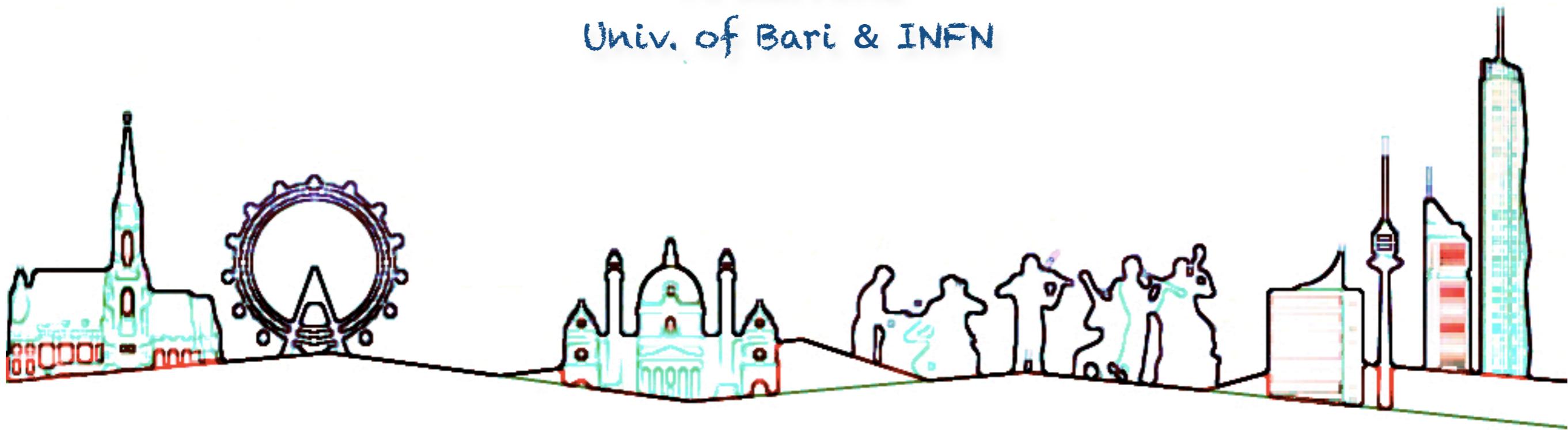


Global fits to neutrino oscillations: status and prospects

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Outline

Present knowledge mixing and masses

What we still don't know

CP phase delta and T2K

Hierarchy and future experiments

Conclusions

Neutrino Mixing

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

Mixing Matrix (PMNS)

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

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

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

(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

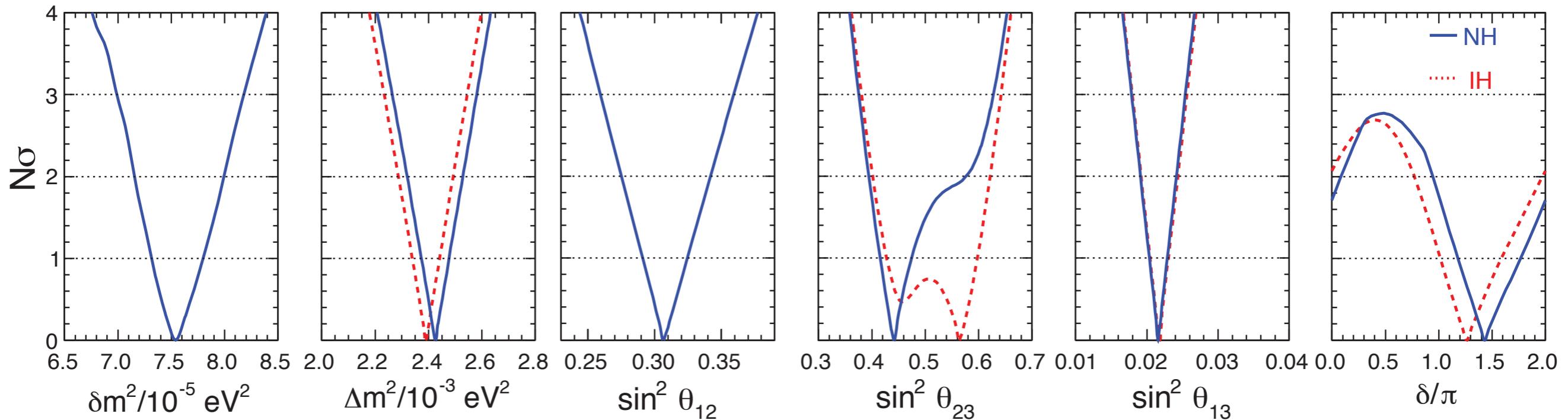
add independent, strong
constraints on θ_{13}

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: Summarizing our present knowledge



Current accuracy:

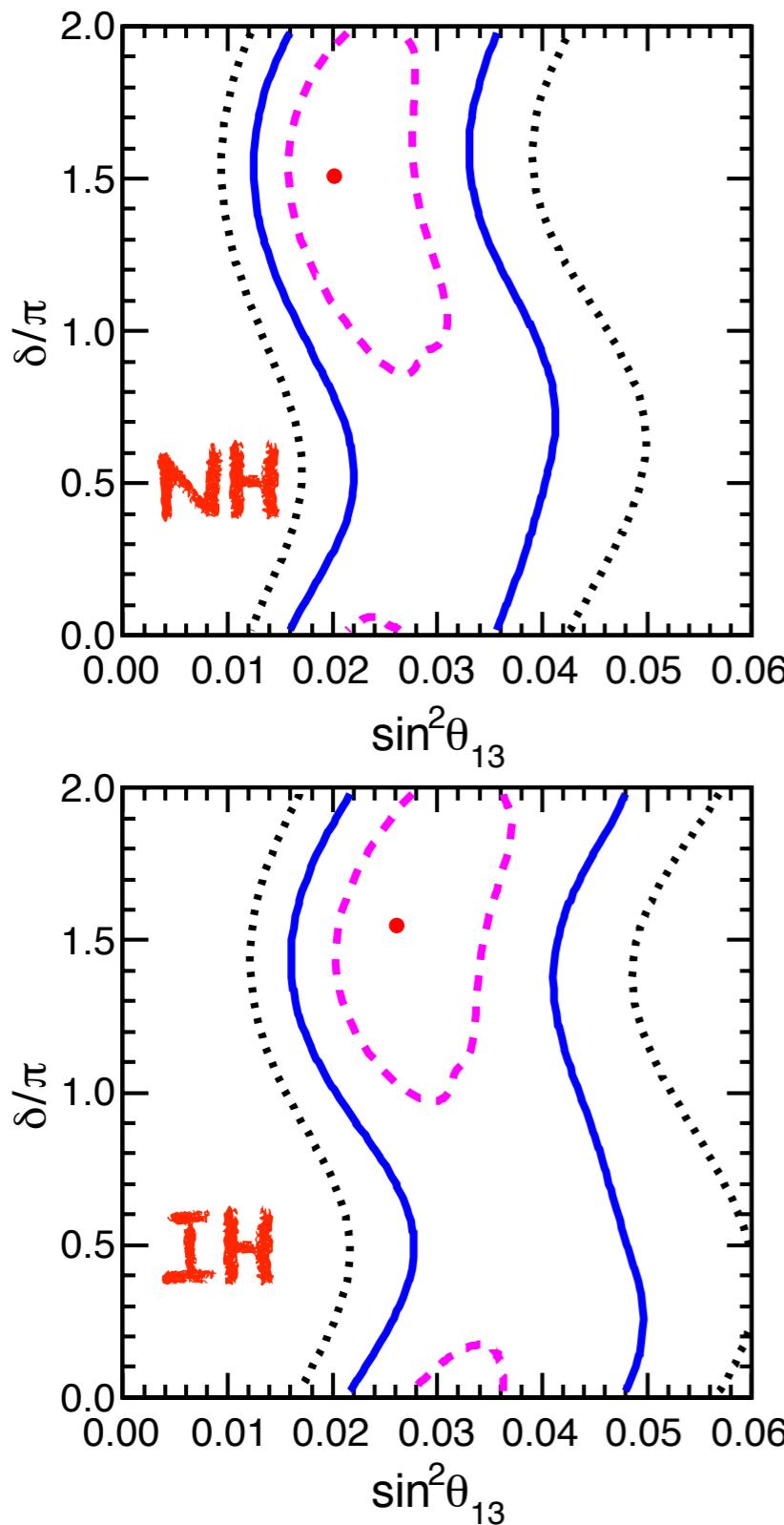
δm^2	2.6 %
Δm^2	2.6 %
$\sin^2 \theta_{12}$	5.4 %
$\sin^2 \theta_{13}$	5.8 %
$\sin^2 \theta_{23}$	~10 %

