Solar neutrinos and θ_{13}

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The physics of the Sun and the solar neutrinos: II
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I. **Solar neutrino data and θ_{13}**

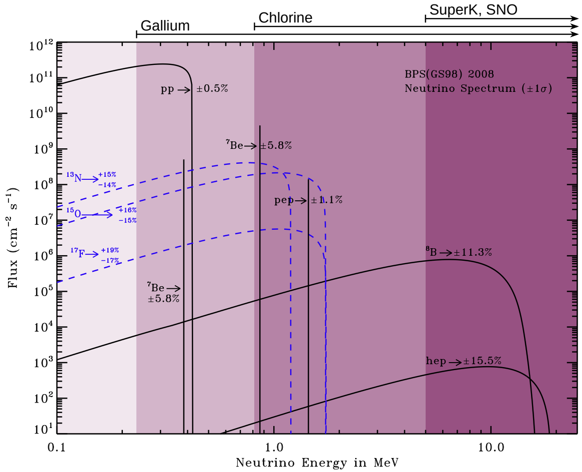
II. **Oscillation parameters and the SSM**

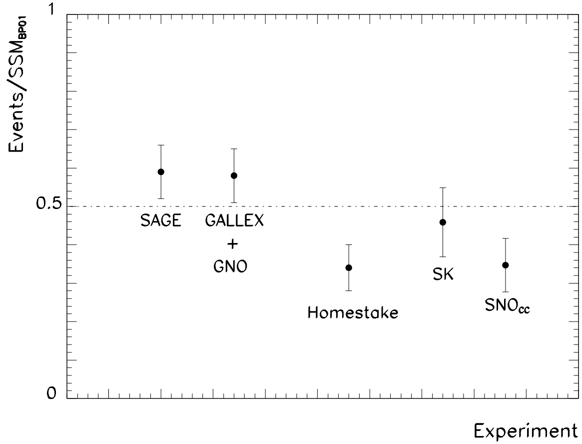
III. **Other hints of non-zero θ_{13}**

Summary

The solar neutrino problem

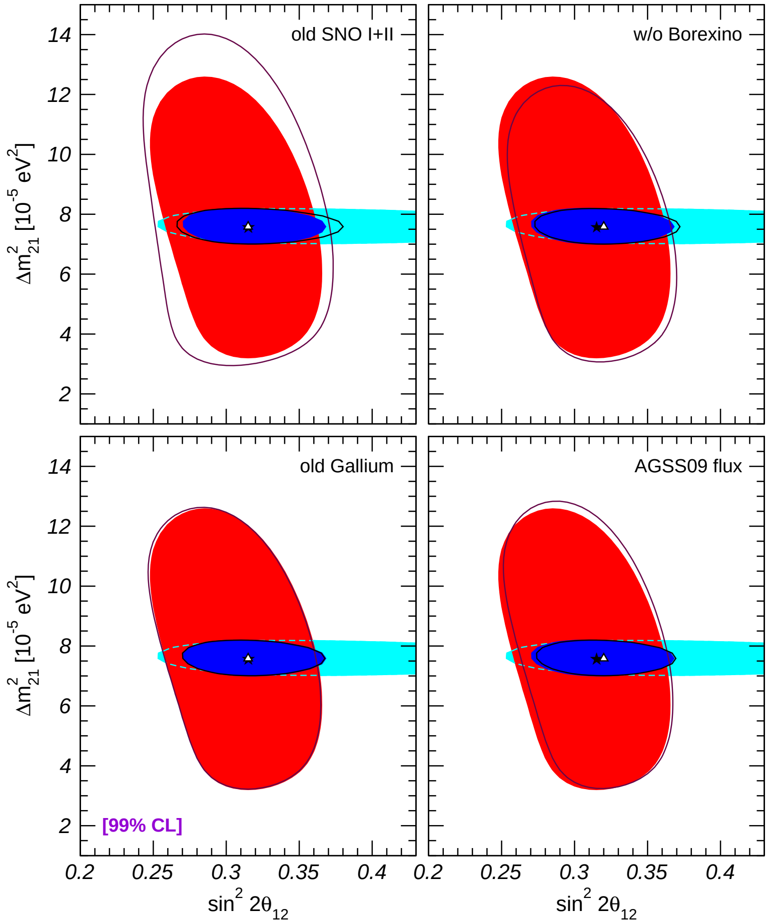
- Nuclear reactions in the core of the Sun produce *electron neutrinos*;
- during the last 40 years, a number of underground experiments has measured their flux in different energy windows;
- it is found that ALL the experiments observe a deficit of about $\mathbf{30 - 60\%}$;
- the deficit is NOT the same for all the experiments, hence the effect is **energy dependent**.
- it is **not possible** to reconcile the data with the Standard Solar Model (SSM) by simply readjusting the parameters of the model;
- solution: neutrino $\nu_e \to \nu_{\text{active}}$ oscillations;
- Effect well understood $\Rightarrow$ **PROBLEM SOLVED.**





The $\theta_{13} = 0$ limit: recent data

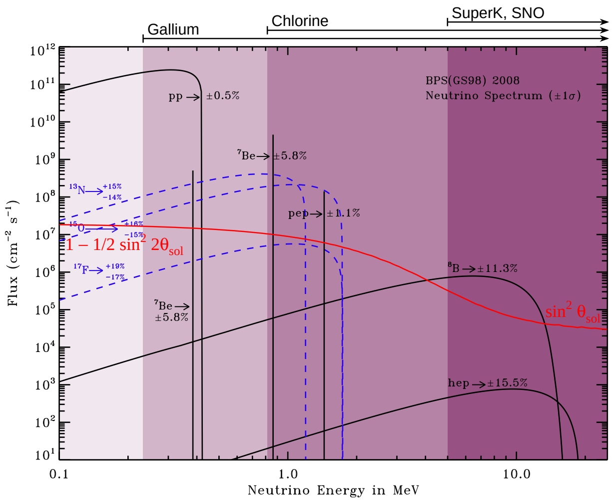
- Most relevant changes since last year:
  - new SNO-leta (low energy threshold analysis) replaces separated SNO-I and SNO-II data sets $\Rightarrow$ bounds on θ_{12} enhanced;
  - inclusion of Borexino results (both ^{7}Be and ^{8}B data) $\Rightarrow$ θ_{12} decreases;
  - new results from SAGE with reduced systematics $\Rightarrow$ negligible effects;
  - new AGSS09 solar model $\Rightarrow$ θ_{12} increases;
- Δm^2_{21} determined by KamLAND $\Rightarrow$ insensitive to details of solar data.

