XLIV Rencontres de Moriond EW

March 13, 2009

Neutrino data and implications for θ_{13}

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Based on work done in collaboration with:

G.L. Fogli, E. Lisi, A. Marrone, A.M. Rotunno

Outline

- Introduction
  The standard 3ν framework

- Re-charting a familiar territory
  The leading mass-mixing parameters

- Exploring an uncharted land
  Hints of non-zero θ_{13}

- Future perspectives and conclusions

The standard 3ν framework

The leptonic mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

$(i = 1, 2, 3)$
$(\alpha = e, \mu, \tau)$

$$U = O_{23}\Gamma_\delta O_{13}\Gamma^\dagger_\delta O_{12}$$

$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$

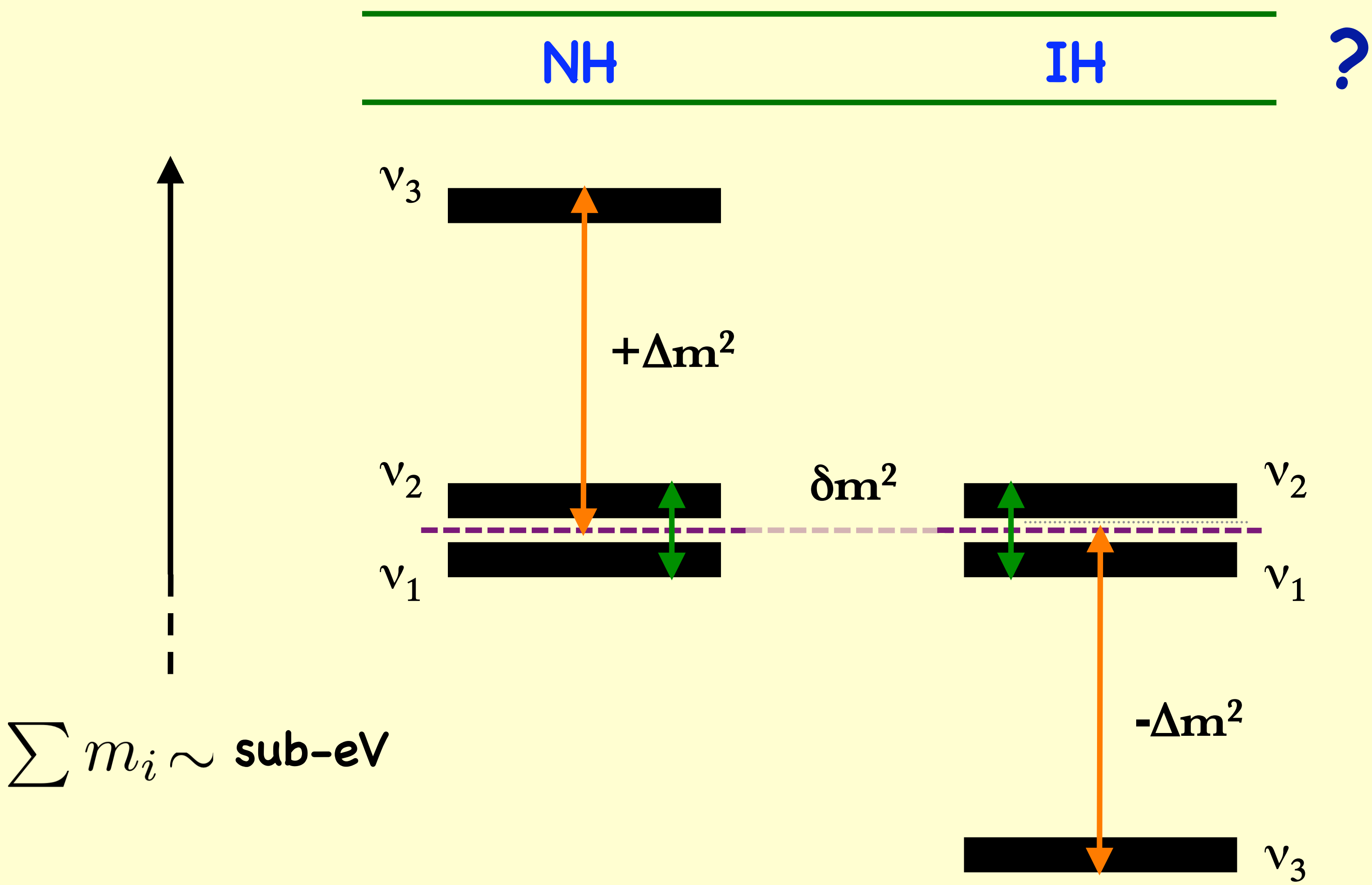
$\delta \in [0, 2\pi]$ Dirac CP-violating phase

unknown

Explicit form:

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

The neutrino mass spectrum



Experimental Sensitivities

leading

Atmospheric, LBL (disapp) → $(\Delta m^2, \ \theta_{23}, \ \theta_{13})$

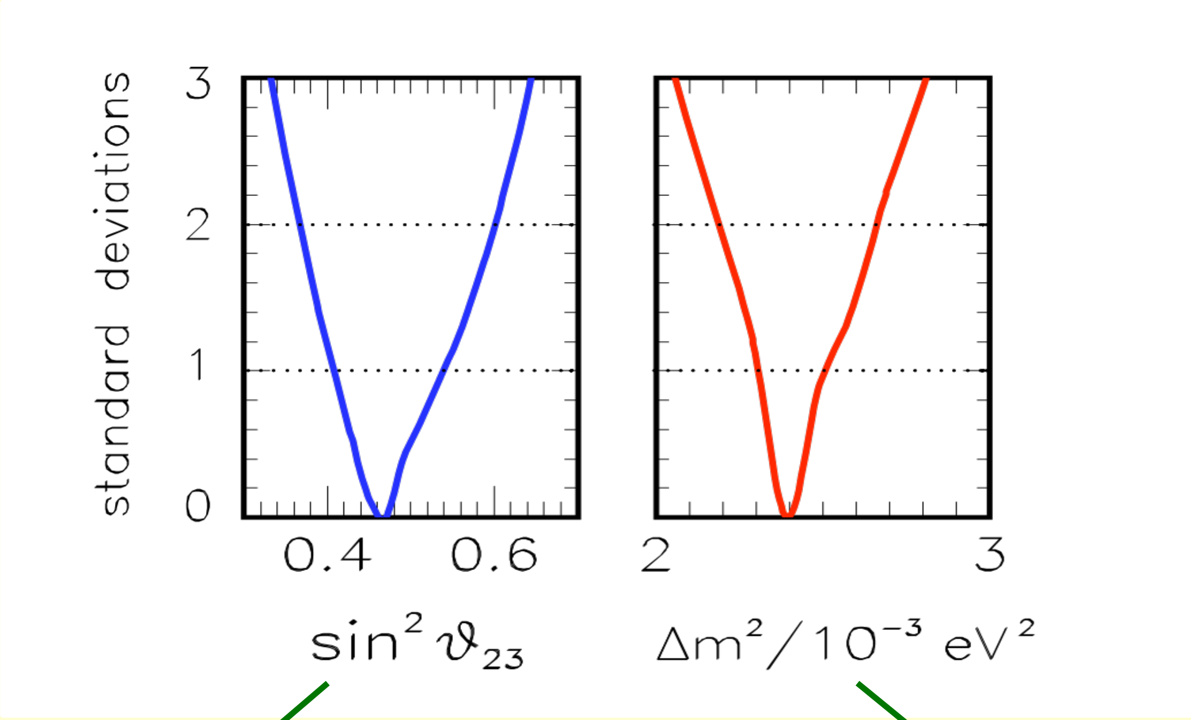
Solar, KamLAND → $(\delta m^2, \ \theta_{12}, \ \theta_{13})$

