

# Status of $3\nu$ mass-mixing parameters



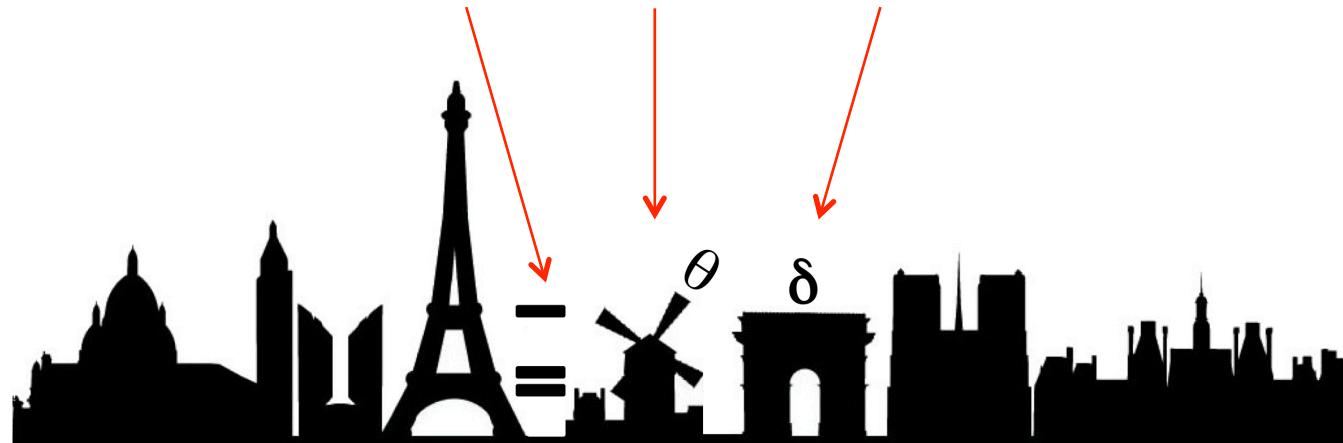
Elvio Lisi, INFN, Bari

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# Outline:

- Intro: data, notation, methodology
- Single oscillation parameter ranges
- Selected parameter covariances
- Conclusions (with a tribute to Nicola Cabibbo)

Emphasis: hierarchy,  $\theta_{23}$  octant, CP phase (unkowns)



Based on arXiv:1312.2878; work done in collaboration 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

# $3\nu$ oscillation parameters: Notation

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

(All parameters free to float in the global fit)

Note:  $1\sigma$  error on  $\Delta m^2 \approx 0.07 \times 10^{-3} \text{ eV}^2 \approx \delta m^2$

## Combined analysis of data sets: Methodology

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

Moreover: CP-violation is a genuine 3v 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  $\sin^2 \theta_{13} \sim 0.02$

# 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.

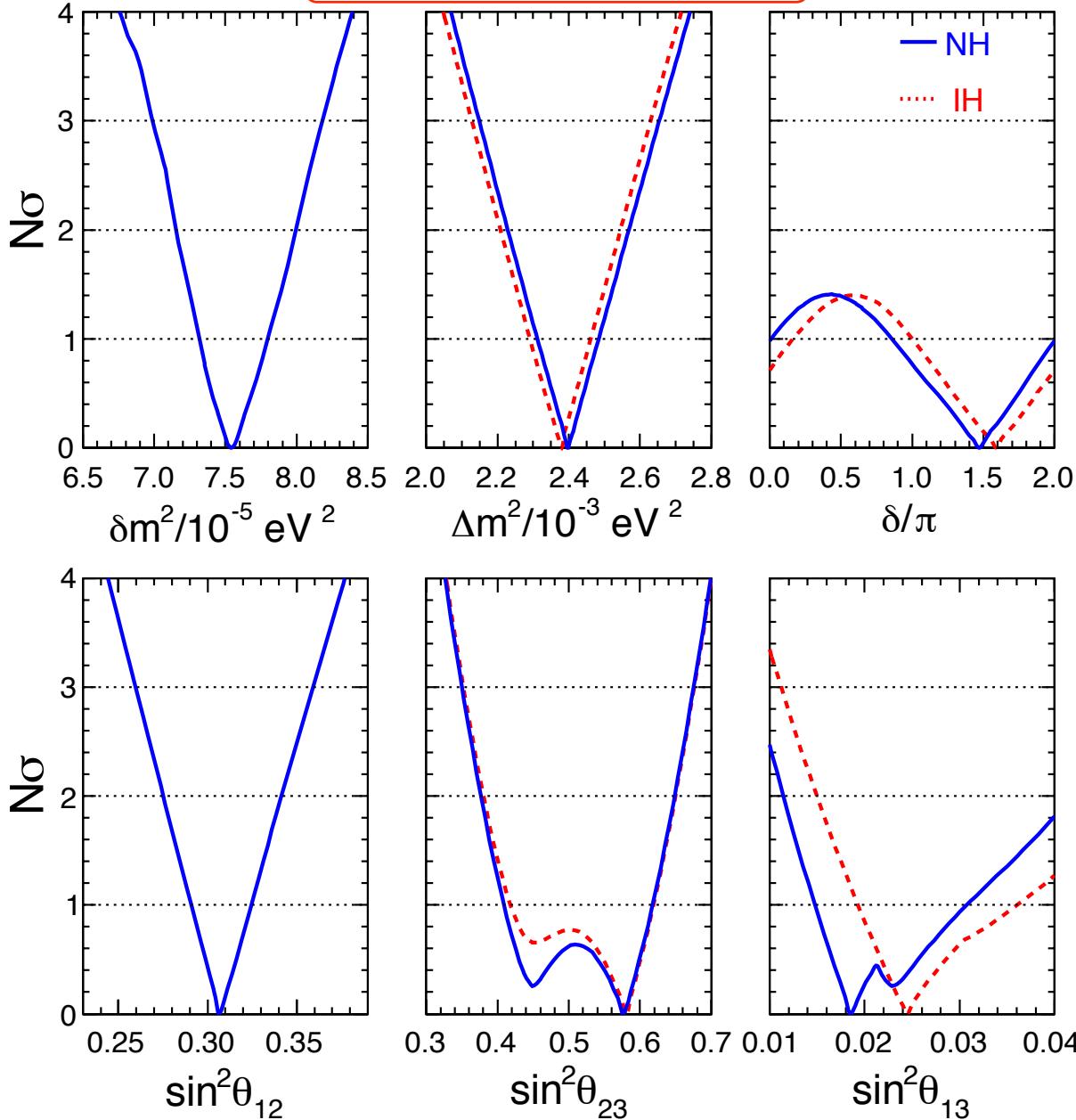
Figures: parameters not shown are marginalized away.

Contours are drawn at  $\Delta\chi^2 = 1, 4, 9 \rightarrow$

$N\sigma = 1, 2, 3$  for projections over single parameters.

