Are there consistent models giving observable NSI?

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Abstract. While the existing direct bounds on neutrino NSI are rather weak, order 10^{-1} for propagation and 10^{-2} for production and detection, the close connection between these interactions and new NSI affecting the better-constrained charged letpon sector through gauge invariance make these bounds hard to saturate in realistic models. Indeed, Standard Model extensions leading to neutrino NSI typically imply constraints at the 10^{-3} level. The question of whether consistent models leading to observable neutrino NSI naturally arises and was discussed in a dedicated session at NUFACT 11. Here we summarize that discussion.

1. Direct bounds on neutrino NSI

The formalism of non-standard neutrino interactions (NSI) is a very widespread and convenient way of parameterizing the effects of new physics in neutrino oscillations [1, 2]. Even though present data constrain NSI to be a subleading effect in neutrino oscillation experiments, the possibility of their eventual detection and interference with standard neutrino oscillation measurements has triggered a considerable interest in the community. Present bounds on NSI are reviewed here and the possibility of saturating them in particular Standard Model (SM) extensions is discussed.

1.1. CC-like NSI

NSI for source and detector charged-current processes, referred as charged-current-like (CC-like) NSI are discussed below. Leptonic NSI are given by the effective Lagrangian density:

$$\mathcal{L}^{\ell}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon^{\alpha\beta P}_{\gamma\delta} [\bar{\ell}_\alpha \gamma^\mu P \ell_\beta][\bar{\nu}_\gamma \gamma_\mu P_L \nu_\delta] \tag{1}$$

where G_F is the Fermi constant and P is either P_L or P_R and, due to Hermiticity, $\varepsilon^{\alpha\beta P}_{\gamma\delta} = \varepsilon^{\beta\alpha P*}_{\delta\gamma}$. For NSI at neutrino production via muon decay $\alpha = \mu$ and $\beta = e$. Notice that $\alpha = \beta = e$ would instead correspond to NSI with electrons in matter. In a similar fashion, the CC-like NSI with quarks are given by:

$$\mathcal{L}^{q}_{\rm NSI} = -2\sqrt{2} G_F \varepsilon^{qq'P}_{\alpha\beta} V_{qq'} [\bar{q} \gamma^\mu P q'][\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta] + \text{h.c.} \tag{2}$$

where q is an up-type and q' is a down-type quark. Only $q = u$ and $q' = d$ are of practical interest for neutrino oscillations, due to their contributions to charged-current interactions with pions and nuclei. In [3] bounds on these production and detection NSI were derived from constraints on the comparison of different measurements of G_F: through μ decay (affected by leptonic NSI of Eq. (1)), β decays (affected by quark NSI of Eq. (2)) and the kinematic measurements of the masses of the gauge bosons M_Z and M_W (not affected by neutrino NSI). Universality tests of G_F from π and τ decays as well as short baseline neutrino oscillation experiments such as KARMEN or NOMAD, were also considered. Notice that in order to derive those bounds only one NSI parameter was switched on at a time in order to avoid the relaxation of the bounds through cancellations among different parameters. Here are the most stringent derived bounds:

$$|\varepsilon^{\mu e}_{\alpha\beta}| < \begin{pmatrix} 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \\ 0.025 & 0.030 & 0.030 \end{pmatrix}, |\varepsilon^{ud}_{\alpha\beta}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ \substack{1.8\cdot 10^{-6} \\ 0.026} & 0.078 & 0.013 \\ \substack{0.087 \\ 0.12} & \substack{0.013 \\ 0.018} & 0.13 \end{pmatrix} \tag{3}$$

Whenever two values are quoted, the upper value refers to left-handed NSI and the lower to right-handed NSI. These bounds stem from the direct effect of the corresponding effective operator and are rather weak. However, Eqs. (1) and (2) are not gauge invariant and can be related to flavour changing processes involving charged leptons when promoting the neutrino fields to full lepton doublets which would lead to much tighter constraints. Possible ways to evade these stronger constraints are discussed in Sect. 2.

