

Neutrino Oscillations: Current Status and Future Prospects



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OUTLINE

Introduction

Global Analysis 2018
and 2019 (preliminary)

Future Prospects

Conclusions

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we know

$$\delta m^2 \sim 7.34 \times 10^{-5} \text{ eV}^2 \quad (2.2\%)$$

$$\Delta m^2 \sim 2.49 \times 10^{-3} \text{ eV}^2 \quad (1.3\%)$$

$$\sin^2 \theta_{12} \sim 0.305 \quad (4.4\%)$$

$$\sin^2 \theta_{13} \sim 2.23 \times 10^{-2} \quad (3.0\%)$$

$$\sin^2 \theta_{23} \sim 0.56 \times 10^{-2} \quad (5.2\%)$$

Note that in our notation

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

What we still do not know

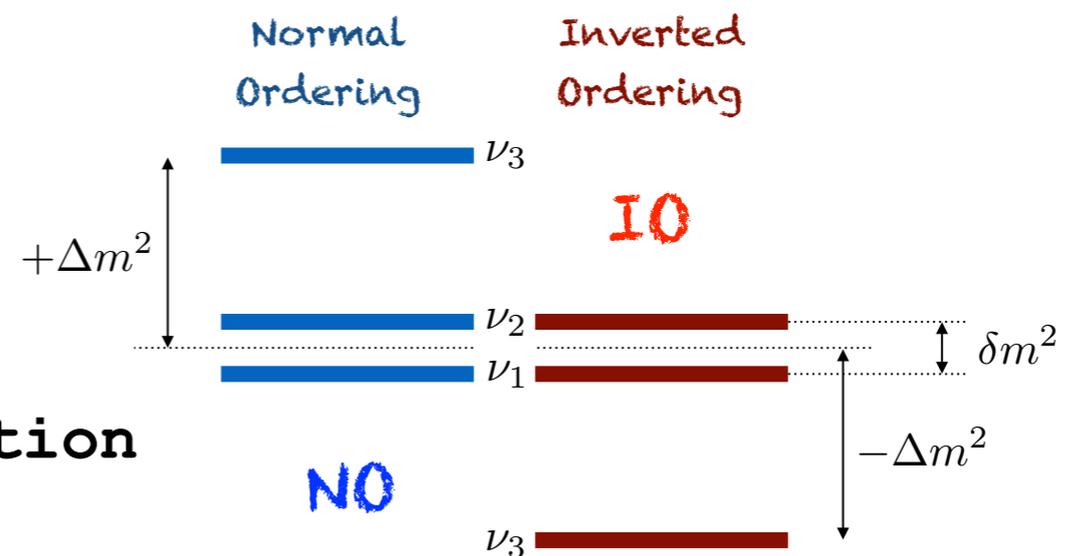
CP-violating phase δ

Octant of θ_{23}

Absolute mass scale

Nature of ν (Dirac/Majorana)

Mass Ordering \rightarrow sign(Δm^2)



ν	Δm^2	θ_{23}	θ_{13}	θ_{12}	δm^2	δ
Atmospheric						
Solar						
Reactor SBL						
LBL		 				
Reactor LBL						
Future Reactor MBL						
Supernovae						

Hierarchy (Y/N)

Disappearance

Appearance

To understand how bounds on the oscillation parameter arise it is useful to look at their correlations and to consider the progressive contribution of different data sets

LBL accelerators (T2K and NOvA) are dominantly sensitive to $(\Delta m^2, \theta_{23}, \theta_{13})$ but also probe δ and **NO vs IO**, if $(\delta m^2, \theta_{12})$ are fixed by solar+KL,

$$\begin{aligned}
 P(\nu_\mu \rightarrow \nu_e) \simeq & \sin^2 \theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta m^2}{A - \Delta m^2} \right) \sin^2 \left(\frac{A - \Delta m^2}{4E} x \right) \\
 & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \left(\frac{\Delta m^2}{A} \right) \left(\frac{\Delta m^2}{A - \Delta m^2} \right) \sin \left(\frac{A}{4E} x \right) \sin \left(\frac{A - \Delta m^2}{4E} x \right) \cos \left(\frac{\Delta m^2}{4E} x \right) \cos \delta \\
 & - \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \left(\frac{\Delta m^2}{A} \right) \left(\frac{\Delta m^2}{A - \Delta m^2} \right) \sin \left(\frac{A}{4E} x \right) \sin \left(\frac{A - \Delta m^2}{4E} x \right) \sin \left(\frac{\Delta m^2}{4E} x \right) \sin \delta \\
 & + \cos^2 \theta_{13} \sin^2 2\theta_{12} \left(\frac{\Delta m^2}{A} \right)^2 \sin^2 \left(\frac{A}{4E} x \right), \tag{13}
 \end{aligned}$$

where $A = 2\sqrt{2}G_F N_e E$ governs matter effects, with $A \rightarrow -A$ and $\delta \rightarrow -\delta$ for $\nu \rightarrow \bar{\nu}$, and $\Delta m^2 \rightarrow -\Delta m^2$ for normal to inverted ordering. At typical NOvA energies ($E \sim 2$ GeV) it is $|A/\Delta m^2| \sim 0.2$,

Therefore we start combining

(1) LBL acc + Solar + KamLAND

Solar + KL data provide the necessary input for $(\delta m^2, \theta_{12})$, but also independent -although weak- constraints on θ_{13} . The data set (1) provides, by itself, a measurement of θ_{13} .

SBL reactors (Daya Bay, RENO, Double Chooz) are dominantly sensitive to $(\Delta m^2, \vartheta_{13})$ and shrink the ϑ_{13} range dramatically, with correlated effects on the other parameters

(2) LBL acc + Solar + KamLAND + SBL Reactors

SBL reactors not only provide the most accurate determination of θ_{13} but also an independent determination of Δm^2

(3) LBL acc + Solar + KamLAND + SBL Reactors + Atmospheric

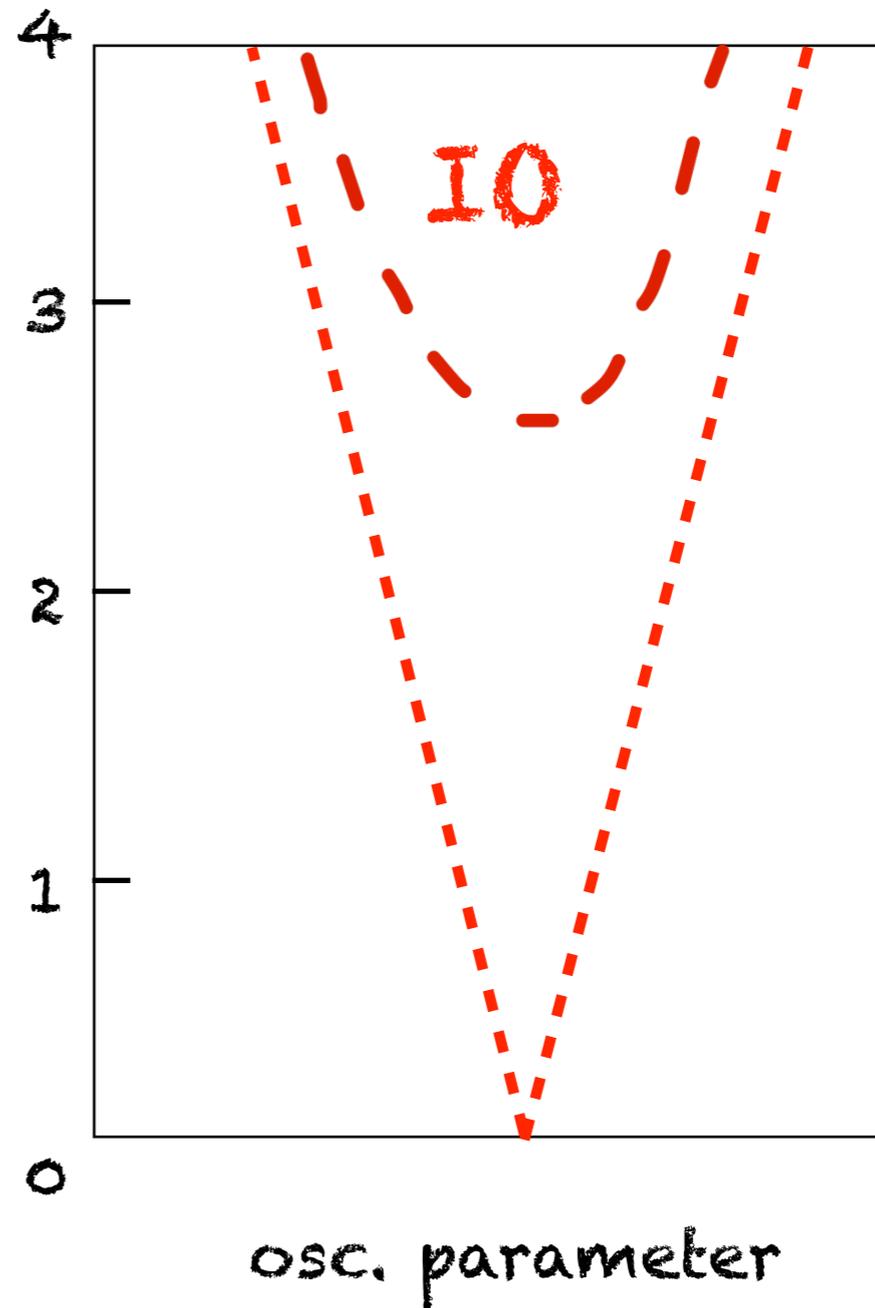
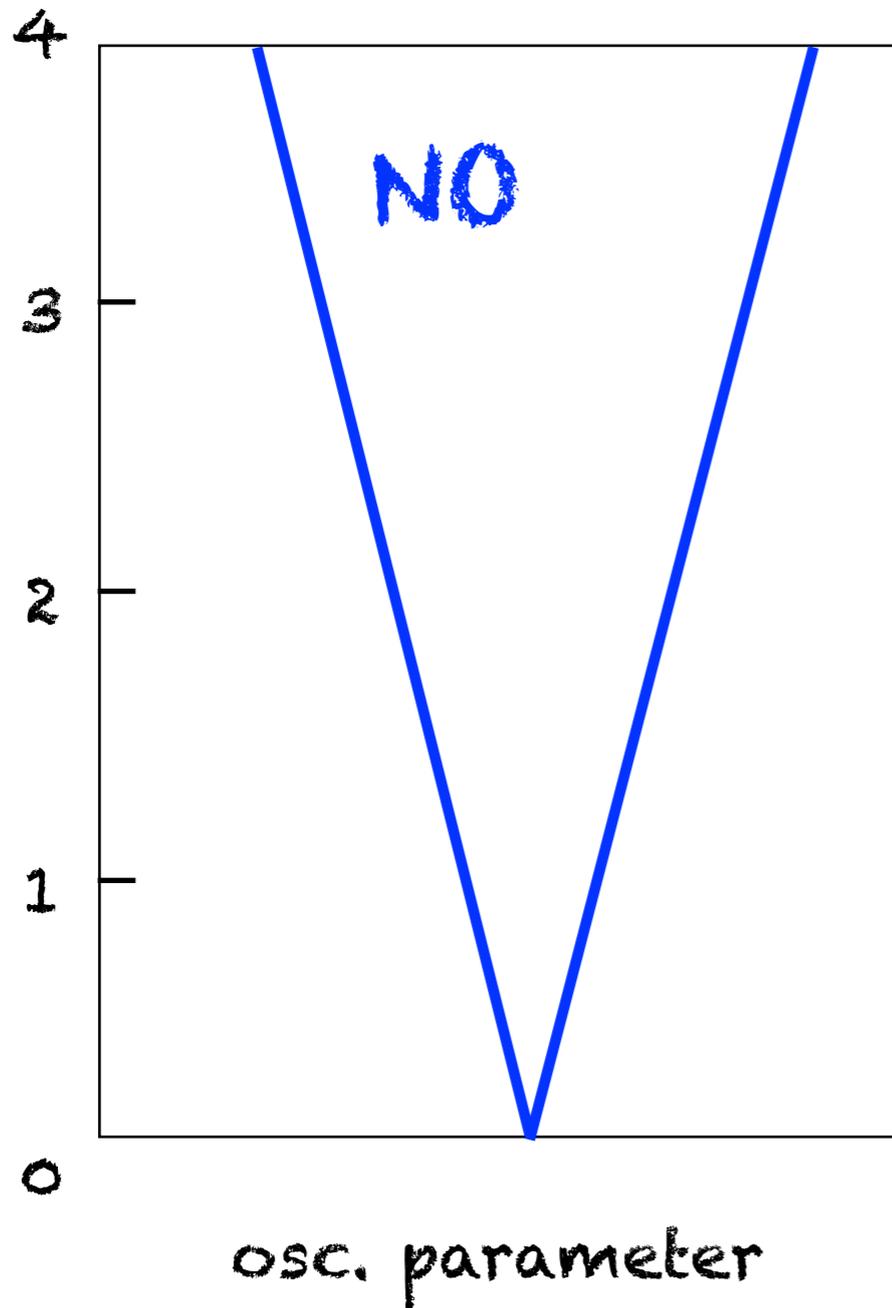
Atmospheric neutrino data (SK + DeepCore) sensitive in different ways to all the oscillation parameters via disappearance and appearance channels. Because of matter effects they depends on all parameters in the 3v framework, but dominantly on $(\Delta m^2, \vartheta_{23})$. Also important to test NO vs IO

