Leading and subleading effects in the standard three-neutrino oscillation scenario

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I. Present status of neutrino oscillations

II. Subleading 3ν effects in neutrino experiments

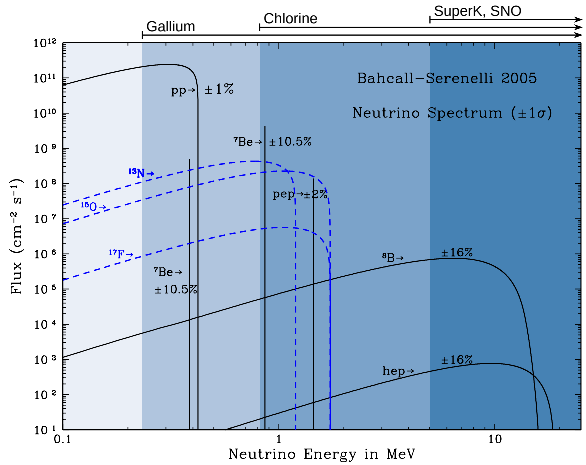
Conclusions

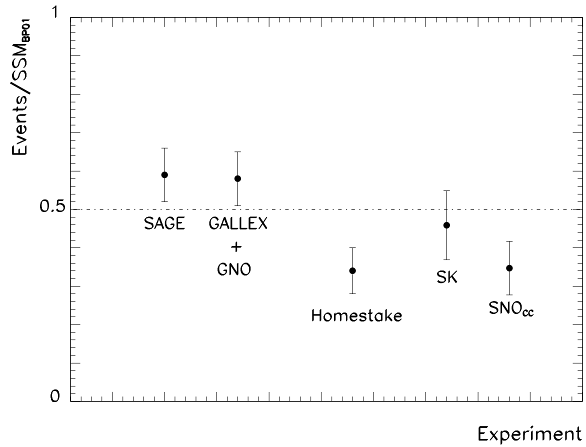
The solar neutrino problem

- 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;

⇒ New Physics **is needed** to explain the data;

⇒ **oscillation** hypothesis: $\nu_e \to \nu_{\text{active}}$.

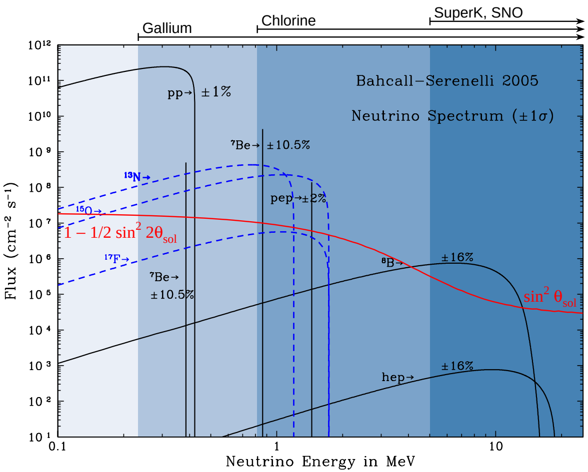


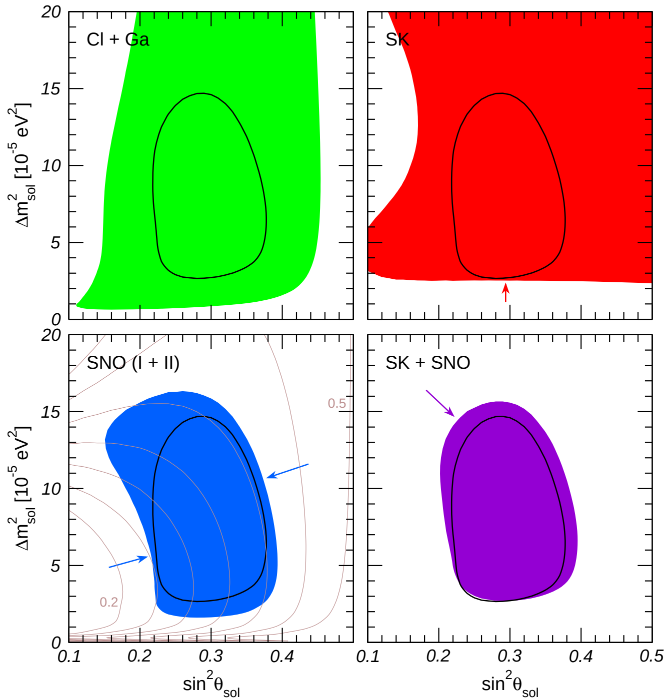


Solar neutrinos: anatomy of the oscillation solution

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

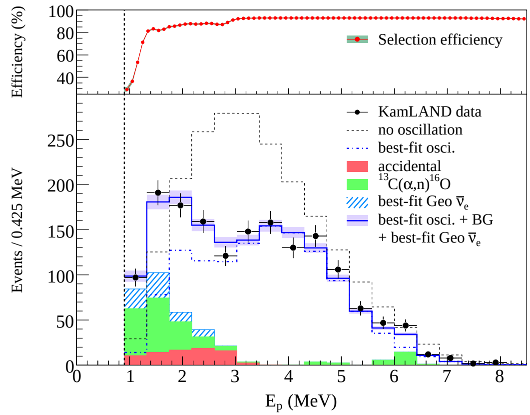
- Data:
  - low-E (Cl, Ga): $P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{\text{sol}}$,
  - high-E (SK, SNO): $P_{ee} \approx \sin^2\theta_{\text{sol}}$;
- fit presently dominated by high-E.





