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A global analysis of neutrino masses, mixings and phases: entering the new era of leptonic CP violation searches

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Outline

1. Why global analyses?
2. From first hints to evidence of $\theta_{13} > 0$
3. Global 3ν analysis: metodological issues
4. Global 3ν analysis: results
   - 4.1 $(\theta_{13}, \theta_{23})$ correlations
   - 4.2 $(\theta_{13}, \delta_{CP})$ correlations
5. Conclusions

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

1. Why global analyses?

- In general, global analyses of data from different experiments are necessary when some physical parameters are not (precisely) measured by any single experiment.

- In this case, the parameters may be at least constrained by a joint, careful comparison of various datasets.

- Even when measurements become available, global analyses often remain useful to perform consistency tests of theoretical scenarios, where possible "tensions" may eventually emerge from the comparison of different datasets.

- Of course, such analyses have obvious limitations: they cannot replace the experimental measurements!

2. From first hints to evidence of $\theta_{13} > 0$

A few years ago (2008), the good agreement of solar and KamLAND data in 2ν analyses was one of the main highlights …

… agreement obtained assuming

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

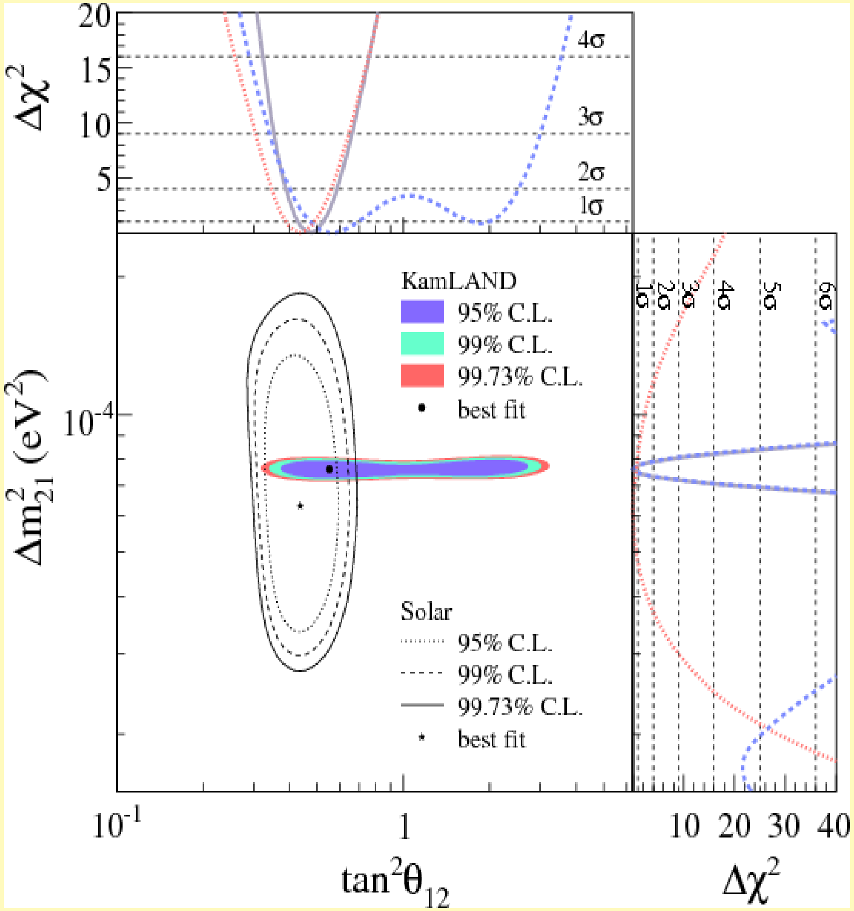
But the agreement could be even improved by going beyond the 2ν approximation and allowing 3ν mixing …

For 3ν:

$$\nu_e = \cos\theta_{13}\ (\cos\theta_{12}\ \nu_1 + \sin\theta_{12}\ \nu_2) + e^{-i\delta} \sin\theta_{13}\ \nu_3$$

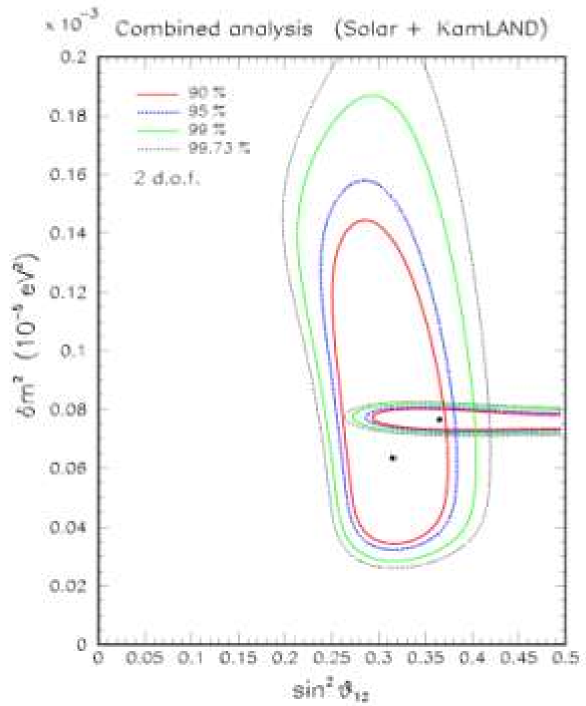
mixing angle θ_{13}

possible ~~CP~~ phase δ_{CP}

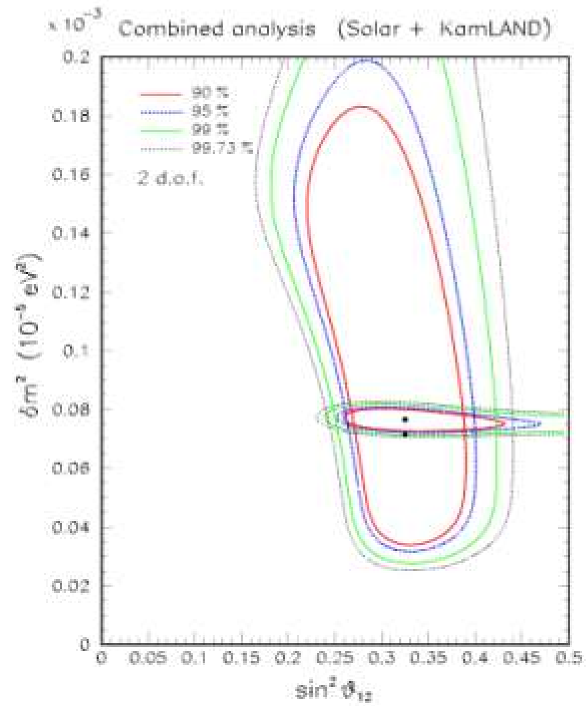


[figure taken from the official KamLAND site (2008)]

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



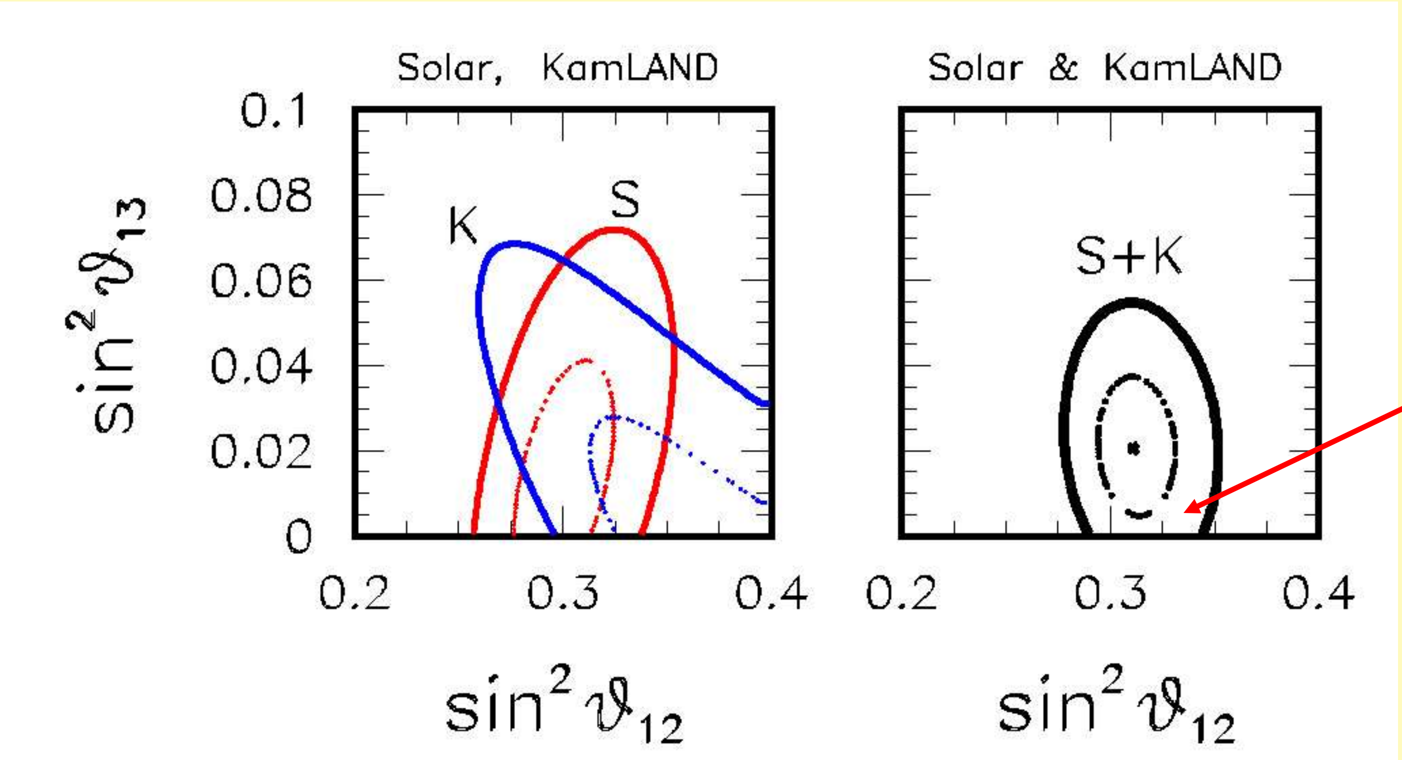
$\sin^2\theta_{13} = 0$



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

[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)

➡ 2008: first hint of ν_e as a superposition of three states.

