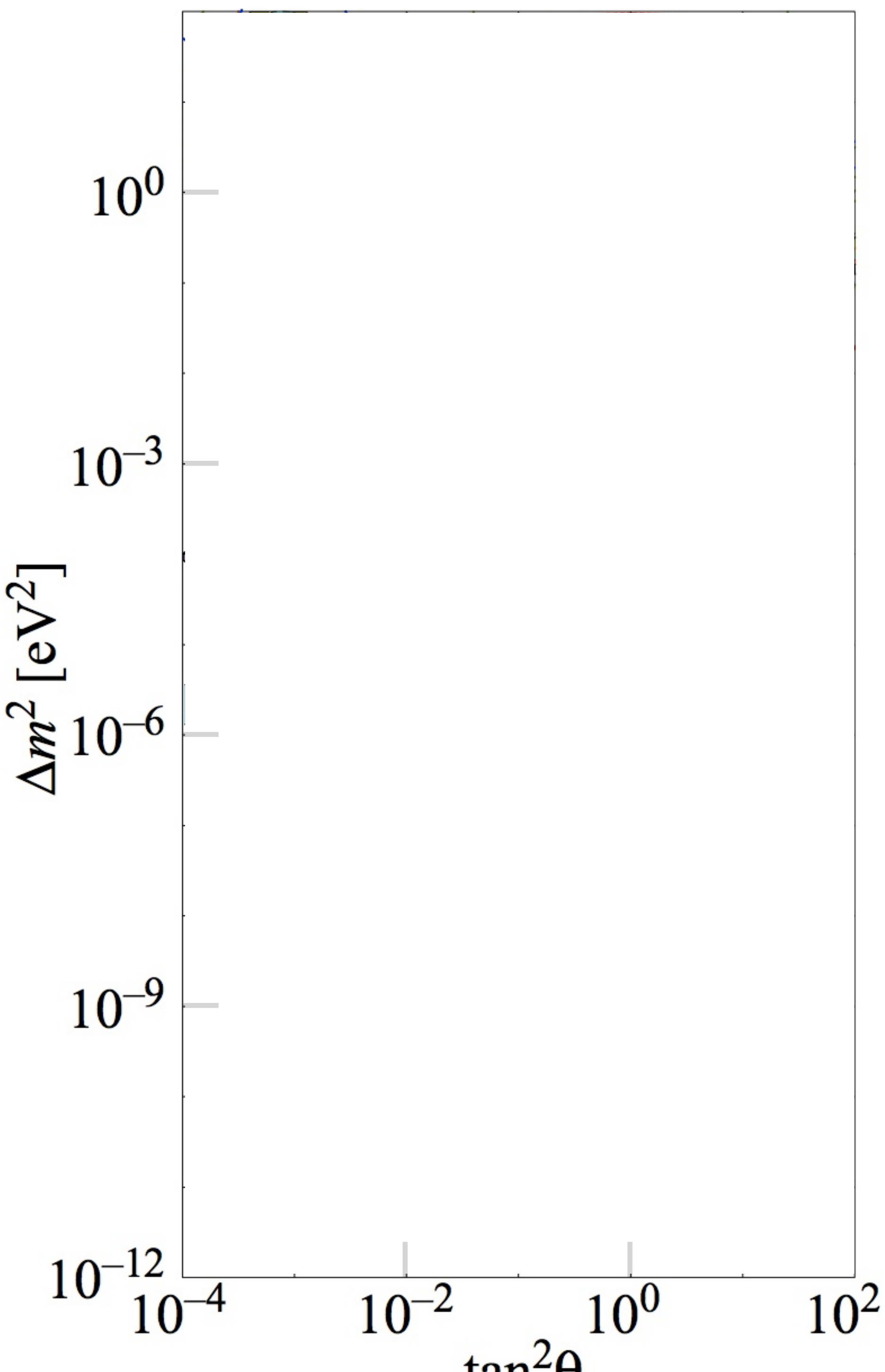
SFB 1258 Neutrinos Dark Matter Messengers

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

elusives neutrinos, dark matter & dark energy physics

Neutrino mass-mixing: an overview

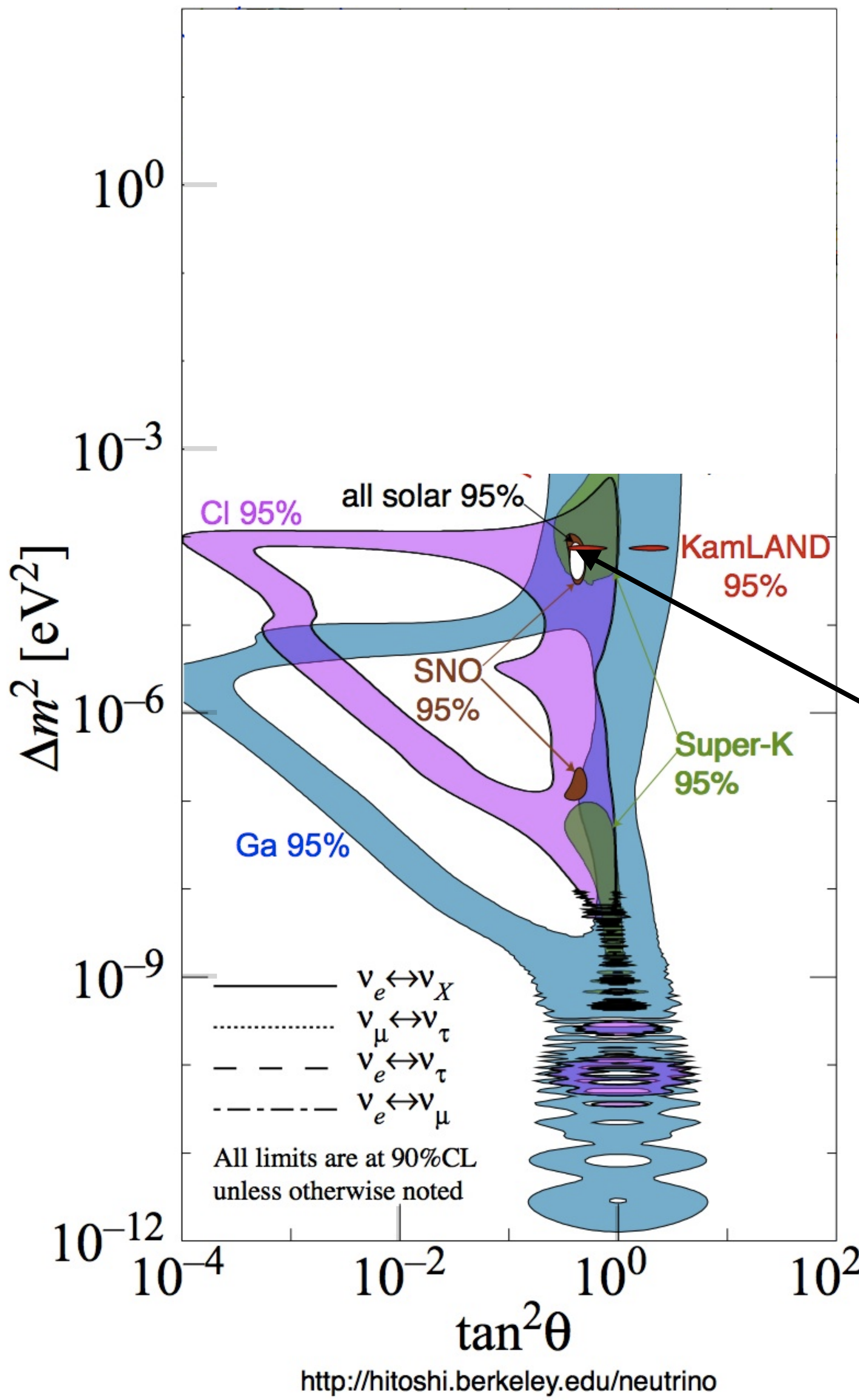
60 years ago we had no idea neutrinos could have mass and mix…



http://hitoshi.berkeley.edu/neutrino

Neutrino mass-mixing: an overview

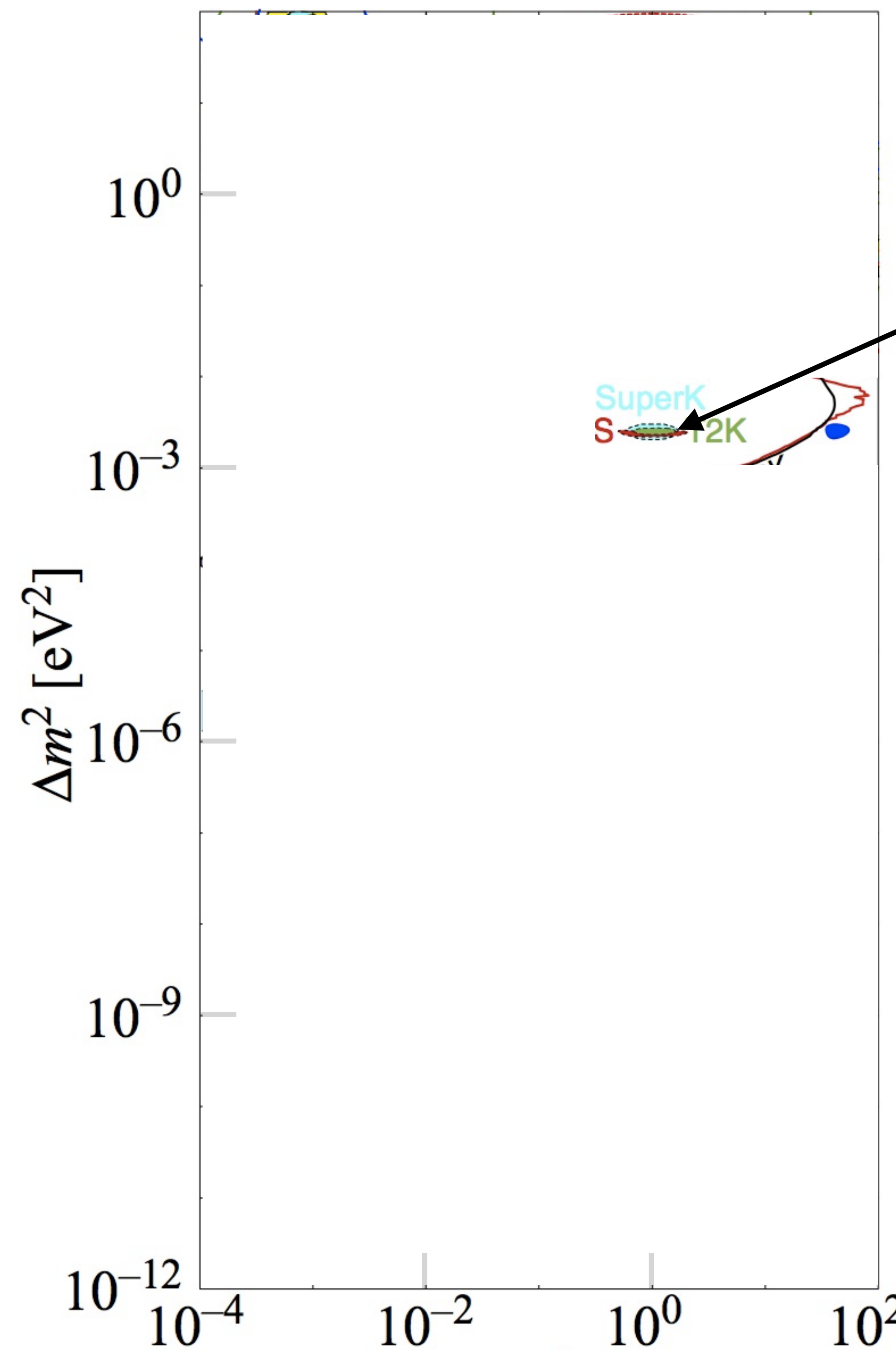
… but Nature provided neutrino sources with the right properties…



Solar sector
$\delta m^2, \theta_{12}$

Neutrino mass-mixing: an overview

… but Nature provided neutrino sources with the right properties…



http://hitoshi.berkeley.edu/neutrino

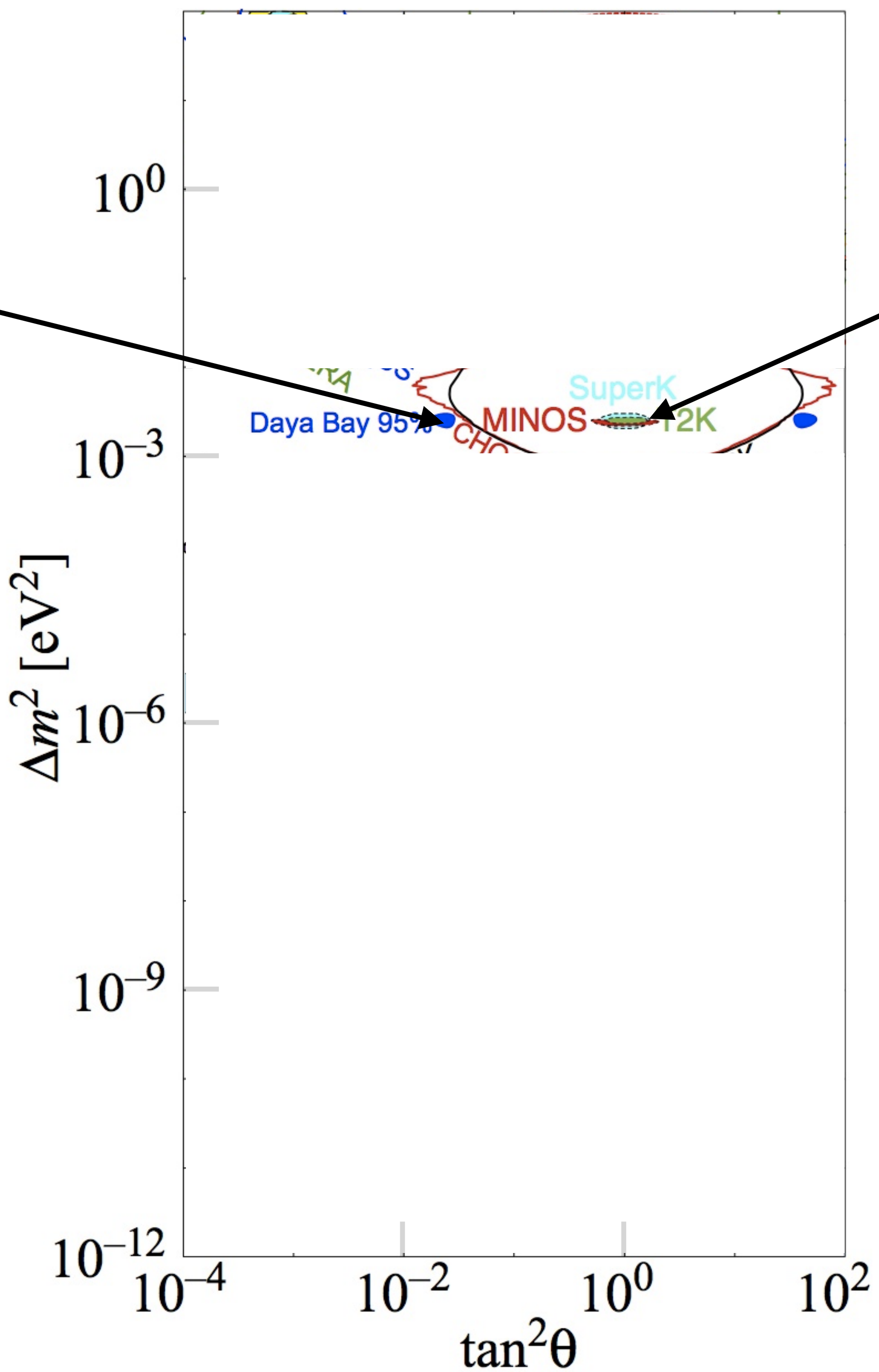
Atmospheric sector
$\Delta m^2, \theta_{23}$

Neutrino mass-mixing: an overview

… then complemented by our artificial sources…

Reactor sector
$\Delta m^2, \theta_{13}$

Accelerator
$\Delta m^2, \theta_{23}$



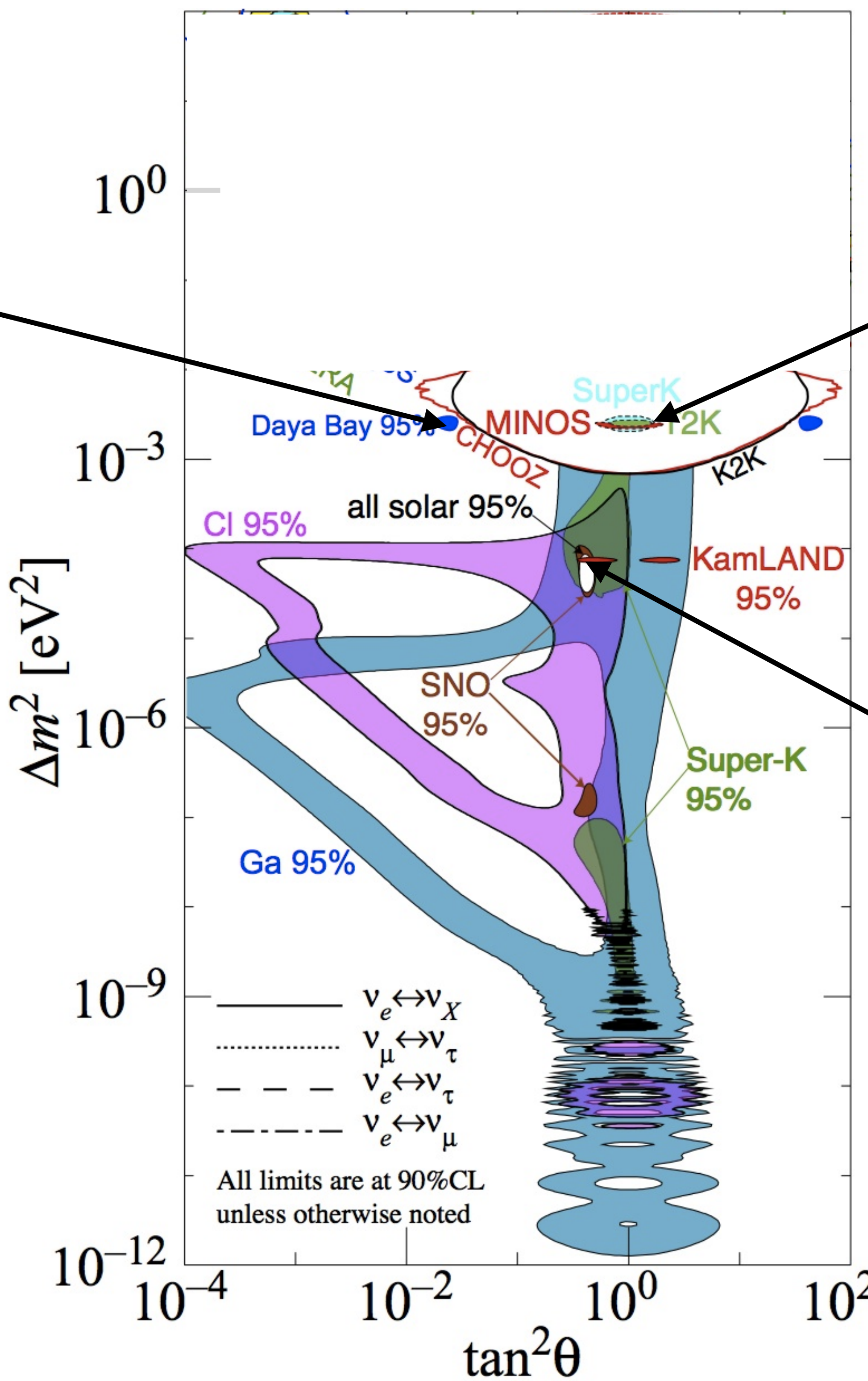
http://hitoshi.berkeley.edu/neutrino

Neutrino mass-mixing: an overview

…leading to a well established 3ν framework!

Reactor sector
$\Delta m^2, \theta_{13}$

Atmospheric
Accelerator
$\Delta m^2, \theta_{23}$



http://hitoshi.berkeley.edu/neutrino

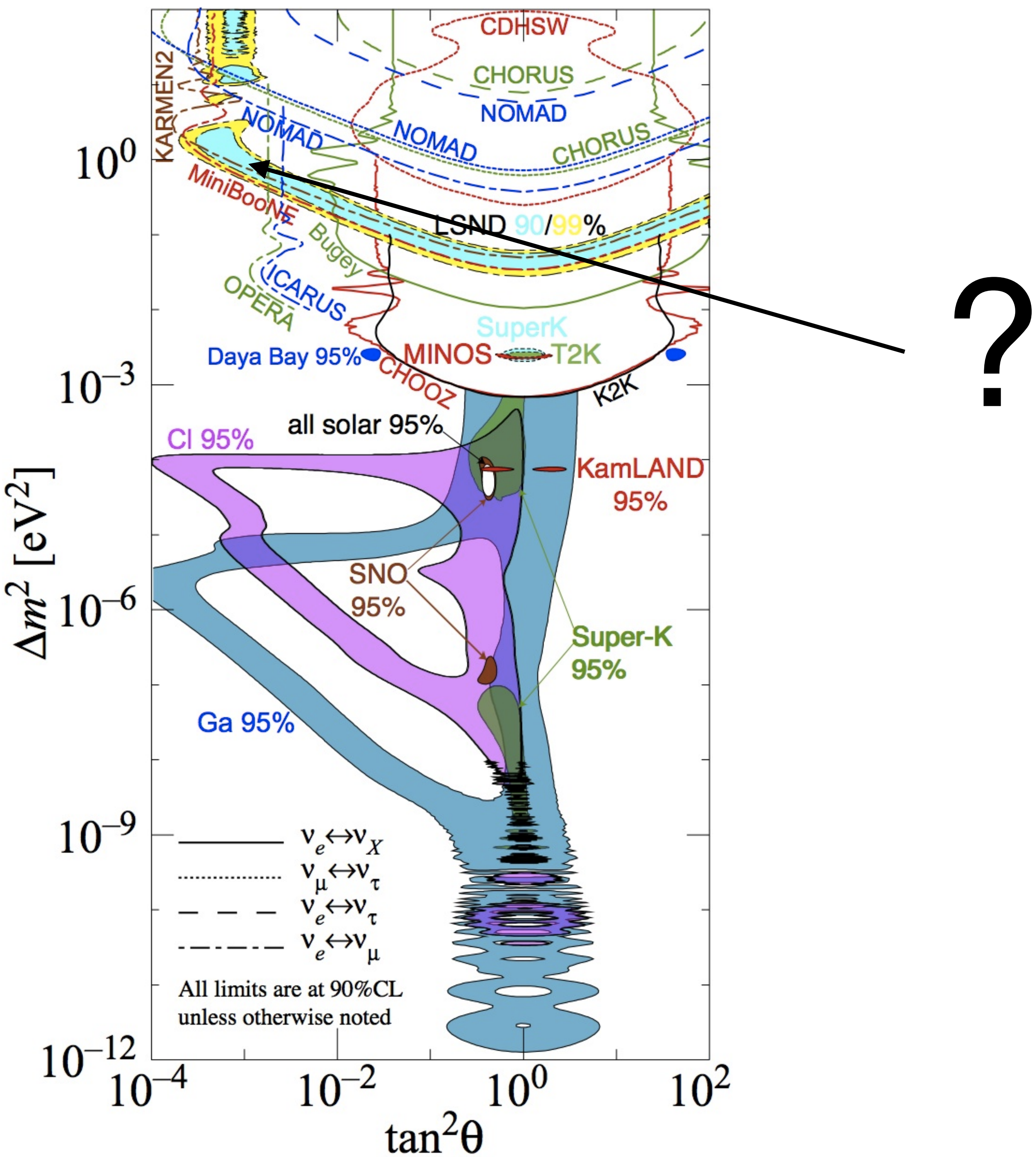
$\Delta m^2 = m^2_3 - m^2_1$

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

Solar sector
$\delta m^2, \theta_{12}$

Neutrino mass-mixing: an overview

…but 3 + ? scenarios are not completely ruled out…



http://hitoshi.berkeley.edu/neutrino

Neutrino mass-mixing: an overview

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

$\boxed{\theta_{12}, \theta_{13}, \theta_{23}}$ **3 mixing angles**

Neutrino mass-mixing: an overview

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

$\boxed{\theta_{12},\ \theta_{13},\ \theta_{23}}$	3 mixing angles
$\boxed{\boldsymbol{\delta}}$	**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

$\theta_{12}, \theta_{13}, \theta_{23}$	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
$\boldsymbol{\Delta m^2, \delta m^2}$	**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

$\theta_{12}, \theta_{13}, \theta_{23}$	3 mixing angles
δ	1 Dirac phase
$\Delta m^2, \delta m^2$	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	
$\boldsymbol{\alpha_1, \alpha_2}$	**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**

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

$\Delta m^2, \delta m^2$ ✔

→ 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**

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

$\Delta m^2, \delta m^2$

→ 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**

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

$\Delta m^2, \delta m^2$

→ 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?