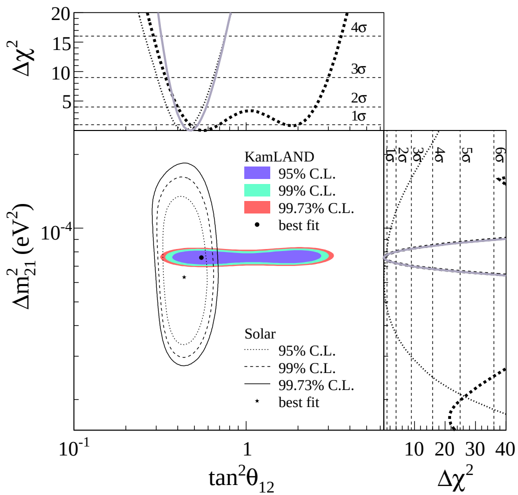
The KamLAND experiment

- Nuclear fission reactions in nuclear power plants produce *electron anti-neutrinos*;
- neutrino flux from many plants in Japan measured by KamLAND (average baseline: ≈ 180 km);
- an energy-dependent deficit of $\bar{\nu}_e$ is observed.



Combining solar & KamLAND data

- Hypothesis: $\nu_e \to \nu_{\text{active}}$ conversion due to **non-zero neutrino masses** and **flavor mixing**;
- CPT conservation $\Rightarrow$ physics of solar (ν) and KamLAND ($\bar{\nu}$) neutrino conversion must be the same;
- only two parameters: Δm^2_{sol} and θ_{sol};
- this model perfectly explains both effects.

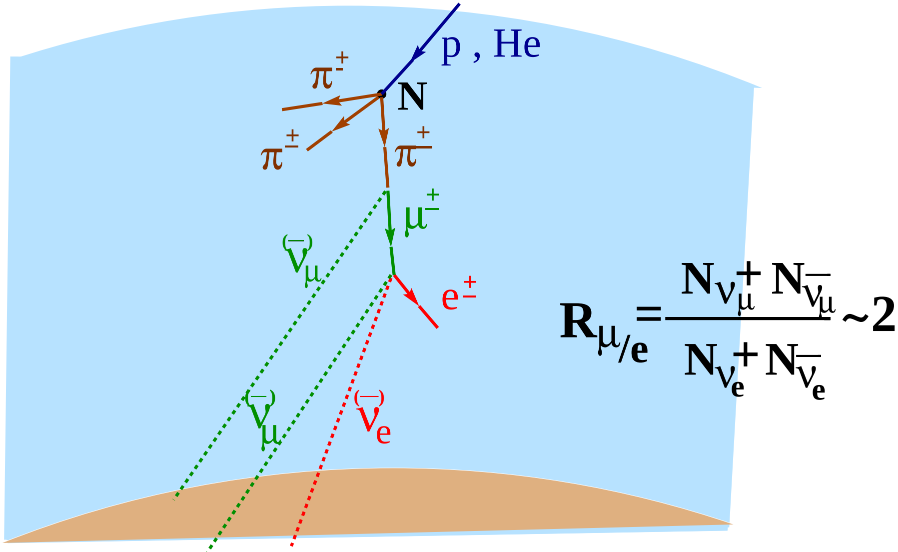


Atmospheric neutrinos

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

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

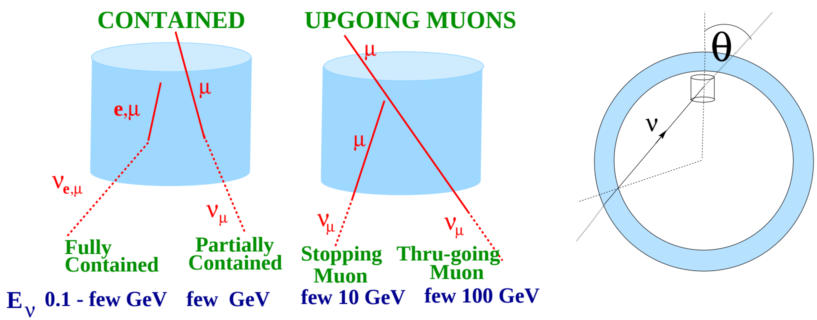
- at the detector, some ν interacts and produces a **charged lepton**, which is observed;
- ν_μ and ν_e fluxes have large ($\approx 20\%$) uncertainties;

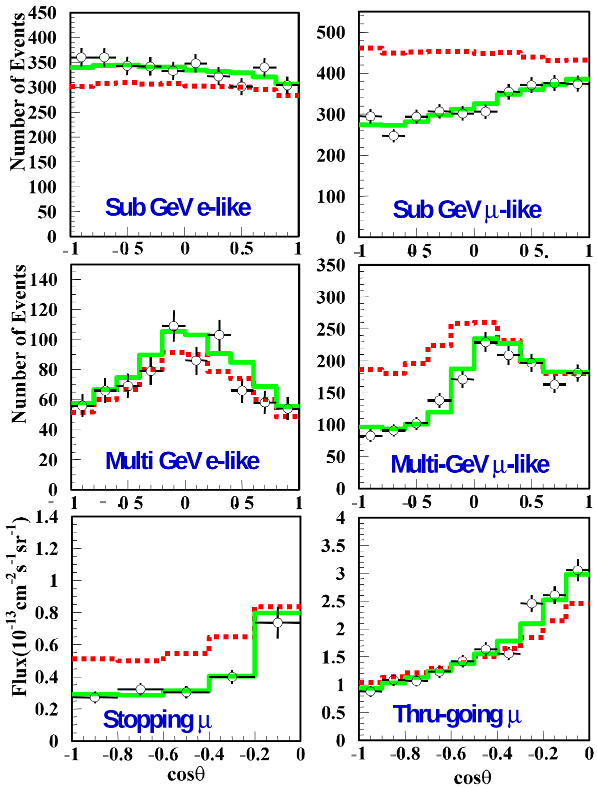


- however, the ν_μ/ν_e ratio is predicted with quite good accuracy ($\approx 5\%$).

