

Three-neutrino mixing: status and prospects

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Outline

Introduction

Global Analysis: data updated to 2015

Impact of new data on the CP-phase δ

Hierarchy and future experiments

Conclusions

Neutrino Mixing

$$\nu_\alpha = U_{\alpha i} \nu_i \quad \begin{array}{l} \alpha = e, \mu, \tau \quad \text{flavor eigenstates} \\ i = 1, 2, 3 \quad \text{mass eigenstates} \end{array}$$

Mixing Matrix (PMNS)

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

$$(\theta_{12}, \theta_{13}, \theta_{23}) \quad \text{3 mixing angles} \quad (\Delta m^2, \delta m^2)$$

$$\delta \in [0, 2\pi] \quad \text{"CP" phase} \quad \text{2 mass squared differences}$$

$$+\Delta m^2 \longrightarrow \text{Normal Hierarchy (NH)}$$

$$-\Delta m^2 \longrightarrow \text{Inverted Hierarchy (IH)}$$

(α, β) Two Majorana phases (unobservable with oscillations)

Global Analysis

To exploit parameter correlations we analyze **increasingly** reach data sets



Long-baseline acc.+
Solar + KamLAND

constrain $(\delta m^2, \theta_{12}) \oplus (\Delta m^2, \theta_{23}) \oplus \theta_{13}$
some info on θ_{23} octant and δ

Short-baseline reactors

add independent, strong
constraints on θ_{13}

SK Atmospheric

further constraints
on $(\Delta m^2, \theta_{23})$ and info
on θ_{23} octant and δ

[No real sensitivity yet to hierarchy in any data set]

Global Analysis *(Preliminary)* (updated to summer 2015)

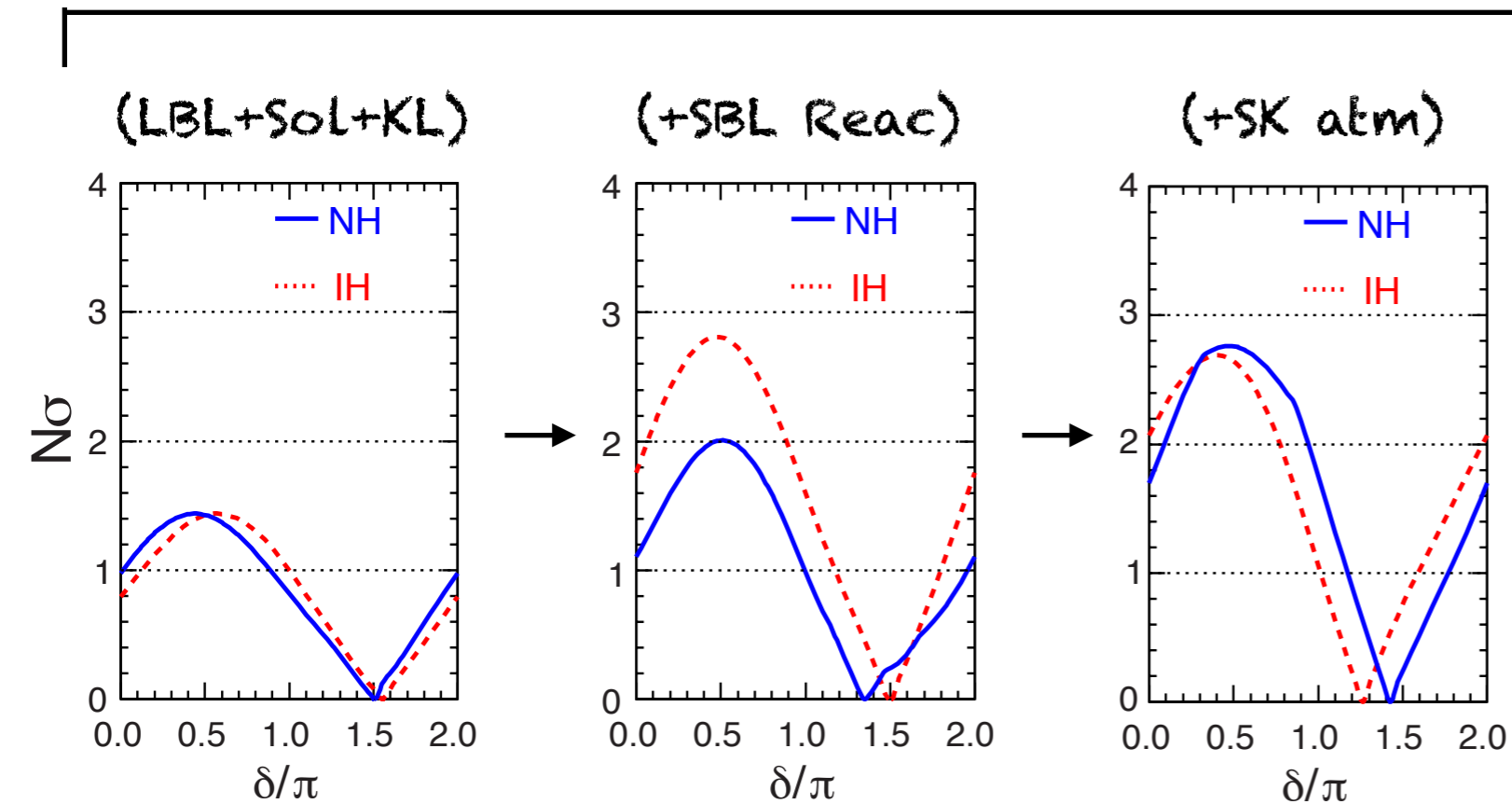
LBL (2015, added T2K $\bar{\nu}$ and NOvA,
appearance and disappearance)

Solar + KamLAND + SBL (2014)

work in progress to update also
atm. + reactors to 2015

Impact of T2K $\bar{\nu}$ and NO ν A
on the CP-phase δ

Impact of T2K and NOvA on the CP-phase δ (2014)



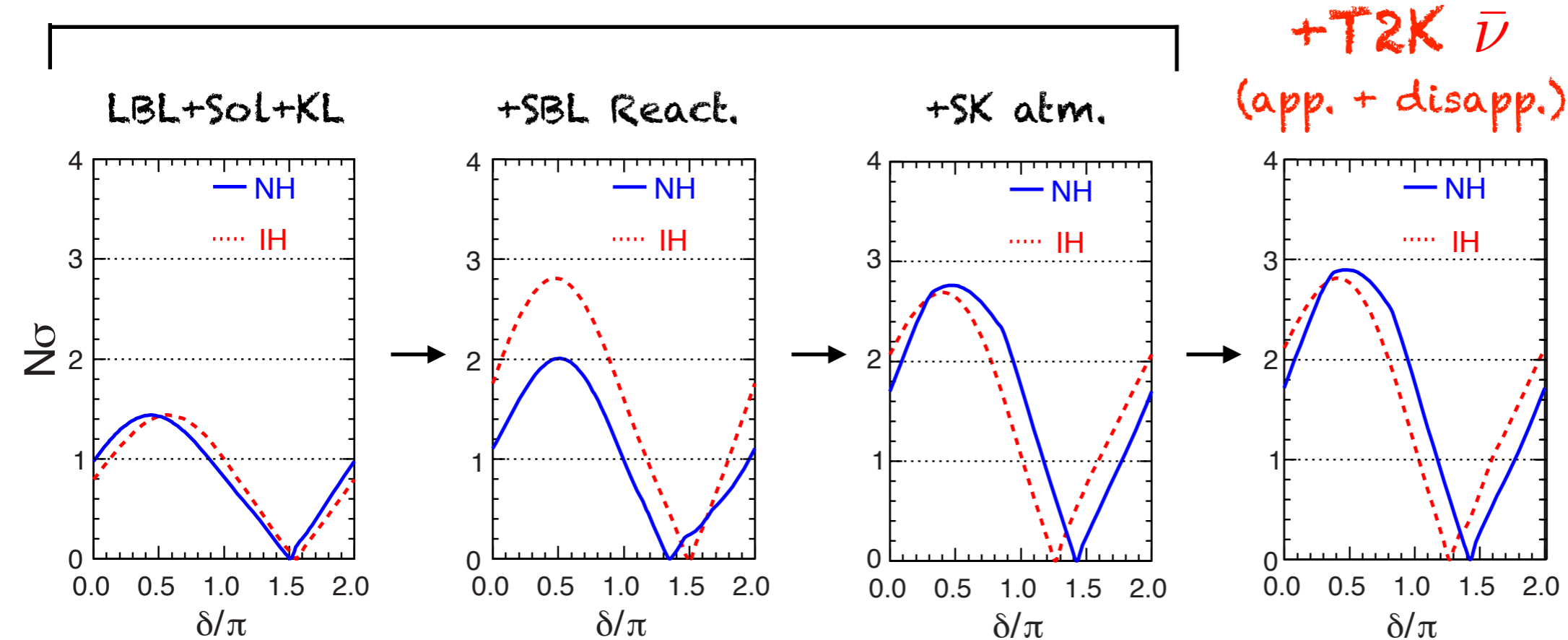
$$\Delta\chi^2_{(IH-NH)} \sim -1.4 \quad \sim -0.9 \quad \sim -0.1$$

intriguing $\sin\delta \sim -1$ preferred

CP-conserving values of δ disfavoured at $\sim 1-2\sigma$

no statistically significant info on the hierarchy

Impact of T2K and NOvA on the CP-phase δ (2014)



$\Delta\chi^2 \sim -1.4$ ~ -0.9 ~ -0.1 $\sim +0.3$
(IH-NH)

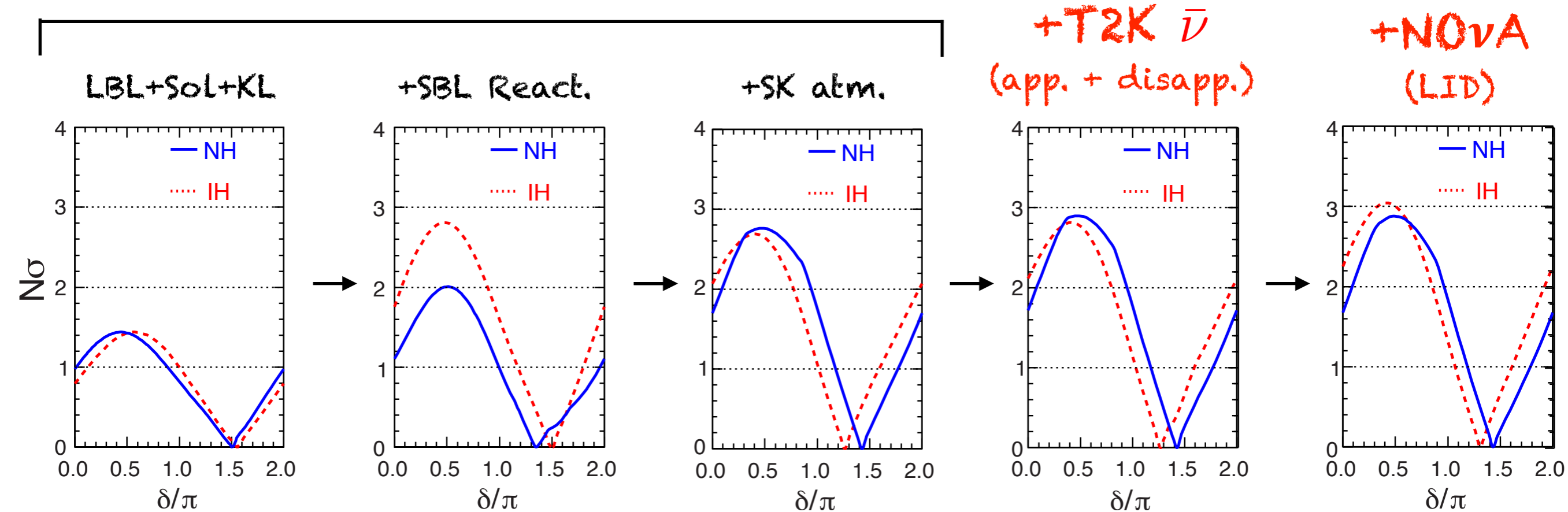
sensitivity to δ slightly increased

CP-conserving values of δ disfavoured at $\sim 1-2\sigma$

no statistically significant info on the hierarchy,
but NH preferred

Impact of T2K and NOvA on the CP-phase δ

(2014)