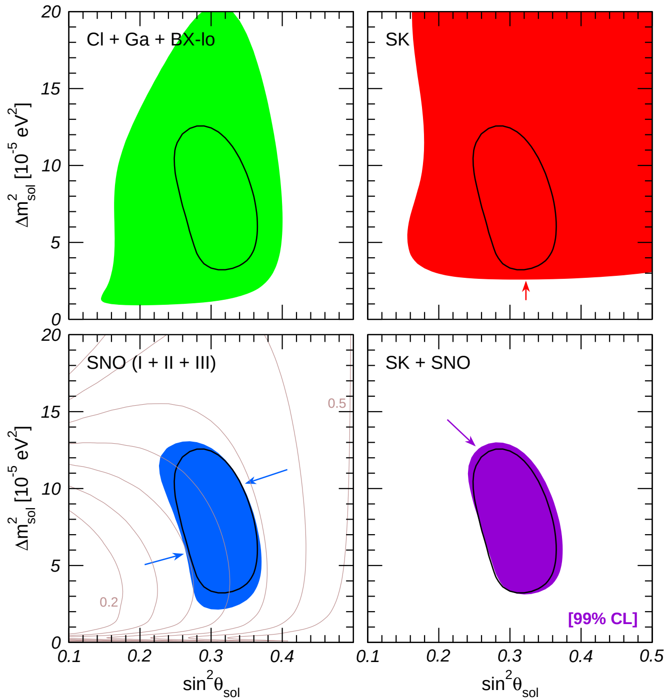


Solar neutrinos: anatomy of the oscillation solution

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{\text{sol}}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{\text{sol}} & \sin 2\theta_{\text{sol}} \\ \sin 2\theta_{\text{sol}} & \cos 2\theta_{\text{sol}}\end{pmatrix} \pm \sqrt{2}G_F\begin{pmatrix}N_e & 0 \\ 0 & 0\end{pmatrix}\right]\vec{\nu}, \quad \text{with} \quad \vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix};$$

- Data: low-E (Cl, Ga): $P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{\text{sol}}$, high-E (SK, SNO): $P_{ee} \approx \sin^2\theta_{\text{sol}}$;
- fit presently dominated by high-E.



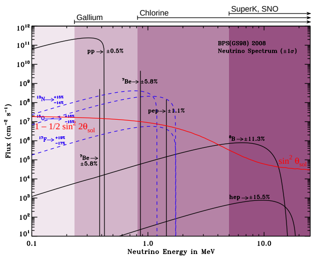


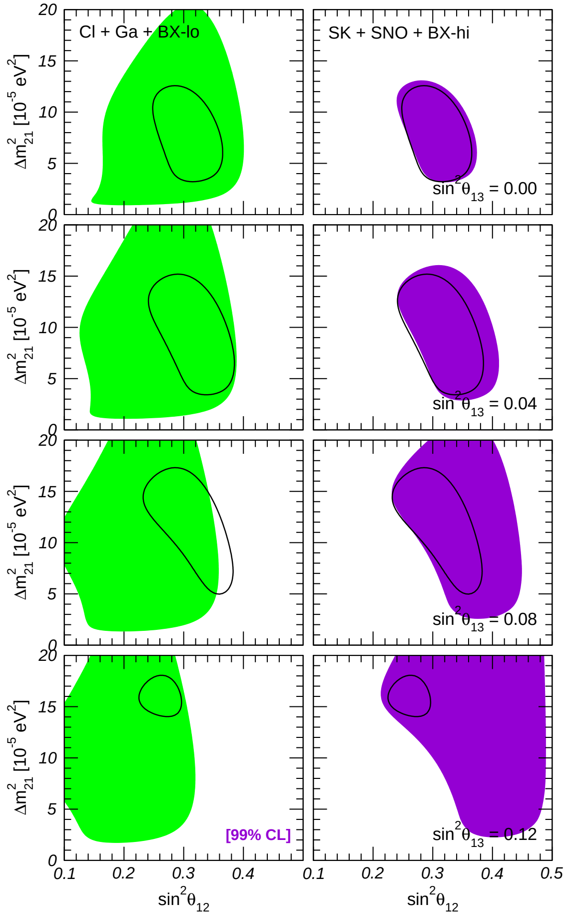
Bound on θ_{13} from solar data

- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific value of Δm^2_{31} irrelevant;

$\Rightarrow$ solar data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- probability: $\begin{cases} \text{low-E: } P_{ee} \approx \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right), \\ \text{high-E: } P_{ee} \approx \cos^4\theta_{13}\sin^2\theta_{12}; \end{cases}$
- as θ_{13} increases, $\cos^4\theta_{13}$ decreases and:
  - low-E data favor **smaller** θ_{12};
  - high-E data favor **larger** θ_{12} and Δm^2_{21}.





Bound on θ_{13} from KamLAND data

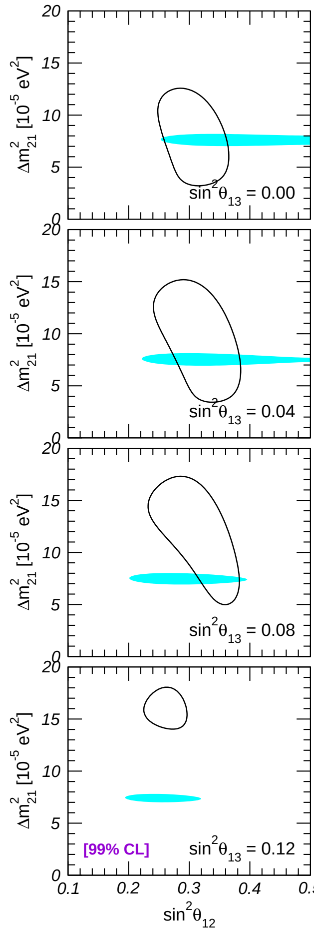
- Only P_{ee} measured $\Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

$\Rightarrow$ KamLAND data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- probability: $P_{ee} \approx \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21} L}{4E}\right)$,
- Δm^2_{21} is determined by $\langle L \rangle$ and by the energy spectrum, hence it does not change with θ_{13};
- as θ_{13} increases, data favor **smaller** θ_{12};
- for large θ_{13} oscillation signal is suppressed $\Rightarrow$ fit gets worse.