Bounds on single parameters, obtained after marginalisation over all other parameters, shown in the following in terms of $N\sigma = \sqrt{\Delta\chi^2}$

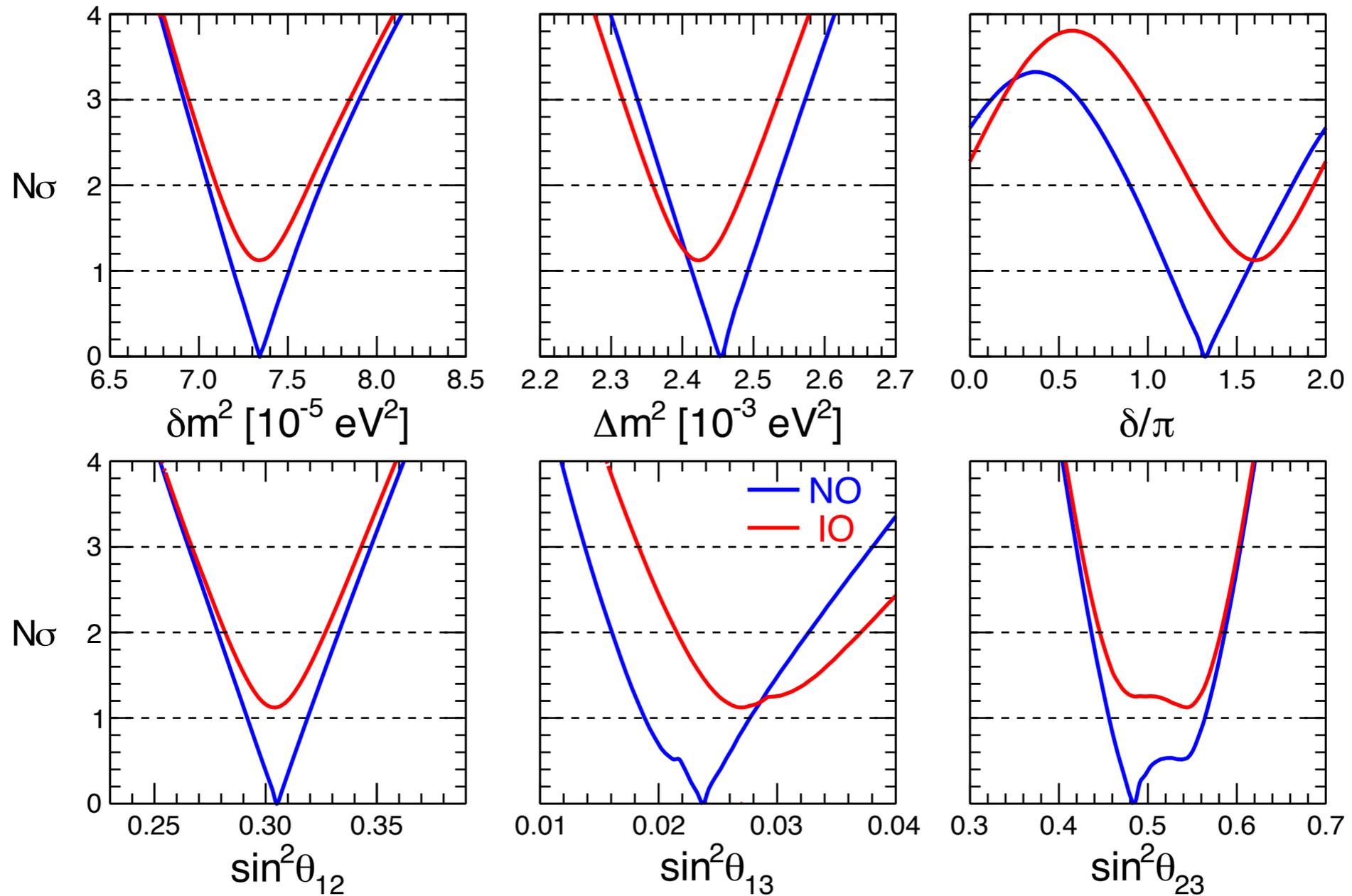
Separate best fits for both NO and IO

Typical bounds would be linear and symmetric for gaussian errors

Bounds for IO move upwards taking into account that currently NO gives the absolute best fit



LBL Acc + Solar + KamLAND



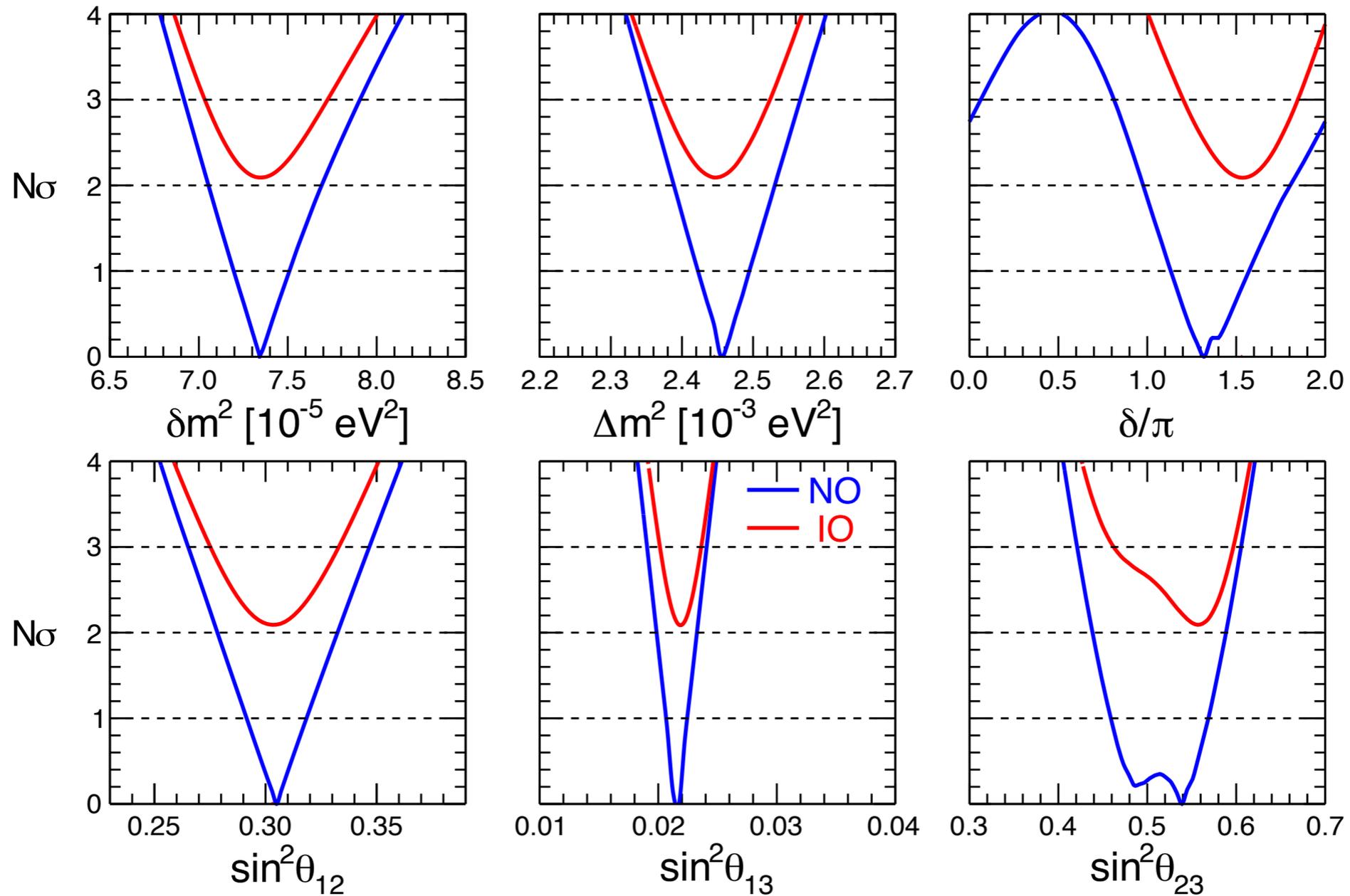
With the exception of δ and ϑ_{13} , all parameters bounded at more than 4σ level

ϑ_{23} nearly maximal but octant undetermined at 1σ

Maximal CP violation favoured

IO slightly disfavoured with respect to NO at $\sim 1\sigma$ level.

LBL Acc + Solar + KamLAND + SBL Reactors



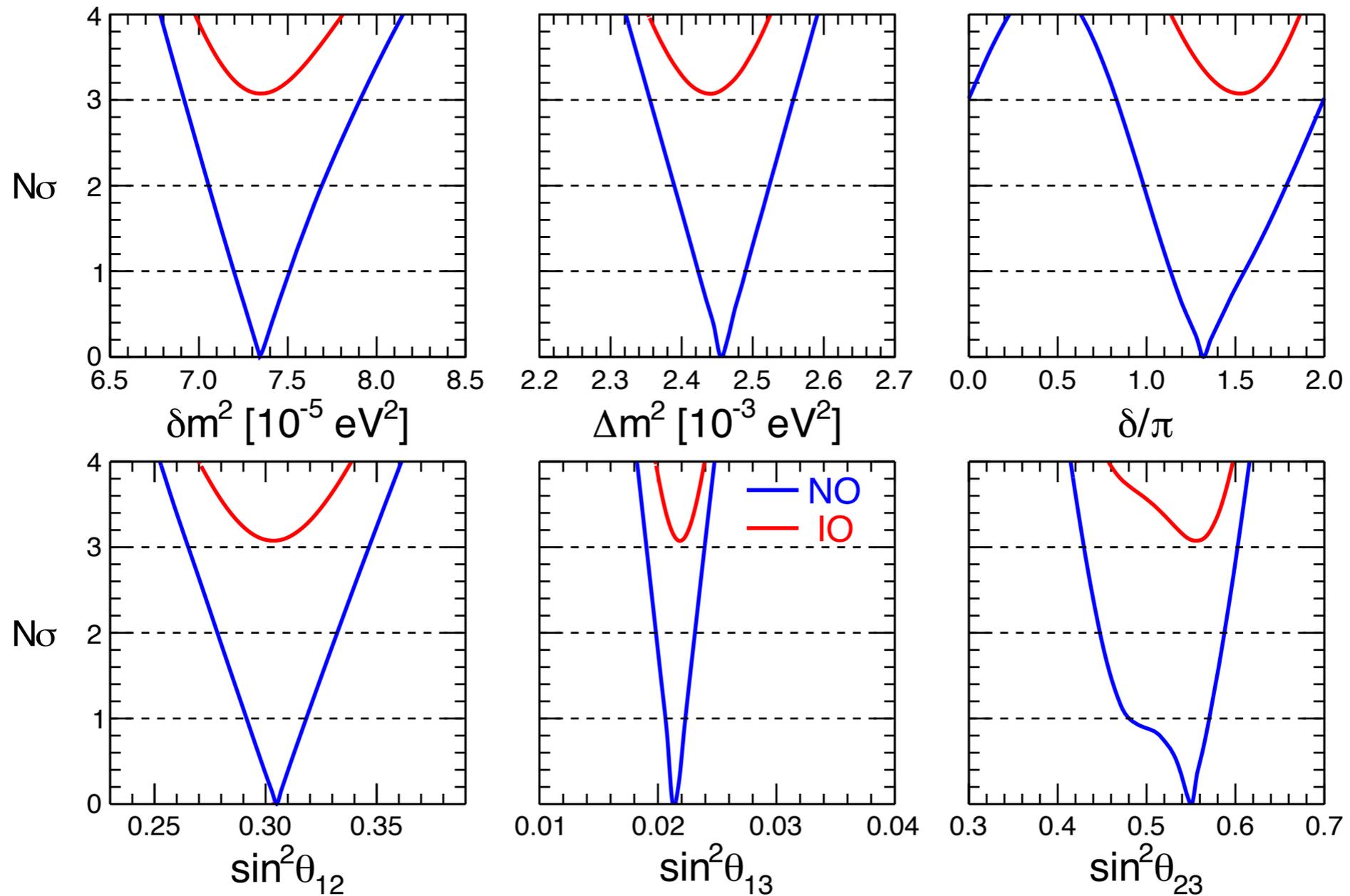
Range of smallest mixing angle ϑ_{13} dramatically reduced

