Standard and non-standard analysis of solar and reactor neutrino data

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Abstract.
We present an updated analysis of solar and reactor neutrino data in the standard framework of neutrino oscillations. We also consider the presence of non-standard neutrino interactions with matter and perform an alternative analysis of neutrino data studying the non-standard effects both on the neutrino detection and propagation through matter.

1. Introduction

Current solar neutrino data in conjunction with reactor data from the KamLAND experiment show that the neutrino oscillation mechanism is the correct picture to explain the solar neutrino physics. The combination between solar and KamLAND determines a unique solution in the mass-mixing parameter space, the so-called Large Mixing Angle solution [1]. However, while constrained by the solar and KamLAND data in an important way, neutrino non-standard interactions (NSI) still provide an important exception to the robustness of the neutrino oscillation interpretation. Indeed, with oscillations still being the underlying mechanism, an additional degenerate oscillation solution in neutrino oscillation parameters can appear for sufficiently intense non-standard interactions [2].

2. Standard oscillation analysis of solar and reactor neutrino data

Here we present the most important results of our global three–neutrino oscillation analysis [1] in the solar sector. The determination of the leading solar oscillation parameters θ_{12} and Δm^2_{21} emerges from the complementarity of solar and reactor neutrinos, as illustrated at Fig. 1. From our analysis of solar and KamLAND data we find the following best fit points and 1σ errors:

$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}\,, \qquad \Delta m^2_{21} = 7.65^{+0.23}_{-0.20}\times 10^{-5}\,\mathrm{eV}^2\,. \tag{1}$$

Spectral information from KamLAND data leads to an accurate determination of Δm^2_{21} with a precision of 8% at 3σ. KamLAND data start also to contribute to the lower bound on $\sin^2\theta_{12}$, whereas the upper bound is dominated by solar data, most importantly by the CC/NC solar neutrino rate measured by SNO.

The determination of θ_{13}, the mixing angle characterizing the magnitude of CP violation in neutrino oscillations, is one of the main challenges for the future neutrino research. The bound on θ_{13} emerges from the interplay of different data sets, the most important contribution

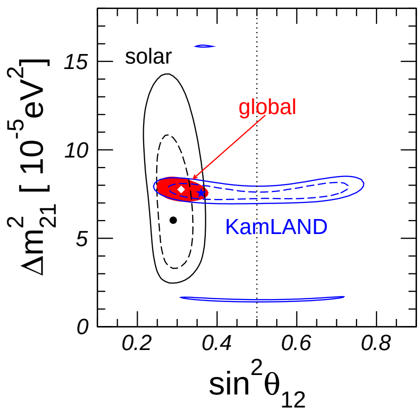

Figure 1. Determination of the leading solar oscillation parameters at 90% CL and 3σ for solar and KamLAND, as well as the 3σ region for the combined analysis.

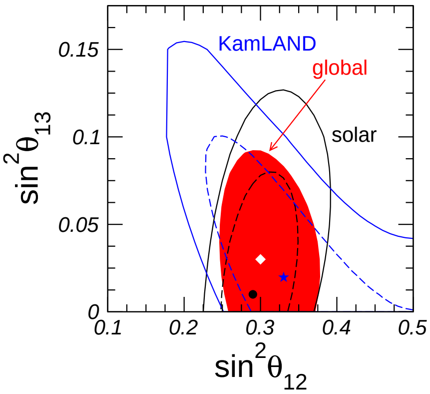

Figure 2. Allowed regions in the $(\theta_{12}-\theta_{13})$ plane at 90% CL and 3σ for solar and KamLAND, together with the 3σ region for the combined analysis.

coming from the CHOOZ reactor experiment combined with the determination of $|\Delta m^2_{31}|$ from atmospheric and long-baseline experiments. Due to the different correlation sign between $\sin^2\theta_{13}$ and $\sin^2\theta_{12}$ for low and high energy solar neutrino data, as well as for solar and KamLAND data, one finds that also solar+KamLAND provide a non-trivial constraint on θ_{13}. The interplay of solar and KamLAND data in constraining θ_{13} is illustrated at Fig. 2. It is also shown the preference of the experimental data for a non-zero value of θ_{13} ($\sin^2\theta_{13} = 0.03$) with an statistical significance of 1.5σ. We obtain at 90% CL (3σ) the following limits:

$$\sin^2\theta_{13} \leq \begin{cases} 0.060\ (0.089) & \text{(solar+KamLAND)} \\ 0.035\ (0.056) & \text{(global data)} \end{cases} \tag{2}$$

3. Non-standard interactions at solar and reactor neutrino data

Most neutrino mass extensions of the standard electroweak model entail non-standard interactions which, in the low energy limit, can be parametrized through the effective four fermion Lagrangian,

$$-\mathcal{L}^{eff}_{\rm NSI} = \varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)\,, \tag{3}$$

where G_F is the Fermi constant and $\varepsilon^{fP}_{\alpha\beta}$ parametrize the strength of the NSI. The chiral projectors P denote $\{R, L = (1 \pm \gamma^5)/2\}$, while α and β denote the three neutrino flavors, and f is a first generation fermion (e, u or d). Here we will focus on the analysis of non-universal (NU) flavor-conserving interactions with electrons [3]. For a recent study on the phenomenology of NSI with quarks see Ref. [2], where an additional degenerate oscillation solution with $\sin^2\theta_{12} > 0.5$ appears for sufficiently intense NSI.

