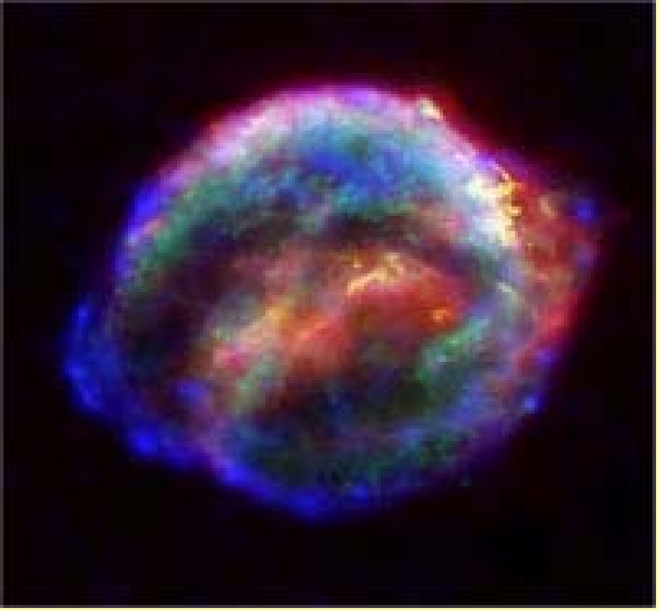
Neutrino masses and mixings: a global analysis

(with a specific emphasis on possible hints in favor of $\theta_{13} \neq 0$)

Gianluigi Fogli



Kepler's Supernova Remnants

Outline (Three-acts structure)

1. FLASH-BACK: From NO-VE 2008
2. ACT ONE: The solar + KamLAND hint for $\theta_{13} \neq 0$
3. ACT TWO: The atmospheric (+ CHOOZ + LBL) hint for $\theta_{13} \neq 0$
4. ACT THREE: An approximate updated value for θ_{13}

Based on work done in collaboration with:
E. Lisi, A. Marrone, A. Palazzo, A.M. Rotunno

Spiral Galaxy in Andromeda

FLASH-BACK: Four slides from NO-VE 2008

NO-VE 2008, April 15

(prepared after the KamLAND 2008 release, but before SNO 2008 release)

Concerning

(1/4)

What we would like to know

- Hierarchy (normal or inverted)
- CP in the ν sector
- θ_{13} mixing

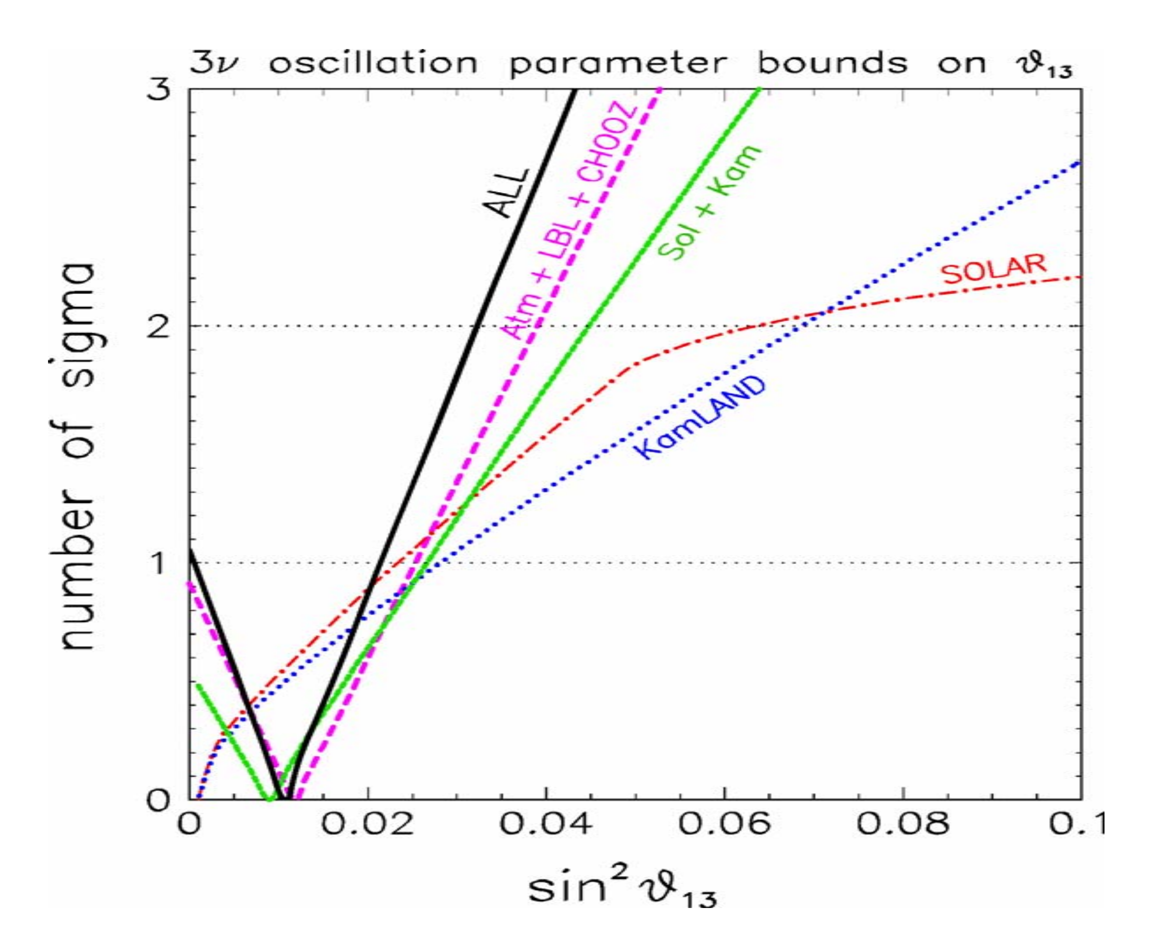
Some aspect is currently "hidden" below **1**σ C.L.

A recent example:

slight preference for

$\sin^2\theta_{13} \sim 0.01$

from the combination of solar+reactor 2008 data
(green curve in the figure)

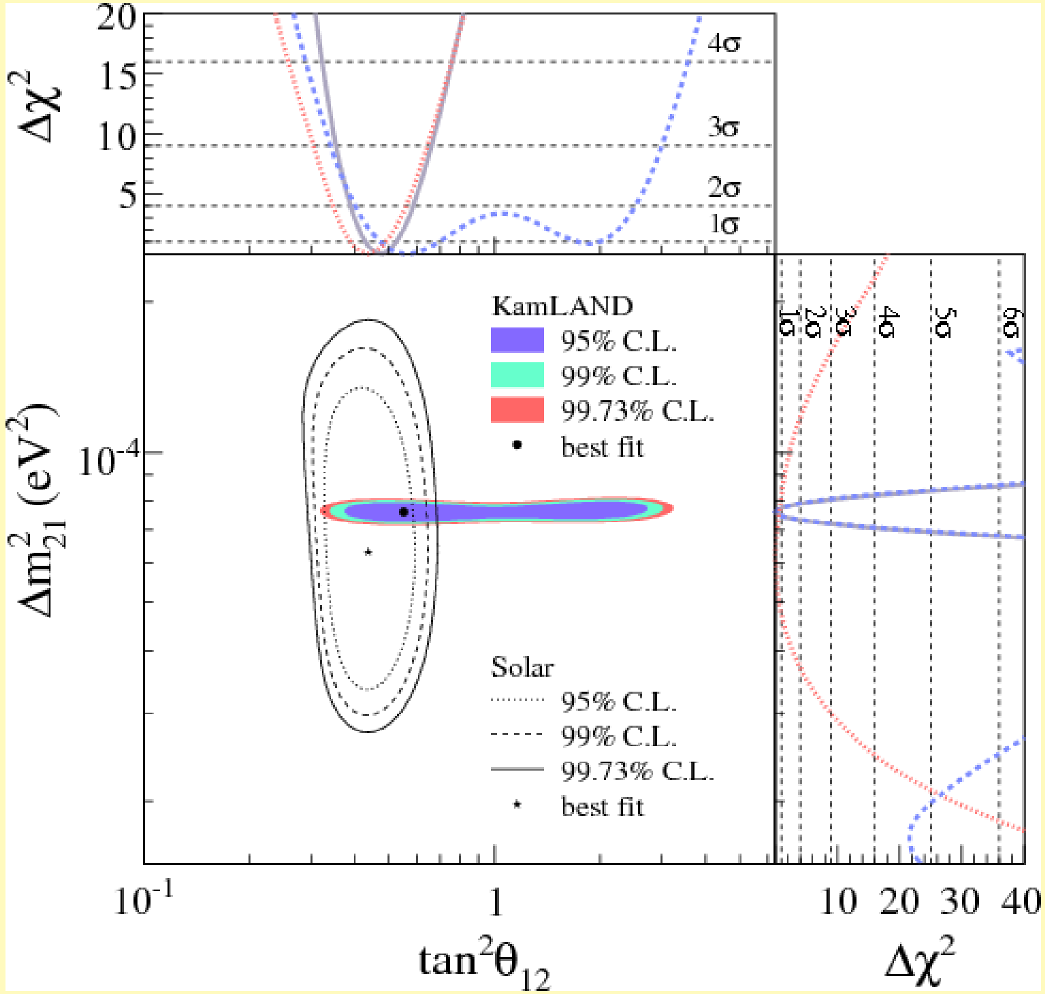


Reason:

Slight disagreement between

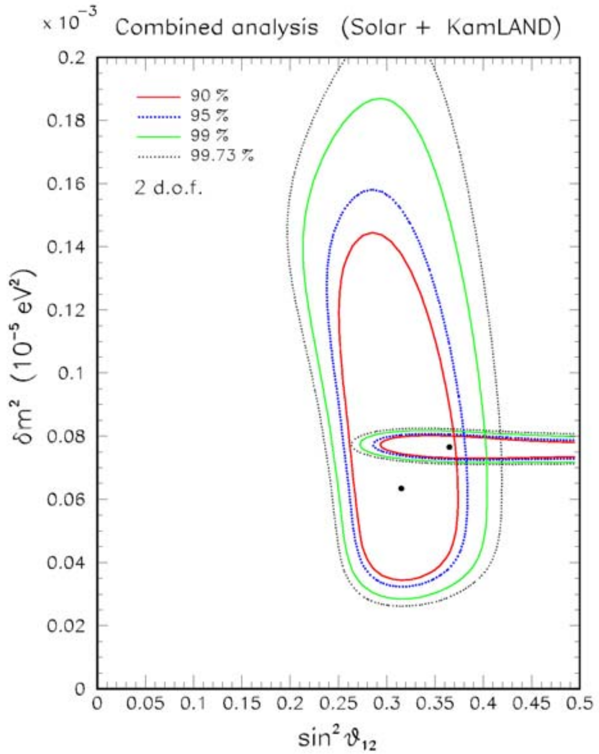
- Solar data (SNO dominated)
- KamLAND data (at $\theta_{13} = 0$)

when the two best-fits are compared in the usual plane (δm^2_{12}, $\tan^2\theta_{12}$)

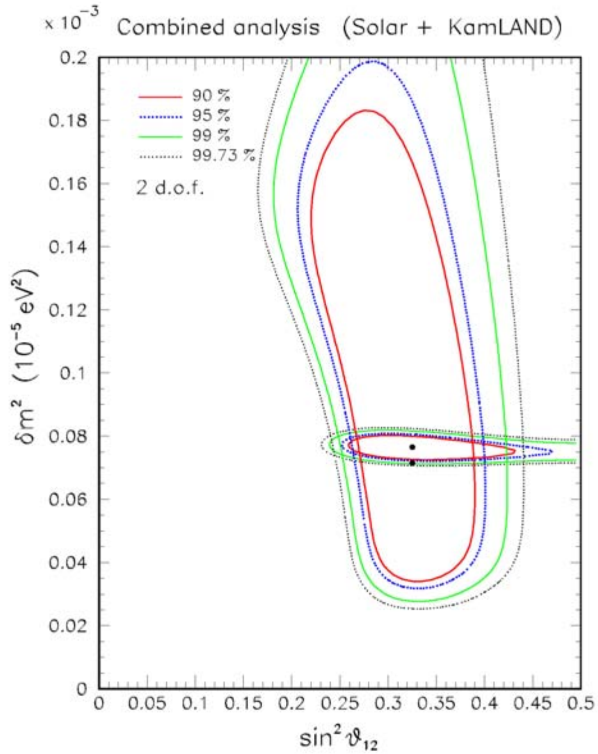


[figure taken from the official Kamland site (2008)]

Disagreement reduced for θ_{13} different from 0 … (3/4)



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



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

(figures prepared by A.M. Rotunno for this talk)

… thanks to the different dependence in SNO and KamLAND from (θ_{12} , θ_{13}).

A tiny effect, of course,

but with some potential for improvement, once final SNO data and further KamLAND data will be available.

This about one year ago ...

... what happened next?

Time-table of "events"

Concerning solar + KamLAND (S+K) neutrinos:

1. 2008, Apr: Effect discussed independently (Balantekin & Yilmaz)
2. 2008, May: SNO-III data release (Neutrino 2008 conference)
3. 2008, Jun: $\sin^2\theta_{13} = 0.021 \pm 0.017$ from our S+K analysis (PRL)
4. 2008, Aug: Independent S+K analysis (Schwetz, Tortola, Valle)

Concerning atmospheric + long-baseline neutrinos:

5. 2008, Jun: $\sin^2\theta_{13} = 0.016 \pm 0.010$ from all data in our analysis (PRL)
6. 2008, Dec: Comments on atmospheric hint of $\theta_{13} \neq 0$ (Maltoni, Schwetz)
7. 2008, ???: New three-flavor atmospheric analysis from SK (upcoming?)
8. 2009, Feb: First MINOS results on electron neutrino appearance

This talk will be concerned with all such 8 **"events"**, and will be concluded with an approximate "update estimate" for

$\sin^2\theta_{13}$ (the number only in the last slide, be patient!)

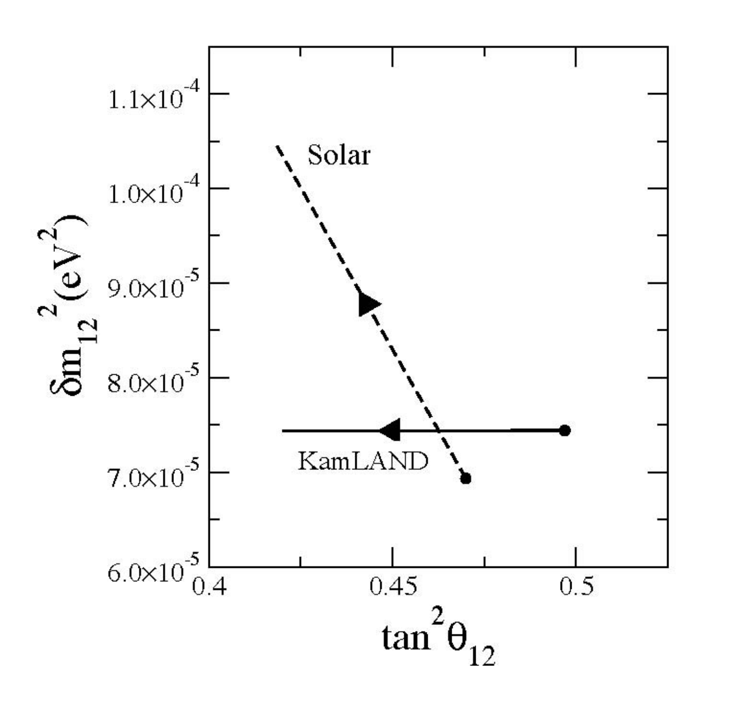
Visible-Light and X-Ray Composite Image of Galaxy Cluster 1E 0657-556

ACT ONE: Solar + KamLAND hint for $\theta_{13} \neq 0$

[where we find out what the main problem is …]

Event 1

Independently, in April, Balantekin & Yilmaz [arXiv:0804.3345, J.Phys. G 35, 075007 (2008)]



studying the "migration" in the plane (δm^2_{12}, $\tan^2\theta_{12}$) of the two best fit points with θ_{13} …

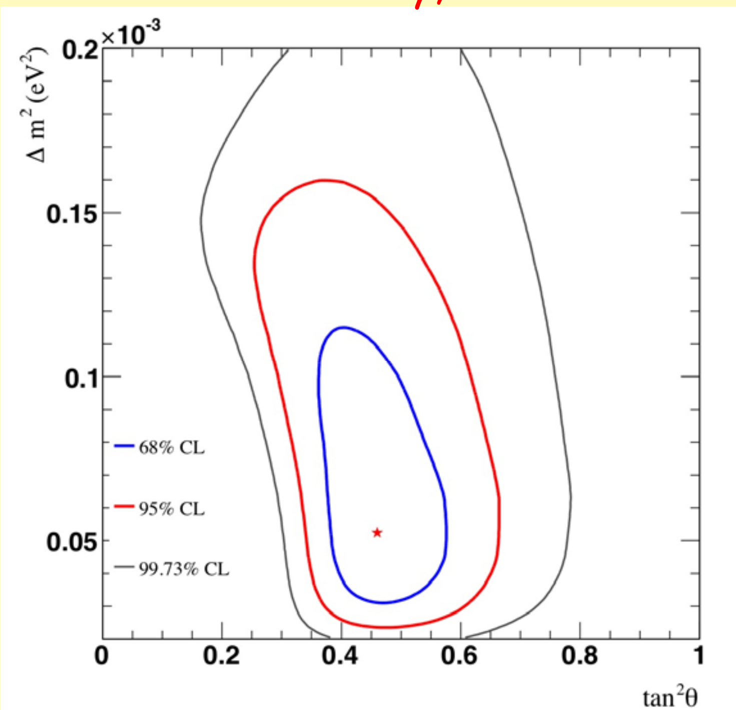
… note a better convergence of solar and KamLAND best fit trajectories for