Largest mixing angle ϑ_{23} close to $\pi/4$, but octant undetermined at 2σ

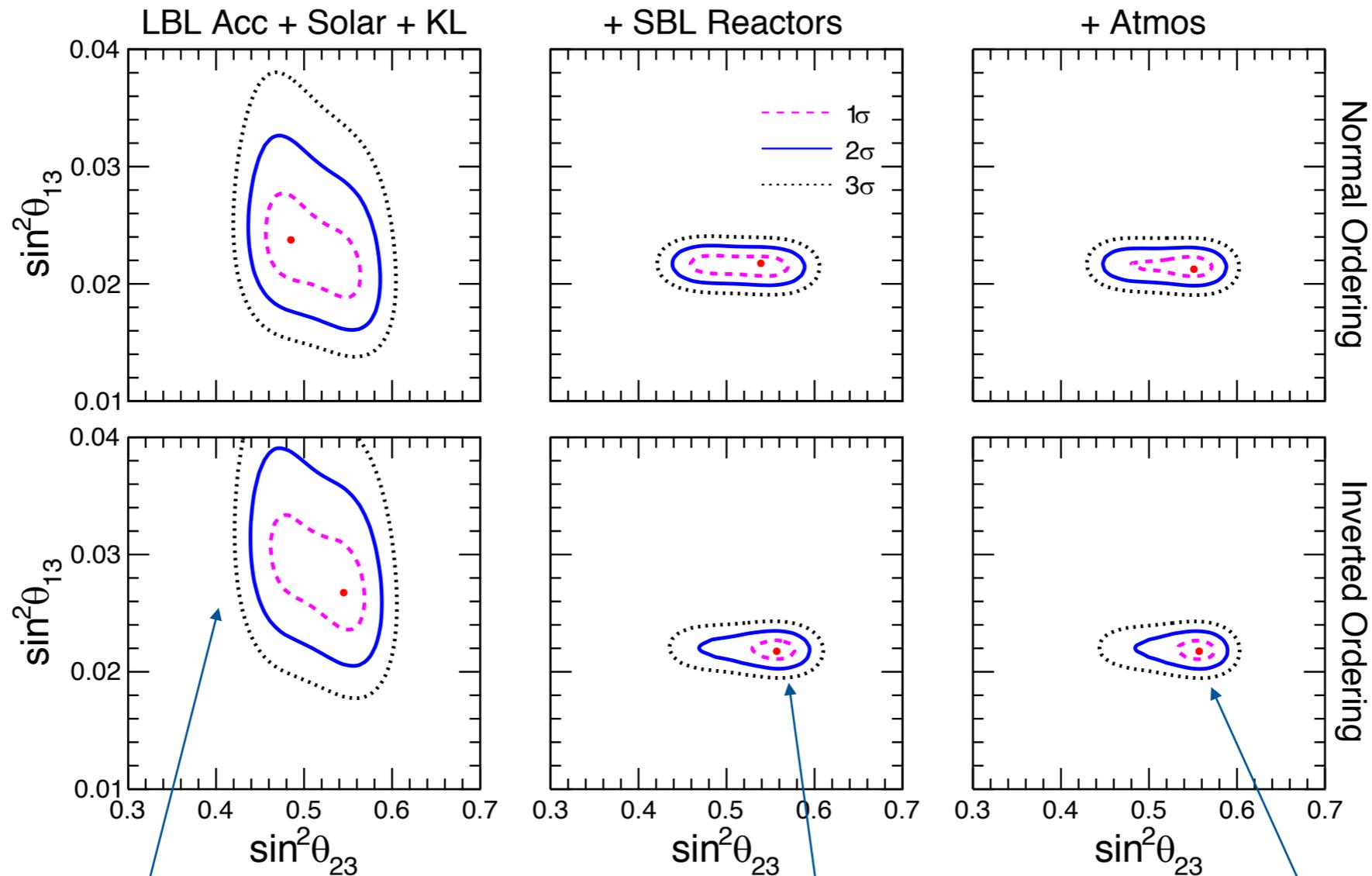
Max CPV at $\sim 3\pi/2$ favored, CP conservation disfavored at $\sim 2\sigma$ in NO

IO disfavored with respect to NO at $\sim 2\sigma$ level.

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



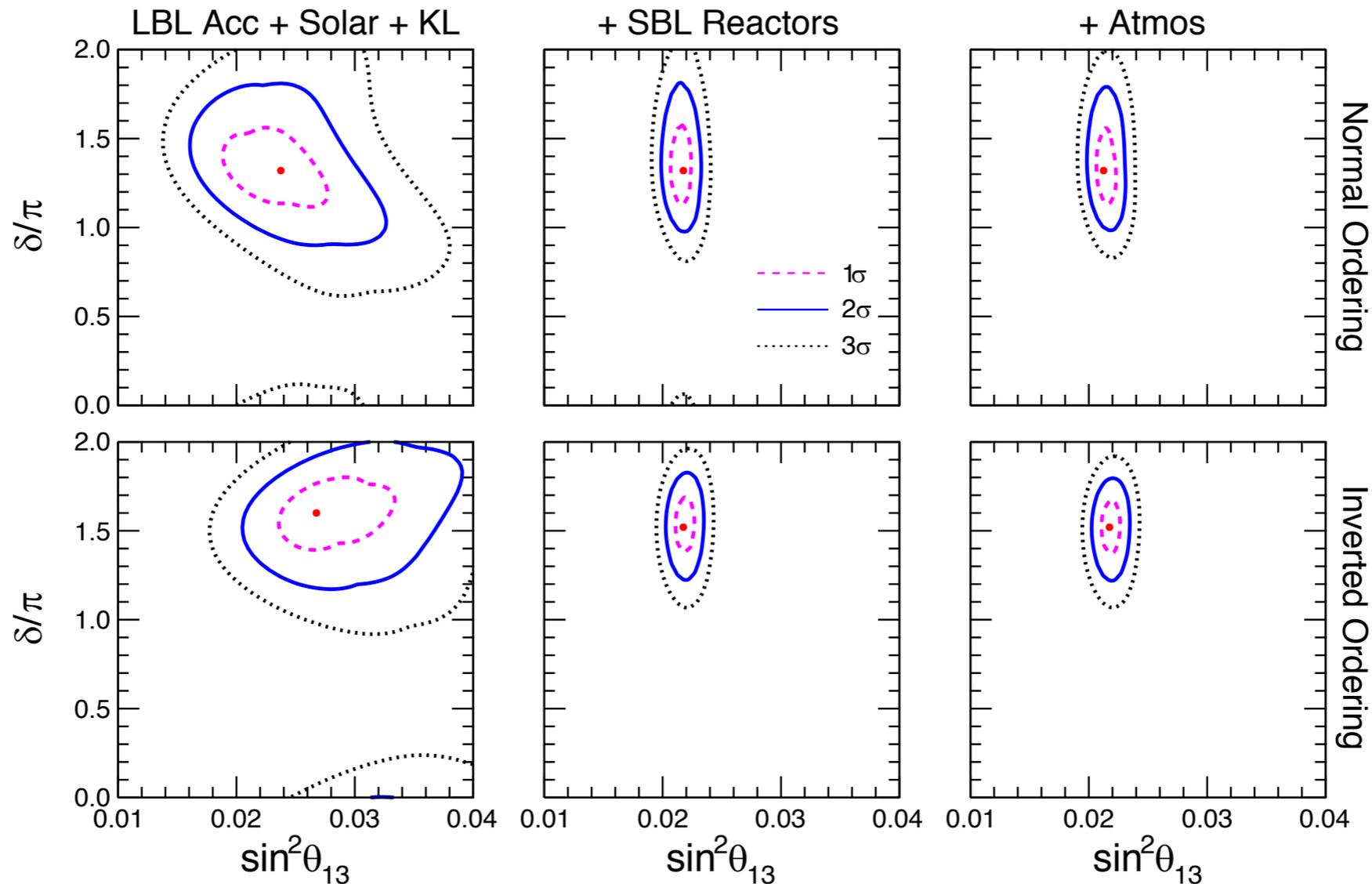
Further improvements for various parameters: 1σ bounds at few % level
 Largest mixing angle ϑ_{23} close to $\pi/4$, but octant undetermined at 2σ
 CPV: $\sin\delta \sim -1$ favored, ~ 0 disfavored, $\sim +1$ excluded. Meaningful bounds at $\sim 3\sigma$.
 IO significantly disfavored with respect to NO, at $\sim 3\sigma$ level



Anticorrelation between $(\vartheta_{23}, \vartheta_{13})$ due to leading term in the appearance channel probability at accelerators

Lower ϑ_{13} value preferred by reactors data favours second octant for ϑ_{23}

second octant favoured also by atmospheric data



Strong correlations (in the left panels) mainly induced by the interplay between δ and θ_{13} in the subleading terms of the appearance probability for LBL experiments

In NO, the best fit of δ remains very close to $\sim 1.3\pi$ by adding first SBL reactor and then atmospheric neutrino data

In IO there is a slight decrease of δ from left to middle panels, correlated to the decrease of θ_{13}

Consistency of all the datasets towards the same best-fit values of both the Δm^2 , θ_{23} , θ_{13} and δ

Global Fit - 2018

Table 1: Best fit values and allowed ranges at $N\sigma = 1, 2, 3$ for the 3ν oscillation parameters, in either NO or IO. The latter 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).

Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	“ 1σ ” (%)
$\delta m^2/10^{-5} \text{ eV}^2$	NO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
	IO	7.34	7.20 – 7.51	7.05 – 7.69	6.92 – 7.91	2.2
$\sin^2 \theta_{12}$	NO	3.04	2.91 – 3.18	2.78 – 3.32	2.65 – 3.46	4.4
	IO	3.03	2.90 – 3.17	2.77 – 3.31	2.64 – 3.45	4.4
$\sin^2 \theta_{13}/10^{-2}$	NO	2.14	2.07 – 2.23	1.98 – 2.31	1.90 – 2.39	3.8
	IO	2.18	2.11 – 2.26	2.02 – 2.35	1.95 – 2.43	3.7
$ \Delta m^2 /10^{-3} \text{ eV}^2$	NO	2.455	2.423 – 2.490	2.390 – 2.523	2.355 – 2.557	1.4
	IO	2.441	2.406 – 2.474	2.372 – 2.507	2.338 – 2.540	1.4
$\sin^2 \theta_{23}/10^{-1}$	NO	5.51	4.81 – 5.70	4.48 – 5.88	4.30 – 6.02	5.2
	IO	5.57	5.33 – 5.74	4.86 – 5.89	4.44 – 6.03	4.8
δ/π	NO	1.32	1.14 – 1.55	0.98 – 1.79	0.83 – 1.99	14.6
	IO	1.52	1.37 – 1.66	1.22 – 1.79	1.07 – 1.92	9.3

Known parameters constrained at few % level

If trend continued, the unknown δ could be known at 10% level

Hints for maximal nearly CP violation and NO

Partial Update - [Capozzi et al. 2019, preliminary, unpublished]

RENO	arXiv:1806.00248	✓
Daya Bay	arXiv:1809.02261	✓
Double Chooz	arXiv:1901.09445	✗