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

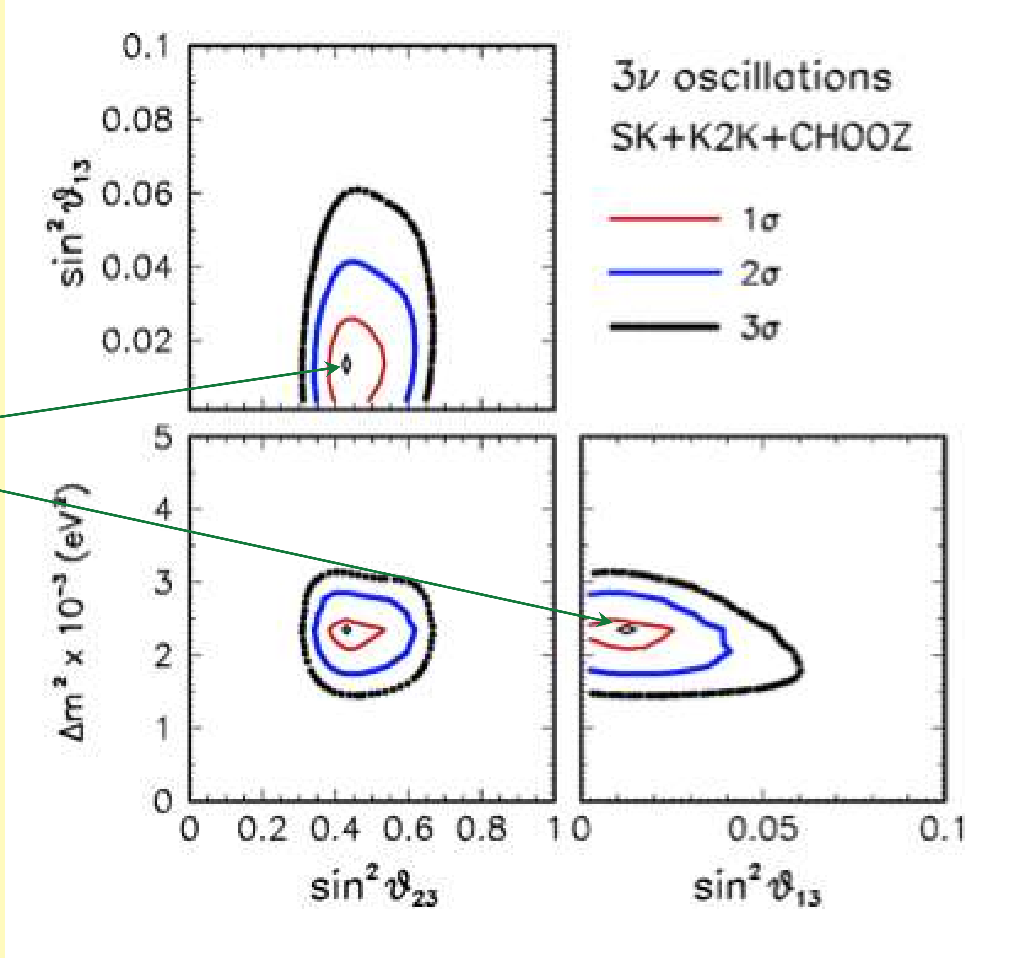
Note: even though statistically weak (~1.5 σ), this hint was quite "clean", as it involved very simple oscillation physics.

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

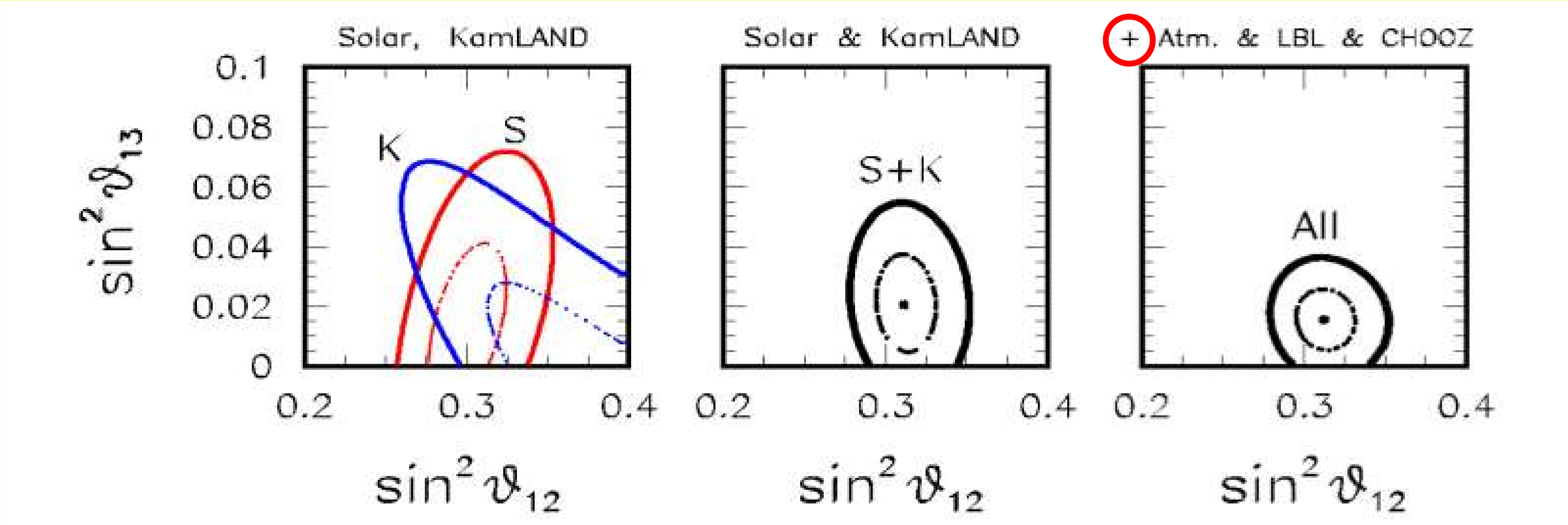


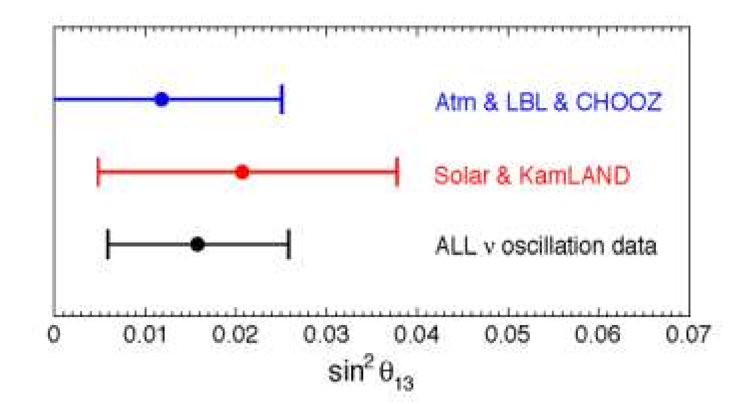
[However, atmospheric ν physics and data analysis are admittedly more involved; statistical significance of the atmospheric hint somewhat debated in the literature.]

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.

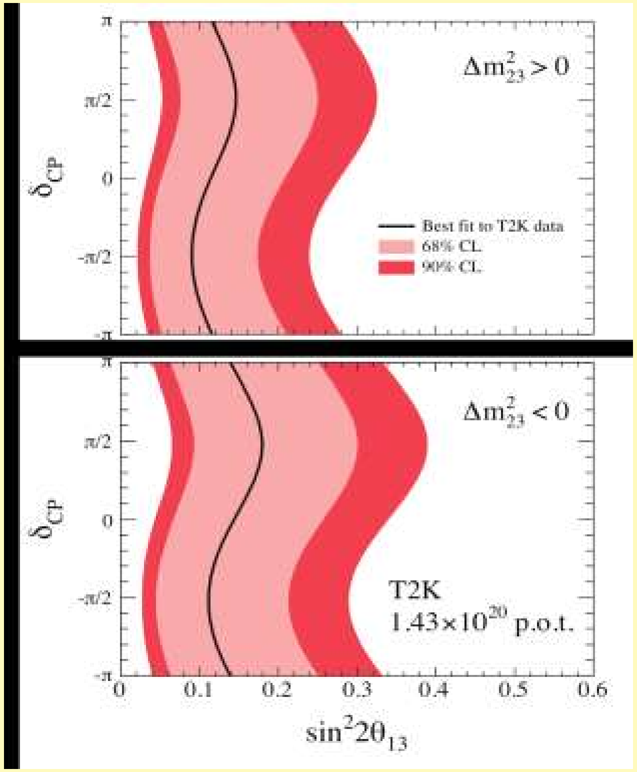
$\sin^2\theta_{13} = 0.016 \pm 0.010$

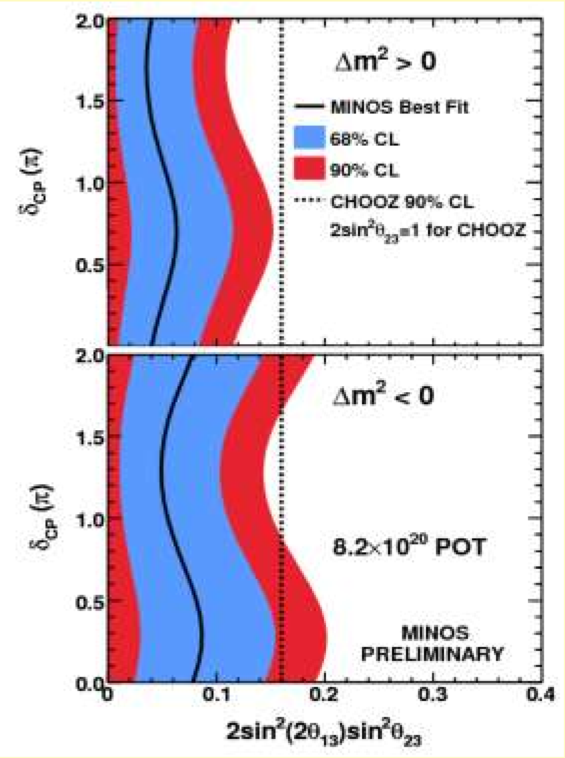
Large literature and debate 2008-2011!

