Non standard neutrino interactions: current status and future prospects

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Abstract

Neutrino oscillations have become well-known phenomena; the measurements of neutrino mixing angles and mass squared differences are continuously improving. Future oscillation experiments will eventually determine the remaining unknown neutrino parameters, namely, the mass ordering, normal or inverted, and the CP-violating phase. On the other hand, the absolute mass scale of neutrinos could be probed by cosmological observations, single beta decay as well as by neutrinoless double beta decay experiments. Furthermore, the last one may shed light on the nature of neutrinos, Dirac or Majorana, by measuring the effective Majorana mass of neutrinos. However, the neutrino mass generation mechanism remains unknown. A well-motivated phenomenological approach to search for new physics, in the neutrino sector, is that of non-standard interactions. In this short review, the current constraints in this picture, as well as the perspectives from future experiments, are discussed.

1. Introduction

The last two decades have seen the great success of many neutrino experiments, in particular, those that have contributed to the first observations of the various types of neutrino oscillation [1–7]. The standard oscillation parameters, defined in the framework of the three active neutrinos, have been determined with significant accuracy [8] apart from the yet unknown mass ordering, or the sign of the mass squared difference relevant for oscillation of atmospheric neutrinos, as well as the CP-violating phase, the most elusive parameter. Non-oscillation experiments that have measured the neutrino cross section with high accuracy, also provided valuable information for neutrino physics [9–11]. On the other hand, there are oscillation experiments [12–15] that have observed hints for neutrino oscillation into an additional sterile neutrino state.

So far, there is no experimental evidence that neutrinos pose some non-standard properties beyond masses and mixing or some extra new interactions, different from the weak interaction, not described by the Standard Model (SM). Such interactions, often called non-standard interactions (NSI) of neutrinos, if they exist, are interesting from a phenomenological point of view, since they directly indicate the presence of some new physics beyond SM.

Possible presence of NSI was first pointed out by Wolfenstein [16, 17], followed by the works done in [18–25] in the early stage (before the experimental discovery of neutrino oscillation [1]) and afterwards, studied by a large number of authors, for example, in [26–87]. In this short review, the current status of NSI is discussed, mainly from the phenomenological point of view.

Phenomenologically, NSI can be described with an effective four fermion Lagrangian [40],

\[
-L_{\text{NSI}}^{\text{eff}} = \bar{e}_{\alpha 1} \gamma_{\mu} 2 \sqrt{2} G_F \left( R_{\alpha} \gamma_{\nu L} \nu_\nu \right) \left( \bar{f} \gamma^\mu P f \right),
\]

where \(G_F\) is the Fermi constant, \(e_{\alpha 1}\) is the parameter which describes the strength of the NSI, \(f\) is a first generation SM fermion (\(e, \mu\) or \(\tau\)), \(P\) denotes the chiral projector \(\{L, R = (1 \pm \gamma^5)/2\}\), and \(\alpha\) and \(\beta\) denote the neutrino
flavors: $e, \mu$ or $\tau$. This Lagrangian describes neutral current (NC) interactions and they will be the focus of this work.

While the Lagrangian in (1) provides the general description of NSI, it is also possible to study NSI using other approaches, defining the parameters depending on whether we are considering the neutrino at the production point, $\epsilon^S$, during propagation (taking into account matter effects) $\epsilon^m$, or at the detection point, $\epsilon^D$. The reader must be aware that there is no universal notation for the NSI parameters, and some authors use similar notation for different quantities, although the definition of the parameters in terms of equations (1) and (2) (see below) is more standard.

