XIX International Workshop on Neutrino Telescopes, 18-26 February 2021

Phenomenology of Three Neutrino Oscillations

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Work done in collaboration with
F. Capozzi, E. Lisi and A. Palazzo

Outline

Oscillation parameters:
updated results of the global analysis

- Single parameters
- Pairs of parameters
- Discussion

Combination with nonoscillation data
(if time allows)

Conclusions

This talk updates for NEUTEL 2021 the results from:

Capozzi, Di Valentino, Lisi, Marrone, Melchiorri, Palazzo,
"Addendum to: Global constraints on absolute neutrino masses and their ordering"
PRD 101 (2020), 11 116013 [arXiv:2003.08511]

by including Neutrino 2020 oscillation results from the following experiments:

SK solar
T2K long-baseline (LBL) accelerator
NOvA LBL accelerator
RENO short-baseline (SBL) reactor

and a discussion of recent changes in results and "tensions" among data.
Update shown in this talk are part of a work in progress.

Nonoscillations results (beta, double beta, cosmo) are unchanged

3ν Paradigm: Parameters

Mixings and phases: CKM-> PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

2-3 rotation

1-3 rotation
+ CPV "Dirac" phase

1-2 rotation

Extra CPV phases
[if Majorana]
not tested in oscillations

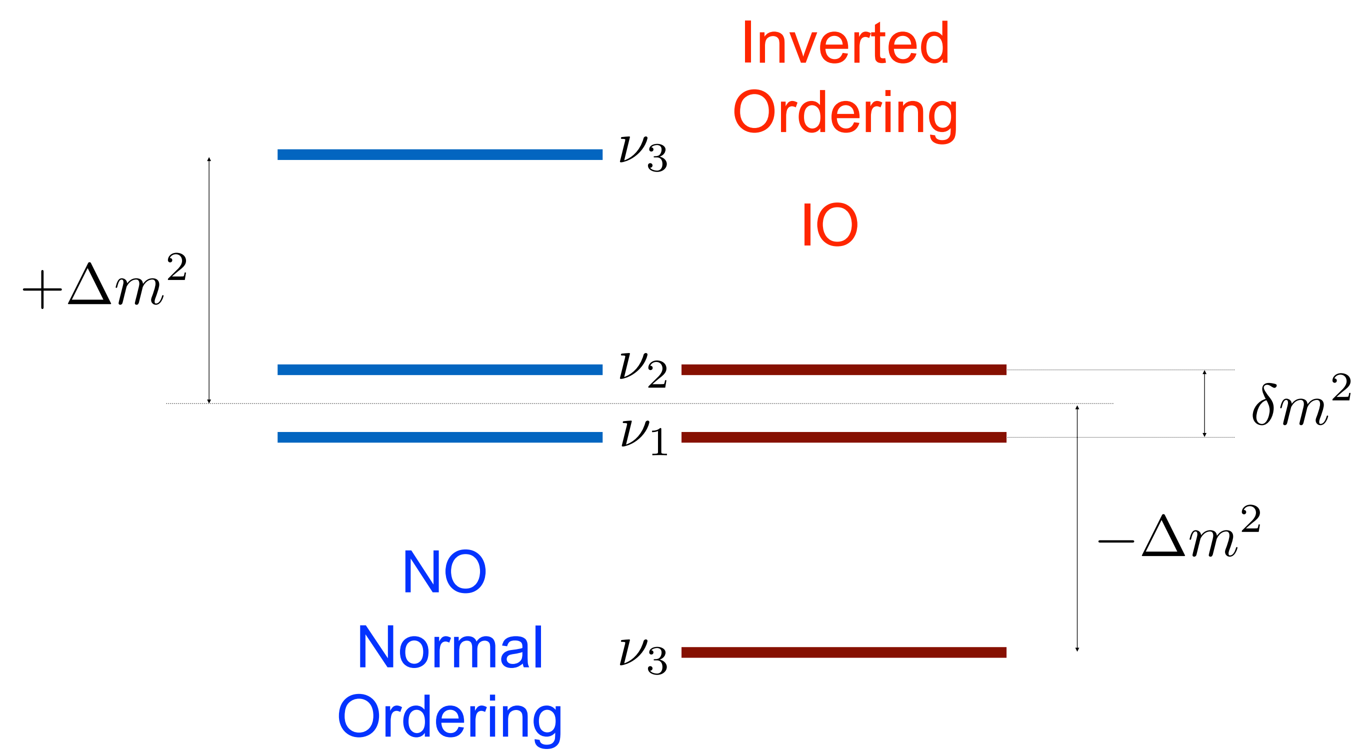
Mass [squared] spectrum
($E \sim p + m^2/2E$ + "interaction energy")

+ interactions in matter ->
effective terms ~ $G_F \cdot E \cdot$ density

+ absolute neutrino mass scale
(not tested in oscillations)

Note that in our notation

$$\Delta m^2 = \frac{\Delta m^2_{31} + \Delta m^2_{32}}{2}$$



Methodology

Useful to analyse oscillation data in the following sequence:

LBL Accel + Solar + KL (KamLAND)

minimal set sensitive to all osc. param.: $\Delta m^2, \delta m^2, \theta_{12}, \theta_{13}, \theta_{23}, \delta,$ NO/IO

LBL Accel + Solar + KL + SBL Reactor

add sensitivity to $\Delta m^2, \theta_{13}$ and affect other parameters via correlations

LBL Accel + Solar + KL + SBL Reactor + Atmosph.

add sensitivity to $\Delta m^2, \theta_{23}, \delta,$ NO/IO (but: entangled information in atm.)

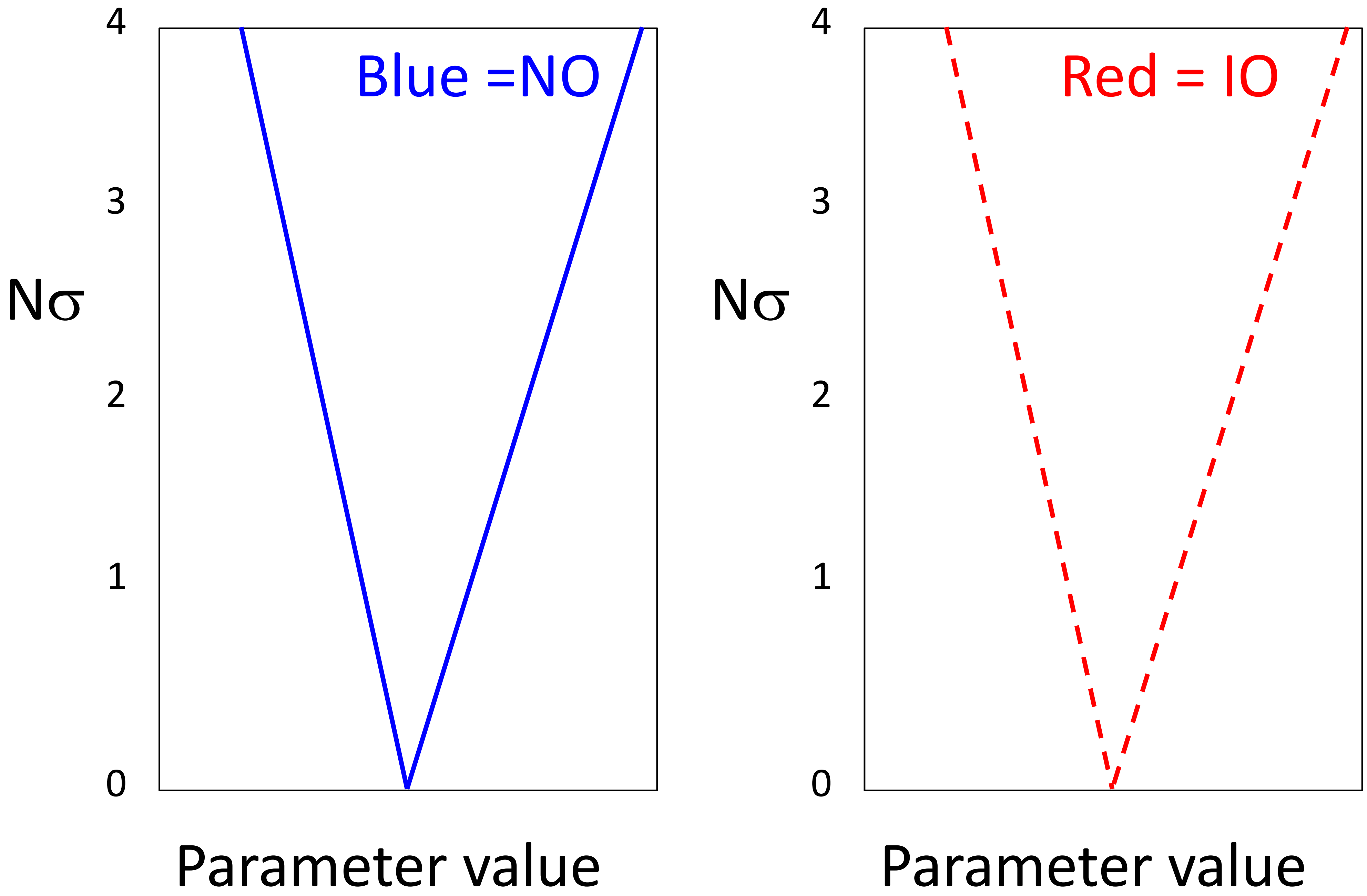
Bounds/contours in terms of Nσ around best fit: $N\sigma = \sqrt{\Delta\chi^2} = 1,2,3,...$

Undisplayed parameters are marginalised (projected) away

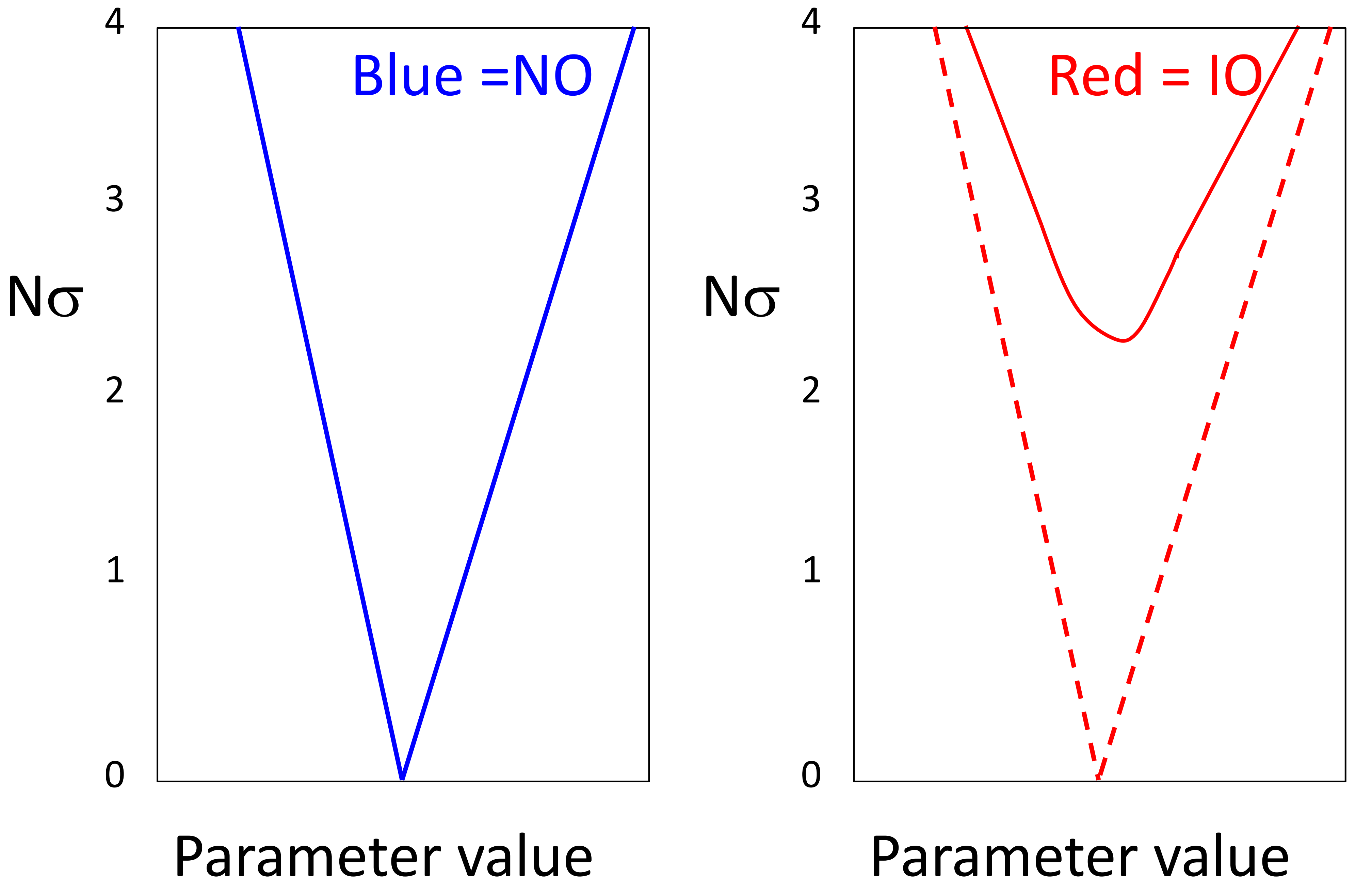
Global Neutrino Oscillation Data Analysis:

Single Parameters

Typical parameter bounds would scale linearly (and symmetrically) in the limit of ~ gaussian errors around best fit values.