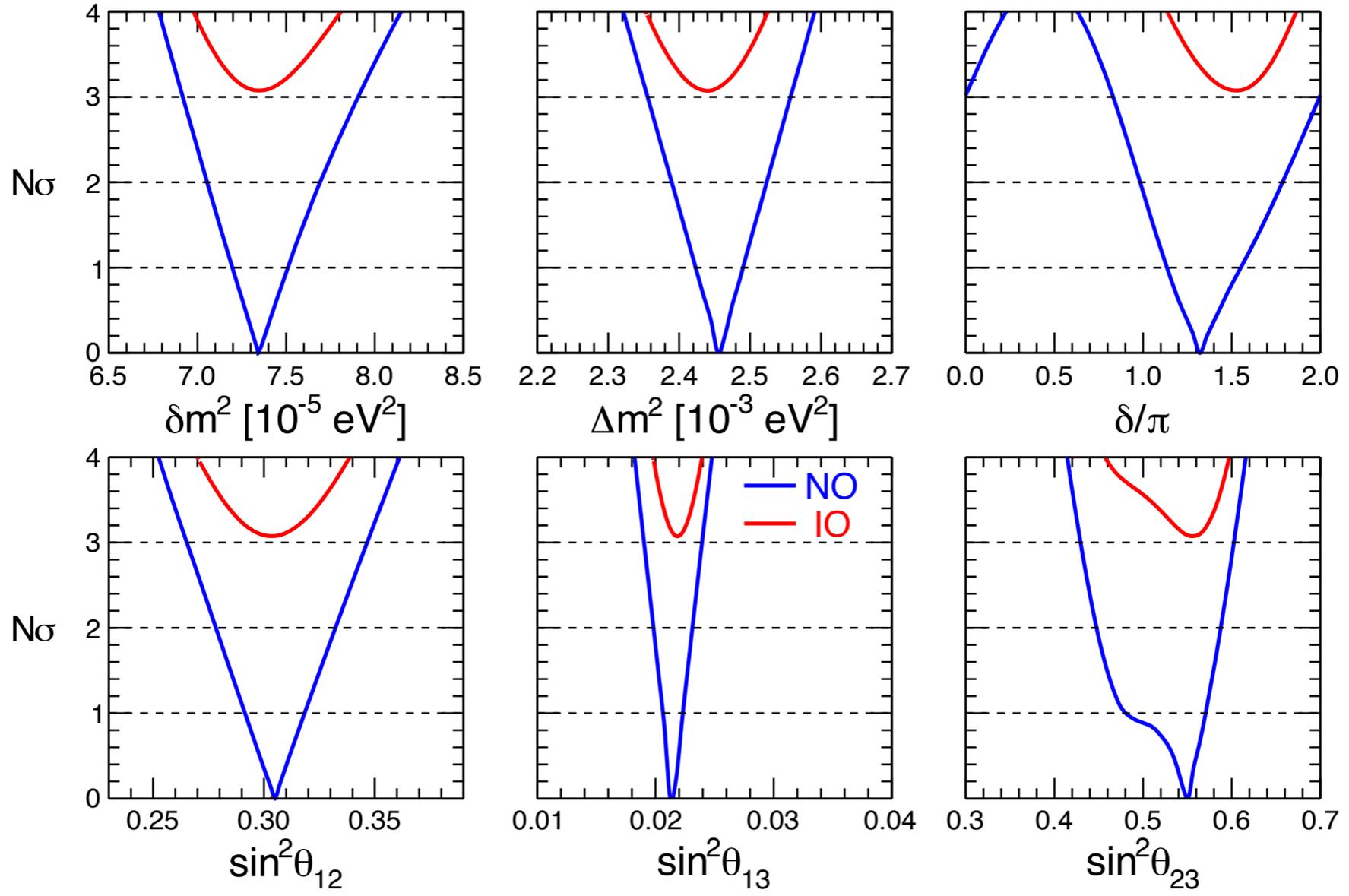
T2K	Neutrino 2018 + other conferences 2018/19	✓
NOvA	Neutrino 2018 + other conferences 2018/early 19	✓

SK-IV atmos.	arXiv:1901.03230, fitQun reconstr. algorithm	✗
DeepCore	arXiv:1902.07771, analyses "A" and "B"	✗

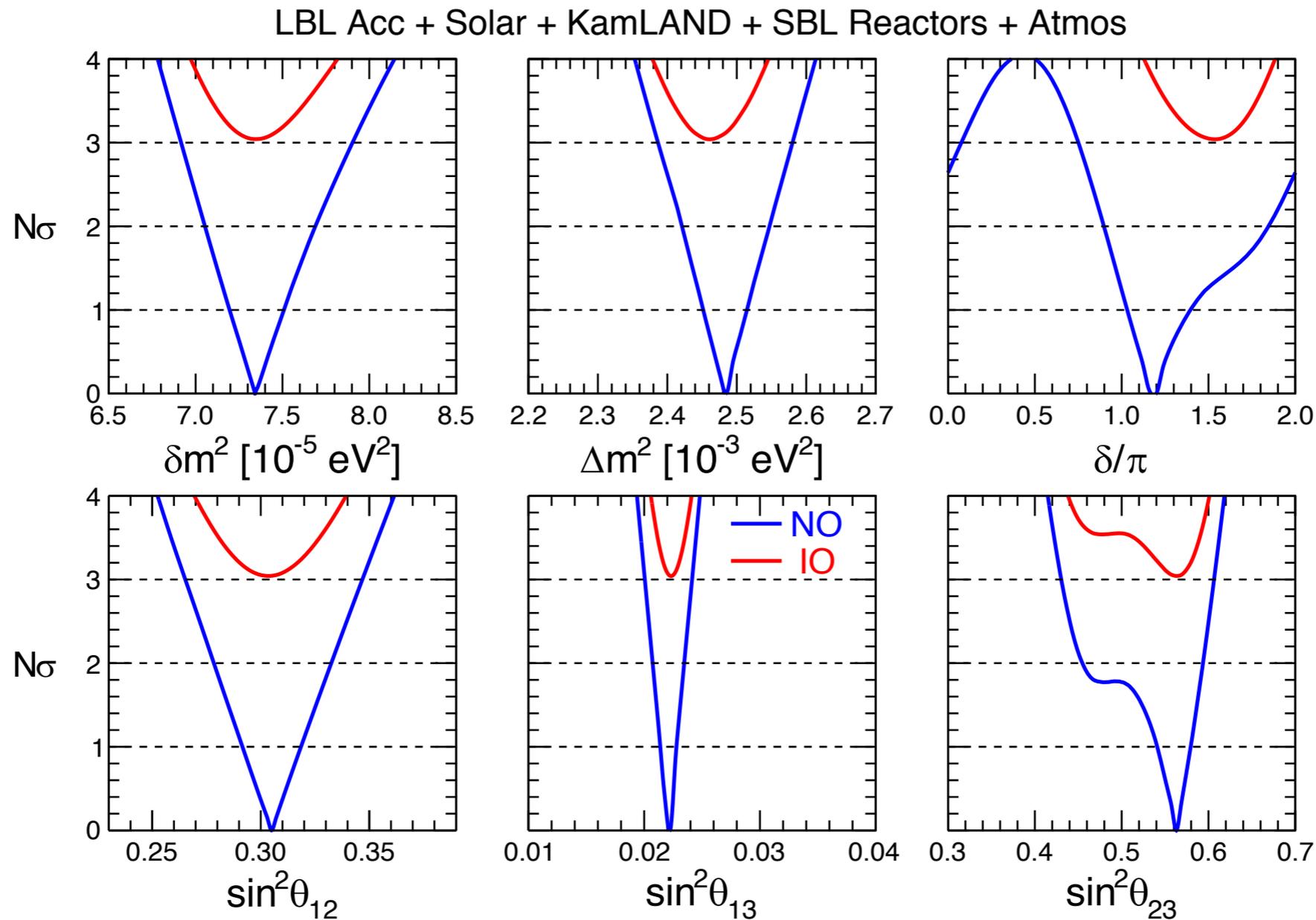
Few days ago: NOvA update arXiv:1906.04907

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos

2018



2019

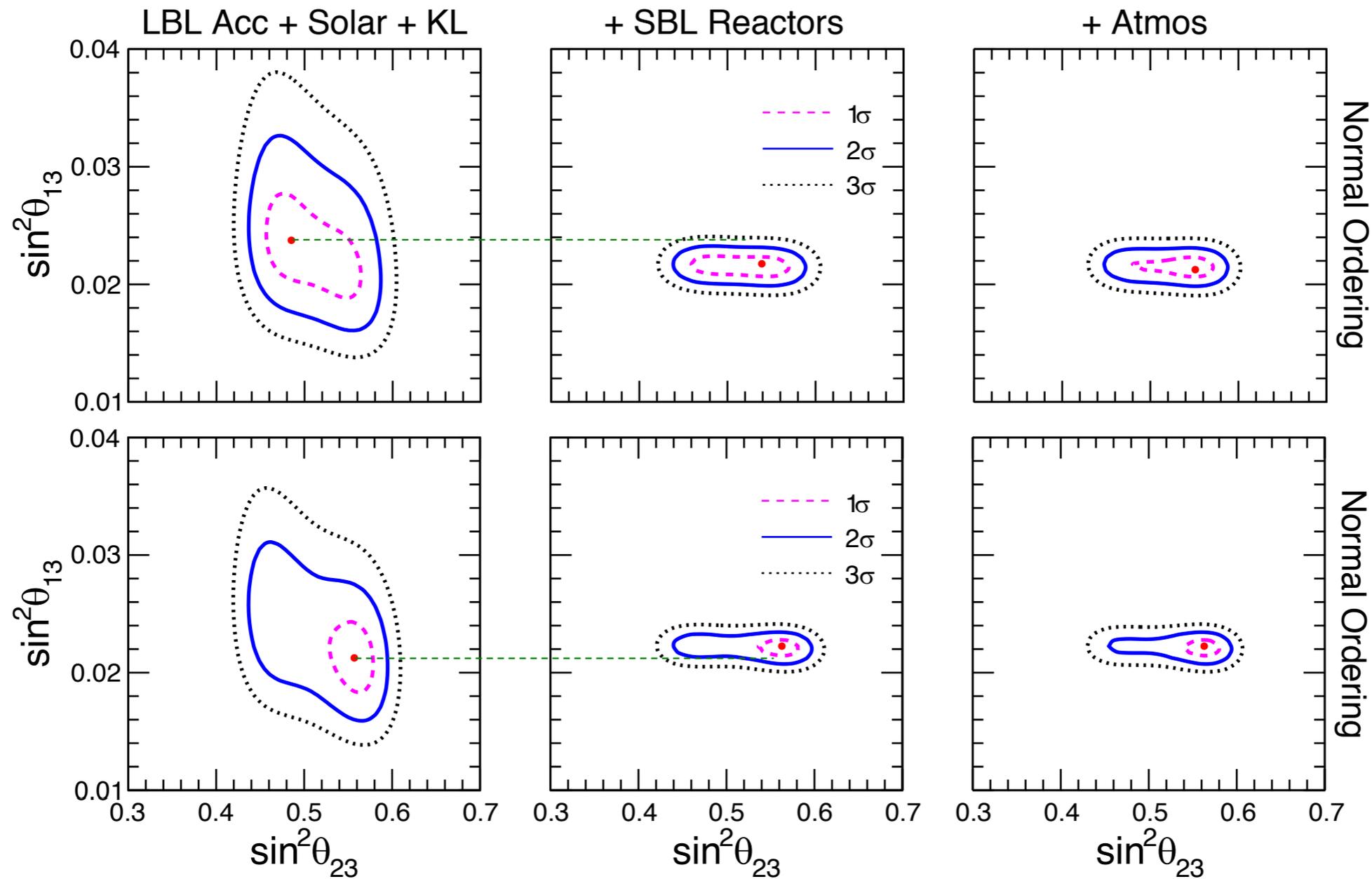


NO - slight increase of best-fit values for $(\Delta m^2, \theta_{23}, \theta_{13})$
with slightly smaller errors

NO - slight decrease of best-fit value of δ
with weaker CPV significance

IO remains disfavoured at 3 σ level \rightarrow stable hint for NO

Covariances of $(\sin^2 \theta_{23}, \sin^2 \theta_{13})$ for NO



2018

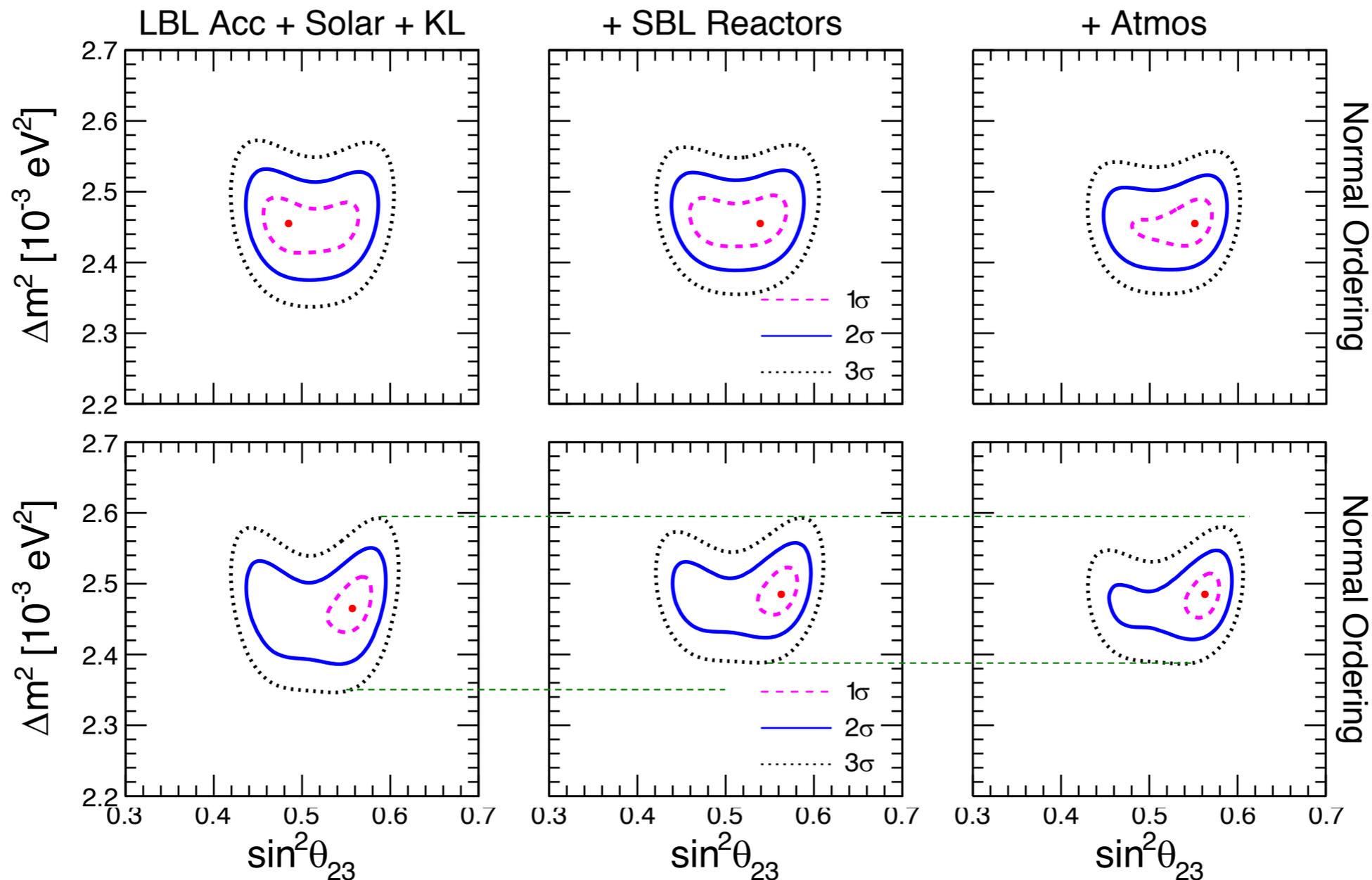
2019

Slight preference for second octant of ν_{23} already from LBL+Solar+KL data

Slightly higher ν_{13} with smaller errors fro SBL reactor data

Best fit for LBL+Solar+KL in better agreement with SBL data indirectly adds preference for second octant of ν_{23}

