Ninth International Symposium on Large TPCs for low-energy rare event detection

Global analysis of neutrino oscillation parameters

Antonio Marrone - U. of Bari & INFN

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Open questions in neutrino Physics

- Dirac/Majorana nature of neutrinos
- Absolute masses
- CP violation
- Mass Ordering
- Sterile neutrinos
- Nonstantard interactions

The knowledge of mass-mixing oscillation parameters can help to answer these questions

In this talk ⟶ status of parameter determination from global analyses with focus on θ_{23}, δ and mass ordering

Based on Bari group, Prog.Part.Nucl.Phys. 102 (2018) 48-72

Precision era in neutrino oscillation phenomenology

Standard 3ν mass-mixing framework parameters

What we known

δm^2	2.2%
Δm^2	1.4%
$\sin^2\theta_{12}$	4.4%
$\sin^2\theta_{13}$	3.8%
$\sin^2\theta_{23}$	5.2%

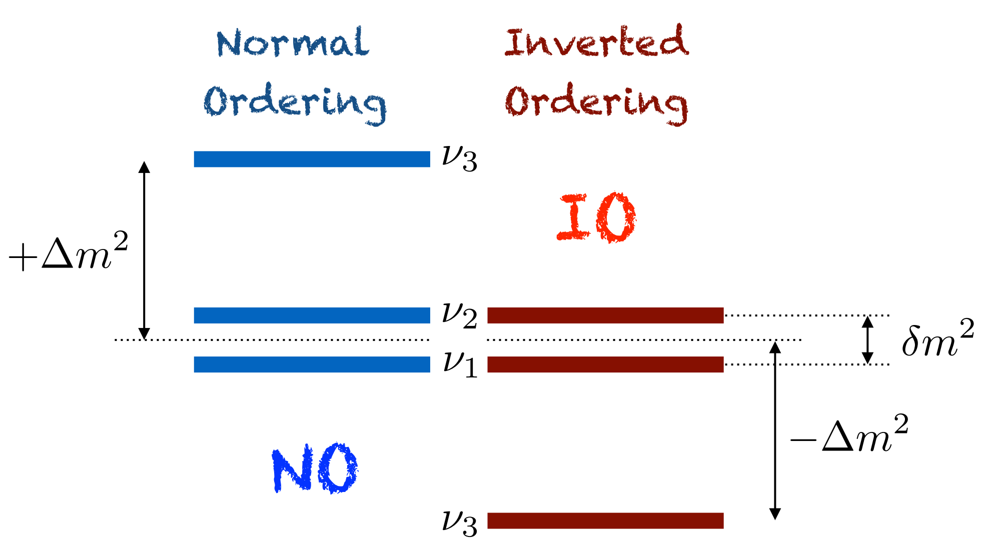
What we still do not know

CP-violating phase δ

Octant of θ_{23}

Mass Ordering -> $\mathrm{sign}(\Delta m^2)$

$$\Delta m^2 = (\Delta m^2_{13} + \Delta m^2_{23})/2$$



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:

(1) LBL acc + Solar + KamLAND

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

(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 3ν framework, but dominantly on (Δm^2, θ_{23})

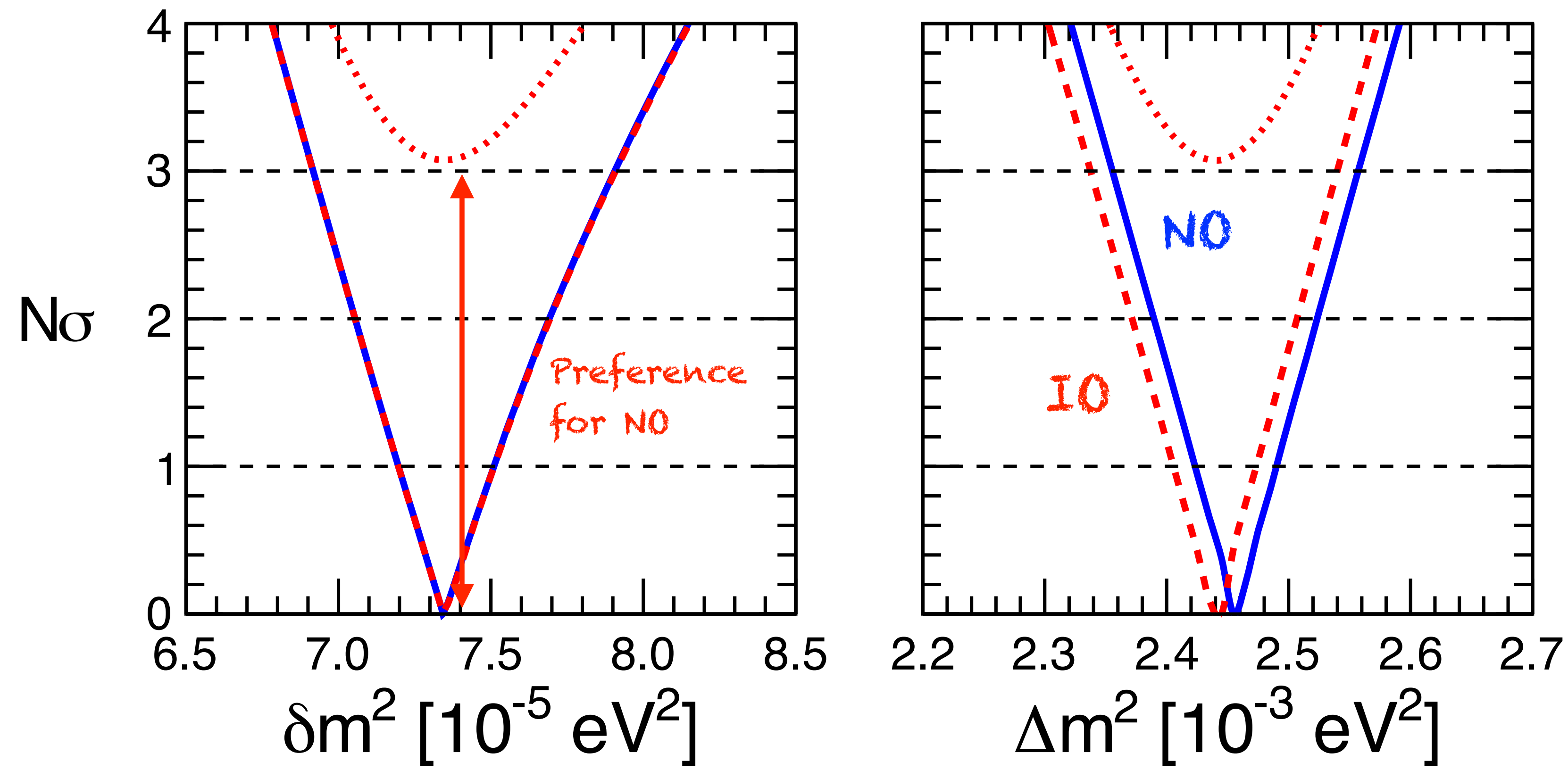
Mass Differences

$$\Delta m^2 = (\Delta m^2_{13} + \Delta m^2_{23})/2$$

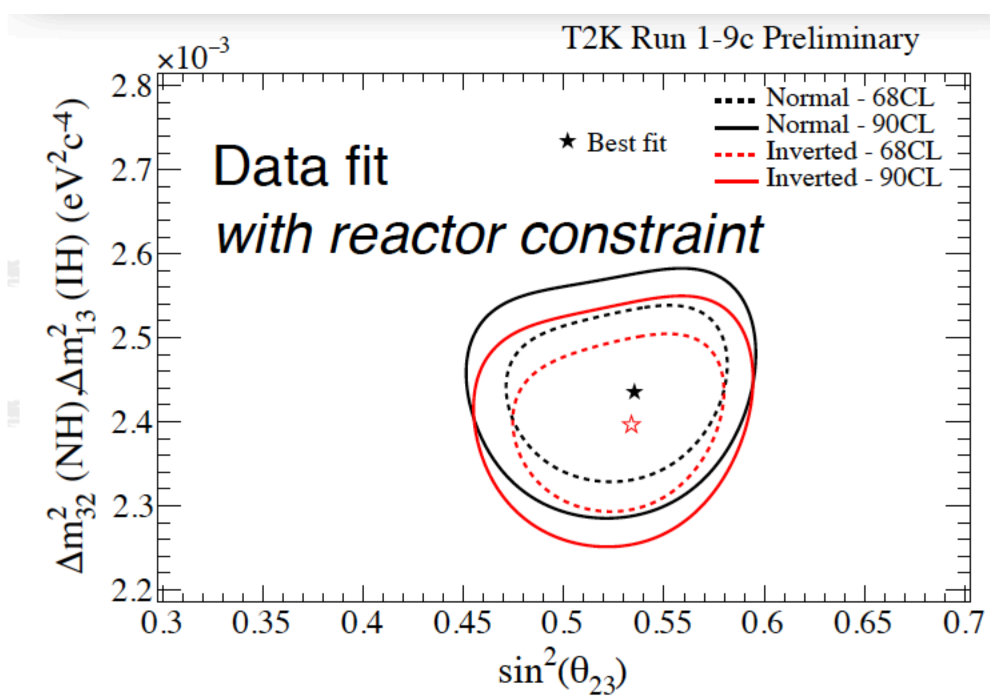
Mass Ordering = sign of Δm^2

Squared mass differences have both lower and upper bounds at more than 3σ

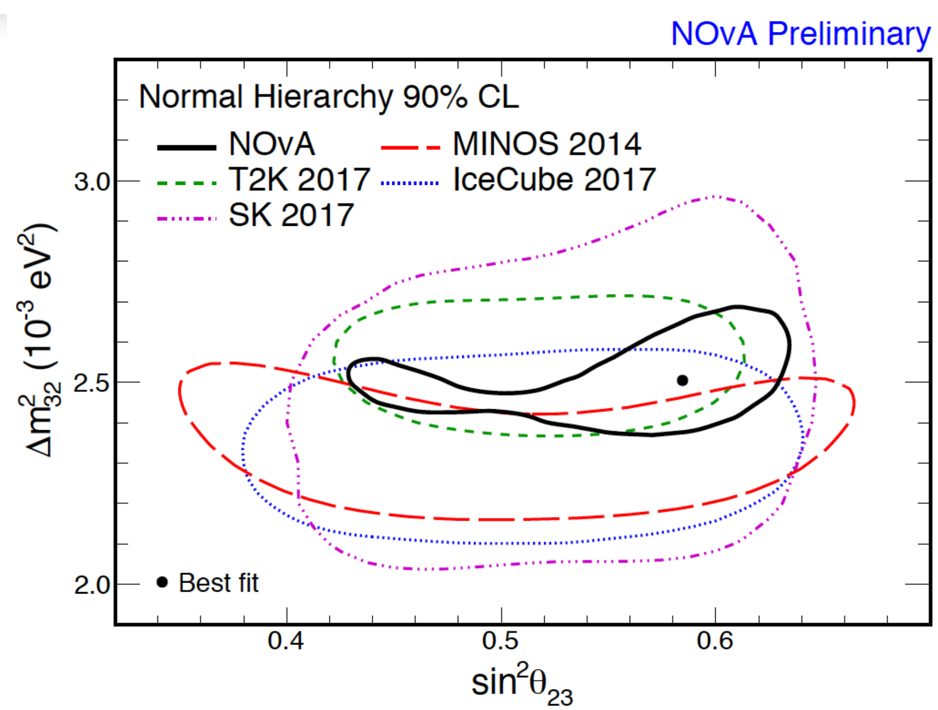
Nearly Gaussian uncertainties for Δm^2 and to a lesser extent for δm^2



Neutrino 2018 updates (still not included)