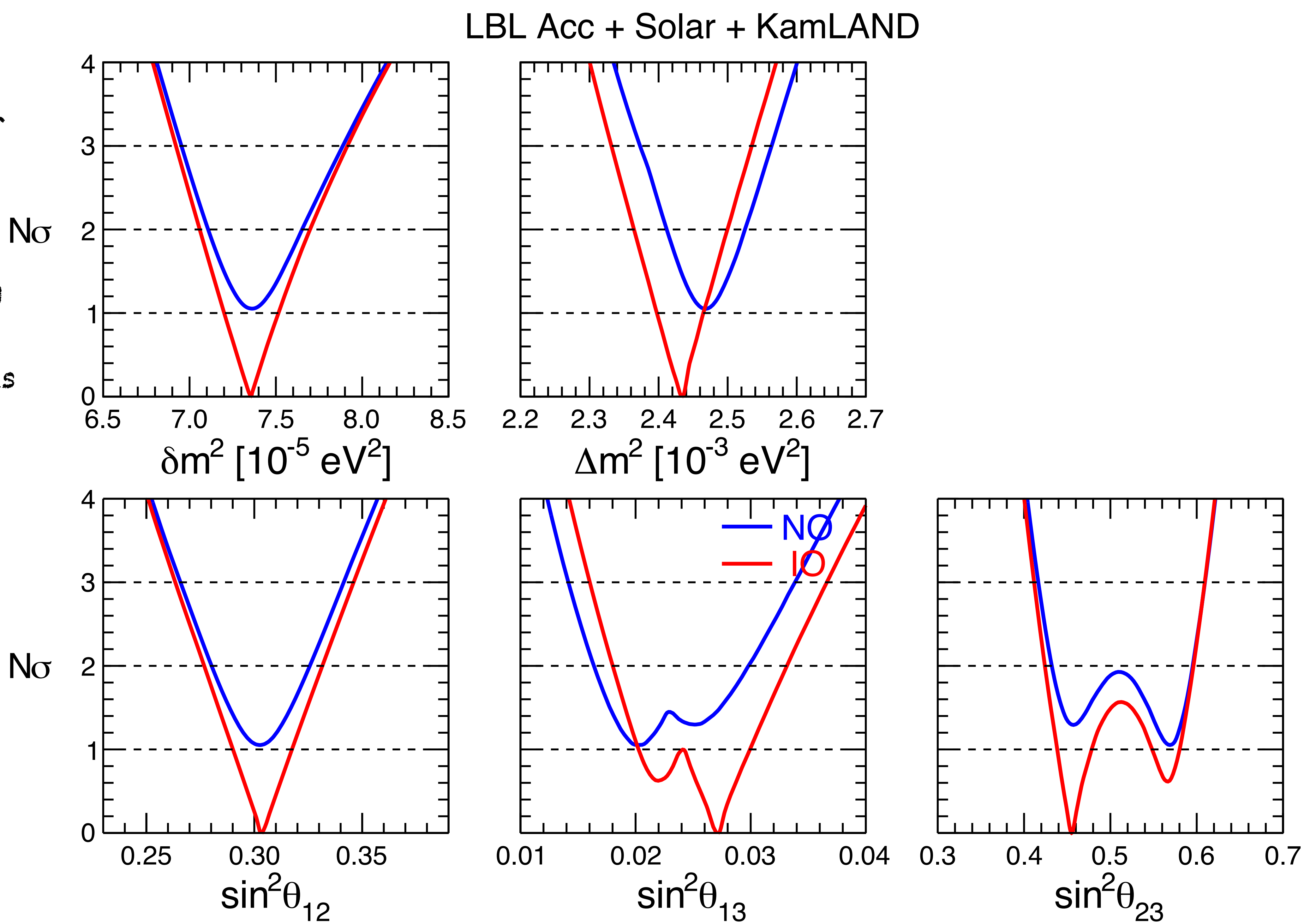
However, bounds for one mass ordering move upwards if the other mass ordering is preferred, e.g.:



Upper and lower bounds at >>3σ for $\delta m^2, \Delta m^2, \theta_{12}, \theta_{13}, \theta_{23}$

Octant degeneracy of θ_{23} also affects θ_{13} via correlations in $\nu_\mu \to \nu_e$

Weak preference for IO at $\sim 1\sigma$. Note different Δm^2 in NO/IO



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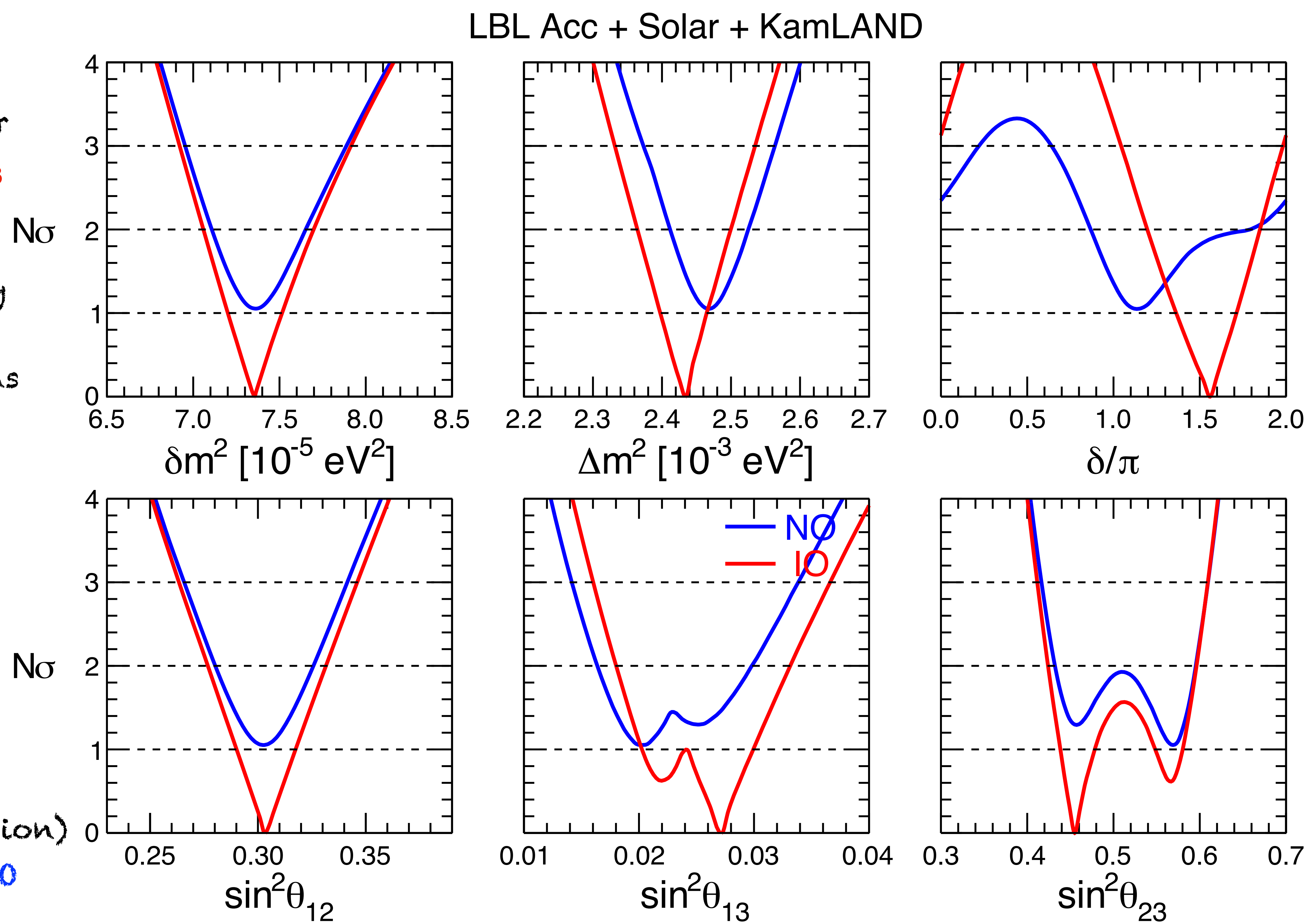
Octant degeneracy of θ_{23} also affects θ_{13} via correlations in $\nu_\mu \to \nu_e$

Weak preference for IO at $\sim 1\sigma$. Note different Δm^2 in NO/IO

Preference for $\delta \sim 3\pi/2$ (CP violation) in IO, but not in NO

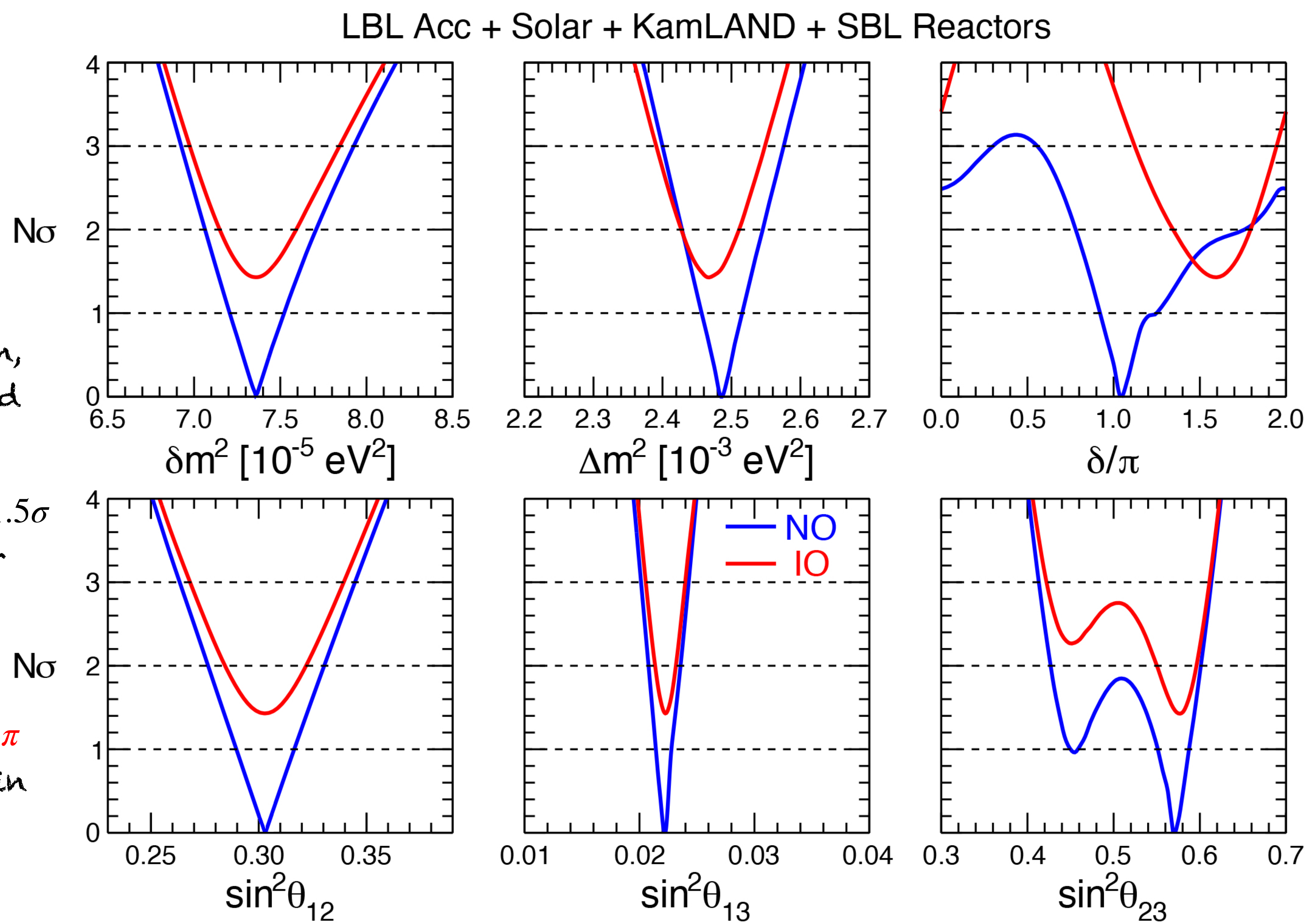


Bounds on θ_{13} and Δm^2 strengthened

Octant degeneracy of θ_{23} partly broken, 2nd octant preferred

NO preferred at $\sim 1.5\sigma$
Note overall higher Δm^2 in NO/IO

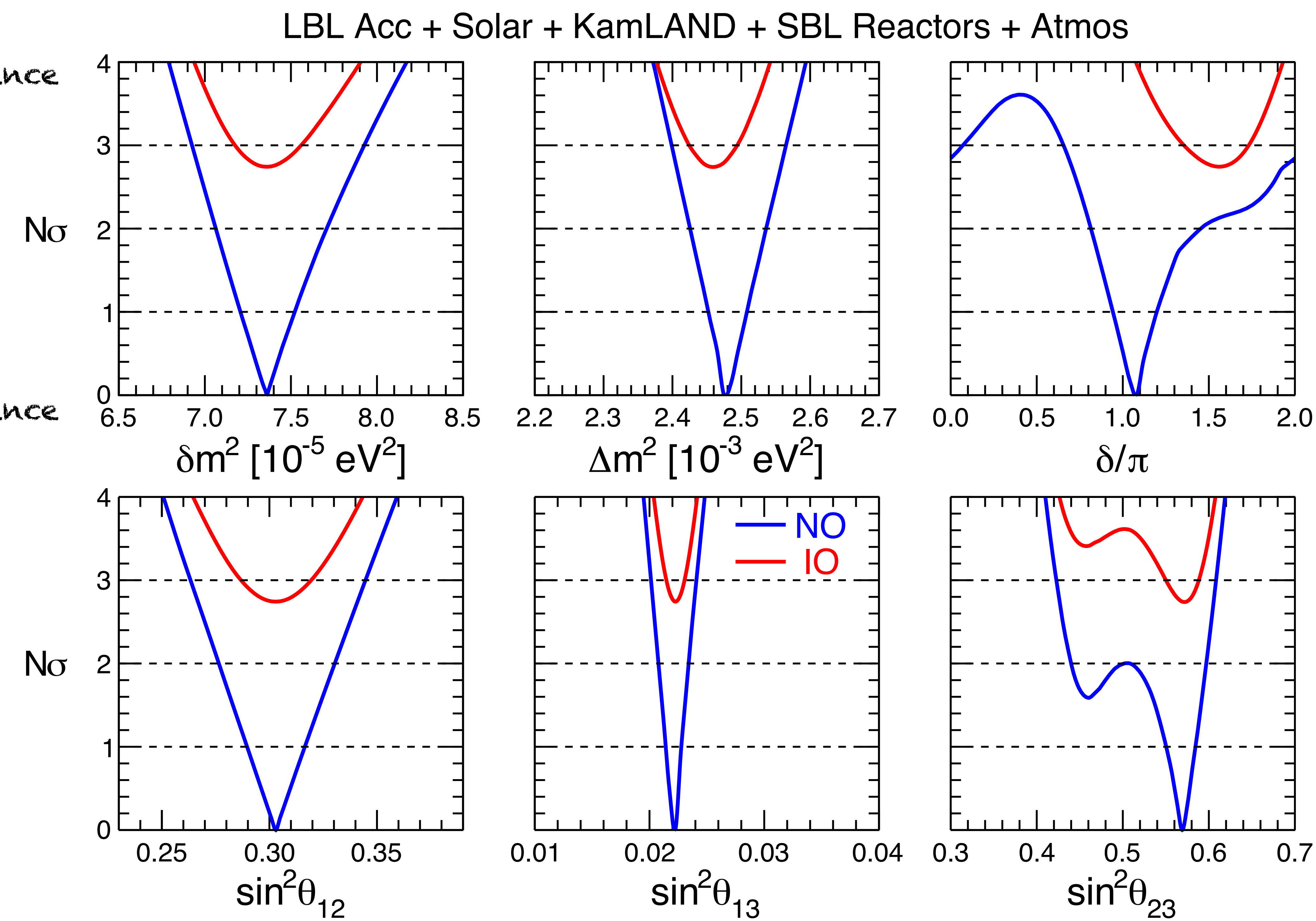
Preference for $\delta \sim \pi$ (CP conservation) in NO but not in IO