sub-leading

CHOOZ, MINOS (app) → $(\Delta m^2, \ \theta_{13})$

"fixed" by Atm + LBL

The leading “atmospheric” parameters

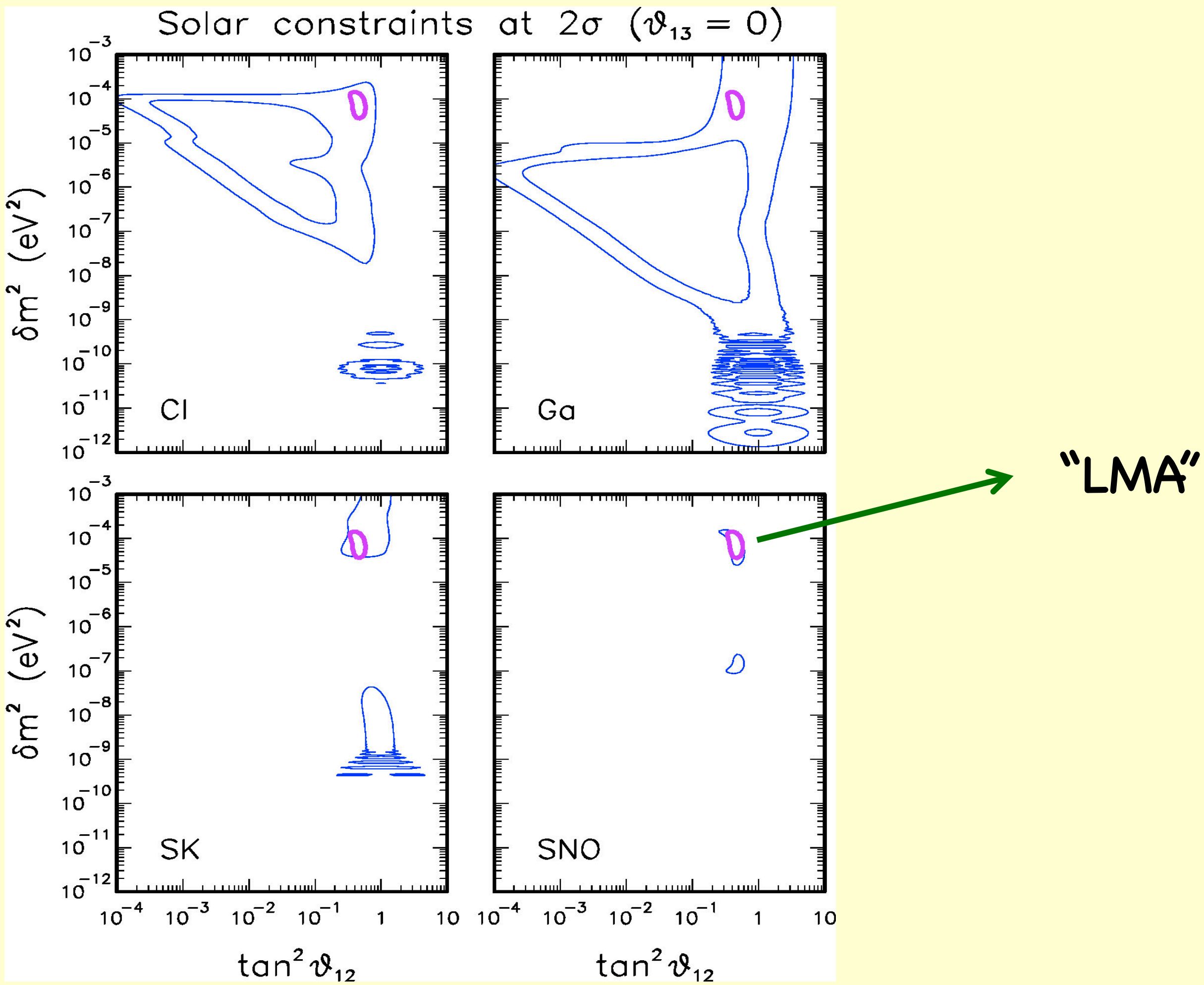


Still dominated by Atm. data
Improvement expected
from MINOS

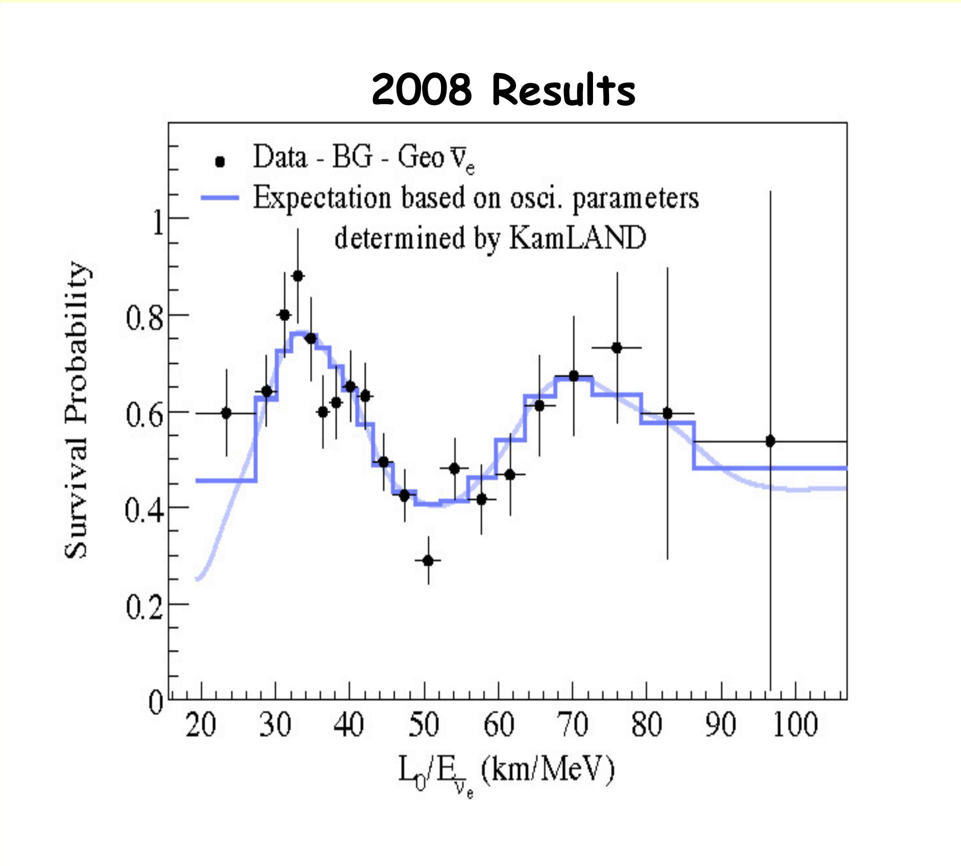
Precision quickly increasing
after each new
MINOS data release

Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

Solar ν data consistent with MSW transitions



Spectacularly confirmed by KamLAND

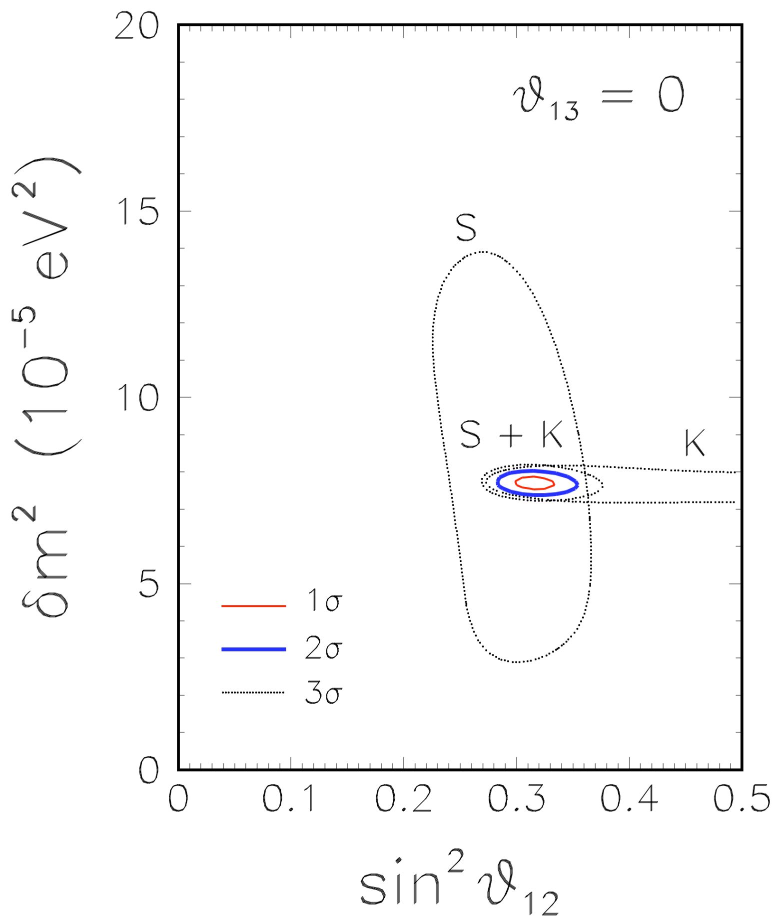


Precision measurement of spectral distortions

Osc. pattern observed over one entire cycle

Determination of δm^2 with high precision

2ν Solar + KamLAND constraints

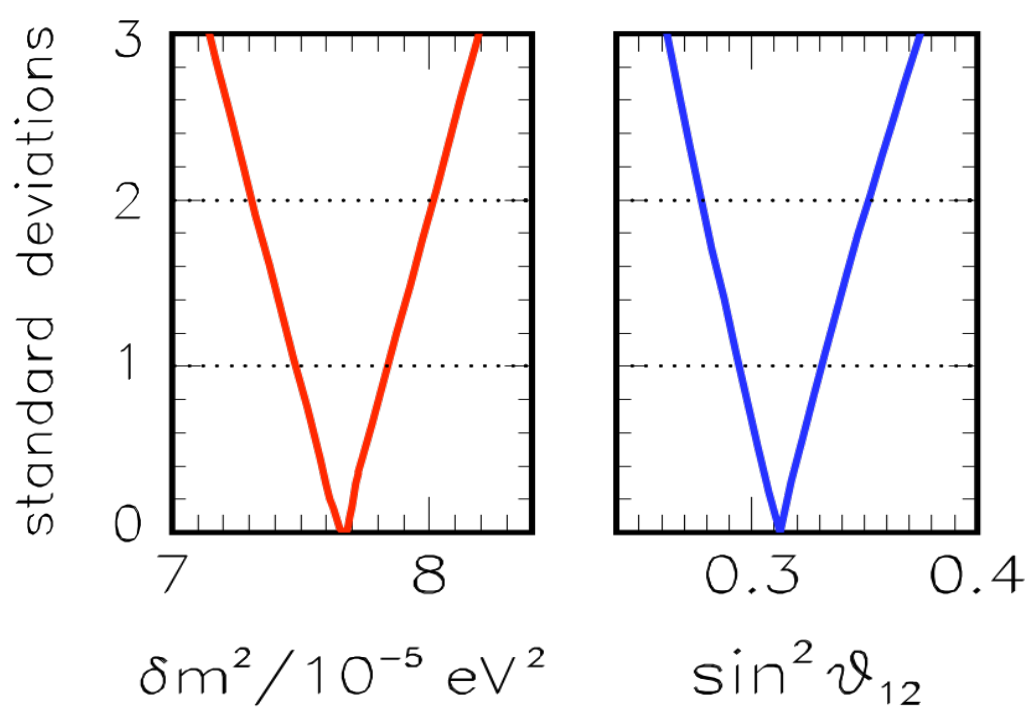


KamLAND dominates δm^2 determination

Interplay of Solar and KamLAND in determining θ_{12}

But small tension among them is present

The leading "solar" parameters



Errors are linear, precision era now entered

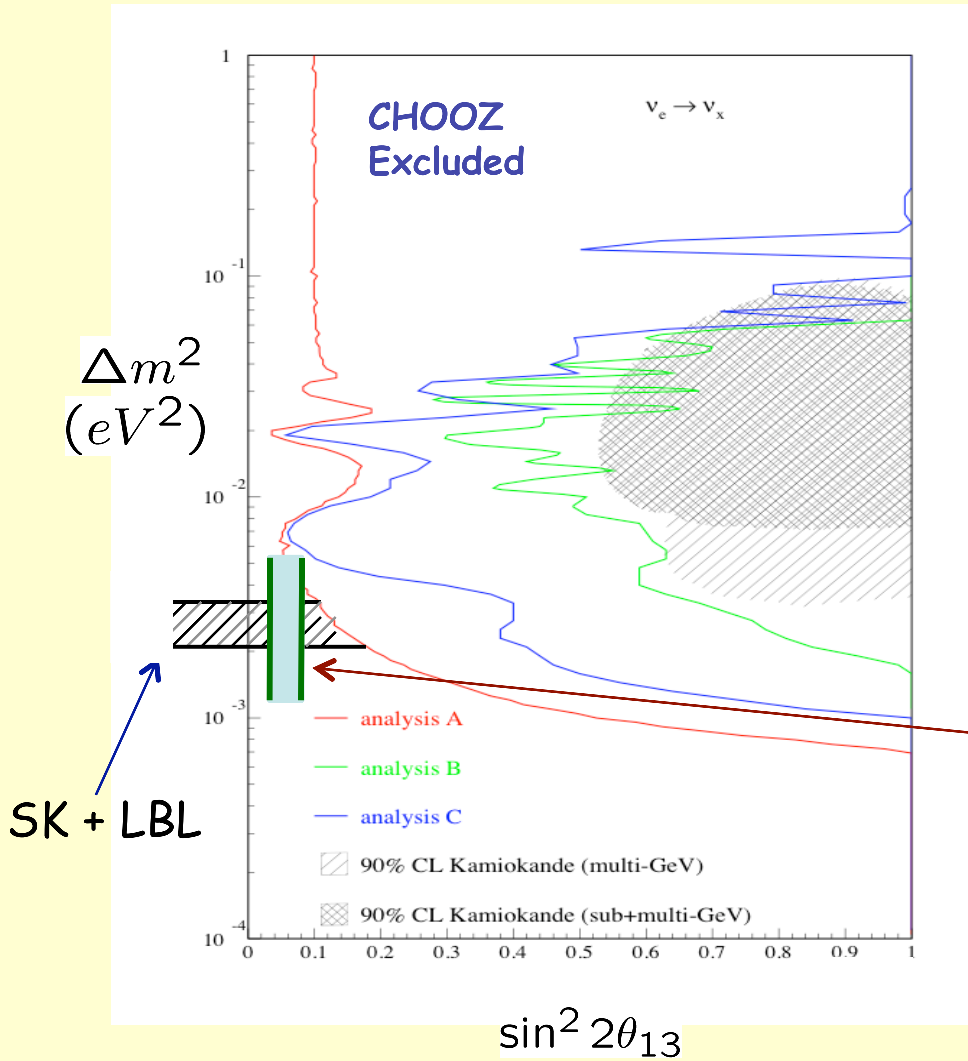
Fogli et al., Phys. ReV. D 78, 033010 (2008) [arXiv:0805.2517v3]

Hints of $\theta_{13} > 0$

G.L Fogli, E. Lisi, A. Marrone, A.P., A.M. Rotunno

arXiv:0806.2649 [hep-ph]
PRL 101, 141801 (2008)

CHOOZ and 3ν global analyses: Interplay in pinning down θ_{13}



In the past

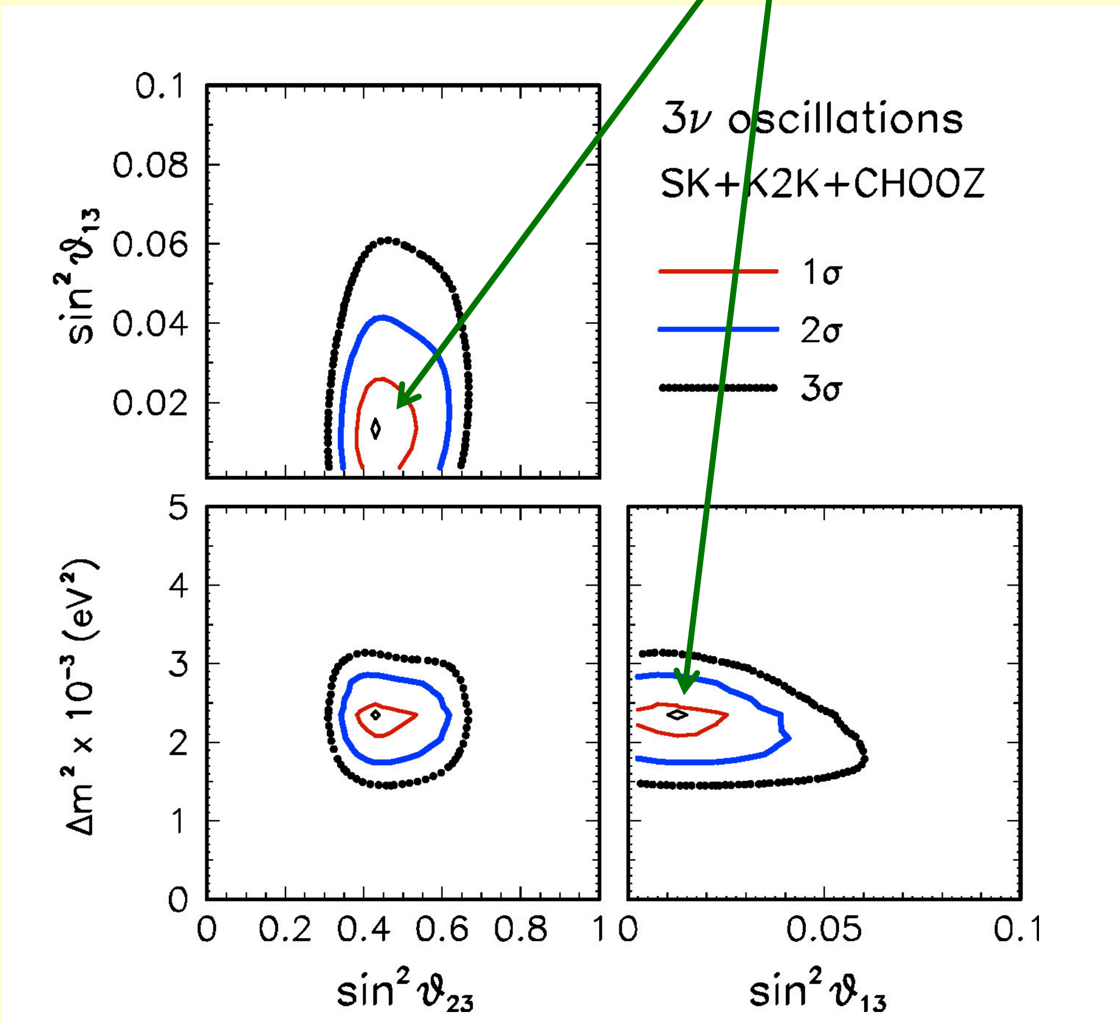
3ν global analyses have
first corroborated
&
then strengthened
the CHOOZ upper bound

Now

They seem capable to
go beyond
the CHOOZ sensitivity

The “old” hint
from atmospheric data

weak (~1 sigma) preference for $\theta_{13}>0$



A possible source:
excess of sub-GeV electron-like events partially explained by 3ν subleading effects driven by the "solar" splitting δm^2

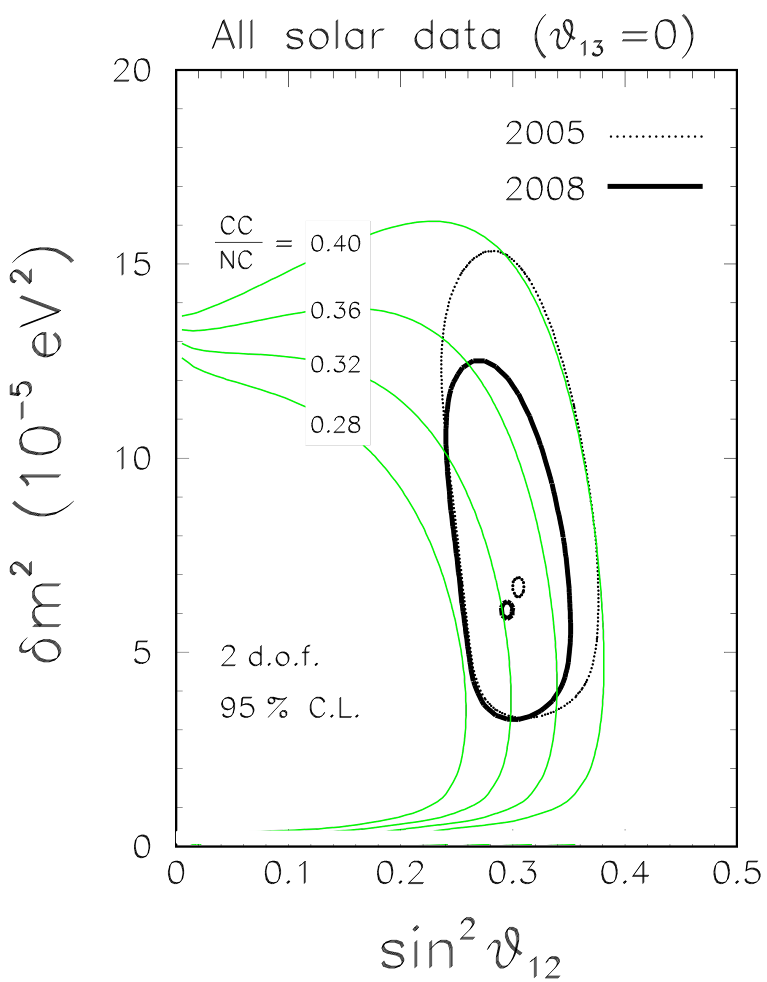
In the past this "hint" was not corroborated by solar & KamLAND, which systematically preferred $\theta_{13} = 0$

But such a trend has recently changed…

G.L. Fogli, E. Lisi, A. Marrone, A.P., Prog. Part. Nucl. Phys. 57, 742 (2006)