Covariances of $(\sin^2 \theta_{23}, \Delta m^2)$ for NO

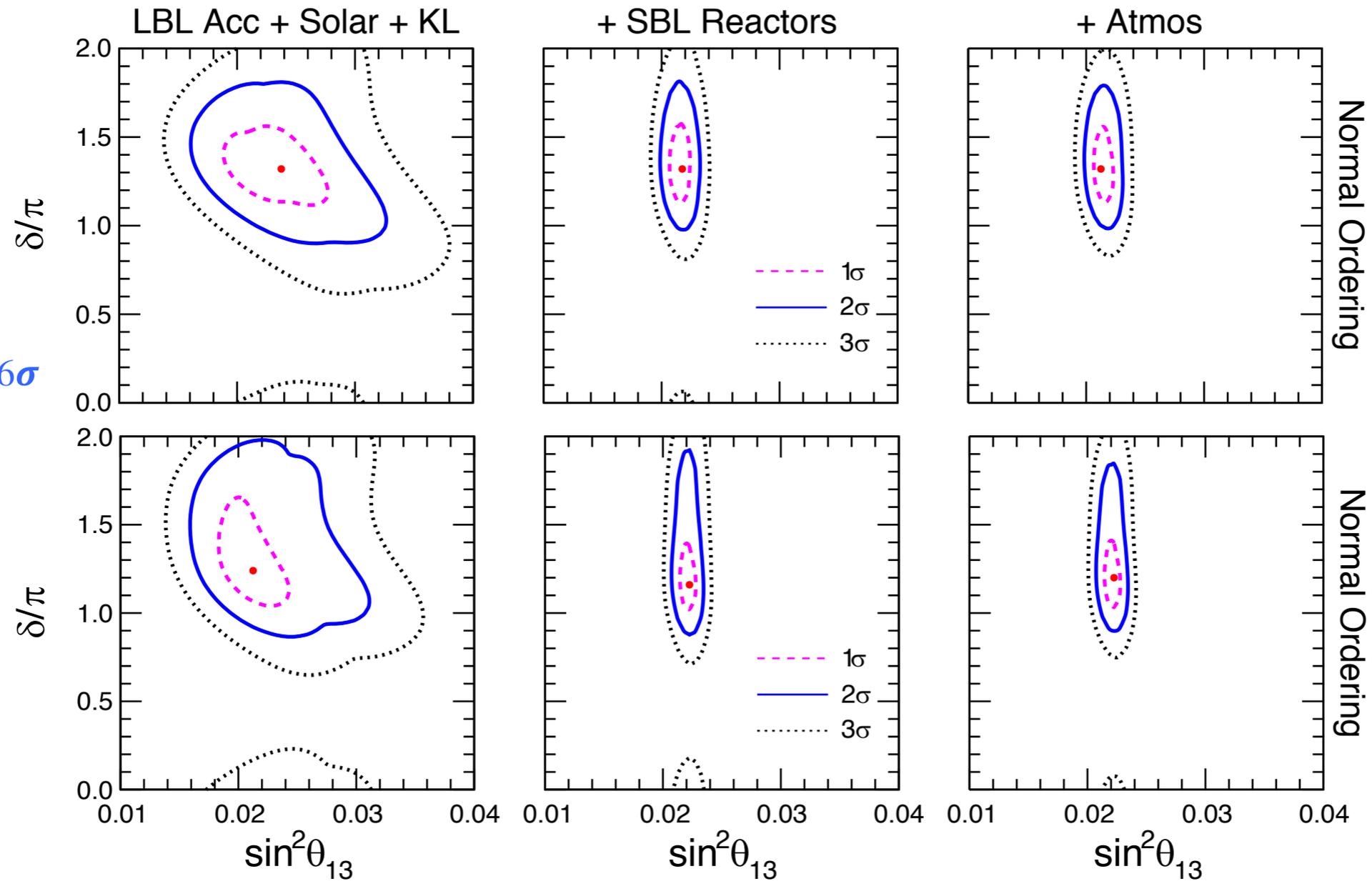


Δm^2 : Note impact of SBL reactors + atmos. data in reducing its range

$\sin^2 \theta_{23}$: As noted, LBL (+SBL) preference for 2nd octant, but... SK-IV?

SK IV weak preference for first octant ...

Covariances of $(\sin^2 \theta_{13}, \delta)$ for NO



CPC

$\delta=0, 2\pi @ 2.6\sigma$

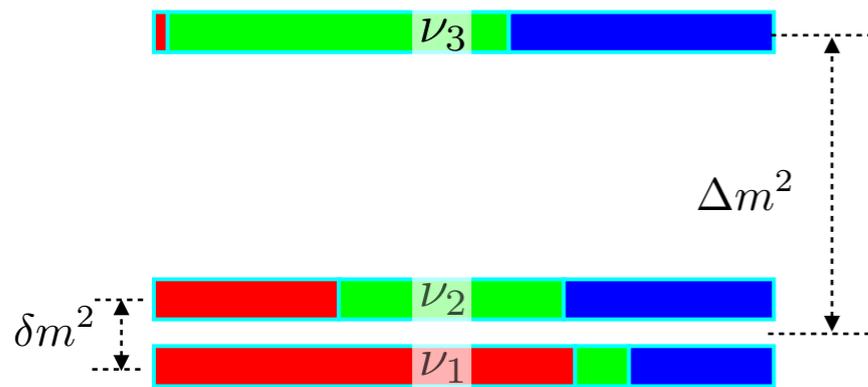
$\delta=\pi @ 1.3\sigma$

2018

2019

CP violation favored, but CP conservation "less disfavored" than in 2018 analysis, mainly due to NOvA constraints being "out of phase" with T2K in NO. Need to wait for higher statistics (and possible T2K+NOvA joint fit)

Comparison of global analyses



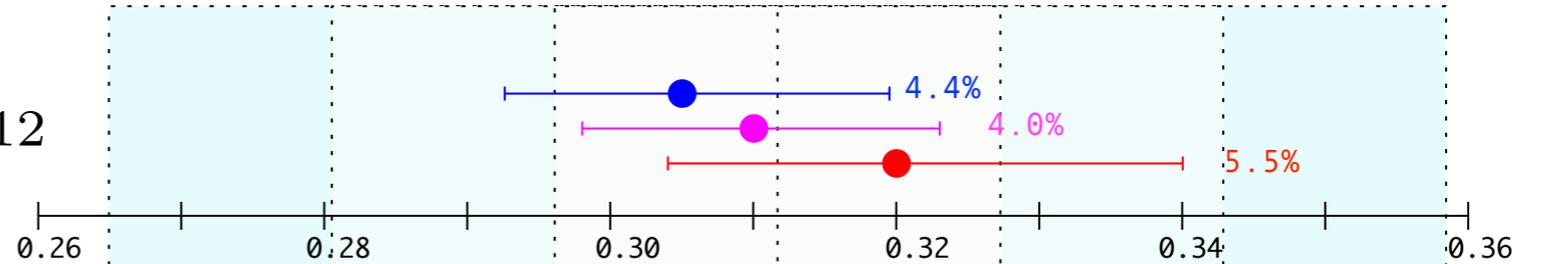
- ν_e
- ν_μ
- ν_τ

- Bari
- NuFit
- Valencia

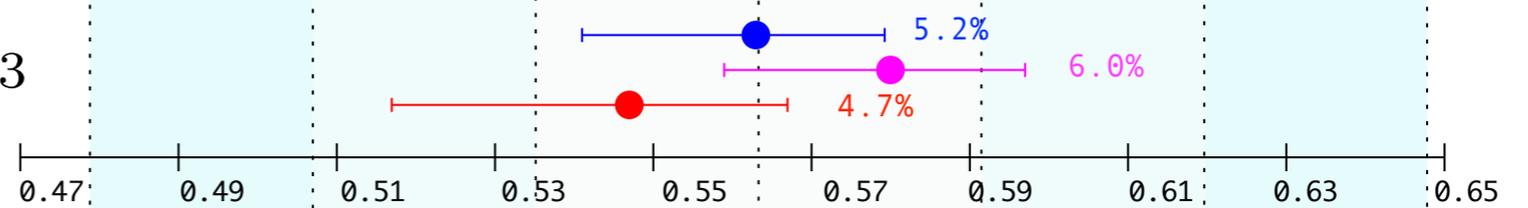
The three global analyses are in good agreement with some difference about θ_{23} ranges & octant