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

$\Delta m^2, \delta m^2$

δ

mass ordering

Neutrino oscillations

α_1, α_2

m_0

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

Cosmology
β, $0\nu\beta\beta$

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

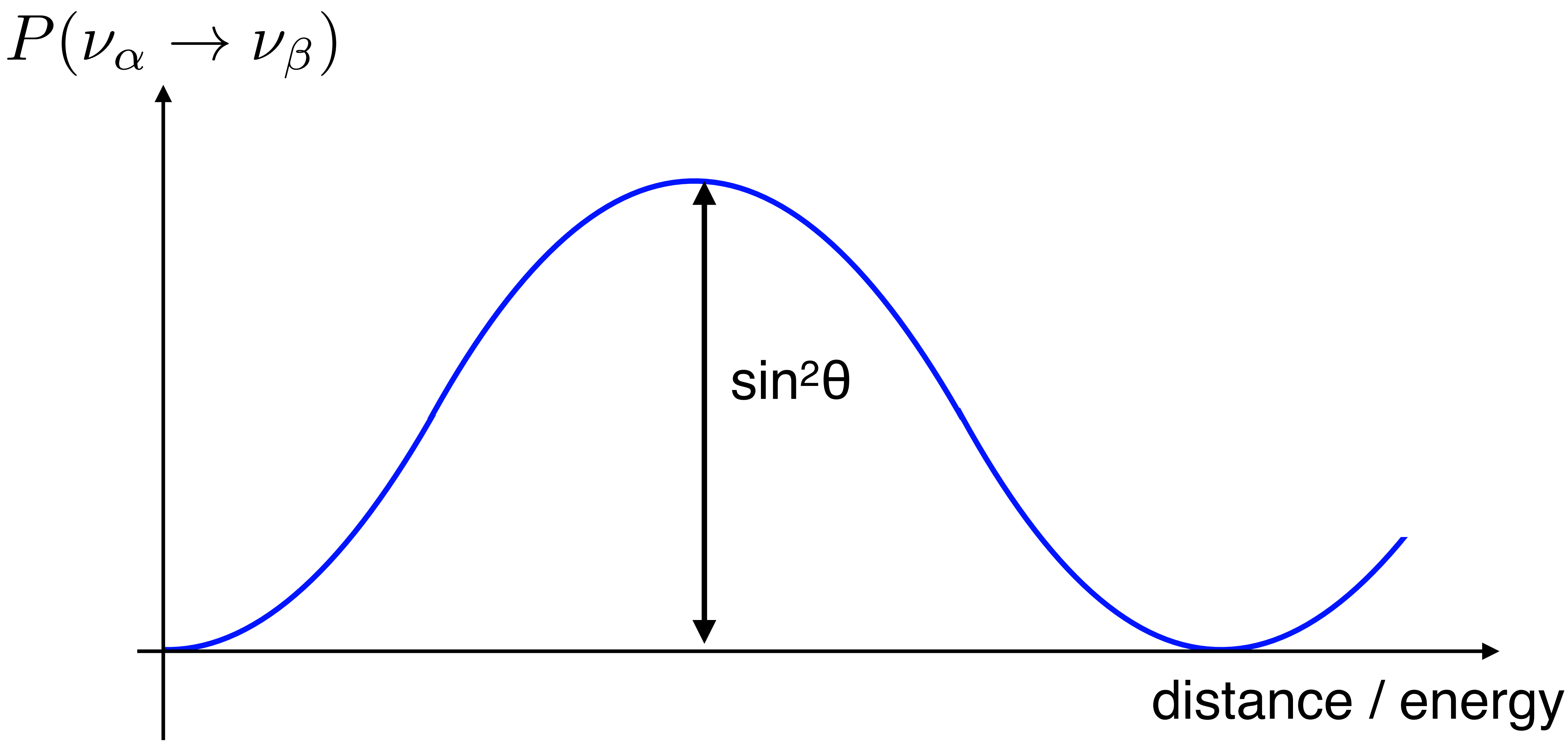
→ **GLOBAL ANALYSIS**

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

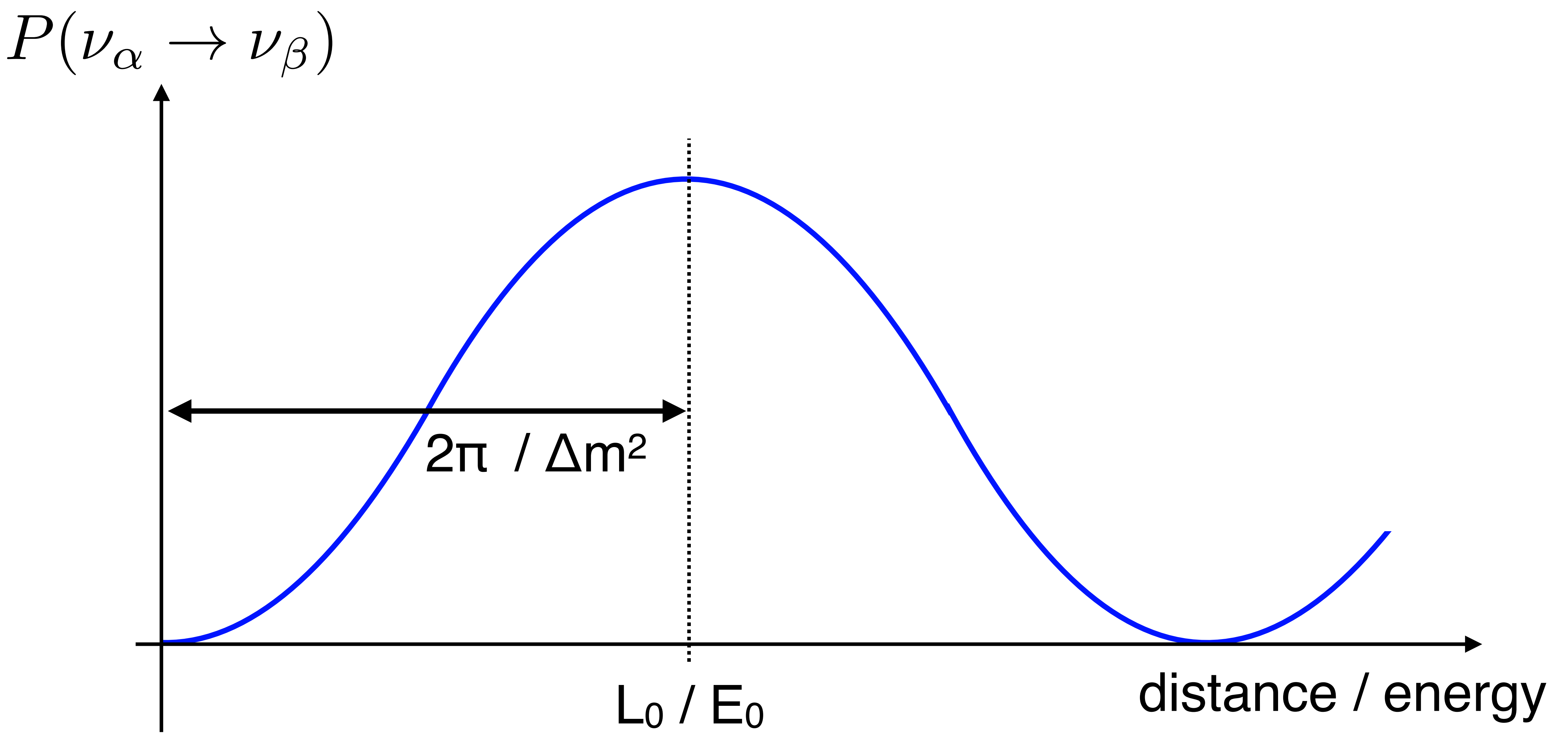
Neutrino oscillation measurements

The **AMPLITUDE** of oscillations give information on the **mixing angles**



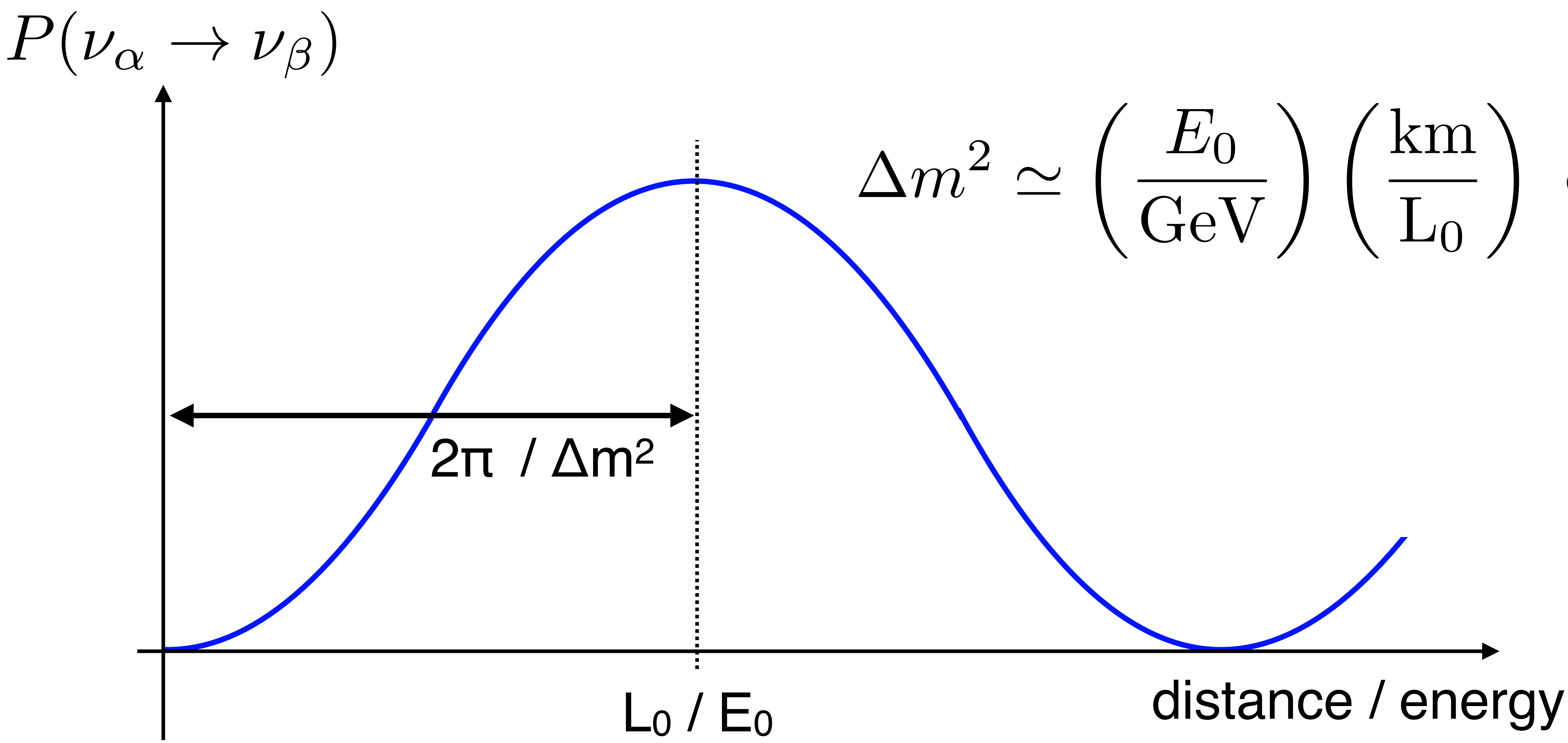
Neutrino oscillation measurements

The **WAVELENGTH** of oscillations give information on **Δm^2**



Neutrino oscillation measurements

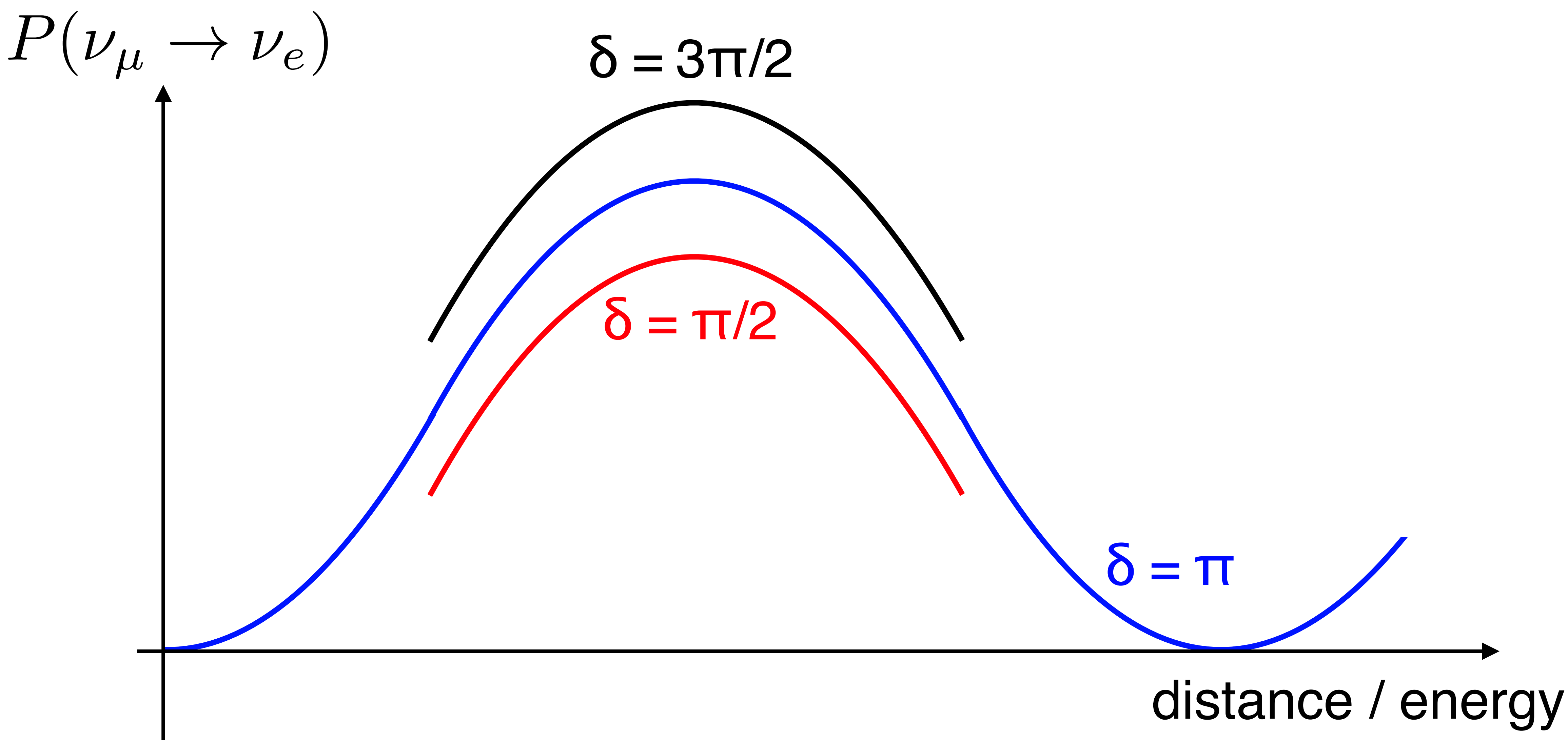
The **WAVELENGTH** of oscillations give information on **Δm²**



$$\Delta m^2 \simeq \left(\frac{E_0}{\mathrm{GeV}}\right)\left(\frac{\mathrm{km}}{\mathrm{L}_0}\right)\ \mathrm{eV}^2$$

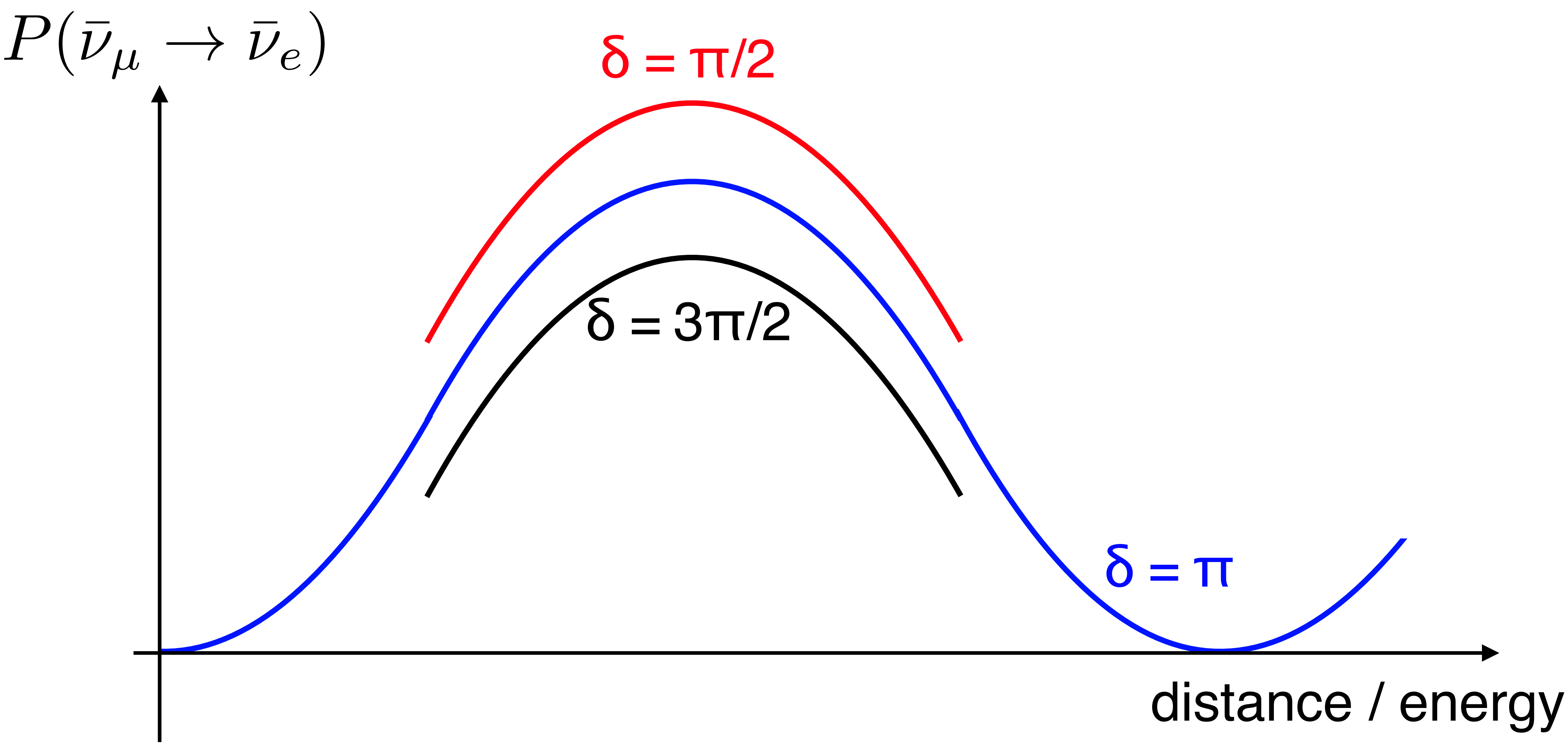
Neutrino oscillation measurements

The **phase δ** modifies the amplitude of oscillations



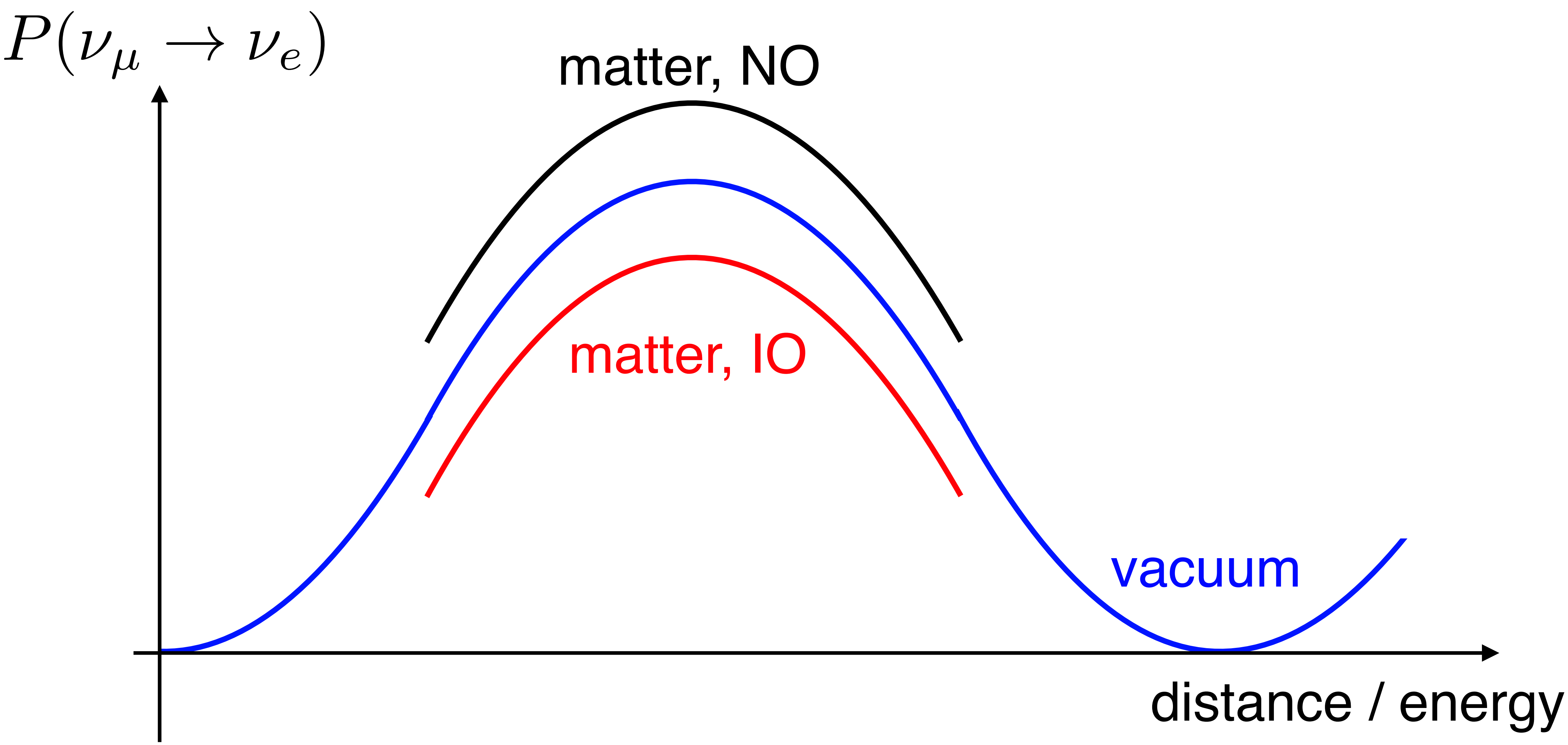
Neutrino oscillation measurements

The **phase δ** modifies the amplitude of oscillations (differently for ν and $\bar{\nu}$)



Neutrino oscillation measurements

Propagation in matter distinguishes normal (NO) and inverted (IO) ordering



Neutrino oscillation measurements

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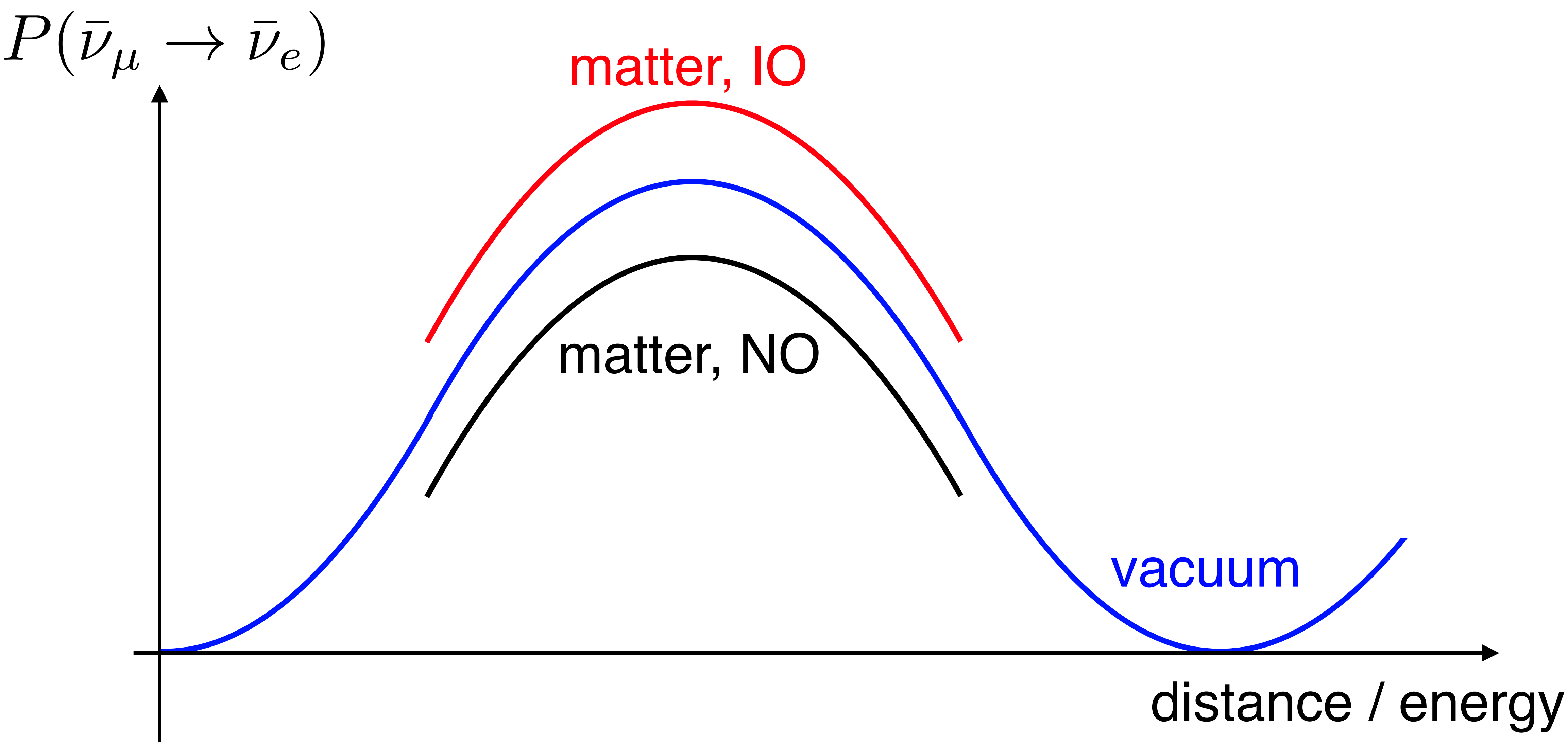
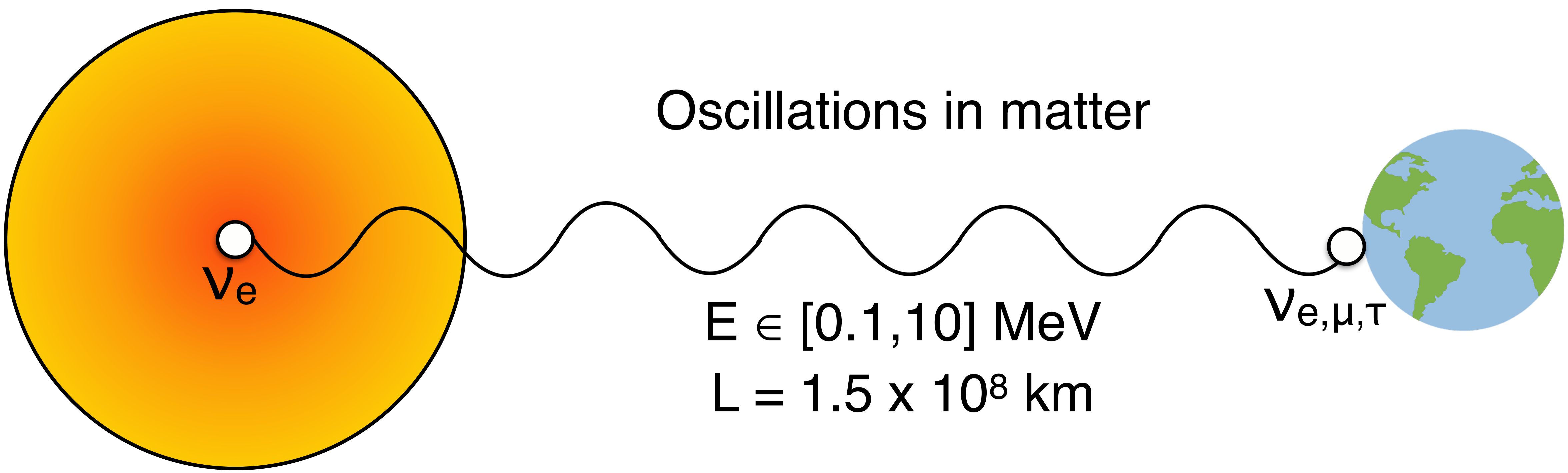


Oscillation data sets

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

(Homestake,Gallex,GNO, Borexino,SNO,SK)



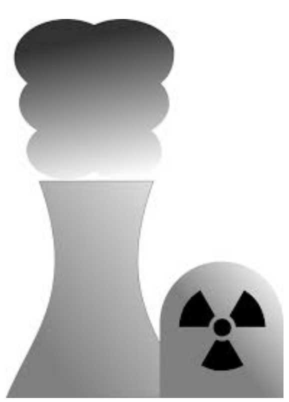
K. Abe *et al.* [Super-Kamiokande Collaboration], Phys. Rev. D 94 (2016) no.5, 052010
B. Aharmim *et al.* [SNO Collaboration], Phys. Rev. C 88 (2013) 025501
B. T. Cleveland, *et al.*, Astrophys. J. 496 (1998) 505
J. N. Abdurashitov *et al.* [SAGE Collaboration], Phys. Rev. C 80 (2009)
F. Kaether, W. 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

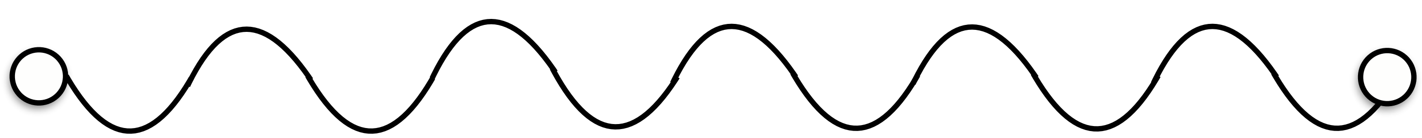
Oscillation data sets

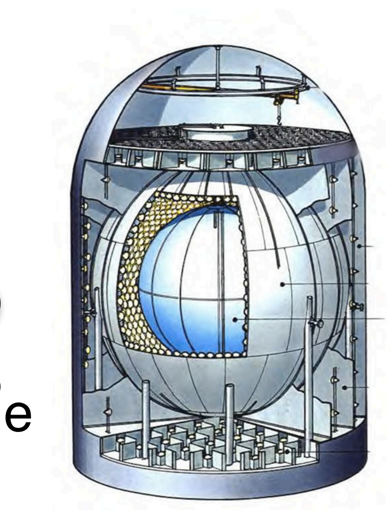
Solar (Homestake,Gallex,GNO, Borexino,SNO,SK) ⟷ $(\theta_{12}, \delta m^2, \theta_{13})$

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

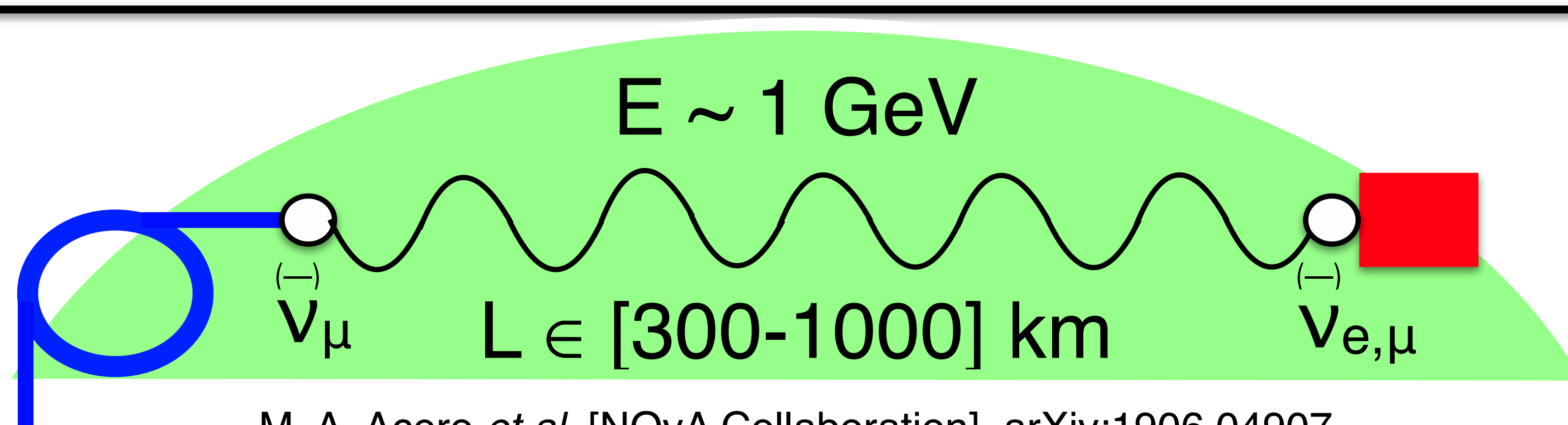
A. Gando *et al.* [KamLAND Collaboration], Phys. Rev. D83 (2011) 052002

Oscillation data sets

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) ⟷ $(\theta_{23}, \Delta m^2, \delta, \mathrm{MO}, \theta_{13})$