The new hint from solar + KamLAND

Solar ν data: from 2005 to 2008



	2005 SNO-II	2008 SNO-III
$\frac{CC}{NC} =$	0.34 ± 0.38	0.301 ± 0.33

- Central value lower than before

best fit of θ_{12}
at a slightly lower value

- Error reduced when combined

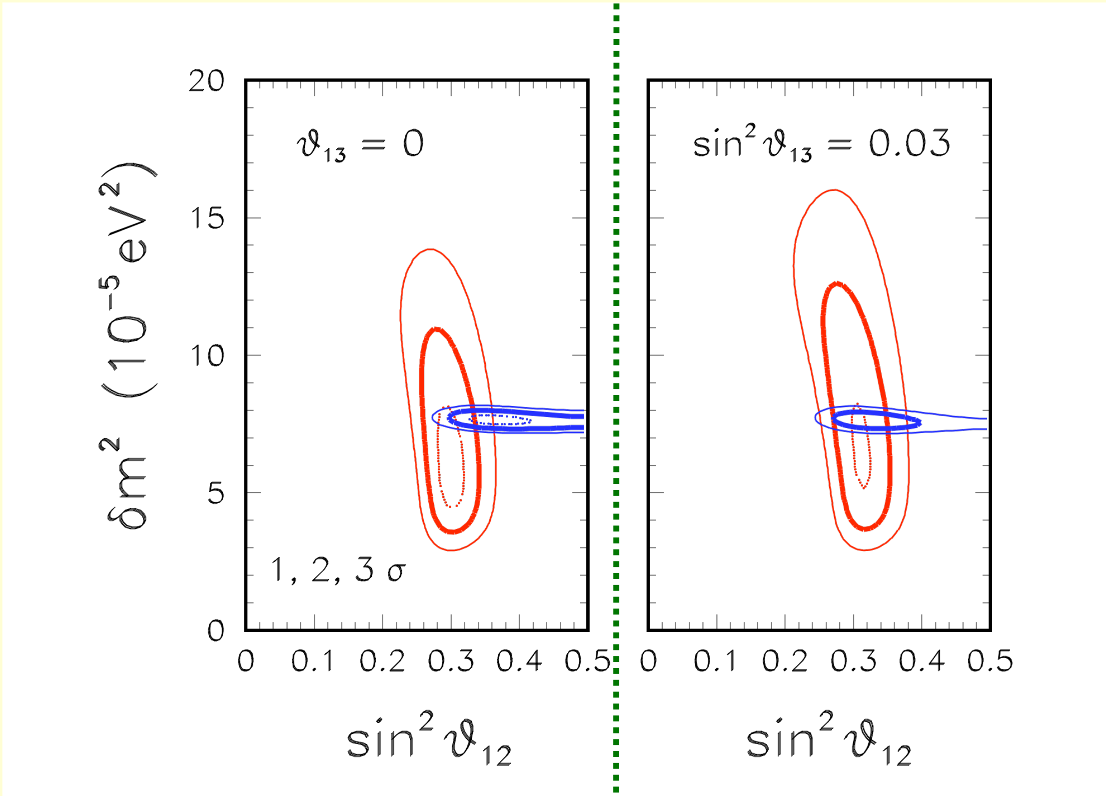
range allowed for θ_{12}
appreciably narrowed
(now ~ symmetric)

apparently
a small change!

…but big enough to give rise to a tension with KamLAND…

…which, however, can be alleviated for $\theta_{13}>0$

$\theta_{13} = 0$



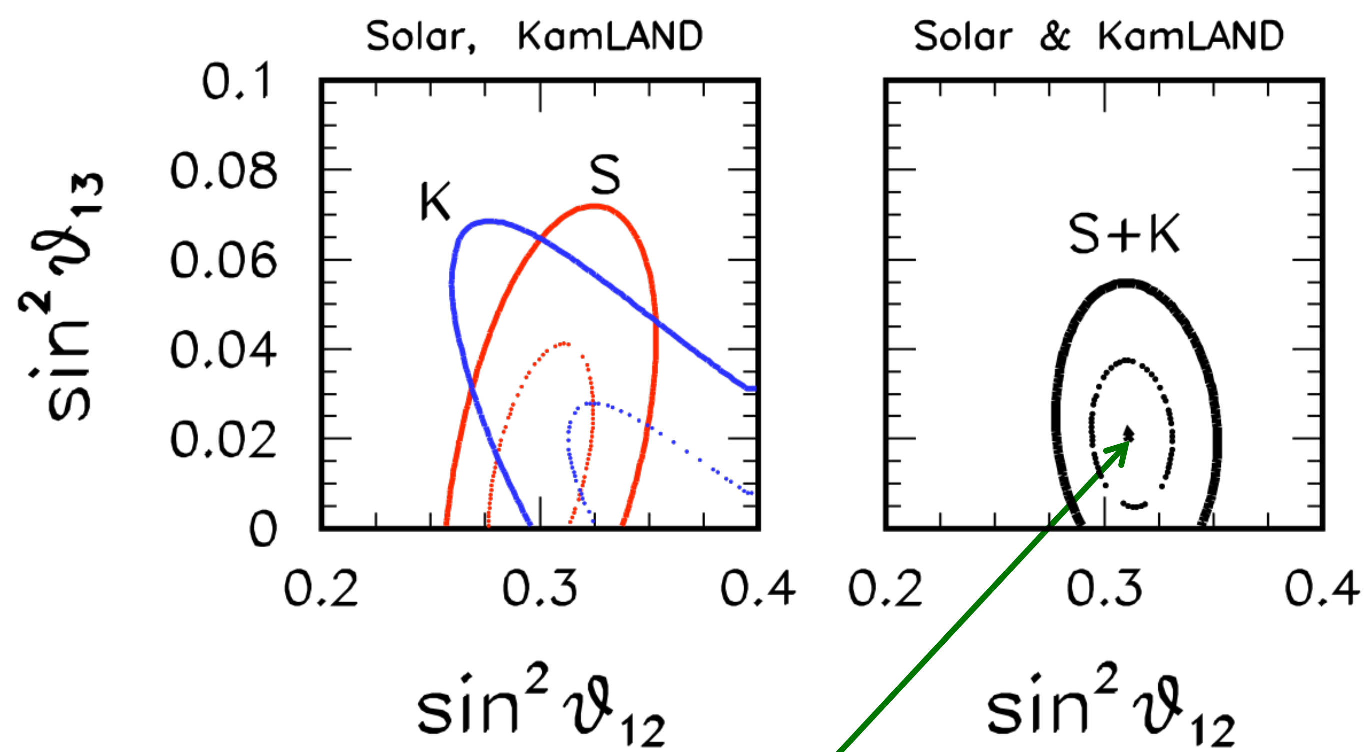
$\theta_{13} > 0$

Solar and KamLAND prefer different values of θ_{12}
No overlap at 1σ level

Solar prefer higher θ_{12}
KamLAND prefers lower θ_{12}
Disagreement reduced*

*See also Balantekin and Yilmaz, J. Phys. G. 35, 075007 (2008)

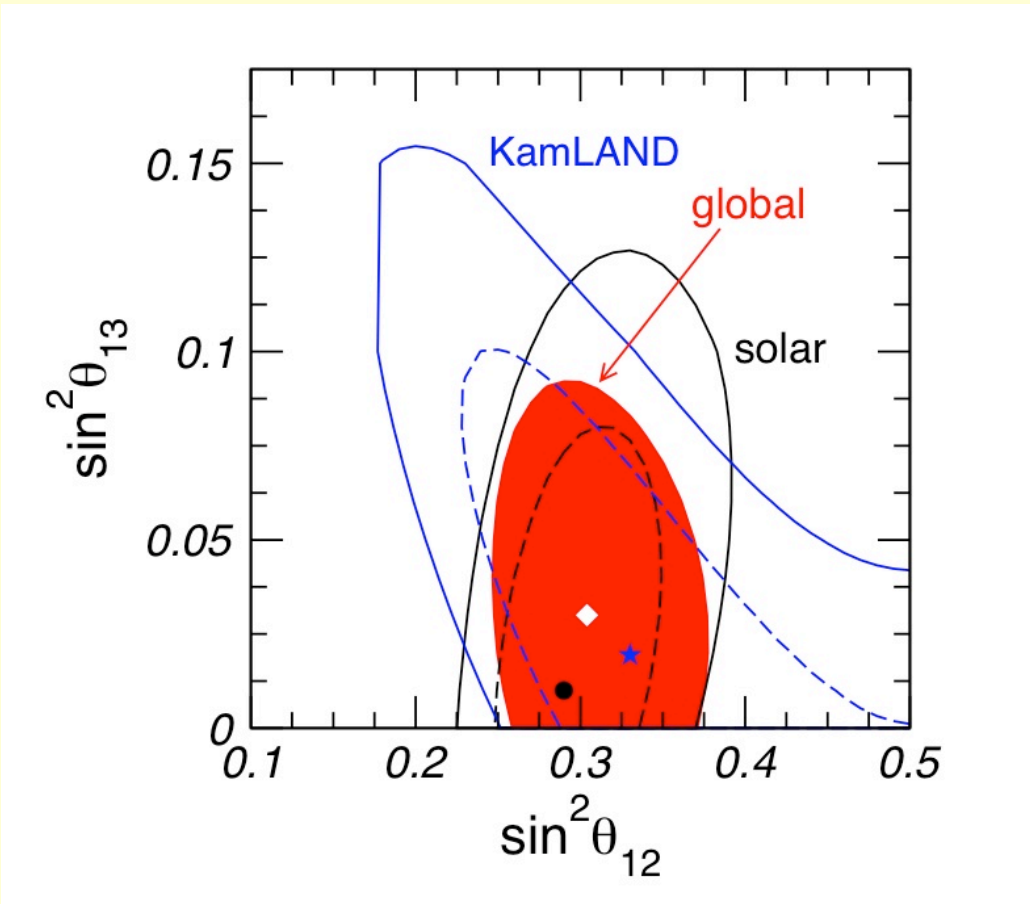
Interplay of Solar and KamLAND



~1.2σ preference for $\theta_{13} > 0$

Comparison with other existing analyses

Schwetz, Tortola, Valle, arXiv:0808.2016



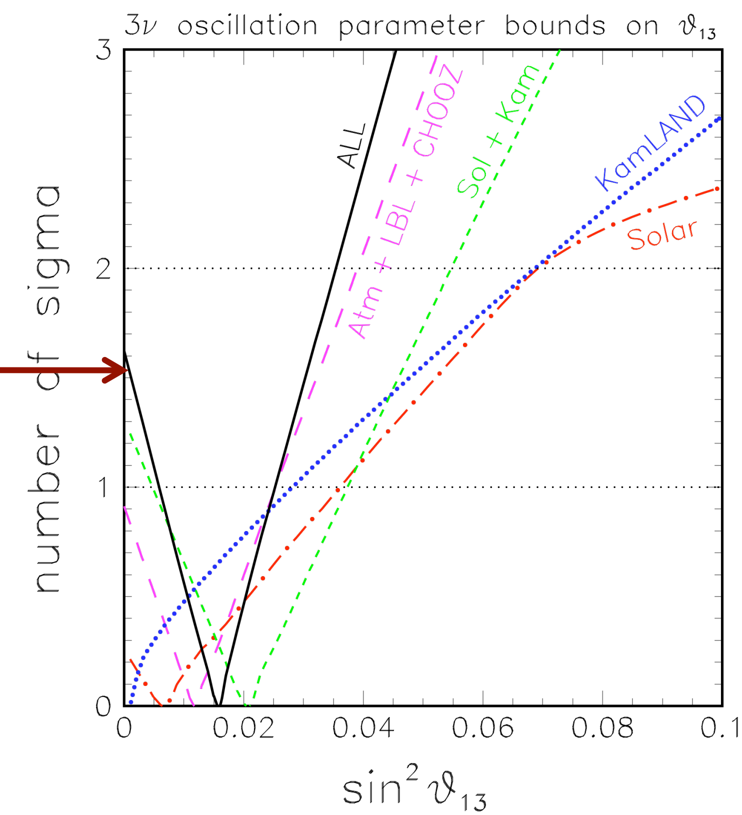
preference for $\theta_{13}>0$ found at a slightly higher CL (~1.5 sigma)

