11TH WORKSHOP

FLASY

ROME 2025

Flavor Symmetries and Consequences in Accelerators and Cosmology

Global 3-neutrino analysis 2025: Knowns and unknowns

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Based on Capozzi+, arXiv:2503.07752, PRD 111 (2025) 9, 093006

Neutrino masses and mixing: Entering the era of subpercent precision

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Contains various new oscillation and nonoscillation inputs after our previous global analysis 2107.00532

OUTLINE:

- Intro and remarks on JUNO
- Current results from oscillation data
- Impact of possible “first year” JUNO results
- Current results from nonoscillation data
- Conclusions

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3ν status (1 digit)

5 knowns:

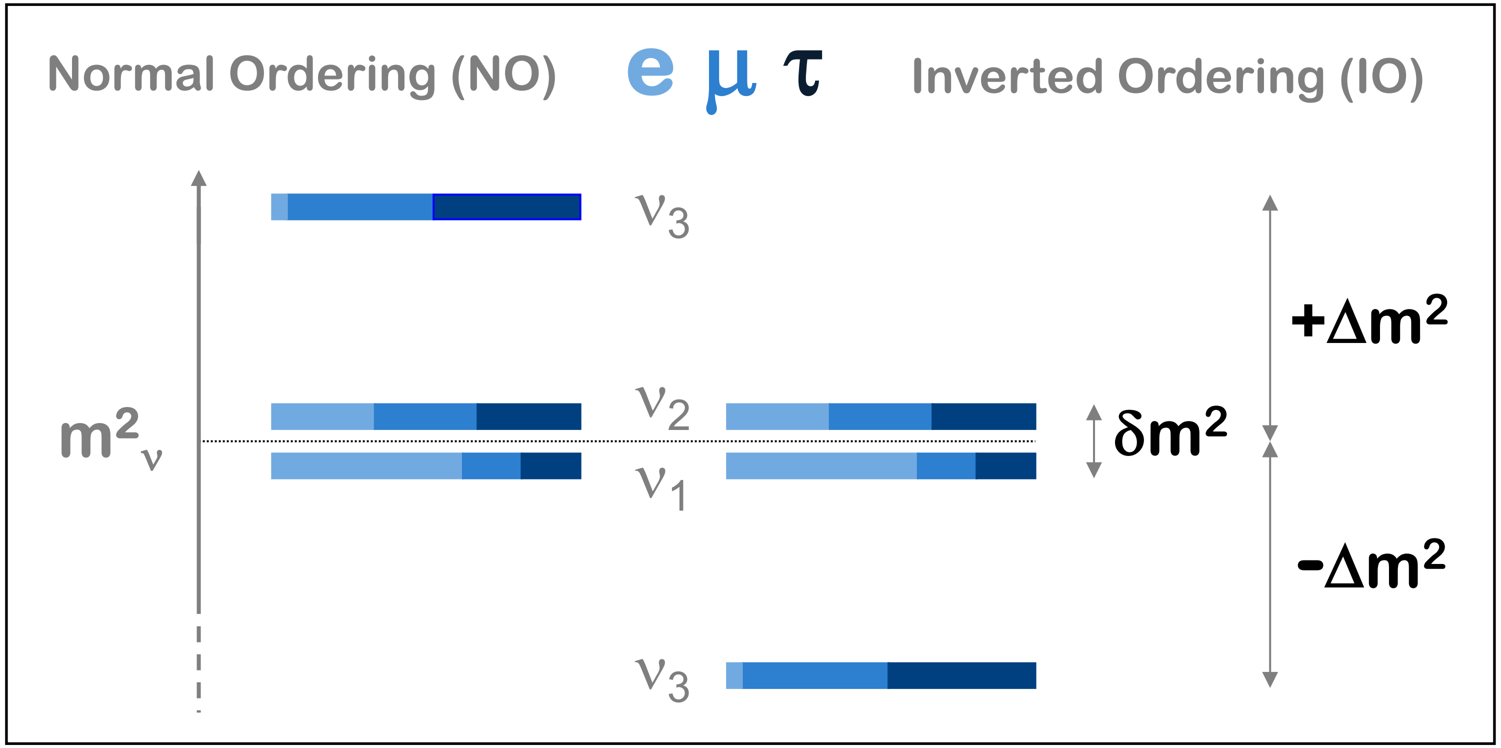
- $\delta m^2 \sim 7 \times 10^{-5}$ eV^2
- $|\Delta m^2| \sim 2 \times 10^{-3}$ eV^2
- $\sin^2\theta_{12} \sim 0.3$
- $\sin^2\theta_{23} \sim 0.5$
- $\sin^2\theta_{13} \sim 0.02$

(all: *Oscillations*)

5 unknowns:

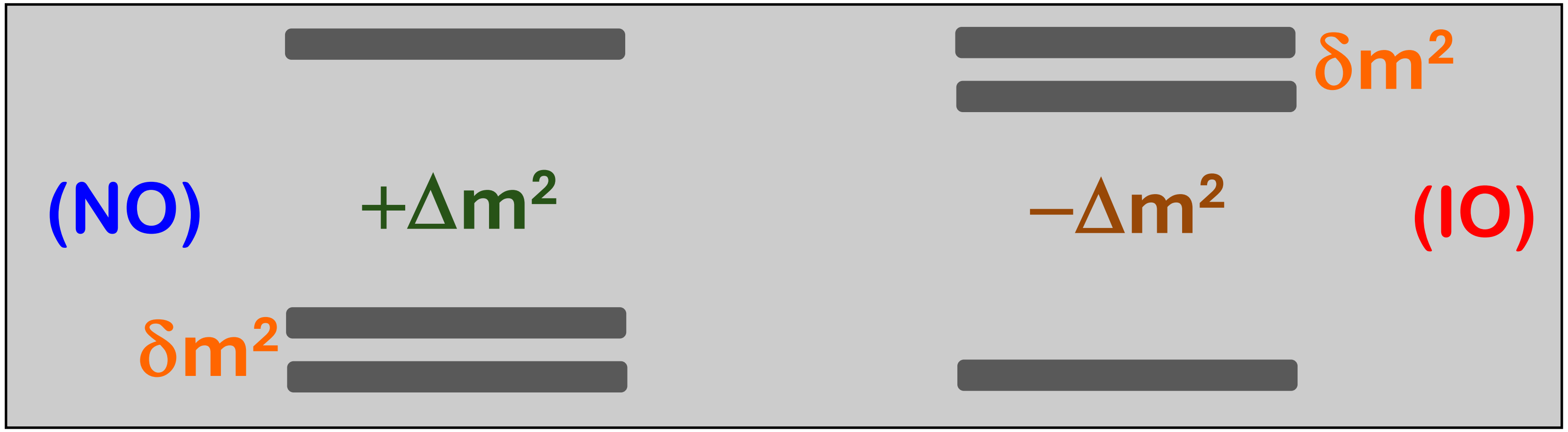
Oscillations:
- δ **CPV** Dirac phase
- **sign(Δm^2)** → NO/IO
- θ_{23} **octant** degeneracy

Non-oscillat.:
- **absolute mass** scale
- **Dirac/Majorana** nature



Each known parameter probed by at least two different kinds of experiments

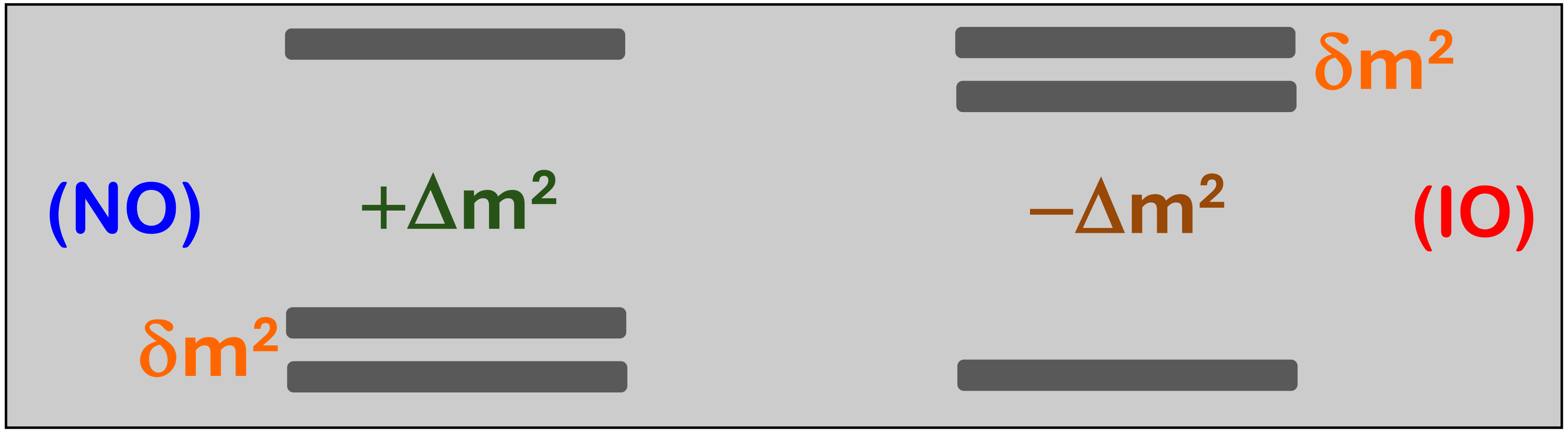
How do oscillation searches probe mass ordering?



Observe interference effects of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity Q with known sign. Options:

$Q \sim \delta m^2$	medium-baseline reac. → JUNO "standalone"
$Q \sim G_F N_e E$	ν–matter effects → atm & LBL accel. expt.
[$Q \sim G_F N_\nu E$	ν–ν collective effects → core-collapse SN]

How do oscillation searches probe mass ordering?



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Additional tool: SYNERGY of $|\Delta m^2|$ data from different experiments,
e.g. two or more $|\Delta m^2|$ data from reactor + accelerator + atmospheric
should converge better in the true ordering than in the wrong one

Our notation about mass^2 splittings (→ JUNO's frequencies)

$$\delta m^2 = \Delta m^2_{21}$$

>0 by convention

$$\Delta m^2 = (\Delta m^2_{32} + \Delta m^2_{31})/2$$

May be >0 or < 0

α = sign(Δm^2) = +1 (NO) or -1 (IO)

(NO or IO)

$$\Delta m^2_{ee} = |\Delta m^2| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$$

>0 by convention

(also in JUNO, see later)

$\Delta m^2_{ee} > 0$ consistent with JUNO's 1507.05613

Neutrino Physics with JUNO

$$P_{\bar\nu_e\to\bar\nu_e} = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \quad (2.1)$$
$$= 1 - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \phi)\right] - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21},$$

JUNO only:	What matters for **"JUNO standalone"** NO/IO discrimination is the relative sign $\alpha=\pm1$ between the dominant L/E oscillation phase $2\Delta_{ee}$ and the non-L/E phase ϕ (depending on δm^2). Timescale: 6-7 years?
JUNO +XYZ expt(s)	What matters for **"JUNO + XYZ synergy"** NO/IO discrimination is the better consistency between different measurements of Δm^2_{ee} in "true" ordering w.r.t. to "wrong" ordering. Timescale: O(1) yr?

- Intro and remarks on JUNO
- Current results from oscillation data
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Global analysis of oscillation data → Useful analysis sequence:

LBL Accel + Solar + KL (KamLAND)

minimal set sensitive to all osc. param. δm^2, Δm^2, θ_{13}, θ_{23}, θ_{12}, δ, NO/IO

LBL Accel + Solar + KL + SBL Reactor

add sensitivity to Δm^2, θ_{13} and affect other parameters via correlations

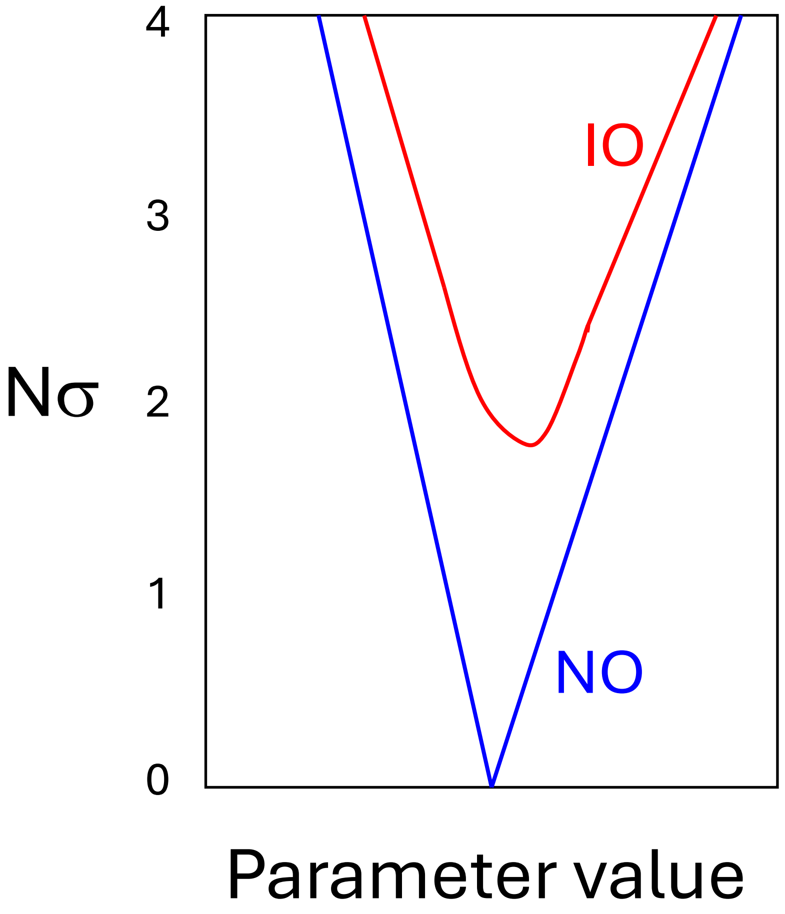
LBL Accel + Solar + KL + SBL Reactor + Atmosph.

add sensitivity to Δm^2, θ_{23}, δ, NO/IO (but: entangled information in atmos.)

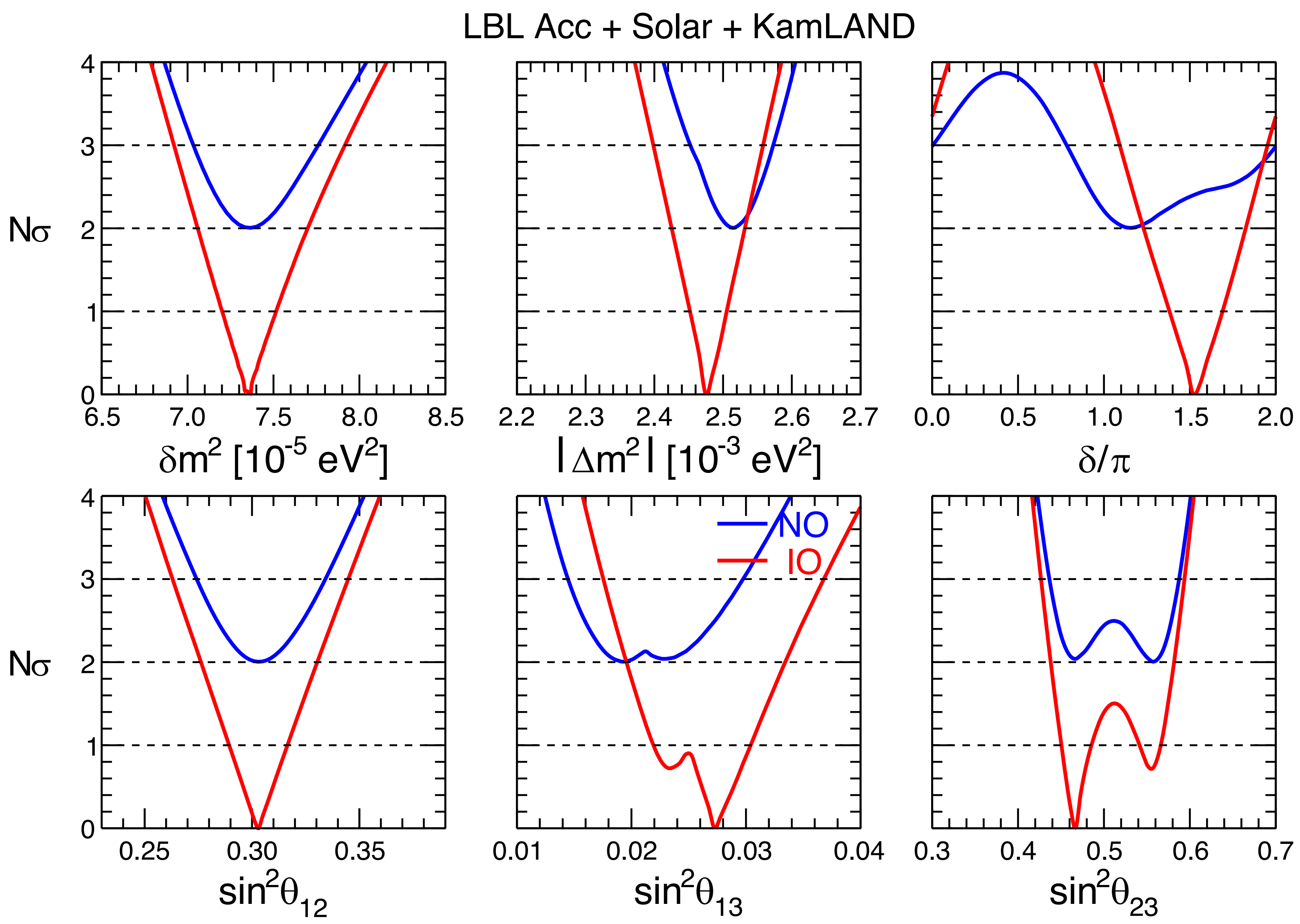
[Some "synergy effects" on NO/IO already showing up since several years…]

