European Strategy for Neutrino Oscillation Physics - II

14-16 May 2012 *CERN*
Europe/Zurich timezone

Neutrino Oscillations: a Phenomenological Overview

(A global analysis in the standard 3ν framework)

Gian Luigi Fogli

Outline

1. From first hints to evidence for $\theta_{13} \neq 0$
2. Status of 3ν oscillation parameters, one year ago (2011)
3. 3ν analysis: metodological issues
4. 2012 3ν results
   - 4.1 $(\theta_{13}, \theta_{23})$ correlations
   - 4.2 $(\theta_{13}, \delta_{CP})$ correlations
5. Conclusions

Mainly based on earlier work and work in progress done in collaboration with:
E. Lisi, A. Marrone, D. Montanino, A. Palazzo, A.M. Rotunno

1. From first hints to evidence for $\theta_{13} \neq 0$

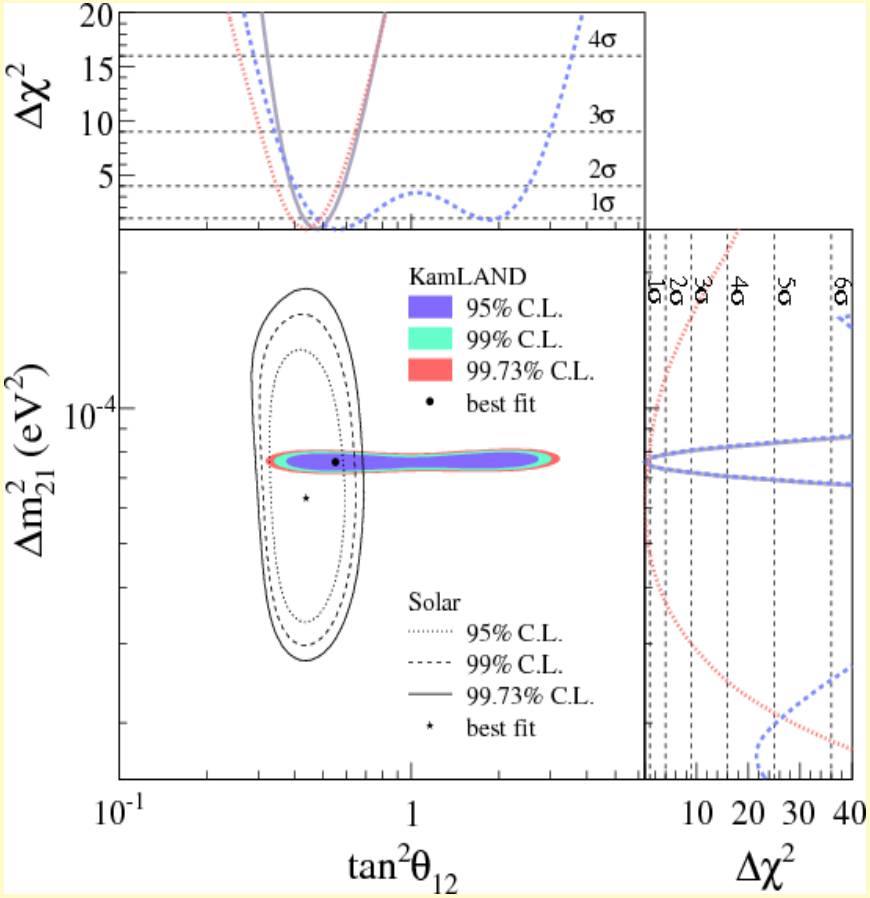
A few years ago (2008), after the presentation of the KamLAND spectral data: impressive agreement of solar and KamLAND constraints in 2ν analyses.

Agreement obtained assuming

$$\nu_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$$

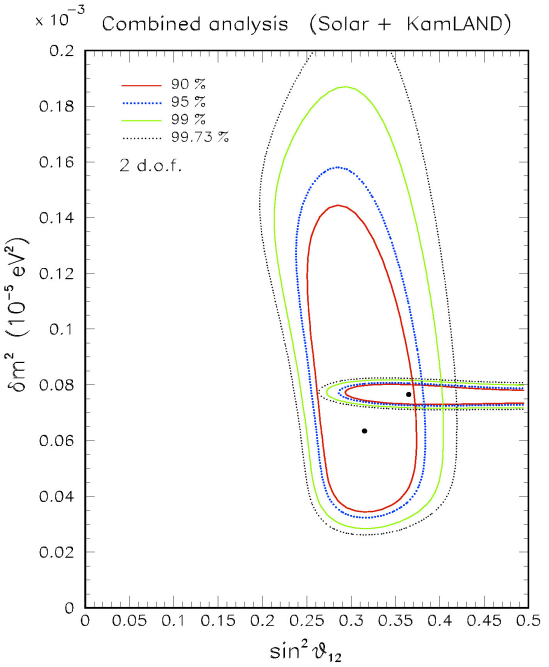
with a small, but acceptable, disagreement between the two best-fit points …

But one can learn more going beyond the 2ν approximation …

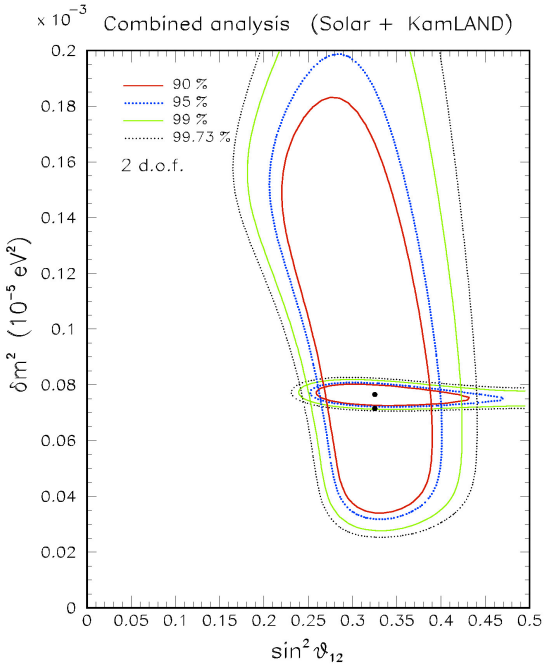


[figure taken from the official KamLAND site (2008)]

nonzero θ_{13} improves the convergence of the two data sets



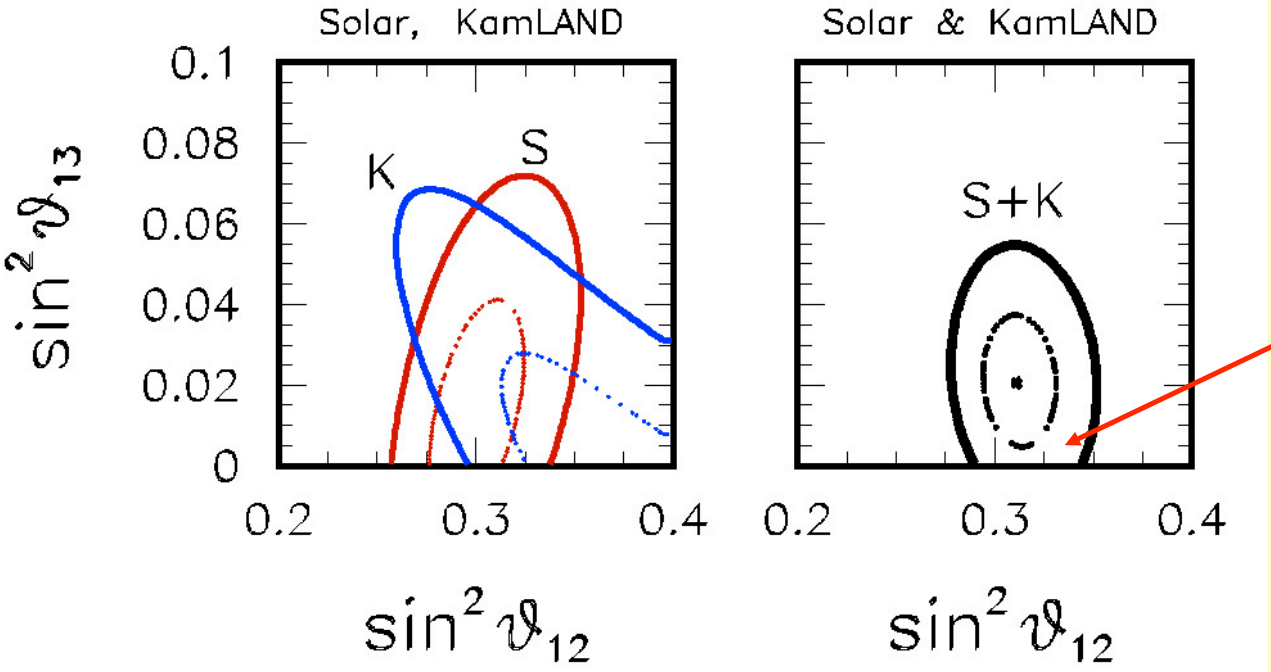
$\sin^2\theta_{13} = 0$



$\sin^2\theta_{13} = 0.03$

[GLF, Lisi, Marrone, Palazzo, Rotunno, Proc. of "NO-VE 2008"]
[Balantekin & Yilmaz, J.Phys. G 35, 075007 (2008), arXiv:0804.3345,]

The solar+KamLAND hint for $\theta_{13} > 0$ can be plotted in the plane of the two mixing angles, where the different correlations of the two datasets are more evident:



Best fit more than 1 sigma away from zero

$\sin^2\theta_{13} = 0.021 \pm 0.017$ (Solar + KamLAND)

Hint of ν_e as a superposition of three states (2008)