End of Intro. Results on single parameters →

LBL Acc + Solar + KL

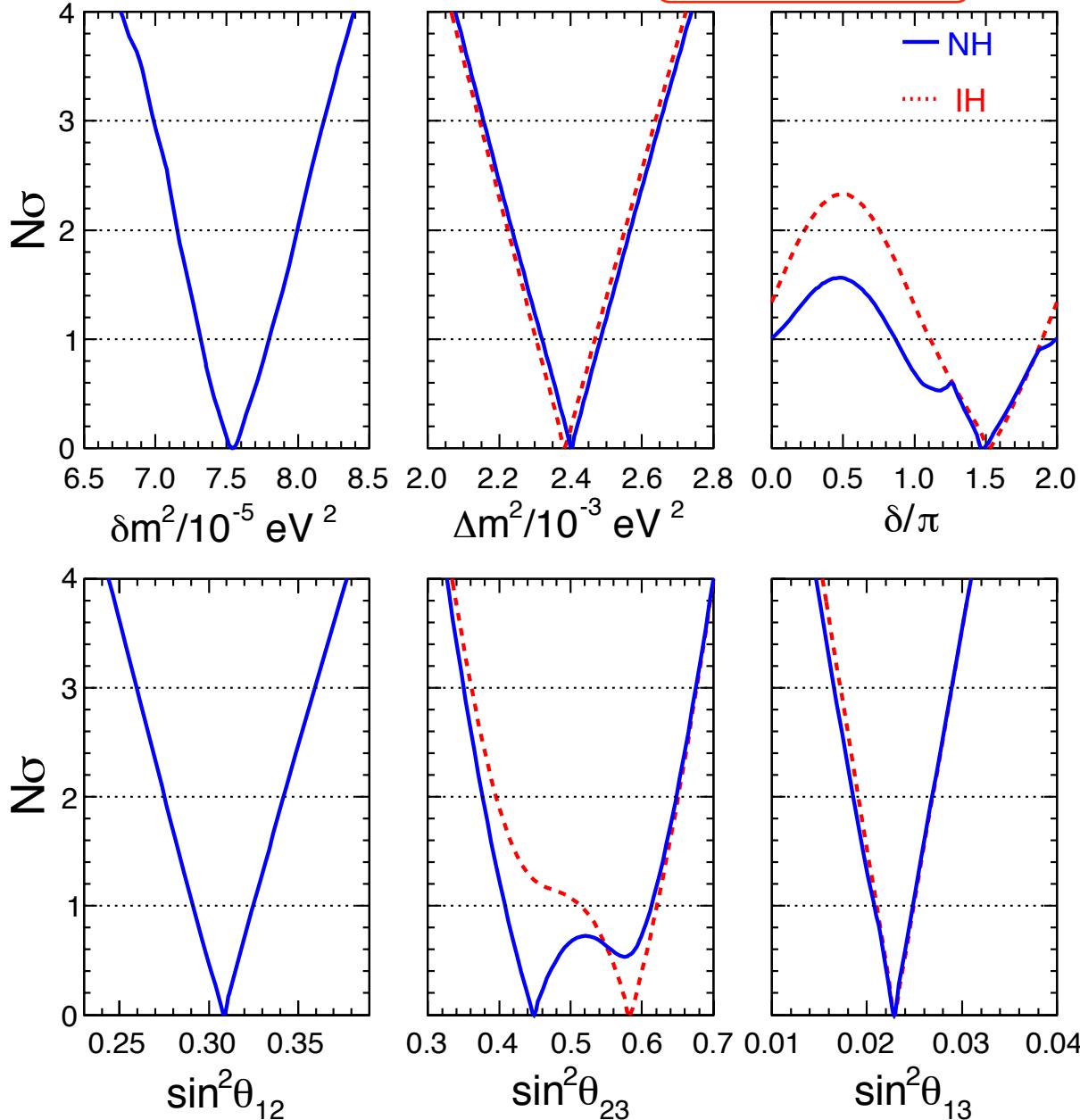


Upper and lower bound on all oscill. parameters but  $\delta$

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

Slight preference for nonmaximal  $\theta_{23}$  and for 2nd octant

# LBL Acc + Solar + KL + SBL Reactors

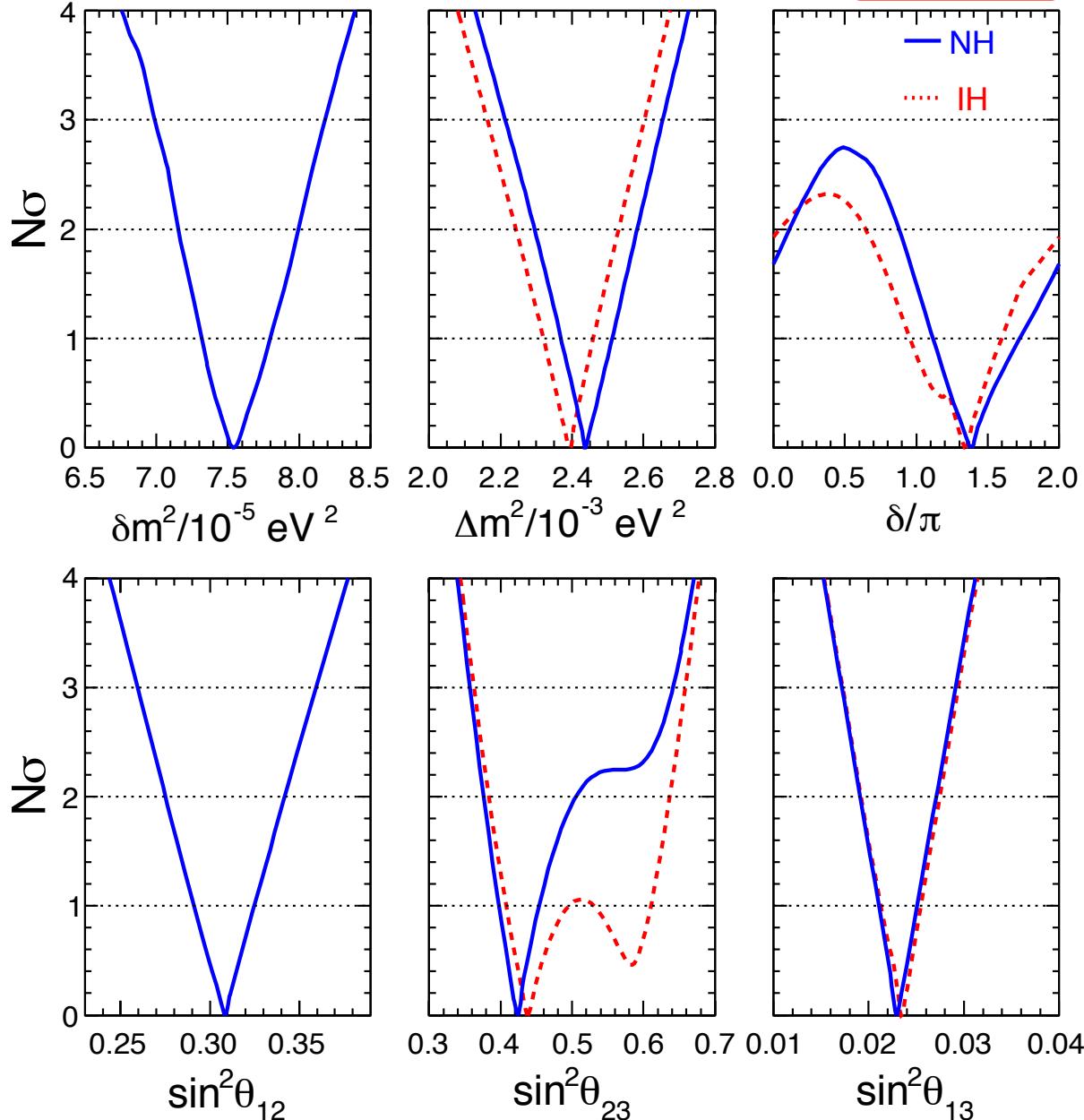


Strong, dominant  
 $\theta_{13}$  bounds

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

Preference for  
nonmaximal  $\theta_{23}$   
but octant flips  
with hierarchy

# LBL Acc + Solar + KL + SBL Reactors + SK Atm



Some effects on the  $\nu_\mu \rightarrow \nu_\tau$  dominant parameters ( $\Delta m^2, \theta_{23}$ )

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

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

# No ranges for single parameters (all data included):

TABLE I: Results of the global  $3\nu$  oscillation analysis, in terms of best-fit values and allowed 1, 2 and  $3\sigma$  ranges for the  $3\nu$  mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that  $\Delta m^2$  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  $\chi^2$  difference between IH and NH is insignificant ( $\Delta\chi^2_{\text{I-N}} = +0.3$ ).

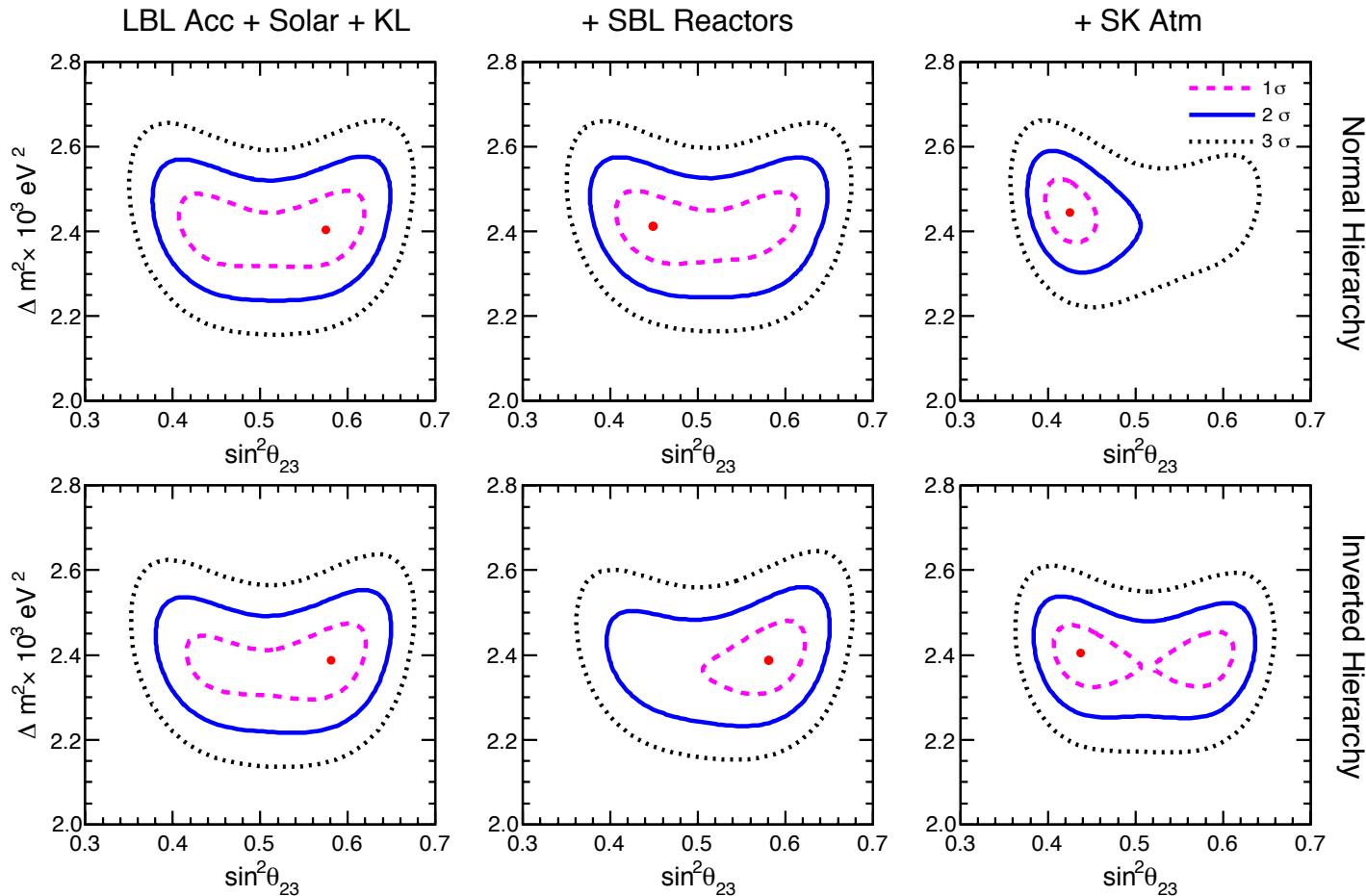
Parameter	Best fit	$1\sigma$ range	$2\sigma$ range	$3\sigma$ range
$\delta m^2/10^{-5} \text{ eV}^2$ (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2 \theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3} \text{ eV}^2$ (NH)	2.44	2.38 – 2.52	2.30 – 2.59	2.22 – 2.66
$\Delta m^2/10^{-3} \text{ eV}^2$ (IH)	2.40	2.33 – 2.47	2.25 – 2.54	2.17 – 2.61
$\sin^2 \theta_{13}/10^{-2}$ (NH)	2.34	2.16 – 2.56	1.97 – 2.76	1.77 – 2.97
$\sin^2 \theta_{13}/10^{-2}$ (IH)	2.39	2.18 – 2.60	1.98 – 2.80	1.78 – 3.00
$\sin^2 \theta_{23}/10^{-1}$ (NH)	4.25	3.98 – 4.54	3.76 – 5.06	3.57 – 6.41
$\sin^2 \theta_{23}/10^{-1}$ (IH)	4.37	4.08 – 4.96 $\oplus$ 5.31 – 6.10	3.84 – 6.37	3.63 – 6.59
$\delta/\pi$ (NH)	1.39	1.12 – 1.72	0.00 – 0.11 $\oplus$ 0.88 – 2.00	—
$\delta/\pi$ (IH)	1.35	0.96 – 1.59	0.00 – 0.04 $\oplus$ 0.65 – 2.00	—

