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Testing sterile neutrinos at the solar sector

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Outline

Preamble

Status of standard 3ν mixing: evidence of θ_{13}>0

Beyond three neutrino families

Hints of light sterile ν_s's

Testing sterile ν's with solar sector data

A stringent upper bound on ν_e-ν_s mixing

Conclusions

PREAMBLE

Status of standard mixing:
from hints to evidence of $\theta_{13}>0$

The leptonic mixing

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

$$U = O_{23}\Gamma_\delta O_{13}\Gamma_\delta^\dagger O_{12}$$

$$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$$

Dirac CP-violating phase δ

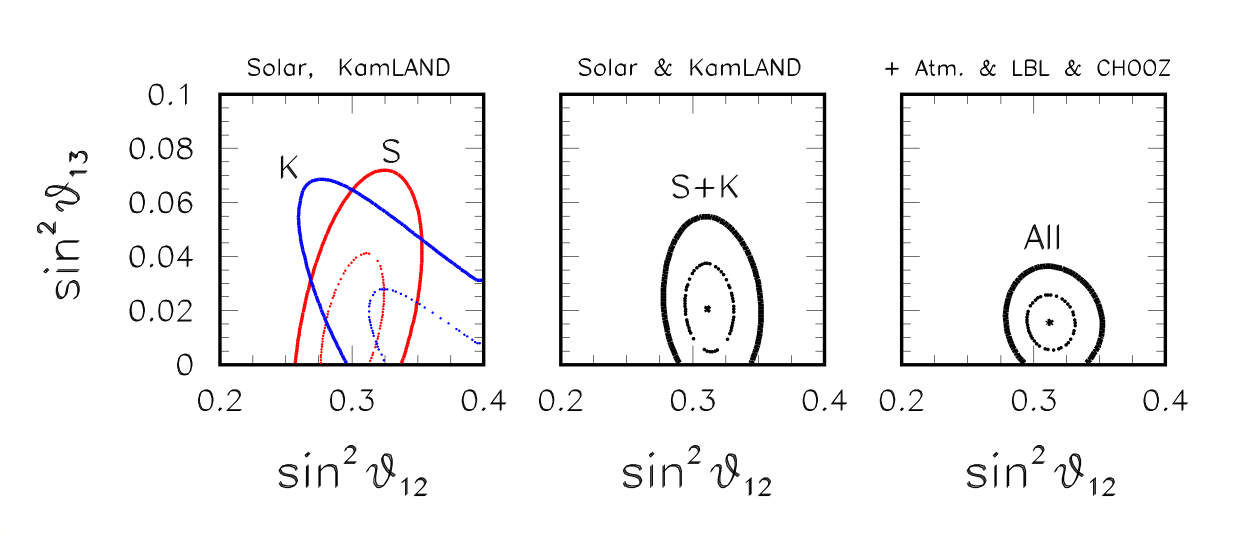
$$\delta \in [0, 2\pi]$$

Explicit form: $$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$s_{23}^2 \sim 0.46$ $s_{13}^2 \sim 0.025$ $s_{12}^2 \sim 0.31$

$\theta_{23} \sim 43^0$ $\theta_{13} \sim 9^0$ $\theta_{12} \sim 34^0$

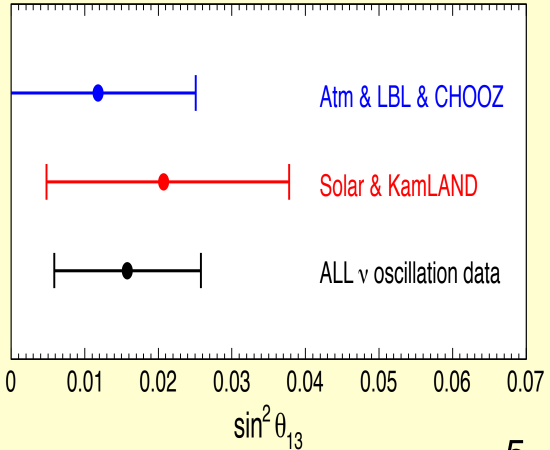
2008: First indication of non-zero θ_{13}



Fogli, Lisi, Marrone, A.P., Rotunno, Phys. Rev. Lett. 101, 141201 (2008)

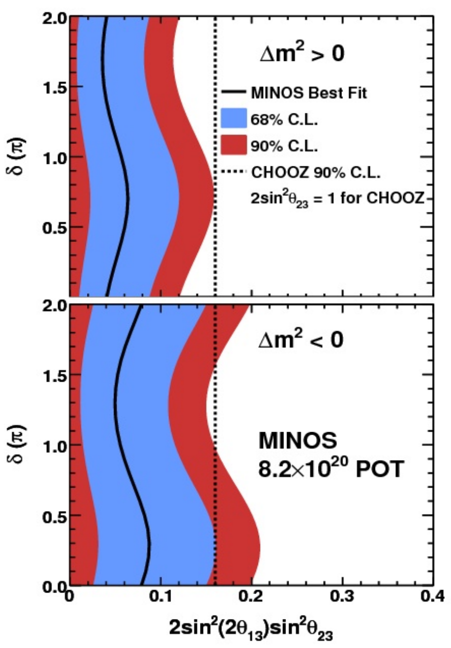
Two independent hints came from solar and atmospheric sectors:

$$\sin^2\theta_{13} \sim 0.016$$

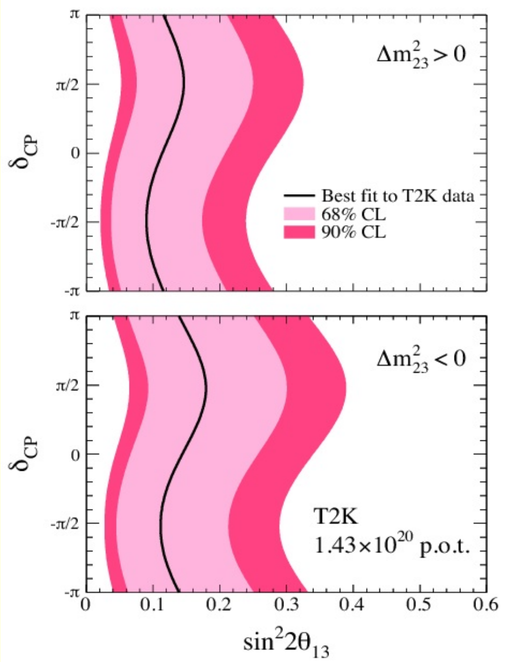


2011: Support by LBL ν_μ->ν_e appearance

MINOS

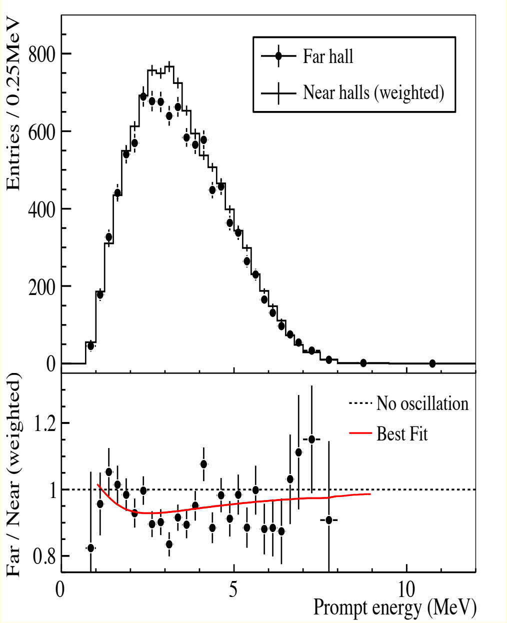


T2K

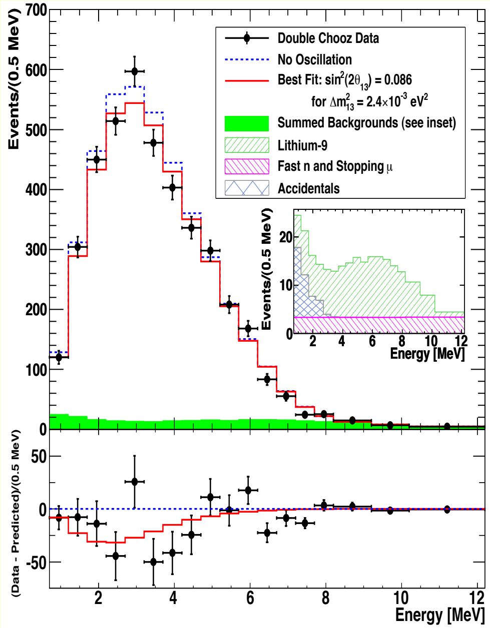


2012: Definitive confirmation from ν_e disap.

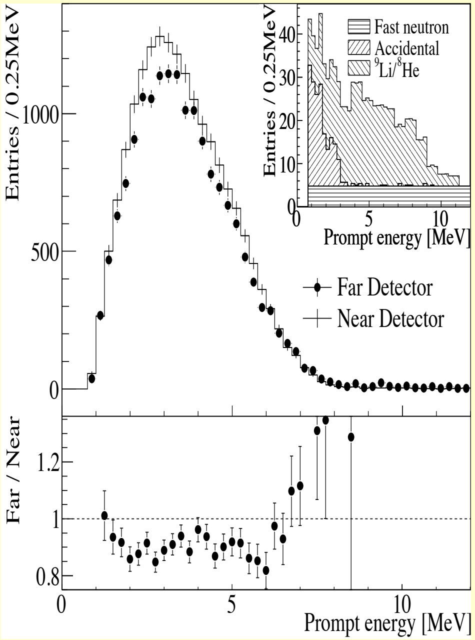
Daya Bay



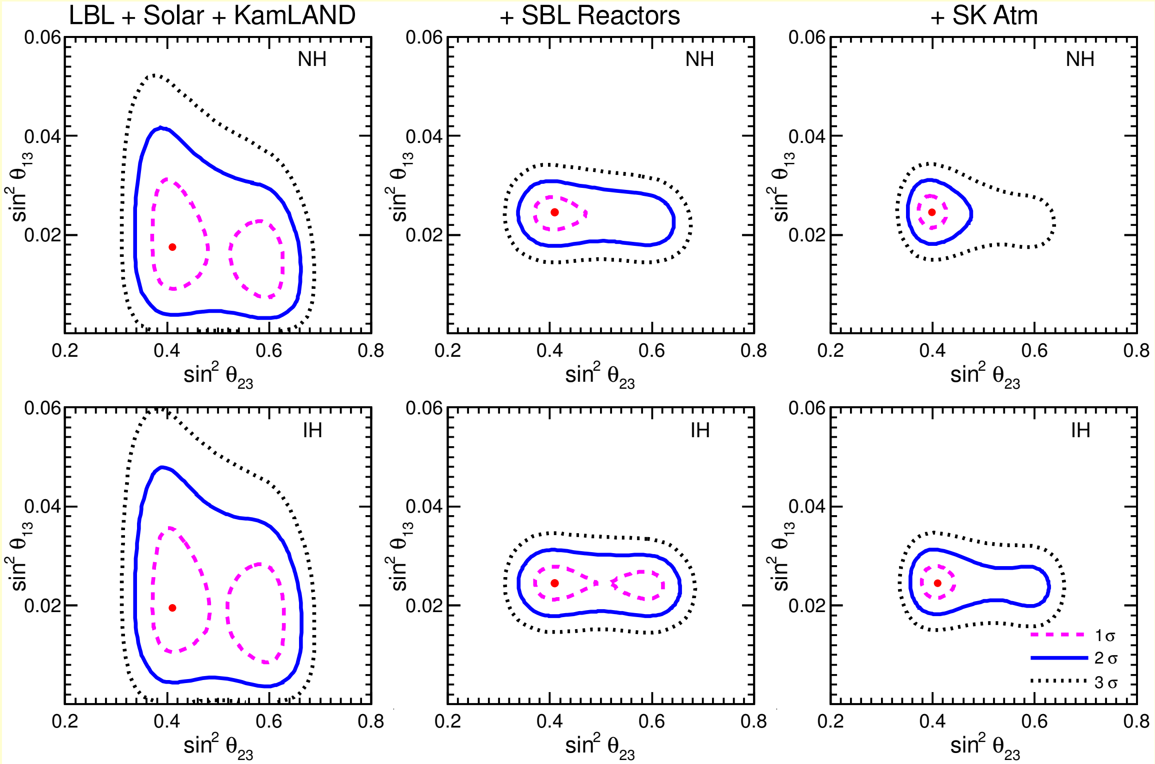
Double-CHOOZ



Reno



May 2012: Global Analysis including reactors



Fogli, lisi, Marrone, Montanino, A.P., Rotunno, arXiv: 1205:5254

$\sin^2\theta_{13} \sim 0.025$

$[\theta_{13},\theta_{23}]$ anti-correlation

Indication of $\theta_{23}<\pi/4$ at the ~ 2σ level

Why a non-zero θ_{13} is so important

$$J = \Im[U_{\mu 3} U_{e2} U^*_{\mu 2} U^*_{e3}]$$

The Jarlskog invariant J gives a parameterization-independent measure of the CP violation induced by the complexity of U

In the standard parameterization the expression of J is:

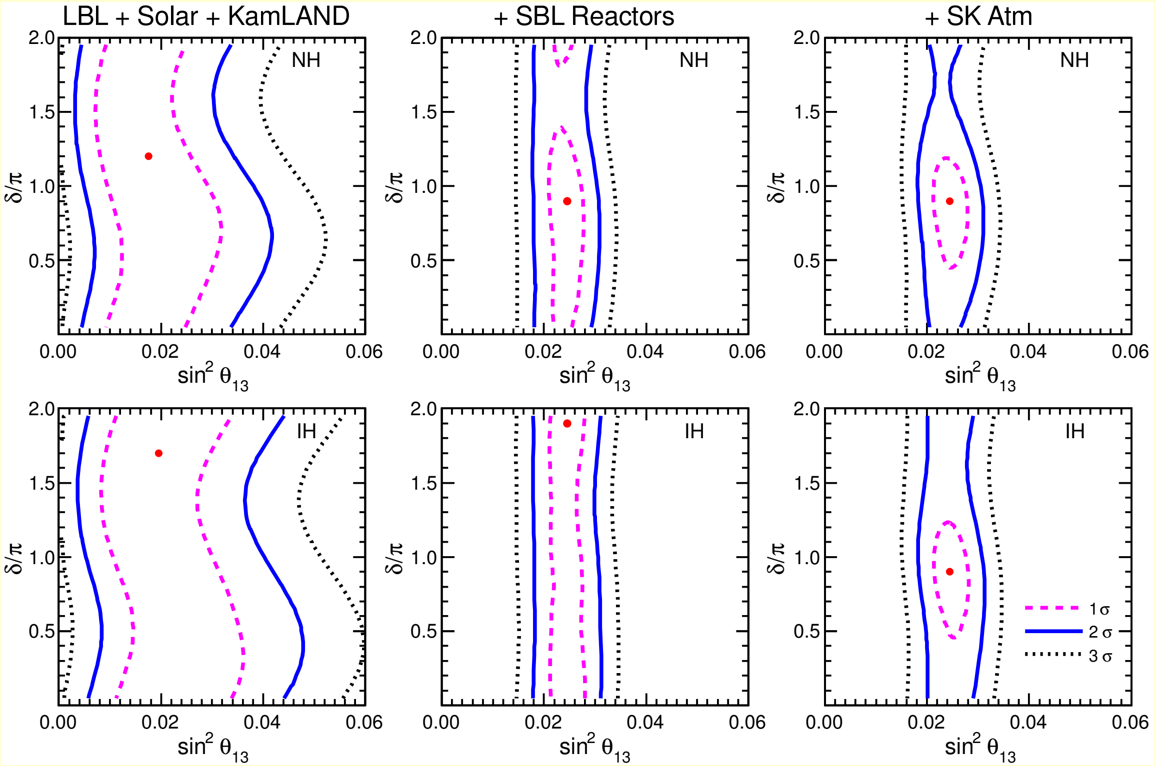
$$J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

Only if all three $\theta_{ij} \neq 0$ CP violation can occur

quark-sector: $J_{CKM} \sim 3 \times 10^{-5}$, much smaller than $|J|_{max} = \frac{1}{6\sqrt{3}} \sim 0.1$

lepton-sector: $|J|$ may be as large as 3×10^{-2} (it will depend on δ ...)

First information about δ



Hint in favor of δ ~ π

Still no info on mass hierarchy

Fogli, lisi, Marrone, Montanino, A.P., Rotunno, arXiv:1205:5254

Long and difficult way towards leptonic CPV observation!

Why go beyond three ν families?

Although the 3ν scheme explains most of data a few anomalies are there

These seem to point towards sterile neutrino species ν_s's [singlets of U(1)xSU(2)]

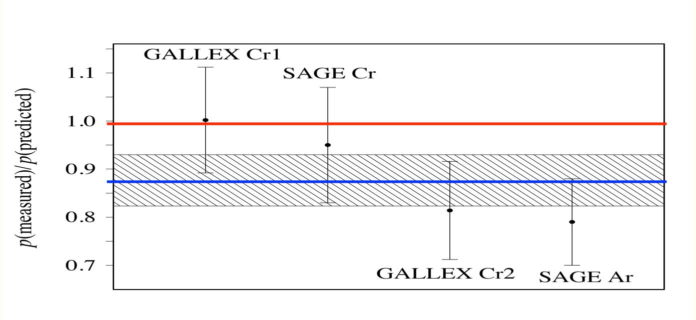
(I) Accumulating hints of eV ν_s's from oscillation phenomenology and cosmology

(II) Indications of "warm" dark matter from astrophysical "small-scale" problems (keV ν_s's are a good option)

I will discuss only type-I ν_s's

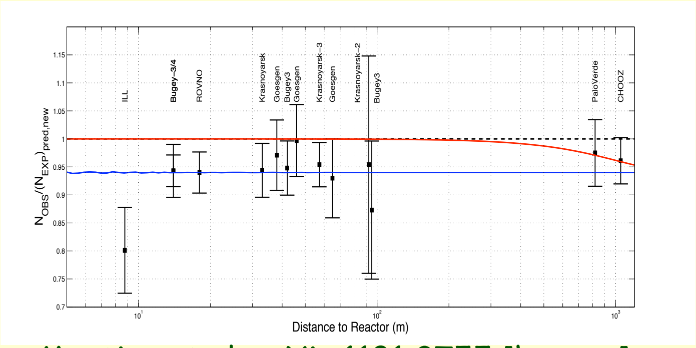
Anomalous ν_e-disappearance at short-distance

Hint #1



SAGE coll., PRC 73 (2006) 045805

Hint #2



Mention et al. arXiv:1101:2755 [hep-ex]

In a 2ν framework:

$$P_{ee} \simeq 1 - \sin^2 2\theta_{new} \sin^2 \frac{\Delta m^2_{new} L}{4E}$$

$$\sin^2 2\theta_{new} \simeq 0.17 \pm 0.1 \ (95\%)$$

In a 3+1 scheme:

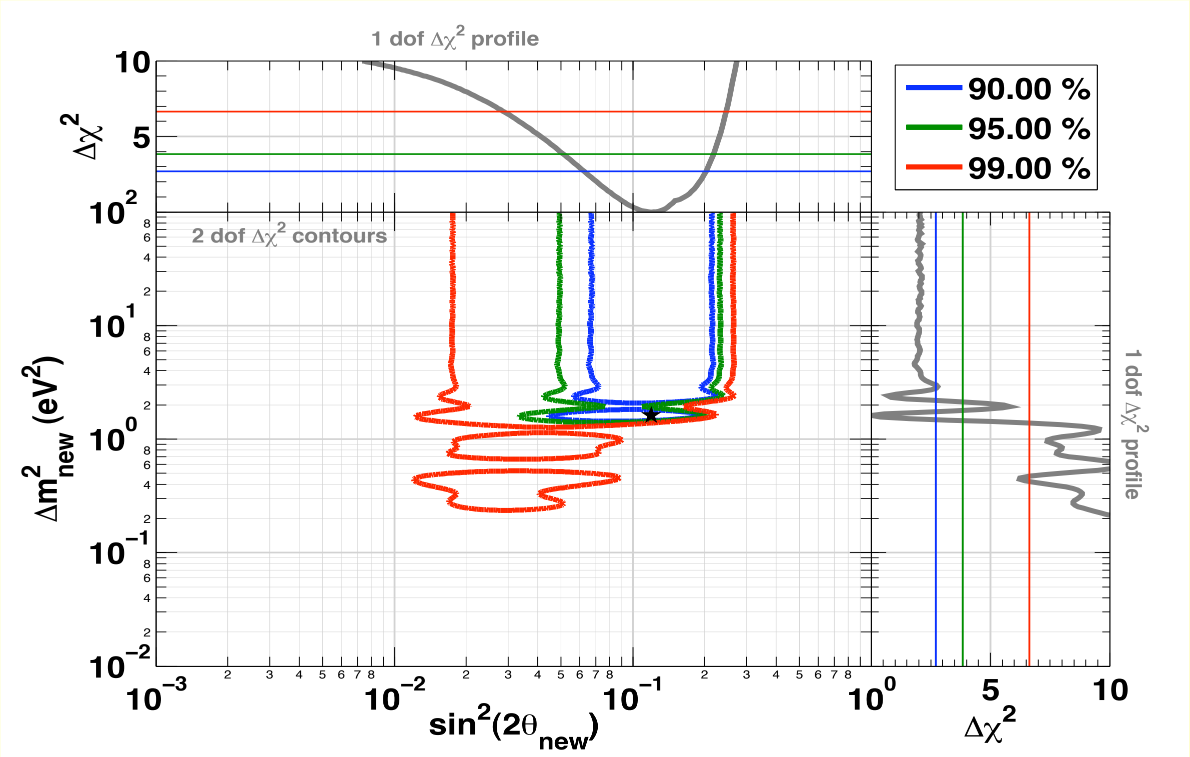
$$P_{ee} = 1 - 4 \sum_{j>k} U^2_{ej} U^2_{ek} \sin^2 \frac{\Delta m^2_{jk} L}{4E}$$

