Neutrino Parameters Review

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I. The $\nu_e \to \nu_{\text{active}}$ oscillation channel: Δm^2_{sol} and θ_{sol}

- *Solar and KamLAND neutrino data*

II. The $\nu_\mu \to \nu_\tau$ oscillation channel: Δm^2_{atm} and θ_{atm}

- *Atmospheric and K2K neutrino data*

III. The three-neutrino scenario: θ_{rea} and α

- *Global analysis*
- *Subleading effects*

IV. The LSND experiment: four-neutrino models and CPT violation

- *Four-neutrino models: (2+2) and (3+1)*
- *CPT-violating three-neutrino models*

Summary and conclusions

Solar neutrinos

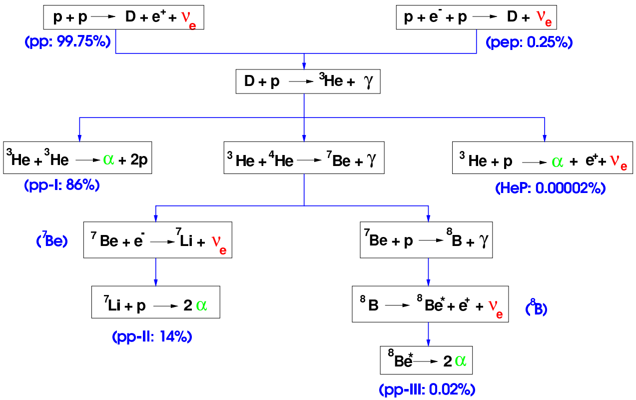
- Nuclear reactions in the core of the Sun produce *electron neutrinos*;
- some of these neutrinos are detected by a number of underground experiments;

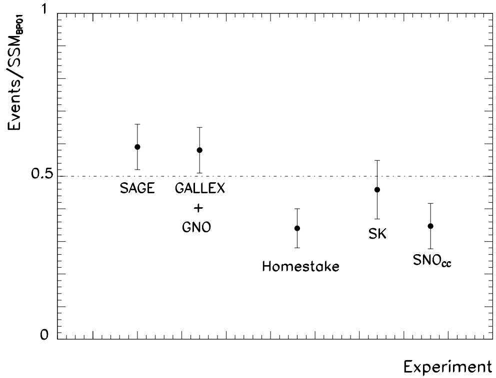
⋆ it is found that ALL the experiments observe a deficit of about $30-60\%$;

- the deficit is NOT the same for different experiments, indicating that the effect is **energy dependent**.
- it is **not possible** to reconcile the data with the SSM by simply readjusting the parameter of the Sun;

⇒ new physics **is needed** to explain the data.

⇒ **Oscillation Hypothesis:** $\nu_e \to \nu_{\text{active}}$.





Solar Neutrino Oscillations

[See M.C. Gonzalez-Garcia talk at NOON2004]

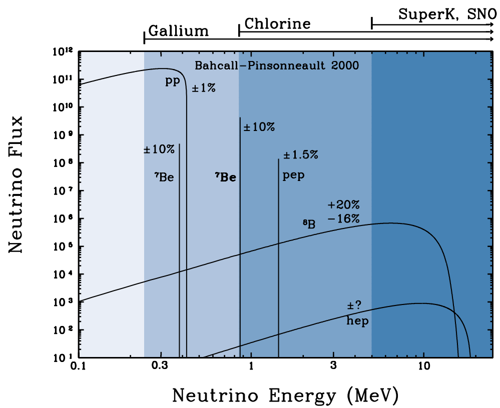
- Equation of motion: **2** parameters (the sign $+/-$ refers to neutrinos/antineutrinos):

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

- Theoretical prediction: $R_i^{\text{th}} = \sum_{f=1}^{8} \phi_f \int dE_\nu\, \lambda_f(E_\nu) \times \sum_{x=e,\mu,\tau} \left[\langle P_{e\to x}(E_\nu,t)\rangle\, \sigma_{x,f}(E_\nu)\right];$

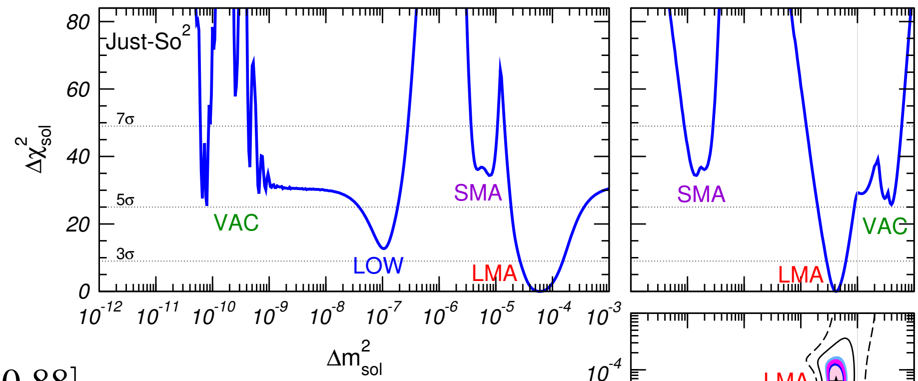
- the Standard Solar Model gives:
  - the fluxes ϕ_f and **their uncertainties**;
  - the flux shapes λ_f (and **its uncertainty** for ^{8}B);
  - the Sun matter density & composition profiles;

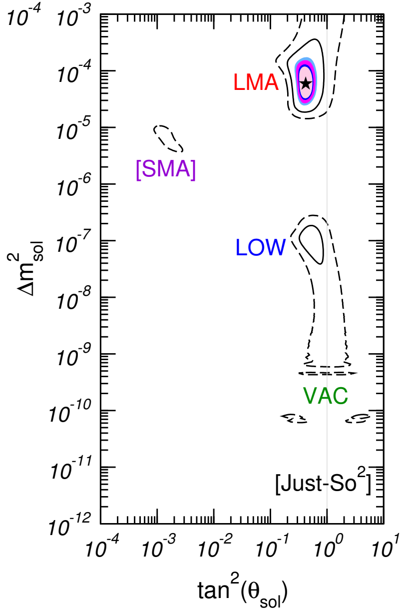
- also, the **energy dependence** of the cross-section **uncertainties** are taken into account.



Solar ν oscillations

- exp. data: **84**
  $3_{\text{rates}} + 44_{\text{SK}} + 37_{\text{SNO}}$;
- parameters: **2** (Δm^2, θ);
- 5σ: $\begin{cases} \tan^2\theta_{\text{sol}} \in [0.20,\ 0.88], \\ \Delta m^2_{\text{sol}} \in [1.9,\ 36] \times 10^{-5}\ \text{eV}^2. \end{cases}$
- maximal mixing $\theta \approx 45^\circ$ excluded at 5σ.