Fractional uncertainties (defined as 1/6 of  $3\sigma$  ranges):

$\delta m^2$	2.6 %
$\Delta m^2$	3.0 %
$\sin^2 \theta_{12}$	5.4 %
$\sin^2 \theta_{13}$	8.5 %
$\sin^2 \theta_{23}$	~11 %

Selected parameter covariances →

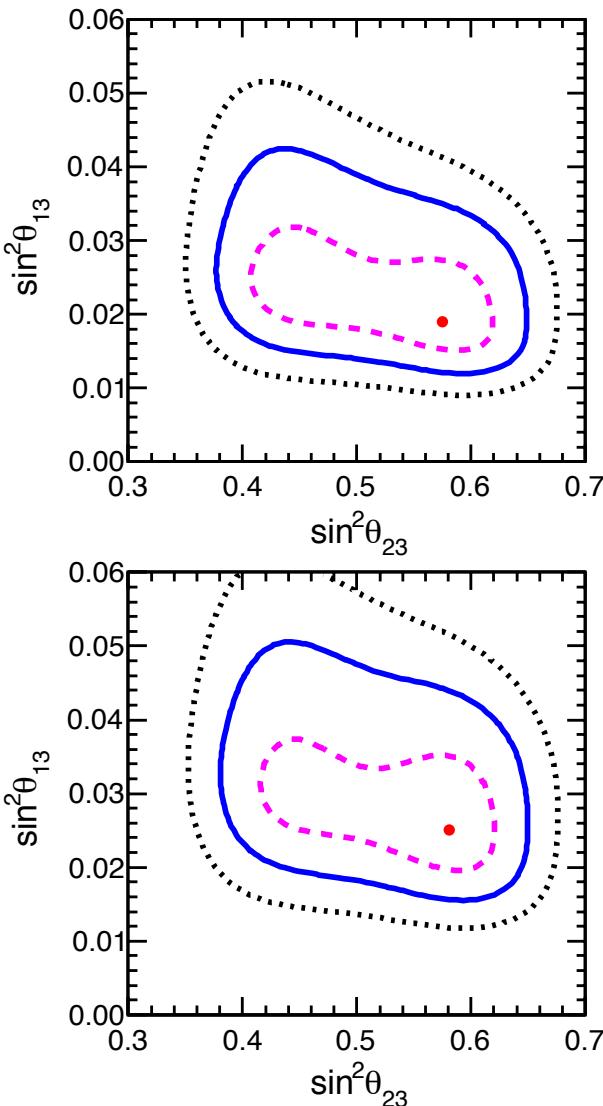
# The $\theta_{23}$ octant “flip” in a more familiar plane:



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

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

LBL Acc + Solar + KL



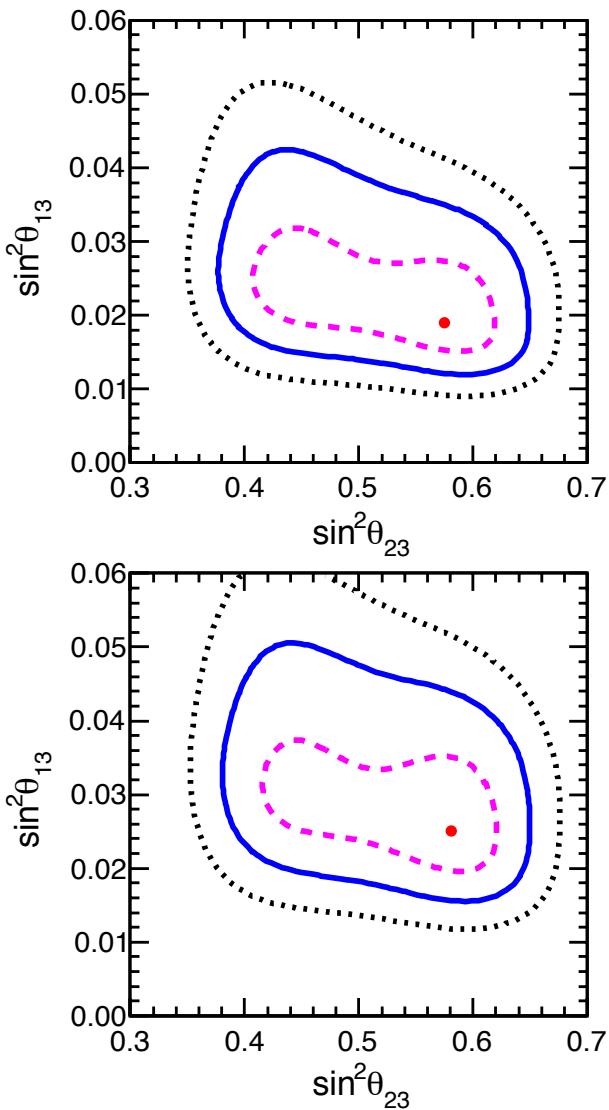
MINOS disappearance prefers nonmaximal mixing (and wins over T2K preference for  $\sim$ maximal)  $\rightarrow$  two degenerate minima for  $\theta_{23}$

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

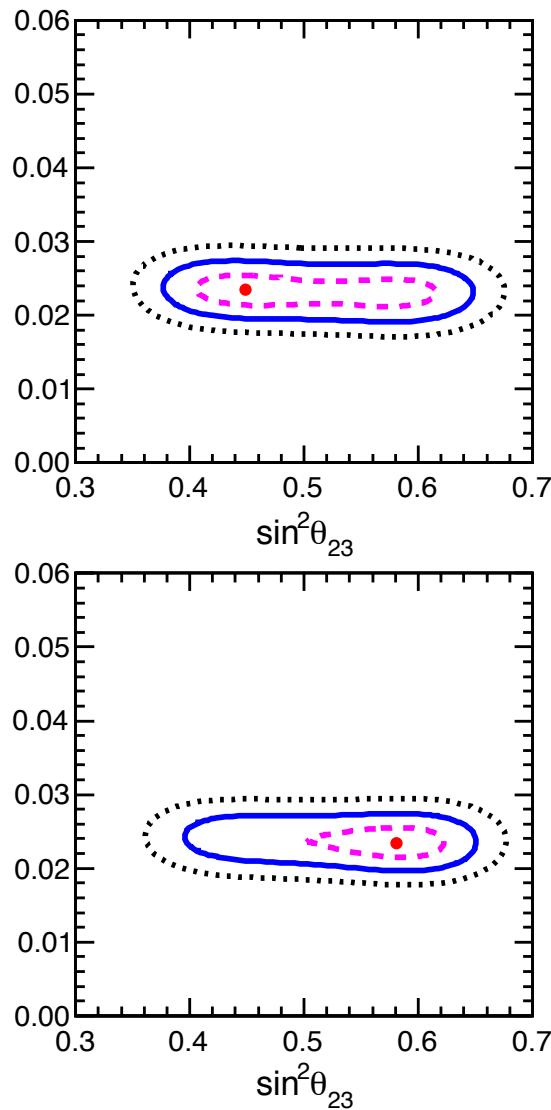
Contours extend to relatively high  $\sin^2 \theta_{13}$  to accommodate the relatively “strong” T2K appearance signal, especially in IH

