Bari Theory Xmas Workshop 20/12/2012

Hint of non-standard dynamics in solar neutrino flavor conversion

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Outline

Introduction

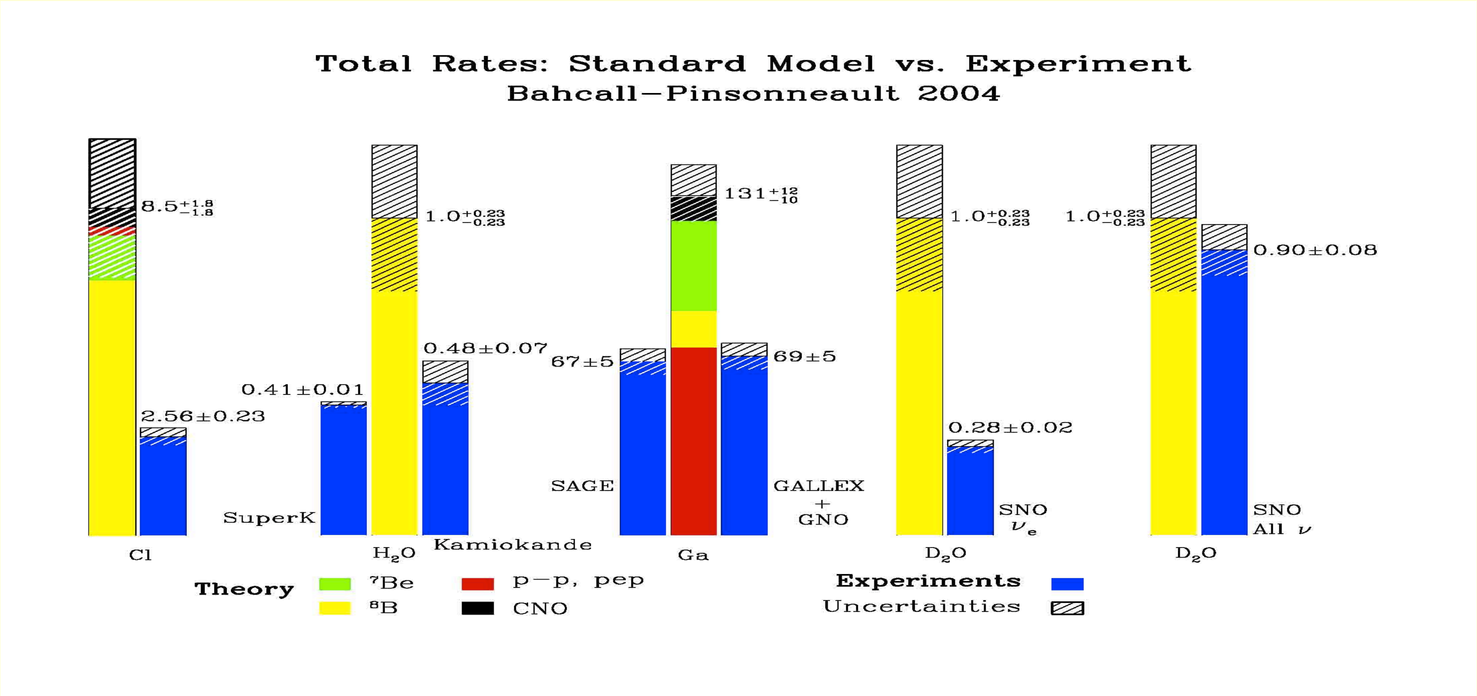
The missing upturn in the solar ν energy spectrum

Hint of non-standard neutrino interactions (NSI)?