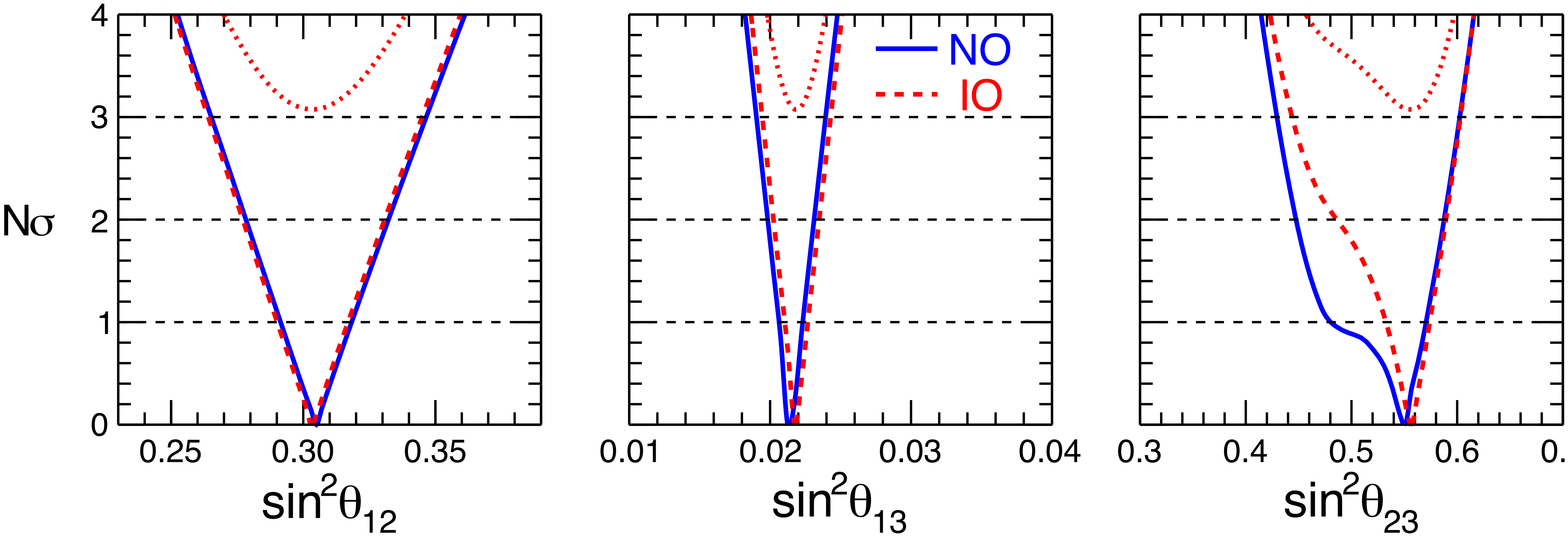


Wascko - Neutrino 2018



Sanchez - Neutrino 2018

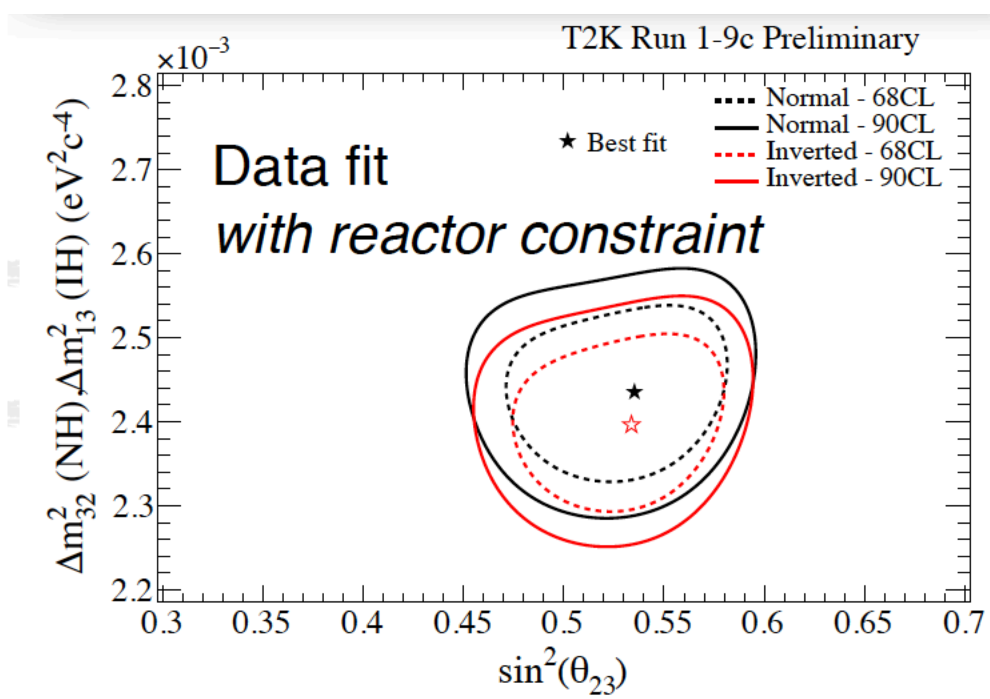
Mixing Angles

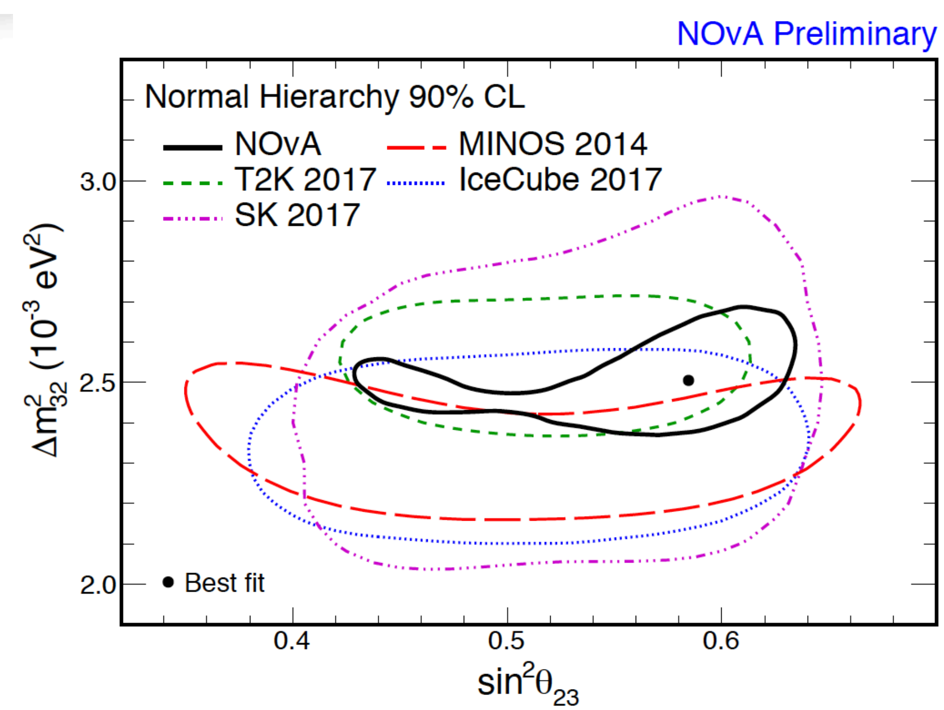


Mixing angles (θ_{23}, θ_{12}) have both lower and upper bounds at more than 3σ

Nearly Gaussian uncertainties for θ_{23} and to a lesser extent for θ_{12}

θ_{23} maximal mixing allowed at about 2σ in both NO and IO





NOvA and MINOS prefer nonmaximal mixing

θ_{23} octant ambiguity

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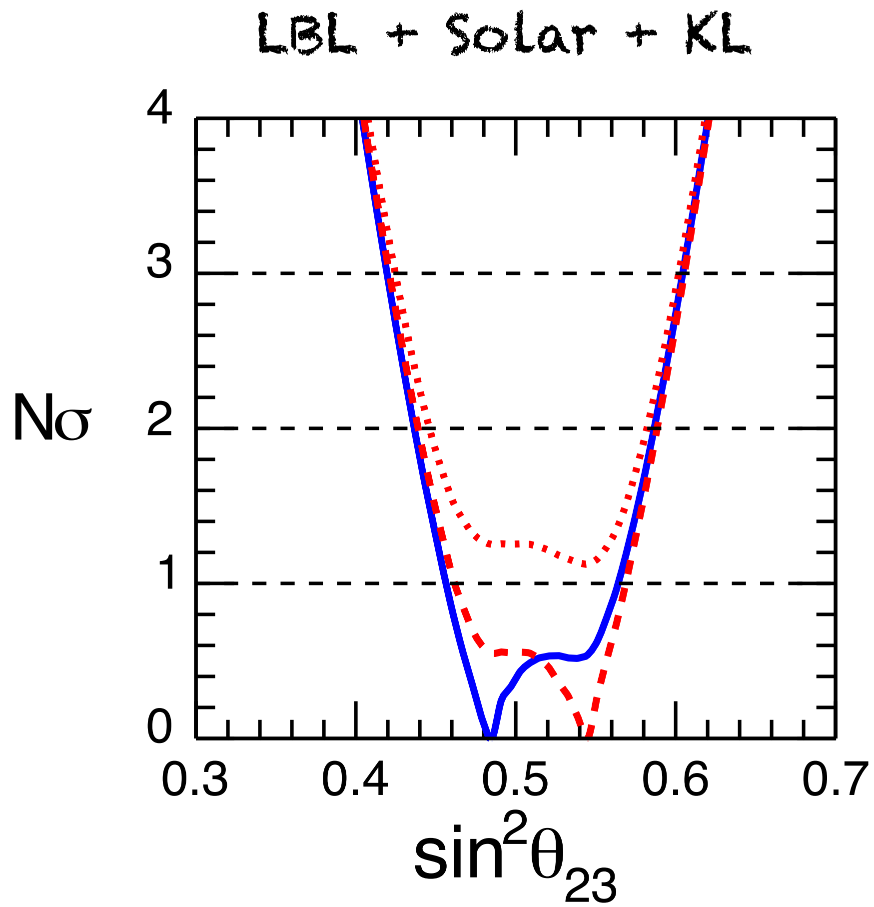
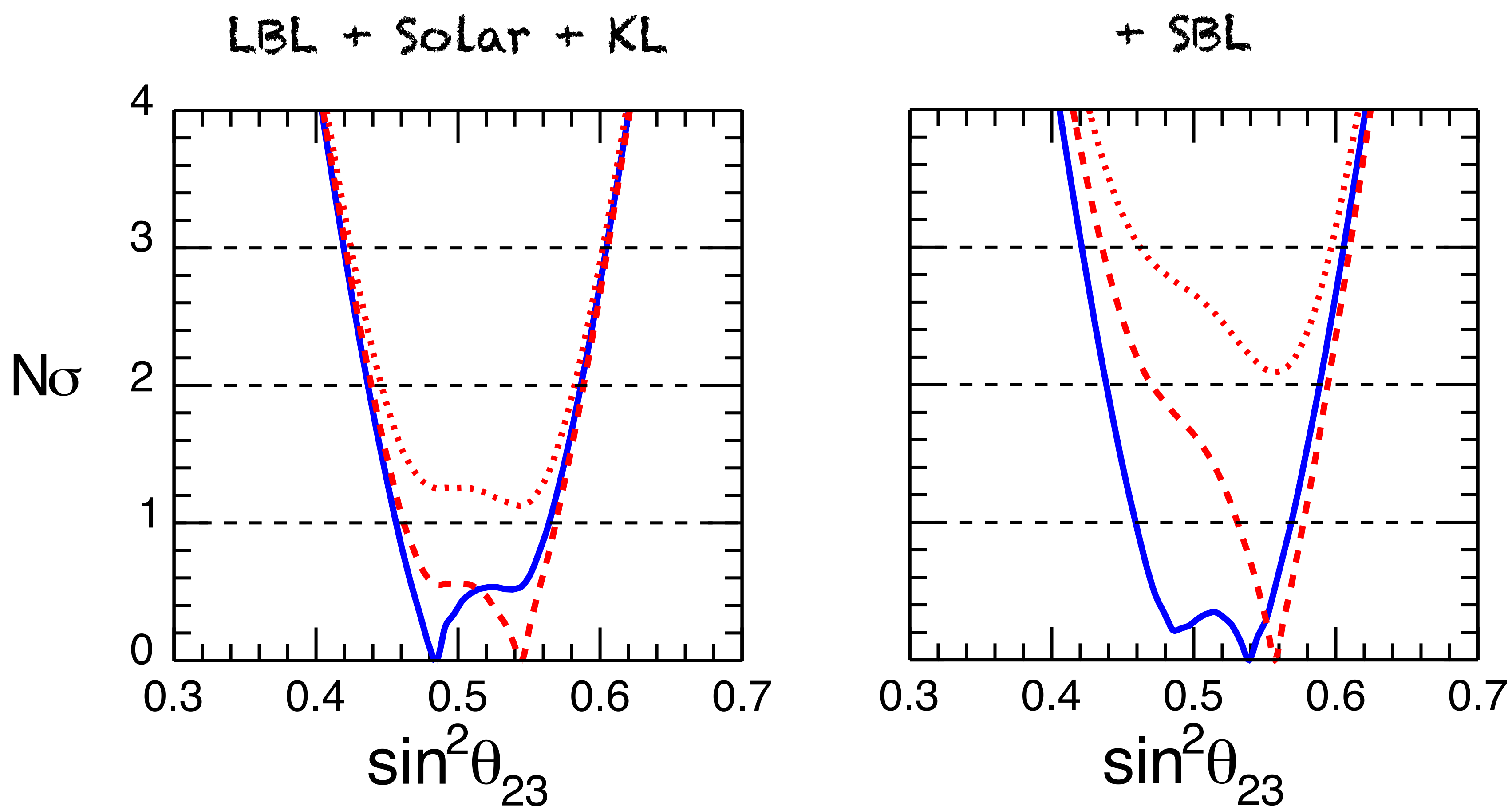


Slight preference for $\theta_{23}<\pi/4$ in NO and $\theta_{23}>\pi/4$ in IO, but both octants are allowed at 1σ

θ_{23} octant ambiguity



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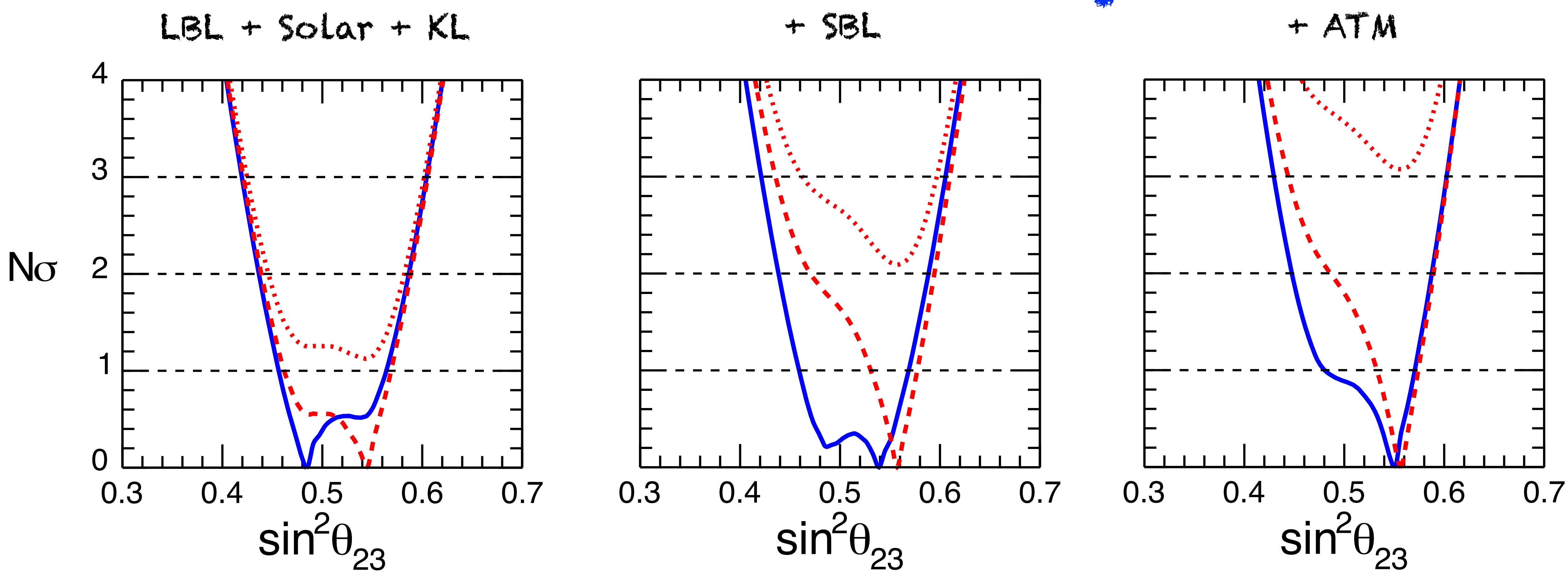

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More pronounced preference for $\theta_{23}>\pi/4$ but both octants allowed at $< 2\sigma$.

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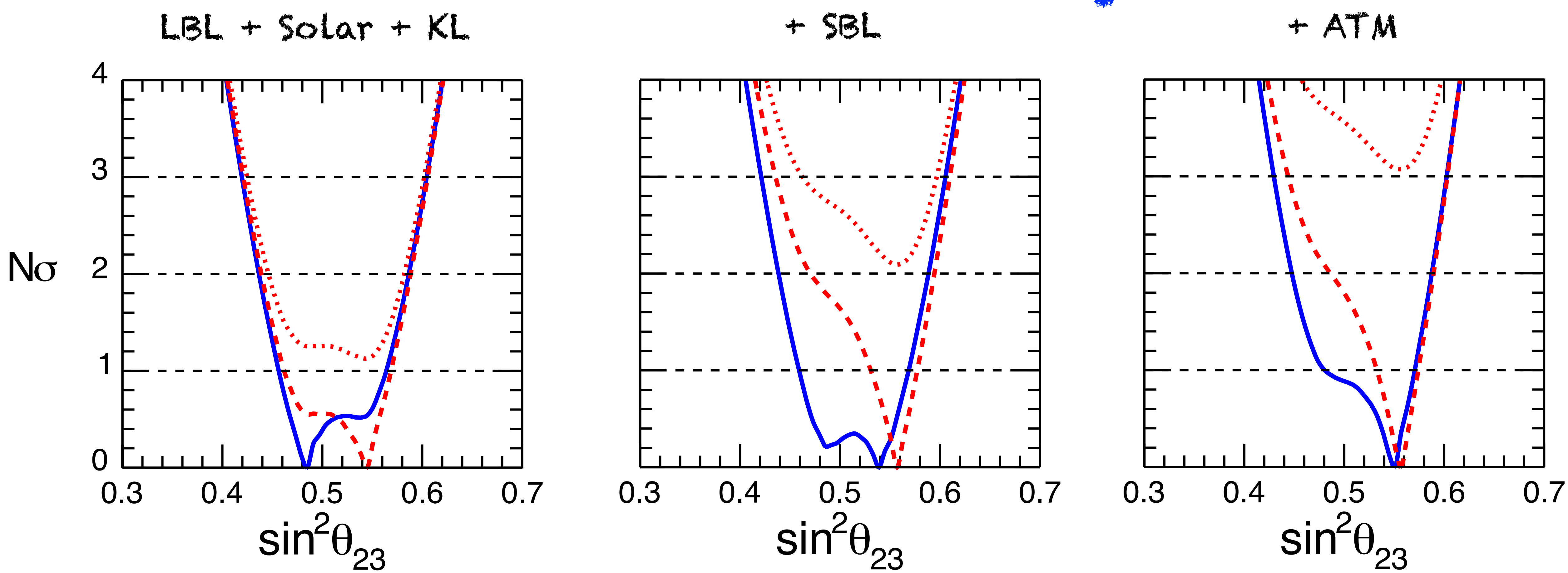

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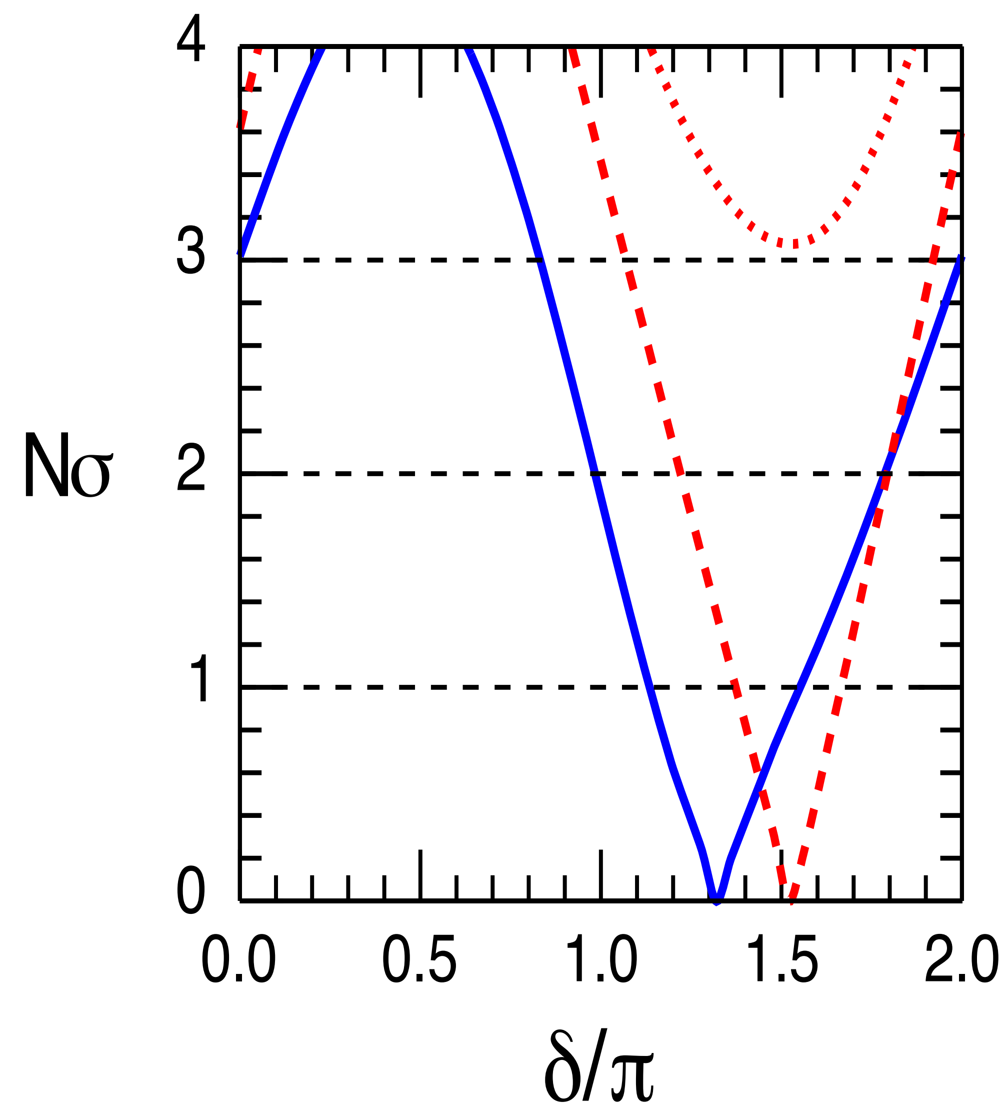
More pronounced preference for $\theta_{23}>\pi/4$ but both octants allowed at $< 2\sigma$.