Consensus on the the sol+kam hint

The global hint

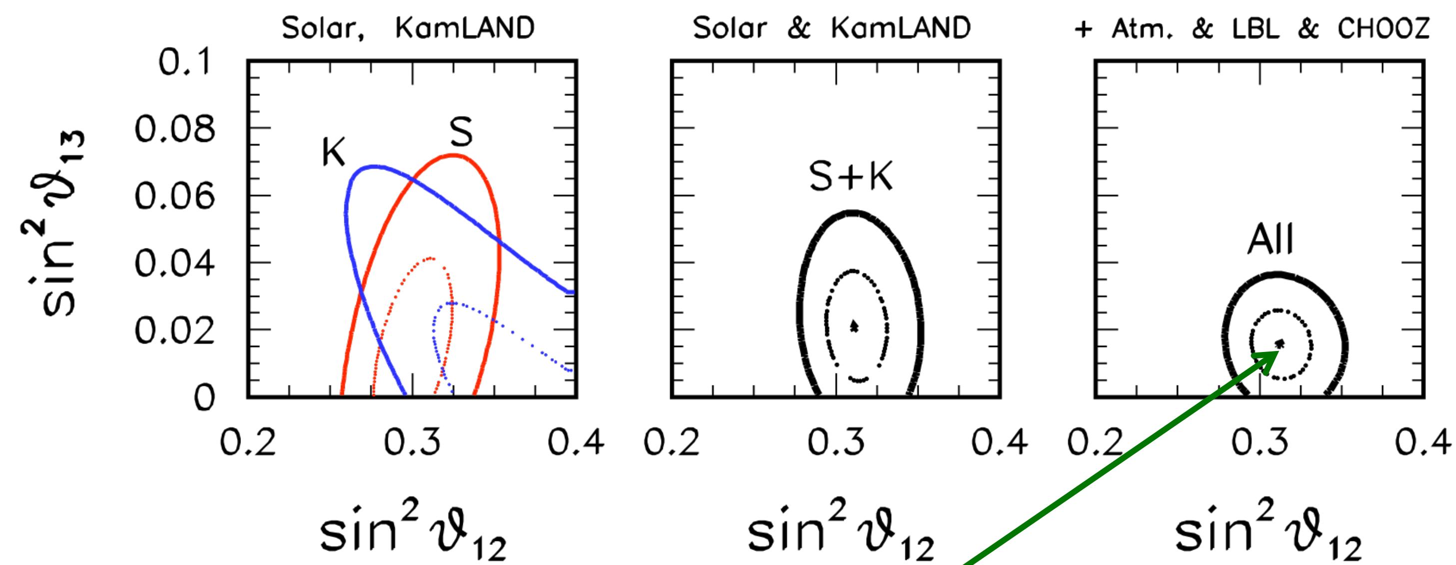
Combining all data
we find an overall
preference for θ_{13}>0 at

1.6 sigma (90% CL)



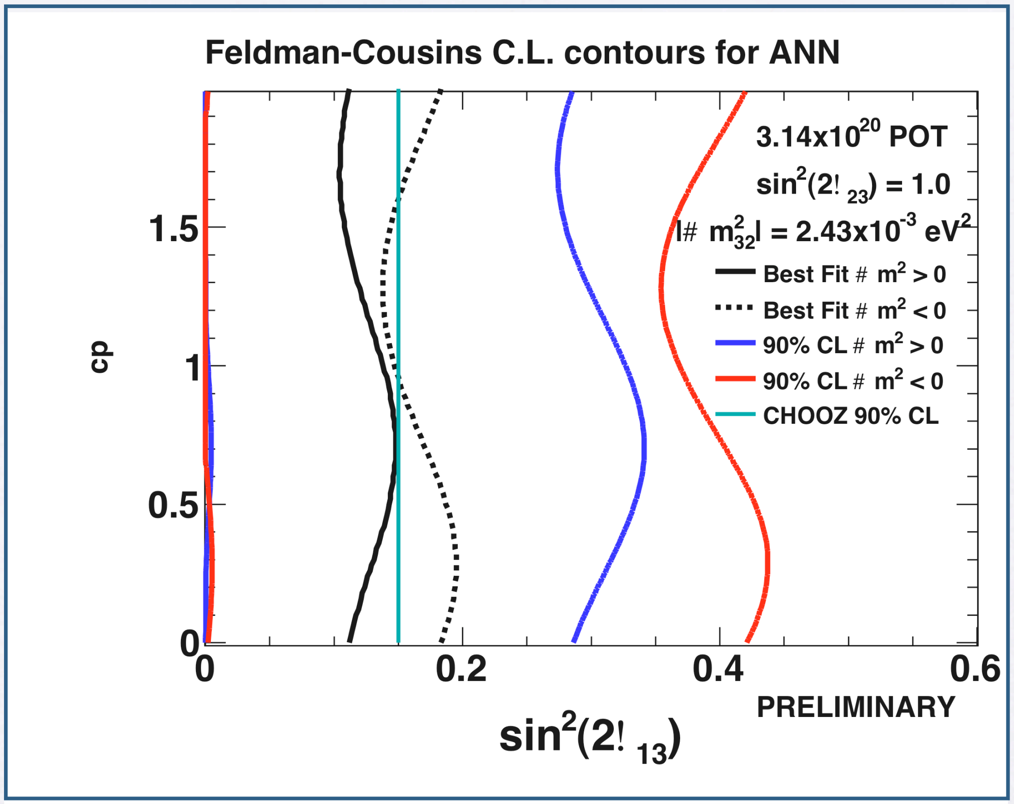
Solar and Kamland
prefer θ_{13}>0
only in combination:
synergy

Status of the electron neutrino mixing



$$
\begin{aligned}
|U_{e1}|^2 &= \cos^2\theta_{13}\cos^2\theta_{12} \sim 0.667 \\
|U_{e2}|^2 &= \cos^2\theta_{13}\sin^2\theta_{12} \sim 0.307 \\
|U_{e3}|^2 &= \sin^2\theta_{13} \sim 0.016
\end{aligned}
$$

27^{th} Feb 2009,
a new hint from MINOS ν_e appearance ?



$\theta_{13} = 0$
disfavored at ~ 90%

The Collaboration,
conservatively,
does not attach any particular
relevance to this fact

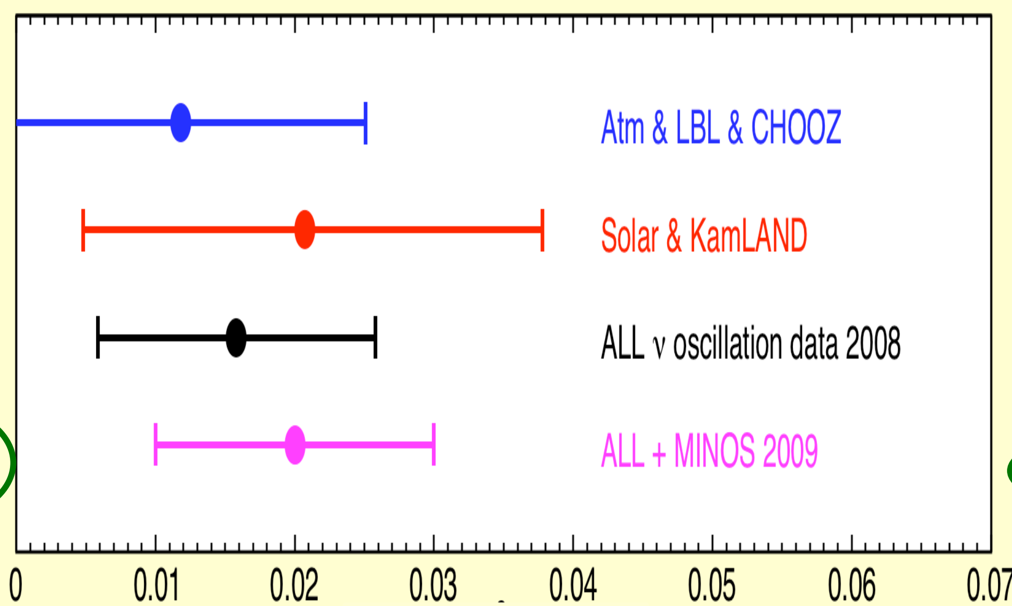
However, combining
their results with ours...