$\Delta\chi^2 \sim -1.4$ ~ -0.9 ~ -0.1 $\sim +0.3$ $\sim +0.3$

(IH-NH)

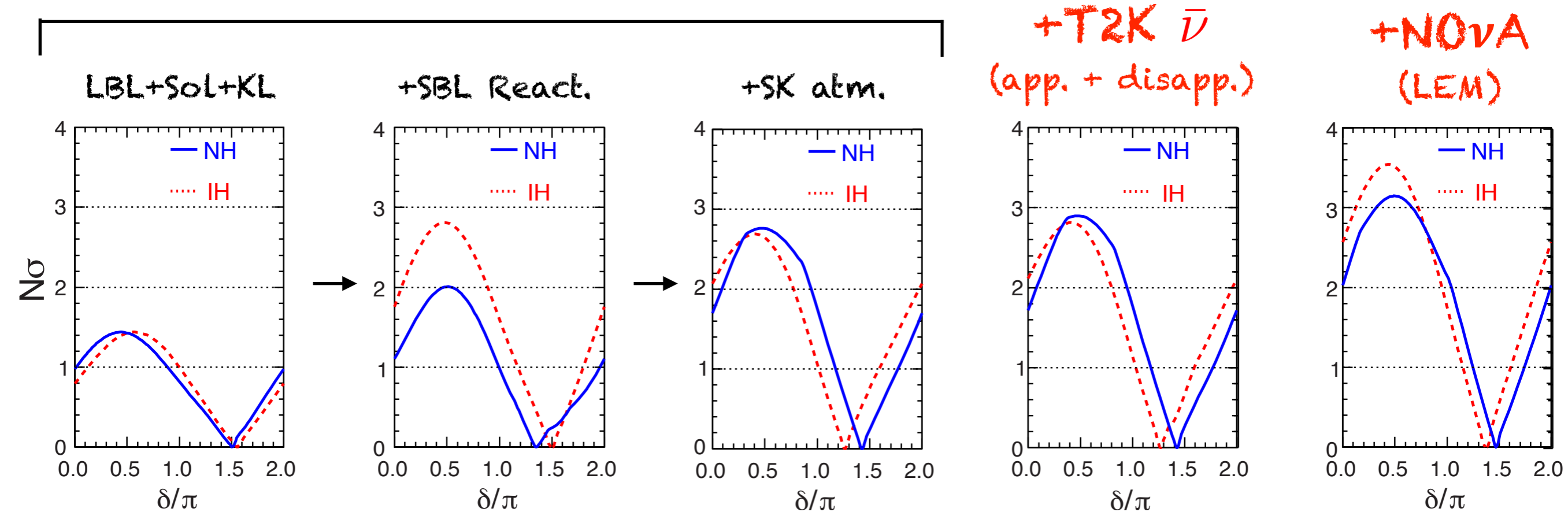
sensitivity to δ slightly increased for IH

CP-conserving values of δ disfavoured at $\sim 1-2\sigma$

no statistically significant info on the hierarchy, but NH preferred

Impact of T2K and NOvA on the CP-phase δ

(2014)



$\Delta\chi^2 \sim -1.4$ ~ -0.9 ~ -0.1 $\sim +0.3$ $\sim +2.2$

(IH-NH)

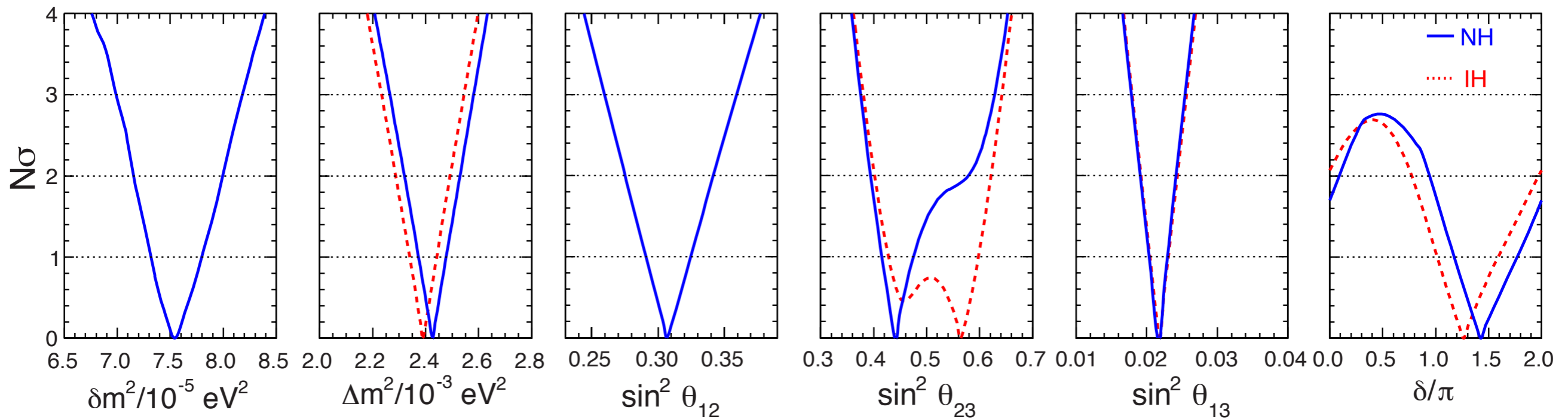
sensitivity to δ slightly increased ($>3\sigma$ for some values)

CP-conserving values of δ disfavoured at $\sim 2\sigma$

Slight preference for NH

Global Analysis 2014-15:
single parameters

Global Analysis 2014



Accuracy (2014):

δm^2	2.6	%
Δm^2	2.6	%
$\sin^2 \theta_{12}$	5.4	%
$\sin^2 \theta_{13}$	5.8	%
$\sin^2 \theta_{23}$	~10	%

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

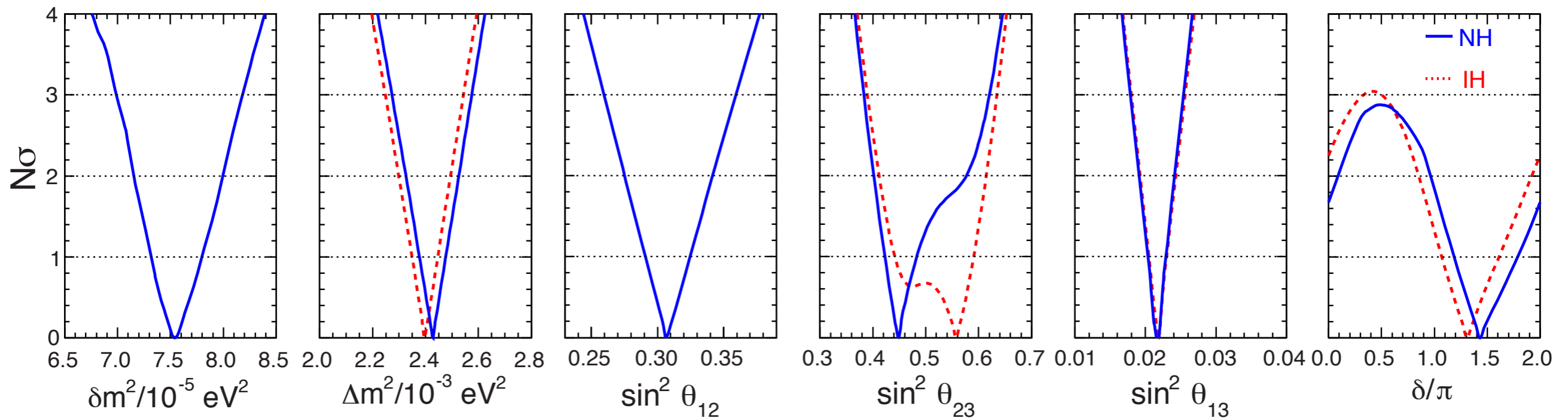
θ_{23} octant: unstable, fragile

hierarchy: negligible sensitivity

δ_{CP} : intriguing preference for $\sin\delta_{CP} \approx -1$

adding T2K $\bar{\nu}$ and NOVA LID \rightarrow

Global Analysis (added T2K $\bar{\nu}$ and NOVA-LID)



Current accuracy:

δm^2	2.6 %	
Δm^2	2.6 %	→ 2.1 %
$\sin^2 \theta_{12}$	5.4 %	
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$\sin^2 \theta_{23}$	~10 %	→ ~9 %

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

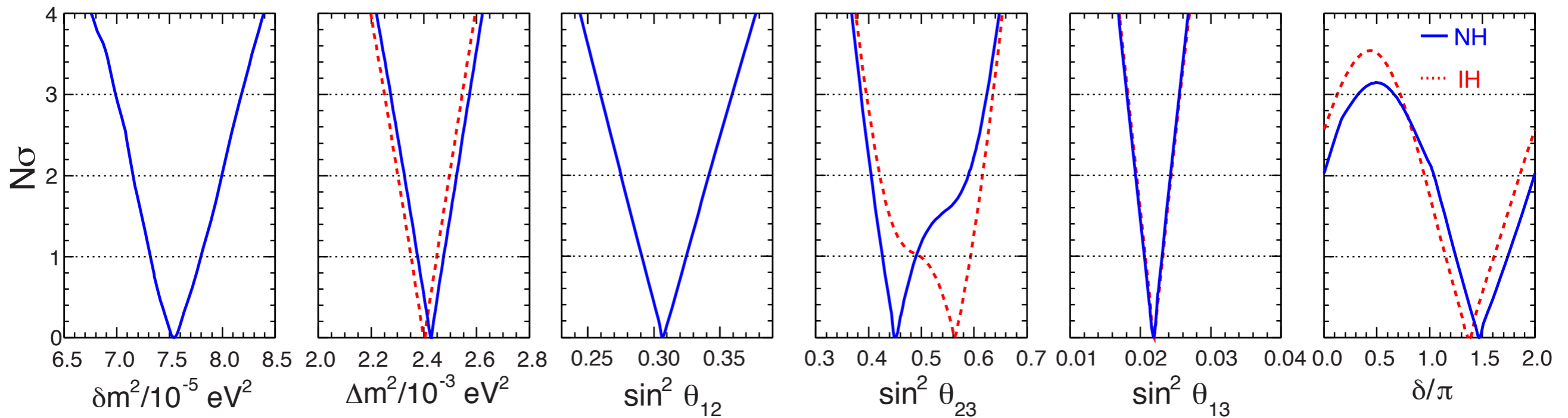
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slight improvement
on δ_{CP} sensitivity

adding T2K $\bar{\nu}$ and NOVA LEM →

Global Analysis (added T2K $\bar{\nu}$ and NOVA-LEM)