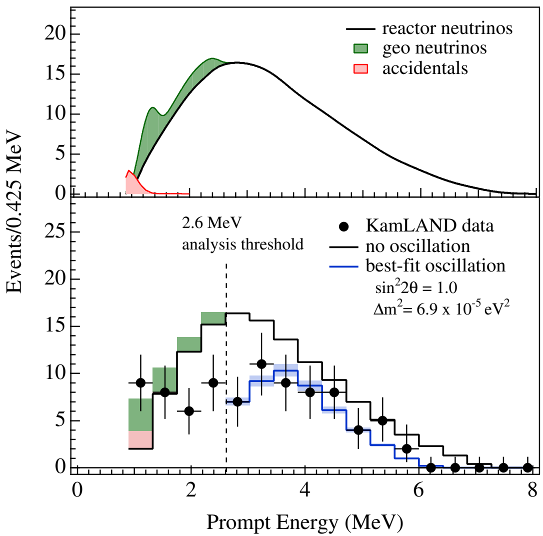


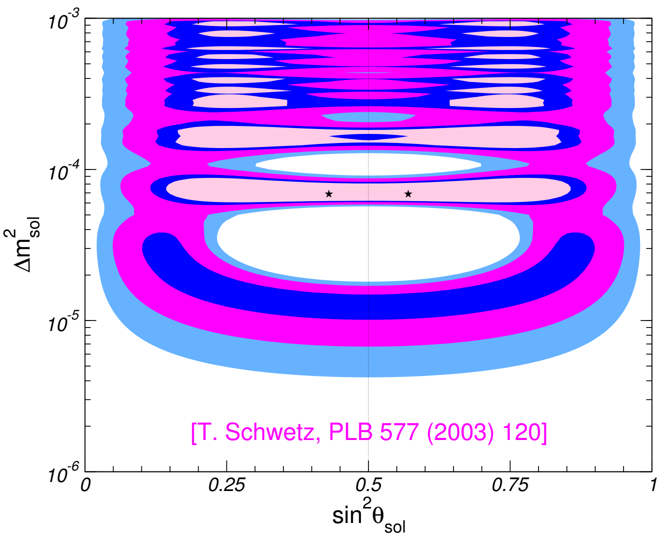
Region	$\tan^2\theta$sol	Δm^2_{sol} [eV^2]	χ^2_{sol}	GOF
LMA	0.42	6.0×10^{-5}	67.6	87%
LOW	0.50	1.0×10^{-7}	80.3	53%
VAC	0.25	7.9×10^{-11}	93.0	19%
SMA	1.4×10^{-3}	7.6×10^{-6}	102.0	7%

The KamLAND experiment

- First *evidence* of $\bar\nu_e$ disappearance (average length: ≈ 180 km);
- Events ($E_{\text{vis}} > 2.6$ MeV): 86.8 ± 5.6 expected, 54 observed; also measured the energy spectrum.

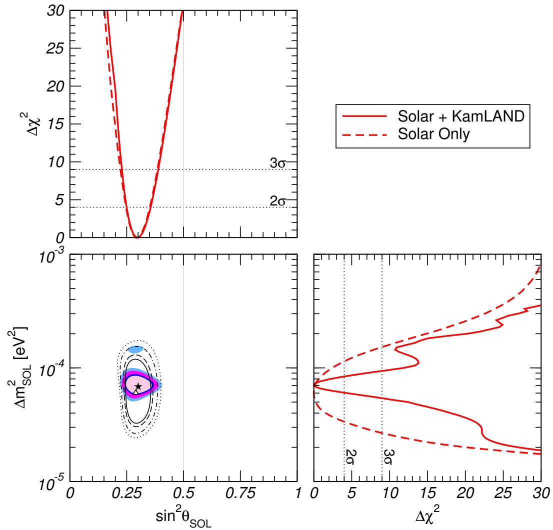
$\Rightarrow$ CPT conservation $\Rightarrow$ same osc. channel as solar data $\Rightarrow$ same parameters (Δm^2, θ).





Combined analysis of Solar + KamLAND data

- KamLAND selects the LMA solution to the solar neutrino problem;
- solar data break the degeneracy $\theta \to (\pi - \theta)$ of reactor experiments;
- 5σ ranges: $\begin{cases} \tan^2\theta_{\text{sol}} \in [0.20,\ 0.89], \\ \Delta m^2_{\text{sol}} \in [2.1,\ 28] \times 10^{-5}\ \text{eV}^2; \end{cases}$
- bound on θ_{sol} mostly unaffected, bound on Δm^2_{sol} strongly improved;



- new SNO-salt data strongly improves upper bounds on Δm^2_{sol} and θ_{sol};
- best fit point position: $\begin{cases} \tan^2\theta_{\text{sol}} = 0.43 & \text{(dominated by solar data);} \\ \Delta m^2_{\text{sol}} = 6.9 \times 10^{-5}\ \text{eV}^2 & \text{(dominated by KamLAND data).} \end{cases}$

The atmospheric neutrino problem

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

$$A_{\text{cr}} + A_{\text{air}} \to \pi^\pm, K^\pm, K^0, \ldots$$

produces $\pi^\pm$ and $K^\pm$ mesons, which then decay producing neutrinos:

$$\begin{aligned} \pi^- &\to \mu^- + \bar\nu_\mu \\ &\quad \mu^- \to e^- + \bar\nu_e + \nu_\mu \end{aligned} \qquad\qquad \begin{aligned} \pi^+ &\to \mu^+ + \nu_\mu \\ &\quad \mu^+ \to e^+ + \nu_e + \bar\nu_\mu \end{aligned}$$

- therefore, theoretically we can roughly expect $R^{\text{MC}}_{\mu/e} = \dfrac{N_{\nu_\mu} + N_{\bar\nu_\mu}}{N_{\nu_e} + N_{\bar\nu_e}} \approx 2$;
- however, this prediction is in clear *disagreement* with the *most* of the experimental results, which indicate instead $R_{\mu/e} \approx 1$.

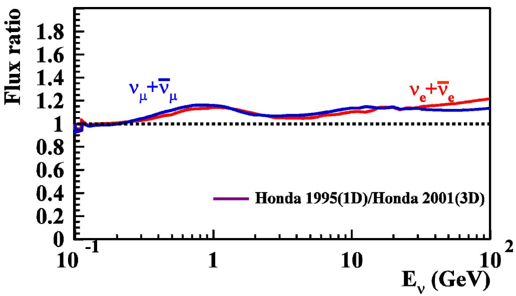
Present status of atmospheric neutrino data

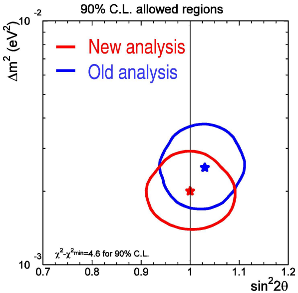
- clear disagreement between the experimental data (dots) and Monte-Carlo (red solid line);

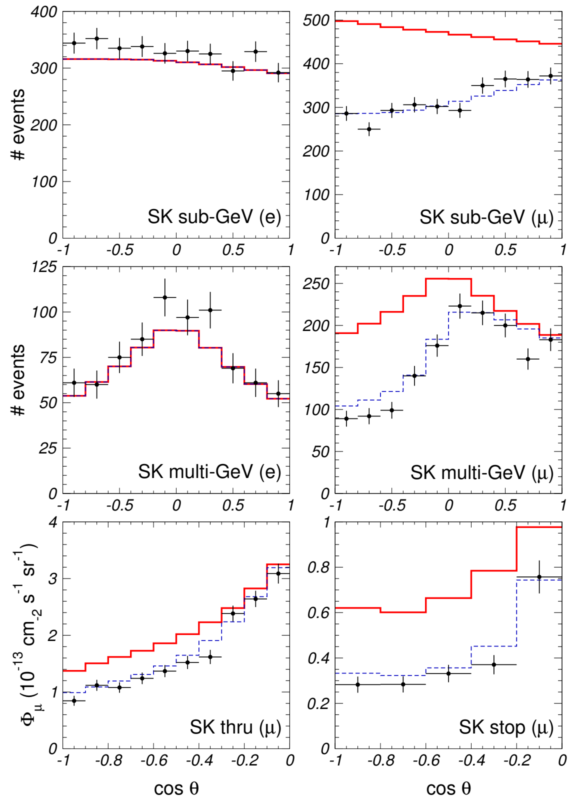
⋆ ν_e data are in good agreement, ν_μ data are not;

⇒ the **oscillations hypothesis** $\nu_\mu \to \nu_\tau$ succeeds in explaining the data (blue dashed line).