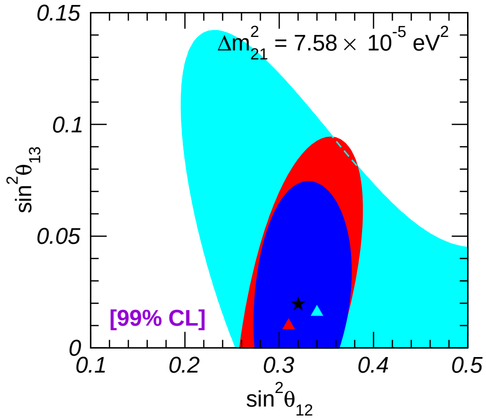
Synergy with solar data

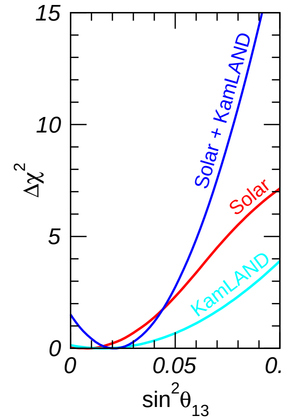
- As θ_{13} increases, solar region moves to larger Δm^2_{21}, while KamLAND region does not;
- also, for large θ_{13} KamLAND adds to low-E solar data in favoring small θ_{12}, increasing the tension with high-E solar data.



Hint for non-zero θ_{13} in solar and KamLAND data

- For $\theta_{13} = 0$, we have $\sin^2\theta_{12} = \begin{cases} 0.30 \text{ from solar data;} \\ 0.36 \text{ from KamLAND data;} \end{cases}$ [Fogli et al, arXiv:0806.2649] [Schwetz et al, arXiv:0808.2016]
- hence there is a tension between solar and KamLAND;
- as we have just seen, when θ_{13} increases:
  - solar region slightly moves to larger θ_{12} (high-E data dominate over low-E ones);
  - KamLAND region definitely shifts to smaller θ_{12};
- therefore, a non-zero value of θ_{13} reduces the tension between solar and KamLAND data;
- new SNO-III data favor smaller $\phi_{CC}/\phi_{NC} \Rightarrow$ smaller θ_{12} from solar $\Rightarrow$ tension with KamLAND is increased $\Rightarrow$ larger θ_{13} favored.





Reconstructing the neutrino fluxes

Flux	Φ_i^{ref} [cm^{-2} s^{-1}]
pp	5.97×10^{10}
^{7}Be	5.07×10^{9}
pep	1.41×10^{8}
^{13}N	2.88×10^{8}
^{15}O	2.15×10^{8}
^{17}F	5.82×10^{6}
^{8}B	5.94×10^{6}
hep	7.90×10^{3}

- Strategy: perform a solar model independent analysis of both solar and terrestrial neutrino data in the framework of 3ν mixing;
- aim: to determine both the flavor parameters and all the solar neutrino fluxes with a minimum set of theoretical priors;
- 11 parameters: θ_{12}, θ_{13}, Δm^2_{21} and 8 reduced fluxes $f_i = \Phi_i/\Phi_i^{\text{ref}}$;
- imposed physical conditions:
  - fluxes must be positive: $\Phi_i \geq 0$
  - the number of nuclear reactions terminating the pp-chain should not exceed the number of nuclear reactions which initiate it: $\Phi_{^7\text{Be}} + \Phi_{^8\text{B}} \leq \Phi_{\text{pp}} + \Phi_{\text{pep}}$
  - the $^{14}\text{N}(p,\gamma)^{15}\text{O}$ reaction must be the slowest process in the main branch of the CNO-cycle: $\Phi_{^{15}\text{O}} \leq \Phi_{^{13}\text{N}}$
  - the CNO-II branch must be subdominant: $\Phi_{^{17}\text{F}} \leq \Phi_{^{15}\text{O}}$
  - pep & pp have the same nuclear matrix element: $f_{\text{pep}}/f_{\text{pp}} = 1.008 \pm 0.010$

Results with the luminosity constraint

- Best-fit fluxes:

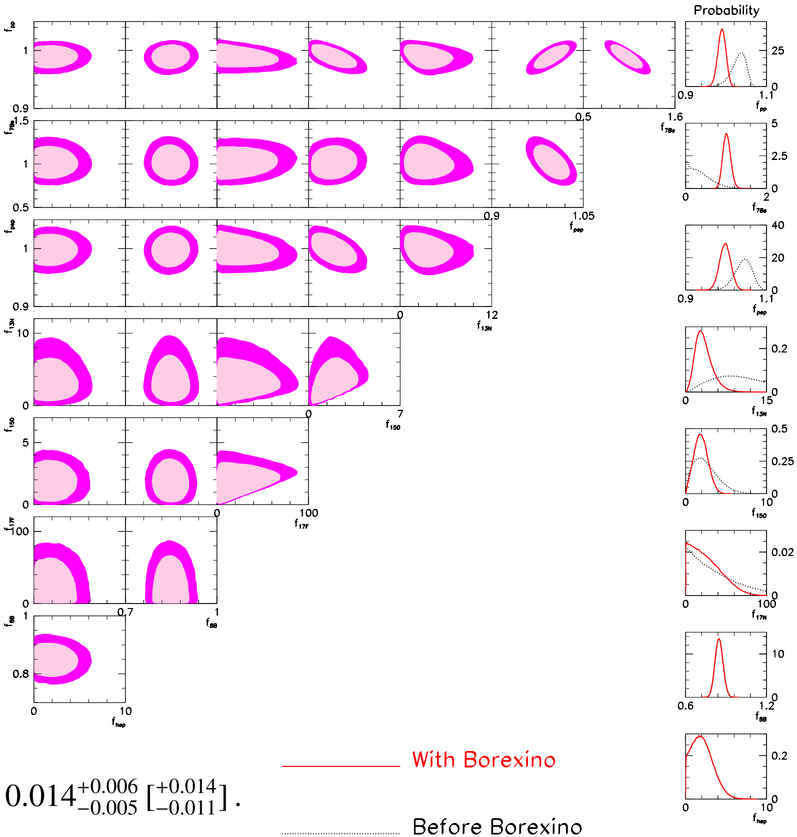
$$
\begin{aligned}
f_{\text{pp}} &= 0.990^{+0.010}_{-0.009}\,[^{+0.023}_{-0.030}]\,, \\
f_{^7\text{Be}} &= 1.00^{+0.10}_{-0.09}\,[^{+0.25}_{-0.21}]\,, \\
f_{\text{pep}} &= 0.998 \pm 0.014\,[\pm 0.04]\,, \\
f_{^{13}\text{N}} &= 2.7^{+1.7}_{-1.2}\,[^{+5.6}_{-2.4}]\,, \\
f_{^{15}\text{O}} &= 1.8 \pm 0.9\,[^{+2.2}_{-1.8}]\,, \\
f_{^{17}\text{F}} &\leq 32\,[72]\,, \\
f_{^8\text{B}} &= 0.85 \pm 0.03\,[\pm 0.08]\,, \\
f_{\text{hep}} &= 1.7^{+1.3}_{-1.4}\,[^{+3.8}_{-1.7}]\,,
\end{aligned}
$$

