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The reactor and Gallium calibration anomalies: Implications for the solar sector

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Outline

Introduction
The 3-flavor framework and the hint of $\theta_{13}>0$

Perturbing the standard scenario
Solar ν MSW conversion in a 3+1 scheme

Solar ν's as a probe of the ν_e mixing
The U_{e3}-U_{e4} indistinguishability

Conclusions

Introduction

The 3-flavor leptonic mixing

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

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

$$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$$
$$\delta \in [0, 2\pi]$$

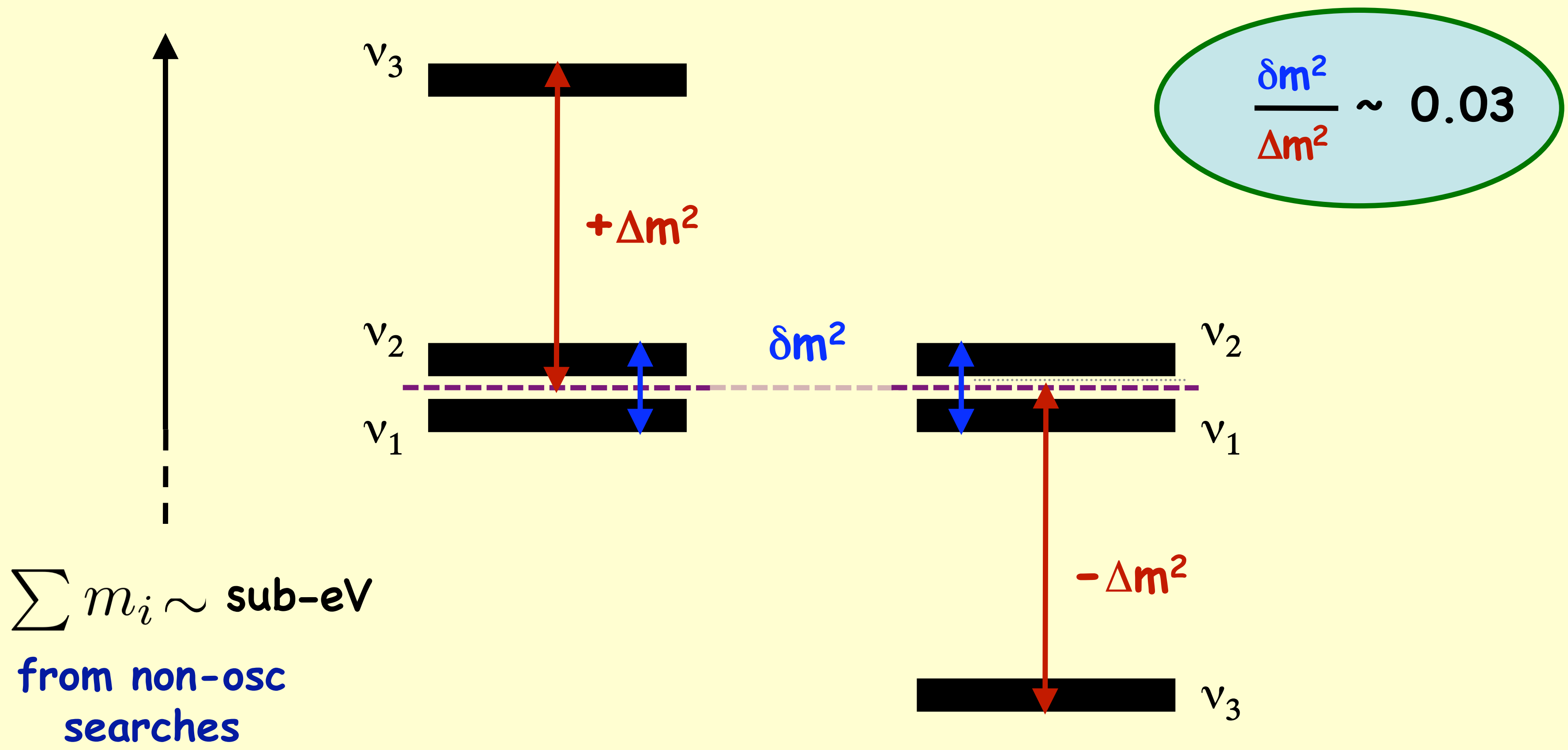
Dirac CP-violating phase is <u>unknown</u>

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

Determination of θ_{13} is vital for the search of possible CP violation in the leptonic sector

The neutrino mass spectrum

NH or IH ?



Basic experimental sensitivities

leading

Atmospheric, LBL (disapp.) → $(\Delta m^2, \ \theta_{23}, \ \theta_{13})$

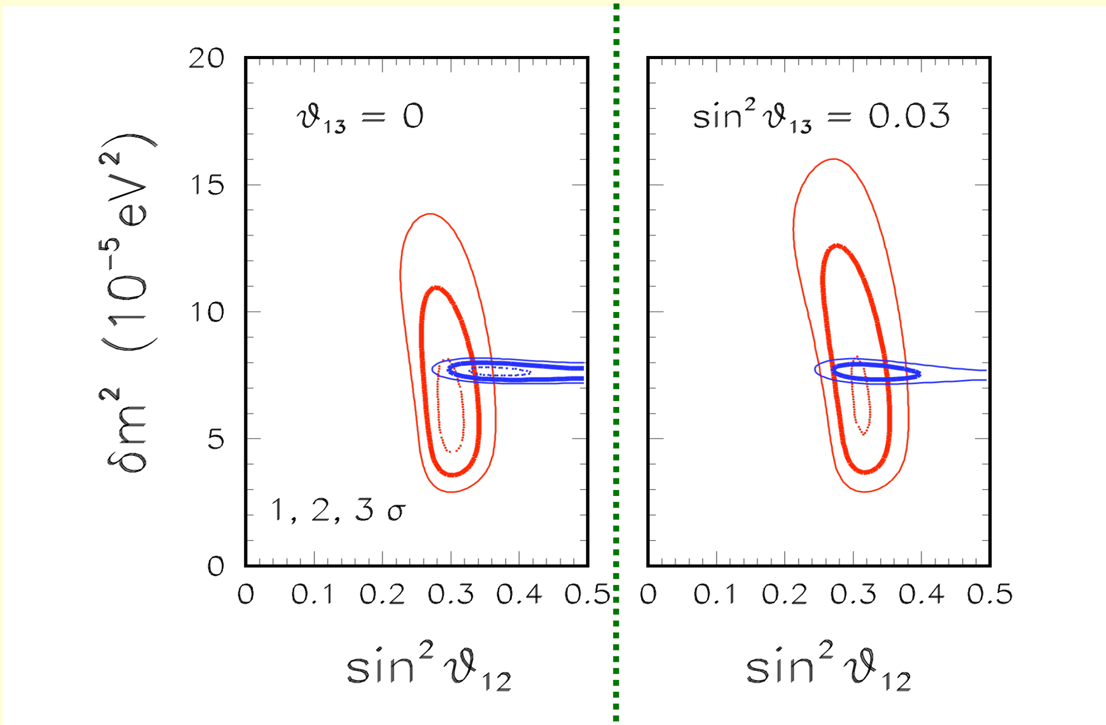
Solar, KamLAND → $(\delta m^2, \ \theta_{12}, \ \theta_{13})$