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

LBL Acc + Solar + KL

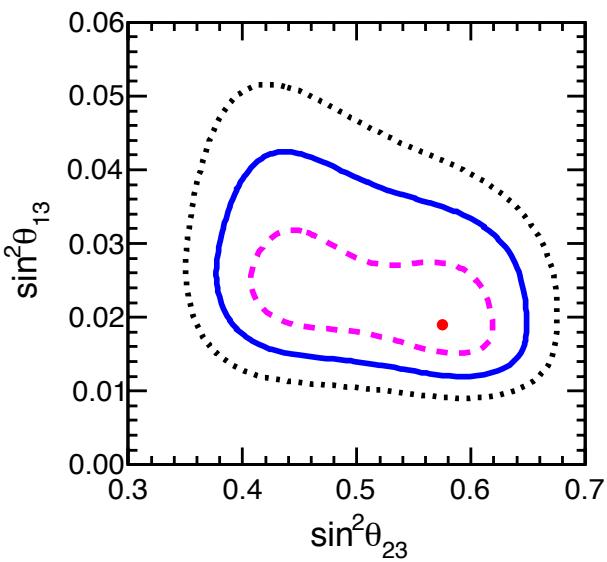


+ SBL Reactors

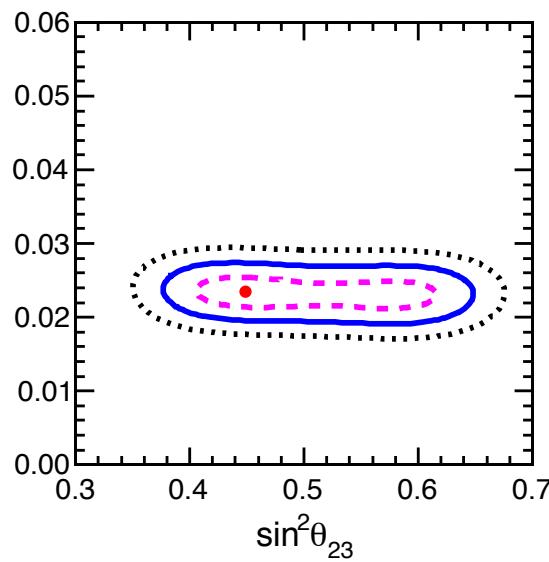


Reactor data prefer  $\sin^2\theta_{13} \sim 0.023$ , slightly higher than Solar+KL: enough to flip the octant in NH, but not enough to do so in IH.

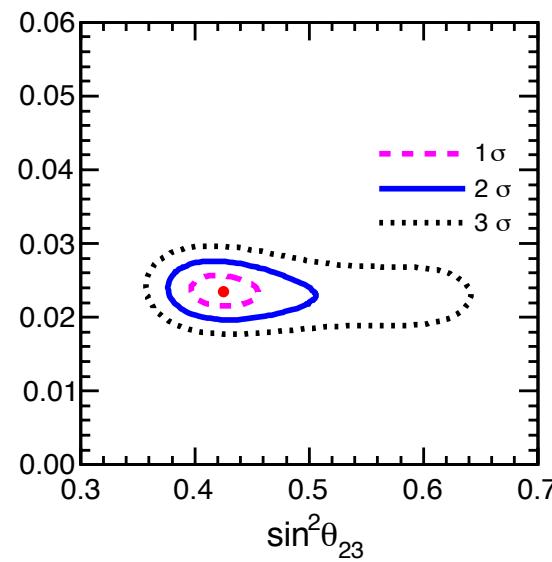
LBL Acc + Solar + KL



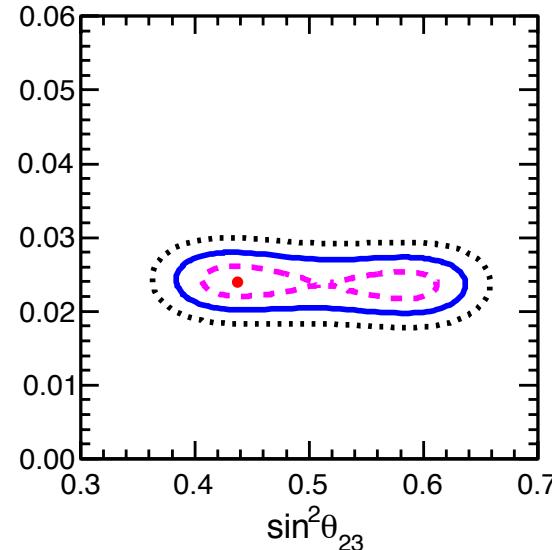
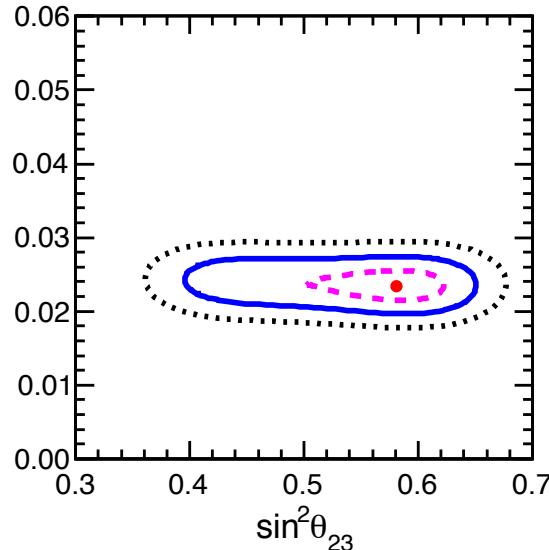
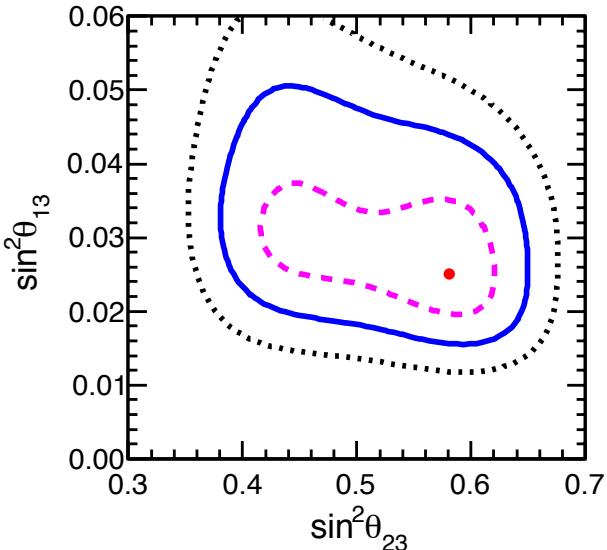
+ SBL Reactors



