Status of 3ν mass-mixing parameters, circa 2013

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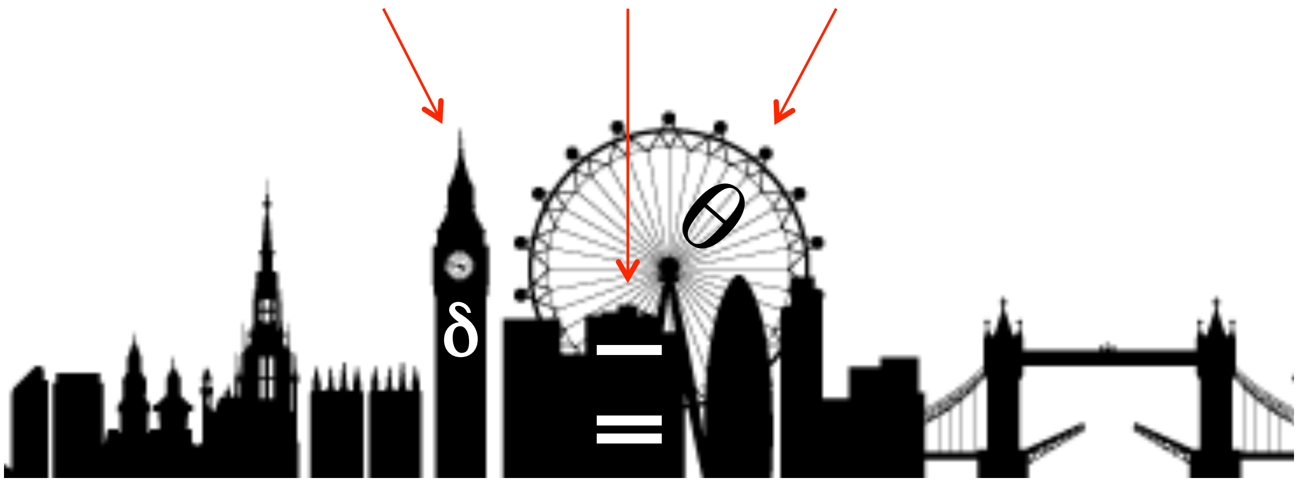
Outline:

- Intro: data, notation, methodology
- **Global analysis: single parameters**
- Global analysis: some covariances
- **[Hierarchy issues at reactors]** [if time allows it]
- Conclusions

Emphasis: CP phase, hierarchy, θ_{23} octant (unkowns)



Based on arXiv:13122878 [hep-ph], arXiv:13091638 [hep-ph]. Work done in collabor. with: F. Capozzi, G.L. Fogli, D. Montanino, A. Marrone, A. Palazzo

Data sets:

LBL Accelerators	=	K2K + T2K + MINOS
Solar	=	All Solar experiments
KL	=	KamLAND reactor expt
SBL Reactors	=	DChooz + RENO + DB
SK Atm	=	Super-K Atmospheric

3ν oscillation parameters: Notation

δm^2	=	Δm^2_{21}
$\theta_{12}, \theta_{23}, \theta_{13}, \delta$	=	as in PDB
δ range	**=**	**$[0, 2\pi]$** (others prefer $[-\pi, +\pi]$)
Δm^2	**=**	**$(\Delta m^2_{31} + \Delta m^2_{32})/2$**

(All parameters free to float in the global fit)

Note: **1σ error on Δm^2** $\approx 0.07 \times 10^{-3}$ eV^2 $\approx$ **δm^2**

Combined analysis of data sets: Methodology

LBL Accelerator data are dominantly sensitive to (Δm^2, θ_{23}, θ_{13}). But, accurate constraints on these parameters do need (δm^2, θ_{12}) input from **Solar + KL** to compute sub-dominant effects.

Moreover: CP-violation is a genuine 3ν effect, it would vanish in the approximation $\delta m^2 \sim 0$.

It makes sense to combine from the start: **LBL Acc + Solar + KL**. Note: Solar + KL data carry a preference ("hint") for $\sin^2\theta_{13}$~0.02

Combined analysis of data sets: Methodology

Analysis includes increasingly rich data sets:

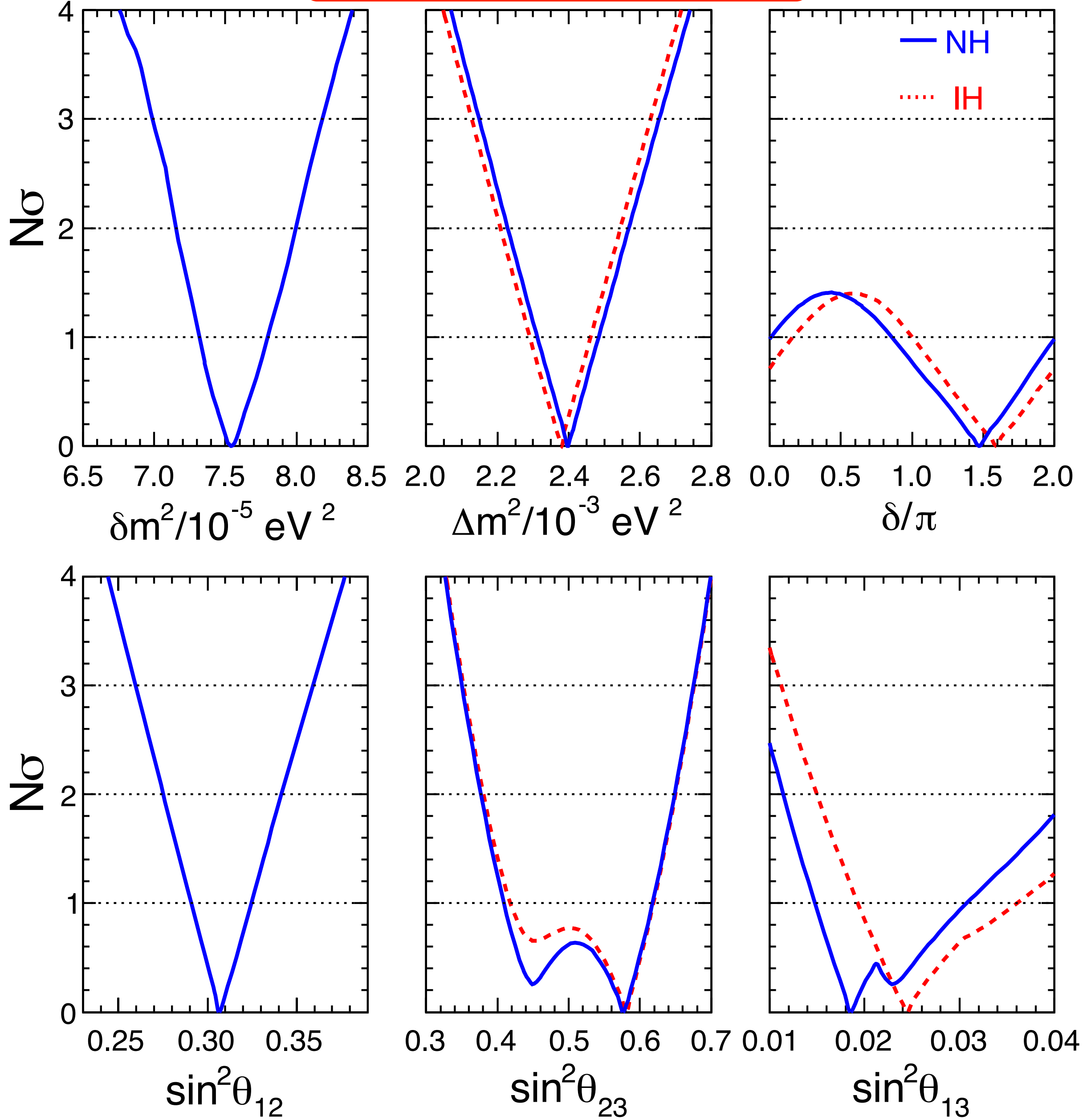
LBL Acc + Solar + KL
LBL Acc + Solar + KL + SBL Reactor
LBL Acc + Solar + KL + SBL Reactor + SK Atm.

Figures: parameters not shown are marginalized away.

Contours are drawn at $\Delta\chi^2 = 1, 4, 9$ →
$N\sigma = 1, 2, 3$ for projections over single parameters.