CHOOZ, MINOS (app.) → $(\Delta m^2, \ \theta_{13})$

sub-leading

A hint of non-zero θ_{13} arises from a slight tension between solar and KamLAND

$\theta_{13} = 0$



$\theta_{13} > 0$

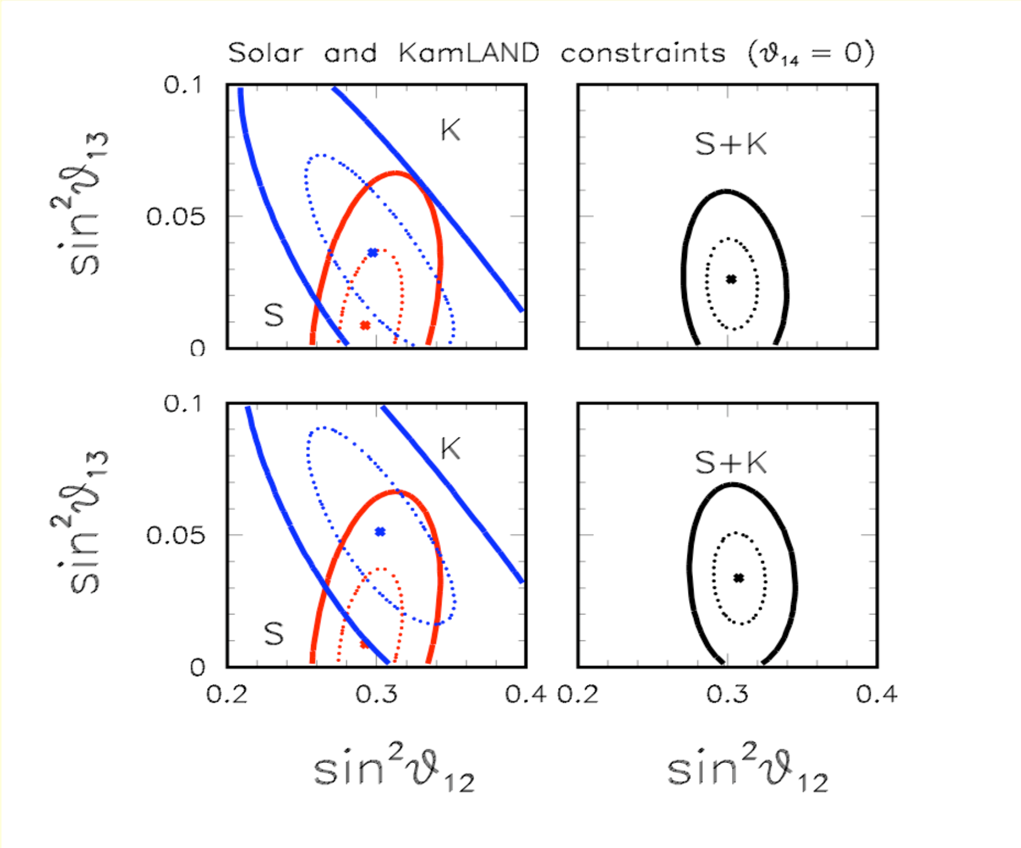
For $\theta_{13} = 0$
Solar and KamLAND
prefer different values of θ_{12}

For $\theta_{13} > 0$
Solar data prefer higher θ_{12}
KamLAND prefers lower θ_{12}

Impact of the new reactor fluxes on θ_{13}

OLD FLUXES

NEW FLUXES



1.3 σ

1.8 σ

KamLAND prefers larger values of θ_{13} with the new (higher) ν fluxes as a bigger rate suppression is needed in this case

Origin of the different correlations

$$\mathrm{P}_{ee}^{3\nu} \simeq s_{13}^4 + c_{13}^4 P_{ee}^{2\nu}$$

$\Delta m^2 \to \infty$

one-mass-scale approximation

For small values of θ_{13} we have:

High-E solar $\longrightarrow$ $P_{ee} \simeq (1 - 2s_{13}^2)(+ s_{12}^2)$

KamLAND (~vacuum) $\longrightarrow$ $P_{ee} \simeq (1 - 2s_{13}^2)(1 - 4s_{12}^2 c_{12}^2 \sin^2\phi)$

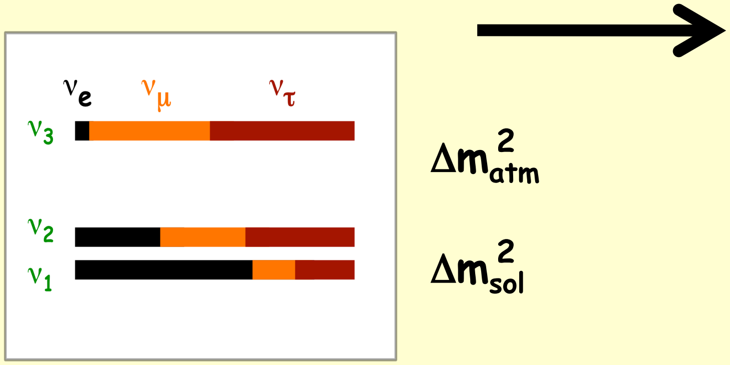
$$\phi = \frac{\delta m^2 L}{4E}$$ **oscillation phase**

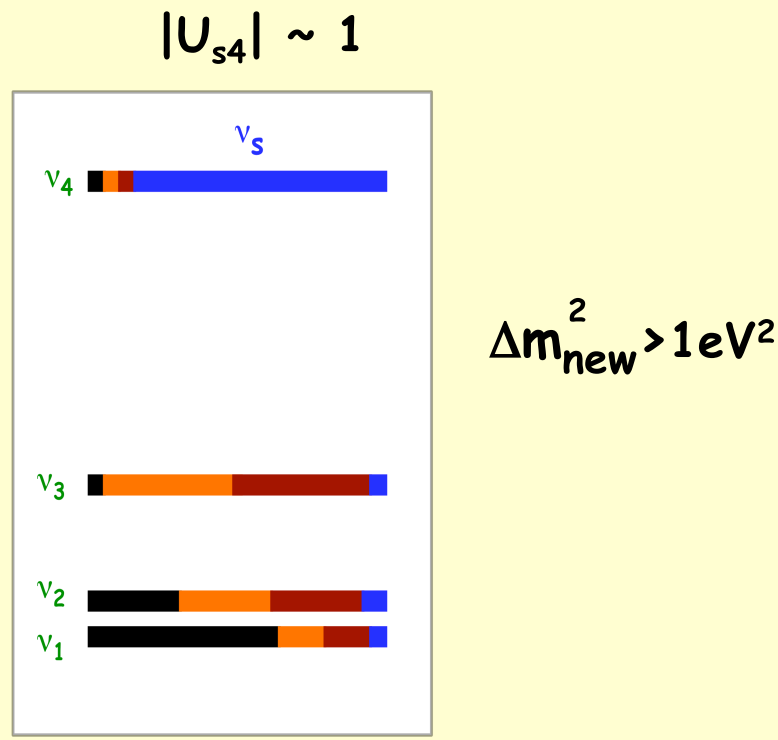
Different relative sign for (θ_{12}, θ_{13}) in P_{ee}

Perturbing the 3-flavor scheme

The 3+1 Scheme

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

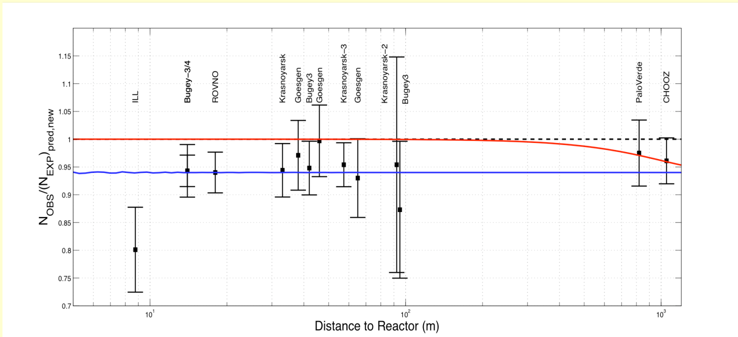




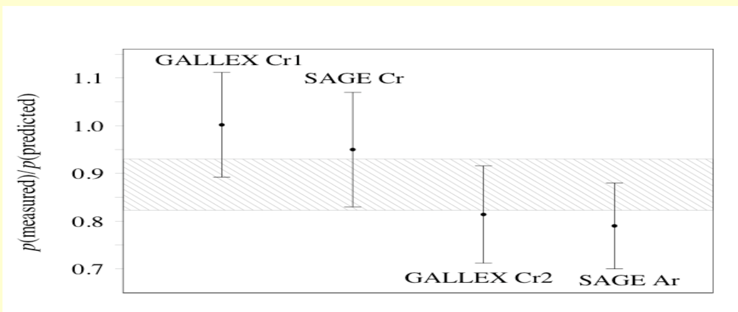
* Solar sector alone cannot distinguish the 3+1 scheme from a scheme where also U_{s3} is big (but this disfavored by the atmospheric sector)

* Hierarchy: reciprocal ordering of (ν_3,ν_4) & respect to (ν_1,ν_2) unknown

The reactor anomaly and the Gallium calibration problem



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



SAGE coll., PRC 73 (2006) 045805

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:

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

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

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

The 3+1 scheme has several consequences: solar, atm, react., accel.