+ SK Atm



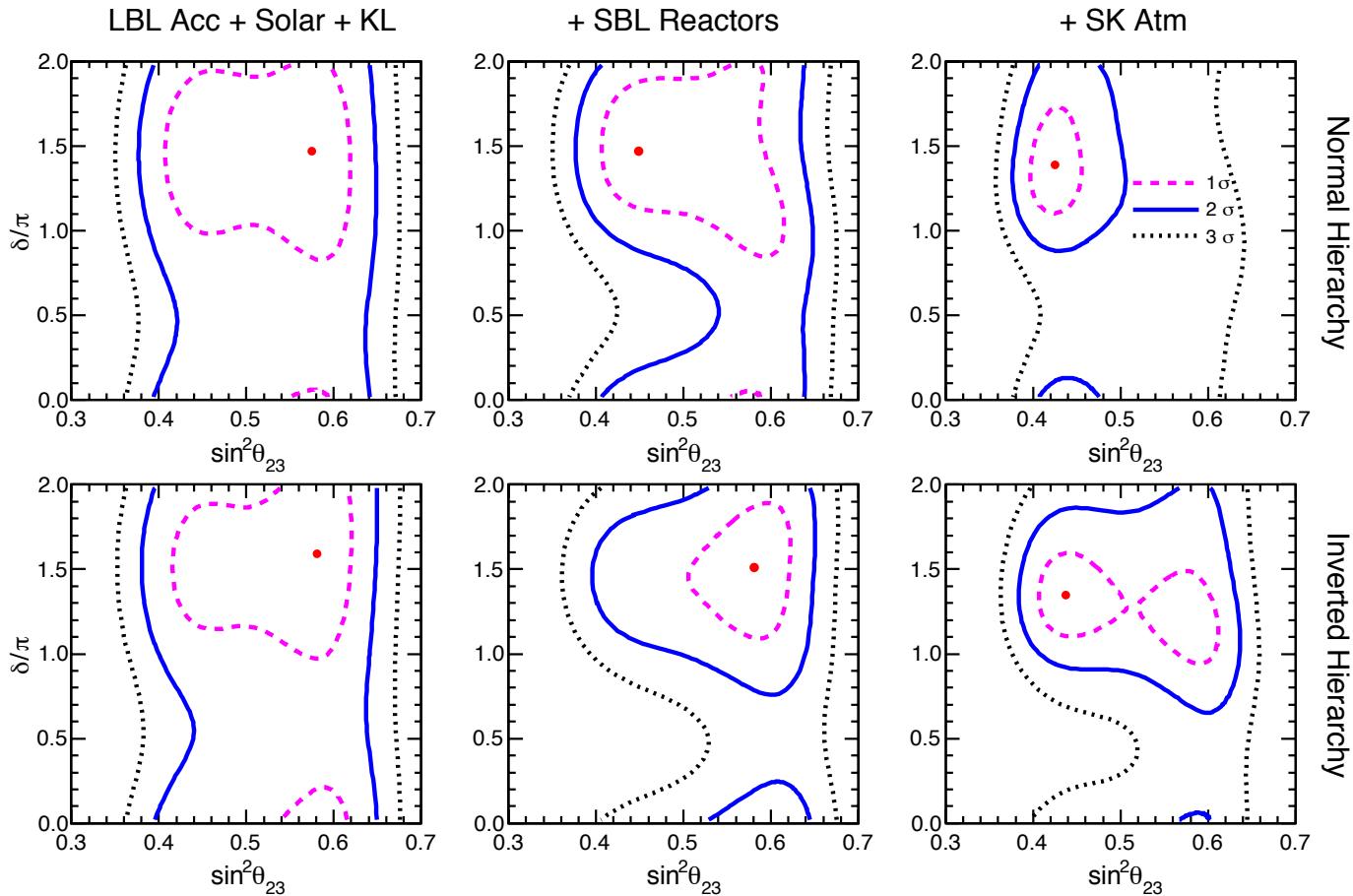
Normal Hierarchy



Inverted Hierarchy

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

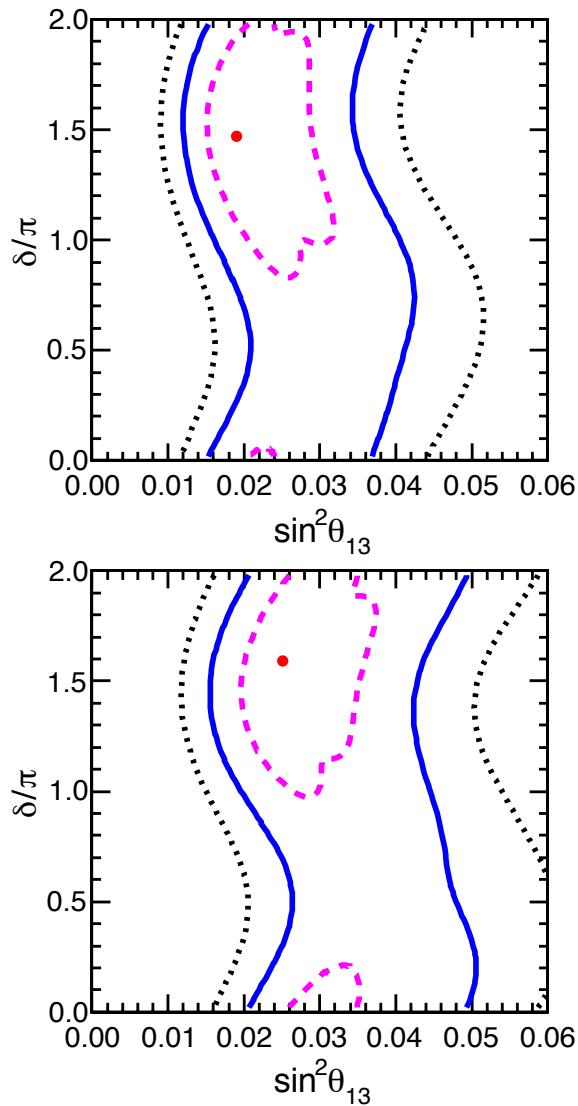
# Interpretation of $\delta \sim 1.4\pi$ preference ...



... easier by looking at  $(\delta, \theta_{13})$  correlations

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

## LBL Acc + Solar + KL



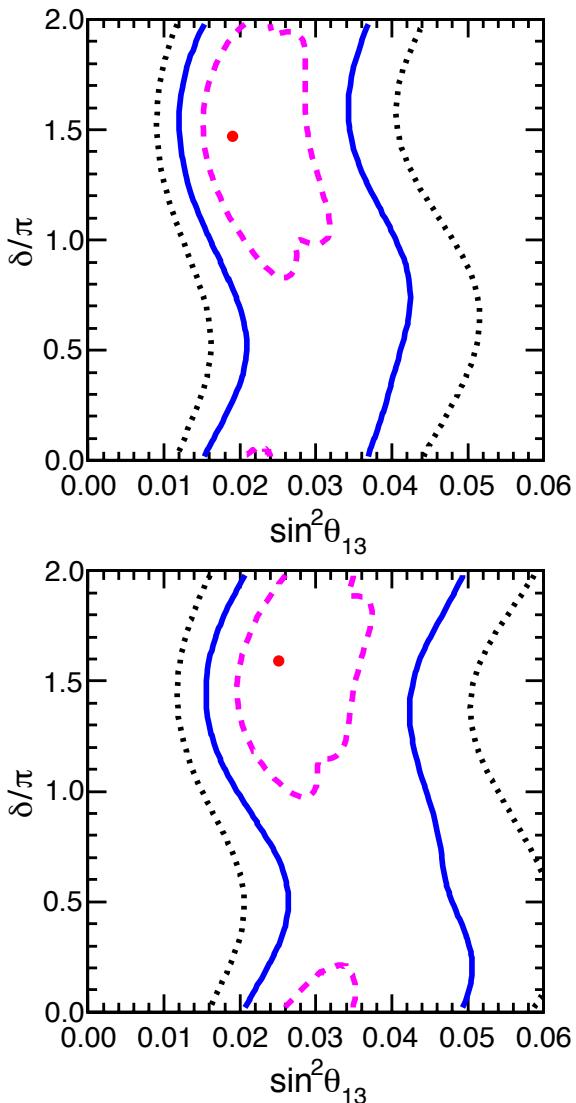
**Each wavy band is in part determined by superposition of “two bands” for the two  $\theta_{23}$  octants**

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

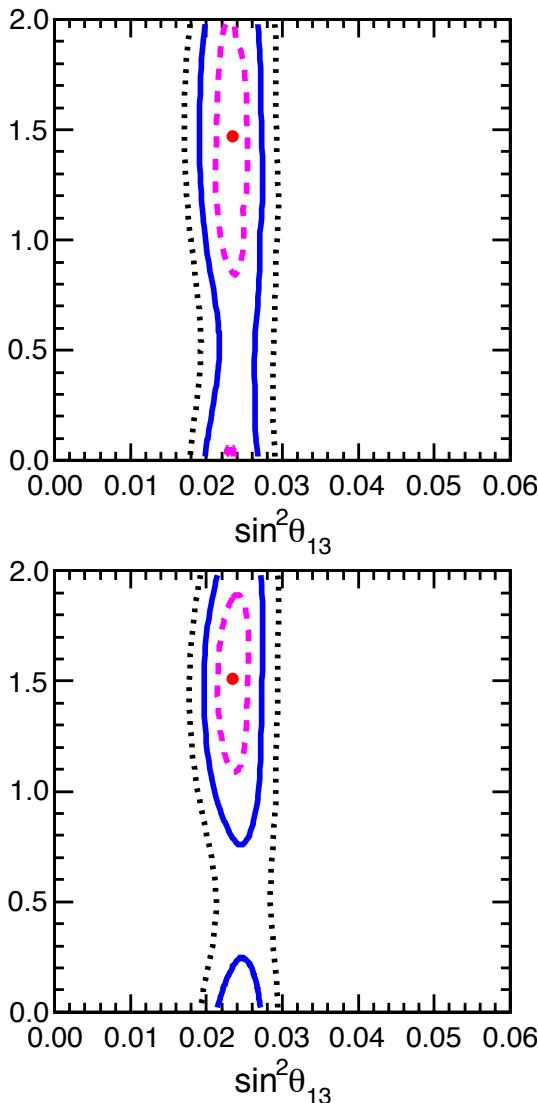
**Best agreement with relatively “strong” T2K appearance signal is for  $\delta/\pi \sim 1.5$ , irrespective of the hierarchy.**