$$\theta_{13} \neq 0$$

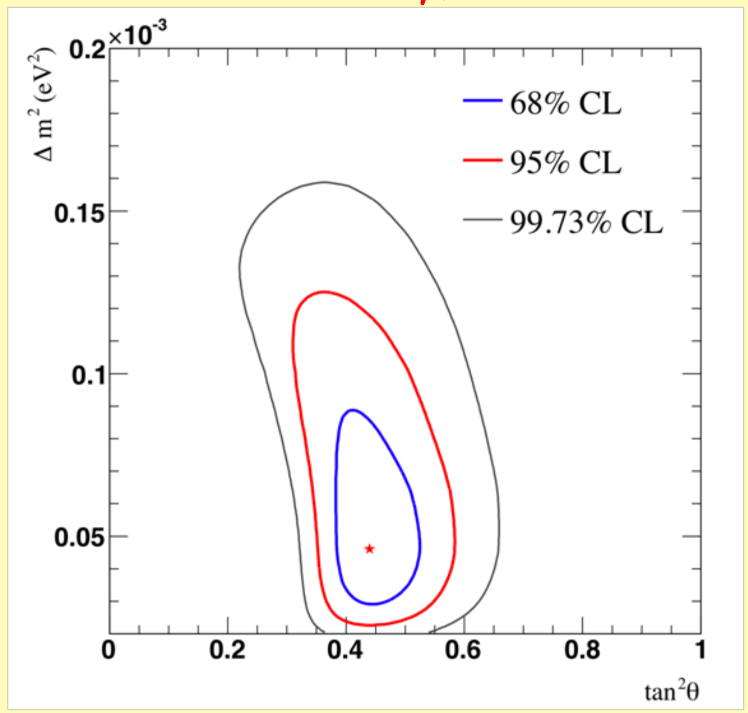
Event 2

Release of the SNO-III data (arXiv:0806.0989) at the Neutrino '08 Conference

SNO only, 2005



SNO only, 2008



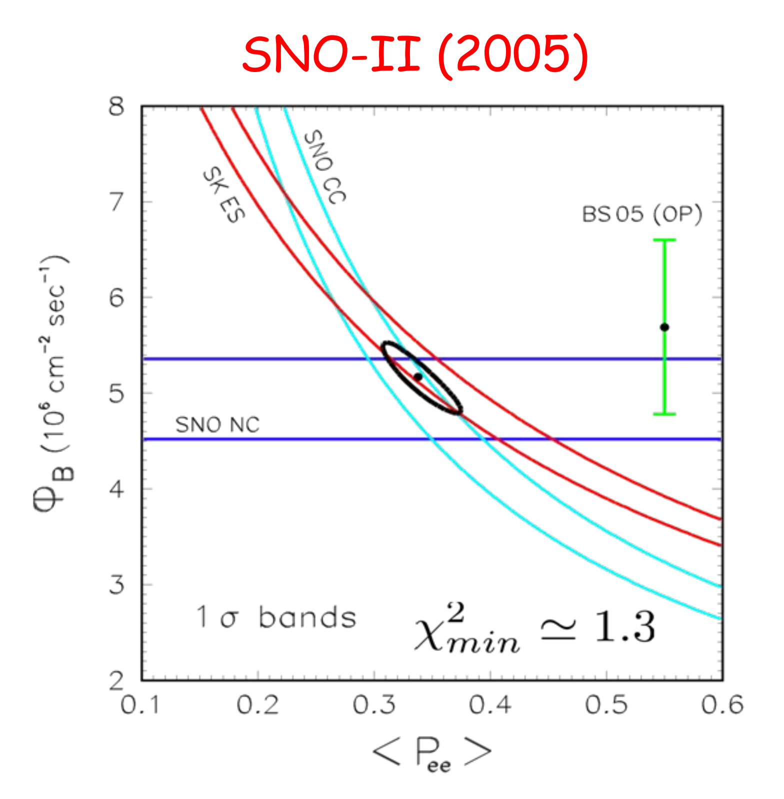
(figures taken from the SNO official website)

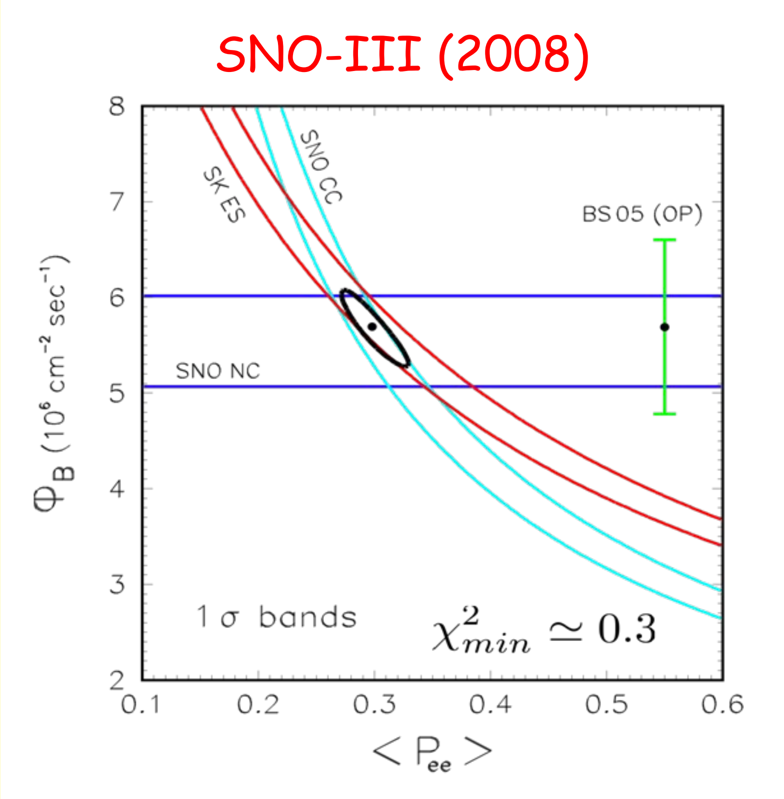
Slightly lower CC/NC ratio, with smaller errors ➡ slightly lower values of θ_{12} preferred

Note: new data are OK from a model-independent viewpoint

- "Internal" consistency among SNO (CC, NC) and SK (ES)
- Also, consistency among NC measurement and BS'05 Standard Solar Model prediction

consistencies already good in SNO-II … … but even better in SNO-III

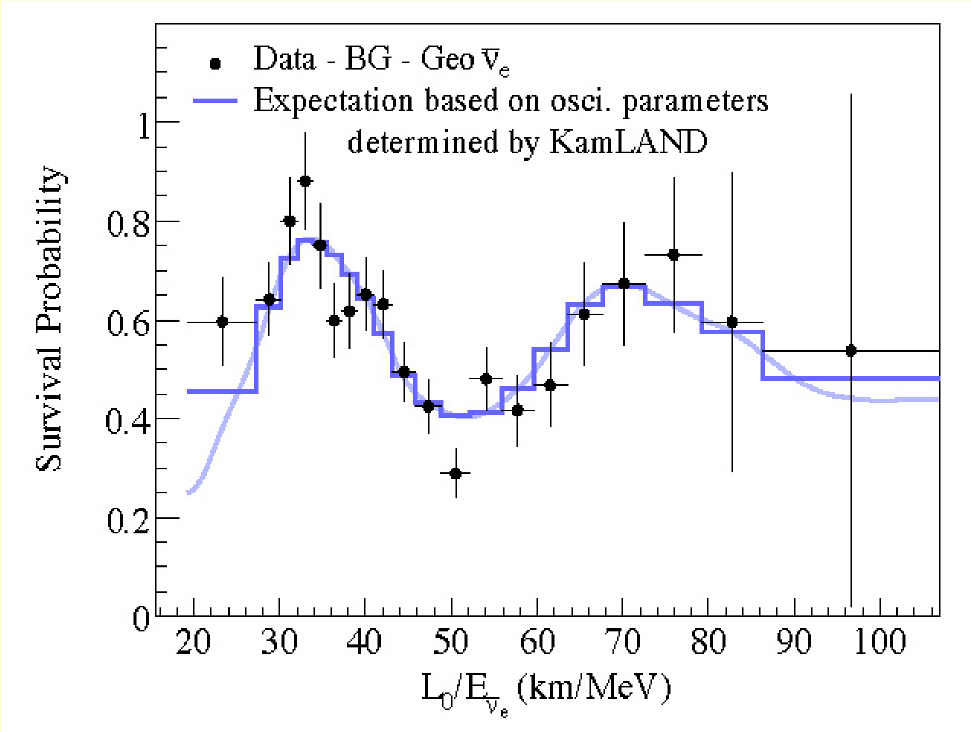




(Our analysis; see also talk by A. Palazzo at NOW 2008)

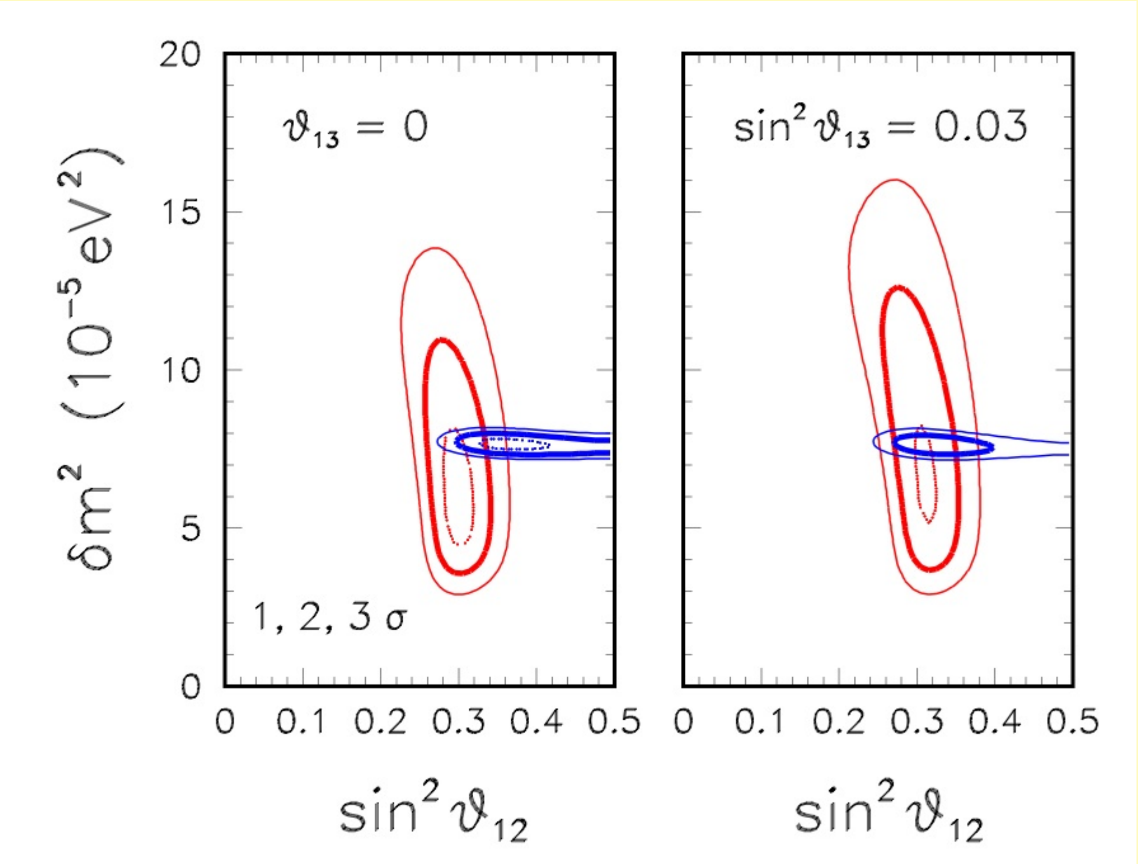
On the other hand, also KamLAND data have their own internal consistency …

… dramatically shown by the reconstruction of the oscillation pattern over one full period:



The fact that the solar and KamLAND datasets are separately OK, but slightly disagree on θ_{12}, unless $\theta_{13} \neq 0$, is thus intriguing.