$\Delta\chi^2$ statistics adopted for all datasets: $N\sigma = \sqrt{\Delta\chi^2}$ →

E.g.,

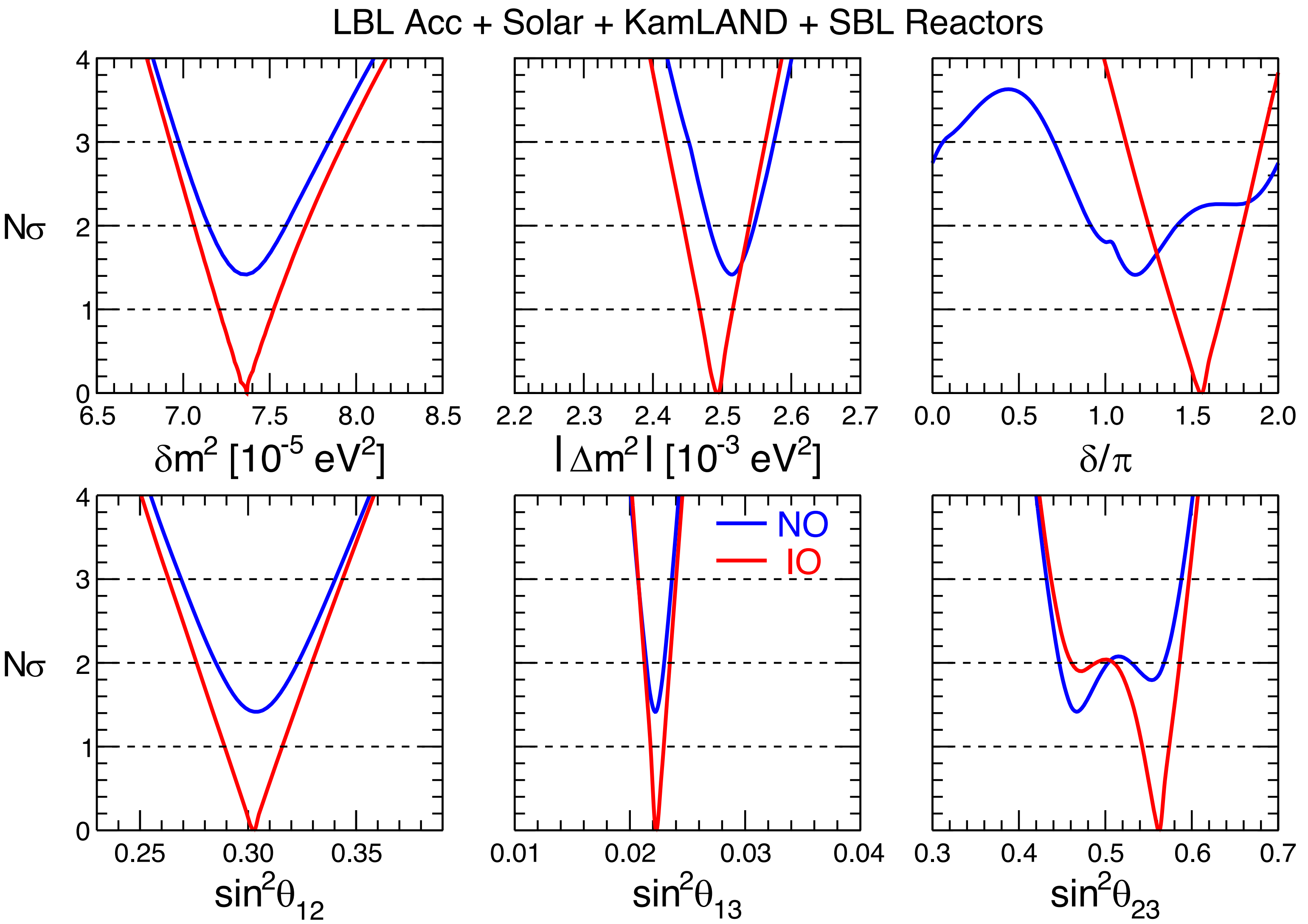


Best-fit "perfectly gaussian" errors would lead to linear and symmetric bounds



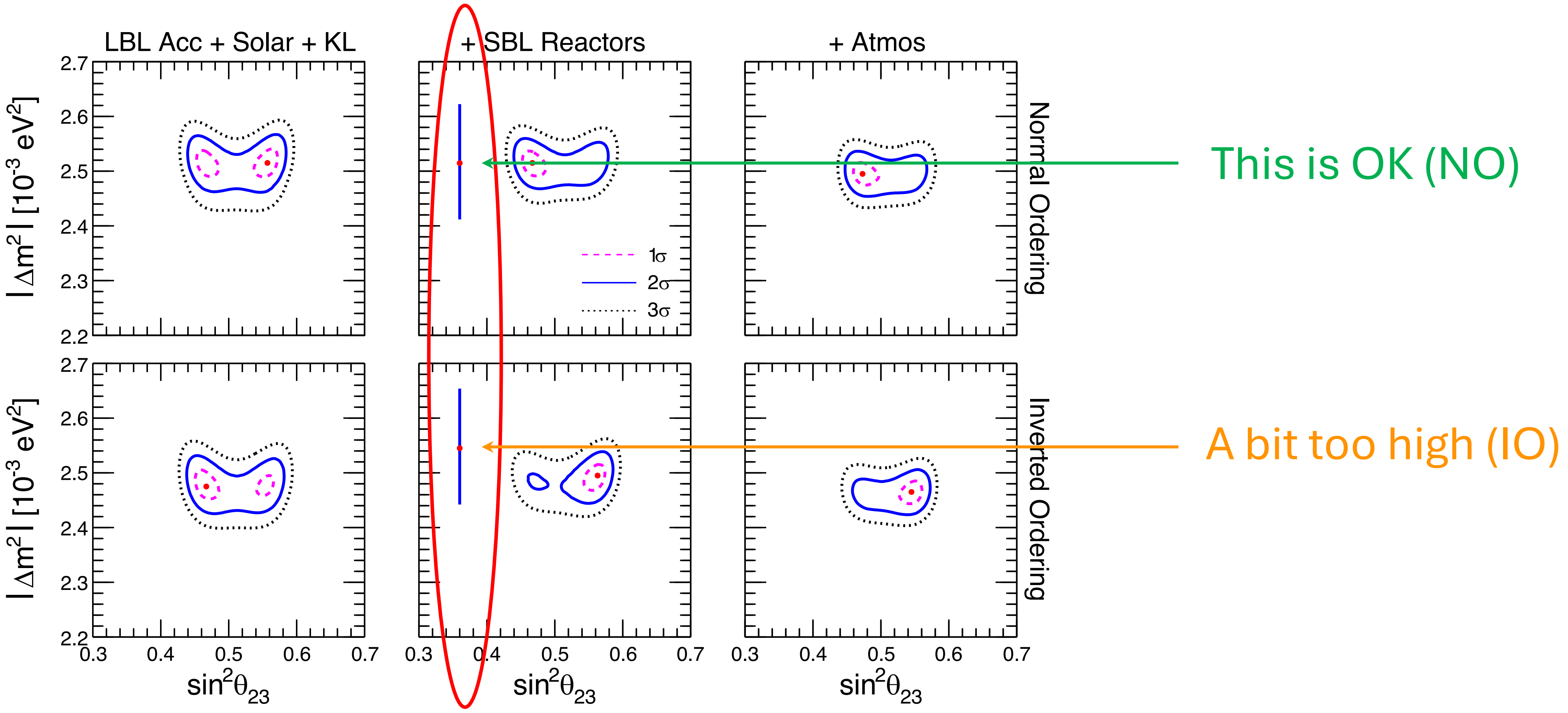
T2K and NOvA prefer NO separately, and IO in combination (at 2σ).

[Due to some tension]. **In IO, indications for CP violation > 3σ!**



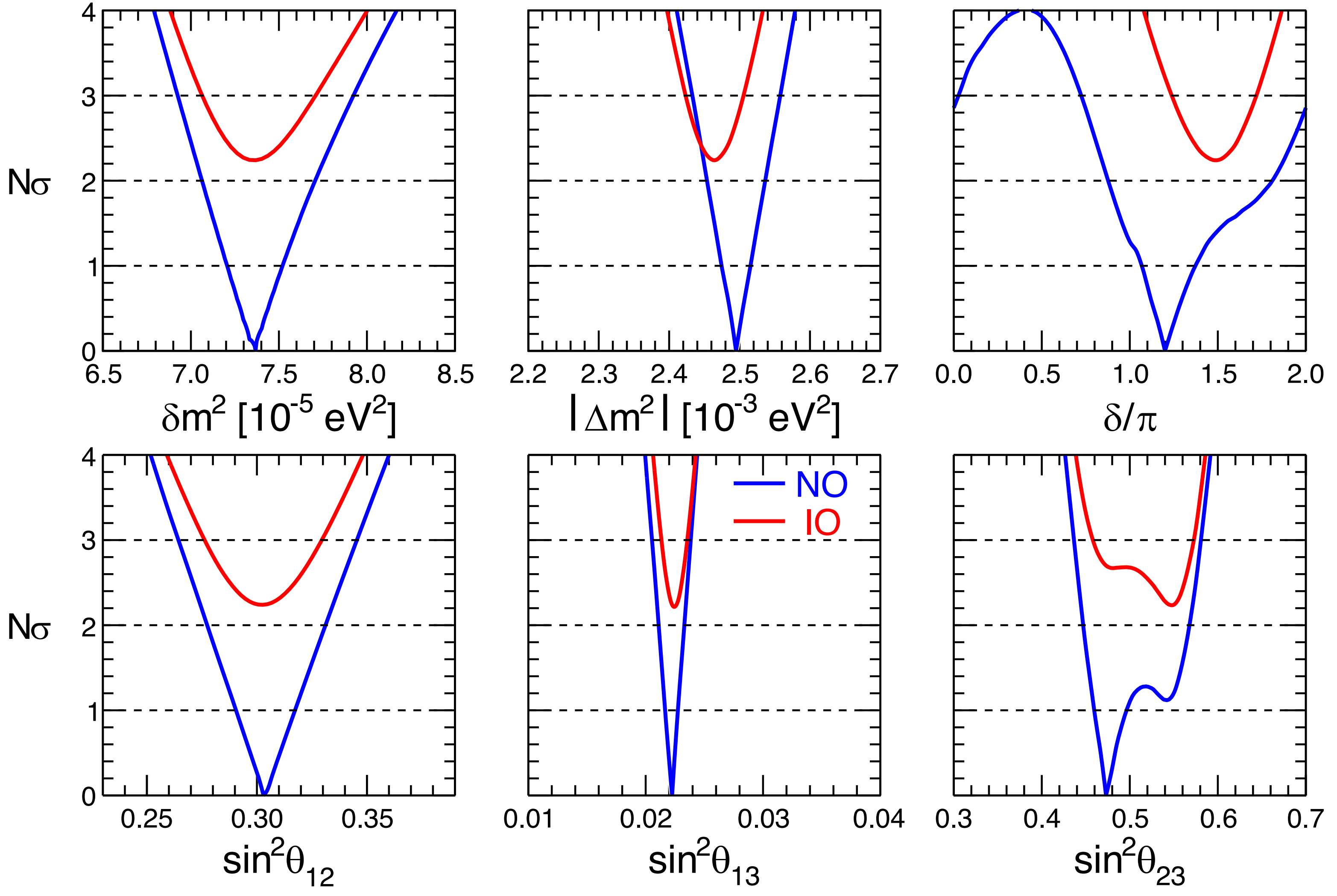
Adding SBL reactors: Still preference for IO, but at lower CL (~1.4σ). Reason →

Standalone SBL reactor measurement of Δm^2 is more synergic with LBL accel. in **NO** than in **IO**



In addition, reac+acc more synergic with atmospheric data in NO wrt IO →

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



ALL DATA: Including atmospheric (SK+IC), overall preference flips from IO to NO (~2.2σ).

In NO: rather weak hints for CPV (~1.3σ) and first octant (~1.1σ)

Overall status of oscillation unknowns is more uncertain than it used to be...

... while fractional accuracy of **known** parameters improved.

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

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

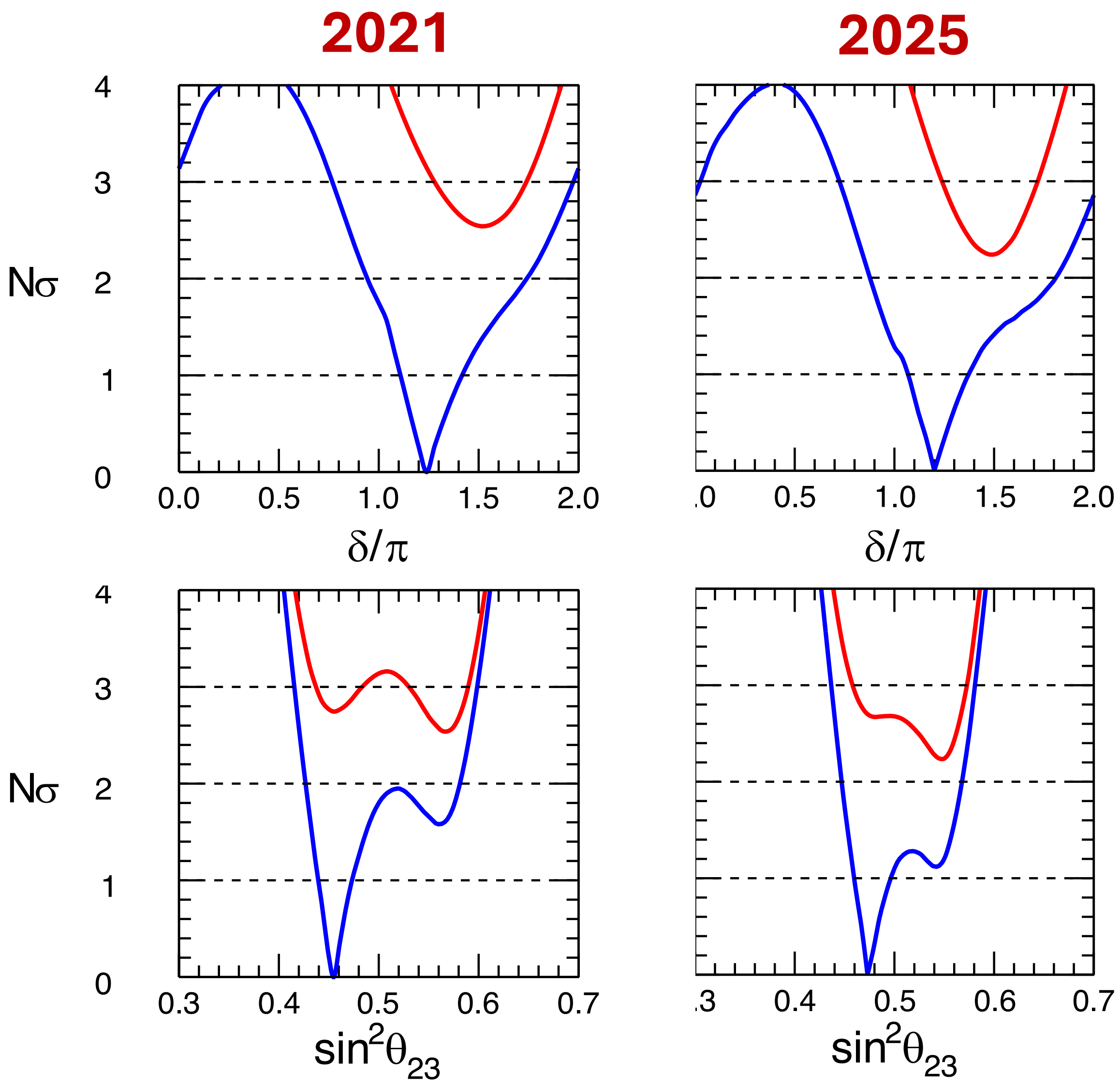
Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91 – 3.17	2.77 – 3.31	2.64 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475 – 2.515	2.454 – 2.536	2.433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

But there are reasons to be cautious about subpercent accuracy levels...

E.g., correlated effects of ν interaction uncertainties in different expts need improvement

As noted, oscillation **unknowns** are somewhat more uncertain than in the past...