- SK @ EPS-2003: **3-dim** ATM fluxes ⇒ lower Δm^2.







Atmospheric Neutrino Oscillations

[See also M.C. Gonzalez-Garcia talk at NOON2004]

- Equation of motion: **2** parameters (no matter effects ⇒ pure vacuum oscillations):

$$i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2}{4E_\nu}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}\right]\vec{\nu}, \quad \text{with} \quad \vec{\nu} = \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix};$$

- pull-approach: $\chi^2 = \min_{\xi_i}\left[\sum_{n=0}^{55}\left(\frac{R_n^{\rm theo} - \sum_i \sigma_n^i \xi_i - R_i^{\rm exp}}{\sigma_n^{\rm stat}}\right)^2 + \sum_{i,\rm theory}\xi_i^2 + \sum_{i,\rm syst}\xi_i^2\right];$

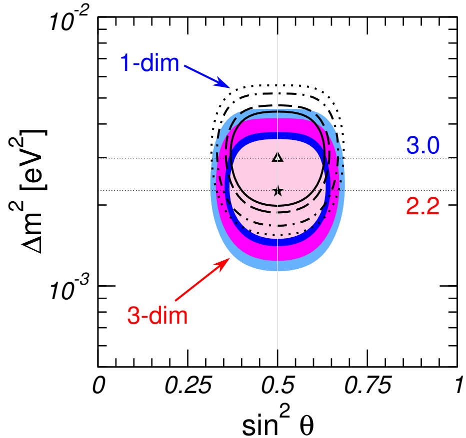
- experimental data:

  $20_{\text{SK-Sub}} + 20_{\text{SK-Multi}} + 5_{\text{SK-stop}} + 10_{\text{SK-thru}} = \mathbf{55}$;

- we perform an accurate comparison between **1-dim** and **3-dim** Honda fluxes;

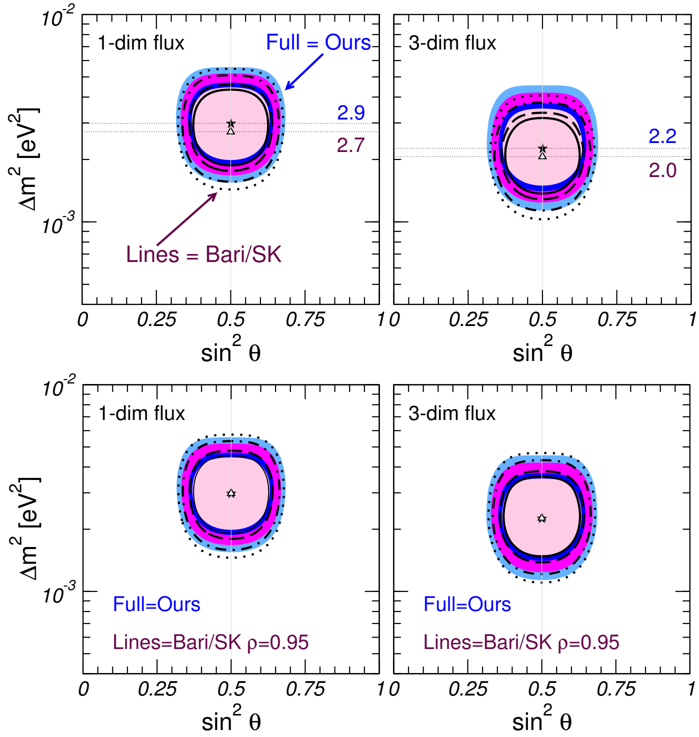
- we confirm the down shift of Δm^2;

- however, we find a slightly higher Δm^2 range than SK.



Atmospheric Neutrino Analysis: Comparison

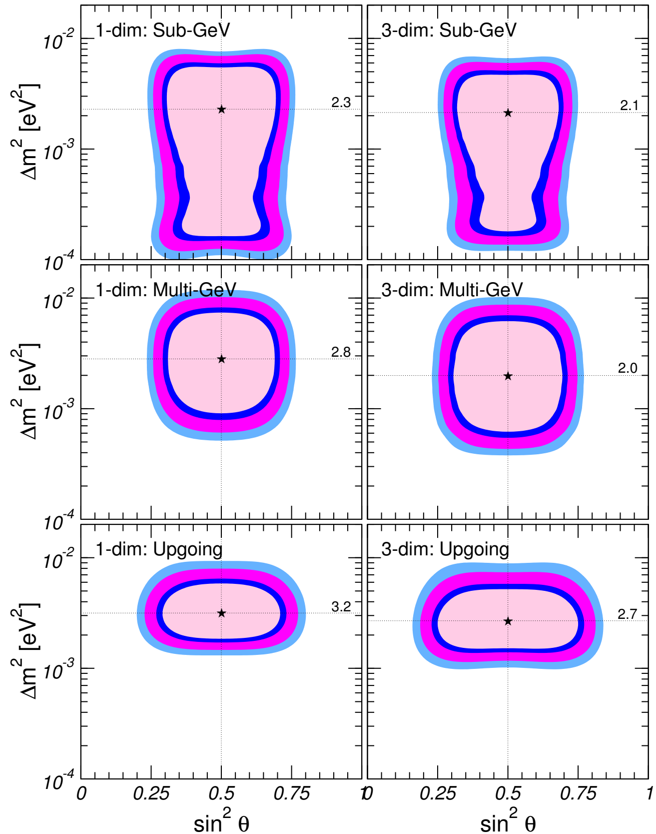
- The main difference between **Our** and **Bari/SK** approach is in the treatment of cross-section errors:
  - **Our**: since $\sigma = \sigma_{\rm QE} + \sigma_{1\pi} + \sigma_{\rm DIS}$, we include a different uncertainty (of 15–20%) for each term;
  - **Bari/SK**: 15% contribution to overall normalization uncertainty + errors in ratios of different data samples;
- in our approach Sub-GeV sample is *less* correlated with other samples;
- modified **Bari/SK** approach ($\rho_{\rm sub/others}$: $1 \to 0.95$): the difference disappear.



[Bari/SK: see hep-ph/0303064 & Kameda PhD Thesis]

Impact of different data samples

- Different sets favor slightly different Δm^2;
- energy dependence of uncertainties relevant in combinations;
- high-statistics $\Rightarrow$ careful treatment required.
- Present approach to flux uncertainties is purely phenomenological: overall normalization (20%), tilt (5%), and ν_μ/ν_e ratio (5%);
- improved experimental accuracy require a more accurate treatment, like for Solar data:
  - identify relevant ATM flux parameters X_i;
  - characterize their uncertainty ΔX_i;
  - give $(\partial\Phi/\partial X_i)\Delta X_i$ **as a function of E_ν**.