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

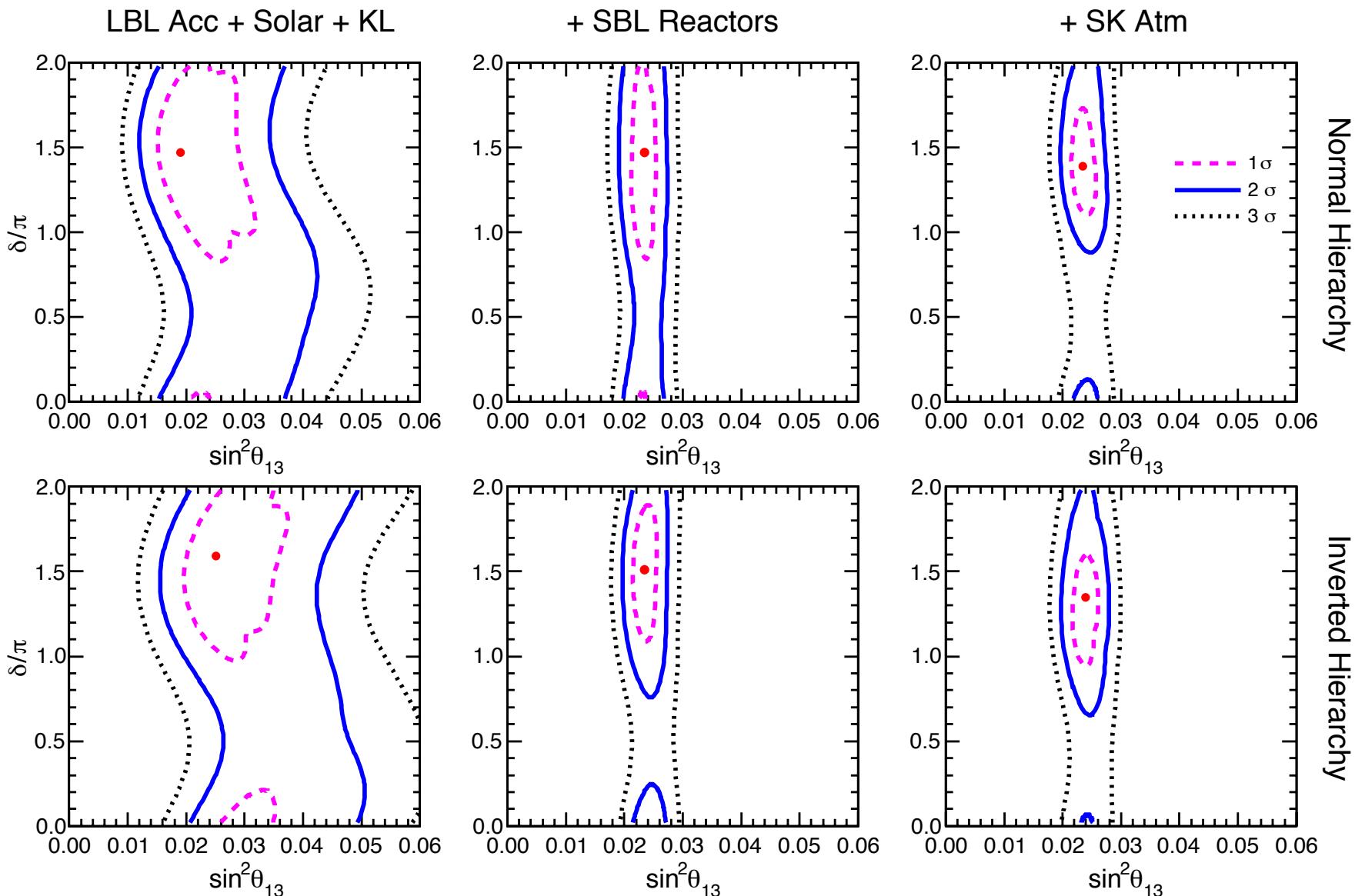
LBL Acc + Solar + KL



+ SBL Reactors



**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.

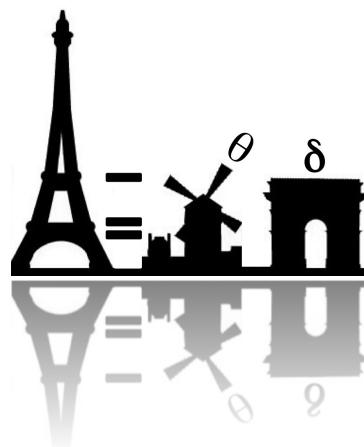
# What about NH vs IH?

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

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.

Unknowns: ...Recap →



LBL + Sol. + KL

+ SBL Reactor

+ SK Atmos.

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

-1.3



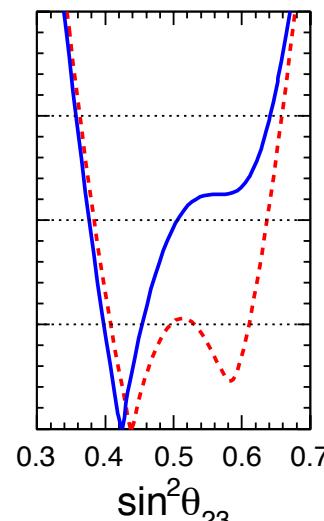
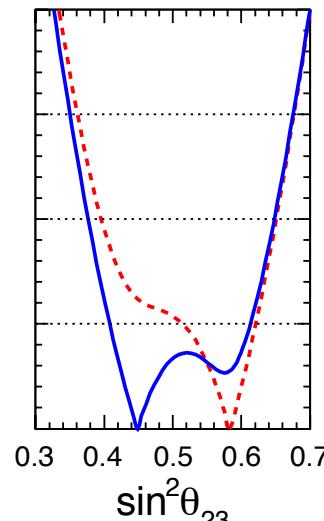
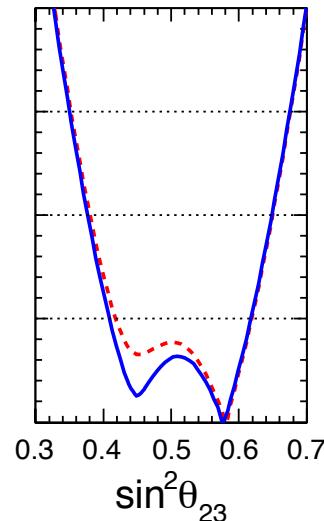
-1.4



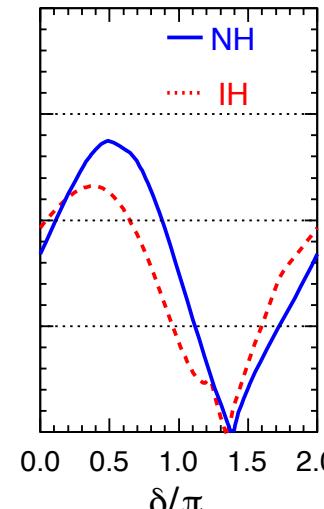
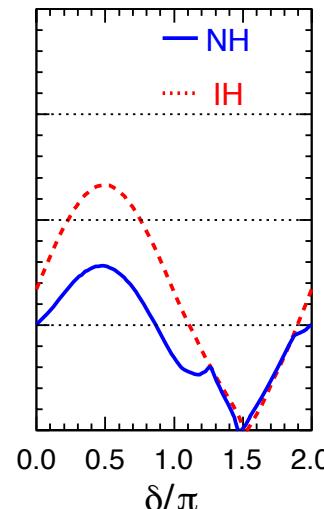
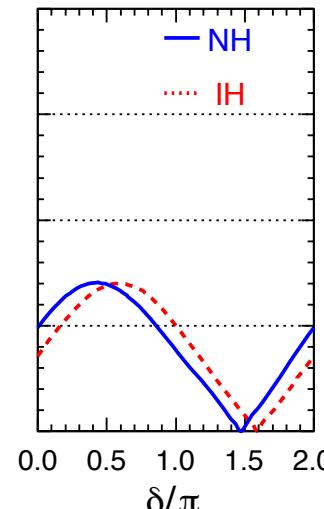
+0.3

No hint NH/IH

$\theta_{23}$



$\delta$

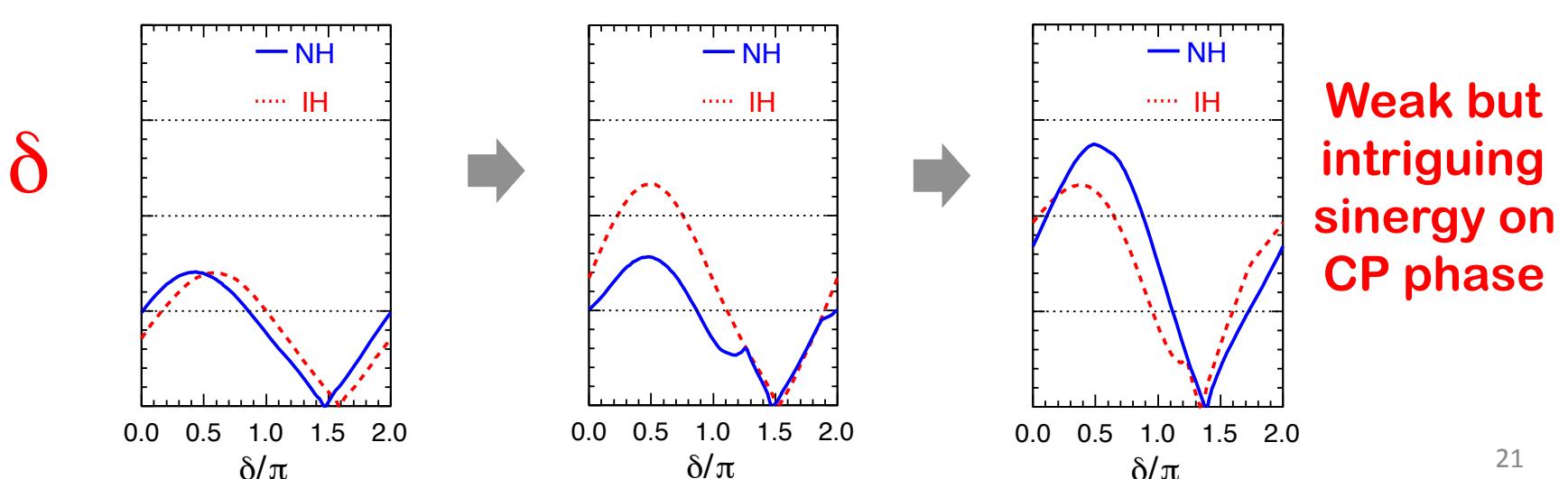


Preference  
for nonmax  
but  
apparent  
instability  
on octant

Weak but  
intriguing  
synergy on  
CP phase

Possible hint of  $\sim$ max CP violation,  $|\sin \delta| \approx 1$  ?

So far, nature has been kind with us ...



# CP violation requires genuine 3 $\nu$ oscillations, distinct from 2 $\nu$ limits...

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## TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

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Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation. CP requires  $\nu_\mu \leftrightarrow \nu_e$  and  $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$  oscillations to be equal. Time reversal invariance requires the oscillation probability to be an even function of time. Both conditions can be violated, even drastically, if more than two neutrinos exist.