Atmospheric neutrino oscillations

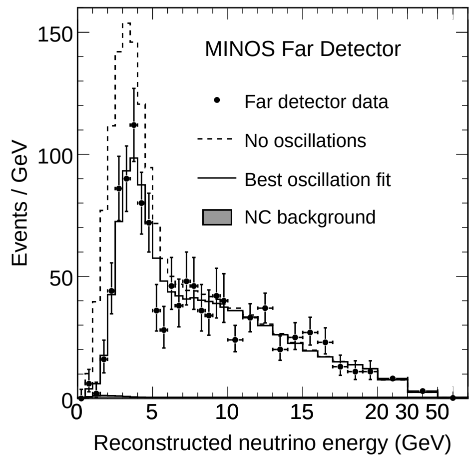
- Data (dots) vs. Monte-Carlo (red dashed line):
  - *small excess* in sub-GeV ν_e;
  - *no problem* in multi-GeV ν_e;
  - *zenith-dependent deficit* in all ν_μ samples;
- deficit in ν_μ: { – grows with L; – decreases with E_ν;
- deficit cannot be explained by flux uncertainties;
- solar $\nu_e \to \nu_{\text{active}}$ conversion does not help. . .





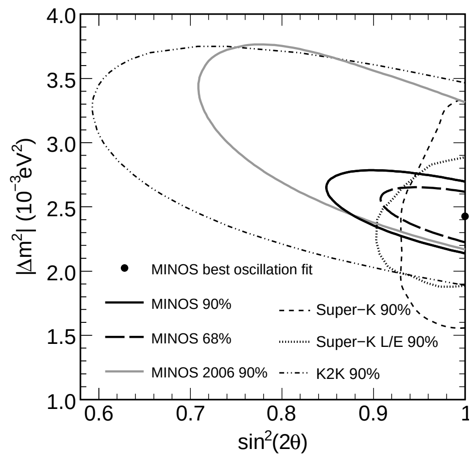
The K2K & Minos experiments

- ν_μ's are produced at accelerators through π decay, with mean energy ~ 1.3 GeV (K2K) and ~ 3 GeV (Minos);
- flux measured at 250 km (K2K) and 735 km (Minos);
- both experiments found a deficit of ν_μ's at low energy.



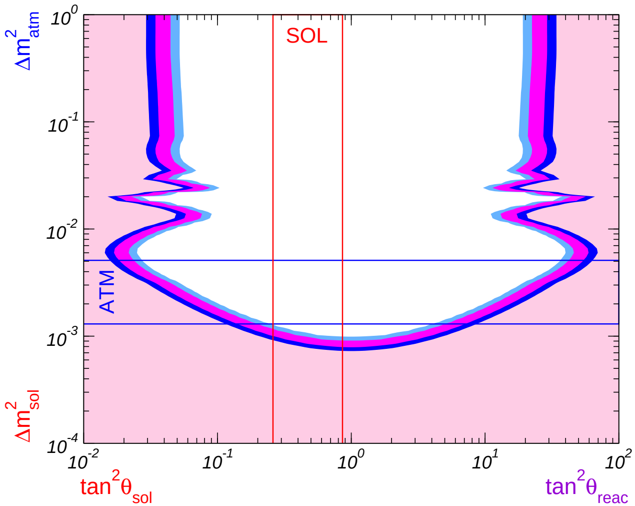
Combining ATM & accelerator data

- Hypothesis: $\nu_\mu \to \nu_\tau$ mass-induced oscillations. Same physics as solar $\nu_e \to \nu_{\text{active}}$ conversion, but in a different channel;
- CPT conservation $\Rightarrow$ same behavior of ν and $\bar{\nu}$ in atmospheric data at Super-Kamiokande;
- only two parameters: Δm^2_{atm} and θ_{atm};
- model perfectly explains all the data.



The Chooz & Palo Verde reactor experiments

- Reactor experiments (length: $\lesssim 1$ km). No $\bar{\nu}_e$ disappearance is observed.



Solar channel

- Like KamLAND, this experiment is sensitive to solar parameters Δm^2_{sol} and θ_{sol};
- from solar & KamLAND: θ_{sol} large but $\Delta m^2_{\text{sol}} < 10^{-4}$ eV^2 $\Rightarrow$ no oscillations expected (OK).

Atmospheric parameters

- given it mean energy and baseline, this experiment is also sensitive to Δm^2_{atm};
- however, the oscillation channel is different (involves ν_e) $\Rightarrow$ the mixing angle **is not** θ_{atm};
- **new parameter** θ_{rea} describes the mixing of ν_e with $\nu_{\mu,\tau}$;
- from atmospheric data: $\Delta m^2_{\text{atm}} \gtrsim 10^{-3}$ eV^2 $\Rightarrow$ **upper** bound on θ_{rea}.

General three-neutrino framework

- Equation of motion: **6** parameters (including CP violating effects):

$$i\frac{d\vec{\nu}}{dt} = \mathbf{H}\,\vec{\nu}; \qquad \mathbf{H} = \mathbf{O}\cdot\mathbf{H}_0^d\cdot\mathbf{O}^\dagger + \mathbf{V};$$

$$\mathbf{O} = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{\text{CP}}} \\ -s_{12}\,c_{23} - c_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{12}\,c_{23} - s_{12}\,s_{13}\,s_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,s_{23} \\ s_{12}\,s_{23} - c_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & -c_{12}\,s_{23} - s_{12}\,s_{13}\,c_{23}\,e^{i\delta_{\text{CP}}} & c_{13}\,c_{23} \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\mathbf{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right); \qquad \mathbf{V} = \mathbf{diag}\left(\pm\sqrt{2}G_F N_e,\ 0,\ 0\right).$$

Connection with two-neutrino oscillations

- **Solar** parameters Δm^2_{sol} and θ_{sol} are identified with Δm^2_{21} and θ_{12};
- **atmospheric** parameters Δm^2_{atm} and θ_{atm} are identified with Δm^2_{31} and θ_{23};
- **reactor** angle θ_{rea} constrained by Chooz corresponds to θ_{13};
- **CP-violating** phase δ_{CP} is a genuine 3ν feature, with no two-neutrino counterpart;
- smallness of θ_{13} and $\Delta m^2_{21}/\Delta m^2_{31}$ implies that solar and atm sectors are decoupled.