All hints on CPV, NO/IO, and octant are a bit weaker



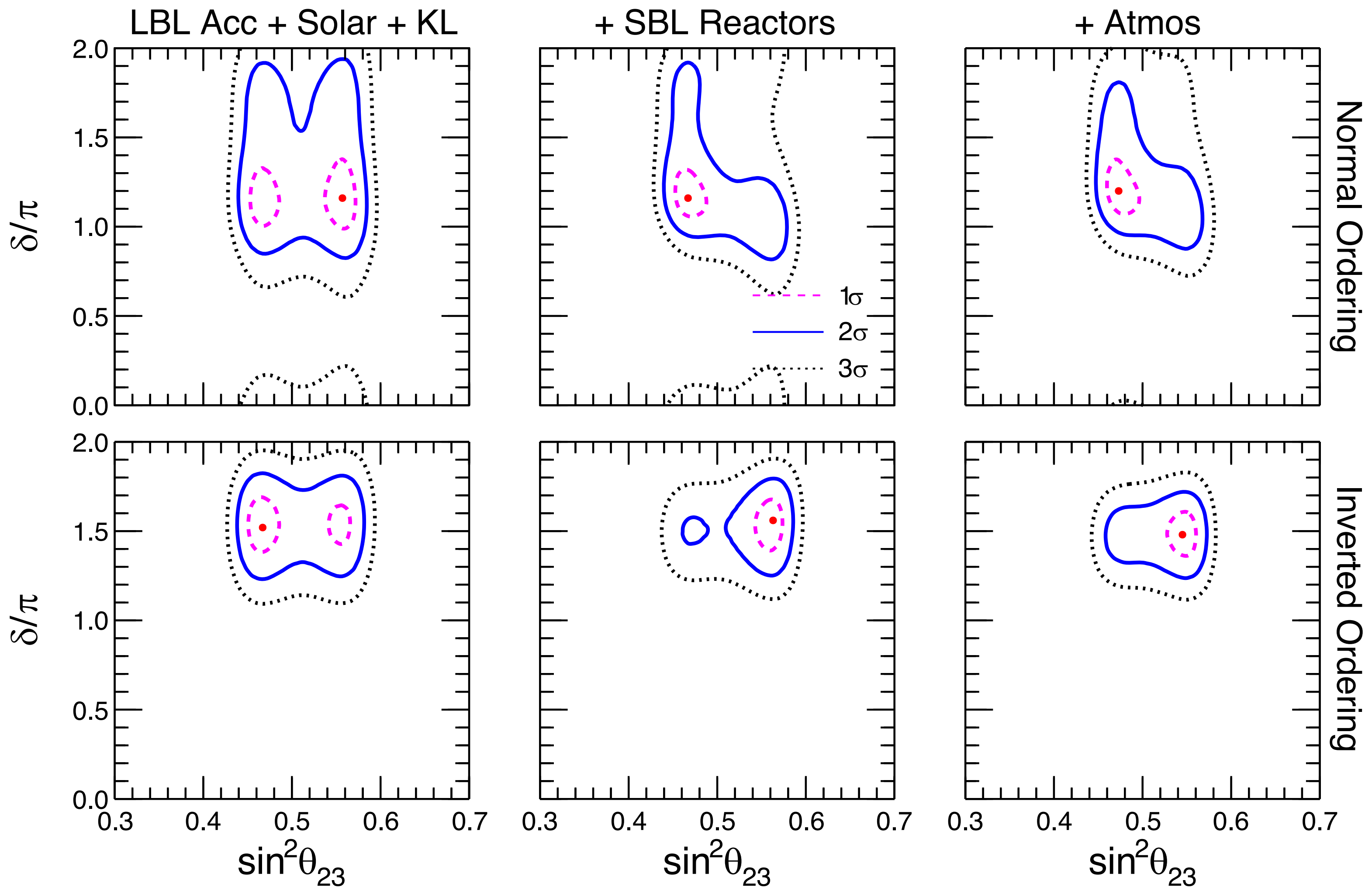
wrt 2021:

← 2025: Weaker hints for NO and CPV

← 2025: Closer and more degenerate octants

In NO will all data, note slight negative correlation among CP phase and octant (absent in IO).

→ Future data might affect the unknown parameters (NO/IO, CP phase, octant) in subtly correlated ways



Next: focus on future JUNO data and impact on NO/IO →

- Intro and remarks on JUNO
- Current results from oscillation data
- **Impact of possible “first year” JUNO results**
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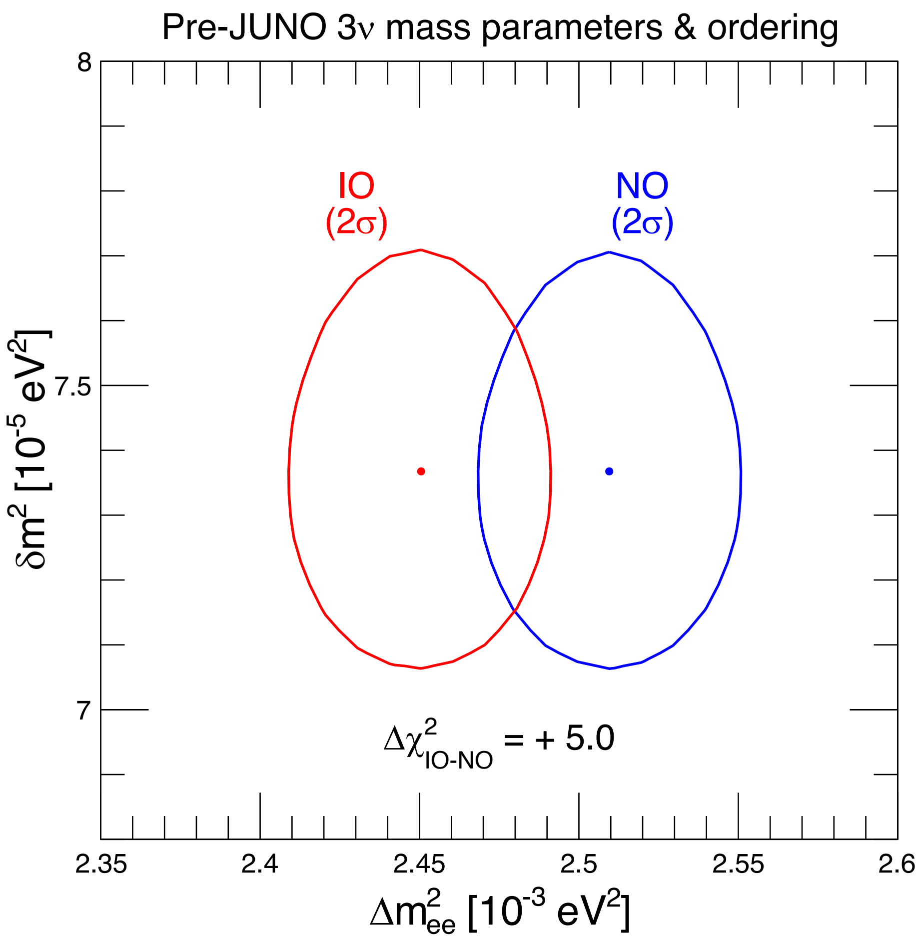
What do we know **in 2025** about the two JUNO oscill. frequencies?

2σ contours shown in IO/NO. Unlikely to change significantly before JUNO starts.



Let's discuss the qualitative impact of first JUNO data!

Here I shall freely elaborate wrt our paper 2503.07752

Note: Any measured JUNO event spectrum will lead to slightly displaced best fits for the two frequencies in NO and IO - see e.g. Capozzi+ 1508.01392:

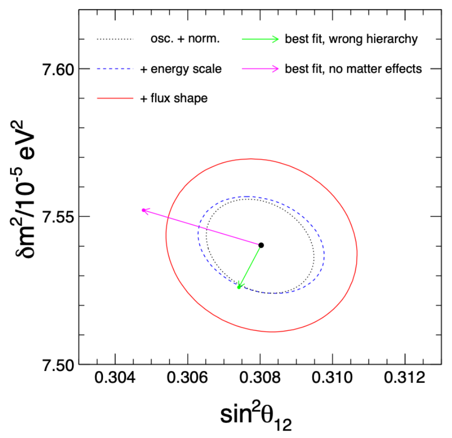


FIG. 16: As in Fig. 9, but with halved energy-scale and flux-shape uncertainties.

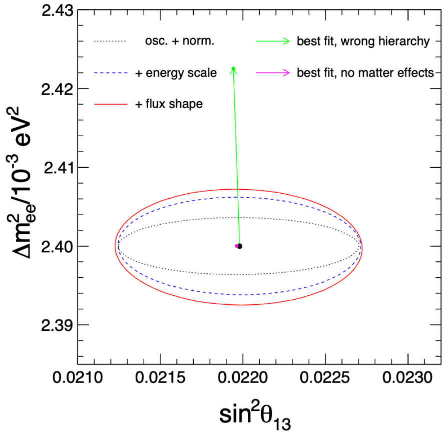


FIG. 17: As in Fig. 10, but with halved energy-scale and flux-shape uncertainties.

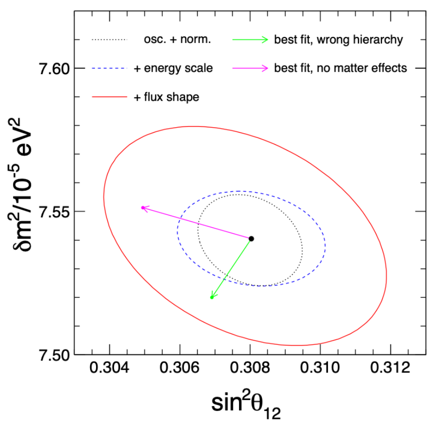


FIG. 9: Mass-mixing parameters (δm^2, s^2_{12}): 1σ contours for true NH and $T = 5$ y, as derived from fits including different systematic uncertainties. The arrows indicate the best-fit displacement in the cases of wrong hierarchy (green) and no matter effects (magenta).

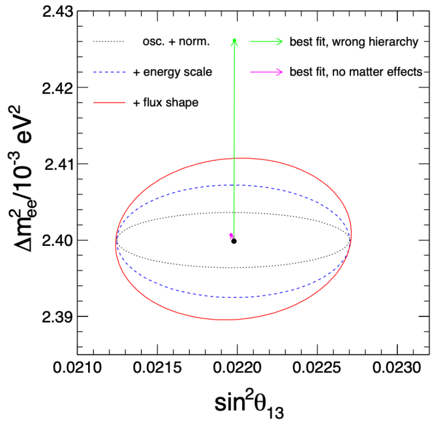


FIG. 10: As in Fig. 9, but for the (Δm^2_{ee}, s^2_{13}) parameters.

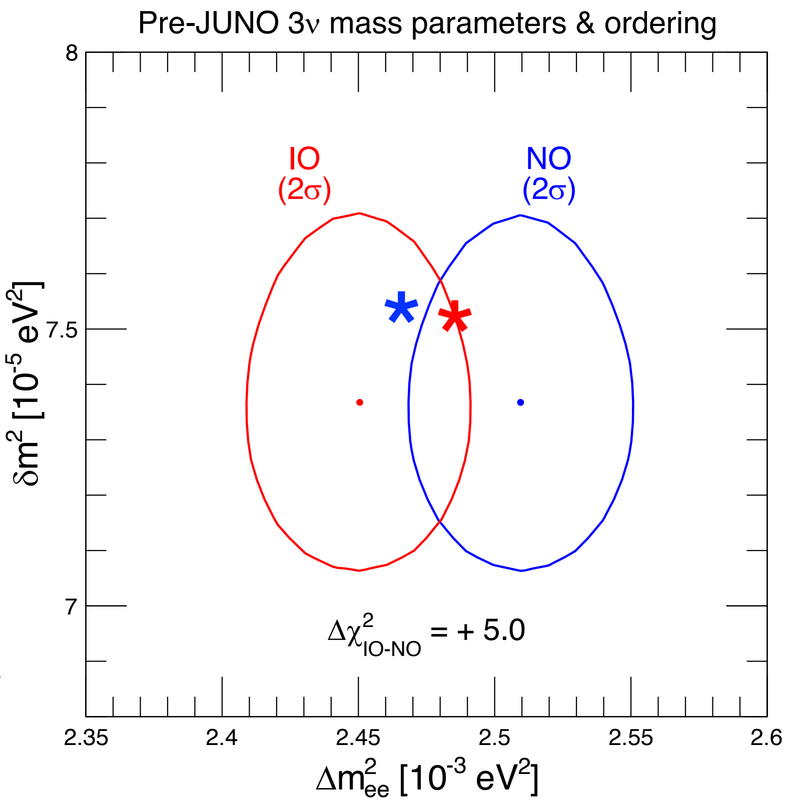
Green arrows: shifts of best fits when passing from NO to IO assumption.

Shift of Δm^2 discussed in many papers. Specific value(s) depend little on fit details.

For a given event spectrum,
typical "relative displacement" between
JUNO best fits in NO (*) and IO (*) looks like this:

Note: relative shift between JUNO best-fit points is "opposite" to pre-JUNO best-fits. Adds to synergy! [Discussed at length in the literature, e.g. by Parke et al.]

NO/IO best fits difference might be initially "blurred" by statistical fluctuations, but will eventually become evident with higher exposure.

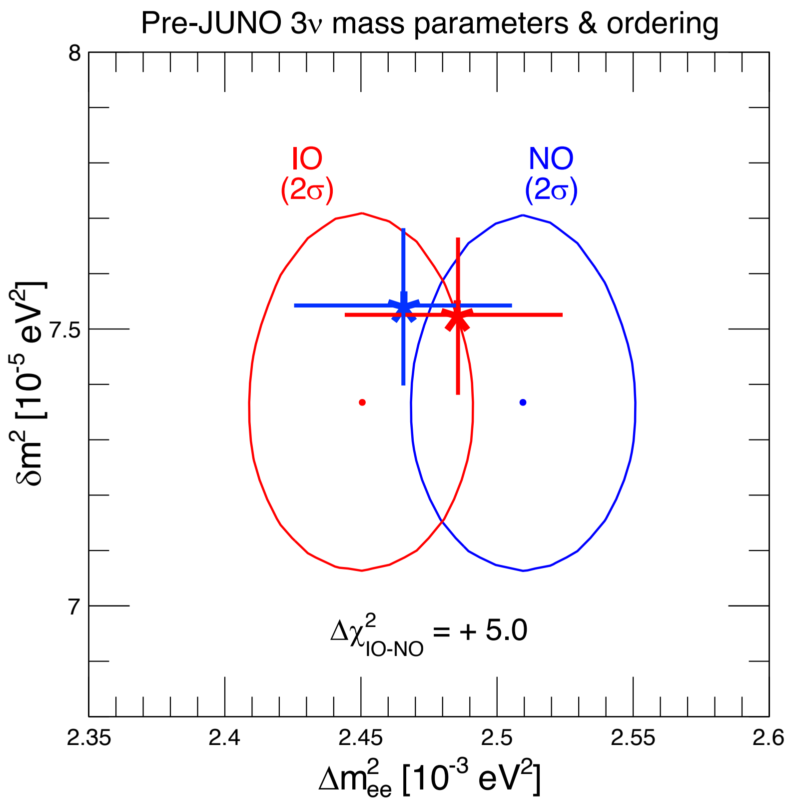


Concerning **error bars** (chosen at 2σ CL in this figure), let's assume for definiteness the 100-day error estimates from JUNO's 2204.13249...

δm^2 error (2σ) ~ 0.15×10^{-5} eV^2

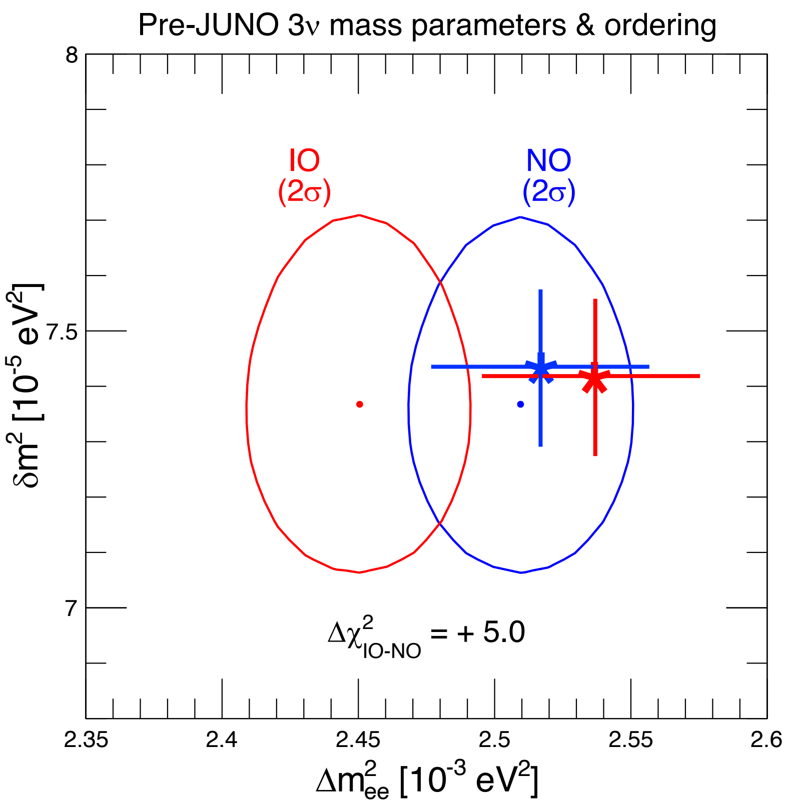
Δm^2 error (2σ) ~ 0.04×10^{-3} eV^2

... and examine possible outcomes!