$$\Delta m^2_{sol} \ll \Delta m^2_{atm} \ll \Delta m^2_{new}$$

$$\sin^2 \theta_{new} \simeq U^2_{e4} = \sin^2 \theta_{14}$$

Warning, both are normalization issues:
The culprit may be hidden systematics

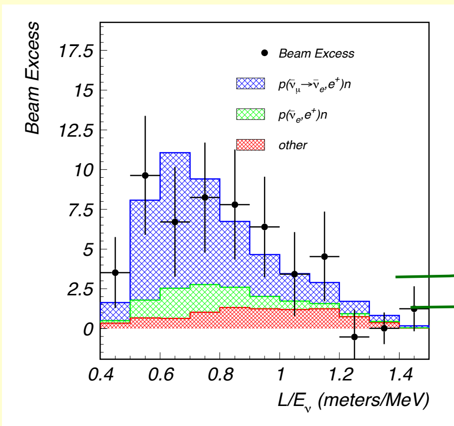
Fitting the short-distance ν_e-disappearance



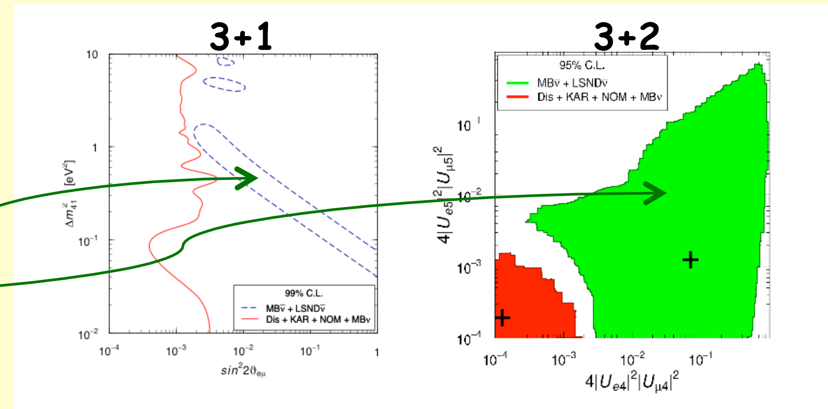
Mention et al., PRD 83 073006 (2011)

$$\sin^2 2\theta_{new} \simeq 0.1 \qquad\qquad \Delta m^2_{new} \gtrsim 1 \text{ eV}^2$$

Hint #3: Anomalous short-distance ν_e-appearance



LSND, PRL 75 (1995) 2650



Giunti and Laveder, arXiv:1107.1452

Warning:

In tension with disappearance searches:

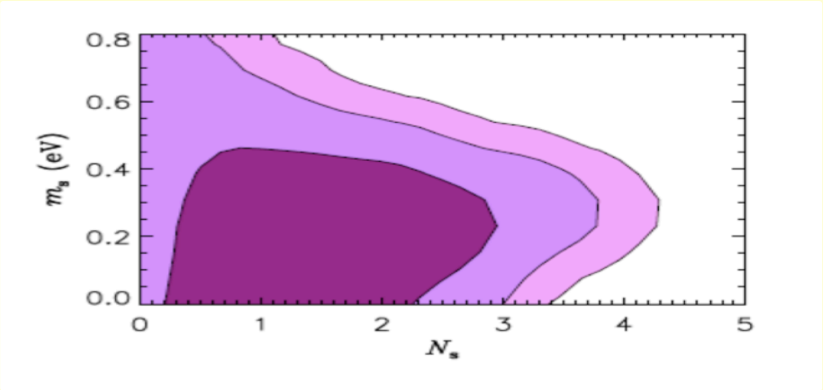
$\nu_\mu \to \nu_e$ positive appearance signal incompatible with joint $\nu_e \to \nu_e$ (positive) & $\nu_\mu \to \nu_\mu$ (negative) searches

Theory:

$$\sin^2 2\theta_{e\mu} \simeq \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu} \simeq 4|U_{e4}|^2|U_{\mu 4}|^2$$

Experiments: ~ few ‰ ~ 0.1 < few %

Hint #4: Cosmology favors extra radiation



CMB + LSS tend to prefer extra relativistic content ~ 2 sigma effect

[Hamann et al., PRL 105, 181301 (2010)]

Warnings:

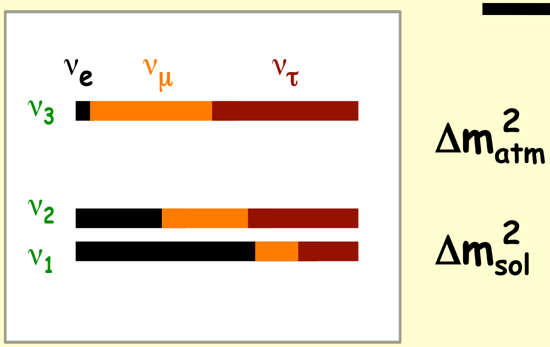
- **eV masses acceptable only abandoning standard ΛCDM**
  (Kristiansen & Elgaroy arXiv:1104.0704 , Hamann et al. arXiv:1108.4136)

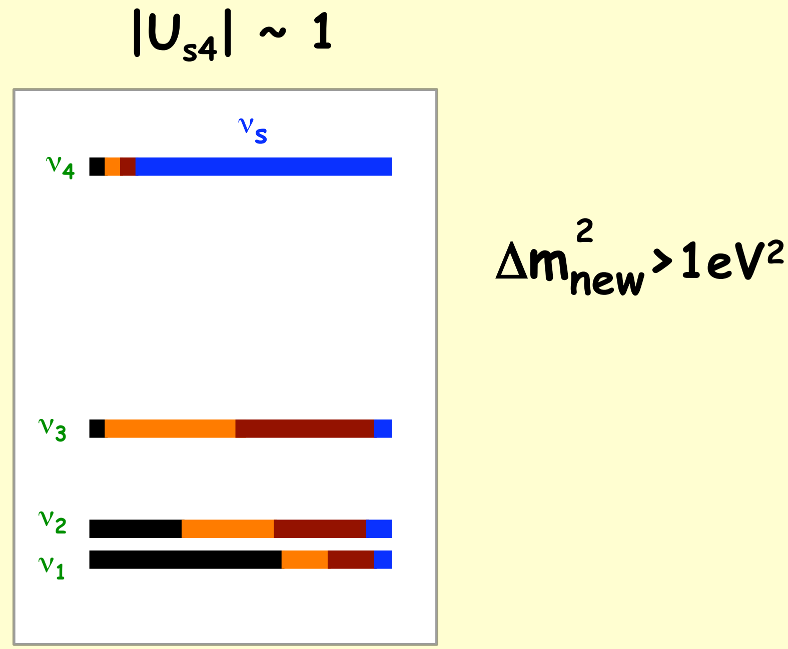
- **N_s is not specific of ν_s**
  (new light particles, decay of dark matter particles, quintessence, …)

Can we get some information on ν_s from the solar neutrino sector?