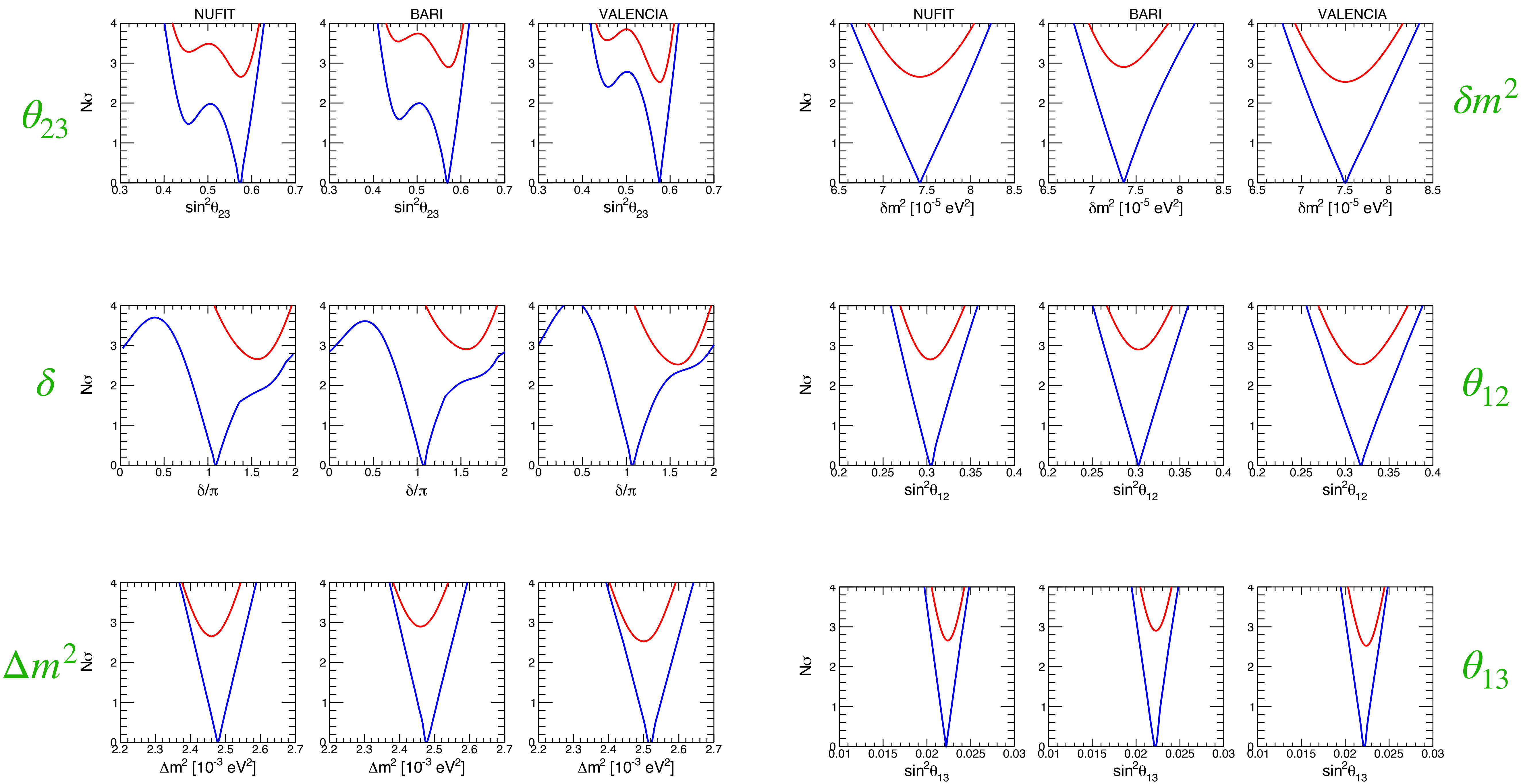
Increased preference for NO (2.7σ)

Increased preference for 2nd octant of θ_{23} (1.6σ)

CP best fits still around $\delta \sim \pi$ in NO and $\delta \sim 3\pi/2$ in IO



Comparison among global neutrino oscillation data analyses



BARI: 2003.08511 updated for this talk

NUFIT: 2007.19742 VALENCIA: 2006.11237 v2

[with Δm^2_{13} and Δm^2_{23} converted to our Δm^2]

TABLE I: **Updated for NEUTEL 2021 from Capozzi+ arXiv:2003.08511 [hep-ph].**

Global 3ν analysis of oscillation data, in terms of best-fit values and allowed ranges at $N_\sigma = 1,\ 2,\ 3$ for the mass-mixing parameters, in either NO or IO. The last column shows the formal "1σ accuracy" for each parameter, 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 $\delta/\pi \in [0,\ 2]$ (cyclic).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.475	2.453 – 2.508	2.426 – 2.536	2.399 – 2.565	1.1
	IO	2.455	2.431 – 2.487	2.403 – 2.516	2.374 – 2.545	1.2
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.15 – 2.28	2.08 – 2.34	2.01 – 2.41	3.0
	IO	2.23	2.16 – 2.29	2.10 – 2.35	2.03 – 2.42	2.9
$\sin^2\theta_{23}/10^{-1}$	NO	5.69	5.50 – 5.84	4.40 – 5.97	4.23 – 6.08	5.4
	IO	5.69	5.54 – 5.85	5.28 – 5.98	4.25 – 6.08	5.4
δ/π	NO	1.08	0.94 – 1.20	0.82 – 1.45	0 – 0.07 $\oplus$ 0.65 – 2	22
	IO	1.56	1.40 – 1.70	1.22 – 1.83	1.06 – 1.94	9

Most accurate parameter is Δm^2: "formal" uncertainty as small as $\sim 1\,\%$!

Q.: Is such accuracy "realistic"? More later.

Global Neutrino Oscillation Data Analysis:
Pairs of Parameters

Some relevant covariances:

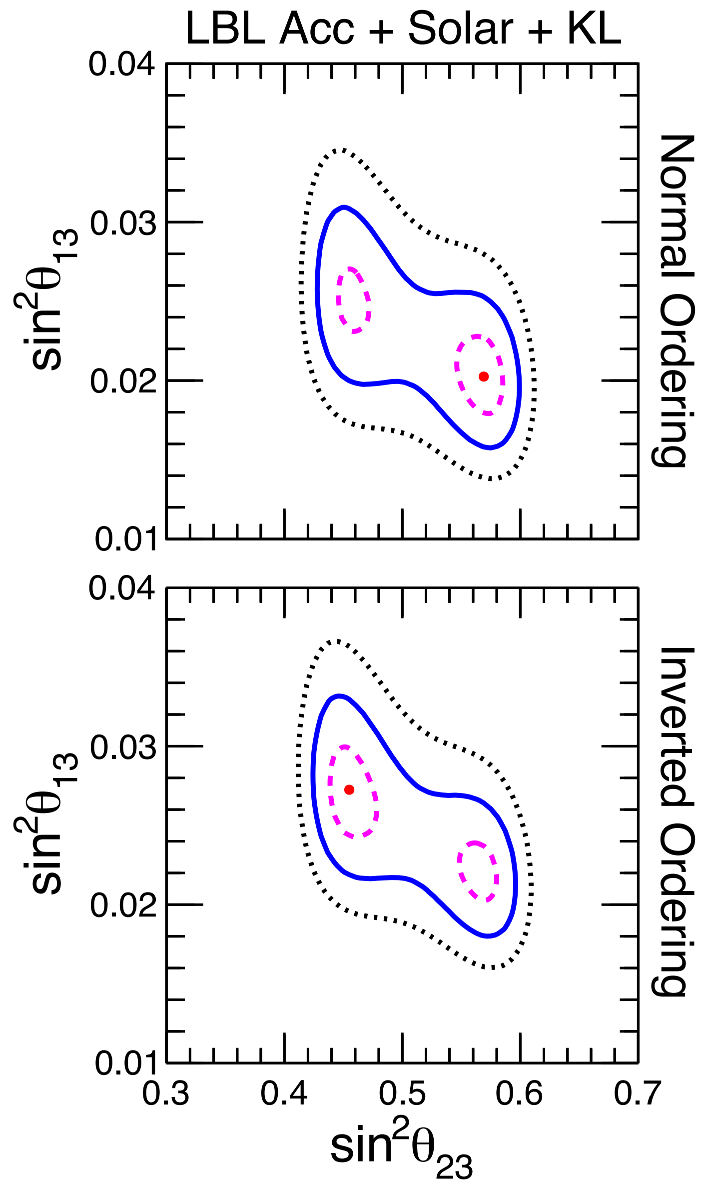
$$(\theta_{13}, \theta_{23})$$

$$(\theta_{13}, \pm\Delta m^2)$$

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

$(\theta_{13}, \theta_{23})$ covariance

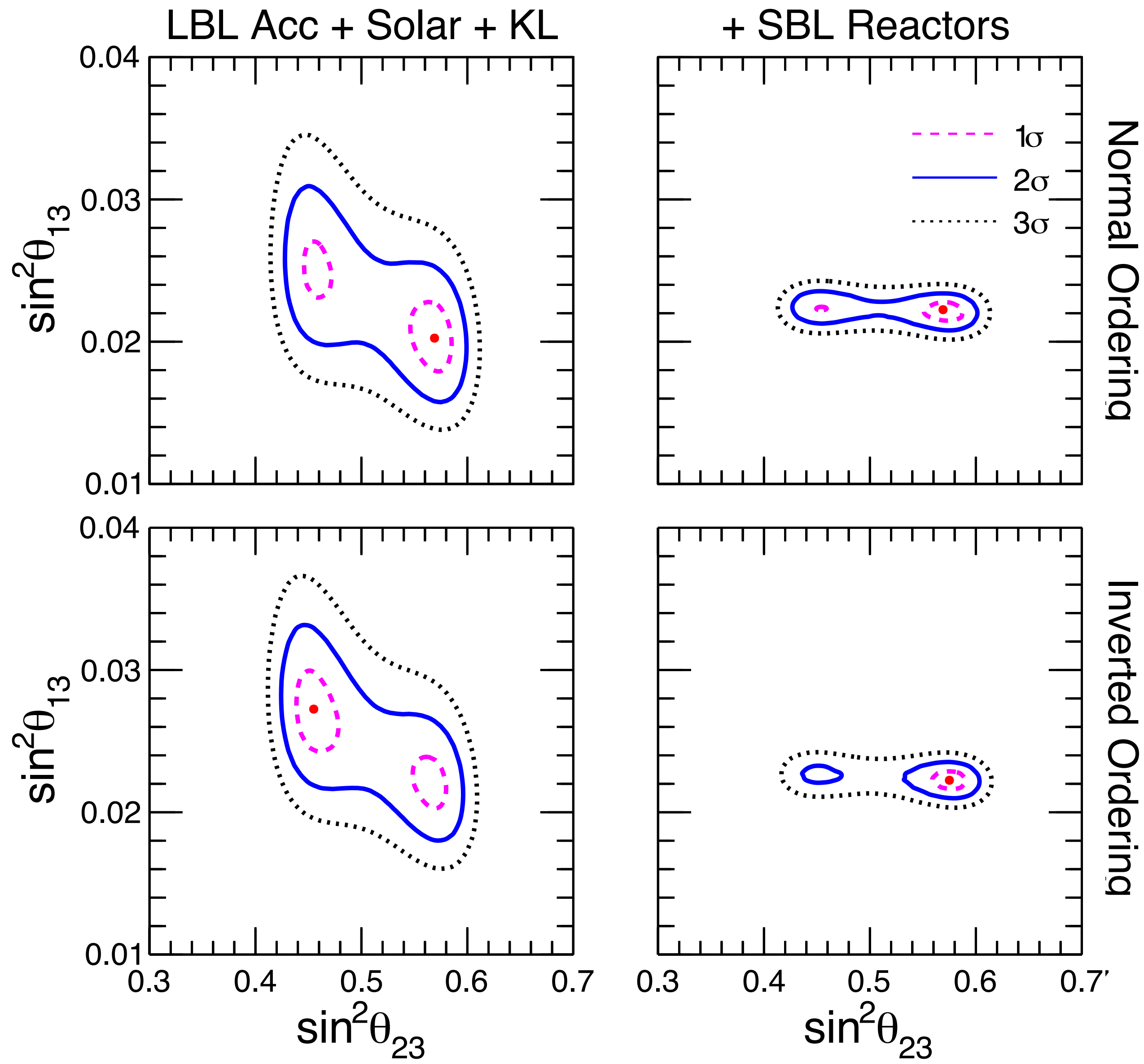
Anticorrelation due to leading $\nu_\mu \to \nu_e$ term $\sim \sin^2\theta_{23} \sin^2 2\theta_{13}$



$(\theta_{13}, \theta_{23})$ covariance

Anticorrelation due to leading $\nu_\mu \to \nu_e$ term $\sim \sin^2\theta_{23} \sin^2 2\theta_{13}$