June 2011 breakthrough: new T2K and MINOS appearance results

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

T2K





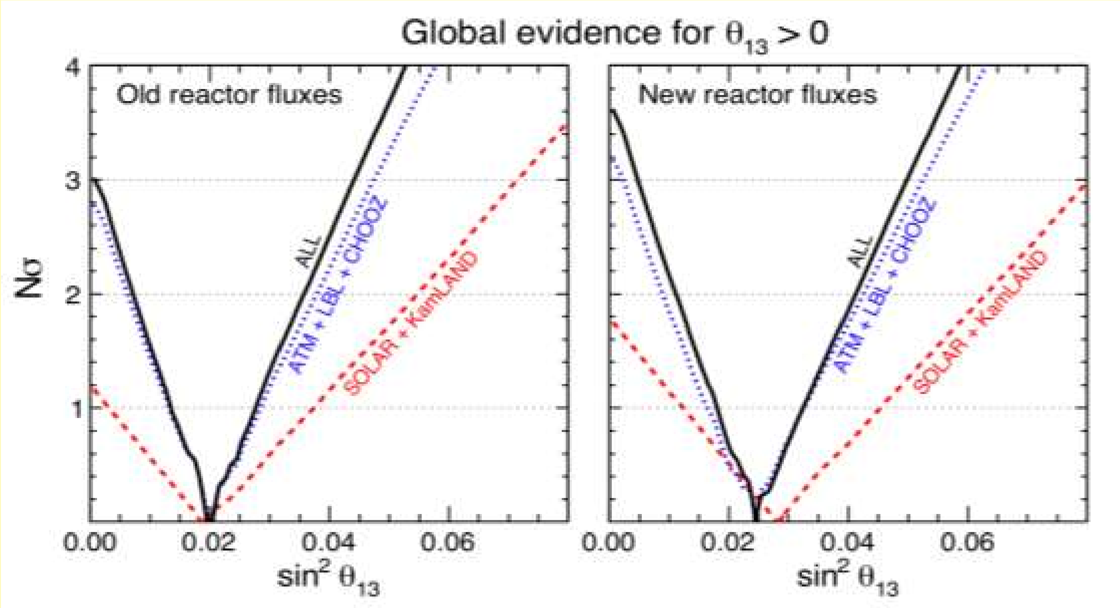
MINOS

$P_{\mu e} = \sin^2\theta_{23}\sin^2(2\theta_{13})\sin^2(\Delta m^2 L/4E_\nu)$ + subleading solar & CP terms (wiggles in the plots)

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"

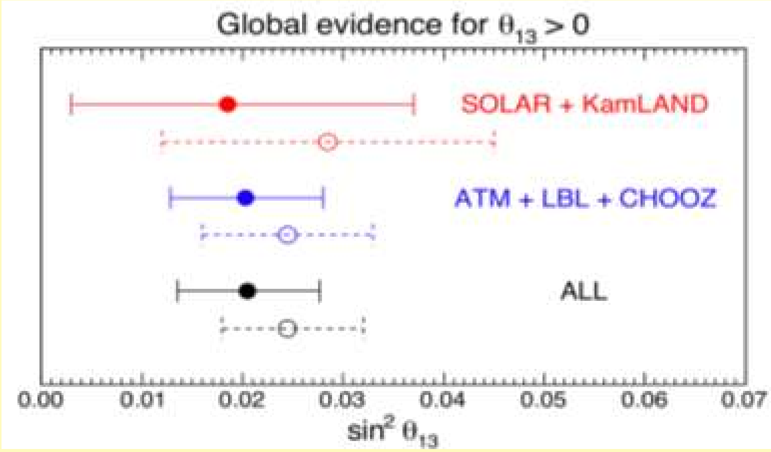
[GLF, Lisi, Marrone, Palazzo, Rotunno, arXiv:1106.6028]



Note:

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

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

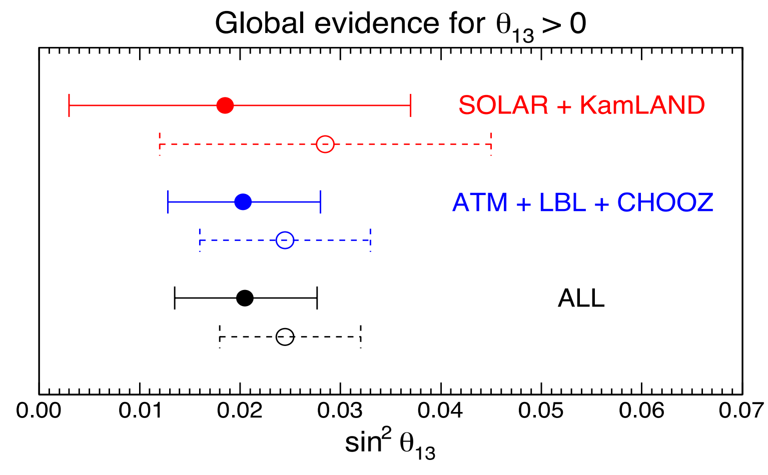


$\sin^2\theta_{13} = 0.021 \pm 0.007$ ("old" reactor fluxes)

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

The 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)

… should be compared with the very recent (2012) SBL reactor data:

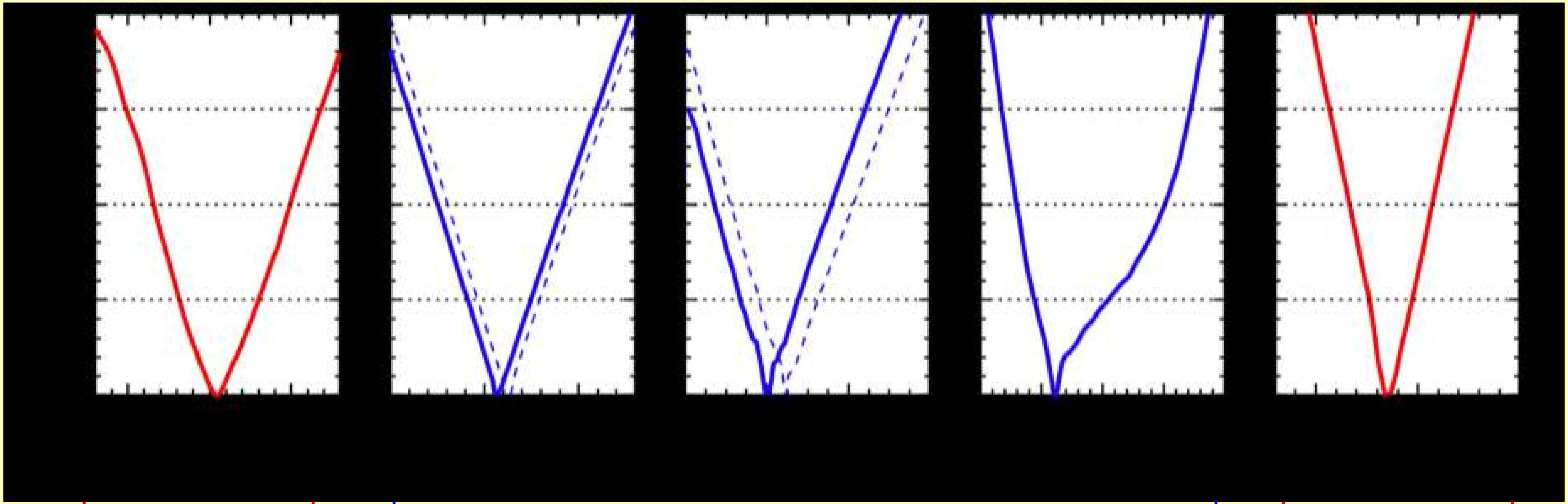
Double Chooz (far detector):	$\sin^2\theta_{13} = 0.022 \pm 0.013$
Daya Bay (near + far detectors):	$\sin^2\theta_{13} = 0.024 \pm 0.004$
RENO (near + far detectors):	$\sin^2\theta_{13} = 0.029 \pm 0.006$

we find a spectacular agreement!