- oscillation parameters:

$$
\begin{aligned}
\Delta m^2_{21} &= 7.6 \pm 0.2\,[\pm 0.5] \times 10^{-5}\ \text{eV}^2\,, \\
\sin^2\theta_{12} &= 0.33 \pm 0.02\,[\pm 0.05]\,, \\
\sin^2\theta_{13} &= 0.02 \pm 0.012\,[^{+0.03}_{-0.02}]\,,
\end{aligned}
$$

- solar luminosity:

$$
\frac{L_{\text{pp-chain}}}{L_\odot} = 0.986^{+0.005}_{-0.006}\,[^{+0.011}_{-0.014}] \iff \frac{L_{\text{CNO}}}{L_\odot} = 0.014^{+0.006}_{-0.005}\,[^{+0.014}_{-0.011}]\,.
$$



Results without the luminosity constraint

- Best-fit fluxes:

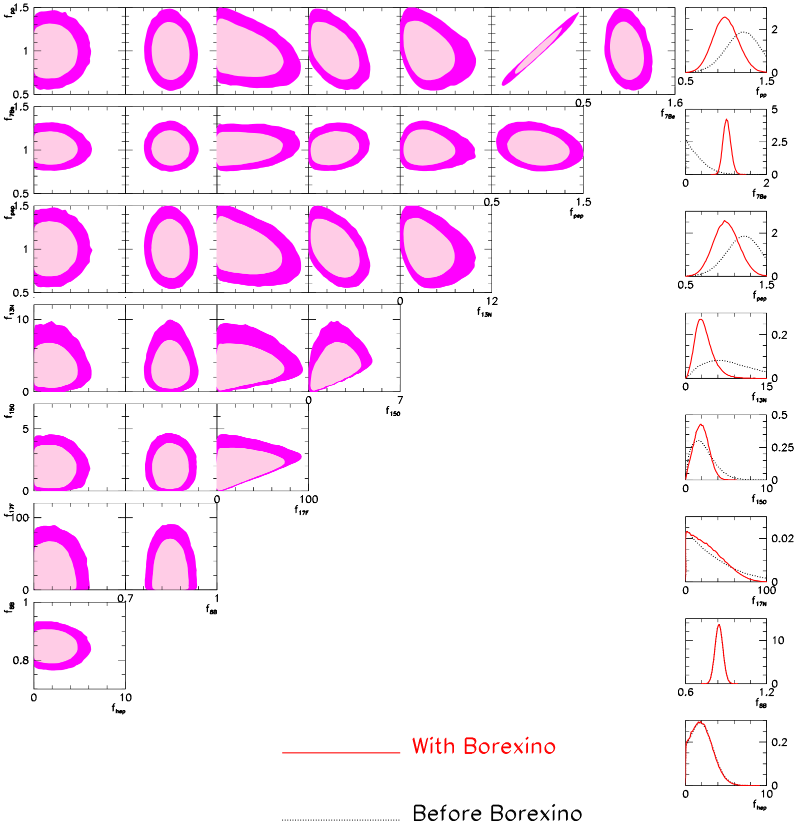
$$f_{pp} = 0.98^{+0.16}_{-0.15}\,[^{+0.47}_{-0.40}]\,,$$
$$f_{^7Be} = 1.01^{+0.10}_{-0.09}\,[^{+0.27}_{-0.22}]\,,$$
$$f_{pep} = 0.98^{+0.16}_{-0.15}\,[^{+0.47}_{-0.40}]\,,$$
$$f_{^{13}N} = 2.7^{+1.8}_{-1.3}\,[^{+5.7}_{-2.5}]\,,$$
$$f_{^{15}O} = 1.9 \pm 1.0\,[^{+2.3}_{-1.9}]\,,$$
$$f_{^{17}F} \leq 34\,[79]\,,$$
$$f_{^8B} = 0.85 \pm 0.03\,[\pm 0.08]\,,$$
$$f_{hep} = 1.7^{+1.3}_{-1.4}\,[^{+3.8}_{-1.7}]\,,$$

- solar luminosity:

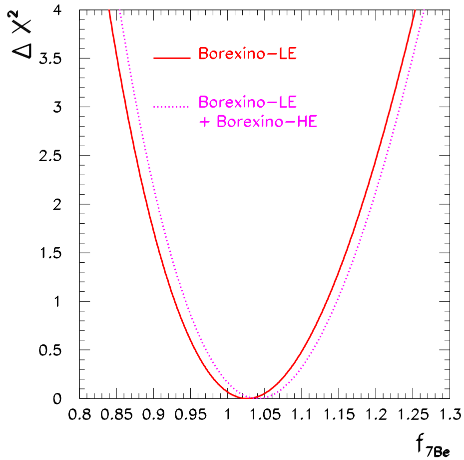
$$\frac{L_{\text{pp-chain}}}{L_\odot} = 0.98^{+0.15}_{-0.14}\,[\pm 0.40]\,,$$
$$\frac{L_{\text{CNO}}}{L_\odot} = 0.015^{+0.005}_{-0.007}\,[^{+0.013}_{-0.014}]\,,$$

- from which we derive:

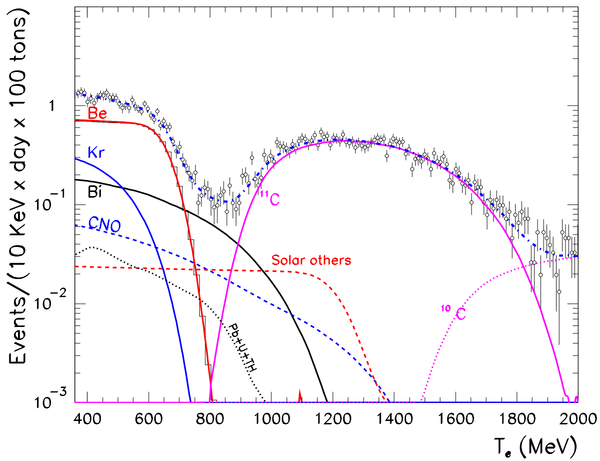
$$\frac{L_\odot(\text{neutrino-inferred})}{L_\odot} = 1.00 \pm 0.14\,[^{+0.37}_{-0.34}]\,.$$



The Borexino experiment

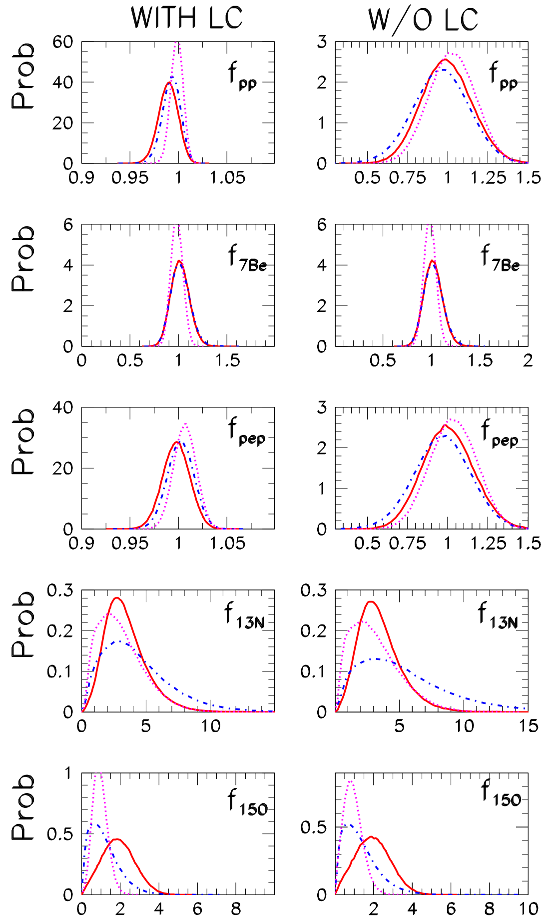


- Borexino has provided a unique measurement of solar neutrinos at low energy [arXiv:0805.3843];
- however, the official analysis only focuses on the extraction of ^{7}Be, and treats CNO neutrinos as "background";
- this is inconsistent with our approach, which aims at a joint determination of **all** the fluxes on the same footing;
- hence, we have performed our own analysis of the Borexino spectrum;
- backgrounds:
  - ^{14}C is removed by a cut $T_e \geq 365$ keV;
  - ^{238}U, ^{214}Pb are assumed to be known;
  - ^{85}Kr, ^{210}Bi, ^{11}C, ^{10}C are left free and fitted;
- our fit is in excellent agreement with the results of the Borexino collaboration.



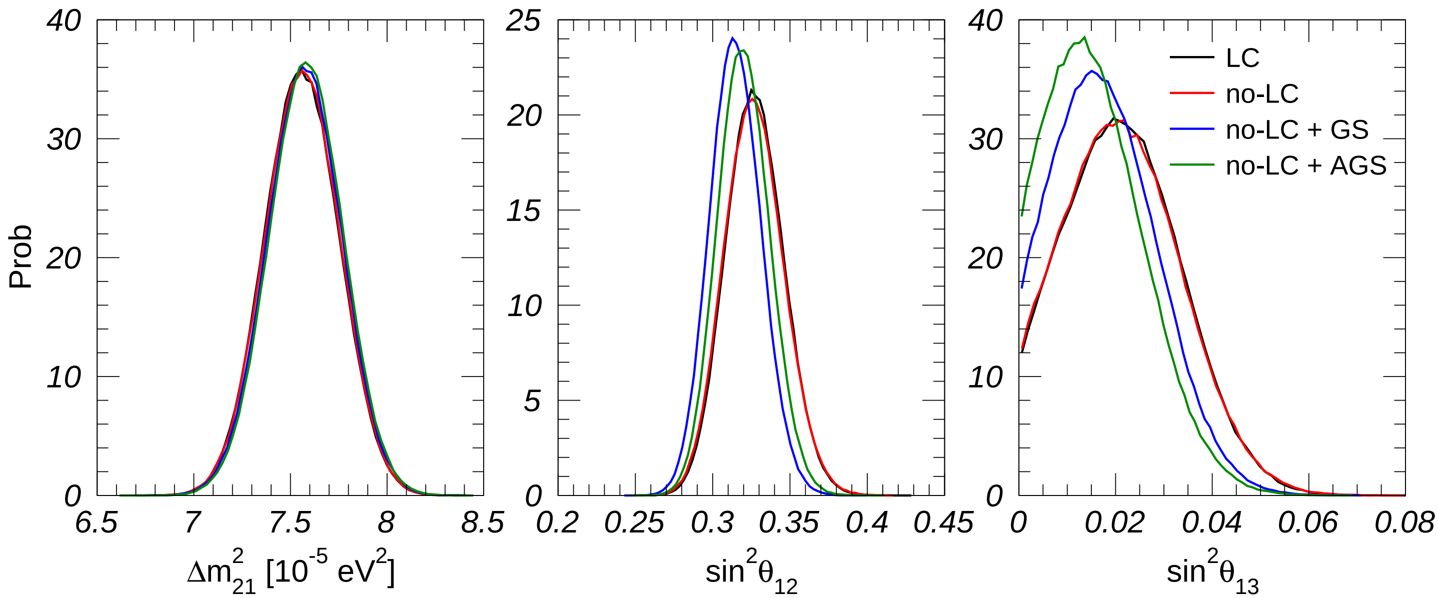
The role and potential of Borexino

- Three types of fit:
  - solid: present, full-spectrum;
  - dash-dotted: present, ^{7}Be line only;
  - dotted: future (no ^{11}C, stat $\times 2$, sys $/ 3$);
- use of spectral info irrelevant for ^{7}Be;
- CNO improves $\Rightarrow$ Borexino can see them, even with unknown ^{210}Bi background;
- CNO also important for Chlorine and Gallium:
  - Gallium mainly sensitive to ^{13}N (lower E_ν);
  - Chlorine mainly sensitive to ^{15}O (higher E_ν);
- Gallium excess $\Rightarrow$ ^{13}N always larger than 1;
- Chlorine deficit $\Rightarrow$ ^{15}O senses tension with Borexino;
- future data will improve fluxes, but not dramatically.