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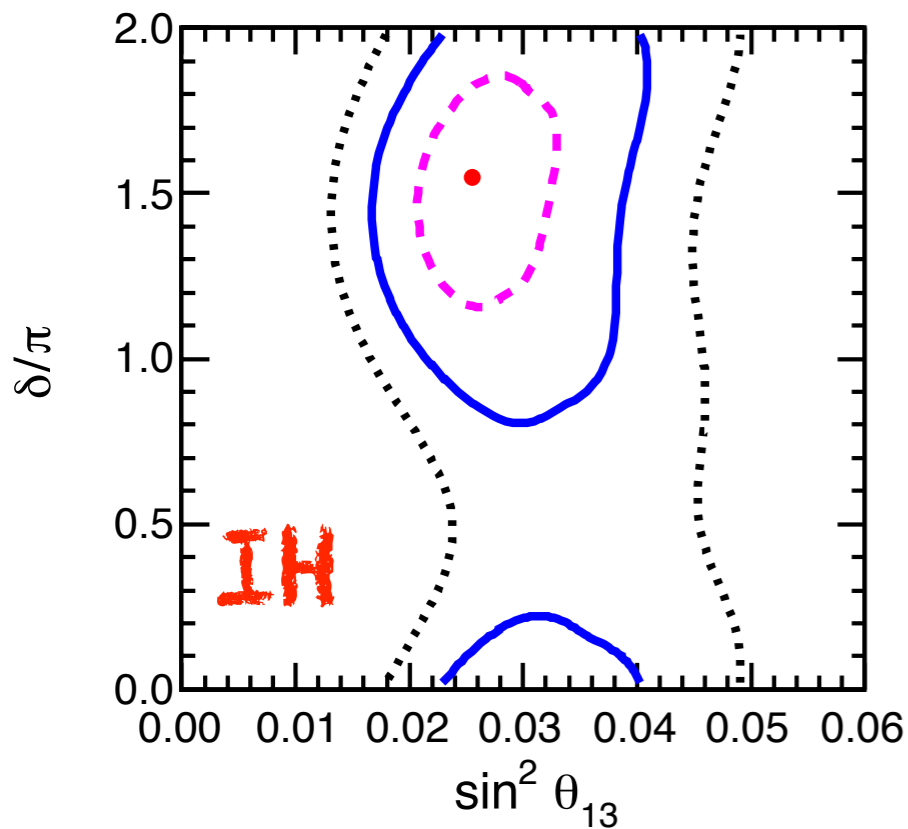
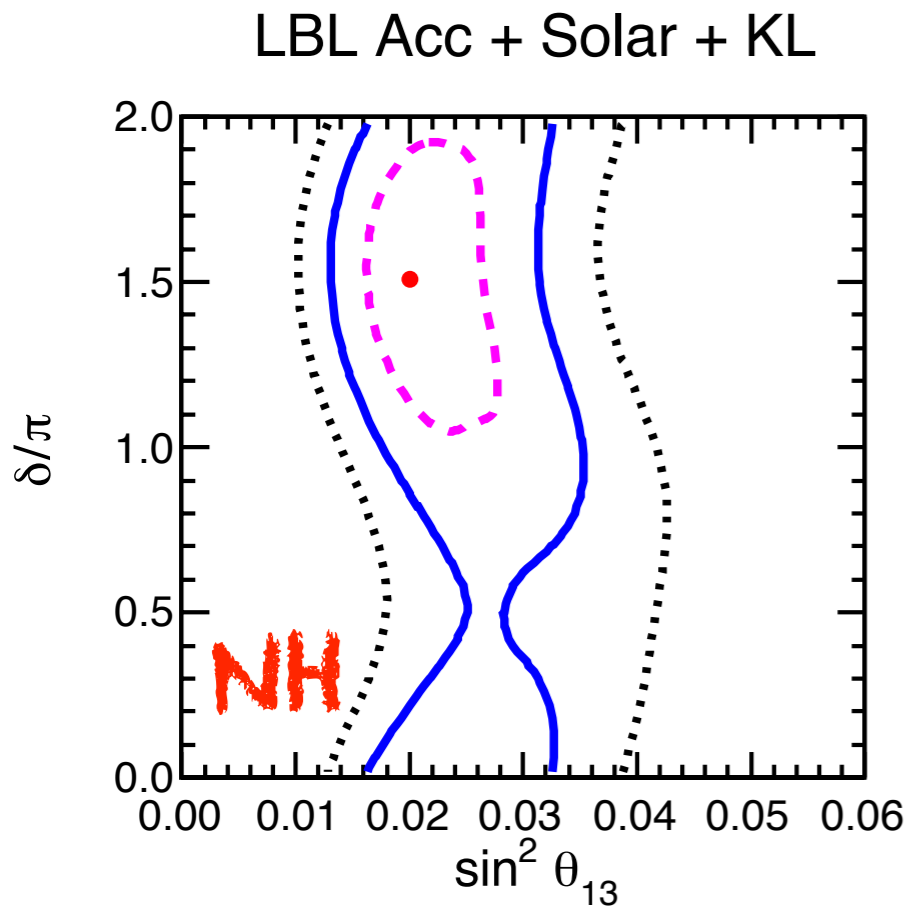
θ_{23} octant: unstable, fragile

hierarchy: negligible sensitivity

slight improvement
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from single parameters to 2-parameter correlations →

(θ_{13}, δ) correlation including T2K and NOvA-LIM



For the relatively "low" value $\sin^2 \theta_{13} \sim 0.02$ preferred by Solar + KL data, appearance signal in T2K and NOvA maximized by subleading CP-odd term for $\sin \delta < 0$ [i.e., $1 < \delta/\pi < 2$].

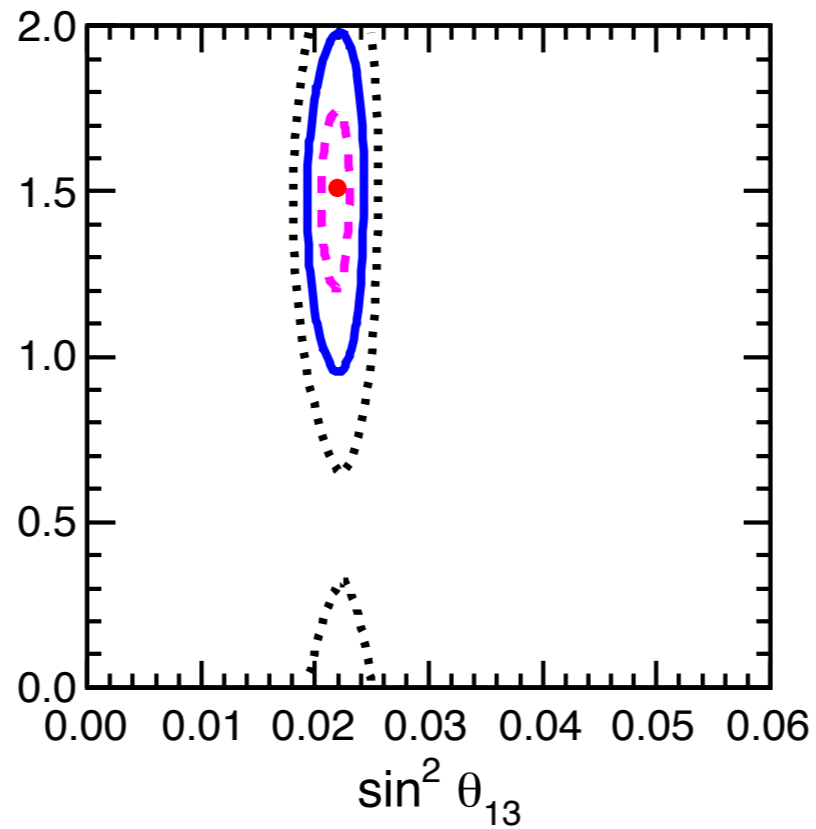
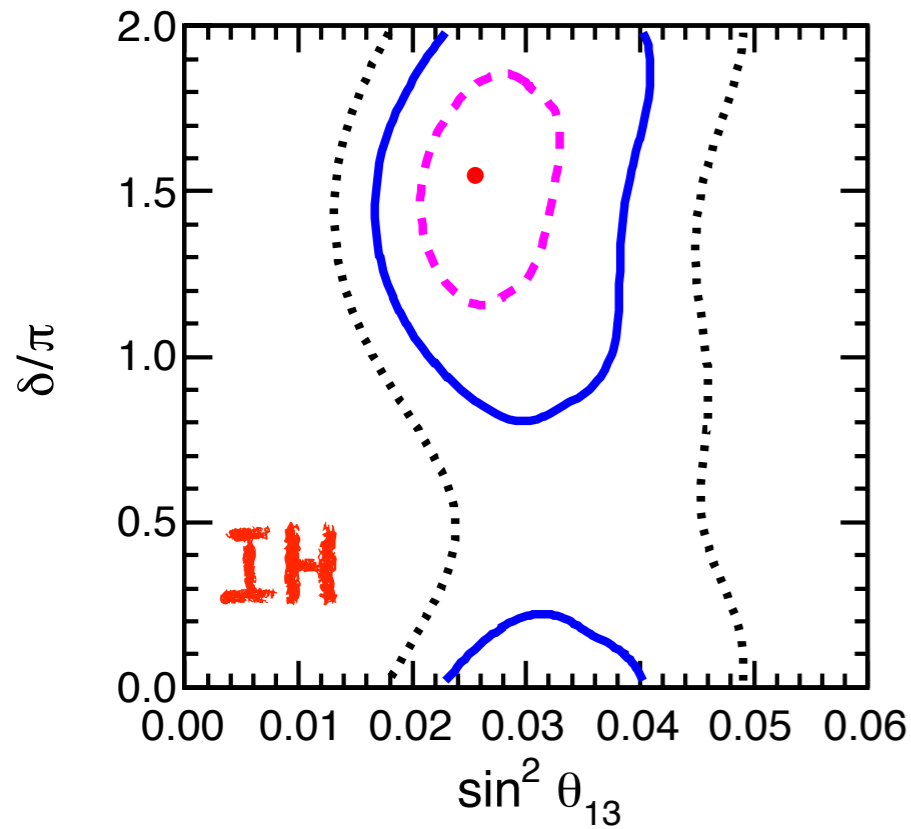
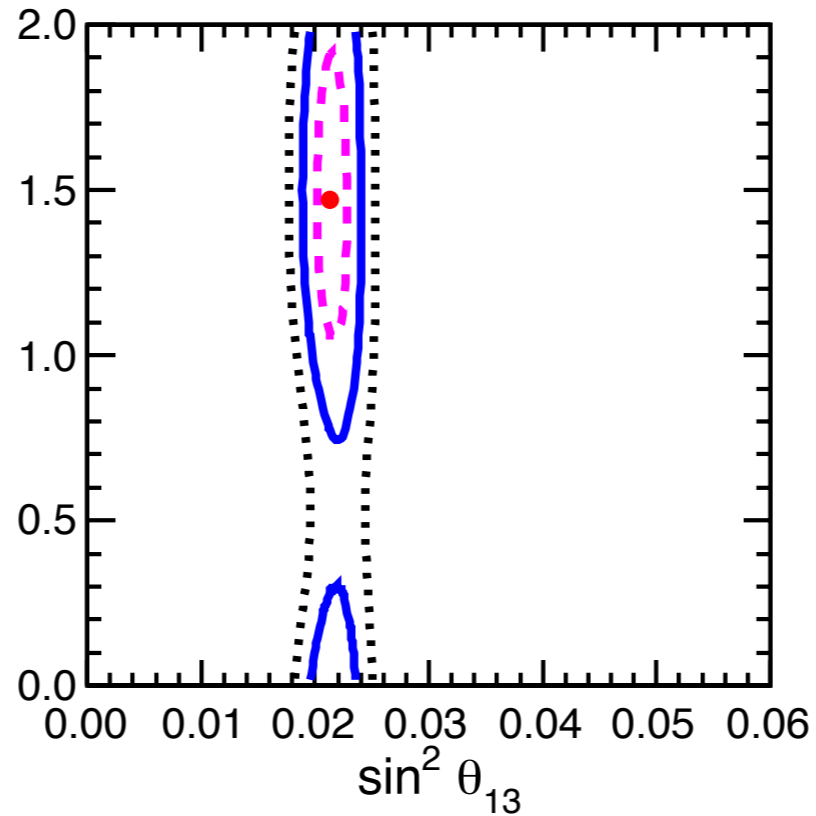
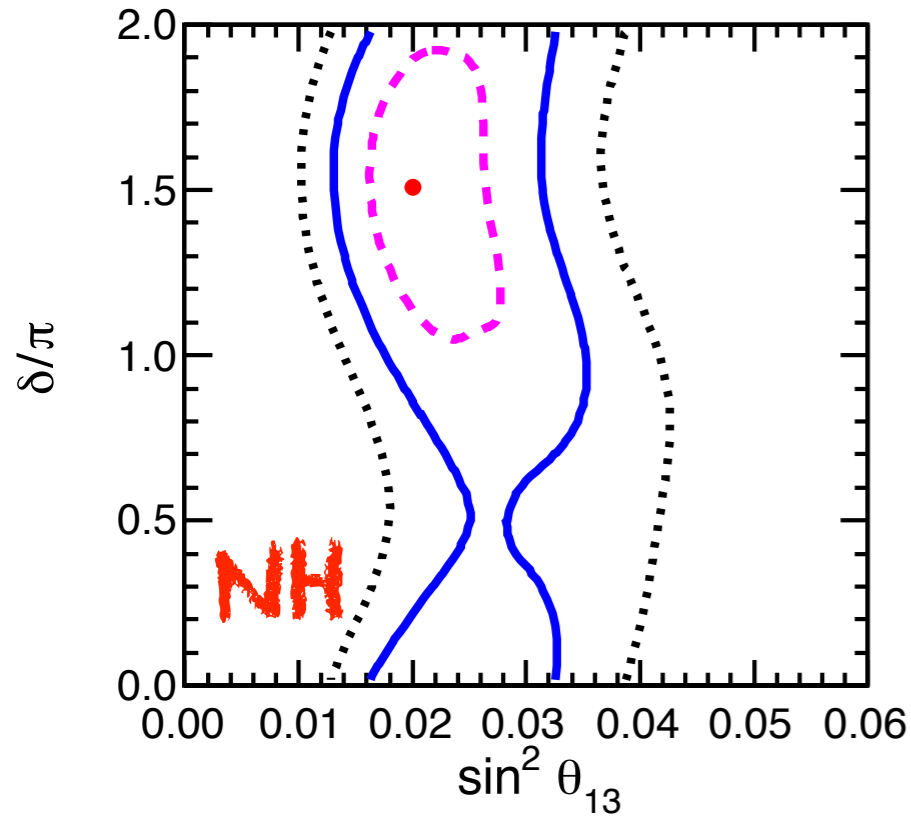
T2K+NOvA neutrino appearance signal consistent with the maximum allowed by $\sin^2 \theta_{13} \sim 0.02$
Best fit for $\delta/\pi \sim 1.5$, for both hierarchies