By courtesy of M. Sanchez

...an overall hint at 2 sigma level emerges

Status as of March 2009

Hint		1σ range
$0.9\ \sigma$	Atm & LBL & CHOOZ	0.012 ± 0.013
$1.2\ \sigma$	Solar & KamLAND	0.021 ± 0.017
$1.6\ \sigma$	ALL ν oscillation data 2008	0.016 ± 0.010
$\sim 2\ \sigma$	ALL + MINOS 2009	$\mathbf{0.02 \pm 0.01}$



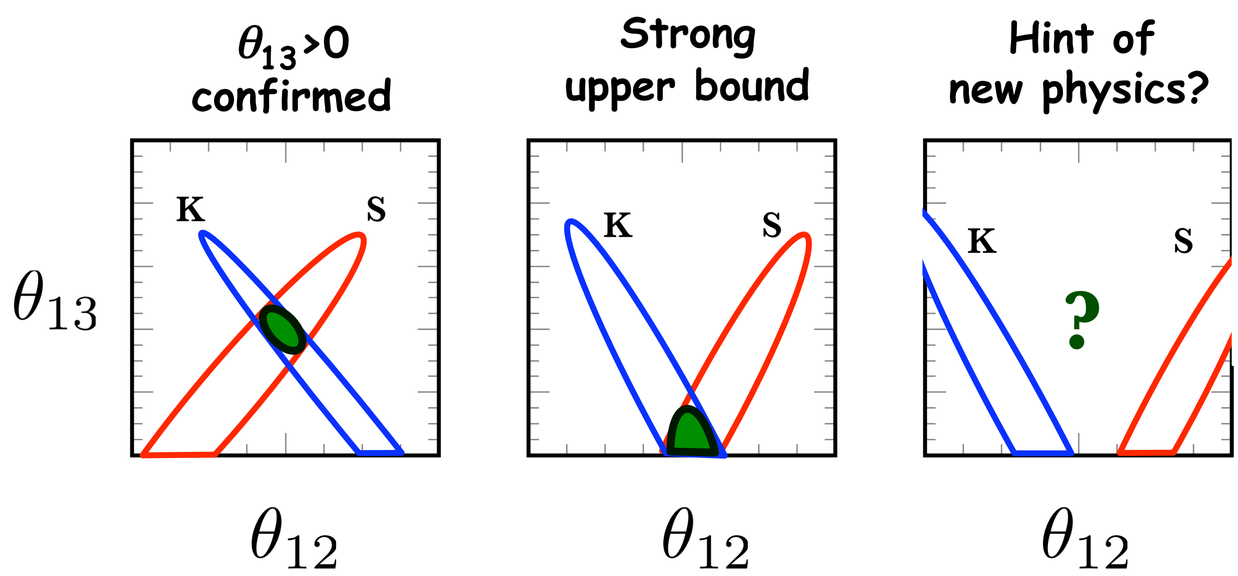
$$\sin^2 \theta_{13}$$

Future perspectives

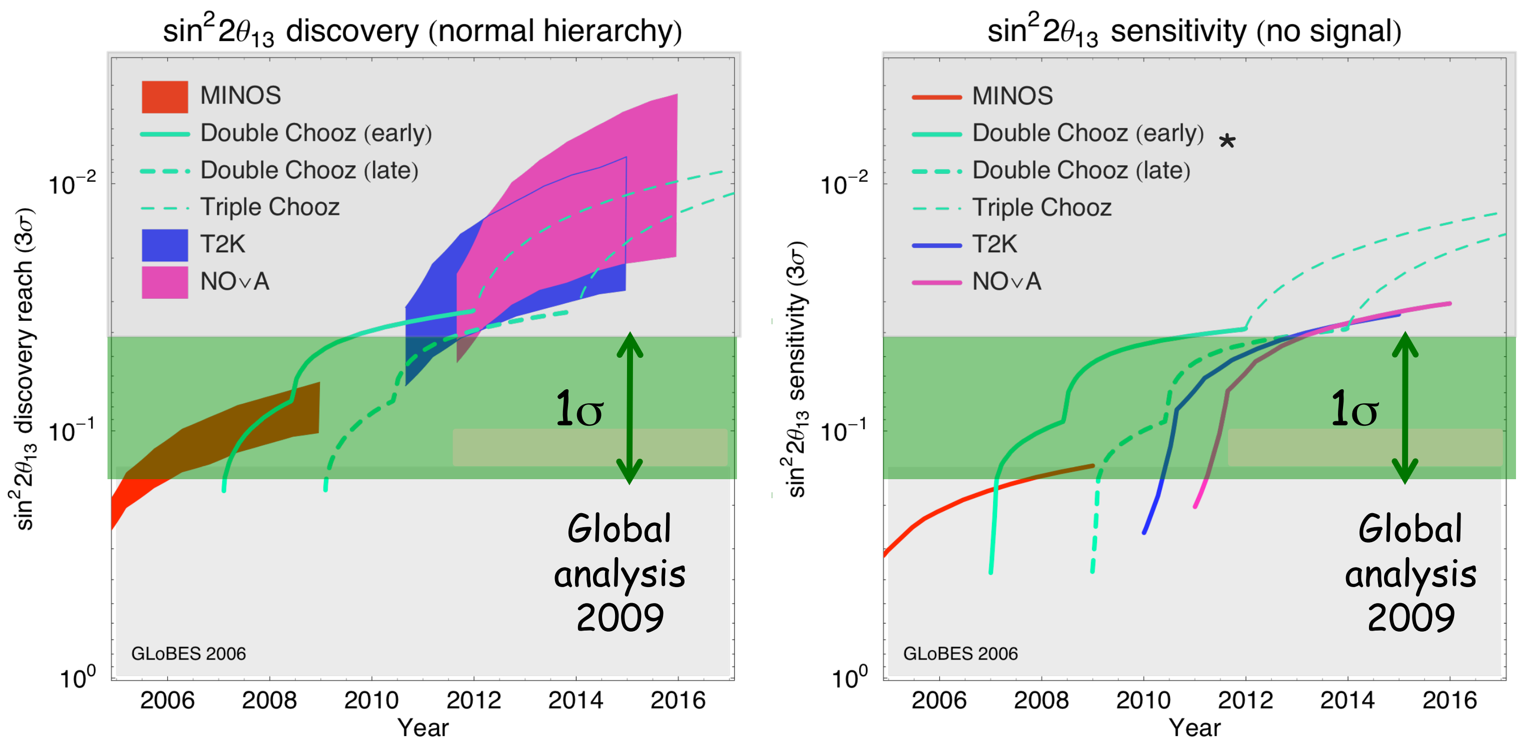
New relevant information expected from:

KamLAND	New data expected. Furthermore, it has been noted that in a multi-reactor setup one expects partial cancellations of random distributed errors (Djurcic et al., 0808.0747 [hep-exp]). Possible impact on the of "S+K hint".
SNO	Low energy threshold analysis (LETA) underway. Increased NC statistics. See talk by A. McDonald, at Neutrino Telescopes 2009.
Atm.	A complete 3ν analysis including subleading effects induced by "solar parameters" is expected from the SK collaboration. See talk by M. Nakahata at Neutrino Telescopes 2009.
MINOS	Results with double statistics expected soon. See talk by M. Sanchez.
D-CHOOZ	First data, using a single detector, to be collected before the end of this year. First results could be expected by the summer of 2010.
Daya-Bay	First results expected in 2011

What we may expect from Solar and KamLAND



What we may expect from reactor and accelerator exp.



Adapted from Huber et. al JHEP 0605, 072 (2006)

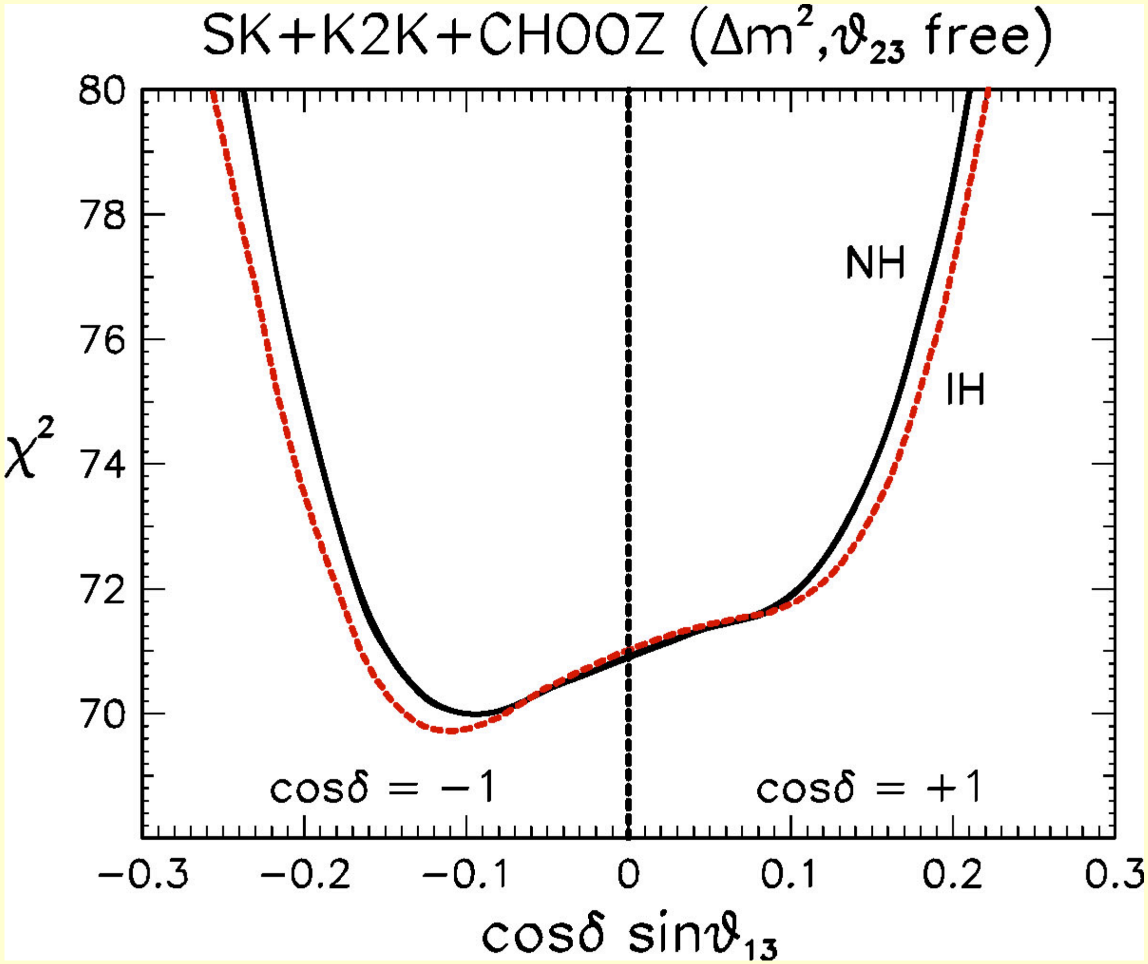
Conclusions

- All data fit within the standard 3ν framework
- Three independent hints of θ_{13}>0
- Global hint now at the 2 sigma level (95% C.L.)
- Further data needed to clarify the issue
- **If the trend persists**:

  In the near future (~2 years) it is conceivable to envisage a scenario with several concurrent hints, each unable to provide decisive indication.