Neutrino oscillations: where we are

- Global six-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK + SNO-I + SNO-II;
  - **Atmospheric**: SK-I + SK-II;
  - **Reactor**: Chooz + KamLAND;
  - **Accelerator**: K2K + Minos (3.4×10^{20} p.o.t.);

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 34.5 \pm 1.4 \left({}^{+4.8}_{-4.0}\right), \quad \Delta m^2_{21} = 7.67\,{}^{+0.22}_{-0.21} \left({}^{+0.67}_{-0.60}\right) \times 10^{-5}\ \text{eV}^2,$$

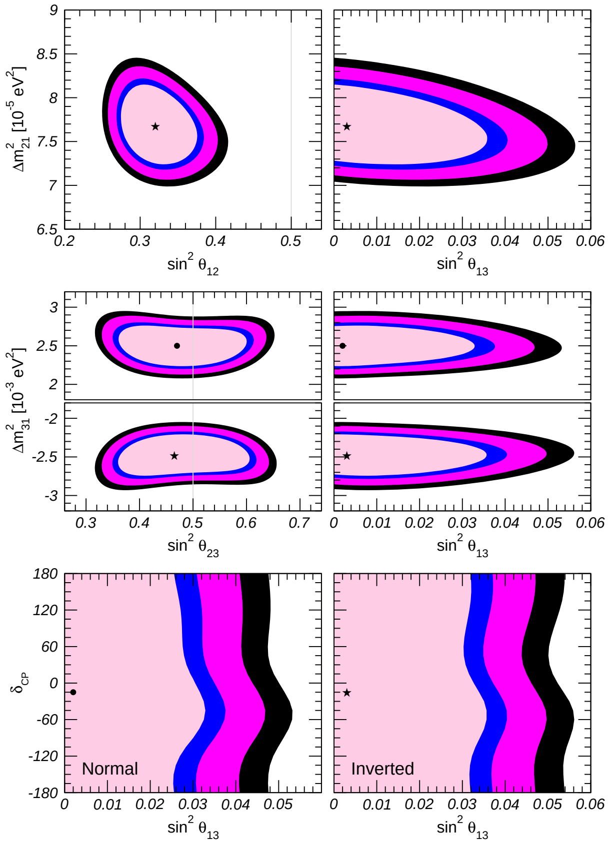
$$\theta_{23} = 43.1\,{}^{+4.4}_{-3.5} \left({}^{+10.1}_{-8.0}\right), \quad \Delta m^2_{31} = \begin{cases} -2.39 \pm 0.12 \left({}^{+0.37}_{-0.40}\right) \times 10^{-3}\ \text{eV}^2, \\ +2.49 \pm 0.12 \left({}^{+0.39}_{-0.36}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 3.2\,^{+4.5} \left(^{+9.6}\right), \qquad \delta_{CP} \in [0,\ 360];$$

- neutrino mixing matrix:

$$|U|_{90\%} = \begin{pmatrix} 0.80 \to 0.84 & 0.53 \to 0.60 & 0.00 \to 0.17 \\ 0.29 \to 0.52 & 0.51 \to 0.69 & 0.61 \to 0.76 \\ 0.26 \to 0.50 & 0.47 \to 0.66 & 0.64 \to 0.79 \end{pmatrix},$$

$$|U|_{3\sigma} = \begin{pmatrix} 0.77 \to 0.86 & 0.50 \to 0.63 & 0.00 \to 0.22 \\ 0.22 \to 0.55 & 0.45 \to 0.73 & 0.57 \to 0.80 \\ 0.21 \to 0.55 & 0.41 \to 0.70 & 0.59 \to 0.82 \end{pmatrix}.$$

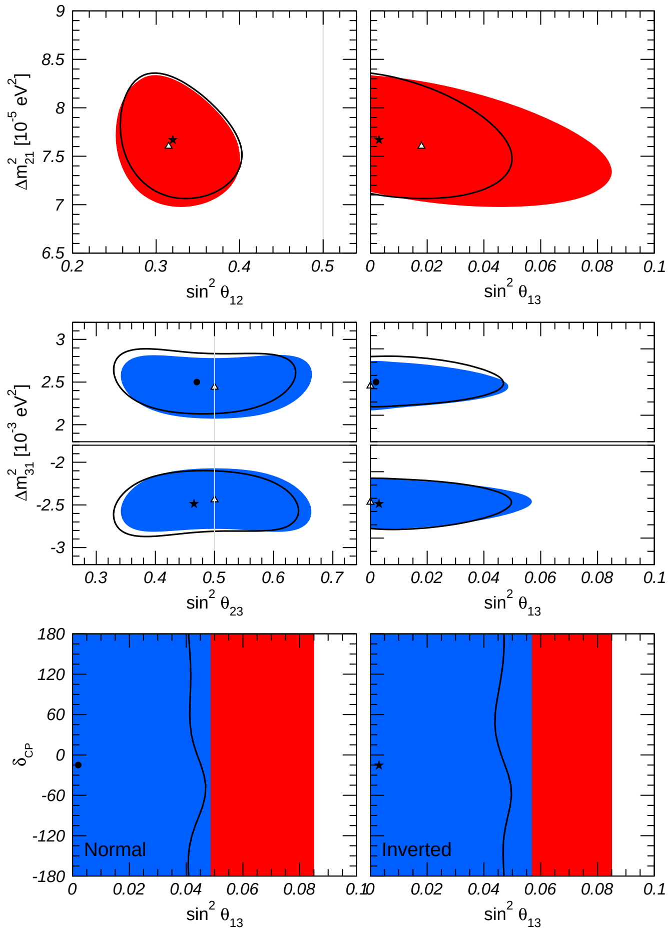


[Gonzalez-Garcia & MM, PREP 460 (2008) 1]

Neutrino oscillations: 2ν versus 3ν

- Determination of the oscillation parameters closely follows 2ν analysis. However:
  - solar+KamLAND also provide a weak but non-negligible bound on θ_{13};
  - solar+KamLAND seem to prefer **non-zero** θ_{13}, whereas ATM+LBL+Chooz do not;
  - ATM+LBL+Chooz (with $\Delta m^2_{21} = 0$) prefer $\theta_{23} = 45°$, whereas global fit does not;
  - δ_{CP} only have an effect in the global fit.