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

θ_{23} octant: currently unstable, fragile
 hierarchy: negligible sensitivity
 δ_{CP} : intriguing preference for $\sin\delta_{CP} \approx -1$

from single parameters to 2-parameter correlations →

LBL Acc + Solar + KL



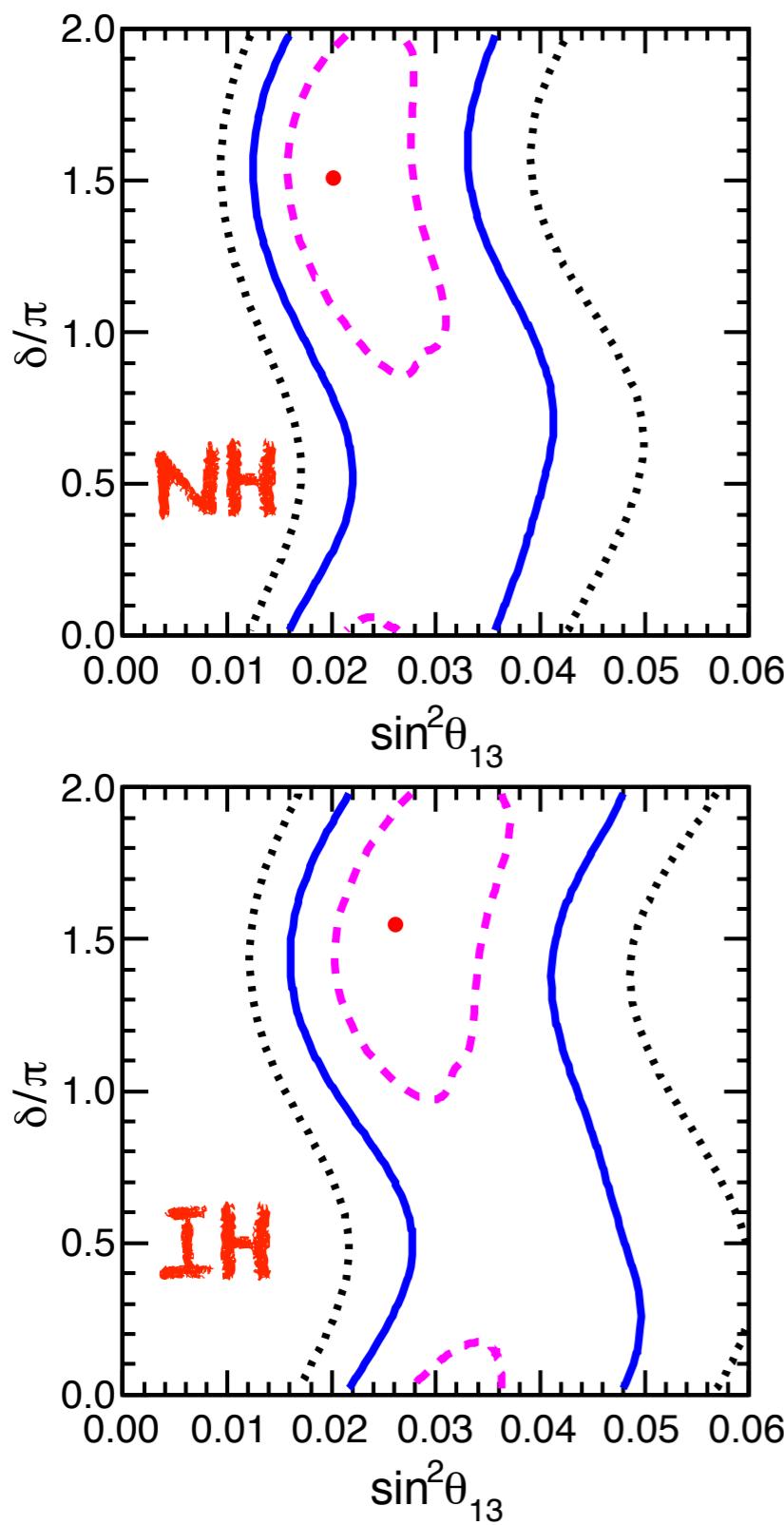
(θ_{13}, δ) correlation

For the relatively "low" value $\sin^2 \theta_{13} \sim 0.02$ preferred by Solar + KL data, appearance ν signal in T2K maximized by subleading CP-odd term for $\sin \delta < 0$ [i.e., $1 < \delta/\pi < 2$].
T2K neutrino appearance signal is consistent with the maximum allowed by $\sin^2 \theta_{13} \sim 0.02$
Best fit for $\delta/\pi \sim 1.5$, for both hierarchies

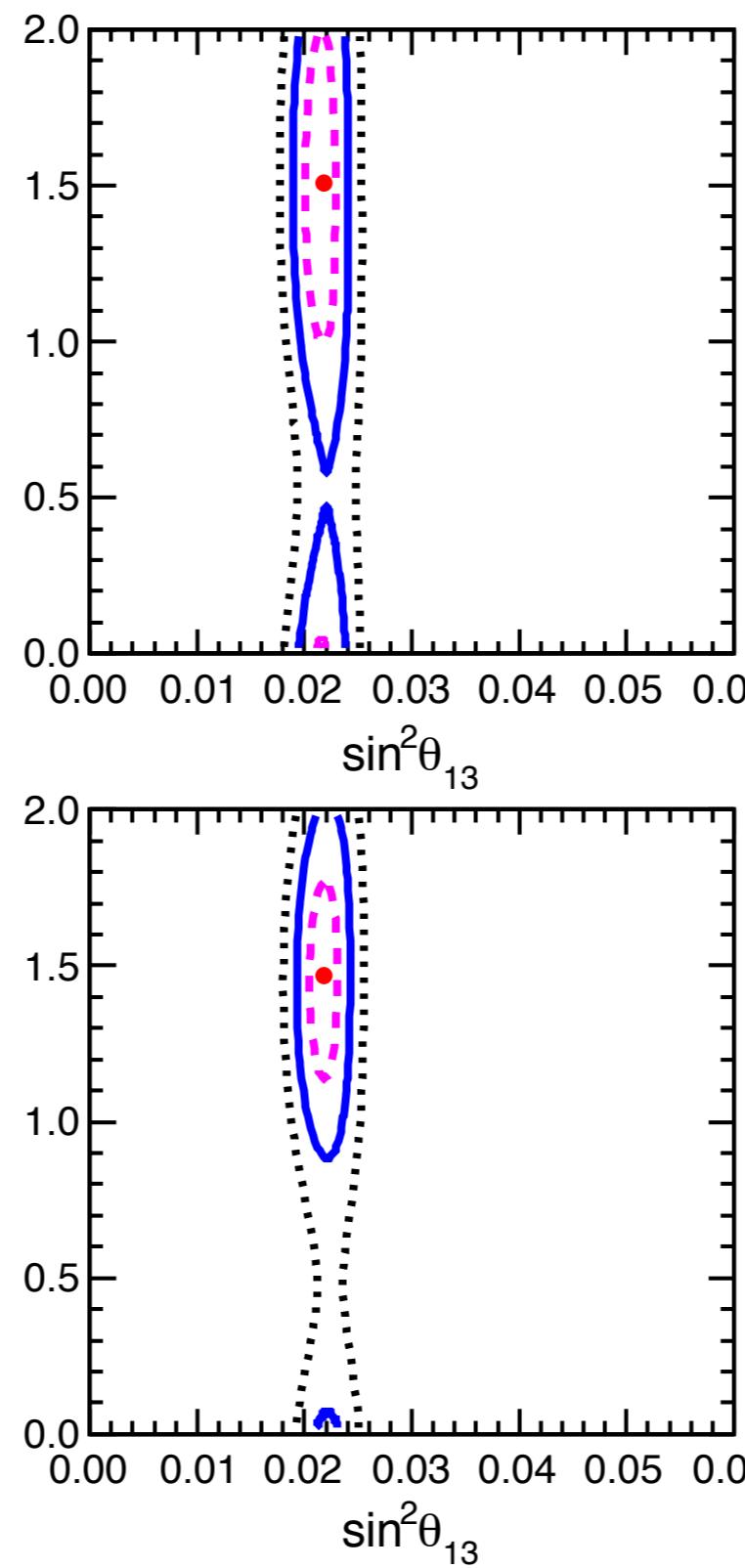
The weaker MINOS signal prefers $\sin \delta > 0$,
"out of phase" w.r.t. T2K. Fluctuation?

First Nova data might soon add new interesting information!
Will NOvA be in phase with T2K or MINOS?