Examples of possible JUNO outcomes wrt pre-JUNO data:

A synergy favoring NO



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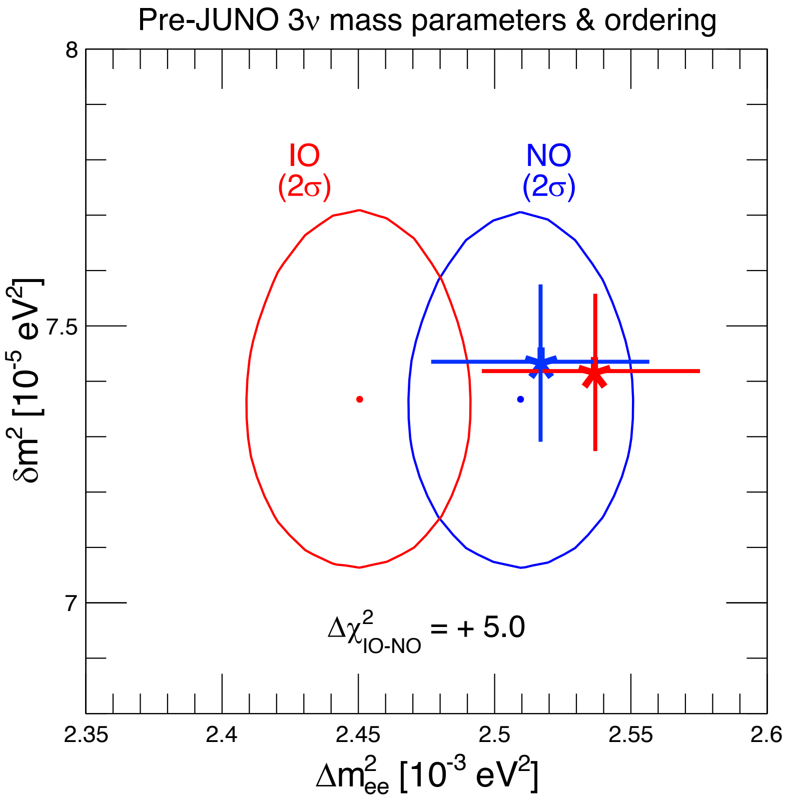
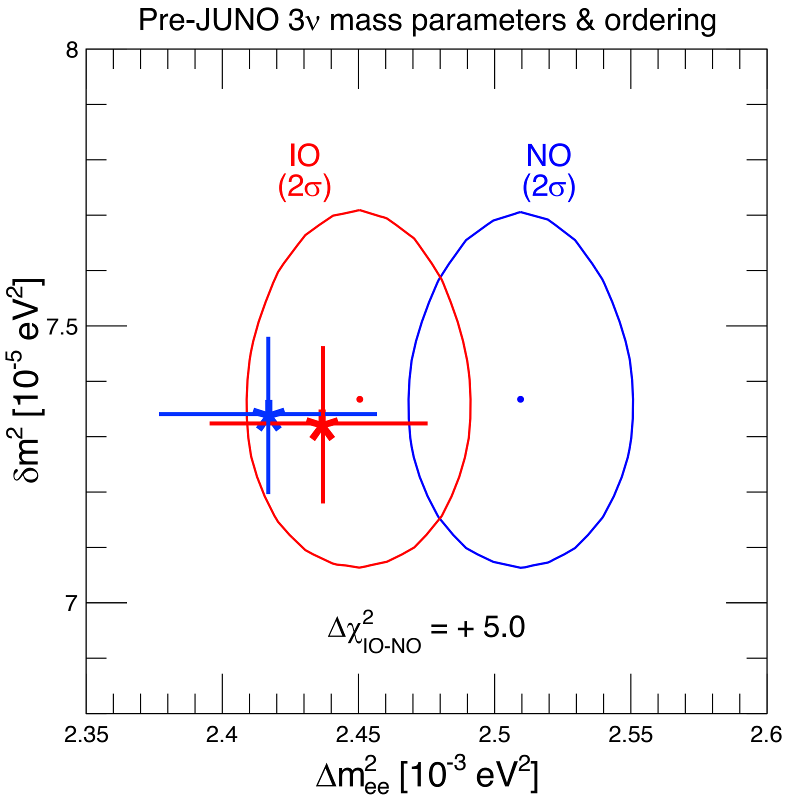


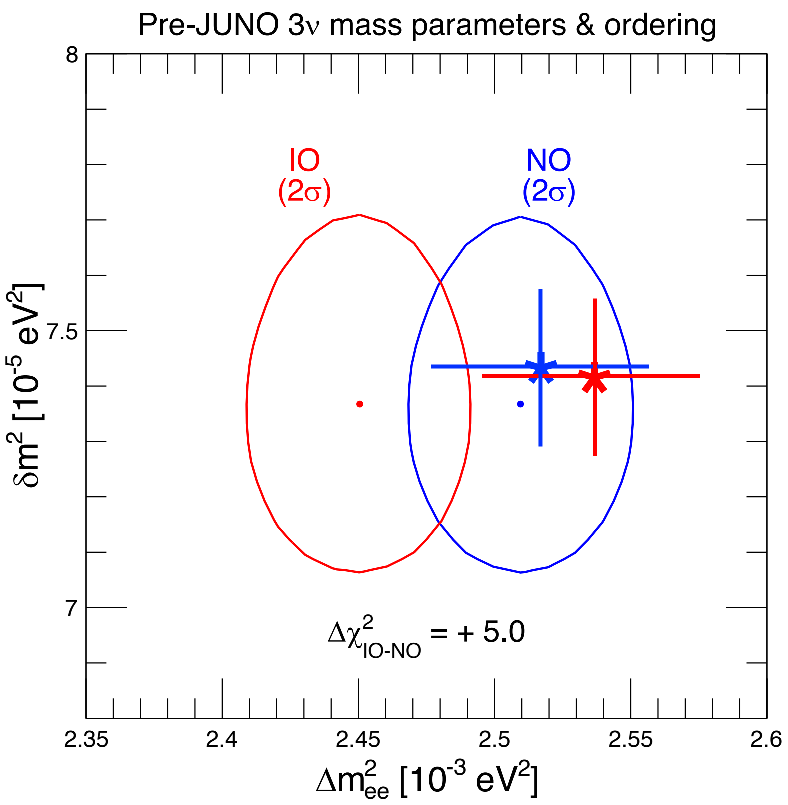
A synergy favoring IO



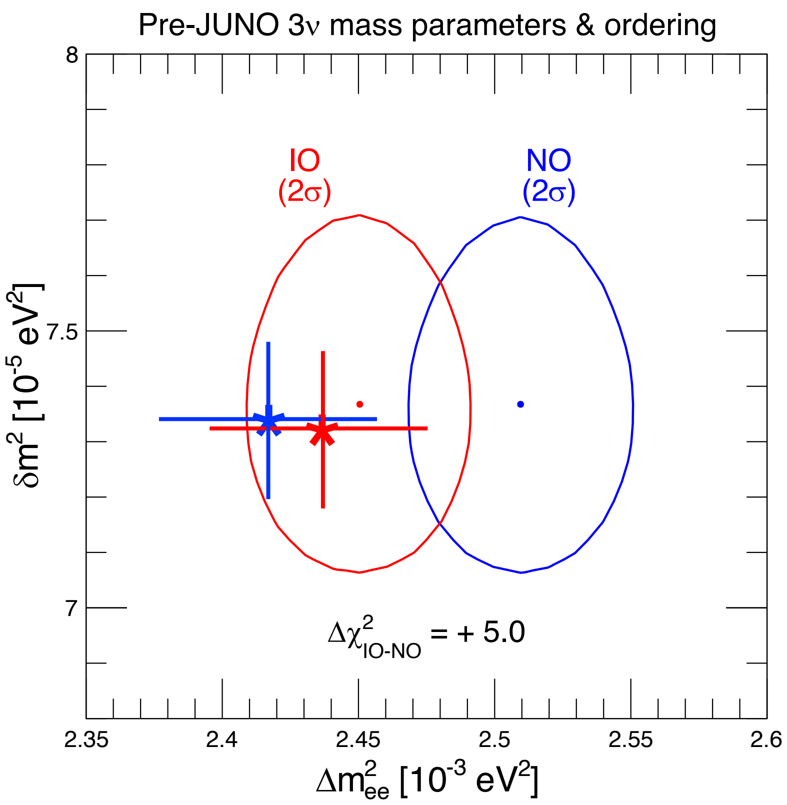
[But what about current NO favored...?]

Examples of possible JUNO outcomes wrt pre-JUNO data:

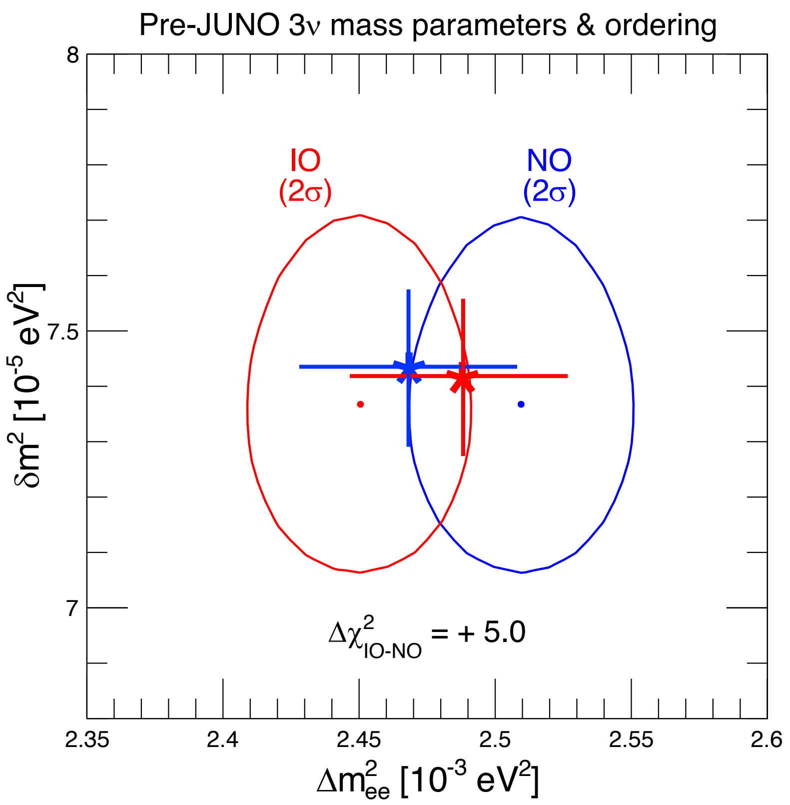
A synergy favoring NO



A synergy favoring IO



An undecided NO/IO...



Examples of possible JUNO outcomes wrt pre-JUNO data:

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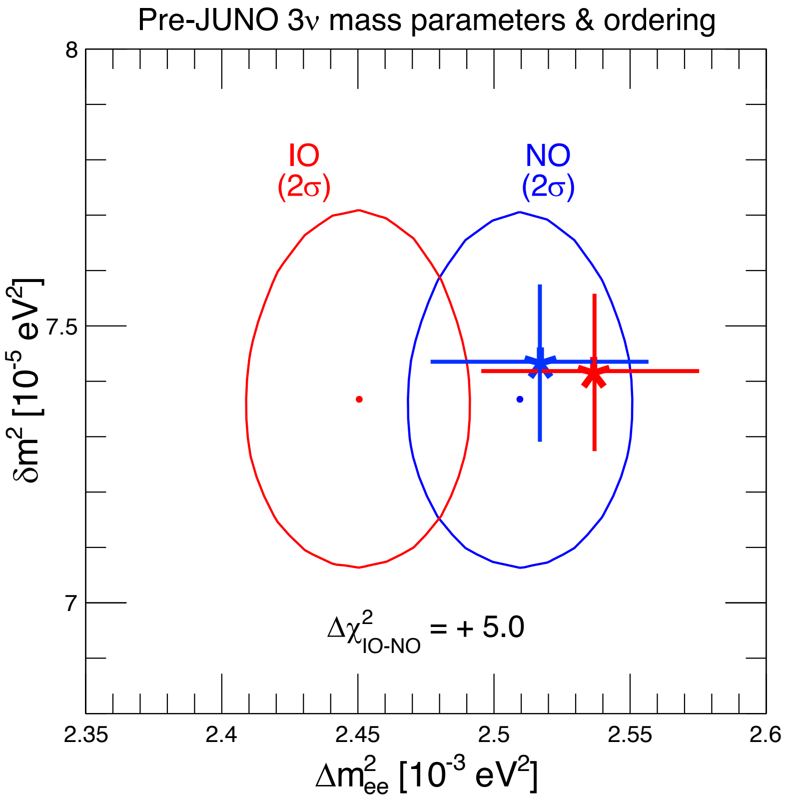
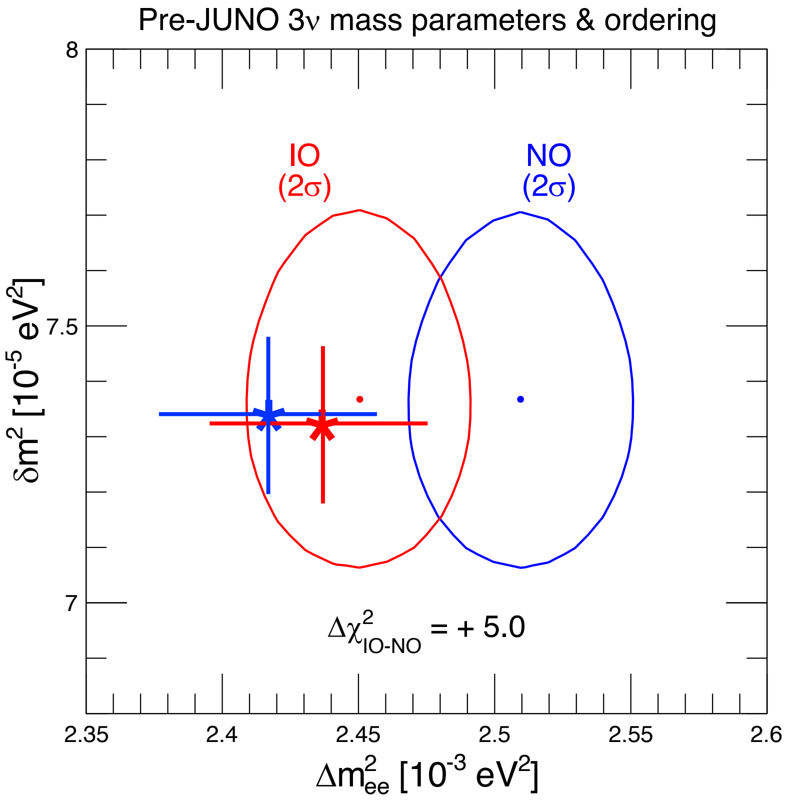
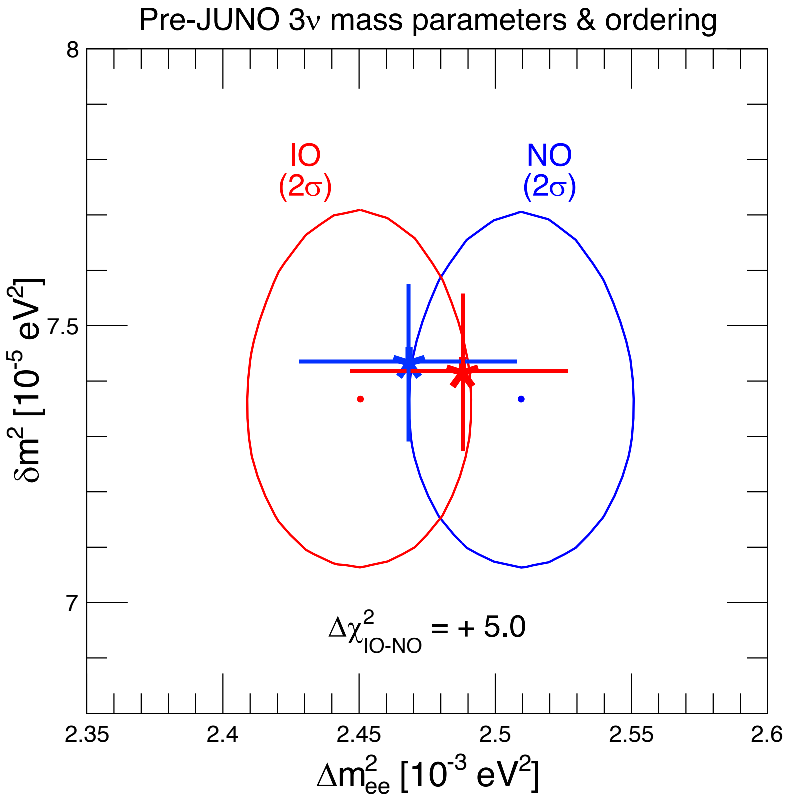


A synergy favoring IO

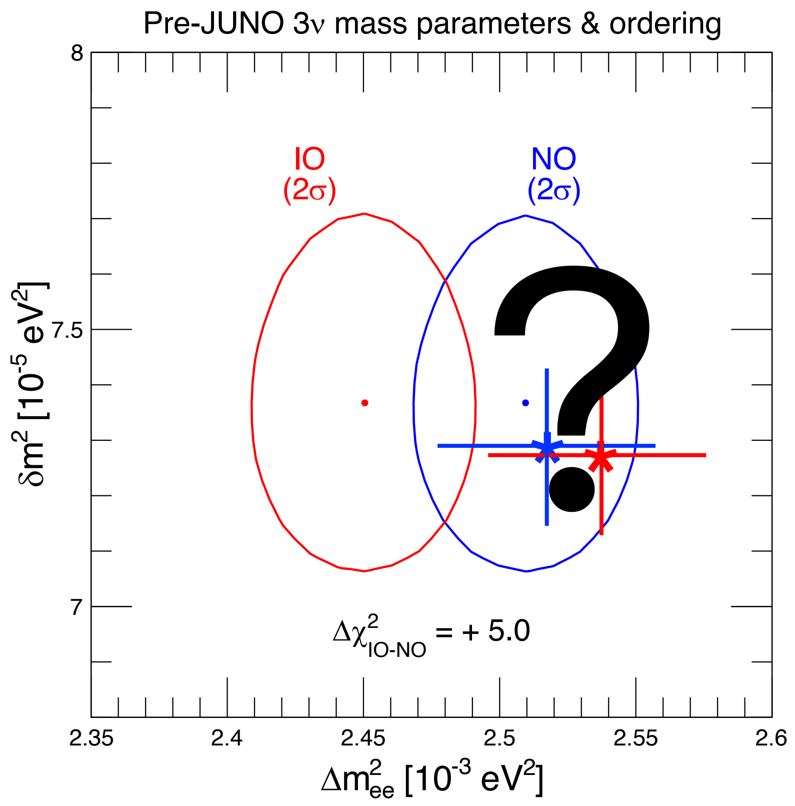


An undecided NO/IO?...



