

Snowmass LOI: Neutrino Non-Standard Interactions

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Neutrino non-standard interactions (NSI) are a parameterization of new physics in the neutrino sector that draws connections across a wide range of particle physics, astrophysics, and cosmology into a unified framework. We first review the basics and discuss some new extensions of NSI. Then we discuss NSI in oscillations and scattering experiments and finally we conclude.

Overview Neutrino non-standard interactions (NSI), first introduced in 1977 [1], provide a useful framework to connect constraints on new physics from scattering experiments and oscillation experiments [2–4]. The typical NSI effective Lagrangian for vector neutral current (NC) and charged current (CC) processes with heavy mediators are

$$\mathcal{L}_{\text{NSI}}^{\text{NC}} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon_{\alpha\beta}^{f,V} (\bar{\nu}_\alpha \gamma^\mu \nu_\beta) (\bar{f} \gamma_\mu f), \quad (1)$$

$$\mathcal{L}_{\text{NSI}}^{\text{CC}} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \epsilon_{\alpha\beta}^{ff',V} (\bar{\nu}_\alpha \gamma^\mu \ell_\beta) (\bar{f} \gamma_\mu f'), \quad (2)$$

where the ϵ parameters quantify the size of the interaction relative to the standard weak interaction, α, β are the lepton flavors, and $f, f' \in \{e, u, d\}$ are matter fermions. CC NSI can modify the production and detection of neutrinos while both CC and NC NSI can affect their propagation in matter.

On the oscillation side, NSI modifies the standard three-flavor oscillation Hamiltonian,

$$H = \frac{1}{2E} \left[U^\dagger \begin{pmatrix} 0 & & \\ & \Delta m_{21}^2 & \\ & & \Delta m_{31}^2 \end{pmatrix} U + a \begin{pmatrix} 1 + \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} \end{pmatrix} \right], \quad (3)$$

where E is the neutrino energy, $U \equiv R_{23}(\theta_{23})U_{13}(\theta_{13}, \delta)R_{12}(\theta_{12})$ is the PMNS mixing matrix [5, 6] that is parameterized in the usual way [7] with two real rotations (R_{ij}) and one complex rotation (U_{ij}), $a \equiv 2\sqrt{2}G_F N_e E$ is associated to the matter potential, and N_e is the electron number density. These parameters are related to the NSI parameters in eq. 1 by $\epsilon_{\alpha\beta} = \sum_f \epsilon_{\alpha\beta}^{f,V} N_f / N_e$. While constructing UV complete models that both predict large NSI in oscillation experiments and are consistent with strong charged lepton flavor violation measurements is notoriously difficult, numerous interesting models exist which can be broadly classified depending on if their mediators are heavy ($M_{Z'} \gtrsim \text{GeV}$) [8–11] or light [12–16].

NSI: Beyond the Epsilons While the above discussion has been the main framework for NSI for some time, in recent years the notion of NSI has expanded in numerous interesting directions.

- Although eqs. 1-2 are written for vector currents, one can extend them to arbitrary **Lorentz structures** $\{S, P, V, A, T\}$ and their combinations, each of which has unique phenomenology [17–22].
- **In oscillations, the mediator mass** is generally considered to be irrelevant for NSI, yet it does have an impact if its Compton wavelength is comparable to the macroscopic size of objects or is massless. In this case the oscillation probabilities are uniquely different than in the heavy mediator limit [20, 23–30].

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- If there is an interaction between neutrinos and matter fermions, then there is also a new **neutrino self-interaction**, sometimes referred to as neutrino non-standard *self* interactions (NSSI) which can alter our understanding of environments where neutrino-neutrino interactions are dominant such as cosmology, supernovae, astrophysical propagation, and neutrinoless double beta decay [31–50].
- **Dark matter** can also induce NSI-like effects [51].
- It has also been noted that, in some cases, other new physics searches including **unitary violation** and **sterile** neutrino oscillations can be mapped onto NSIs [52].

NSI in Oscillations The impact of NSI in oscillations has a very rich phenomenology including many degeneracies which has been explored in a large number of studies [3, 53–83]. To numerically examine these there have been a number of experimental constraints [84, 85] and fits to a wide range of oscillation data over the years, some of which also include various scattering data sets including CHARM, NuTeV, and COHERENT [74, 78, 82, 86]. These global fits show that, while some parameters are fairly well constrained by oscillation data to the $\epsilon \sim 0.01$ level, others allow for very large $\epsilon \sim 1$ NSI. In addition, there have been several slight oscillation anomalies which could be interpreted as hints of NSI [15, 87–91].

NSI in Scattering Any complete model of NSI introduces a mediator. Depending on the mass of the mediator, different scattering experiments are relevant. For light enough mediators only oscillation experiments (see the caveats in the Beyond the Epsilons paragraph) and NSSI constraints apply. For mediators $M_{Z'} \gtrsim 10$ MeV the low threshold experiment COHERENT [18, 75, 78, 83, 92–98] places constraints on most NSI flavor combinations via the coherent elastic neutrino nucleus scattering process (CEvNS) [99–101] and can also constrain non-vector NSI as well. Future reactor CEvNS experiments look to improve this picture to even lighter mediators. COHERENT’s CEvNS measurement also draws a connection between our constraints on NSI and the neutrino floor relevant for dark matter direct detection searches [102–105]. At the GeV scale experiments like CHARM and NuTeV place constraints. NSI models also often lead to connections with colliders [106–111].

NSI in the Future The interconnected nature of neutrino scattering and neutrino oscillations provides for a very rich phenomenology to search for new physics. Looking to the future we see signs indicating considerable improvement on multiple fronts. First, as new long-baseline oscillation experiments such as DUNE, T2HK, and JUNO [112–115] measure the remaining oscillation parameters in different matter densities, our standard three-flavor oscillation should come into stark contrast illuminating any inconsistencies in the standard three-flavor picture due to NSI. Long-baseline experiments at the second oscillation maximum such as possibly DUNE as well as T2HKK and ESSnuSB [116, 117] as well as the low-energy component of the IceCube upgrade [118] and KM3NeT [119, 120] will provide key cross checks to further reduce degeneracies. Next, as crucial reactor CEvNS measurements are made with very low thresholds, we can be sensitive to NSI down to $M_{Z'} \sim 1$ MeV possibly ruling out key NSI degeneracies in combination with early universe data [95]. On the high energy collider side, as energy, luminosity, and analyses at the LHC improve, the sensitivity to NSI with heavier mediators should continue to improve. Finally, we hope that the considerable experimental efforts to measure the remaining oscillation parameters are met with a matching model building effort to fully understand what kinds of new physics can be present in the neutrino sector.

To summarize, as the neutrino data allows for new physics of a comparable size as the weak interaction, NSI is an excellent place to look for new physics and improving our understanding of NSI on all fronts should be a top priority not only for neutrino physics, but for particle physics in general to ensure we have a robust understanding of the Standard Model.

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