Impact of the SSM on the oscillation parameters

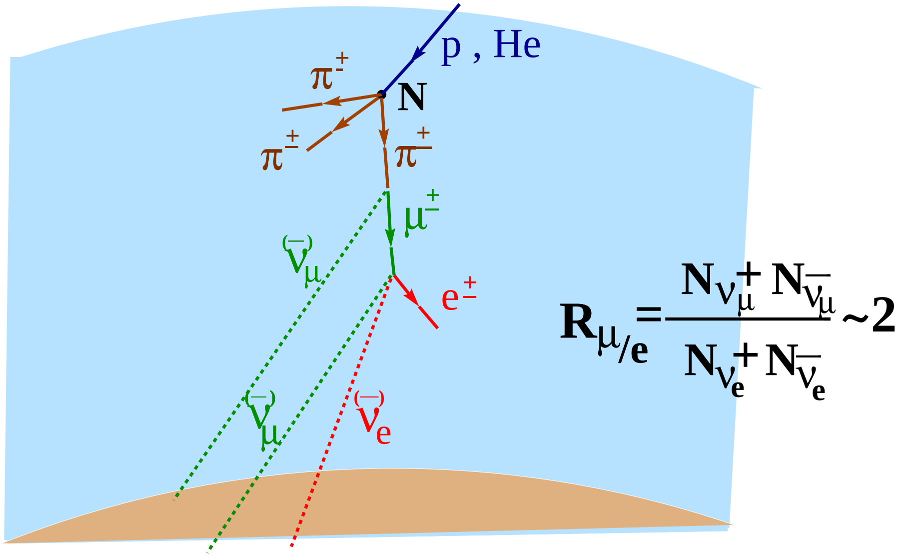
- Imposing the luminosity constraint has no effect on the oscillation parameters;
- Δm^2_{21} completely dominated by KamLAND $\Rightarrow$ insensitive to the SSM's details;
- conversely, the preferred range of θ_{12} and θ_{13} depends on the SSM.



Atmospheric neutrinos

- Atmospheric neutrinos are produced by the interaction of *cosmic rays* (p, He, ...) with the Earth's atmosphere:

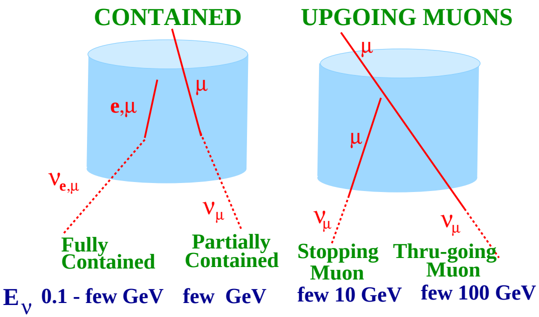
1	$A_{cr} + A_{air} \to \pi^\pm, K^\pm, K^0, \dots$
2	$\pi^\pm \to \mu^\pm + \nu_\mu$,
3	$\mu^\pm \to e^\pm + \nu_e + \nu_\mu$;

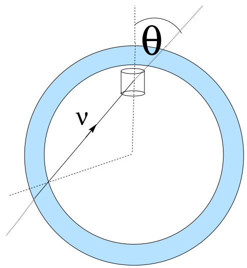


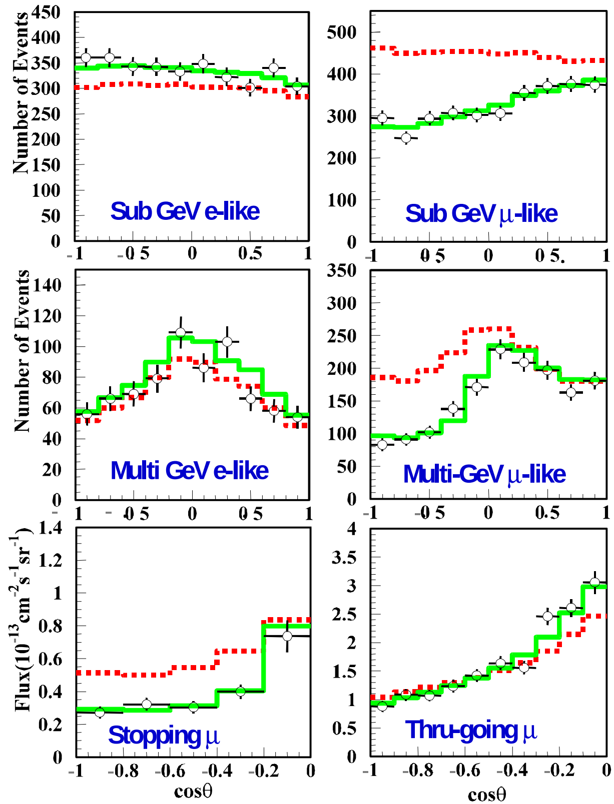
- at the detector, some ν interacts and produces a **charged lepton**, which is observed;
- ν_μ and ν_e fluxes have large ($\approx 20\%$) uncertainties;
- however, the ν_μ/ν_e ratio is predicted with quite good accuracy ($\approx 5\%$).

Atmospheric neutrino oscillations

- Data (dots) vs. Monte-Carlo (red dashed line):
  - *small excess* in sub-GeV ν_e;
  - *no problem* in multi-GeV ν_e;
  - *zenith-dependent deficit* in <u>all</u> ν_μ samples;
- deficit in ν_μ: $\left\{ \begin{array}{l} \text{– grows with } L; \\ \text{– decreases with } E_\nu; \end{array} \right.$
- deficit cannot be explained by flux uncertainties;
- solution: $\nu_\mu \to \nu_\tau$ oscillations (green solid line).