Globally, relatively low uncertainty of ~5% on $\sin^2\theta_{23}$ (NOvA data in better agreement with quasi-maximal mixing). Maximal mixing allowed at less than 2σ in both NO and IO (but Neutrino 2018 NOvA analysis prefers again nonmaximal mixing)

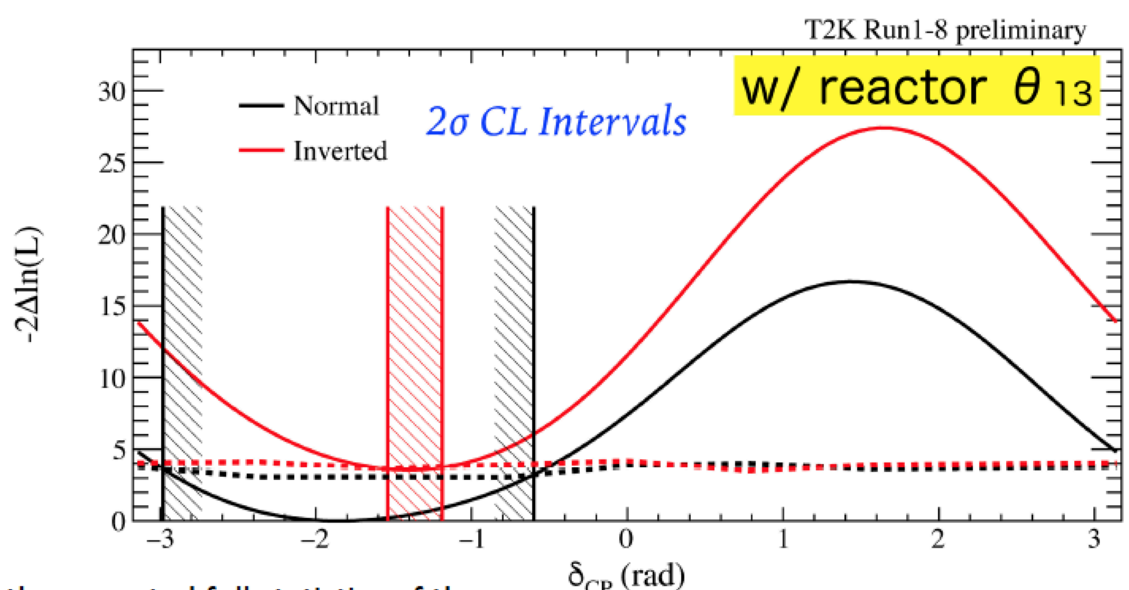
CP phase δ

CP phase: $\delta \sim 1.3\pi$ (1.5π) at best fit
CP-conserving cases $(\delta = 0, \pi)$ disfavoured at ~2σ level or more
Significant fraction of the $[0,\pi]$ range disfavoured at $>3\sigma$ in NO, at $>4\sigma$ in IO



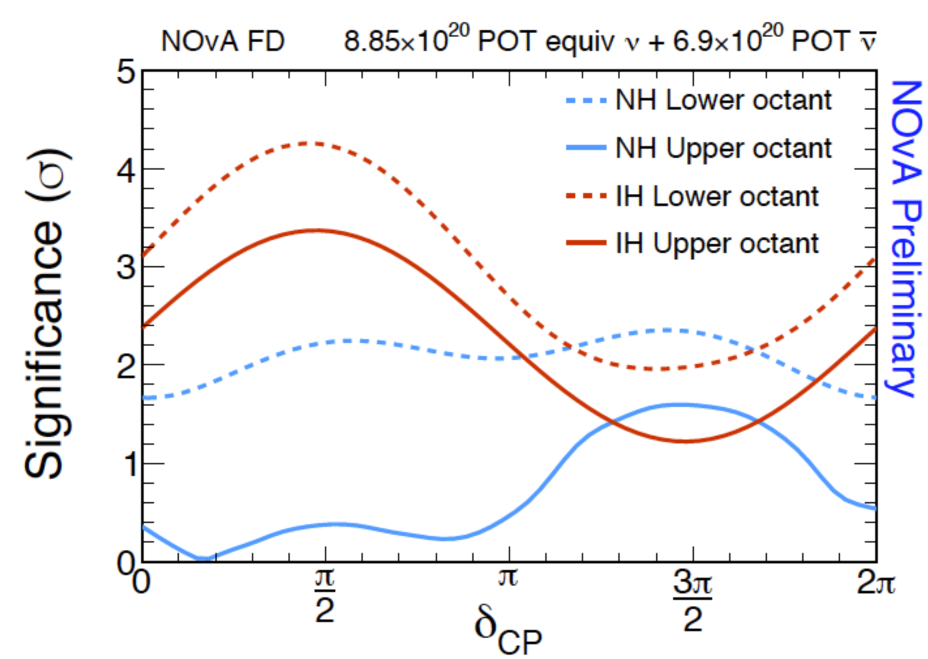
New T2K results: KEK seminar on 4 August 2017

Based on 89 ν_e and 7 $\overline{\nu}_e$ events



- 30% of the expected full statistics of the experiment
- 30% improvement in efficiency x acceptance
- Important improvements in neutrino interactions modelling

- δ_{CP} determination is very important for future searches of MH in long baseline experiments



CP phase δ

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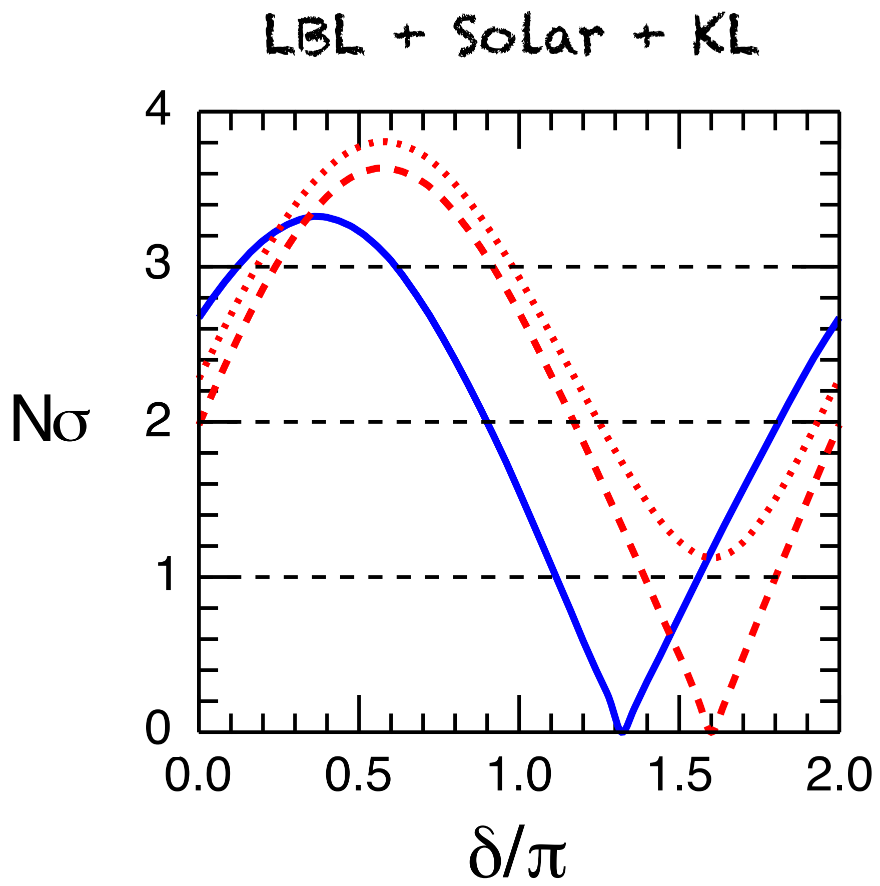

CP-conserving values δ={0,π} allowed at ~2σ (3σ) in NO (IO). Clear preference δ~3π/2. δ~π/2 disfavoured at more than 3σ

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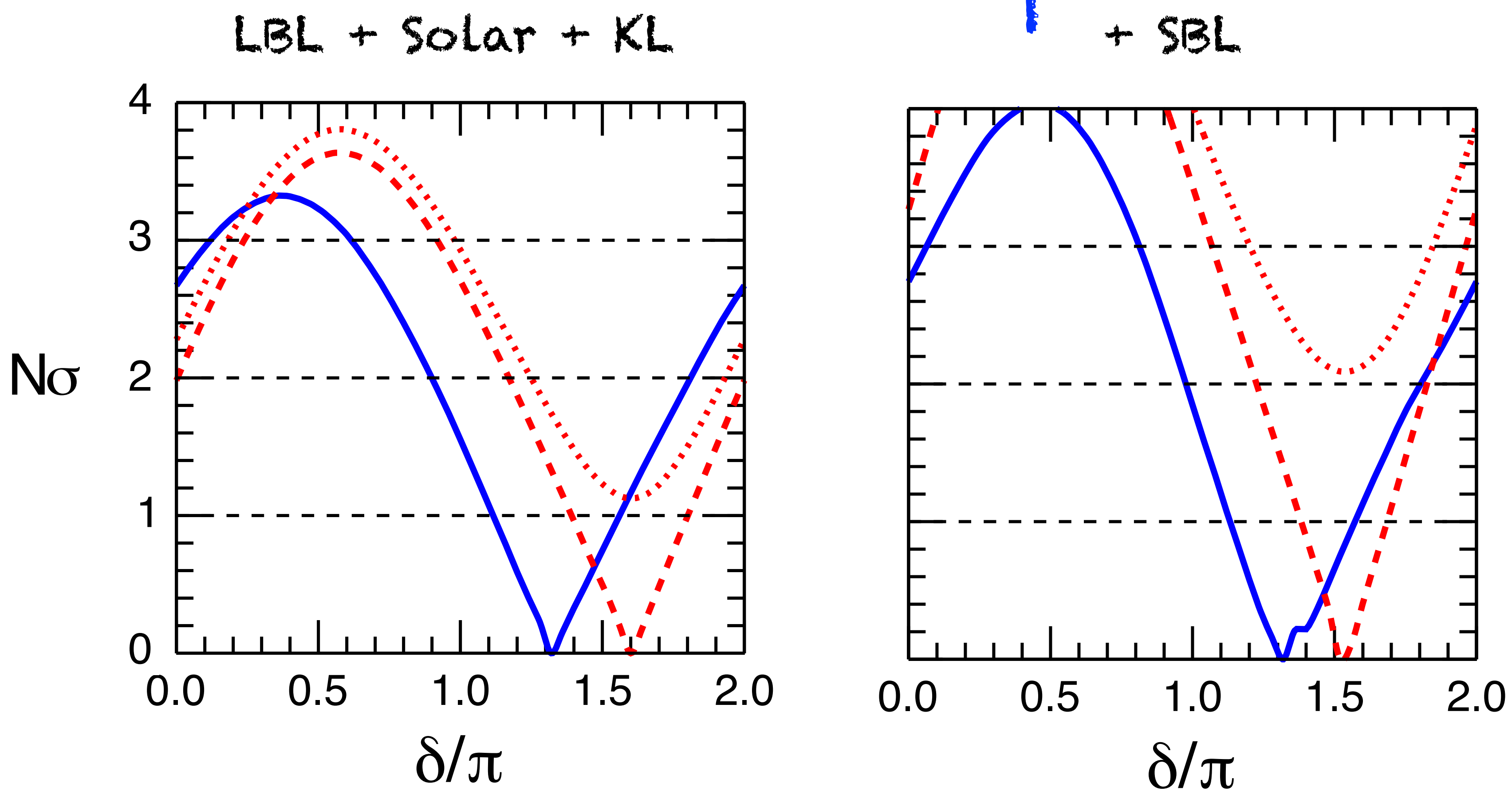

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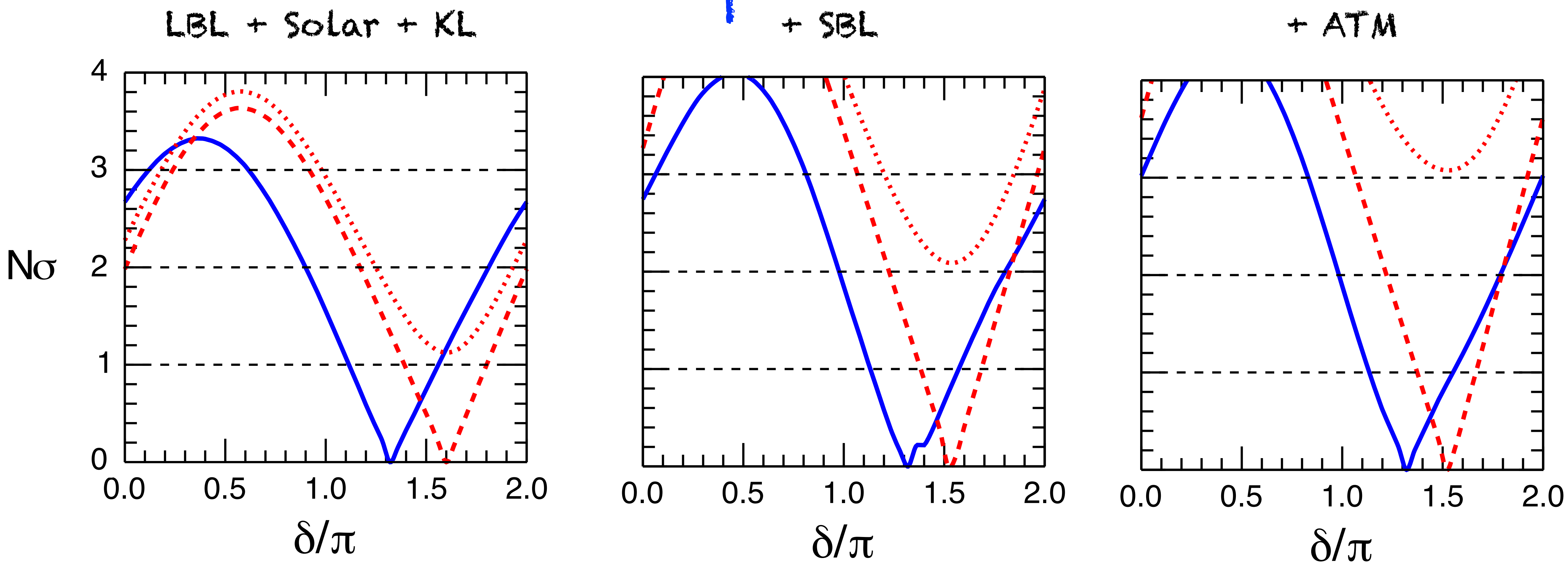
Indications on δ~3π/2 strengthened. CP-conserving values disfavoured at >1.8σ in NO and > 3σ in IO. Significant ranges excluded at > 3σ in both NO and IO.

CP phase δ



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Preference for CP violation with sinδ<0 confirmed, while CP conservation is disfavoured at >1.9σ for NO and >3.5σ for IO.

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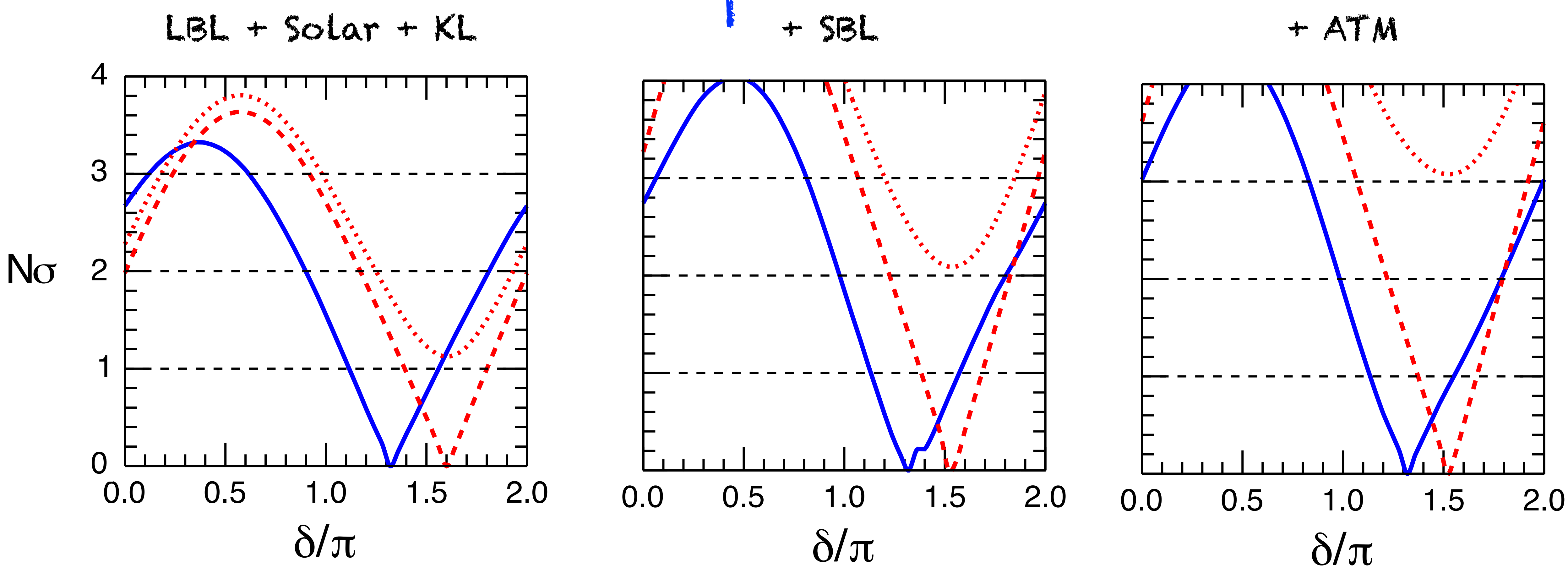