Narrow and "low" reactor θ_{13} range selects 2nd octant

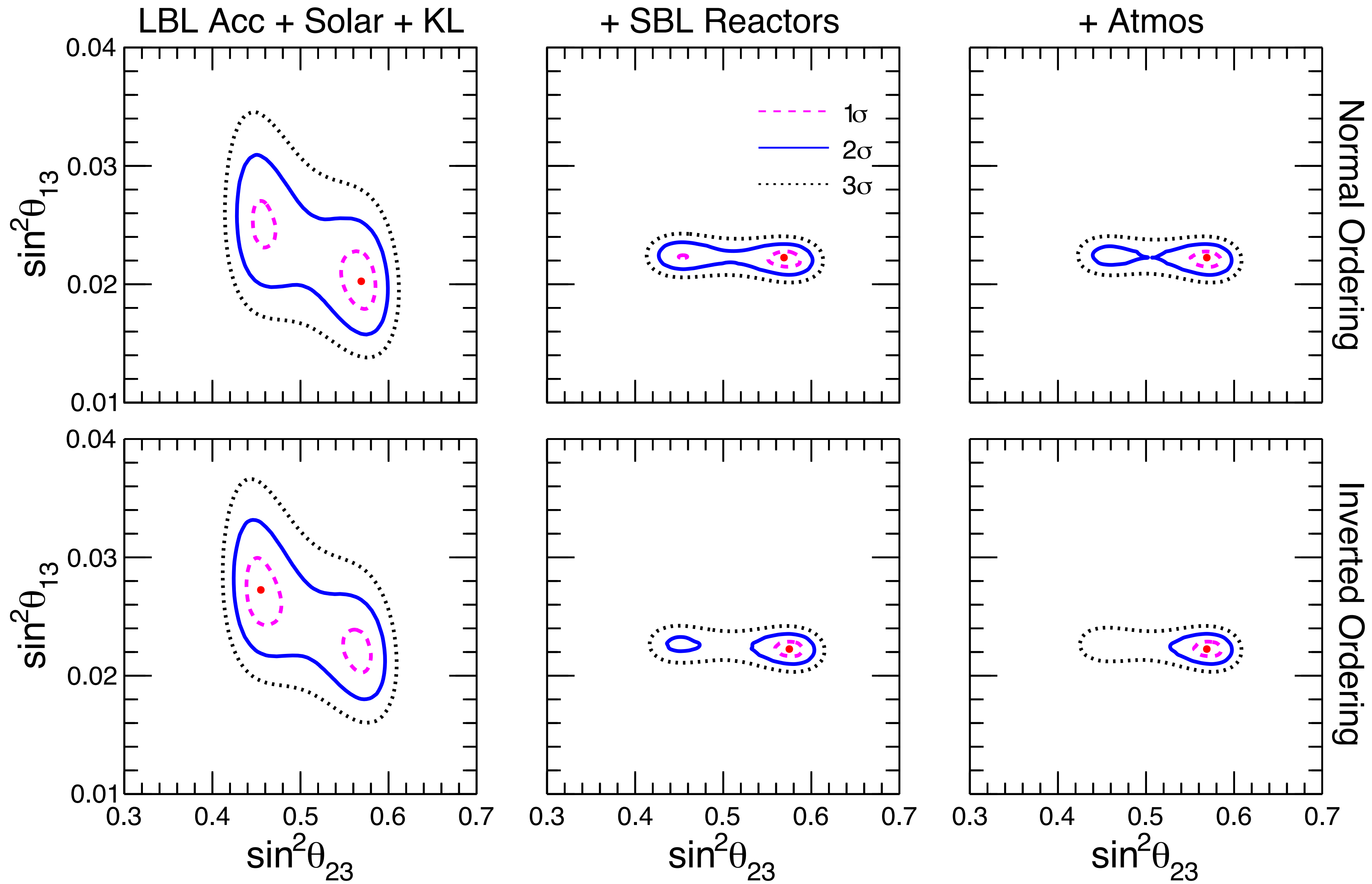


$(\theta_{13}, \theta_{23})$ covariance

Anticorrelation due to leading $\nu_\mu \to \nu_e$ term $\sim \sin^2\theta_{23}\sin^2 2\theta_{13}$

Narrow and "low" reactor θ_{13} range selects 2nd octant

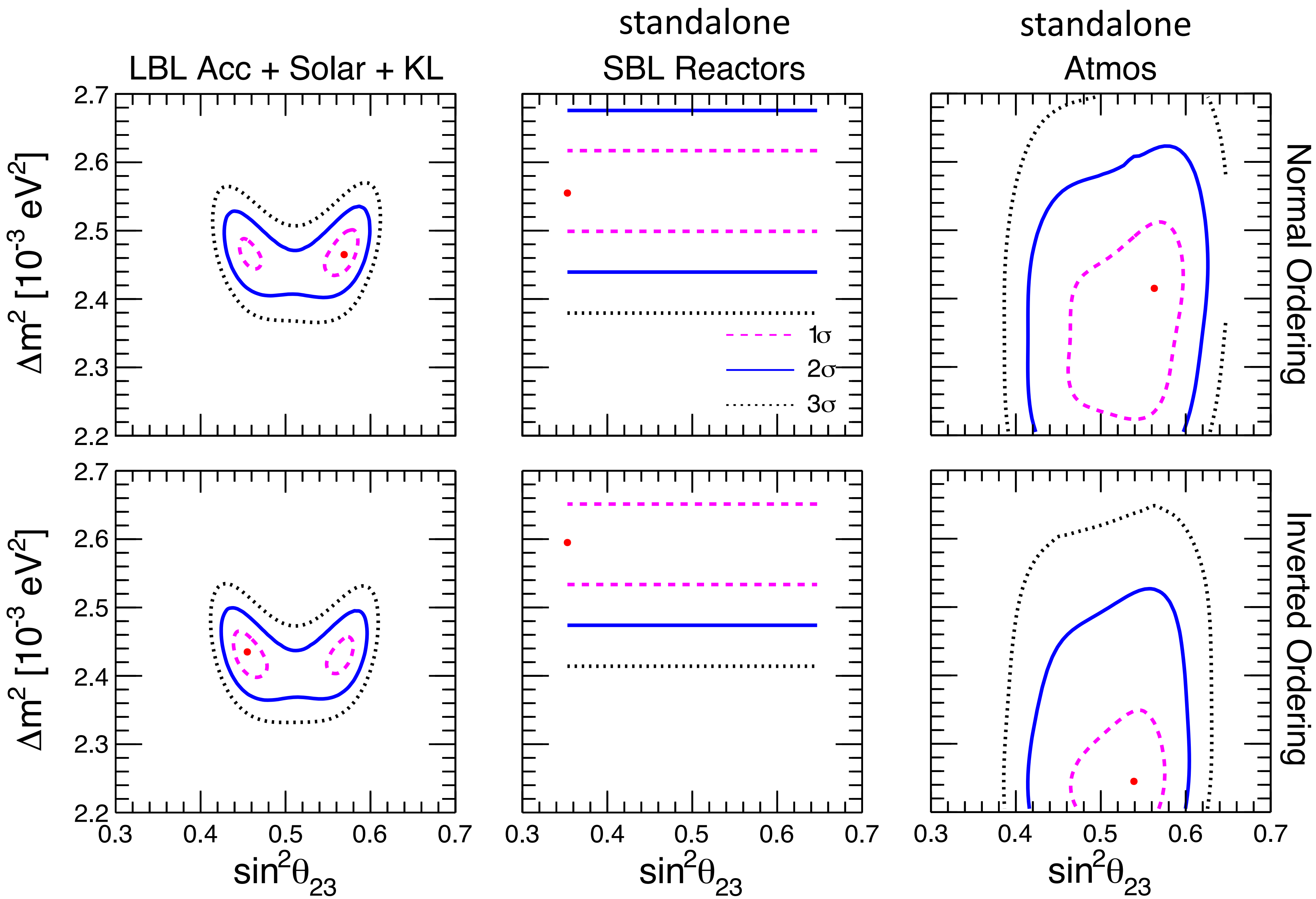
2nd octant confirmed by atmospheric data in both NO and IO



$(\theta_{13}, \pm \Delta m^2)$ covariance

Reactors prefer higher Δm^2 than LBL accelerator and atmospheric expts

Difference higher for IO and maximal θ_{23} mixing

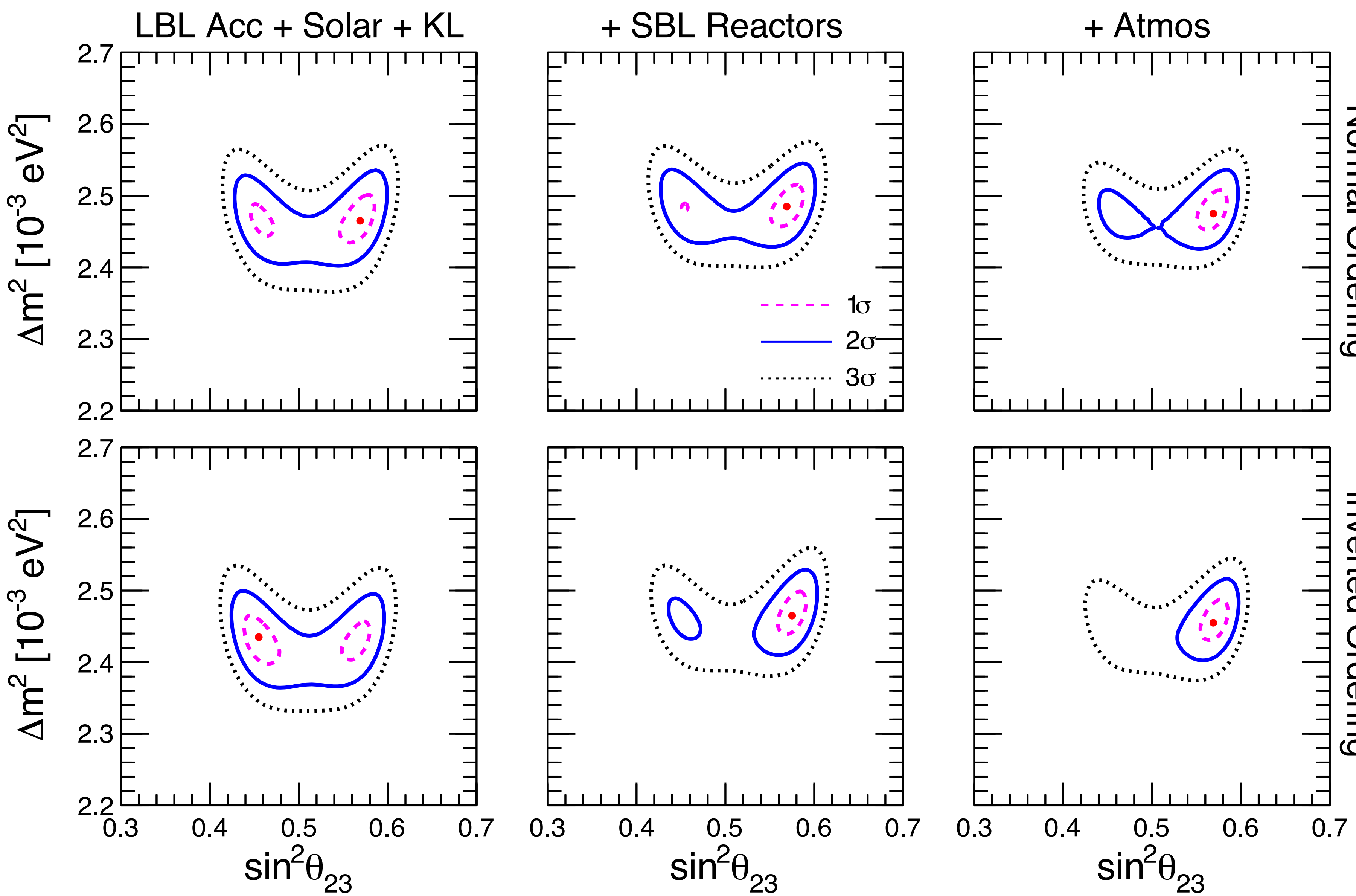


$(\theta_{13}, \pm\Delta m^2)$ covariance

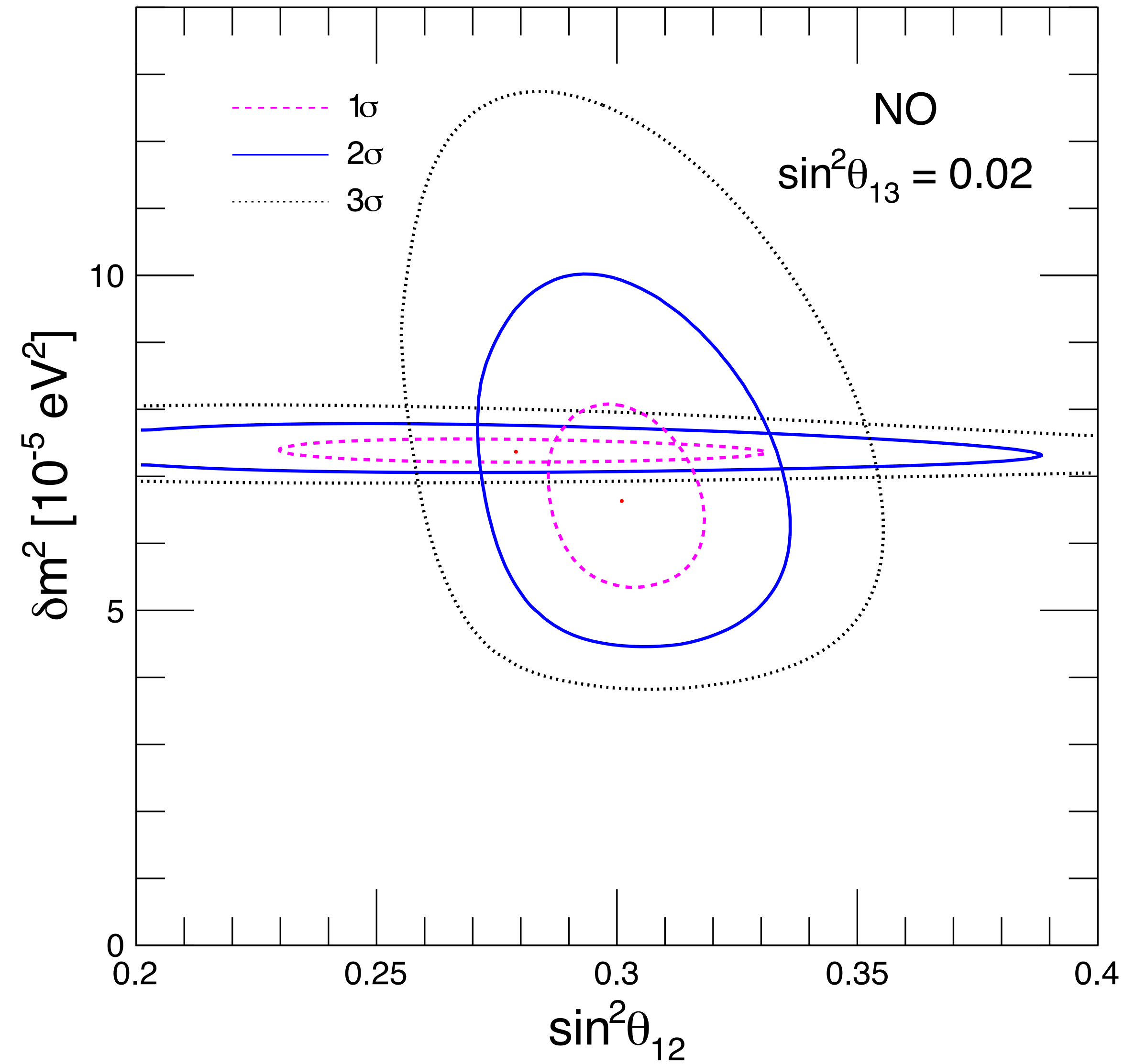
Reactors prefer higher Δm^2 than LBL accelerator and atmospheric expts