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

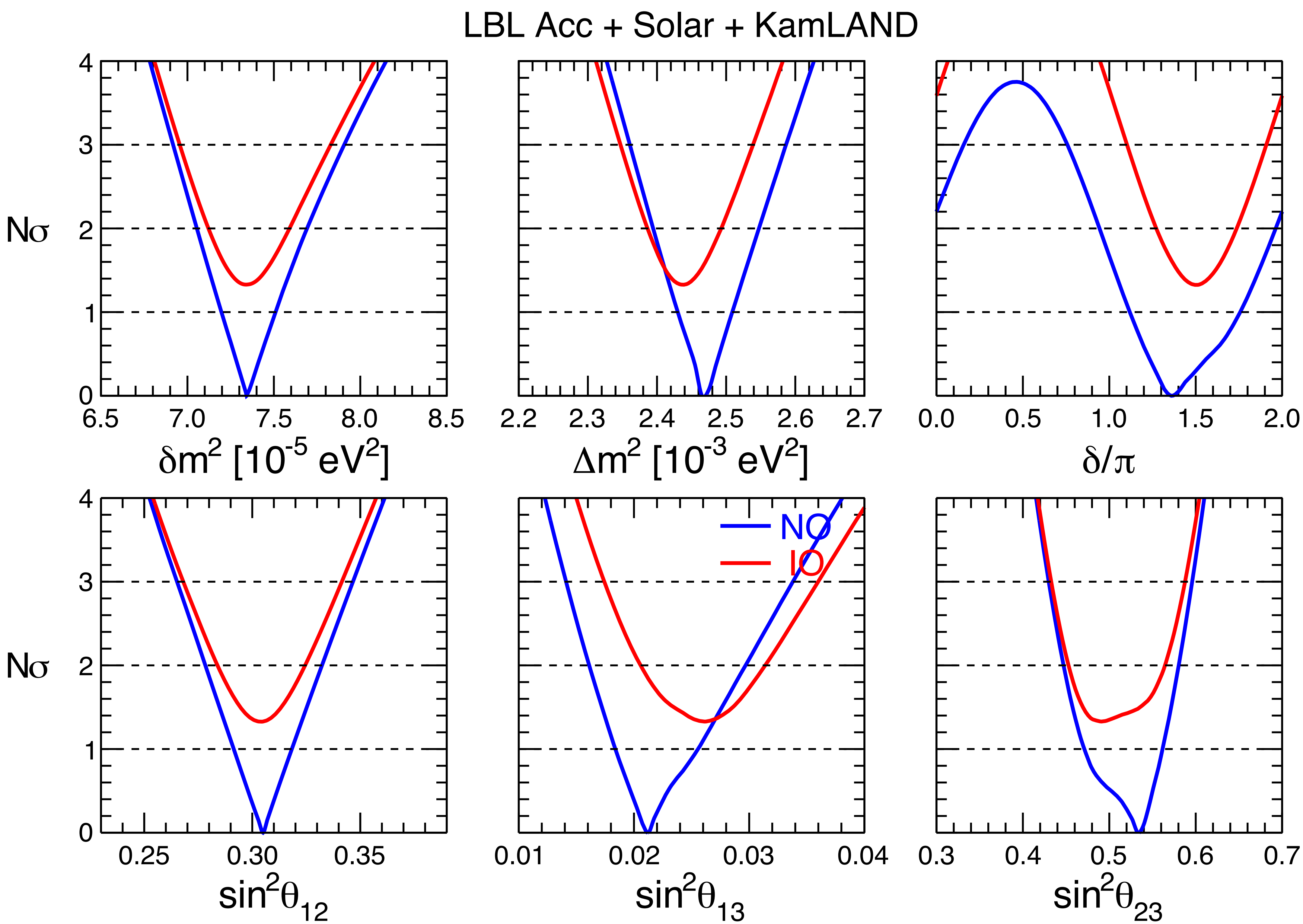
Oscillation data sets

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

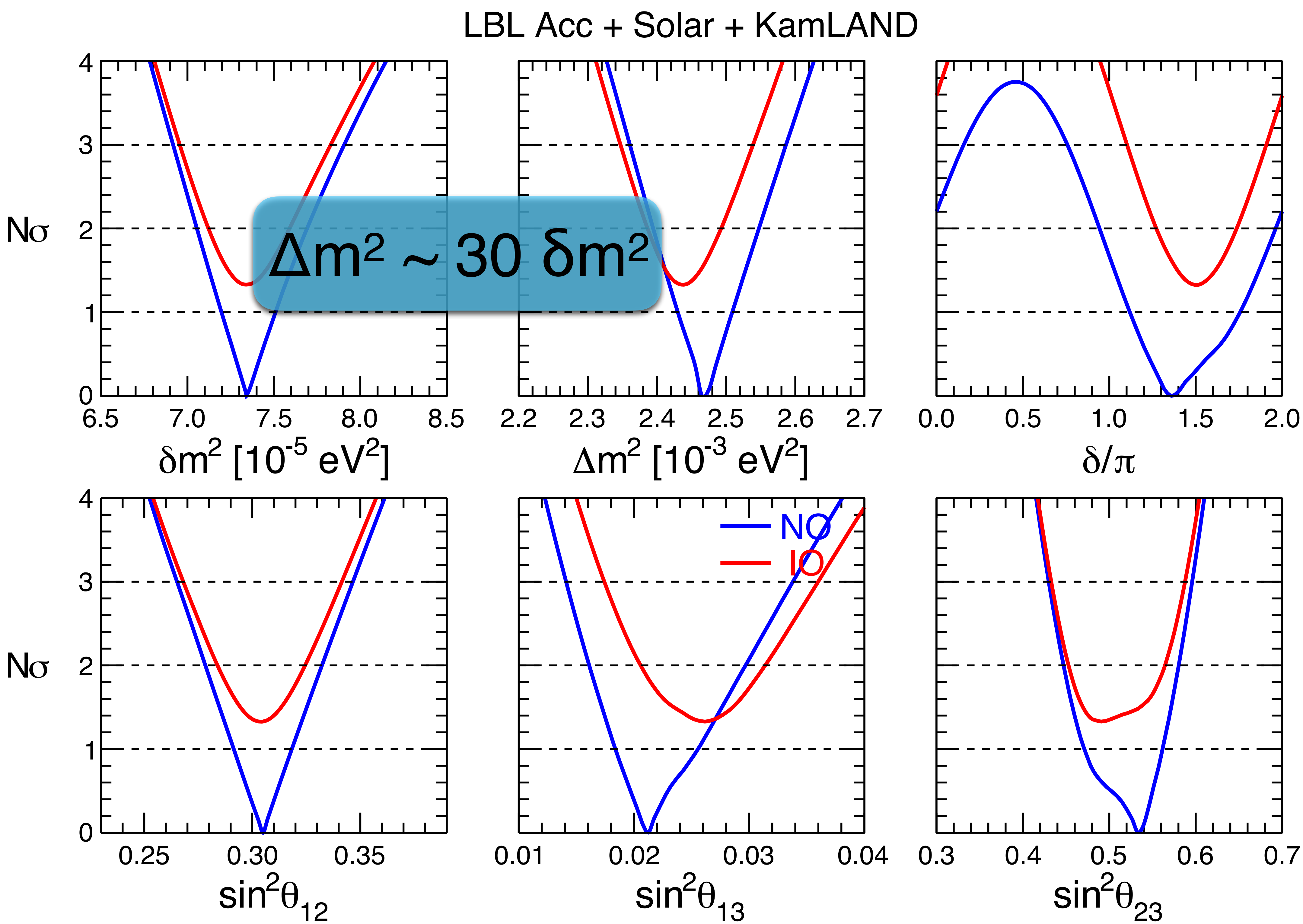
Combined they are sensitive to **all parameters**

LBL Acc + Solar + KamLAND

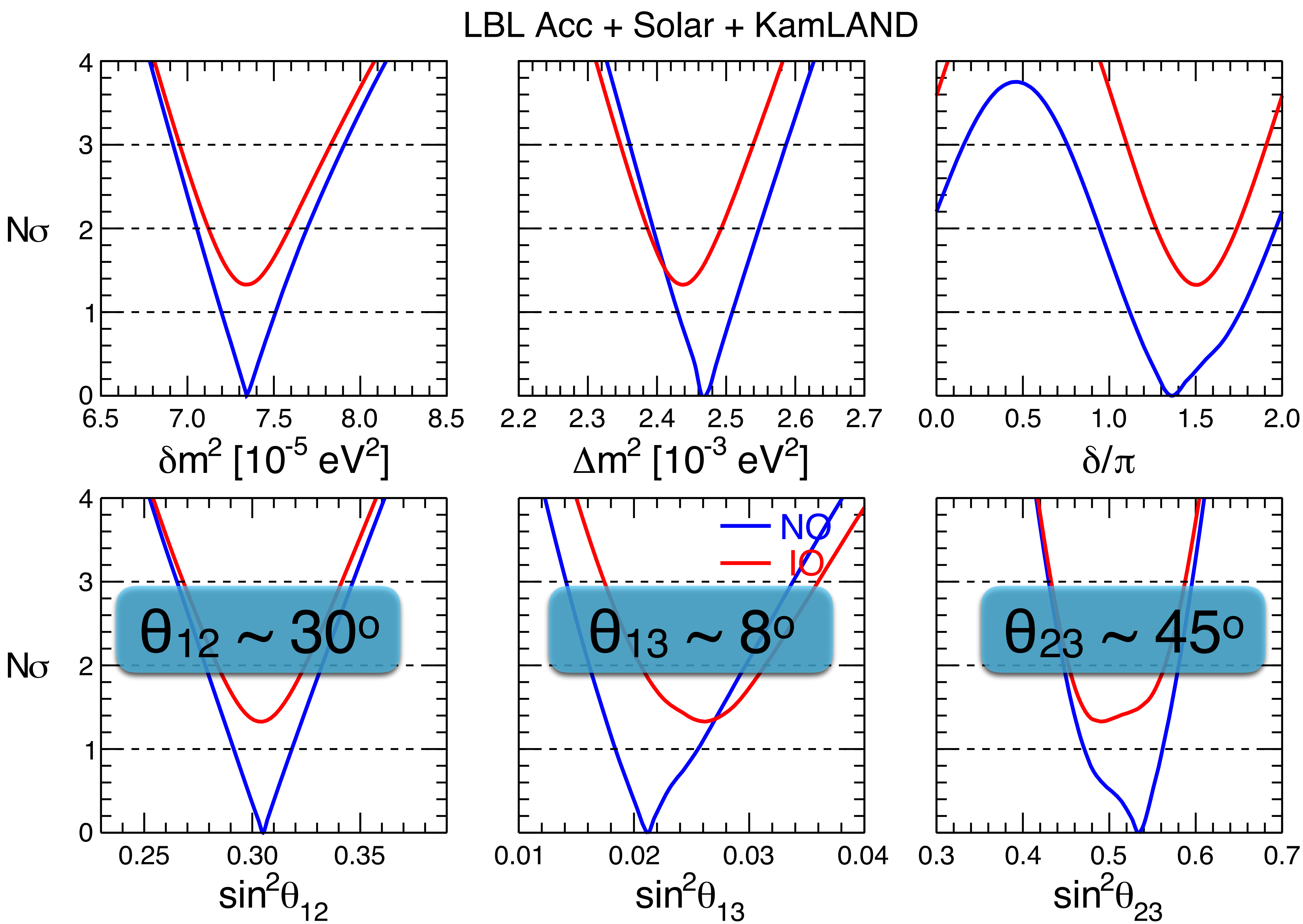
Analysis results



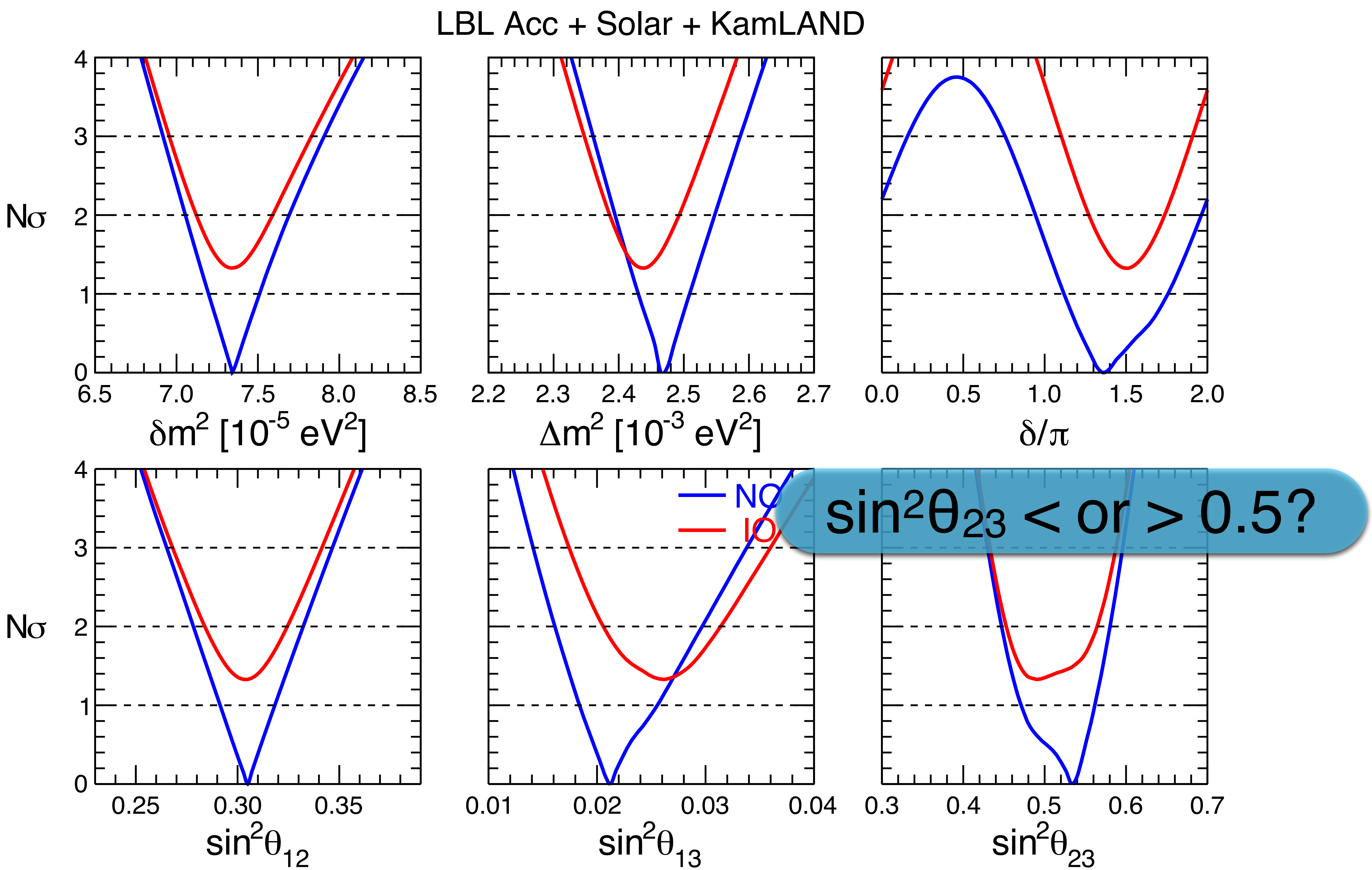
Analysis results: mass differences



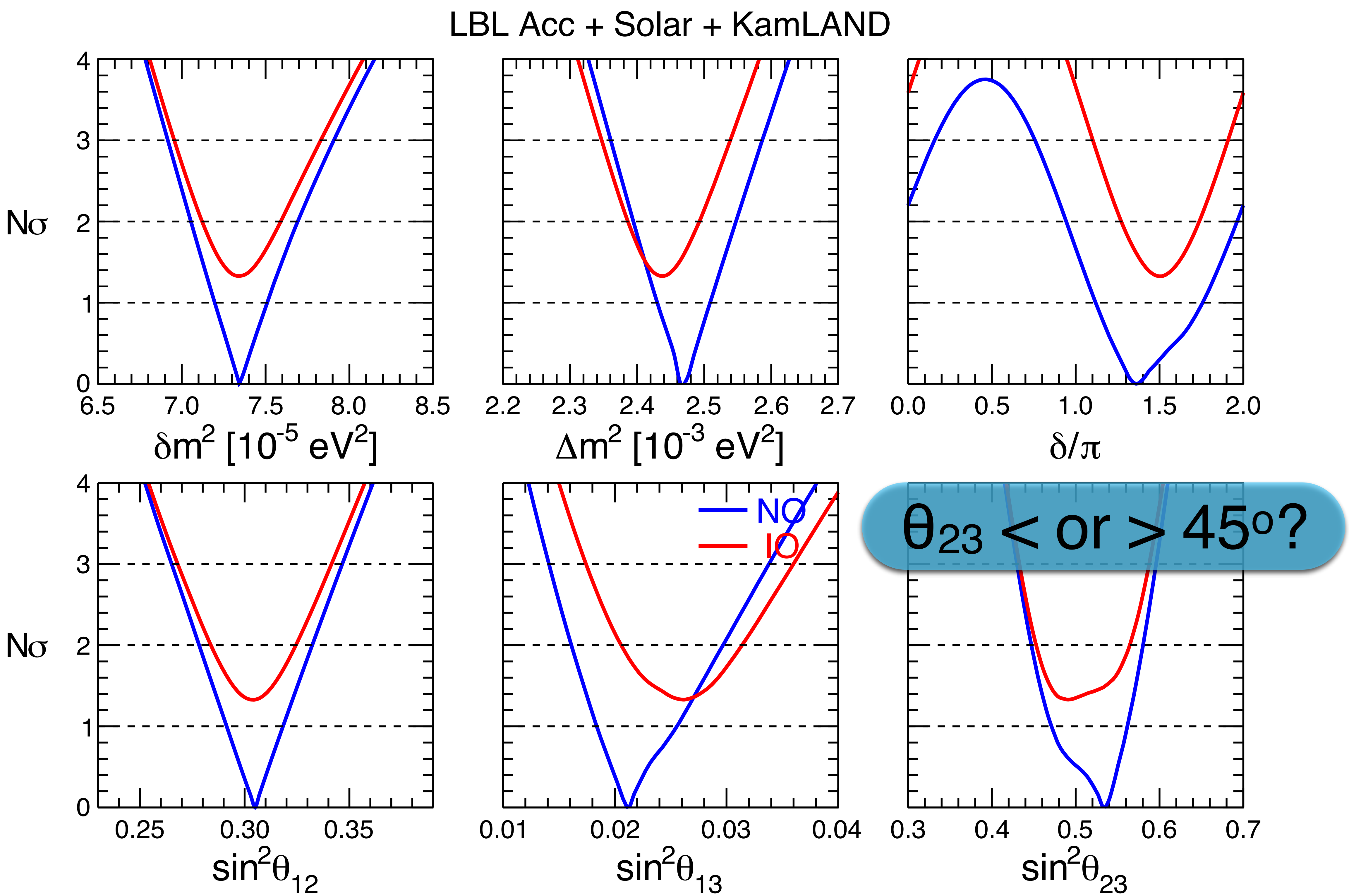
Analysis results: mixing angles



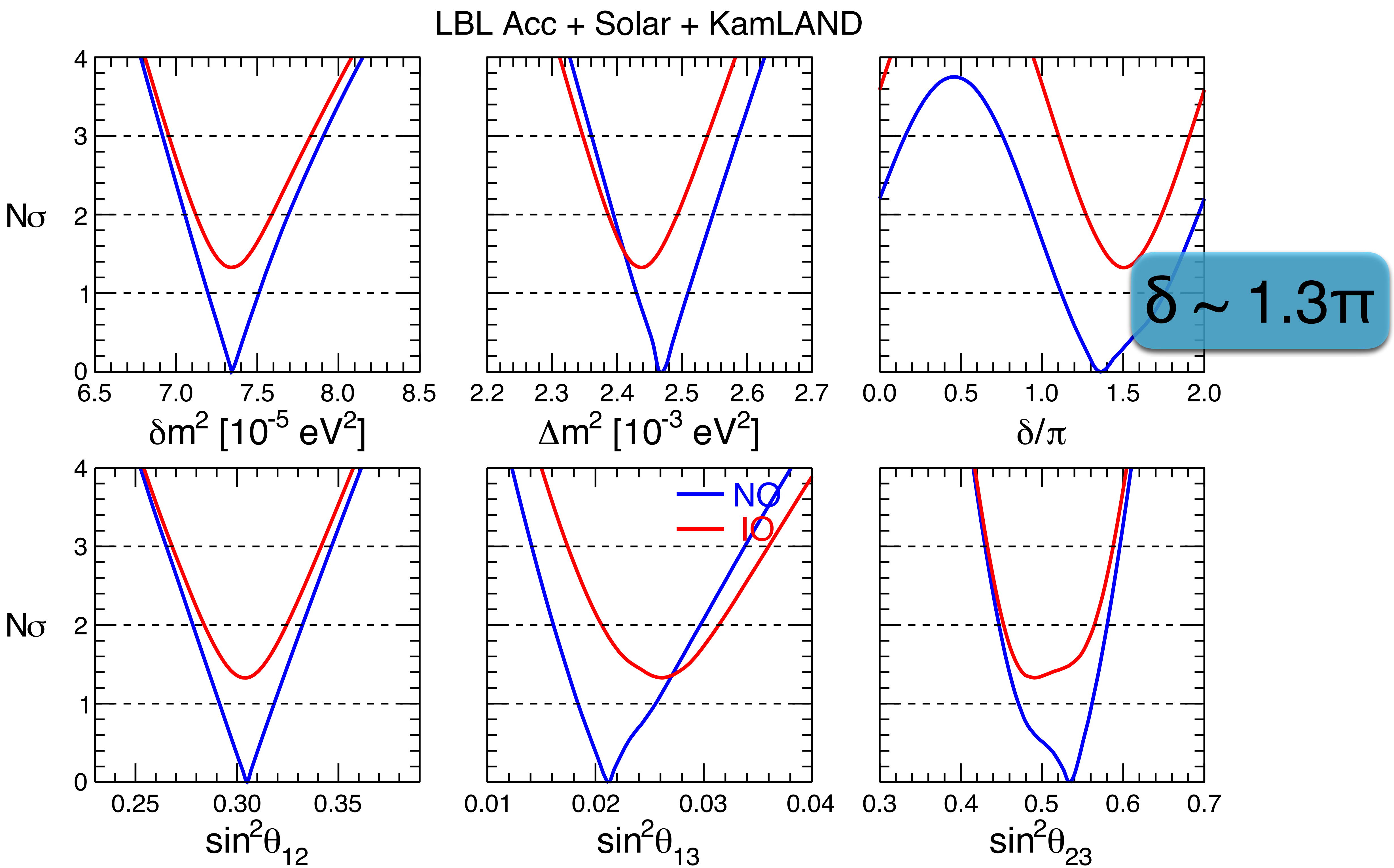
Analysis results: θ_{23} octant



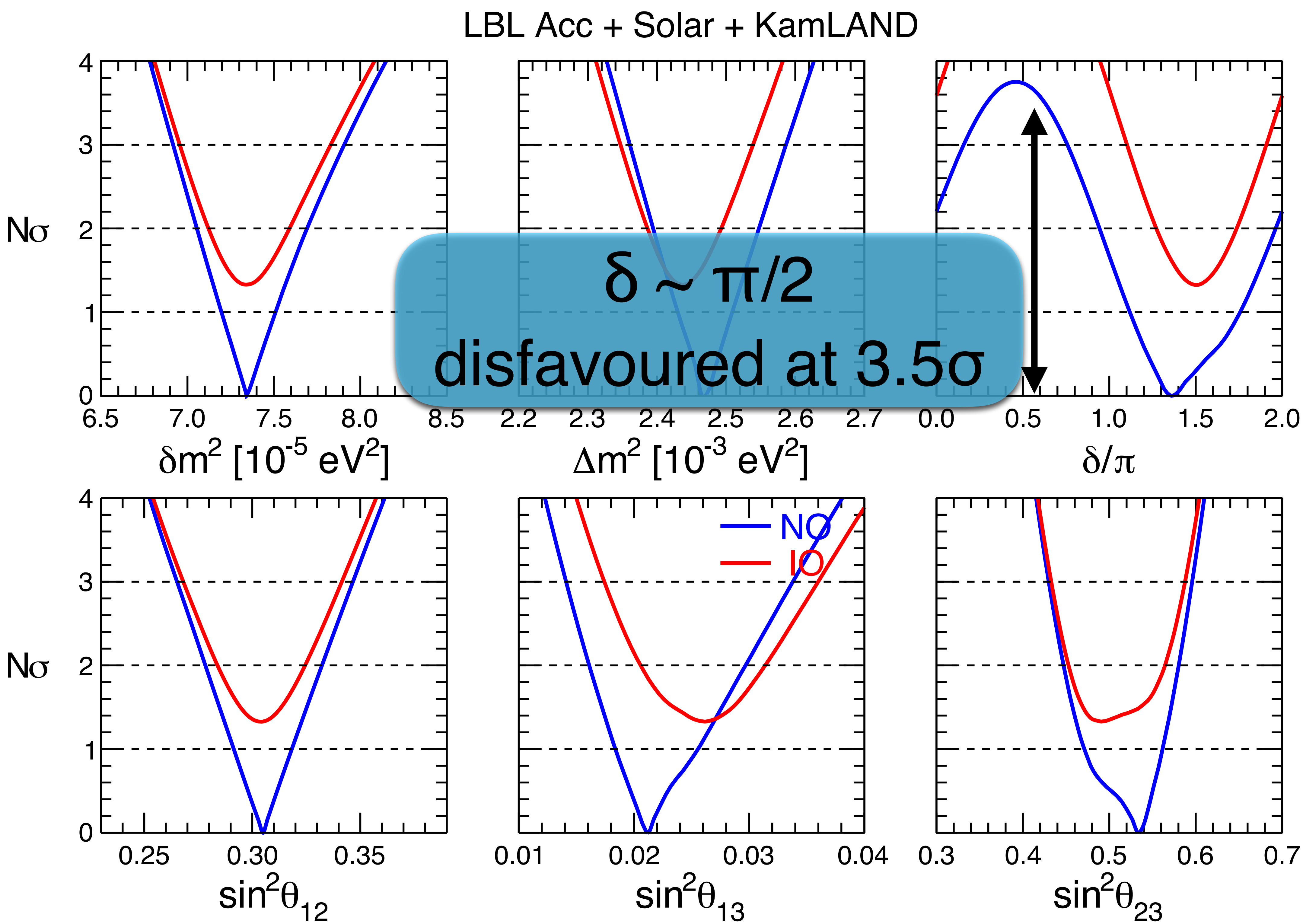
Analysis results: θ_{23} octant



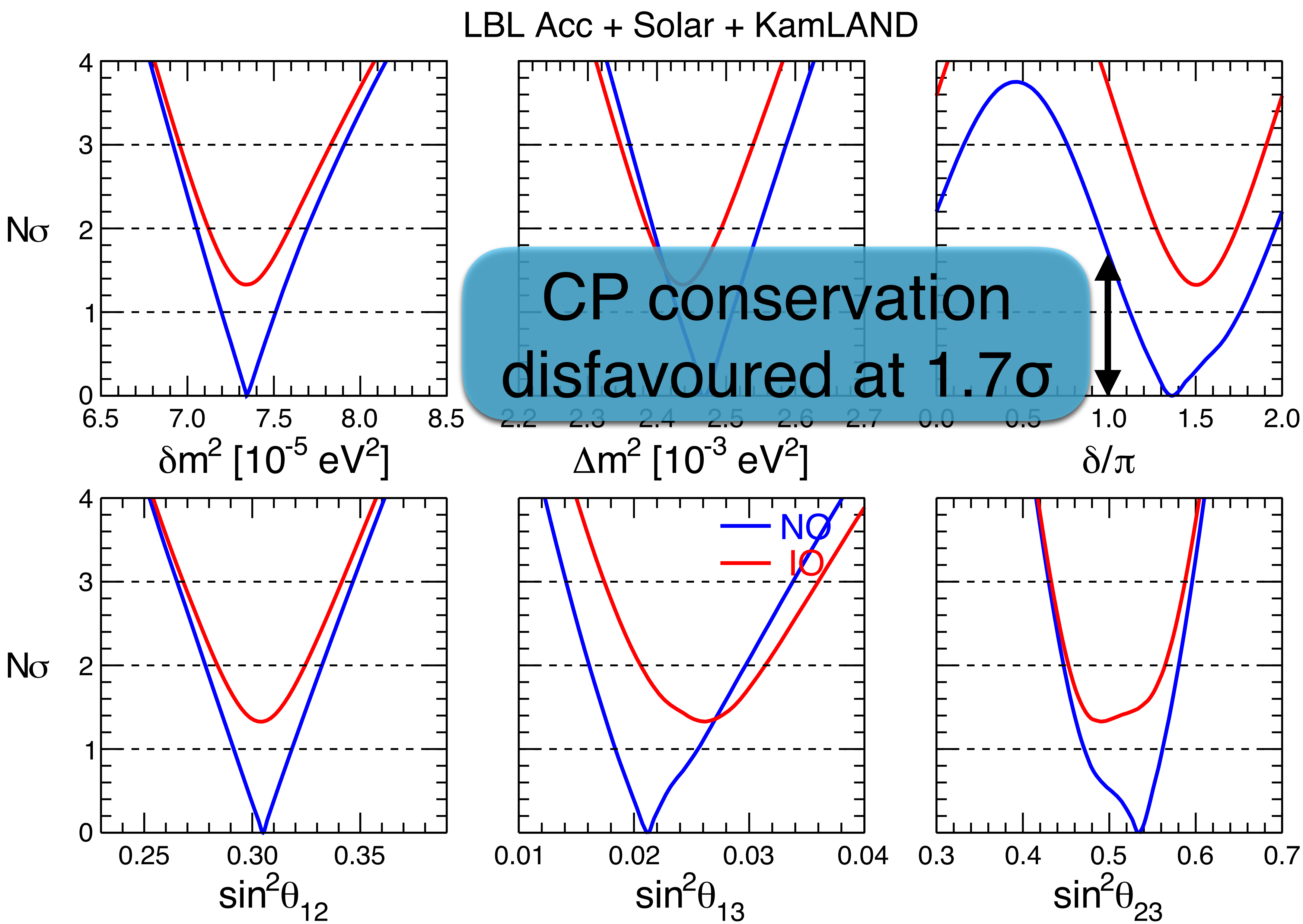
Analysis results: CP violation



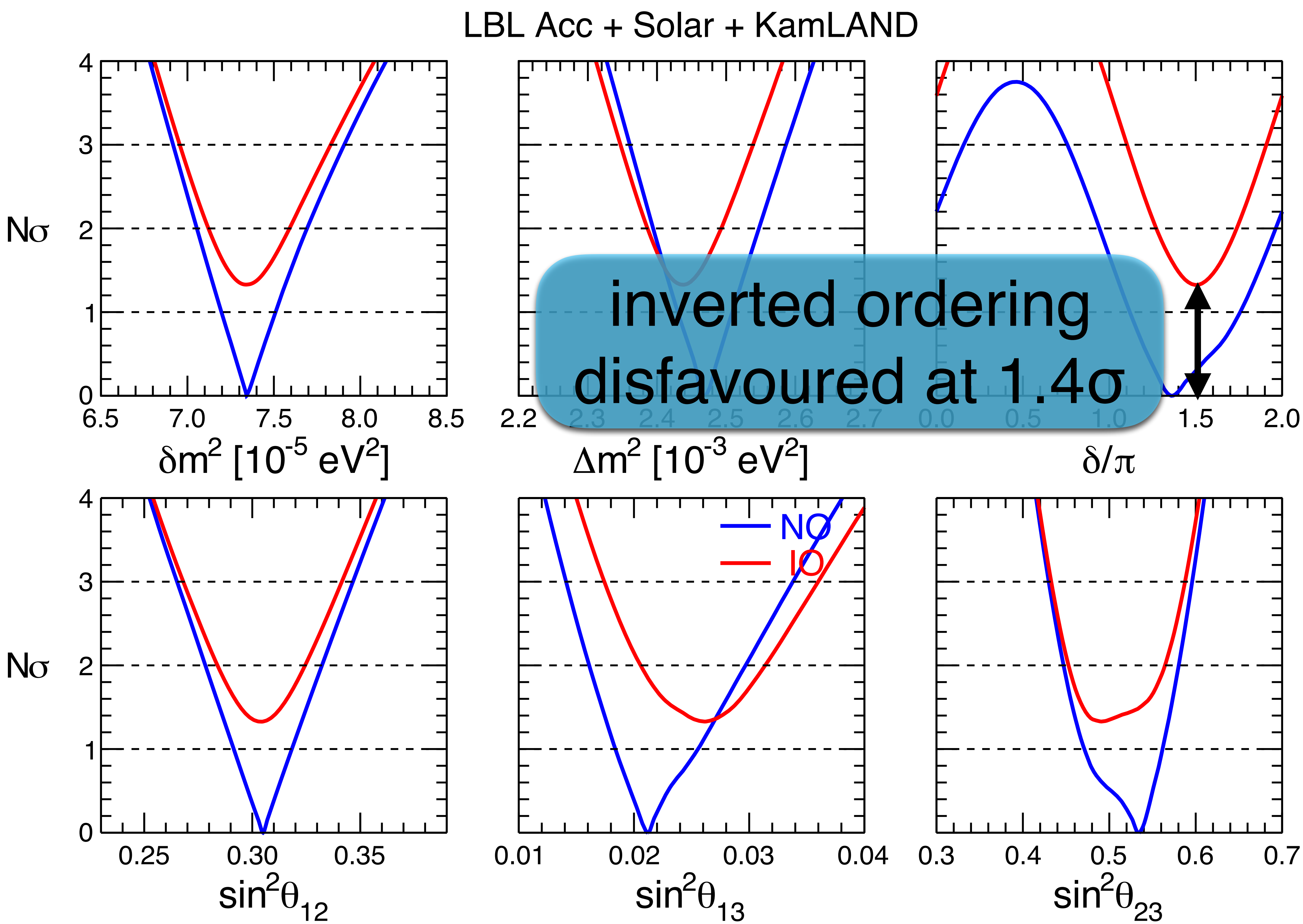
Analysis results: CP violation



Analysis results: CP violation



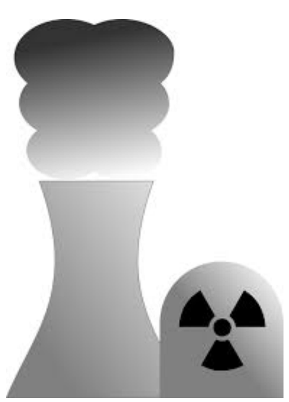
Analysis results: mass ordering



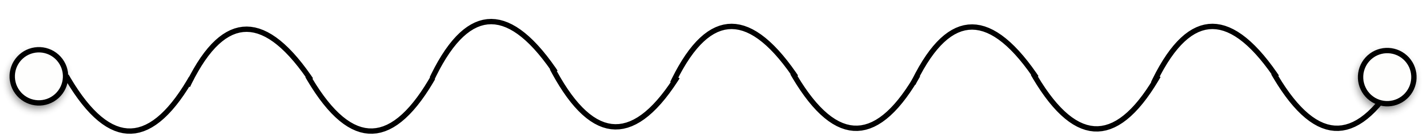
Oscillation data sets

We then strongly constrain θ_{13} with:

SBL reactors (Daya Bay, Double Chooz, RENO)	⟷	$(\theta_{13}, \Delta m^2)$



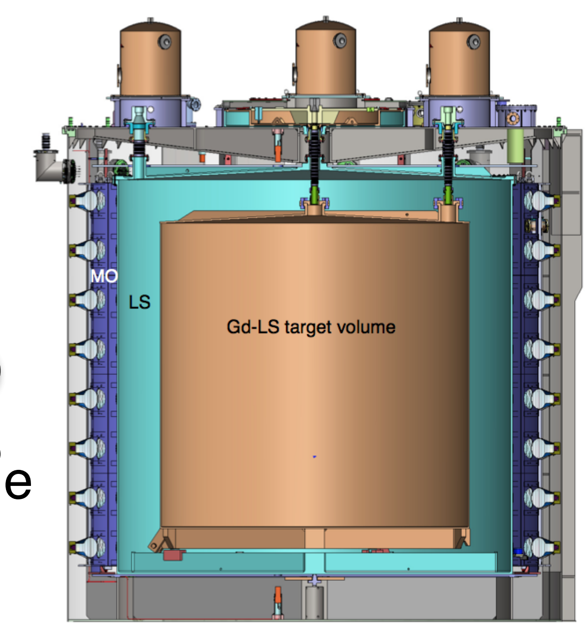
Oscillations in vacuum



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

$L \sim 1$ km

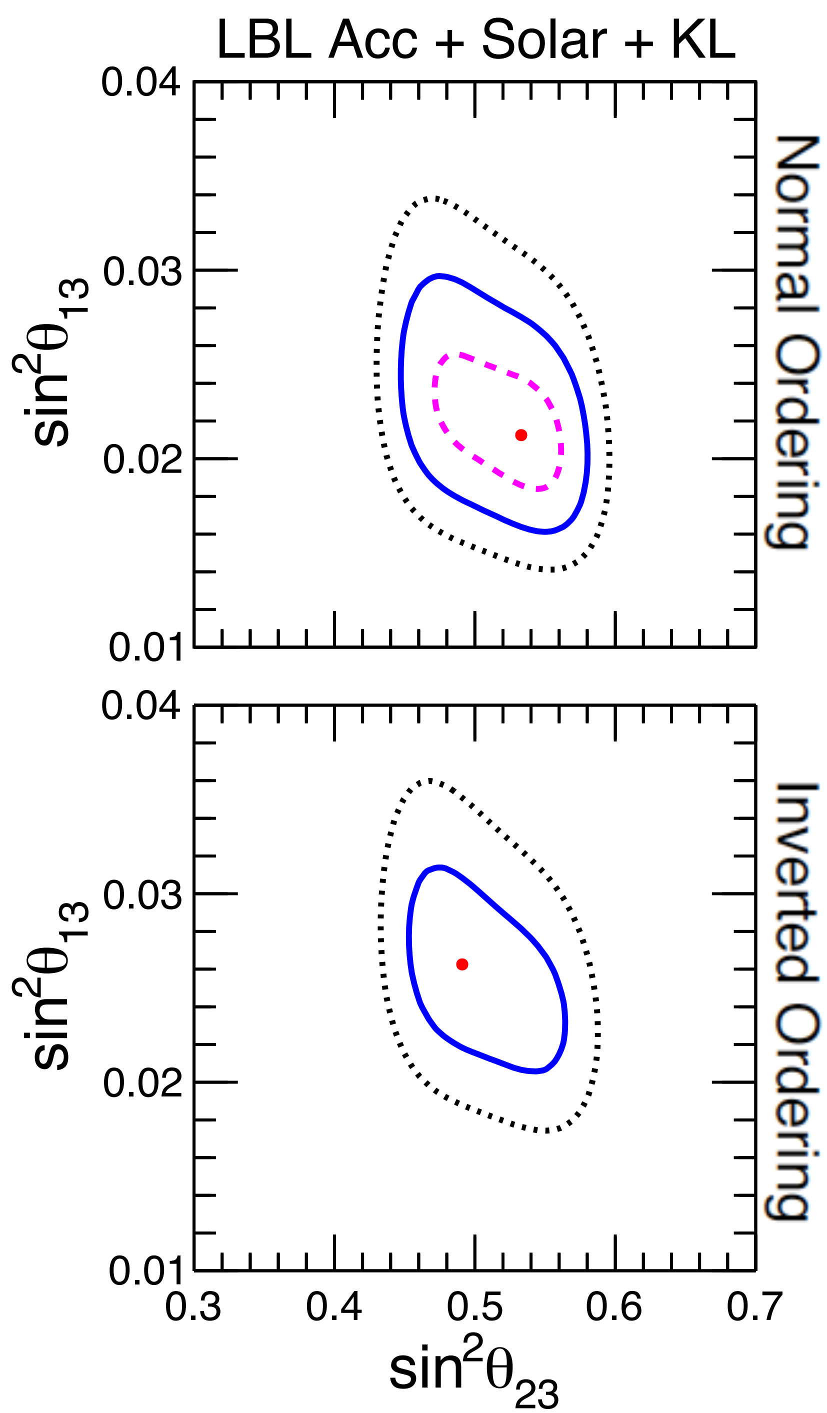
$E \in [0,10]$ MeV



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.

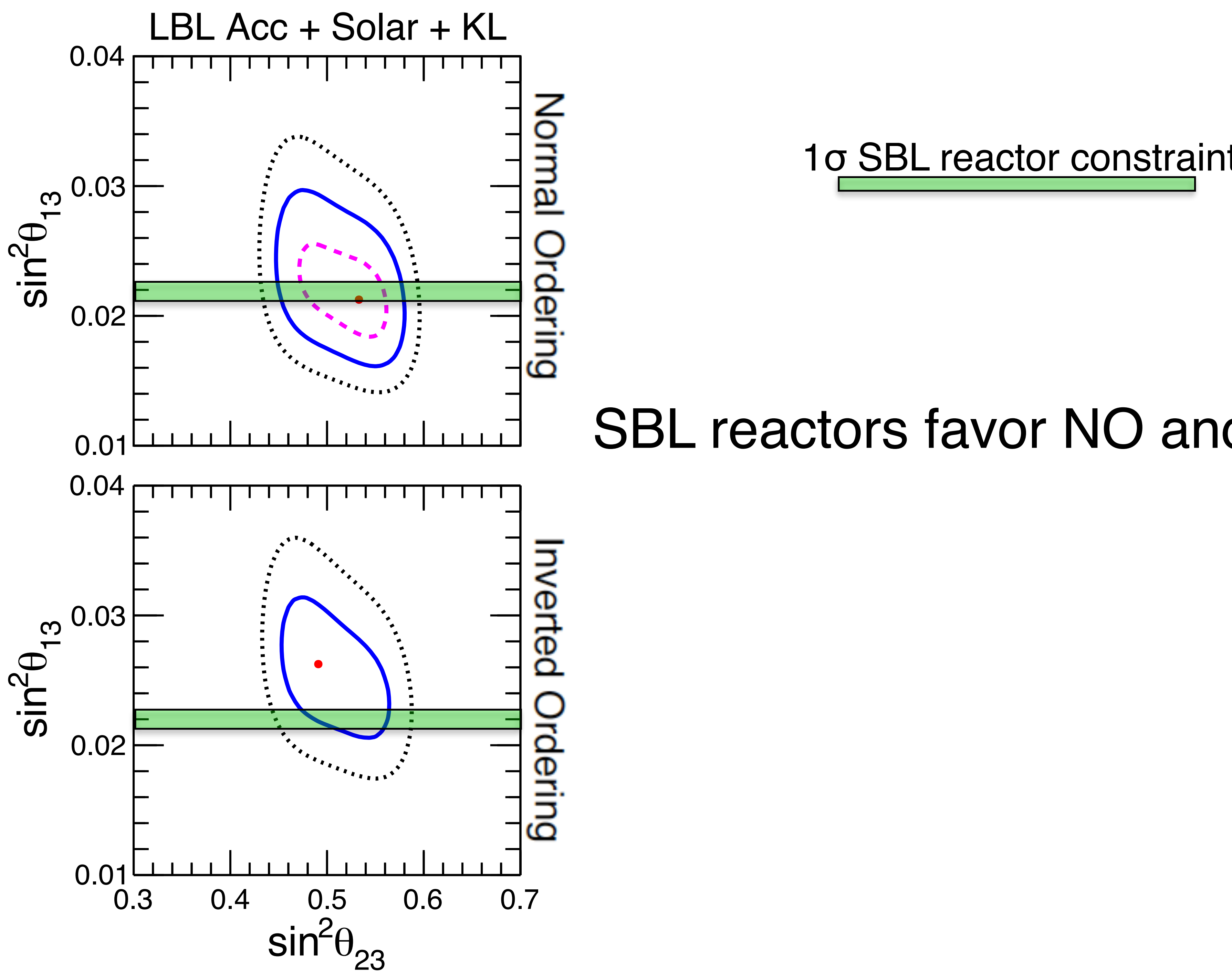
Analysis results: covariance (θ_{23},θ_{13})



θ_{23} and θ_{13} are anti-correlated

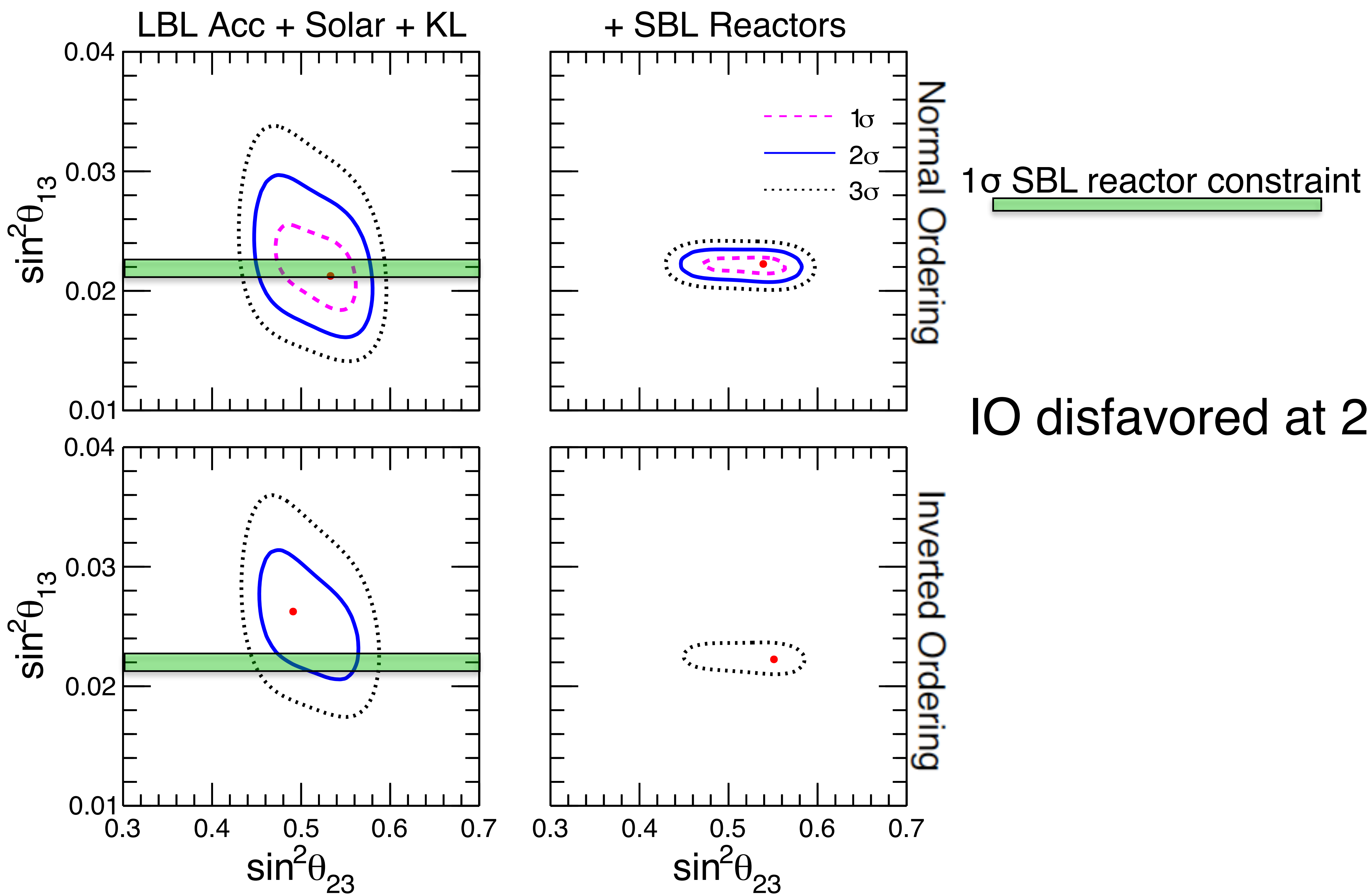
$$P_{\nu_\mu \to \nu_e}(\mathrm{LBL}) \propto \sin^2\theta_{13}\sin^2\theta_{23}$$

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



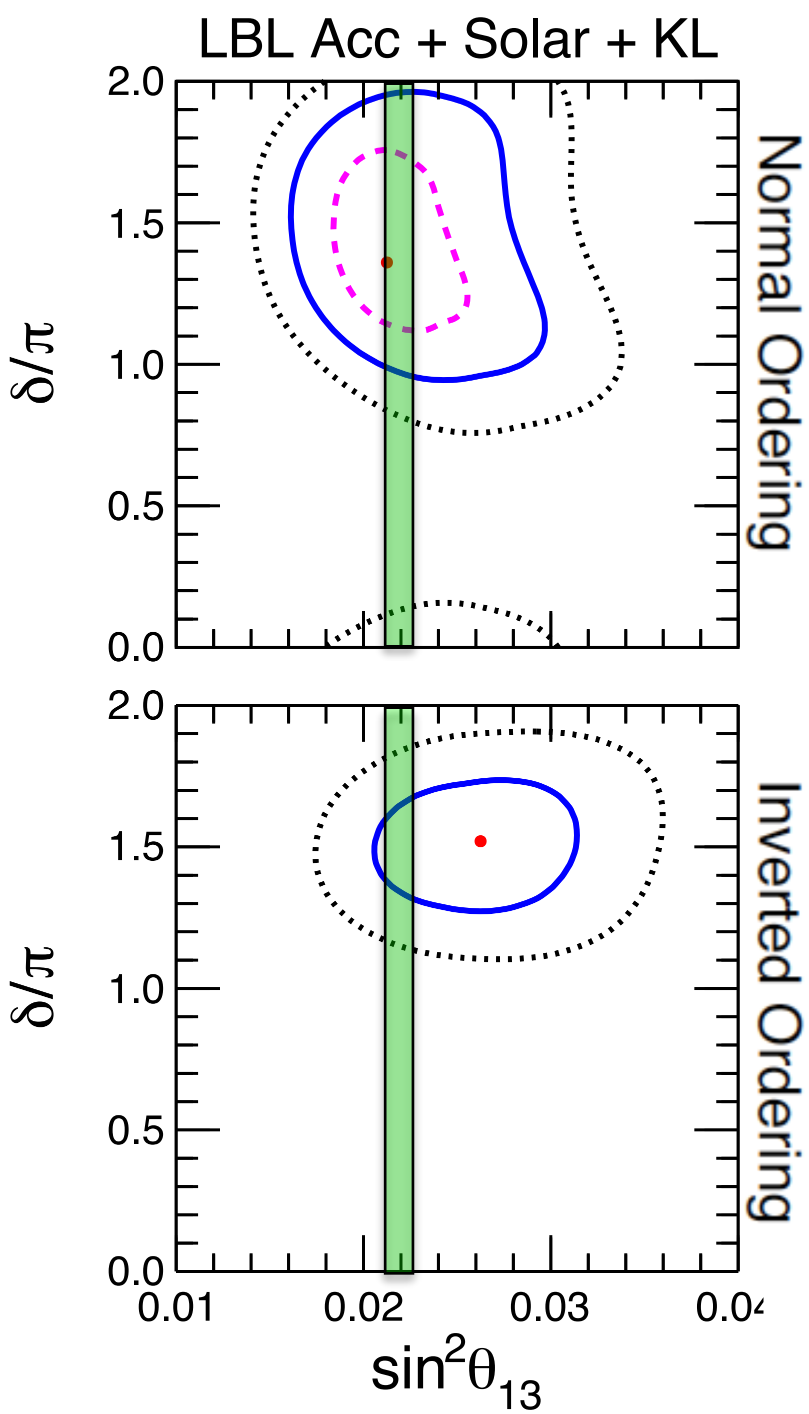
SBL reactors favor NO and θ_{23} 2nd octant

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



IO disfavored at 2σ

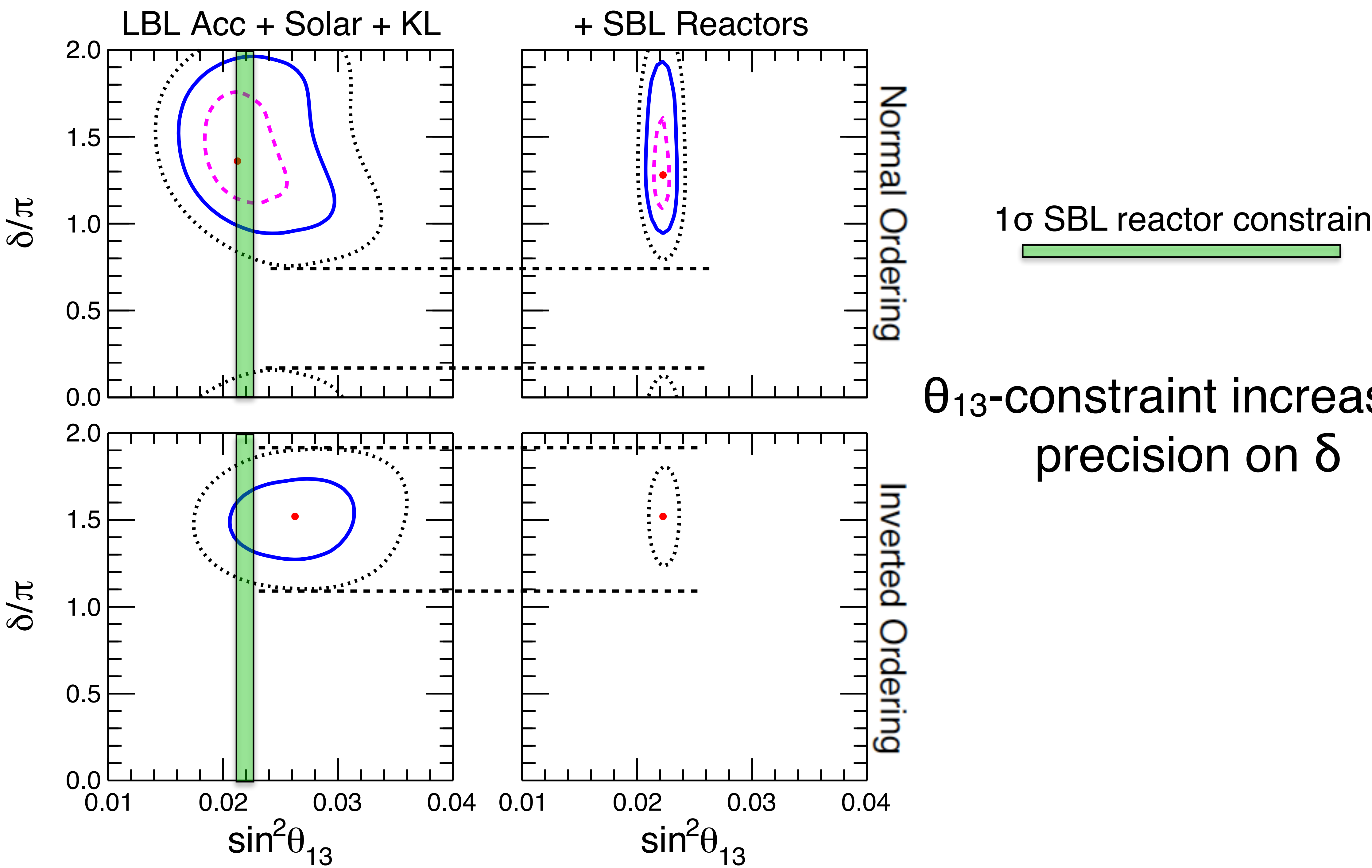
Analysis results: covariance (θ_{13},δ)



1σ SBL reactor constraint

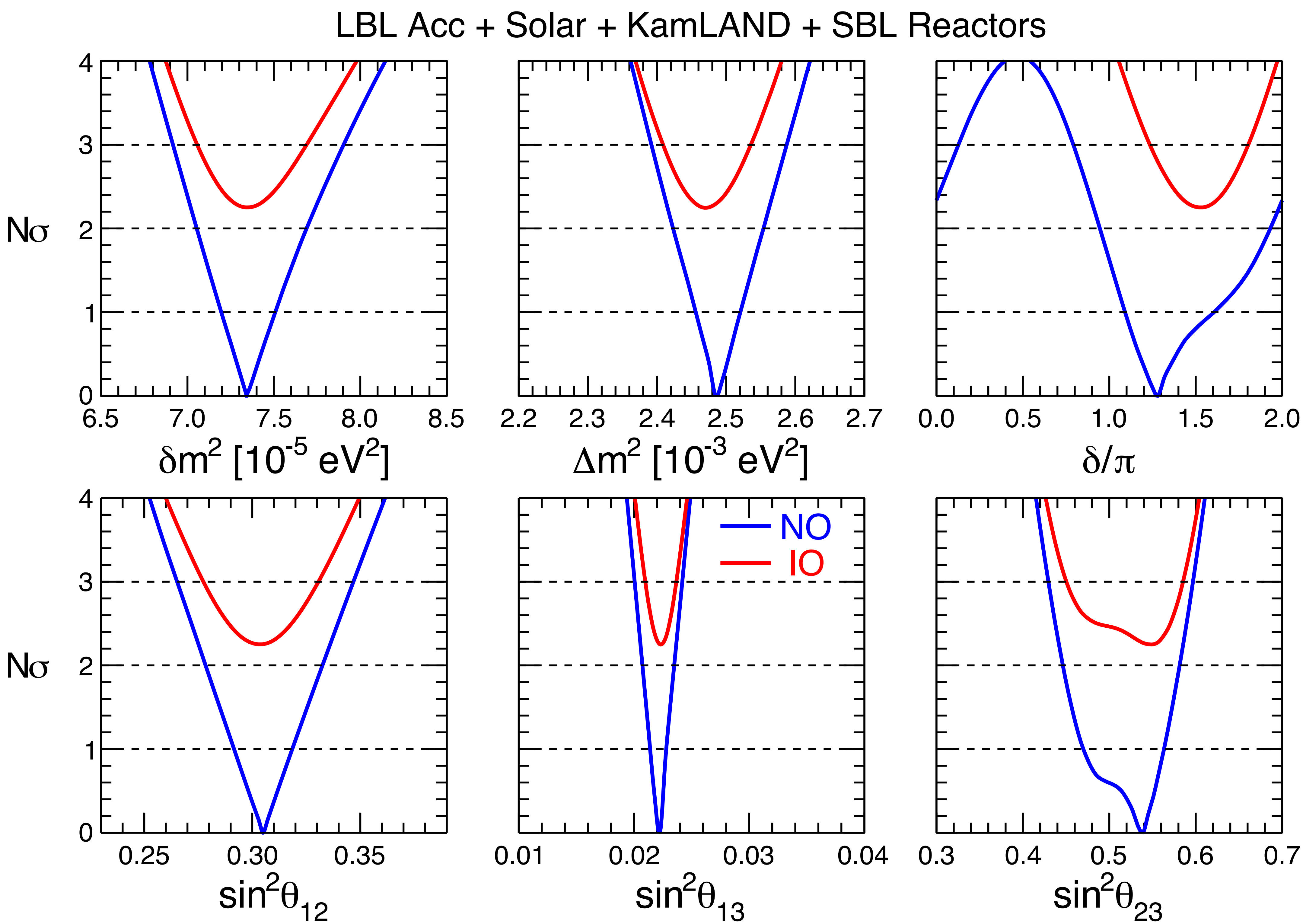
θ_{13}-constraint increases precision on δ