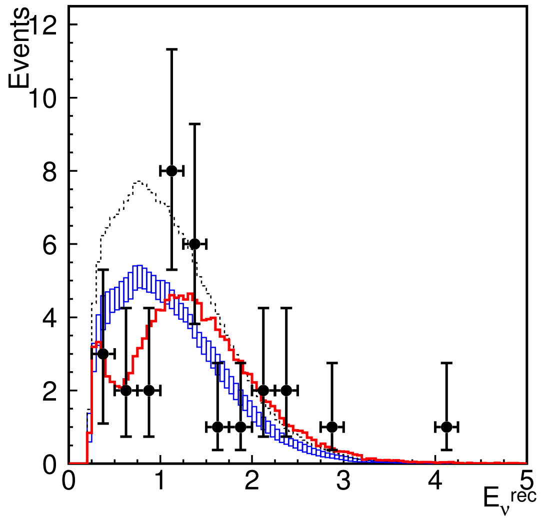


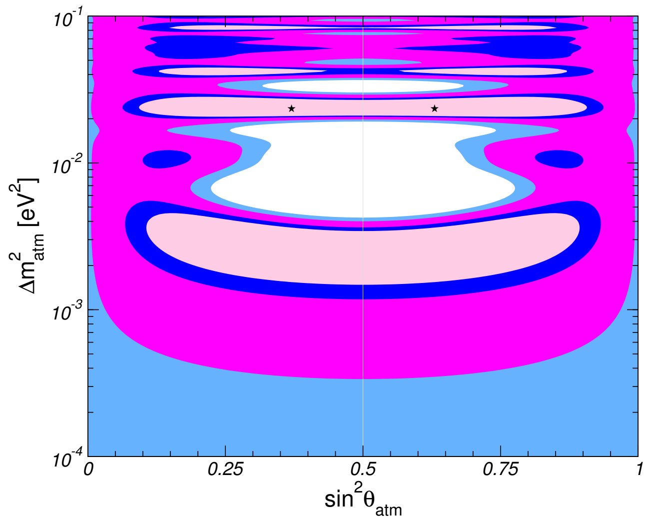
The K2K accelerator experiment

- *evidence* of ν_μ disappearance (length: ≈ 250 km);
- single-ring μ-like events: 44 expected, 29 observed; also measured the energy spectrum.

$\Rightarrow$ same oscillation channel as atmospheric data $\Rightarrow$ same parameters (Δm^2, θ).

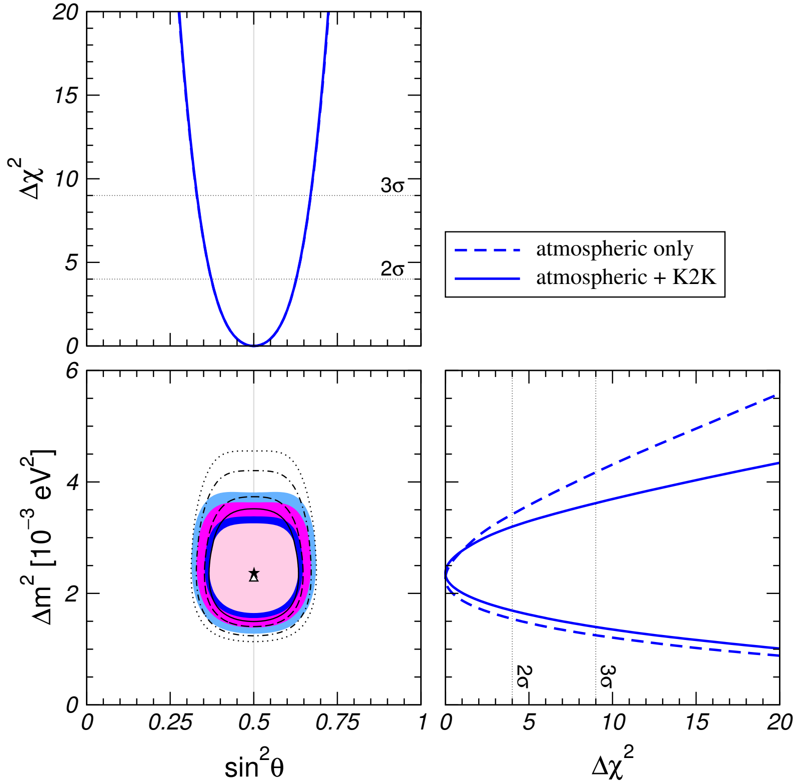
$\Rightarrow$ *fully consistent* with atmospheric data if oscillations are assumed.





Combined analysis of Atmospheric + K2K data

- no matter effects $\Rightarrow$ both atmospheric and K2K regions are symmetric for $\theta \to (\pi - \theta)$;
- bound on $\theta_{\rm atm}$ completely unaffected by K2K; upper bound on $\Delta m^2_{\rm atm}$ strongly improved;
- 3σ ranges:
$$\begin{cases} \sin^2\theta_{\rm atm} \in [0.33,\ 0.67], \\ \Delta m^2_{\rm atm} \in [1.4,\ 3.6] \times 10^{-3}\ \text{eV}^2; \end{cases}$$
- best fit position:
$$\begin{cases} \sin^2\theta_{\rm atm} = 0.5, \\ \Delta m^2_{\rm atm} = 2.4 \times 10^{-3}\ \text{eV}^2. \end{cases}$$

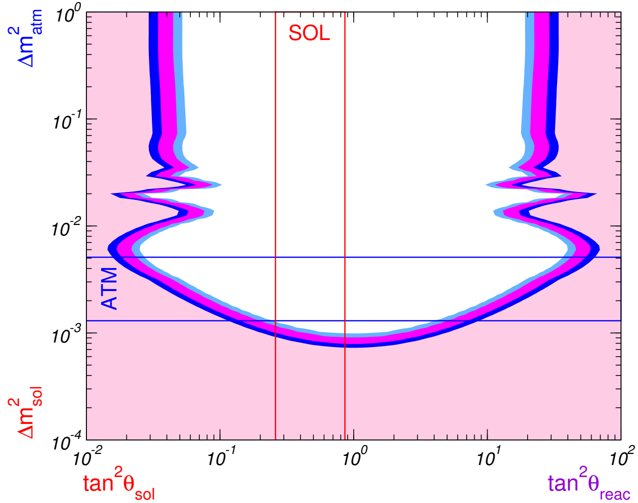


The Chooz & Palo Verde reactor experiments

- Bound from *non-observation* of $\bar{\nu}_e$ disappearance (length: $\lesssim 1$ km).

Solar parameters

- Like KamLAND, this experiment is sensitive to solar parameters Δm^2_{sol} and θ_{sol};
- from solar data: $0.20 \le \tan^2\theta_{sol} \le 0.88$ (at 5σ) $\Rightarrow$ **upper** bound on Δm^2_{sol};



Atmospheric parameters

- given it short baseline, this experiment is also sensitive to Δm^2_{atm};
- however, the osc. channel is different, so the corresponding mixing angle **is not** θ_{atm};

⋆ **new parameter** $\boxed{\theta_{rea}}$ describes the mixing of ν_e with $\nu_{\mu,\tau}$.

- from atmospheric data: $\Delta m^2_{atm} \gtrsim 10^{-3}$ eV^2 $\Rightarrow$ **upper** bound on θ_{rea}.