Here an updated example with currently available data (including Borexino):

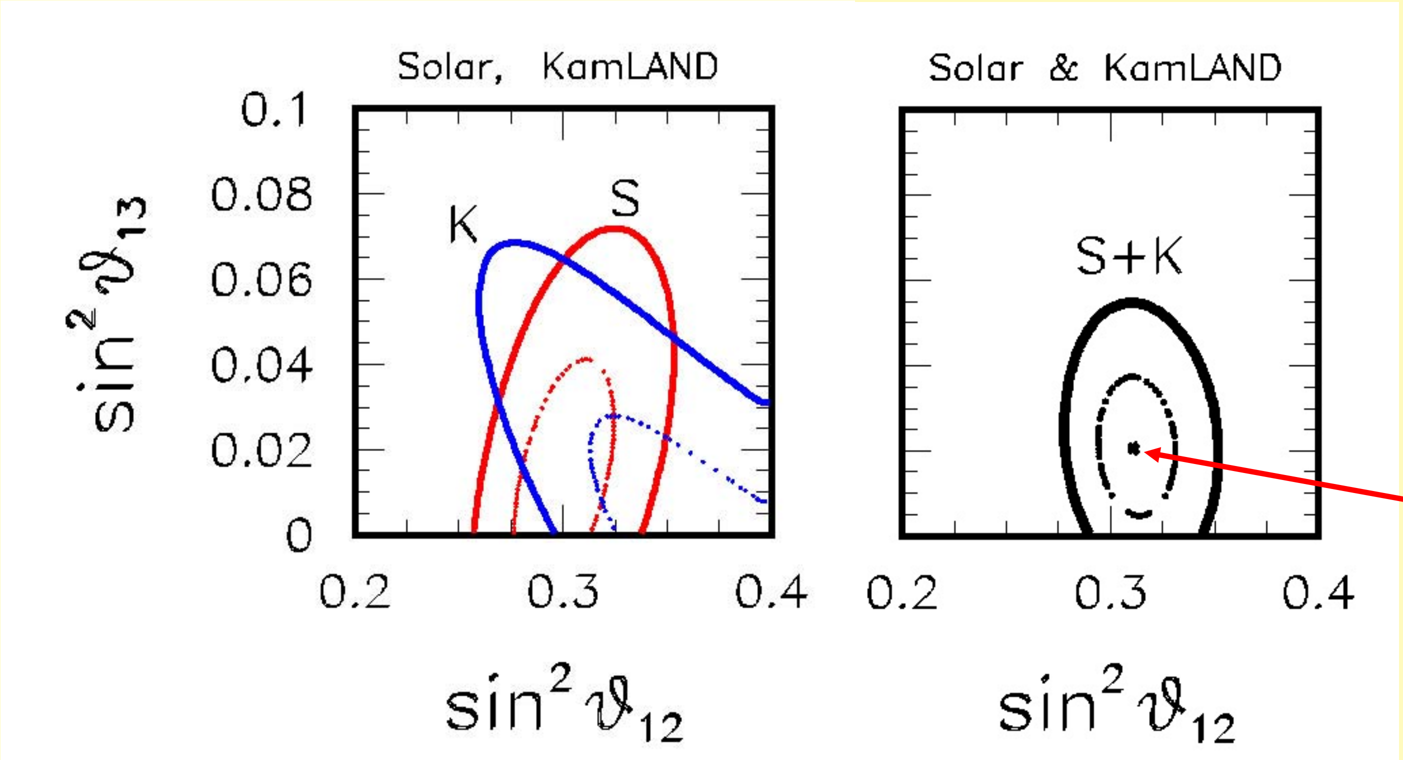


(Our analysis; see also talk by A. Palazzo at NOW 2008)

Event 3

Hints of $\theta_{13} \neq 0$ from global analysis [GLF, Lisi, Marrone, Palazzo, Rotunno arXiv:0806.2649 (PRL 101:141801 (2008)]

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



By combining the two sets of data …

Best fit more than 1 sigma away from zero

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

Reason of the different correlation between the two mixing angles: different relative sign of mixings in P_{ee} (the ν_e survival probability) of SNO vs KamLAND

Low E, vacuum

$$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 2s_{12}^2 c_{12}^2)$$

$-$ $-$

High E, adiabatic MSW (SNO !)

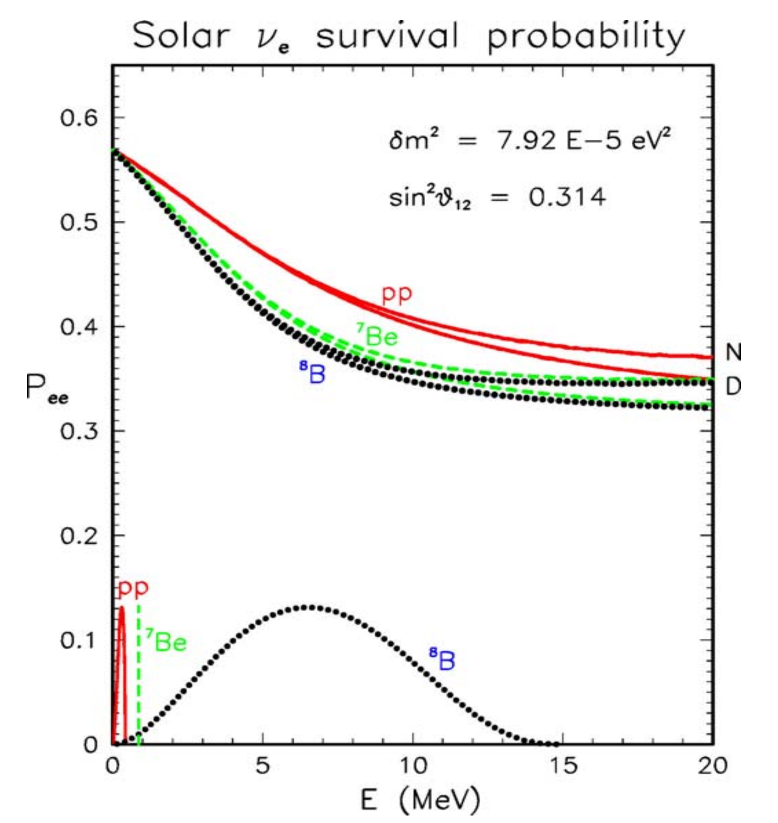
$$P_{ee} \simeq (1 - 2s_{13}^2)(+s_{12}^2)$$

$-$ $+$

KamLAND, vacuum

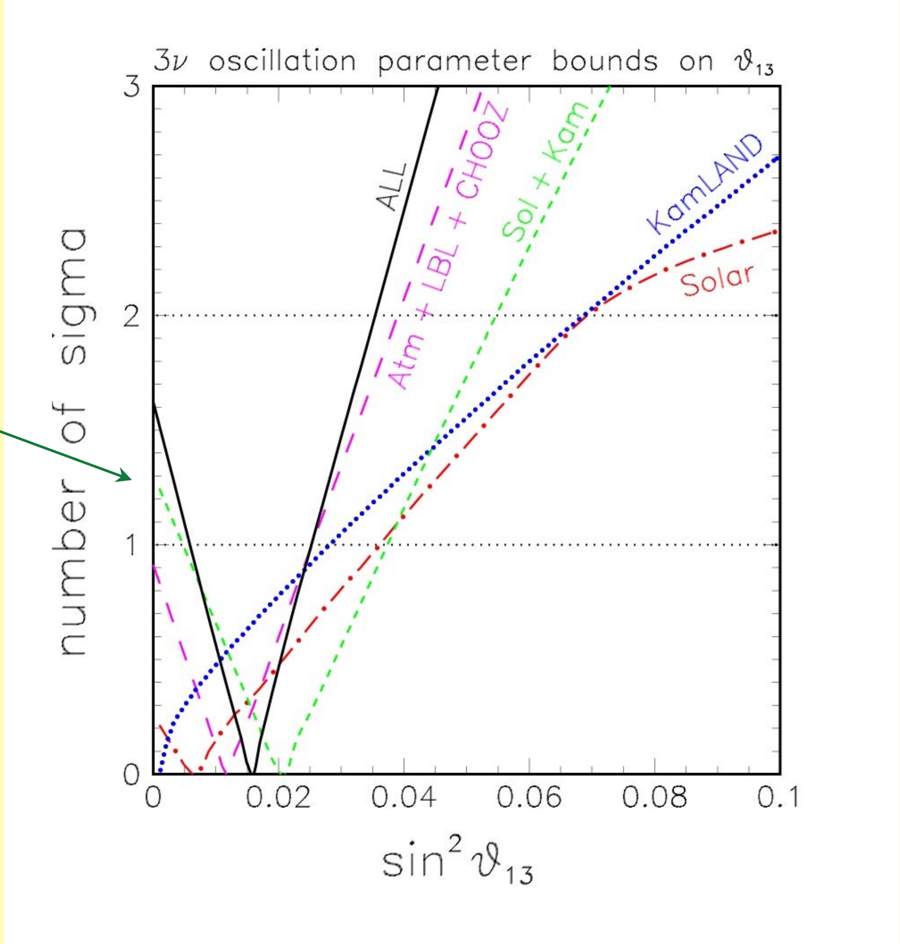
$$P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2 c_{12}^2 \sin^2(\delta m^2 L/4E))$$