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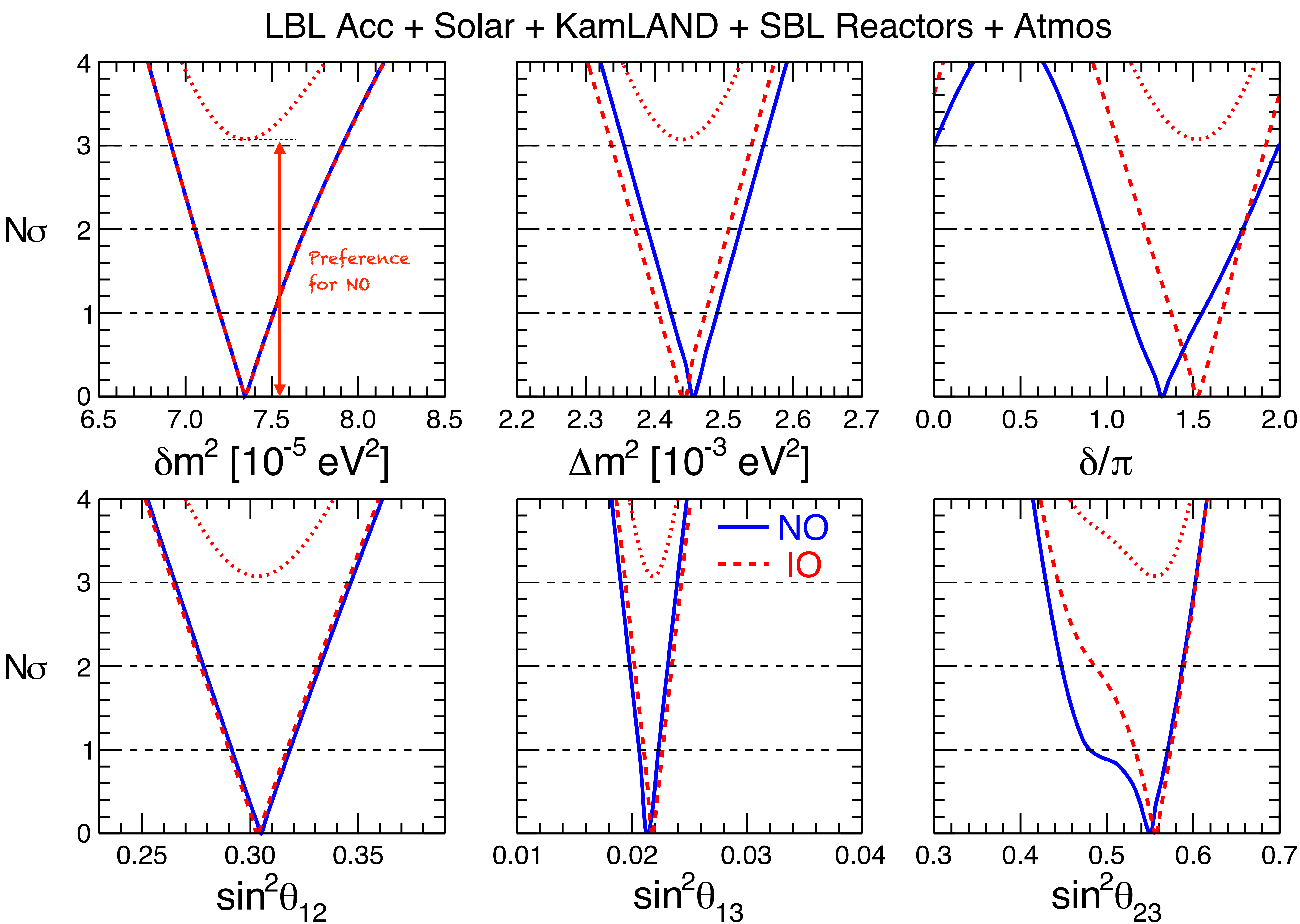
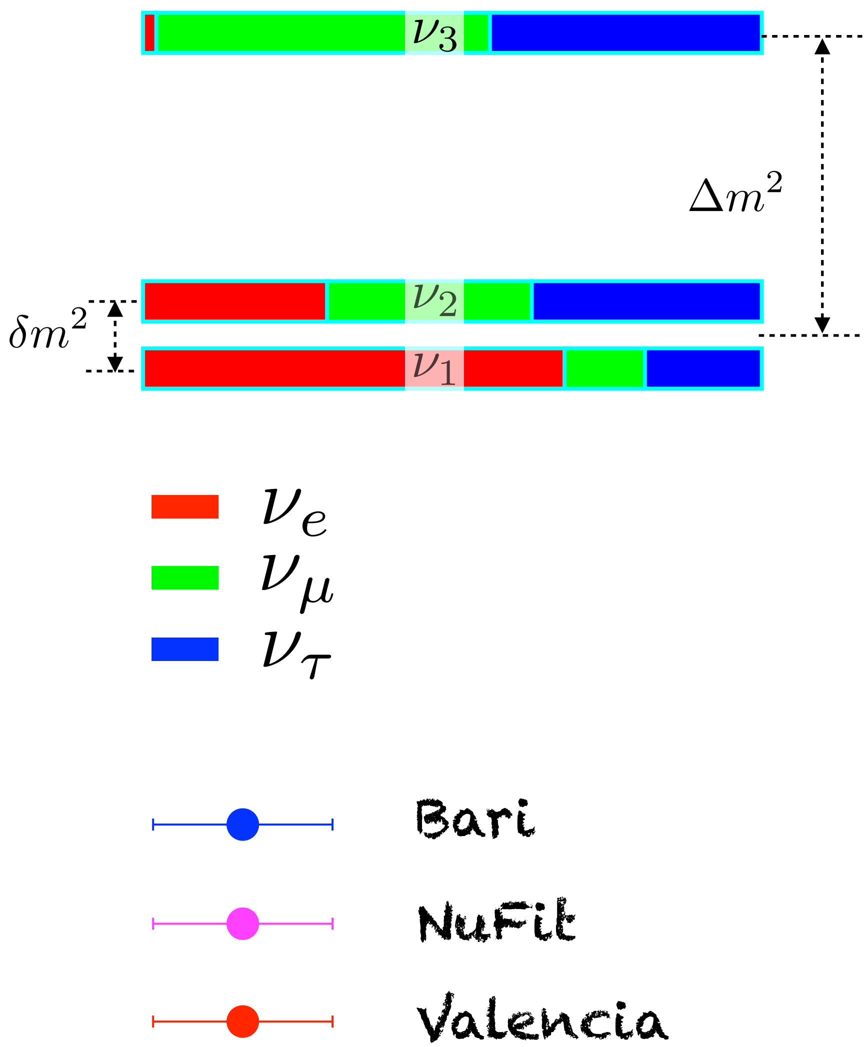
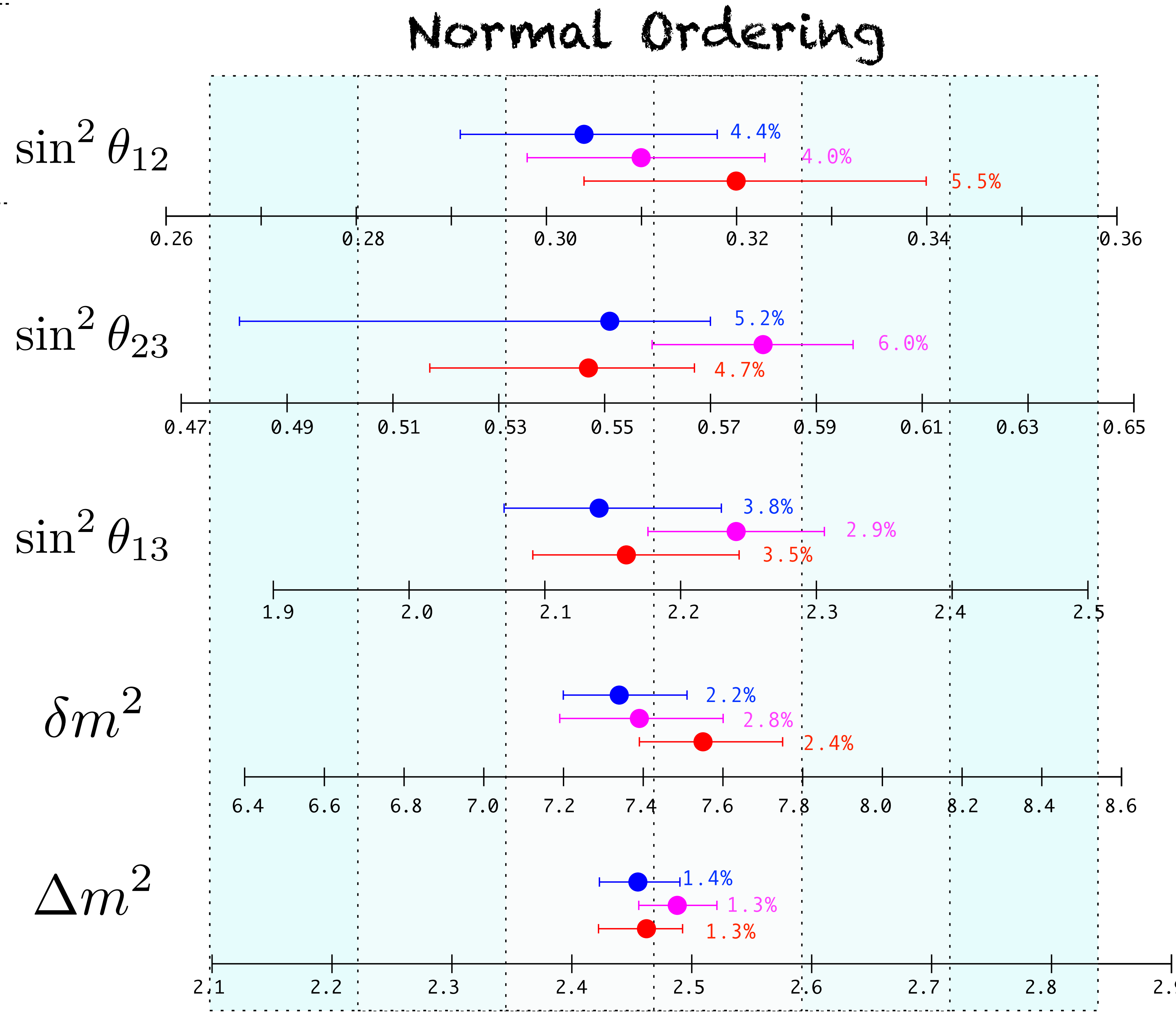
"Effective" 1σ accuracy of ~15% in NO and ~9% in IO. Rejection of the CP-conserving case δ=0 at 3σ in NO, but not enough to exclude δ=π at 2σ. Both cases excluded at 3σ in IO.



LBL Acc + Solar + KamLAND + SBL Reactors + Atmos
Nσ
Preference for NO
δm² [10⁻⁵ eV²]
Δm² [10⁻³ eV²]
δ/π
sin²θ12
sin²θ13
sin²θ23
NO
IO

Comparison of global analyses





The three global analyses are in good agreement with some difference about θ_{23} ranges & octant (differences on θ_{13} mostly due to Oct 2018 Day Bay update, included in NuFit)

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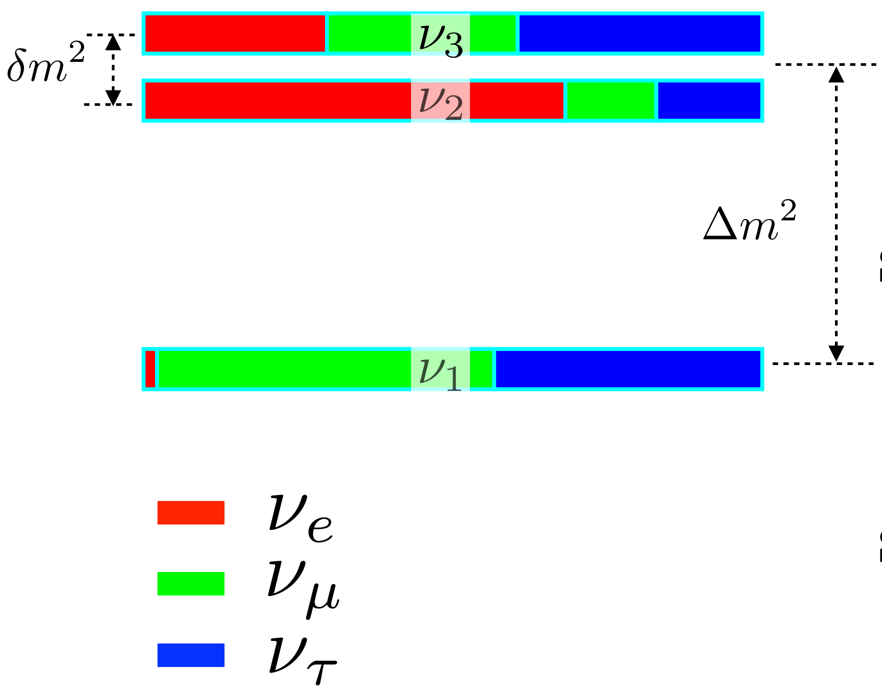

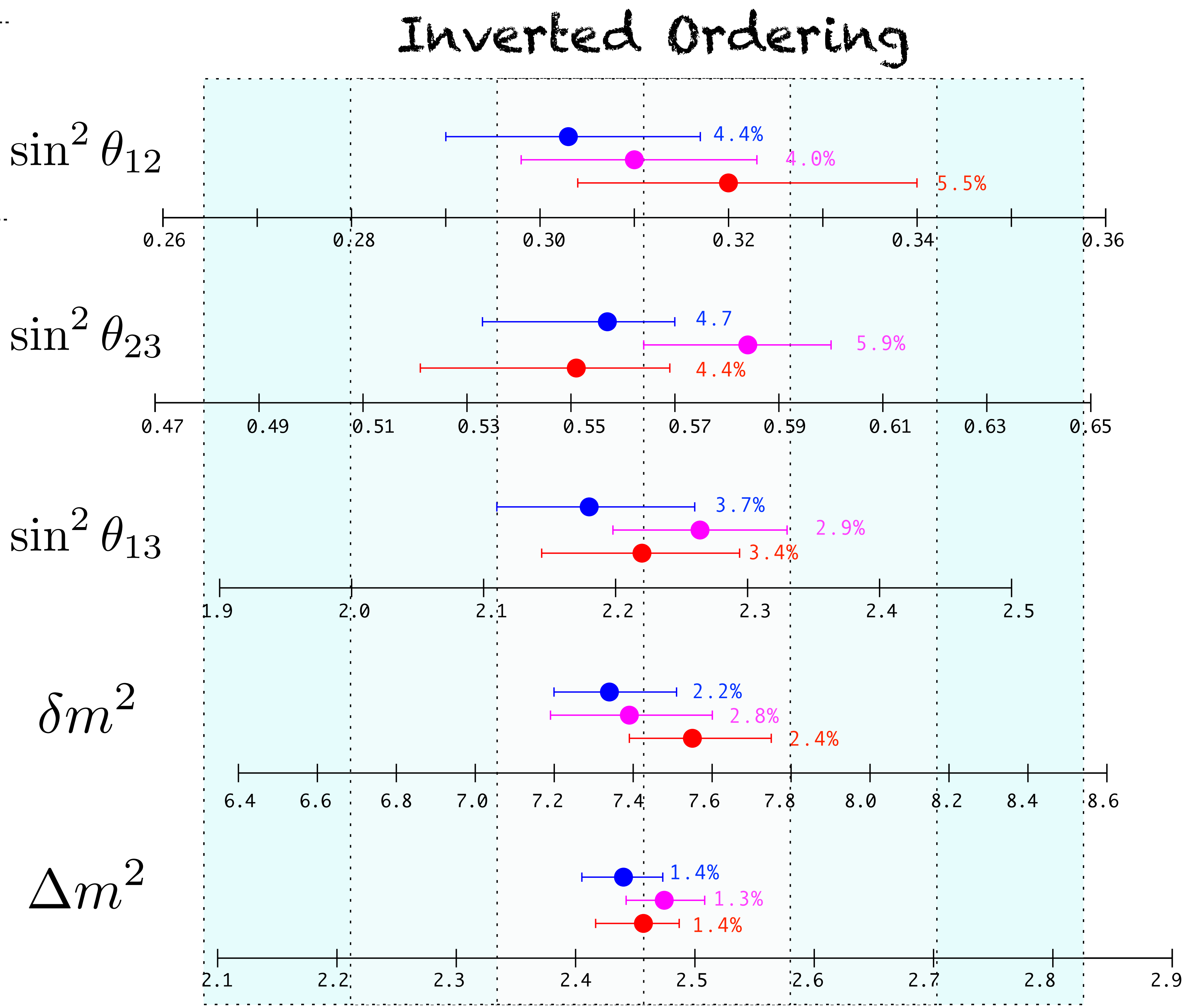

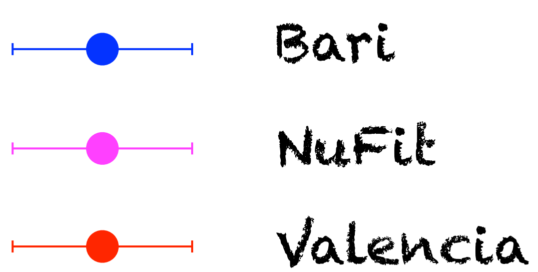

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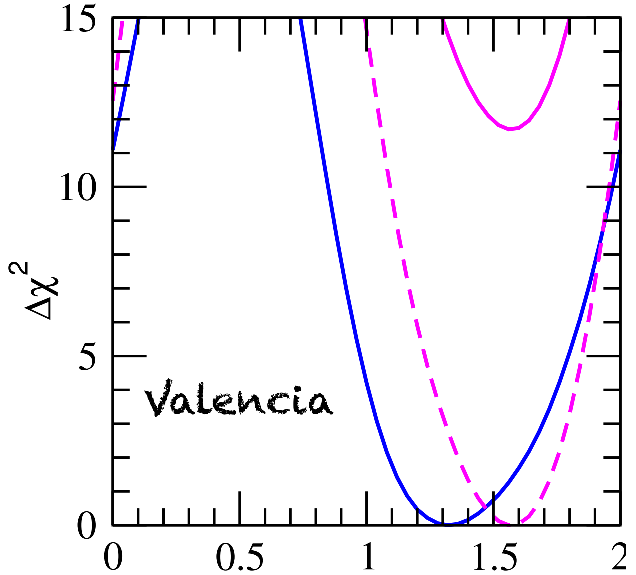
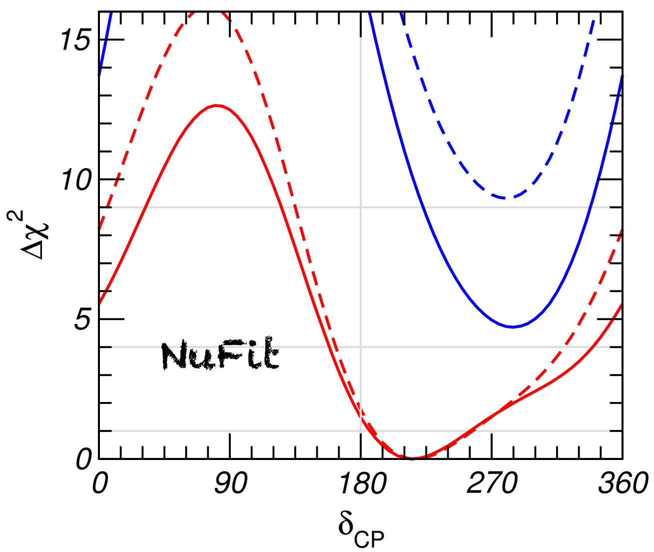
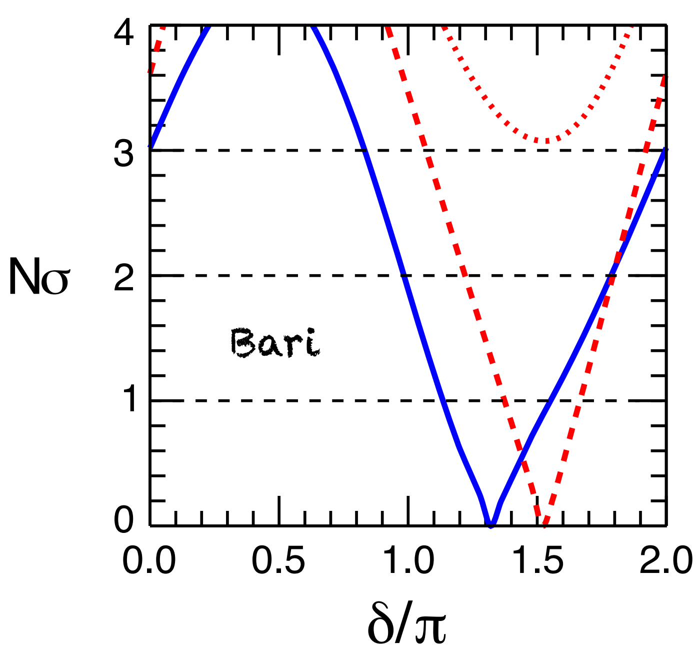
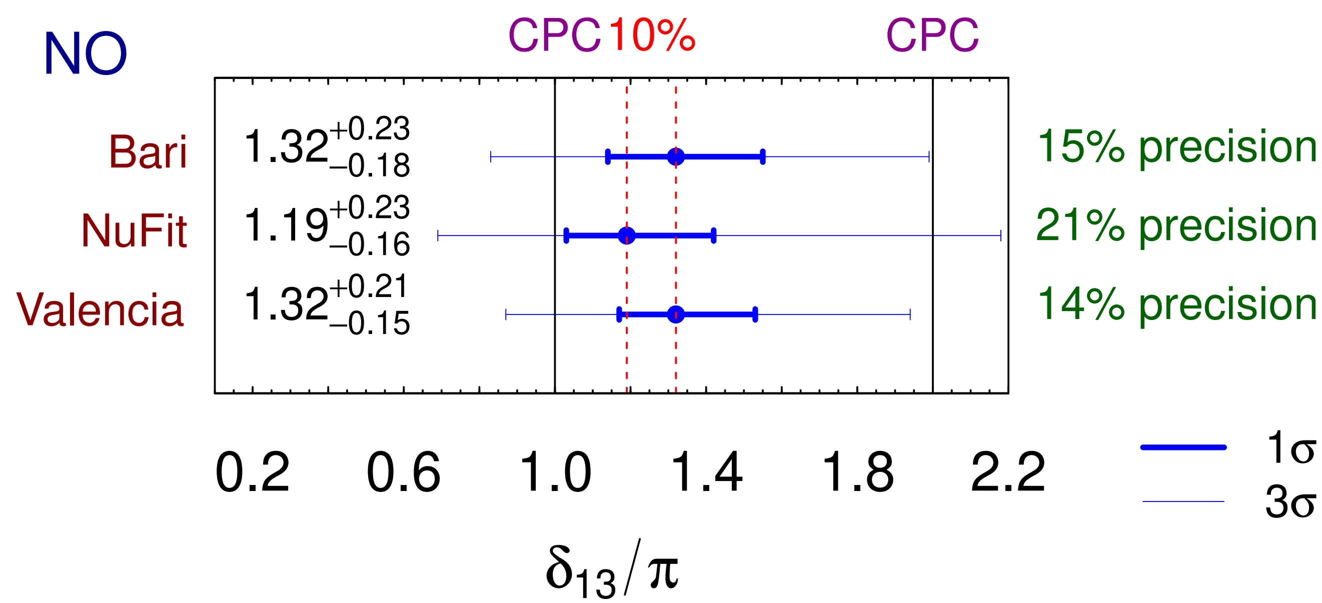
10–15% "Determination" of δ