End of Intro. **Results on single parameters →**

LBL Acc + Solar + KL

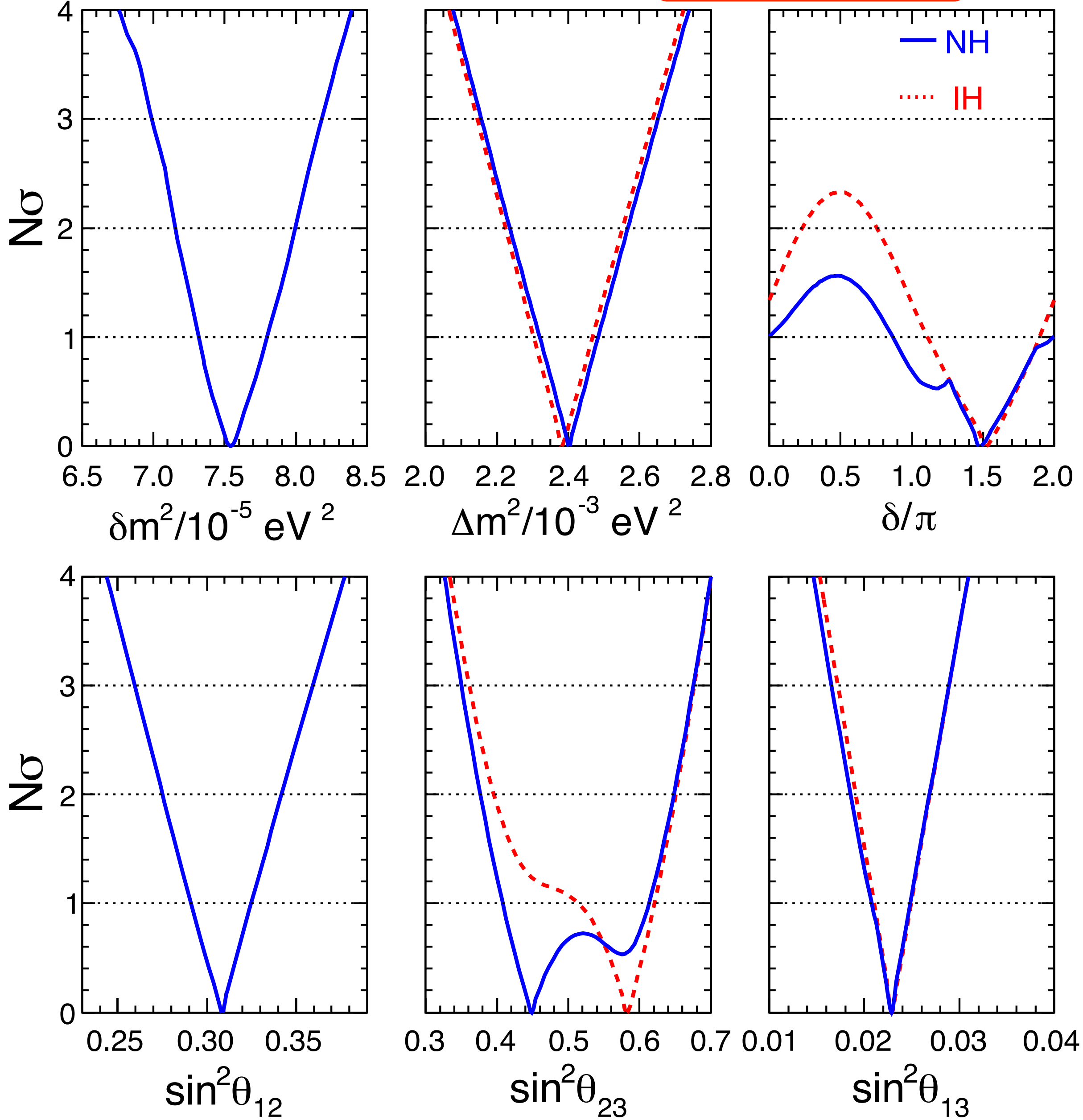


Upper and lower bound on all oscill. parameters but δ

Slight preference for $\delta \sim 1.5\,\pi$

Slight preference for nonmaximal θ_{23} and for 2nd octant

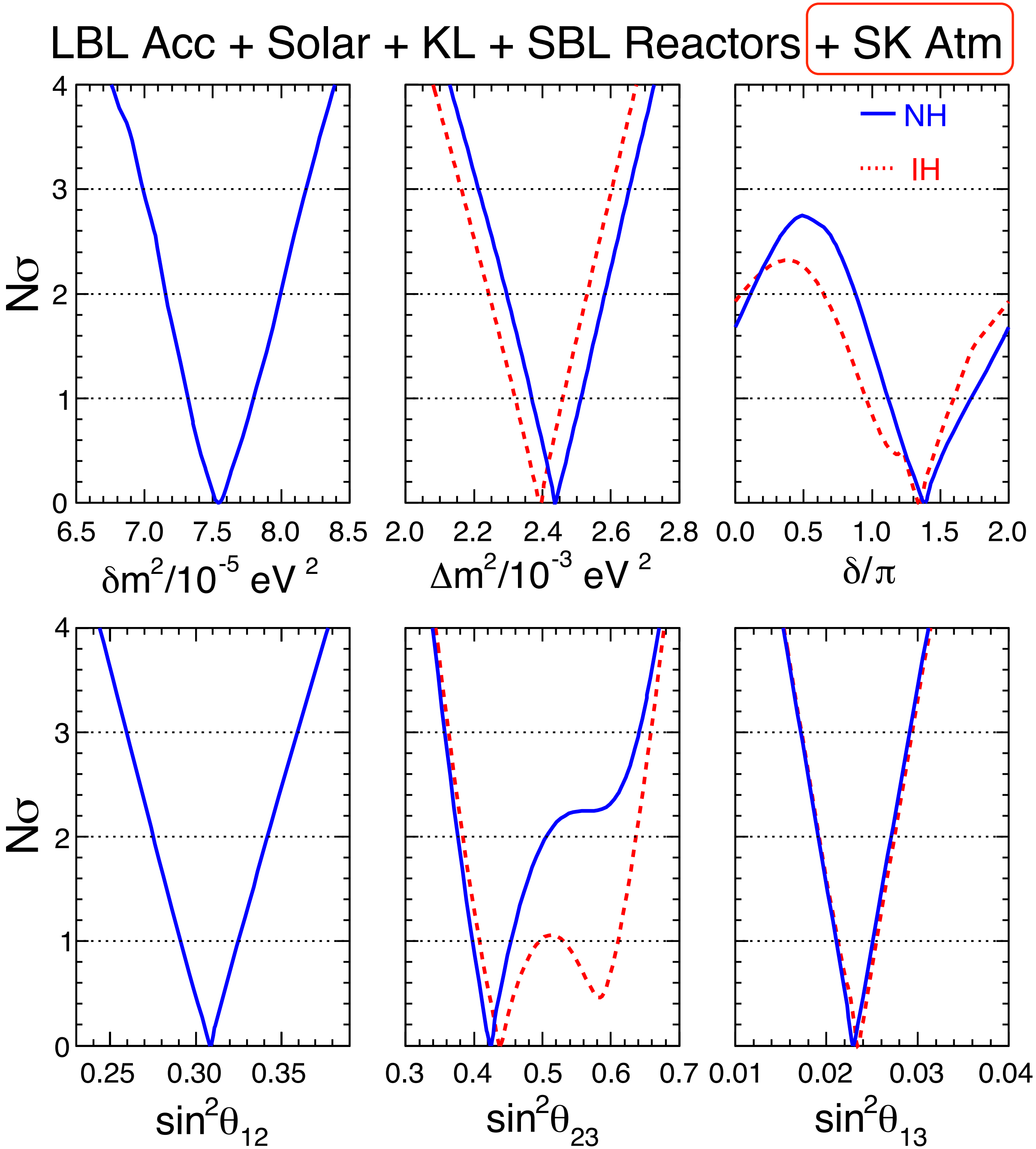
LBL Acc + Solar + KL + SBL Reactors



Strong, dominant θ_{13} bounds

Still a preference for $\delta \sim 1.5\,\pi$

Preference for nonmaximal θ_{23} but octant flips with hierarchy



Some effects on the $\nu_\mu \to \nu_\tau$ dominant parameters (Δm^2, θ_{23})

Preference for $\delta \sim 1.4\,\pi$ and, in NH, for $1 < \delta/\pi < 2$ ($\sin\delta<0$ @90% CL)

Some preference for nonmaximal θ_{23} and for 1st octant, but weaker in IH

Nσ ranges for single parameters (all data included):

[F. Capozzi, G.L. Fogli, E. Lisi, D. Montanino, A. Marrone, and A. Palazzo, arXiv:1312.2878]

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = +0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
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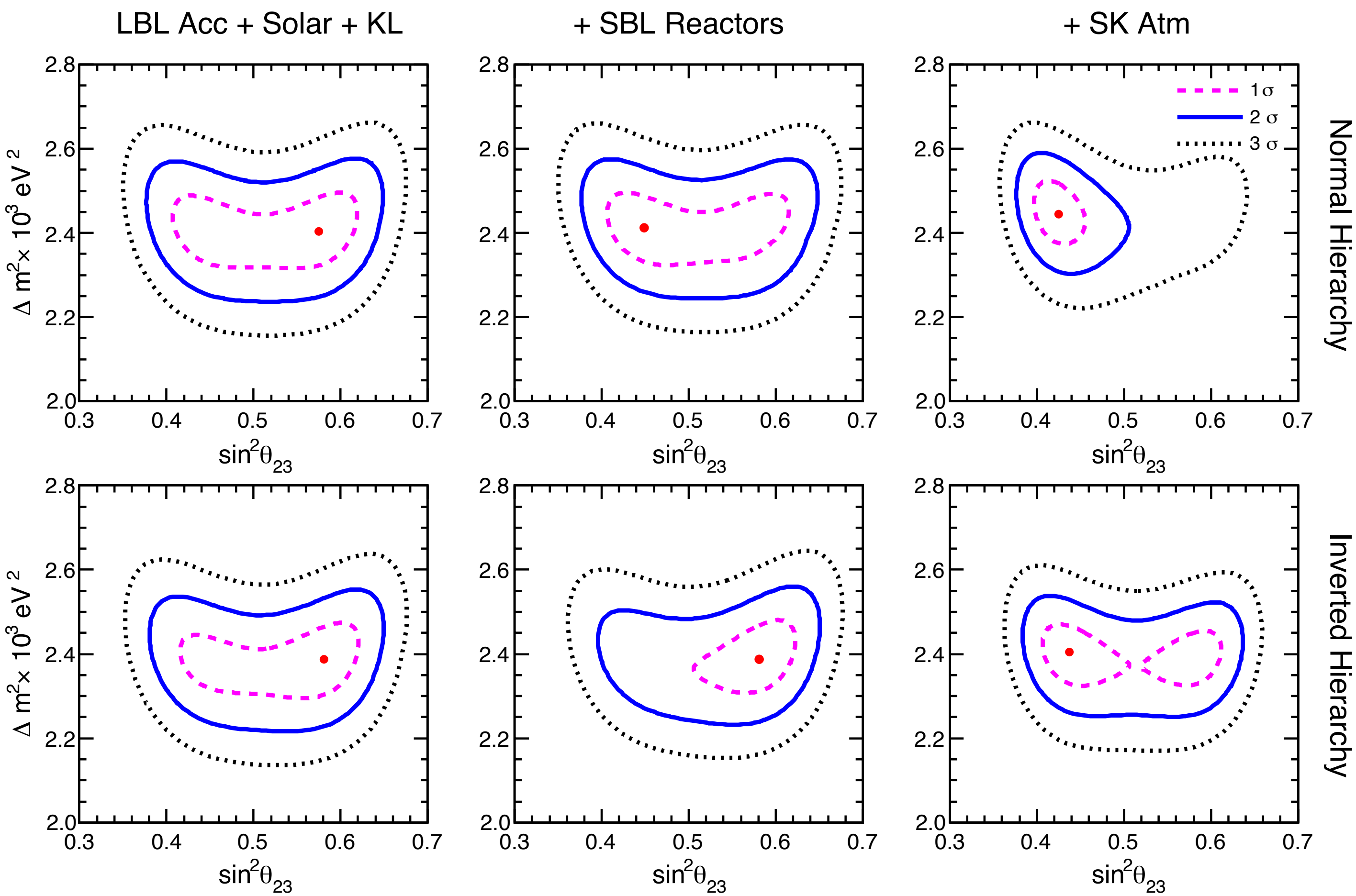
δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 ⊕ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 ⊕ 0.65 – 2.00	—

Fractional uncertainties (defined as 1/6 of 3σ ranges):

δm^2	**2.6 %**
Δm^2	**3.0 %**
$\sin^2\theta_{12}$	**5.4 %**
$\sin^2\theta_{13}$	**8.5 %**
$\sin^2\theta_{23}$	**~ 11 %**

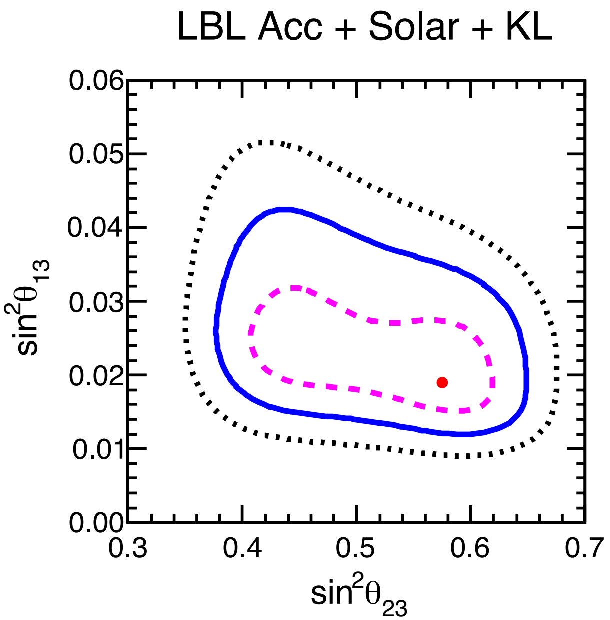
Selected parameter covariances →

The θ_{23} octant "flip" in a more familiar plane:



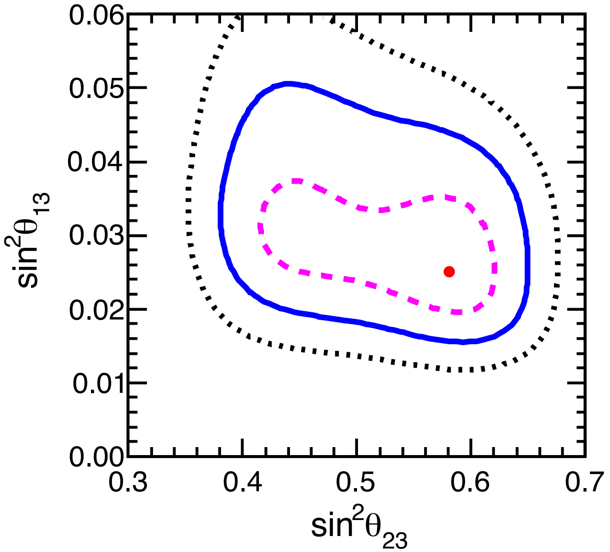
but ... easier to understand in $(\theta_{23}, \theta_{13})$ plane

[Note, however, relevance of future reactor data in breaking correlations in above figure.]