The 3+1 scheme:

The 4^{th} ν state induces a small perturbation of the 3-flavor framework





From the "point of view" of the solar doublet (ν_1, ν_2) we expect similar sensitivity to U_{e3} & U_{e4}

KamLAND: vacuum propagation

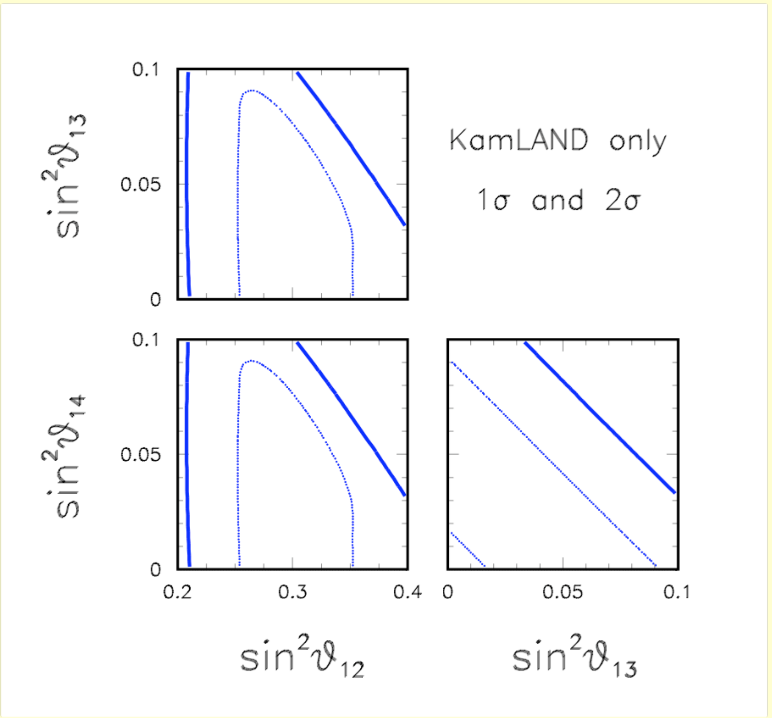
$$P_{ee} = 1 - 4 \sum_{j>k} U_{ej}^2 U_{ek}^2 \sin^2 \frac{\Delta m_{jk}^2 L}{4E}$$

$$\Delta m_{sol}^2 \ll \Delta m_{atm}^2 \ll \Delta m_{new}^2$$

Δm^2_{atm}, Δm^2_{new} **-driven osc. averaged**

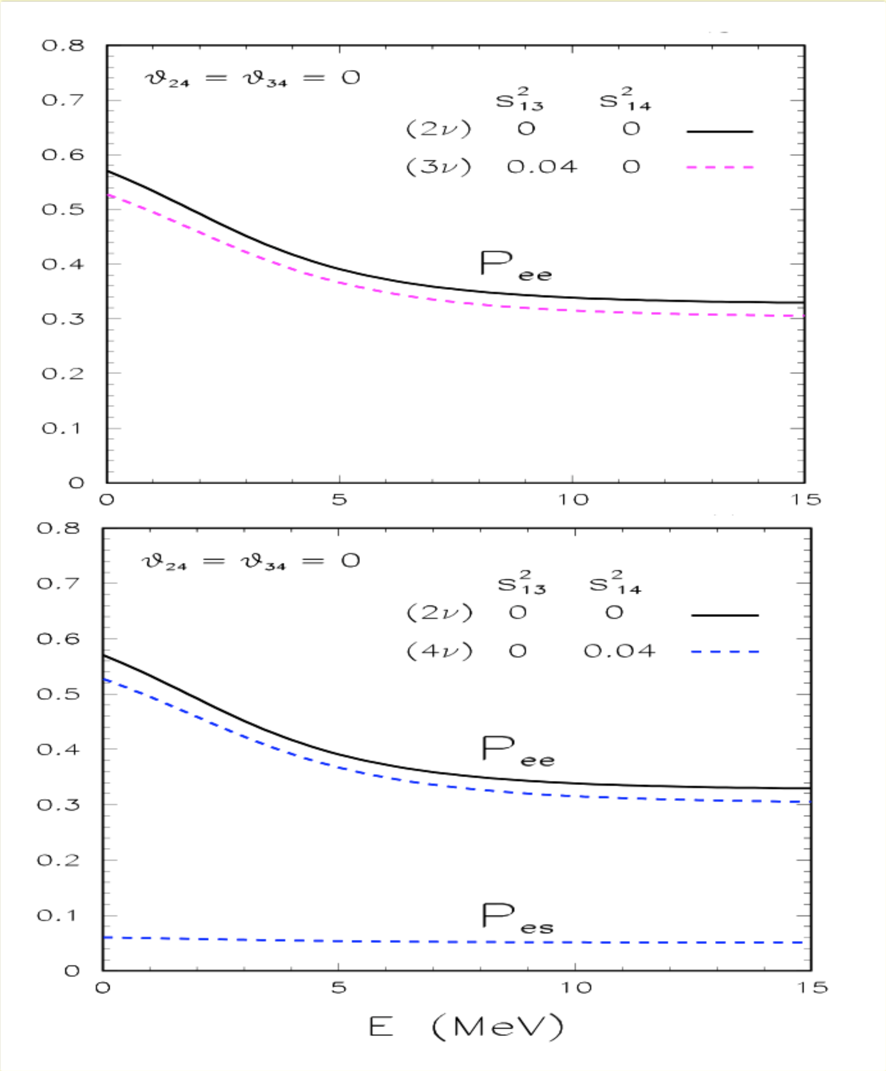
$$P_{ee} = (1 - U_{e3}^2 - U_{e4}^2)^2 P_{ee}^{2\nu} + U_{e3}^4 + U_{e4}^4$$