$-$ $-$



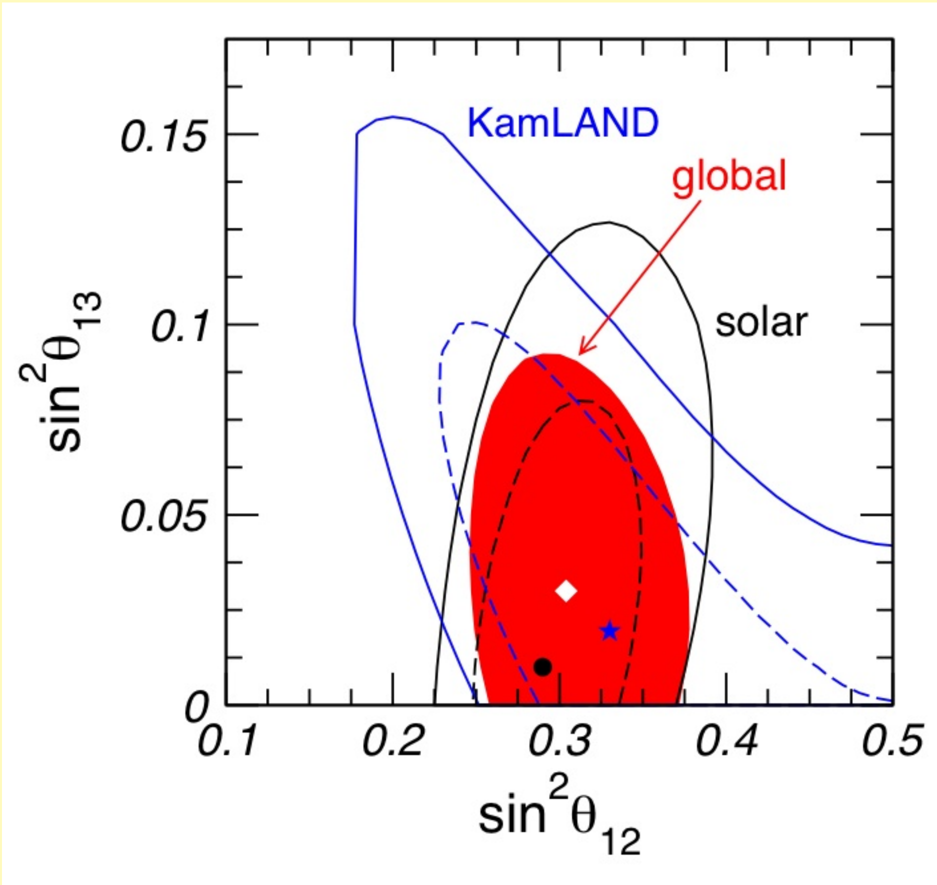
Complementarity: solar or KamLAND data, taken separately, prefer $\theta_{13} \sim 0$. Only their combination hints to $\theta_{13} \neq 0$ at ~ 1.2 sigma:

~ 1.2 sigma for the combination solar + KamLAND (green line):



Event 4

In August, Schwetz, Tortola, Valle (arXiv:0808.2016) also found a preference for $\theta_{13} \neq 0$ from the latest solar+KamLAND data, at a slightly higher CL (~ 1.5 sigma):



From Schwetz, Tortola, Valle
New J.Phys.10:113011,2008
(arXiv:0808.2016)

In conclusion of this ACT ONE …

- A weak preference for $\theta_{13} \neq 0$ from Solar + KamLAND data seems now accepted at the level of ~ 1.2-1.5 sigma.

- The question now is:

  Is this preference also supported by atmospheric + accelerator data?

- In our paper (arXiv:0806.2649) we used, as independent support for $\theta_{13} \neq 0$, an older hint coming from our atmospheric + CHOOZ + long-baseline analysis.

We start from this hint in opening …

Orion Nebula

ACT TWO: The atmospheric (+CHOOZ+LBL) hint for $\theta_{13} \neq 0$

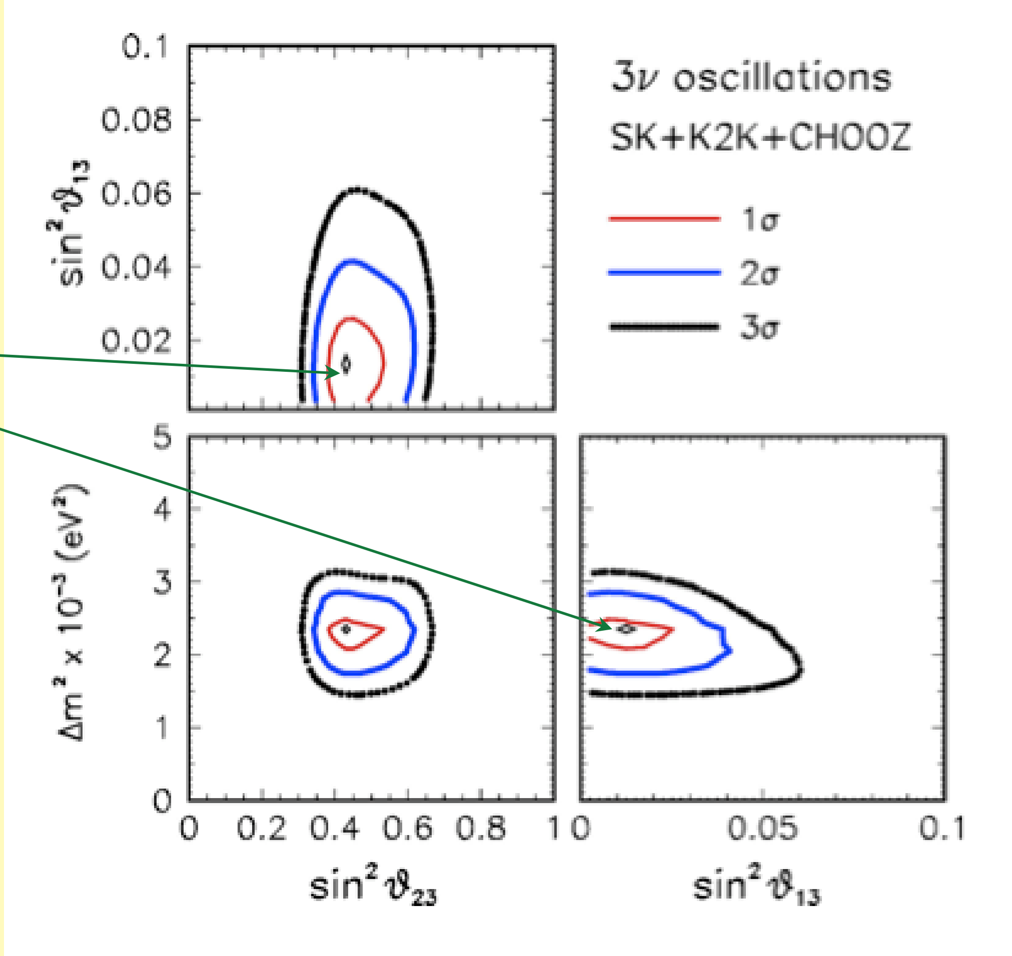
[where the complication usually comes out …]

Event 5

An older (but persisting) hint for $\theta_{13} \neq 0$ comes from our 3-neutrino analysis of atmospheric + LBL + Chooz data ...

GLF, Lisi, Marrone, Palazzo
Progr. Part. Nucl. Phys. 57, 742 (2006)
See also Escamilla et al., arXiv:0805.2924

best fit ~ 1 sigma away from zero



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

We find also that the hint is NOT killed by adding latest MINOS disappearance data.

Excess of electron events induced by 3ν subleading effects

Our calculations of atmospheric ν oscillations are based on a full three-flavor numerical evolution of the Hamiltonian along the ν path in the atmosphere and (below horizon) in the known Earth layers …

… however, semi-analytical approximations can be useful to understand the behavior of the oscillation probability of some of the atmospheric neutrino observables.

A particularly important observable is the excess of expected electron events compared to the no oscillation case, i.e. [O.L.G. Peres and A.Yu. Smirnov , Nucl. Phys. B 456, 204 (1999); ibidem 680, 479 (2004)]

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

with P_{ee} and $P_{e\mu}$ oscillation probabilities

r = ν_μ/ν_e flux ratio $\begin{cases} \text{sub-GeV} & r \sim 2 \\ \text{multi-GeV} & r \sim 3.5 \end{cases}$

zero when both $\begin{cases} \theta_{13} = 0 \\ \delta m^2 = 0 \end{cases}$ but can have contribution from $\theta_{13} \neq 0$ and/or $\delta m^2 \neq 0$

Constant density approximation

By assuming

$A(x) = 2\sqrt{2}\, G_F N_e(x) E = \text{const}$

(assumption made only in the spirit of simplifying the present example)

From an estimate of the

order of magnitude of the potential

$$\begin{cases} \dfrac{A}{\Delta m^2} \simeq 1.3 \left(\dfrac{2.4\times 10^{-3}\ \text{eV}^2}{\Delta m^2}\right)\left(\dfrac{E}{10\ \text{GeV}}\right)\left(\dfrac{N_e}{2\ \text{mol/cm}^3}\right) \\[2ex] \dfrac{A}{\delta m^2} \simeq 3.8 \left(\dfrac{8\times 10^{-5}\ \text{eV}^2}{\delta m^2}\right)\left(\dfrac{E}{1\ \text{GeV}}\right)\left(\dfrac{N_e}{2\ \text{mol/cm}^3}\right) \end{cases}$$

we see that in SK data Earth matter effects take place, Δm^2-driven for multi-GeV and δm^2-driven for sub-GeV events.