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, Phys. Rev. D84 (2011) 053007, arXiv:1106.6028v2]

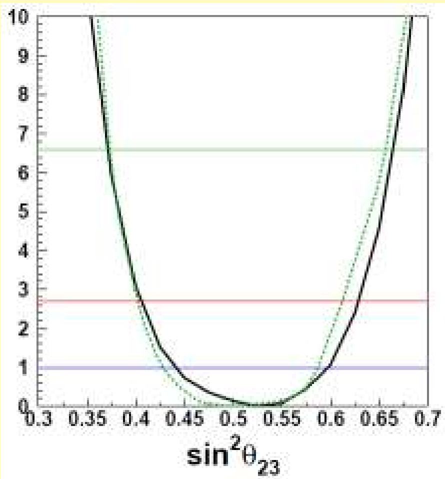
[Similar results in Schwetz, Tortola and Valle, arXiv:1108.1376 and in Gonzales-Garcia, Maltoni and Salvado, arXiv:1001.4524, and Maltoni talk at EPS-HEP 2011]

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

1 3ν mass-mixing hierarchy → no hints so far

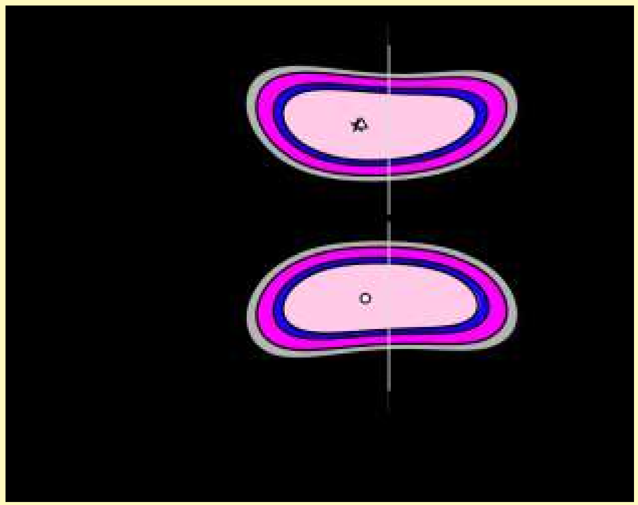
2 $\sin^2\theta_{23}$: ν_μ-ν_τ mixing, maximal or not ? → weak hints ?...

SK@Neutrino2010



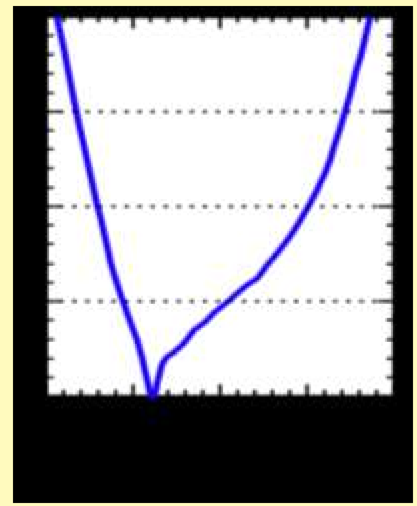
Nearly maximal...

Gonzalez-Garcia et al. 2010



Slightly nonmaximal...

Our analysis, 2011

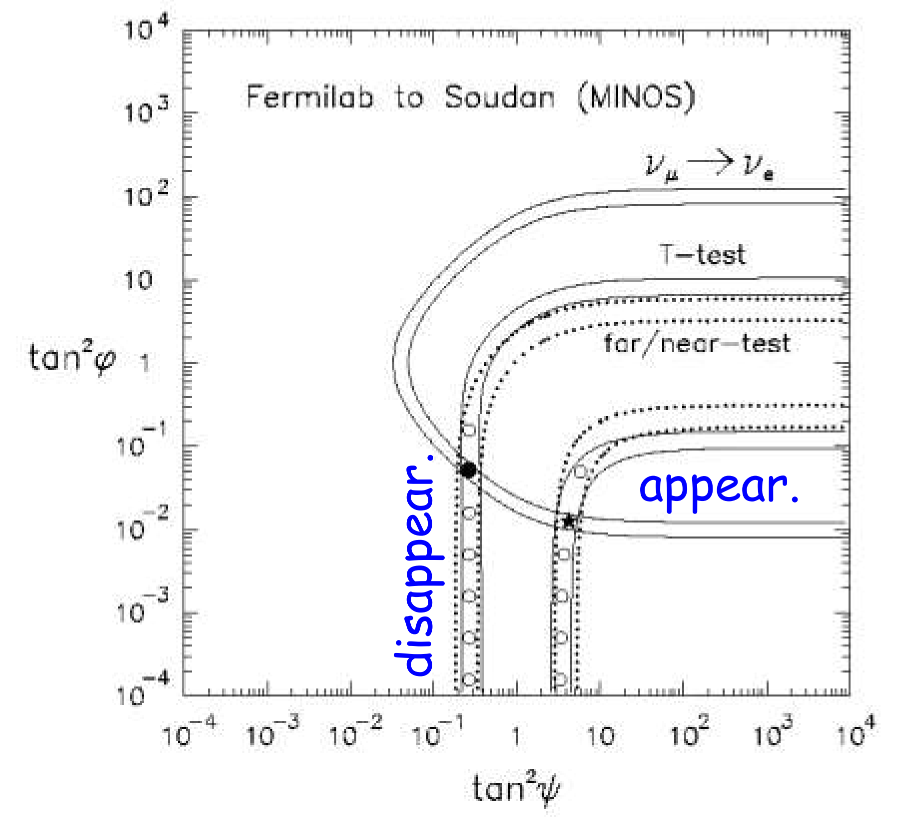


Slightly more nonmaximal...

It includes now SK I+II+III data with both θ_{13} ¯0 and δm^2 ¯0

3. Global 3ν analysis: methodological issues

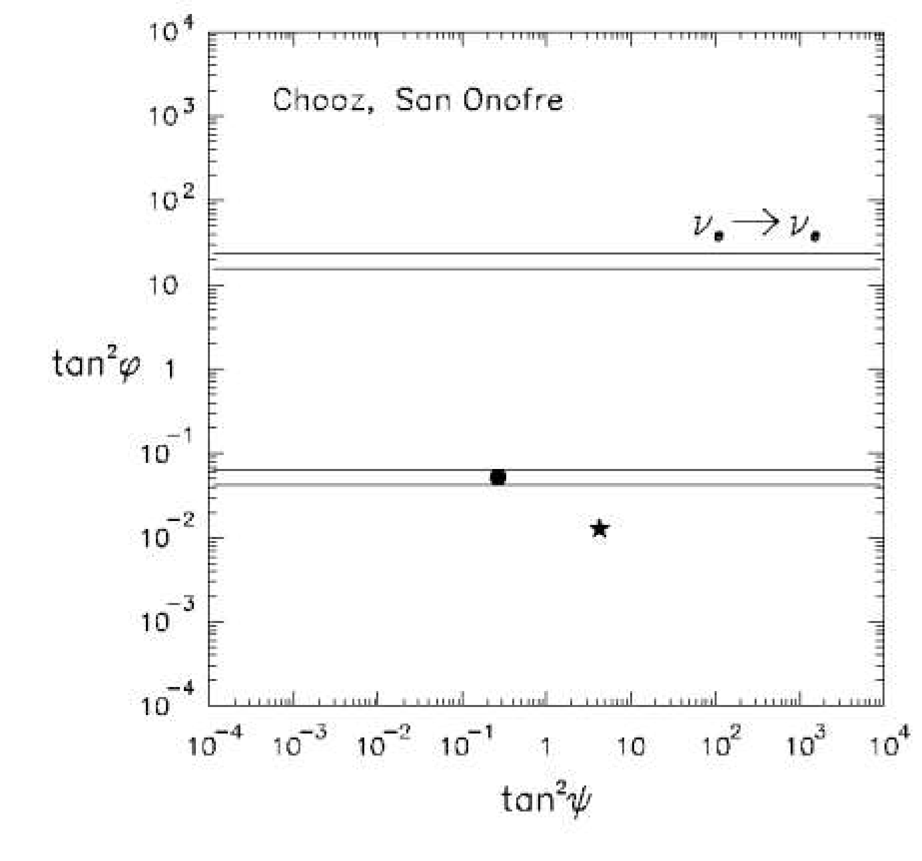
There is an interesting interplay between LBL appearance + disappearance data, SBL reactor data, and octant degeneracy, as pointed out long ago [GLF & Lisi, Phys. Rev. D54 (1996) 3667, hep-ph/9604415]



1

For (slightly) non-maximal mixing, LBL appearance + disappearance 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 data), 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

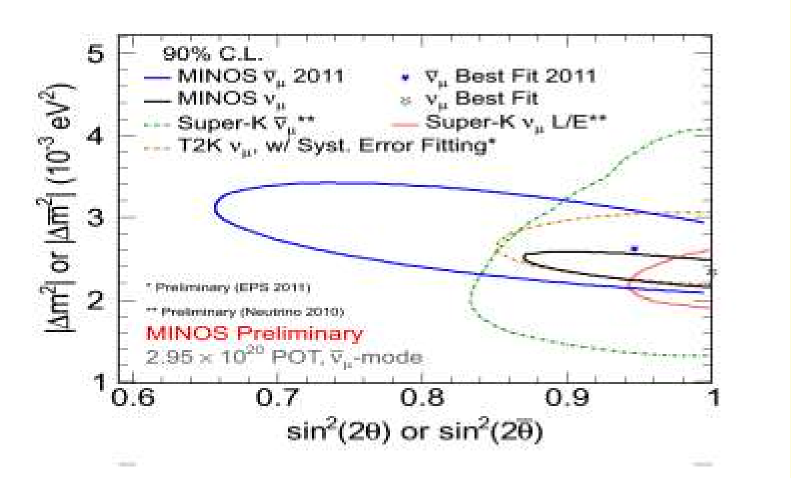
So, they may distinguish "high" from "low" θ_{13}