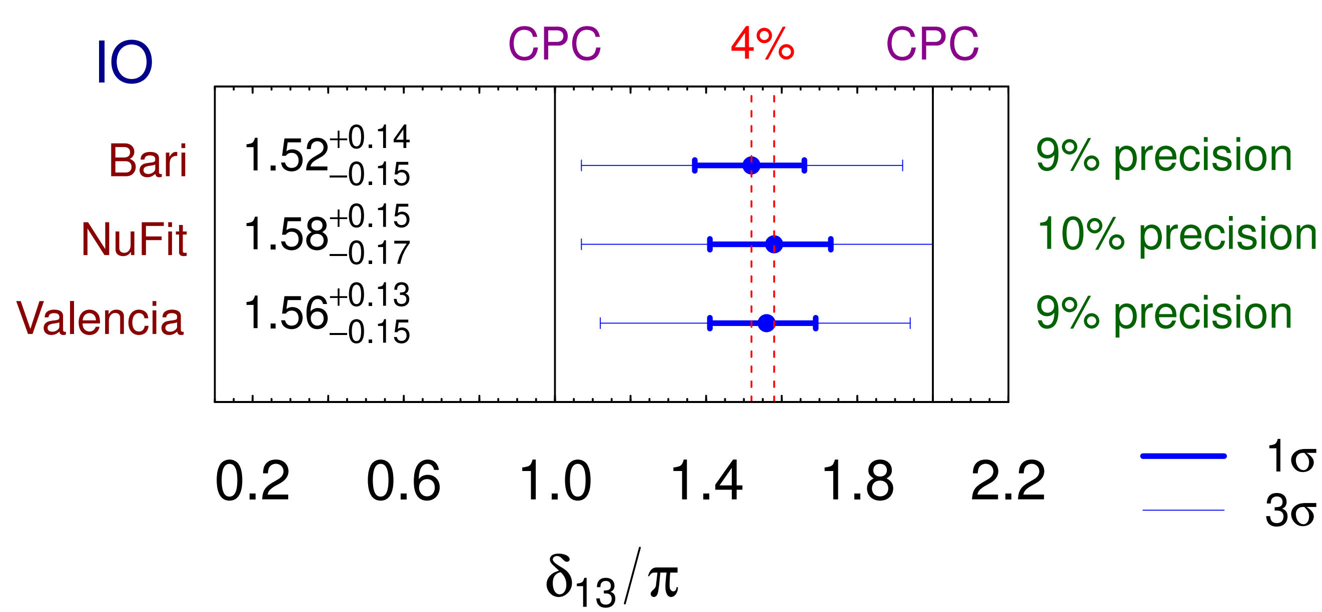






CP Violation?





Mass Ordering: present situation

	LBL + Solar + KL	(+ SBL)	(+Atm)
$\Delta\chi^2_{IO-NO}$	+1.3	+4.4	+9.5

@Neutrino 2018

T2K – preference for NO
$\Delta\chi^2_{IO-NO} \sim 4$

NOvA – weak preference for NO, $\Delta\chi^2_{IO-NO} \sim 1.3$

Other groups findings

http://www.nu-fit.org/ ………………. $\Delta\chi^2_{IO-NO} = +9.3$ (4.7, No SK)

M. Tortola @Neutrino 2018 ……….. $\Delta\chi^2_{IO-NO} = 11.7$

	$\Delta\chi^2_{IO-NO}$	$N\sigma$
Bari	9.5	3.1
NuFit	9.1	3.0
Valencia	11.7	3.4

NO favoured over IO at about 3 sigma level

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

Solar Neutrinos + KamLAND

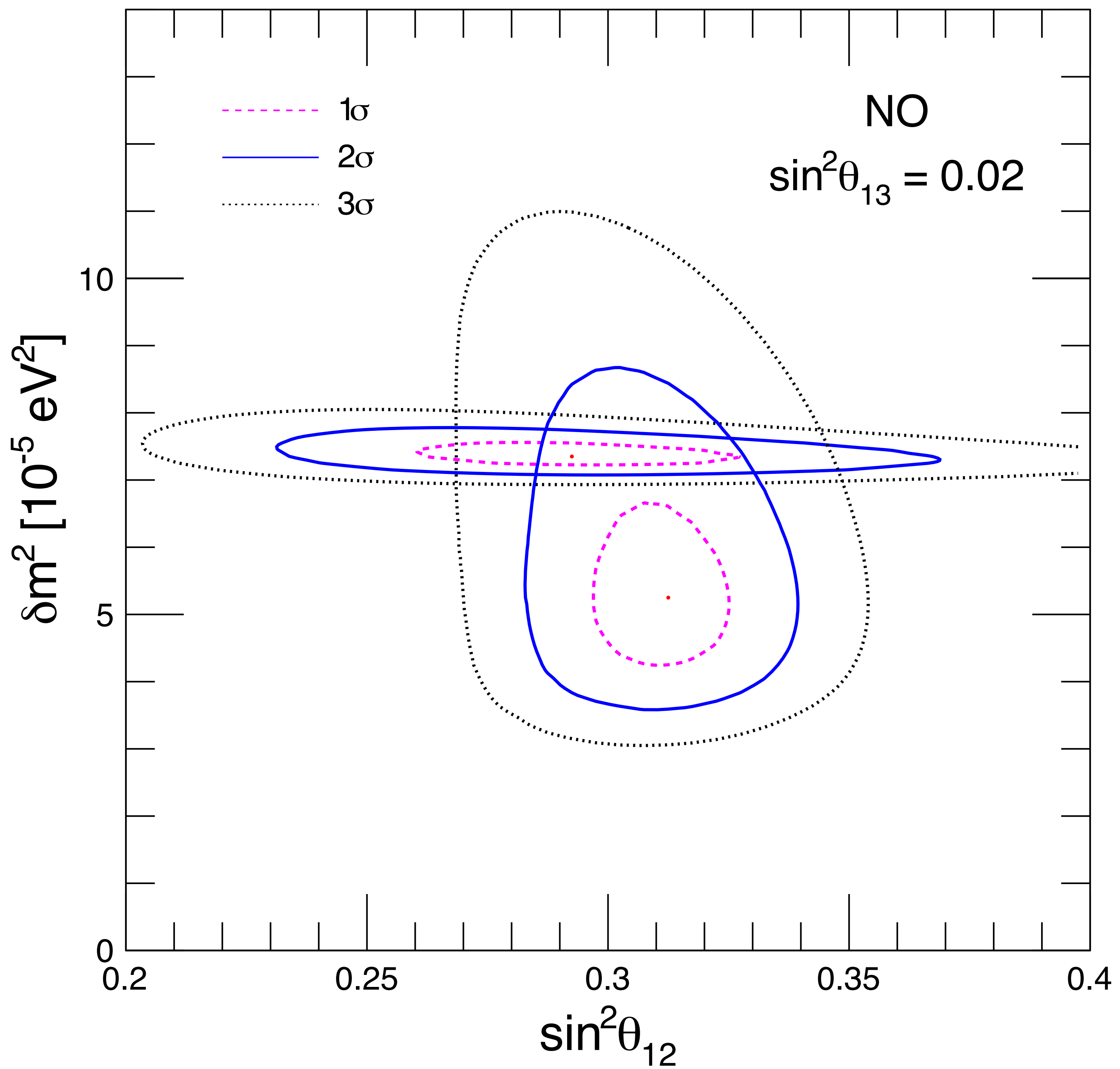
We include the latest low-energy Borexino and SK-IV data

Many input updated. Ga neutrino absorption cross-section leads to a reduction of the unoscillated solar neutrino rate by ~ 6 SNU

Slightly decrease of θ_{12} and increase of δm2 for nonzero θ_{13}

slight tension between the preferred mass-mixing value

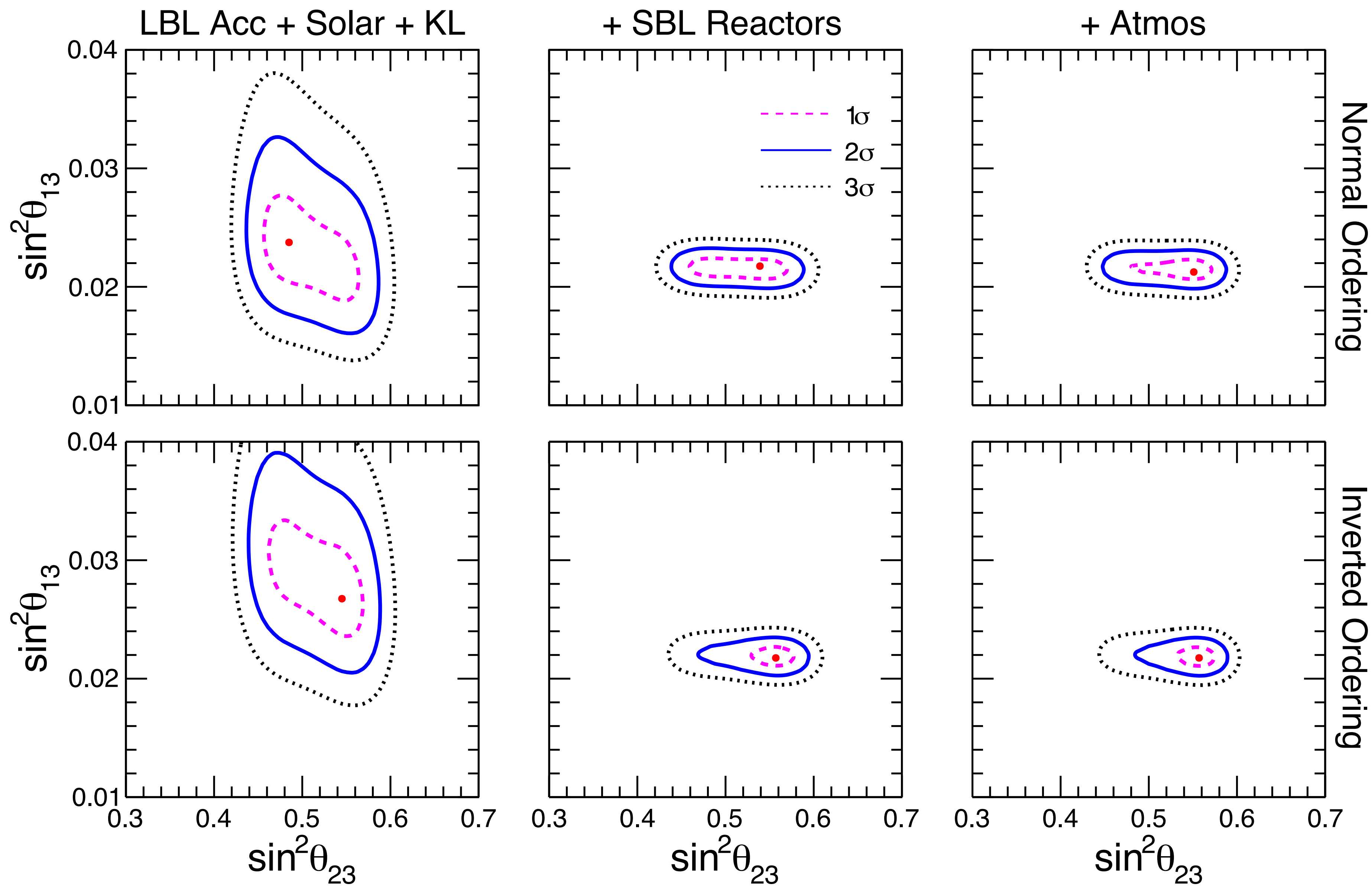
$$\Delta\chi^2 = \chi^2_{\rm sol+KL} - (\chi^2_{\rm sol} + \chi^2_{\rm KL}) \sim 2$$



Solar neutrino contours would be slightly different in IO, shifted leftwards with δ(sin2 θ12) ≃ −0.02 to compensate the slightly higher survival probability for IO as compared to NO. In combination with (mass-ordering insensitive) KamLAND data, the overall shift of the best-fit mixing angle amounts to δ(sin2 θ12) ≃ −0.01

Δχ2 = 0.08 in favor of IO with respect to NO

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



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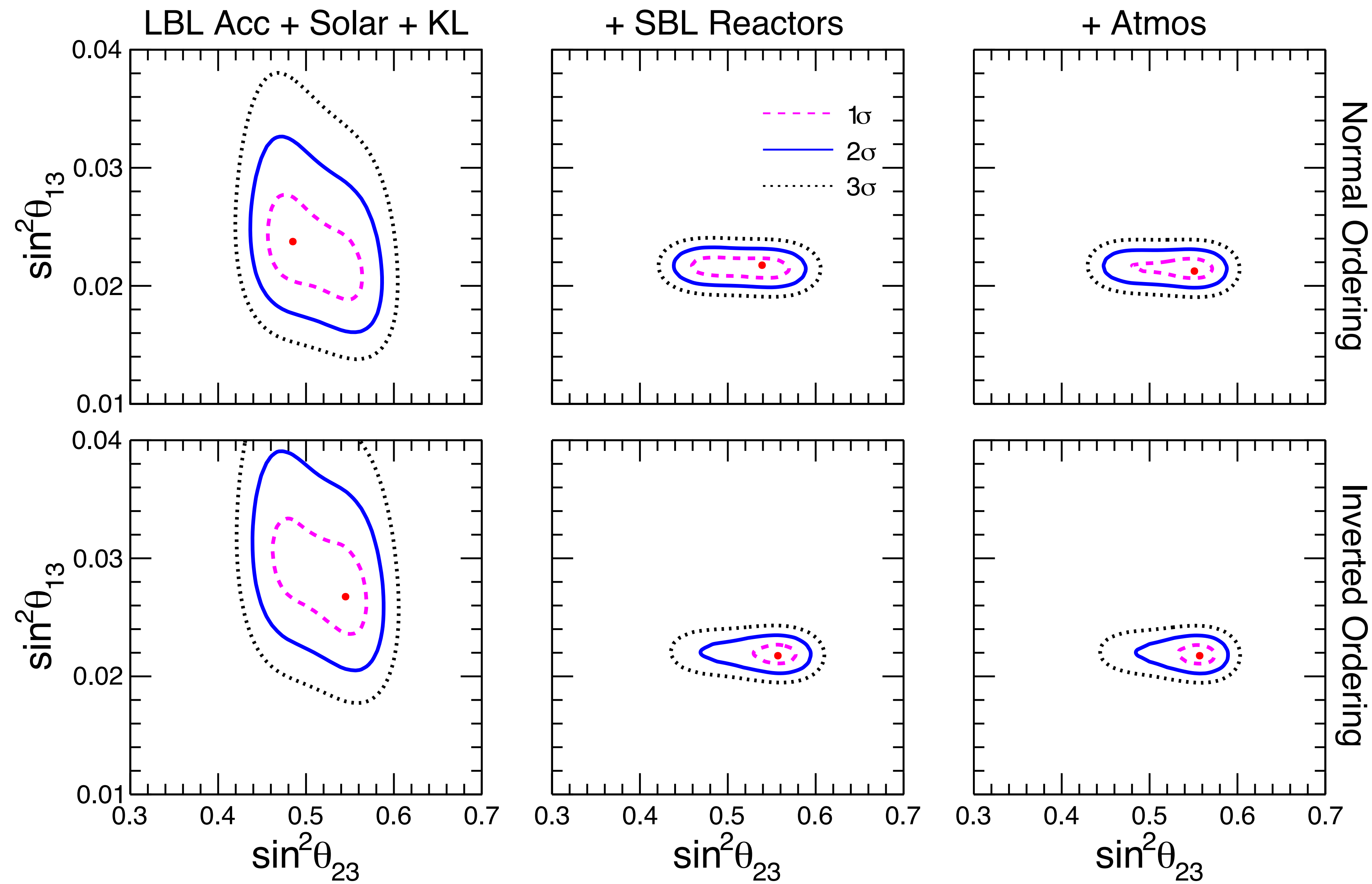
In LBL accelerator θ_{23} and θ_{13} are anticorrelated via appearance data



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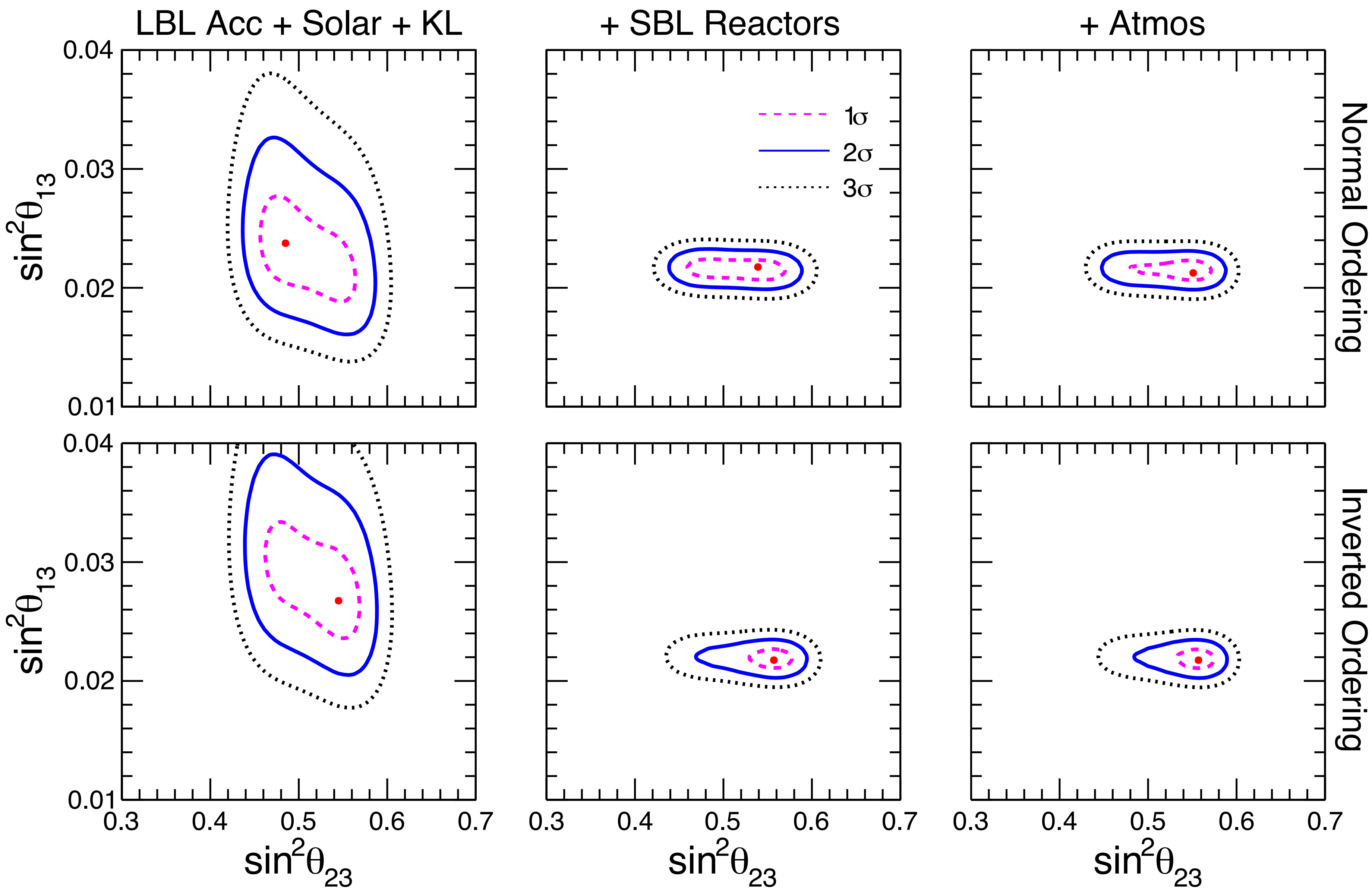
Subleading effects sensitive to sign(Δm^2) generate a difference in the allowed θ_{13} ranges for NO and IO, the latter ones being generally higher. $\Delta\chi^2$ increases from 1.3 to 4.4