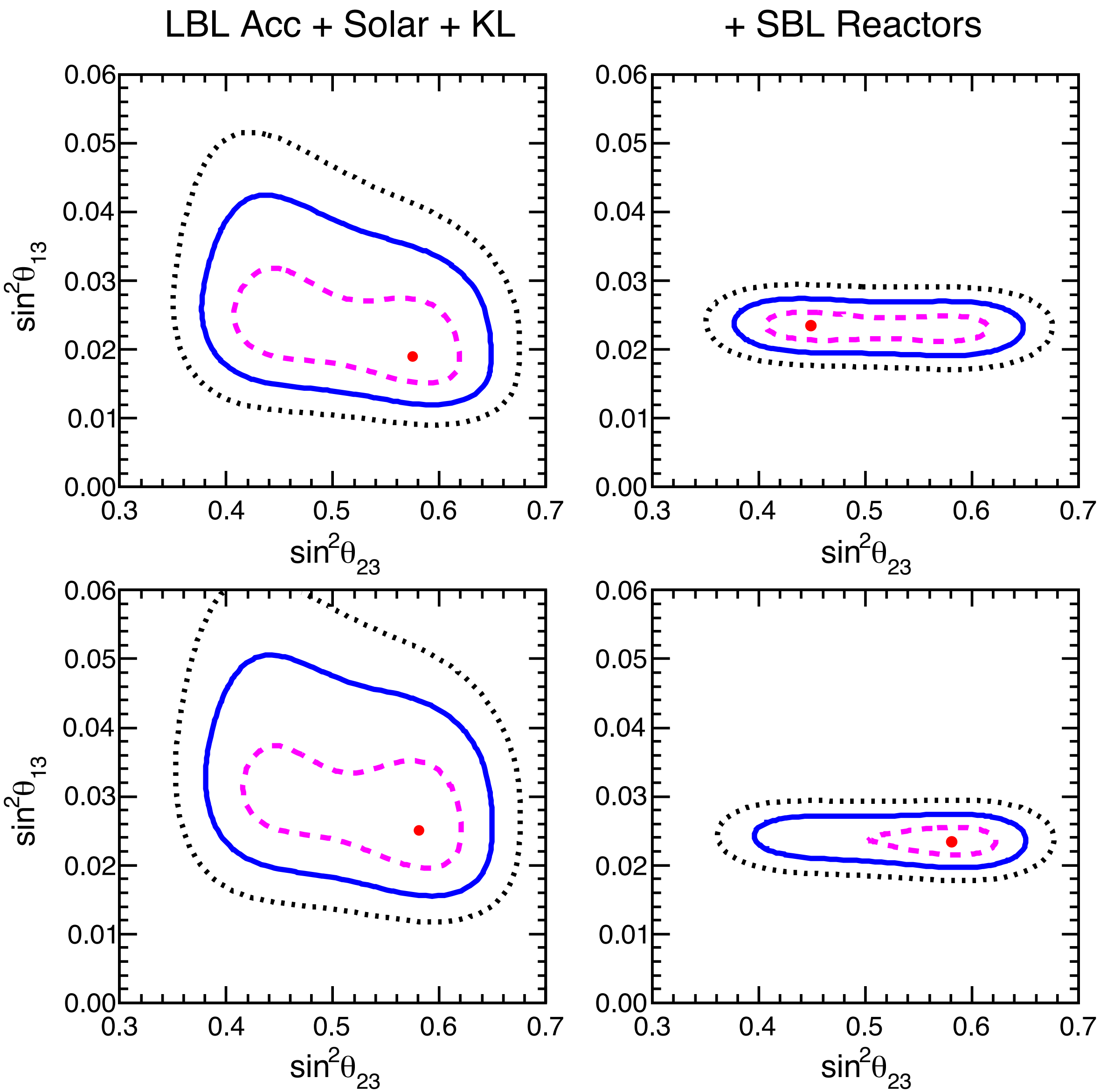
MINOS disappearance prefers nonmaximal mixing (and wins over T2K preference for ~maximal) → two degenerate minima for θ_{23}

T2K + MINOS appearance anticorrelate the minima with θ_{13}: the higher θ_{23}, the lower θ_{13}
[appearance amplitude ~ $\sin^2\theta_{23}\sin^2(2\theta_{13})$]

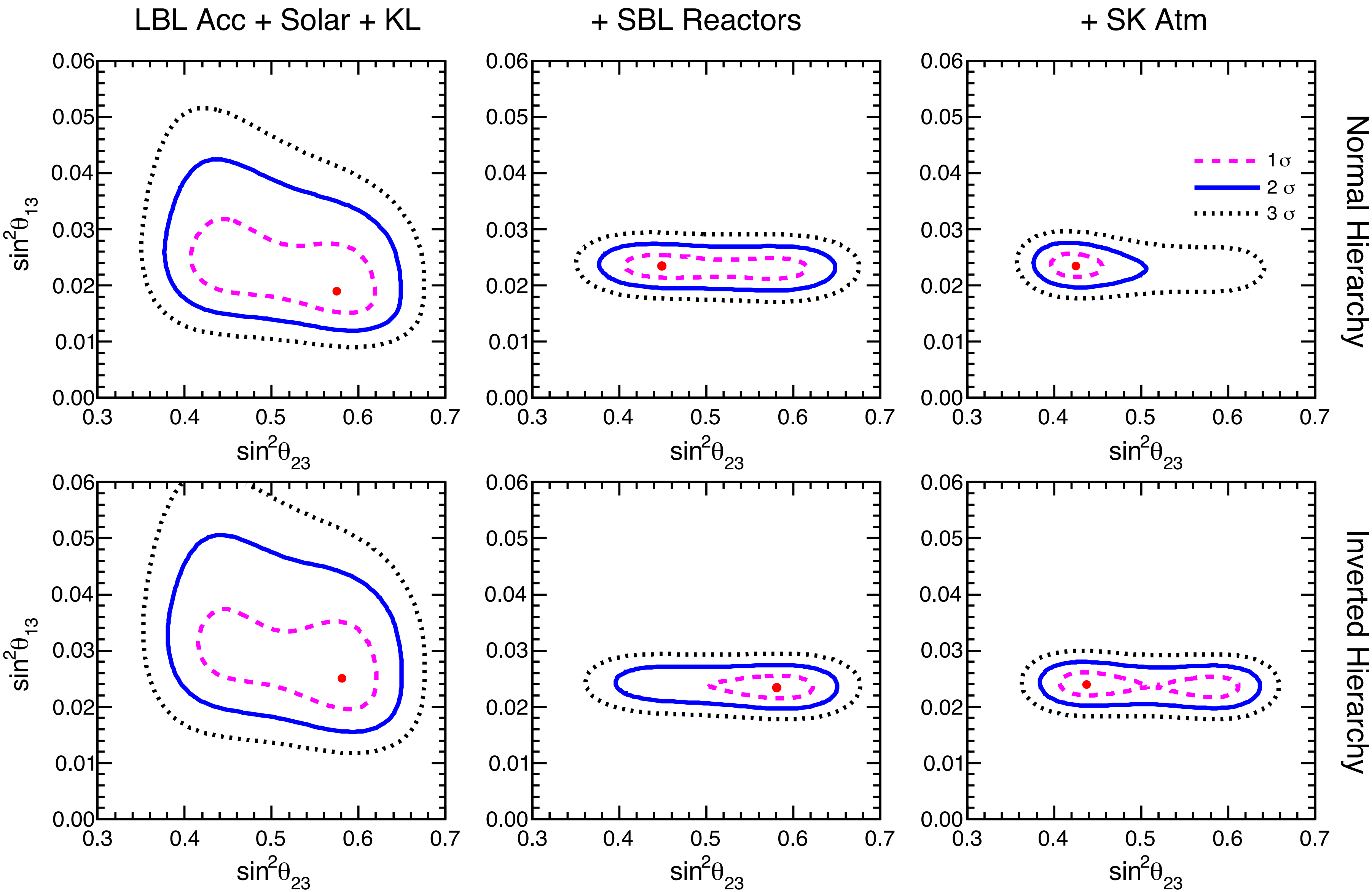


Contours extend to relatively high $\sin^2\theta_{13}$ to accommodate the relatively "strong" T2K appearance signal, especially in IH

In the combination, Solar + KL data lift the degeneracy and prefer the second octant solution, associated with "low" $\sin^2\theta_{13}$~0.02

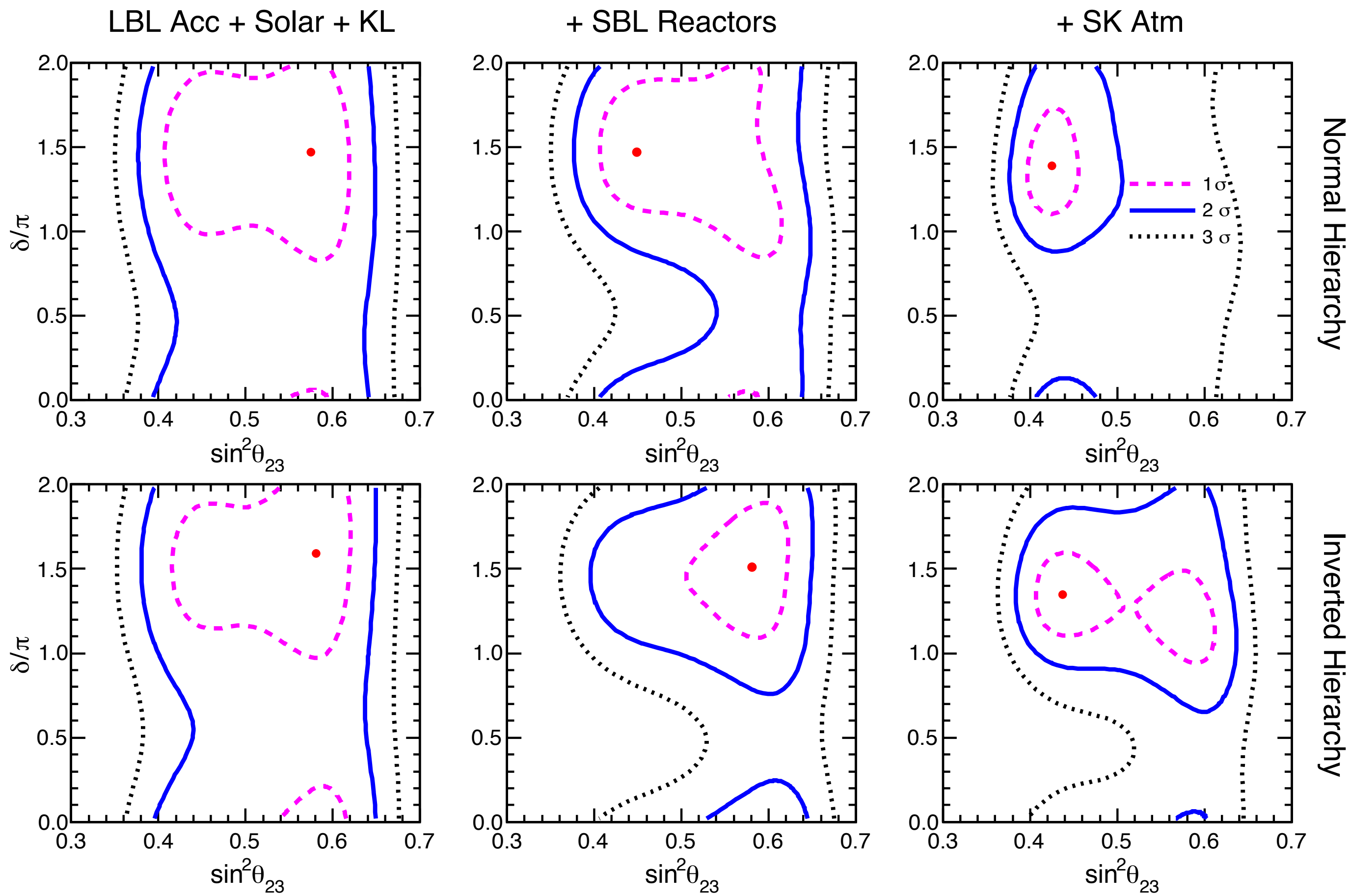


Reactor data prefer $\sin^2\theta_{13}$~0.023, slightly higher than Solar+KL: enough to flip the octant in NH, but not enough to do so in IH.