Results of a quantitative analysis

Conclusions

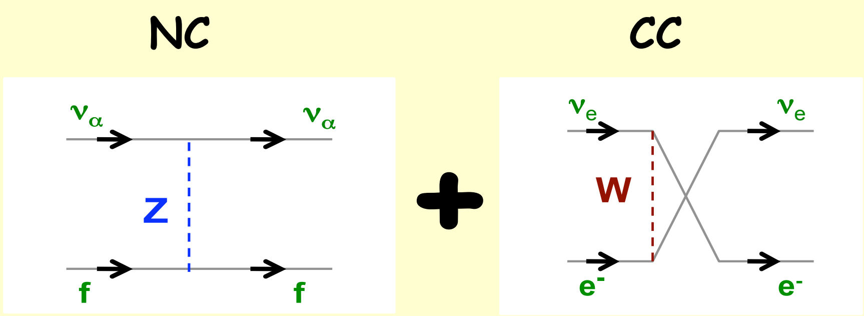
The solar neutrino problem



We need a mechanism providing:

I) Pee < 1 (flavor conversion)
II) Pee (E) (peculiar energy dependence)

MSW effect provides both features



all ν flavors have the same NC interactions

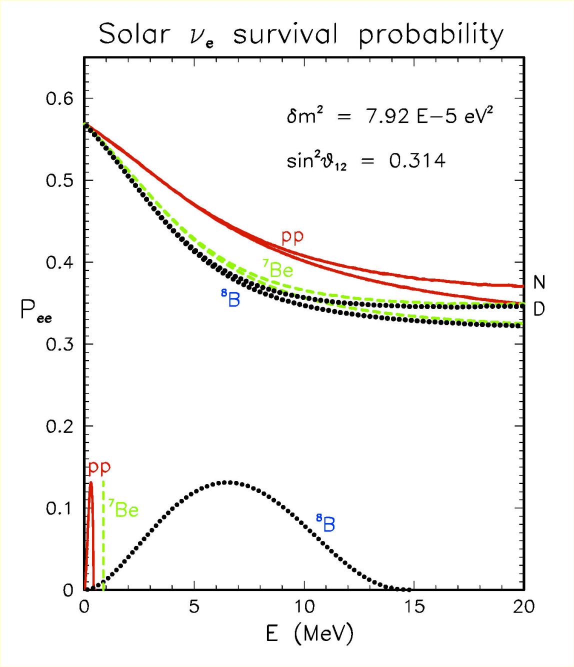
ν_e in addition has CC interactions with electrons

Energy difference described by the potential:

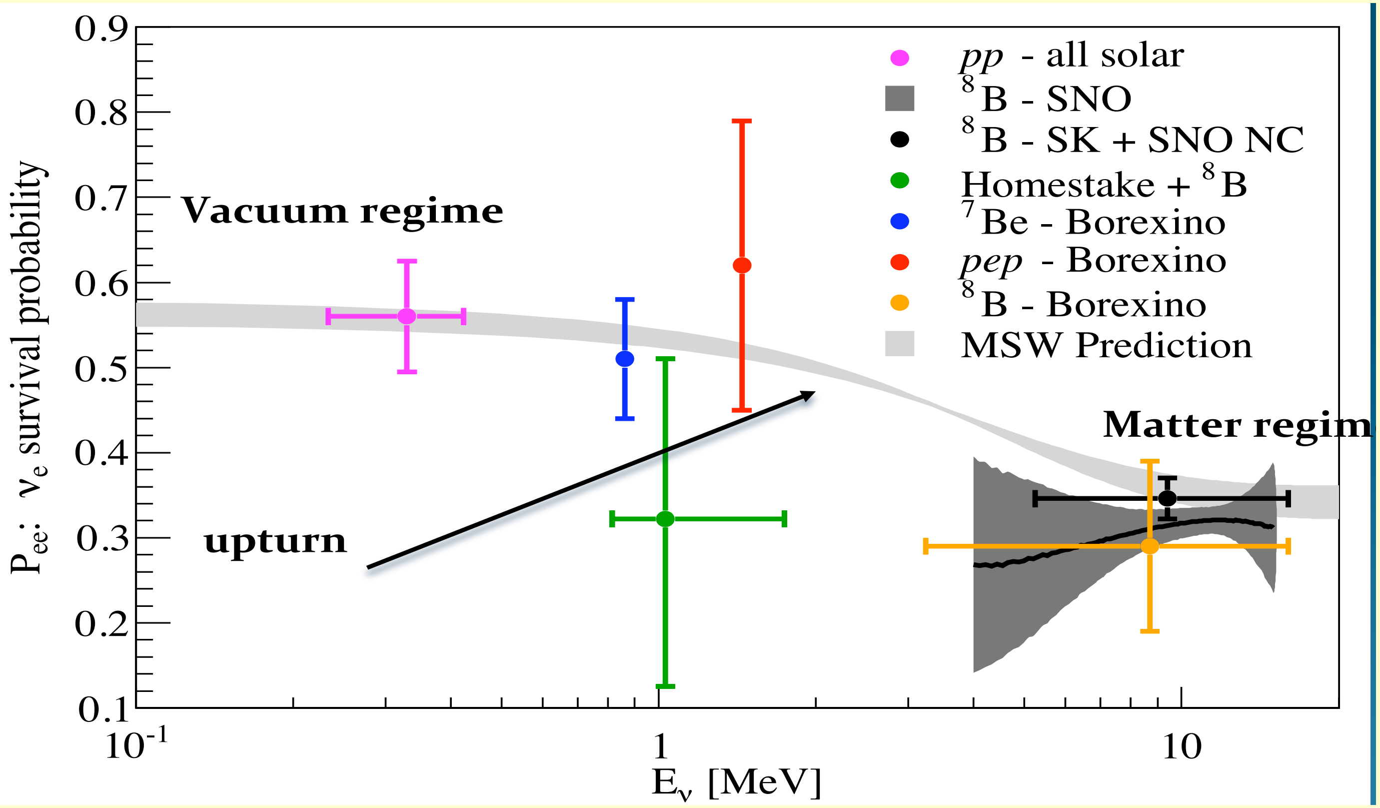
$$V = \sqrt{2}\, G_F\, Ne(x)$$

$$H_{flav} = U\frac{M^2}{2E}U^\dagger + \begin{pmatrix} V & 0 \\ 0 & 0 \end{pmatrix}$$

Electron number density

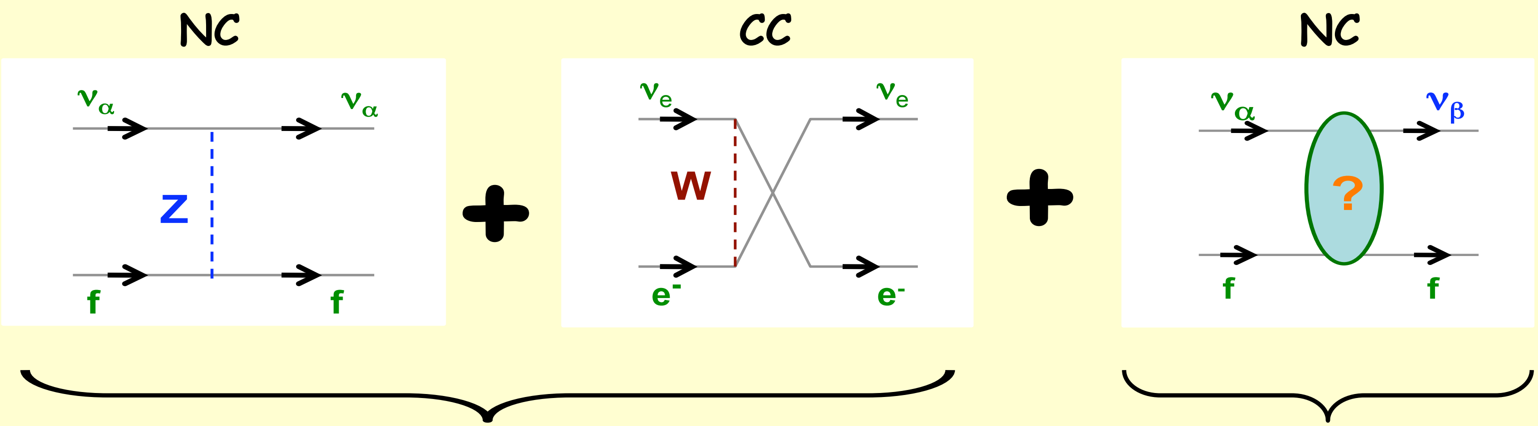


But where is the MSW upturn?