... as said, with cascade (correlated) effects on the other oscillation unknowns -difficult to be anticipated!

So, it will be very interesting to see where first JUNO data will fall in this plane...
and, in the long term, compare with (convergent?) JUNO standalone results on NO/IO



New global analyses will be mandatory to understand correlated impact on other param's!

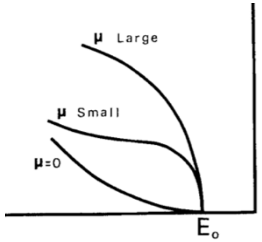
- Intro and remarks on JUNO
- Current results from oscillation data
- Impact of possible “first year” JUNO results
- Current results from nonosc. data (if time allows!)
- Conclusions

Absolute neutrino mass observables: (m_β , $m_{\beta\beta}$, Σ)

Probe absolute neutrino masses in different ways
May provide extra handles to distinguish NO vs IO

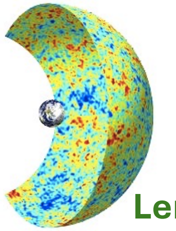
β decay (kinematics) - Sensitive to the "effective electron neutrino mass":

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



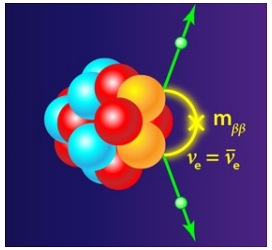
Cosmology (gravity) - Dominantly sensitive to sum of neutrino masses:

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

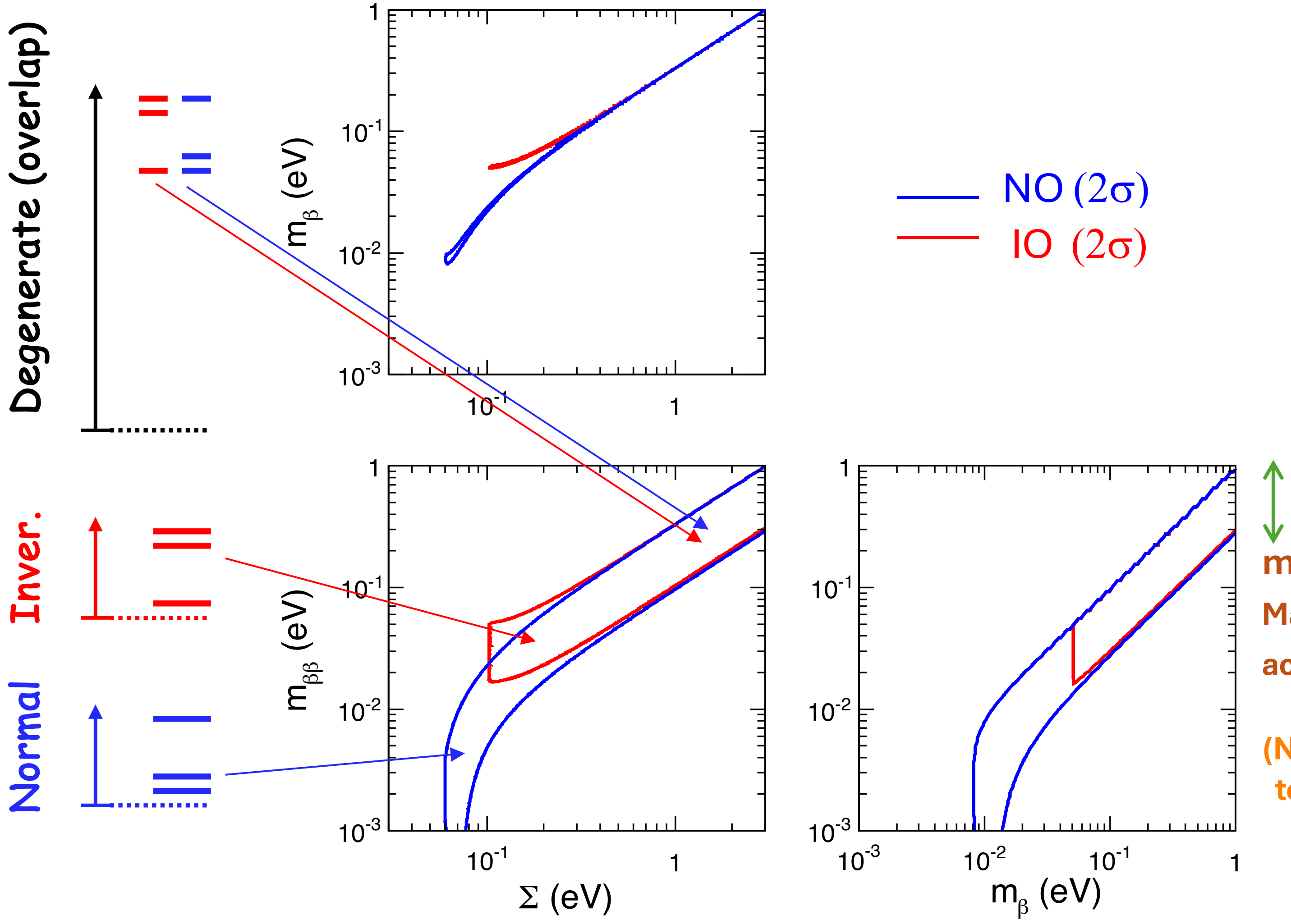


0νββ decay: only if Majorana. "Effective Majorana mass" (+new CPV phases):

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



(m_β , $m_{\beta\beta}$, Σ) observables: bands allowed by oscillations in NO/IO

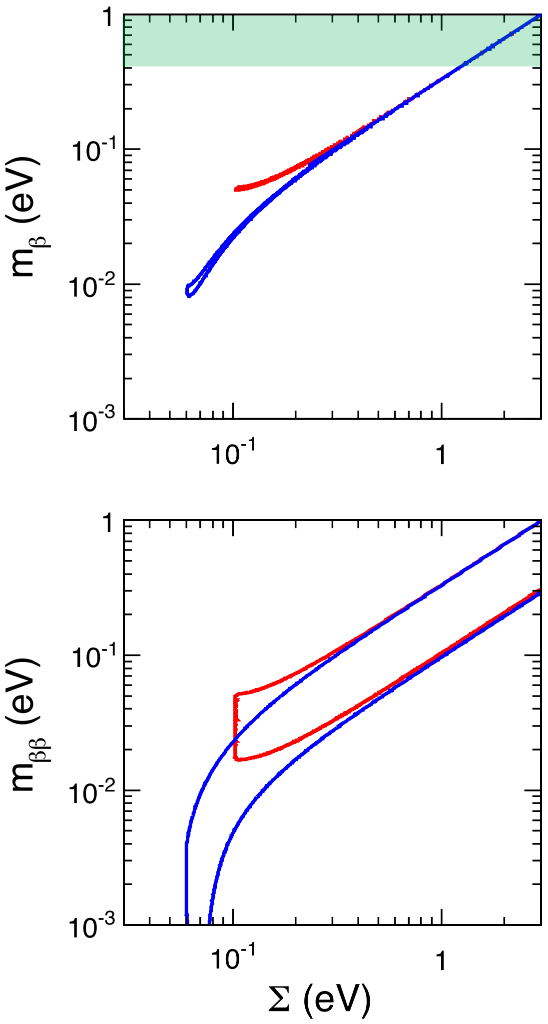


$m_{\beta\beta}$ spread due to Majorana CP phase(s): accessible in principle

(NME uncertainties to be considered...)

β: KATRIN

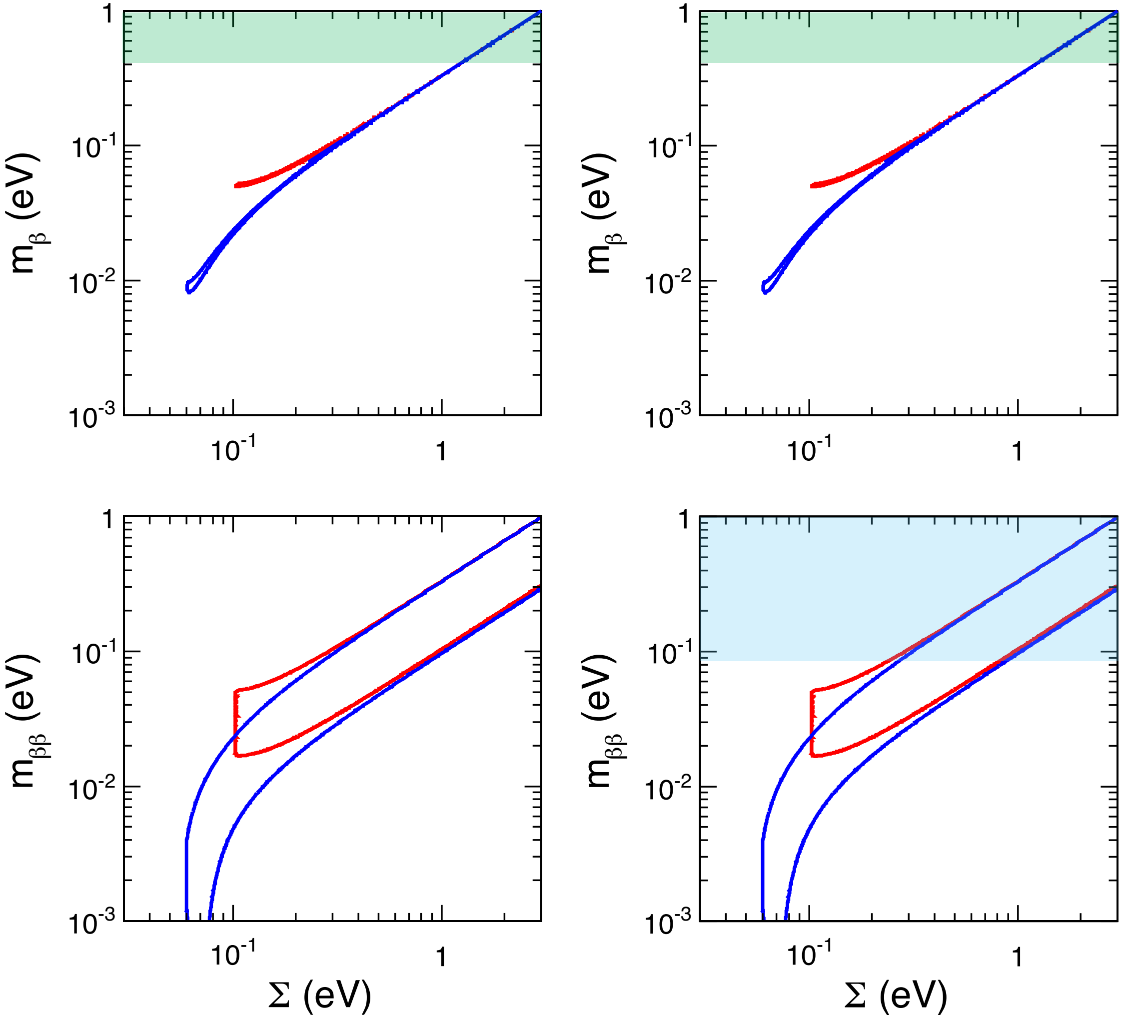
← **No signal so far. Current upper bounds from β decay**



β: KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

[+ nuclear model uncert.]



← **Current upper bounds from 0νββ decay including correlated NME uncertainties**

Cosmology: data tensions in the standard ΛCDM model

Possible systematics (e.g., lensing?)

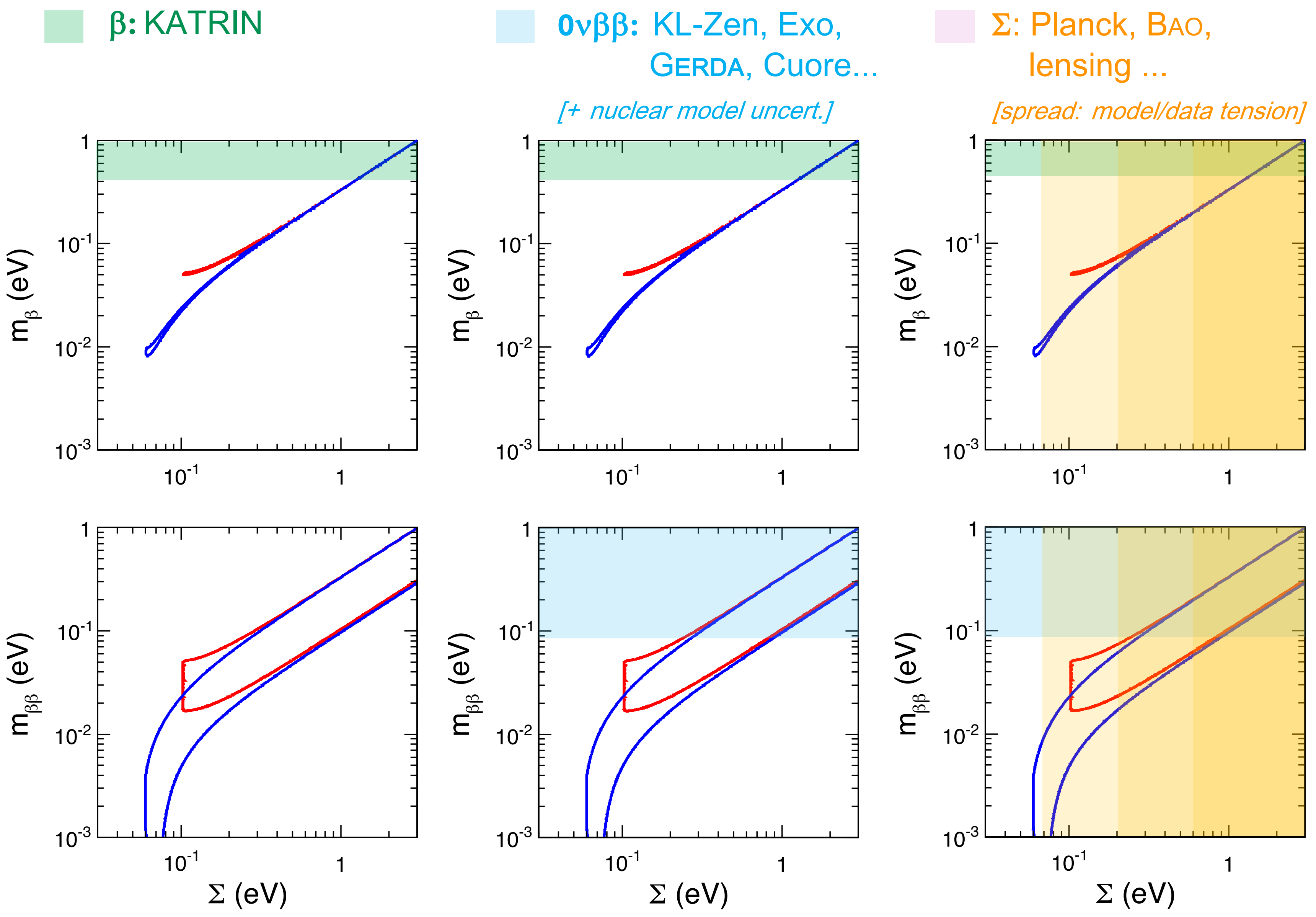
Possible new physics (e.g., dynamical dark energy?)