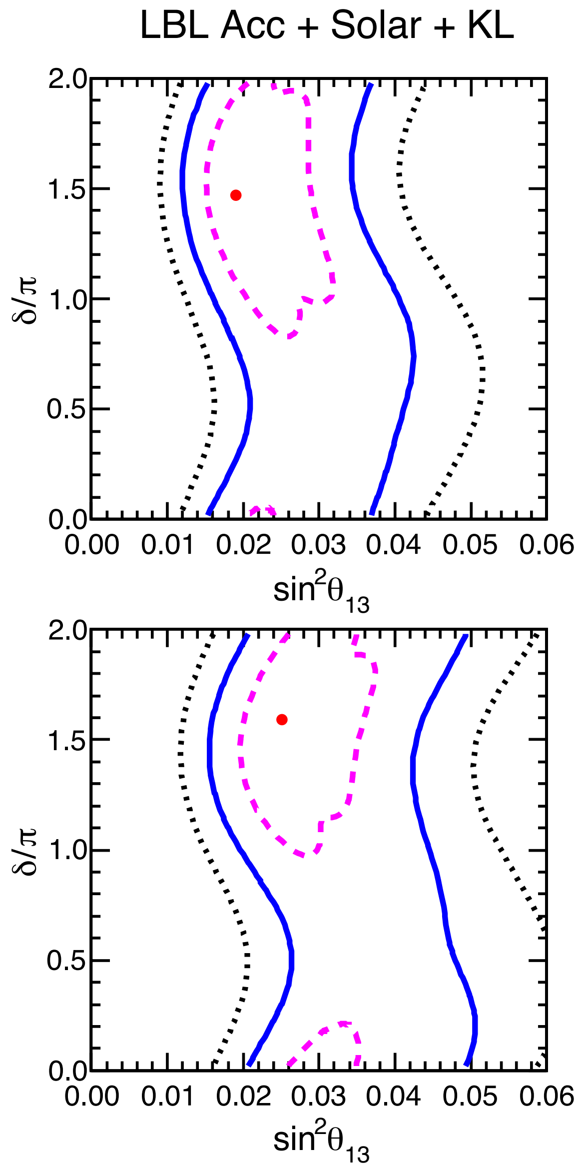
SK atm: We continue to find an overall preference of atmospheric data for the first octant – which currently wins over other data.

Interpretation of $\delta \sim 1.4\,\pi$ preference ...



... easier by looking at (δ, θ_{13}) correlations

[Note, however, strong asymmetry of allowed regions with respect to octant.]

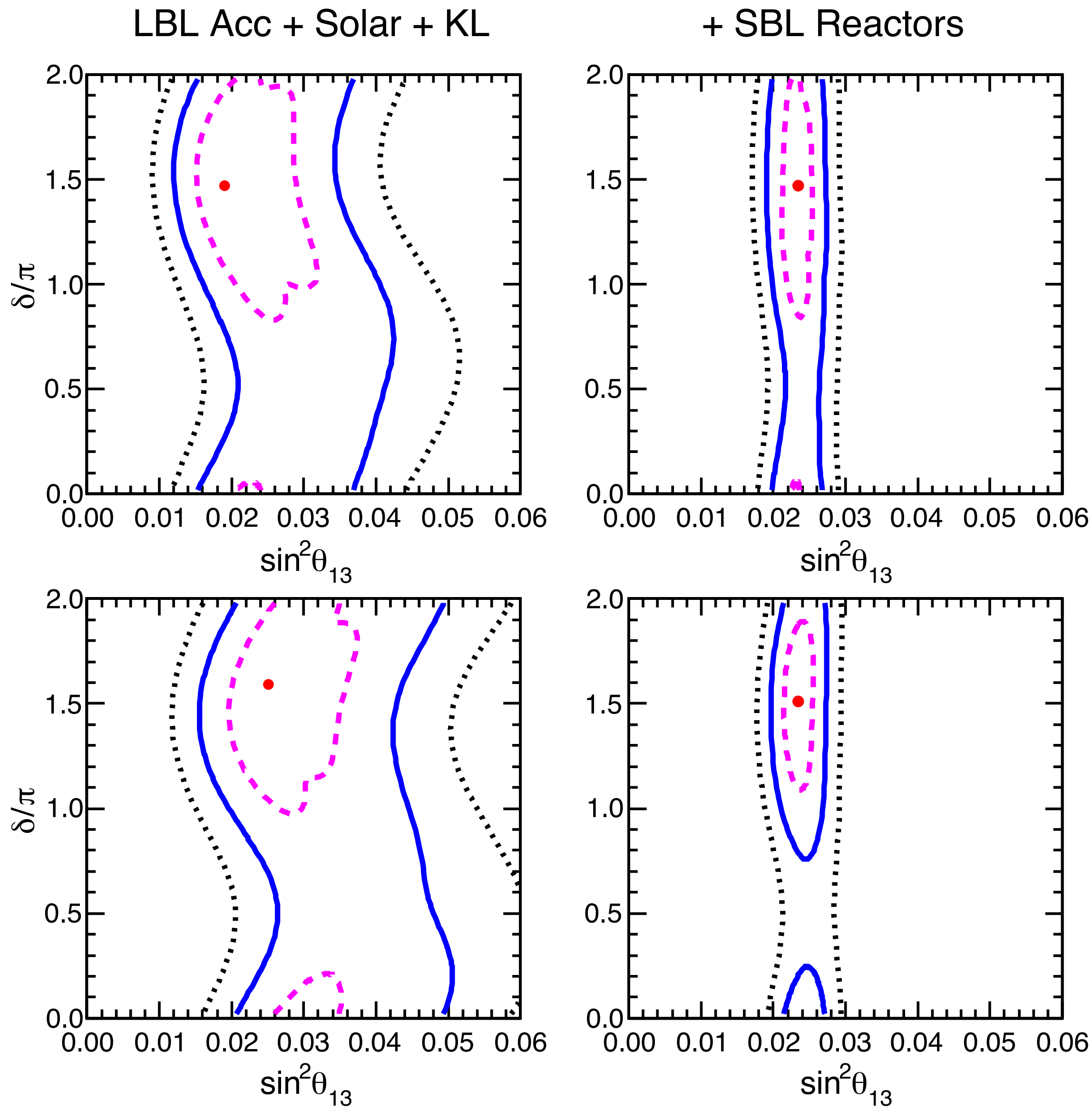


Each wavy band is in part determined by superposition of "two bands" for the two θ_{23} octants

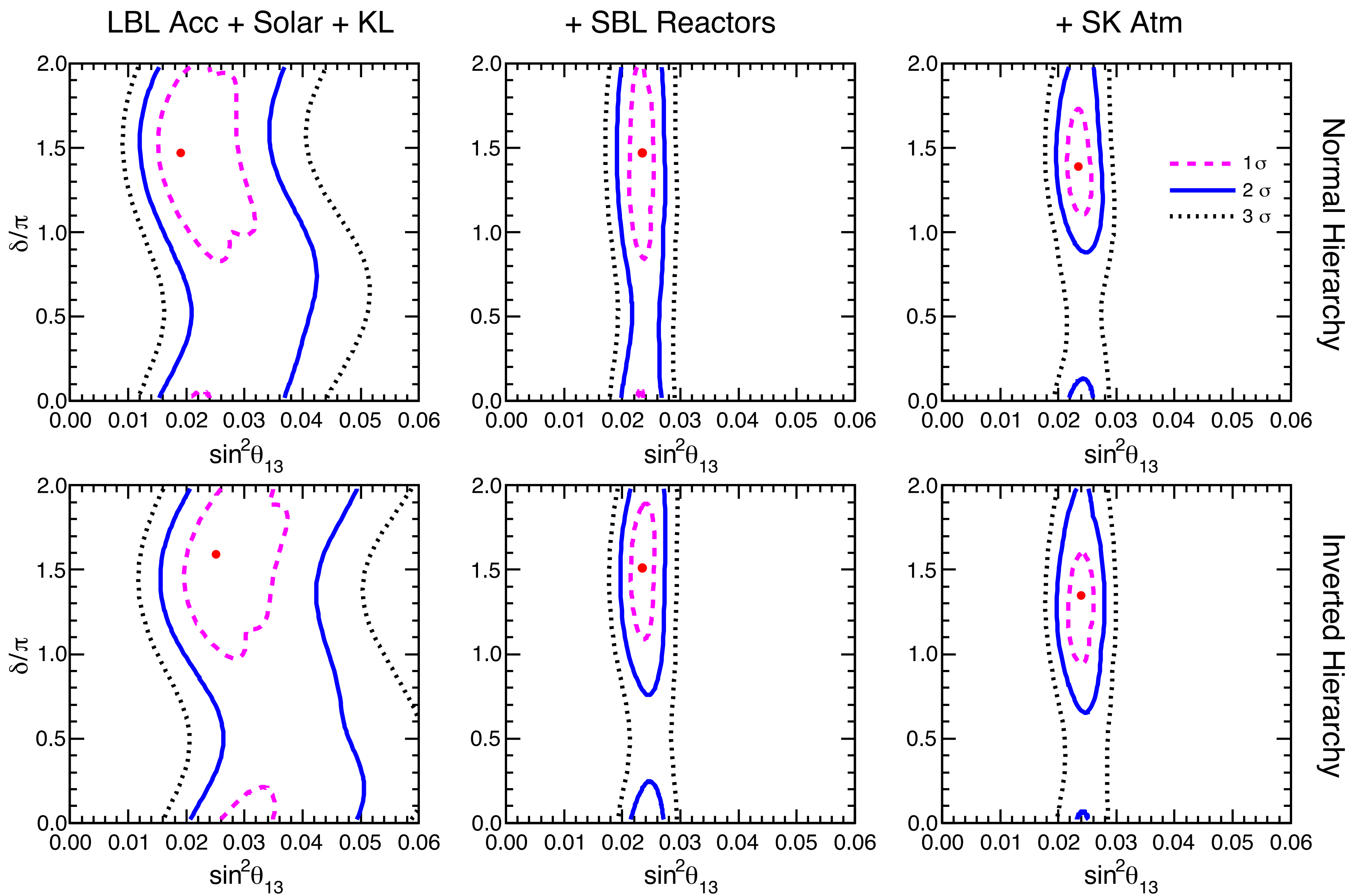
For the relatively "low" value $\sin^2\theta_{13}$~0.02 preferred by Solar + KL data, appearance ν signal in T2K maximized by subleading CP-odd term for $\sin\delta < 0$ [i.e., $1<\delta/\pi<2$]

Best agreement with relatively "strong" T2K appearance signal is for $\delta/\pi \sim 1.5$, irrespective of the hierarchy.

This trend wins over weaker MINOS appearence signal, which generally prefers $\sin\delta < 0$ at best fit.



Reactor data shrink the band around $\sin^2\theta_{13} \sim 0.023$, a bit higher than Solar+SK but still on the leftmost side of the band: **preference for $\delta/\pi \sim 1.5$ persists**



SK atm: We continue to find an overall preference for $\delta/\pi \sim 1$ (with $\delta \sim 0$ disfavored). In combination, $\delta/\pi \sim 1.4$ and $\sin\delta < 0$ favored.

What about NH vs IH?

Figure of merit: $\Delta\chi^2 = \chi^2_{min}(NH) - \chi^2_{min}(IH)$

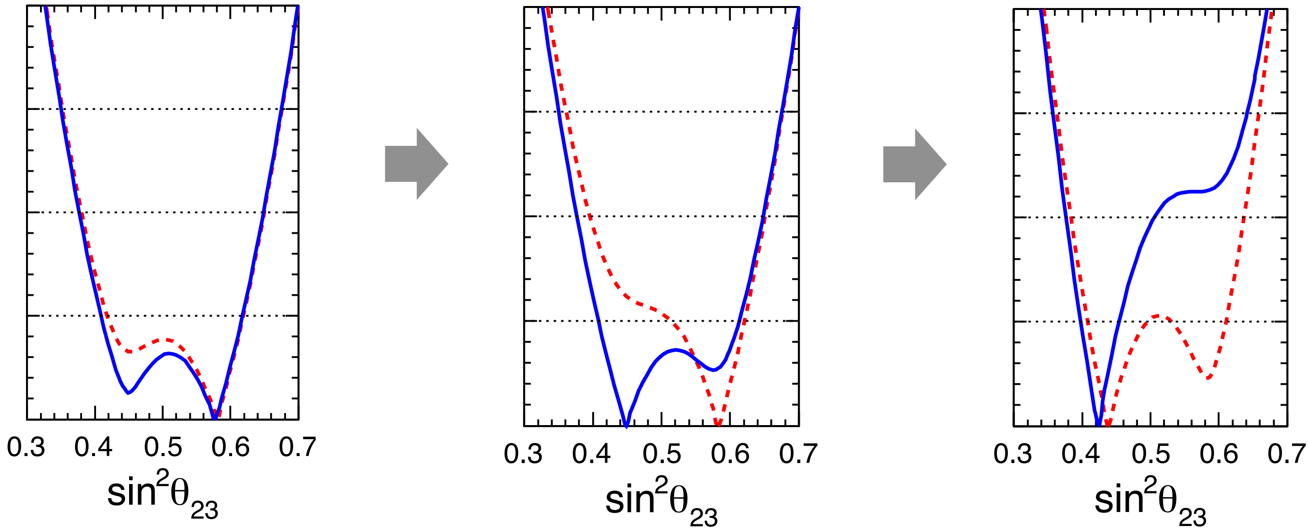
LBL Acc + Solar + KL	:	$\Delta\chi^2 = +1.3$
LBL Acc + Solar + KL + SBL Reactor	:	$\Delta\chi^2 = +1.4$
LBL Acc + Solar + KL + SBL Reactor + SK Atm.	:	$\Delta\chi^2 = -0.3$

No significant sensitivity yet.