The weaker MINOS signal prefers $\sin \delta > 0$, "out of phase" w.r.t. T2K+NOvA. Fluctuation?

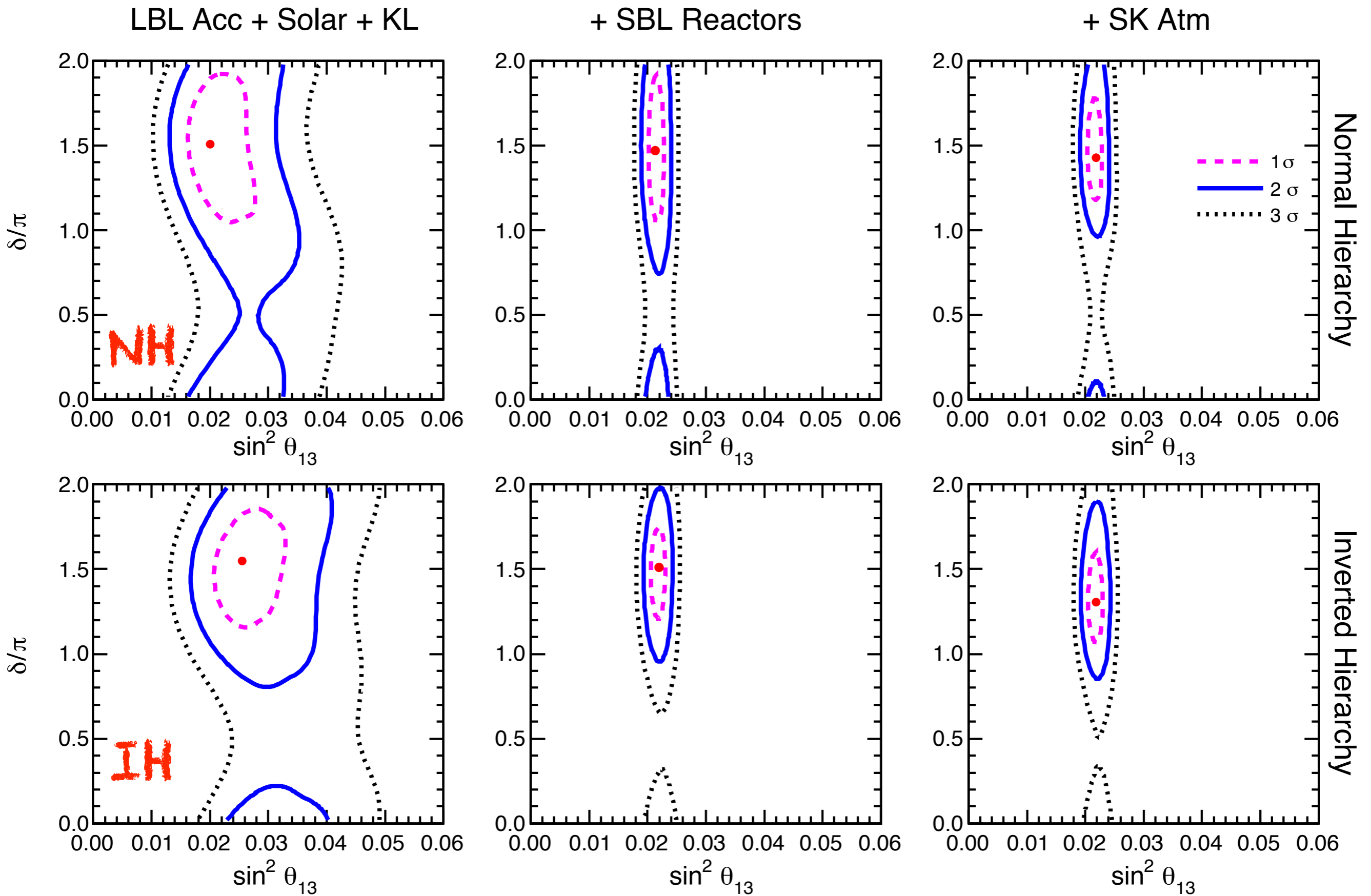
NOvA more in phase with T2K than MINOS

LBL Acc + Solar + KL

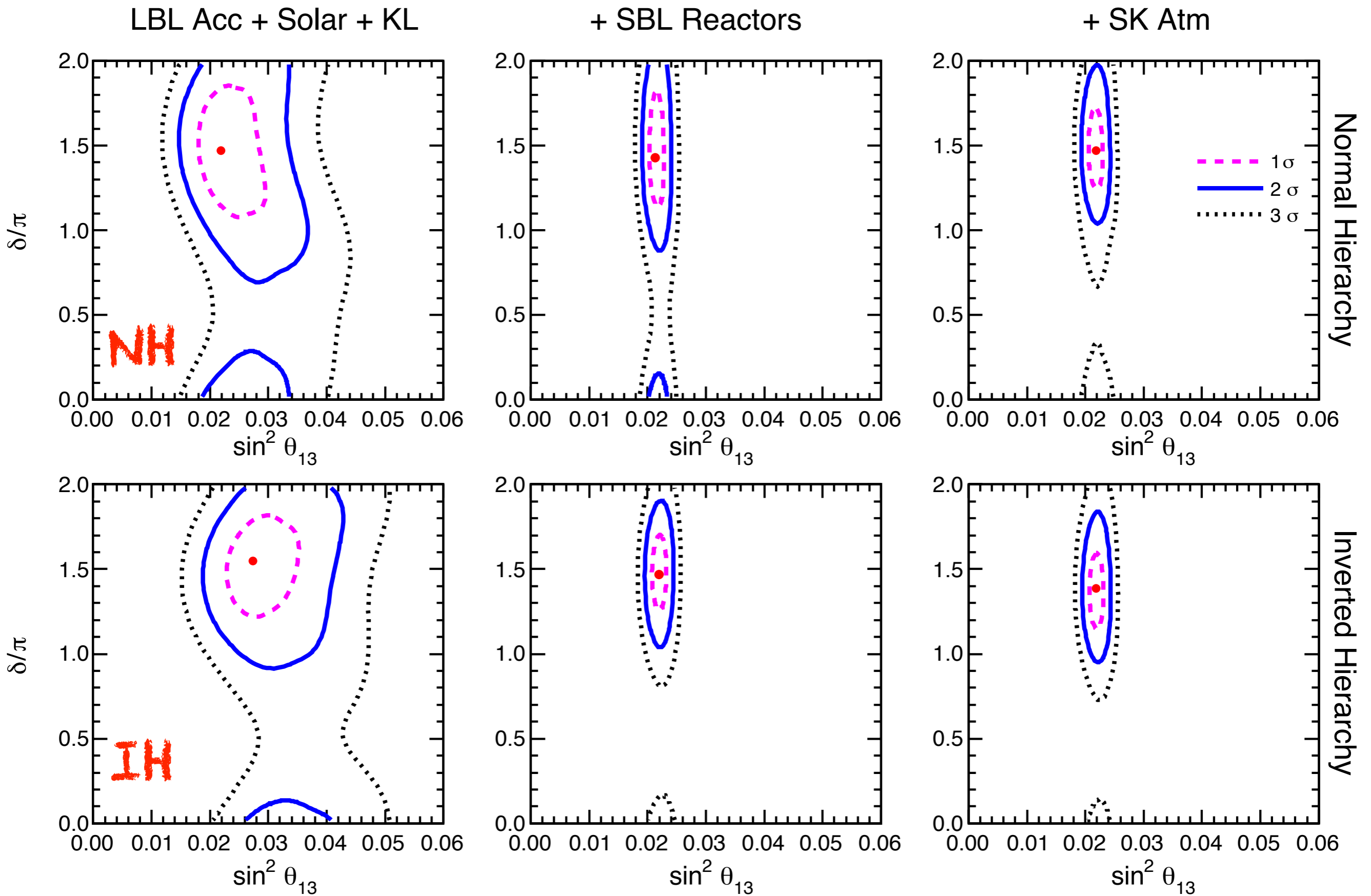
+ SBL Reactors



Reactor data strongly constrain $\sin^2 \theta_{13}$ close to 0.022, corroborate previous preferences for $\sin \delta \sim -1$ and shrink allowed region (leftmost part of the LBL+Sol.+KL band)



The combination with SK atm. data moves δ to $\delta/\pi \sim 1.3-1.4$ and slightly shrinks its allowed range



Allowed regions reduced with NOVA-LED

(2014)

Another correlation plot: δ vs θ_{23} . Note octant instability.
Future constraints on θ_{23} will indirectly improve hints on δ