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



θ_{13}-constraint increases precision on δ

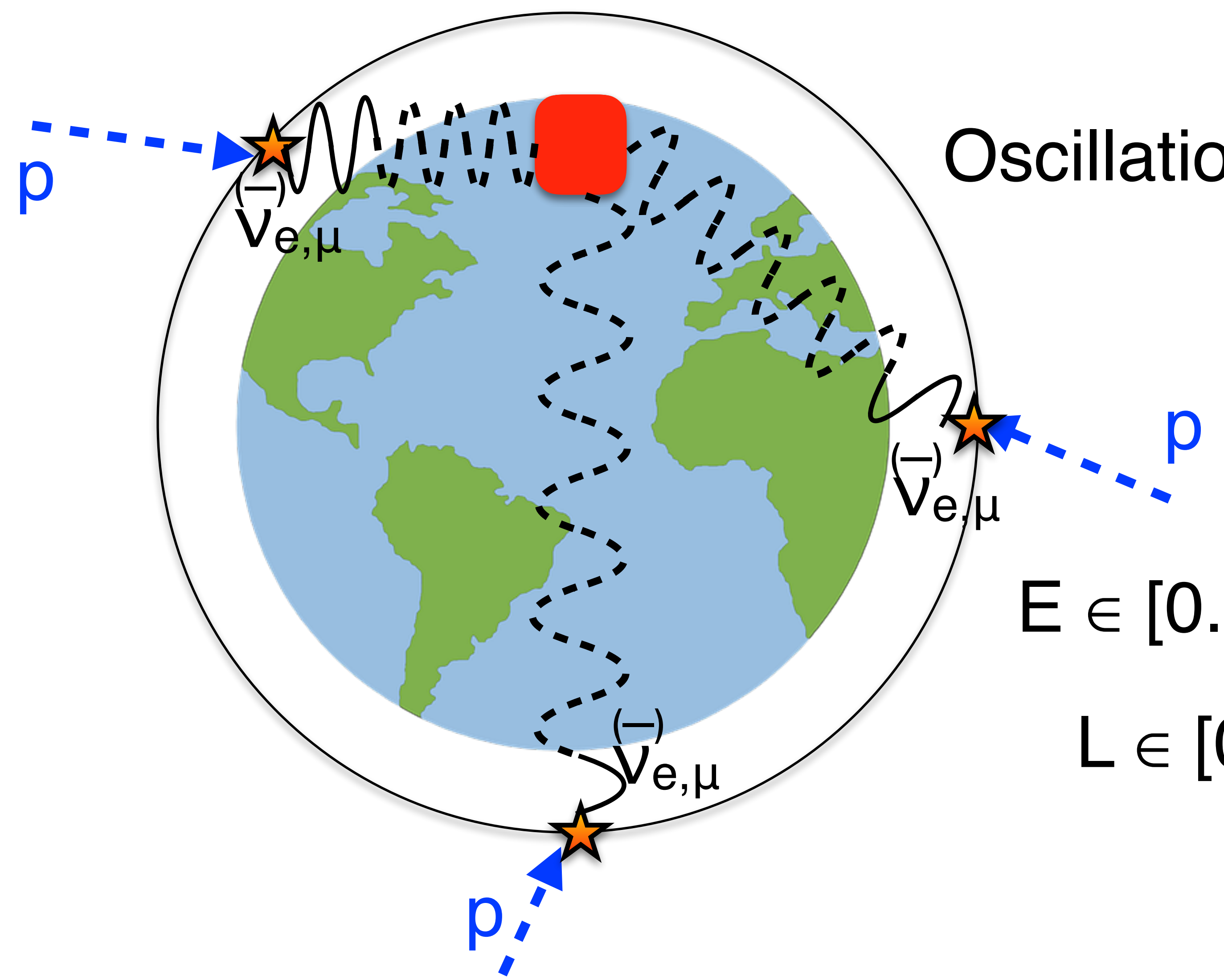
Analysis results



Oscillation data sets

We finally add the rich phenomenology of atmospheric neutrinos

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



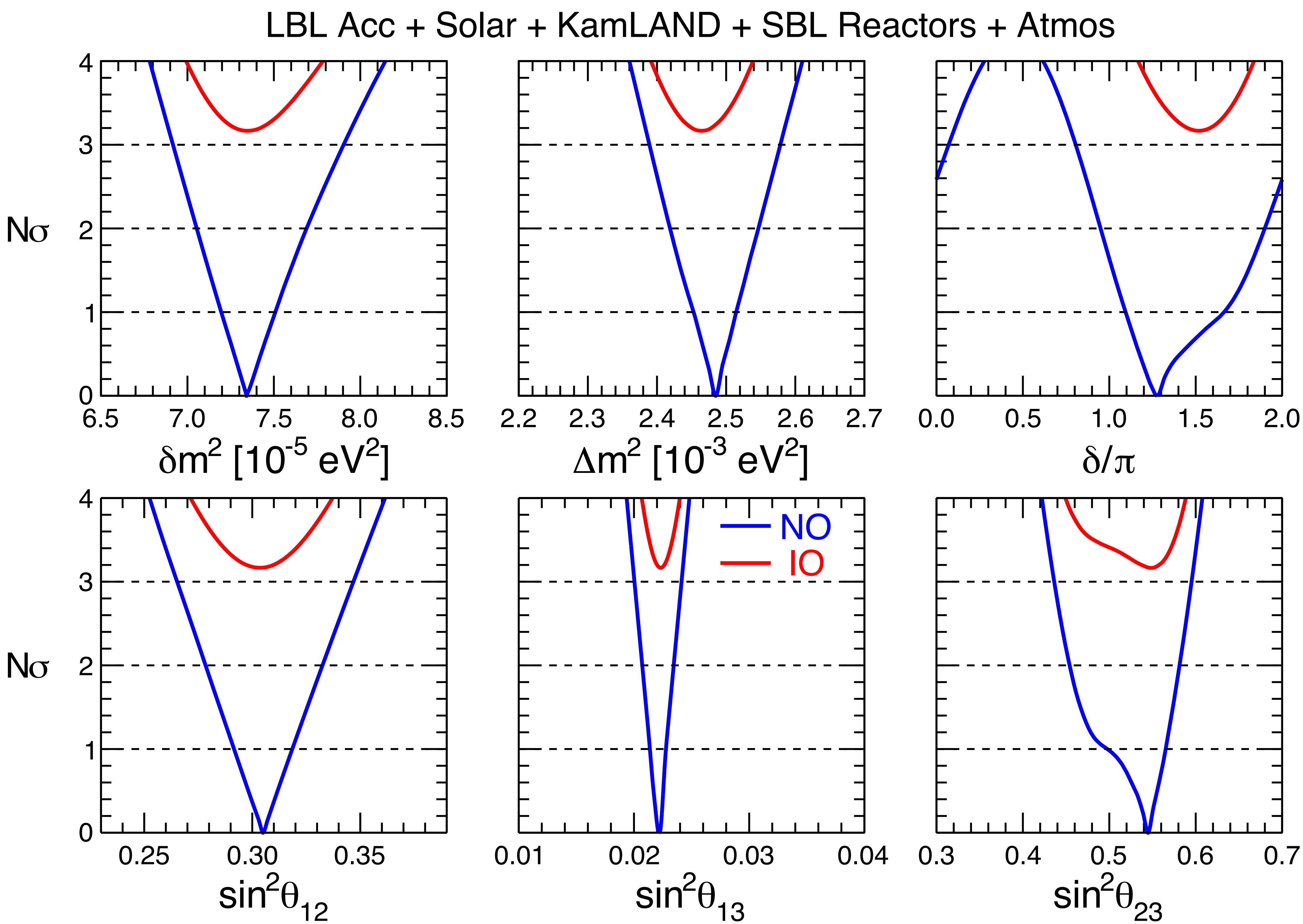
Oscillations in matter

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

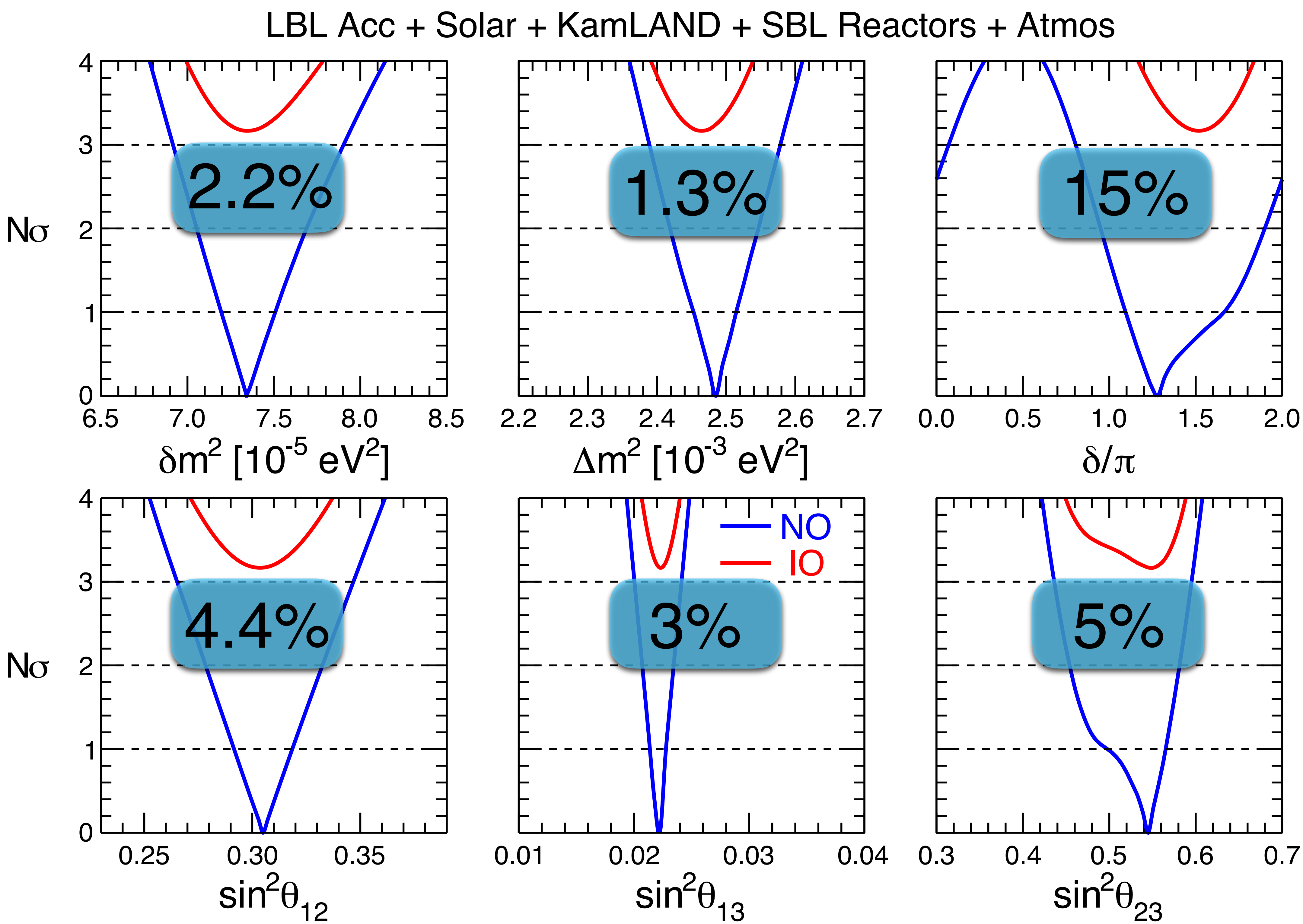
$L \in [0, 10^4]$ km

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

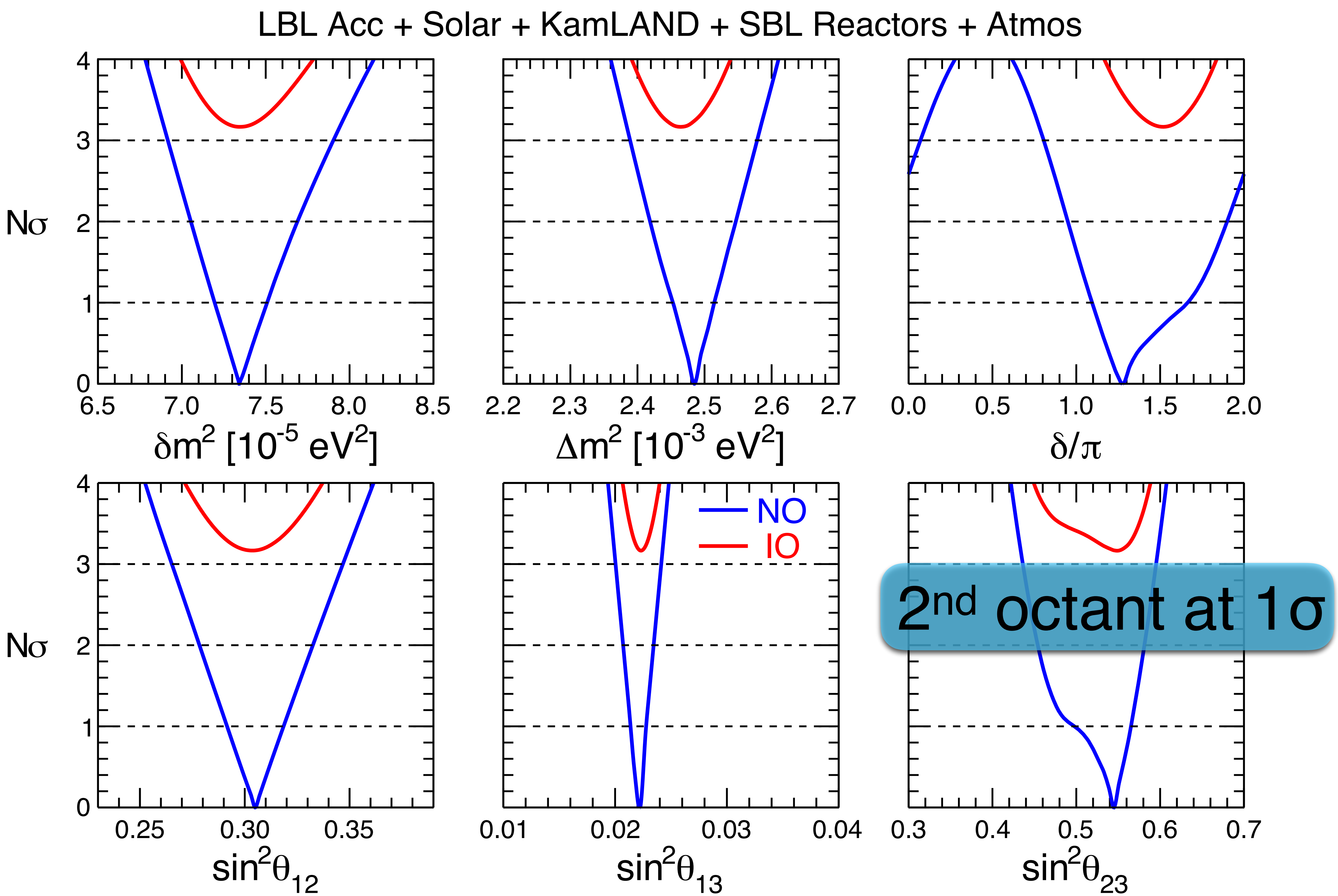
Analysis results



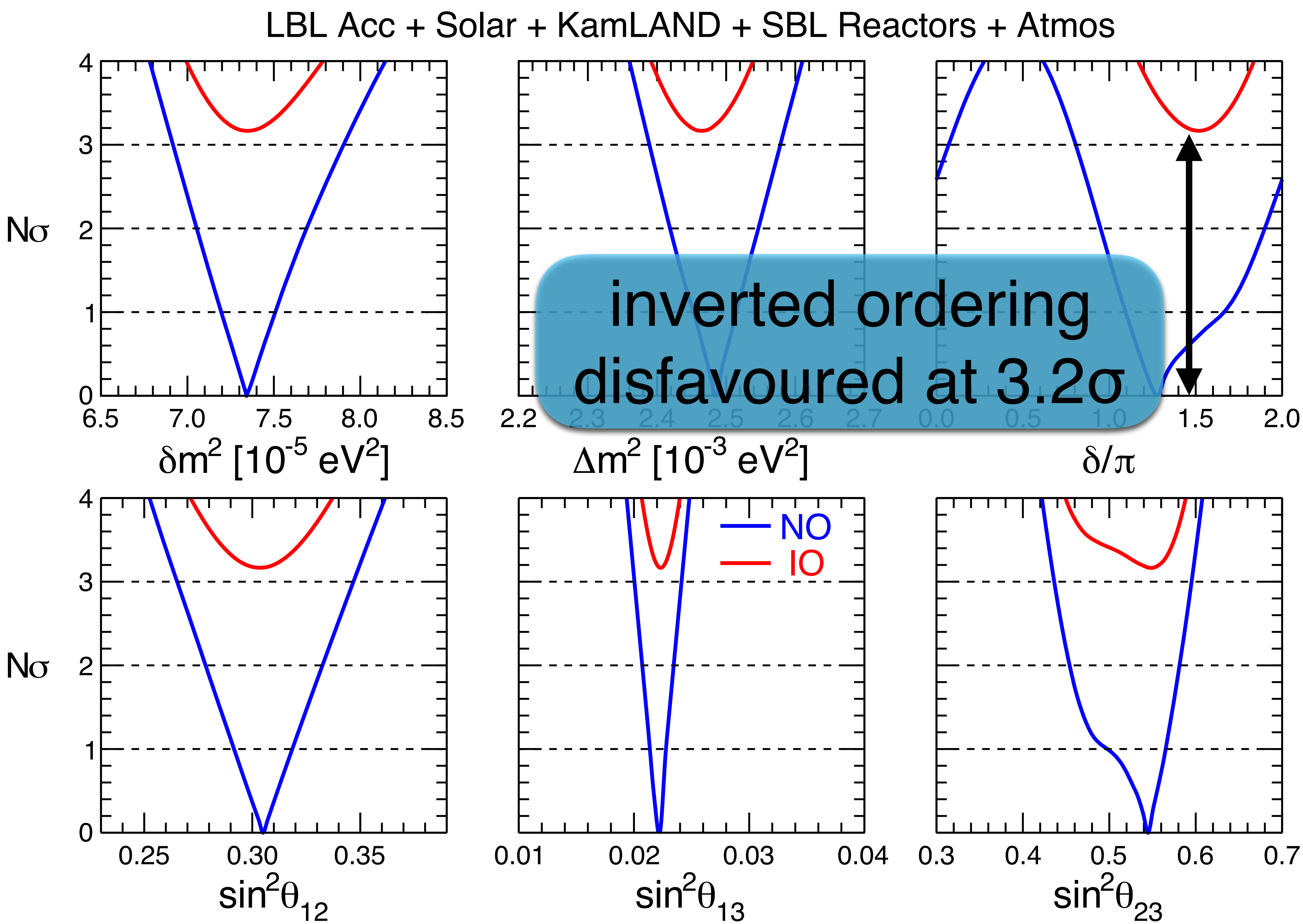
Analysis results



Analysis results



Analysis results

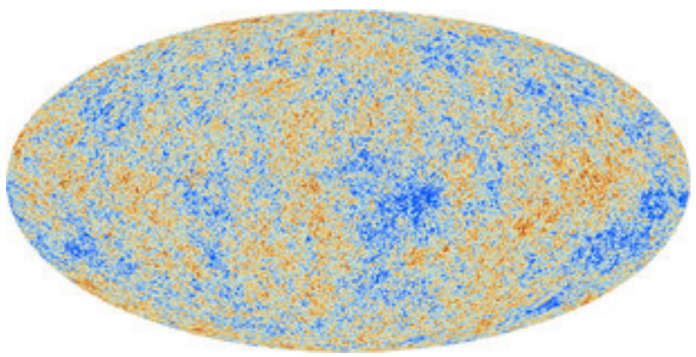


Non-oscillation data

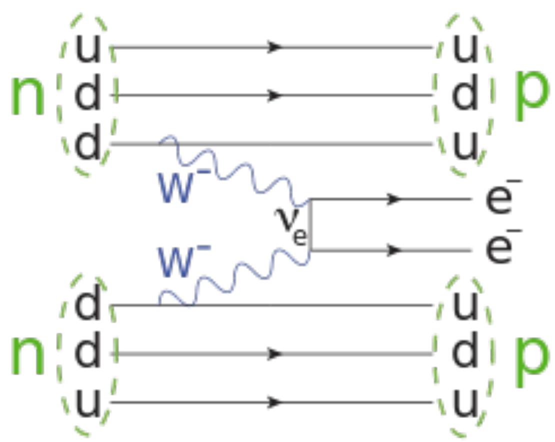
Phys. Rev. D 95 (2017) no.9, 096014)
in collaboration with E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri and A. Palazzo

Non oscillation data: variables

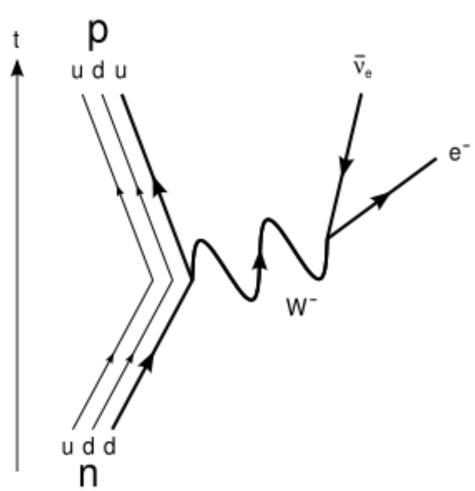
Cosmology, β and 0νββ decays can probe:



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



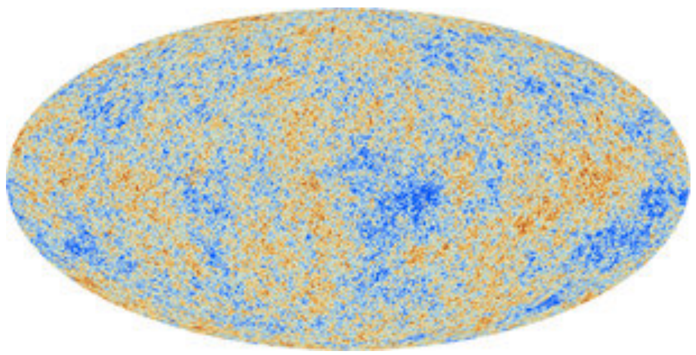
$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



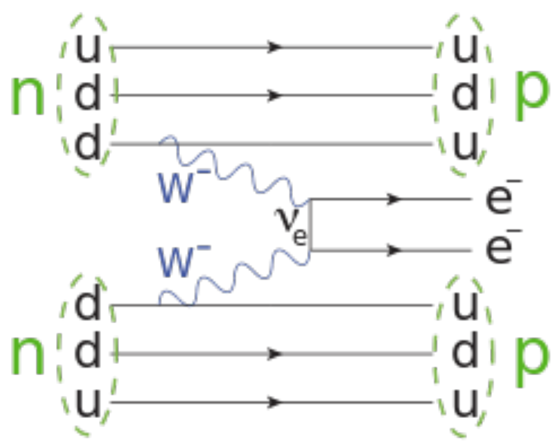
$$m_\beta^2 = \sum_{i=1}^{3} \left| U_{ei} \right|^2 m_i^2$$

Non oscillation data: variables

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



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

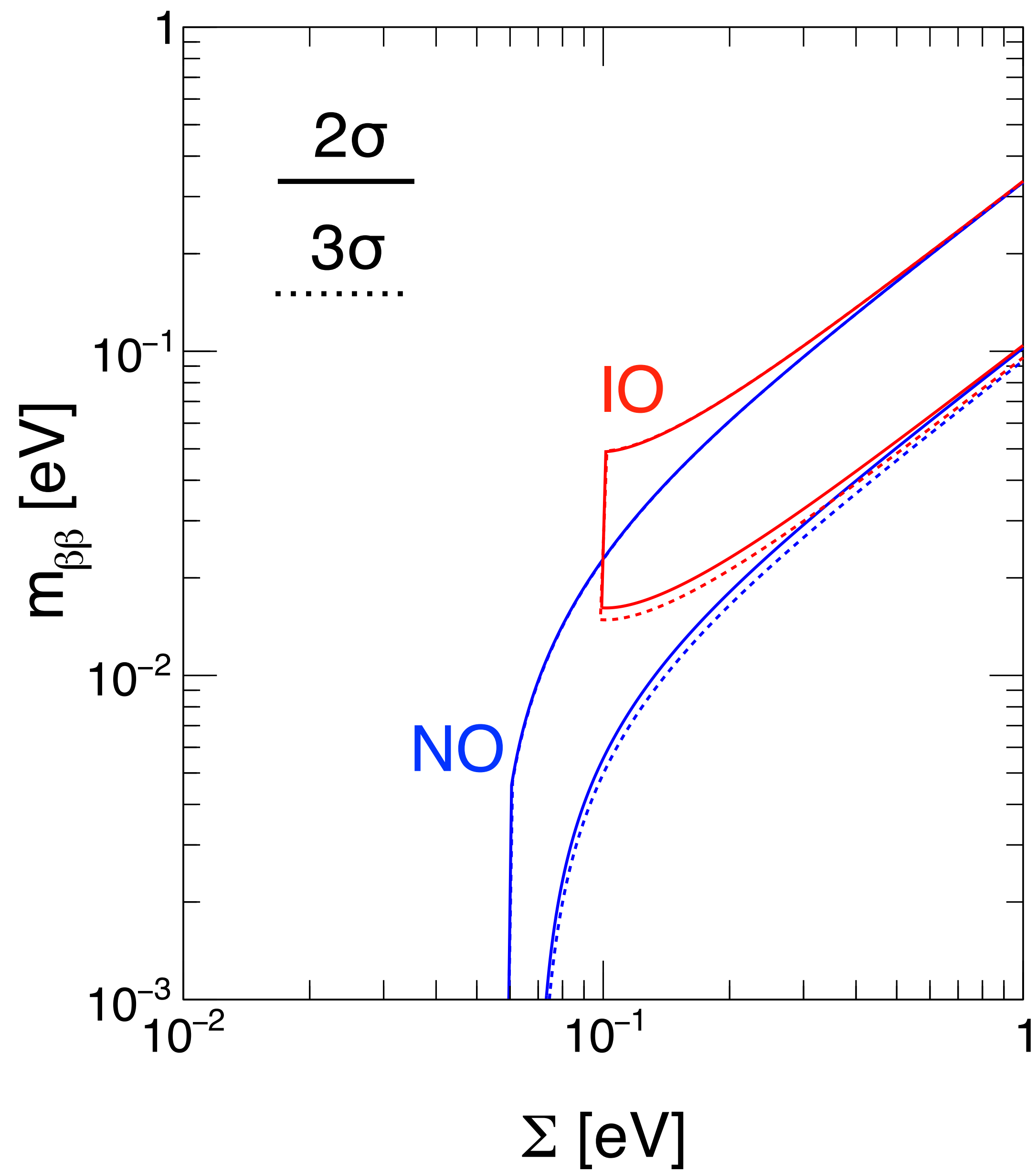


$$m_{\beta\beta} = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

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

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

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

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

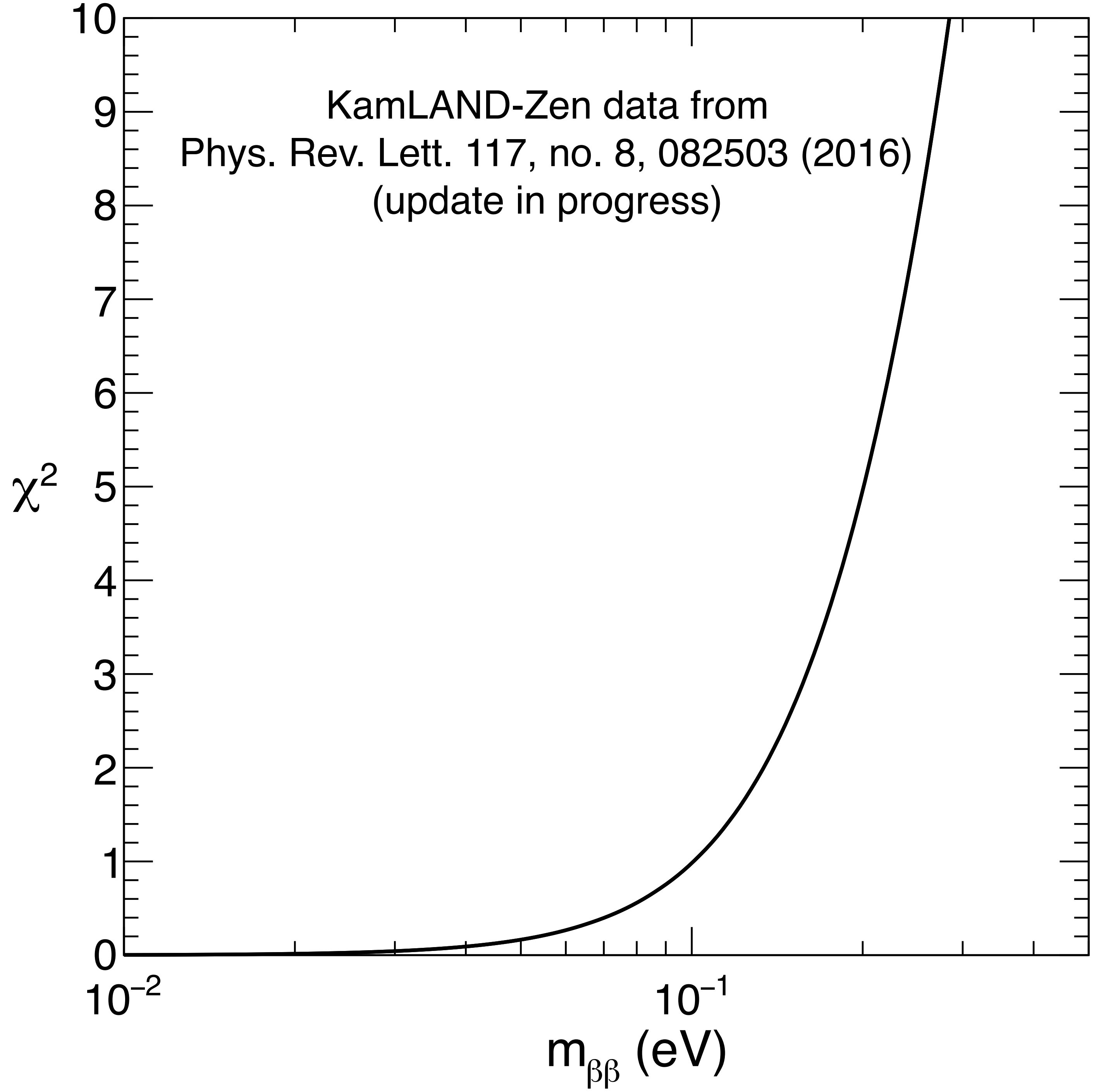
We convert the constraint on $T_{0\nu\beta\beta}$ from KamLAND-ZEN to $m_{\beta\beta}$

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

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

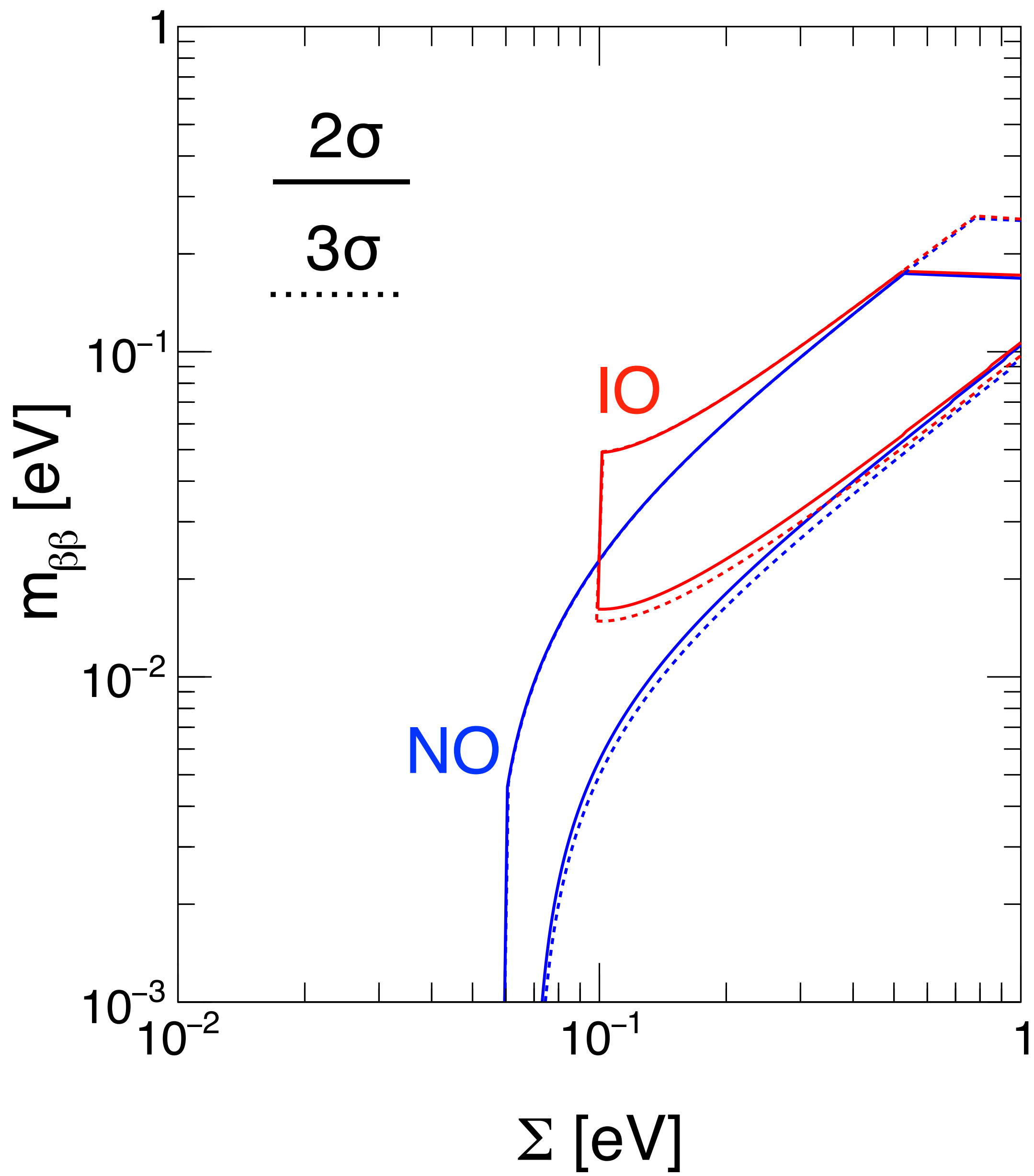
We convert the constraint on $T_{0\nu\beta\beta}$ from KamLAND-ZEN to $m_{\beta\beta}$