Let us consider the presence of NSI in the neutrino source with more detail. In general, source neutrino fluxes are produced from charged current (CC) interactions such as pion and muon decay and, in the presence of additional non-standard CC interactions, it would be necessary to consider contributions that would include terms proportional to

$$2G_F \sum_{\alpha} \epsilon_{\alpha}^{CC} \left[ \frac{1}{2} \gamma_5 \gamma_{\nu} \right].$$

(2)

In this case, the experimental value of the Fermi constant will be given by [36]

$$G^\text{exp} = G_F \sqrt{1 + \epsilon_{ee}^{CC} \epsilon_{ee}^{\alpha}}$$

and would imply that the new interactions could be parameterized as [31]

$$\epsilon_{\alpha}^{S} = \frac{\epsilon_{\alpha}^{CC}}{\sqrt{1 + \epsilon_{ee}^{CC} \epsilon_{ee}^{\alpha}}}.$$

(3)

A similar expression could be obtained for the case of neutrino detection $\epsilon^D$ if we are interested in CC interactions. It is important to notice that for NC NSI the corresponding expression for $\epsilon^{S,D}$ is different. As will be discussed below, for NSI coming from NC, the left and right couplings $\epsilon^{L,R}$ appears naturally, while the $\epsilon^{CC}$ for the CC case are considered to be left handed.

For the case of neutrino propagation, there is a direct relation between $\epsilon^m$ and the NSI parameters coming from the Lagrangian in equation (1). It will be seen in section 3 that, during propagation in matter, the neutrino potential will be sensitive only to vector currents ($\epsilon^V = \epsilon^L + \epsilon^R$) and, therefore, we will end up with the relation,

$$\epsilon_{\alpha\beta}^m = \frac{V_f}{V_e} \left( \epsilon_{\alpha\beta}^L + \epsilon_{\alpha\beta}^R \right),$$

(4)

where $V_f = V_f(r) = \sqrt{2} G_F N_f(r)$ with $f = e, \mu$ or $\tau$ (see section 3).

Solar, atmospheric and long baseline neutrino oscillation experiments are expected to give better constraints on propagation NSI parameters coming from matter effects, while non-oscillation experiments are more sensitive to NSI in production and/or detection. Both types of experiments provide valuable complementary information on NSI. One of the main disadvantages of non-oscillation experiments is that the flavor changing NSI will be present in the interaction only at the second order level ($\epsilon^2$) while propagation effects appear at first order ($\epsilon$). However, non-oscillation experiments also have some advantage, for instance, they may also be sensitive to axial currents, while oscillation experiments are not.

A model independent analysis that considers all the contributions coming from equation (1) will imply a large number of free parameters, $\epsilon_{\alpha\beta}$. To our knowledge, an analysis considering all the NSI contributions at the same time has never been done. In practice, one must constrain the analysis to a number of parameters that could be handled by current computational methods and give useful information about the freedom for new physics in the neutrino sector.

In this work we will discuss the current status of NSI studies. We will start by giving some examples, in section 2, of the kind of new physics that can be tested by using this formalism. Although we will stress the case of NC interaction, the result could be converted into constraints for new physics in the CC sector. We will show the current constraints coming from both oscillation and non-oscillation experiments in sections 3 and 4 along with a brief explanation of the phenomenological procedure to obtain such bounds. Future perspectives to improve the current constraints will be discussed in section 5. Finally, conclusions will be given in section 6.

2. NSI and models for new physics

Although the NSI formalism appears as a correction to the vector and axial couplings, it can account for different types of new physics. In this section, three different classes of Standard Model extensions are described, in term of the NSI parameters, and a particular example is shown in every case as an illustration of the formalism.
2.1. Extended gauge symmetries

Any extension of the SM local gauge symmetry $SU(2)_L \otimes U(1)_Y$, in general, introduces new gauge bosons that modify the vector and axial coupling. Typical examples are $E_6$ string inspired models, that at low energies introduce the extra groups $U(1)_A \otimes U(1)_R$, leading to an additional $Z'$ neutral gauge bosons. A similar situation happens with the left-right symmetric model $SU(2)_L \otimes U(1)_V \otimes SU(2)_R \otimes U(1)_Y$ where one extra neutral and one extra charged gauge bosons, $Z'$ and $W'$, appear.