In the assumed constant density approximation, the electron excess can be written as the sum of three terms

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

In particular, for the case [ν, normal hierarchy, δ=0]

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

“θ_{13} term”
(~ quadratic in θ_{13})

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

“δm^2 term”
(~ θ_{13}-independent)

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

“interference term”
(~ linear in θ_{13})

mixing angles in matter

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

The corresponding expressions in the other cases are obtained by making use of the following

“swapping” relations

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

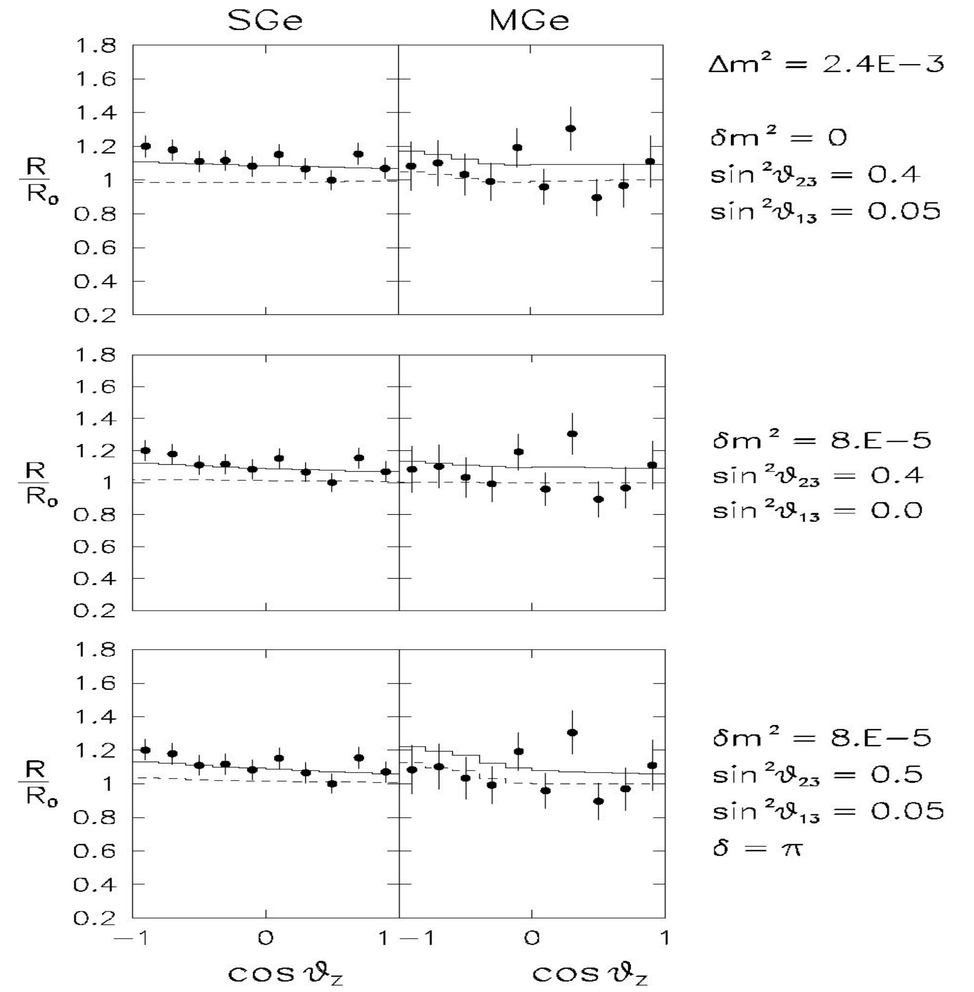
Exact numerical examples for SubGeV and MultiGeV events

□θ_{13} term□ dominant

□δm^2 term□ dominant

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

GLF, Lisi, Marrone, Palazzo, Progr. Part. Nucl. Phys. 57, 742 (2006)



These terms help fitting the small electron excess in SubGeV and MultiGeV data, with the interference term helping, in particular, for SubGeV data at $\delta=\pi$.

More about the "subleading" solar terms

The atmospheric three-neutrino analyses in

- SK Collaboration, hep-ex/0604011
- Schwetz, Tortola, Valle, arXiv:0808.2016

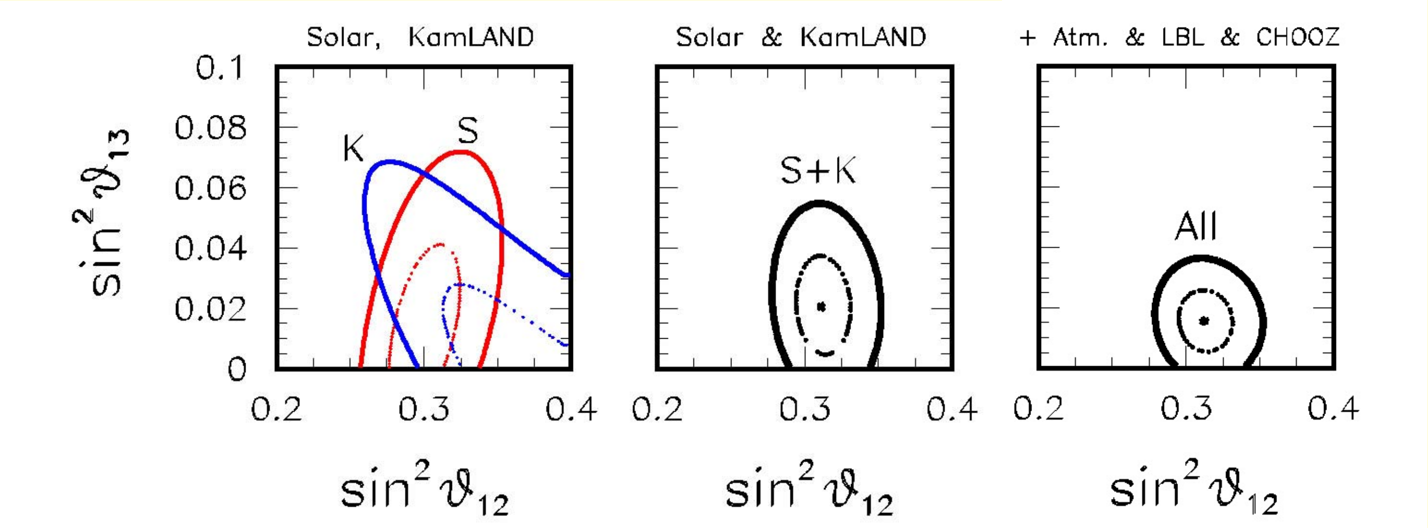
(also based on the same **SK-I** data), adopt the so-called one-mass-scale-dominance, and thus do not include the two subleading solar terms.

⬇

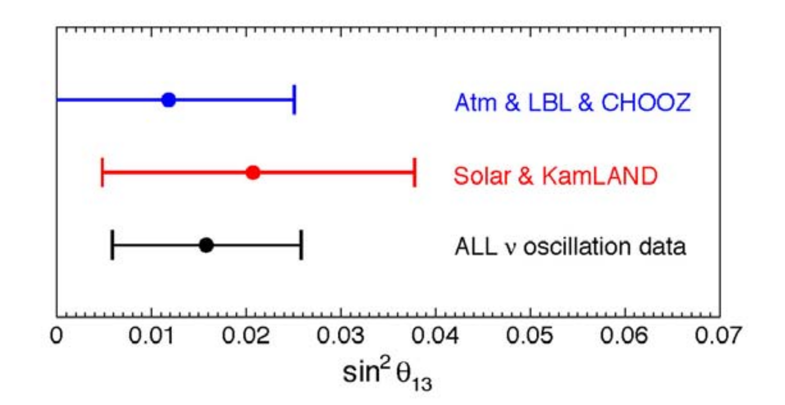
As a consequence, their results (which prefer $\theta_{13} \sim 0$) cannot be directly compared with ours (while Gonzalez-Garcia & Maltoni, arXiv 0704.1800, do include all terms).

Sticking to our analysis

Taken together, the two hints (solar+KamLAND, and atmospheric+CHOOZ+LBL), provide a possible indication in favor of $\theta_{13} \neq 0$ at the level of ~ 1.6 sigma = 90% CL: not so bad!



By combining all data together …



$\sin^2\theta_{13} = 0.016 \pm 0.010$ (all data)

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

Event 6

In the last December Maltoni & Schwetz (arXiv:0812.3161) study the variations of a full 3-neutrino atmospheric data analysis containing all terms (as well as preliminary SK-II data).

Their results can be summarized as follows:

- Using SK-I data, they find at most a 0.5 sigma hint from atmospheric + CHOOZ analysis.

  This is weaker than our 0.9 sigma, but shows similar qualitative features – e.g., the role of the interference term.

- Varying the χ^2 definition, they find a possible reduction of the hint to 0.2 sigma.

- Multi-GeV electron data also contribute to the likelihood of θ_{13}, and the fact that in SK-II such data show no longer an upgoing excess can suppress the hint.

⬇

The latter two points bring us to a discussion of …

Event 7

SK-I+II (+ III + …) data and ongoing analyses (not yet published)

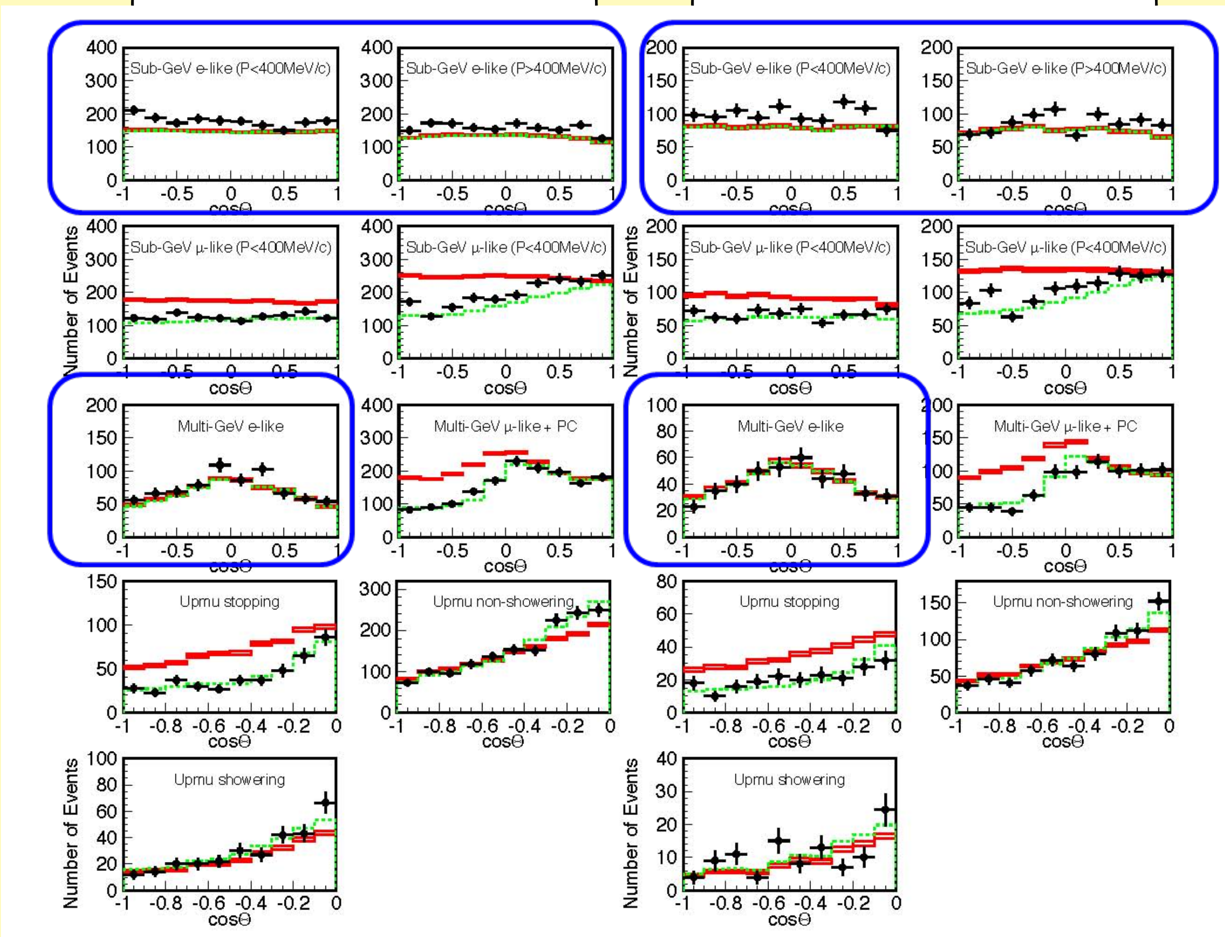
- There exist ongoing three-flavor analyses in SK after phase I, as detailed in recent (2008) PhD theses using SK-I+II data (available at www-sk.icrr.u-tokyo.ac.jp/sk/pub/):