Combining Solar with Atmospheric data (1)

- Solar/KamLAND data and Atmospheric/K2K data require *two different* mass-squared differences;
- a complete three-neutrino description is needed to accommodate all the experimental results;
- Equation of motion: **5** parameters (neglecting CP violating effects):

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

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

$$\mathbf{H}_0^d = \frac{1}{2E_\nu}\,\mathbf{diag}\left(-\Delta m^2_{21}, 0, \Delta m^2_{32}\right); \qquad \mathbf{V} = \mathbf{diag}\left(\pm\sqrt{2}G_F N_e, 0, 0\right).$$

Combining Solar with Atmospheric data (2)

– Solar parameters (Δm^2_{sol}, θ_{sol}) are identified with (Δm^2_{21}, θ_{12});

– atmospheric parameters (Δm^2_{atm}, θ_{atm}) are identified with (Δm^2_{32}, θ_{23});

– the reactor parameter θ_{rea} is identified with θ_{13}.

$\Rightarrow$ in the limit $\theta_{rea} \to 0$, solar and atmospheric data **decouple**.

The hierarchy approximation

- From SOL and ATM data, we have $\Delta m^2_{21} \ll \Delta m^2_{32}$;

Atmospheric analysis

- approximation: $\Delta m^2_{21} \approx 0$;
- θ_{12} cancels out from equations;

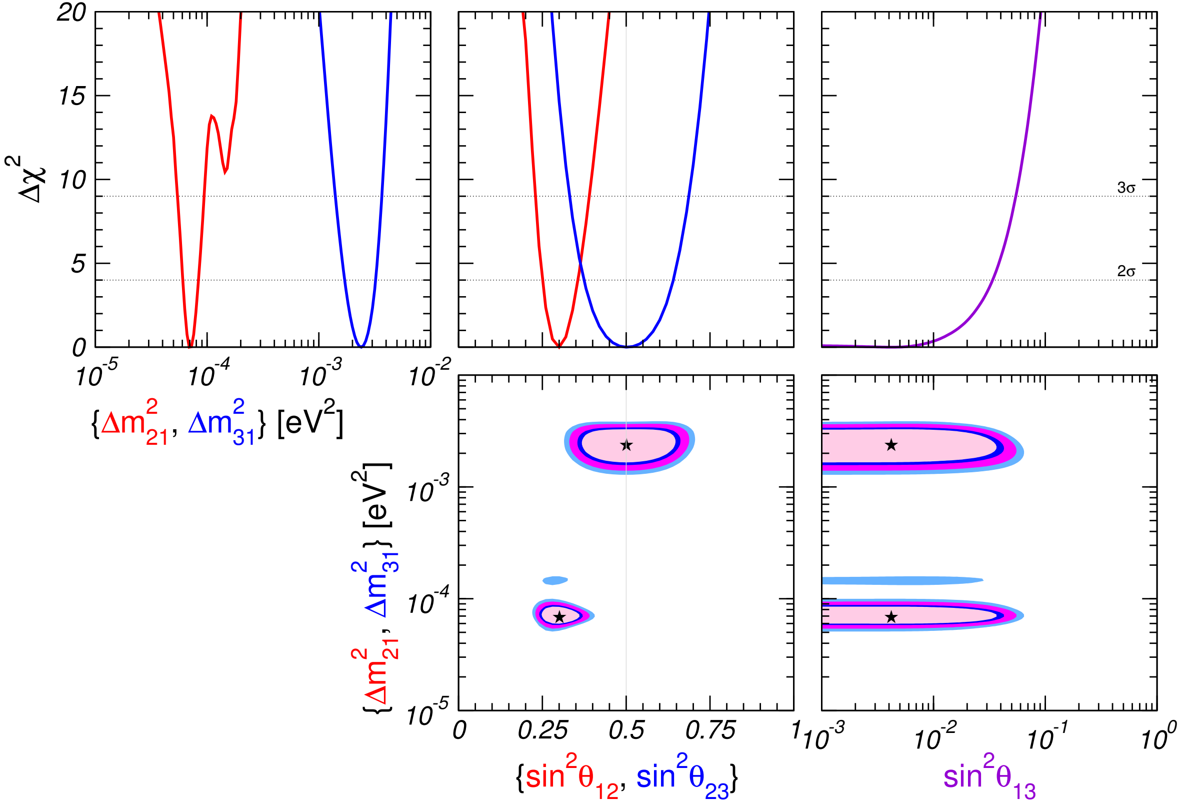
$\Rightarrow$ only **3** parameters: Δm^2_{32}, θ_{23}, θ_{13}.

Solar analysis

- approximation: $\Delta m^2_{32} \approx \infty$;
- θ_{23} cancels out from P_{ee};

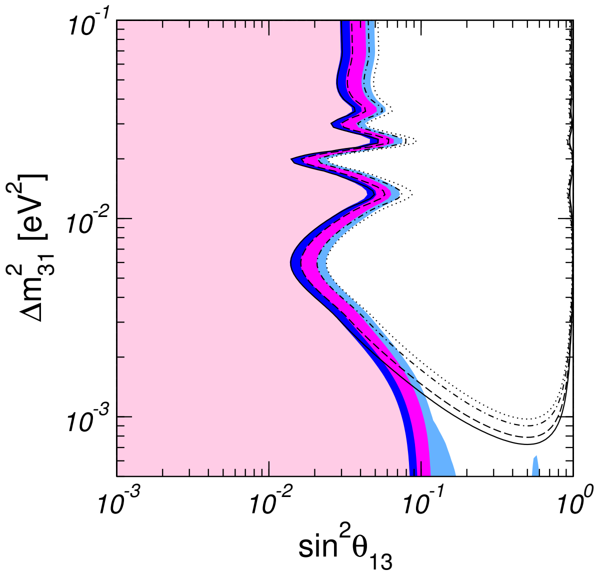
$\Rightarrow$ only **3** parameters: Δm^2_{21}, θ_{12}, θ_{13}.

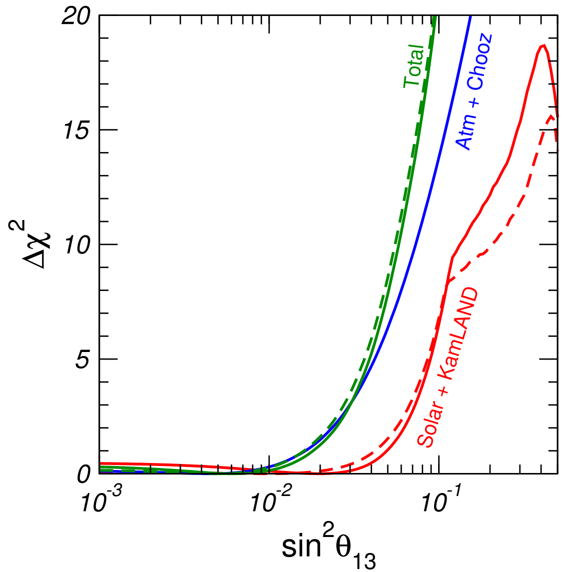
Global analysis (SOL + ATM + Reactor + K2K)



Bound on θ_{13}

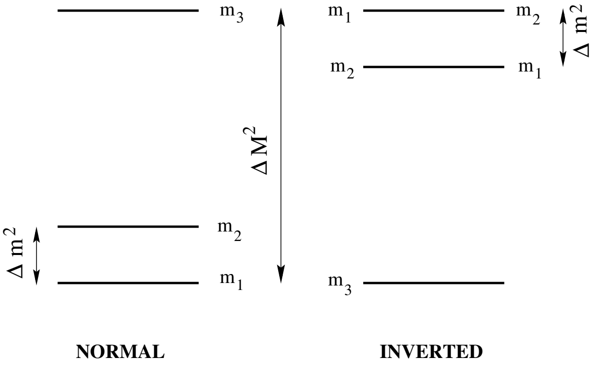
- recent KamLAND and SNO-salt data help improving the sensitivity to θ_{13} of solar data;
- however, present bound is still dominated by Chooz, together with atmospheric data;
- 3σ range: $\sin^2\theta_{13} \le 0.054$.