[GLF, Lisi, Marrone, Palazzo, Rotunno, PRL 101, 141801 (2008), hep-ph/0806.2649]

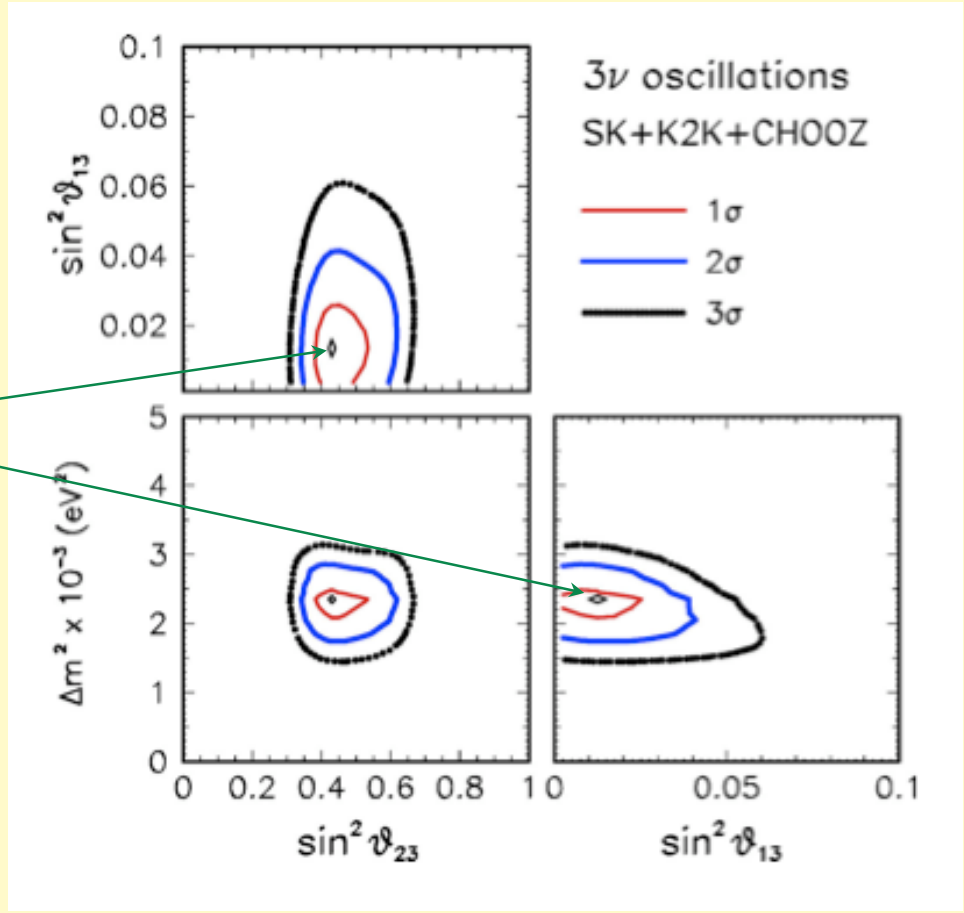
Note: even though statistically weak (~1.5 σ), this hint is quite "clean", as it involves very simple oscillation physics.

In addition, the solar + KL hint was consistent with a previous preference for $\theta_{13} > 0$, found from our 3ν analysis of atmospheric + LBL + Chooz data …

[GLF, Lisi, Marrone, Palazzo, Progr. Part. Nucl. Phys. 57, 742 (2006), hep-ph/0506083]

… mainly due to subleading "solar term" effects which help fitting atmospheric electron event data (especially sub-GeV).

best fit ~ 1 sigma away from zero

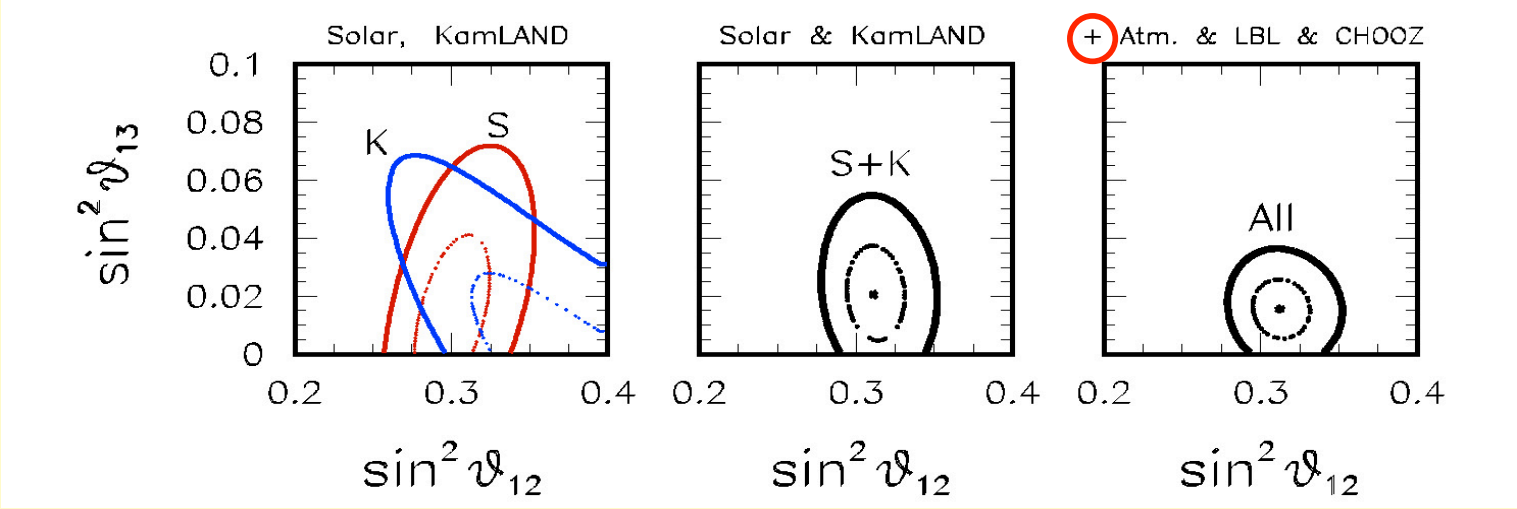


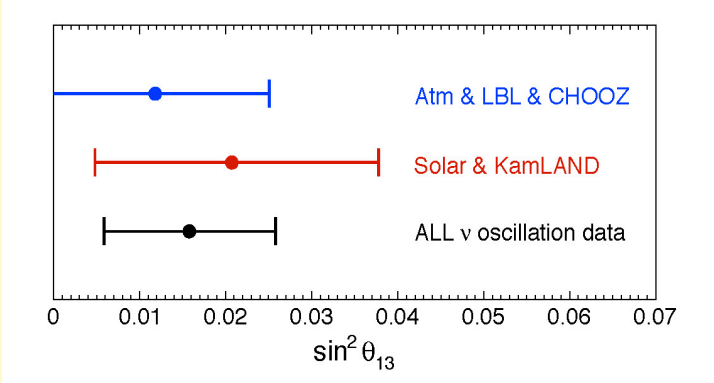
[However, atmospheric ν physics and data analysis are admittedly more involved; statistical significance of the atmospheric hint somewhat debated in the literature.]

Our summary in 2008 …

"Hints of $\theta_{13} > 0$ from global neutrino data analysis"

[GLF, Lisi, Marrone, Palazzo, Rotunno, PRL 101, 141801 (2008), hep-ph/0806.2649]





Hint significance: 90% C.L.

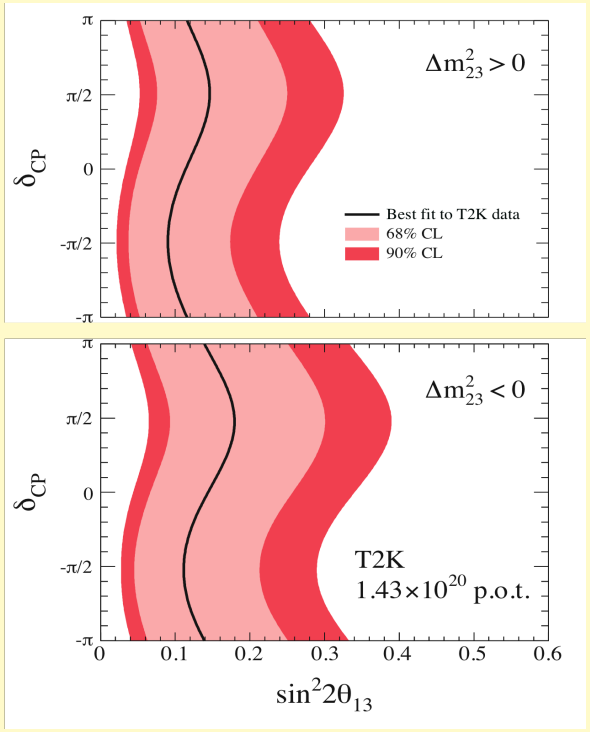
$\sin^2\theta_{13} = 0.016 \pm 0.010$

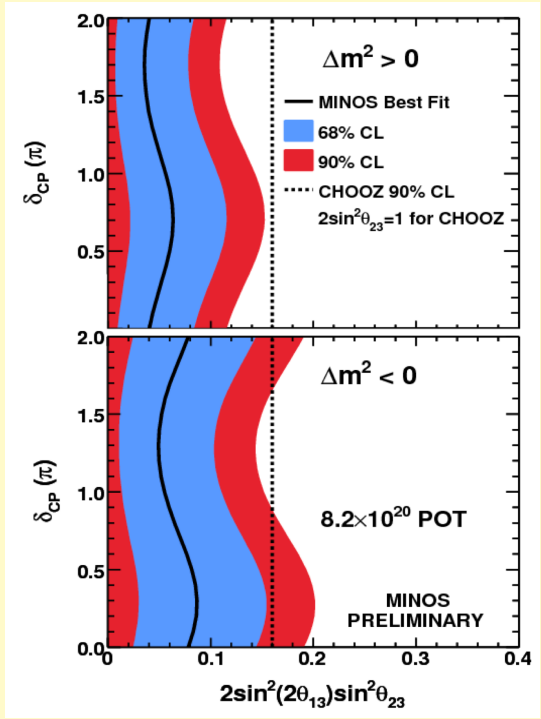
Large literature and debate 2008-2011!

