Non-standard neutrino interactions in the type-II seesaw model

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Abstract. Within the framework of the type-II seesaw model, we investigate in detail the non-standard neutrino interactions (NSIs). Non-trivial correlations between NSI parameters and neutrino masses and mixing parameters are established. We show that sizable NSIs can be generated as a consequence of a nearly degenerate neutrino mass spectrum. Significant zero distance effects in the near detector of a future neutrino factory, as well as characteristic decays of the doubly charged Higgs at the Large Hadron Collider are discussed.

1. Introduction
Non-standard neutrino interactions (NSIs) emerge from the effective Lagrangian of the form

\[ \mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \epsilon_{\alpha \beta}^{(ff'C)} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_C f') , \]

where \( f \) and \( f' \) denote charged lepton or quark fields, \( G_F \) is the Fermi coupling constant, and \( P_L \) and \( P_C \) (with \( C = L, R \)) stand for different chiral projectors. It is generally expected that the effective operator comes out of an underlying theory respecting the Standard Model (SM) gauge symmetry upon integrating out a certain set of “heavy” degrees of freedom. For purely leptonic NSIs, i.e., the two charged-fermions in Eq. (1) are leptons, the heavy mediators can be either charged scalars or vector bosons, which may usually induce interactions involving four charged leptons. For a fermion mediated NSI operator, non-unitarity effects usually arise due to the mixing between the neutral components of heavy fermions and light neutrinos [1, 2]. Generally, the mass scale of seesaw particles is chosen to be much higher than the electroweak scale and close to the Grand Unified scale in order to sufficiently suppress the light neutrino masses. Therefore, no significant NSI effects could be expected. Here, instead, we focus on a particular extension of the SM featuring an extra \( SU(2)_L \)-triplet Higgs not far away from the electroweak scale, which provides a very popular and simple scheme for accommodating Majorana masses of neutrinos within a renormalizable framework, and indeed, can induce significant NSI effects [3].

1 In collaboration with Michal Malinský and Tommy Ohlsson.
2. NSIs from the type-II seesaw model

In the simple extension of the SM with an extra Higgs triplet \( \Delta \), gauge invariance allows one to add the couplings between the Higgs triplet and two lepton doublets [4, 5, 6]

\[
\mathcal{L}_Y = Y_{\alpha\beta} \left[ \Delta^0 \nu_{\alpha} P_{\nu} \nu_{\beta} - \frac{1}{\sqrt{2}} \Delta^+ \left( \bar{P}_{\nu} P_{\nu} \right) \Delta^0 \nu_{\alpha} P_{\nu} \nu_{\beta} - \Delta^\pm \bar{P}_{\nu} P_{\nu} \nu_{\alpha} \right] + \text{H.c.},
\]

where \( Y \) is a 3 \( \times \) 3 symmetric matrix in flavor space. Integrating out the heavy triplet field at tree level, one can obtain effective dimension five and six operators, which are responsible for light neutrino masses, NSIs and non-standard four charged-lepton interactions, respectively, [7]

\[
\mathcal{L}^m = Y_{\alpha\beta} \frac{\lambda_0 v^2}{m_\Delta} (\nu_\alpha P_\nu \nu_\beta) = \frac{1}{2} (m_\nu)_{\alpha\beta} \nu_\alpha P_\nu \nu_\beta,
\]

\[
\mathcal{L}_{\text{NSI}} = Y_{\alpha\beta} \frac{\lambda_0}{m_\Delta} (\bar{\nu}_\alpha \gamma_\mu P_\nu \nu_\beta) (\bar{\nu}_\rho \gamma^\mu P_\nu \nu_\sigma),
\]

\[
\mathcal{L}_{4\ell} = Y_{\alpha\beta} \frac{\lambda_0}{m_\Delta} (\bar{\nu}_\alpha \gamma_\mu P_\nu \nu_\beta) (\bar{\nu}_\rho \gamma^\mu P_\nu \nu_\sigma),
\]

where \( v \simeq 174 \text{ GeV} \) is the vacuum expectation value of the SM Higgs field and \( \lambda_0 \) denotes the coupling of the scalar triplet to the SM Higgs doublet. Comparing Eqs. (3) and (4) with Eq. (1), we can establish relations between the light neutrino mass matrix and NSI parameters as

\[
\varepsilon_{\alpha\beta}^\mu = \frac{m_\Delta^2}{8\sqrt{2} G_F v^4 \lambda_0^2} (m_\nu)_{\sigma\beta} \left( m_\nu^2 \right)_{\alpha\rho}.
\]