Within the NSI formalism, there is an easy direct relation between the phenomenological parameters and the parameters coming from these models. We can consider, for instance, the neutrino dispersion off nuclei, described in the SM Lagrangian

$$L^{NC}_{\nu} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left[ \frac{\left(1 - \gamma^5 \right)}{2} \gamma_\mu \left(1 - \gamma^5 \right) q \right] \left\{ f^{qL} \left[ \tilde{\gamma}_\nu \left(1 - \gamma^5 \right) q \right] + f^{qR} \left[ \tilde{\gamma}_\nu \left(1 + \gamma^5 \right) q \right] \right\},$$

where $f^{qL, R}$ are the SM coupling constants defined elsewhere. For the case of $E_6$ models, where two additional neutral vector bosons arise, there will be an additional contribution to these couplings constants given by [49]

$$e^{\nu R} = -\frac{4}{M_Z^2} \frac{M_{Z'}}{M_Z^2} \sin^2 \theta_W \rho_{\nu,NC}^{ER} \left( \cos \frac{\beta}{\sqrt{24}} - \frac{\sin \beta}{3} \frac{\sqrt{5}}{8} \right) \left( \frac{3 \cos \beta}{2 \sqrt{24}} + \frac{\sin \beta}{6} \frac{\sqrt{5}}{8} \right),$$

$$e^{\nu L} = e^{\nu R} = -e^{\nu R},$$

where $M_Z$ is the mass of the SM neutral gauge boson; $M_{Z'}$ accounts for the mass of an additional, heavier, new gauge boson; $\theta_W$ is the weak mixing angle; $\rho_{\nu,NC}^{ER}$ is the parameter which accounts for the radiative corrections; and the angle $\beta$ describes the mixing between the two extra gauge bosons that arise from the $U(1)_A$ and $U(1)_Y$ symmetries. These models have yet another extra gauge boson that is considered to be heavier than the $Z'$ and decoupled from the above Lagrangian.

2.2. Additional neutral leptons

An extension of the SM fermion content can give rise to a rich phenomenology, especially when it contains extra neutral leptons, usually assumed to be heavy. Within this framework, it is possible to work in the standard $SU(2) \otimes U(1)$ gauge symmetry and consider the additional mixing of isodoublet and isosinglet neutral leptons [88]. As a result, the $V - A$ couplings will deviate from the SM prediction. For example, for the case of the CC, the ordinary light isodoublet neutrinos will mix with the extra heavy isosinglets; this mixing will be described by a matrix

$$K = \begin{pmatrix} K_L & K_{RH} \end{pmatrix},$$

where $K_L$ and $K_{RH}$ describe, respectively, the mixing of ordinary isodoublet light neutrinos and extra heavy isosinglets. Notice that the signals of new physics coming from this matrix might appear in charged currents through the deviations from the standard interactions (that is, in the detection) as well as in oscillation experiments, since the mixing matrix $K_{RH}$ is no longer unitary. Moreover, regarding the NC interactions, they will be described by the interaction

$$L = \frac{i g'}{2 \sin \theta_W} \bar{Z}_{\nu} \nu_{\nu} K^\dagger K \nu_{\nu},$$

where the matrix $K^\dagger K$ can be considered as a natural source for NSI in the neutral sector [88].

The enriched structure that arise from these models can be parameterized in different forms that must take into account all the new mixing angles and phases. One of the most studied schemes in this context is the seesaw model [88–92], which gives a natural explanation for the smallness of the neutrino mass. In these models, however, the sizeable signals at low energies are expected to be negligible and, therefore, the effective NSI should be negligible. There are, however, other models where the low energy effects, though small, may be sizeable in the near future, such as the so-called inverse seesaw model [93, 94].

Although it is not common in the literature to consider these analyses in term of the NSI formalism, it is possible to include them in the formalism. For example, for the simple case of only one extra neutral heavy lepton, the effects on a neutrino electron scattering off electrons will be a global factor in the Lagrangian, due to the non-unitarity of the mixing matrix. In this case the corresponding NSI parameters for an electron neutrino experiment will be given as

$$c^{ee}_{ee} = -g_L \sin^2 \theta_{14}, \quad c^{ee}_{ee} = -g_R \sin^2 \theta_{14},$$

where $g_L$ and $g_R$ are the parameters of the seesaw mechanism.
where $\theta_{14}$ is the mixing angle between the light neutrino and the extra heavy fermion and $g_{L,R}$ are the SM coupling constants for the neutrino electron scattering process.