⇒ subleading 3ν effects **small but visible**:
  - solar+KamLAND contribute to θ_{13};
  - ATM data can see two-mass effects;
  - δ_{CP} also does its (tiny) bit.

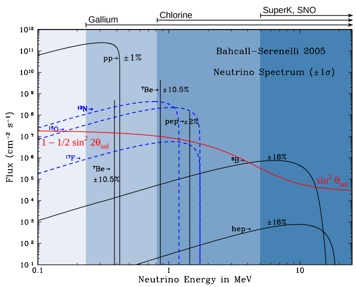


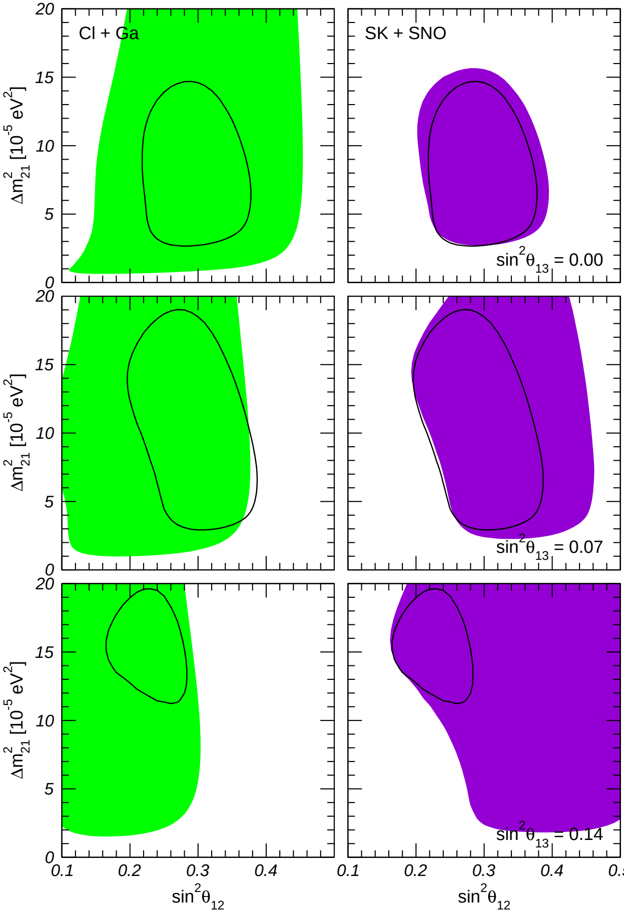
Bound on θ_{13} from solar data

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

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

- data: low-E: $P_{ee} \approx \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right)$, high-E: $P_{ee} \approx \cos^4\theta_{13}\sin^2\theta_{12}$;
- 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

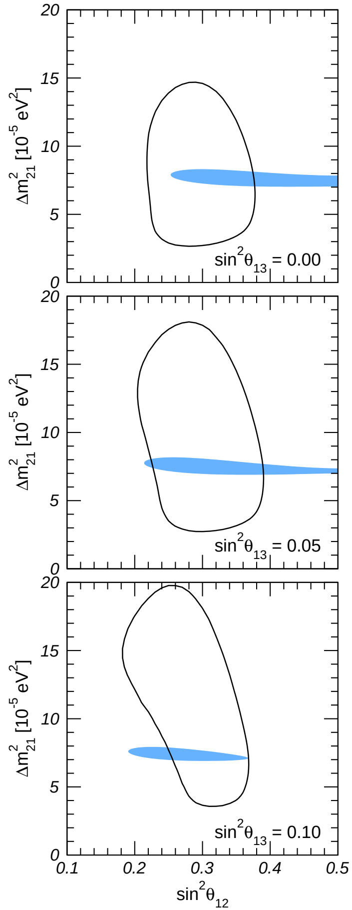
- Only P_{ee} measured $\Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

$\Rightarrow$ 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.

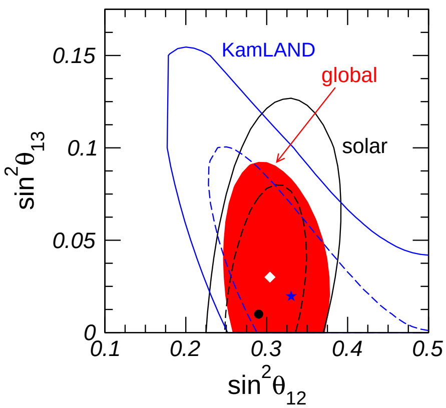
Synergy with solar data

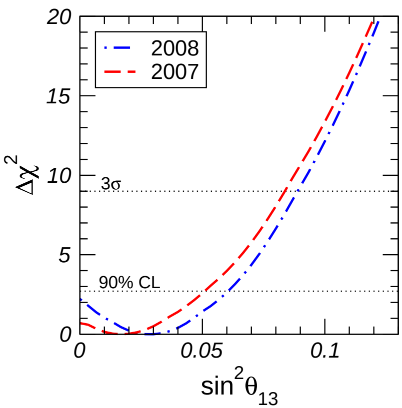
- As θ_{13} increases, solar region moves to larger Δm^2_{21}, while KamLAND region does not;
- also, for large θ_{13} KamLAND adds to low-E solar data in favoring small θ_{12}, increasing the tension with high-E solar data.