Unknown parameters: summary of our results →

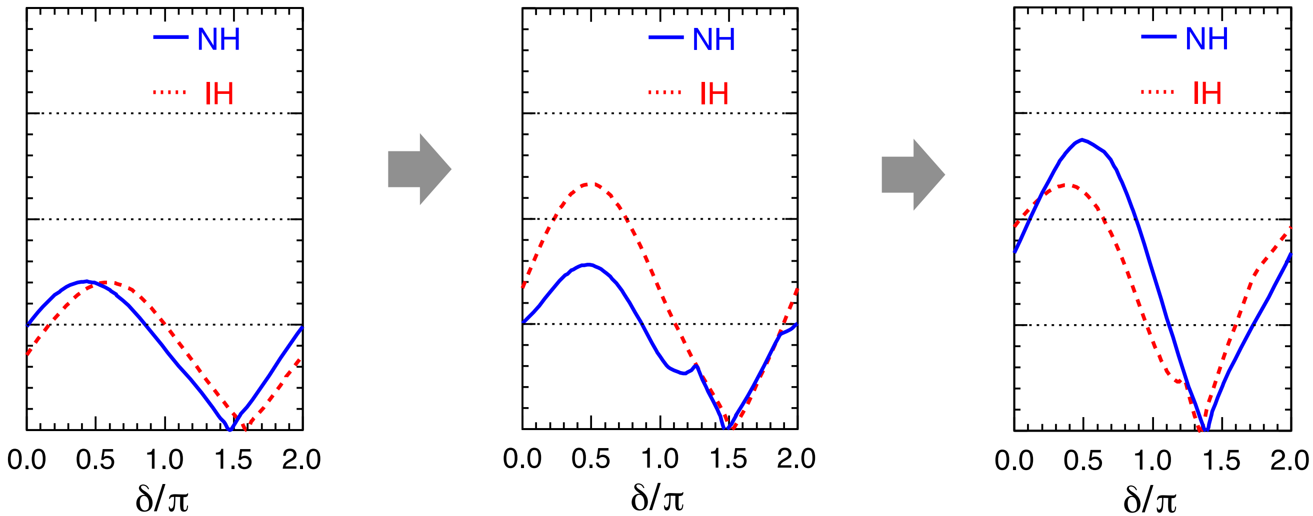
	LBL + Sol. + KL	+ SBL Reactor	+ SK Atmos.

θ_{23}



Apparent instability on octant

δ



Weak but intriguing sinergy on CP phase

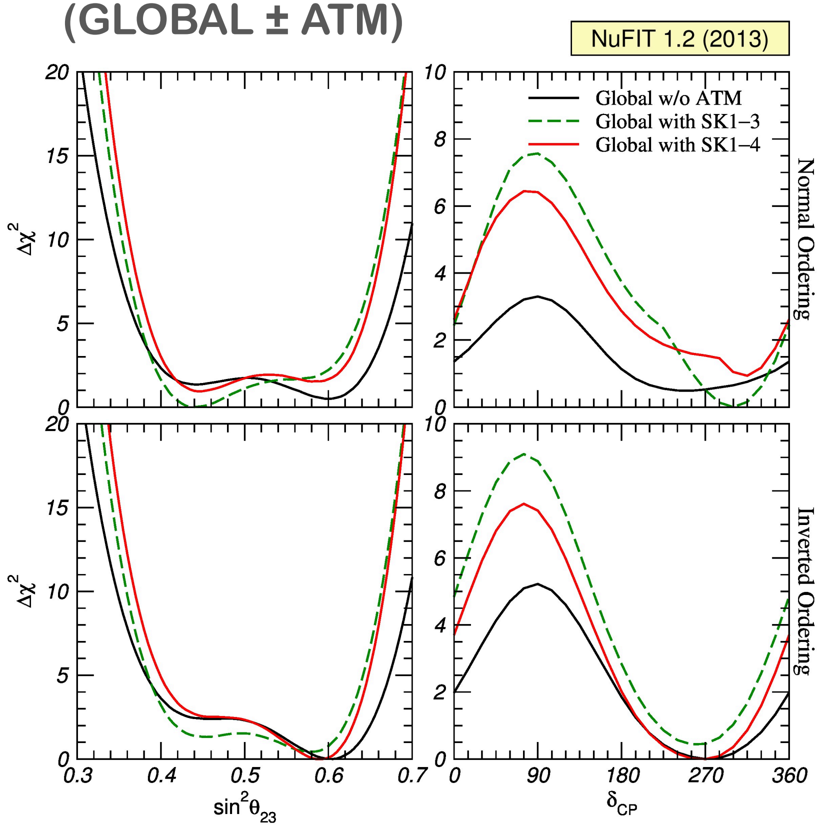
$\Delta\chi^2$ (IH-NH)

-1.3 → **-1.4** → **+0.3**

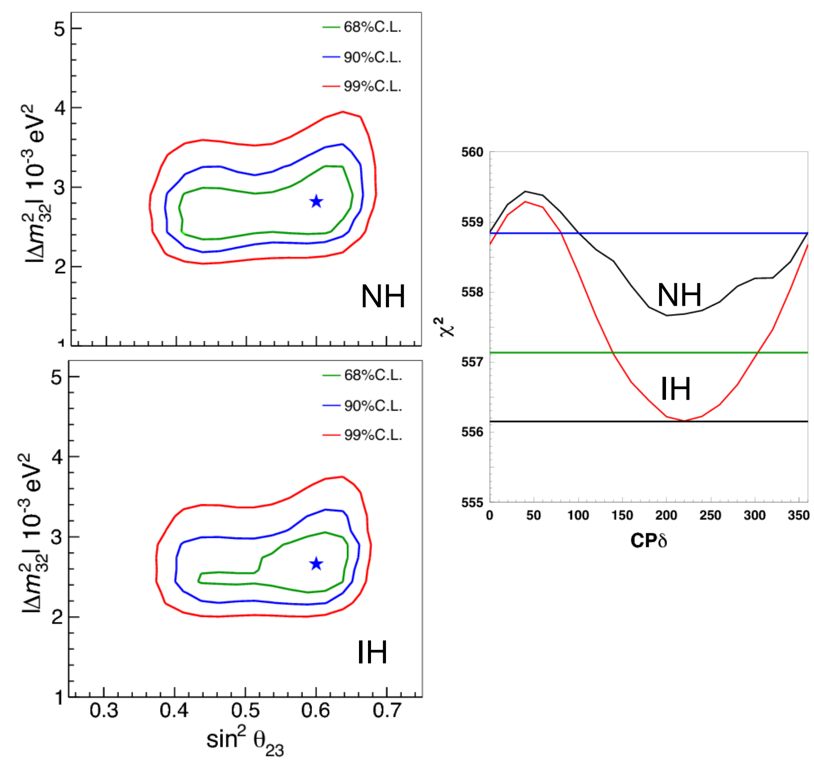
No hint NH/IH

Unknown parameters: comparison wrt ...

Gonzalez-Garcia et al. 2013 (GLOBAL ± ATM)

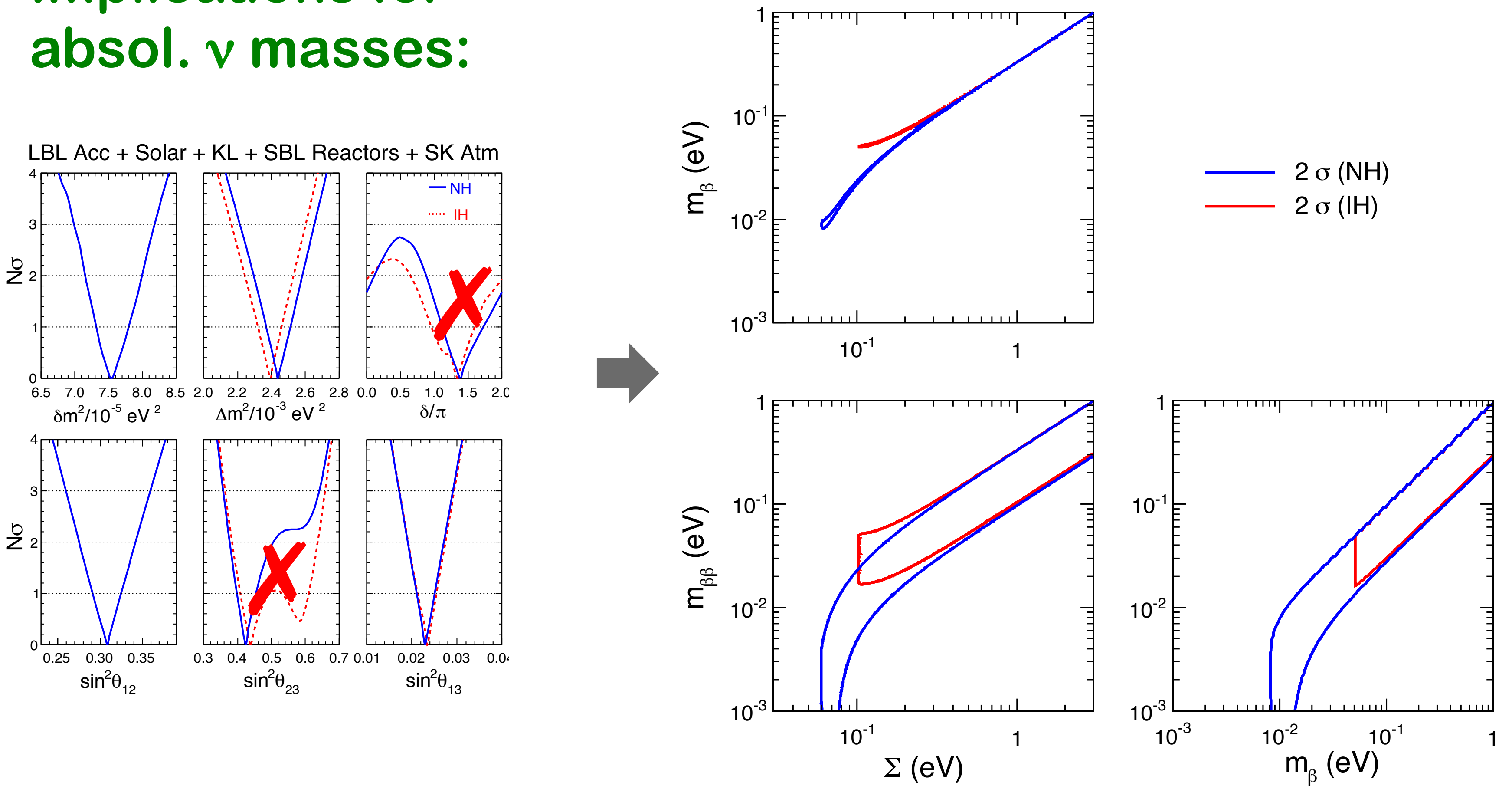


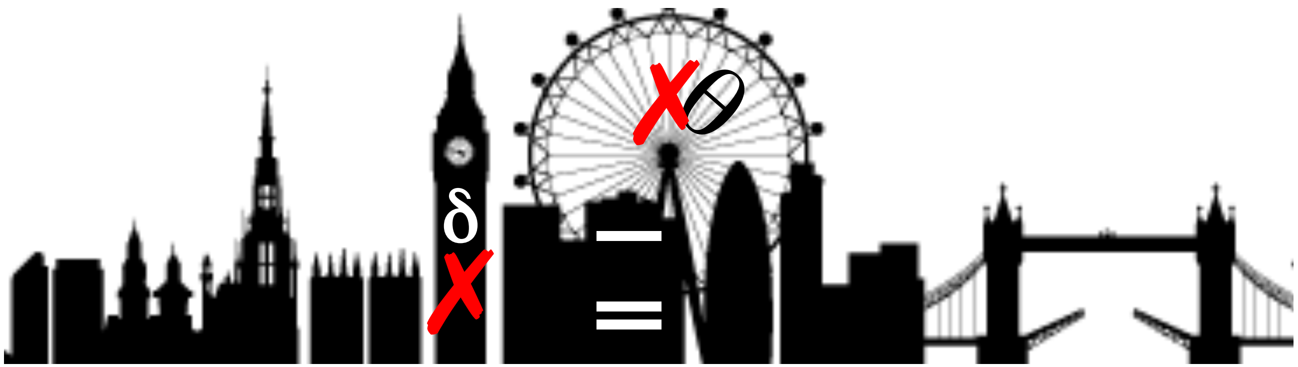
Super-Kamiokande, arXiv:1310.6677 (REACTOR + ATM)