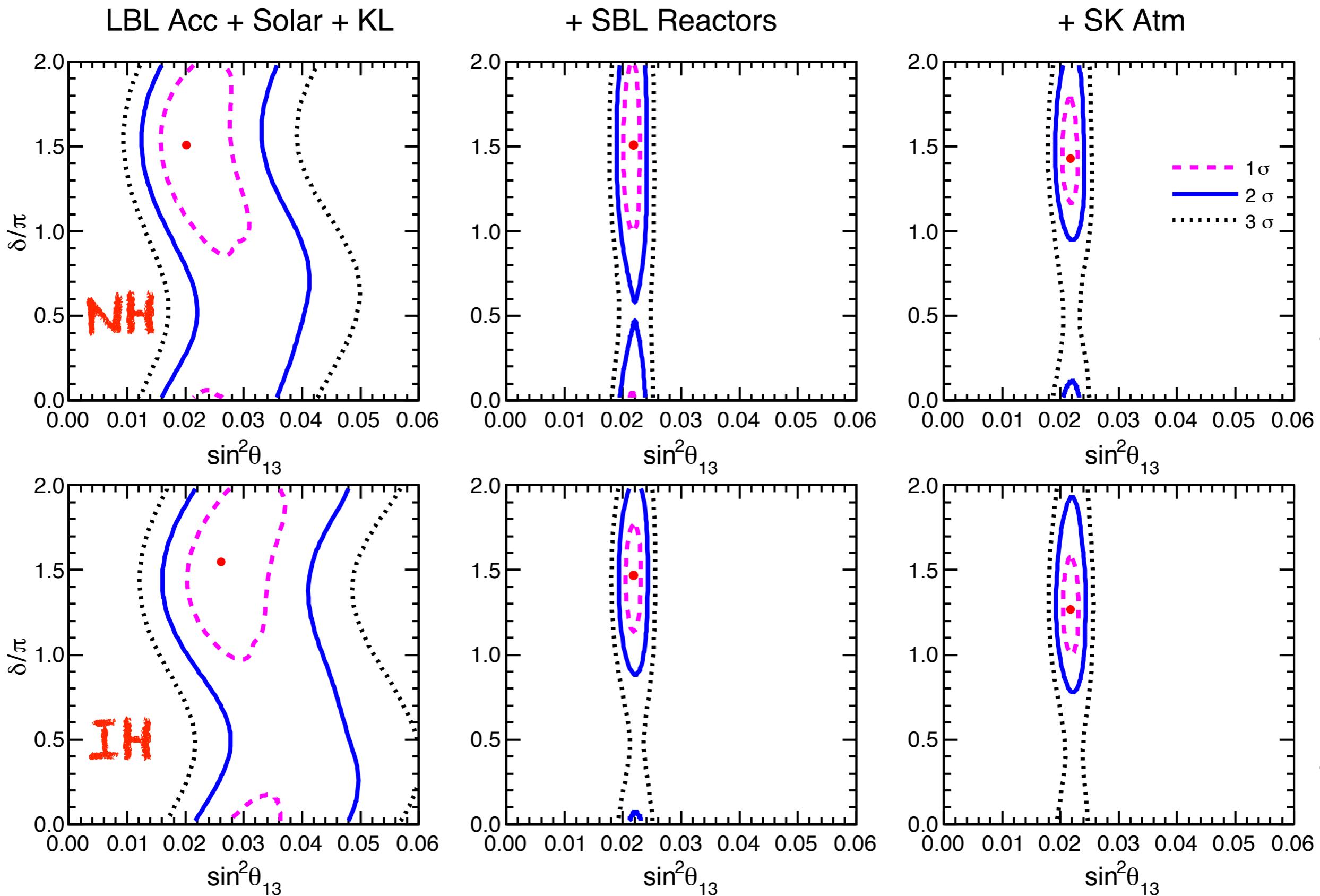
LBL Acc + Solar + KL



+ SBL Reactors



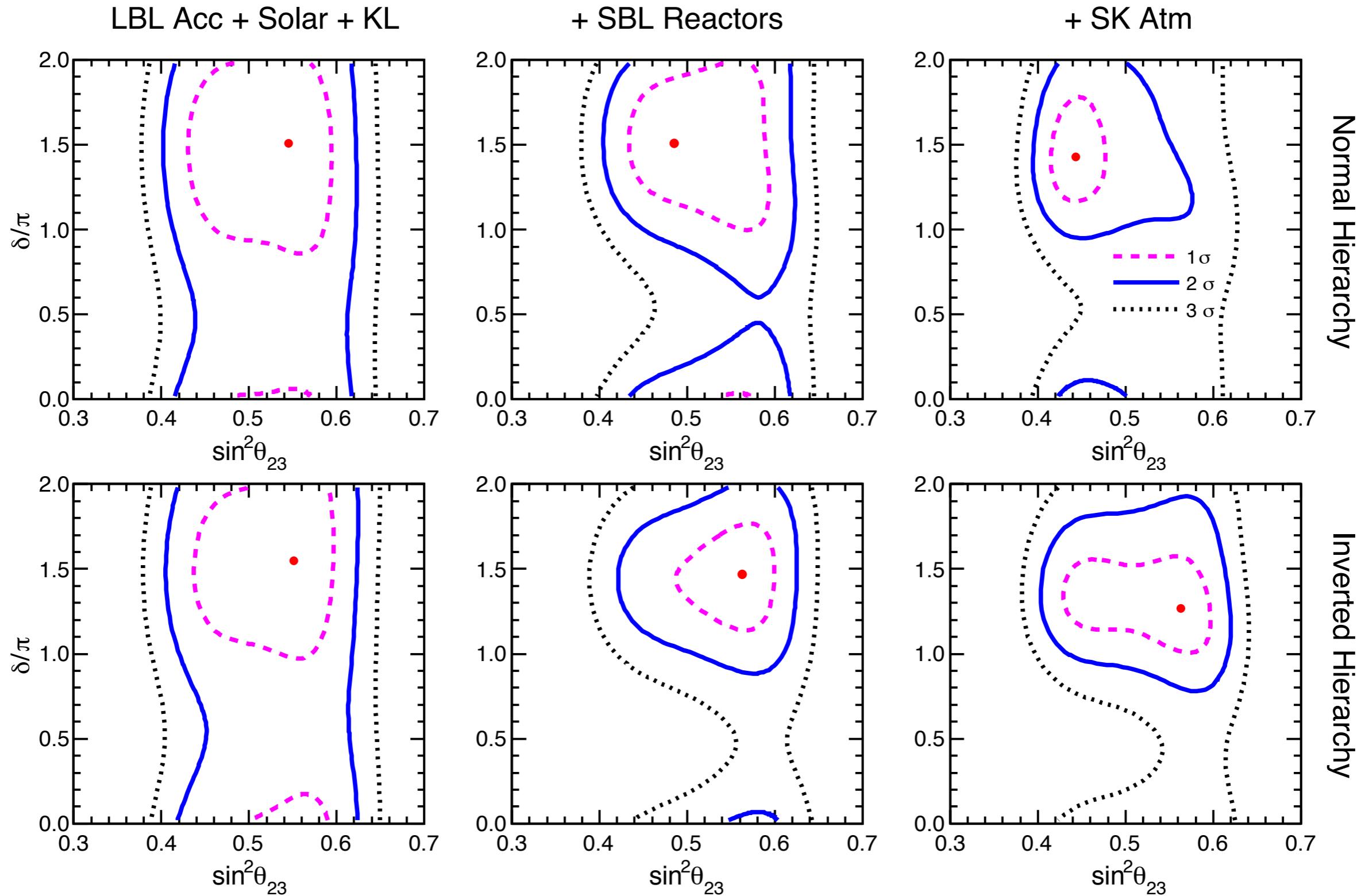
Reactor data strongly constrain $\sin^2 \theta_{13}$ close to 0.022, corroborate previous preferences for $\sin \delta \sim -1$ and shrink allowed region (leftmost part of the LBL+Sol.+KL band)



