SNO, KamLAND and neutrino oscillations: $\theta_{13}$

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Outline (Three-acts structure)

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

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

What we would like to know

Hierarchy (normal or inverted)

$CP$ in the $\nu$ sector

$\theta_{13}$ mixing

Some aspect is currently “hidden” below $1\sigma$ 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 ($m^2_{12}, \tan^2\theta_{12}$)

[figure taken from the official Kamland site (2008)]
Disagreement reduced for $\theta_{13} > 0$ ...

\[
\sin^2 \theta_{13} = 0
\]

\[
\sin^2 \theta_{13} = 0.03
\]

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

... thanks to the different dependence in SNO and KamLAND from $(\theta_{12}, \theta_{13})$. 
A tiny effect, of course,

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

This one year ago ...

... what happened next?
Concerning solar + KamLAND (S+K) neutrinos:

1. 2008, Apr: Effect discussed independently (Balantekin & Yilmaz)
3. 2008, Jun: $\sin^2 \theta_{13} = 0.021 \pm 0.017$ from our S+K analysis (PRL)

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 $\theta_{13} > 0$ (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!)
ACT ONE: Solar + KamLAND hint for $\theta_{13} > 0$

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

... note a better convergence of solar and KamLAND best fit trajectories for $\theta_{13} > 0$. 

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**Event 1**

studying the “migration” in the plane ($\delta m_{12}^2$, $\tan^2 \theta_{12}$) of the two best fit points with $\theta_{13}$ ...
**Event 2**

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

Slightly lower CC/NC ratio, with smaller errors  $\Rightarrow$  slightly lower values of $\theta_{12}$ preferred

(figures taken from the SNO official website)
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

... 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:

![Graph showing survival probability vs. L/E (km/MeV)]
The fact that the solar and KamLAND datasets are separately OK, but slightly disagree on $\theta_{12}$, unless $\theta_{13} > 0$, is thus intriguing.

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

(Our analysis; see also talk by A. Palazzo at NOW 2008)
Hints of $\theta_{13} > 0$ from global analysis [GLF, Lisi, Marrone, Palazzo, Rotunno arXiv:0806.2649 (PRL 101:141801 (2008))]

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 datasets are more evident:

$$\sin^2 \theta_{13} = 0.021 \pm 0.017 \text{ (solar + KamLAND)}$$
Reason of the different correlation between the two mixing angles: different relative sign of mixings in \( P_{ee} \) (the \( \nu_e \) survival probability) of SNO vs KamLAND

Low E, vacuum
\[
P_{ee} \simeq (1 - 2s_{13}^2)(1 - 2s_{12}^2c_{12}^2)
\]

High E, adiabatic MSW (SNO !)
\[
P_{ee} \simeq (1 - 2s_{13}^2)(+s_{12}^2)
\]

KamLAND, vacuum
\[
P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2c_{12}^2 \sin^2(\delta m^2L/4E))
\]
Complementarity: solar or KamLAND data, taken separately, prefer $\theta_{13} \sim 0$. Only their combination hints to $\theta_{13} > 0$ at $\sim 1.2$ sigma:

$\sim 1.2$ sigma for the combination solar + KamLAND (green line):
In August, Schwetz, Tortola, Valle (arXiv:0808.2016) also found a preference for \( \theta_{13} > 0 \) from the latest solar+KamLAND data, at a slightly higher CL (~ 1.5 sigma):

\[
\sin^2 \theta_{13}
\]

From Schwetz, Tortola, Valle
In conclusion of this ACT ONE ...

- A weak preference for $\theta_{13} > 0$ 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 $\theta_{13} > 0$, an older hint coming from our atmospheric + CHOOZ + long-baseline analysis.

We start from this hint in opening ...
**ACT TWO:** The atmospheric (+CHOOZ+LBL) hint for $\theta_{13} > 0$

[where the complication usually comes out ...]
An older (but persisting) hint for $\theta_{13} > 0$ comes from our 3-neutrino analysis of atmospheric + LBL + Chooz data ... 