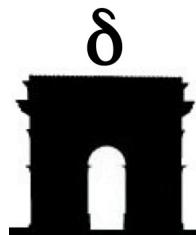


**CP violation requires genuine  $3\nu$  oscillations,  
distinct from  $2\nu$  limits...**

- 3 mixing angles should be nonvanishing** ✓
- 2 mass gaps should be nonvanishing** ✓
- 1 phase sine should be nonvanishing** ...

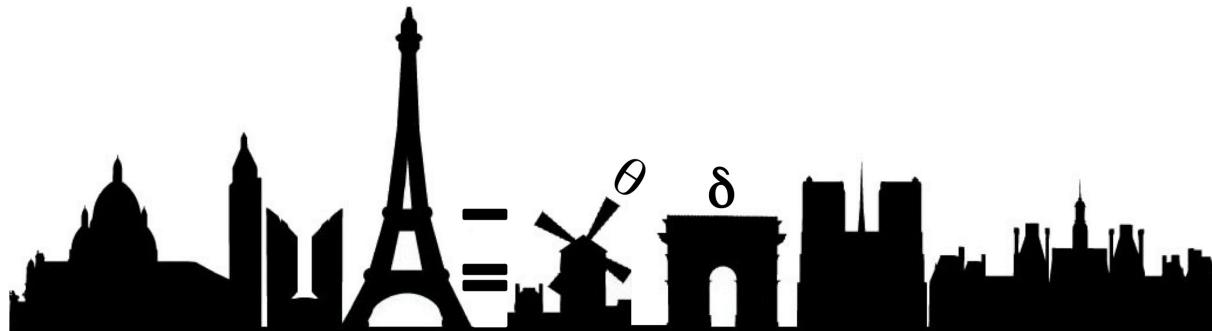
Nature has already provided us with 5  
favorable conditions at terrestrial scales ...

**Let us hope that the 6<sup>th</sup> is also realized !**



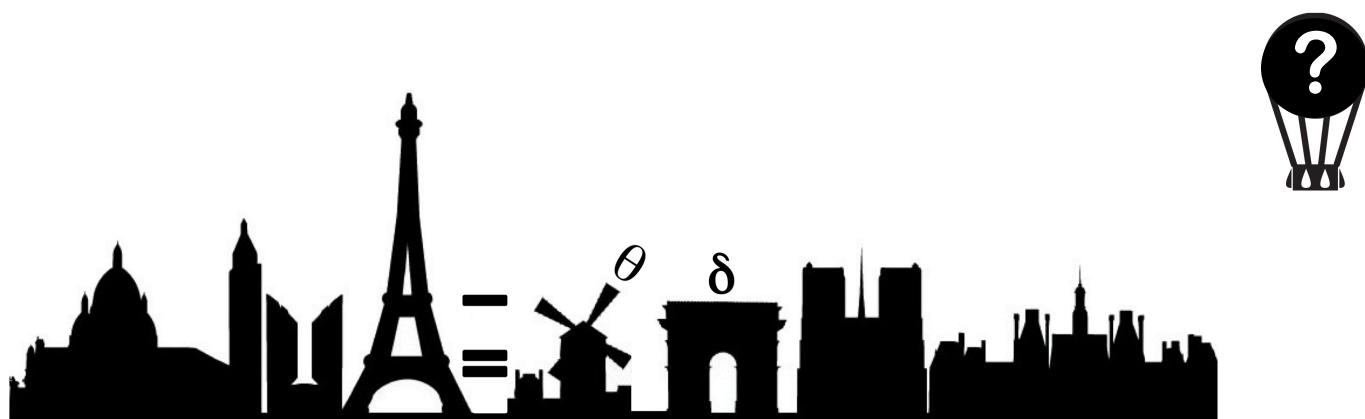
# Conclusions:

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 features. In this process, we should never forget that...



# Conclusions:

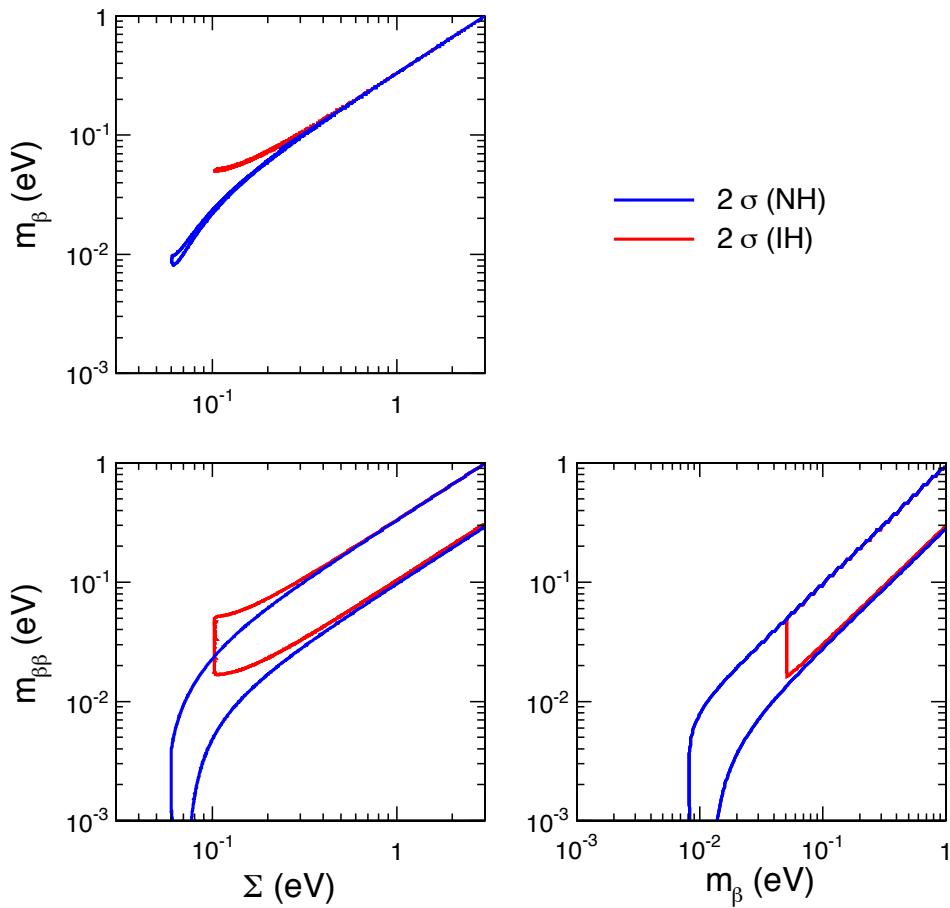
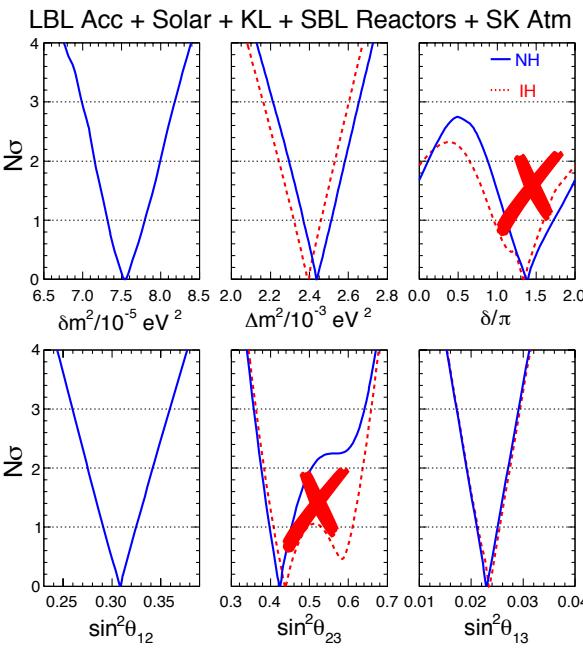
Beautiful neutrino experiments have sketched the current “**three-neutrino skyline**”, sometimes with amazing accuracy. But basic pieces, which may profoundly change the landscape, are still missing. In this context, global analyses may provide some guidance on emerging features. In this process, we should never forget that... **surprises may lead us towards new horizons!**