Do this anomalous behavior point towards new physics?

One interesting possibility:
Non-standard neutrino interactions (NSI)



Standard interaction terms

NSI term(s)

NSI described by an effective four-fermion operator

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

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

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

3-flavor evolution in the presence of NSI

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

$$H_{\rm kin} = UKU^\dagger \;\begin{cases} K = \dfrac{1}{2E}{\rm diag}(0, \delta m^2, \Delta m^2) \\ U = R_{23}\tilde{R}_{13}R_{12} \end{cases}$$

Standard dynamics

$$H_{\rm dyn}^{\rm std} = {\rm diag}(V,\, 0,\, 0) \qquad V(x) = \sqrt{2} G_F N_e(x)$$

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 problem

One-mass-scale dominance ($\Delta m^2 \to \infty$) approx. allows to simplify the problem

$$\frac{\delta m^2}{\Delta m^2} \simeq 3 \times 10^{-2}$$

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

$$s_{13}^2 \simeq 0.024$$

$$H_{kin}^{\rm STD} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \delta m^2 \end{pmatrix} \begin{pmatrix} c_\theta & -s_\theta \\ s_\theta & c_\theta \end{pmatrix}$$

only solar splitting and one mixing angle $\theta = \theta_{12}$

$$H_{\rm dyn}^{\rm STD} = \sqrt{2} G_F N_e(x) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix}$$

θ_{13} induces small effect

$$H_{\rm dyn}^{\rm NSI} = \sqrt{2} G_F N_f(x) \begin{pmatrix} \epsilon' & \epsilon \\ \epsilon & 0 \end{pmatrix}$$

ε and ε' are effective parameters related to the fundamental couplings

$$\begin{cases} \epsilon' \simeq \varepsilon_{ee} - 0.5(\varepsilon_{\mu\mu} + \varepsilon_{\tau\tau}) + \varepsilon_{\mu\tau} \\ \epsilon \simeq 0.7(\varepsilon_{e\mu} - \varepsilon_{e\tau}) \end{cases}$$

We will focus on the off-diag perturbations ε

Solution of the two flavor problem

In the region of interest the propagation is adiabatic: conversion depends only on production and detection points