  - R.A. Wendell: allows $\theta_{13}>0$, but sets $\delta m^2=0$; finds no hint for $\theta_{13}>0$.
  - Y.Takenaga: allows $\delta m^2>0$, but sets $\theta_{13}=0$.

- Unfortunately, none of the above analyses allows both $\theta_{13}>0$ and $\delta m^2>0$, and thus they do not include interference effects linear in θ_{13} (which, as noted, may play some role at sub-GeV energies).

However, the trend of the data may tell us something about the expectations for θ_{13} …

SK-I data SK-II data



(zenith distributions from Takenaga thesis, 2008)

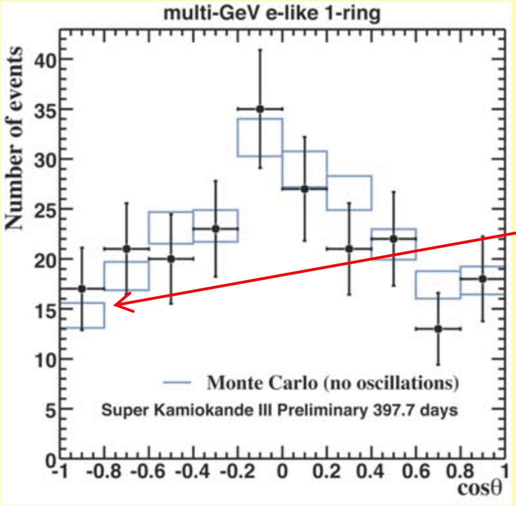
Trend from SK-I to SK-II:

Sub-GeV electron excess persists in both phases I and II

Conversely, slight excess of upgoing MGe present in SK-I but not in SK-II

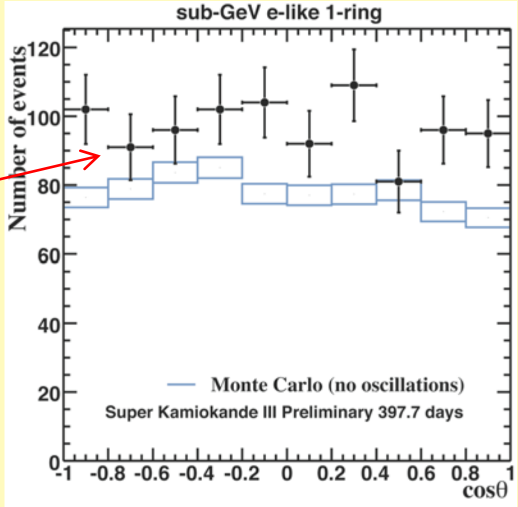
Actually, this downward MGe fluctuation may disfavor $\theta_{13} \neq 0$ (as noted by Maltoni and Schwetz)

… however, going to SK-III …



…in **SK-III** data, a slight excess of upgoing MGe seems to be back …

(SK-III data, from J. Raaf at Neutrino 2008)



…together with a persisting excess of SGe data!

Question: Can all this be interpreted away from { statistical fluctuations / systematic uncertainties } ?

↓

The answer requires a refined statistical analysis …

The analysis SK-I+II Collaboration currently includes:

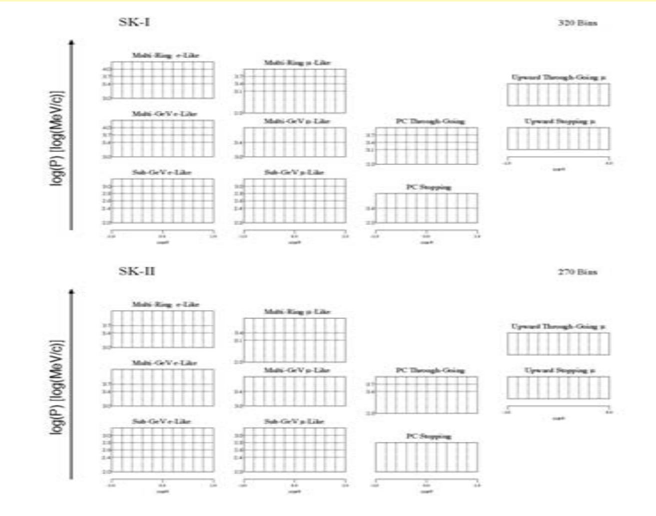


Figure 8.5: Binning for SK-I (top) and SK-II (bottom) for each of the ten samples used in the analysis. SK-I has a total of 320 bins and SK-II has 270.

R. Wendell thesis, 2008

- 320+270 energy-angle bins for SK-I + SK-II
- 20+26+20 sources of systematics for SK-I + SK-II (26 being **common** to both phases)

to be handled within the so-called "pull method" (that we advocated in hep-ph/0206162 and hep-ph/0303064)

Such a level of refinement, with ~ 600 bins and ~ 70 systematics, partly shared in SK-I+II, is difficult to be reproduced in detail outside the SK collaboration.

⬇

Independent analyses of atmospheric data searching for small effects (or hints) at the level of ~ 1 sigma, like ours, are thus getting harder and harder to perform.

Therefore …

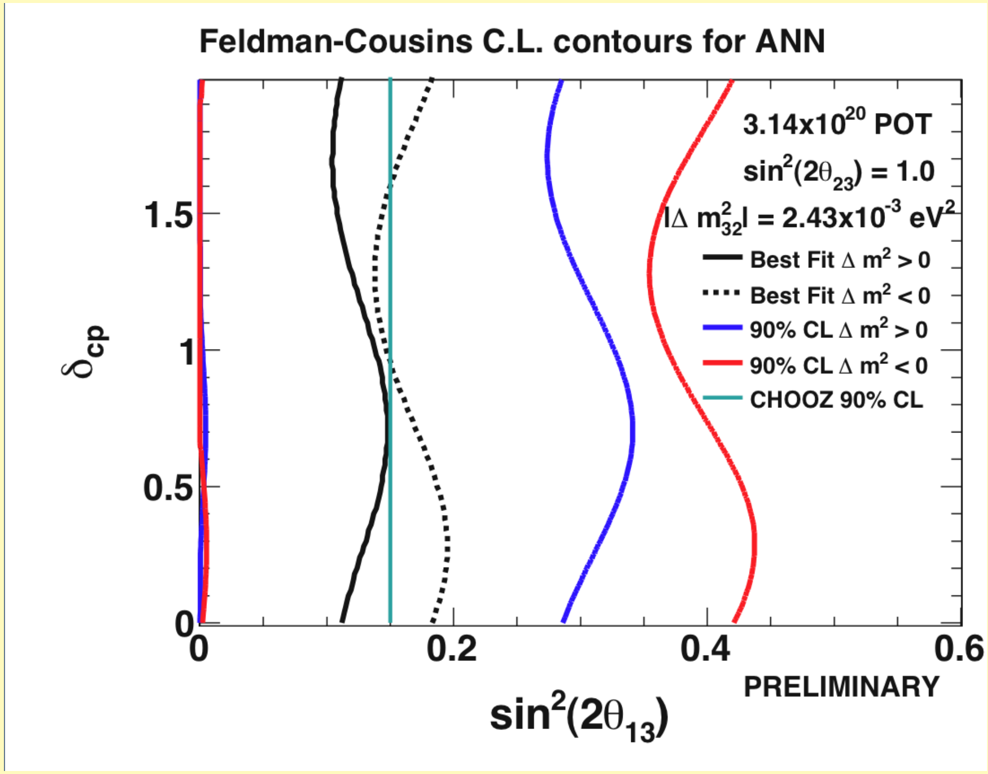
… it will be very important to see the next official SK data release and especially the official SK oscillation analysis, hopefully including a complete treatment of three-flavor oscillations with both $\delta m^2 > 0$ and $\theta_{13} > 0$ (and possibly including also SK-III data).

In the meantime, we do not have compelling reasons to revise our 0.9 sigma hint in favor of $\theta_{13} \neq 0$ obtained from the published SK-I data, although it may have, admittedly, a more fragile status than the ~1.2 sigma hint from the analysis of solar + KamLAND data.

In any case, the whole discussion about $\theta_{13} \neq 0$ must be taken with a grain of salt, since we are talking about really small and indirect effects, which will never pre-empt the discovery potential of direct searches at reactors and accelerators.

Event 8

First preliminary MINOS results on electron neutrino appearance:



(Mayly Sanchez, talk at FNAL, Feb 27th)

MINOS 90% C.L. limits in the plane (δ_{CP}, $\sin^2 2\theta_{13}$), fitting the oscillation hypothesis to the data

It can be seen that MINOS's best fit for θ_{13} sits around the CHOOZ limit, and is away from zero at ~ 90% C.L. (even though the Collaboration, conservatively, does not attach any particular relevance to this point).