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

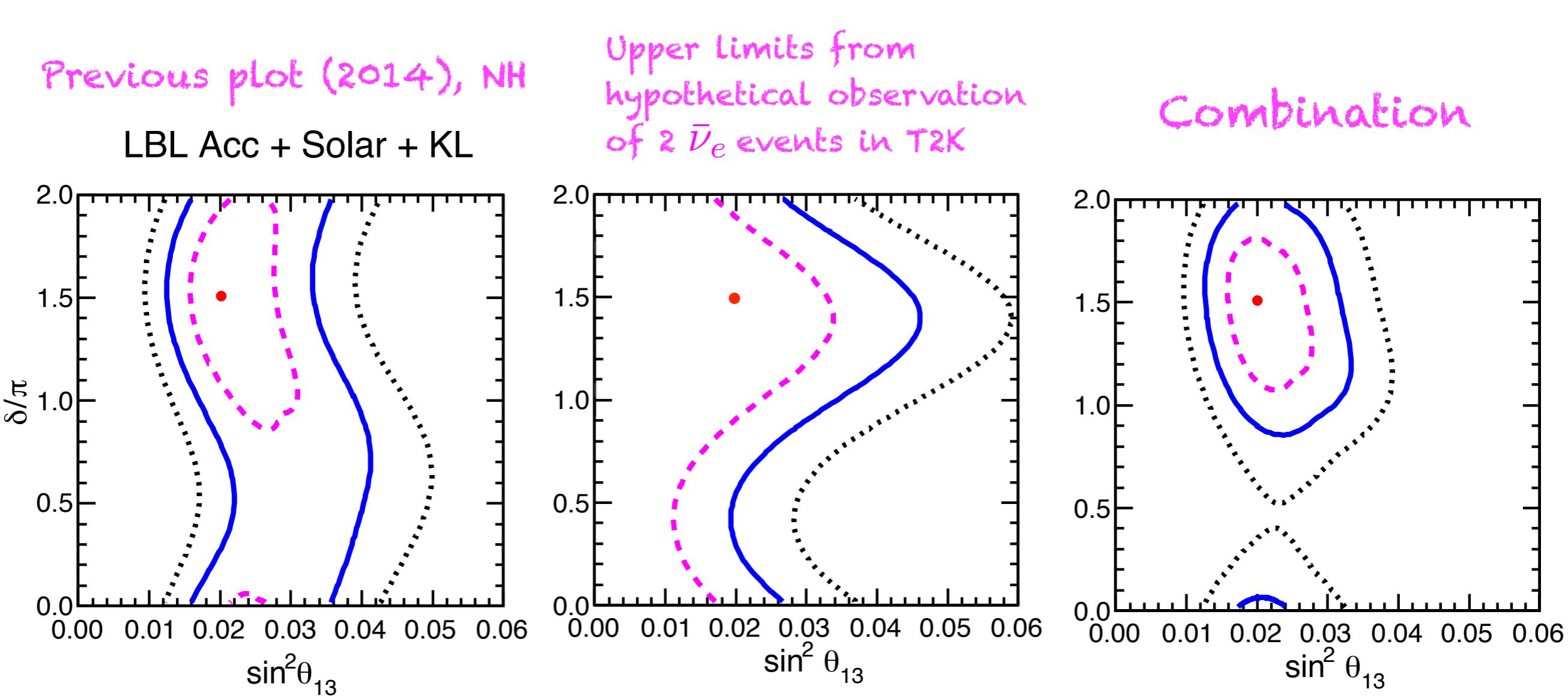
Normal Hierarchy
Inverted Hierarchy

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



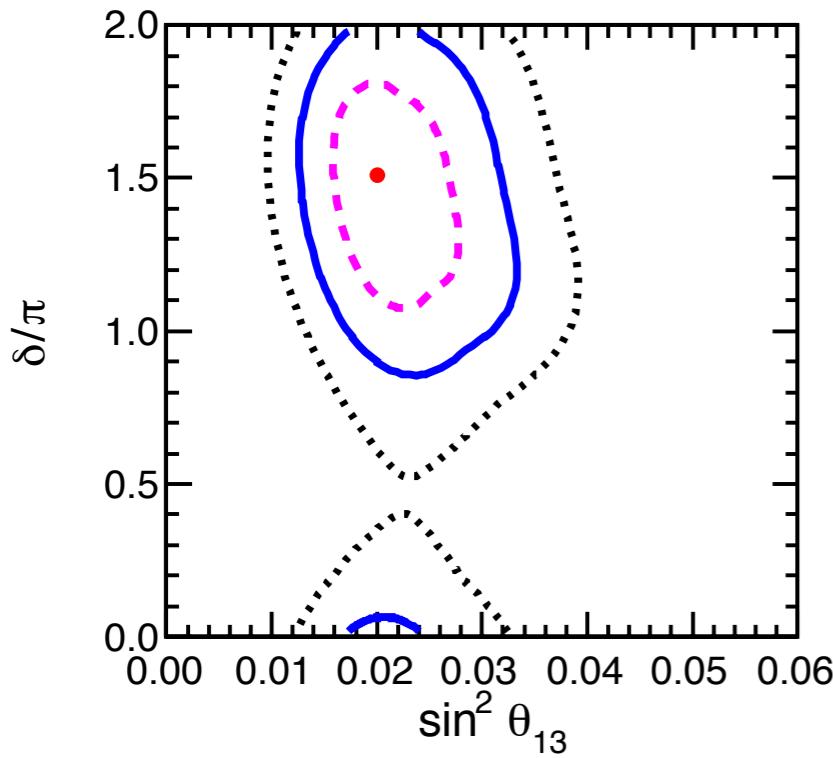
Back to the “money plot”: δ vs θ_{13}
 What can we expect from upcoming T2K **antineutrino**
 appearance data if $\delta=3/2\pi$? A **qualitative** exercise.

34.9 signal event expected for 7.8×10^{21} P.O.T. (PTEP 2015, 043C01).
 Rescale for (presumably) $\sim 4.5 \times 10^{20}$ P.O.T $\rightarrow \sim 2$ signal events expected
 for $\delta=3/2\pi$, otherwise more events.

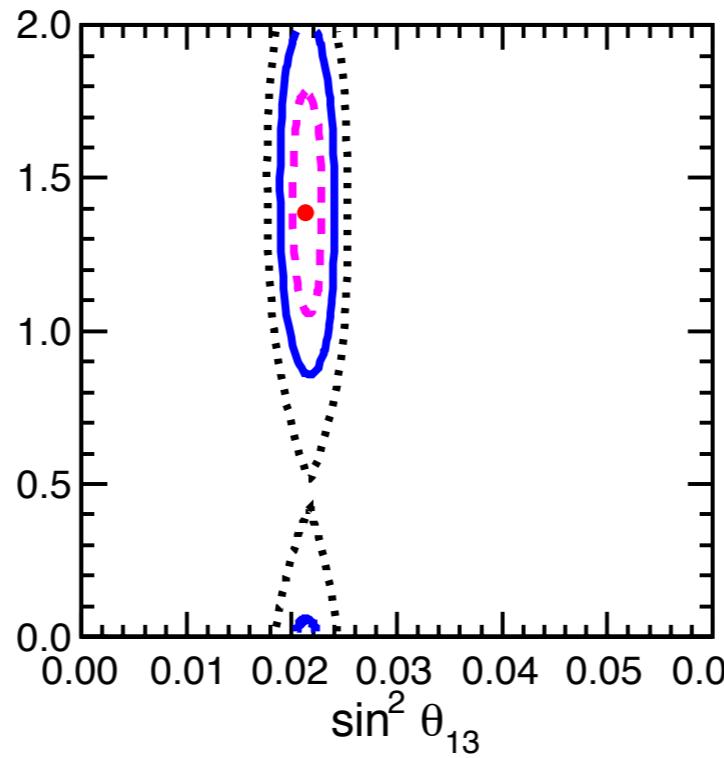


Available data with hypoth. observation of 2 T2K $\bar{\nu}_e$ events
 ("minimum # of events"): $\delta=3/2\pi$ strengthened
 [but: hierarchy difference still < 1 sigma]