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



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

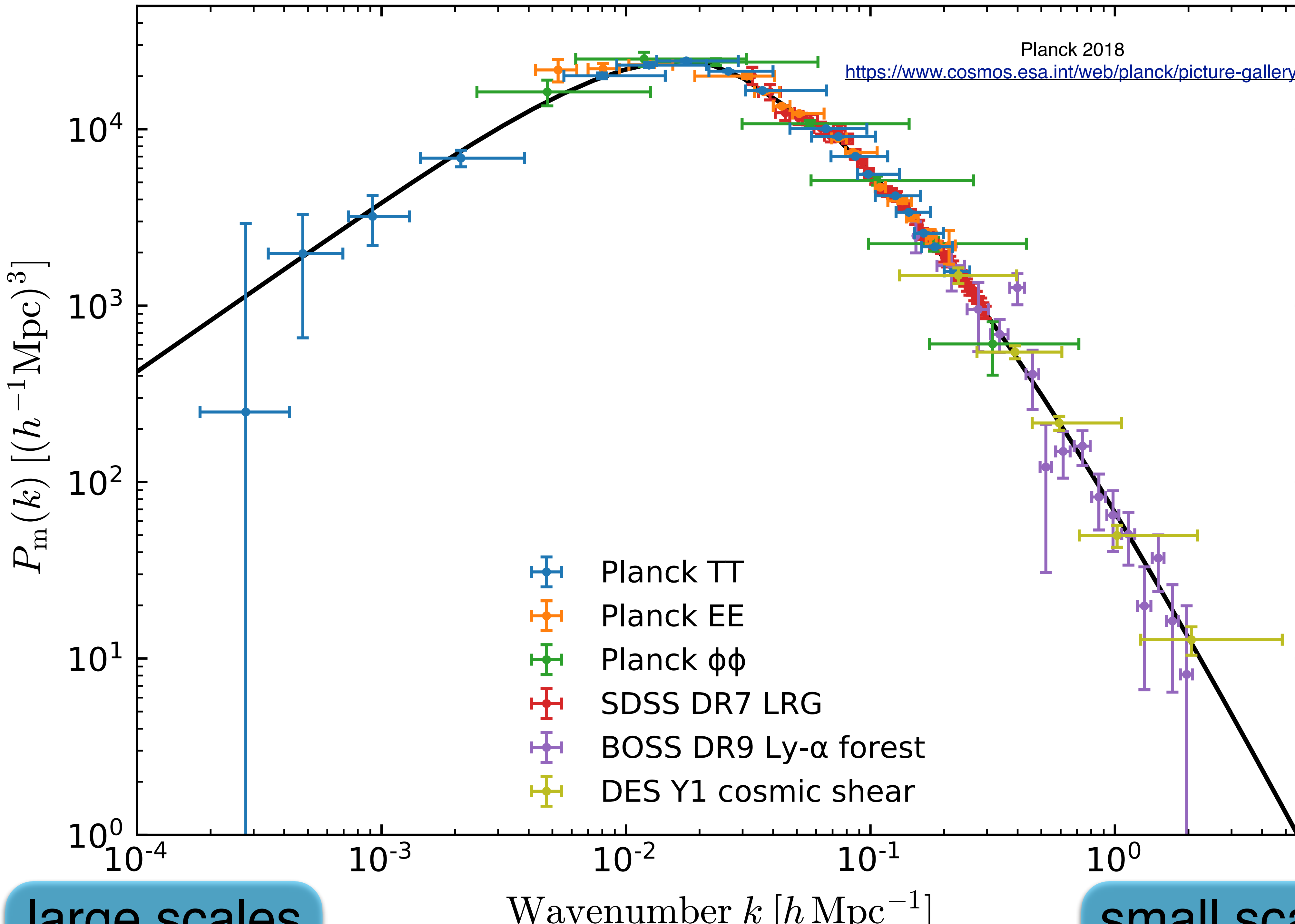
Oscillation + 0νββ constraints, with $\Delta\chi^2(IO) = \chi^2 - \chi^2_{min}(IO)$



$m_{\beta\beta} < 0.2$ eV (2σ)

Cosmological constraints on Σ

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

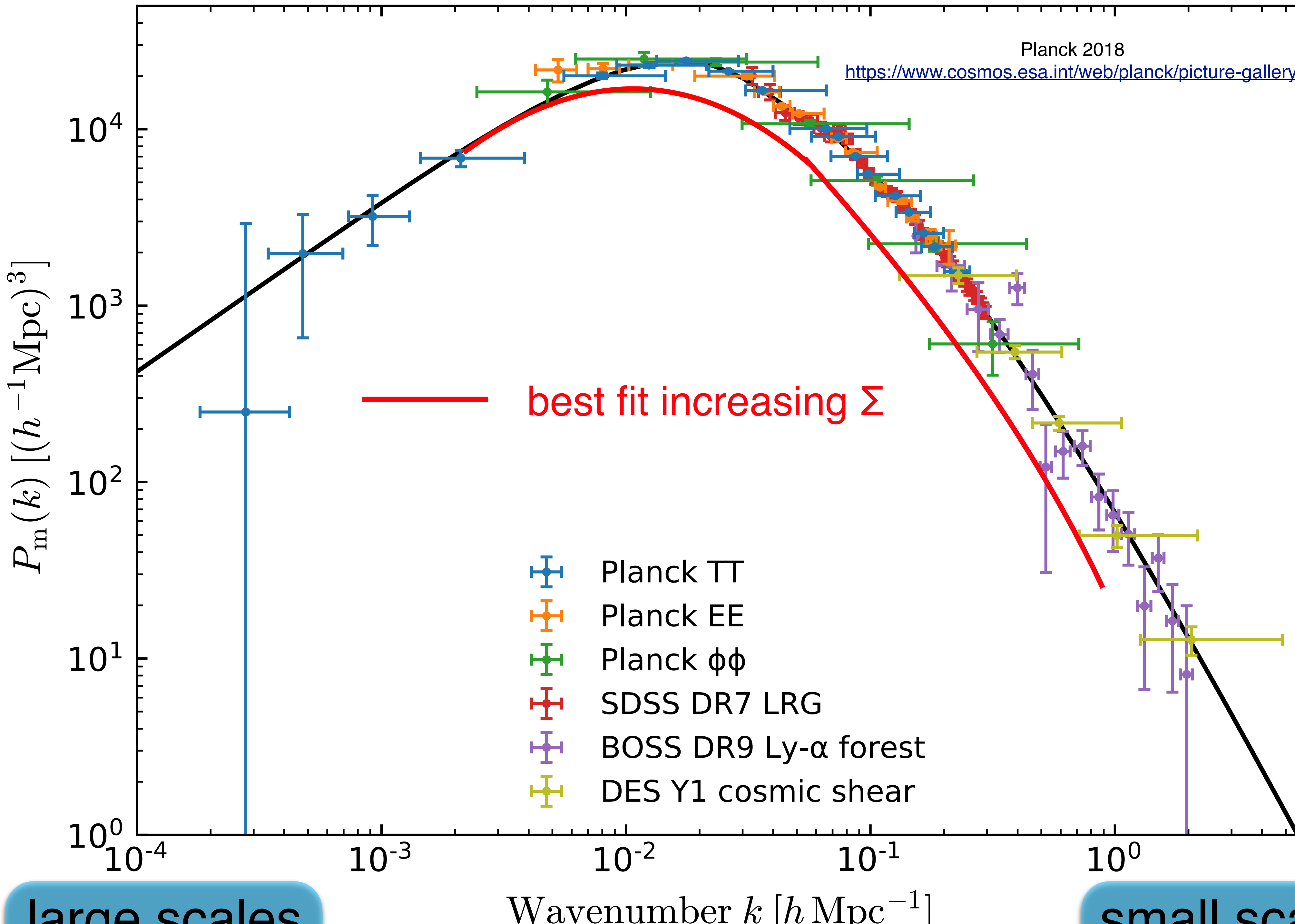


large scales

small scales

Cosmological constraints on Σ

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



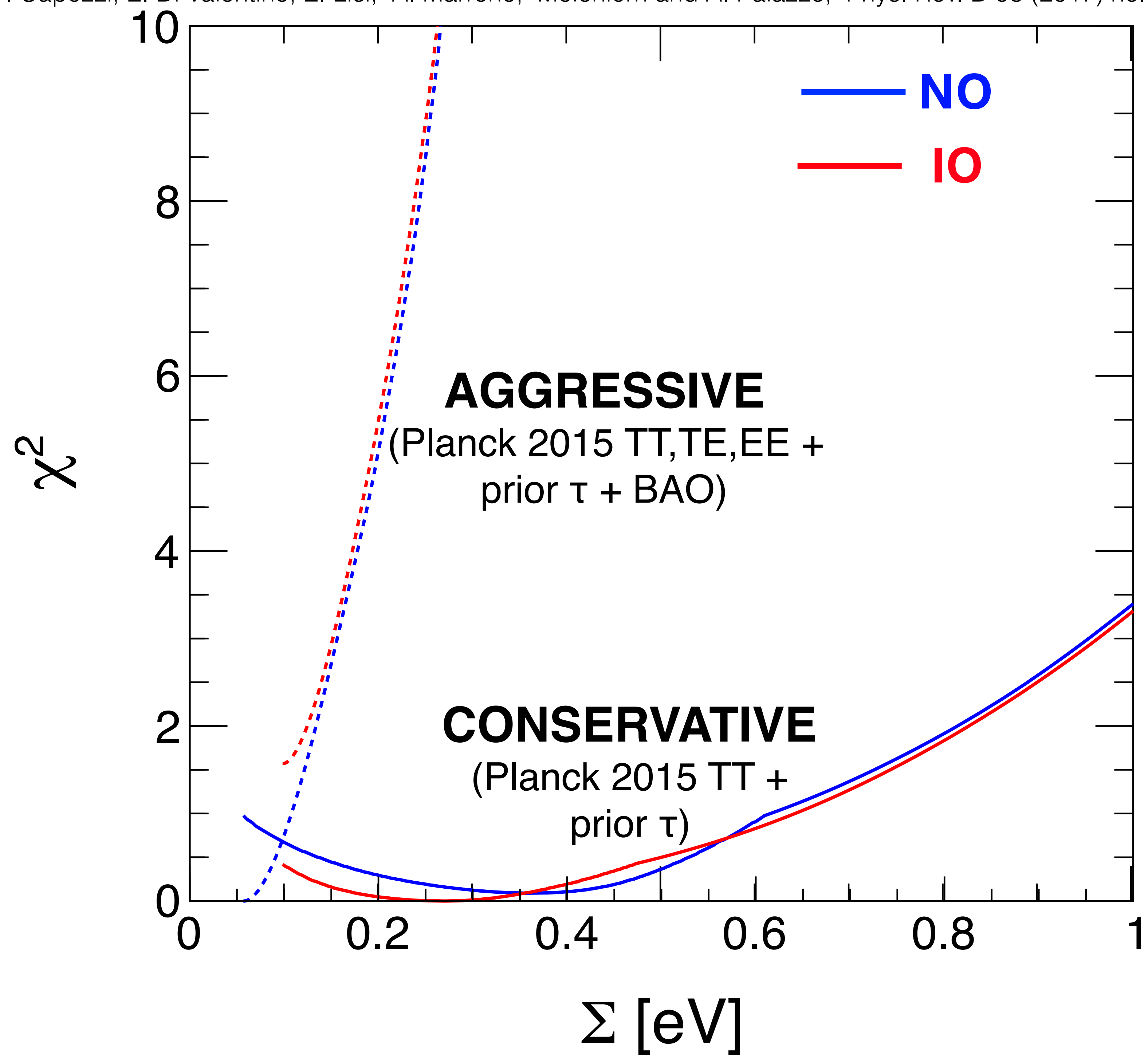
large scales

small scales

Cosmological constraints on Σ

We take the constraint from different cosmological observations

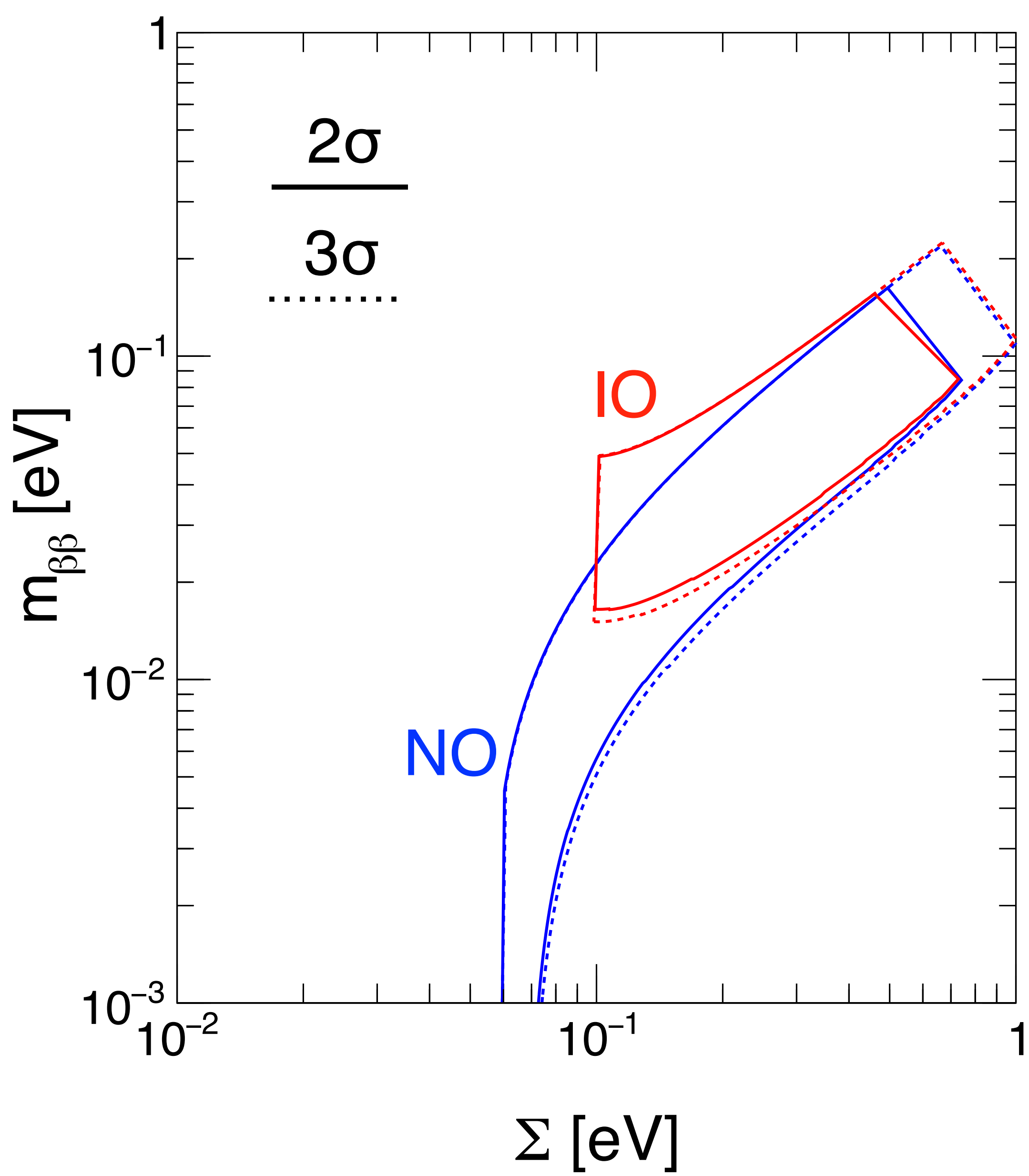
F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, Melchiorri and A. Palazzo, Phys. Rev. D 95 (2017) no.9, 096014



Constraints on (Σ,$m_{\beta\beta}$)

Oscillation + 0νββ + cosmology (conservative) constraints

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

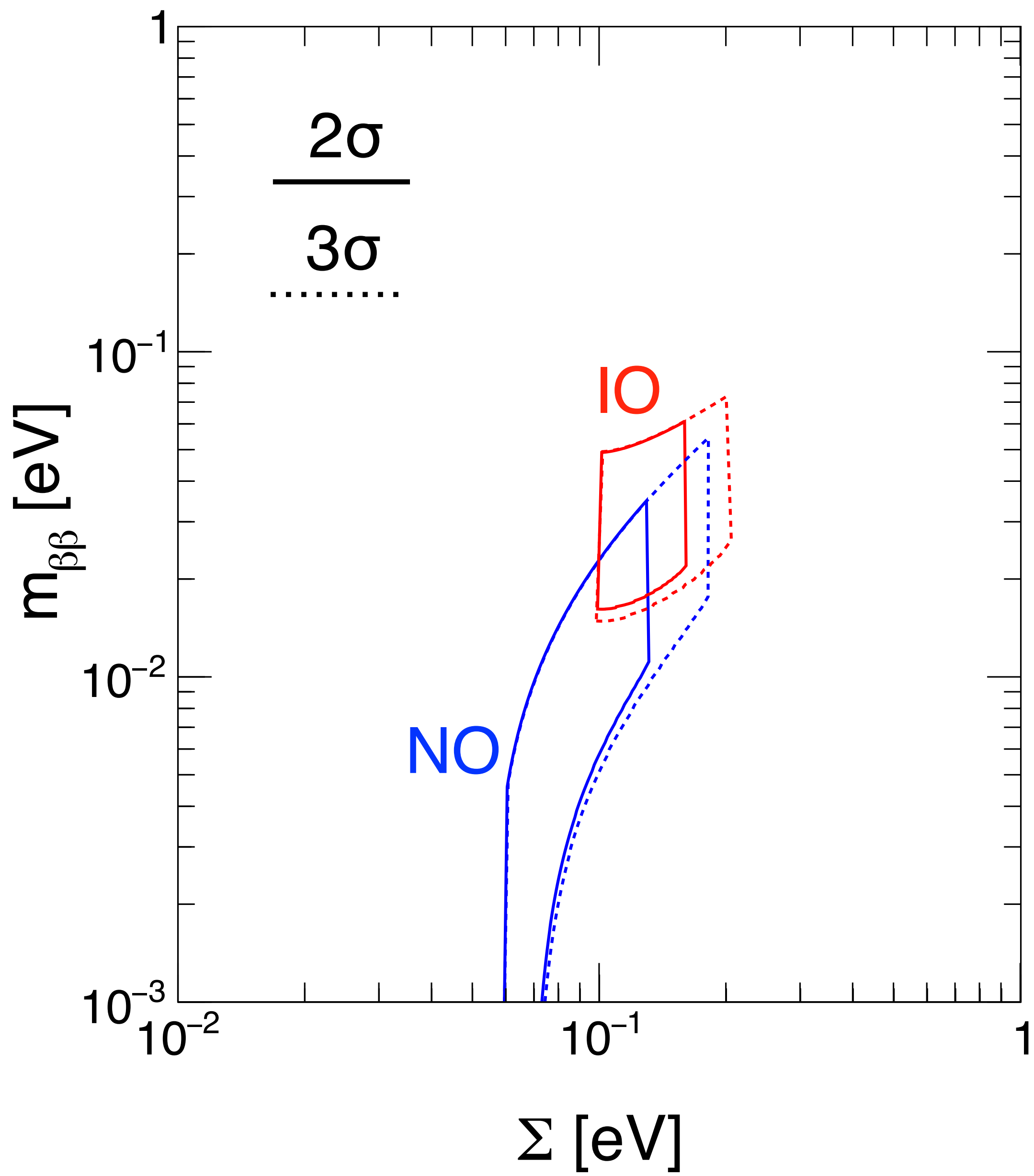


$\Sigma < 0.7$ eV (2σ)

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

Oscillation + 0νββ + cosmology (aggressive) constraints

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

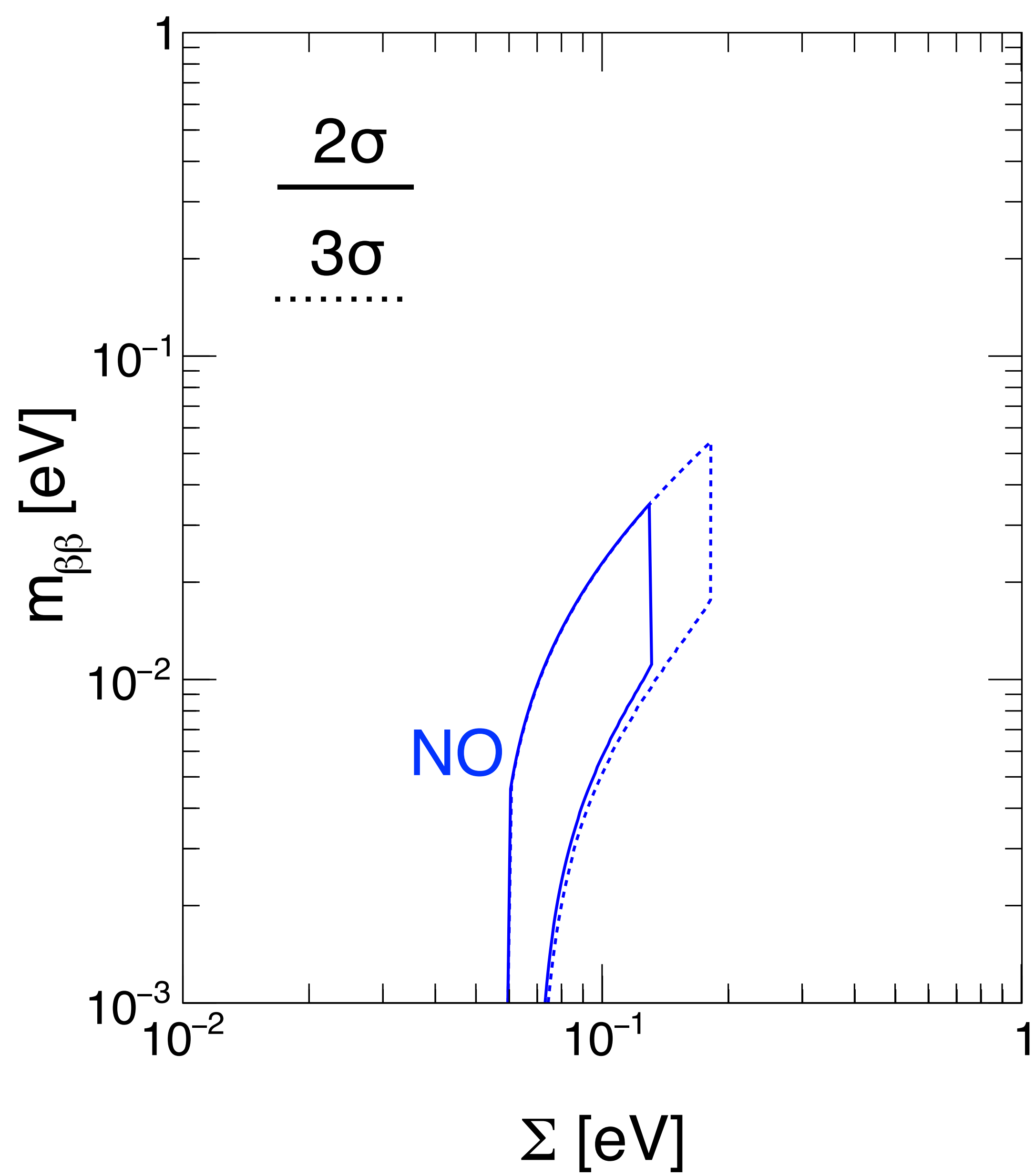


$\Sigma < 0.2$ eV (2σ)

Constraints on (Σ,$m_{\beta\beta}$)

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

- 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**

Thank you

Neutrino oscillation measurements

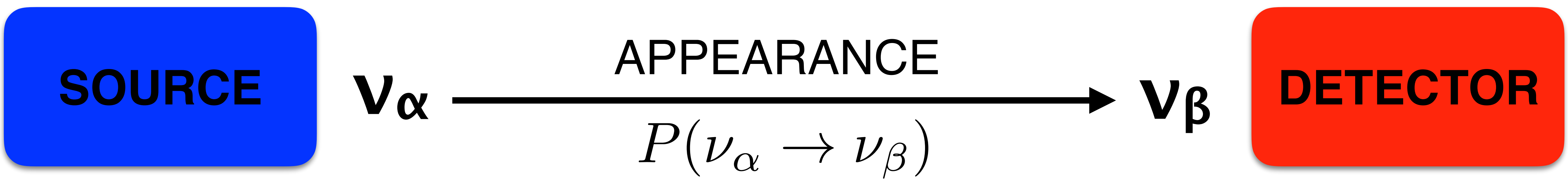
We want to measure the oscillation probability

SOURCE ν_α $\xrightarrow[P(\nu_\alpha \to \nu_\alpha)]{\text{DISAPPEARANCE}}$ ν_α **DETECTOR**

$$P(\nu_\alpha \to \nu_\alpha) = \frac{N_{\nu_\alpha}^{\text{detector}}}{N_{\nu_\alpha}^{\text{source}}}$$

Neutrino oscillation measurements

We want to measure the oscillation probability



$$P(\nu_\alpha \to \nu_\beta) = \frac{N_{\nu_\beta}^{\text{detector}}}{N_{\nu_\alpha}^{\text{source}}}$$

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 $\Delta\chi^2$

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

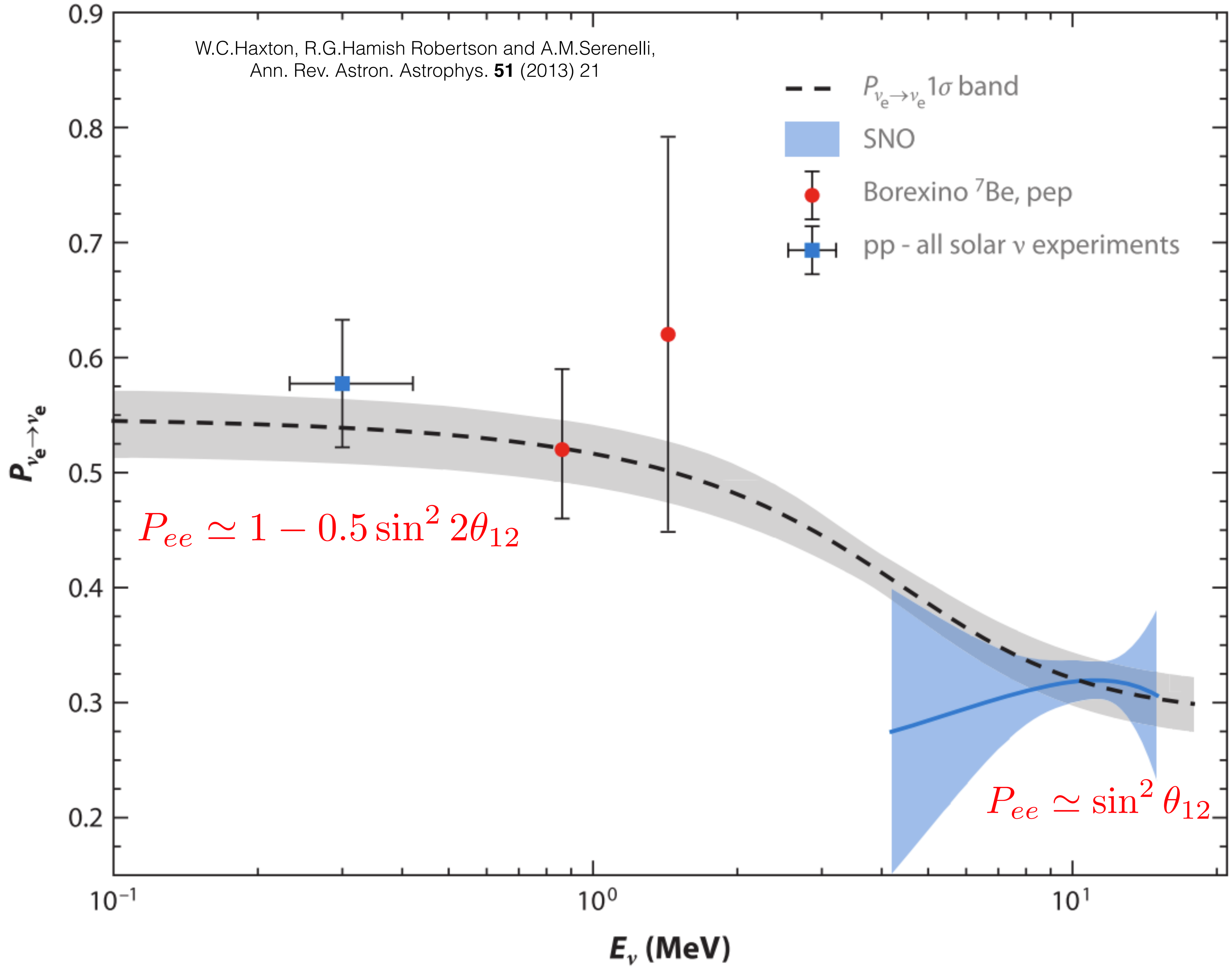
$$\Delta\chi^2({\rm IO}) = \chi^2_{\rm osc}(\Delta m^2 < 0) - {\rm min}[\chi^2_{\rm osc}(\Delta m^2 < 0)]$$

We report the results in terms of

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

Solar sector (θ_{12},δm^2)