We are then ready to open …

Black Hole in Galaxy M87 Emits Jet of High-Speed Electrons

ACT THREE: Approximate update for θ_{13}

[where the resolution of the problem is given …]

If, optimistically, we see the glass "half full" rather then "half empty", then we might have

two independent 90% CL hints in favor of $\theta_{13} \neq 0$

- one coming from our global analysis (2008)

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

- and one coming from MINOS (2009), that we roughly symmetrize and approximate with only one significant digit as

$$\sin^2\theta_{13} \sim 0.05 \pm 0.03$$

[Note that being more refined about MINOS would not really matter in this context.]

A combination at face value gives …

$$\sin^2\theta_{13} \sim 0.02 \pm 0.01$$

namely, an overall indication at ~ 2 sigma (95% CL)

In other words …

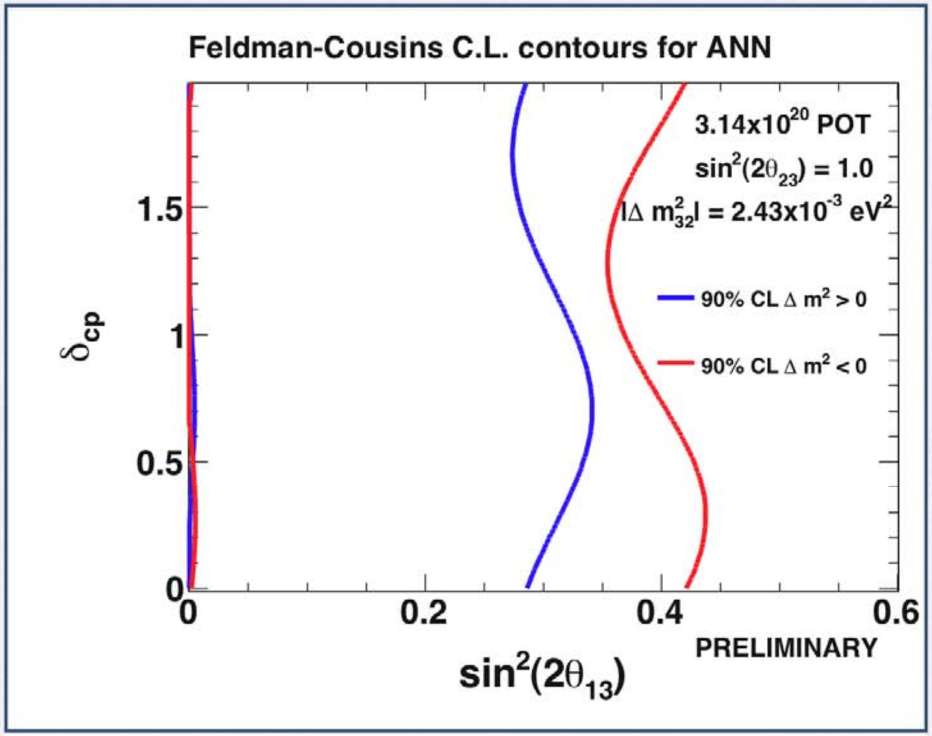
the odds against null θ_{13} are now 20 to 1 !

BACKUP

MINOS 90% CL in $\sin^2 2\theta_{13}$

Fitting the oscillation hypothesis to our data

- Plot shows 90% limits in δ_{CP} vs. $\sin^2 2\theta_{13}$
  - shown at the MINOS best fit value for Δm^2_{32} and $\sin^2 2\theta_{23}$.
  - for both mass hierarchies
- A Feldman-Cousins method was used.
- Results are for primary selection and primary separation method.



Mayly Sanchez - ANL 60 FNAL W&C Seminar - 02/27/09

MINOS 90% CL in $\sin^2 2\theta_{13}$

Fitting the oscillation hypothesis to our data

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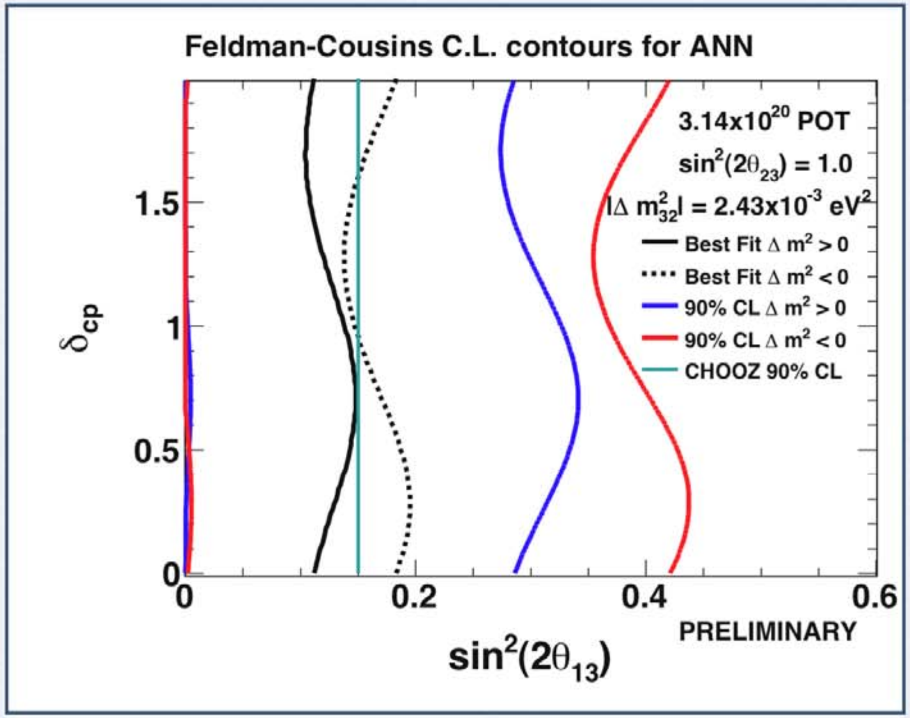
- A Feldman-Cousins method was used.
- Results are for primary selection and primary separation method.



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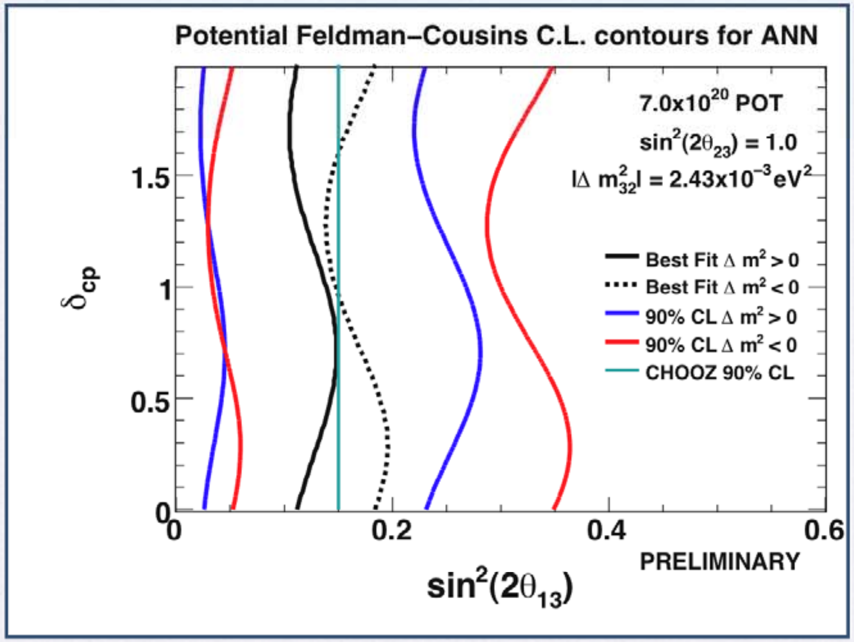
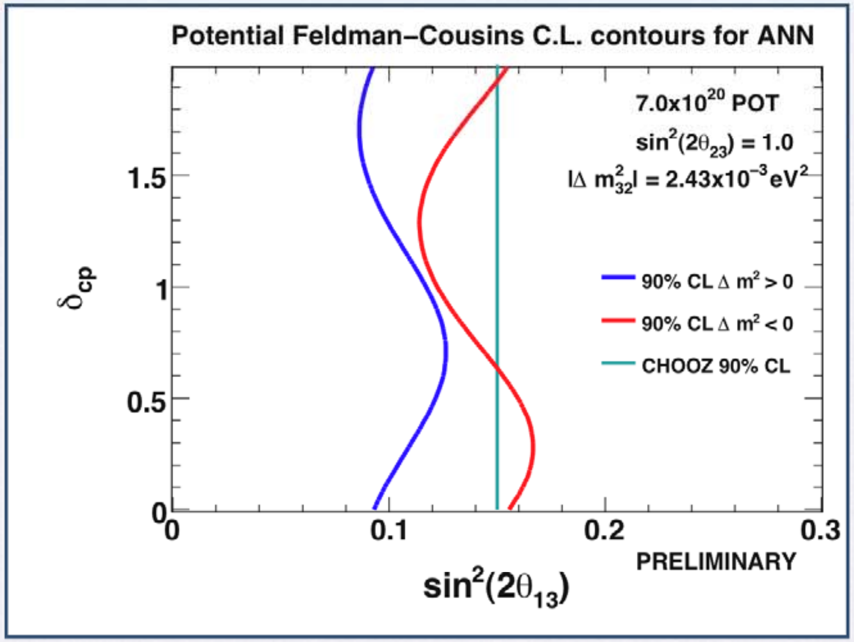
Future 90% CL contours

7.0×10^{20} POT





Future measurement if data excess persists.

Future limit if excess cancels with more data.

We are close to doubling the data in current running!

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Summary

- We have completed an **initial search for ν_e appearance** in the MINOS data.
- We developed two ν_e selections that have a rejection of >92% for NC and >99% for ν_μ CC, the main background components for this analysis.
- We used **two data-driven techniques** to estimate the background in the Far Detector.
- We studied **sideband** Far Detector data to check the extrapolation techniques:
  - Sidebands show adequate agreement, with an excess of 1-2 σ.
  - Observed excess could be a statistical fluctuation or a hint of a Far/Near difference.

More data will clarify these issues.