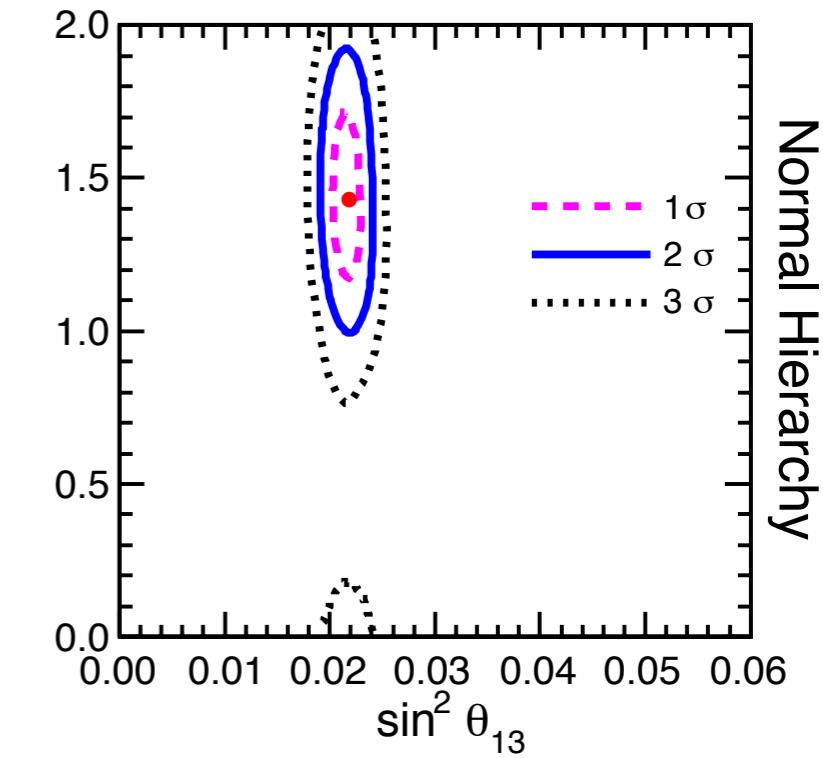
LBL Acc + Solar + KL



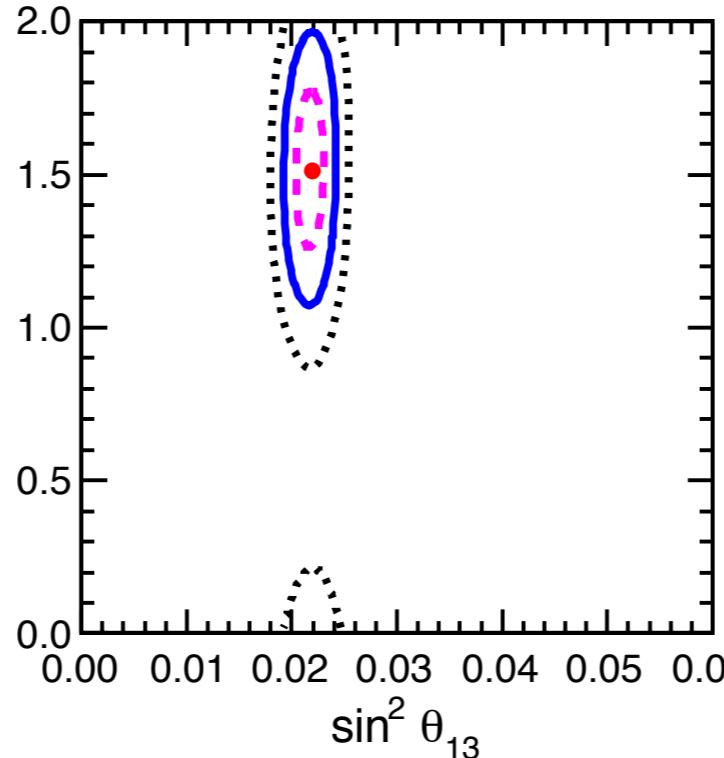
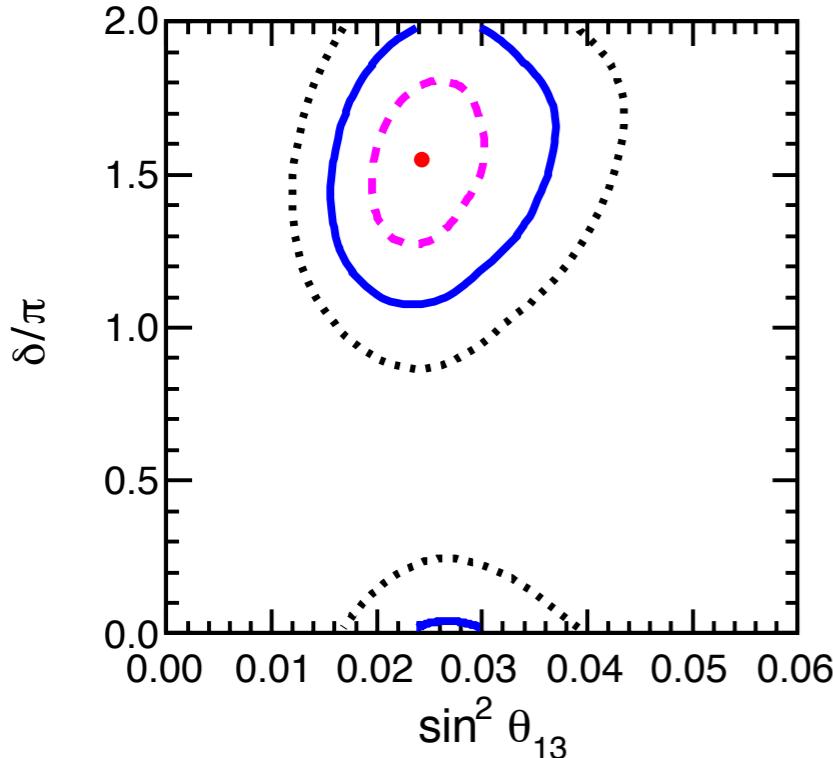
+ SBL Reactors