$$U_{e3}^2 = c_{14}^2 s_{13}^2 \qquad U_{e4}^2 = s_{14}^2$$



Exact degeneracy between U_{e3} and U_{e4}

Solar ν: Two simple limit cases



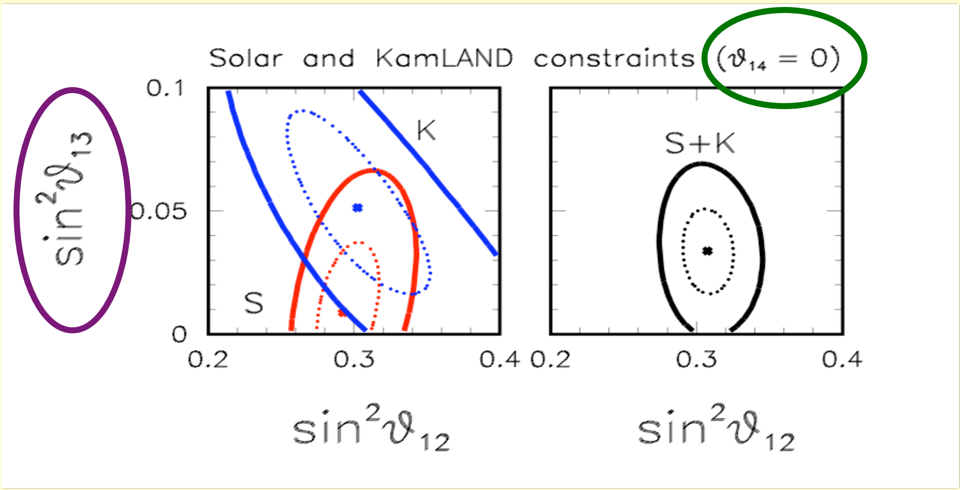
$\theta_{13} \neq 0 \quad \theta_{14} = 0 \quad$ **(3ν)**

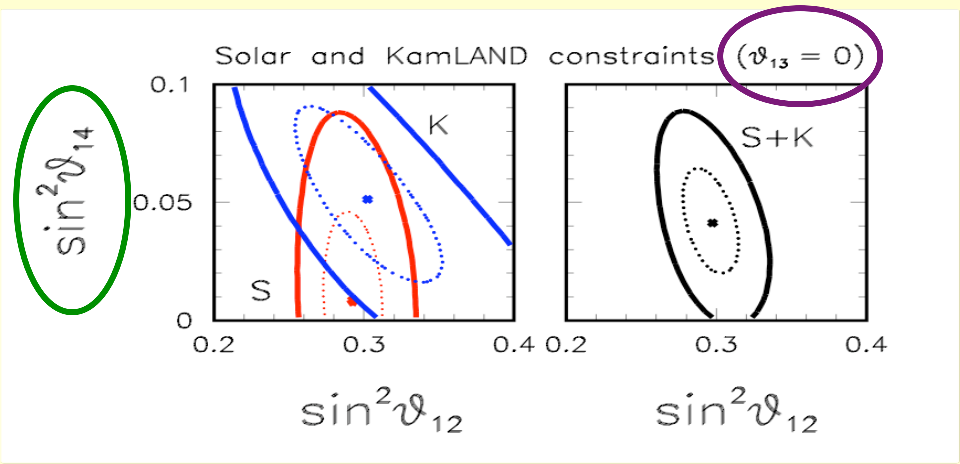
$$\begin{cases} P_{ee} = c_{13}^4 P_{ee}^{2\nu}\Big|_{V \to V c_{13}^2} + s_{13}^4 \\ P_{es} = 0 \end{cases}$$

$\theta_{13} = 0 \quad \theta_{14} \neq 0 \quad$ **(4ν)**

$$\begin{cases} P_{ee} = c_{14}^4 P_{ee}^{2\nu}\Big|_{V \to V c_{14}^2} + s_{14}^4 \\ P_{es} \simeq s_{14}^2 P_{ee}^{2\nu}\Big|_{V \to V c_{14}^2} + s_{14}^2 \end{cases}$$

(θ_{13},θ_{12}) vs (θ_{14},θ_{12}) constraints (new reactor fluxes)





$$\begin{cases} CC \sim \Phi_B\, P_{ee} \\ NC \sim \Phi_B\, (1-P_{es}) \\ ES \sim \Phi_B\, (P_{ee} + 0.15\, P_{ea}) \end{cases}$$

Solar ν sensitive to Pes
CC/NC (SNO) & ES (SK)

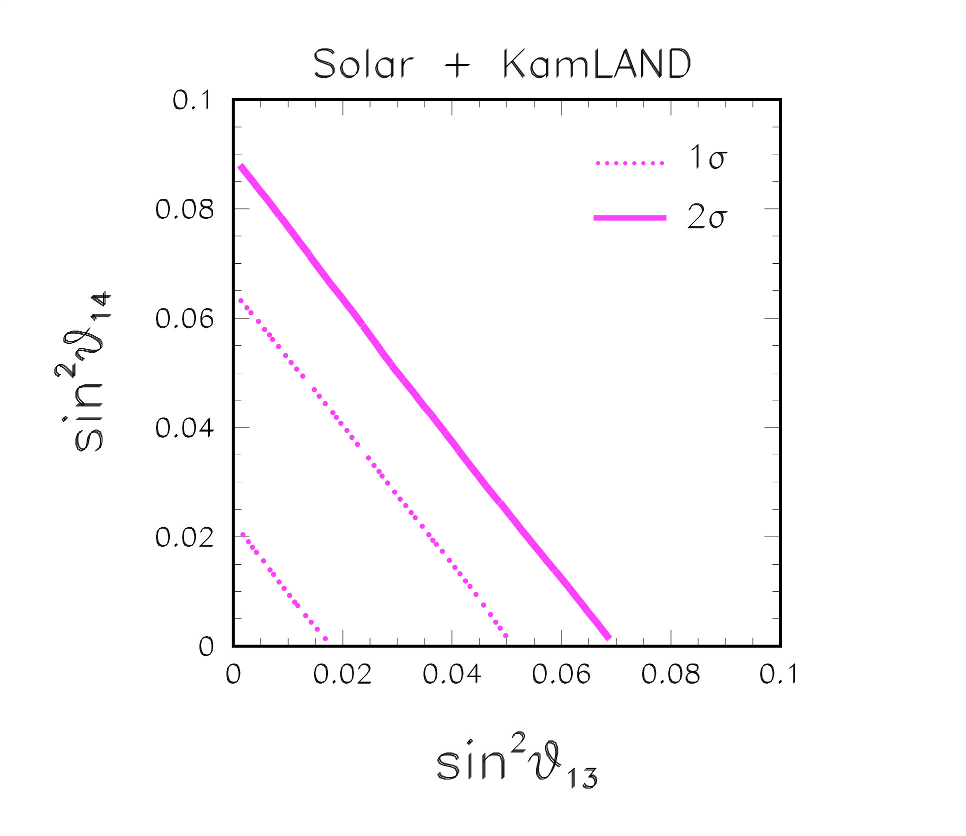
Different correlations

Two similar indications at 1.8σ (1.3σ with old fluxes)

We expect a degeneracy among θ_{13} and θ_{14}

A.P. PRD 83 113013 (2011) [arXiv: 1105.1705 hep-ph]