1.2. NC-like NSI

The neutral-current-like (NC-like) NSI effective Lagrangian density is defined as:

$$\mathcal{L}^M_{\mathrm{NSI}} = -2\sqrt{2} G_F \varepsilon^{fP}_{\alpha\beta} [\bar{f}\gamma^\mu P f][\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta], \mathrm{f} = \mathrm{e, u, d} \tag{4}$$

This type of NSI is the most extensively studied in the literature, since the constraints on the CC-like NSI are generally stronger. Indeed, the bounds from [4, 5, 6, 7], but discarding the loop constraints on $\varepsilon^{fP}_{e\mu}$ given the discussion in [8], result in the following $\mathcal{O}(10^{-1})$ constraints:

$$|\varepsilon^{e}_{\alpha\beta}| < \begin{pmatrix} \substack{0.06 \\ 0.14} & 0.10 & \substack{0.4 \\ 0.27} \\ 0.10 & 0.03 & 0.10 \\ \substack{0.4 \\ 0.27} & 0.10 & \substack{0.16 \\ 0.4} \end{pmatrix}, |\varepsilon^{u}_{\alpha\beta}| < \begin{pmatrix} \substack{1.0 \\ 0.7} & 0.05 & 0.5 \\ 0.05 & \substack{0.003 \\ 0.008} & 0.05 \\ 0.5 & 0.05 & \substack{1.4 \\ 3} \end{pmatrix}, |\varepsilon^{d}_{\alpha\beta}| < \begin{pmatrix} \substack{0.3 \\ 0.6} & 0.05 & 0.5 \\ 0.05 & \substack{0.003 \\ 0.015} & 0.05 \\ 0.5 & 0.05 & \substack{1.1 \\ 6} \end{pmatrix} \tag{5}$$

Again, the operator in Eq. (4) is not gauge invariant. The simplest gauge invariant extension of Eq. (4) promoting the left-handed fields to full SU(2) doublets would lead to flavour changing operators with charged leptons, allowing to derive much stronger bounds than the ones above.

2. Models to evade charged lepton NSI

In [9, 10] extensions of the SM leading to neutrino NSI but avoiding their charged current counterparts were studied both through $d = 6$ and $d = 8$ operators. Only two examples of SM extensions giving rise to matter NSI but avoiding their charged lepton counterpart exist at $d = 6$. The most direct one involves an antisymmetric 4-lepton operator, generated from the exchange of virtual singly charged scalar fields. In the second possibility NSI are induced through the $d = 6$ operator modifying the neutrino kinetic terms, generated by the exchange of virtual fermionic singlets. The latter operator generates the NSI in an indirect way, i.e. after canonical normalisation of the neutrino kinetic terms. In the first case, NSI with electrons in matter appear through the operator [11, 12, 13]:

$$\mathcal{L}^{d=6,as}_{NSI} = c^{d=6,as}_{\alpha\beta\gamma\delta} (\overline{L^c}_\alpha i\sigma_2 L_\beta)(\bar{L}_\gamma i\sigma_2 L^c_\delta) \tag{6}$$

which is generated after integrating out a charged scalar SU(2) singlet coupling to the SM lepton doublets:

$$\mathcal{L}^S_{int} = -\lambda^i_{\alpha\beta} \overline{L}^c_\alpha i\sigma_2 L_\beta S_i = \lambda^i_{\alpha\beta} S_i (\overline{\ell}^c_\alpha P_L \nu_\beta - \overline{\ell}^c_\beta P_L \nu_\alpha) \tag{7}$$

Integrating out the heavy scalars S_i generates the $d = 6$ operator of Eq. (6) at tree level. We find that, given the antisymmetric flavour coupling of Eq. (7), the only NSI induced are those between ν_μ and ν_τ with electrons in matter. Bounds on these NSI can be derived from μ and τ decays:

$$|\varepsilon^{m,e_{\rm L}}_{\mu\mu}| < 8.2 \cdot 10^{-4}, |\varepsilon^{m,e_{\rm L}}_{\tau\tau}| < 8.4 \cdot 10^{-3}, |\varepsilon^{m,e_{\rm L}}_{\mu\tau}| < 1.9 \cdot 10^{-3} \tag{8}$$

NSI in production and detection are also induced with similar strengths. The second realization of NSI at $d = 6$ is via the operator:

$$\mathcal{L}^{d=6}_{kin} = -c^{d=6,kin}_{\alpha\beta} (\bar{L}_\alpha \cdot H^\dagger)\, i\partial\!\!\!/\, (H \cdot L_\beta) \tag{9}$$

which induces non-canonical neutrino kinetic terms [14, 15, 16] though the vev of the Higgs field. After diagonalising and normalising the neutrino kinetic terms, a non-unitary lepton mixing matrix is produced from this operator and hence non-standard matter interactions as well as related NSI at the source and detector are induced. The tree level generation of this operator, avoiding a similar contribution to charged leptons that would lead to flavour changing neutral currents, requires the introduction of SM-singlet fermions which couple to the Higgs and lepton doublets via the Yukawa couplings (see e.g. [17]). Electroweak decays set the following bounds on the operator of Eq. (9) due to the effects a deviation from unitarity of the mixing matrix would imply [18, 16, 9]:

$$\frac{v^2}{2}|c^{d=6,kin}_{\alpha\beta}| < \begin{pmatrix} 4.0 \cdot 10^{-3} & 1.2 \cdot 10^{-4} & 3.2 \cdot 10^{-3} \\ 1.2 \cdot 10^{-4} & 1.6 \cdot 10^{-3} & 2.1 \cdot 10^{-3} \\ 3.2 \cdot 10^{-3} & 2.1 \cdot 10^{-3} & 5.3 \cdot 10^{-3} \end{pmatrix} \tag{10}$$

These bounds can be translated to constraints in the matter NSI that would be induced by a non-unitary mixing:

$$|\varepsilon_{\alpha\beta}| < \frac{v^2}{4} | \left(\frac{n_n}{n_e} - \delta_{\alpha e} - \delta_{e\beta} \right) c^{d=6,kin}_{\alpha\beta} | \tag{11}$$

Since the ratio of the neutron to electron density $\frac{n_n}{n_e}$ is in general close to 1, this implies that the bounds on $|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$ are significantly stronger than the bounds on the individual $\varepsilon_{\alpha\beta}$. For the main constituents of the Earth's crust and mantle the factor $\frac{n_n}{n_e} - 1$ means an additional suppression of two orders of magnitude of the NSI coefficient [9]. Thus, even if two $d = 6$ possibilities exist to induce neutrino NSI while avoiding the corresponding charged lepton NSI, they cannot saturate the mild direct bounds from Eqs. (3) and (5) and stronger $\mathcal{O}(10^{-3})$ bounds apply. In [9, 10] the generation of matter NSI avoiding similar operators involving charged leptons was also studied through $d = 8$ operators. In [9] the analysis was restricted to new physics realizations that did not involve cancellations between diagrams involving different messenger particles and, under those conditions, the bounds derived for the $d = 6$ realizations can be translated also to the $d = 8$ operators and, even if charged fermion NSI are avoided, no large neutrino NSI are obtained. In [10] it was shown that, allowing cancellation between diagrams involving different messengers, large neutrino NSI could be obtained by tunning away all other dangerous contributions to the charged lepton sector. However, this cancellation is only exact at zero momentum transfer, therefore constraints can be derived when probing larger energies at colliders, as studied in [19], and strong constraints $\varepsilon < 10^{-2} - 10^{-3}$ are again recovered through LEP2 data. Finally, the analyses of [9, 10] were limited to tree level effective operators. Therefore, they do not cover the possibility of loop-induced NSI or lighter mediators that cannot be integrated out of the theory. These can thus be ways out of the stringent constraints derived and potential sources of large NSI. Unfortunately, neither the loop generation nor lighter mediators seem to provide ways in which to evade gauge invariance and avoid the more stringent bounds leaking from the charged lepton sector. The generation of NSI via loop processes was studied in detail in [20] and applied in particular to the MSSM contributions. It was found that charged lepton flavour-violating processes constrain the induced NSI to the $\sim 10^{-3}$ level, as with the other alternatives explored. Concerning lighter mediators, this is a way out of the effective theory treatment presented in [9, 10], but gauge invariance still poses strong constraints and, indeed, flavour-conserving interactions, much more weakly constrained in the charged lepton sector than the flavour-violating counterparts, are usually considered instead.

3. Conclusions

We have reviewed the present model independent bounds on NSI. We find that production and detection NSI are bounded to be $< \mathcal{O}(10^{-2})$. Conversely the bounds on matter NSI are around one order of magnitude weaker. Saturating these mild direct bounds could lead to large observable signals at neutrino experiments. Matter NSI are however related to production and detection NSI and to flavour changing operators for charged leptons through gauge invariance. Exploring gauge invariant realizations we find that gauge invariant NSI are constraint to be $\mathcal{O}(10^{-3})$ making them very challenging, but not impossible, to probe at present [21, 22] facilities with dedicated new detectors or future neutrino oscillation facilities such as the Neutrino Factory [23, 24, 25, 26, 27, 28]. Furthermore, the stringent constraints from gauge invariance mainly apply to flavour-violating processes, thus, fully $SU(2)_L$ invariant operators can be considered with $\mathcal{O}(10^{-2})$ entries in some of the diagonal elements, see e.g. [29].

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