Survival probability

$$P_{ee} = \frac{1}{2} + \frac{1}{2} \cos 2\theta \cos 2\theta_m$$

~ vacuum **~ sun center**

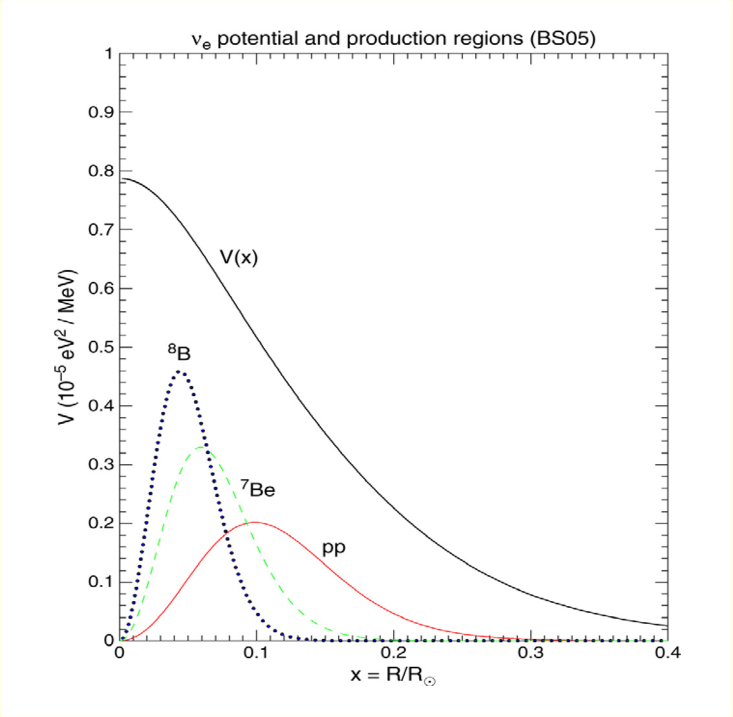
Mixing angle in matter

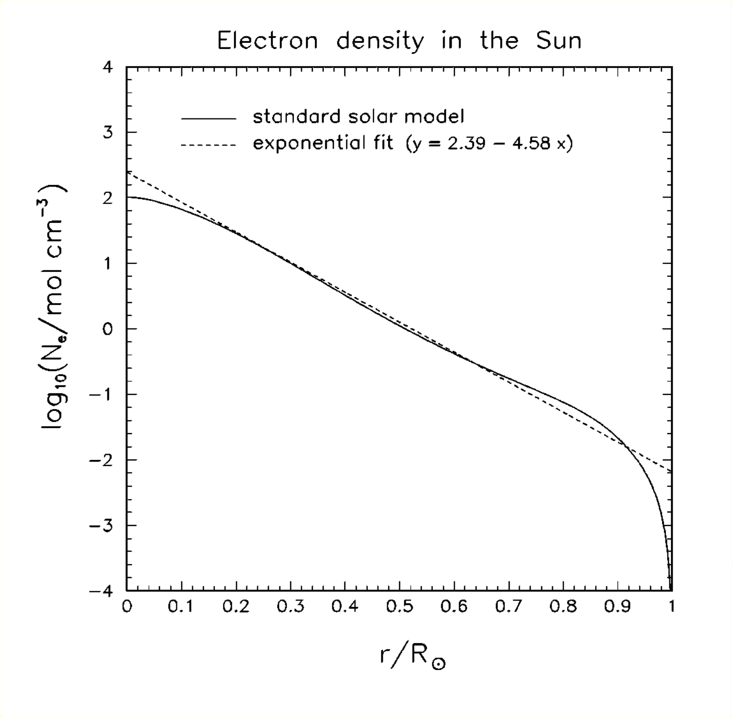
$$\cos 2\theta_m = \frac{\cos 2\theta - v}{\sqrt{(\cos 2\theta - v)^2 + (\sin 2\theta + 2\epsilon v)^2}}$$

$$v = v(x) = \frac{2V(x)E}{\delta m^2} \simeq 1.53 \times 10^{-7} \left(\frac{\delta m^2}{E} \frac{\text{MeV}}{\text{eV}^2} \right)^{-1} \left(\frac{N_e(x)}{\text{mol/cm}^3} \right)$$

$$E \sim few \text{ MeV} \qquad \delta m^2 \simeq 7.6 \times 10^{-5} \text{eV}^2 \qquad \cos 2\theta \simeq 0.4$$