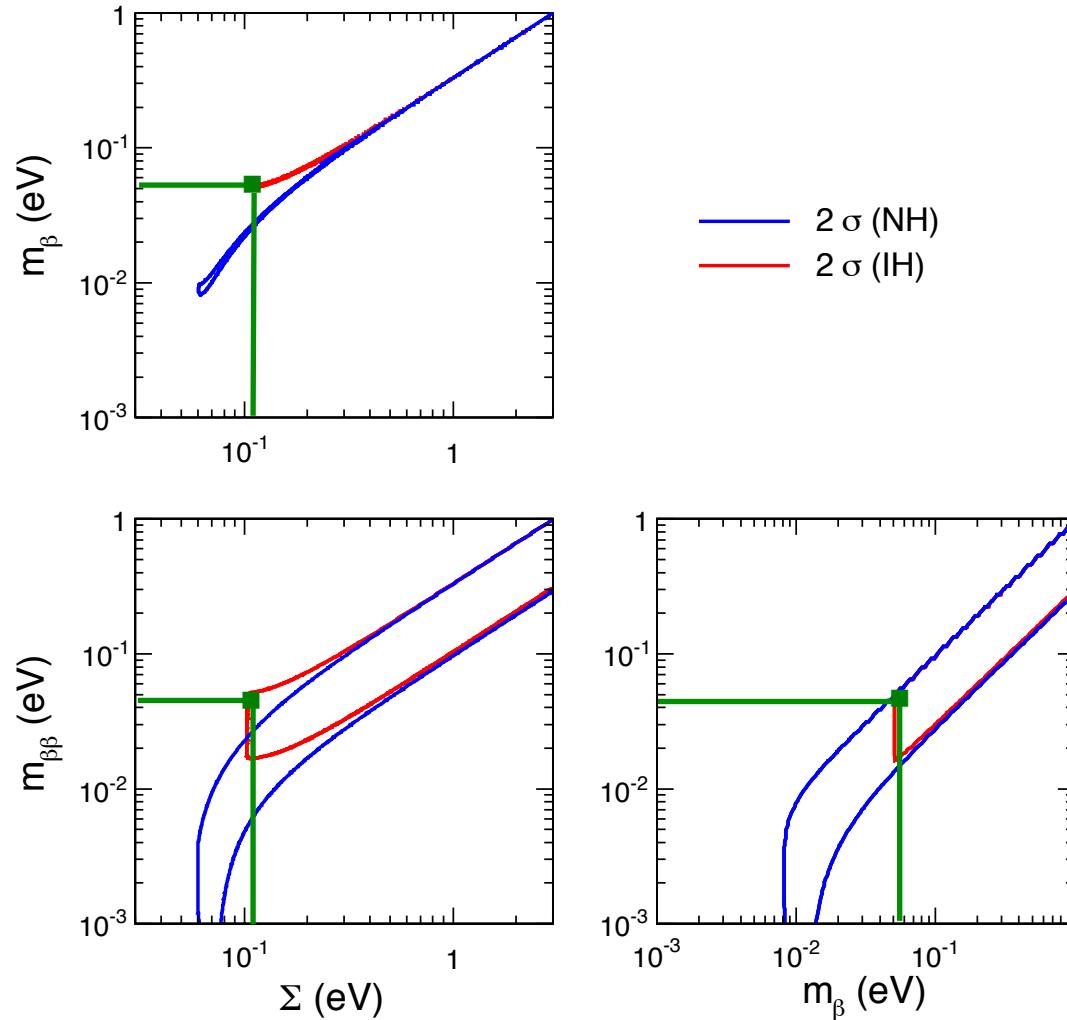
Thank you for your attention.

# Back-up slides

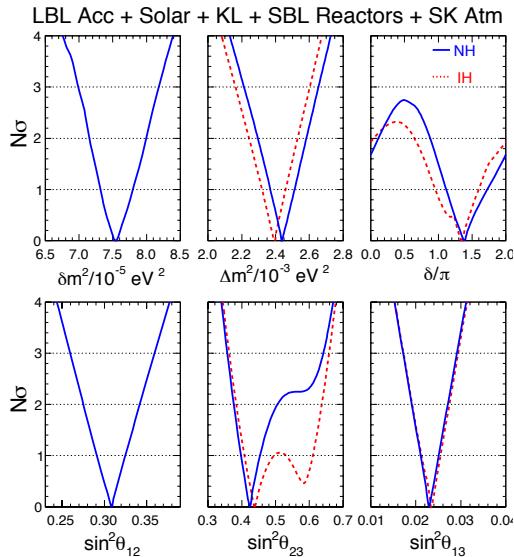
# Implications for absol. $\nu$ masses:



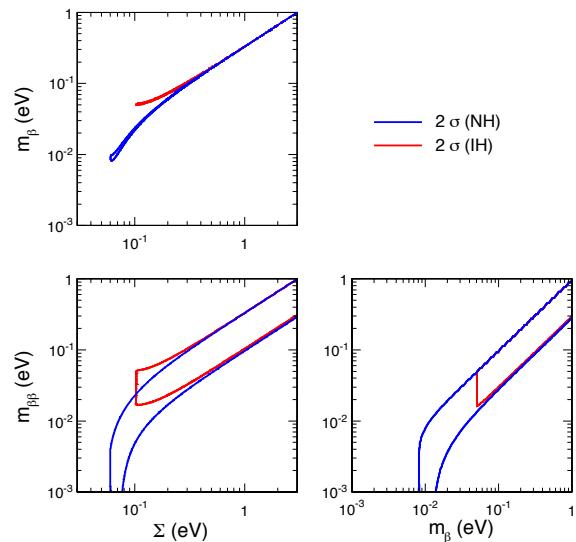
**Absolute  $\nu$  mass observables may provide an independent handle, or at least constraints, on NH vs IH discrimination. An ideal case:**



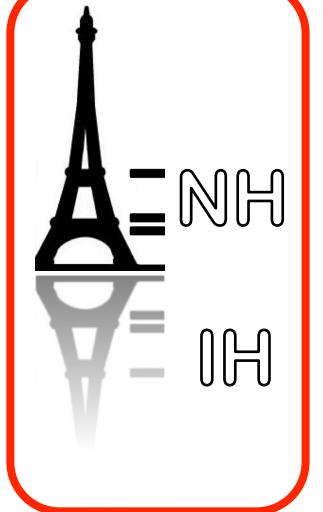
## Oscillation data



## Nonoscillation data

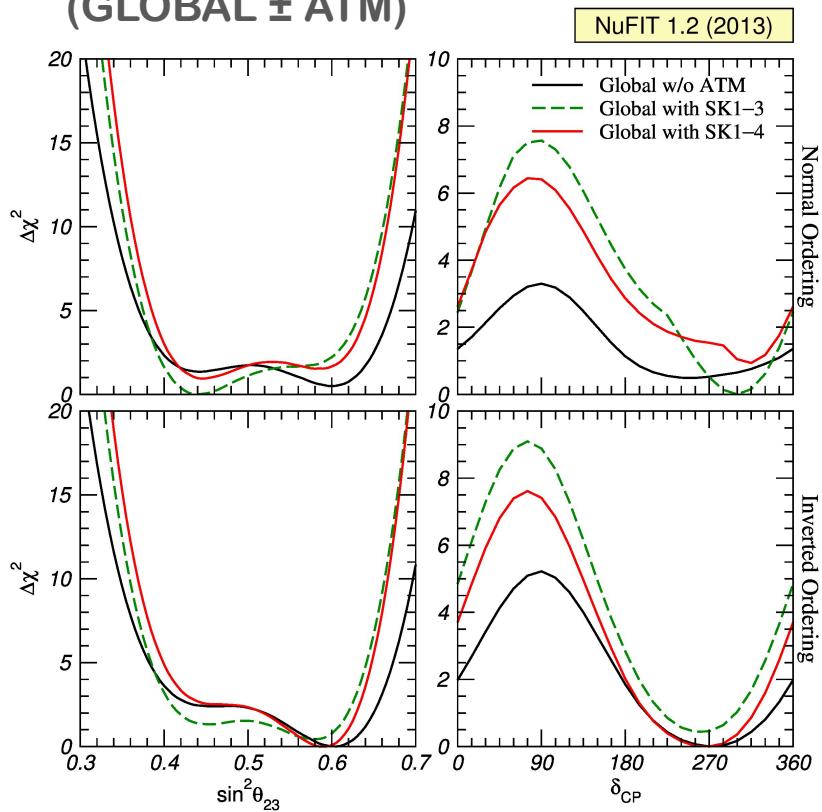


Sinergy

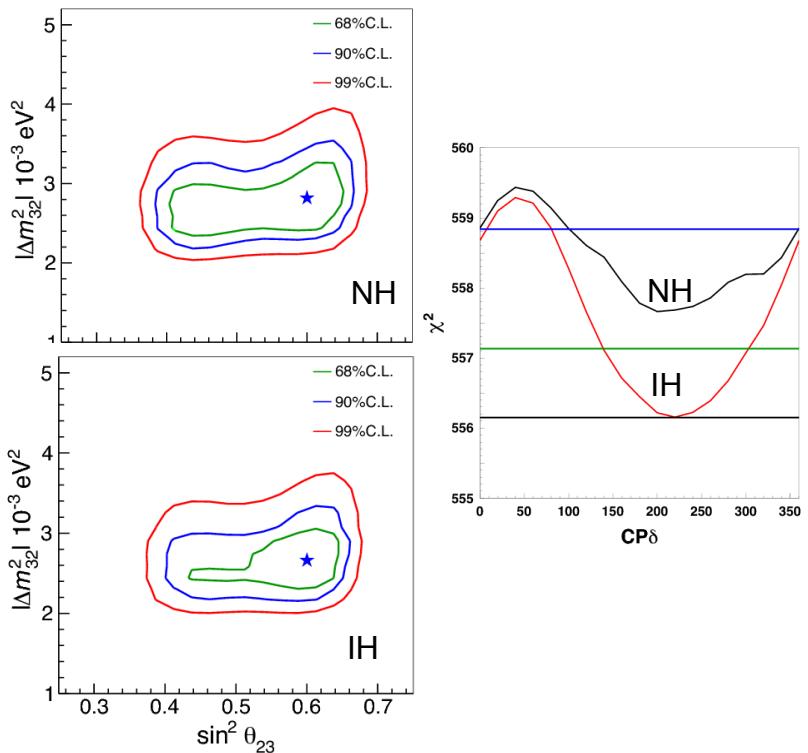


# Unknown parameters: comparison wrt ...

Gonzalez-Garcia et al. 2013  
(GLOBAL  $\pm$  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  $\sin\delta < 0$