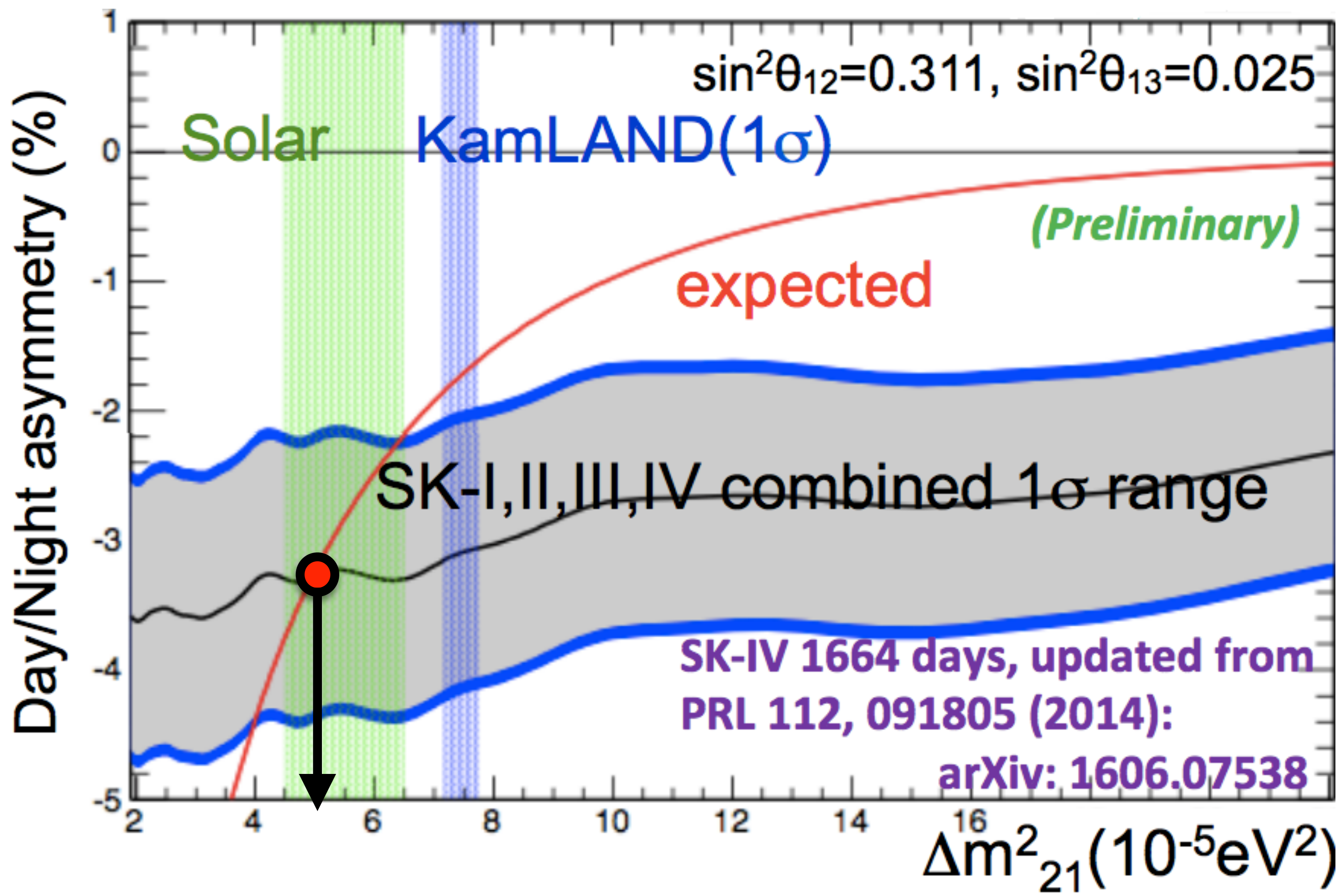
Daytime survival probability of ν_e as a function of energy



Solar sector (θ_{12},δm^2)

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

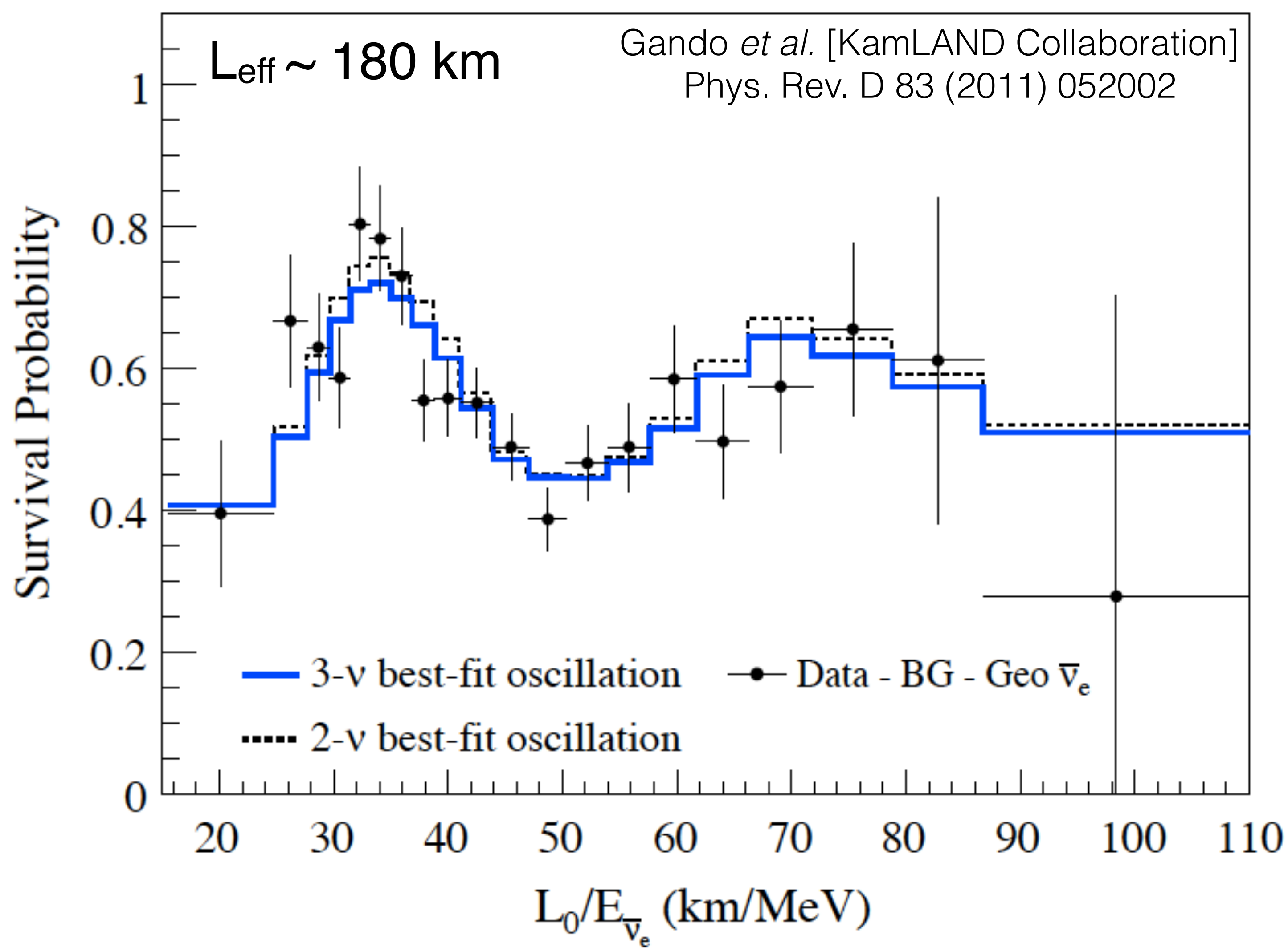
Super-Kamiokande Collaboration, Neutrino 2016



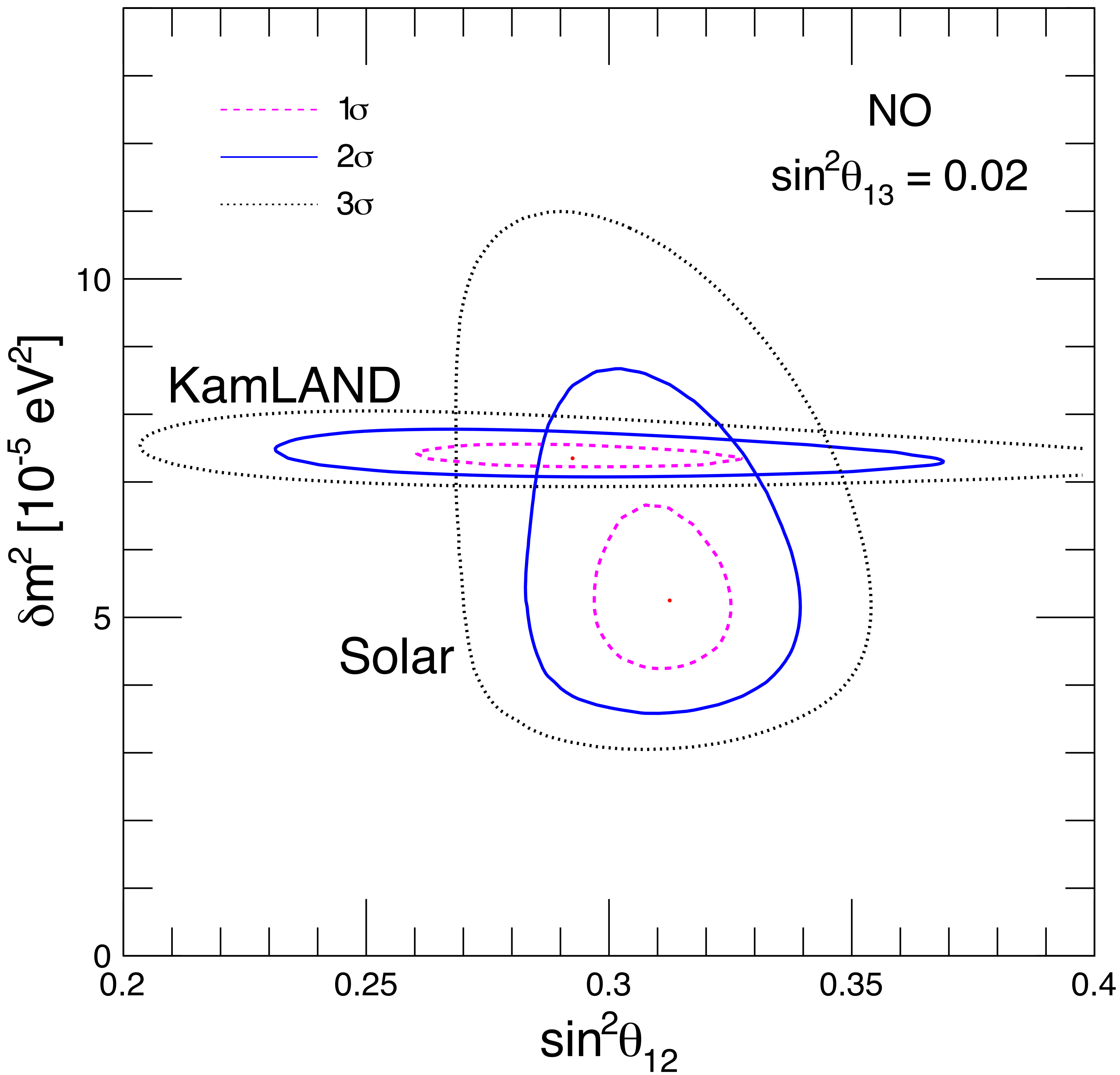
$\Delta m^2_{21} \sim 5 \times 10^{-5}$ eV^2

Solar sector (θ_{12},δm^2): KamLAND

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



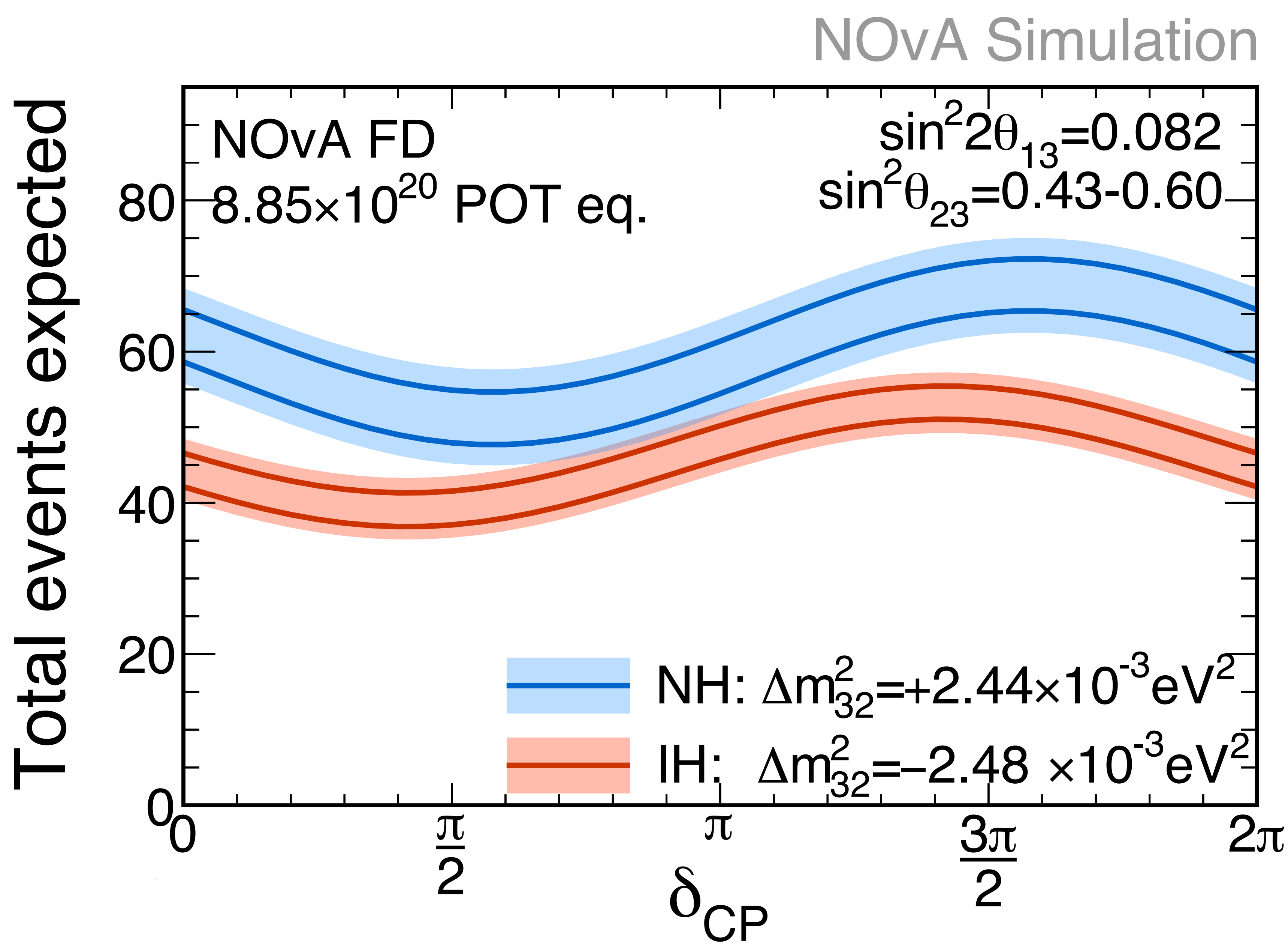
Covariance (θ_{12},δm^2)



~ 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**

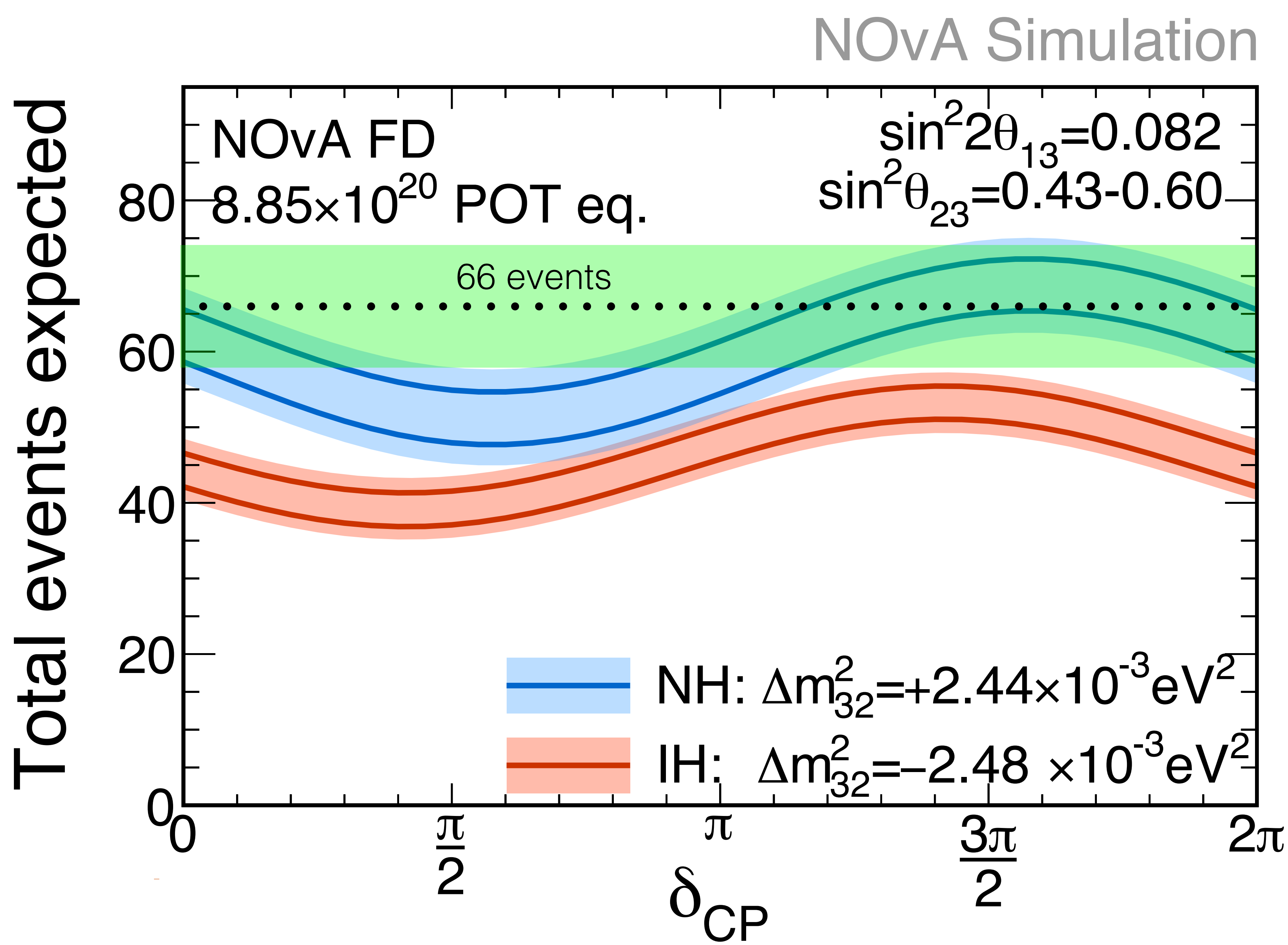


Alex Radovic, Fermilab Seminar, 12th January 2018

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+1π^+ 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

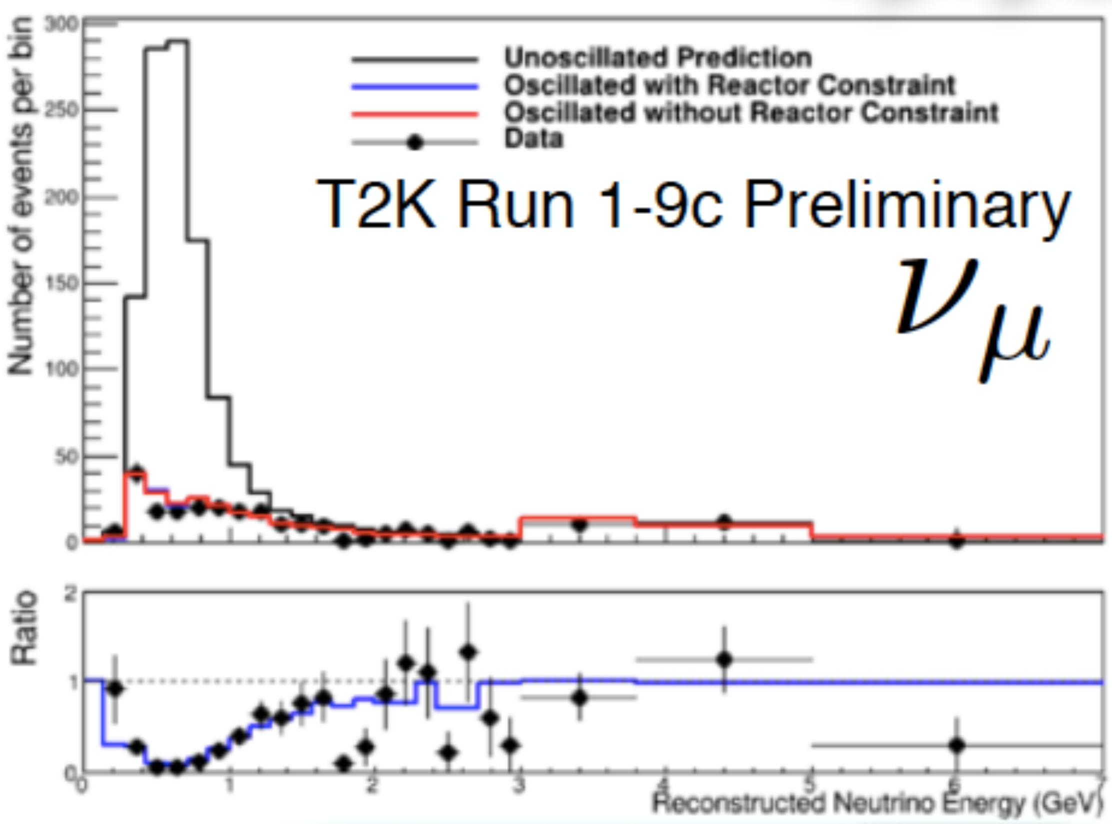
Preference for $\delta = 3\pi/2$ ($-\pi/2$) and NO

Long baseline accelerator experiments

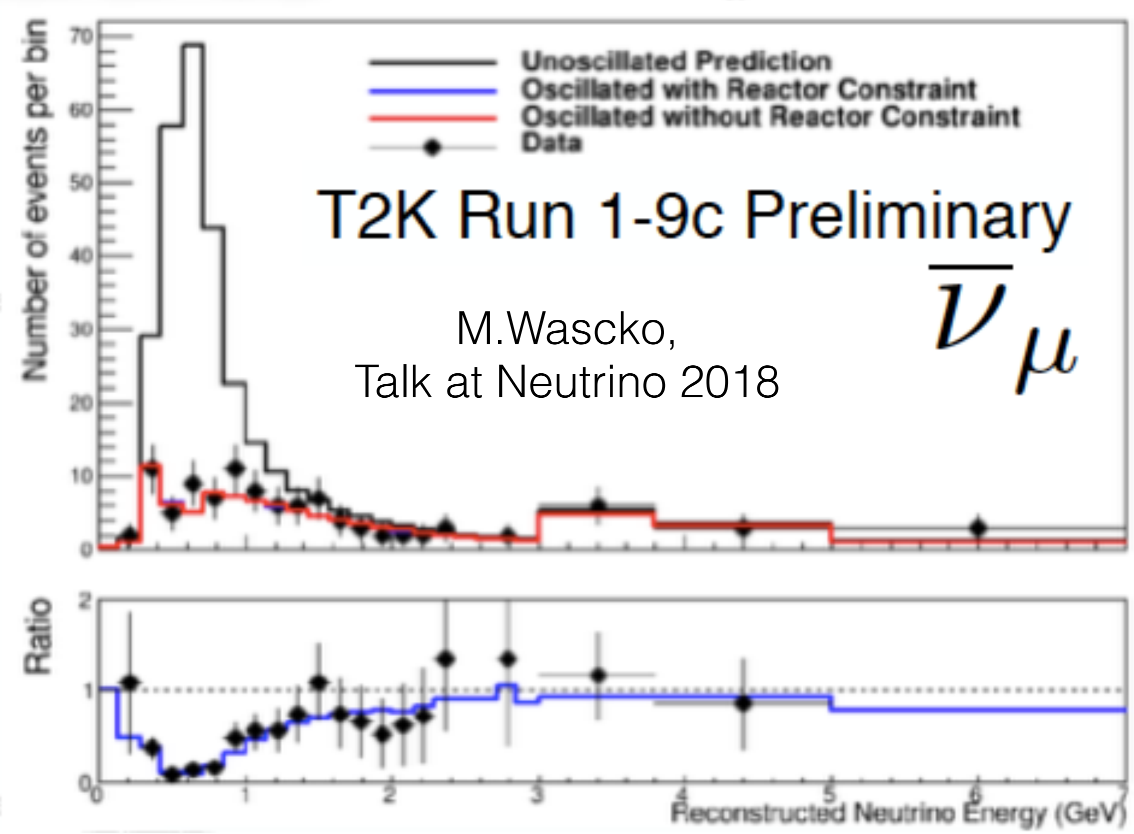
$$P_{\nu_\mu \to \nu_\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