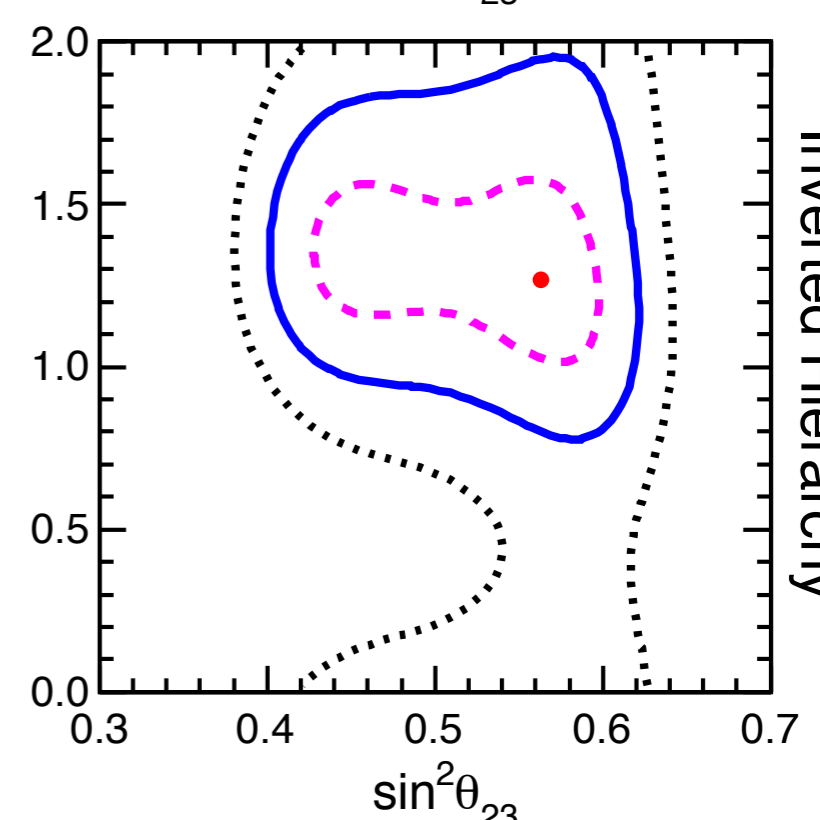
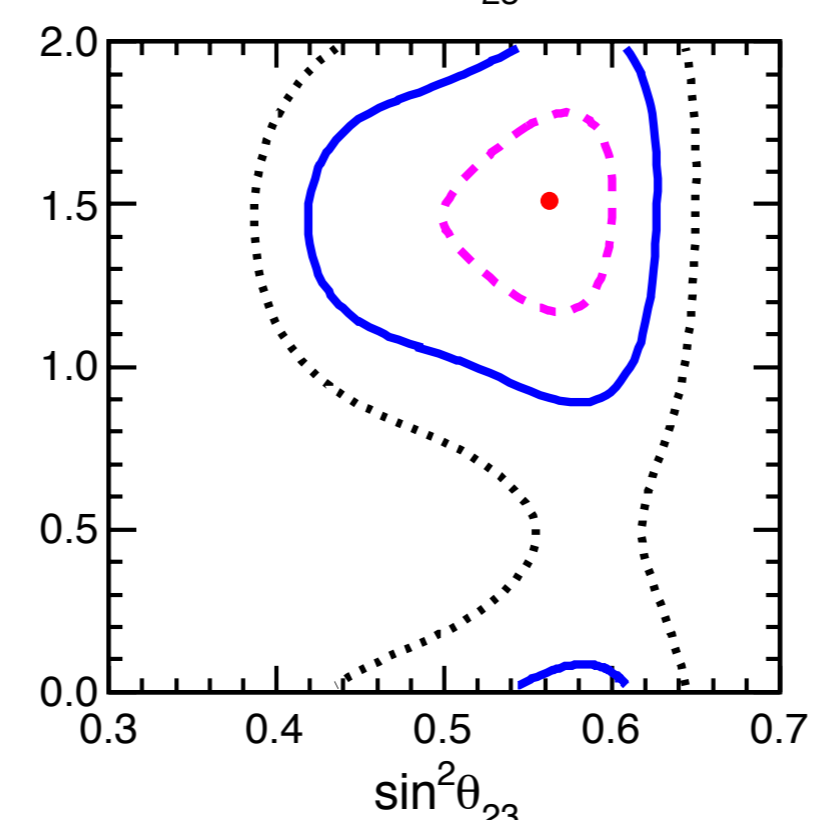
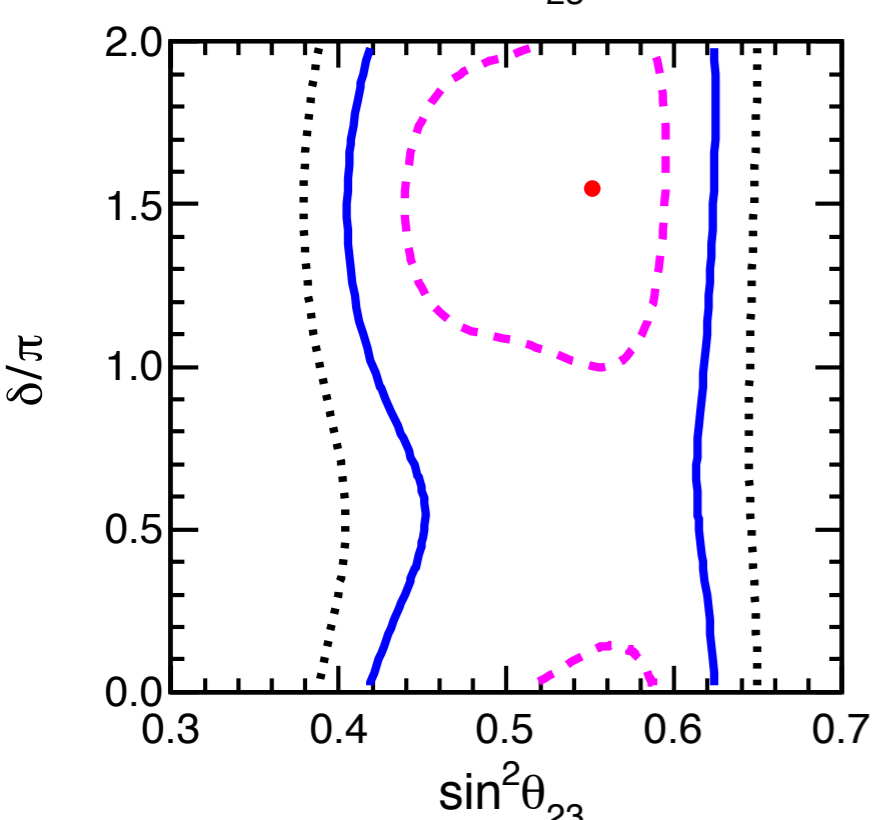
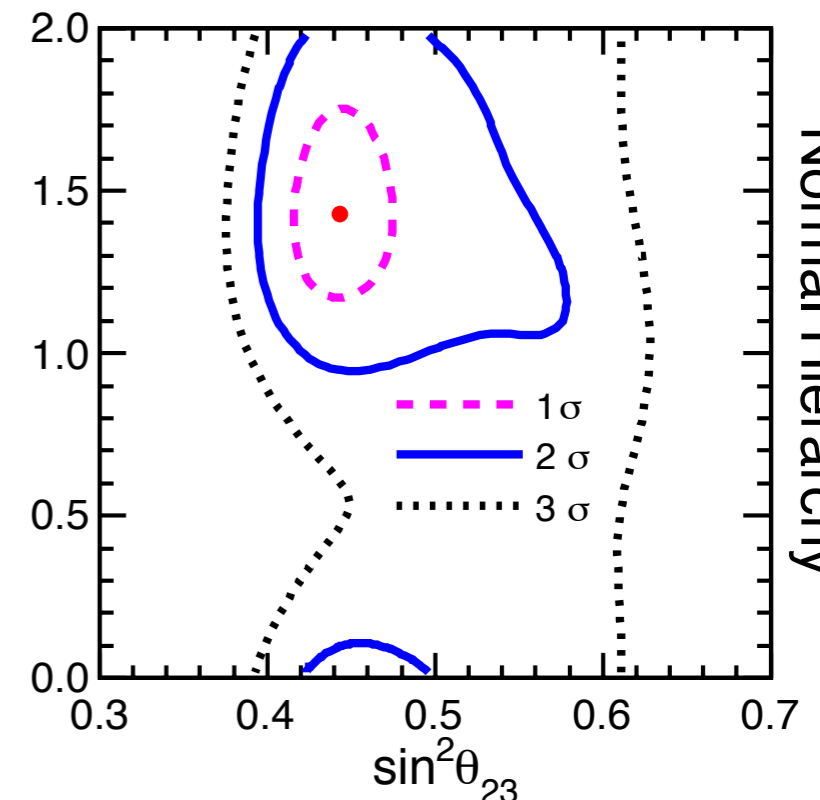
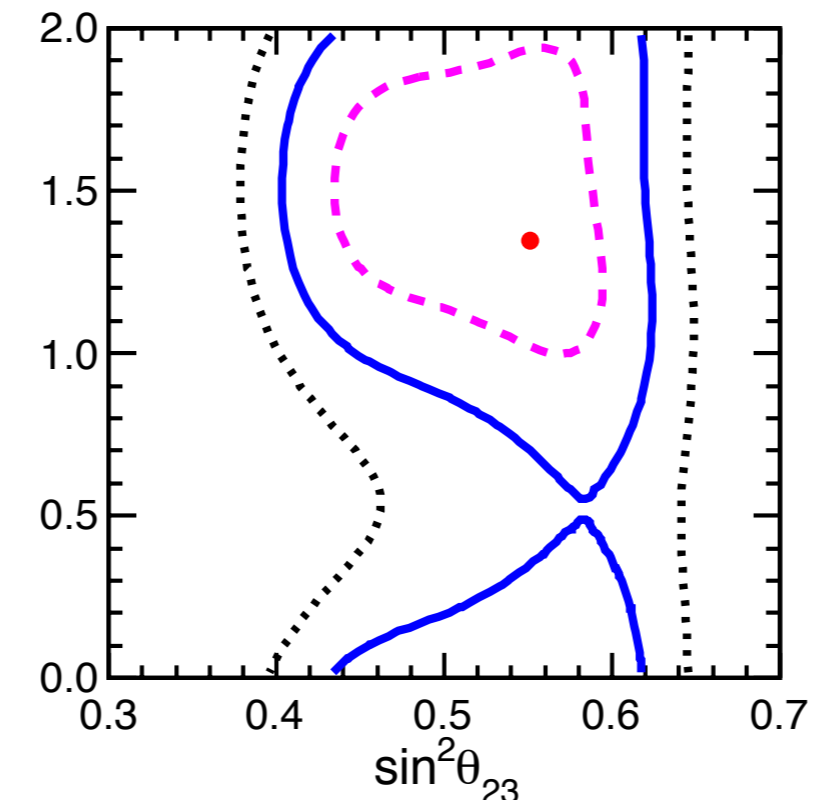
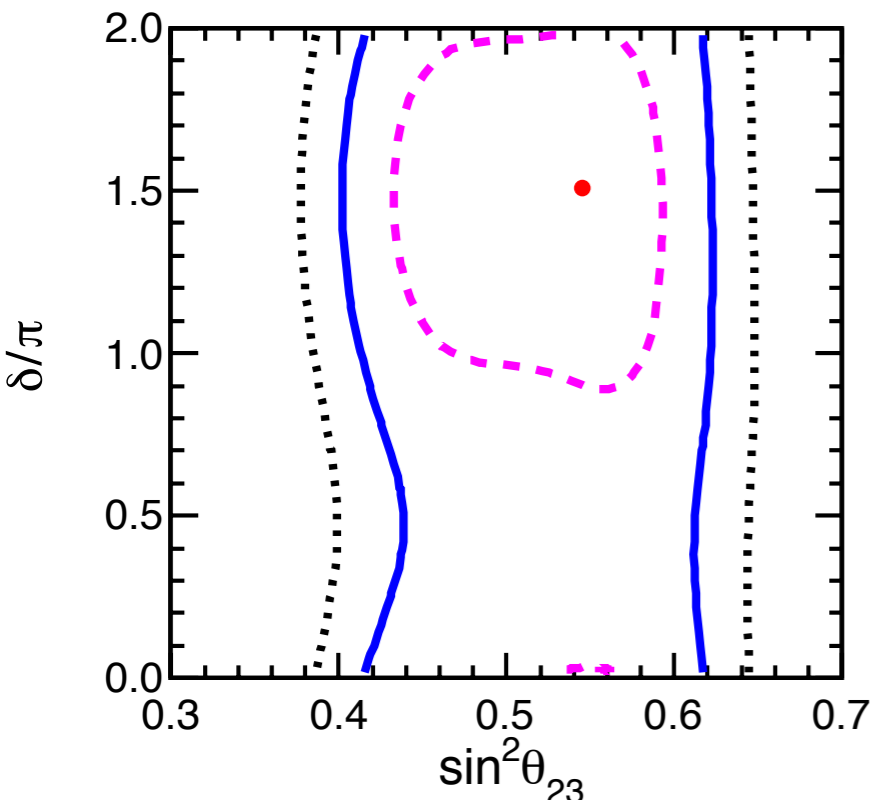
LBL Acc + Solar + KL