June 2011 breakthrough: new T2K and MINOS appearance results

Both experiments favor $\sin^2\theta_{13}$ ~ few % !

T2K



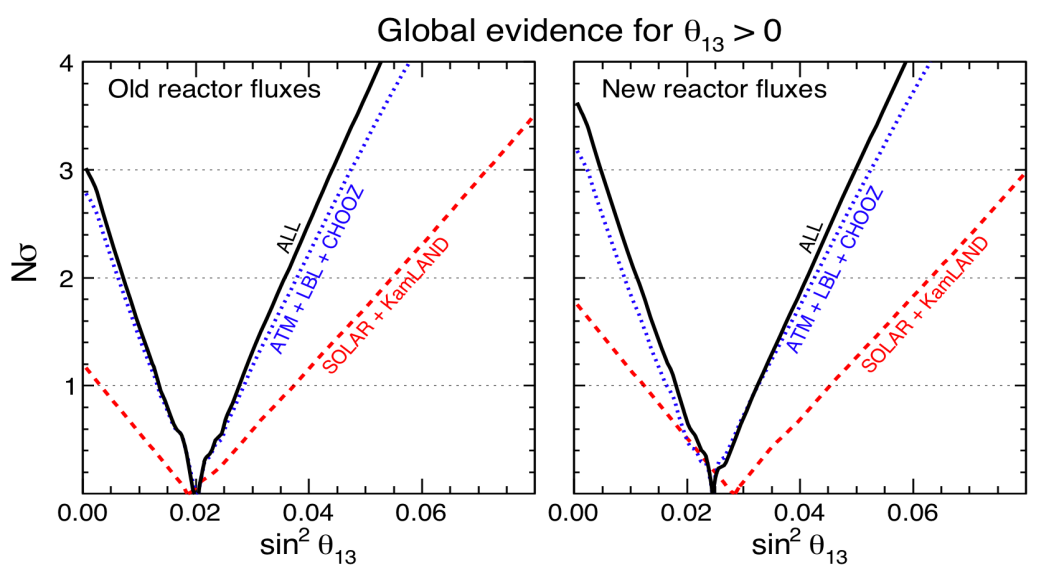


MINOS

So, it makes sense to combine these with all the other oscillation data …

2011 data: "Evidence of $\theta_{13} > 0$ from global neutrino data analysis"

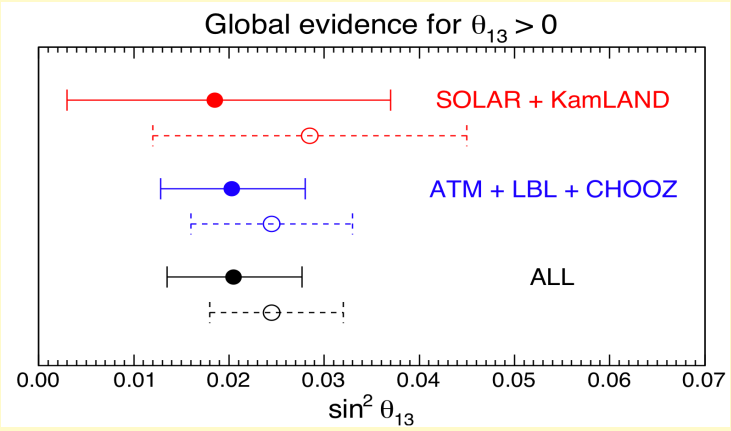
[GLF, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028]



Note:

ATM + LBL + CHOOZ
now more significant that
Solar + KamLAND

Very good agreement of two totally independent sets of data on $\sin^2\theta_{13}$

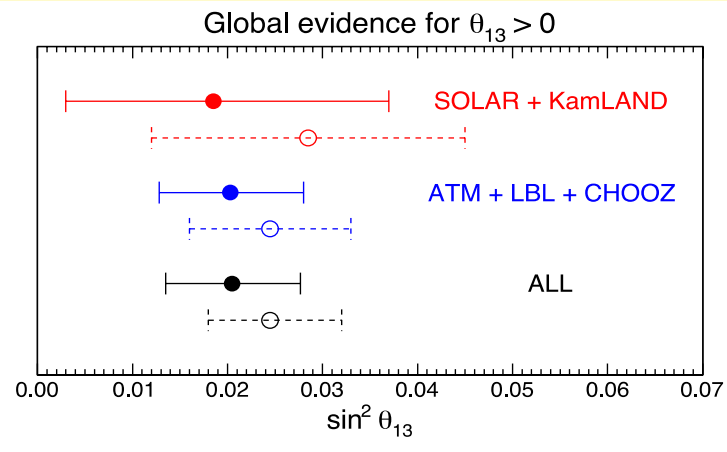


$\sin^2\theta_{13} = 0.021 \pm 0.007$ ("old" reactor fluxes)

$\sin^2\theta_{13} = 0.025 \pm 0.007$ ("new" reactor fluxes)

In conclusion, evidence for $\sin^2\theta_{13} > 0$ at $> 3\sigma$
(with small changes for new/old reactor fluxes assumed in the fit)

Comparing 2011 evidence for $\sin^2\theta_{13} > 0$ ...



$\sin^2\theta_{13} = 0.021 \pm 0.007$ (old reactor fluxes)

$\sin^2\theta_{13} = 0.025 \pm 0.007$ (new reactor fluxes)

... with new (2012) SBL reactor data:

Double Chooz (far detector): $\sin^2\theta_{13} = 0.022 \pm 0.013$

Daya Bay (near + far detectors): $\sin^2\theta_{13} = 0.024 \pm 0.004$

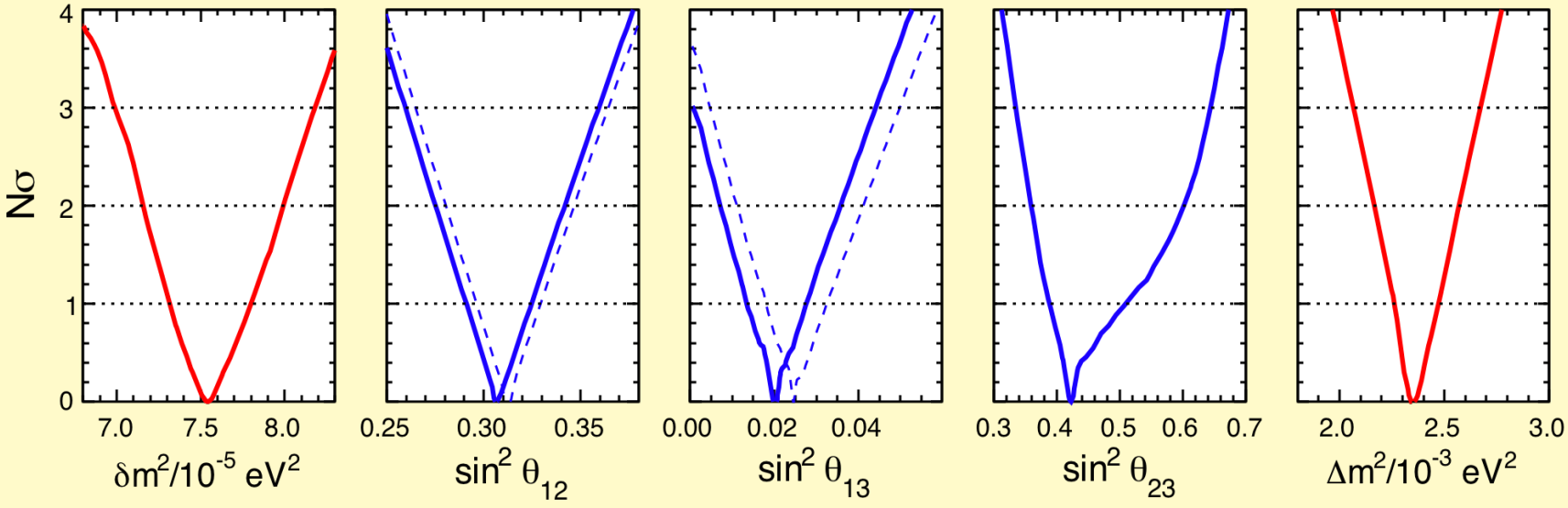
RENO (near + far detectors): $\sin^2\theta_{13} = 0.029 \pm 0.006$

we find a spectacular agreement!