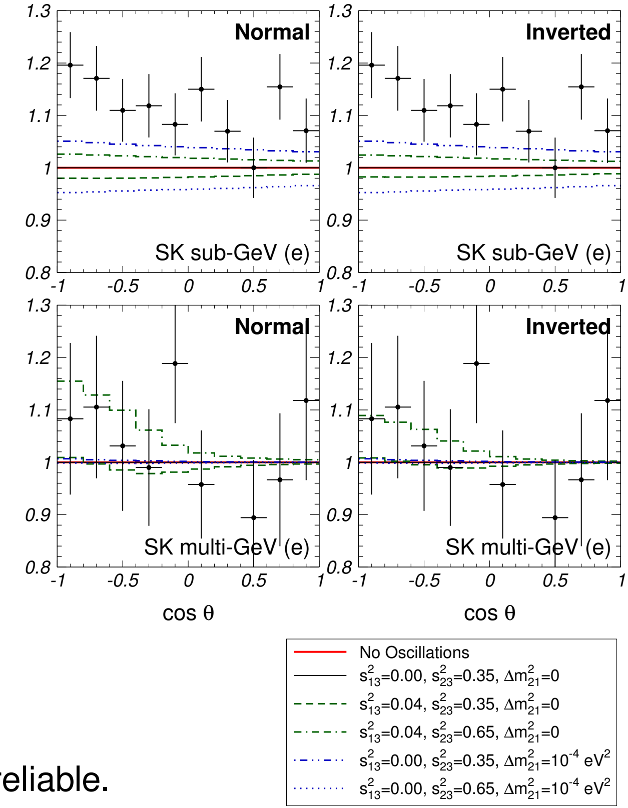




Beyond the one-mass scale approximation

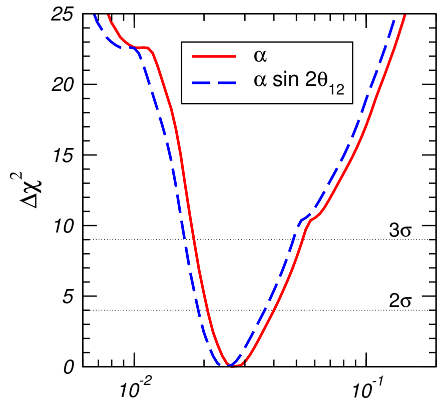
- Two mass spectra: **normal** and **inverted**:





- present ATM data do not allow to discriminate between normal and inverted hierarchy;
- hierarchy parameter: $\alpha = \Delta m^2 / \Delta M^2$;
- effects of α mainly visible in ν_e samples;
- $\alpha \ll 1 \Rightarrow$ the one-mass scale approximation is reliable.

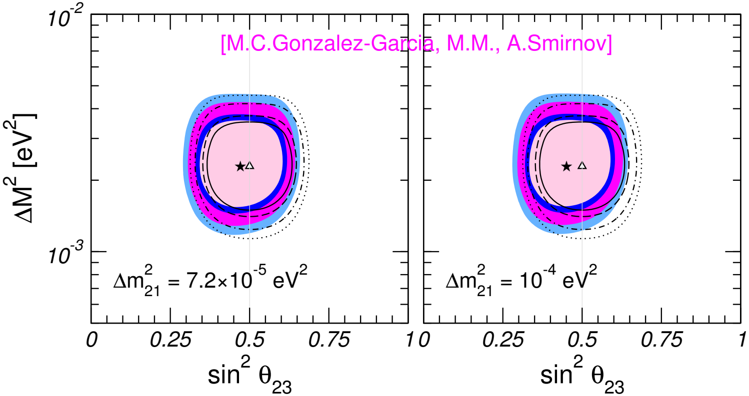
Relevance of the mass hierarchy parameter α



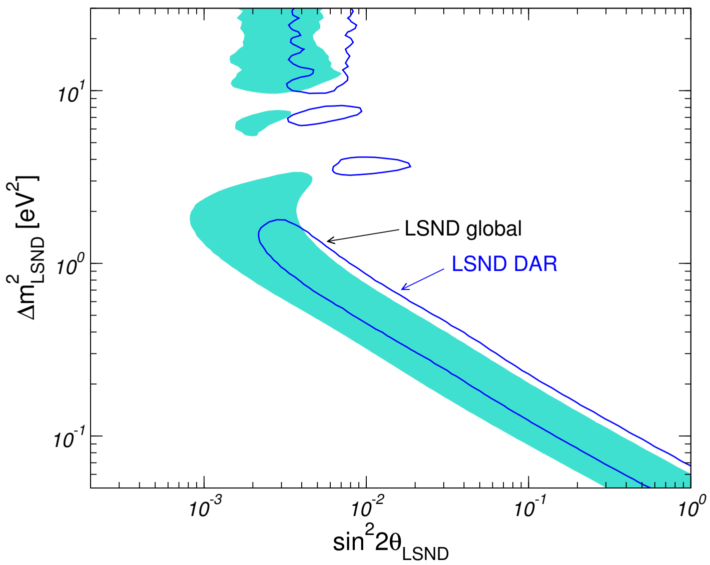
- the parameter α is important for the exploration of genuine three-flavor effects such as CP-violation;
- the combination $\alpha \sin^2 2\theta_{12}$ is relevant for long-baseline $\nu_e \to \nu_\mu$ oscillation probability;
- 3σ ranges: $\begin{cases} \alpha \in [0.018,\ 0.053], & \text{best} = 0.026; \\ \alpha \sin 2\theta_{12} \in [0.016,\ 0.049]; & \text{best} = 0.024. \end{cases}$

Relevance of α for ATM data

- effect of $\Delta m^2_{\rm sol}$ in ATM oscillations is small **but already visible**;
- subdominant effects in ATM conversion are becoming relevant.



Beyond the "standard" three-neutrino oscillations



The LSND result

- *evidence* of $\bar{\nu}_\mu \to \bar{\nu}_e$ conversion (length: $\lesssim 100$ m);
- neutrino oscillation interpretation: requires $\Delta m^2 \gtrsim 0.1$ eV^2;

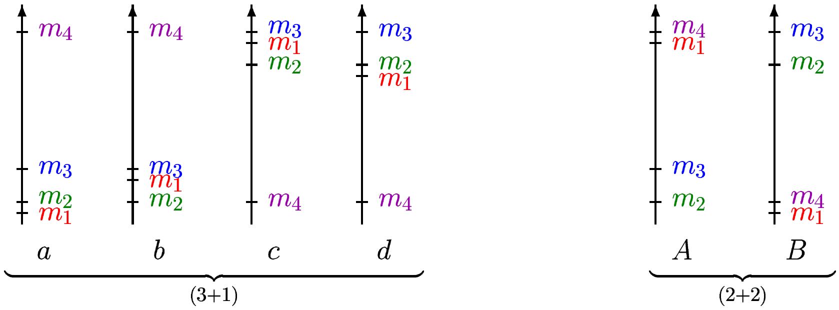
$\Rightarrow$ *incompatible* with solar and atmospheric data in a 3ν scenario.