We will focus on the implications for Solar (S) & KamLAND (K)

KamLAND in a 3+1 scheme

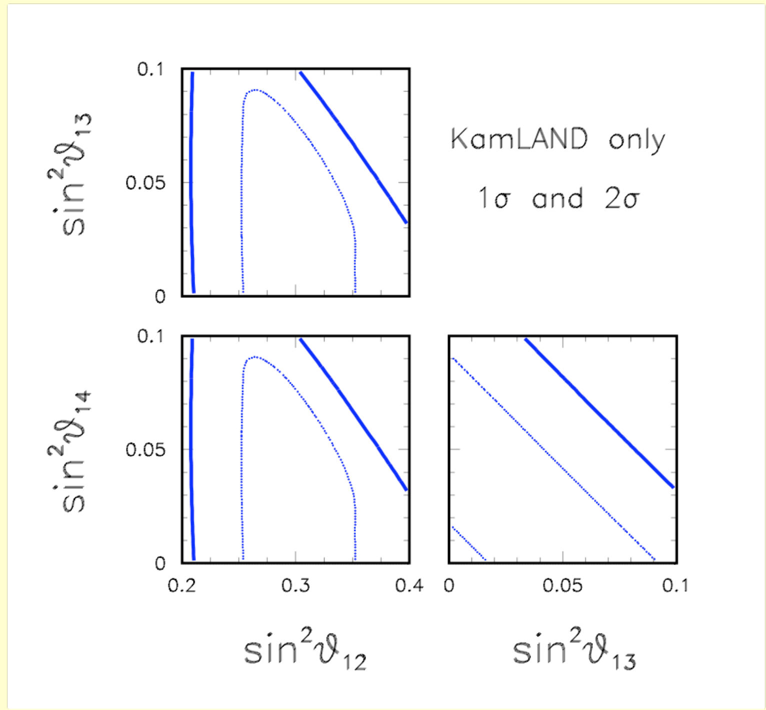
$$P_{ee} = 1 - 4\sum_{j>k} U_{ej}^2 U_{ek}^2 \sin^2 \frac{\Delta m_{jk}^2 L}{4E}$$

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

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

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

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



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

Solar ν conversion in a 3+1 scheme

Work in preparation

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

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

wavenumbers in vacuum

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

$\theta_{14}=\theta_{24}=\theta_{34}=0$ --> $S = I$ --> 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 and 4th state evolve independently from the 1st and 2nd

The dynamics reduces to that of a 2x2 system

See also C. Giunti and Y.F. Li, PRD 80 113007 (2009)

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 …

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)

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

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

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

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

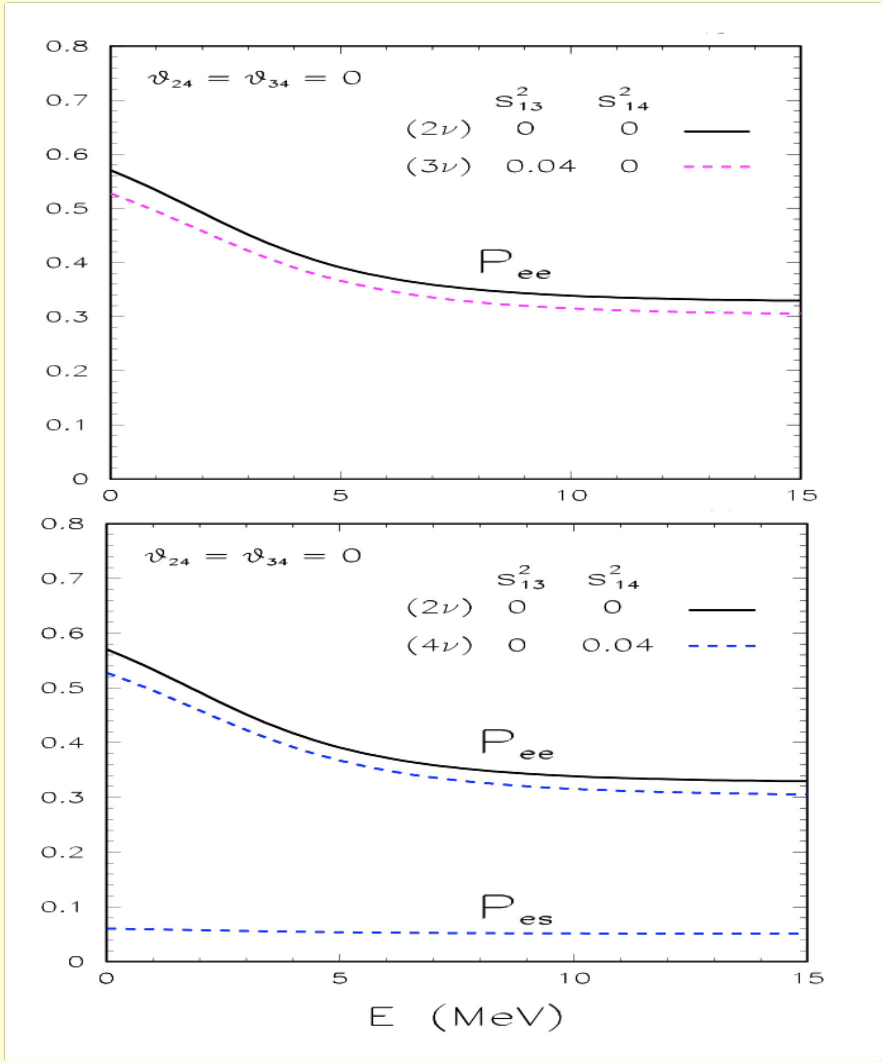
$$\left.\begin{array}{l} U_{s1}^2 = s_{14}^2 c_{13}^2 c_{12}^2 \\ U_{s2}^2 = s_{14}^2 c_{13}^2 s_{12}^2 \end{array}\right\} \sim s_{14}^2$$

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

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

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

Two simple limit cases



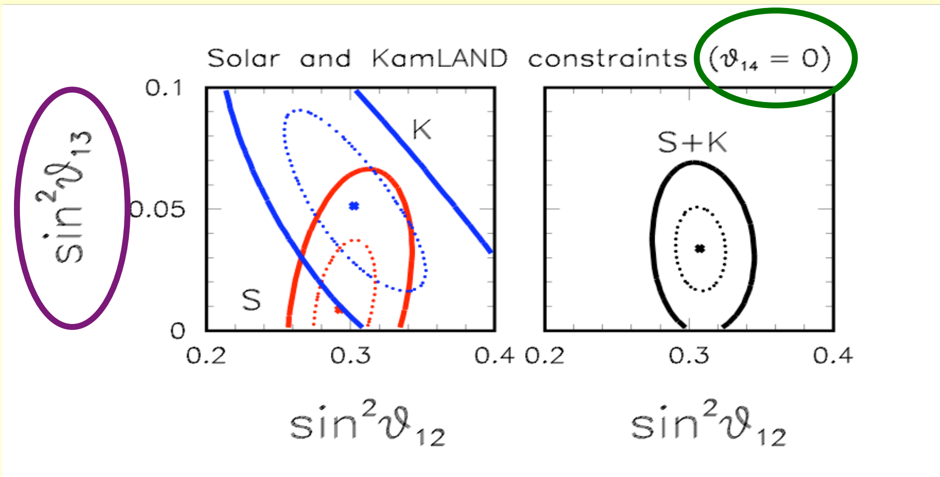
$\theta_{13} \neq 0$ $\theta_{14} = 0$ **(3ν)**