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

1.49e21 POT



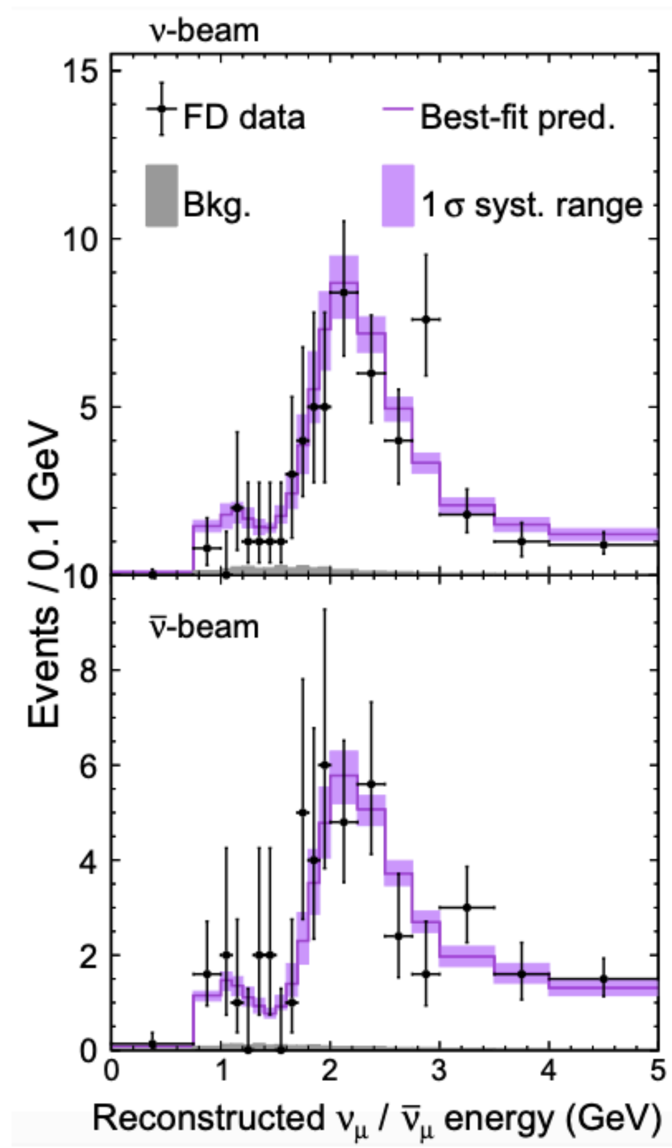
1.12e21 POT



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

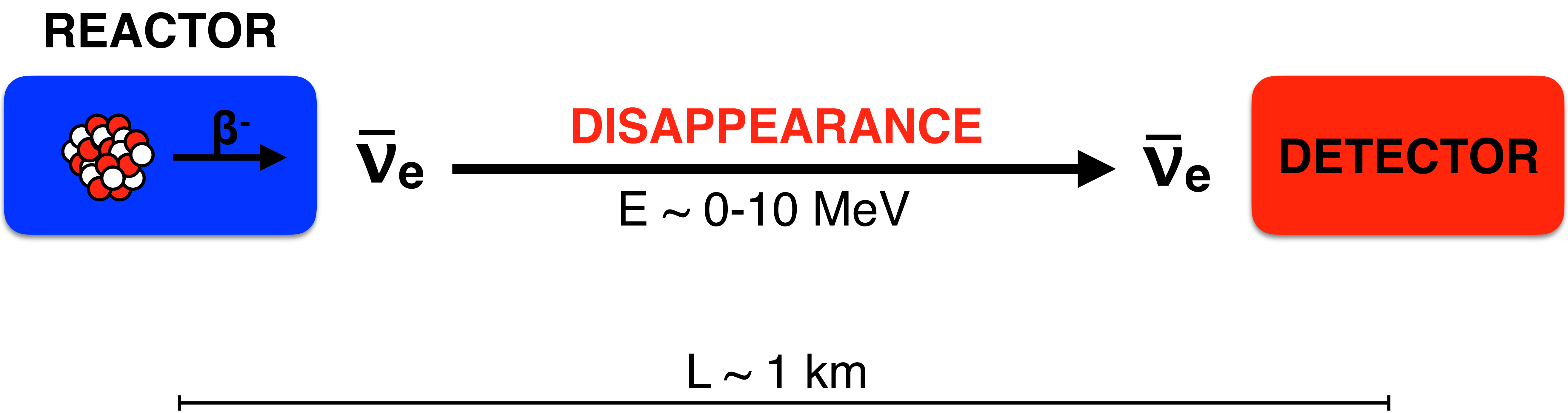
Long baseline accelerator experiments

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



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

Short baseline reactor experiments

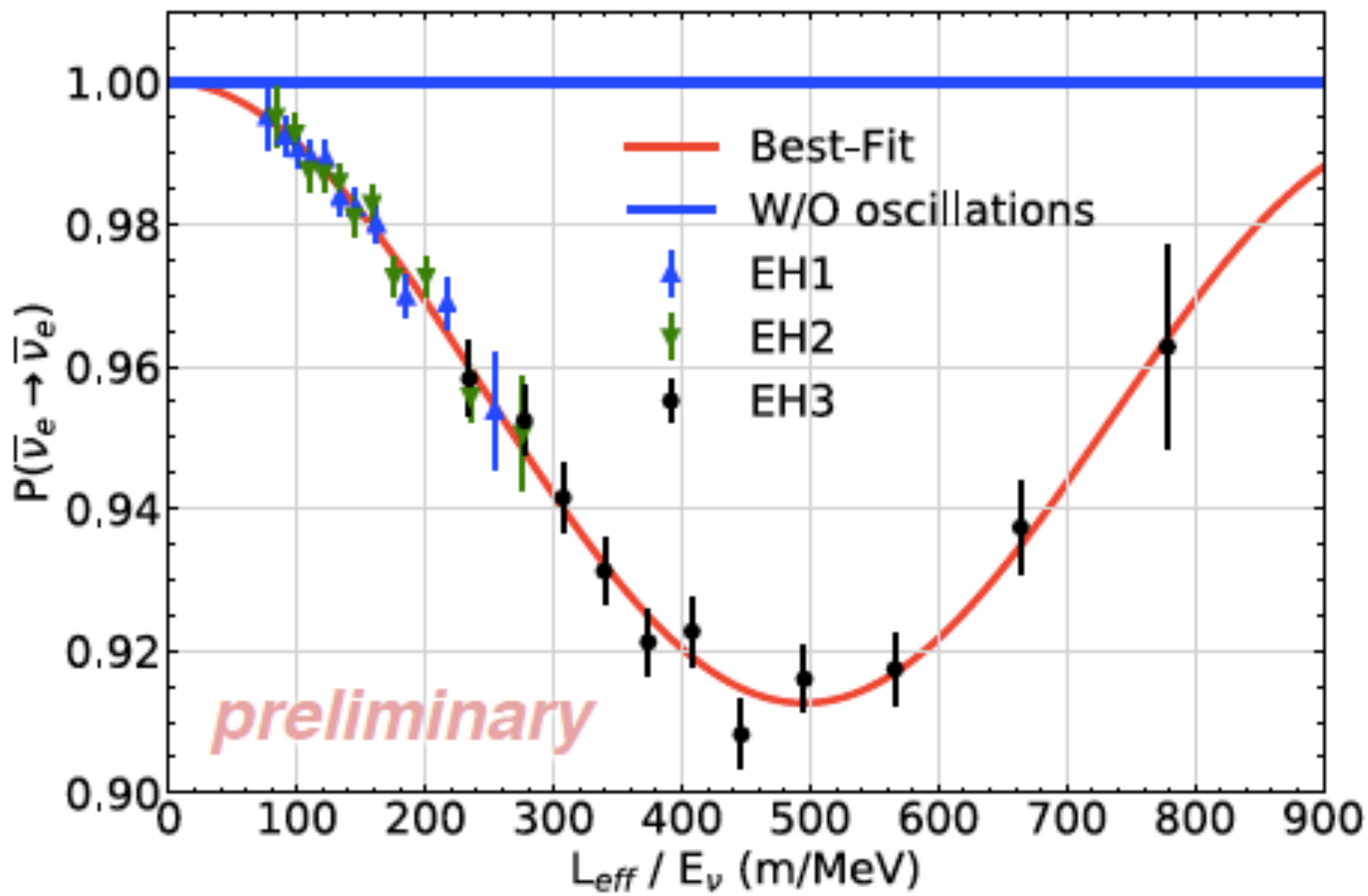


$$P_{\bar{\nu}_e \to \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$

Short baseline reactor experiments

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

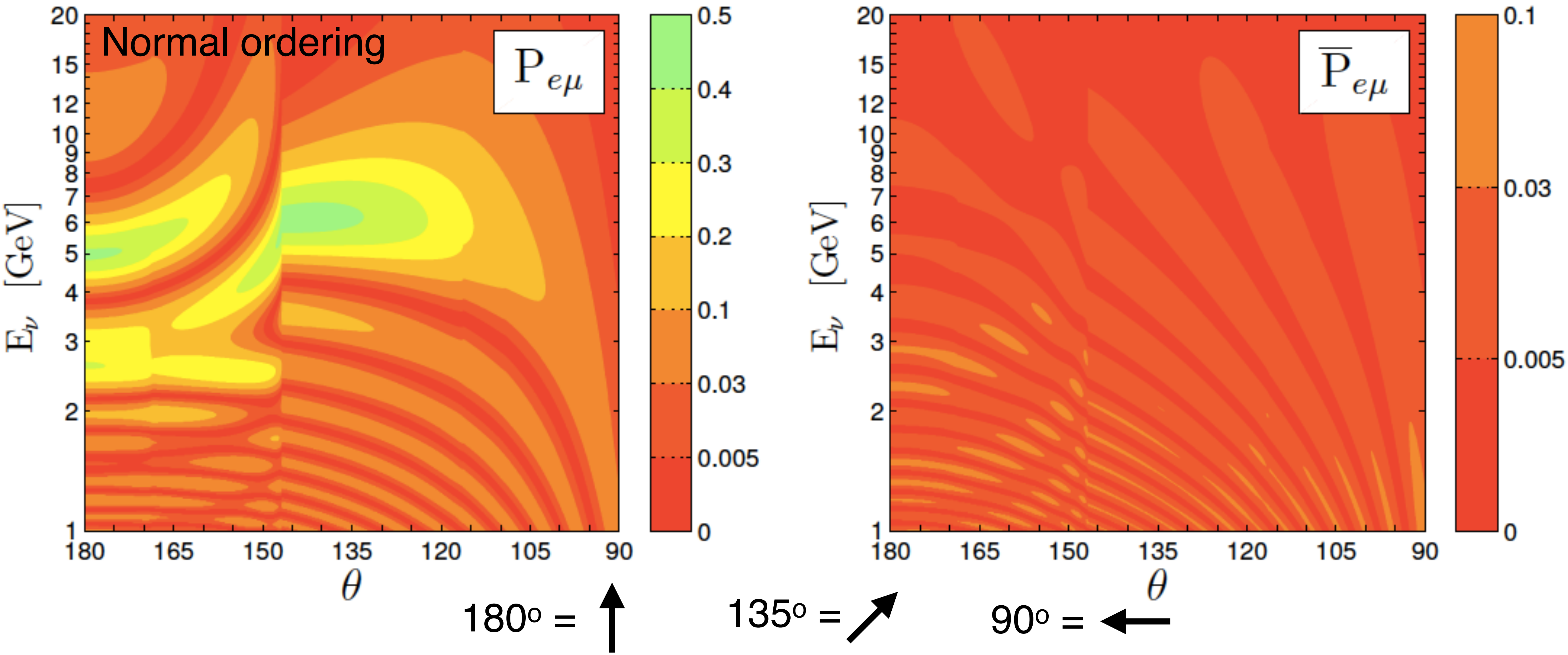
J. Pedro Ochoa-Ricoux, Talk at Neutrino 2018



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

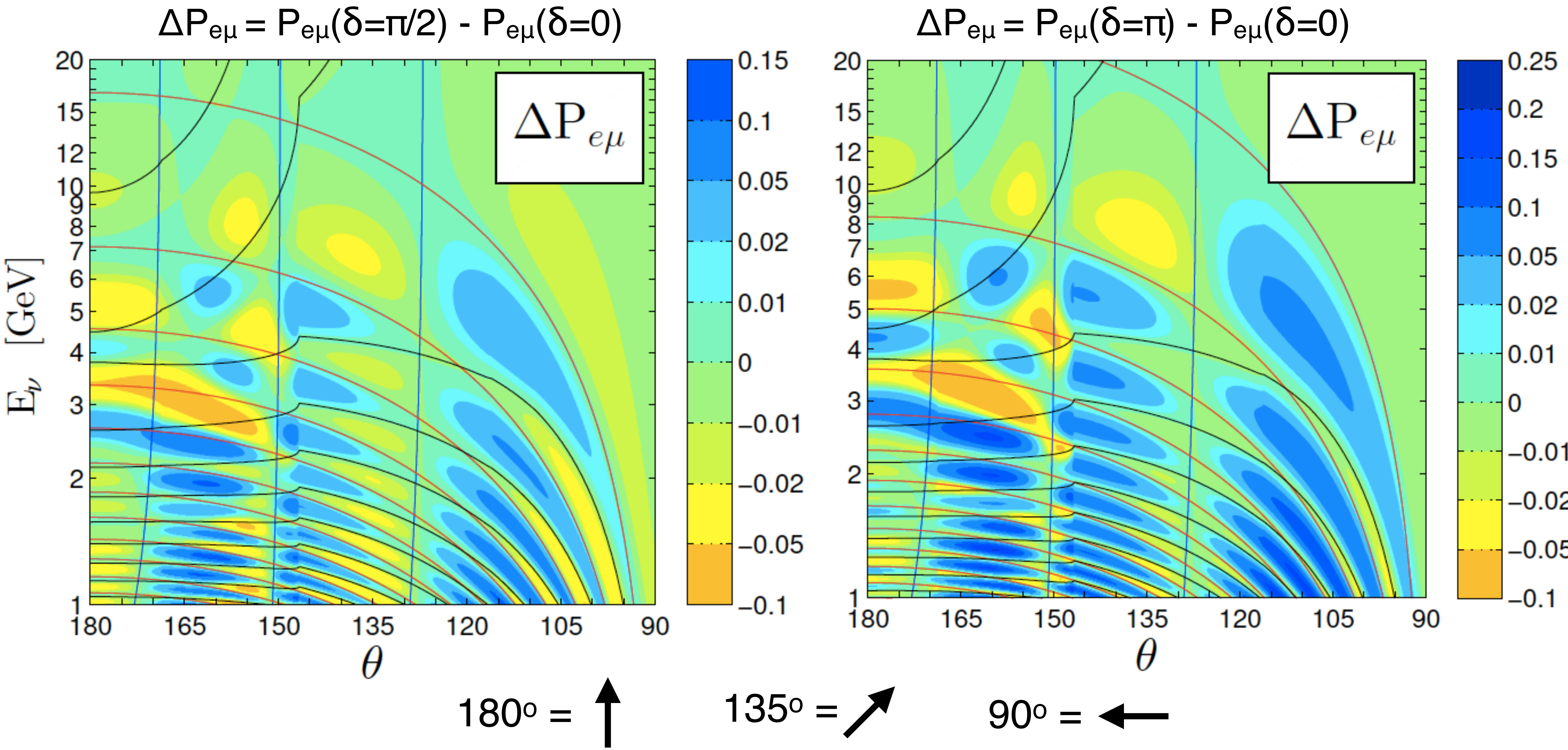
$\Delta m^2_{31} \sim 2.5 \times 10^{-3}\ \mathrm{eV}^2$

Atmospheric neutrino experiments



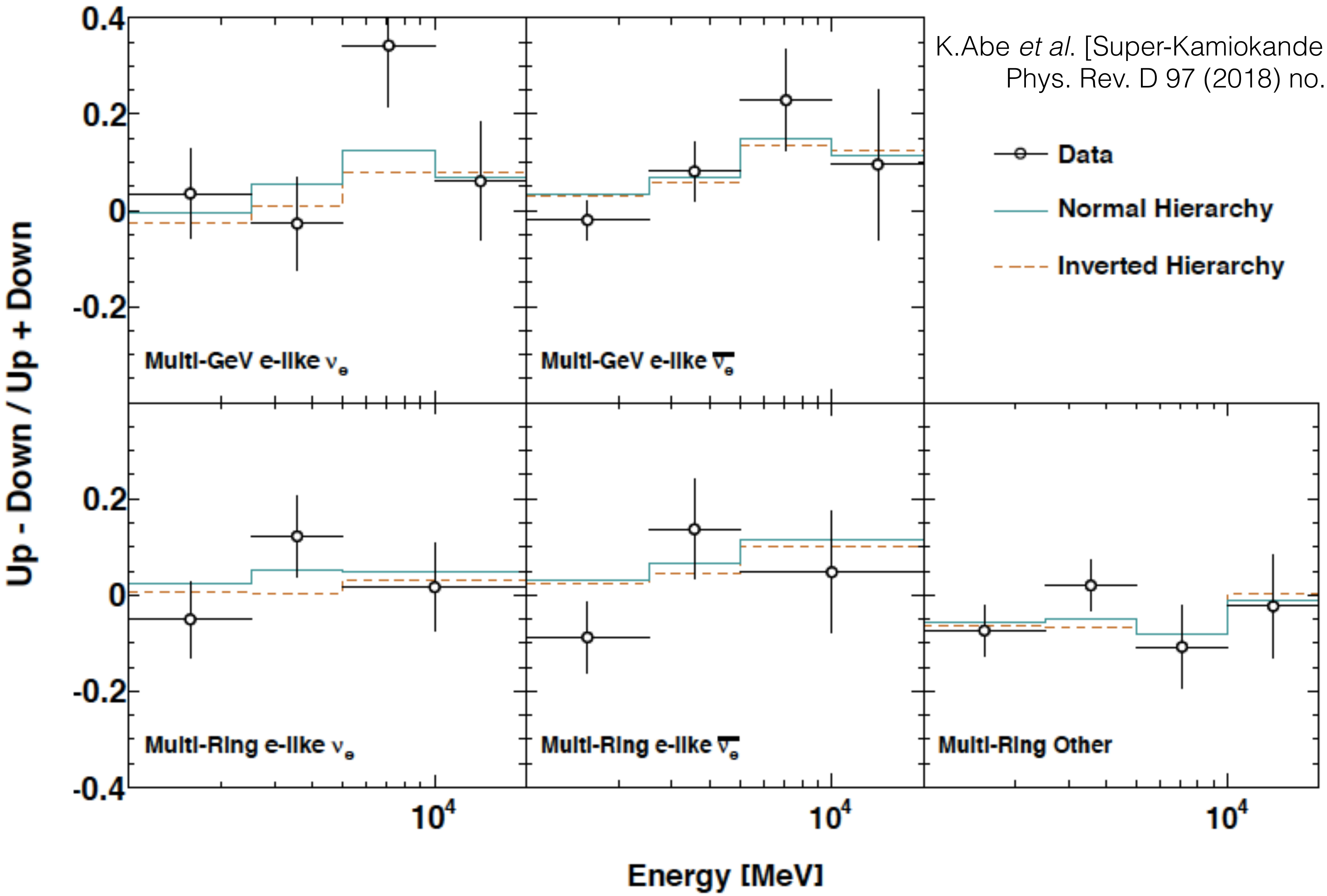
Matter effects make $P_{e\mu}$ very different from $\overline{P}_{e\mu}$

Atmospheric neutrino experiments



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

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

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

Ordering	δ	±cos(δ±Δm²₃₁L/(4E))
normal	3π/2	+1
normal	π/2	-1
normal	0	0
normal	π	0

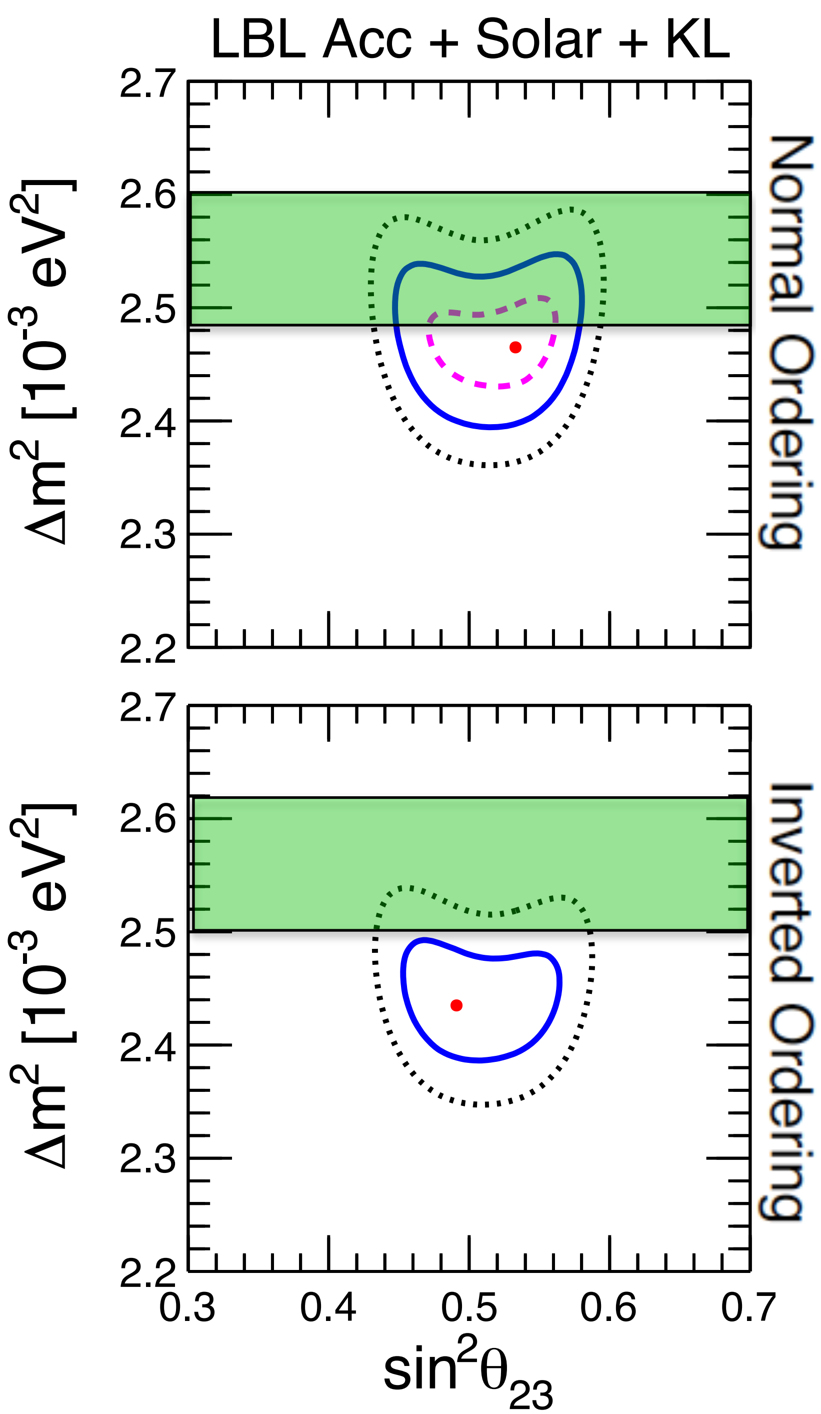
Long baseline accelerator experiments

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

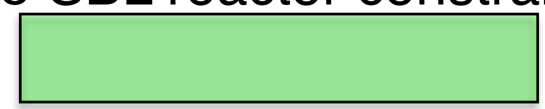
Experiment work near oscillation maximum: $\Delta m^2_{31} L/(4E) \sim \pi/2$

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

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

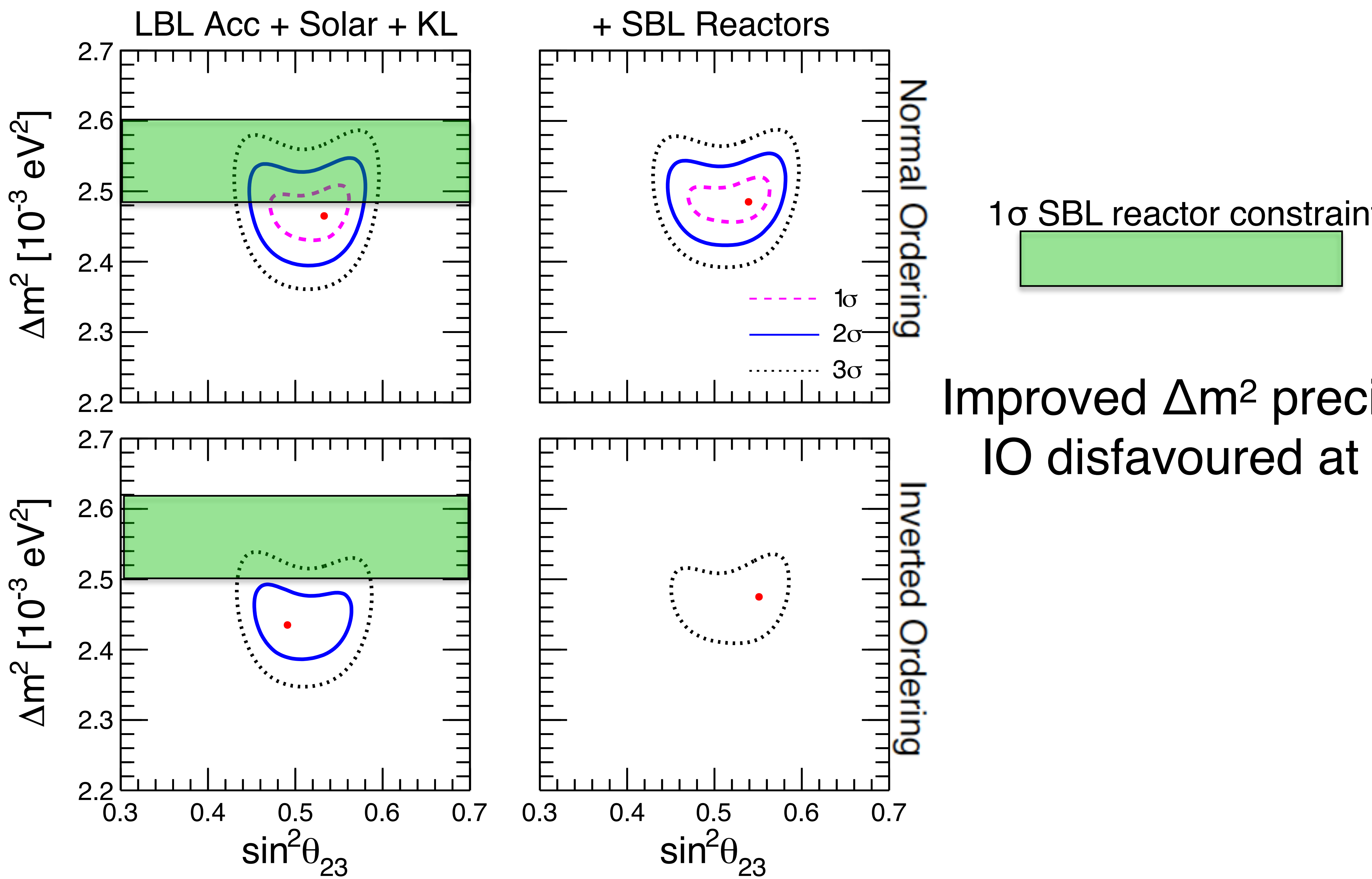


1σ SBL reactor constraint



Δm^2 more compatible in NO

Analysis results: covariance ($\theta_{23}, \Delta m^2$)



Improved Δm^2 precision
IO disfavoured at 2σ

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

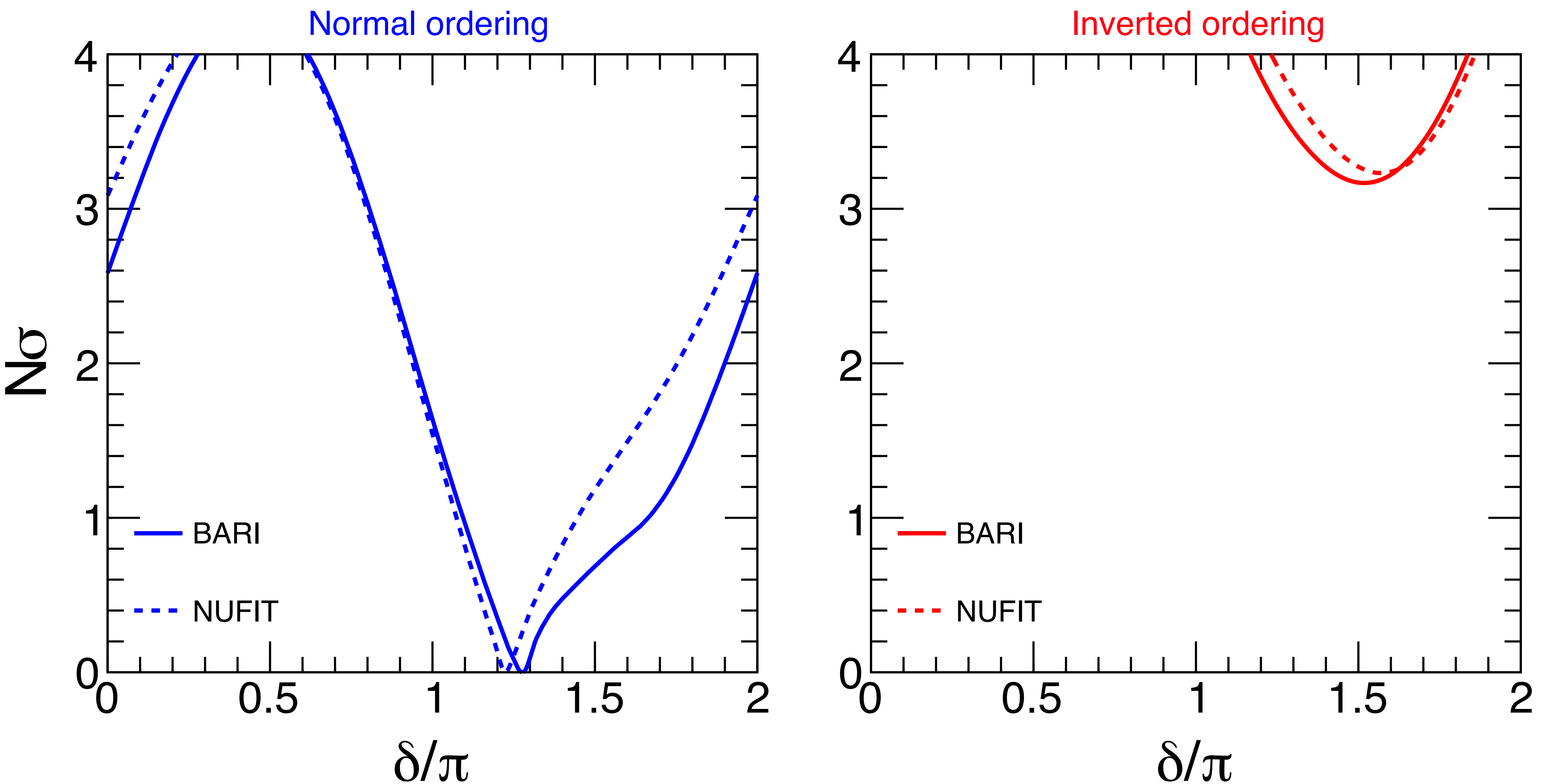
Valencia Group

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

Phys. Lett. B 782, 633 (2018)

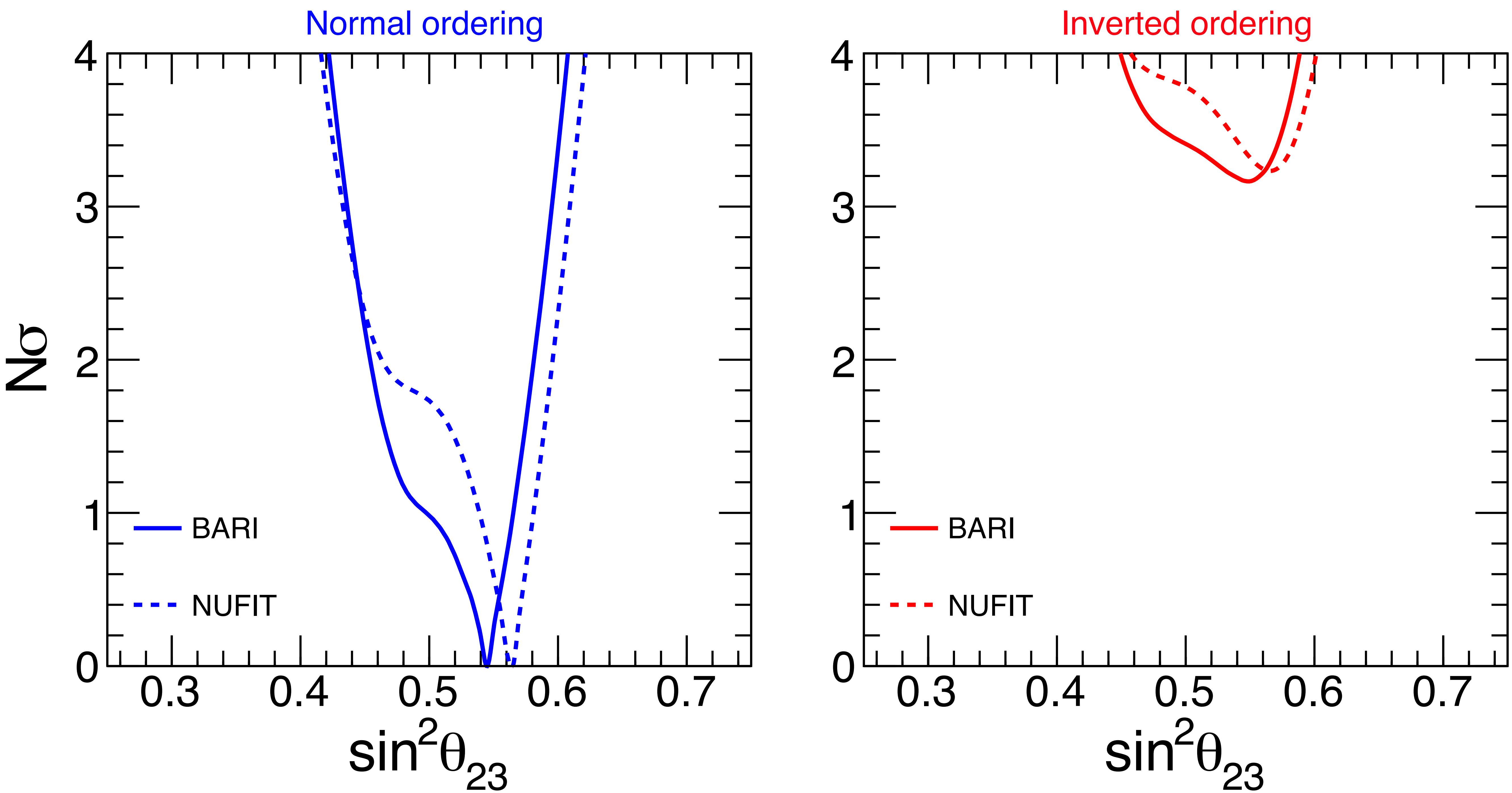
Global analyses comparison

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 $m_{\beta\beta}$

$$\chi^2(m_{\beta\beta}) = \min_{|\mathrm{M}|}\Big[\underbrace{\boxed{\chi^2(T_{0\nu\beta\beta}(m_{\beta\beta},|M|))}}_{\text{given by the collaboration}} + \underbrace{\boxed{\chi^2(|M|)}}_{\text{our calculation}}\Big]$$

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

our calculation

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

$$\eta = \log_{10}(|M|) = \bar{\eta} + \underbrace{\boxed{\alpha(g_A-1)}}_{\text{gA quenching uncertainty}} + \underbrace{\boxed{s\beta}}_{\text{short-range correlations}} \pm \underbrace{\boxed{\sigma}}_{\text{residual uncertainty}}$$

gA quenching uncertainty

residual uncertainty

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

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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2	$\Lambda\text{CDM}+\Sigma$	Planck TT + τ_{HFI} + lensing	< 0.64	< 0.63	0.2
3	$\Lambda\text{CDM}+\Sigma$	Planck TT + τ_{HFI} + BAO	< 0.21	< 0.23	1.2
4	$\Lambda\text{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI}	< 0.44	< 0.48	0.6
5	$\Lambda\text{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.45	< 0.47	0.3
6	$\Lambda\text{CDM}+\Sigma$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.18	< 0.20	1.6
7	$\Lambda\text{CDM}+\Sigma+A_{\text{lens}}$	Planck TT + τ_{HFI}	< 1.08	< 1.08	-0.1
8	$\Lambda\text{CDM}+\Sigma+A_{\text{lens}}$	Planck TT + τ_{HFI} + lensing	< 0.91	< 0.93	0.0
9	$\Lambda\text{CDM}+\Sigma+A_{\text{lens}}$	Planck TT + τ_{HFI} + BAO	< 0.45	< 0.46	0.2
10	$\Lambda\text{CDM}+\Sigma+A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI}	< 1.04	< 1.03	0.0
11	$\Lambda\text{CDM}+\Sigma+A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI} + lensing	< 0.89	< 0.89	0.1
12	$\Lambda\text{CDM}+\Sigma+A_{\text{lens}}$	Planck TT, TE, EE + τ_{HFI} + BAO	< 0.31	< 0.32	0.3

conservative dataset

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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

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:

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