Status of neutrino-quark NSI parameters

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Abstract. Experimental observations, as neutrino oscillations, require neutrinos as massive particles. Most neutrino mass generation mechanisms imply the existence of non-standard neutrino interactions (NSI). In order to grant the relevance that it deserves, here we will see a review of neutrino NSI with quark parameters using the most recent solar, reactor, accelerator and atmospheric data.

1. Introduction

Neutrino oscillations provide the unique evidence of physics beyond the Standard Model (SM) introducing the neutrino mass. Models beyond the SM are required in order to introduce this new characteristic and it may imply new interactions with matter, which can be parameterized as “Non-Standard Interactions” (NSI).

The presence of these new interactions may affect the neutrino oscillations because they could have influence in neutrino propagation and detection processes.

A wide class of non-standard neutrino interactions may be parameterized at low energies by the effective Lagrangian [1, 2, 3, 4]:

\[ L_{NSI} = -\varepsilon_{\alpha\beta}^{fP} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta) (f^* \gamma^\mu f) \]  

where \( G_F \) is the Fermi constant, \( P \) denotes the chiral projectors \( \{ R, L = (1 \pm \gamma^5)/2 \} \) and \( f \) is a first generation fermion: \( e, u, d \). The coefficients \( \varepsilon_{\alpha\beta}^{fP} \) denote the strength of the NSI between the neutrinos of flavors \( \alpha \) and \( \beta \) and the P-handed component of the fermion \( f \). For definiteness, we consider interactions with down and up quarks.

2. Effects of NSI in neutrino oscillations

Non-standard interactions may in principle affect neutrino propagation properties in matter as well as detection cross sections. NSI effects in neutrino propagation affect the analysis of data from solar neutrino and KamLAND experiments, through the vector NSI couplings. On the other hand, detection shows sensitivity also to the axial NSI couplings in the SNO experiment.

In order to reanalyze the robustness of the oscillation interpretation of the solar neutrino data in presence of NSI, we will use the most recent results from Homestake, SAGE, GALLEX/GNO, Super-Kamiokande, SNO, Borexino and combining them with the latest data from KamLAND.

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2.1. Effects in neutrino propagation

The Hamiltonian describing solar neutrino evolution in the presence of NSI contains an extra term involving NSI:

\[
H = \left( \frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2} G_F \epsilon \right) \left( \frac{\Delta m^2}{4E} \sin 2\theta \right) + \sqrt{2} G_F \epsilon' \left( \begin{array}{c} 0 \\ \epsilon \\ \epsilon' \end{array} \right)
\]  

Here \( \epsilon \) and \( \epsilon' \) are two effective parameters related with the vectorial components of NSI [1] which affect the neutrino propagation by:

\[
\epsilon = -\sin \theta_{23} \epsilon_{V}^{\nu} \\
\epsilon' = \sin \theta_{23} \epsilon_{V}^{\nu} - \epsilon_{e}^{\nu} 
\]

The quantity \( N_f \) is the density of a determined fermion along the neutrino path, and \( \theta_{23} \) is the atmospheric neutrino mixing angle.

From the combined solar + KamLAND analysis we obtain the Fig. 1 [1, 2] where we compare the results without NSI and including them. As we can see the presence of NSI will lead to the appearance of the LMA-D solution and thus to the ambiguous determination of the solar mixing angle.

![Figure 1](image)

Figure 1. Left panel [1]: 90\%, 95\%, 99\% and 99.73\% C.L. allowed regions from solar data (hollow lines) and KamLAND data (colored regions) where we can observe that only one region is permitted. Right panel [2]: 90\%, 95\% and 99\% allowed regions from the solar + KamLAND analysis introducing NSI. We can observe the appearance of so-called “dark region”.

2.2. Effects in neutrino detection

The presence of NSI can also affect the detection processes at some experiments. In particular, the cross section for the neutral current detection reaction at SNO is proportional to \( g_A^2 \), which is the coupling of the neutrino current to the axial isovector hadronic current, giving an extra contribution to the NC signal at SNO experiment [4]. This nonstandard contribution can be parameterized as:

\[
\phi_{NC} = f_B (1 + 2\epsilon_A) \quad \Rightarrow \quad \epsilon_A = -\sum_{\alpha=e,\mu,\tau} \left( \begin{array}{c} P_{e\alpha} \\ P_{\mu\alpha} \\ P_{\tau\alpha} \end{array} \right) \epsilon_{dA}^{\alpha} 
\]

where \( f_B \) is the boron neutrino flux and the nonstandard axial couplings with up-type quark are set to zero.
In our previous analysis we assumed that $\epsilon_A = 0$ but in a generalized 5-parameters (analysis including the axial component of NSI) we observe that the inclusion of the axial parameter only extends the allowed region [2].

3. Constraints on $\nu - q$ NSI

In this section we will focus on the study of NSI, combining the results of solar, accelerator, reactor and atmospheric neutrinos in order to obtain stronger constrains on the NSI parameters for neutrino-quark interactions.