TABLE IV: Results of the cosmological data analysis under three model assumptions: standard cosmology with neutrino masses (ΛCDM+Σ), an extended model accounting for lensing systematics (ΛCDM+Σ+A_{lens}), and a nonstandard cosmology with dynamical dark energy and neutrino masses (w_0w_aCDM+Σ). The datasets used are listed in Section III C. For Planck, we consider both Plik and CamSpec likelihoods, which yield very similar results in all cases (shown explicitly only for ΛCDM+Σ). Upper bounds on Σ are reported at the 2σ level.

#	Model	Data set	Σ (2σ)
1	$\Lambda\mathrm{CDM} + \Sigma$	Plik	< 0.175 eV
2		Plik+DESI	< 0.065 eV
3		Plik+DESI+PP	< 0.073 eV
4		Plik+DESI+DESy5	< 0.091 eV
5		camspec	< 0.193 eV
6		camspec+DESI	< 0.064 eV
7		camspec+DESI+PP	< 0.074 eV
8		camspec+DESI+DESy5	< 0.088 eV
9	ΛCDM+Σ+A_{lens}	Plik	< 0.616 eV
10		Plik+DESI	< 0.204 eV
11		Plik+DESI+PP	< 0.255 eV
12		Plik+DESI+DESy5	< 0.287 eV
13	w_0w_aCDM+Σ	Plik	< 0.279 eV
14		Plik+DESI	< 0.211 eV
15		Plik+DESI+PP	< 0.155 eV
16		Plik+DESI+DESy5	< 0.183 eV

Wide range of bounds: $\Sigma < 0.2$ eV within factor of 3 (up/down)

Using the same data, limit depends on the underlying model (unlike beta decay))



IO "under pressure" from cosmo data. But: lively debate after recent (too strong?) DESI constraints

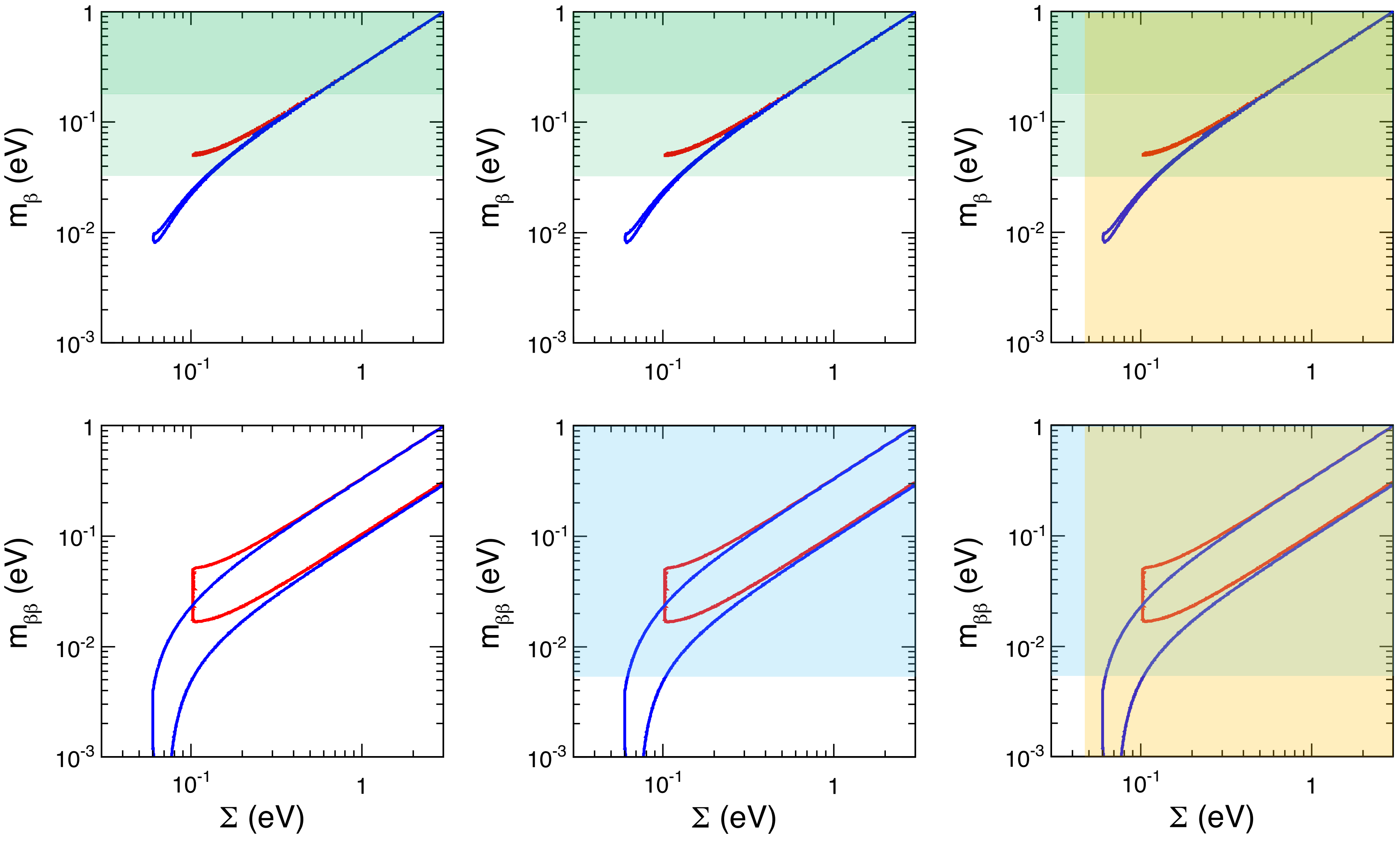
... systematics? dynamical dark energy? ... Our conservative view: **Σ < 0.2 eV** "within a factor of three"

FRONTIERS in 5-10 yrs?

β: ~0.2 eV (KATRIN) and hopefully below in ← **PROJECT-8 + Ho + ...**

0νββ: Well below IO limit @Ton scale **(LEGEND, NEXO, CUPID...)** w/ improved **NME**

Σ: complete covering seems possible within a “robust” **cosmo model**



Large phase space for possible mass discoveries in sub-eV range. First claims on ν mass may come from cosmology, but laboratory detection via β (0νββ) decay is mandatory !

- Intro and remarks on JUNO
- Current results from oscillation data
- Impact of possible “first year” JUNO results
- Current results from nonoscillation data
- Conclusions

3ν status

Precision frontier entering the sub% accuracy

5 knowns:

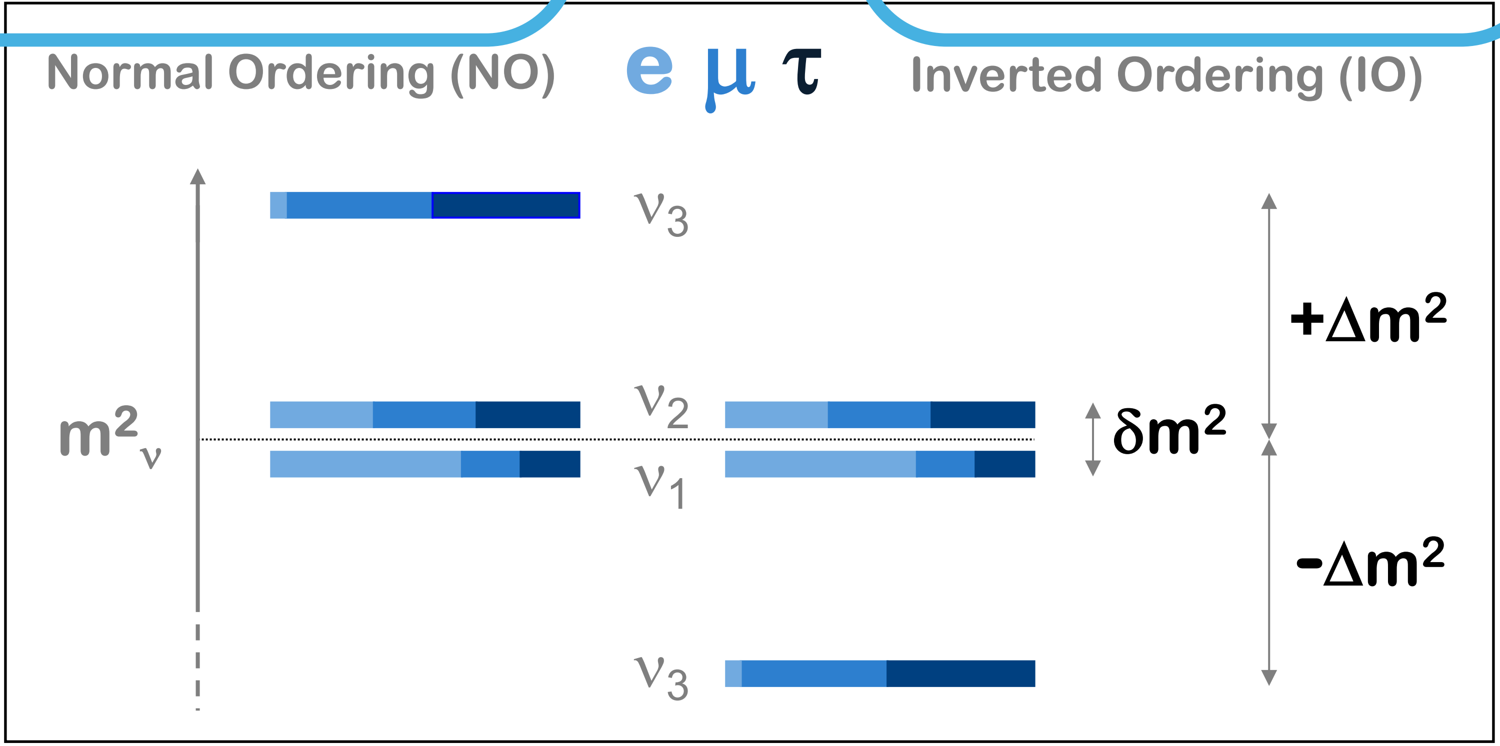
- $\delta m^2 \sim 7 \times 10^{-5}\ eV^2$
- $|\Delta m^2| \sim 2 \times 10^{-3}\ eV^2$
- $\sin^2\theta_{12} \sim 0.3$
- $\sin^2\theta_{23} \sim 0.5$
- $\sin^2\theta_{13} \sim 0.02$

Oscillations

5 unknowns:

- *Oscillations*:
  - δ **CPV** Dirac phase
  - **sign(Δm^2)** → NO/IO
  - θ_{23} **octant** degeneracy
- *Non-oscillat.*:
  - **absolute mass** scale
  - **Dirac/Majorana** nature

Discovery frontier quite open to different outcomes



JUNO will soon affect both frontiers - plus other lab/cosmo expts in the pipeline. In general, remain open to possible SURPRISES beyond the standard 3ν and cosmological frameworks!

FLASY
ROME 2025
11TH WORKSHOP
Flavor Symmetries and Consequences in Accelerators and Cosmology

Thank you for your attention!

EXTRA SLIDES

Ratio of "non-L/E phase" to "L/E oscillation phase" (from arXiv:2006.01648)

Mapping reactor neutrino spectra from TAO to JUNO

Francesco Capozzi,[1] Eligio Lisi,[2] and Antonio Marrone[3,2]

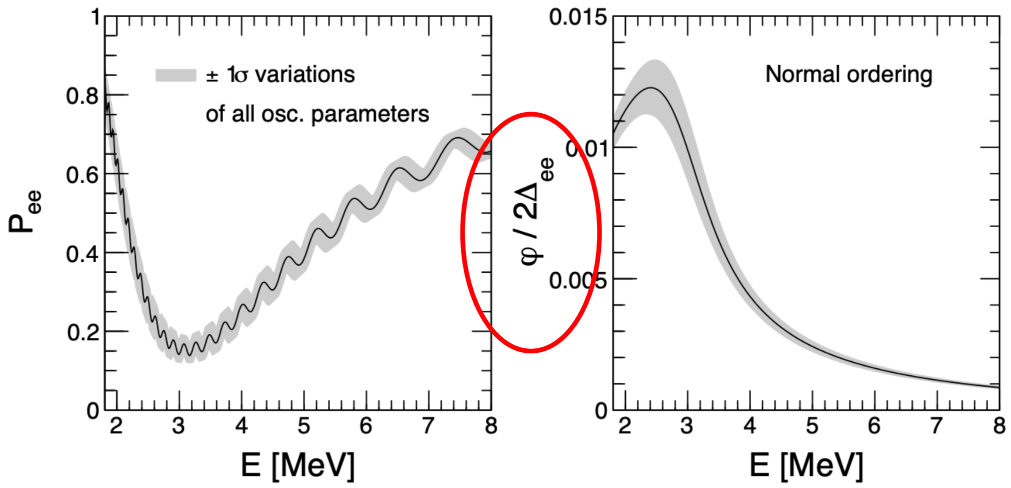
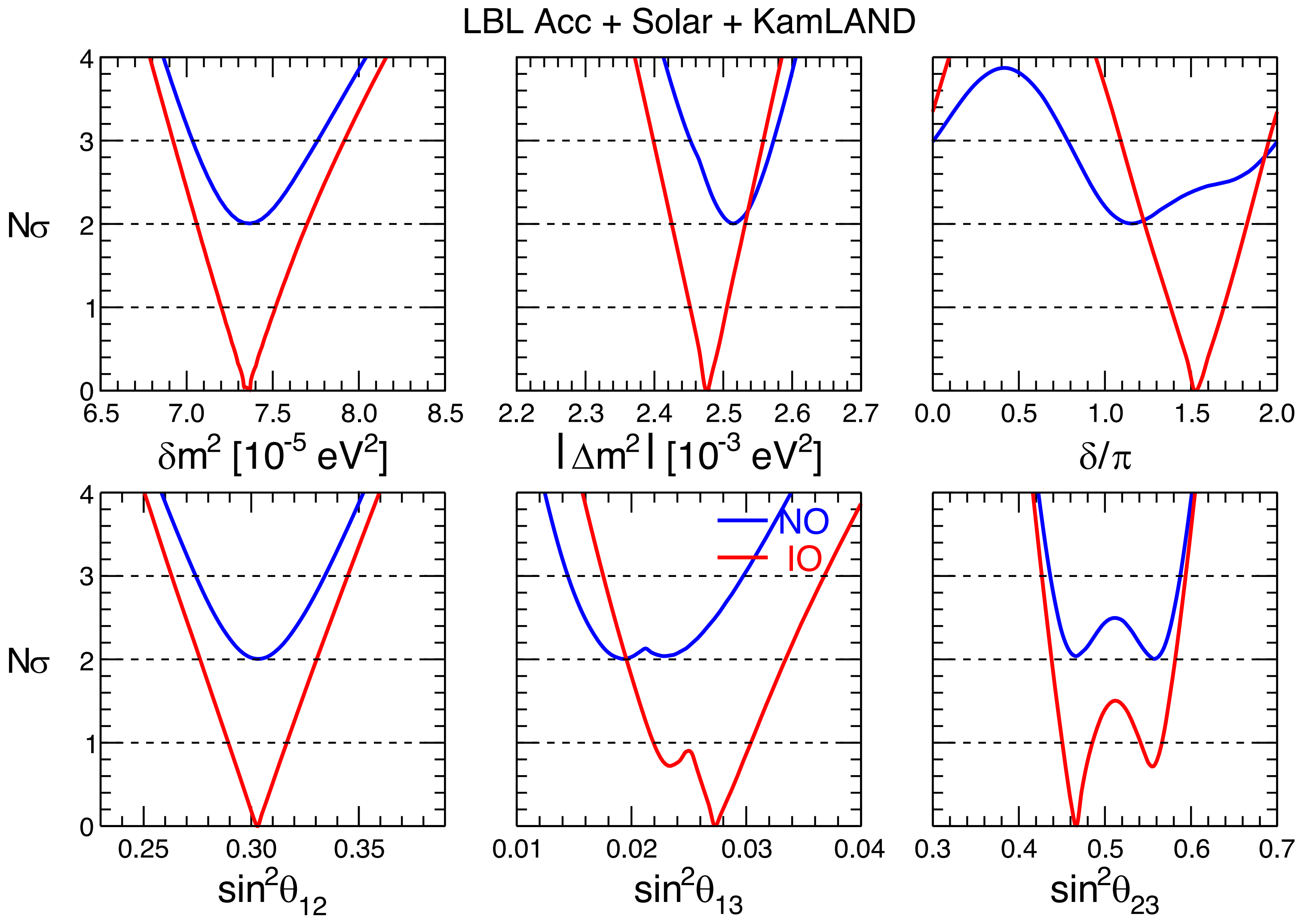


FIG. 4: Survival probability P_{ee} (left panel) and oscillation phase ratio $\varphi/2\Delta_{ee}$ (right panel) for electron antineutrinos with energy E in JUNO. Solid lines are computed for central values of the oscillation parameters, while the gray bands correspond to the envelope of $\leq 1\sigma$ variations in the prior ranges (see the text). Normal ordering is assumed. For inverted ordering, P_{ee} would be similar while $\varphi/2\Delta_{ee}$ would reverse its sign (not shown).