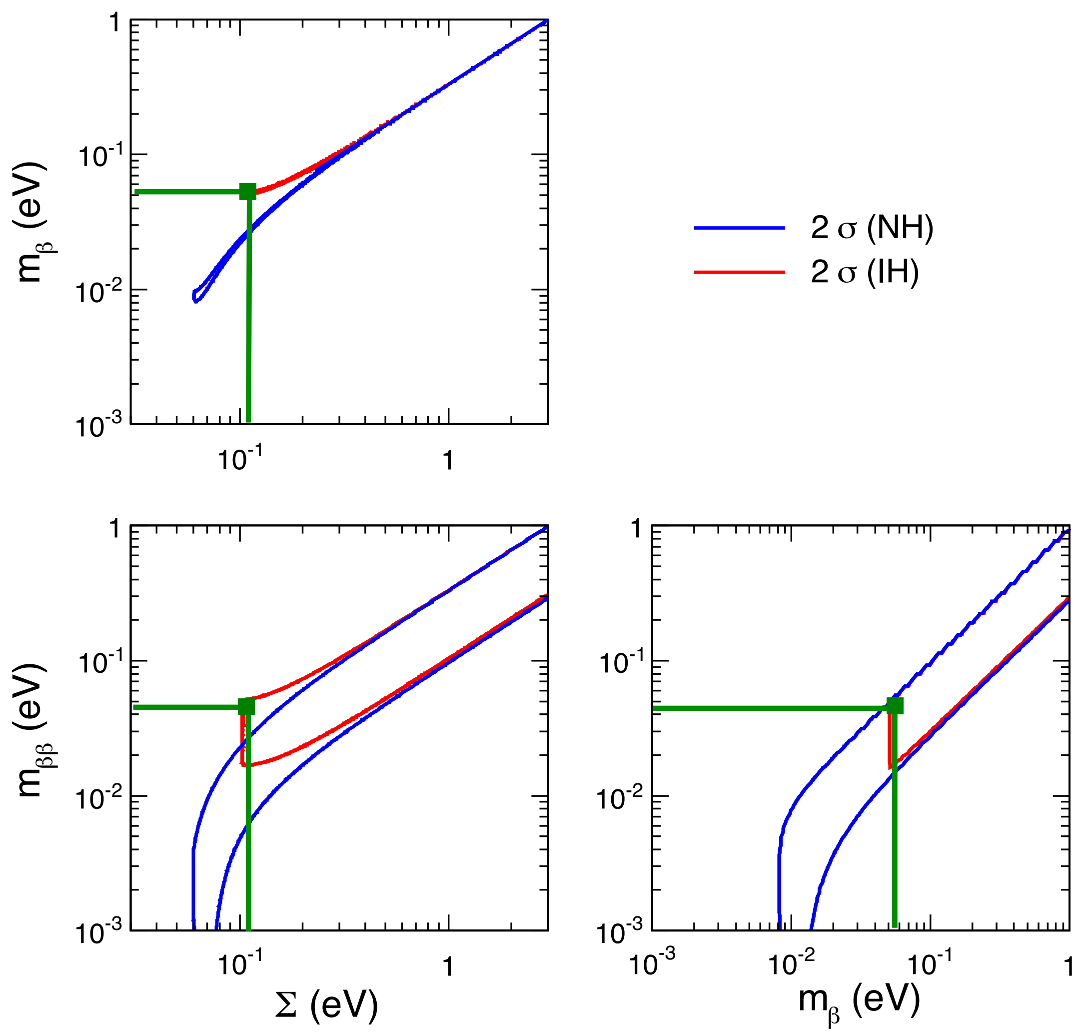
Relative fluctuations of best-fit octant and hierarchy within errors, but interesting convergence on best-fit CP phase at sinδ < 0

Implications for absol. ν masses:

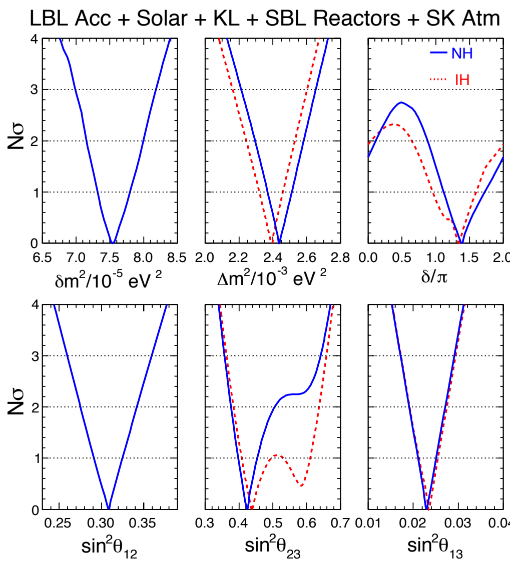




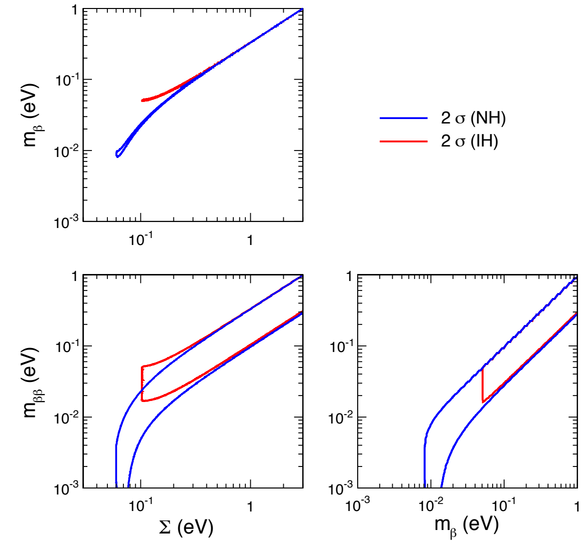
Absolute ν mass observables may provide an independent handle, or at least constraints, on **NH vs IH discrimination.** An ideal case:



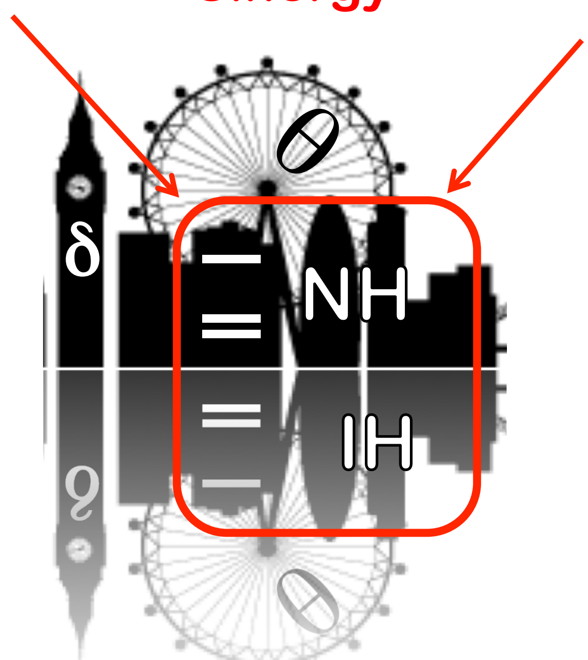
Oscillation data



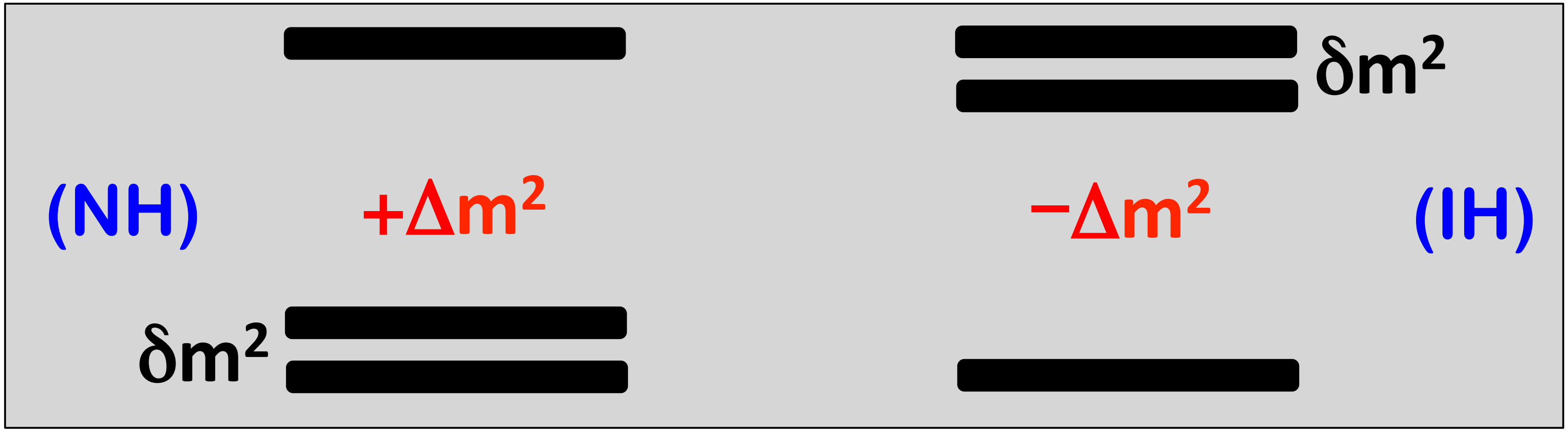
Nonoscillation data



Sinergy



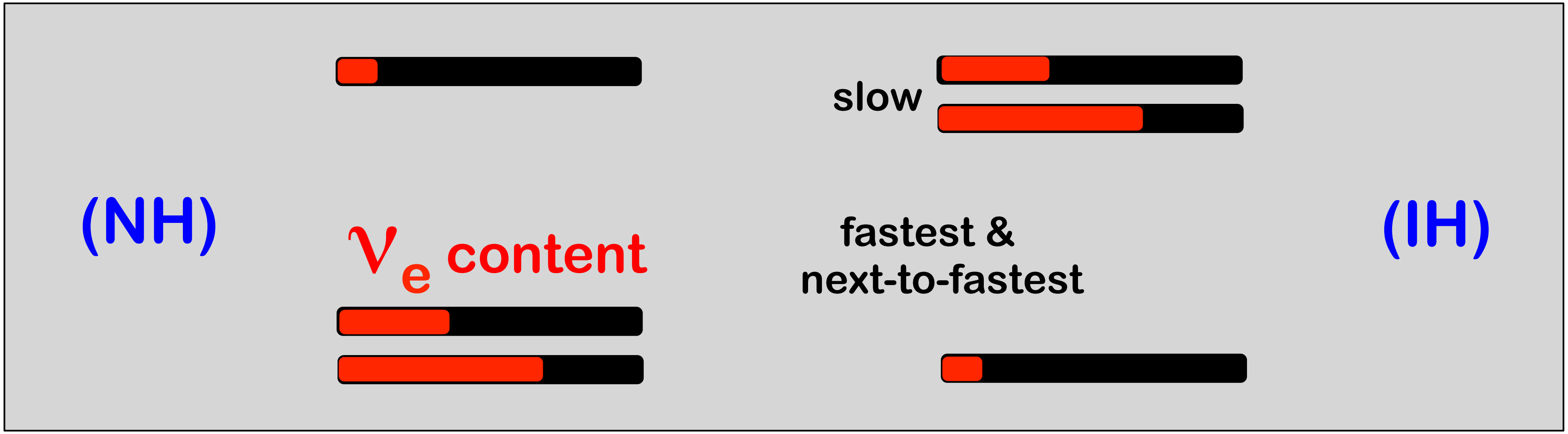
Neutrino flavor oscillations can probe the hierarchy...