Difference higher for IO and maximal θ_{23} mixing

Overall convergence for NO, nonmaximal θ_{23} (2nd octant) intermediate Δm^2



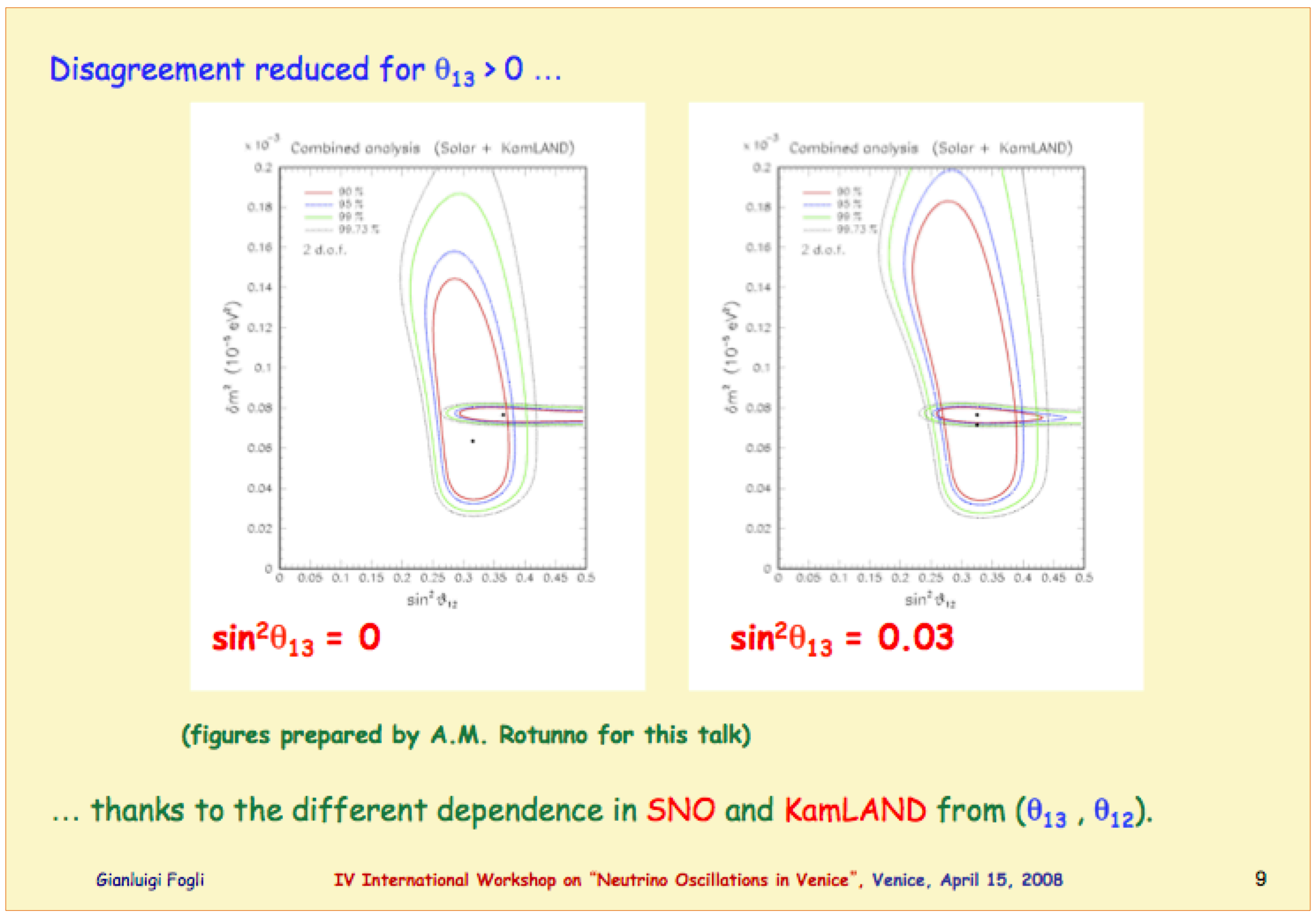
$(\theta_{12}, \delta m^2)$ covariance

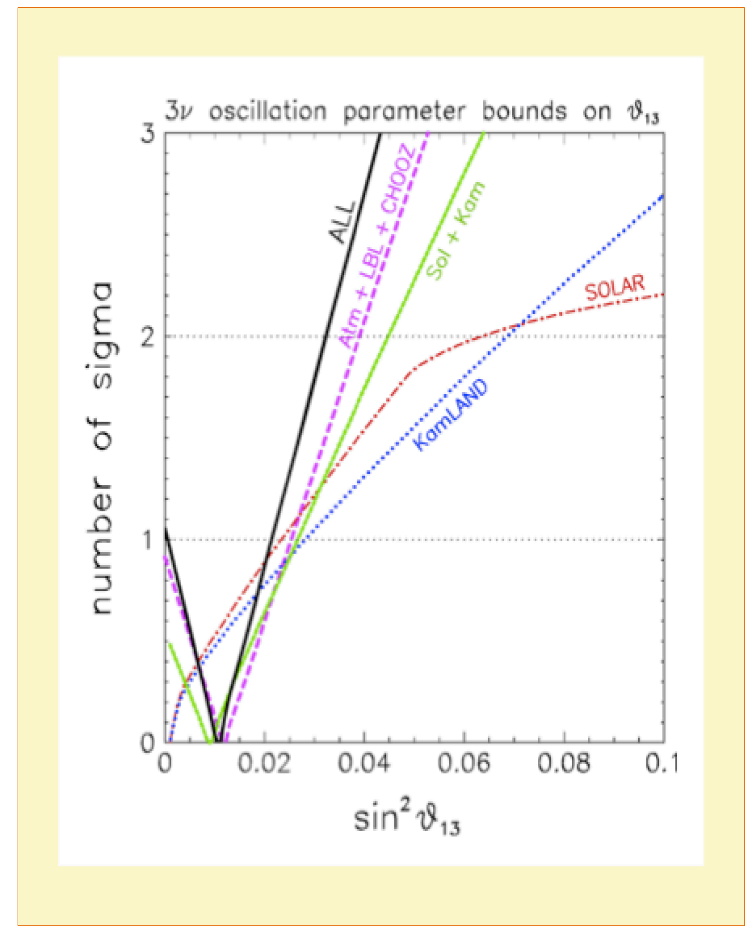


After the latest SK solar neutrino data (Neutrino 2020),
no significant "tension" between δm^2 values of Solar vs KamLAND

$(\theta_{12}, \delta m^2)$ covariance

Memories from NO-VE (Neutrino Oscillations in Venice) 2008...
...tension between solar and KL in both parameters was relaxed for $\theta_{13} > 0$





Hints of $\theta_{13} > 0$ from global neutrino data analysis

G.L. Fogli[1,2], E. Lisi[2], A. Marrone[1,2], A. Palazzo[3], and A.M. Rotunno[1,2]

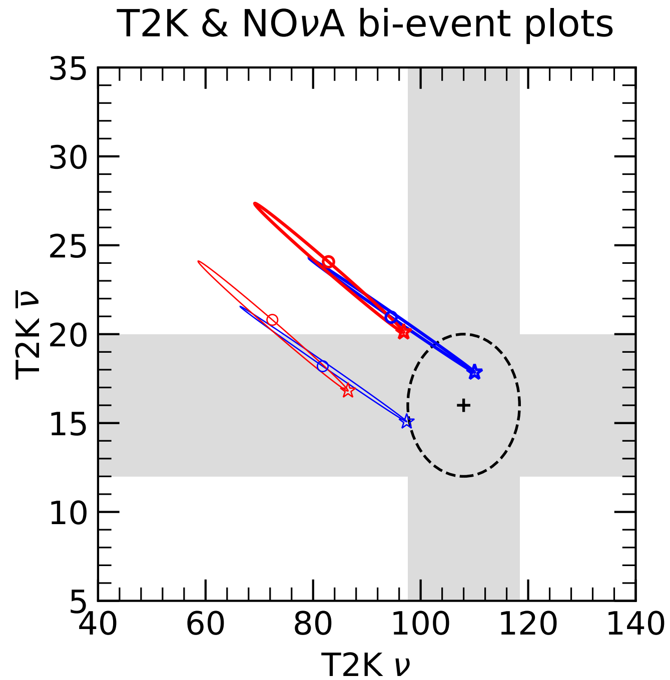
The fate of hints can be favorable sometimes!

Origin of weaker hints on NO and δ

Looking at the T2K-NOνA tension through bi-event plots:

Possible role of cross section uncertainties

Integrated info on ν and $\bar{\nu}$, stat errors only
(but analysis uses spectral data)



$s^2_{23} = \begin{matrix} 0.57 \\ 0.45 \end{matrix}$ NO IO $\delta = \begin{matrix} \pi & \circ \\ 3\pi/2 & \star \end{matrix}$

T2K alone prefers:

NO

$\delta \sim 3\pi/2$

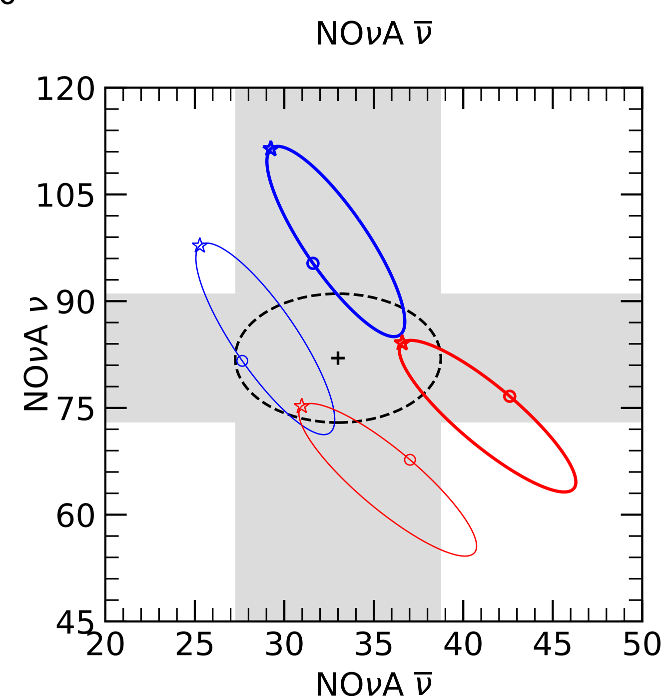
2nd octant of θ_{23}

NOνA alone prefers:

NO

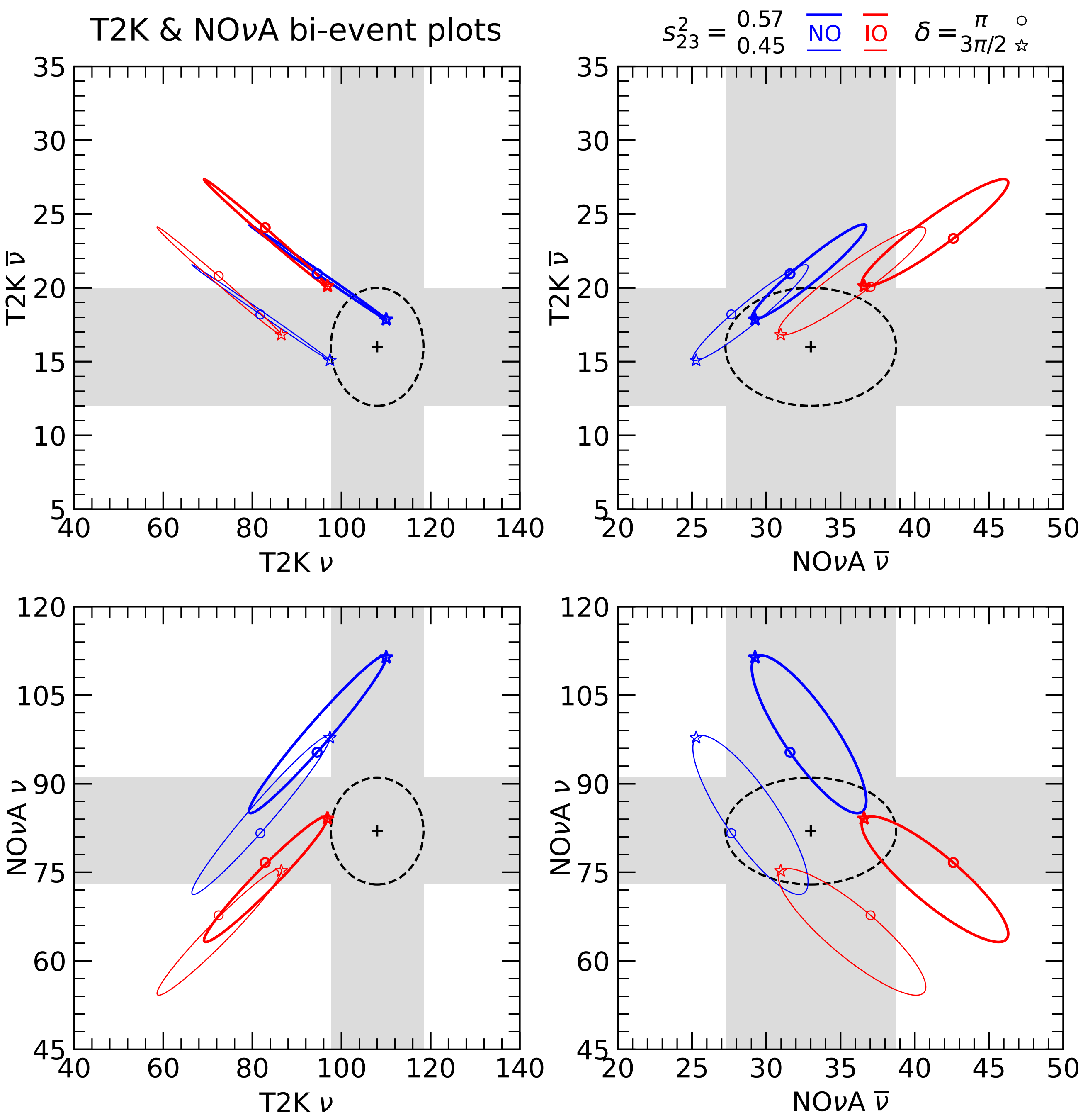
CP conservation

(~octant degenerate)