(θ_{13},θ_{14}) constraints



Complete degeneracy
θ_{13}-θ_{14} indistinguishable

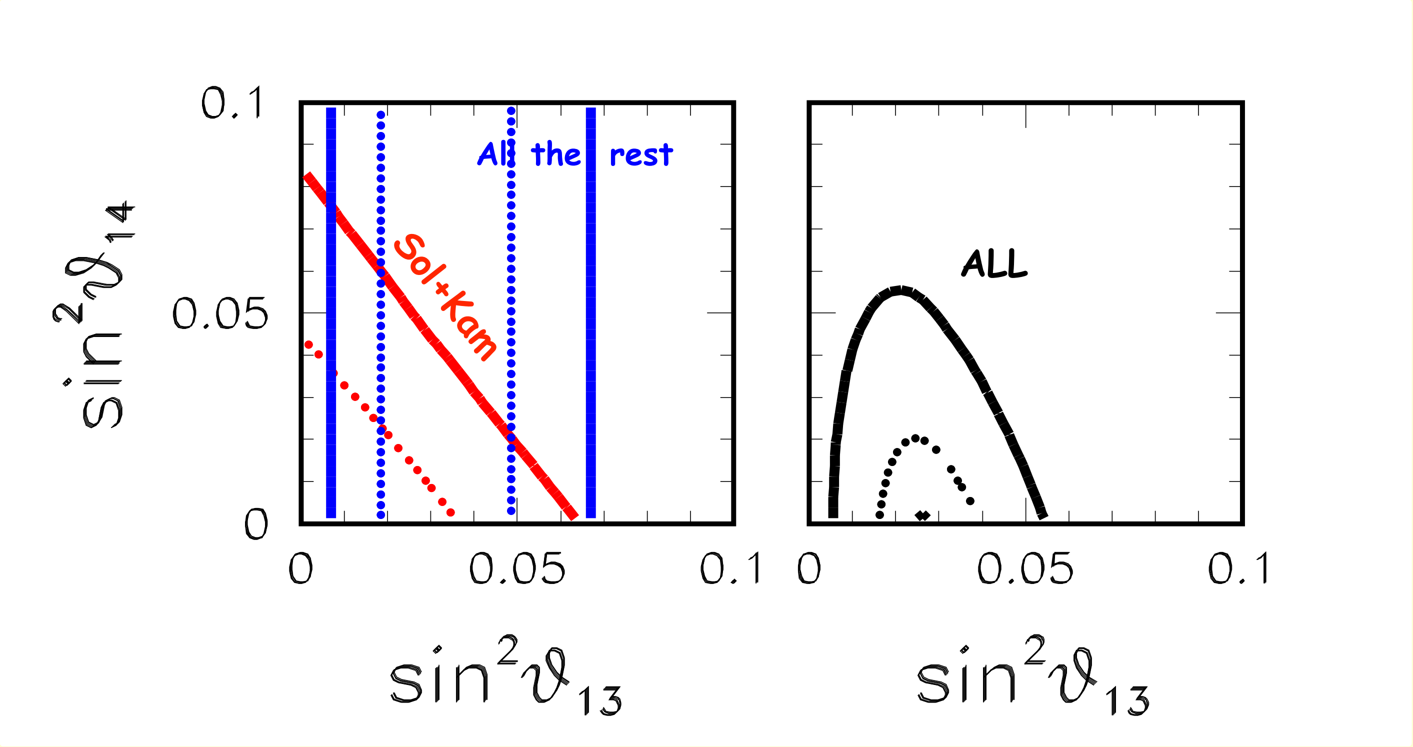
Solar sector essentially sensitive to ~ $U_{e3}^2 + U_{e4}^2$

Hint for ν_e mixing with states others than (ν_1,ν_2)

Different probes are necessary to determine if ν_e mixes with ν_3 or ν_4

A.P. PRD 83 113013 (2011) [arXiv: 1105.1705 hep-ph]

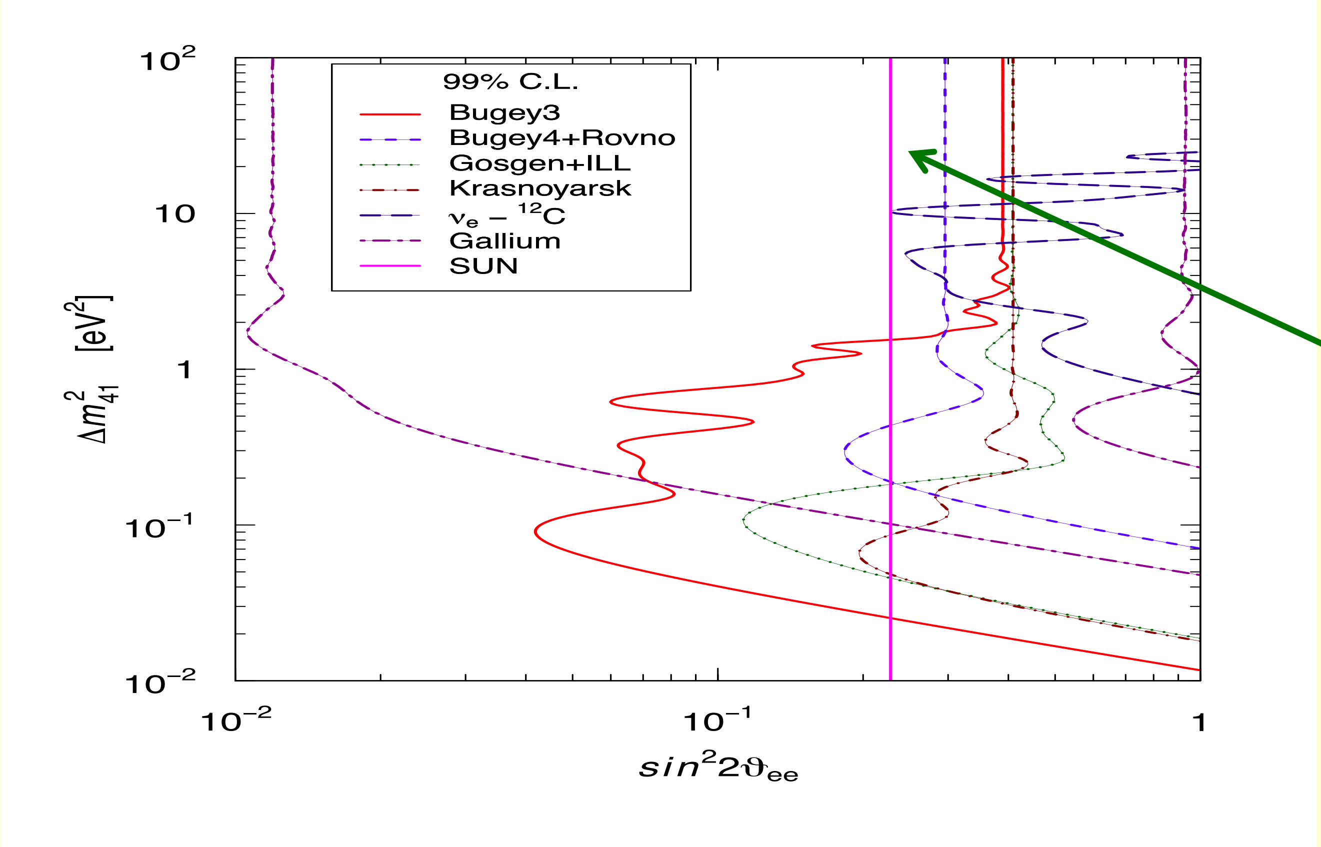
But evidence of $\theta_{13}>0$ eats up hint of $\theta_{14}>0$



Upper limit → $\sin^2\theta_{14} < 0.04 \quad (90\%\ \mathrm{C.L.})$

A.P. PRD 85 077302 (2012) [arXiv: 1201.4280 hep-ph]

Compilation of all the existing limits on θ_{14} (= θ_{ee})



Solar bound

From C. Giunti @ νTURN 2012

Summary

- 3ν standard paradigm acquired a new piece: θ_{13} >0; to be taken into account when going beyond 3ν's.