... if oscillations driven by $\pm\Delta m^2$ interfere with oscillations driven by another "squared mass gap" Q with known sign. Three options:

$Q = \delta m^2$	(focus of the following slides →)
$Q = 2\sqrt{2}\, G_F N_e E$	(matter effects in Earth or SNe)
$Q = 2\sqrt{2}\, G_F N_\nu E$	(collective effects in SNe)

Simple physics: One slow & two fast oscillations



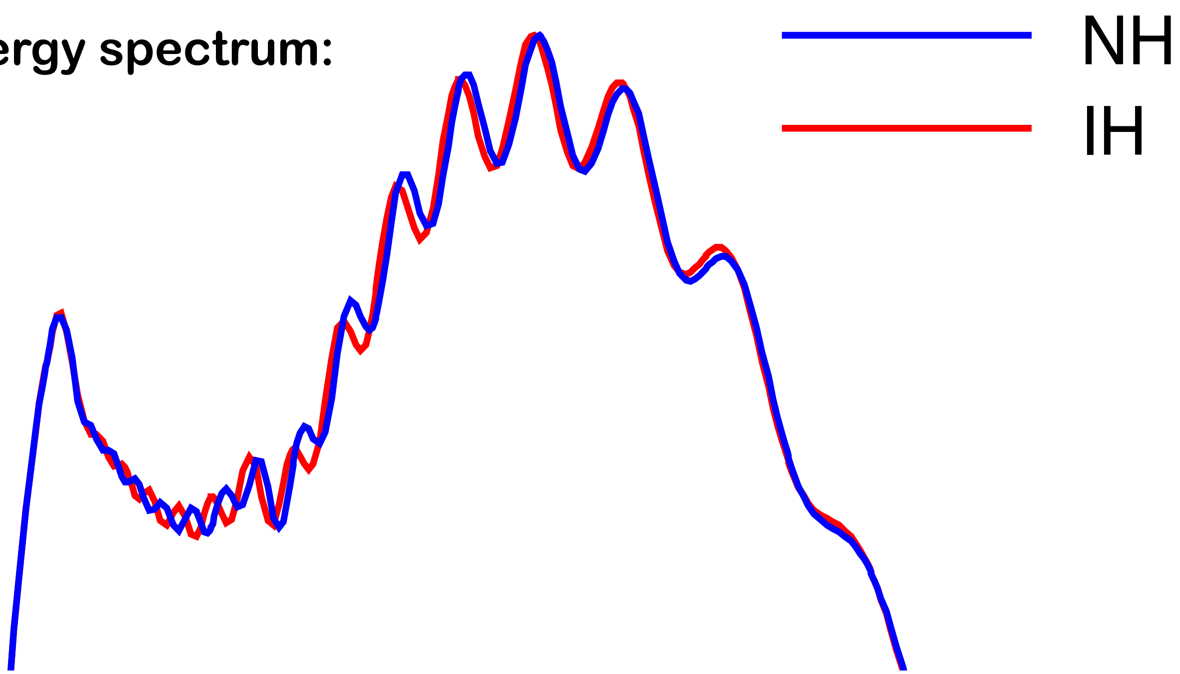
ν_e oscillation amplitude = product of two **red bars**

Under hierarchy swap:

Amplitude of the slow oscillation does not change,
while the (different) amplitudes of the fastest and next-to-fastest oscillations are interchanged

(unless closest red bars were equal, i.e., $\theta_{12}=\pi/4$)

Typical energy spectrum:



Peaks in oscillated reactor spectrum at O(50) km are displaced from NH to IH: one cannot exactly mimic the other in the ideal case of no errors, even if all other osc. parameters are varied.

However, within statistical errors, a "morphing" NH ←→ IH may be tolerated to some extent: debate on statistical significance of $\Delta\chi^2$ difference.

We have discussed* an analytical form for the reactor 3ν oscill. probability, including matter & damping effects, which allows a **continuous morphing between NH and IH:**

$$P^{3\nu}_{\mathrm{mat}} \simeq c^4_{13} P^{2\nu}_{\mathrm{mat}} + s^4_{13} + 2 s^2_{13} c^2_{13} \sqrt{P^{2\nu}_{\mathrm{mat}}}\, w \cos(2\Delta_{ee} + \alpha\varphi)$$

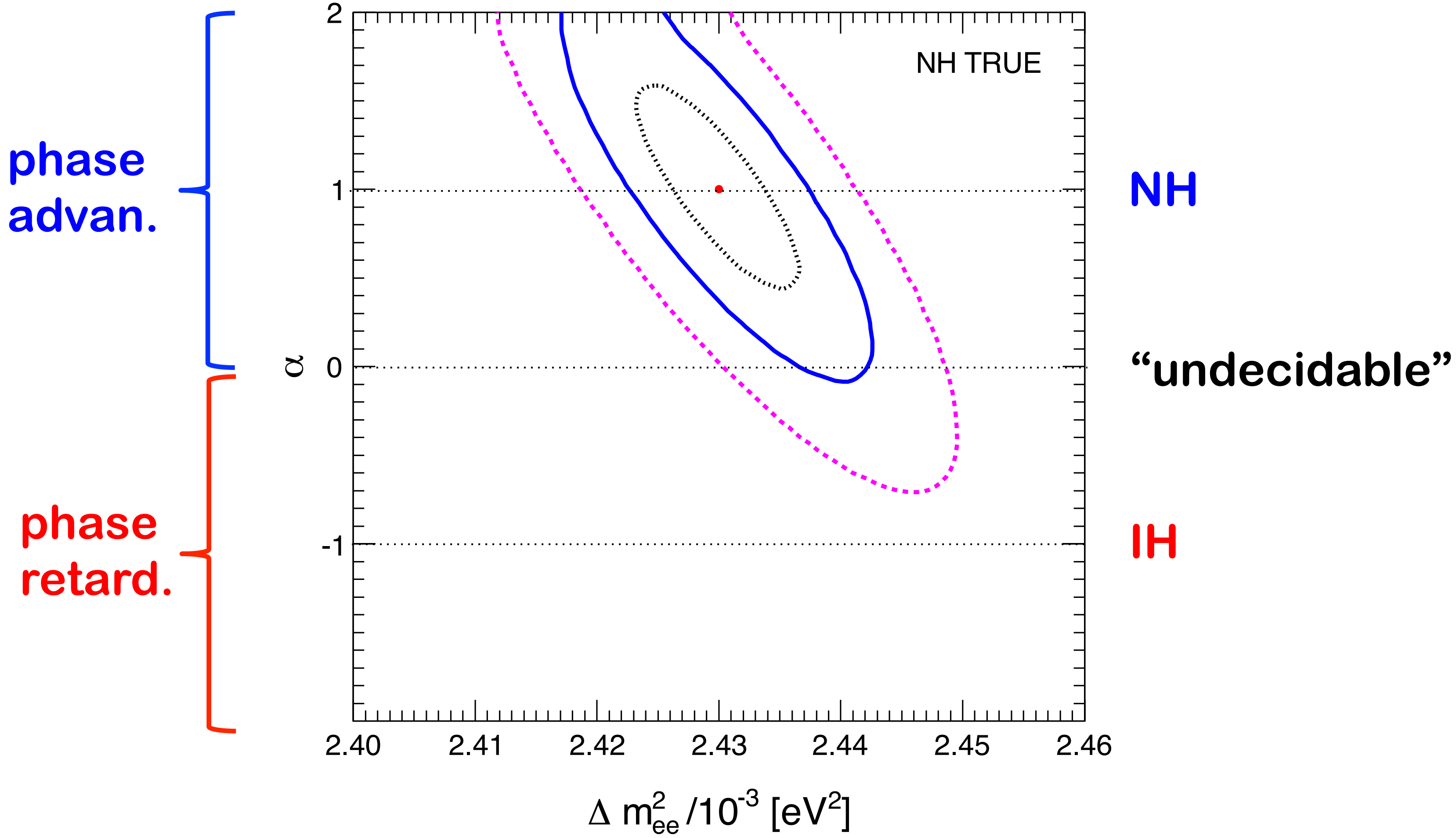
$$\alpha = \pm 1\ (\mathrm{NH/IH}) \longrightarrow \alpha = \mathrm{free}$$

Prospective results for a JUNO-like setting (5 yrs) →

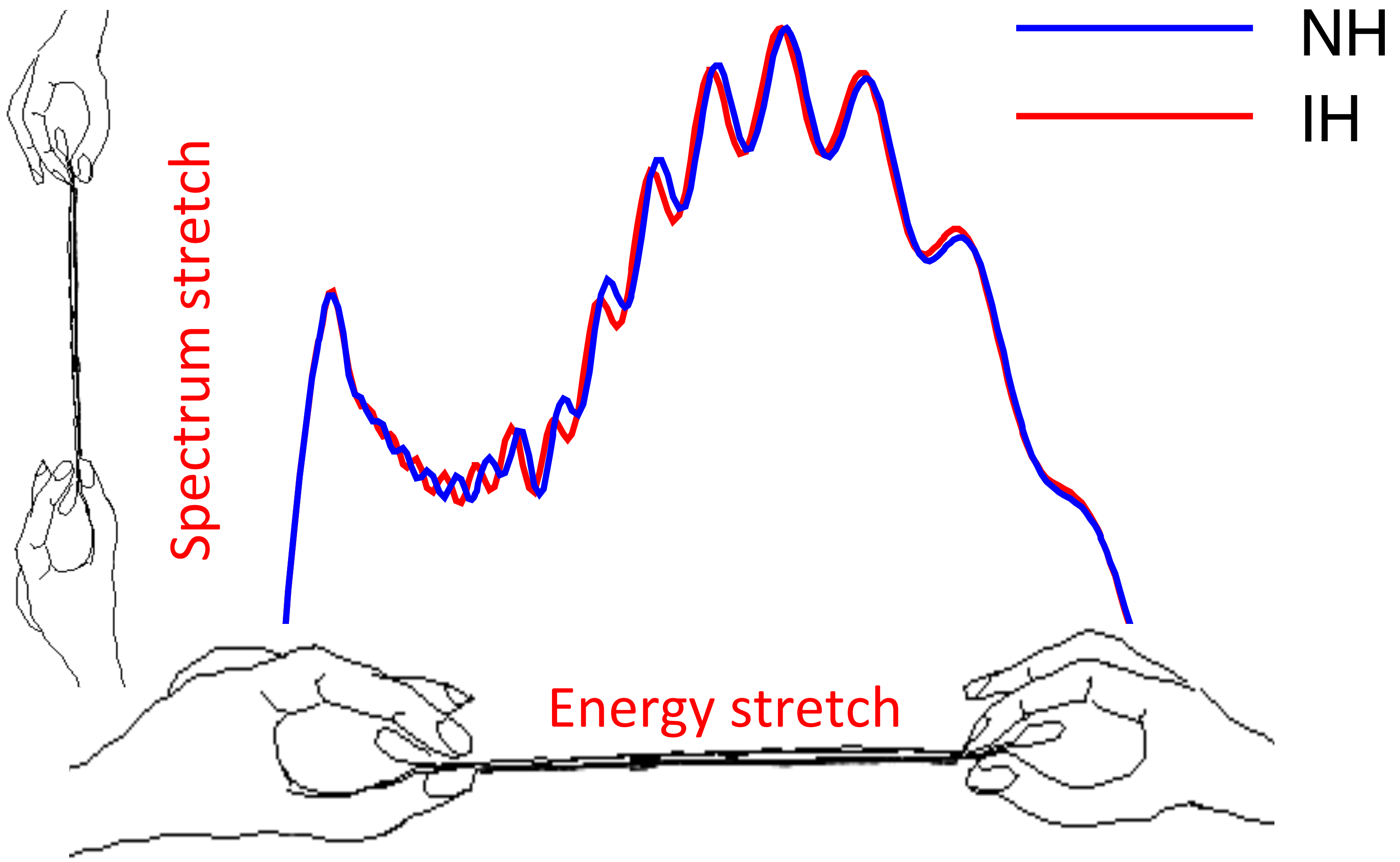
[including stat. errors + osc. par. errors + normalization syst.]