-> In NO: confusing indications about CP

The same info can be reorganised in terms of T2K vs NOνA:



Integrated info on ν and $\bar{\nu}$, stat errors only
(but analysis uses spectral data)

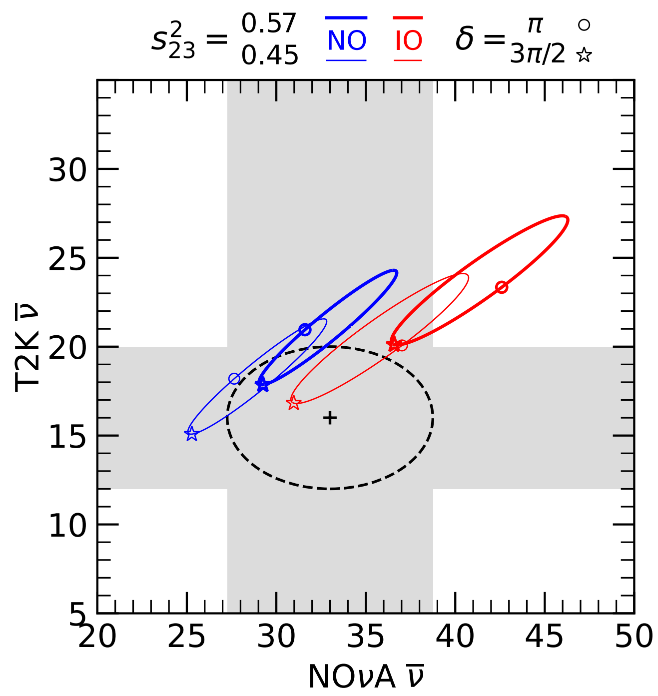
T2K & NOνA bi-event plots

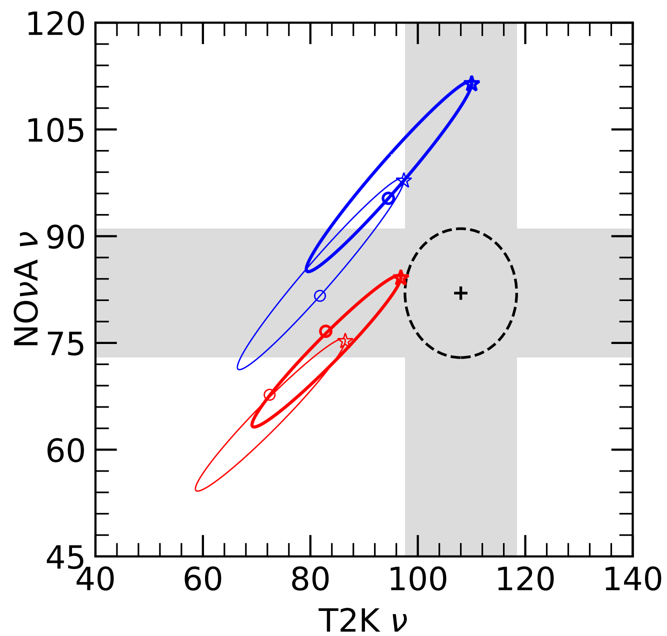
T2K + NOνA ($\bar{\nu}$) prefer:

IO

$\delta \sim 3\pi/2$

1st octant of θ_{23}





T2K + NOνA (ν) prefer:

IO

$\delta \sim 3\pi/2$

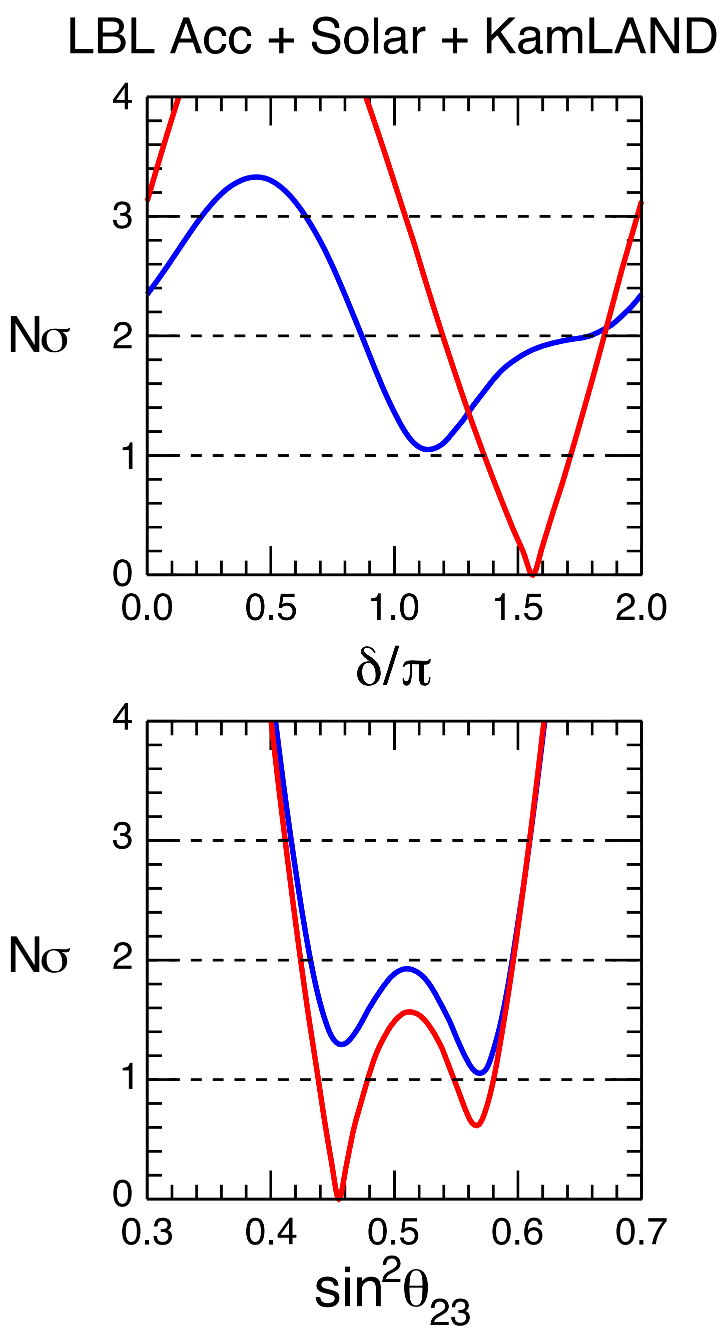
2nd octant of θ_{23}

-> T2K and NOνA alone: NO preferred

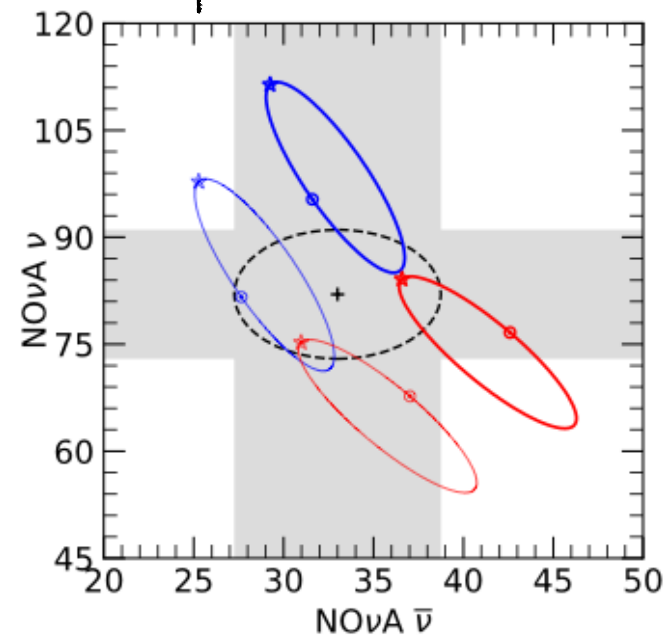
-> T2K and NOνA combined: IO preferred

-> In IO: CP violation preferred

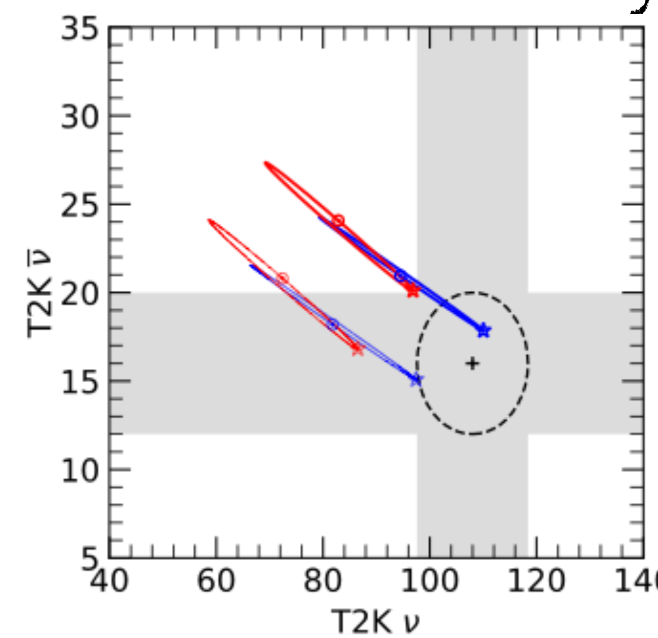
In the LBL combination, dominated by T2K+NOνA, IO wins, but results on NO/IO, octant and CP are "unstable" (subject to change with fluctuations)



E.g., NOνA still close to different options within 1σ



E.g., T2K is close to the edge of expected CPV Asimov sensitivity

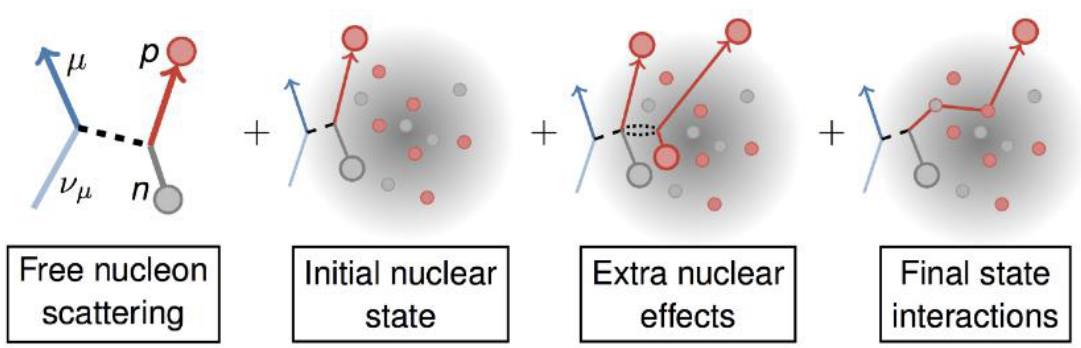


Is there only statistics behind the T2K-NOνA: tension?

Parameter covariances and data tensions show the delicate interplay between knowns [$\Delta m^2, \theta_{23}$] and unknowns [NO/IO, δ, octant]

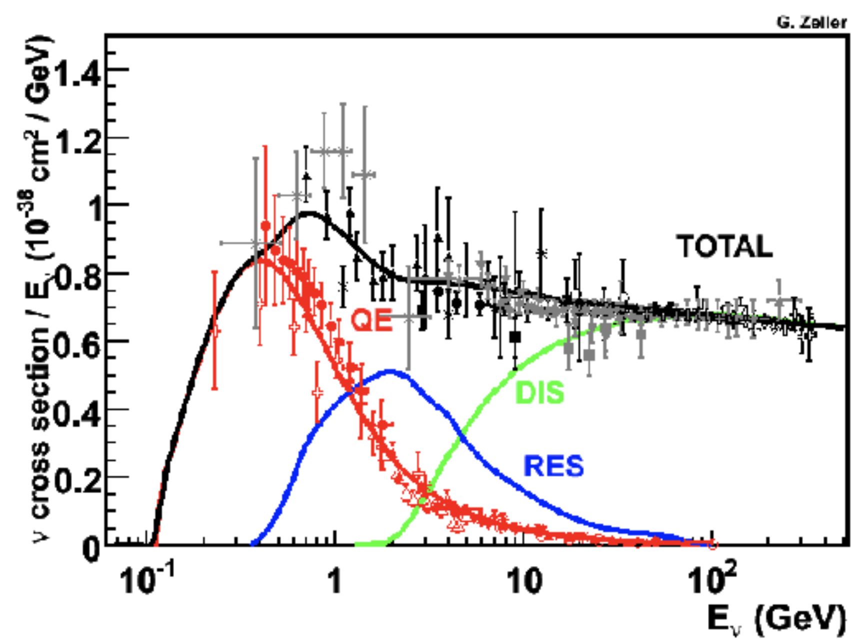
There is a general issue that affects all these (un)knowns: neutrino interactions in nuclei are not known as precisely as desired

Theory: complex nuclear effects



Kajetan Niewczas @ NuFact2018

Experiment: relatively few data



Great effort to improve the situation through dedicated experiments (including near detectors, ND) and improved nuclear models (including tuning to the above experiments), but non-negligible uncertainties remain