Solar ν production zones and $N_e(x)$



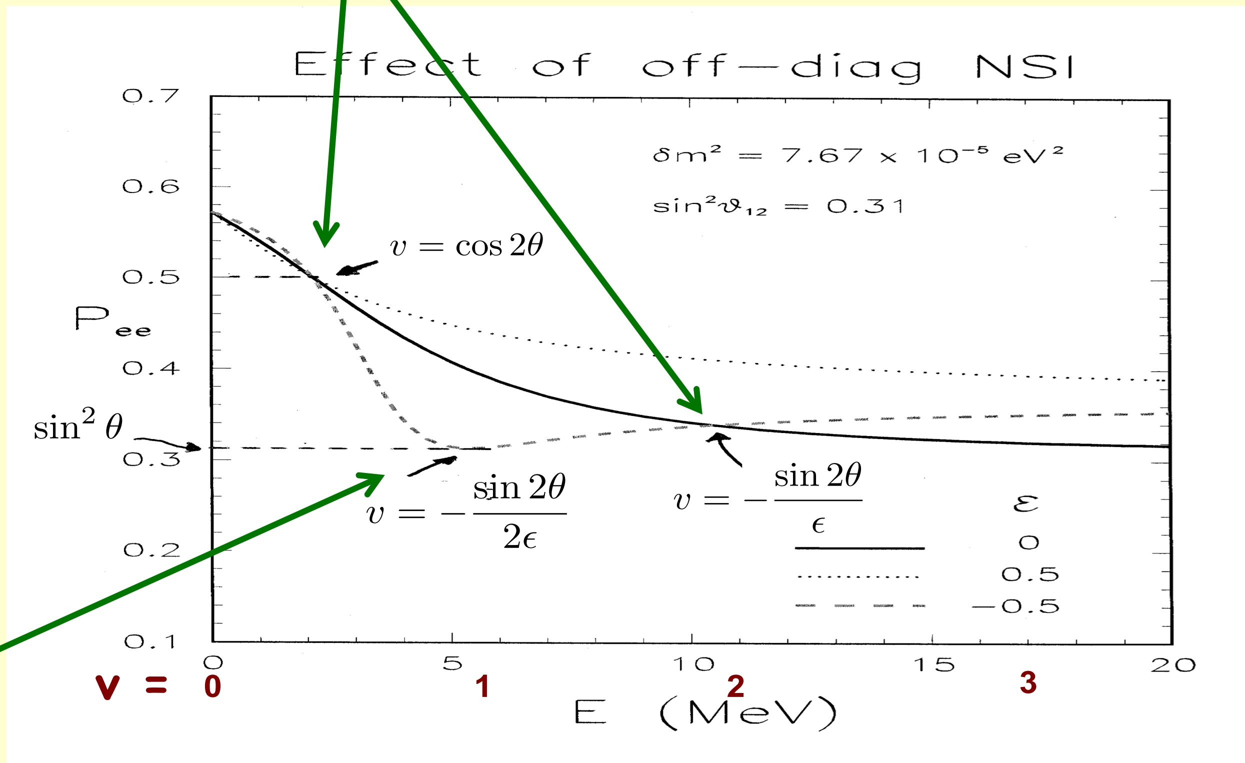


^{8}B νs $\begin{cases} x = R/R_{sun} \sim 0.04 \\ N_e \sim 10^2\ \mathrm{mol/cm^3} \end{cases}$

$$v(x = 0.04) \simeq 0.18 \frac{E}{\mathrm{MeV}}$$

Behavior of P_{ee} in the presence of NSI

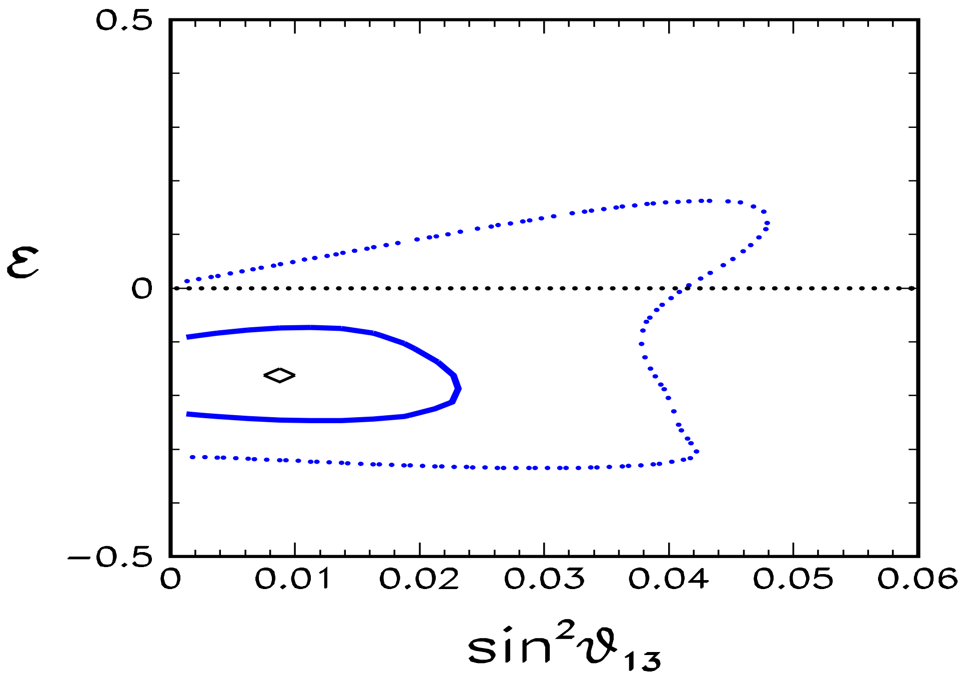
In these two points P_{ee} is identical to the standard case