Normal Ordering

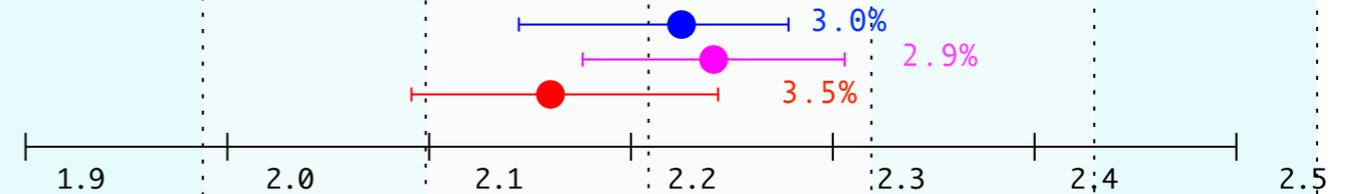
$\sin^2 \theta_{12}$



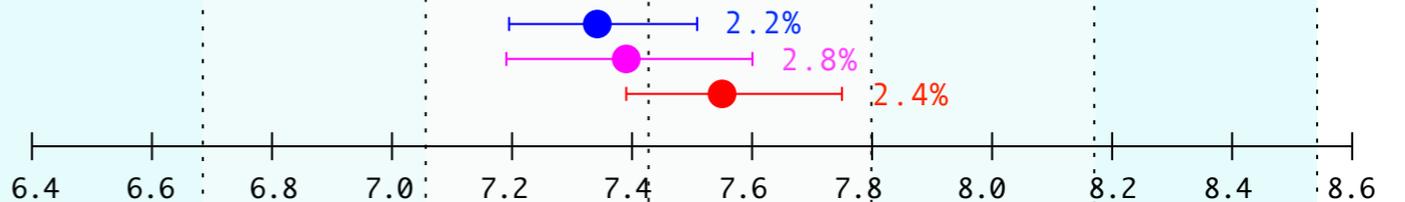
$\sin^2 \theta_{23}$



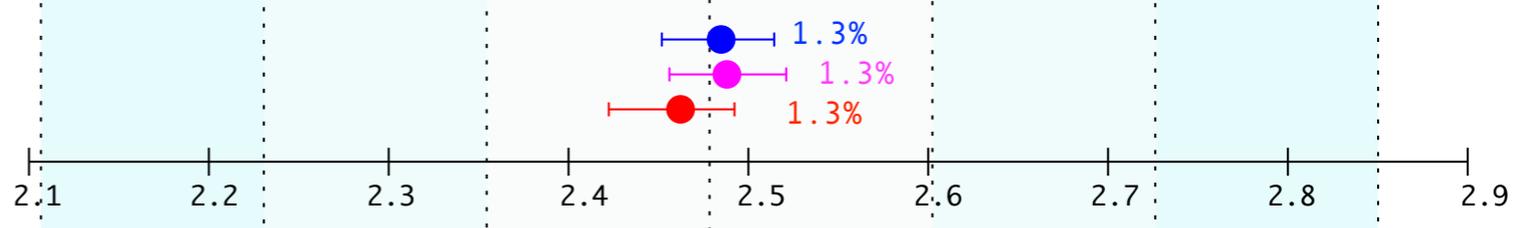
$\sin^2 \theta_{13}$



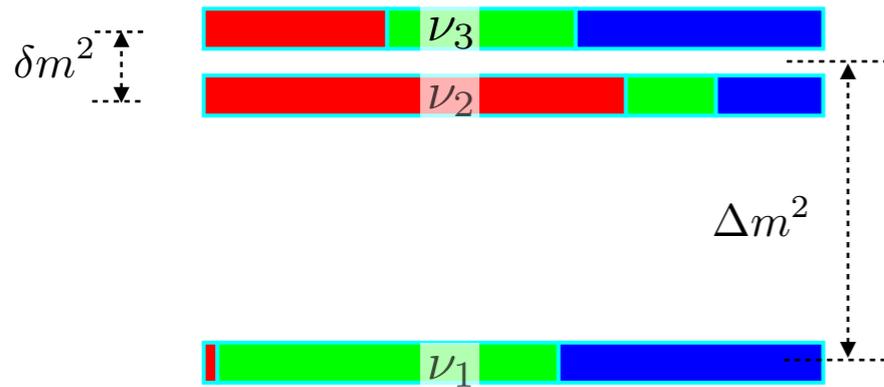
δm^2



Δm^2



Comparison of global analyses



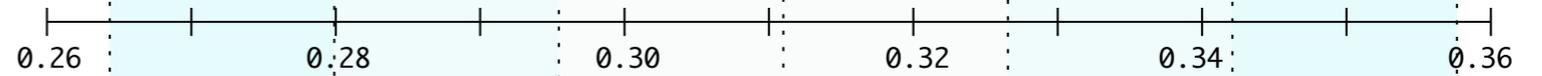
- ν_e
- ν_μ
- ν_τ

- Bari
- NuFit
- Valencia

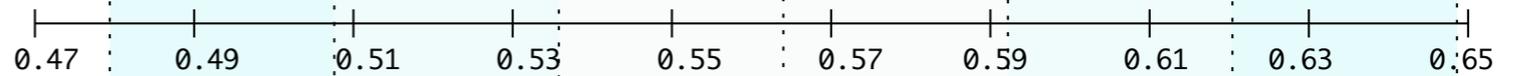
The three global analyses are in good agreement with some difference about θ_{23} ranges & octant)

Inverted Ordering

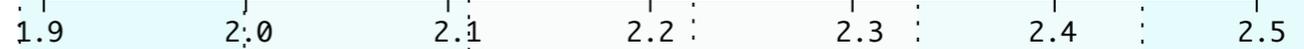
$\sin^2 \theta_{12}$



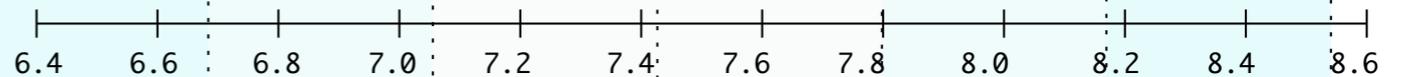
$\sin^2 \theta_{23}$



$\sin^2 \theta_{13}$



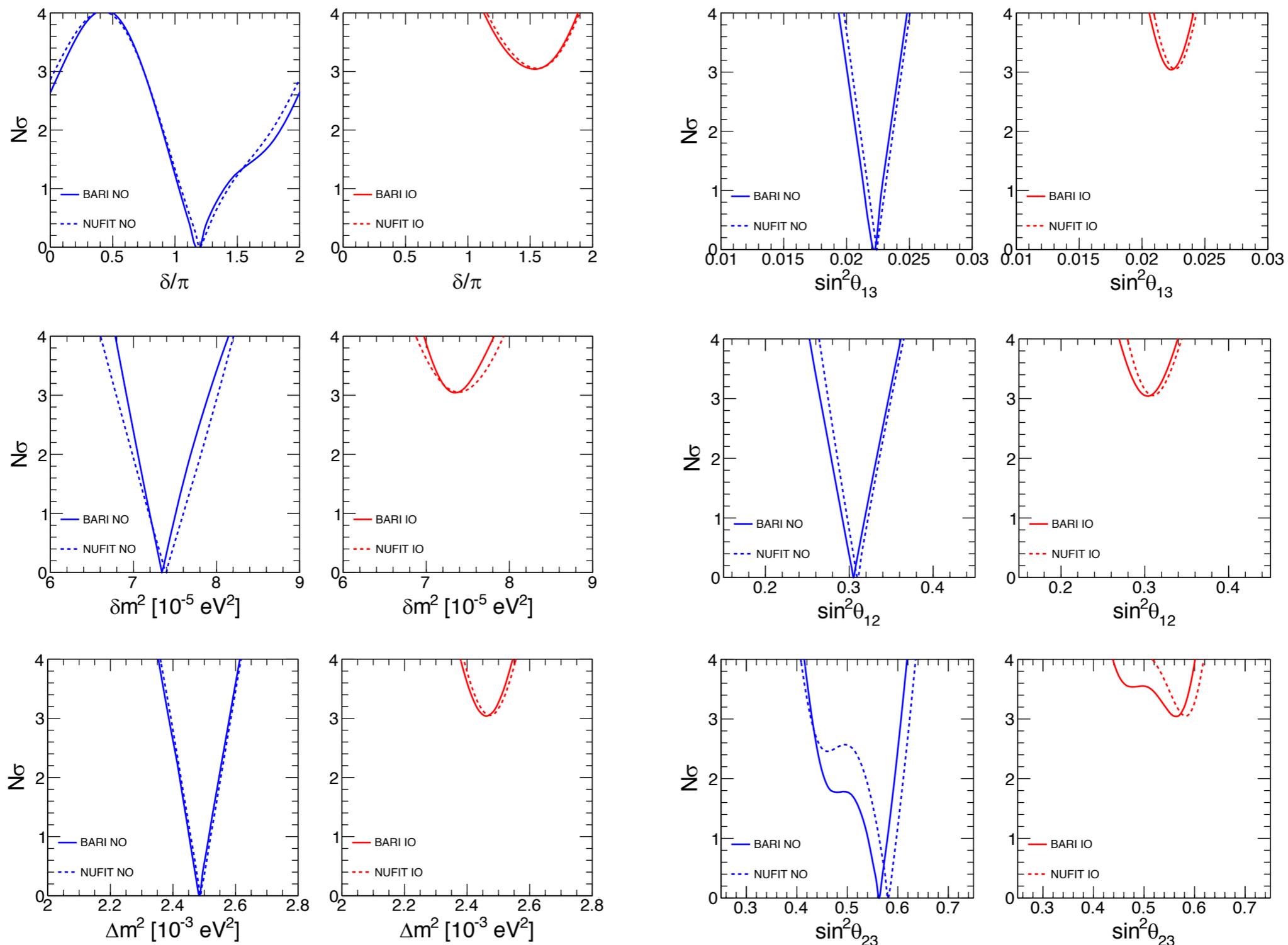
δm^2



Δm^2



Comparison of this 2019 partial update ("BARI") with NuFIT 4.0 results ("NUFIT")



Agreement as good as it can be expected from independent phenom. analyses
 [except perhaps for the "bimodal" -and relatively fragile- pdf of $\sin^2\theta_{23}$]

New $\nu + \bar{\nu}$ Oscillation

Results from NOvA

Jeremy Wolcott (Tufts University)
52nd Fermilab Users Meeting
June 13, 2019

NOvA update

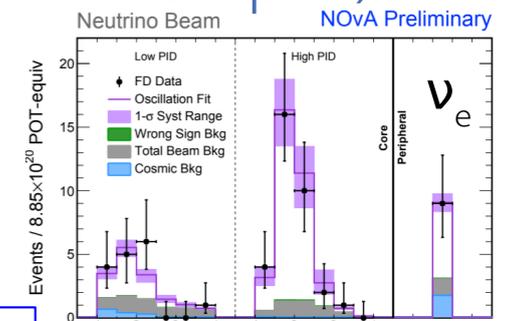
J. Wolcott @Fermilab, June 13, 2019

[arxiv:1906.04907](https://arxiv.org/abs/1906.04907)

4.4 σ observation of $\bar{\nu}_e$ appearance
27 $\bar{\nu}_\nu \rightarrow \bar{\nu}_e$ events (10 background)

FD data (with new $\bar{\nu}$ sample!)

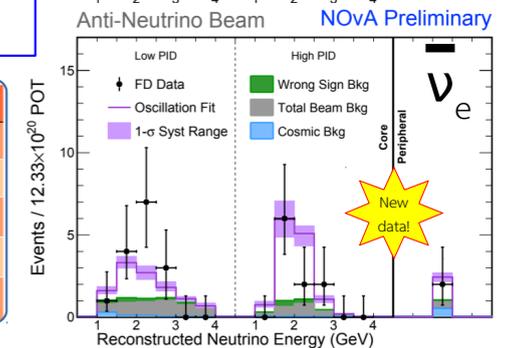
Data neutrino candidates	58
Best fit total prediction	59
total bkgd.:	15.0
↳ cosmic bkgd.	3.3
↳ beam bkgd.	11.1
↳ wrong-sign (app. $\bar{\nu}_e$)	0.7



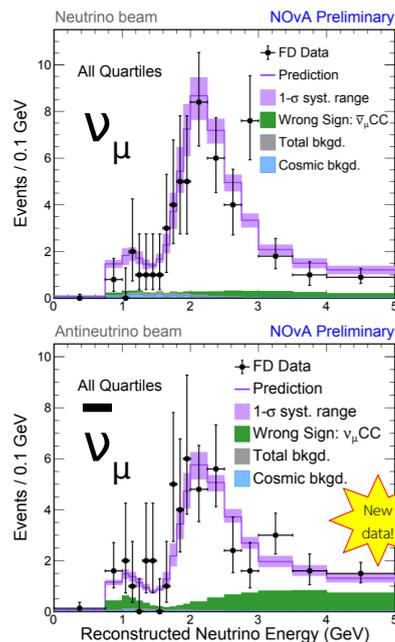
Evidence for $\bar{\nu}_e$ appearance at 4.4 σ

Now with 78% more $\bar{\nu}$ data!

Data antineutrino candidates	27
Best fit total prediction	27
total bkgd.:	10.3
↳ cosmic bkgd.	1.1
↳ beam bkgd.	7.0
↳ wrong-sign (app. ν_e)	2.2



FD data (with new $\bar{\nu}$ sample!)



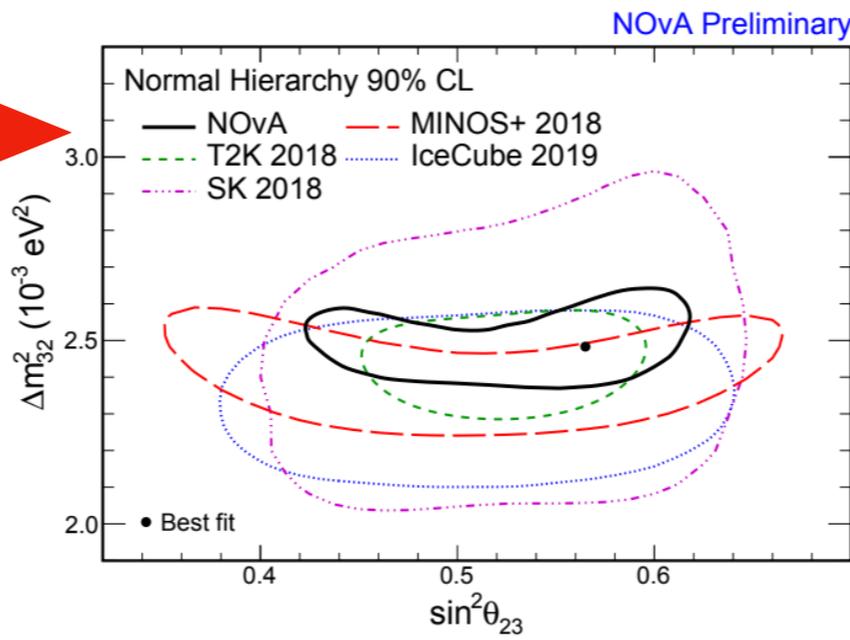
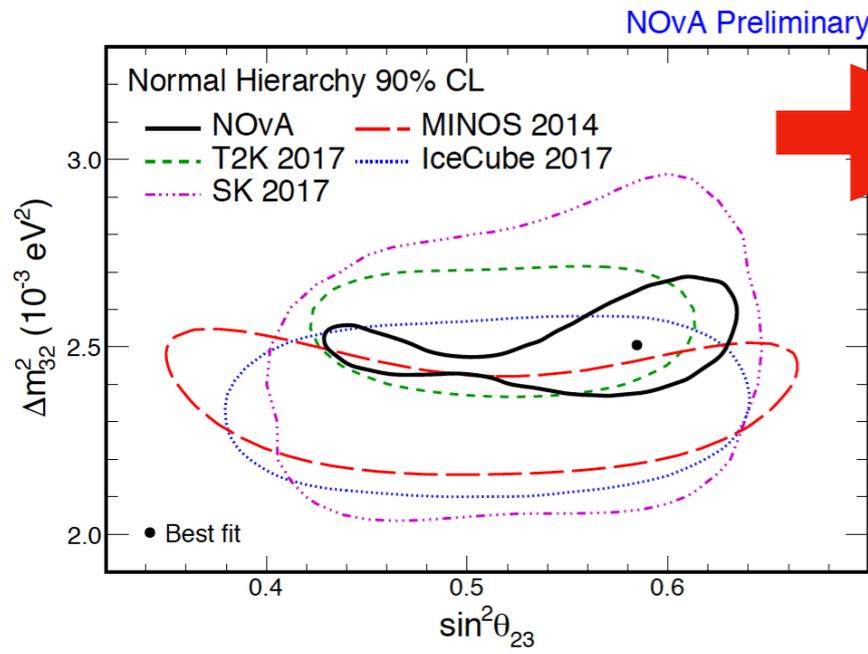
Data neutrino candidates	113
Best fit total prediction	124
total bkgd.:	4.2
↳ cosmic bkgd.	2.1
↳ beam bkgd.	2.1