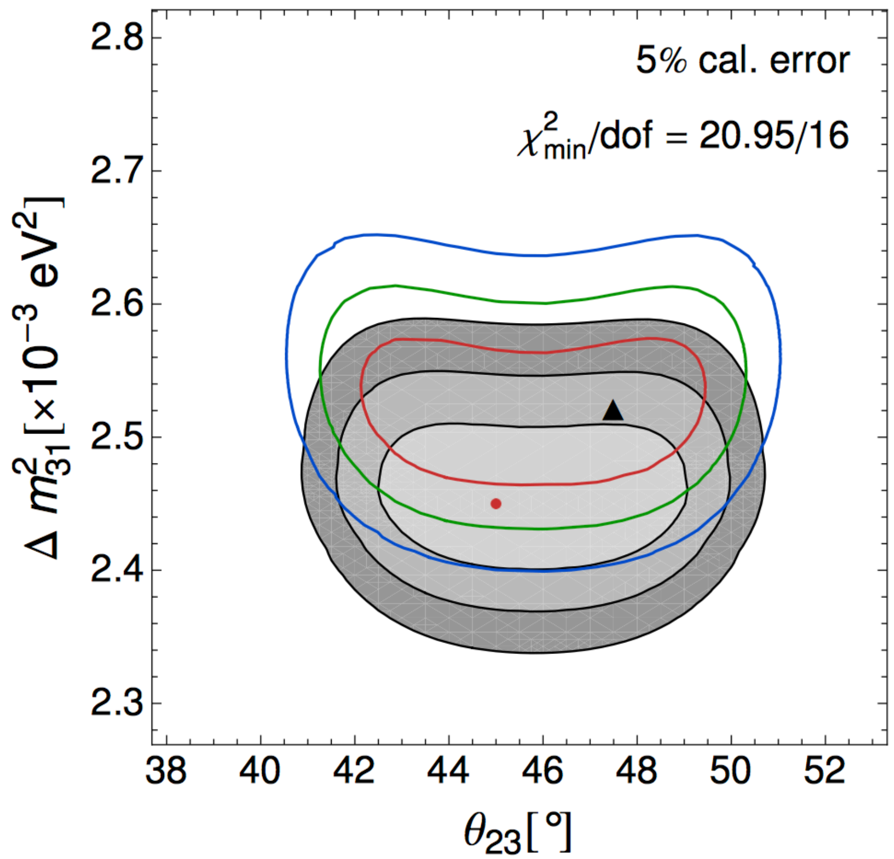
Discussion ->

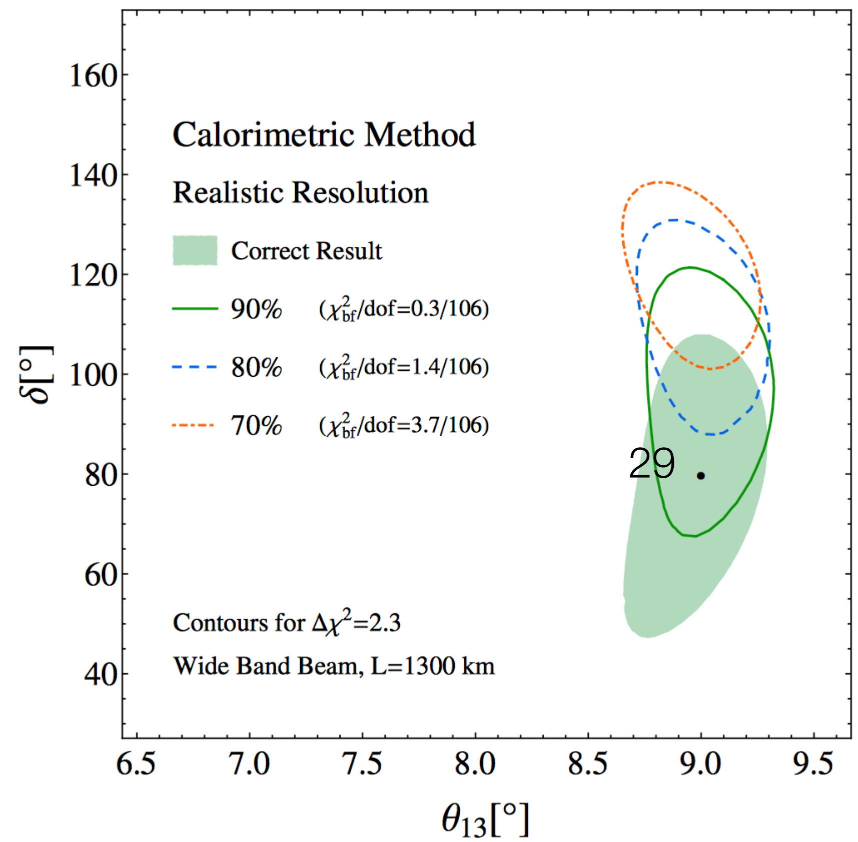
Case 1: Single LBL accelerator experiment

Cross section uncertainties may bias:
Δm^2 (via Erec), θ_{23} (via spectra norm+shape), δ (via nu-nubar differences)

Exercise to estimate biases:
Generate data with one Xsec model and analyse them with same or different model

Significant biases may emerge [Benhar+ 1501.06448, Alvarez-Ruso+ 1706.03621, and refs. therein]





Note shift in
- Δm^2
- CP/CPV
- octant

at best fit

Effects reduced but not zeroed by tuning model(s) to ND data.
No model explains all Xsection data!

Case 2: Two LBL accelerator experiments

T2K uses NEUT generator with T2K-ND tuning
NOvA uses GENIE generator with NOνA-ND tuning

Ideally one would like to use one and the same nuclear model in both expts, based on world cross section data at sub/multi-GeV energy.

While waiting for a joint T2K+NOνA analysis (202X?) with a common model…
… a simpler exercise is to swap GENIE vs NEUT in generating/analysing data:

GENIE NU EVENTS → T2K ANALYSIS PIPELINE (with **NEUT)** → PARAMETERS
NEUT NU EVENTS → NOνA ANALYSIS PIPELINE (with **GENIE**) → PARAMETERS

By comparing true vs reconstructed oscillation parameters in both experiments, we'll definitely learn something about their relative Xsec systematics!

[see also Barrow+ 2008.06566]

Warning:

Approximate implementation of theory uncertainties common to two or more experiments induce unavoidable limitations in global data analyses

Correlations of common Xsec model systematics in T2K and NOνA are difficult to estimate -> tentatively ignored in LBL accelerator data combination. Note also that SK+IceCube (atm) depend on nu Xsec in H_2O as T2K (LBL)

Ignoring correlations artificially reduce systematic effects in the combination. Probably a small effect, but we do not really know how small at present. Lesson learned from the reactor spectrum bump: errors may be larger than thought!

E.g., if E_{rec} were hypothetically biased by >1% in all LBL data inputs, then the current 1% global-fit output accuracy on Δm^2 might be too optimistic...

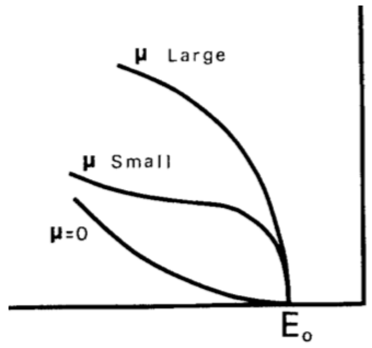
Important to keep this limitation in mind in current/prospective data fits

Constraints from nonoscillation Data

3ν framework via non-oscillation searches:
Absolute neutrino masses and observables $(m_\beta, m_{\beta\beta}, \Sigma)$

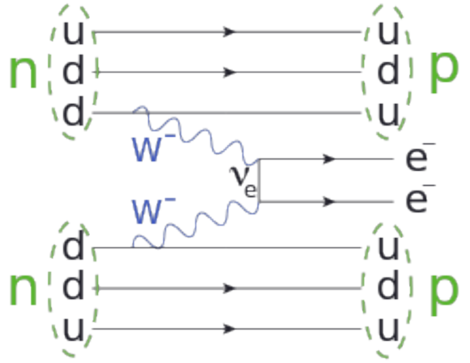
β decay, sensitive to the "effective electron neutrino mass":

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



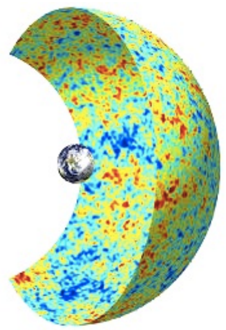
$0\nu\beta\beta$ decay: only if Majorana. "Effective Majorana mass":

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



Cosmology: Dominantly sensitive to sum of neutrino masses:

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

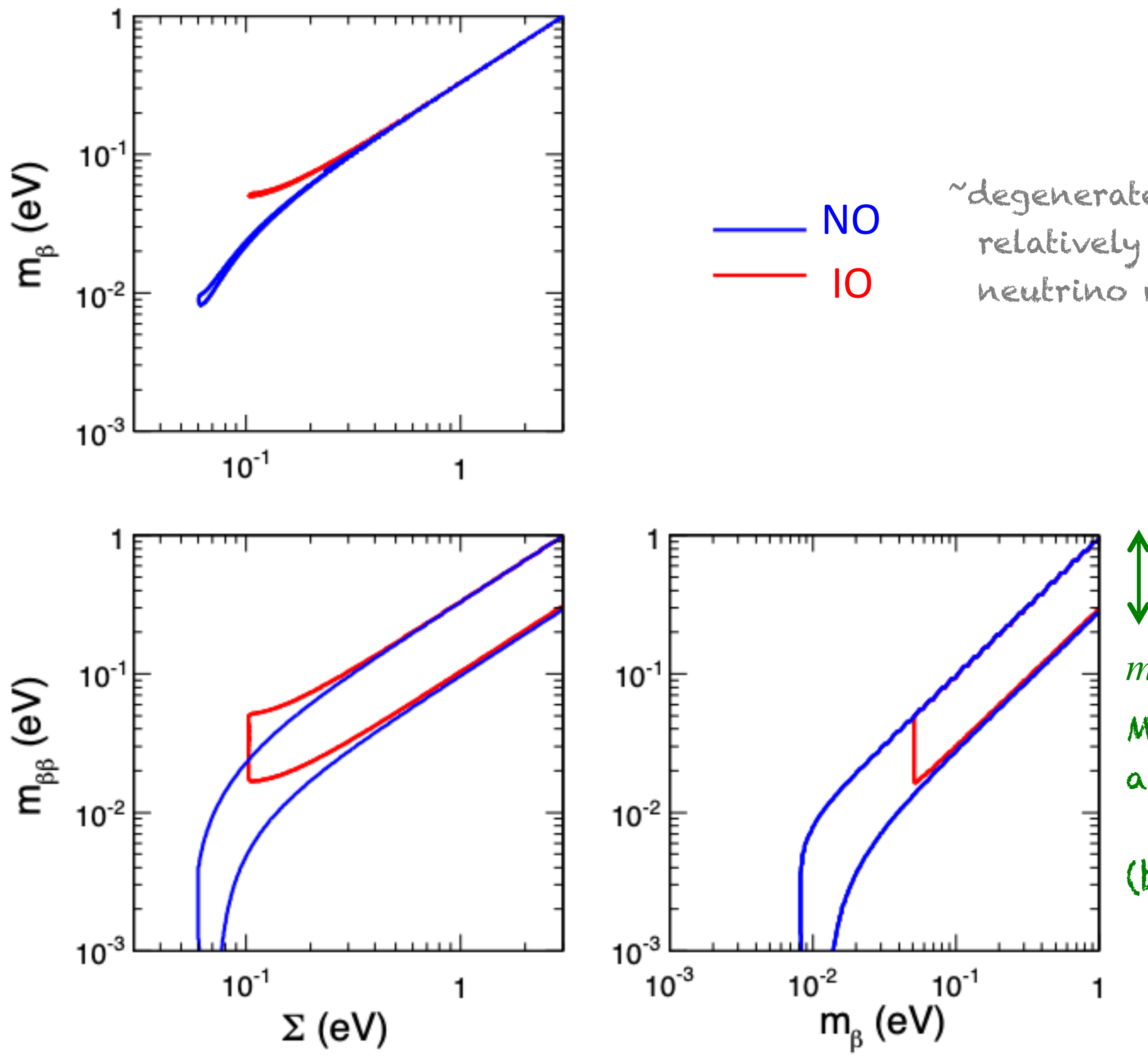


Note 1: These observables may provide handles to distinguish NO/IO.