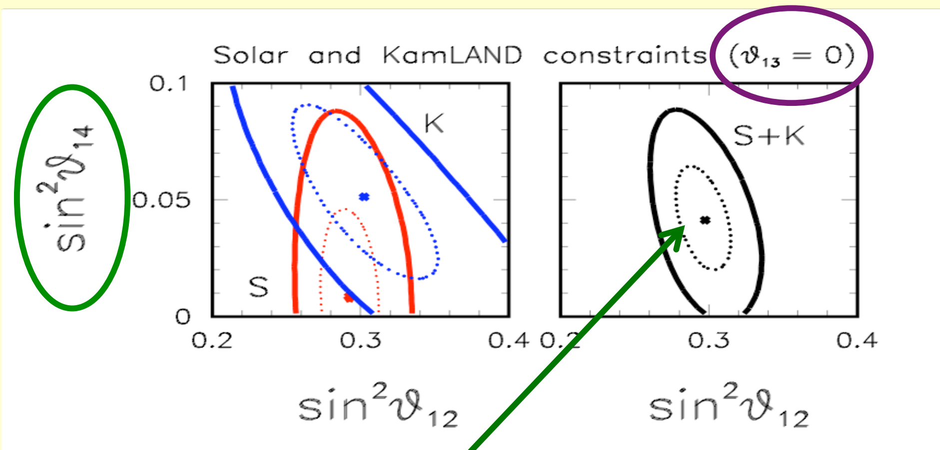
$$\begin{cases} P_{ee} = c_{13}^4 P_{ee}^{2\nu}\Big|_{V \to V c_{13}^2} + s_{13}^4 \\ P_{es} = 0 \end{cases}$$

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

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

$(\theta_{13},\theta_{12})$ vs $(\theta_{14},\theta_{12})$ constraints (new reactor fluxes)





Work in preparation

Best fit (0.04) equal to that obtained from reactor+Ga

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

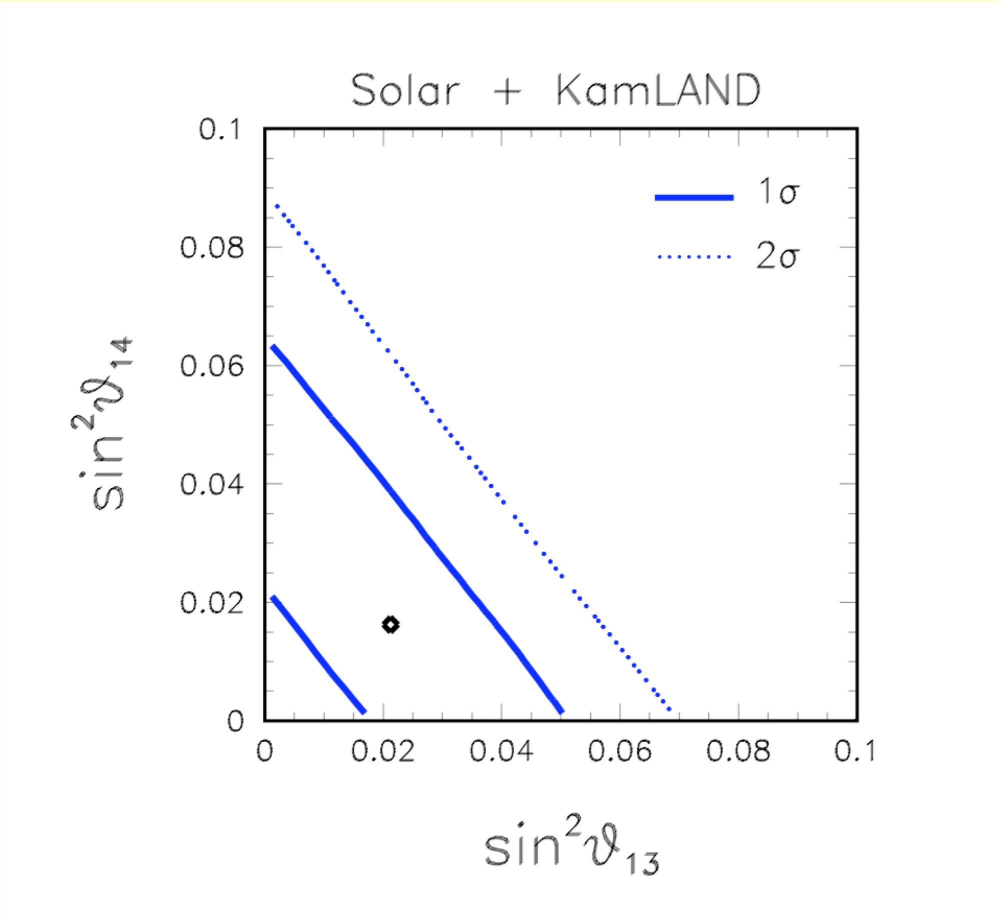
Solar ν sensitive to Pes
CC/NC (SNO) & ES (SK)

Different correlations

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

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

$(\theta_{13},\theta_{14})$ constraints (new reactor fluxes)



Work in preparation

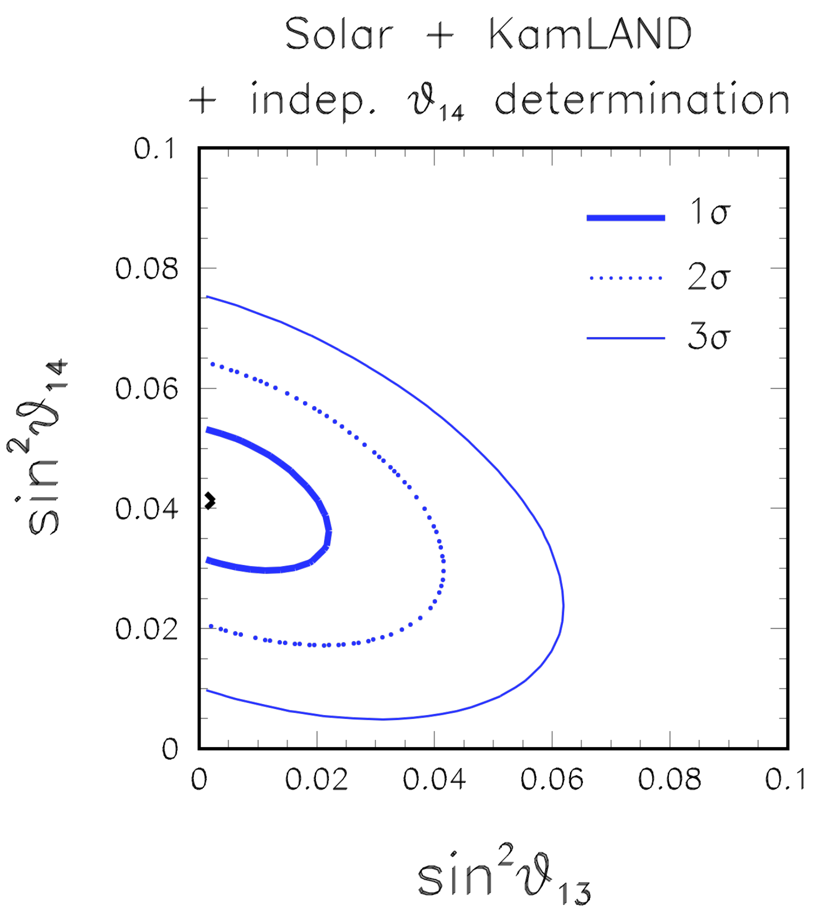
Complete degeneracy
θ_{13}-θ_{14} indistinguishable

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

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

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

Impact of the indication for $U_{e4}>0$ from reactor+Ga anomalies



Work in preparation

The S+K hint is in agreement with reactor+Ga indication: it makes sense a combination

The SBL+Ga anomaly lifts the degeneracy in favor of θ_{14} at the "expense" of θ_{13}

Global indication for
$\theta_{14}>0$ at ~ 3.4σ
Assuming $\theta_{13} = 0$
$\theta_{14}>0$ at almost 4σ

Conclusions

- The solar sector (solar + KamLAND) data fit within the standard 3ν framework and show a weak indication for non-zero θ_{13}.

- The statistical significance of the indication is sensitive to the reactor fluxes and is enhanced with the new calculations.

- The reactor anomaly and Gallium calibration problem suggest the existence of a 4th ν, which must be incorporated in a 3+1 scheme.