3-flavor oscillations describe data well
(goodness-of-fit $p = 0.91$)

Data antineutrino candidates	102
Best fit total prediction	96
total bkgd.:	2.2
↳ cosmic bkgd.	0.8
↳ beam bkgd.	1.4

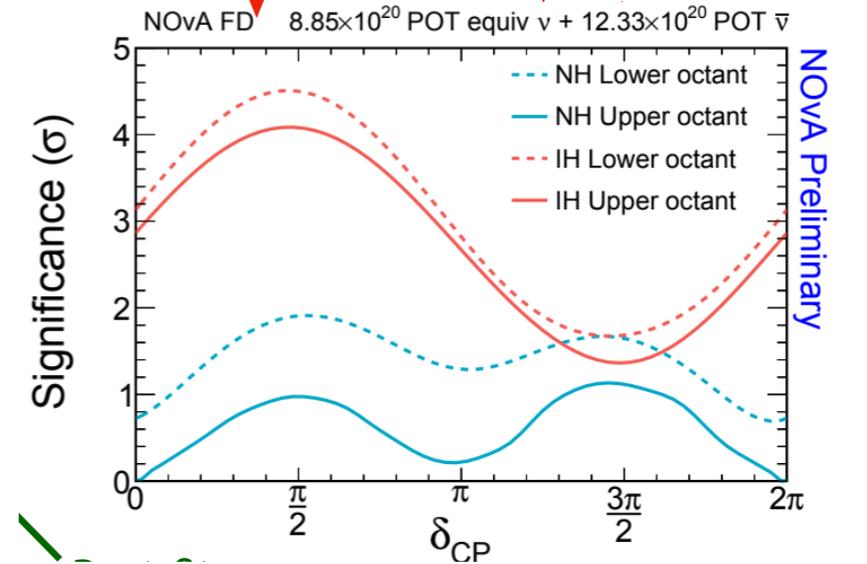
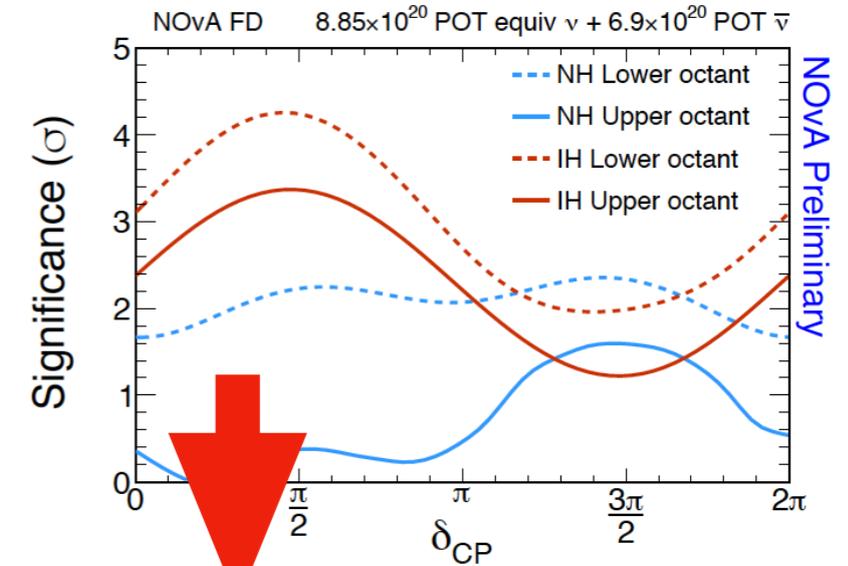
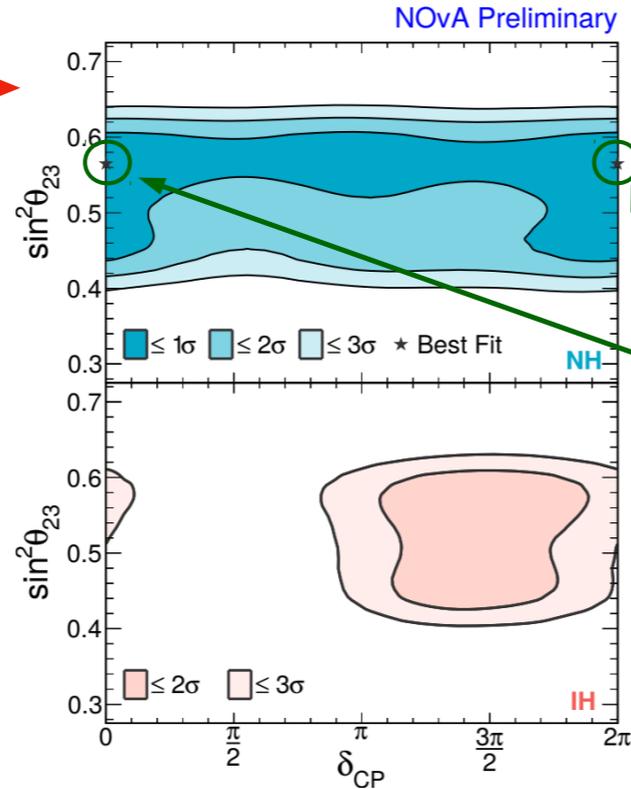
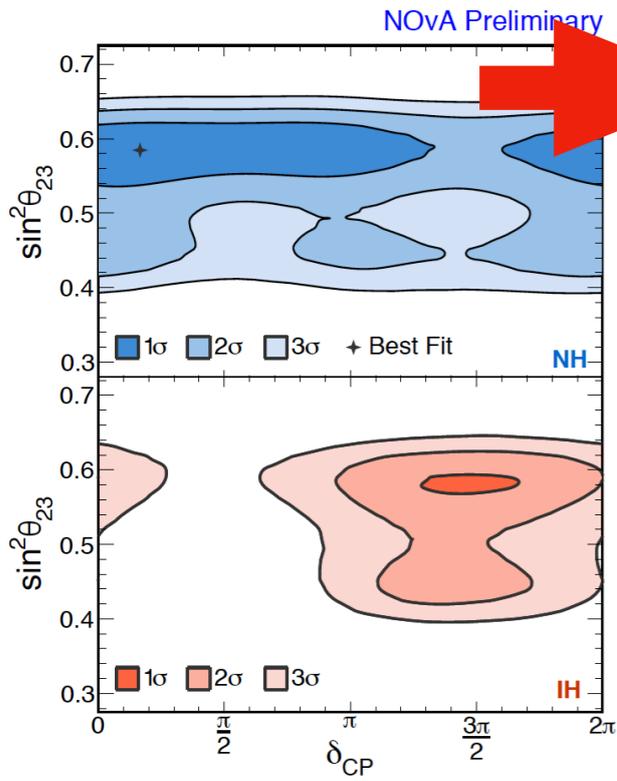
Now with 78% more $\bar{\nu}$ data!

102 $\bar{\nu}_\nu \rightarrow \bar{\nu}_\mu$ candidates



Maximal ϑ_{23} less disfavoured

Weaker bounds on δ for NO



NO favoured with respect to IO at 1.9σ (it was 1.8σ)

Probably Less "tension" with T2K data

Future Prospects

Open issues

Mass Ordering
CP phase δ
T23 maximal mixing/octant
Precision at $\leq 1\%$ level

Open issues

Absolute mass scale
Dirac/Majorana neutrinos
Mass Ordering

Oscillation Experiments

DUNE
HyperKamiokande
INO
JUNO
ORCA
PINGU

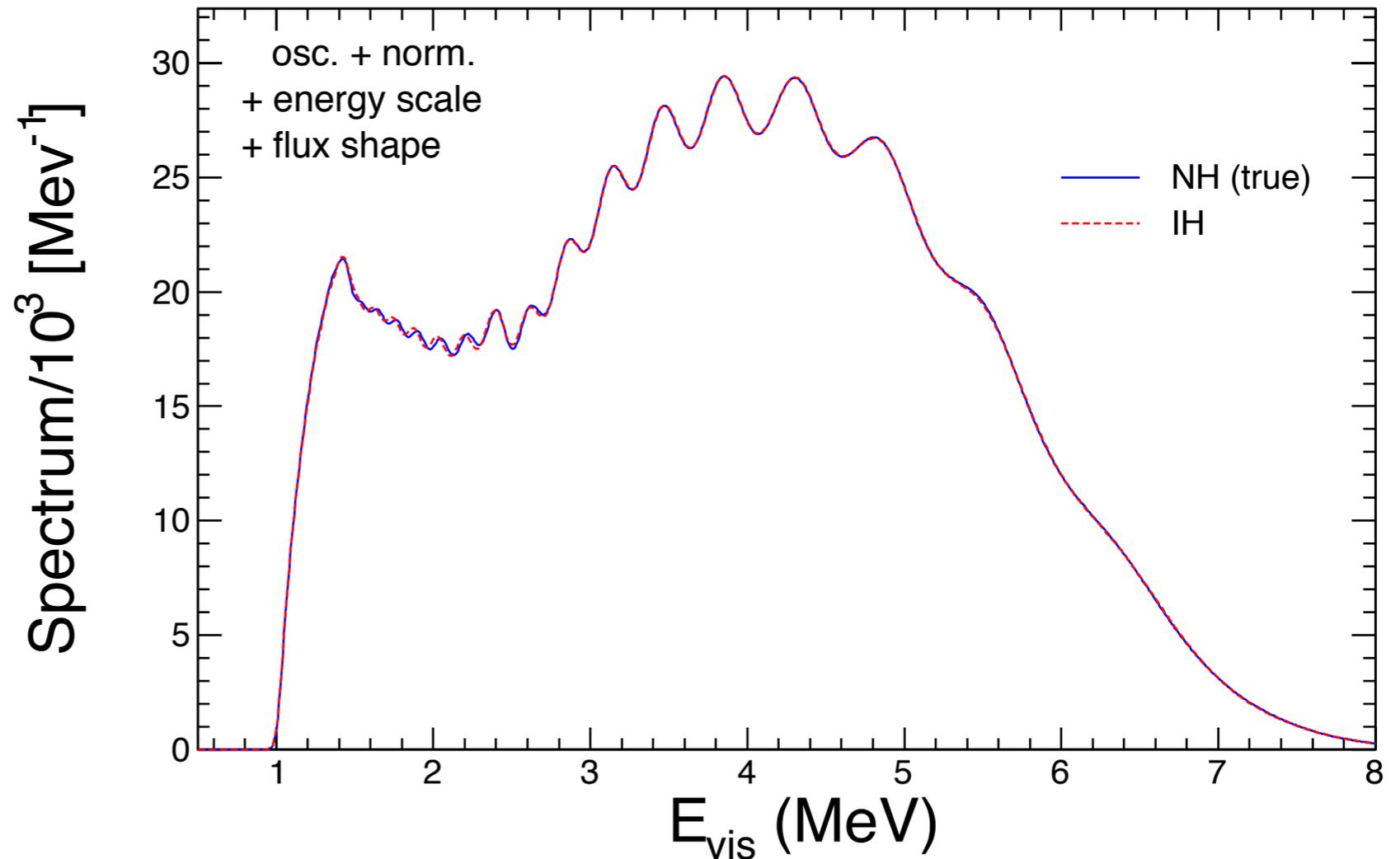
Non-Oscillation Experiments

$0\nu\beta\beta$ experiments
Cosmology + Astrophysics

Expectations for JUNO reactor experiment

"Medium" baseline
~50 km

Main goal:
distinguish NO vs
IO at 3-4 σ in 6y



Expected improvements
on oscillation parameters

$$\delta m^2 \sim 7.34 \times 10^{-5} \text{ eV}^2 \quad (2.2\%) \quad \rightarrow \quad (0.6\%)$$