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

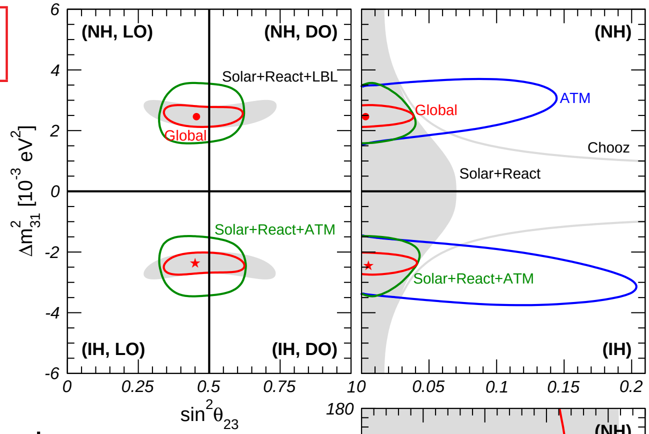
- For $\theta_{13} = 0$, we have $\sin^2\theta_{12} = \begin{cases} 0.29 \text{ from solar data;} \\ 0.35 \text{ from KamLAND data;} \end{cases}$ [Schwetz et al, arXiv:0808.2016]
- hence there is a tension between solar and KamLAND.
- as we have just seen, when θ_{13} increases:
  - solar region slightly moves to larger θ_{12} (high-E data dominate over low-E ones);
  - KamLAND region definitely shifts to smaller θ_{12}.
- hence, non-zero θ_{13} reduces the tension between solar and KamLAND.
- 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.



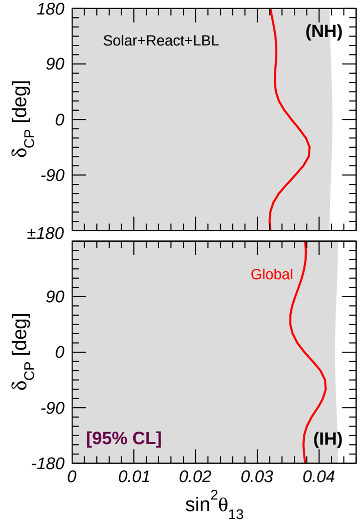


Subleading effects in the ATM sector

- Present reactor and accelerator data dominate $|\Delta m^2_{31}|$ and θ_{13} but give no info on:
  - the **mass hierarchy** (sign of Δm^2_{31});
  - the **octant** (sign of $\theta_{23} - \pi/4$);
  - the **CP phase**;



- note the high degree of symmetry of the gray regions;
- conversely, regions including ATM are visibly sensitive to:
  - **octant**: definite shift from maximal mixing;
  - **hierarchy**: relevant for the bound on θ_{13};
  - **CP phase**: impact on θ_{13} bound;



- with the **present** accuracy of atmospheric and long-baseline data, the sensitivity to subleading effects in the ATM sector (Δm^2_{31}, θ_{23}) is completely dominated by **atmospheric** data.

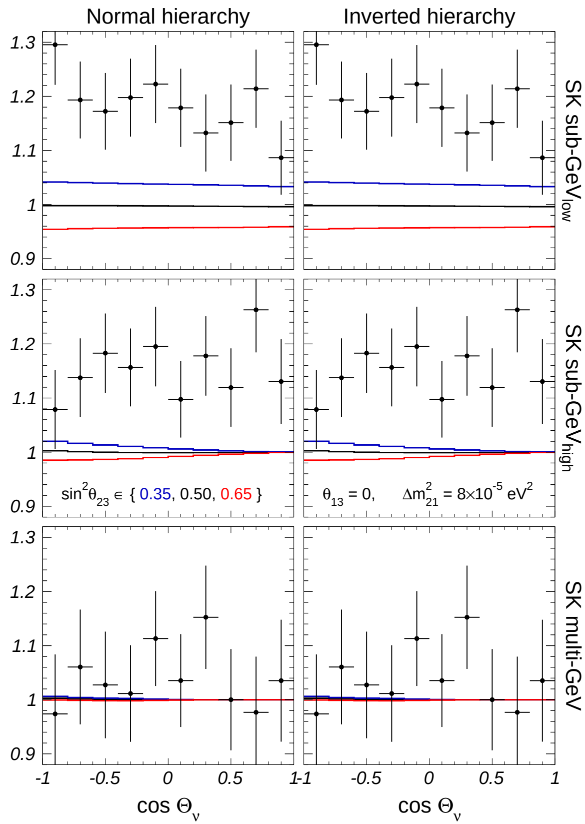
Beyond the one-mass scale approximation in ATM data

- Excess of e-like events for $\theta_{13} = 0$:

$$\delta_e \equiv \frac{N_e}{N_e^0} - 1 = \left(\bar{r}\cos^2\theta_{23} - 1\right) P_{2\nu}(\Delta m^2_{21}, \theta_{12})$$

with $\bar{r} \equiv \Phi^0_\mu / \Phi^0_e$;

- for **sub-GeV** we have $\bar{r} \approx 2$ so that:
  - for $\theta_{23} \approx 45^\circ$ δ_e vanish;
  - δ_e change sign between light and dark side $\Rightarrow$ **octant discrimination**;
- for **multi-GeV** effects suppressed by $\Delta m^2_{21}/E_\nu$;
- a similar effect arises also in μ-like data, but is suppressed by a factor ~ 4;
- **present data**: excess in e-like sub-GeV events $\Rightarrow$ preference for light side.