2.3. Additional scalars

Despite the NSI formalism preserves the $V - A$ structure of the theory, it is also possible to consider the impact of scalar couplings. For example, if we consider the case of low energy supersymmetry with broken R-parity [95–97] where one has trilinear $L$ violating couplings of the form

$$\lambda_i g_i L_j E^c_k = \lambda'_{ijk} L_j Q_k D^c_l$$

(10)

with $L$ and $Q$ super-fields that contain the usual lepton and quark $SU(2)$ doublets, $E^c$, and $D^c$ super-fields that contain the singlets, and $i, j, k$ the generation indices. These couplings give rise, for example, to the following four-fermion effective Lagrangian for neutrino interactions with $d$-quark

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2} G_F \sum_{\alpha, \beta} \varepsilon^{\text{DR}}_{\mu \beta} \bar{\nu}_{\alpha} \gamma^{\mu} \nu_{\beta} \bar{b}_d \gamma^{\mu} b_d,$$

(11)

where we have, among others, flavor-conserving and changing NSI, given, respectively, by

$$\varepsilon^{\text{DR}}_{\mu \beta} = \sum_j \frac{|\lambda'_{j2k}|^2}{4 \sqrt{2} G_F m_{\tilde{d}_j}^2} \quad \text{and} \quad \varepsilon^{\text{DR}}_{\mu \beta} = \sum_j \frac{|\lambda'_{j2k}|}{4 \sqrt{2} G_F m_{\tilde{d}_j}^2}.$$

(12)

Here, $m_{\tilde{d}_j}$ denotes the masses of the squarks, while $j = 1, 2, 3$ stands for $\tilde{d}_1, \tilde{d}_2, \tilde{d}_3$, respectively. This is just one example, but other NSI couplings can be studied in this context [98]; moreover, constraints on generic scalar NSI can also be studied by using Fierz transformations [99].

3. NSI phenomenology in propagation

In this section, we discuss the phenomenological impact of the presence of NSI in propagation. The effect of NSI can be present through the modification of the matter potential that can exist not only in the diagonal but also in the off-diagonal elements in the effective Hamiltonian. Before starting our discussion on NSI we will briefly review the current standard oscillation status.

3.1. Standard neutrino oscillations picture

Unless otherwise stated, the standard three-flavor picture of neutrinos is assumed, $\nu_e, \nu_\mu$ and $\nu_\tau$ and corresponding anti-particles. In vacuum, the mixing of neutrinos is supposed to be described by the usual flavor mixing without NSI,

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}^\dagger |\nu_i\rangle \quad (\alpha = e, \mu, \tau),$$

(13)

where $U$ is the $3 \times 3$ matrix which describes the flavor mixing [100] of neutrinos. In this review, we use the standard parameterization found, e.g. in [8],

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{12} & s_{12} e^{-i \delta_{CP}} \\
0 & -s_{12} & c_{12}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i \delta_{CP}} \\
0 & 1 & 0 \\
-s_{13} e^{i \delta_{CP}} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
g_{12} & s_{12} \\
-s_{12} & c_{12}
\end{pmatrix} \begin{pmatrix}
c_{23} & s_{23} e^{-i \delta_{CP}} \\
-s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
g_{13} \\
0
\end{pmatrix} \begin{pmatrix}
s_{13} e^{-i \delta_{CP}} \\
0 \\
0
\end{pmatrix} \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{13} & s_{13} e^{-i \delta_{CP}} \\
0 & -s_{13} e^{i \delta_{CP}} & c_{13}
\end{pmatrix} \begin{pmatrix}
g_{23} c_{13} \\
s_{23} c_{13} \\
-s_{23} c_{13}
\end{pmatrix} \begin{pmatrix}
s_{12} & c_{12}
\end{pmatrix} \begin{pmatrix}
s_{12} & c_{12} & s_{13} e^{-i \delta_{CP}} \\
-s_{12} & c_{12} & s_{13} e^{i \delta_{CP}} \\
-s_{13} e^{-i \delta_{CP}} & -s_{12} c_{12} & c_{13}
\end{pmatrix} \begin{pmatrix}
1 \\
0 \\
0
\end{pmatrix}.$$

(14)

where $s_{ij} \equiv \sin \theta_{ij}, c_{ij} \equiv \cos \theta_{ij}$, and $\delta_{CP}$ is the Kobayashi-Maskawa [101] type CP phase for neutrinos.