In order to accommodate sizable NSIs, one naturally expects the triplet Higgs to be rather light, typically at the TeV scale. Notice that, in such a case, the dimensionful parameter \( \lambda_0 \), associated with the trilinear Higgs coupling must be small enough to keep the absolute neutrino mass scale proportional to \( \lambda_0 v^2/m_\Delta^2 \) in the sub-eV range. However, this could be natural, since the symmetry is enhanced in the zero \( \lambda_0 \) limit. It is also easy to see that the NSI parameters are not independent, and in fact, they are strongly tied to the structure of the light neutrino mass matrix \( m_\nu \). However, not all the \( \varepsilon \)'s are physically interesting parameters. For the propagation process in long baseline experiments, neutrinos encounter Earth matter effects and only electron type of NSIs \( \varepsilon_{\alpha\beta}^{ee} \equiv \varepsilon_{\alpha\beta}^{ee} \) contributes to the matter potential. In addition, Eq. (6) affects neutrino production at neutrino sources, especially for a neutrino factory. More generally, both the processes \( \mu^- \rightarrow e^- \nu_\mu \bar{\nu}_\tau \) (corresponding to the NSI parameter \( \varepsilon_{\alpha\beta}^{\mu\tau} \)) and \( \mu^- \rightarrow e^- \nu_\alpha \bar{\nu}_\tau \) (corresponding to \( \varepsilon_{\alpha\beta}^{\tau\mu} \) with \( \alpha \neq \mu \)) may occur, and their contributions have to be added to the SM transition rate either coherently or incoherently, depending on the specific situation.

The most stringent experimental bounds on these NSI parameters come from the lepton flavor violating (LFV) decays \( \mu \rightarrow 3e \) and \( \tau \rightarrow 3\ell \), the rare radiative lepton decays \( \ell_{\alpha} \rightarrow \ell_{\beta} \gamma \), and the Bhabha scattering and muonium to antimuonium conversion. In order to receive sizable NSIs effects in neutrino experiments and avoid large LFV processes at the same time, one expects the flavor non-diagonal parts of \( m_\nu \) to be relatively small. Hence, \( m_\nu \) should take an approximately diagonal form, which is quite favorable in the case of a nearly degenerate (ND) neutrino mass spectrum \( m_1 \simeq m_2 \simeq m_3 \). Then, \( m_\nu \) approximates to a unit matrix, and the only relevant NSI parameters are \( \varepsilon_{ee}^{ee} \) and \( \varepsilon_{\mu\tau}^{ee} = (\varepsilon_{ee}^{\mu\tau})^* \). Note that another possible way to evade the LFV constraints is discussed in Ref. [8]. We illustrate in Fig. 1 the generic upper bounds on the NSI parameters with respect to the lightest neutrino mass \( m_1 \). One can find that only \( \varepsilon_{ee}^{ee} \) and \( \varepsilon_{\mu\tau}^{ee} \) are significant at large \( m_1 \) regions, and they are similar in size. The upper bound \( |\varepsilon_{ee}^{ee}|, |\varepsilon_{\mu\tau}^{ee}| < 3 \times 10^{-3} \) can be obtained according to Fig. 1. As for the other NSI parameters, the upper bounds are rather strong, which means that there is no hope for them to be discovered in the near-future experiments.
3. Signatures at a neutrino factory and the LHC

Wrong sign muons at a near detector: The most striking signal of the type-II seesaw model at a neutrino factory corresponds to the processes \( \mu^- \rightarrow e^- \nu_e \bar{\nu}_\mu \) and \( \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \) leading to would-be observable rates of the “wrong sign” muon tracks in a near detector, the so-called zero-distance effect. We find in our numerical analysis that a neutrino factory provides an excellent sensitivity to probe this type of NSI effects. The precision of \( \varepsilon \) is limited by the baseline length \( L \), especially for a large \( \theta_{13} \). Thus, a distance \( L < 10 \text{ km} \) would be favorable for the detector [9].

Earth matter density profile uncertainties: Precision measurements of \( \varepsilon \) are related to how well the matter density uncertainty can be constrained. Once an accurate geophysical estimate of the Earth matter density uncertainties becomes available, one then may hope to perform a high sensitivity test on \( \varepsilon \) in practice [10].

Like-sign di-lepton production at the LHC: According to the above analysis, in the case of sizable NSIs, \( \Delta^{\pm \pm} \) should predominantly decay into a pair of identical leptons [11]. Therefore, one can expect significant NSI effects, if the branching ratios of decays \( \Delta^{\pm \pm} \rightarrow \ell^+_{\alpha} \ell^-_{\alpha} \) are dramatically larger than the other channels at the LHC.

4. Conclusions

The NSI effects in the type-II seesaw were discussed in detail. We found upper bounds for the effective couplings like \( |\varepsilon| < 3 \times 10^{-3} \). We argued that a combined analysis of the neutrino oscillation experiments and the future LHC results would be very helpful to figure out the underlying physics behind the neutrino masses and mixing as well as non-standard interactions.

Acknowledgments

This work was supported by the Göran Gustafsson Foundation and the Royal Institute of Technology (KTH), project no. SII-56510.

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