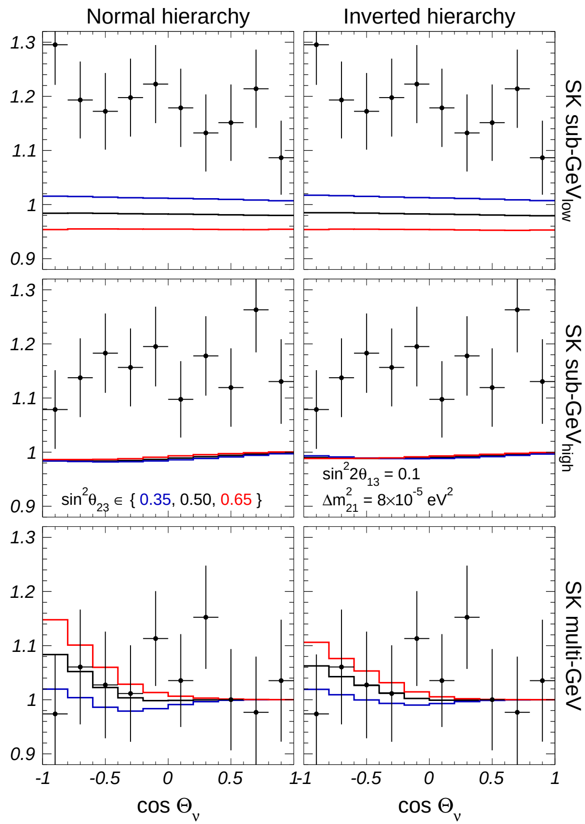


θ_{13} effects and impact of the mass hierarchy

- For $\theta_{13} \neq 0$:

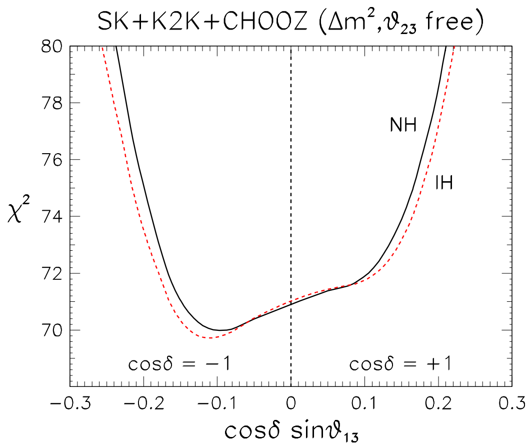
$$\delta_e \simeq (\bar{r}\cos^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{21},\, \theta_{12}) \quad [\Delta m^2_{21} \text{ term}]$$
$$+ (\bar{r}\sin^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) \quad [\theta_{13} \text{ term}]$$
$$- \bar{r}\sin\theta_{13}\sin 2\theta_{23}\, \mathrm{Re}(A^*_{ee} A_{\mu e})\,; \quad [\delta_{CP} \text{ term}]$$

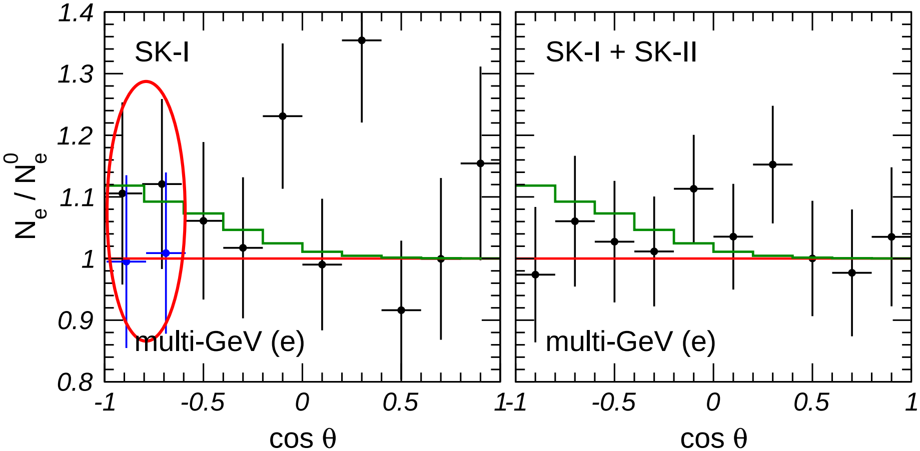
- similar but less evident effects also appear in μ-like events (not discussed here);
- for **sub-GeV** effect of Δm^2_{21} is diluted by θ_{13};
- for **multi-GeV** resonance in $P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) \Rightarrow$ enhancement of ν ($\bar{\nu}$) oscillations for normal (inverted) hierarchy;
- more ν than $\bar{\nu}$ events $\Rightarrow$ θ_{13} effects are more prominent for normal hierarchy;
- sensitivity to θ_{13} is larger for θ_{23} in the **dark side**.

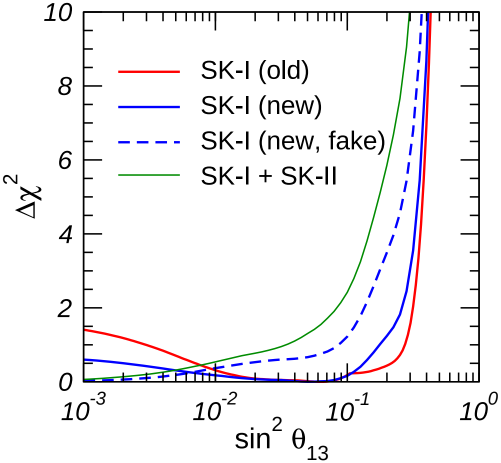


Hint of non-zero θ_{13} in atmospheric data?

- Claim for an hint of non-zero θ_{13} in atm (+ LBL) data;
  [Fogli et al, hep-ph/0506083 & arXiv:0806.2649]
- its strength depends on the detail of the simulation;
- it is linked to a peculiar SK-I signature in multi-GeV e-like data, which **disappear** after SK-II data.