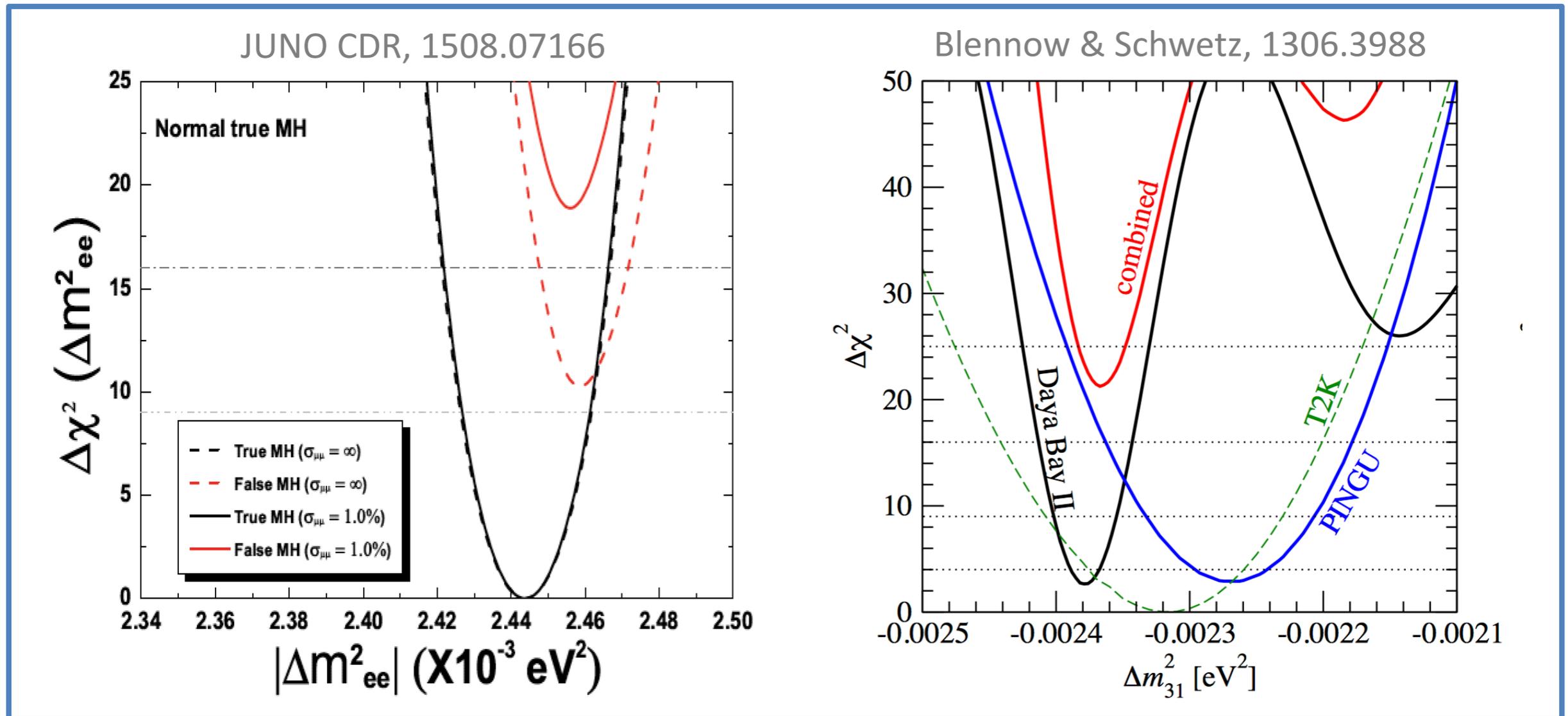
$$\Delta m^2 \sim 2.49 \times 10^{-3} \text{ eV}^2 \quad (1.3\%) \quad \rightarrow \quad (0.5\%)$$

$$\sin^2 \theta_{12} \sim 0.305 \quad (4.4\%) \quad \rightarrow \quad (0.4\%)$$

$$\sin^2 \theta_{13} \sim 2.23 \times 10^{-2} \quad (3.0\%) \quad \rightarrow \quad (\sim 3\%)$$

JUNO + improved Δm^2 from LBL accel. and Atmospheric expts

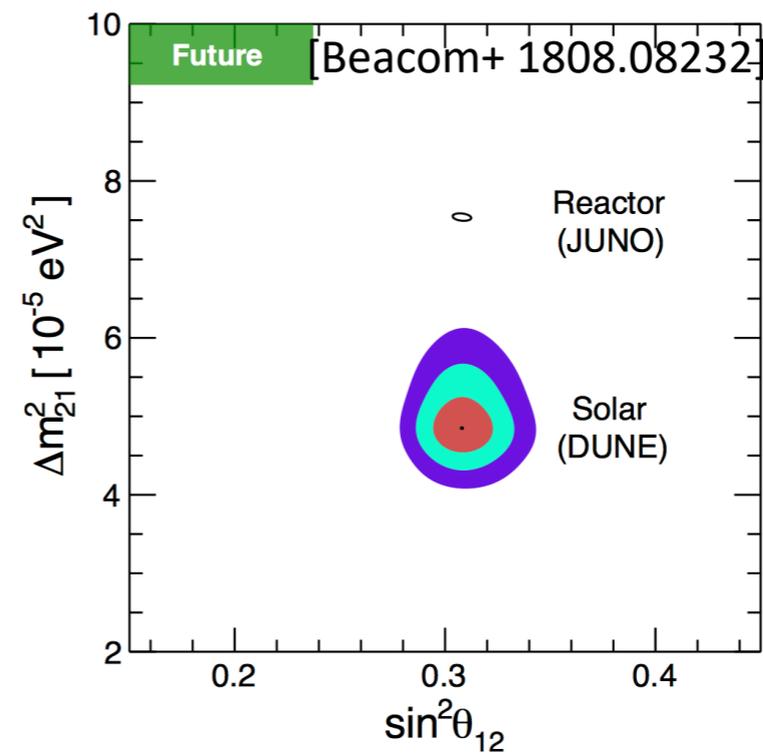
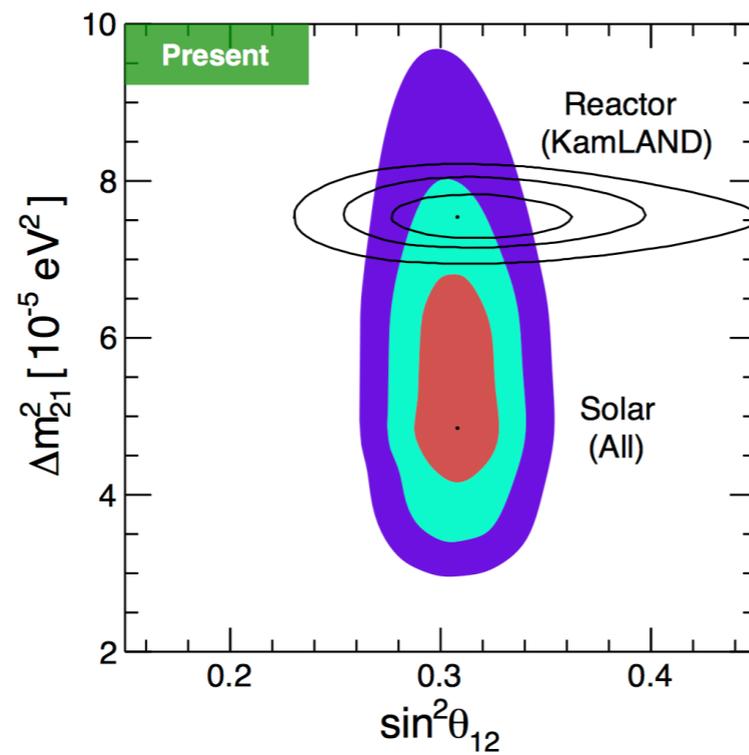
Complementarity: different measurements of Δm^2 give better NO/IO discrimination because of misfits differ in different expts



At lower significance, this complementarity is already at work in available data

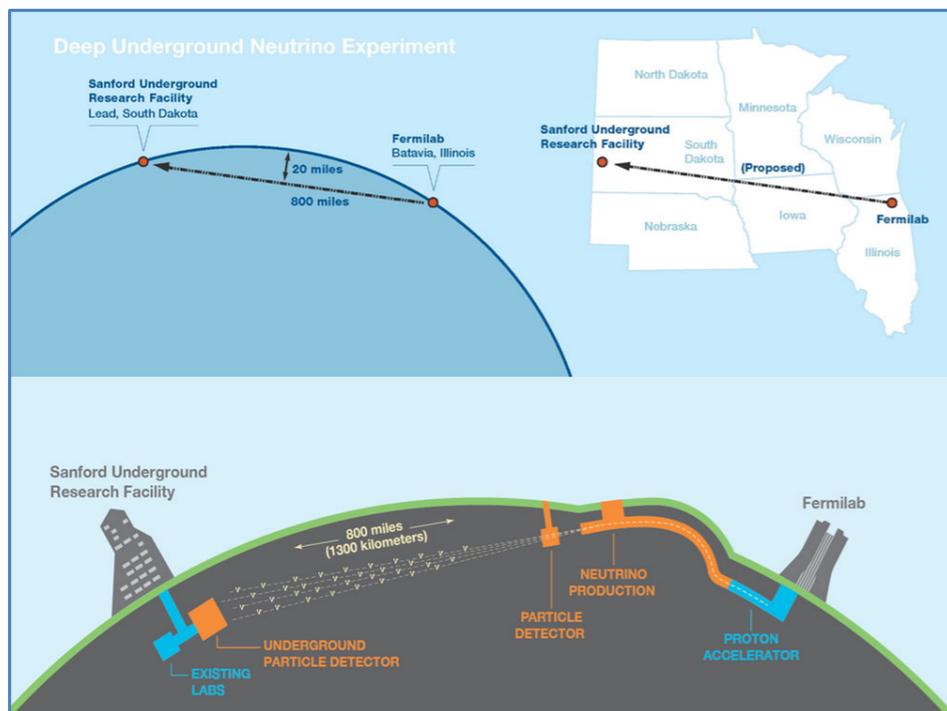
(Very) Long term: JUNO (osc. in vacuum) + high-precision solar ν data (osc. in matter) might test the slight solar vs KamLAND "tension" ($\sim 2\sigma$) currently emerging from global fits in the determination of δm^2

Hypothetical outcome of a proposed DUNE-based solar ν experiment vs JUNO:



Expectations for DUNE, LBL accel. expt

Disappearance + appearance enable to probe several 3ν knowns and unknowns



Physics milestone	Exposure (kt · MW · year)	Exposure (years)
$1^\circ \theta_{23}$ resolution ($\theta_{23} = 42^\circ$)	29	1
CPV at 3σ ($\delta_{CP} = -\pi/2$)	77	3
MH at 5σ (worst point)	209	6
$10^\circ \delta_{CP}$ resolution ($\delta_{CP} = 0$)	252	6.5
CPV at 5σ ($\delta_{CP} = -\pi/2$)	253	6.5
CPV at 5σ 50% of δ_{CP}	483	9
CPV at 3σ 75% of δ_{CP}	775	12.5
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	857	13.5

$$\Delta m^2 \sim 2.49 \times 10^{-3} \text{ eV}^2 \quad (1.3\%) \quad \rightarrow \quad (0.3\%)$$

$$\sin^2 \theta_{13} \sim 2.23 \times 10^{-2} \quad (3.0\%) \quad \rightarrow \quad (\sim 3\%)$$

$$\sin^2 \theta_{23} \sim 0.55 \quad (5.2\%) \quad \rightarrow \quad (\sim 1\%)$$

Conclusions

- 3ν framework established by convergence of many data sets
 - Five known parameters are being measured with increasing accuracy
 - Five unknowns remain to be determined, with hints in favor of:
 - **NO** vs IO at the level of $\sim 3\sigma$ from oscillation data (+ cosmology)
 - **CPV** with $\delta \sim 1.2\pi$ (but CPC allowed at 1.3σ)
 - θ_{23} in 2nd octant (but 1st octant allowed at $< 2\sigma$ level)
- [All very interesting... but not robust yet]

Absolute mass scale: \rightarrow sub-eV range, help from cosmology in the next future

Dirac/Majorana nature: probably need to wait much longer...

Thank you for your attention