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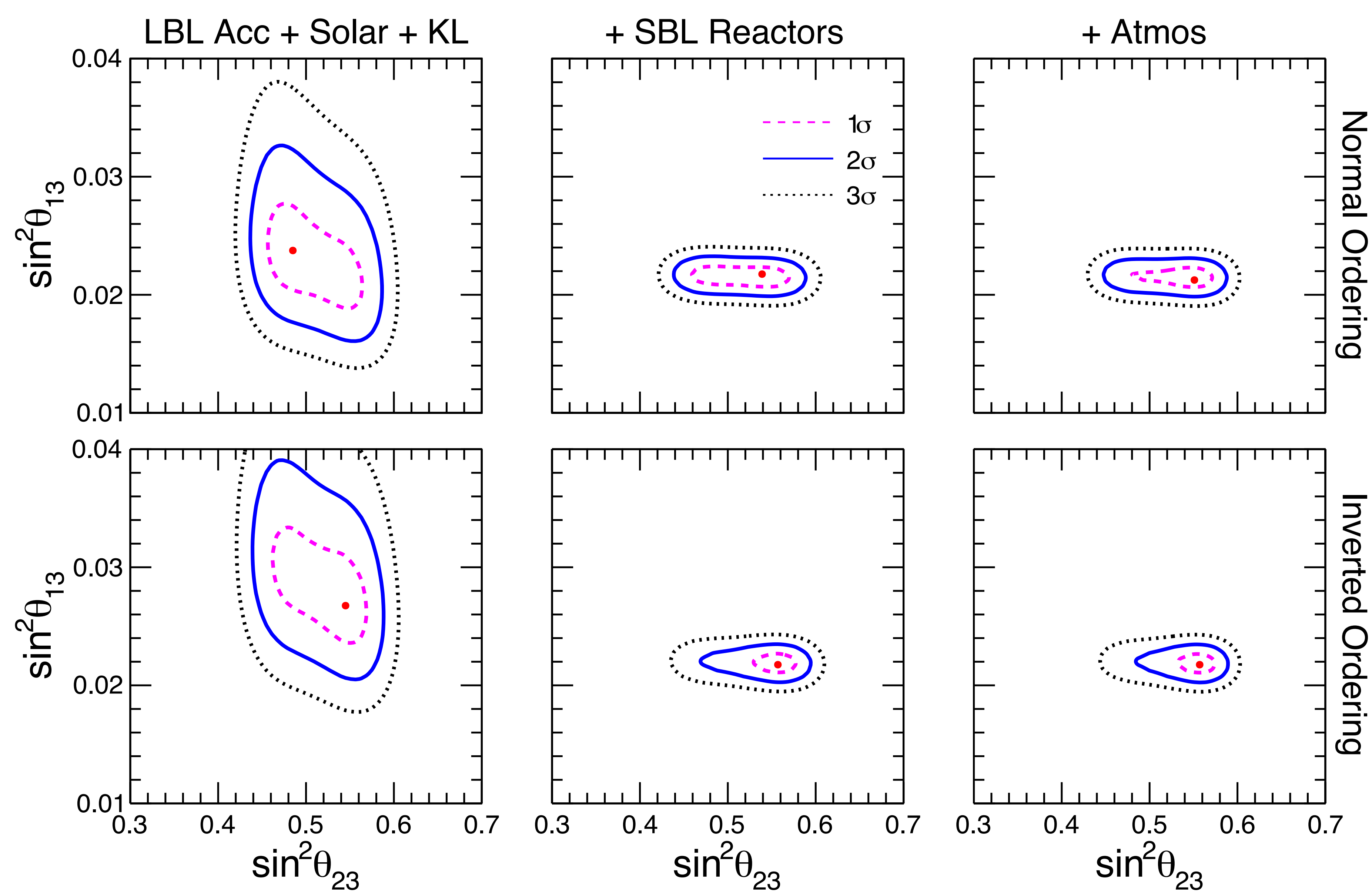

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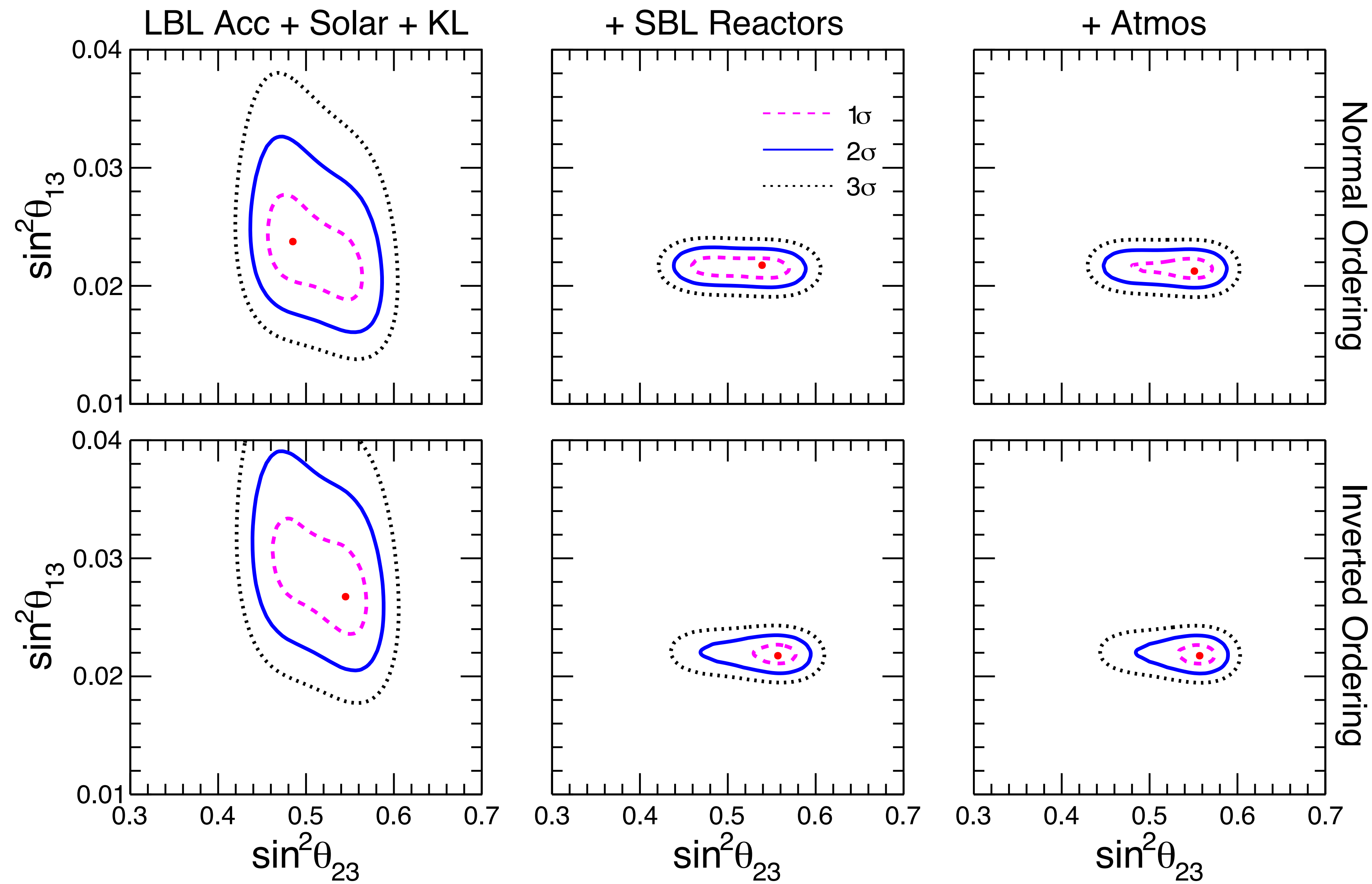

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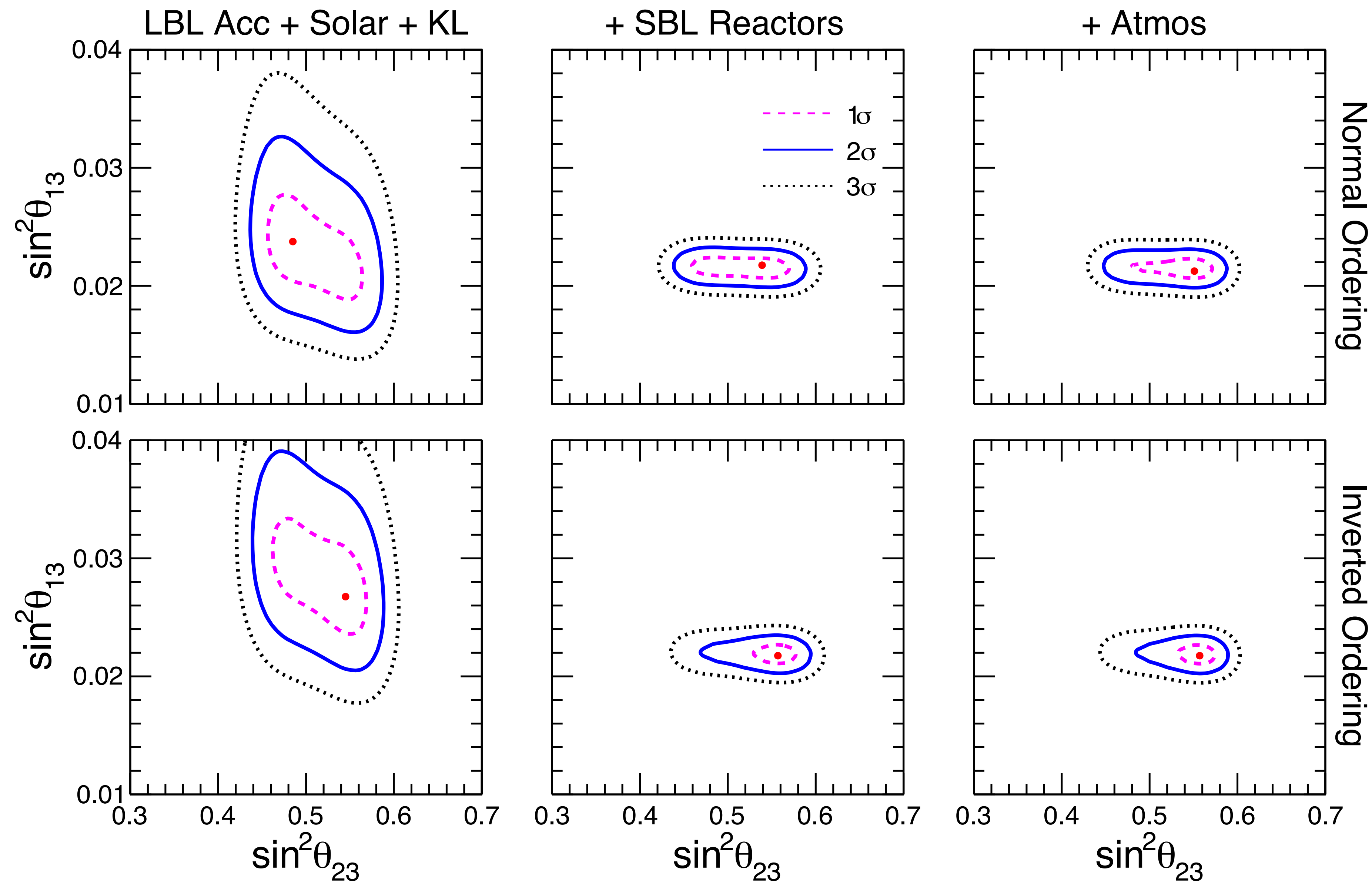

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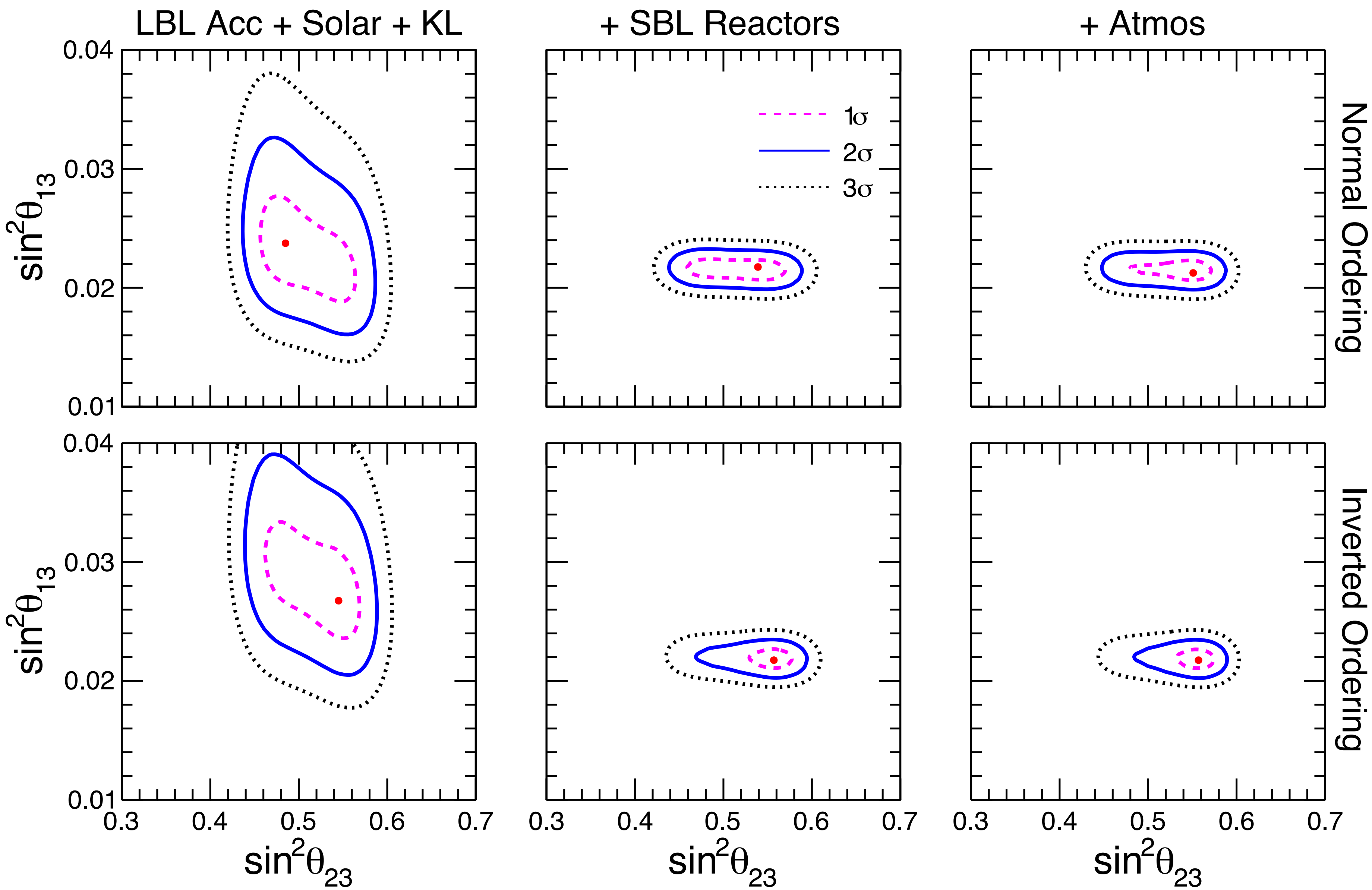