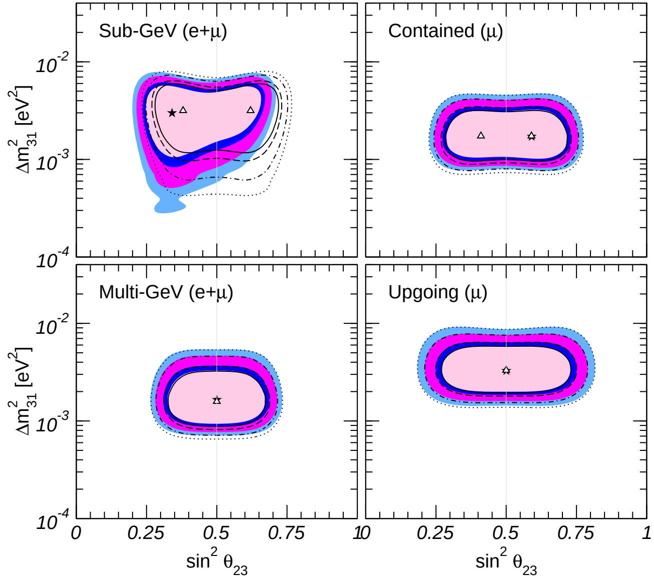






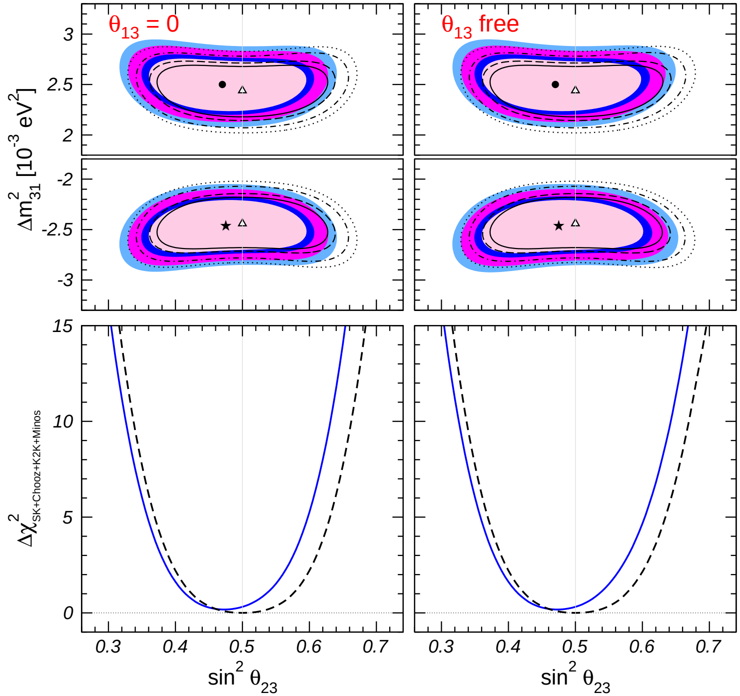
Impact of Δm^2_{21} on different data samples

- Pull-approach: $\chi^2 = \min_{\xi_i} \left[\sum_{n=1}^{90} \left(\frac{R_n^{\text{theo}} - \sum_i \sigma_n^i \xi_i - R_i^{\text{exp}}}{\sigma_n^{\text{stat}}} \right)^2 + \sum_{i,\text{theory}} \xi_i^2 + \sum_{i,\text{syst}} \xi_i^2 \right];$
- main features of the data:
  - no sensitivity of high-energy samples;
  - marginal sensitivity of ν_μ data alone;
  - main effect in sub-GeV ν_e events;
- ...can be understood in terms of pulls:
  - ν_μ and high-energy events fix the overall normalization and the tilt pulls;
  - sub-GeV ν_e data fix the ν_μ/ν_e ratio pulls;
  - ν_e excess partially compensated by Δm^2_{21} oscillations $\Rightarrow$ less tension in ν_μ/ν_e ratio pulls $\Rightarrow$ smaller χ^2.



Determination of the atmospheric neutrino parameters

- Deviation of θ_{23} from maximal mixing **is a physical effect**, which follows from the observation of an excess of events in low-energy e-like data;



- the effect is still not statistically significant, but it is already clearly visible;
- it still appears if uncertainties on total normalization or flux tilt are increased;
- it is not washed-out by possible non-zero θ_{13} or δ_{CP}, which we consider in this analysis;
- best-fit: $\begin{cases} \sin^2\theta_{23} = 0.47, \\ \Delta m^2_{31} = 2.46 \times 10^{-5}\ \text{eV}^2. \end{cases}$
- octant discrimination: the symmetry $\theta_{23} \to \pi/2 - \theta_{23}$ is broken.

- We have presented a global analysis of solar, atmospheric, reactor and accelerator data in the context of the standard three-neutrino oscillation scenario;
- all data sets agree among them and are perfectly compatible;
- at the **leading** order, the 3ν allowed region tracks the partial 2ν fits of solar + KamLAND (θ_{12} & Δm^2_{21}), atmospheric + MINOS (θ_{23} & Δm^2_{31}) and atmospheric + Chooz (θ_{13}) data;
- in addition, **subleading** 3ν effects are visible:
  - solar + KamLAND data slightly favor non-zero θ_{13};
  - atmospheric data (SK-I) also prefer a small non-zero θ_{13}. However, this effect disappear **once** SK-II data are also added;
  - atmospheric data (both SK-I and SK-II) favor a small deviation of θ_{23} from maximal;
- these effects are at the 1σ level, and **should not be taken more seriously than that**.

$\Rightarrow$ [Gonzalez-Garcia & MM, PREP 460 (2008) 1, arXiv:0704.1800]
[Schwetz, Tortola & Valle, arXiv:0808.2016]
[Fogli et al, hep-ph/0506083 & arXiv:0806.2649]