2. Status of 3ν oscillation parameters, one year ago (2011)

Global data analysis in terms of $N\sigma = \sqrt{\Delta\chi^2}$

(the more linear and symmetric, the more gaussian errors)



"small" δm^2 ("solar" ν)

mixing angles θ_{12}, θ_{13}, θ_{23}

"large" Δm^2 ("atmospheric" ν)

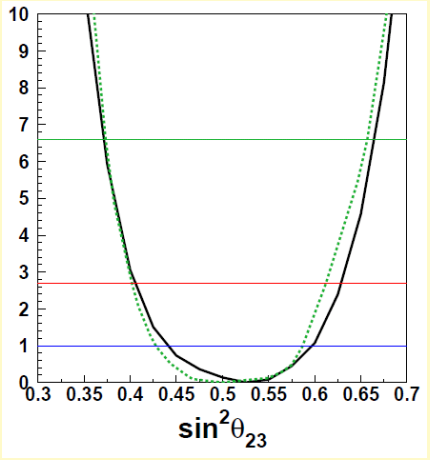
[G.L.F., E. Lisi, A. Marrone, A. Rotunno, A. Palazzo, "Evidence of $\theta_{13} > 0$ from global neutrino data analysis", Phys. Rev. D84 (2011) 053007, arXiv:1106.6028v2]

Still open problems (2011), apart from δ_{CP} …

1. 3ν mass-mixing hierarchy: sign($\pm\Delta m^2$) → no hints so far

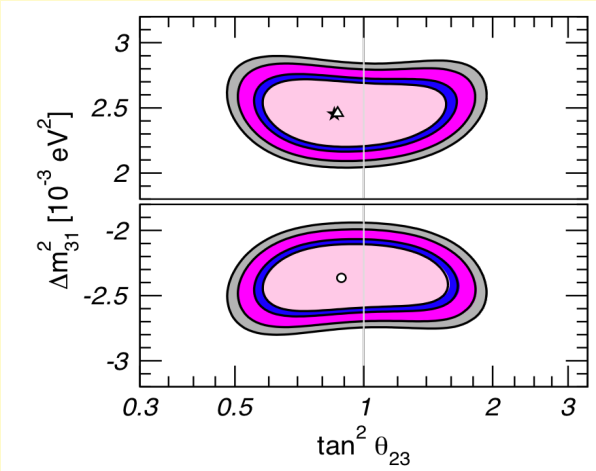
2. $\sin^2\theta_{23}$: ν_μ-ν_τ mixing, maximal or not ? → a few hints …

SK@Neutrino2010



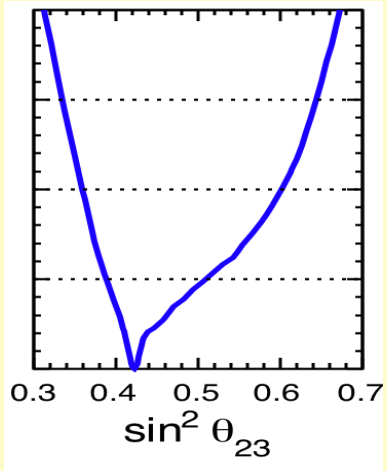
Nearly maximal…

Gonzalez-Garcia et al. 2010



Slightly nonmaximal…

Our analysis, 2011

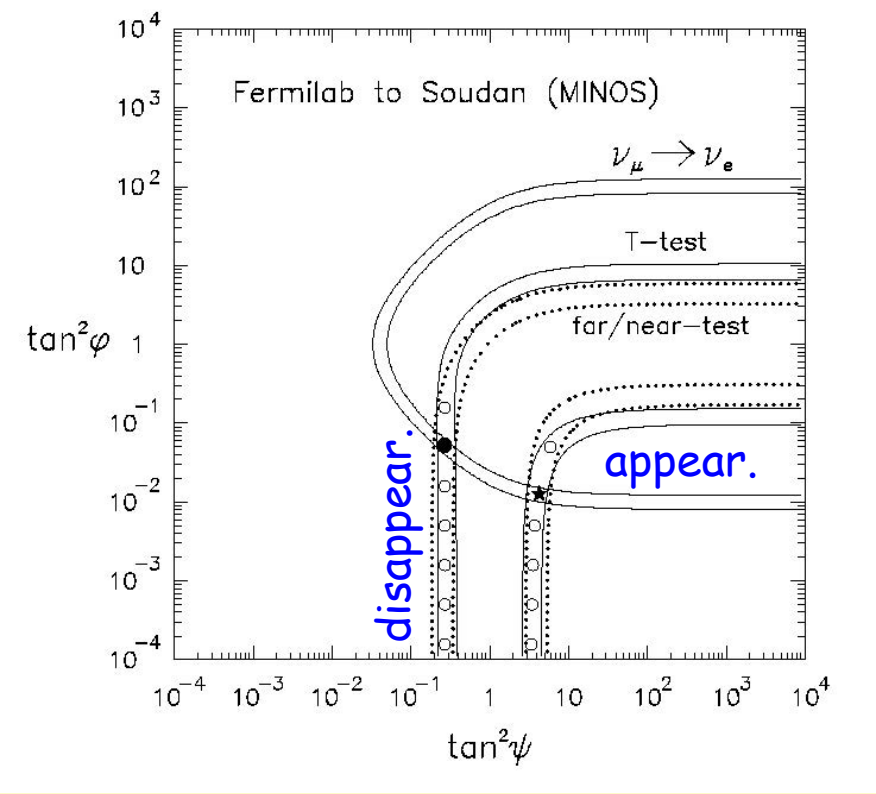


Slightly more nonmaximal…

It includes now SK I+II+III data with both $\theta_{13} \neq 0$ and $\delta m^2 \neq 0$

3. 3ν analysis: methodological issues

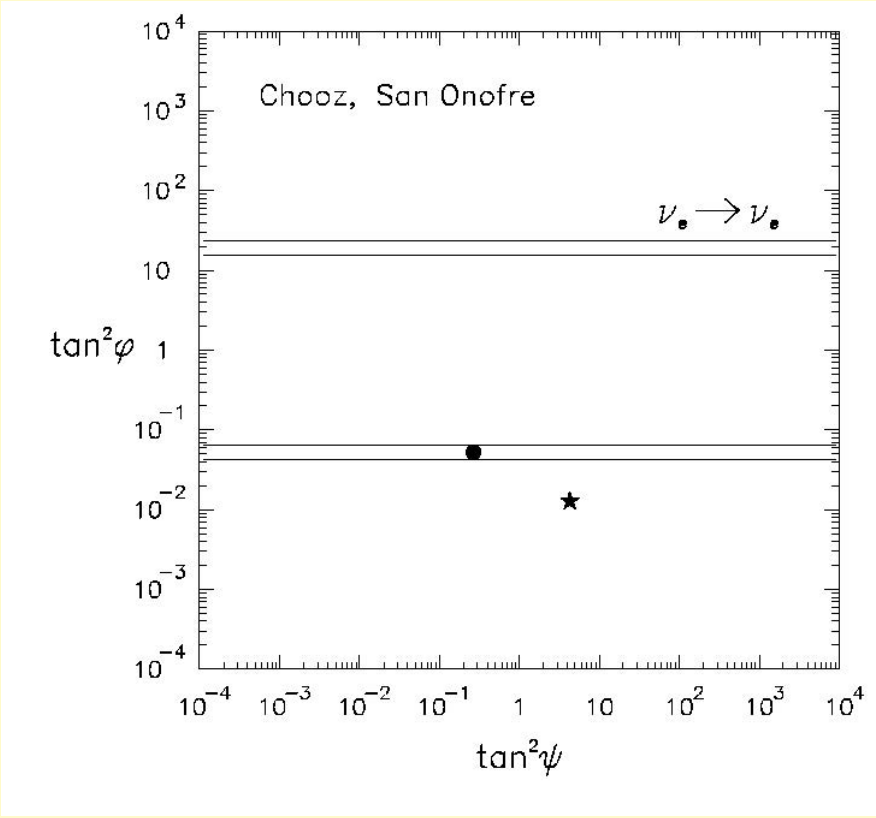
There is an interesting interplay between LBL appearance + disappearance data, SBL reactor data, and octant degeneracy, as pointed out long ago
[GLF & Lisi, Phys. Rev. D54 (1996) 3667, hep-ph/9604415]



(1)

For (slightly) non-maximal mixing, LBL app. + disapp. data give rise to two quasi-degenerate solutions with a (slight) anticorrelation between θ_{13} and θ_{23}.

[In our 1996 notation: $\varphi = \theta_{13}$, $\psi = \theta_{23}$]



2

On the other hand, SBL reactor data, or any other constraint on θ_{13} (eg, solar + KamLAND), may "select" or at least "prefer" one of the two solutions, lifting (part of) the degeneracy.

As we shall see in a moment, this hypothetical 1996 scenario seems to emerge from 2012 data …

… even though only at the level of hints!

This interplay is simply an effect of 3ν oscillation physics.

In first approximation, Δm^2-driven vacuum oscillation probabilities are generalized as (2ν → 3ν):

$$P_{\alpha\beta} \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \longrightarrow P_{\alpha\beta} \simeq 4|U_{\alpha 3}|^2|U_{\beta 3}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

$$P_{\alpha\alpha} \simeq 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \longrightarrow P_{\alpha\alpha} \simeq 1 - 4|U_{\alpha 3}|^2(1 - |U_{\alpha 3}|^2) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

LBL appearance: $P_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2(\Delta m^2 L/4E_\nu)$ + corrections

NOT octant symmetric, anticorrelates θ_{23} and θ_{13}: the lower θ_{23}, the higher θ_{13}

SBL reactors: $P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2 L/4E_\nu)$ + corrections

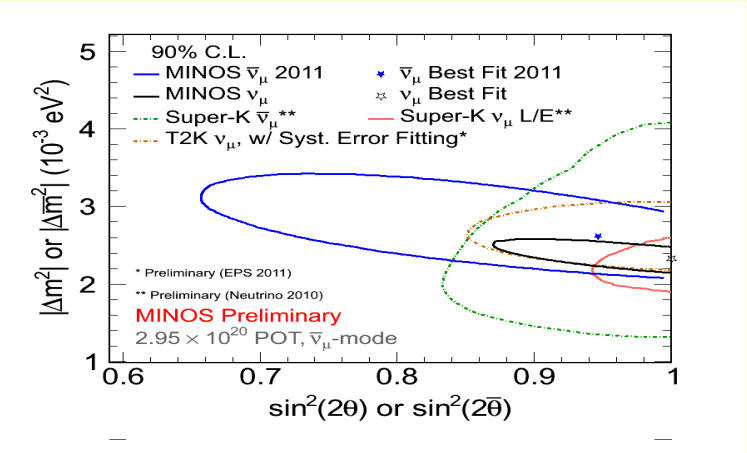
So, they may distinguish "high" from "low" θ_{13}

→ 3ν combination of LBL accelerator and SBL reactor data may already provide some slight preference for one θ_{23} octant versus the other.