➡ 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

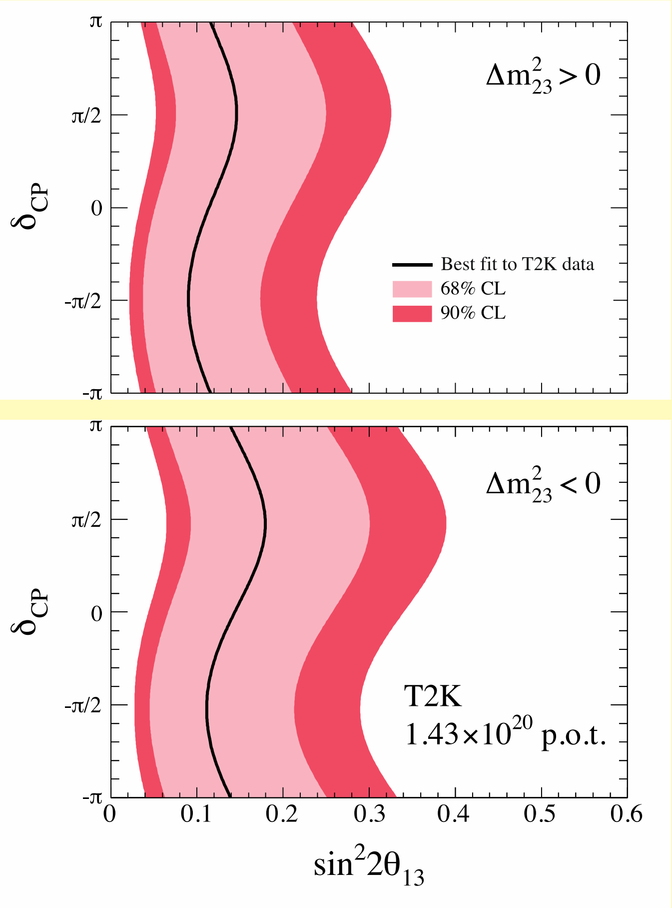
We use:

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

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.

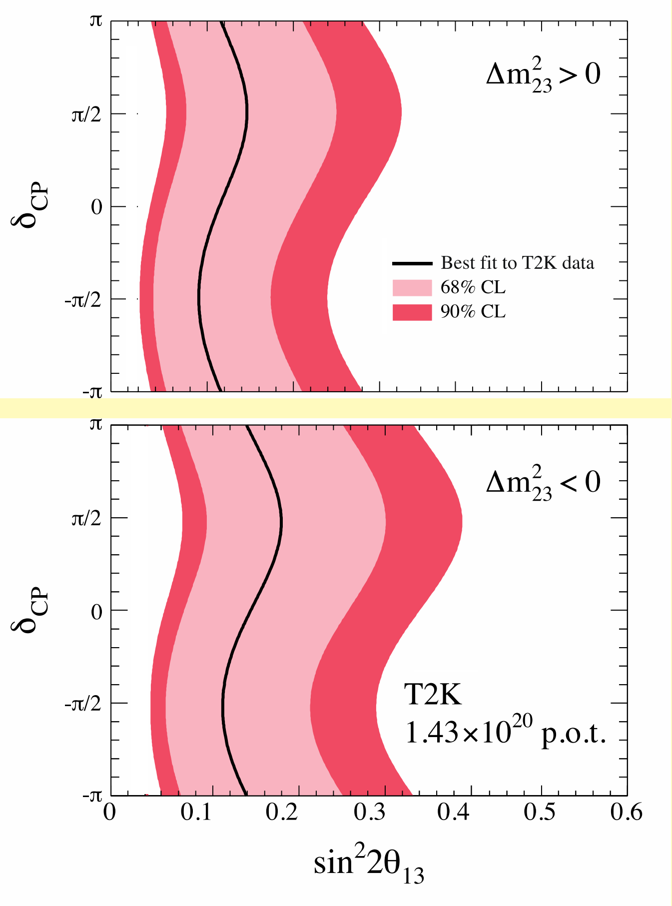
T2K



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

… 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!

Final "methodological note":

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)

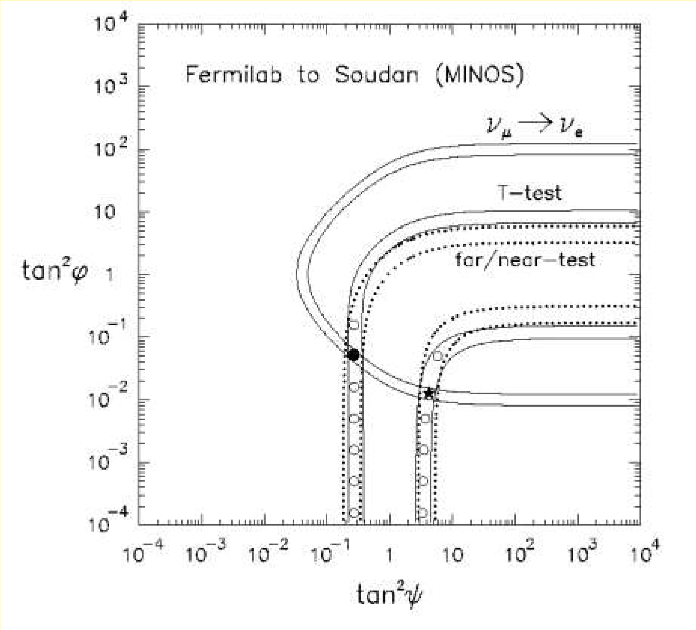
4. Global 3ν analysis: results *

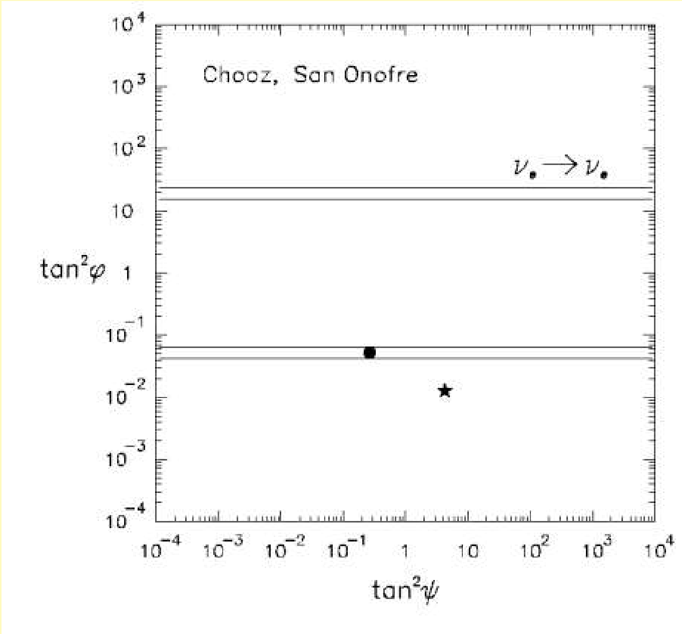
(updated including the data presented at Neutrino 2012
by Daya Bay, Reno, T2K and MINOS)

* G.L.F., E. Lisi, A. Marrone, D. Montanino, A. Rotunno, A. Palazzo, "Global analysis of neutrino masses, mixings and phases: entering the era of leptonic CP violation searches", Phys. Rev. D 86, 013012 (2012)

4.1 (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…

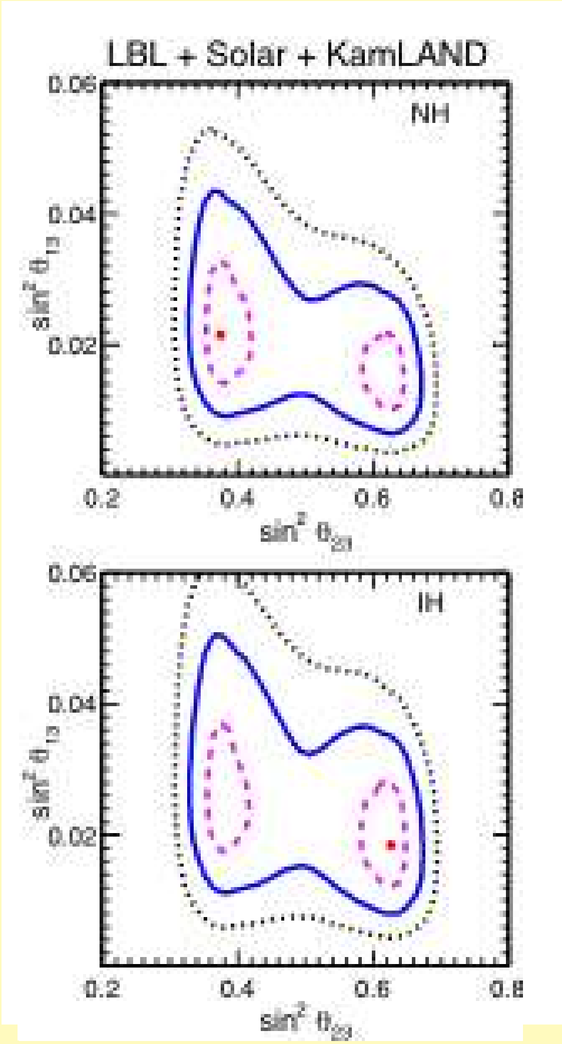
… are solved in favor of higher θ_{13} and 1st θ_{23} octant by SBL reactor data …

From 2012 $\underbrace{\text{LBL appearance + disappearance}}$ data plus $\underbrace{\text{solar + KamLAND}}$ data:

normal hierarchy

including
ν 2012 data

inverted hierarchy



we obtain for both hierarchies, NH & IH:

- two quasi-degenerate and anticorrelated solutions (merging above 1σ)

Moreover:

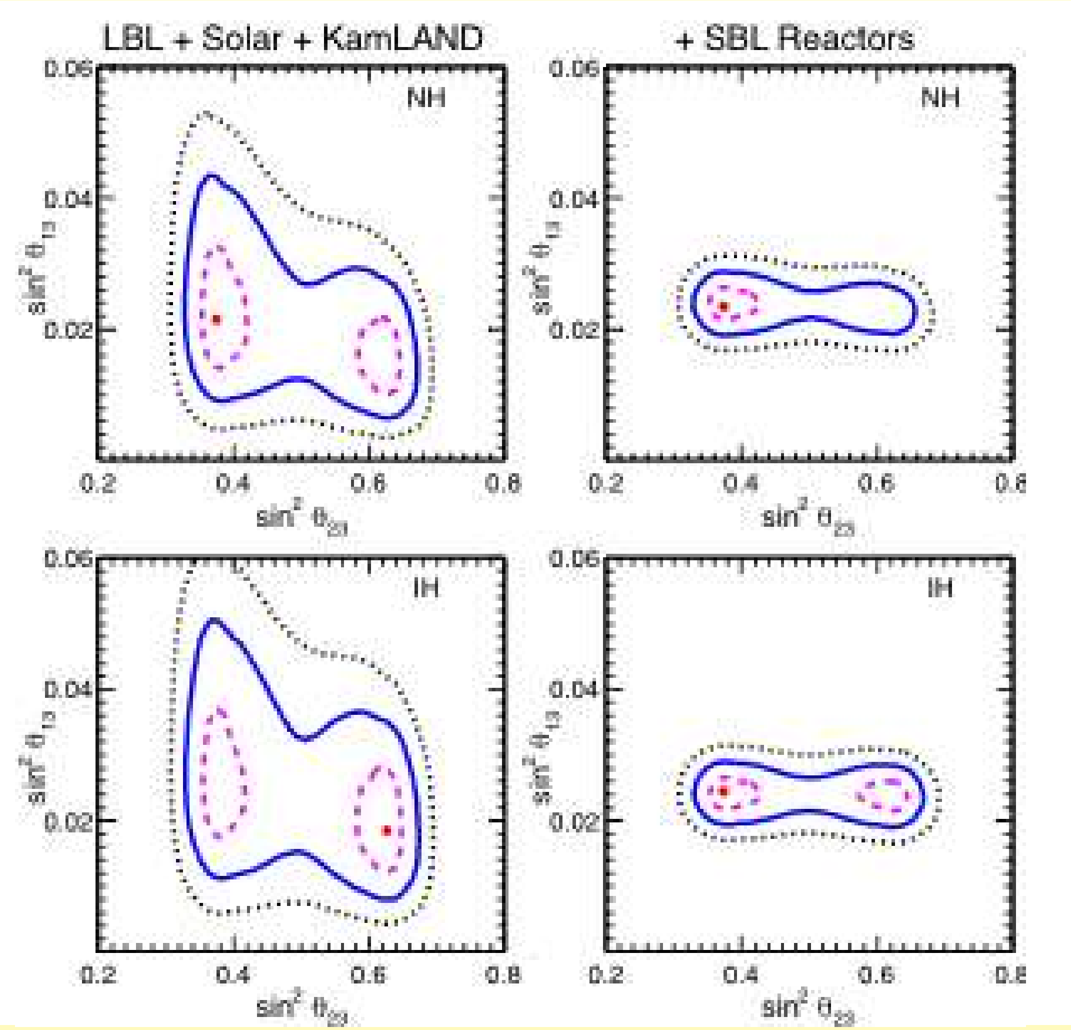
- a weaker constraint on θ_{13} for inverted hierarchy
(as already known from T2K, MINOS)

Adding $\underbrace{\text{SBL reactor data}}$ (Chooz, Double Chooz, Daya Bay, RENO):

normal hierarchy

including ν 2012 data

inverted hierarchy



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

NH

further preference for the solution with

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

IH

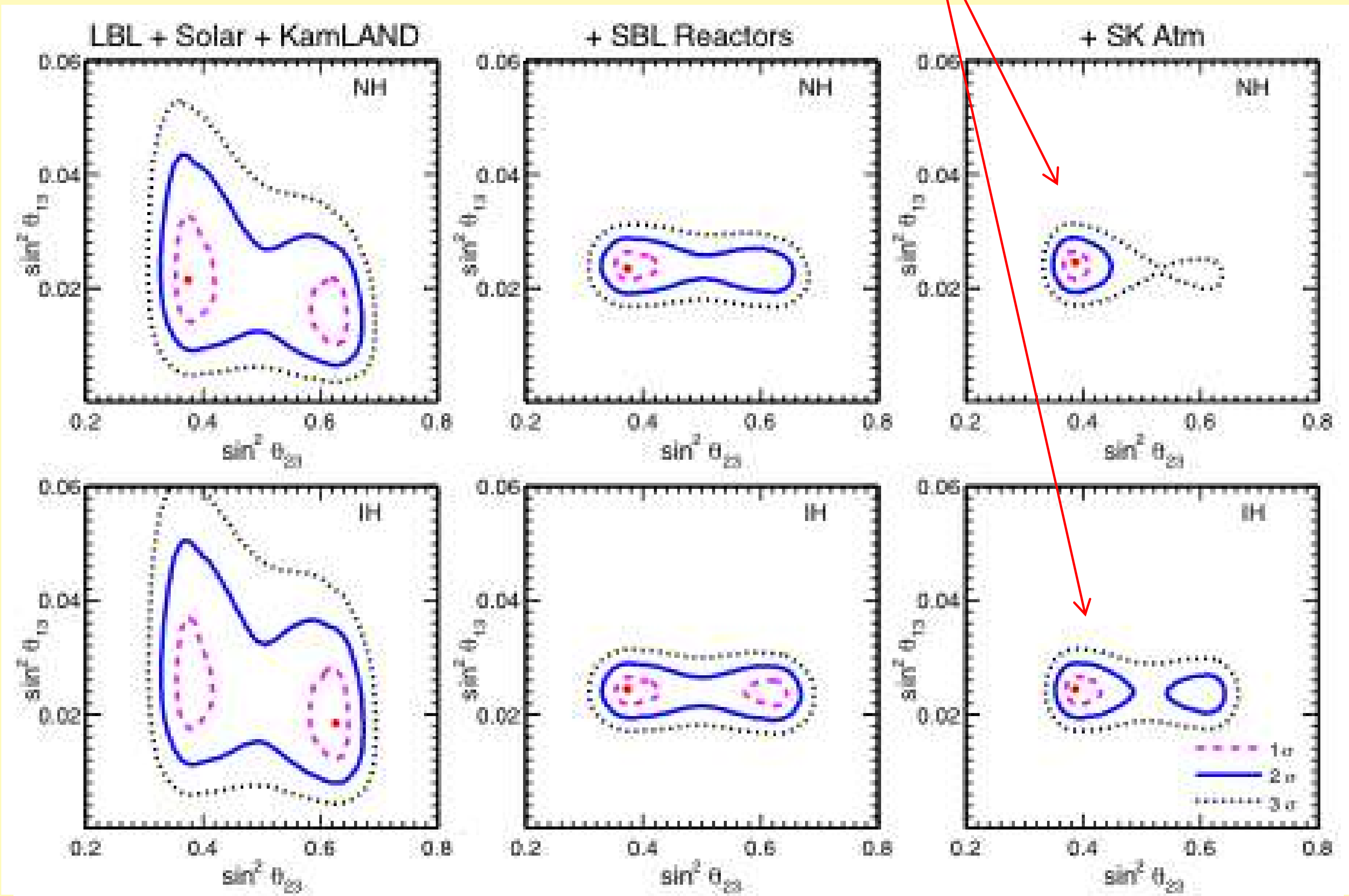
only a marginal preference for 1st octant

Adding $\underbrace{\text{SK atm data}}$: some preference for θ_{23} in the 1st octant

normal hierarchy

including ν 2012 data

inverted hierarchy



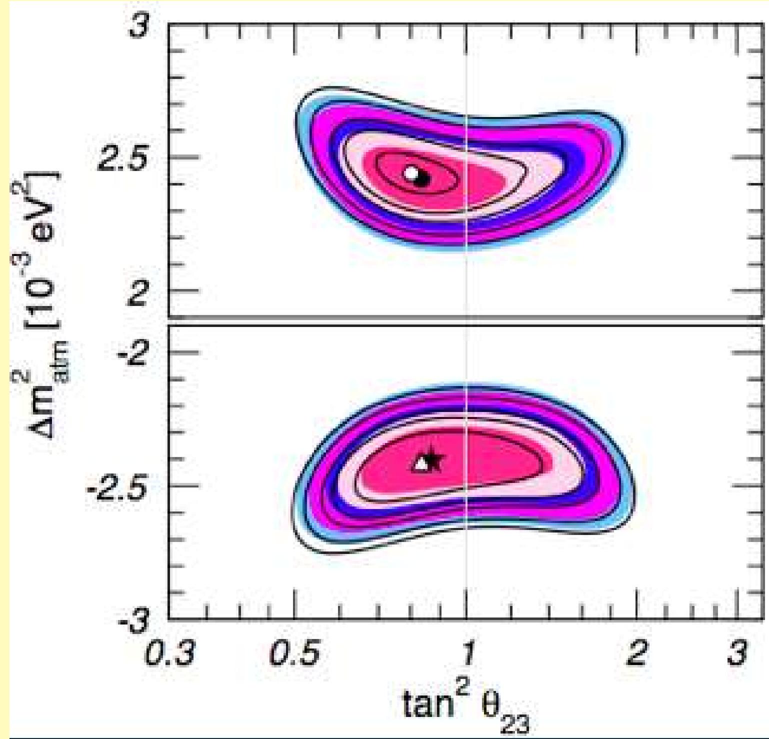
Note: overall goodness of fit very similar in NH and IH. No hint about hierarchy yet...

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

To this regards let us note that:

- The SK collaboration had found no significant "hint" of non-maximal mixing in their official 3ν data analysis of 2010.
  [ditto for Forero, Tortola & Valle 2012, which however is not a full 3ν for atmospheric data].