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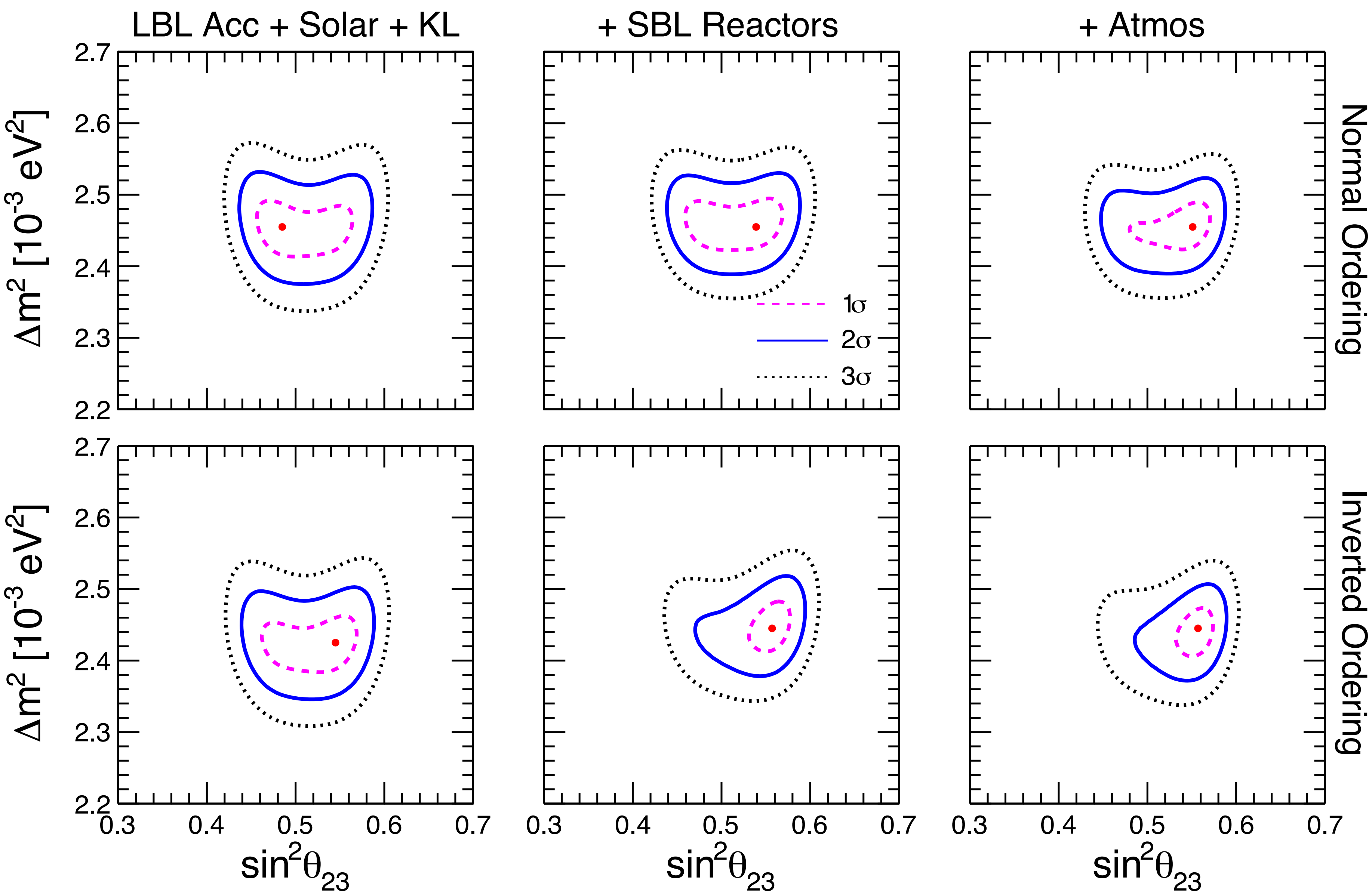
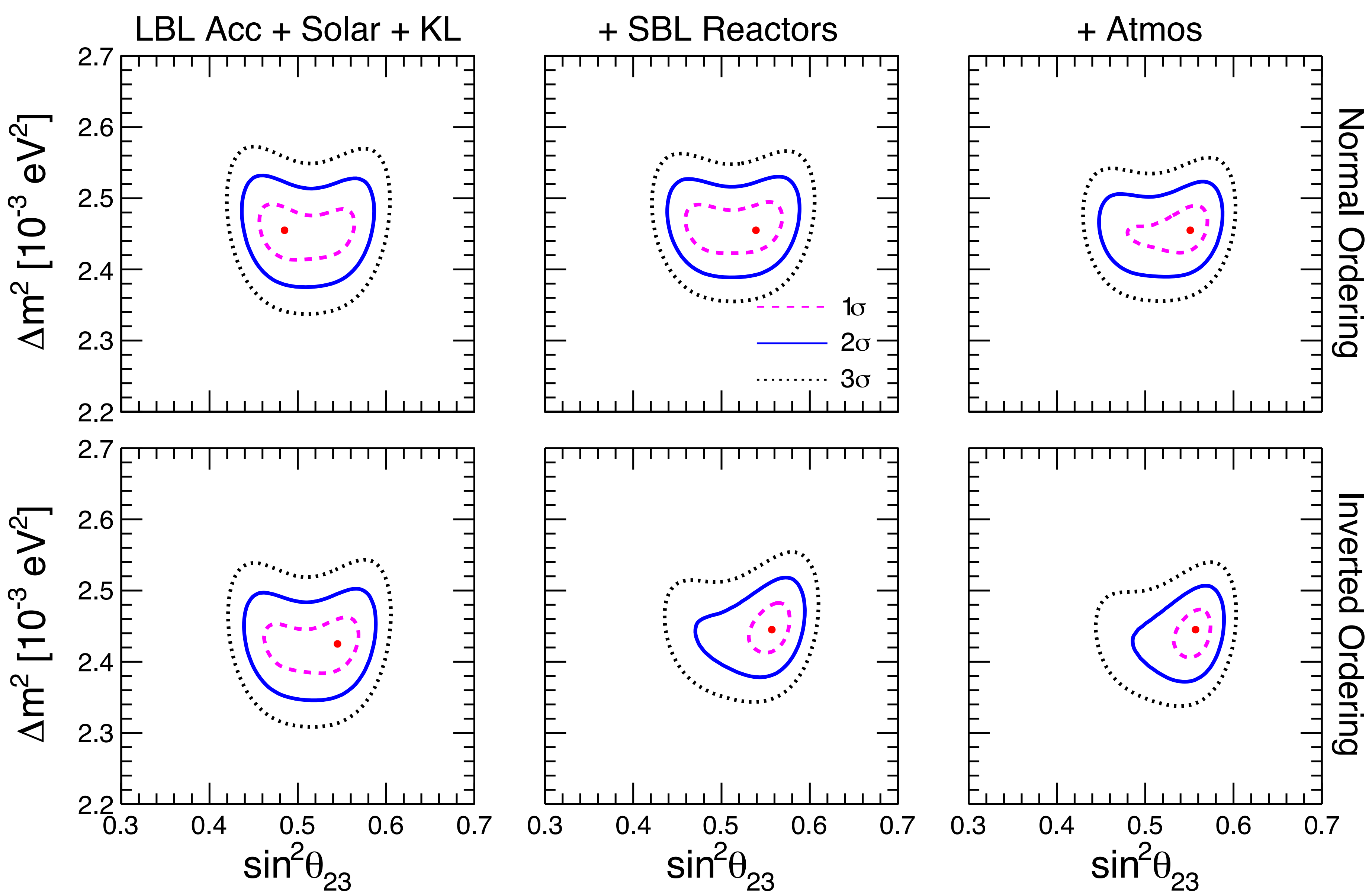


Correlations: (Δm^2, θ_{23})

Very good consistency of all the data on Δm^2, whose best-fit value remains practically constant in the three upper panels.



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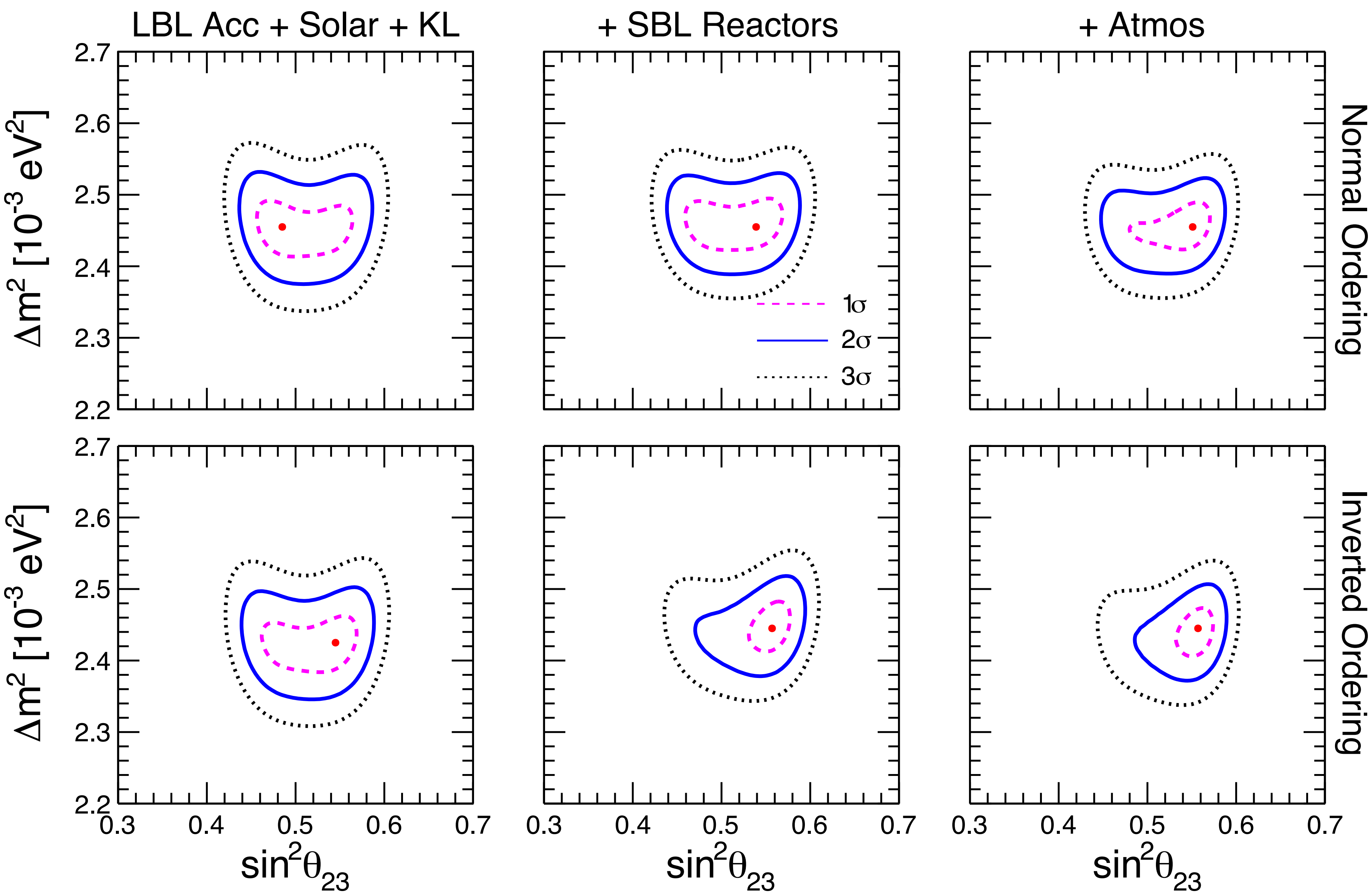
Δm^2 slightly increases in IO after the addition of SBL reactor data as consequence of the slight increment in $\sin^2\theta_{23}$



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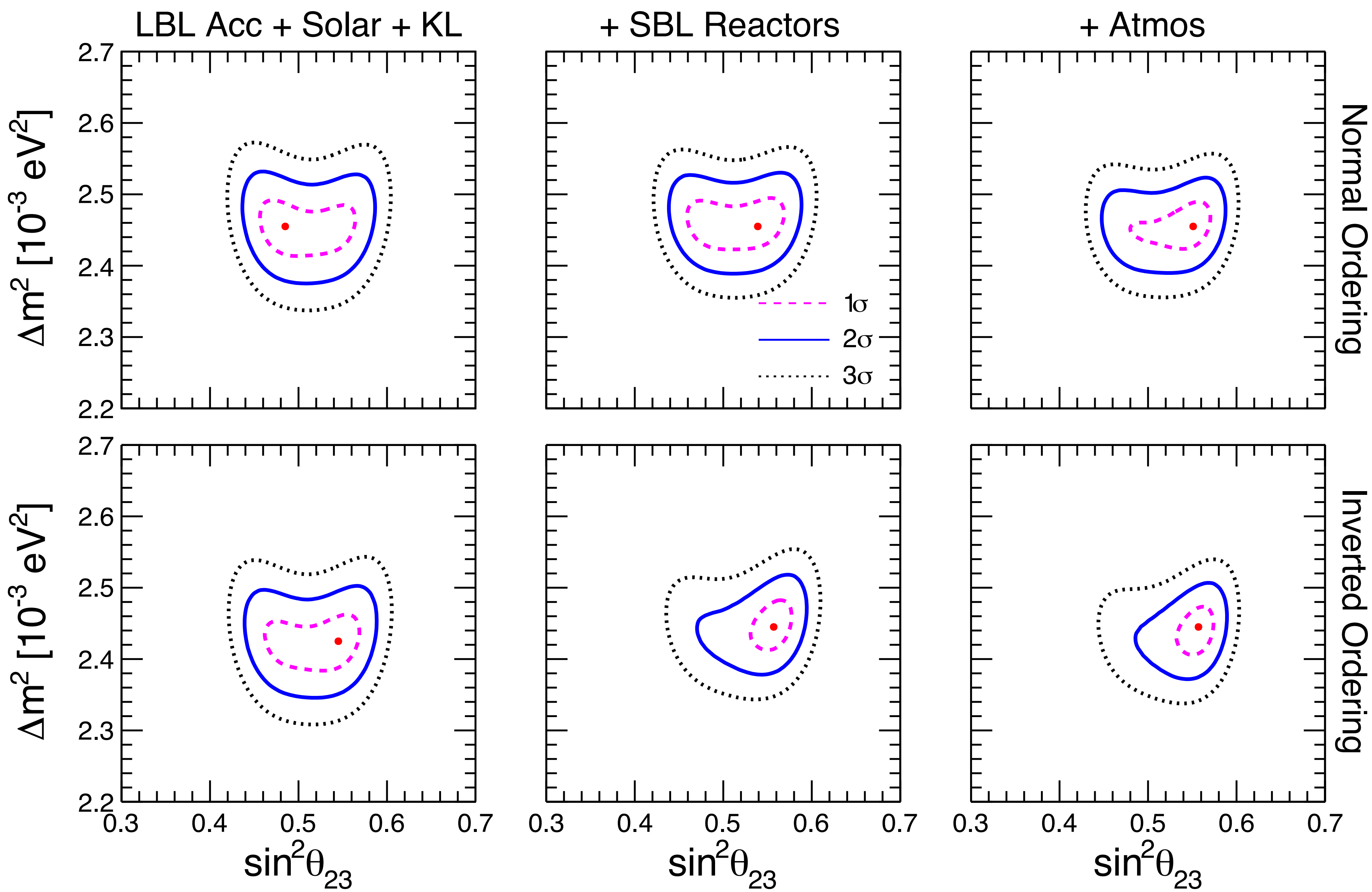

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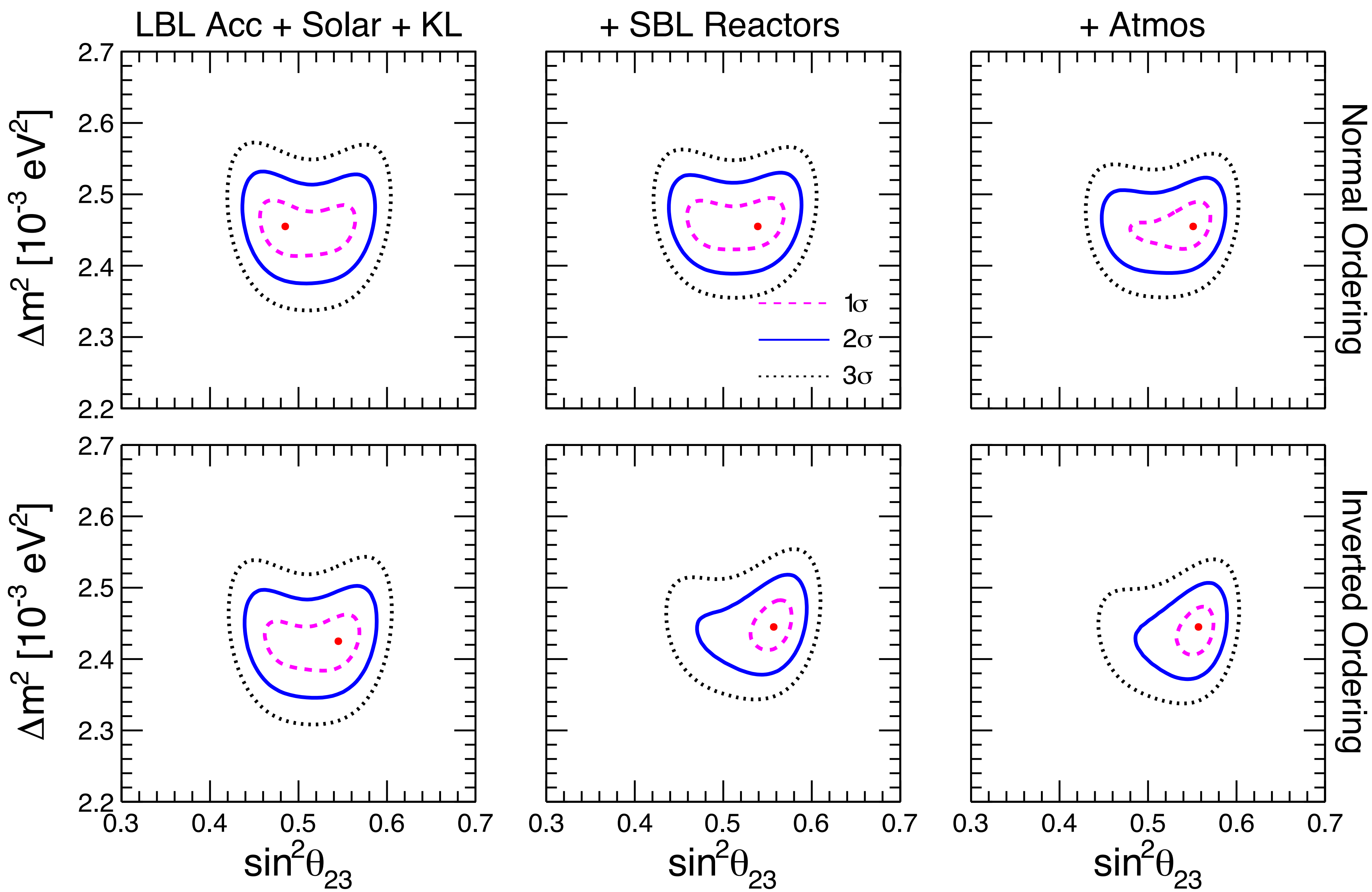
In general, at nearly maximal mixing one gets the lowest allowed values of Δm^2, while for nonmaximal mixing (in either octants) the preferred values of Δm^2 increases. Correlation mainly from disappearance data in LBL where a decrease of the leading oscillation amplitude governed by $\sin^2 2\theta_{23}$ can be compensated by an increase of the leading oscillations phase governed by Δm^2