In order to reveal a similar effect, one needs a full 3ν analysis of LBL accelerator data (appearance + disappearance).

In particular it is important that T2K & MINOS abandon their (no longer defensible) 2ν approximation in disappearance mode:

OBSOLETE! ⟶



We suggest:

On the x-axis, put $\sin^2\theta_{23}$, NOT $\sin^2 2\theta_{23}$

On the y-axis, put some 3ν (NOT 2ν) definition of Δm^2

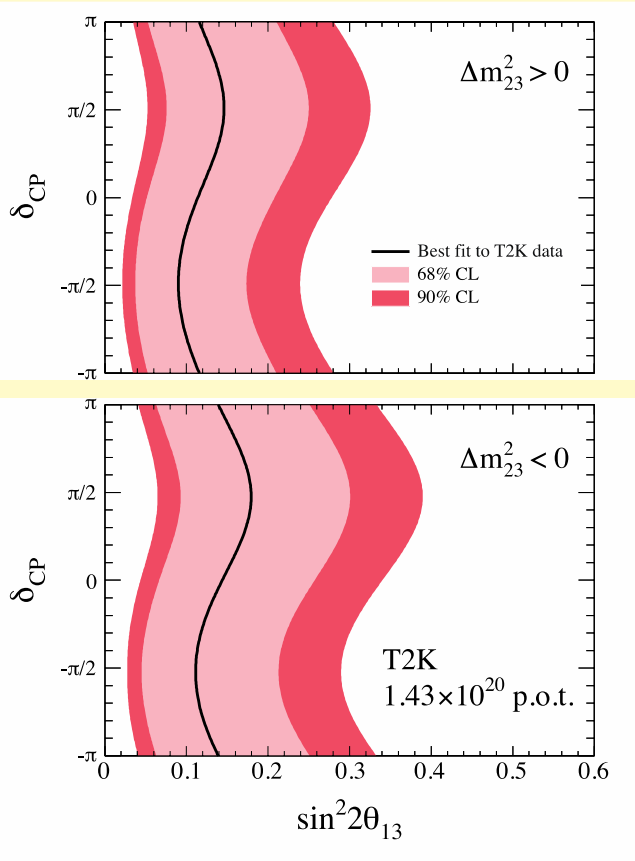
We use:

$$\Delta m^2 = \frac{1}{2}(\Delta m^2_{31} + \Delta m^2_{32})$$

in both normal and inverted hierarchy (the sign just flips)

… it is also important that T2K and MINOS combine their own disappearance + appearance data in a "full-fledged" 3ν analysis without approximation or assumption a priori.

T2K



These LBL contours may be shifted to the left (right) for higher (lower) θ_{23}, due to the anti-correlation effect seen before …

… this introduces obvious consequences for the comparison with θ_{23}-independent SBL reactor data

Suggestion: never assume maximal mixing a priori, let the data decide!

A final "methodological note" before presenting our updated 2012 analysis:

We prefer to group LBL accelerator data with solar + KamLAND data, since the latter provide the "solar parameters" needed to calculate the

full 3ν LBL probabilities in matter

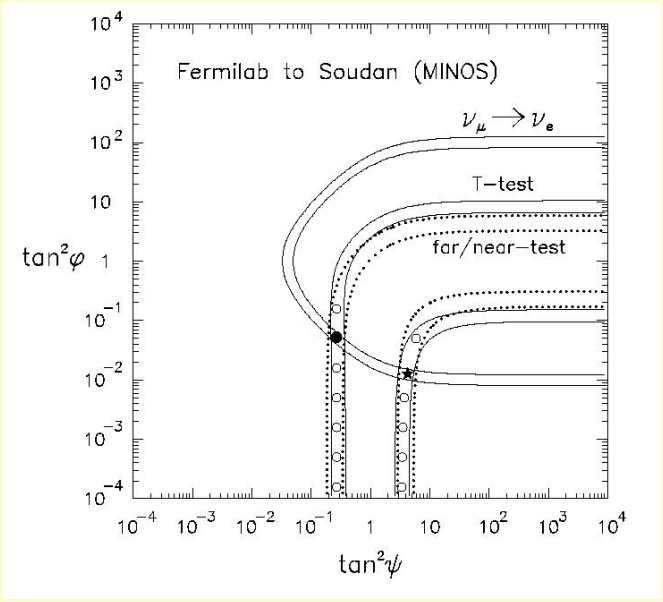
So, the sequence of contraints will be shown as:

(LBL + Solar + KamLAND) + (SBL reactor) + (SK atm)

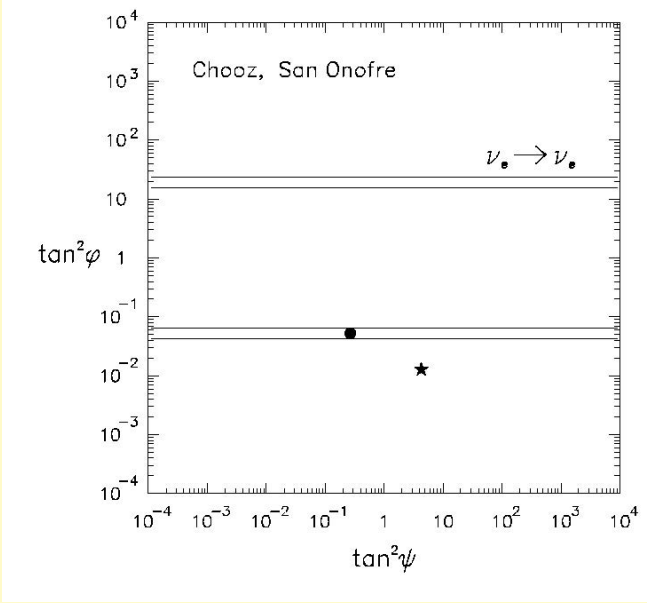
4. 2012 3ν results (work in progress)

5.1 (θ_{13}, θ_{23}) correlations

Let us remind the 1996 hypothetical example [hep-ph/9604415], in which …



… two quasi-degenerate solutions from LBL app + disapp. data…

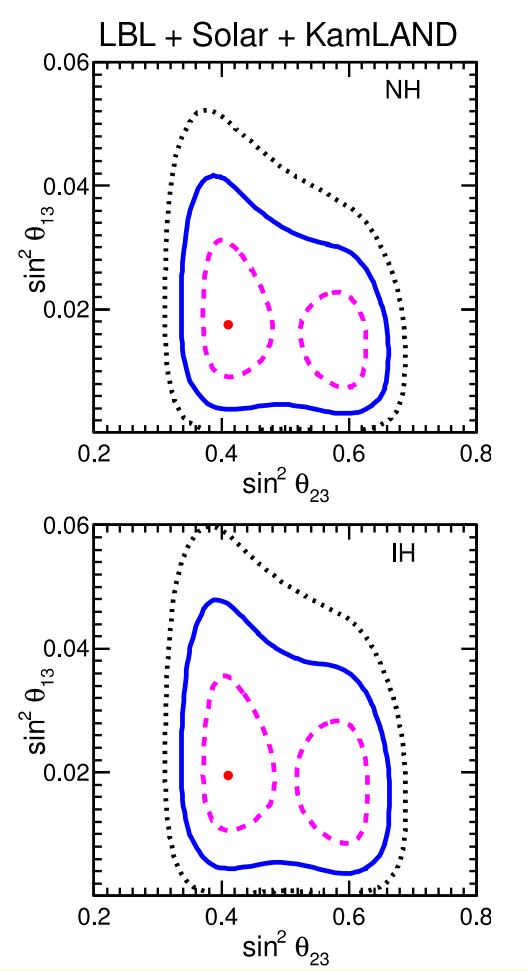


… are solved in favor of higher θ_{13} and 1st θ_{23} octant by SBL reactor data …

From 2012 LBL appearance + disappearance data plus solar + KamLAND data:

normal hierarchy

inverted hierarchy



for both hierarchies, NH & IH, we obtain:

- two quasi-degenerate and anticorrelated solutions (merging above 1σ)
- with a marginal preference for the first octant (< 1σ)