* F. Capozzi, E. Lisi, A. Marrone, arXiv:1309.1638, to appear in PRD (2013)

(Δm^2_{ee}, α) fit for true NH



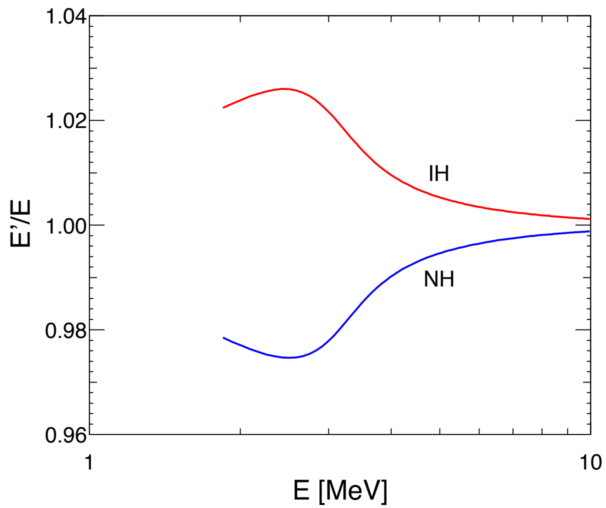
Although the "wrong" hierarchy is ~3.4σ away from the true one, the experiment is already compromised when the "undecidable" case is reached at ~1.7σ = effective sensitivity. Under debate!



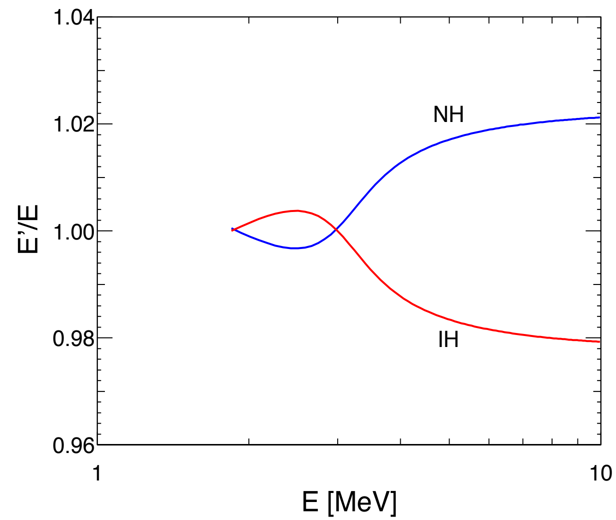
In the previous fit we have not included possible nonlinear stretch of the x-axis **(energy scale systematics)** or of the y axis **(spectrum shape systematics)** which could allow an easier **"morphing" NH/IH** by realigning the peaks and renormalizing their heights.

There are infinite ways to do so! Just two examples, involving x,y stretch localized at low E or at high E:

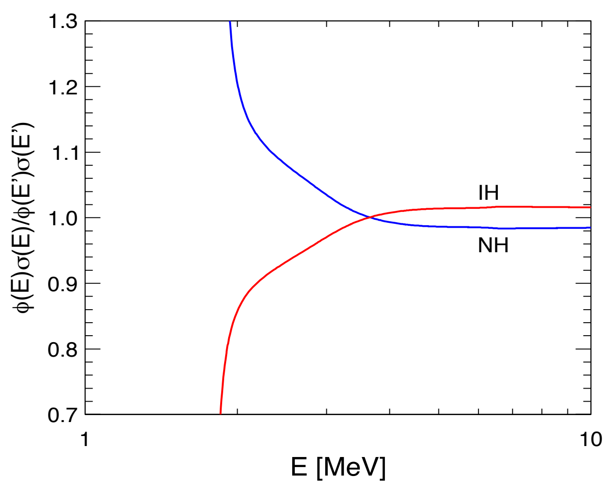
low E



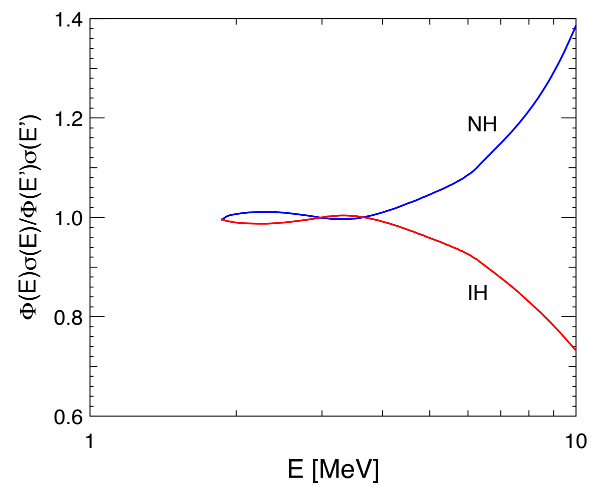
high E



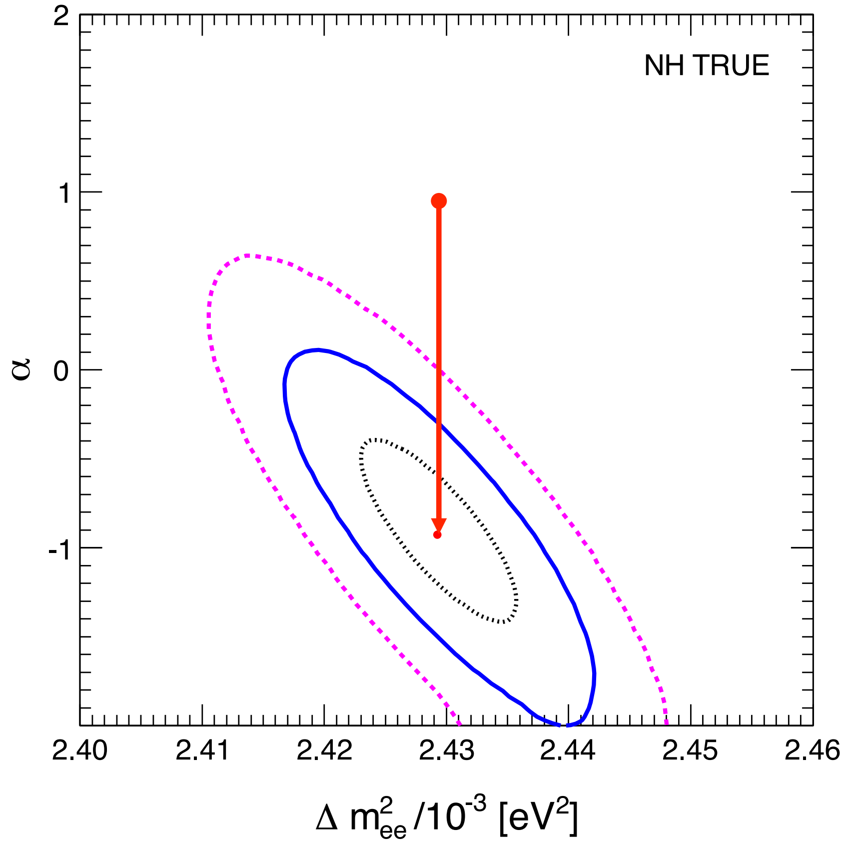
X-axis stretch



Y-axis stretch



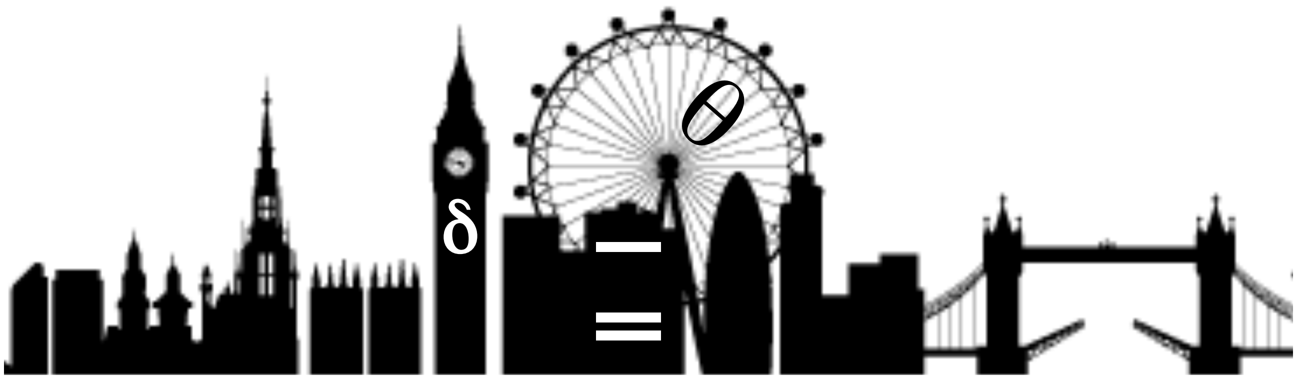
Stretch effect: true hierarchy → wrong hierarchy



Quantifying these **systematics** and their possible **functional shapes** represent a new frontier of precision reactor experiments and of their analysis.

Conclusions:

Beautiful neutrino experiments have sketched the current "three-neutrino skyline", sometimes with amazing accuracy. **But basic pieces, which may profoundly change the landscape, are still missing.** In this context, global analyses may provide some guidance on emerging profiles and on unprecedented challenges in the field.
In this process, let's never forget that…



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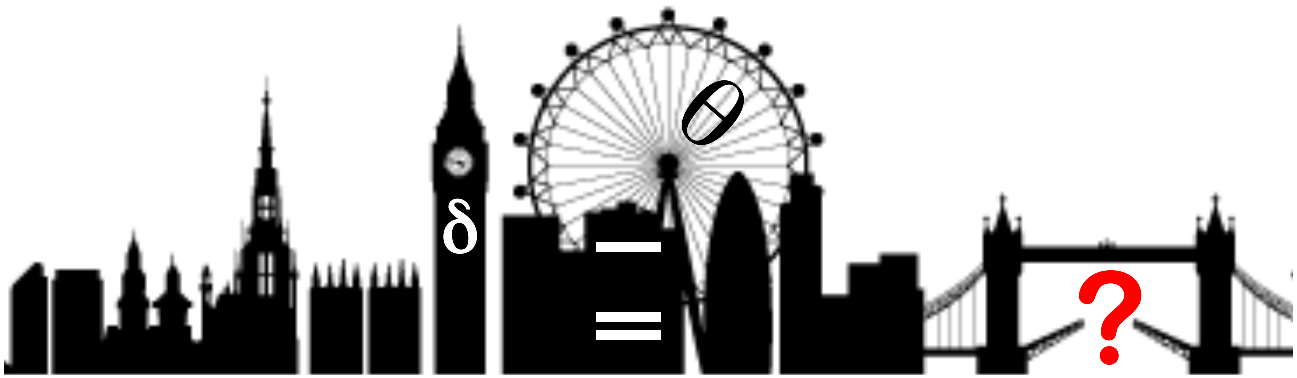
In this process, let's never forget that …

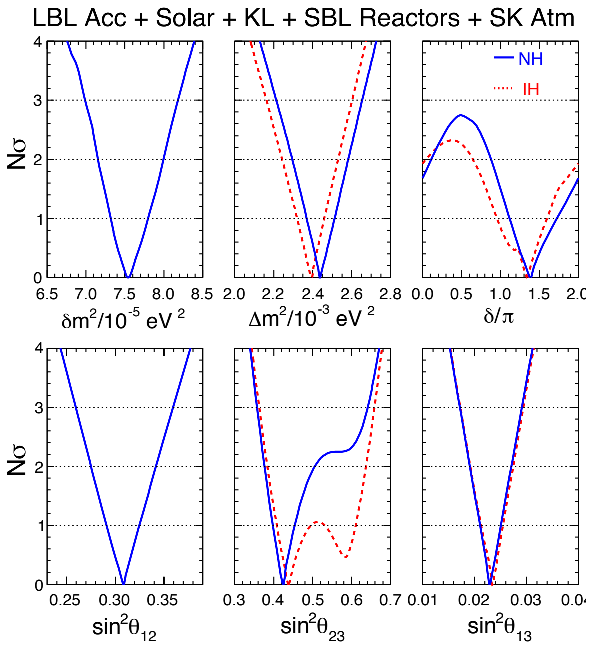
surprises may appear & may open new gates!



Thank you for your attention.

Synopsis:

[F. Capozzi, G.L. Fogli, E. Lisi, D. Montanino, A. Marrone, and A. Palazzo, arXiv:1312.2878]



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δ/π (NH)	1.39	1.12 – 1.72	0.00 – 0.11 $\oplus$ 0.88 – 2.00	—
δ/π (IH)	1.35	0.96 – 1.59	0.00 – 0.04 $\oplus$ 0.65 – 2.00	—