The simplest solution: adding a neutrino

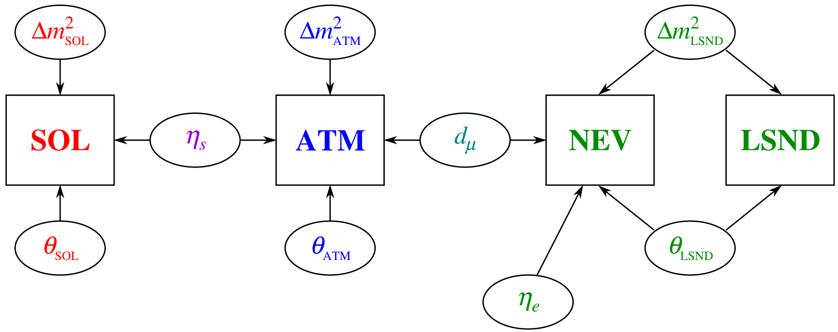
- the new neutrino must be *sterile* (from LEP measure of Z width);

Four-neutrino schemes

- Approximation: $\Delta m^2_{\text{sol}} \ll \Delta m^2_{\text{atm}} \ll \Delta m^2_{\text{LSND}} \Rightarrow$ 6 different mass schemes:



- different set of experimental data *partially decouple*:



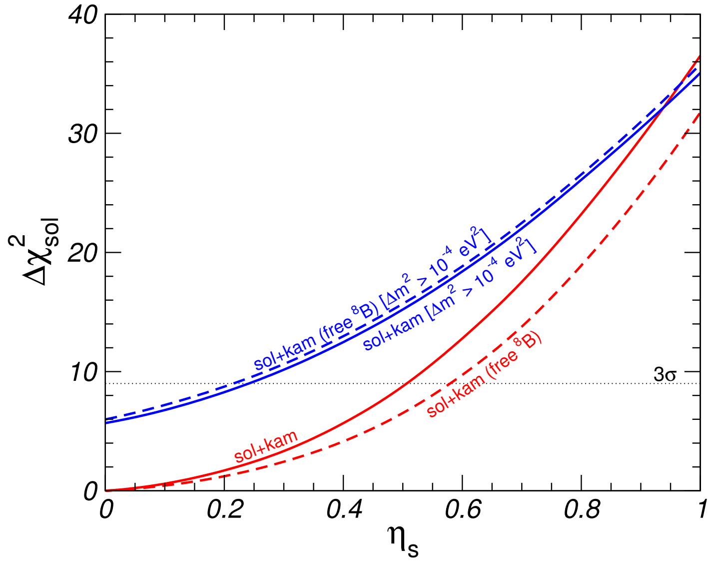
Bounds on sterile neutrino: solar data

- fraction of ν_s in solar oscillations: $\eta_s \equiv |U_{s1}|^2 + |U_{s\odot}|^2$;
- **3** parameters: Δm^2_{sol}, θ_{sol}, η_s.

$\Rightarrow$ Preferred value: $\eta_s = 0$;

$\Rightarrow$ 3σ: $\begin{cases} \eta_s \leq 0.51 \text{ (boron-fixed)}, \\ \eta_s \leq 0.58 \text{ (boron-free)}; \end{cases}$

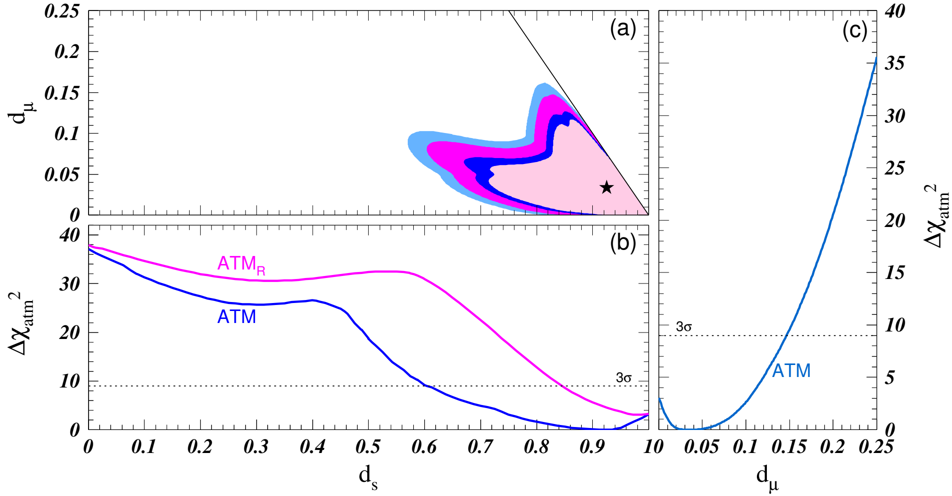
- determination of best-fit Δm^2_{sol} and θ_{sol} is unaffected.



Bounds on sterile neutrino: atmospheric data

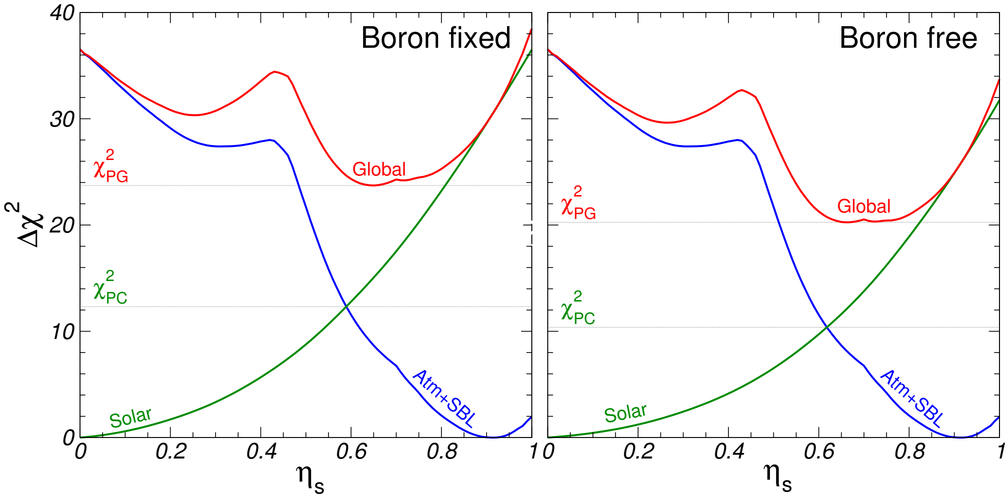
- Fraction of ν_μ in atmospheric oscillations: $1 - d_\mu \equiv |U_{\mu 2}|^2 + |U_{\mu 3}|^2$;
- fraction of ν_s in atmospheric oscillations: $1 - d_s \equiv |U_{s2}|^2 + |U_{s3}|^2$;
- **4** parameters: Δm^2_{atm}, θ_{atm}, d_s, d_μ.

$\Rightarrow$ 3σ bounds: $d_s \geq 0.61$ and $d_\mu \leq 0.15$.