- The solar sector is sensitive to the perturbations induced by the 4th ν basically through kinematical effects. New genuine 4ν dynamical (matter) effects are present in principle but negligible in practice.

- The solar hint of U_{e3}>0 can be exchanged by one of U_{e4}>0. The reactor and Ga anomalies favor θ_{14} over θ_{13}. Important info on U_{e3} should come from D-CHOOZ-like exp. by rate and spectrum (difficult) and from T2K. Smoking gun for θ_{14} is the oscillation pattern at future VSBL.

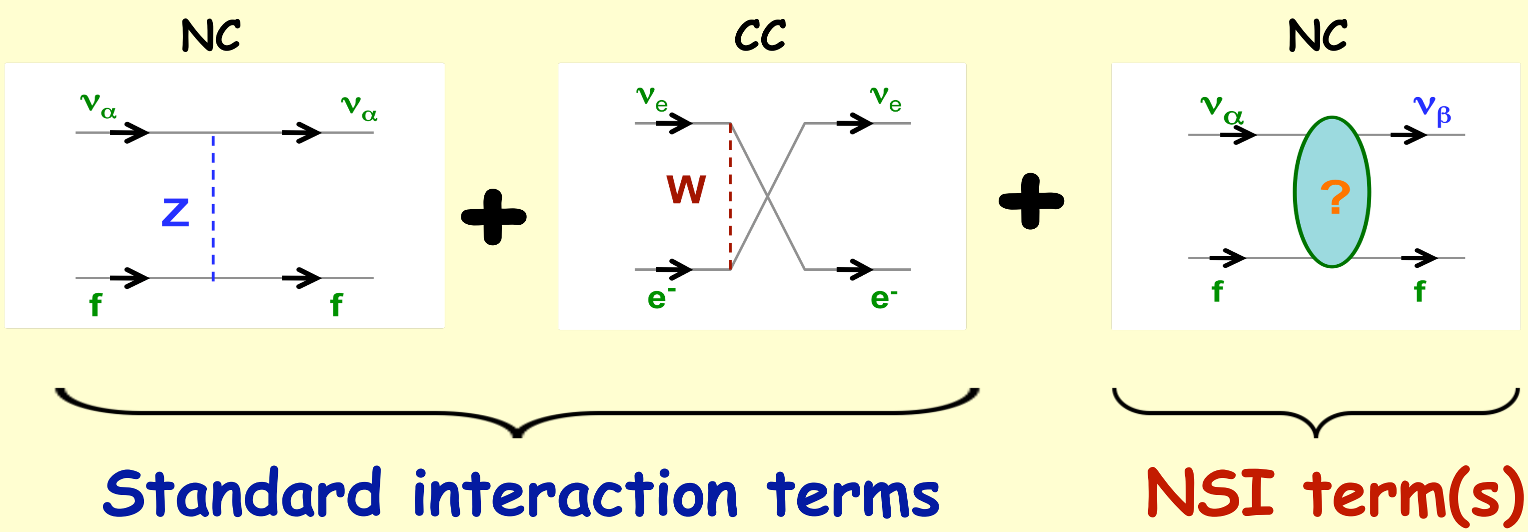
- In the mean while important to study the consequences of the 3+1 scheme in the remaining phenomenology (Atm, LSND, MINOS, etc).

BACK UP

Non-standard interactions: an other potential source of confusion?

Breaking the NSI-θ_{13} degeneracy with the solar neutrino spectrum

Coherent forward scattering in the presence of NSI : a pictorial view



NSI described by an effective four-fermions operator

$$O^{\rm NSI}_{\alpha\beta} \sim \overline{\nu}_\alpha \nu_\beta \overline{f} f$$

$(\alpha, \beta) = e, \mu, \tau$

$f \equiv (e, u, d)$

Coherent forward scattering in the presence of NSI : math. view

Evolution in the flavor basis:

$$i\,\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

H contains three terms:

$$H = H_{\rm kin} + H_{\rm dyn}^{\rm std} + H_{\rm dyn}^{\rm NSI}$$

Kinematics

$$H_{\rm kin} = U\begin{pmatrix}-\delta k/2 & 0 & 0\\ 0 & +\delta k/2 & 0\\ 0 & 0 & k/2\end{pmatrix}U^\dagger$$

$$\delta k = \delta m^2/2E$$

$$k = m^2/2E$$

Standard MSW dynamics

$$H_{\rm dyn}^{\rm std} = {\rm diag}(V,\,0,\,0)$$

$$V(x) = \sqrt{2}G_F N_e(x)$$

Non-standard dynamics

$$(H_{\rm dyn}^{\rm NSI})_{\alpha\beta} = \sqrt{2}\,G_F\,N_f(x)\epsilon_{\alpha\beta}$$

Reduction to an effective two flavor dynamics

One mass scale approximation: $\Delta m^2 \to \infty$

$$P_{ee} = c_{13}^4 P_{ee}^{\rm eff} + s_{13}^4$$ **survival probability**

$$i\,\frac{d}{dx}\left(\begin{array}{c} \nu_e \\ \nu_a \end{array}\right) = H^{\rm eff}\left(\begin{array}{c} \nu_e \\ \nu_a \end{array}\right)$$ **effective evolution**

$$H^{\rm eff} = V(x)\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2}G_f N_d(x)\begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$$ **d-quark**

For $\theta_{13} = 0$:

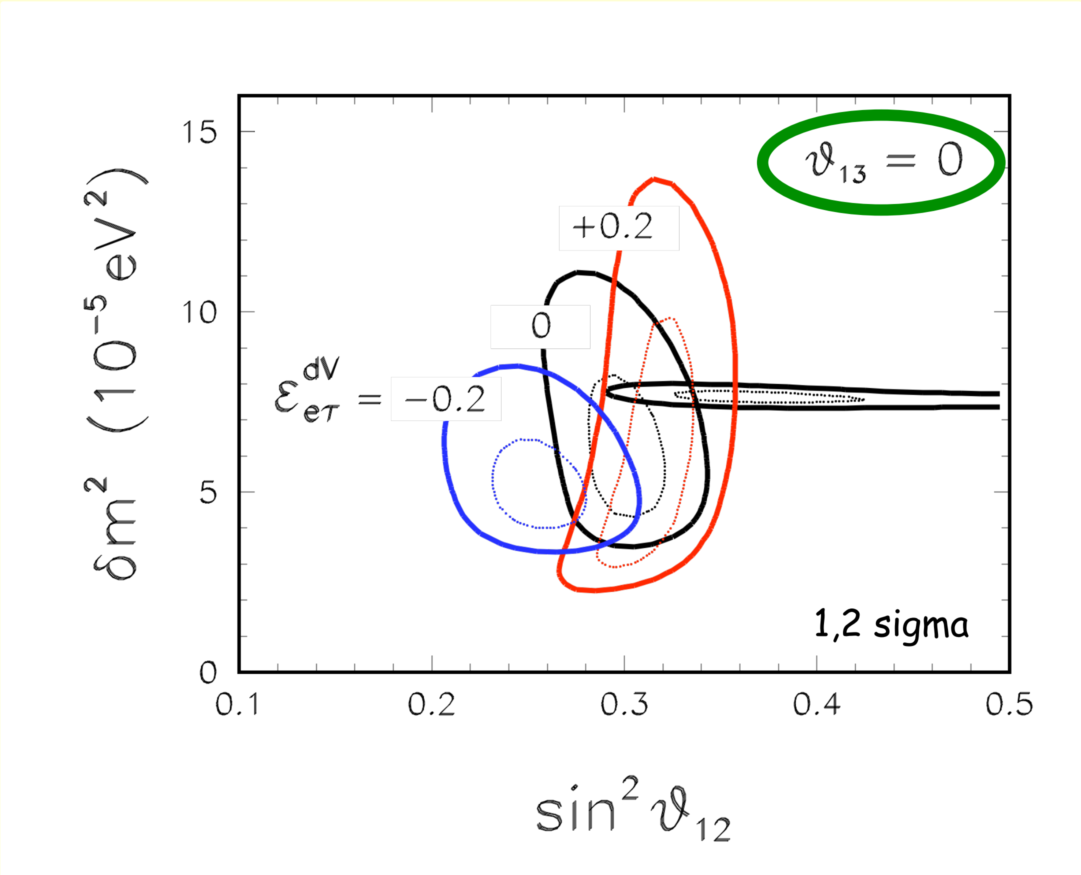
$$\varepsilon = -\varepsilon_{e\mu}c_{23} - \varepsilon_{e\tau}s_{23}$$

$$\varepsilon' = -2\varepsilon_{\mu\tau}s_{23}c_{23}$$

$\varepsilon_{\mu\tau}$ ~ 0 (strong bounds from atmospheric ν)