+ SBL Reactors

+ SK Atm

Normal Hierarchy

Inverted Hierarchy

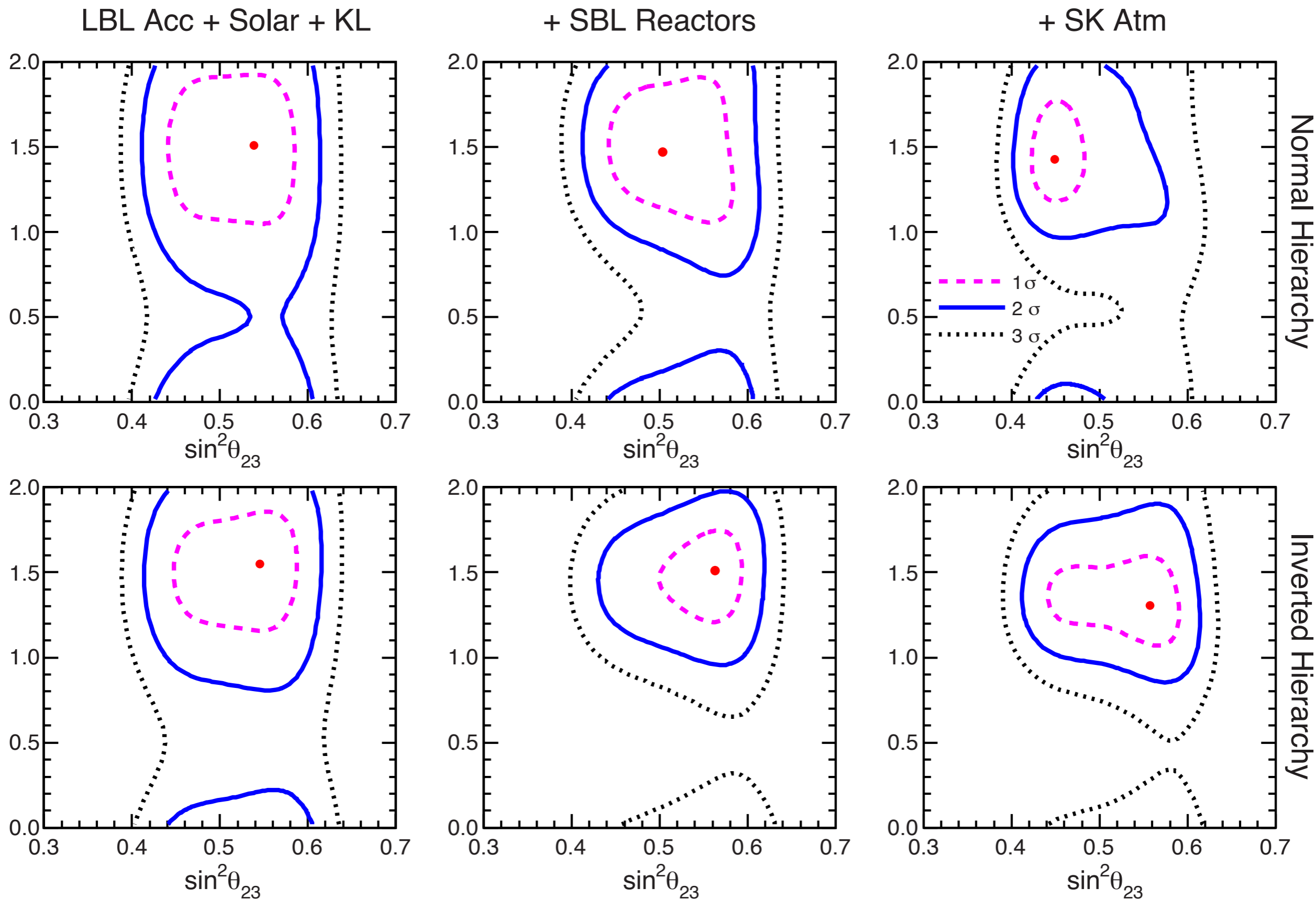


1 σ
2 σ
3 σ

(2015)

NOVA-LID

Allowed regions reduced in both hierarchies



(2015)