We have analysed the impact of neutrino-electron NSI on the phenomenology of solar neutrinos, taking into account their effect both at the level of propagation where they modify the standard MSW behavior, and at the level of detection. Non-standard couplings of neutrinos with electrons affect the elastic scattering ($\nu_a e \to \nu_a e$) process modifying the number of events and their spectral distribution expected in the solar neutrino detectors. The standard differential cross section for the scattering processes is given by:

$$\frac{d\sigma_a}{dT}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left[(g^a_L)^2 + (g^a_R)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - g^a_L g^a_R \frac{m_e T_e}{E^2_\nu}\right], \tag{4}$$

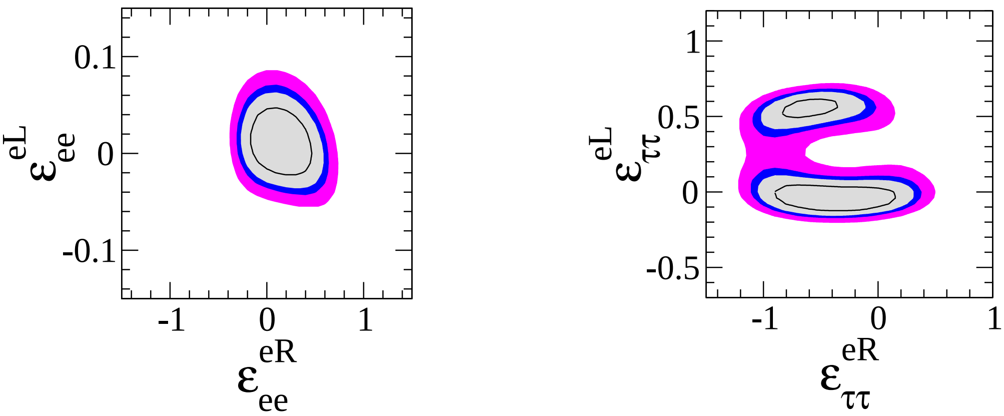

Figure 3. Constraints on the electron and tau neutrino NSI couplings at 68%, 90% 95% and 99% for 2 d.o.f.. The mass-mixing parameters have been marginalized away.

where m_e is the electron mass, E_ν is the incident neutrino energy, T_e is the electron recoil energy. In the presence of NU NSI, the standard left and right SM couplings g_L and g_R get an extra contribution, being replaced at Eq. (4) by the effective non-standard couplings $\tilde{g}_L^a = g_L^a + \varepsilon_{aa}^{eL}$ and $\tilde{g}_R^a = g_R^a + \varepsilon_{aa}^{eR}$. Given the strong limits on ν_μ NSI, in our analysis we focus on possible non-standard couplings of ν_e and ν_τ.

Let's consider now the non-standard effects on the neutrino propagation. The Hamiltonian describing solar neutrino evolution in the presence of NSI contains, in addition to the standard oscillations term, a new term accounting for an effective potential induced by the NSI with matter:

$$H_{\rm NSI} = \sqrt{2} G_F N_e \left(\begin{array}{cc} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{array} \right) , \tag{5}$$

where the effective parameters ε and ε', neglecting $\varepsilon_{\alpha\mu}^{fP}$, are given by $\varepsilon = -\sin\theta_{23}\, \varepsilon_{e\tau}^{eV}$ and $\varepsilon' = \sin^2\theta_{23}\, \varepsilon_{\tau\tau}^{eV} - \varepsilon_{ee}^{eV}$. Since we focus on the flavor conserving NU couplings, the flavor-changing off-diagonal coupling ε is set to zero, and in the treatment of solar neutrino propagation we consider only the NU coupling ε'. The vectorial couplings above are related with the left and right couplings through: $\varepsilon_{\alpha\alpha}^{eV} = \varepsilon_{\alpha\alpha}^{eL} + \varepsilon_{\alpha\alpha}^{eR}$.

The main results of our joint analysis of solar and KamLAND data in the $(\Delta m_{21}^2, \sin^2\theta_{12}, \varepsilon_{ee}^{eL}, \varepsilon_{ee}^{eR})$ parameter space are presented at Fig. 3, where the allowed regions for the effective NSI couplings are plotted. The limits on the effective couplings we find (at 90% CL):

$$-0.04 < \varepsilon_{ee}^{eL} < 0.06 \qquad -0.27 < \varepsilon_{ee}^{eR} < 0.59 \tag{6}$$
$$-0.16 < \varepsilon_{\tau\tau}^{eL} < 0.11 \qquad -1.05 < \varepsilon_{\tau\tau}^{eR} < 0.31 \tag{7}$$

are comparable with those found by laboratory experiments. See Ref. [3] for more details.

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