Parameter space: $[\delta m^2, \theta_{12}, \varepsilon]$

Impact of NSI for θ_{13} = 0



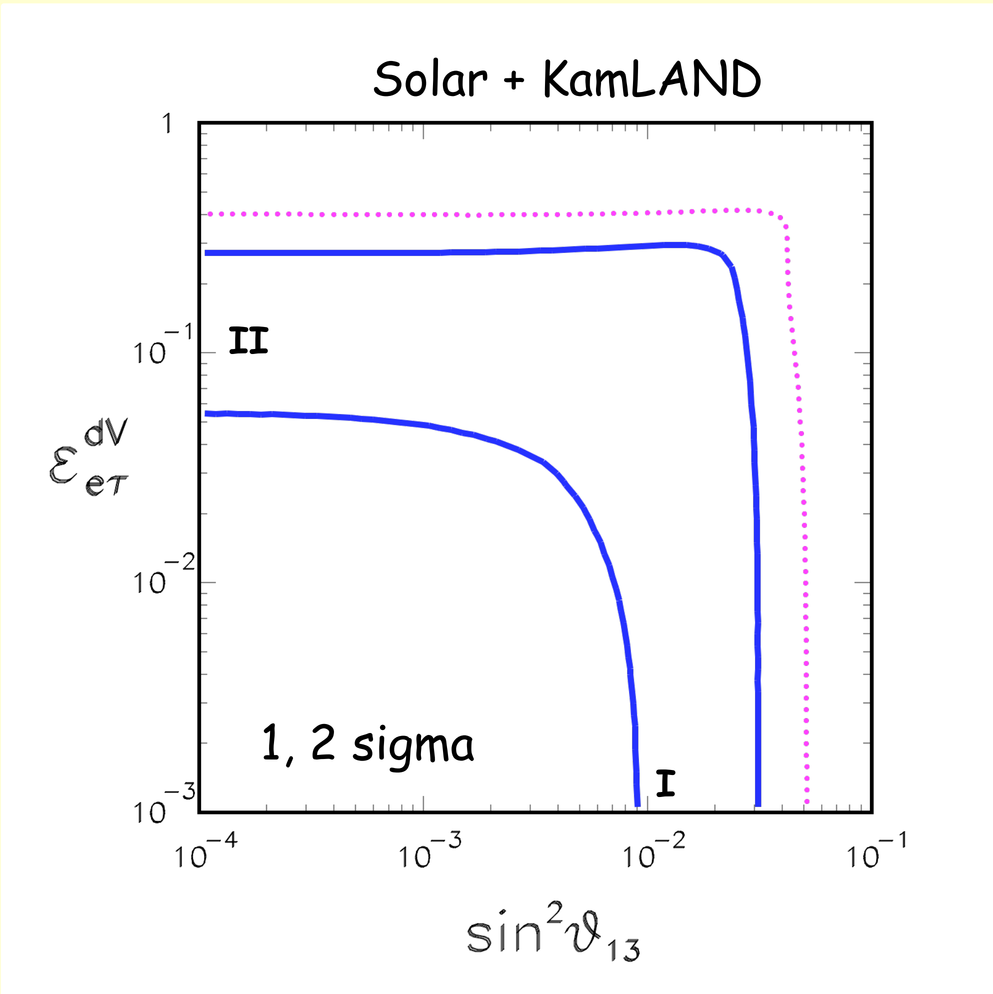
Positive values of $\varepsilon_{e\tau}$ (negative effective ε) shift the LMA towards bigger values of θ_{12}

Tension with KamLAND is alleviated, similarly to non-zero θ_{13}

We expect a degeneracy

A.P. and J.W.F. Valle, PRD 80, 091301 (R) (2009)
arXiv:0909.1535 [hep-ph]

If both NSI and θ_{13} are allowed (2009)



The goodness of the global fit (Sol+Kam) is ~ identical for the two limit cases:

I) $[\theta_{13} > 0 \quad \varepsilon_{e\tau} = 0]$ (3ν)

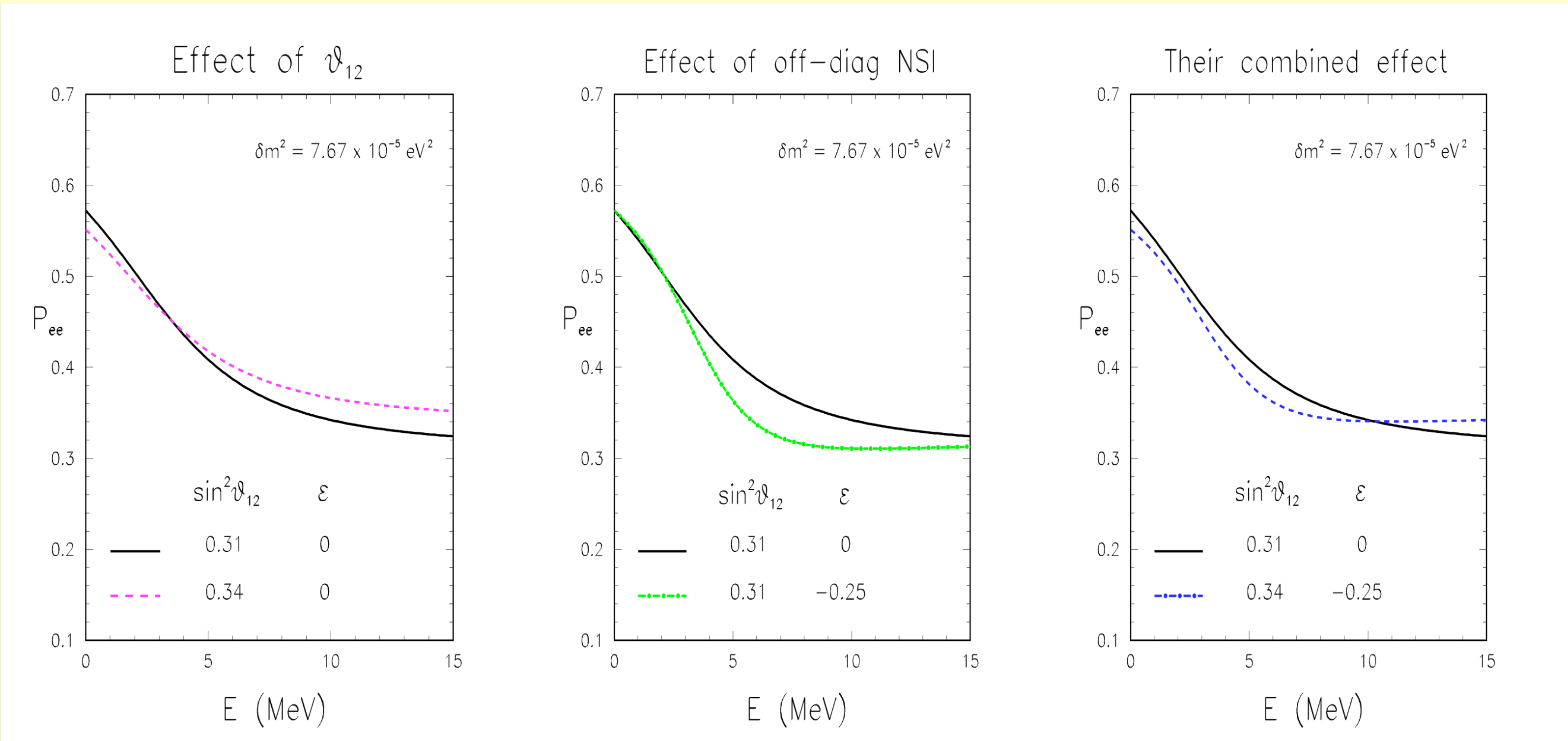
II) $[\theta_{13} = 0 \quad \varepsilon_{e\tau} > 0]$ $(2\nu$ + NSI)