Back-up slides

3ν analysis including sub-leading LMA effects



G.L. Fogli, E. Lisi, A. Marrone, A.P., Prog. Part. Nucl. Phys. 57, 742 (2006)

Excess of electron events induced by 3ν subleading effects

$$\frac{N_e}{N_e^0} - 1 = (P_{ee} - 1) + r\, P_{e\mu} \longrightarrow$$

zero when both θ_{13}=0 & δm^2 = 0

ν_μ / ν_e flux ratio

sub-GeV $r \sim 2$

multi-GeV $r \sim 3.5$

Constant density approximation

$$\frac{N_e}{N_e^0} - 1 \simeq \Delta_1 + \Delta_2 + \Delta_3$$

"θ_{13} term"

$$\Delta_1 \simeq \sin^2 2\tilde{\theta}_{13} \sin^2\left(\Delta m^2 \frac{\sin 2\theta_{13}}{\sin 2\tilde{\theta}_{13}} \frac{L}{4E}\right) \cdot (r s_{23}^2 - 1)$$

"δm^2 term"

$$\Delta_2 \simeq \sin^2 2\tilde{\theta}_{12} \sin^2\left(\delta m^2 \frac{\sin 2\theta_{12}}{\sin 2\tilde{\theta}_{12}} \frac{L}{4E}\right) \cdot (r c_{23}^2 - 1)$$

"Interference term" *

$$\Delta_3 \simeq \sin^2 2\tilde{\theta}_{12} \sin^2\left(\delta m^2 \frac{\sin 2\theta_{12}}{\sin 2\tilde{\theta}_{12}} \frac{L}{4E}\right) \cdot r s_{13} c_{13}^2 \sin 2\theta_{23} (\tan 2\tilde{\theta}_{12})^{-1}$$

*O.L.G Peres and A.Yu. Smirnov , Nucl. Phys. B 456, 204 (1999); ibidem 680, 479 (2004)

Expressions valid for $[\nu, \quad \text{N.H.}, \quad \delta = 0]$:

Mixing angles in matter

$$\frac{\sin 2\theta_{13}}{\sin 2\tilde{\theta}_{13}} \simeq \sqrt{\left(\frac{A}{\Delta m^2 + \frac{\delta m^2}{2}\cos 2\theta_{12}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}$$

$$\frac{\sin 2\theta_{12}}{\sin 2\tilde{\theta}_{12}} \simeq \sqrt{\left(\frac{Ac_{13}^2}{\delta m^2} - \cos 2\theta_{12}\right)^2 + \sin^2 2\theta_{12}}$$

Order of magnitude of the potential

$$\frac{A}{\Delta m^2} \simeq 1.3 \left(\frac{2.4 \times 10^{-3}\ \text{eV}^2}{\Delta m^2}\right)\left(\frac{E}{10\ \text{GeV}}\right)\left(\frac{N_e}{2\ \text{mol/cm}^3}\right)$$

$$\frac{A}{\delta m^2} \simeq 3.8 \left(\frac{8 \times 10^{-5}\ \text{eV}^2}{\delta m^2}\right)\left(\frac{E}{1\ \text{GeV}}\right)\left(\frac{N_e}{2\ \text{mol/cm}^3}\right)$$

"Swapping" relations

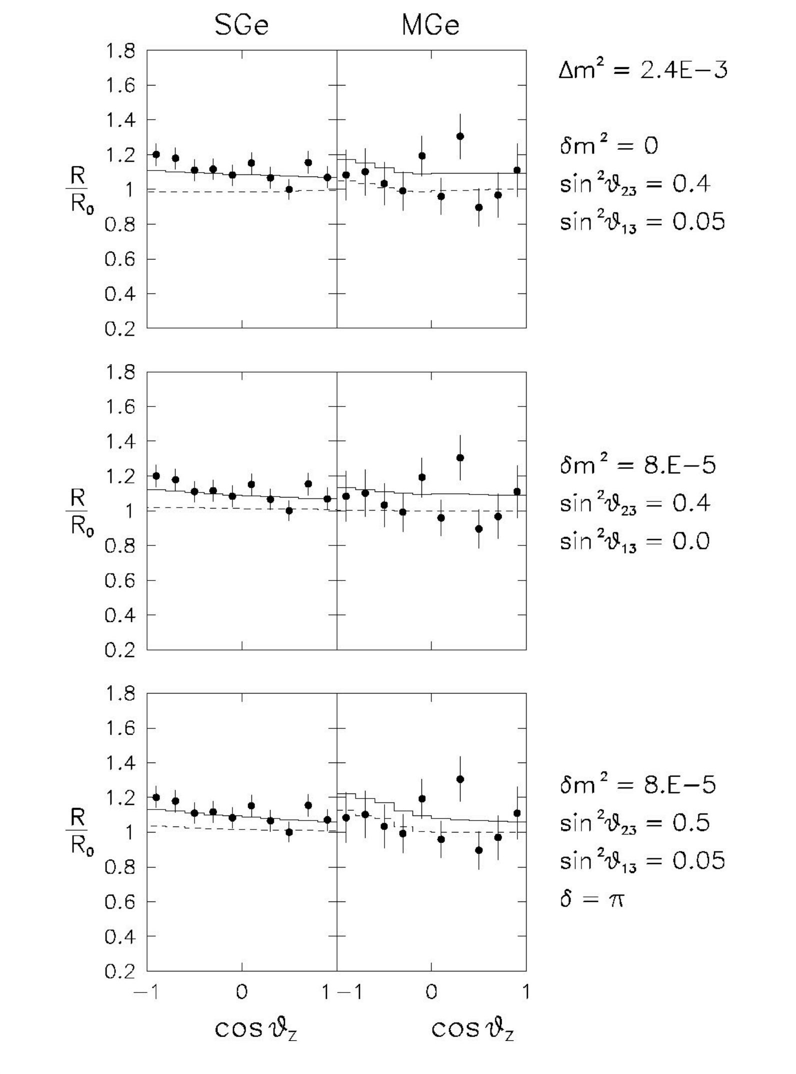
$$\begin{aligned} +A &\to -A & &(\nu \to \bar{\nu}) \\ +\Delta m^2 &\to -\Delta m^2 & &(\text{N.H.} \to \text{I.H.}) \\ +s_{13} &\to -s_{13} & &(\delta = 0 \to \delta = \pi) \end{aligned}$$

Exact numerical examples

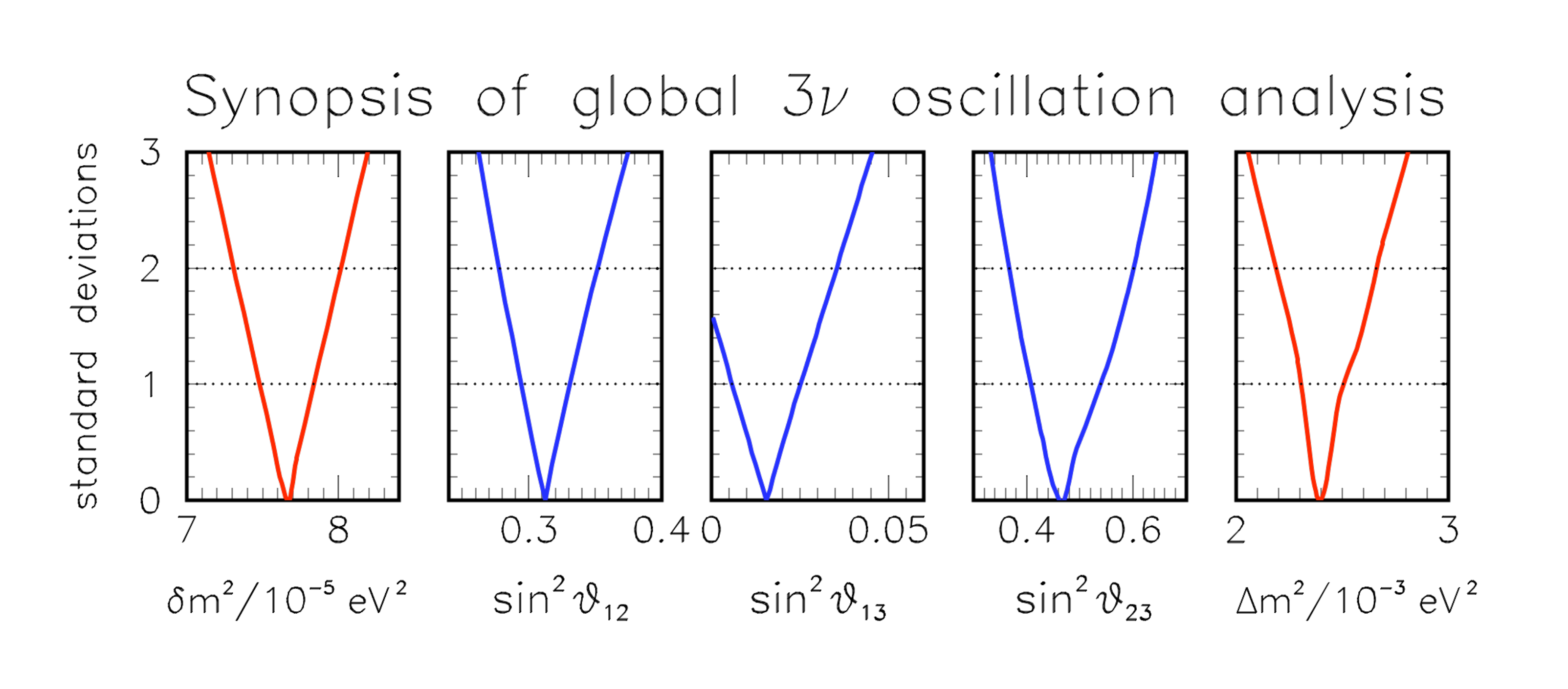
"θ_{13} term" dominant

"δm^2 term" dominant

"Interference term" dominant
(only in sub-GeV)