Status of four-neutrino oscillations (1)

(2+2): ruled out by solar and atmospheric data

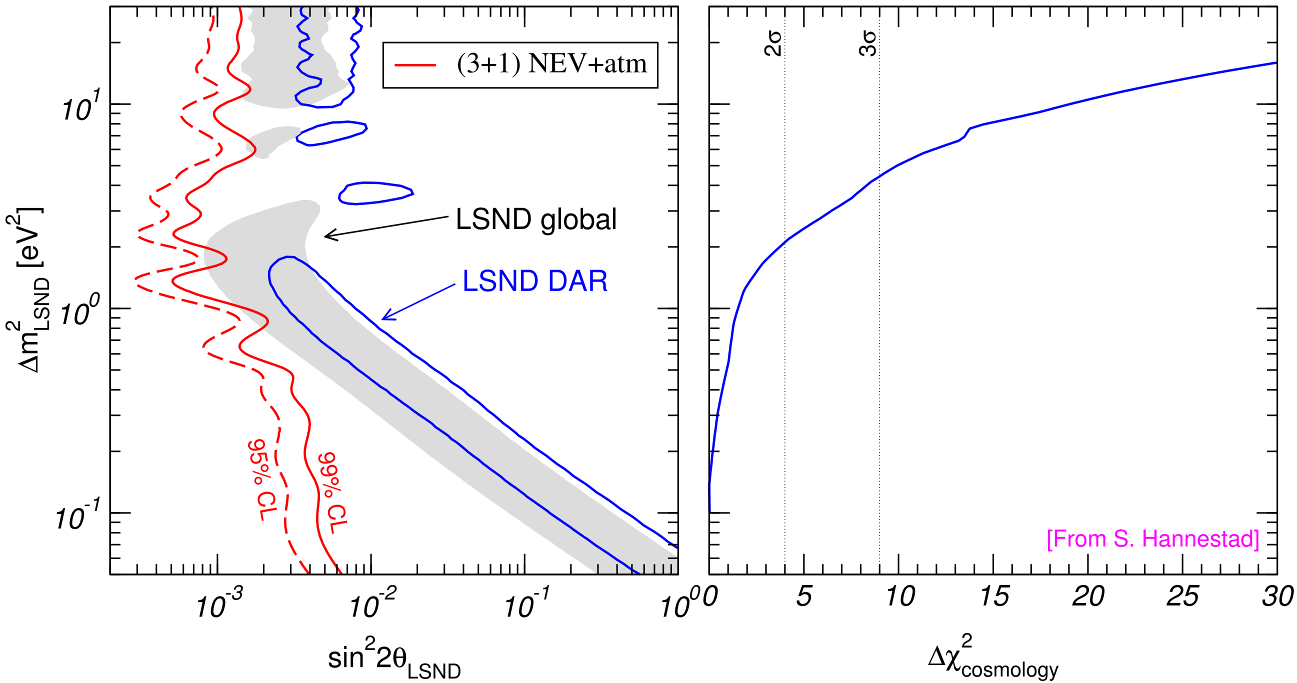


$$\begin{cases} \chi^2_{\rm PC} = 12.3 & (3.5\sigma) \\ \chi^2_{\rm PG} = 23.7 & (\mathrm{PG} = 1.1 \times 10^{-6}) \end{cases} \qquad \begin{cases} \chi^2_{\rm PC} = 10.4 & (3.2\sigma) \\ \chi^2_{\rm PG} = 20.3 & (\mathrm{PG} = 6.8 \times 10^{-6}) \end{cases}$$

[For a rigorous definition of PG, see hep-ph/0304176]

Status of four-neutrino oscillations (2)

(3+1): strongly disfavored by SBL data



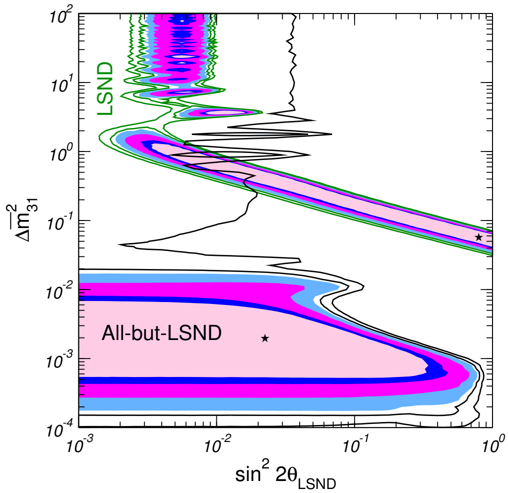
CPT violation

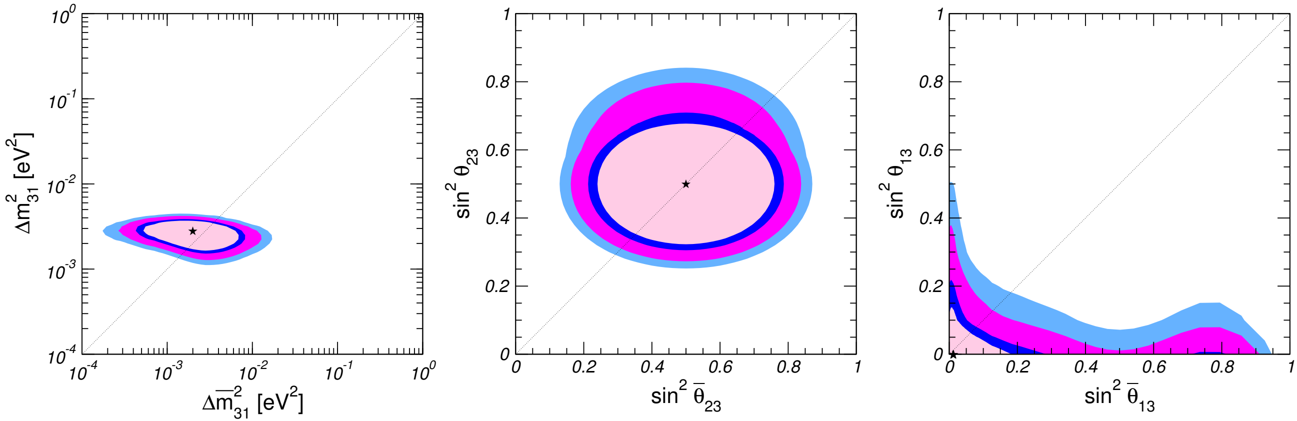
- CPT has been proposed as a possible solution of the LSND problem [see, e.g., hep-ph/0212116]. **But**:

— experimental data clearly favor CPT conservation;

— All-but-LSND and LSND regions do not overlap at 3σ.

⇒ CPT-violating scenarios **fail** to explain LSND.





Summary

- We have presented various analyses of solar (+ KamLAND), atmospheric (+ K2K), Chooz and LSND data, in the context of 2ν, 3ν, 4ν and CPT-violating models.

Results

- **Solar**, **Atmospheric**, **Chooz** data are perfectly compatible;
- the only solar solution after KamLAND data is LMA, with $\Delta m^2_{\rm sol} \approx 7 \times 10^{-5}$ eV^2 and *large but non-maximal* mixing;
- atmospheric & K2K data favor $\Delta m^2_{\rm atm} \approx 2 \times 10^{-3}$ eV^2 and maximal mixing;
- all data sets indicate $\theta_{\rm rea} \approx 0$;
- subleading effects in atmospheric oscillations start being visible;
- neither four-neutrino nor CPT-violating models succeed in reconciling LSND with other neutrino experiments $\Rightarrow$ need for MiniBOONE.