+ SK Atm

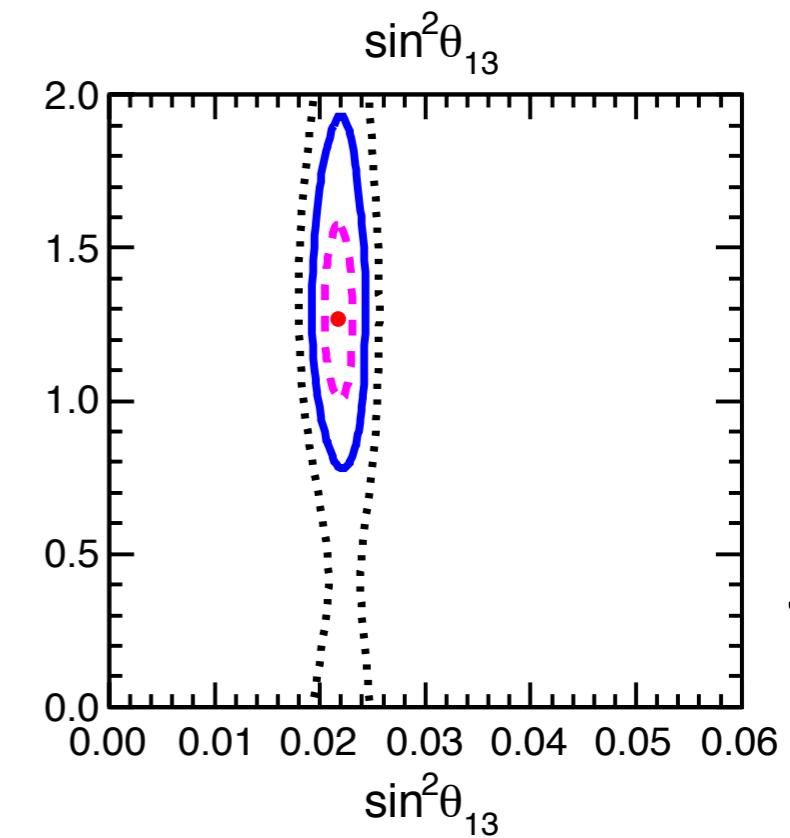
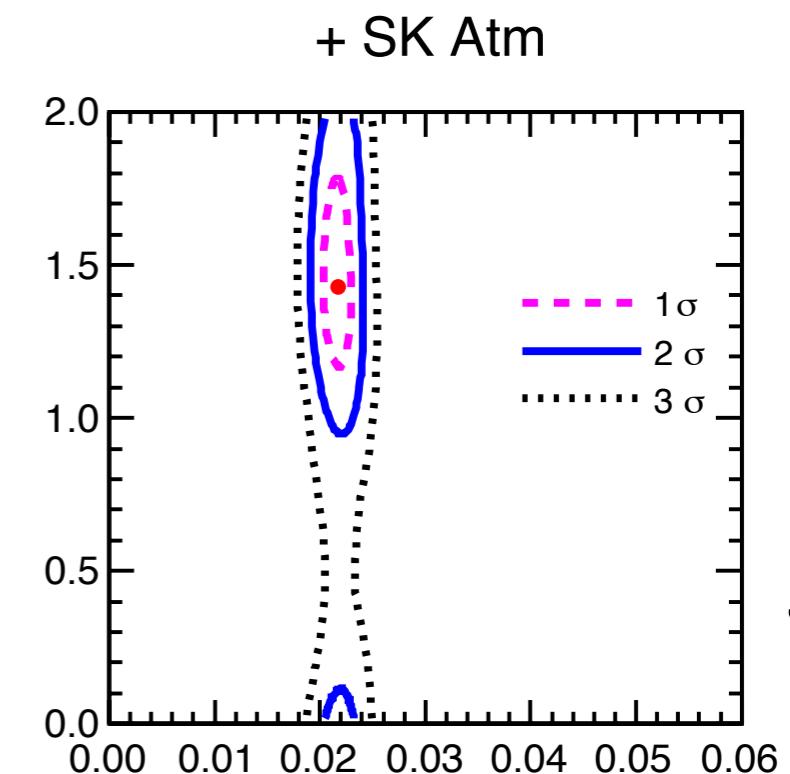
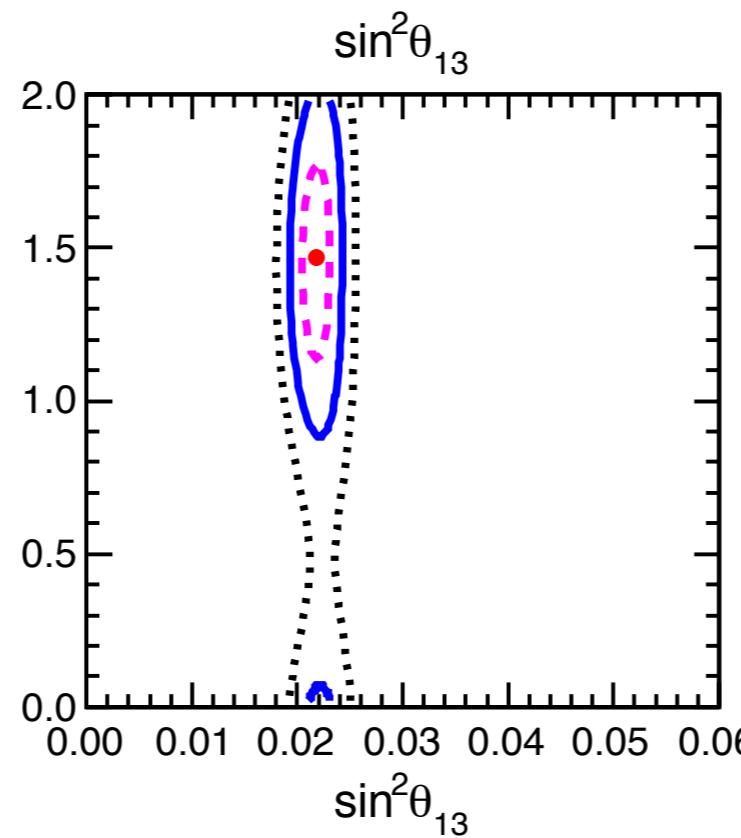
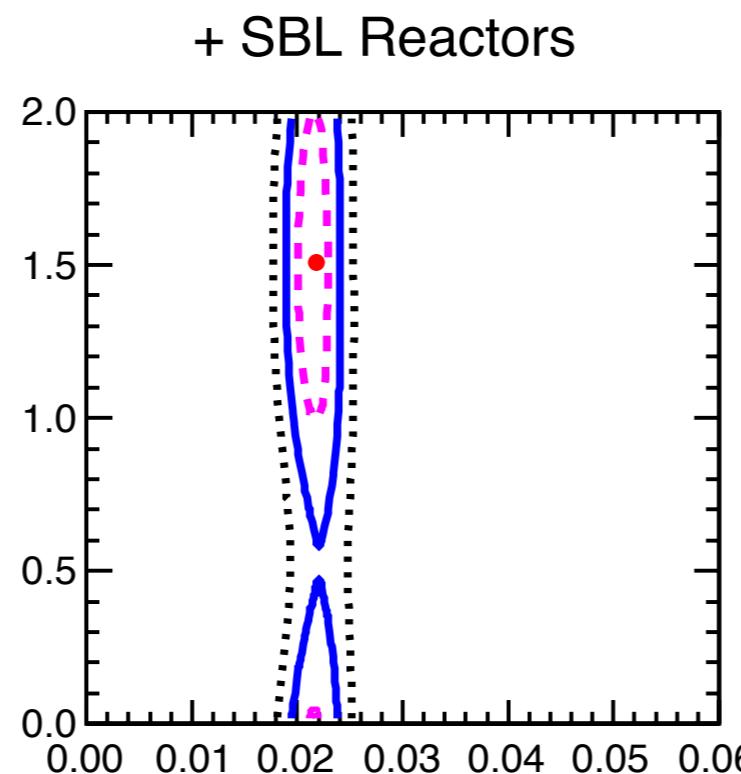
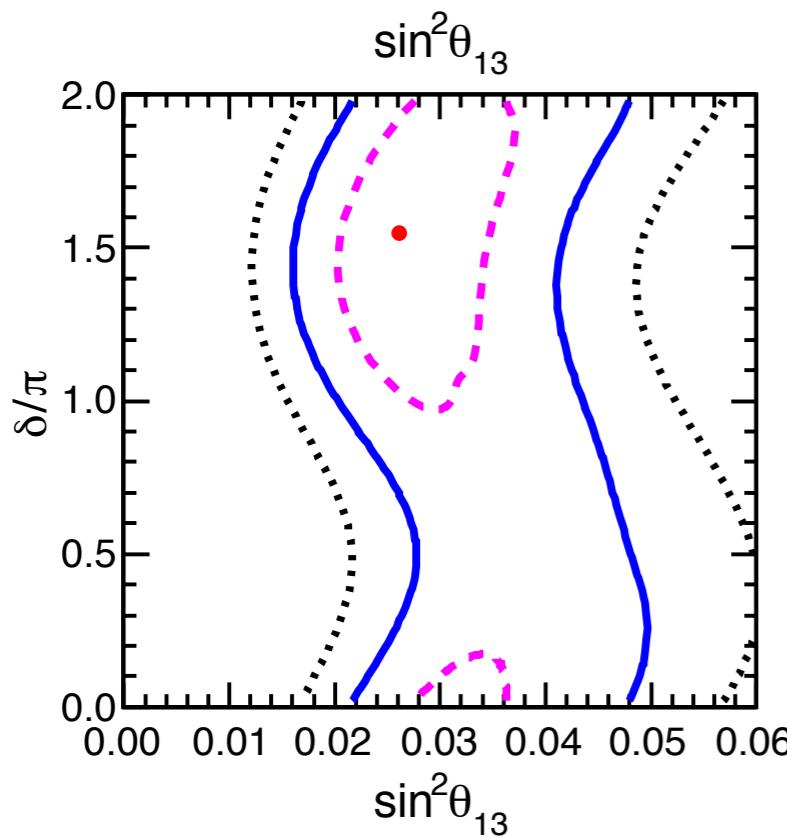
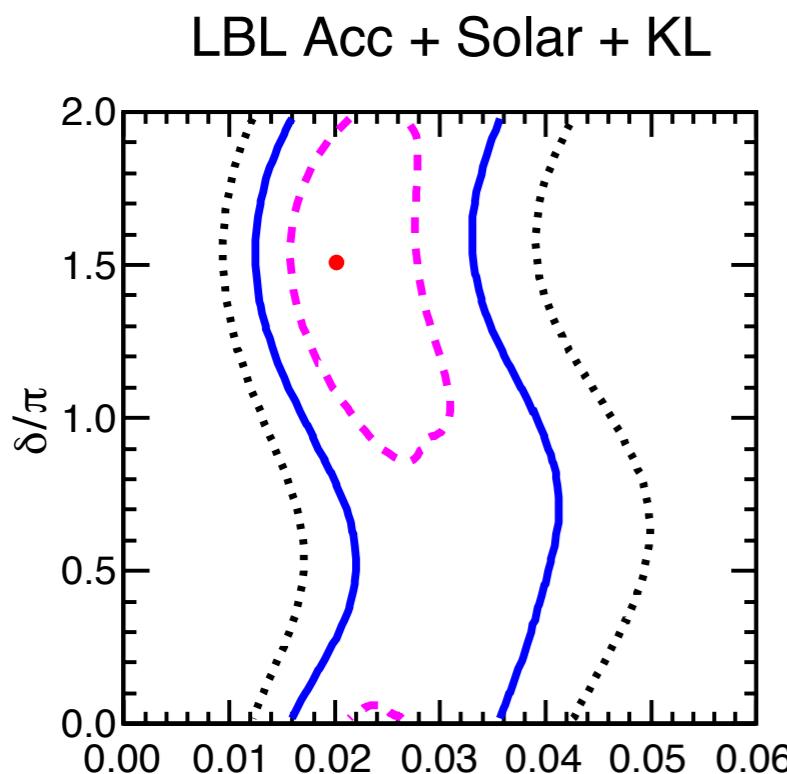