- First interesting information on CPV phase ($\delta \sim \pi$) & $\theta_{23}<\pi/4$

- A few anomalies suggest active ν's mix with new sterile states and require an enlarged framework (3+1 or 3+n).

- However, each indication is problematic per se and/or conflicting with other ones. Further scrutiny is needed.

- Evidence of θ_{13}>0 + solar sector data provide the stringent and robust upper limit: $\sin^2\theta_{14} < 0.04 \quad (90\%\ \mathrm{C.L.})$

- A new experiment indispensable to probe such low values.

Backup slides

Solar ν conversion in a 3+1 scheme

$$i\,\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_s\end{pmatrix} \qquad H = UKU^T + V(x)$$

$$K = \frac{1}{2E}\mathrm{diag}(k_1,\, k_2,\, k_3,\, k_4) \qquad k_i = \frac{m_i^2}{2E}$$

wavenumbers in vacuum

Useful to write the mixing matrix as*: **$U = R_{23}\, S\, R_{13}\, R_{12}$** **$S = R_{24}\, R_{34}\, R_{14}$**

$\theta_{14}=\theta_{24}=\theta_{34}=0$ --> $S = I$ --> 3-flavor case

$$V = \mathrm{diag}(V_{CC},\, 0,\, 0,\, -V_{NC})$$

$$V_{CC} = \sqrt{2}\,G_F\,N_e \qquad V_{NC} = \frac{1}{2}\sqrt{2}\,G_F\,N_n$$

MSW potential

* We assume U to be real but in general it can be complex due to CP phases

Change of basis: $\nu' = (R_{23}\, S\, R_{13})^T\, \nu = A^T \nu = R_{12} U^T$

In the new basis: $H' = A^T H A = R_{12} K R_{12}^T + R_{13}^T S^T V S R_{13}$

At zeroth **order in:**

$\frac{V}{k_{atm}}$ **and** $\frac{V}{k_{new}}$

$$H' \simeq \left(\begin{array}{c|cc} H'_{2\nu} & & \\ \hline & k_3 & \\ & & k_4 \end{array}\right)$$

The 3rd **& 4**th **state evolve independently from the 1**st **& 2**nd

The dynamics reduces to that of a 2x2 system

Diagonalization of the Hamiltonian

The 2x2 Hamiltonian is diagonalized by a 1-2 rotation

$$\tilde{R}_{12}^{T} H'_{2\nu} \tilde{R}_{12} = diag(\tilde{k}_1, \tilde{k}_2)$$

which defines the solar mixing angle in matter

$$\tilde{\theta}_{12}(x)$$

wavenumbers in matter

$$\tilde{k}_i$$

The starting Hamiltonian is then diagonalized by

$$\tilde{U} = A\tilde{R}_{12}$$
$$\tilde{U}^T H \tilde{U} = diag(\tilde{k}_1, \tilde{k}_2, k_3, k_4)$$

For ν_3 and ν_4 (averaged) vacuum-like propagation

The 2x2 Hamiltonian: $H'_{2\nu} = H'^{\,kin}_{2\nu} + H'^{\,dyn}_{2\nu}$

$$H'^{\rm kin}_{2\nu} = \begin{pmatrix} c_{12} & s_{12} \\ -s_{12} & c_{12} \end{pmatrix} \begin{pmatrix} -k_{sol}/2 & 0 \\ 0 & k_{sol}/2 \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} \\ s_{12} & c_{12} \end{pmatrix} \qquad k_{sol} = \frac{m_2^2 - m_1^2}{2E}$$

$$H'^{\rm dyn}_{2\nu} = V_{CC}(x) \begin{pmatrix} \gamma^2 + r(x)\,\alpha^2 & r(x)\,\alpha\beta \\ r(x)\,\alpha\beta & r(x)\,\beta^2 \end{pmatrix}^{*} \qquad r(x) = \frac{V_{NC}(x)}{V_{CC}(x)}$$

$$\begin{cases} \alpha^2 + \beta^2 = U_{s1}^2 + U_{s2}^2 \\ \gamma^2 = 1 - (U_{e3}^2 + U_{e4}^2) \end{cases} \qquad \begin{cases} \alpha = c_{24}c_{34}c_{13}s_{14} - s_{34}s_{13} \\ \beta = s_{24}c_{34} \\ \gamma = c_{13}c_{14} \end{cases}$$

All the dynamical effects induced by the 4th (and 3rd) state are 2nd order in the s_{ij}: small deviations from the standard MSW.

But important new kinematical effects are present …

* A.P. PRD 83 113013 (2011) [arXiv: 1105.1705 hep-ph]

For adiabatic propagation (valid for small deviations around the LMA)

$$P_{ee} = \sum_{i=1}^{4} U_{ei}^2 \tilde{U}_{ei}^2 = U_{e1}^2 \tilde{U}_{e1}^2 + U_{e2}^2 \tilde{U}_{e2}^2 + U_{e3}^4 + U_{e4}^4$$

$$P_{es} = \sum_{i=1}^{4} U_{si}^2 \tilde{U}_{ei}^2 = U_{s1}^2 \tilde{U}_{e1}^2 + U_{s2}^2 \tilde{U}_{e2}^2 + U_{s3}^2 U_{e3}^2 + U_{s4}^2 U_{e4}^2$$

Expressions for U_{ei}'s (always valid)

$$\left.\begin{aligned} U_{e1}^2 &= c_{14}^2 c_{13}^2 c_{12}^2 \\ U_{e2}^2 &= c_{14}^2 c_{13}^2 s_{12}^2 \end{aligned}\right\} \sim 1 - s_{14}^2 - s_{13}^2$$

$$U_{e3}^2 = c_{14}^2 s_{13}^2 \quad \sim s_{13}^2$$

$$U_{e4}^2 = s_{14}^2$$

Expressions for U_{si}'s valid for $\theta_{24} = \theta_{34} = 0$

$$\left.\begin{aligned} U_{s1}^2 &= s_{14}^2 c_{13}^2 c_{12}^2 \\ U_{s2}^2 &= s_{14}^2 c_{13}^2 s_{12}^2 \end{aligned}\right\} \sim s_{14}^2$$

$$U_{s3}^2 = s_{14}^2 s_{13}^2 \quad \sim 0$$

$$U_{s4}^2 = c_{14}^2 c_{13}^2 \quad \sim 1 - s_{14}^2$$

The elements of $\tilde{U}$ are obtained replacing θ_{12} with $\tilde{\theta}_{12}$ calculated in the production point (near the sun center)