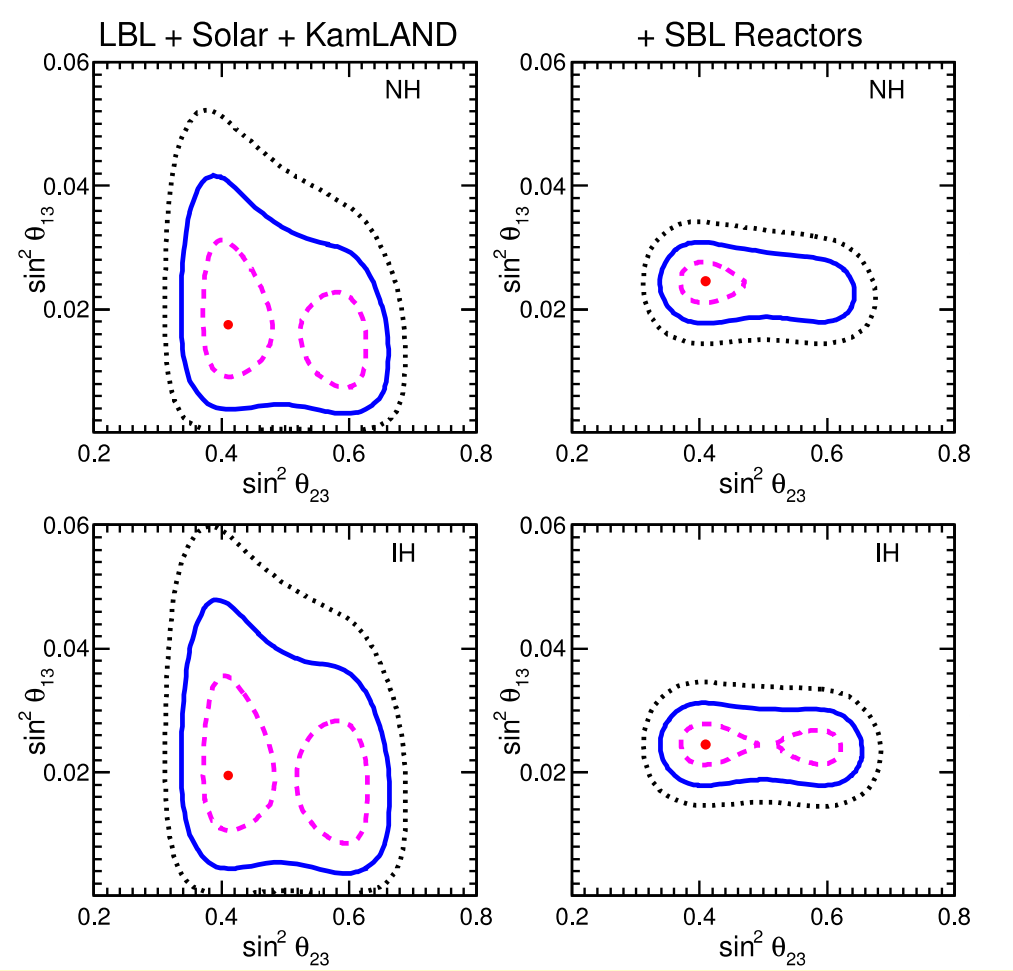
Moreover:

- weaker the constraint on θ_{13} for inverted hierarchy (as already known from T2K, MINOS)

Adding SBL reactor data (Chooz, Double Chooz, Daya Bay, RENO):

normal hierarchy

inverted hierarchy



large θ_{13} preferred !
for both NH & IH

NH

further preference for the solution with

- higher θ_{13}
- lower θ_{23} (1st octant)

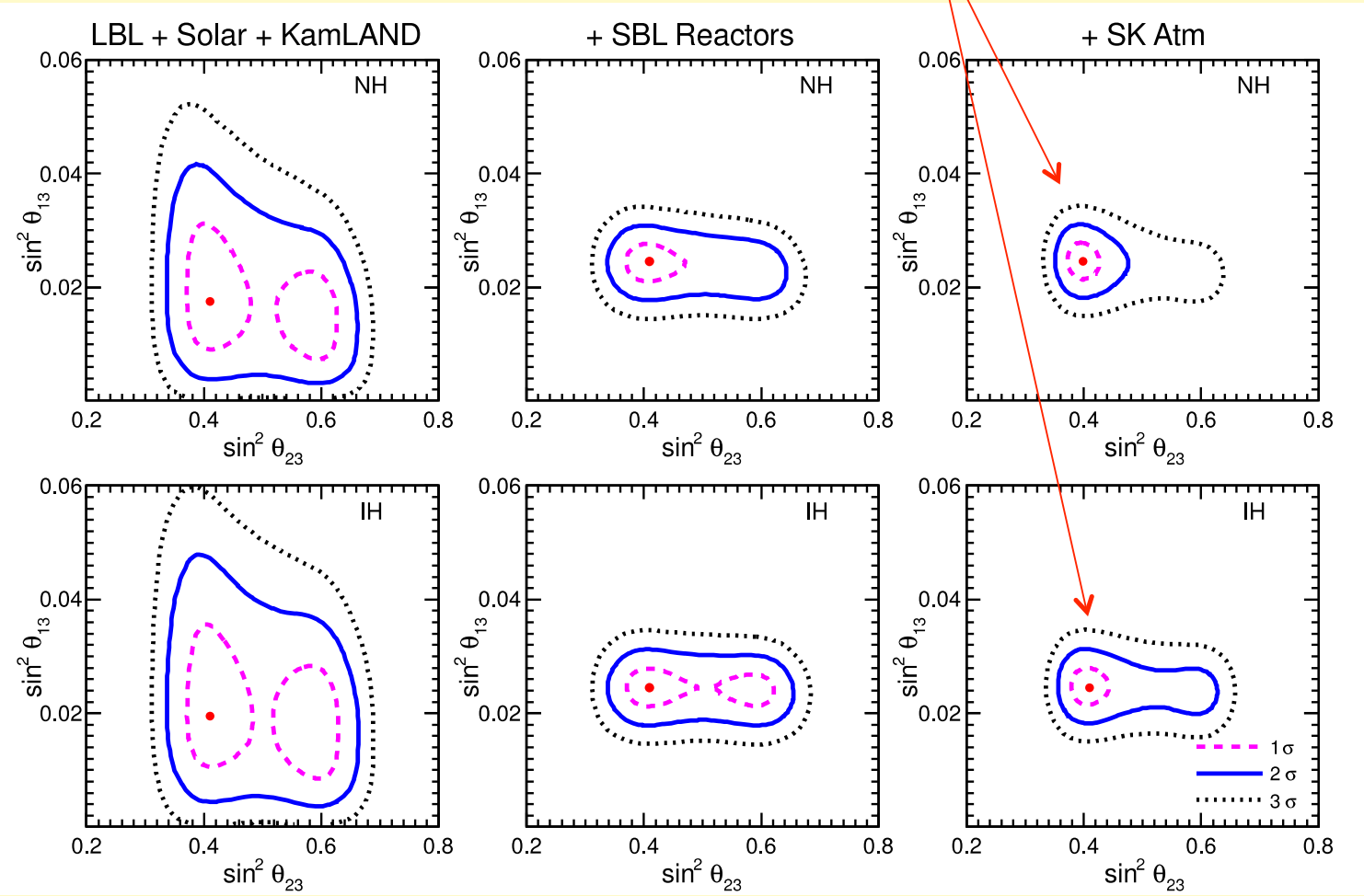
IH

marginal preference for 1st octant

Adding SK atm data: the preference for θ_{23} in the 1st octant is clearly corroborated

normal hierarchy

inverted hierarchy



Note: overall goodness of fit very similar in NH and IH. No hint about hierarchy yet…

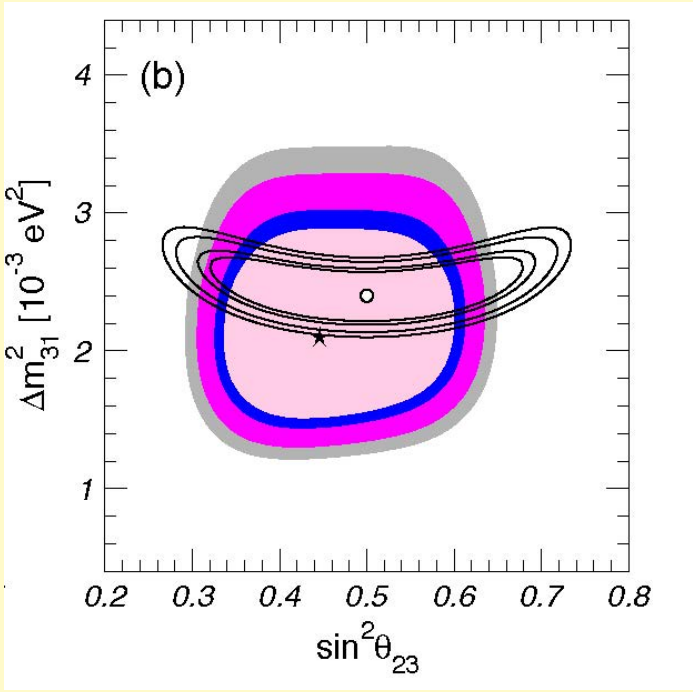
We find a significant role of SK atm data in favoring θ_{23} in the 1st octant.

To this regards let us note that:

- So far, the SK collaboration has found no significant "hint" of non-maximal mixing in their official 3ν data analysis.

- However, another recent, full 3ν data analysis does find some preference for the 1st octant in atm. data:

  M. Maltoni @ EPS-HEP 2011



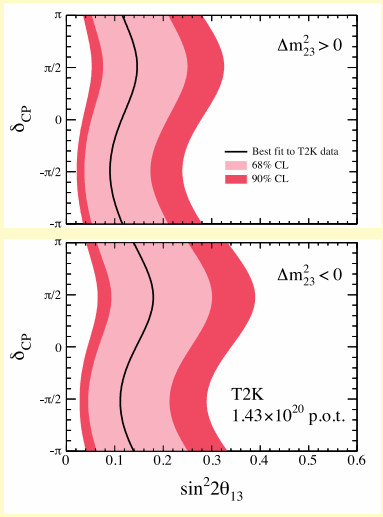
A final message is in order:

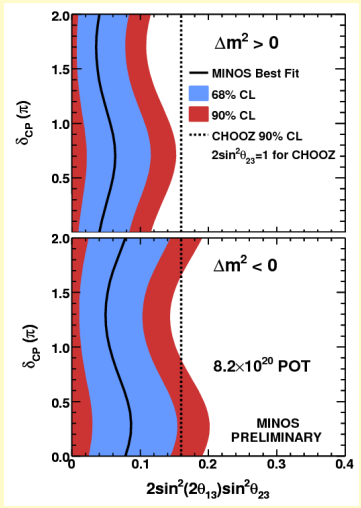
These are still "fragile" features, but worth of further studies in both LBL and ATM data analyses!