3.1. Constraints on NSI for electron and tau neutrinos: Solar + KamLAND + CHARM

Laboratory experiments measuring neutrino-nucleon scattering show sensitivity to neutrino NSI on quarks. In particular, here we will combine the results of the accelerator experiment, CHARM [5], together with the ones in Sec. 2 in order to obtain stronger constraints on the NSI parameters.

The regions for the vector (left) and axial (right) NSI couplings allowed by the global analysis are given in the Fig. 2 [2]. In the vectorial case we can appreciate the existence of two allowed islands corresponding to the usual LMA solution (lower one) and to the dark solution (upper one).

The results are summarized in the Table 1.

![Figure 2: Constraints on the vector (left panel) and axial (right panel) NSI coupling from our global analysis at 90%, 95% and 99% C.L. In both pictures we can observe the band coming from solar + KamLAND data and the CHARM contribution [2].](image)

3.2. Constraints on NSI for muon neutrinos: NuTeV + atmospheric + CHARM + CDHS

Collider experiments produce well-controlled and clean muon-neutrino beams, with just a small component of electron neutrinos. As a result, one can expect that the muon-neutrino NSI parameters are well constrained. This is accomplished for interactions with electrons. In the case of interactions with quarks these constraints are based in the NuTeV experiment [7], which measured the $\nu_\mu - N$ interactions with a very high accuracy reporting a discrepancy with the Standard Model prediction.

Recently, two different analysis of the NuTeV results for the electroweak mixing parameter $\sin^2 \theta_W$ have been performed (NNDPDF coll. [8] and Bentz et al. [9]), including new uncertainties related with nuclear structure in order to eliminate the discrepancy.

Using these new values of the electroweak mixing parameter we will review the status of constrains for the $\nu_\mu - q$ NSI combining NuTeV reanalysis [8, 9] with atmospheric [10] and accelerator (CHARM [5] + CDHS [6]) data. The results derived from such combined analysis are summarized in the Table 1.
Table 1. New constraints on the vectorial and axial $(v_e, v_\mu, v_\tau) - (u, d - \text{quark})$ NSI couplings at 90% C.L. obtained from combining solar + KamLAND + CHARM data [2] and NuTeV (NNPDF coll. and Bentz et al.) + atmospheric + CHARM + CDHS data [3].

| Down quark | Up quark |
|------------|----------|
| Vectorial couplings | |
| CHARM + Sol + Kaml | NNPDF | Bentz et al. | NNPDF | Bentz et al. |
| $-0.2 < \varepsilon_{ee}^{dV} < 0.5$ | $-0.042 < \varepsilon_{\mu\mu}^{dV} < 0.042$ | $-0.044 < \varepsilon_{\mu\mu}^{dV} < 0.044$ |
| $-1.1 < \varepsilon_{\mu\mu}^{dV} < 0.4$ & $\varepsilon_{\mu\mu}^{dV} < 2.2$ | $-0.007 < \varepsilon_{\mu\mu}^{dV} < 0.007$ | $-0.007 < \varepsilon_{\mu\mu}^{dV} < 0.007$ |
| $-0.08 < \varepsilon_{\mu\mu}^{dV} < 0.58$ | $-0.007 < \varepsilon_{\mu\mu}^{dV} < 0.007$ | $-0.007 < \varepsilon_{\mu\mu}^{dV} < 0.007$ |
| Axial couplings | |
| $-0.2 < \varepsilon_{\mu\mu}^{dA} < 0.3$ | $-0.091 < \varepsilon_{\mu\mu}^{dA} < 0.091$ | $-0.072 < \varepsilon_{\mu\mu}^{dA} < 0.057$ | $-0.15 < \varepsilon_{\mu\mu}^{dA} < 0.18$ | $-0.094 < \varepsilon_{\mu\mu}^{dA} < 0.140$ |
| $-0.2 < \varepsilon_{\mu\mu}^{dA} < 0.4$ | $-0.039 < \varepsilon_{\mu\mu}^{dA} < 0.039$ | $-0.039 < \varepsilon_{\mu\mu}^{dA} < 0.039$ |

4. Conclusions
We have shown that neutrino oscillation data is still fragile in the presence of NSI. Using the last data from SNO-III, Borexino and KamLAND we have observed that the dark solution (LMA-D) still survives. Further information may come from atmospheric and laboratory data to lift the degeneracy.

We have obtained improved bounds on the vector and axial parameters involving electron and tau neutrino interactions with down-type quarks after studying the limits on the NSI couplings combining solar, KamLAND (reactor experiment) and CHARM (accelerator experiment).

Finally, a reanalysis of the constraints on non-standard muon neutrino interactions with quarks have been done. In particular we have reconsidered the results of NuTeV experiment in view of a new evaluation of the NuTeV systematic uncertainties. We have combined the restrictions from accelerator data with those coming from recent atmospheric data analysis. We have found that, although constraints for muon neutrinos are better than those applicable to tau or electron neutrinos, they are not as strong as previously believed.

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