Full degeneracy between θ_{13} and the NSI coupling

Tension between Sol & Kam is shared among θ_{13} and ε

A.P. and J.W.F. Valle, PRD 80, 091301 (R) (2009), arXiv:0909.1535 [hep-ph]

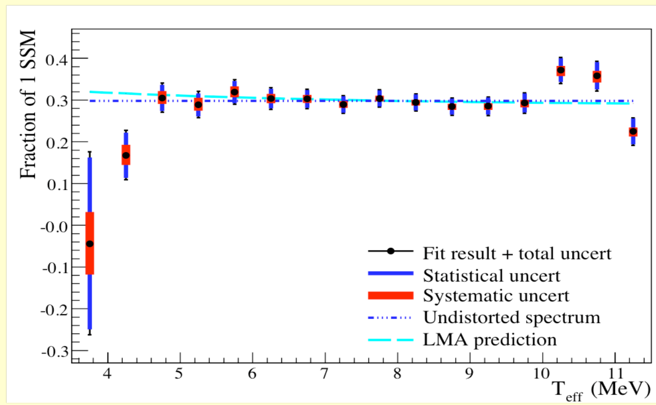
Origin of the θ_{12}-ε degeneracy



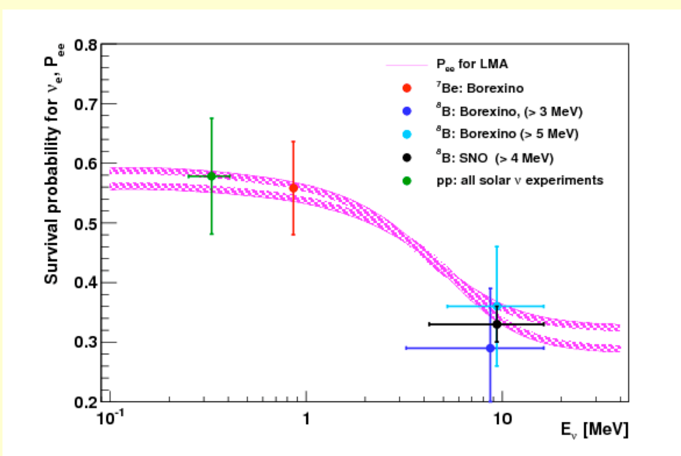
At high energies (~10 MeV) where solar data are more sensitive effect of θ_{12} is balanced by NSI. But with NSI spectrum flatter…

…in better agreement with new spectral measurements. No sign of the upturn of the spectrum !

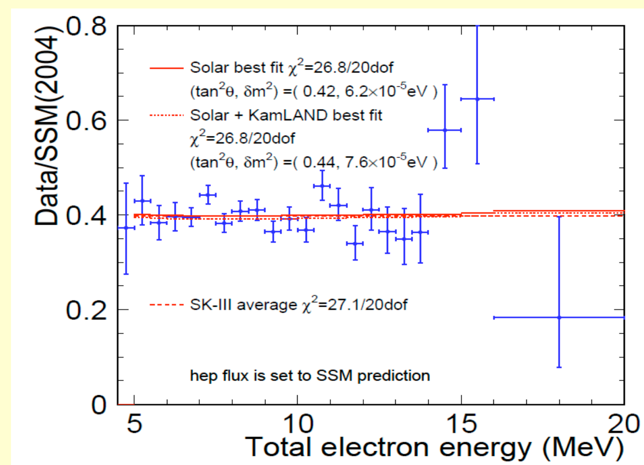
SNO LETA



BOREXINO



SK-III



Testing the spectral distortions

The response functions of SK, SNO, Borexino are centered around E_0 = 10 MeV, where they have maximal sensitivity

Assuming a regular behavior for the survival probability we can parameterize its high energy behavior as a second order polynomial

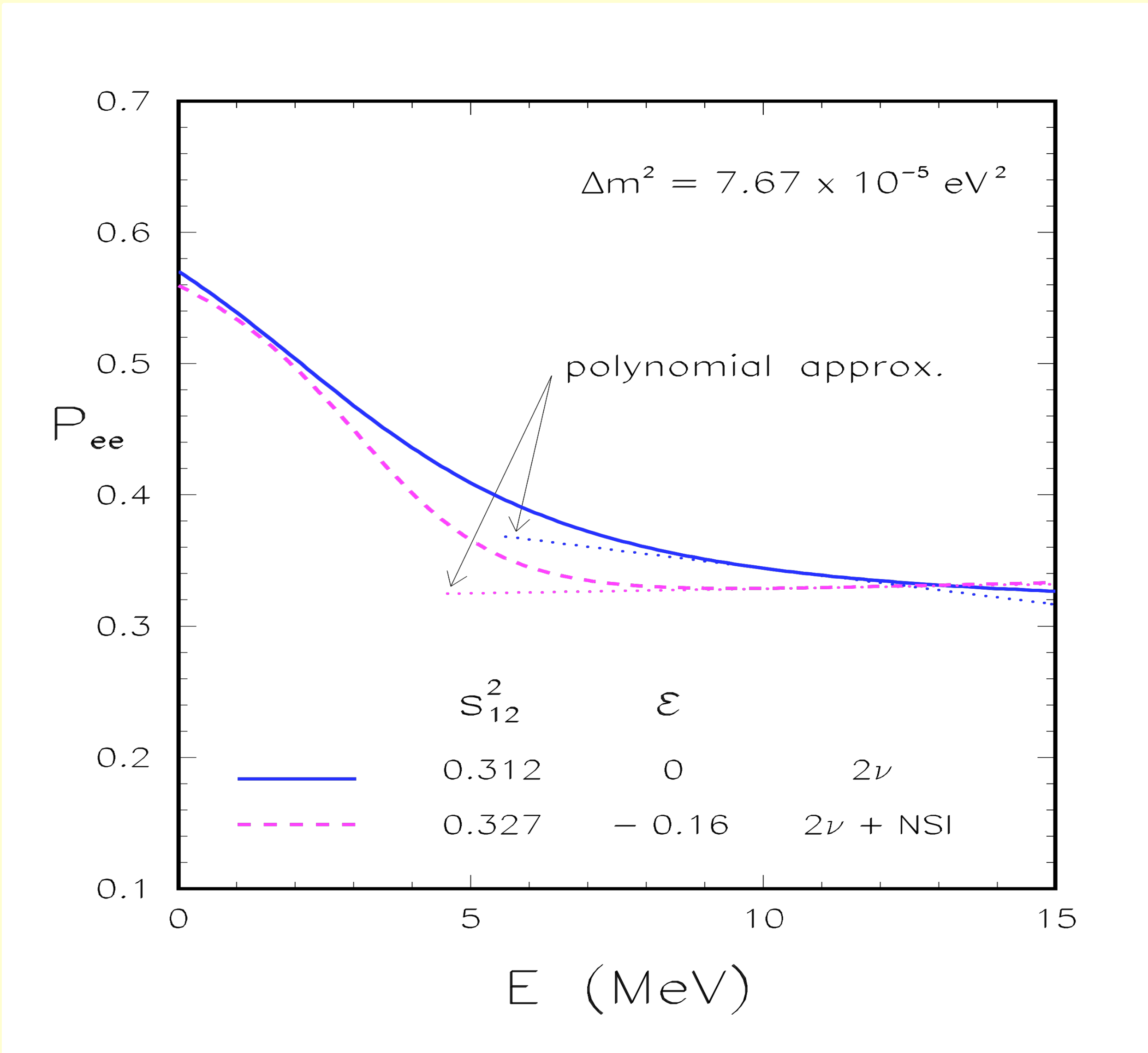
$$P_{ee} = c_0 + c_1 (E-E_0) + c_2 (E-E_0)^2$$

It is then possible to:

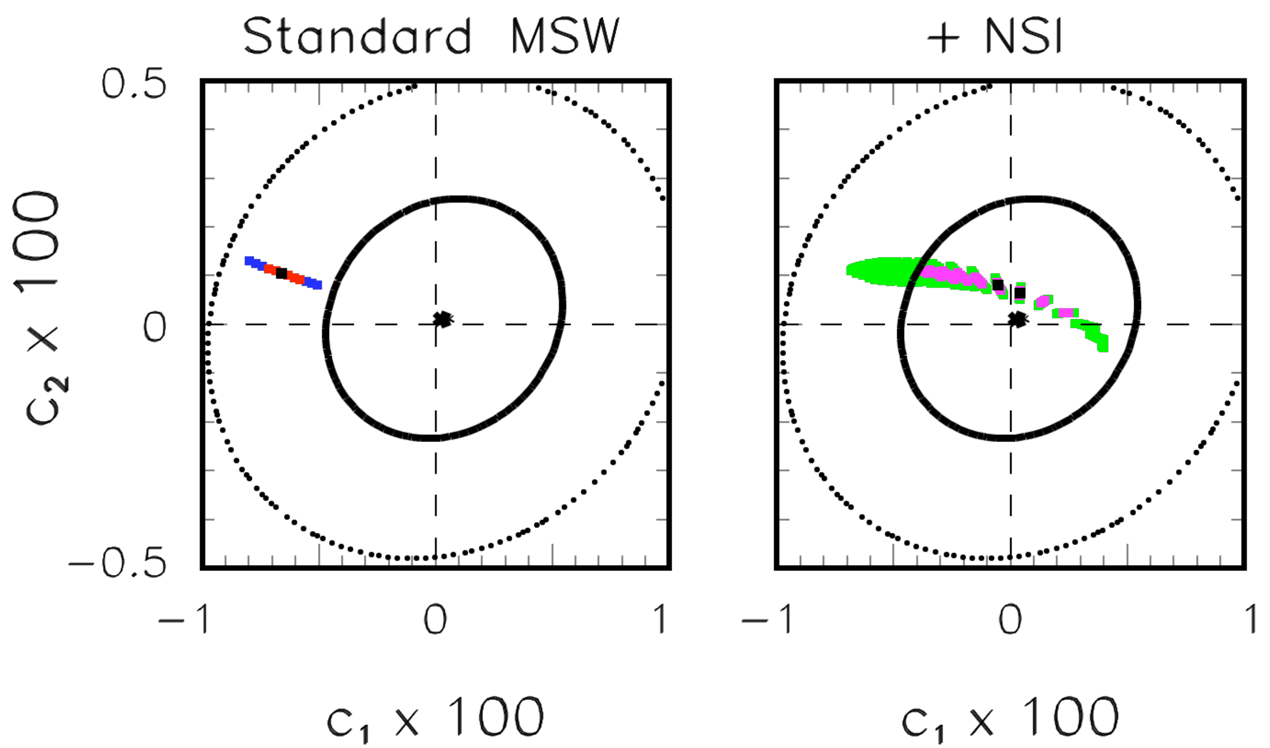
1) Extract the coefficients from the combination of all the experiments sensitive to the high-energy neutrinos.

2) Check where a given theor. model (standard MSW,+NSI, etc.) "lives" in the space of the coefficients c_i's.

Polynomial expansion is accurate for both standard and NSI case



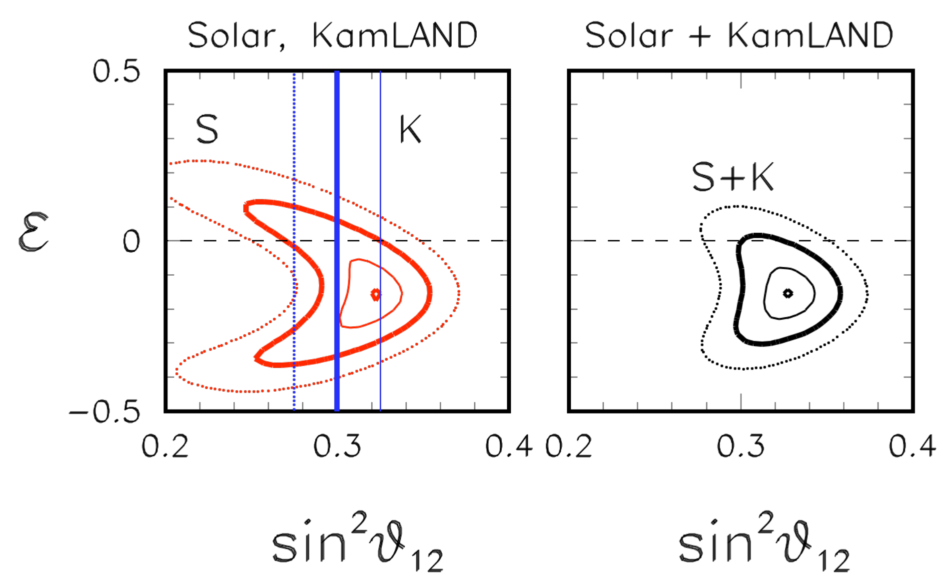
Exp. constraints on (c1,c2) and their relation with the theoretical models



A.P. arXiv: 1101.3875 [hep-ph]

NSI gains a $\Delta\chi^2 \sim 2.0$ from better description of the spectrum

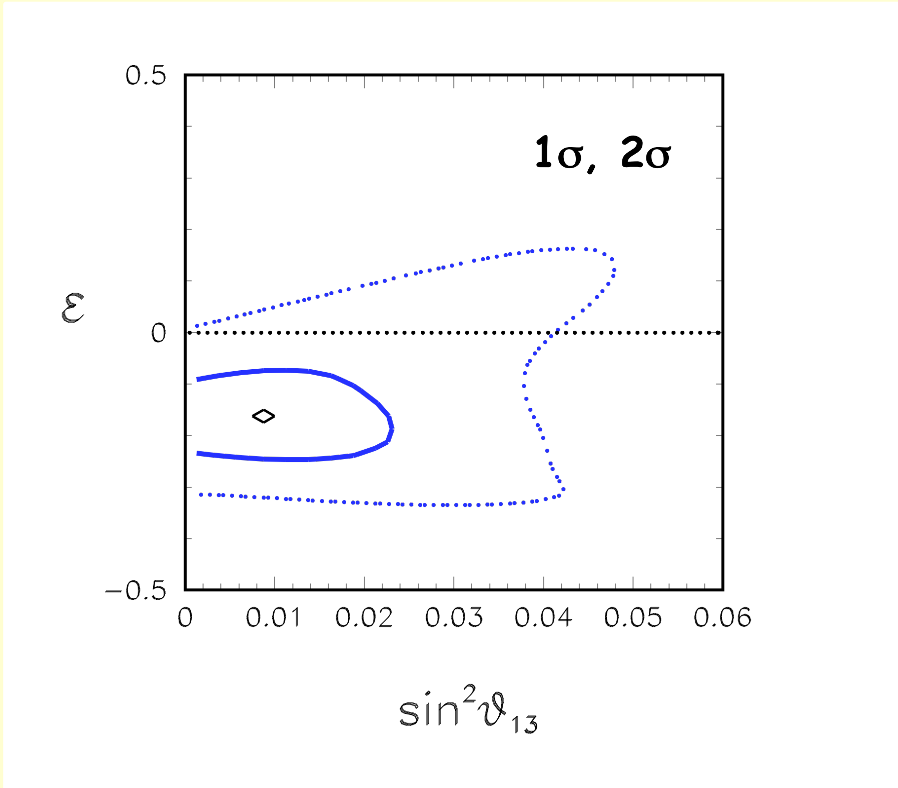
Numerical analysis (2011) favors NSI at $\Delta\chi^2 \sim 3.6$ (1.9σ)



A.P. arXiv: 1101.3875 [hep-ph]

NSI gains an additional $\Delta\chi^2 \sim 1.6$ from the better agreement among the values of θ_{12} determined by solar and KamLAND

3-flavor analysis including spectral info (2011)



- **The spectral information breaks the degeneracy in favor of NSI**

- The hint for NSI is robust (1.5σ) with respect to 3-flavor effects