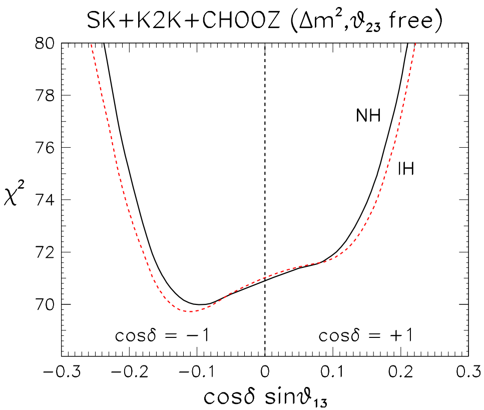


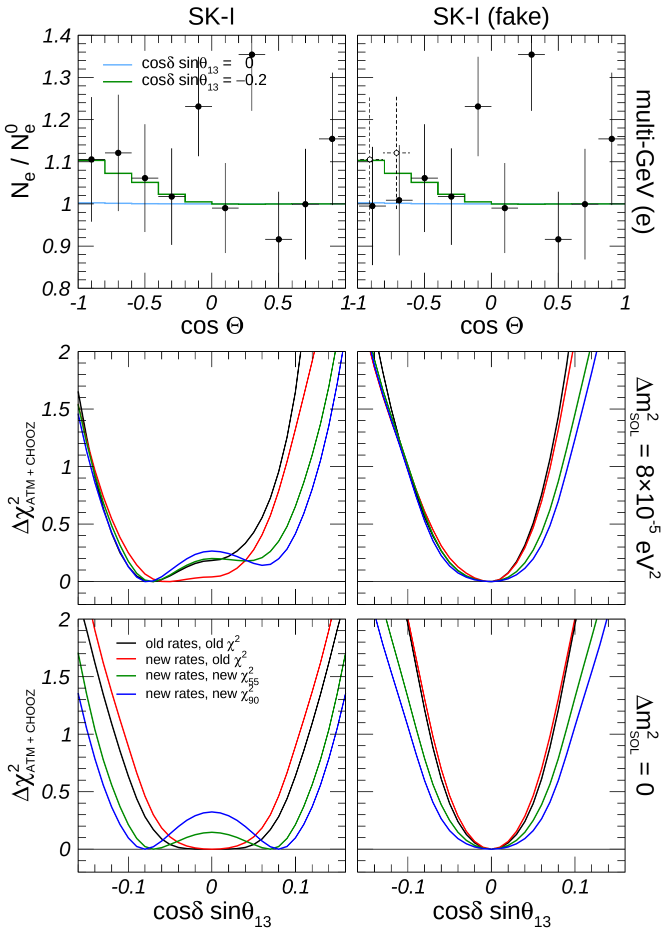




θ_{13} from atmospheric SK-I data

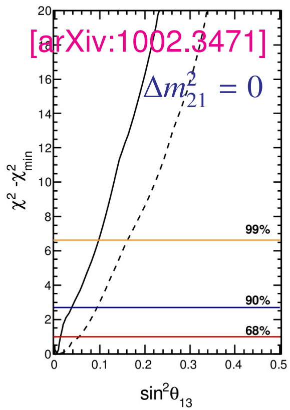
- Hint of non-zero θ_{13} in atm SK-I (+ LBL) data; [Fogli et al, hep-ph/0506083 & arXiv:0806.2649];
- characteristics affected by δ_{CP} $\Rightarrow$ inclusion of subleading Δm^2_{21} effects important;
- hint triggered by a peculiar signature of multi-GeV e-like events in SK-I data;
- details of the simulation very important.

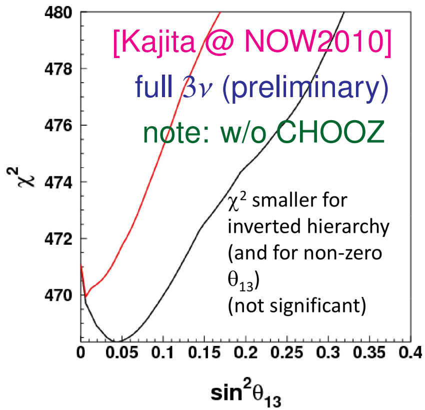


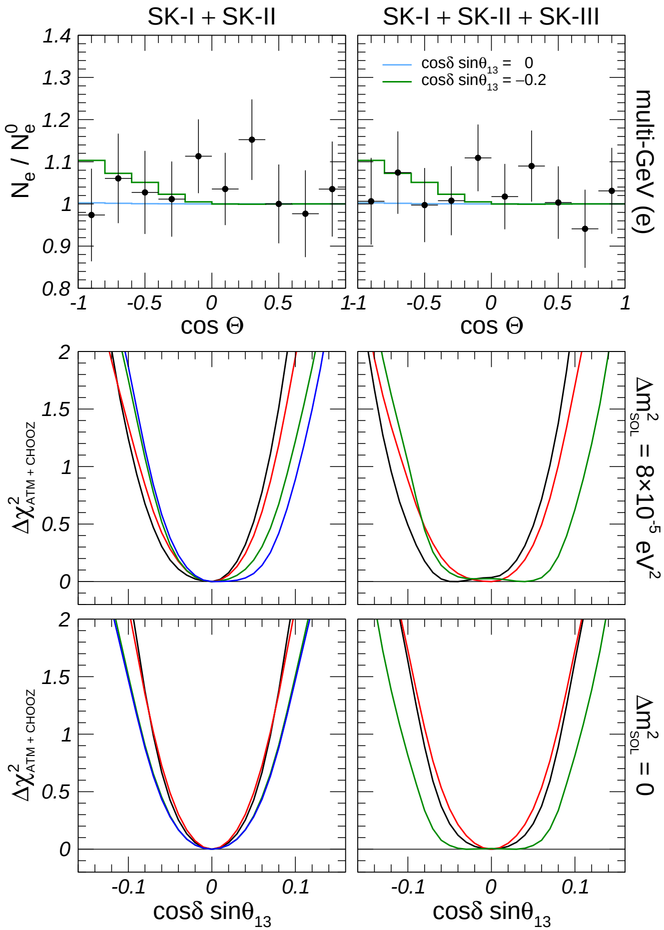


θ_{13} after atmospheric SK-III data

- Peculiar signature of multi-GeV e-like SK-I data not present in SK(I+II) data;
- however, a weak excess reappear after the inclusion of SK-III data;
- SK analysis for $\Delta m^2_{31} = 0$ confirms $\theta_{13} = 0$;
- preliminary results from a full 3ν fit suggest weak deviations may be present for IH.