GLF, Lisi, Marrone, Palazzo
See also Escamilla et al., arXiv:0805.2924

... 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 $3\nu$ subleading effects

Our calculations of atmospheric $\nu$ oscillations are based on a full three-flavor numerical evolution of the Hamiltonian along the $\nu$ 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)]

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

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

$$r = \frac{\nu_\mu/\nu_e}{\text{flux ratio}} \begin{cases} \text{sub-GeV} & r \sim 2 \\ \text{multi-GeV} & r \sim 3.5 \end{cases}$$

zero when both $\theta_{13} = 0$ and $\delta m^2 = 0$ 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

\[
\begin{align*}
\frac{A}{\Delta m^2} &\approx 1.3 \left( \frac{2.4 \times 10^{-3} \text{ eV}^2}{\Delta m^2} \right) \left( \frac{E}{10 \text{ GeV}} \right) \left( \frac{N_e}{2 \text{ mol/cm}^3} \right) \\
\frac{A}{\delta m^2} &\approx 3.8 \left( \frac{8 \times 10^{-5} \text{ eV}^2}{\delta m^2} \right) \left( \frac{E}{1 \text{ GeV}} \right) \left( \frac{N_e}{2 \text{ mol/cm}^3} \right)
\end{align*}
\]

we see that in SK data Earth matter effects take place, \( \Delta m^2 \)-driven for multi-GeV and \( \delta m^2 \)-driven for sub-GeV events.

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

\[
\frac{N_e}{N^0_e} - 1 \approx \Delta_1 + \Delta_2 + \Delta_3
\]
In particular, for the case \([\nu, \text{ normal hierarchy, } \delta=0]\)

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

\[\text{“}\theta_{13}\text{ term”} \quad (\sim \text{quadratic in } \theta_{13})\]

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

\[\text{“}\delta m^2\text{ term”} \quad (\sim \theta_{13}\text{-independent})\]

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

\[\text{“interference term”} \quad (\sim \text{linear in } \theta_{13})\]

\[
\begin{align*}
\sin 2\theta_{13} / \sin 2\tilde{\theta}_{13} &\approx \sqrt{\left( \frac{A}{\Delta m^2 + \frac{\delta m^2}{2} \cos 2\theta_{12} - \cos 2\theta_{13}} \right)^2 + \sin^2 2\theta_{13}} \\
\sin 2\theta_{12} / \sin 2\tilde{\theta}_{12} &\approx \sqrt{\left( \frac{A c_{13}^2}{\delta m^2 - \cos 2\theta_{12}} \right)^2 + \sin^2 2\theta_{12}}
\end{align*}
\]

mixing angles
in matter

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

“swapping”
relations

\[
\begin{align*}
+ A &\rightarrow -A & (\nu \rightarrow \bar{\nu}) \\
+ \Delta m^2 &\rightarrow -\Delta m^2 & (\text{N.H. } \rightarrow \text{I.H.}) \\
+ s_{13} &\rightarrow -s_{13} & (\delta = 0 \rightarrow \delta = \pi)
\end{align*}
\]
Exact numerical examples for SubGeV and MultiGeV events

“$\theta_{13}$ term” dominant

“$\delta m^2$ term” dominant

“Interference term” dominant (only in sub-GeV)

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

(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 $\theta_{13} > 0$ at the level of $\sim 1.6$ sigma = 90% CL: not so bad!

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

GLF, Lisi, Marrone, Palazzo, Rotunno

**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, and the irrelevance of K2K+MINOS disappearance data).

- **Varying the $\chi^2$ definition**, they find a possible reduction of the hint to 0.2 sigma.

- **Multi-GeV electron data also contribute** to the likelihood of $\theta_{13}$, 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 $\theta_{13}$ (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 $\theta_{13}$...
SK-I data

SK-II data

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 $\theta_{13} > 0$ (as noted by Maltoni and Schwetz)

(zenith distributions from Takenaga thesis, 2008)

... 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:

- 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)

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 of $\theta_{13} > 0$ obtained from 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 $\theta_{13} > 0$ 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.
First MINOS results on electron neutrino appearance

These preliminary results have been released recently by the MINOS collaboration (Mayly Sanchez, talk at FNAL, Feb. 27th)

It would be unfair to anticipate results and slides that will be presumably shown by Milind Diwan later in this Workshop ...

... but I can’t help noticing that MINOS’s best fit for $\theta_{13}$ sits around the CHOOZ limit, and is away from zero at ~ 90% C.L. (although the Collaboration, conservatively, does not attach any particular relevance to this fact).

We are then ready to open ...
ACT THREE: Approximate update for $\theta_{13}$

[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 $\theta_{13} > 0$

- 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 $\theta_{13}$ are now 20 to 1!