Normal Hierarchy



Inverted Hierarchy

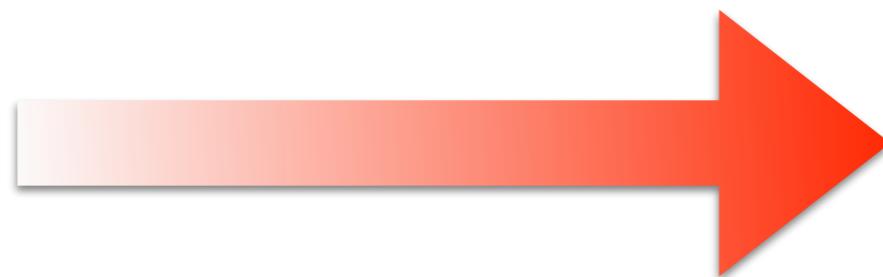
Available data without hypoth. observation of 2 T2K $\bar{\nu}_e$ events



Normal Hierarchy
Inverted Hierarchy

Higher # of appearance events in T2K
would weaken preference for $\delta=3/2\pi$
and enlarge allowed ranges

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



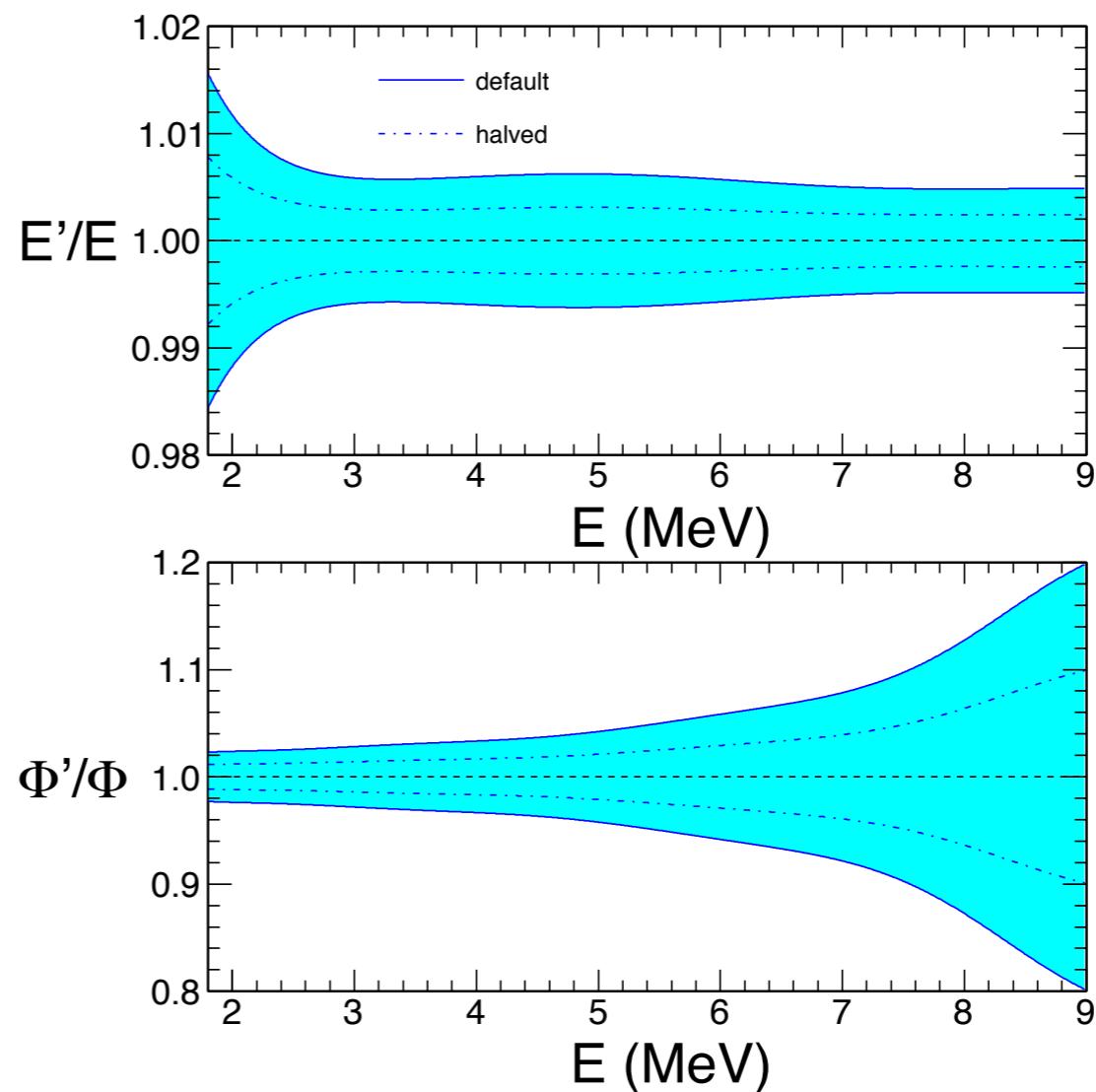
Hierarchy determination

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

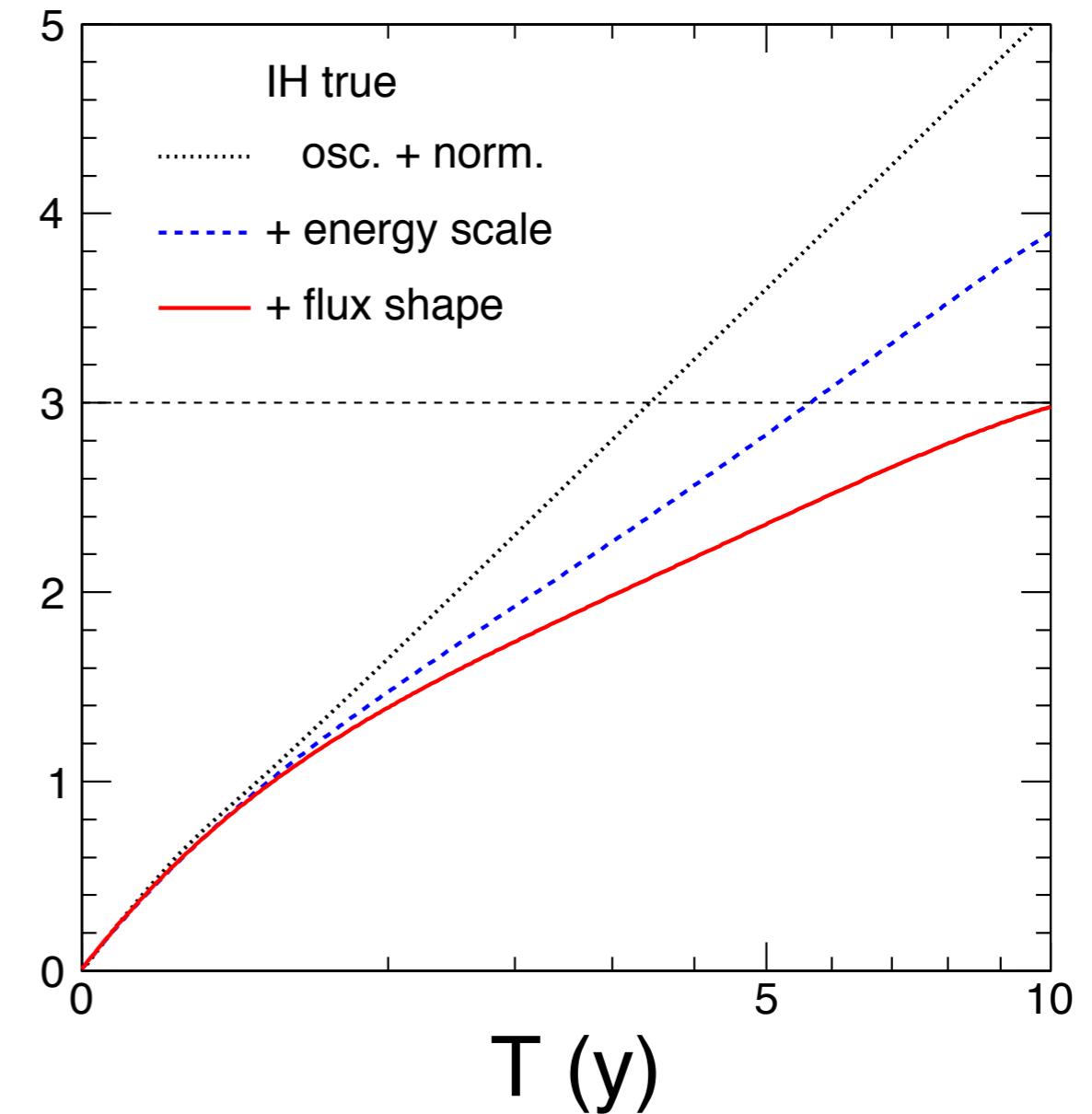
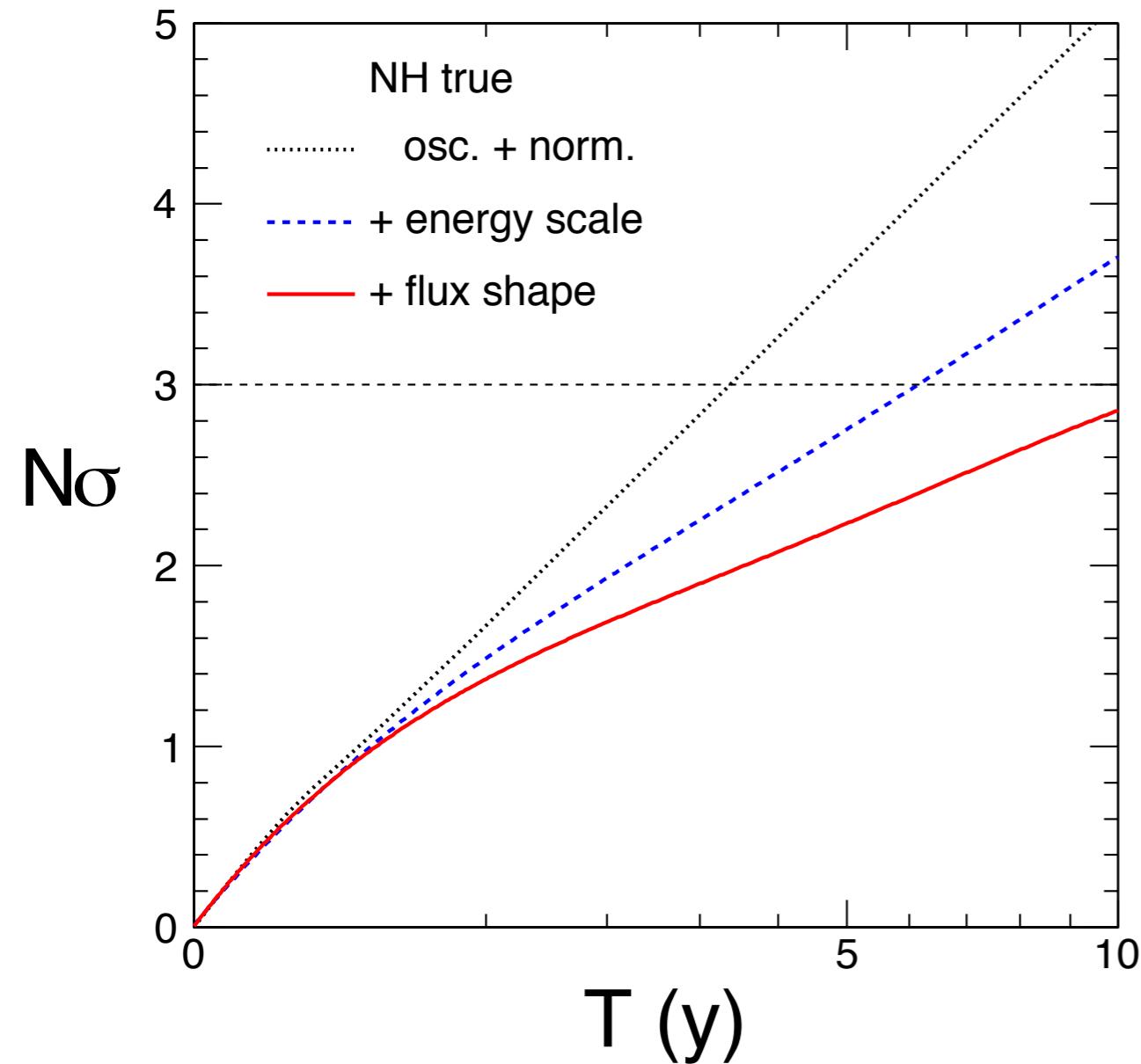
Two examples: PINGU and JUNO

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