NOvA-LEM

Allowed regions reduced in both hierarchies

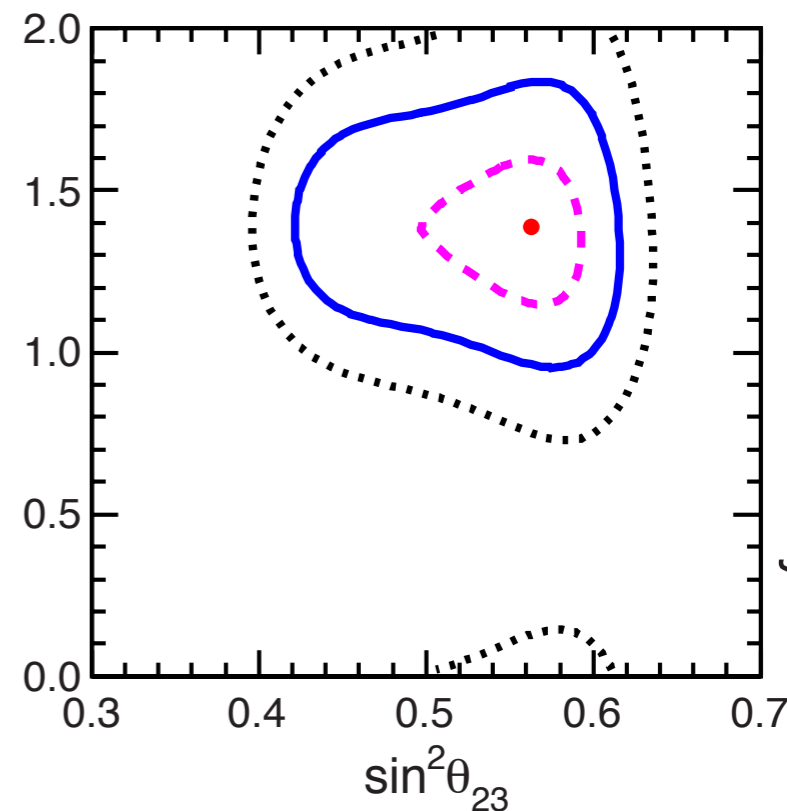
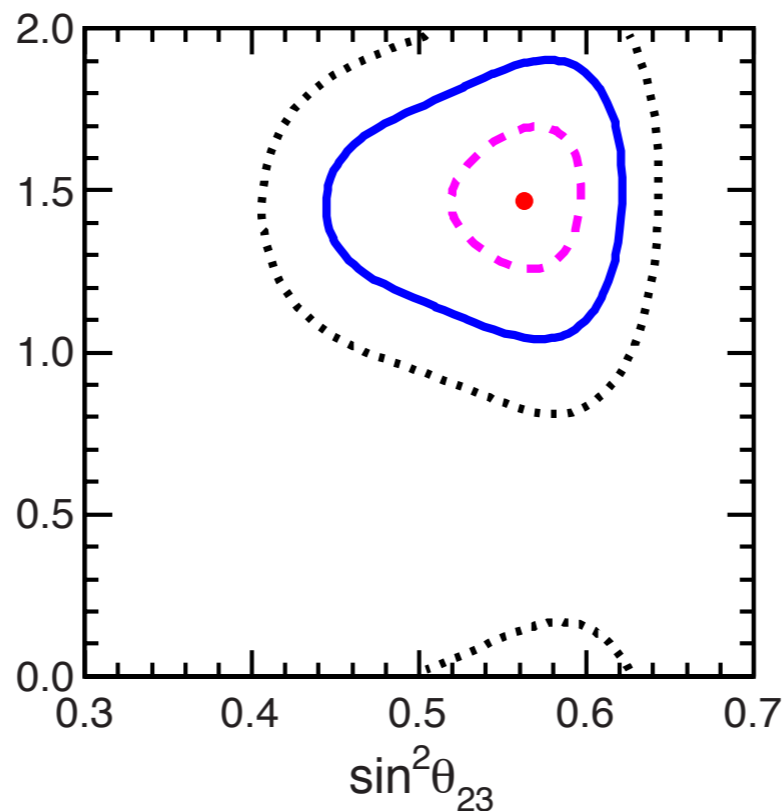
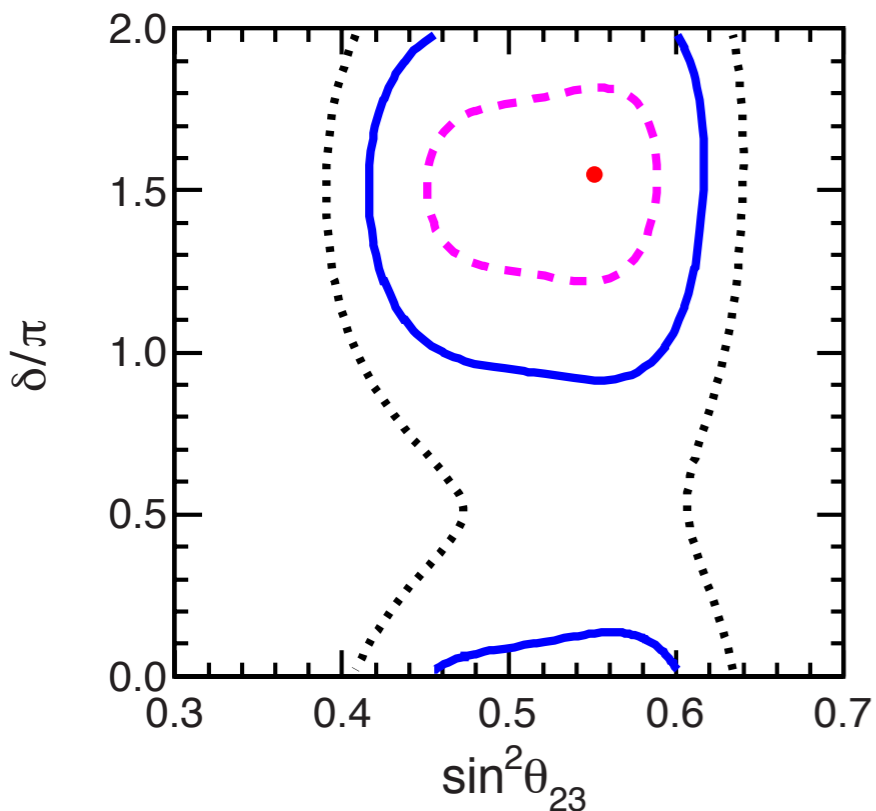
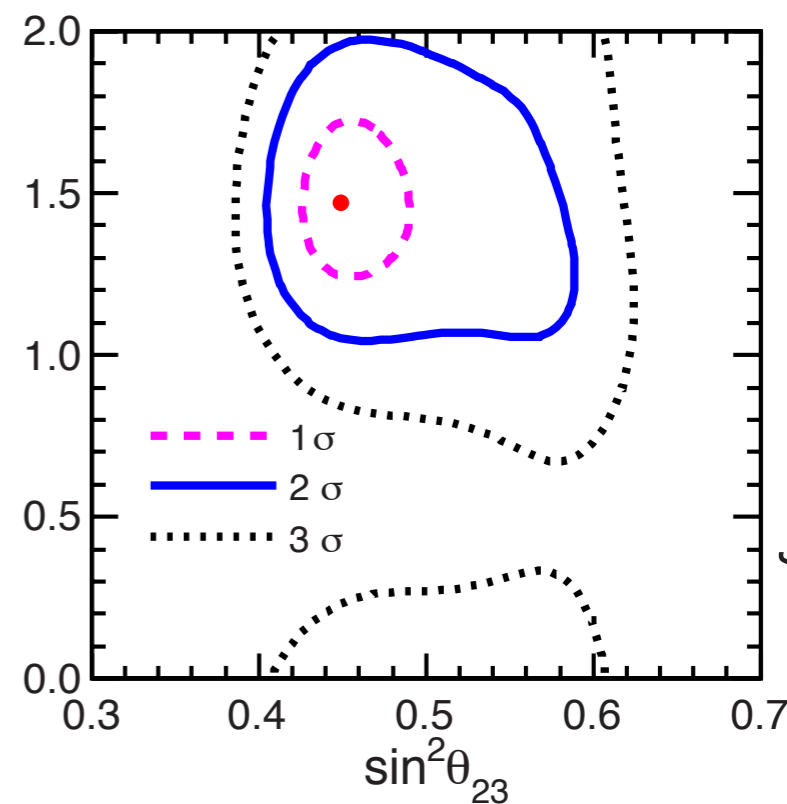
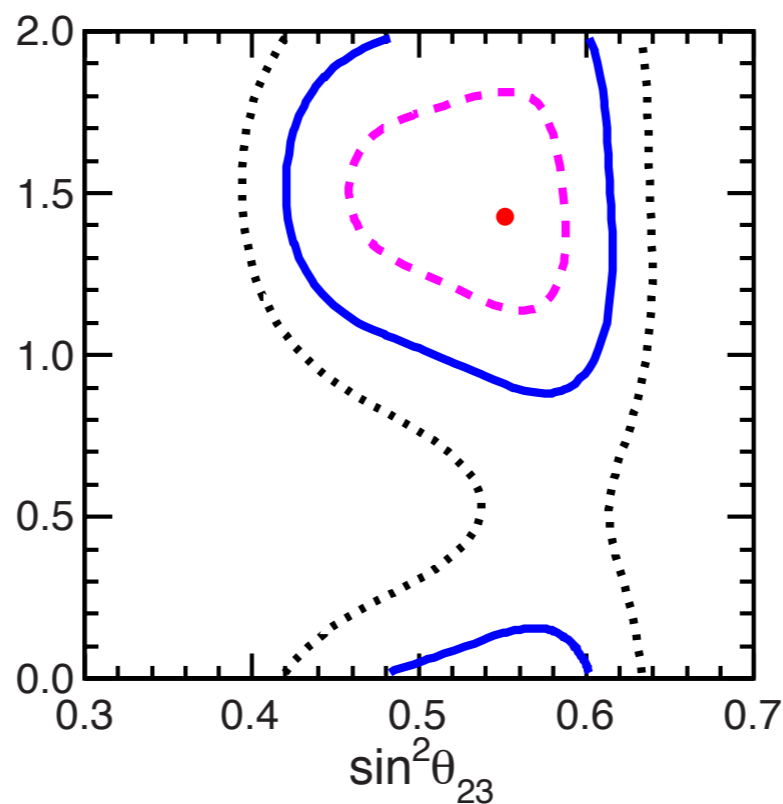
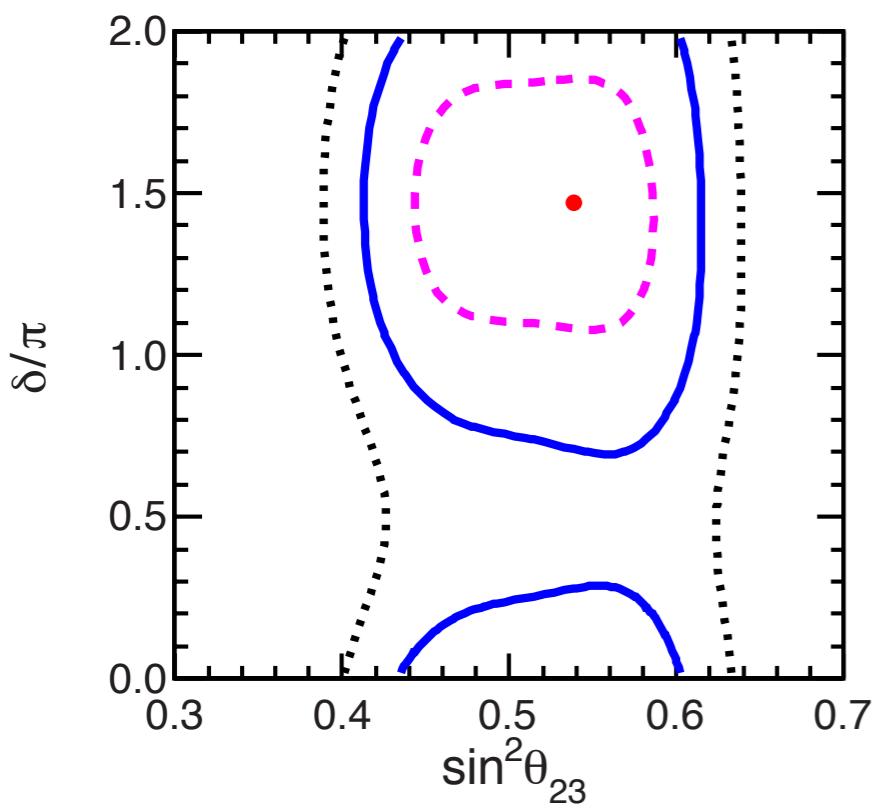
LBL Acc + Solar + KL

+ SBL Reactors

+ SK Atm

Normal Hierarchy

Inverted Hierarchy



Hierarchy might remain undetermined for quite some time, may need new dedicated projects (e.g., PINGU/ORCA and JUNO/RENO-50)



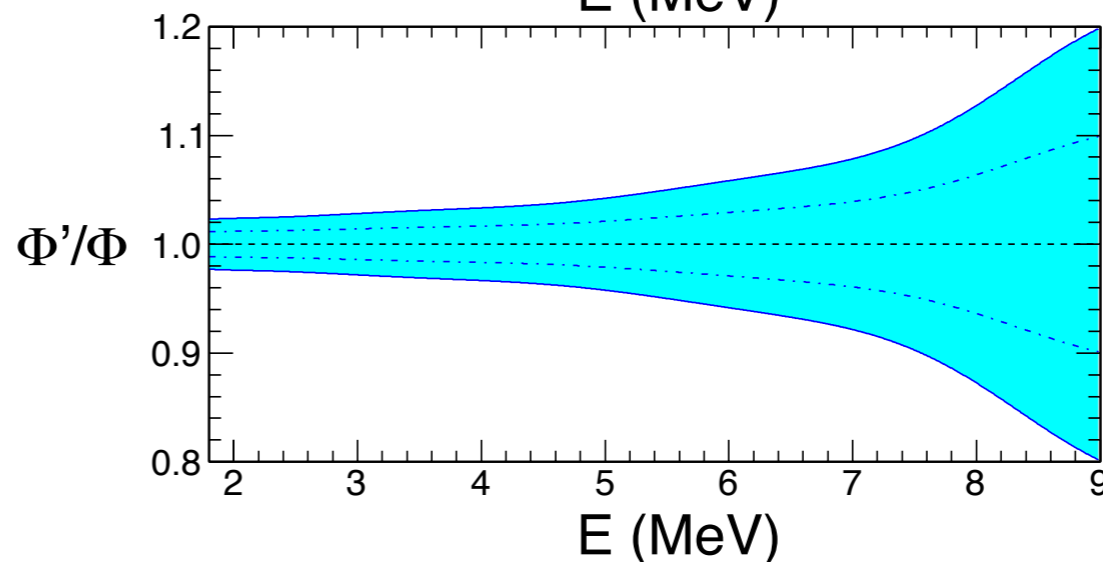
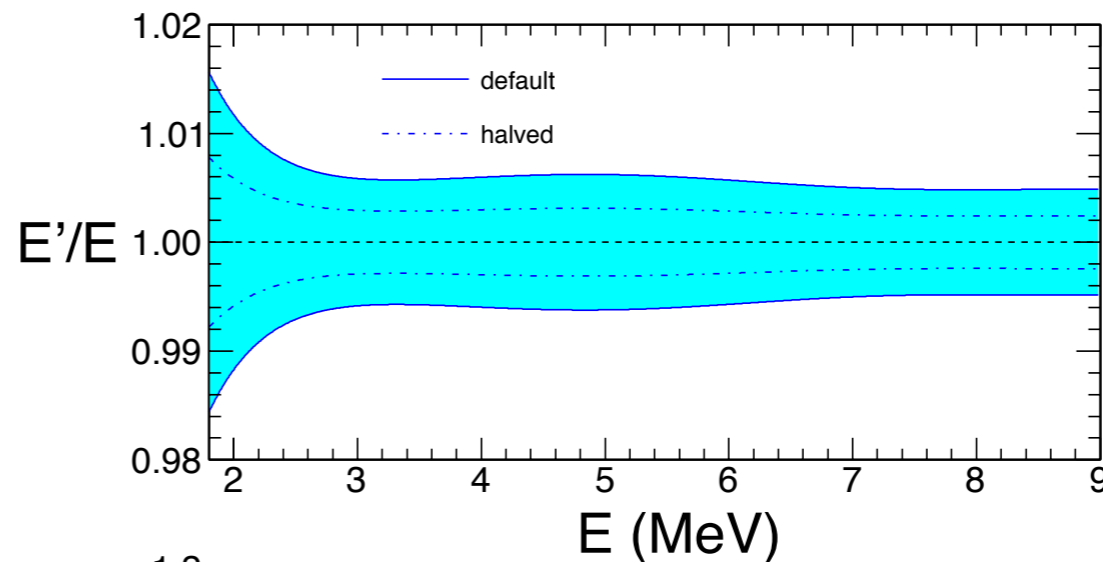
Hierarchy determination

Need precision studies of systematics that could weaken the sensitivity to the Hierarchy