Note 2: Majorana case gives a new source of CPV (unconstrained)

Note 3: The three observables are correlated by oscillation data->

Impact of oscillations on nonoscillation parameter space

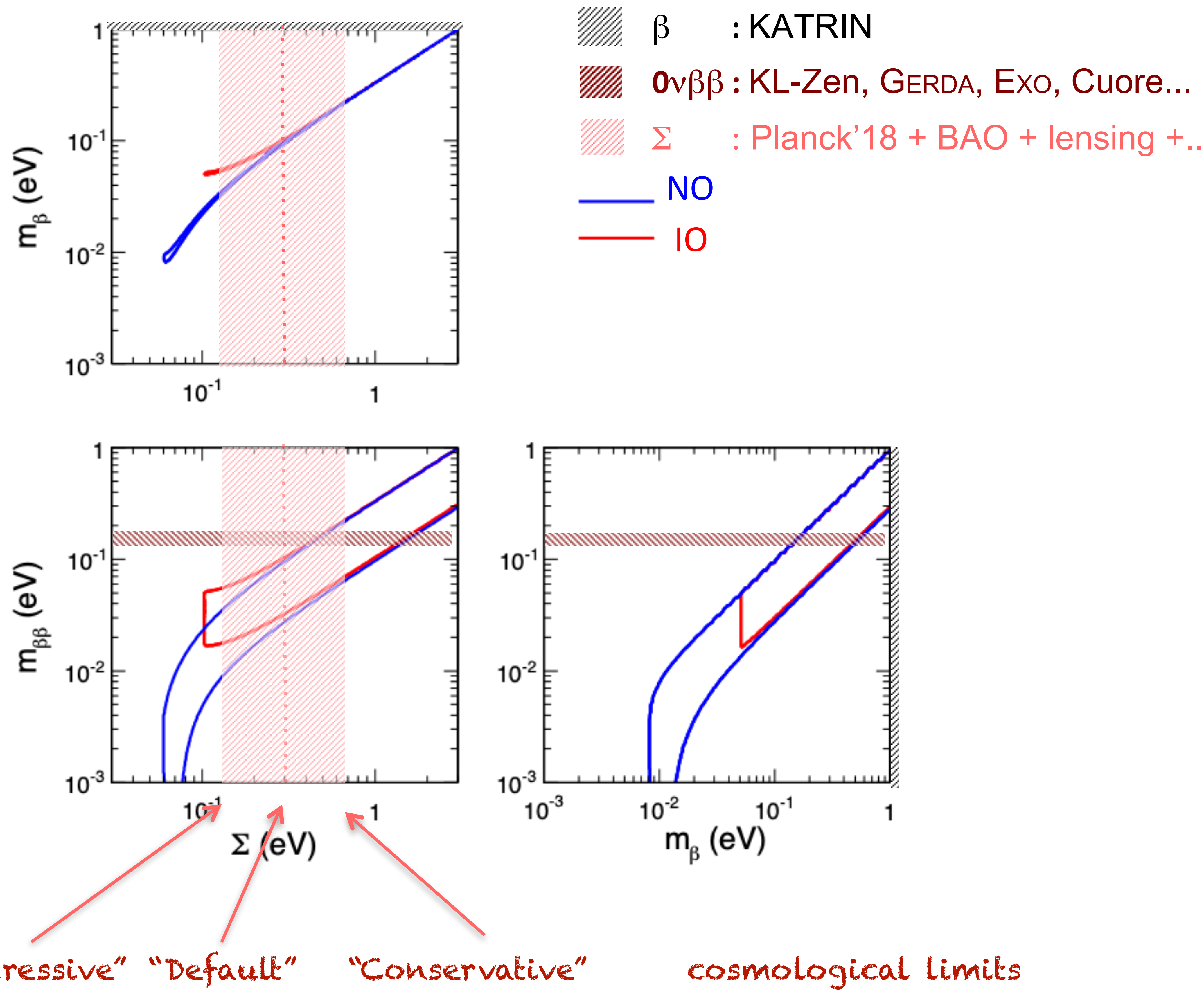


~degenerate for relatively large neutrino masses

$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(but: no NME errors included here!)

No signal (yet) but upper limits on $(m_\beta, m_{\beta\beta}, \Sigma)$ (up to some syst.)



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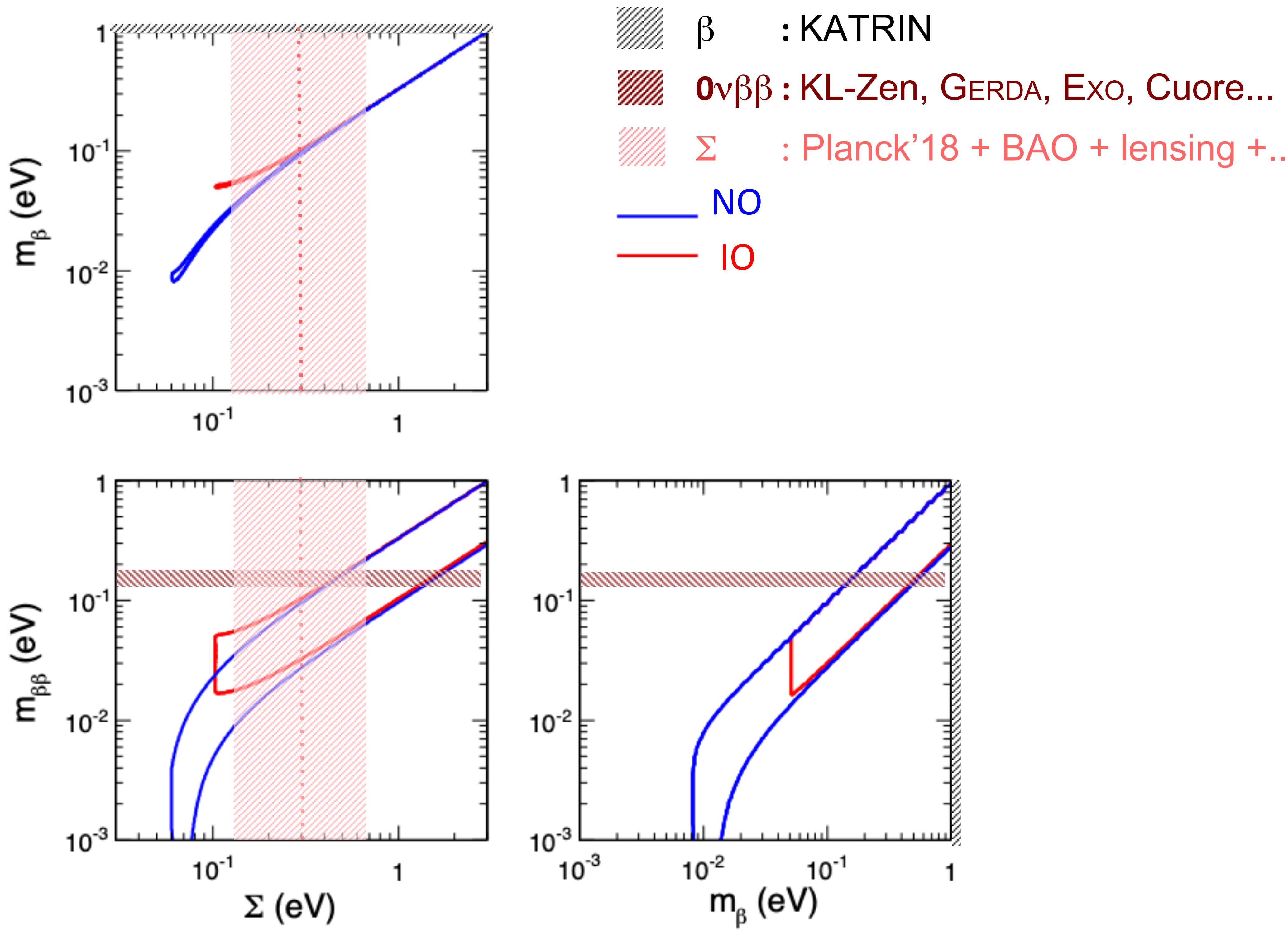
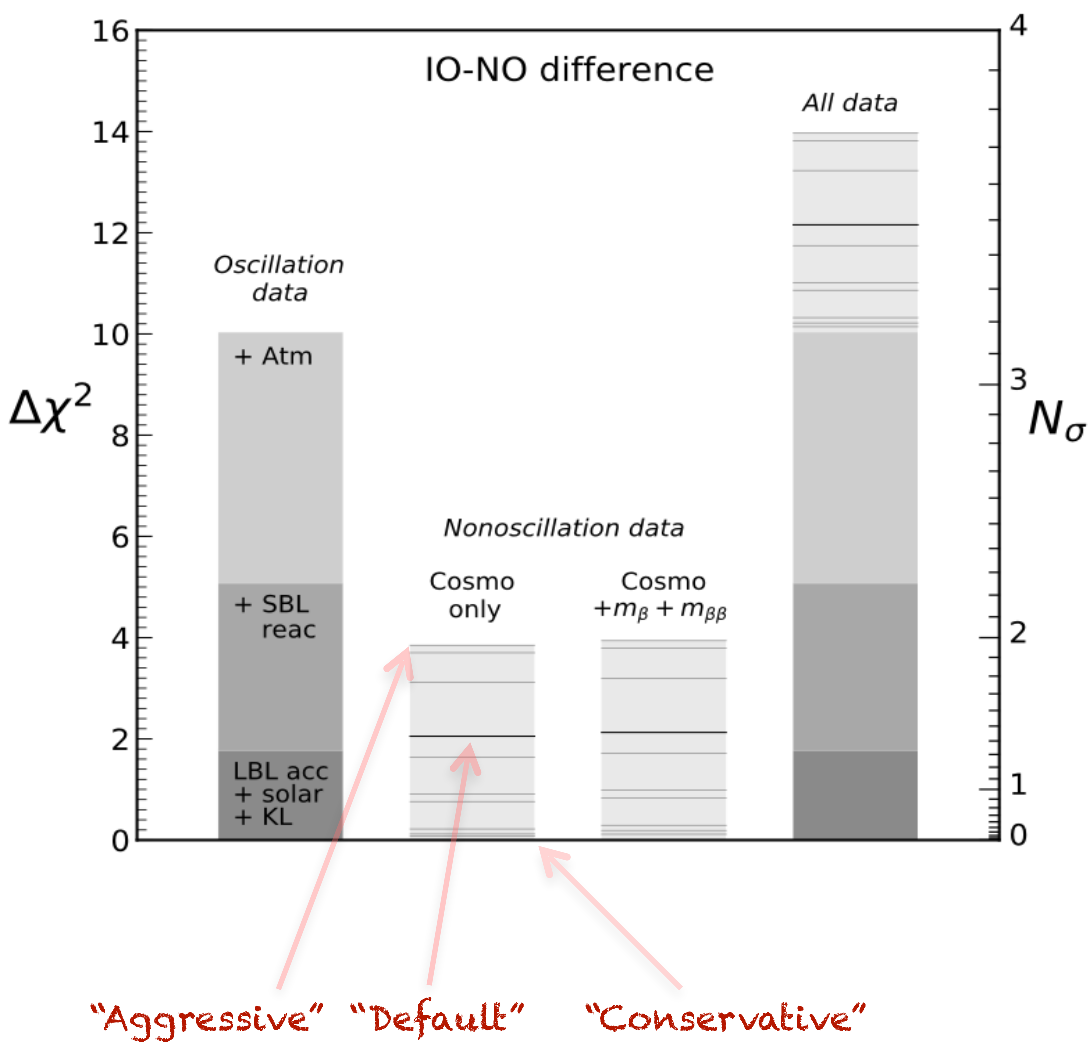


Cosmo data constrain masses and generally put IO "under pressure" ->

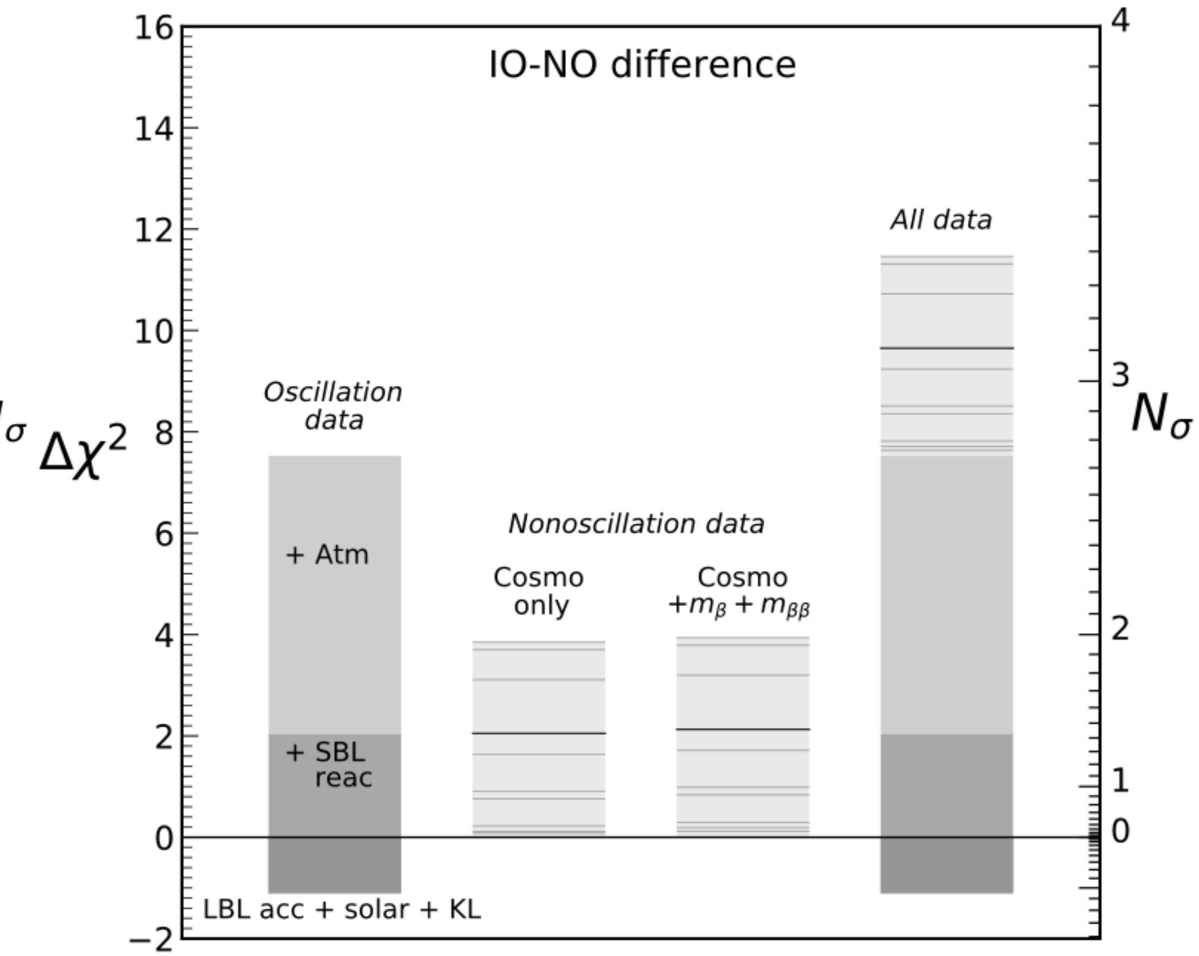
Impact of cosmology on global oscillation fit w.r.t. IO-NO difference

(envelope of conservative, default, aggressive case = horizontal lines)

arXiv:2003.08511 (pre v2020)



Update for this talk, NEUTEL 2021



Cosmo data may add from ~ 0 to $\sim 0.7\sigma$ to the 2.7σ oscillation preference for NO

-> overall typical $\sim 3\sigma$ hint for NO vs IO

Update of cosmological bounds with latest cosmo data: work in progress with E. Di Valentino and A. Melchiorri.

Conclusions

Three-neutrino mixing framework well established

Accuracy on $(\theta_{13}, \theta_{12}, \theta_{23}, \delta m^2, \Delta m^2)$ at few percent level

Now weaker hints about Mass Ordering,
CP violation and θ_{23} octant

-> partly due to the T2K-NOvA tension

Thank you for your attention

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