Fogli et al., Prog. Part. Nucl. Phys. 57, 742 (2006)

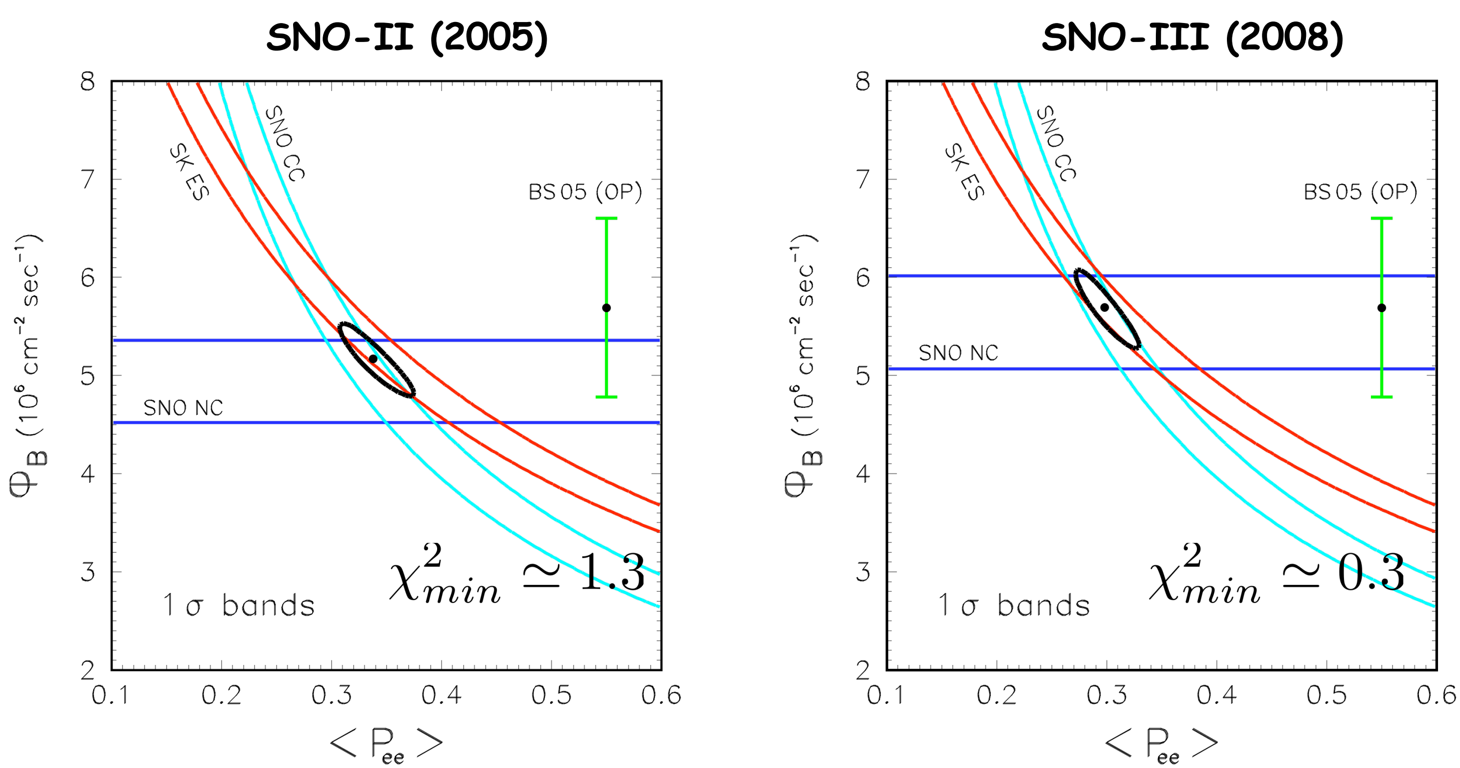


Parameter	$\delta m^2/10^{-5}$ eV^2	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}$ eV^2
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48 – 7.83	0.294 – 0.331	0.006 – 0.026	0.408 – 0.539	2.31 – 2.50
2σ range	7.31 – 8.01	0.278 – 0.352	< 0.036	0.366 – 0.602	2.19 – 2.66
3σ range	7.14 – 8.19	0.263 – 0.375	< 0.046	0.331 – 0.644	2.06 – 2.81

Model-independent consistency checks

1) "internal" consistency among SNO (CC,NC) and SK (ES)
2) consistency among NC measurement and Solar Model

both already good ...and... now even better



Origin of the different correlations

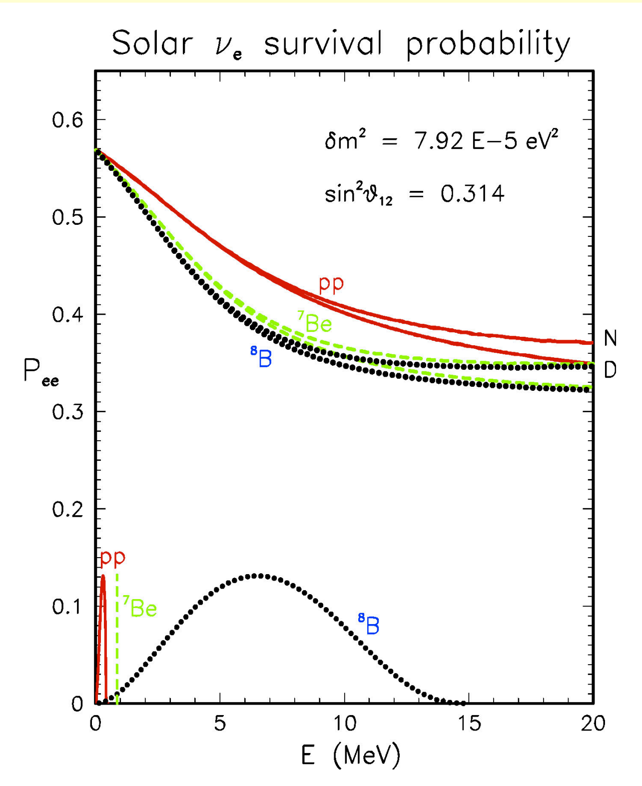
Different relative sign for $(\theta_{12}, \theta_{13})$ in P_{ee}
of Solar (high-E dominated) vs KamLAND

High-E solar
(adiabatic MSW) $\longrightarrow$ $$P_{ee} \simeq (1 - 2s_{13}^2)(+ s_{12}^2)$$

KamLAND
(vacuum) $\longrightarrow$ $$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2 c_{12}^2 \sin^2 \phi)$$

oscillation phase $\phi = \dfrac{\delta m^2 L}{4E}$

Solar ν's probe two different regimes



High-E matter dominated

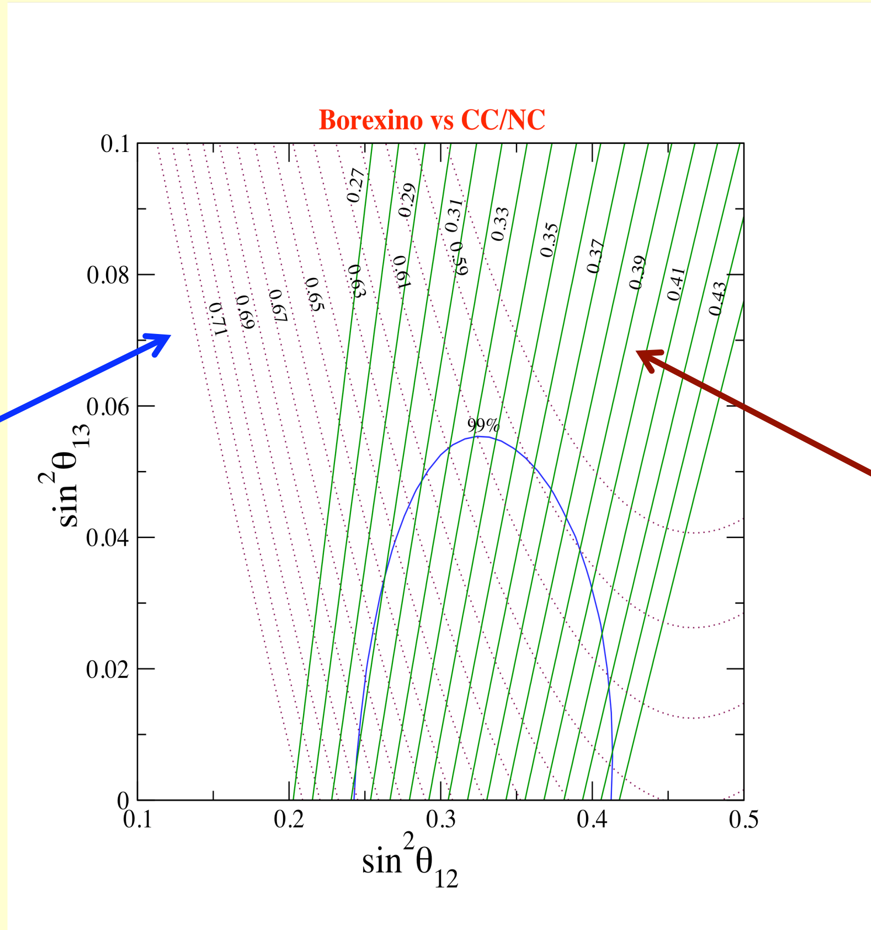
$$P_{ee} \simeq (1 - 2s^2_{13})(+ s^2_{12})$$

Low-E averaged "vacuum-like"

$$P_{ee} \simeq (1 - 2s^2_{13})(1 - 2s^2_{12}c^2_{12})$$

Low-E behavior is similar to that probed in KamLAND, so we expect an analogous complementarity of high-E and (future) low-E

“Contrasting” low-E with high-E data



Low-E

(Borexino)

High-E

(SNO)

Goswami and Smirnov, PRD 72, 053011 (2005)