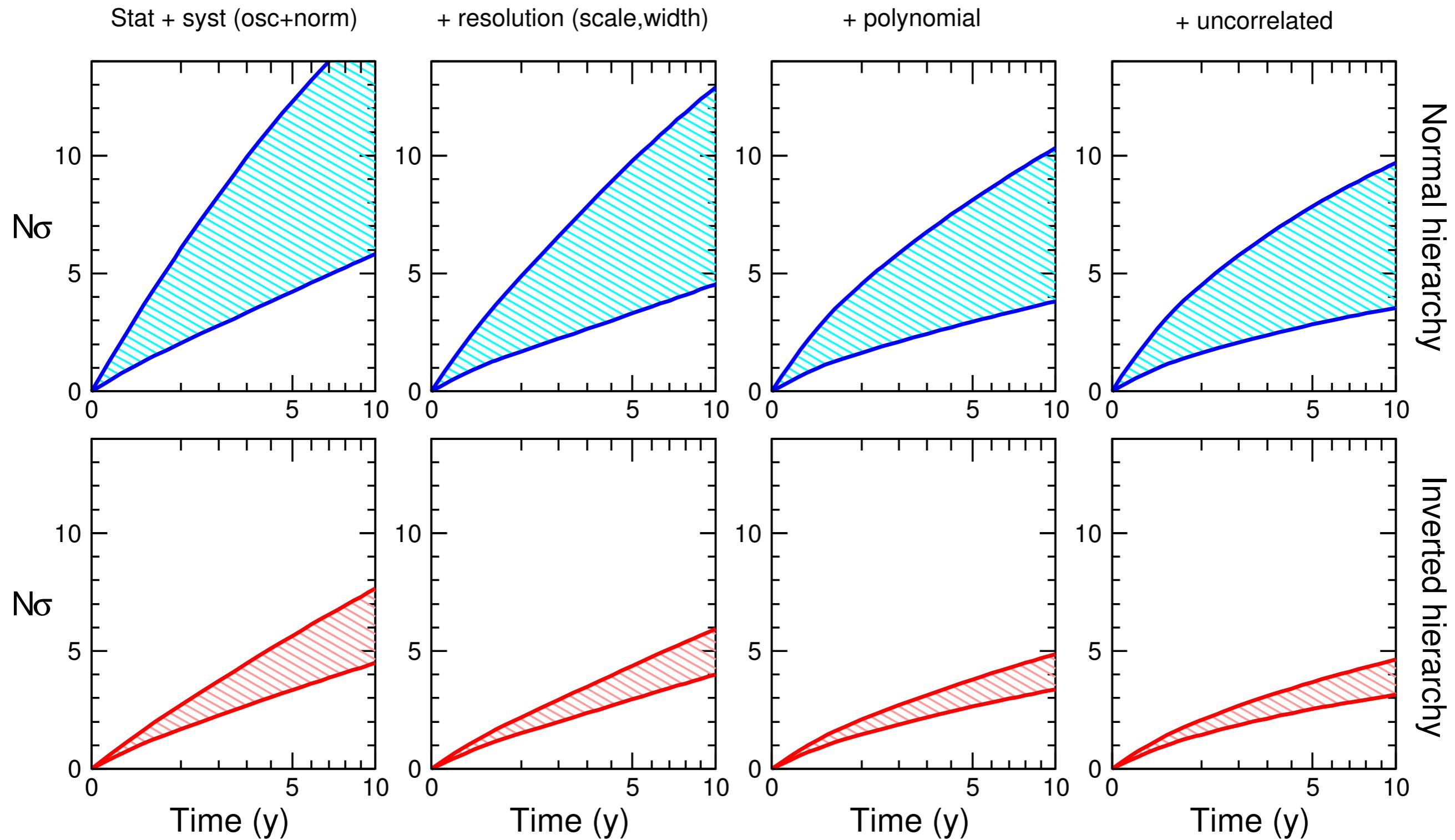


JUNO: sensitivity to hierarchy



to appear this summer

PINGU: sensitivity to hierarchy



Conclusions

3ν framework well established and oscillation parameters measured at few % level

CP phase δ and θ_{23} still unknown but some preference for $\sin\delta \sim -1$ that could be strengthened by T2K antineutrino appearance if "minimum # of events" observed

Future constraints on θ_{23} will indirectly improve hints on δ

Still no statistically significant information on Hierarchy from available data. Mass Hierarchy might remain undetermined for quite some time (need new experiment like PINGU/ORCA and JUNO/RENO-50)