- However, another recent, full 3ν data analysis also find a (weaker) preference for the 1^{st} octant in atmospheric data:
  [T. Schwetz with Gonzalez-Garcia and Maltoni]



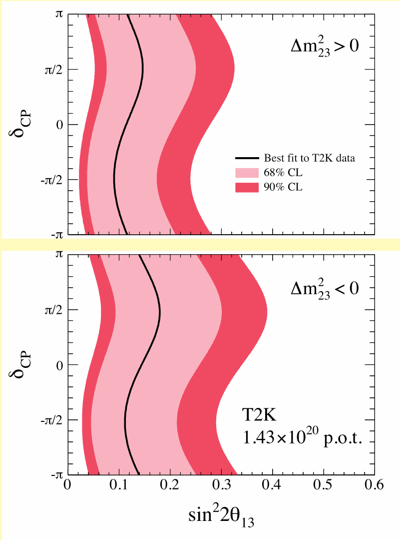
Therefore, concerning (non)maximal θ_{23}:

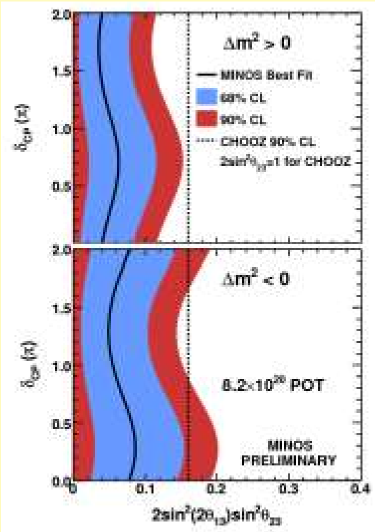
The possible preference for the 1^{st} octant is still a "fragile" feature, but worth of further studies in both LBL and ATM data analyses, provided that full 3ν oscillation probabilities are included!

4.2 (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 update 2012). [We agree under the same inputs and priors.]
- Similarly Forero, Tortola & Valle 2012 [but ignoring $\delta_{CP} \neq 0$ and $\delta m^2 \neq 0$ effects in atmospheric data].

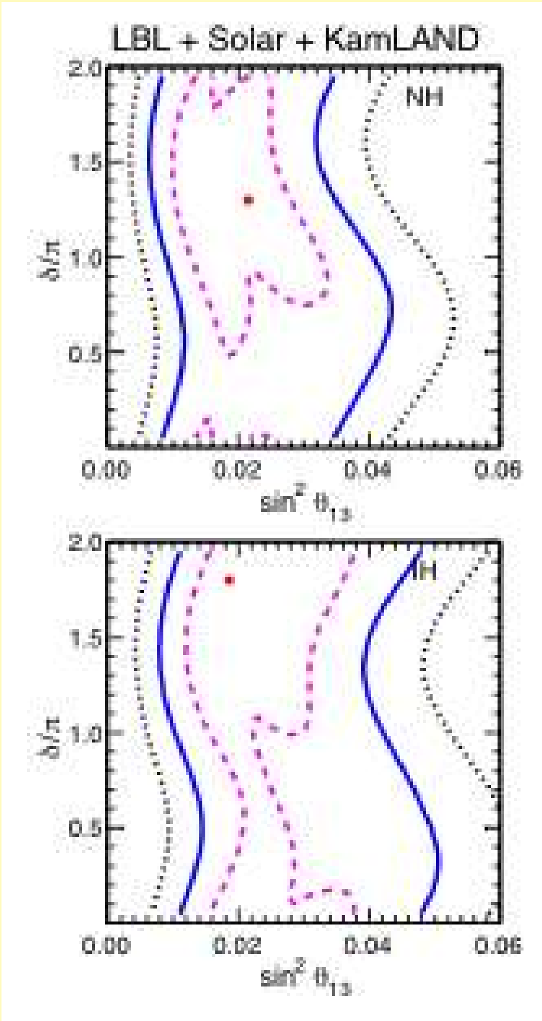
Our analysis includes all data and treats all 3ν parameters as free (no prior assumptions).

With only $\underbrace{\text{LBL + solar + KamLAND}}$ data:

normal hierarchy

including ν 2012 data

inverted hierarchy



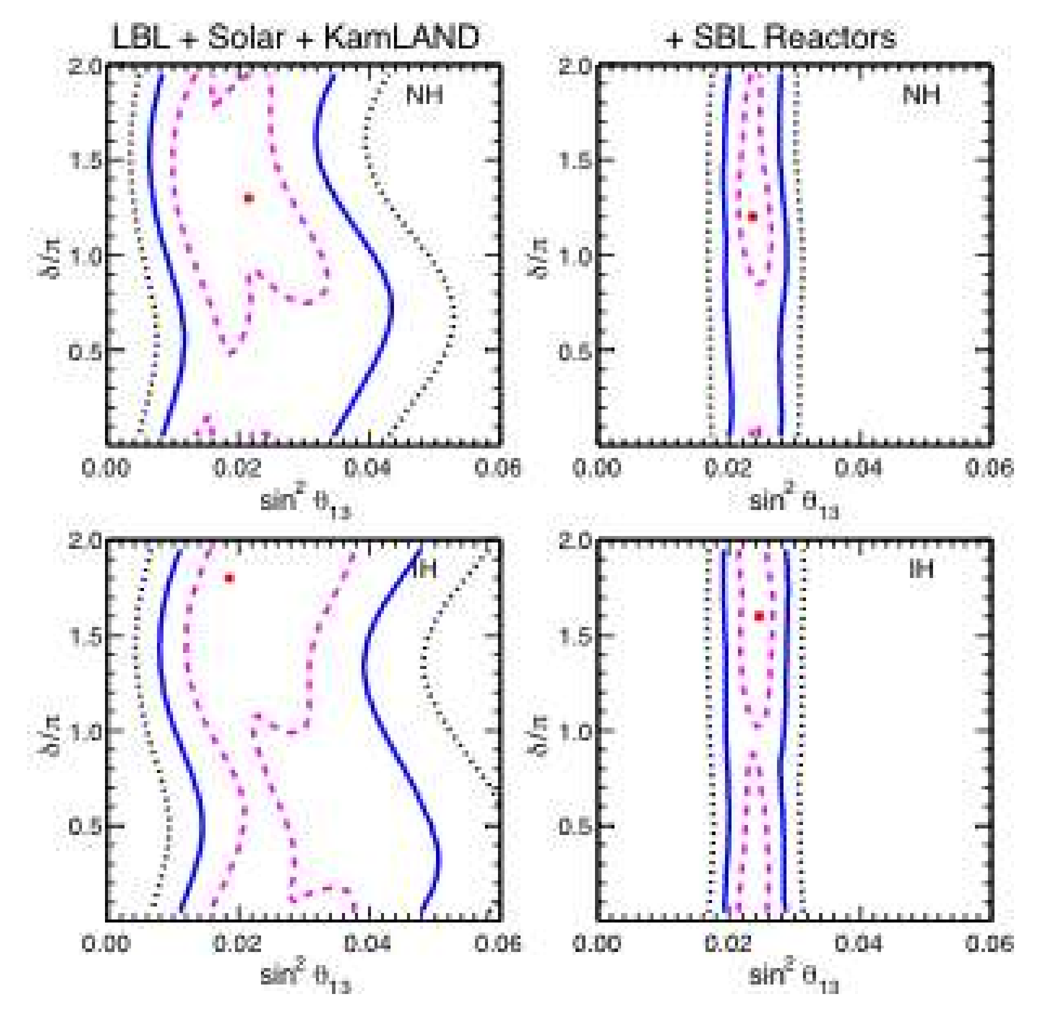
no significant sensitivity to δ_{CP} yet

Adding $\underbrace{\text{SBL reactor}}$ data:

normal hierarchy

including ν 2012 data

inverted hierarchy



NH

at most ~ 1σ sensitivity

IH

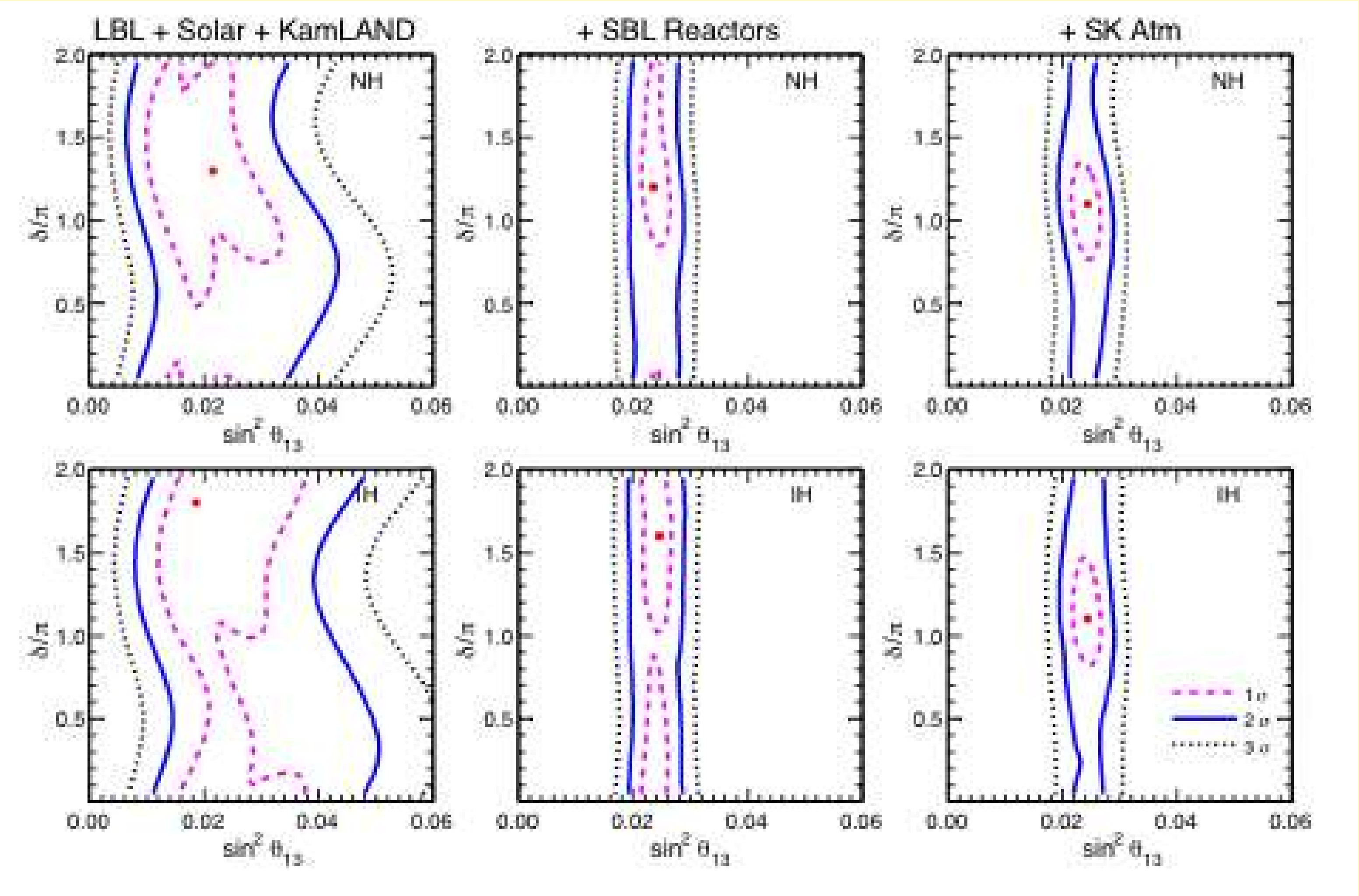
not yet sensitivity at ~ 1σ

Adding SK atmospheric data:

normal hierarchy

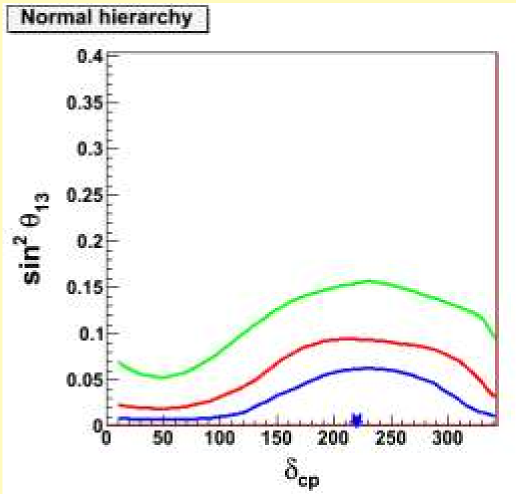
including ν 2012 data

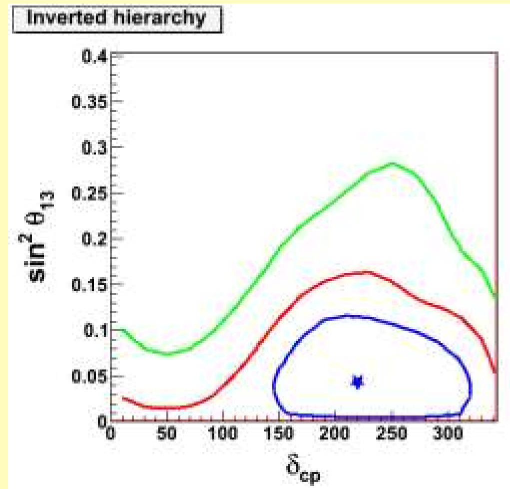
inverted hierarchy



We find a ~ 1σ preference for θ ~ π as in the early analysis of hep-ph/0506083.

We note that $\delta \sim \pi$ is compatible with previous SK atmospheric official results presented at "Neutrino 2010" by Y. Takeuchi,





favored $\delta \sim 1.2\,\pi$
in both hierarchies

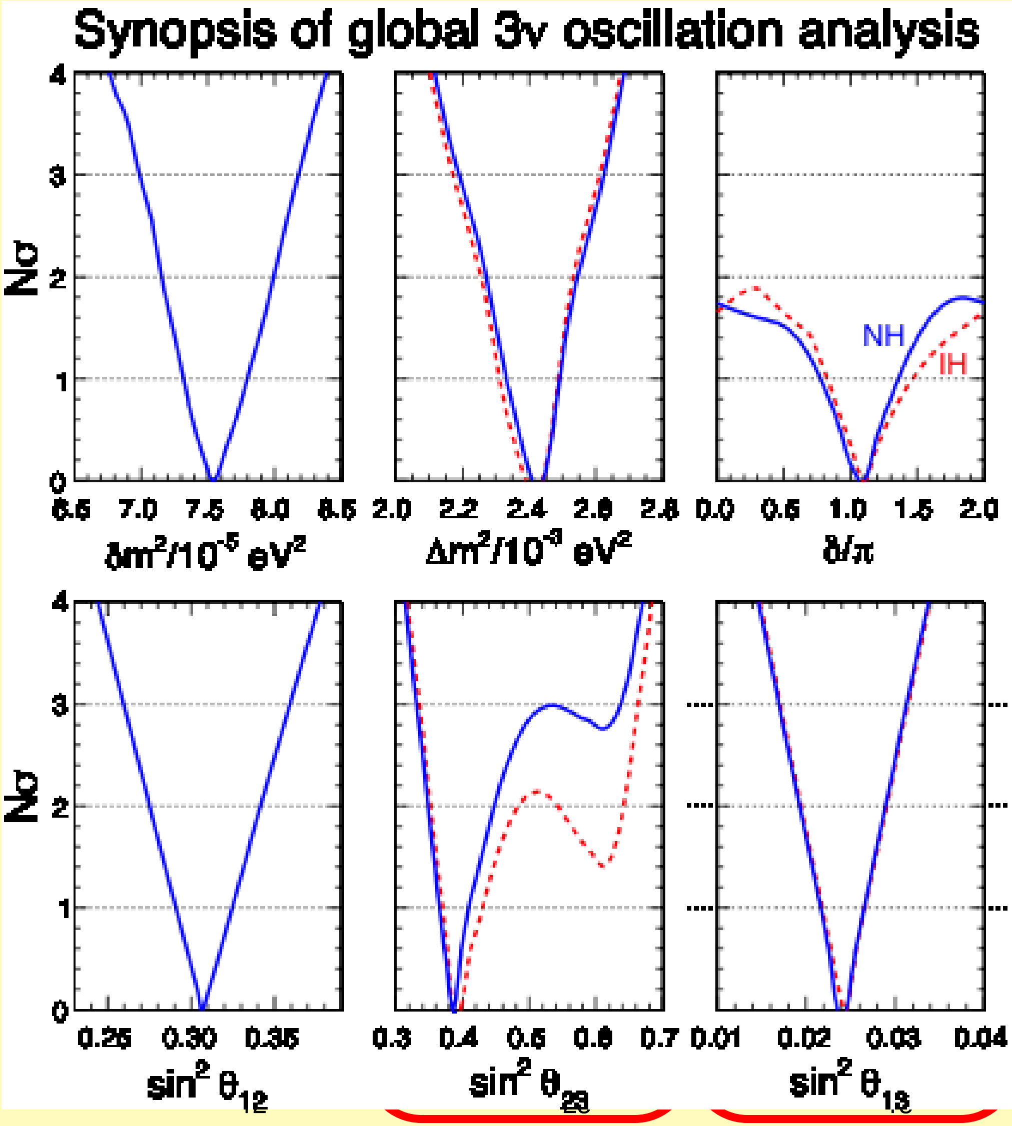
Let us remind you our interpretation, proposed in hep-ph/0506083:

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

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

5. Conclusions

including
ν 2012 data



- Previous hints of $\theta_{13} > 0$ are now measurements! (and basically independent of old/new reactor fluxes)
- Some hints of θ_{23} in the 1st octant are emerging at ~ 2σ, worth exploring by means of atm. and LBL+reac. data
- A possible hint of $\delta_{CP} \sim \pi$ is emerging from atm. data [Is the PMNS matrix real?]
- So far, no hints for NH $\Leftrightarrow$ IH

Numerical 1σ, 2σ, 3σ ranges:

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
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.33 – 2.49	2.27 – 2.55	2.19 – 2.62
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42	2.31 – 2.49	2.26 – 2.53	2.17 – 2.61
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41	2.16 – 2.66	1.93 – 2.90	1.69 – 3.13
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44	2.19 – 2.67	1.94 – 2.91	1.71 – 3.15
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86	3.65 – 4.10	3.48 – 4.48	3.31 – 6.37
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92	3.70 – 4.31	3.53 – 4.84 $\oplus$ 5.43 – 6.41	3.35 – 6.63
δ/π (NH)	1.08	0.77 – 1.36	—	—
δ/π (IH)	1.09	0.83 – 1.47	—	—

Note: above ranges obtained for "old" reactor fluxes. For "new" fluxes, ranges are shifted (by ~ 1/3 σ) for two parameters only: $\Delta\sin^2\theta_{12}/10^{-1} \simeq +0.06$ and $\Delta\sin^2\theta_{13}/10^{-2} \simeq +0.10$

Fractional 1σ accuracy [defined as 1/6 of $\pm 3\sigma$ range]

δm^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	Δm^2
2.6%	5.4%	10%	14%	3.0%

We were already in the precision era for ν physics!

Thanks for your attention!