Within **JUNO standalone**, finding the mass ordering is equivalent to asses that the above (small) ratio is NOT a constant in the energy domain. High stats needed. With **JUNO + XYZ synergic combination,** more rapid assessment of NO/IO



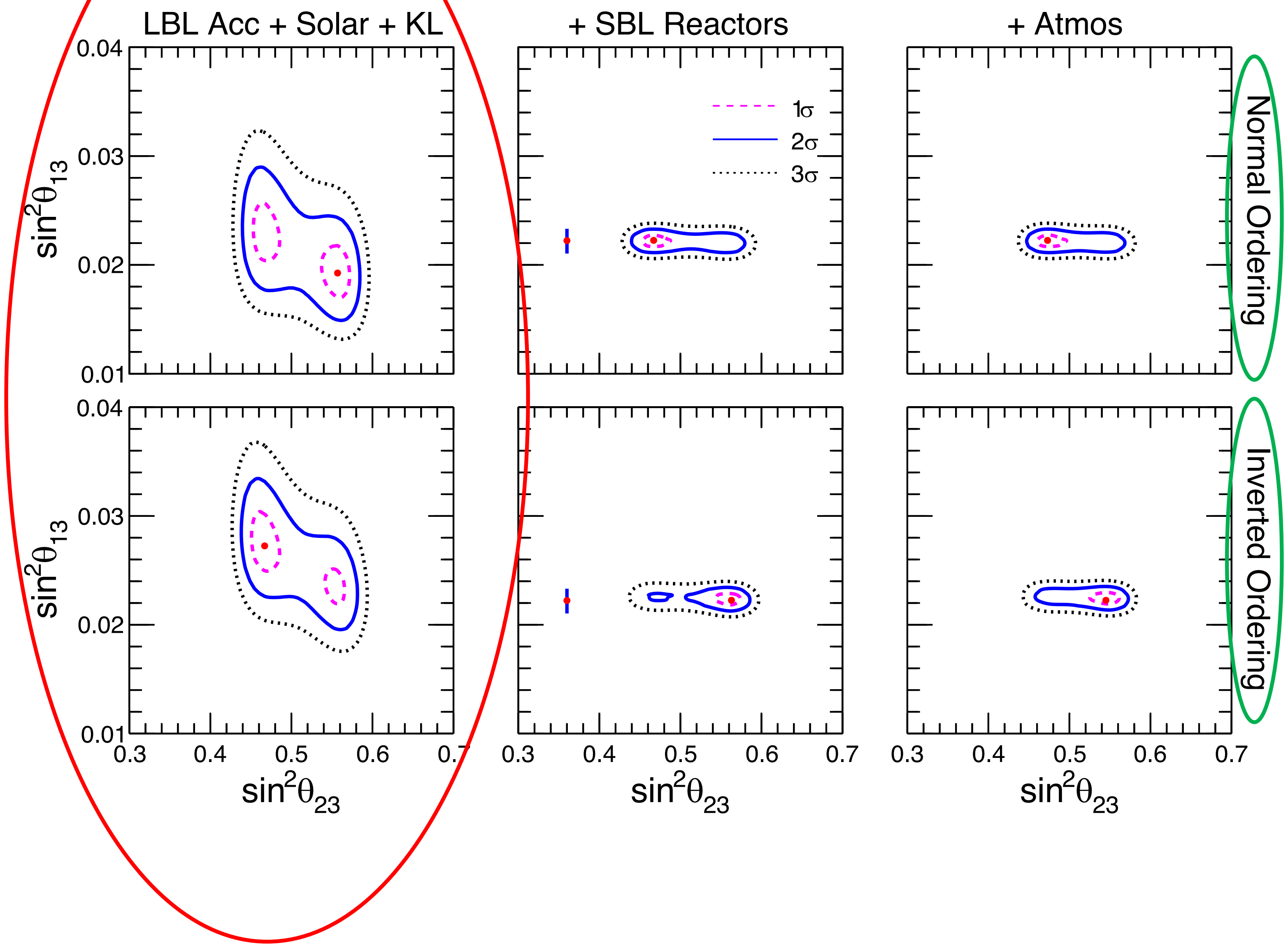
T2K and NOvA prefer NO separately, and IO in combination (at 2σ).

In IO, evidence for CP violation emerges at 3σ!

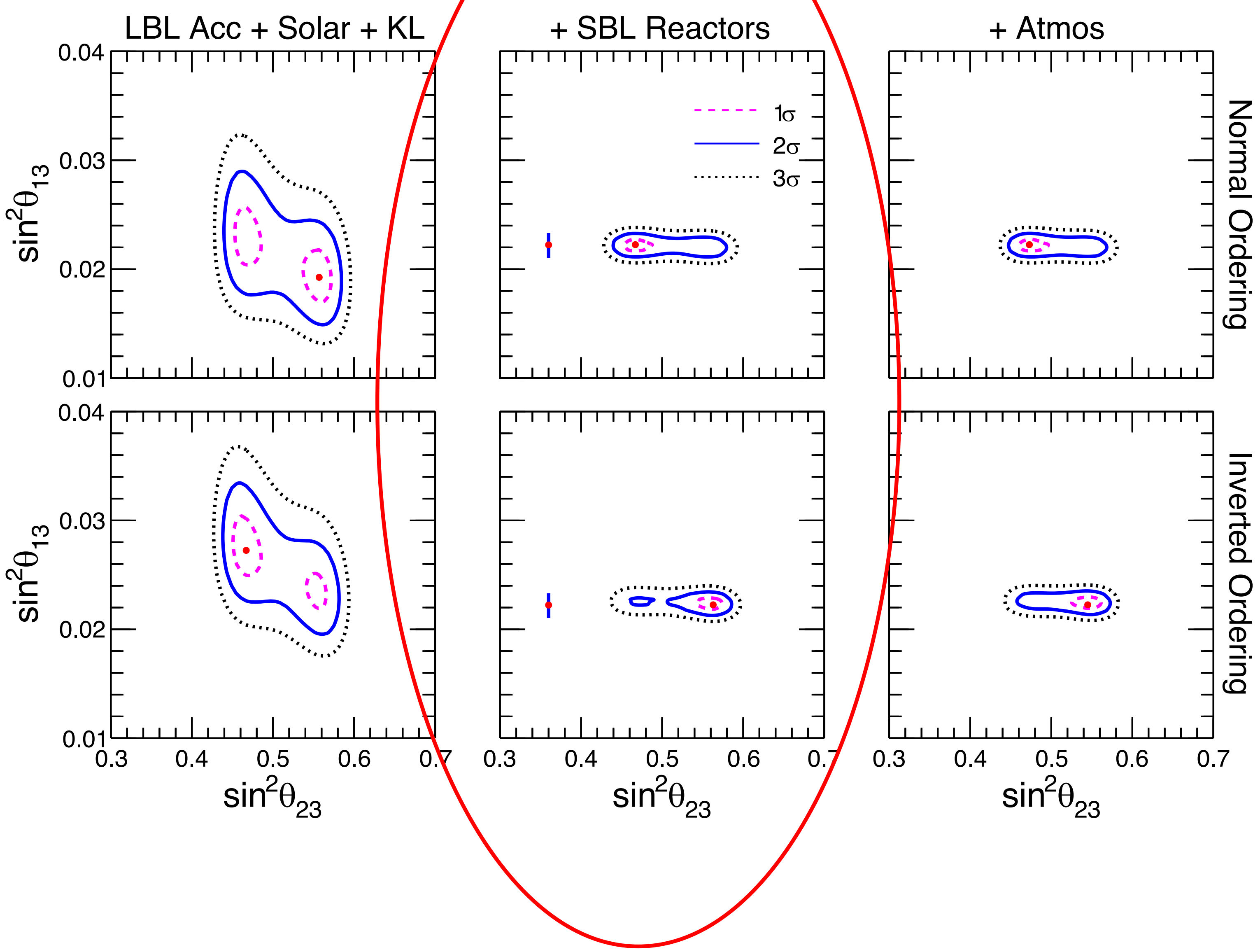
Note bimodal distribution of θ_{13} , related to θ_{23} octant ambiguity

LBL accel.: Bimodal in both θ_{13} and θ_{23}

(anticorrelated via appearance, in NO and IO)



LBL accel. + SBL reactors
θ_{13} “fixed”, only θ_{23} bimodal



How do $\nu_\mu \rightarrow \nu_e$ appearance searches probe CPV?

Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*
*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \longleftrightarrow \nu_e$ and $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

For two neutrinos, no CPV:

$$\overset{(-)}{\nu}_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$$

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For two neutrinos, no CPV:

$$\overset{(-)}{\nu}_e = \cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2$$

For three neutrinos: new possible CPV phase δ, tested via ν / $\bar{\nu}$

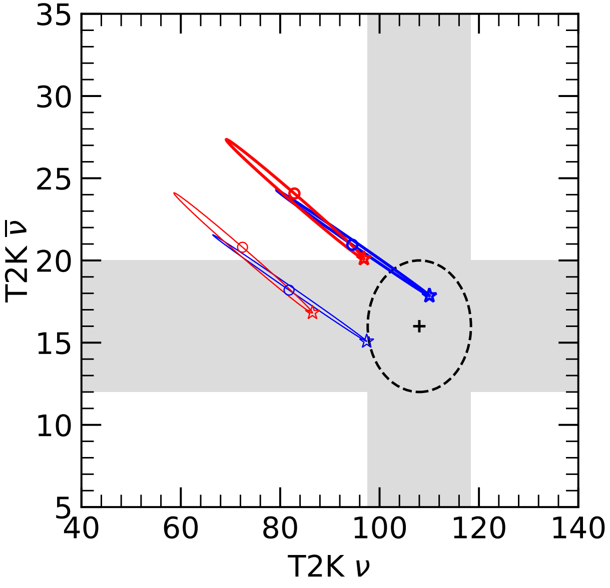
$$\overset{(-)}{\nu}_e = \cos\theta_{13}\, (\cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2) + e^{\pm i\delta} \sin\theta_{13}\, \nu_3$$

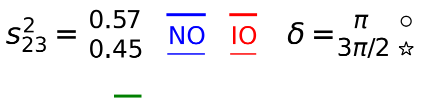
CPV is a genuine 3ν effect → all parameters (known+unknown) involved/entangled → difficult!

CPV currently tested in T2K, NOvA, atm. oscillations *(with some T2K-NOvA tension...)*

Integrated info on ν and ν̄, stat. errors only. [Not used in fits]

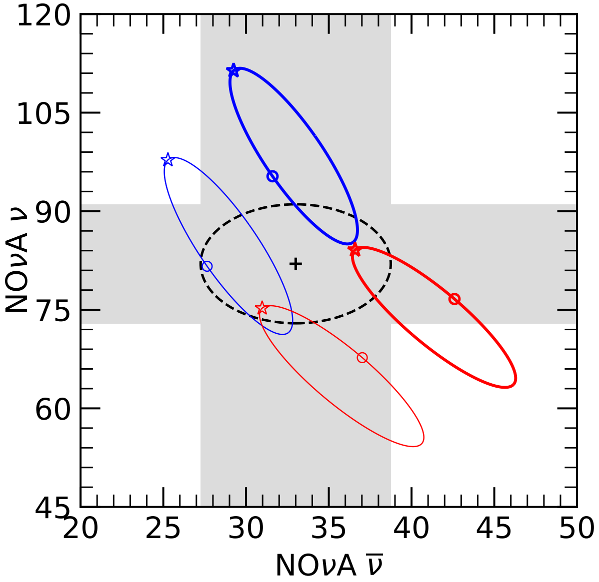
T2K & NOνA bi-event plots





T2K (ν+ν̄) prefers:
NO
δ~3π/2 (~max CPV)
2nd octant

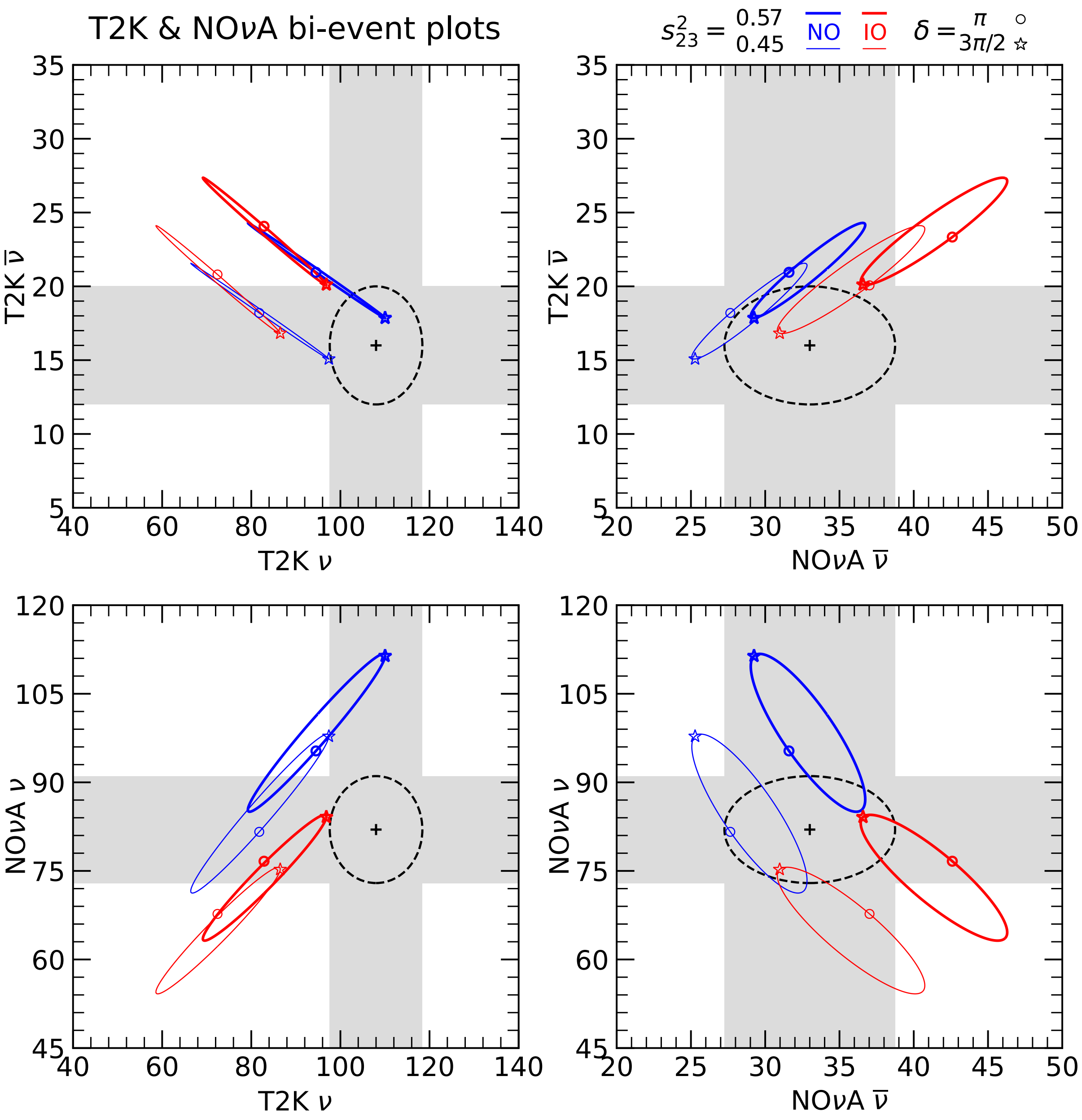
NOVA (ν+ν̄) prefers:
NO
CP conservation
octants ~degenerate



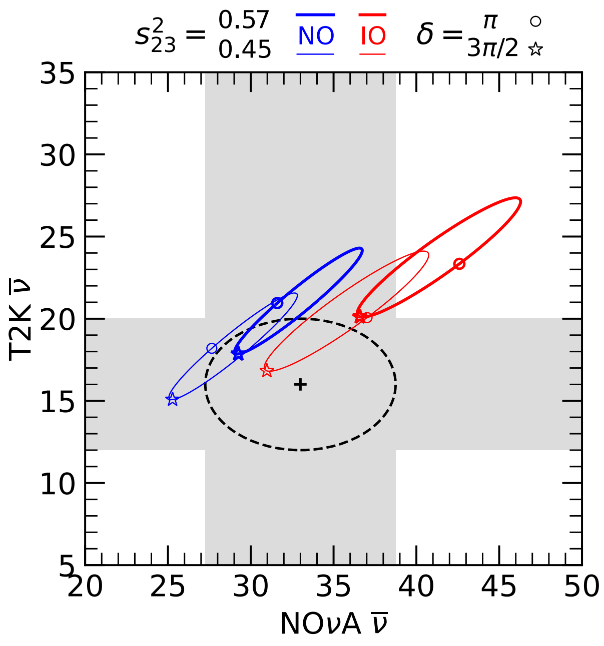
→ T2K and NOVA, separately: NO preferred; CP and octant ambiguous

The same info can be reorganized in terms of T2K vs NOvA:

[2021 data]



T2K & NOνA bi-event plots

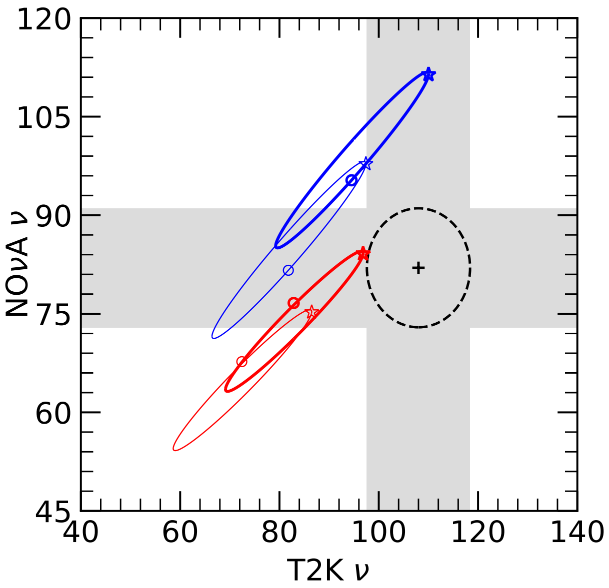


T2K+NOvA (ν) prefer:

IO

δ~3π/2

1st octant



T2K+NOvA ($\bar{\nu}$) prefer:

IO

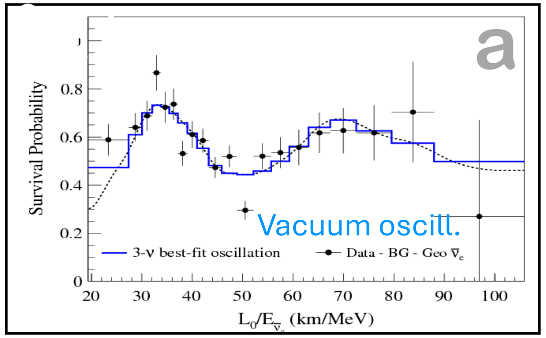
δ~3π/2

2nd octant

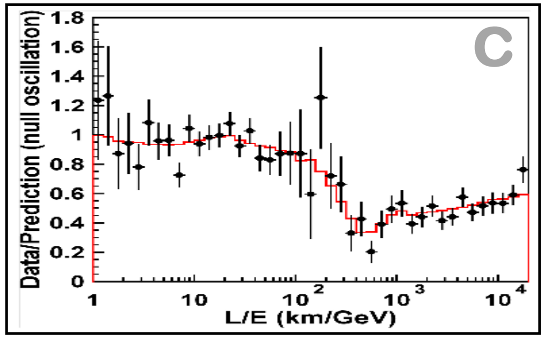
→ T2K and NOVA, jointly: IO and CPV preferred; octant ambiguous

3ν oscillations probed by many experiments in different flavor channels…

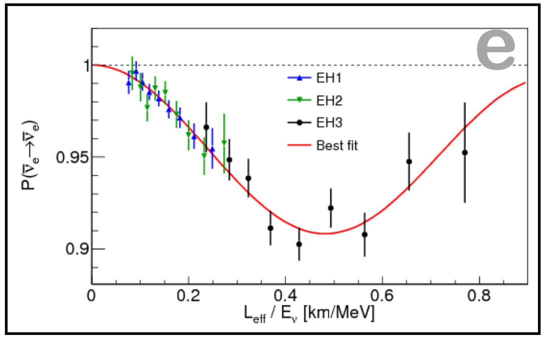
e→e (KamLAND, KL)



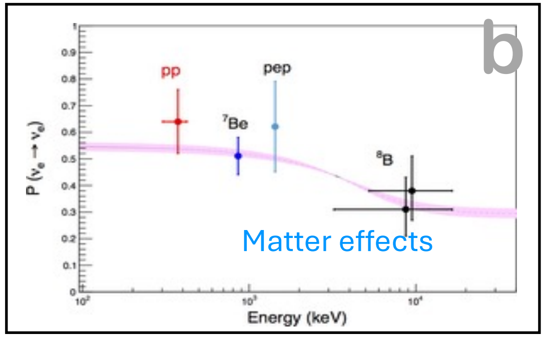
μ→μ (Atmospheric)



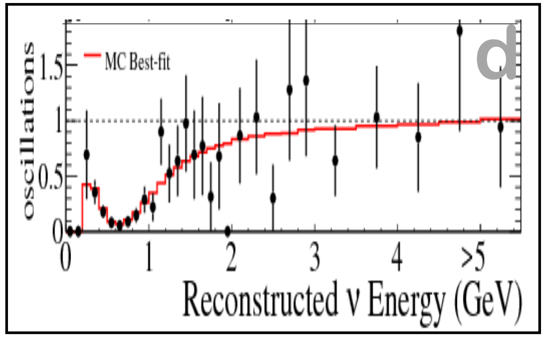
e→e (SBL Reac.)



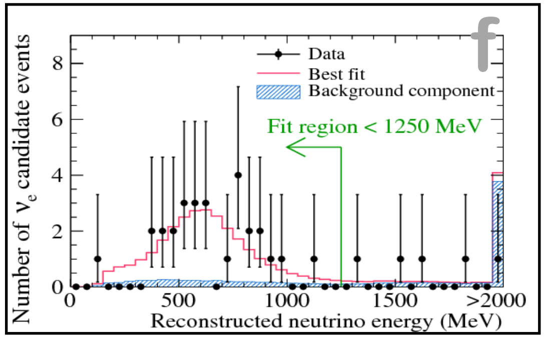
e→e (Solar)



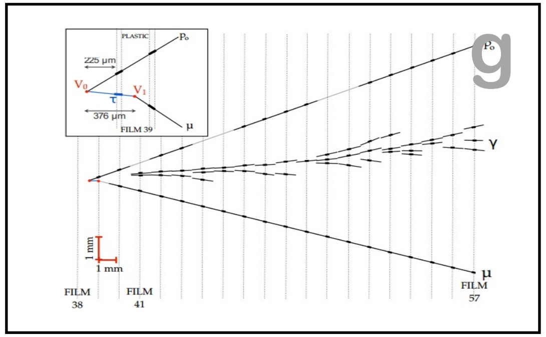
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

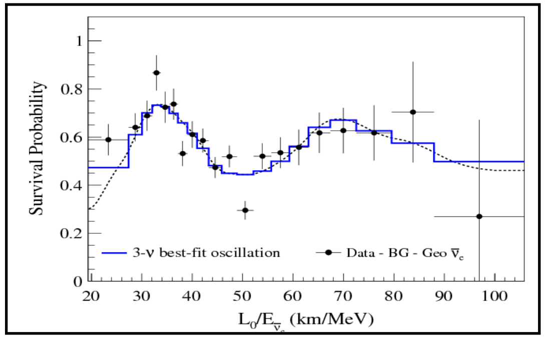


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

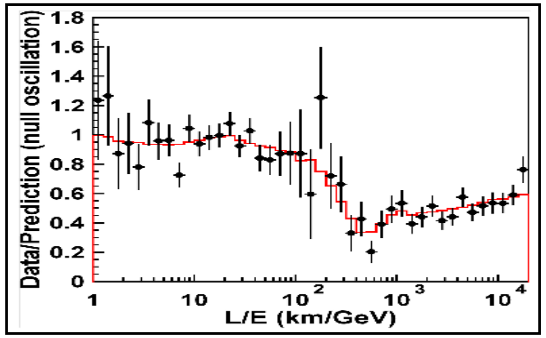
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], DeepCore, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

… with amplitude and frequency governed by 2 (or 3) leading parameters

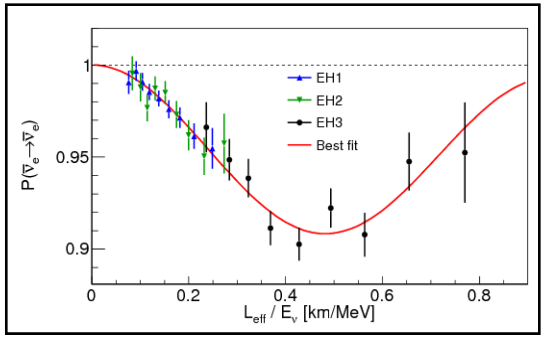
e→e (δm^2 , θ_{12})



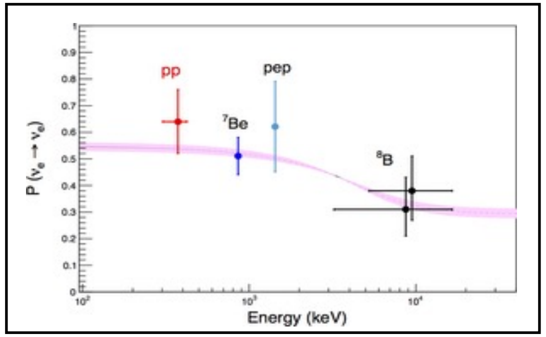
μ→μ (Δm^2 , θ_{23})



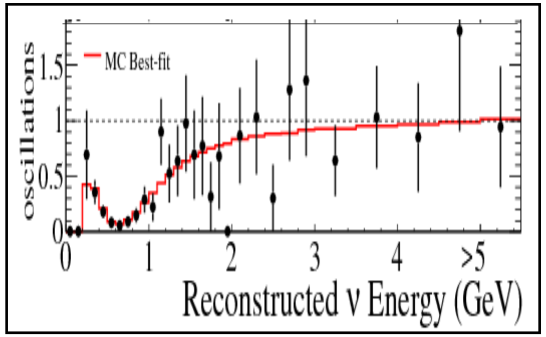
e→e (Δm^2 , θ_{13})



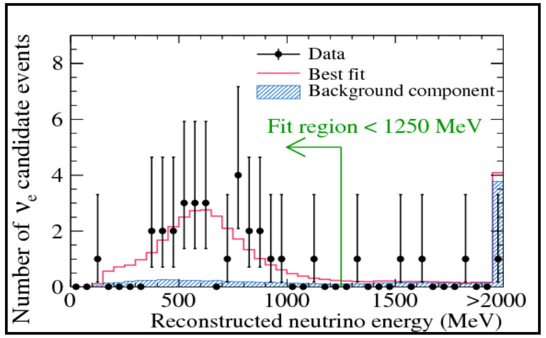
e→e (δm^2 , θ_{12})



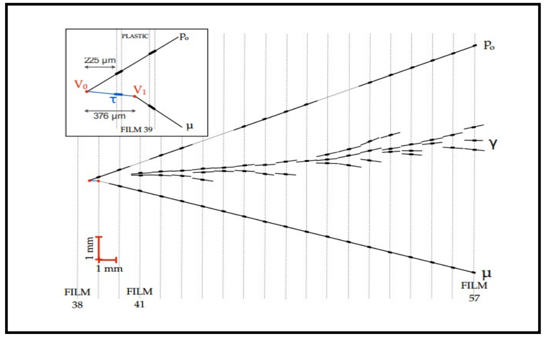
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



5 param.'s known & (over)constrained → consistency

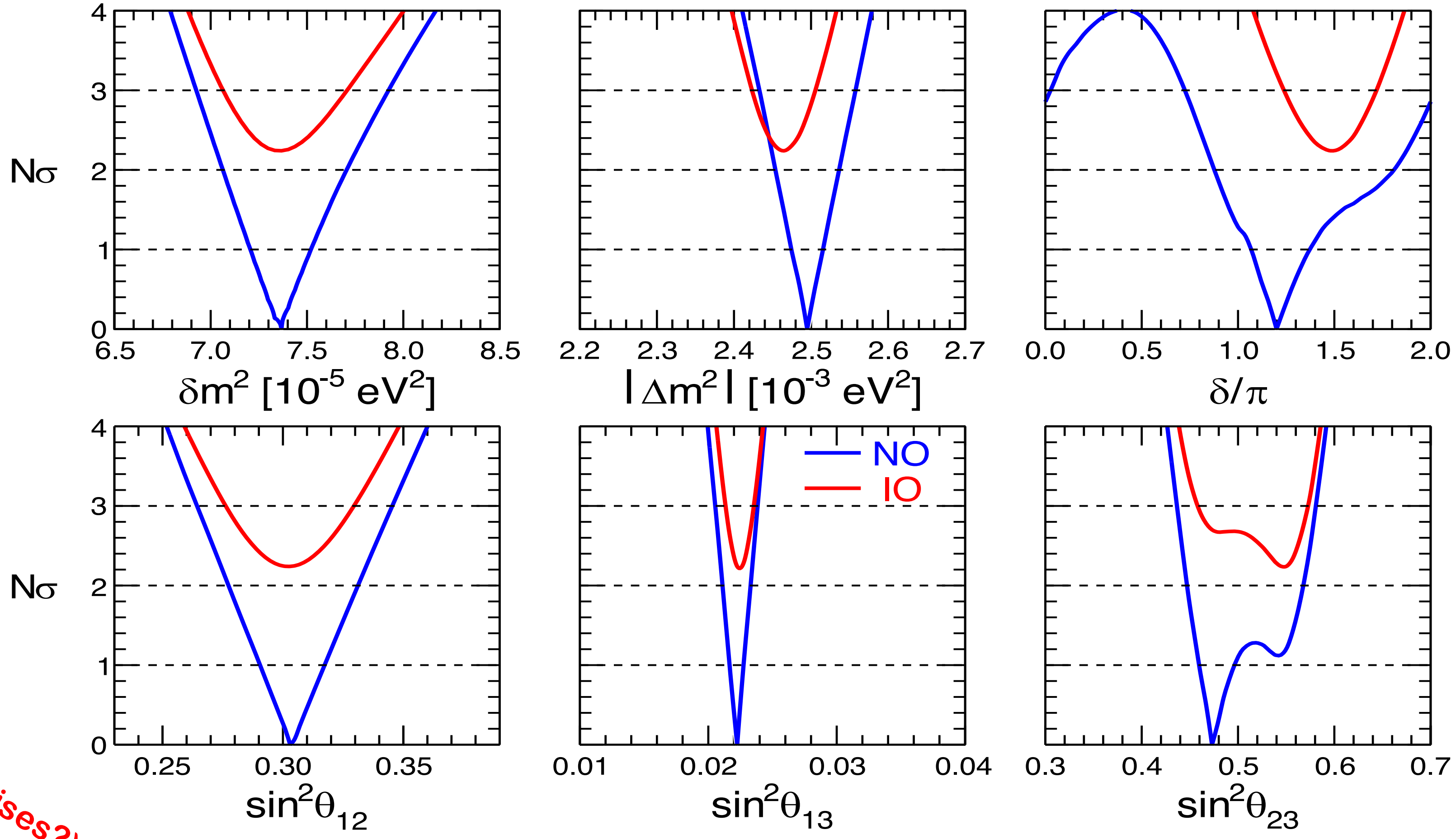
Currently: focus on unknown par. & subleading effects, especially CPV via $\nu_\mu \to \nu_e$ in LBL accel. and atmos. expts and NO/IO mass spectrum via reactor + accel + atmos.

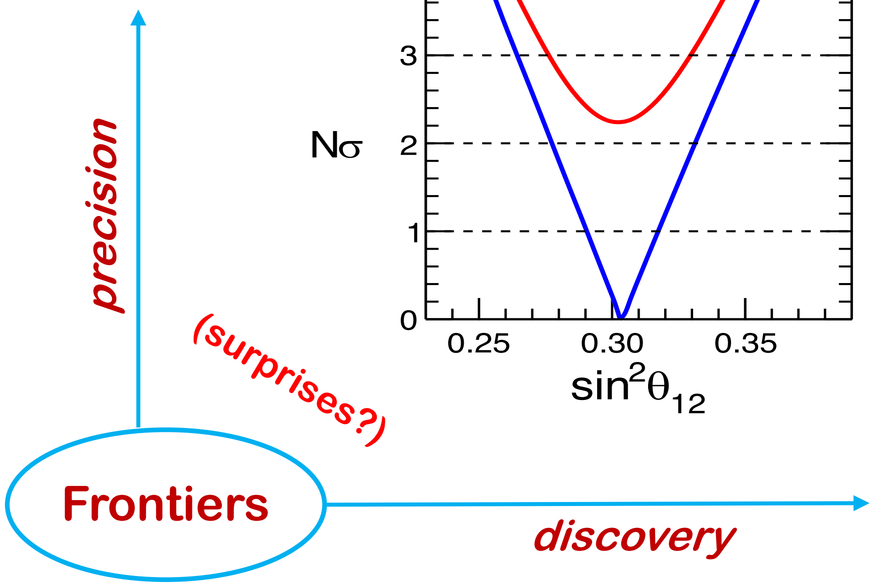
Status of known and unknown 3ν oscillation parameters [arXiv:2503.07752]

1σ error of **known** parameters

$\lvert\Delta m^2\rvert$	0.8%
δm^2	2.3%
θ_{13}	2.4%
θ_{12}	4.5%
θ_{23}	~ 5%

All ν oscillation data





Hints on oscillation **unknowns**

NO	$2.2\,\sigma$
$\sin\delta < 0$	$1.3\,\sigma$
$\theta_{23} < \pi/4$	$1.1\,\sigma$