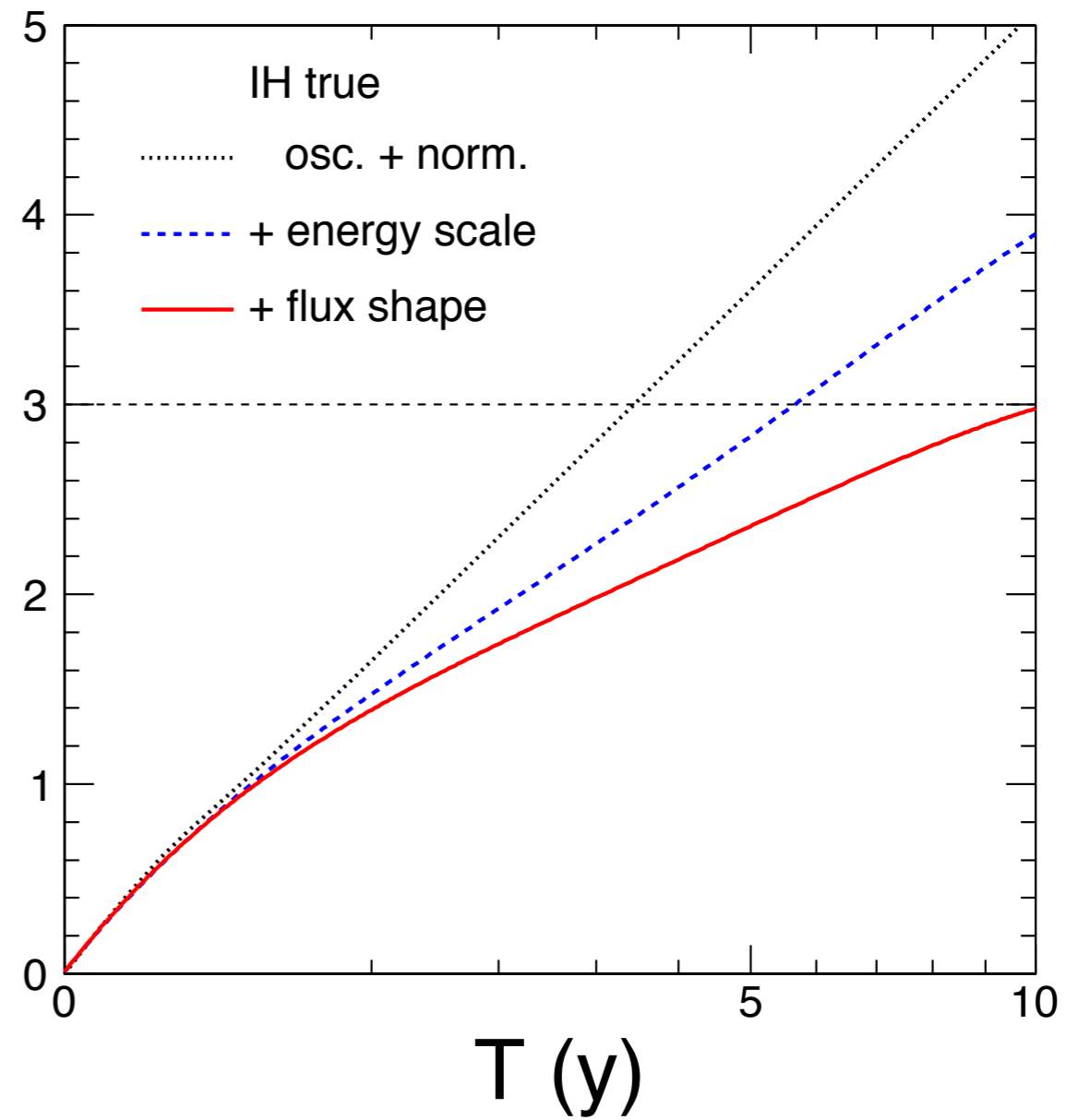
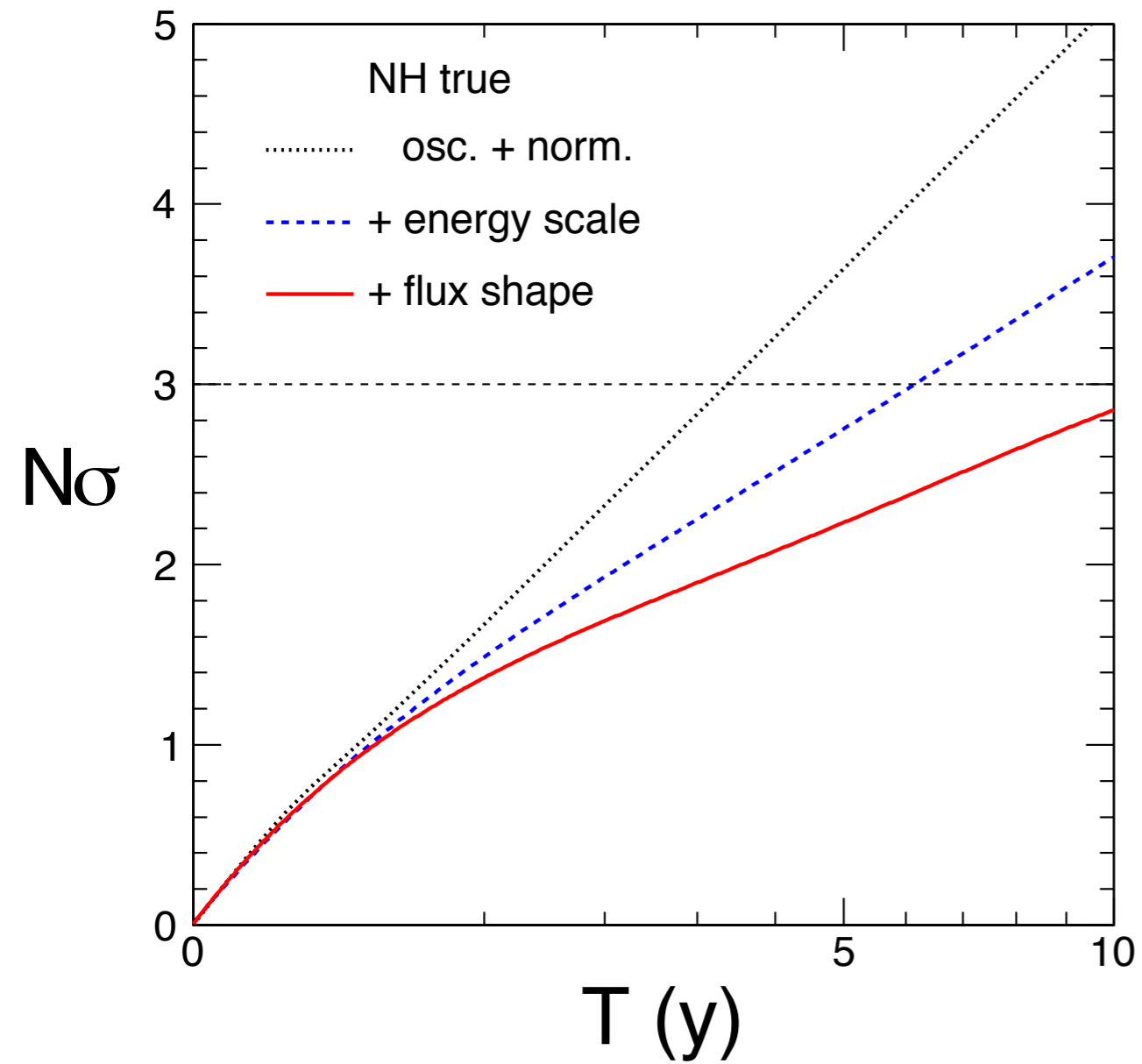
Two examples: PINGU and JUNO

Consider flux errors and non-linear energy scale errors parametrized in terms of (up to 5th order) polynomials

The coloured bands represent 1σ errors for the JUNO experiment



JUNO: sensitivity to hierarchy



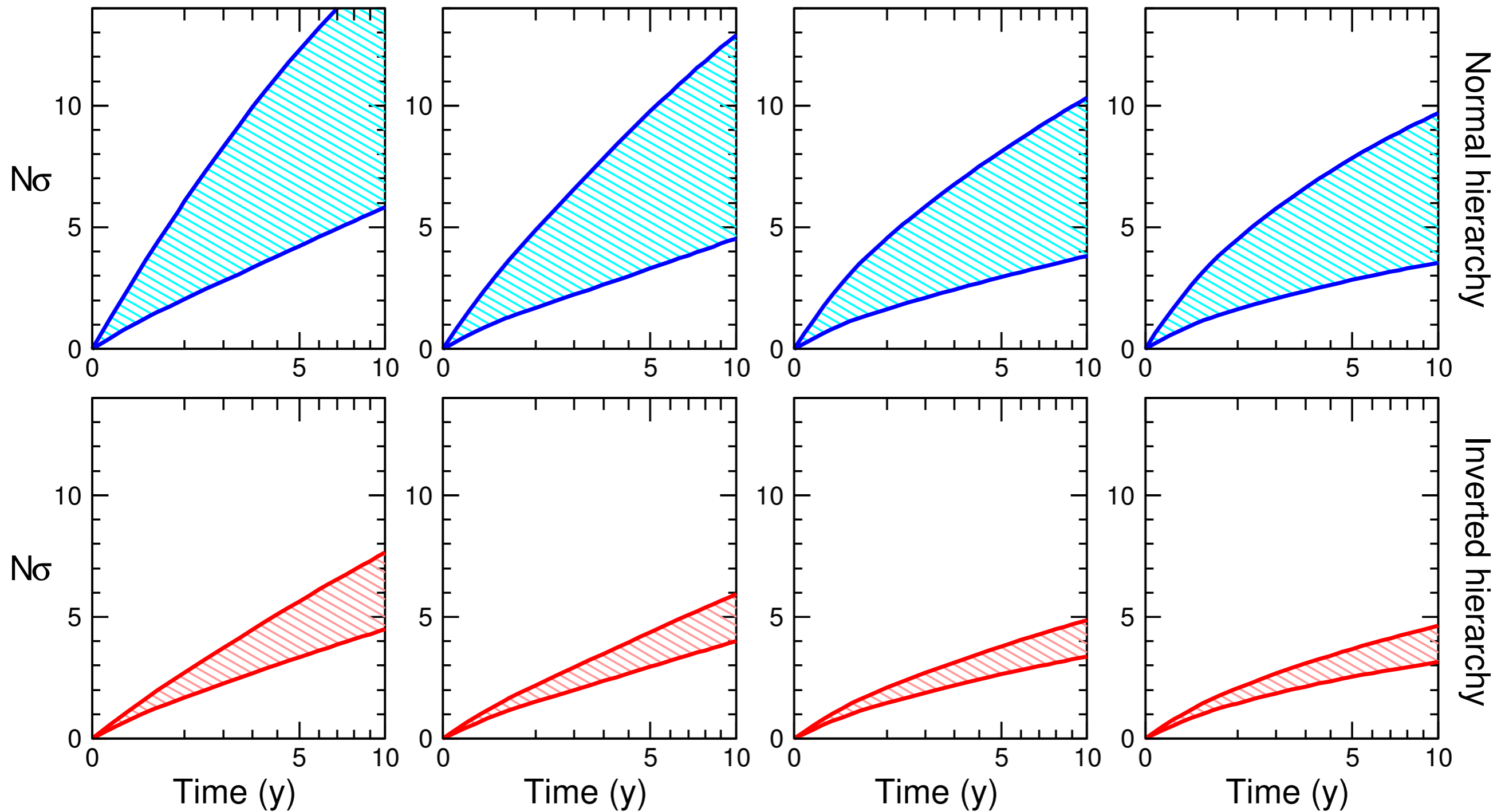
PINGU: sensitivity to hierarchy

Stat + syst (osc+norm)

+ resolution (scale,width)

+ polynomial

+ uncorrelated



Conclusions

3 ν framework well established and (almost all) oscillation parameters measured at few % level

CP phase δ and θ_{23} octant still unknown but preference for $\sin\delta \sim -1$ strengthened by T2K antineutrino and NOvA

CP-conserving values $\delta=0, \pi$ disfavoured at 2σ

$\delta \sim \pi/2$ now disfavoured at more than 3σ

Still no statistically significant info on Hierarchy (NH slightly preferred)

Hierarchy might remain unknown for quite some time (may need new experiment like PINGU/ORCA and JUNO/RENO-50)