minimum

Negative values of ε induce sizable modifications mostly in the intermediate energy region

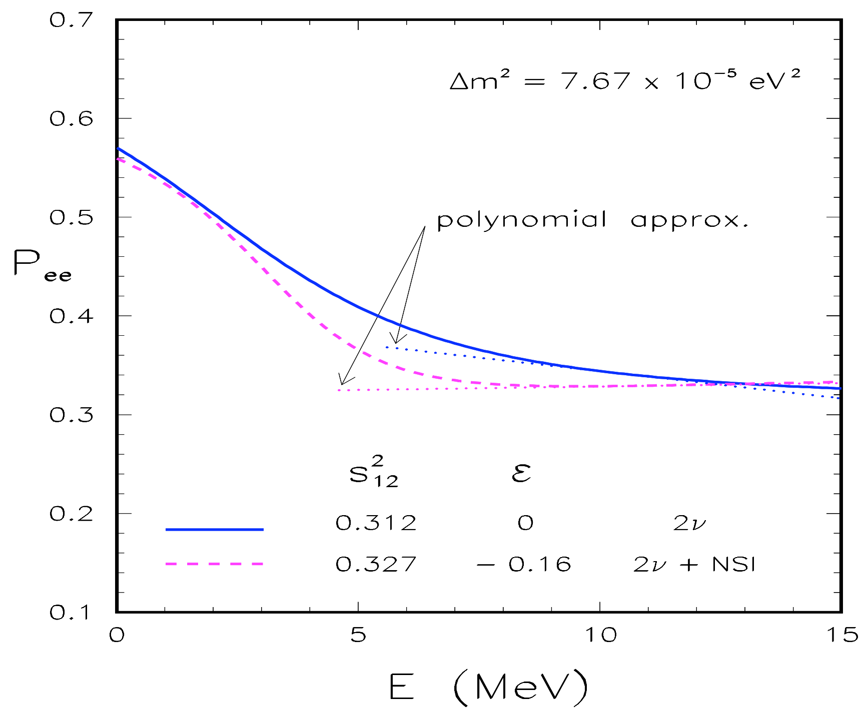
3-flavor numerical analysis with NSI



A.P, PRD 83, 101701 (2011) (Rapid Communications)

A weak preference for non-zero NSI emerges

Is this preference related to the spectrum?