5.2 (θ_{13}, δ_{CP}) correlations

We reproduce well the T2K and MINOS contours under their same assumptions:

T2K





MINOS

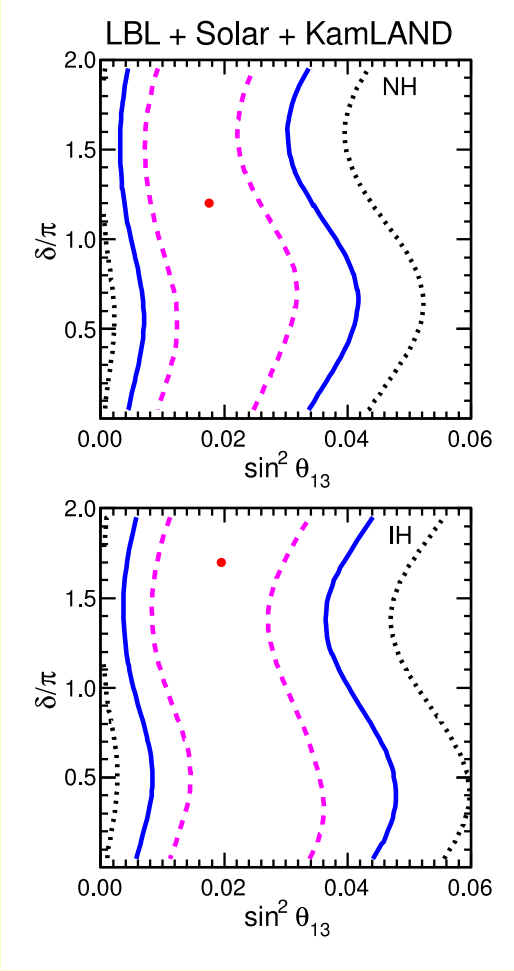
Let us note that an analysis of (θ_{13}, δ_{CP}) has been performed by Minakata et al. using the recent LBL + SBL reactor data (Machado, Minakata, Nunokawa, Zukanovich Funchal, arxiv 1111.3330 and next talk). [We agree under the same inputs and priors.]

Our analysis, however, includes all data and treats all parameters as free (no prior assumptions).

With only LBL + solar + KamLAND data:

normal hierarchy

inverted hierarchy

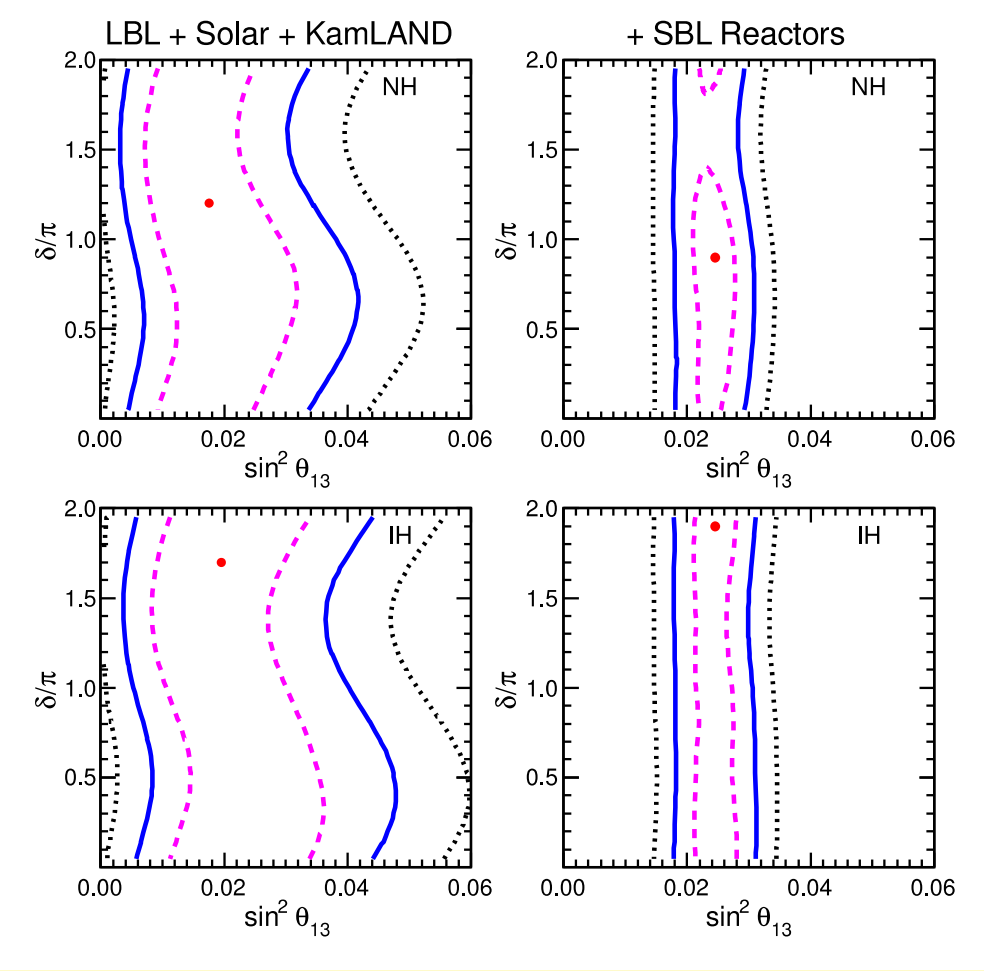


no significant sensitivity to δ_{CP} yet,
all values allowed at < 1σ

Adding SBL reactor data:

normal hierarchy

inverted hierarchy



NH

at most ~ 1σ sensitivity

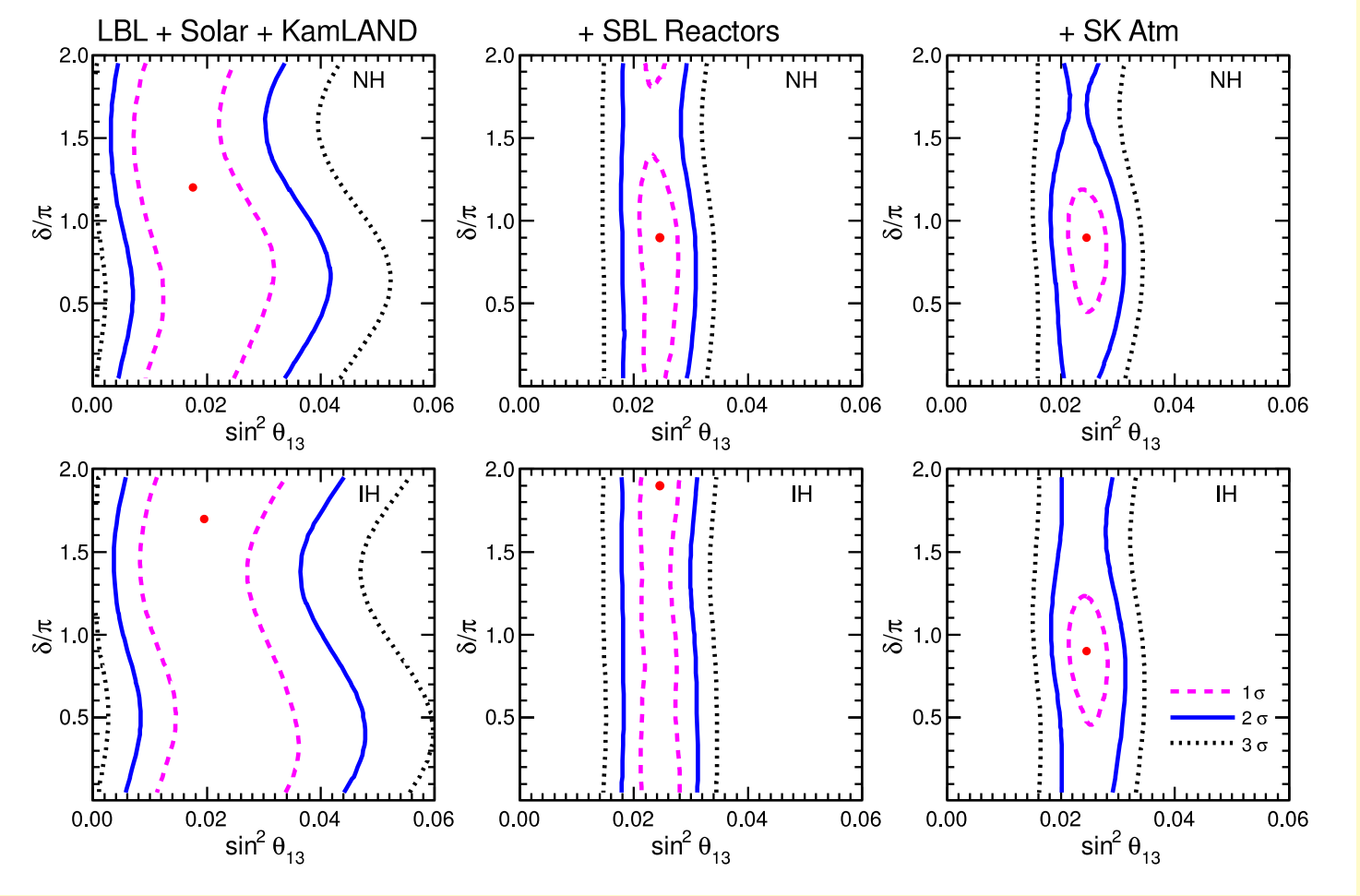
IH

not yet sensitivity at ~1σ

Adding SK atmospheric data:

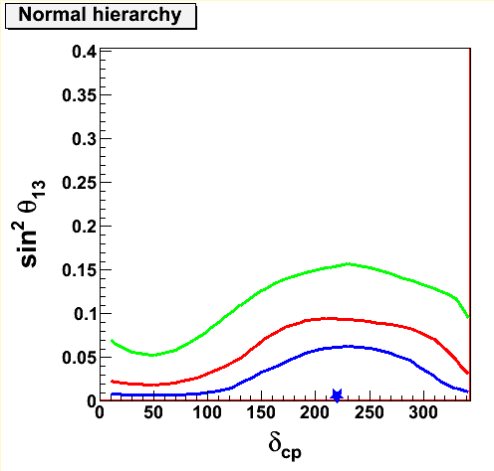
normal hierarchy

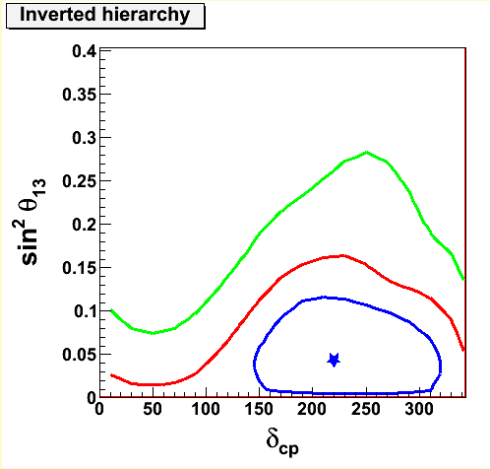
inverted hierarchy



We find a ~ 1σ preference for $\theta \sim \pi$ as in the early analysis of hep-ph/0506083.

We note that $\delta \sim \pi$ is compatible with SK atm. official results presented at "Neutrino 2010" by Y. Takeuchi, which favor $\delta \sim 1.2\,\pi$ in both hierarchies



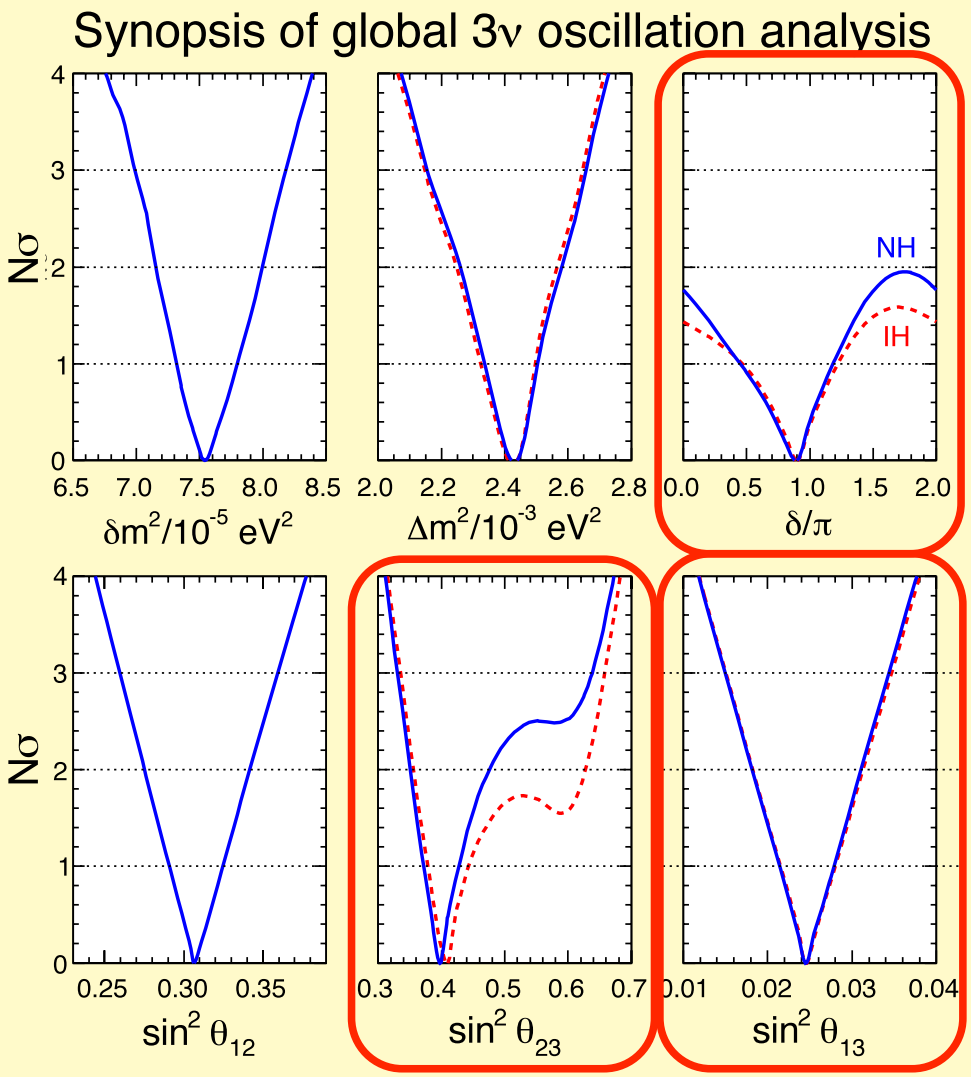


Let us remind you our interpretation, proposed in hep-ph/0506083:

$\delta \sim \pi$ enhances the interference oscillation term and gives extra electron appearance for O(GeV) atmosph. events, "explaining" part of the persisting SK electron excess.

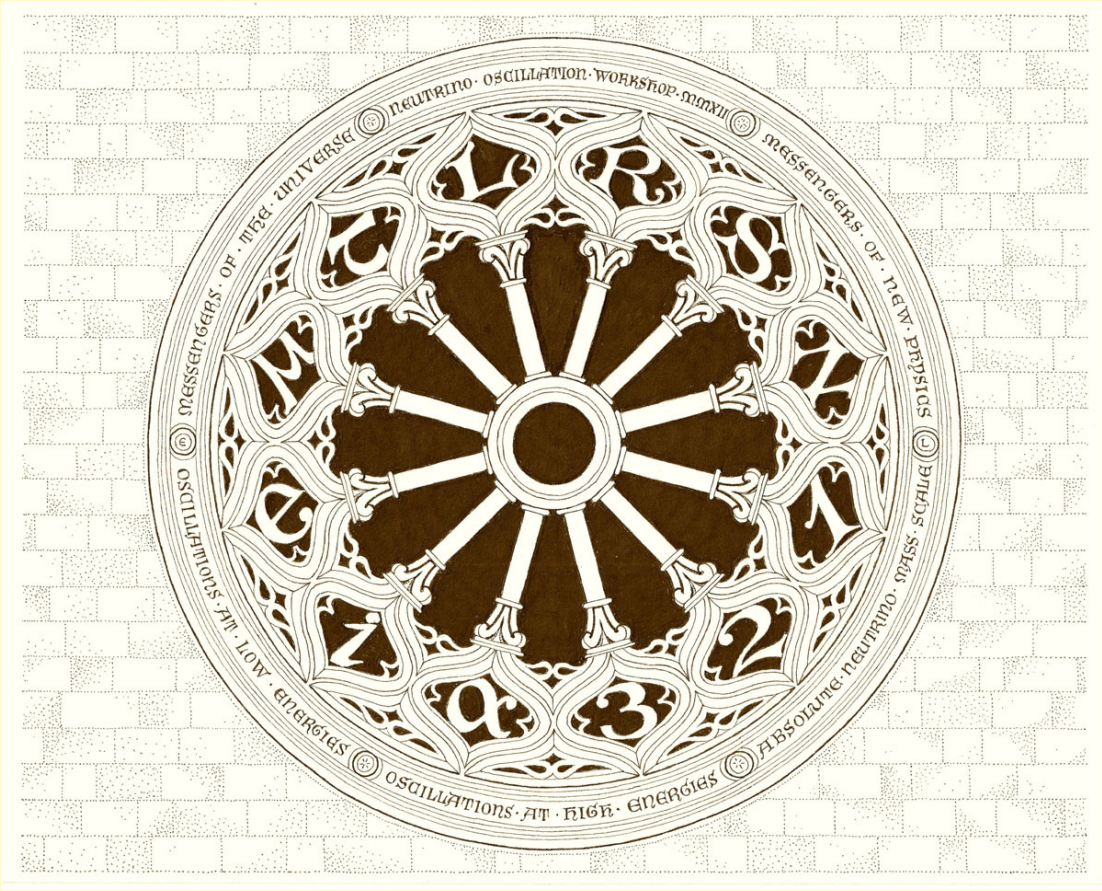
Once more: this is a "fragile" feature, but worth further studies with current data.

5. CONCLUSIONS: Summary of our 2012 analysis



- Previous hints of $\theta_{13} > 0$ are now measurements! (and basically independent of old/new reactor fluxes)
- Some hints of $\theta_{23} < \pi/4$ are emerging at ~ 2σ , worth exploring by means of atm. and LBL+reac. data
- A possible hint of $\delta_{CP} \sim \pi$ emerging from atm. data [Is the PMNS matrix real?]
- So far, no hints for NH ⟷ IH

You are cordially invited to discuss the current oscillation picture, from "hints" to "measurements" and beyond, at NOW 2012 (9-16 Sept) in Conca Specchiulla, Otranto, Lecce, Italy - www.ba.infn.it/now



Thank you for your attention!