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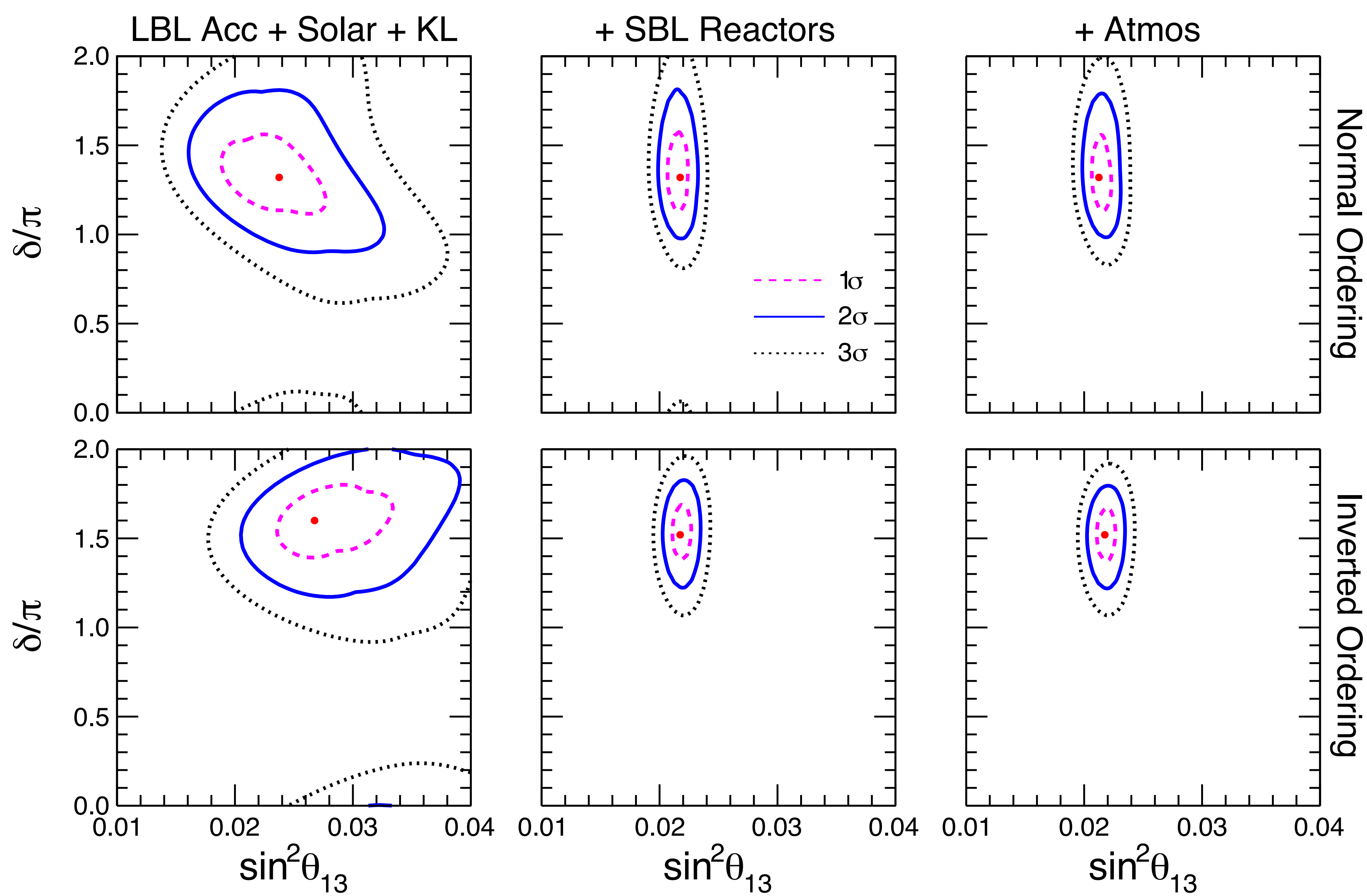

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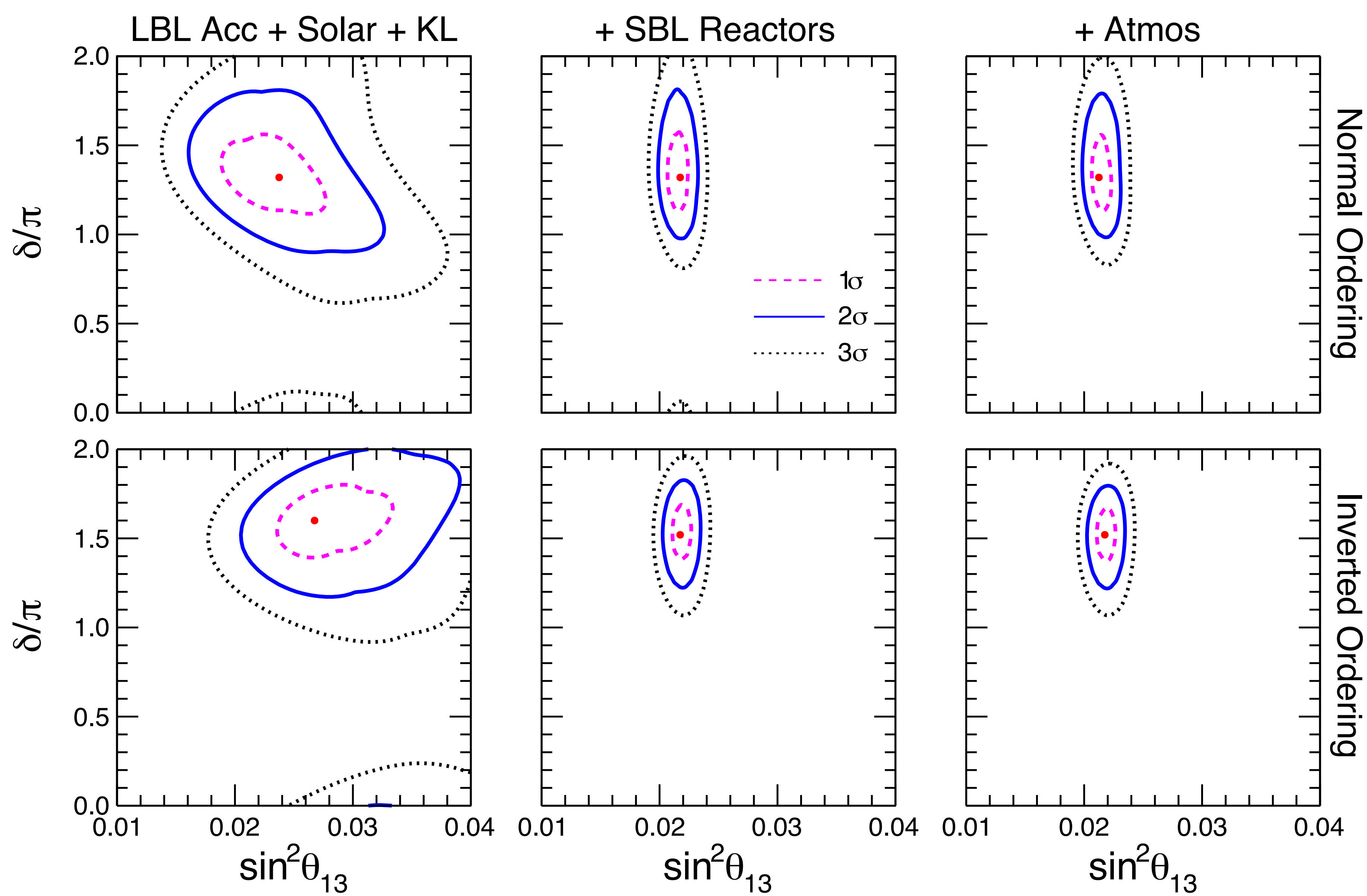
Strong correlations (in the left panels) mainly induced by the interplay between δ and θ_{13} in the subleading terms of the appearance probability for LBL experiments



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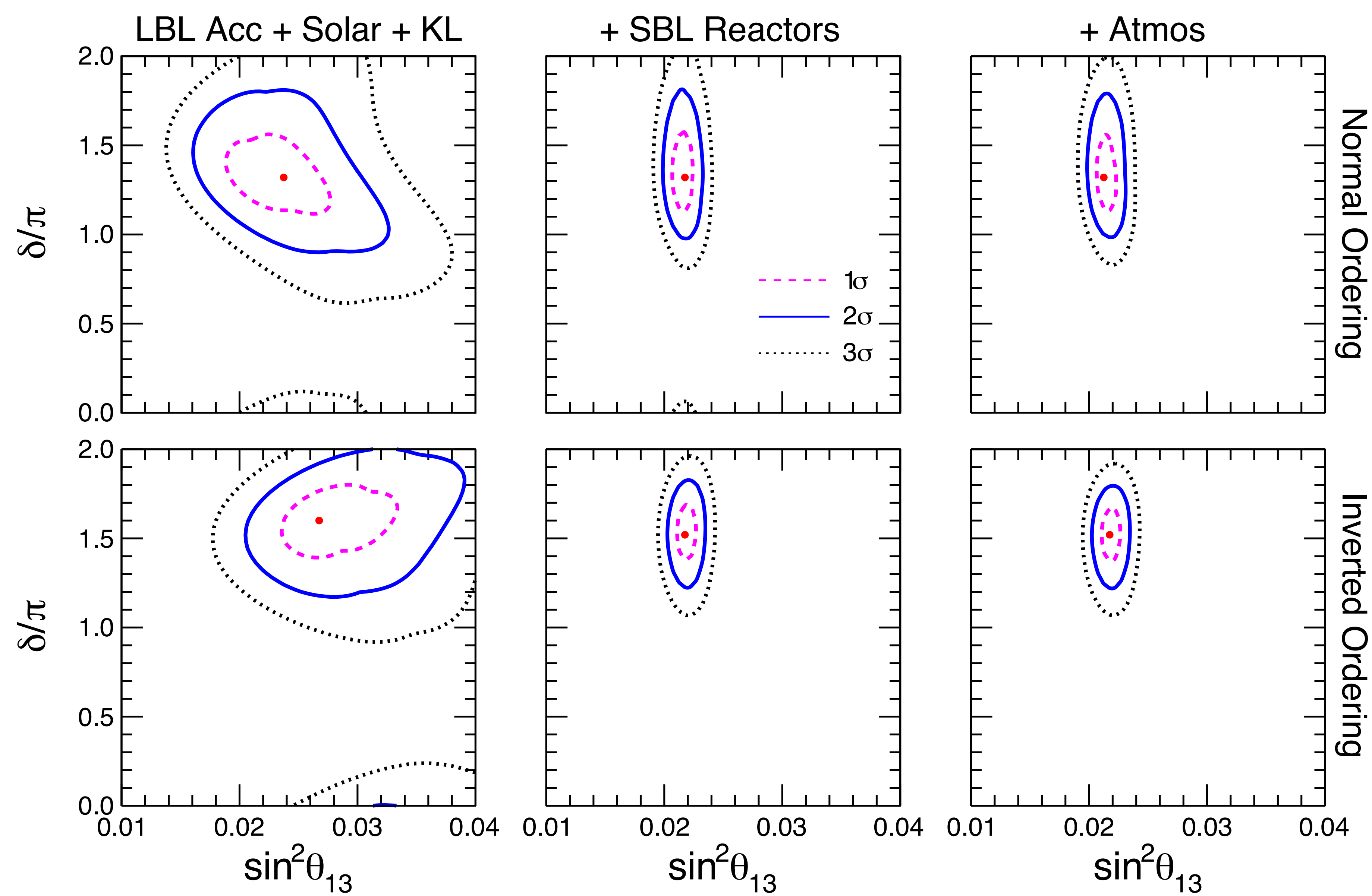

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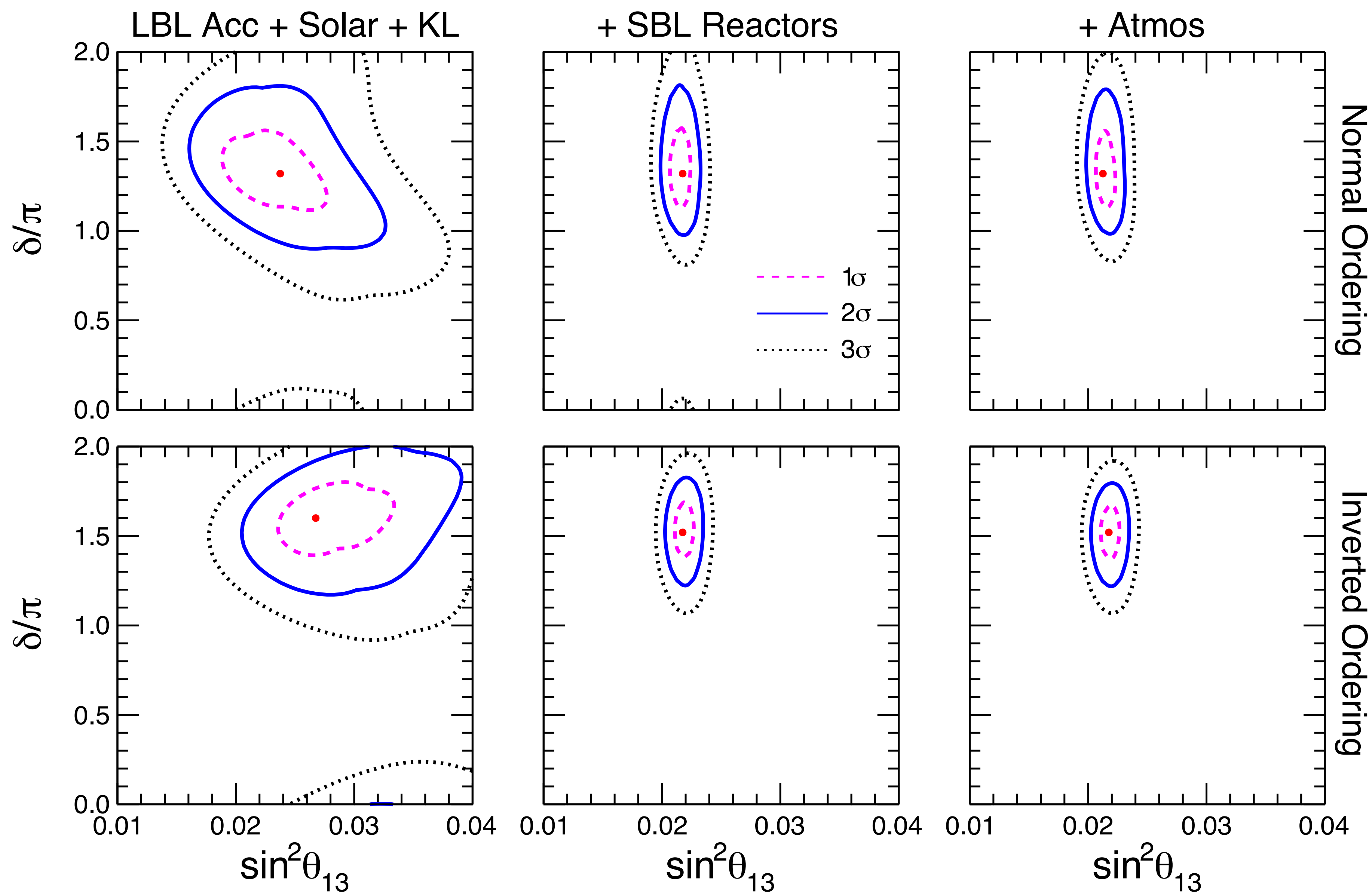

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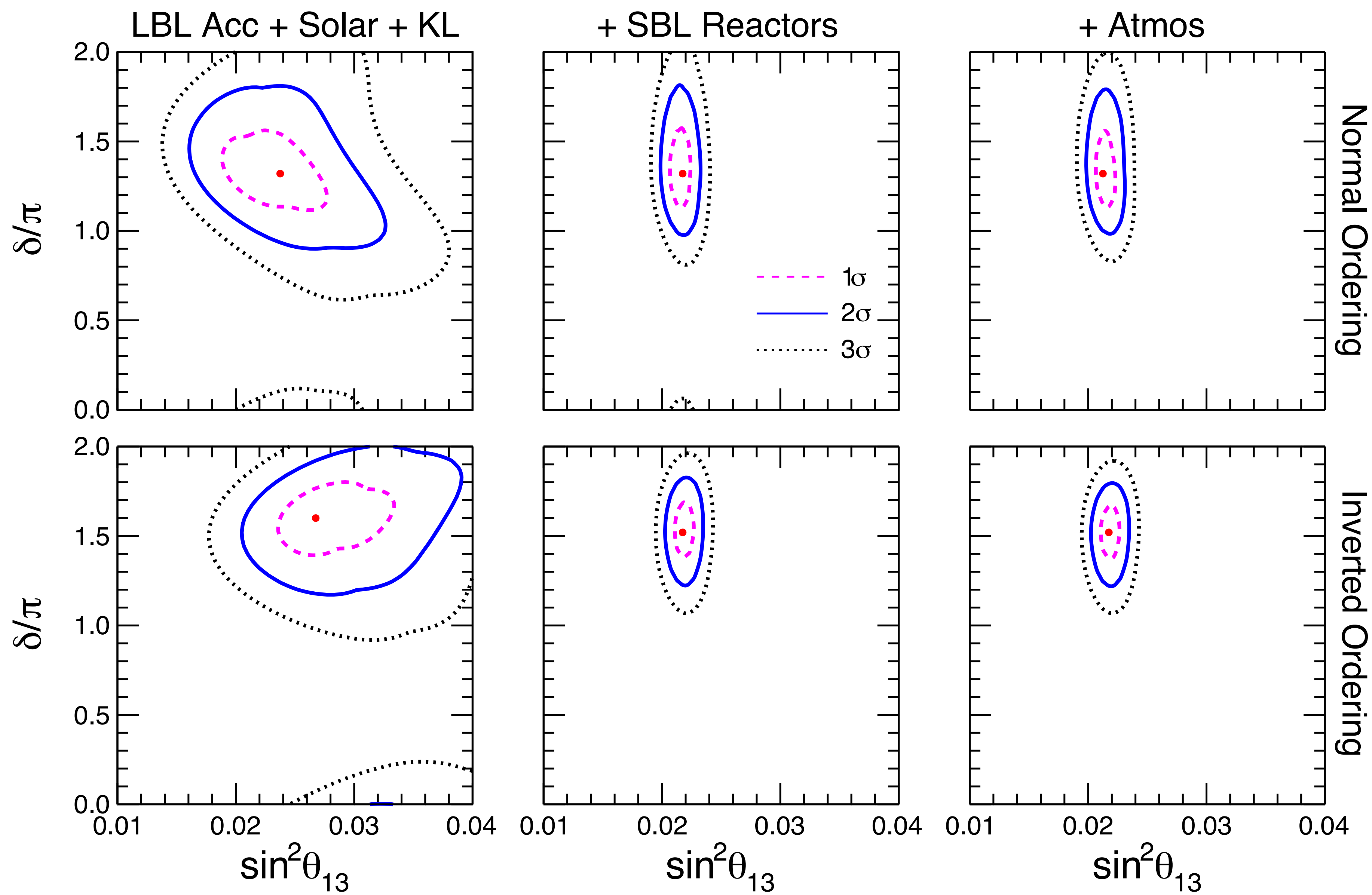

In IO there is a slight decrease of δ from left to middle panels, correlated to the decrease of θ_{13}.

Conclusions

- Ranges of well-known 3ν parameters ($\delta m^2, \theta_{12}$) & ($\Delta m^2, \theta_{13}$) confirmed by ν2017-8 data updates

- CPV: $\sin\delta<0$ preferred

  best fit: $\delta/\pi \sim 1.3\text{–}1.4 \pm 0.2$ (1σ)

  $\delta \sim 0$ (π) disfavoured at 2σ (3σ)

  $\sin\delta \sim +1$ disfavoured at $> 4\sigma$

- Octant info: $\theta_{23} > \pi/2$, but still fragile

- Mass Ordering: IO disfavored by oscillation data:

	LBL+Sol+KL	+SBL	+ATM
$\Delta\chi^2$(IO−NO)	1.3	4.4	9.5

(Non oscillation data corroborate NO)

- Info from ongoing - near future experiments