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Best fit

$$\epsilon = -0.16$$

$$(\epsilon_{e\tau} = +0.23)$$

for interaction with d-quark

Best fit solution with NSI has a reduced upturn as needed

Quantitative assessment

Solar ^{8}B expts. have max. sensitivity around E_0 = 10 MeV

We can parameterize Pee(E) as a second order polynomial

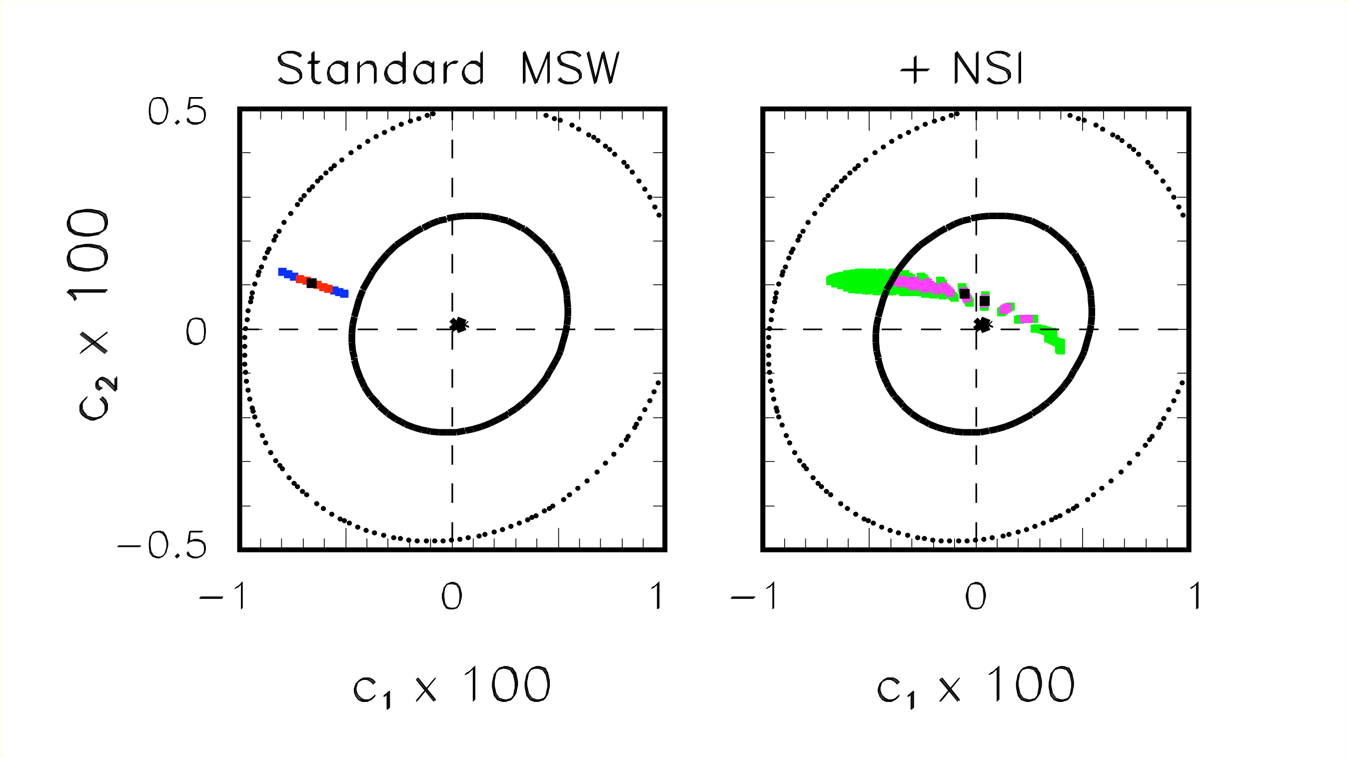
$$P_{ee} = c_0 + c_1 (E-E_0) + c_2 (E-E_0)^2$$

It is then possible to:

1) Extract the coefficients from the combination of all the experiments sensitive to the ^{8}B neutrinos.

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

Constraints on [c1,c2]



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

Conclusions

- The solar neutrino energy spectrum presents an anomaly: the upturn predicted by standard MSW is not observed

- Non-standard neutrino interactions (NSI) can alter the Pee behavior in the intermediate energy region and thus are good candidates to solve the anomaly

- A quantitative analysis shows that NSI with strength $0.2\,G_F$ are preferred as they flatten the spectrum

- New low-energy data are needed to settle the issue