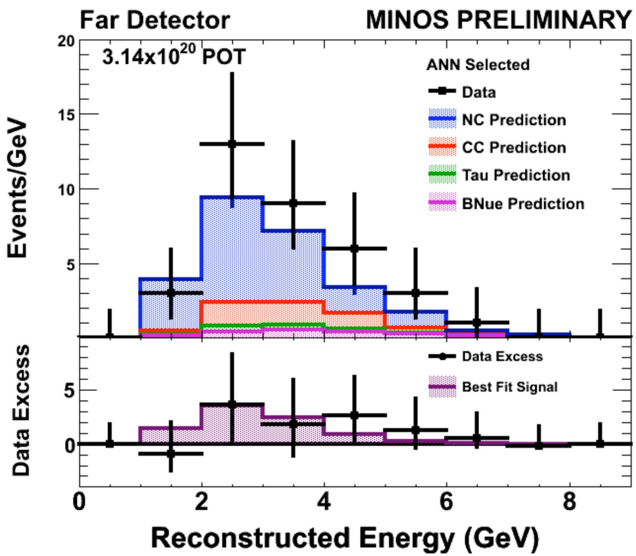


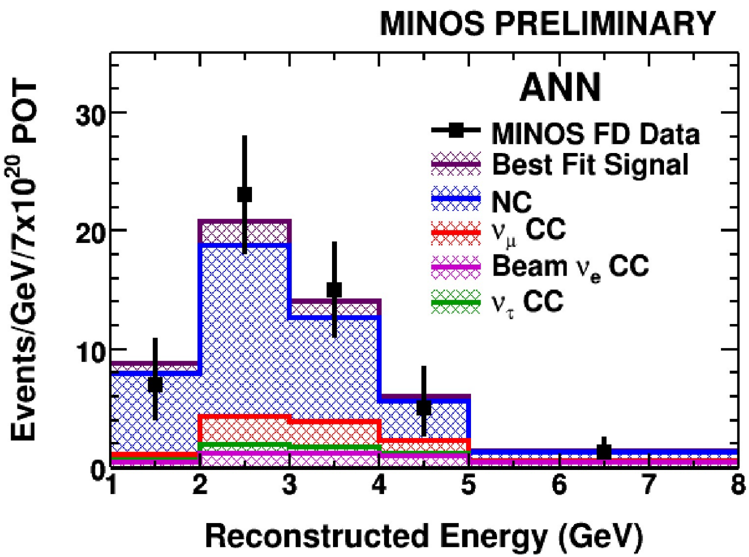




ν_e appearance at the Minos experiment

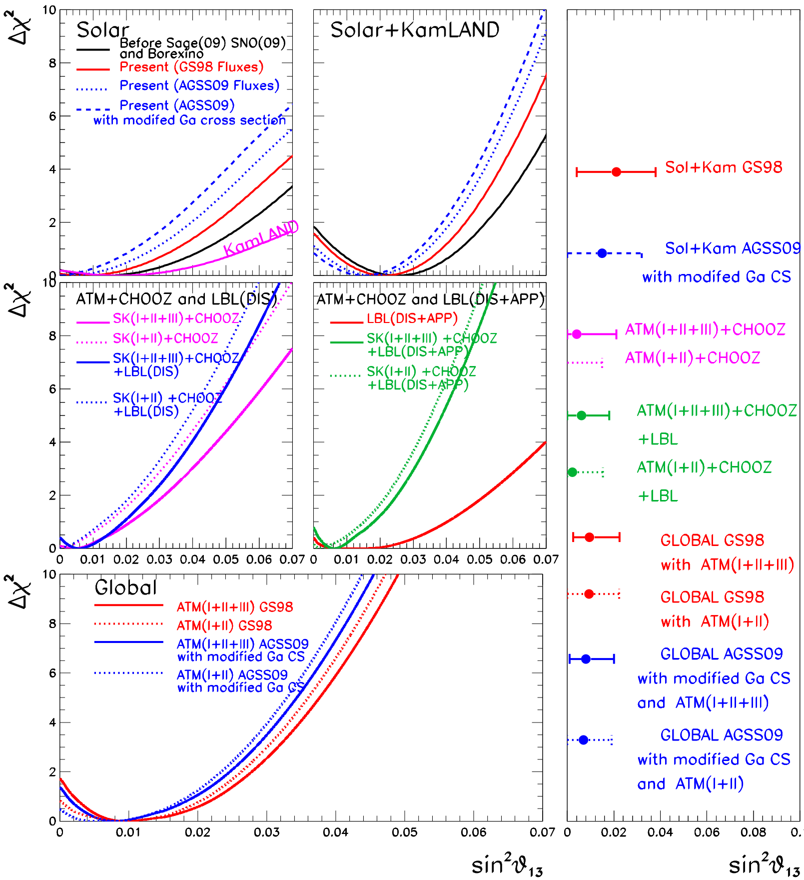
- ν_μ's are produced at accelerator through π decay, with mean energy ~ 3 GeV;
- flux measured at 735 km $\Rightarrow$ deficit of ν_μ's observed $\Rightarrow$ atm $\nu_\mu \to \nu_\tau$ conversion confirmed;
- ν_e appearance: $\begin{cases} 3.1 \times 10^{20} \text{ pot: 35 observed, } 27.0 \pm 5.2 \pm 2.0 \text{ expected} \Rightarrow 1.5\sigma \text{ excess;} \\ 7.0 \times 10^{20} \text{ pot: 54 observed, } 49.1 \pm 7.0 \pm 2.7 \text{ expected} \Rightarrow 0.7\sigma \text{ excess.} \end{cases}$





Summary

- Solar neutrino data alone can impose an upper bound on θ_{13};
- in combination with KamLAND this bound becomes stronger;
- a small non-zero θ_{13} improves the agreement between solar and KamLAND data;
- these results are <u>qualitatively</u> robust with respect to the details of the SSM (GS, AGSS, free);
- weak preference for non-zero θ_{13} in atmospheric data still to be properly quantified;
- hint of non-zero θ_{13} in Minos ν_e appearance sample strongly reduced by the new data.



[Gonzalez-Garcia, MM & Salvado, JHEP 04 (2010) 056]