In addition to the mixing angles and CP phase, the mass squared differences of neutrinos, $\Delta m^2_{ij} \equiv m_{i}^2 - m_{j}^2$ with $m_i (i = 1 - 3)$ being the neutrino masses, are the relevant parameters to describe neutrino oscillation. So far, all of these parameters have been measured with reasonably good accuracies except for the value of the CP phase and sign of $\Delta m^2_{31}$ ($\Delta m^2_{32}$). The positive (negative) sign of $\Delta m^2_{31}$ corresponds to the normal (inverted) mass ordering, often referred to as normal (inverted) mass hierarchy.

Different groups have carefully studied the neutrino data and obtained accurate values for most of the three-flavor neutrino oscillation parameters [103–105]. Their most important results are summarized in table 1, where a reasonable agreement can be seen.
3.2. Neutrino evolution with NSI

Phenomenologically, the evolution equation of neutrinos in the flavor basis in the presence of propagation NSI in unpolarized matter can be generically written as,

$$\frac{d}{dr} \begin{bmatrix} \nu_e \cr \nu_\mu \cr \nu_\tau \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} + \sum_f V_f \begin{bmatrix} \delta_{ef} + \xi_{ef} & \xi_{em} & \xi_{et} \\ \xi^*_{me} & \xi_{mm} & \xi_{mt} \\ \xi^*_{te} & \xi^*_{tm} & \xi^*_{tt} \end{bmatrix} \begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix},$$

(15)

where $\nu_\alpha \equiv \langle \nu_\alpha | \nu(r) \rangle$ ($\alpha = e, \mu, \tau$) denotes the probability amplitude to find neutrino as $\nu_\alpha$ at the position $r$, $\Delta_{ij} \equiv |\Delta m^2_{ij}|/2E$, $E$ being the neutrino energy. $V_f = V_f(r) \equiv \sqrt{2} G_f N_i(r)$ where $N_f (f = e, \mu$ or $\tau$) denotes the fermion number density along the neutrino trajectory in matter. Note that $V_e(r)$ is the standard matter potential [16] which induces the usual MSW effect [16, 102].

Since NSI effects in propagation enter only through the vector couplings, $\xi_{\alpha \beta}$ must be interpreted as $\xi_{\alpha \beta} = \xi^{d}_{\alpha \beta} + \xi^{a}_{\alpha \beta}$. For simplicity, throughout this review, we consider the case where only $d$-quark has the propagation NSI with neutrinos, and write NSI parameters simply as $\xi_{\alpha \beta}$ by omitting the fermion superscript. Note that the case of $u$-quark NSI is very similar in most cases to be discussed in this section because in the usual matter, $N_u \sim N_d \sim 3N_e$.

In this review, unless otherwise stated, for certainty, we use the following values of the mixing parameters as our reference values: $\sin^2 \theta_{12} = 0.31, \sin^2 \theta_{13} = 0.023, \sin^2 \theta_{23} = 0.5, \Delta m^2_{21} = 7.5 \times 10^{-5}$ eV$^2$ and $|\Delta m^2_{31}| = 2.4 \times 10^{-3}$ eV$^2$, and $\bar{\delta}_{CP} = 0$, which are consistent at $2\sigma$ with the results obtained by the recent global analysis [103–105].

Equation (15) defines the framework for neutrino propagation in matter with NSI. The parameters $\xi_{\alpha \beta}$ ($\alpha, \beta = e, \mu, \tau$) describe the magnitude of NSI. The diagonal NSI parameters, $\xi_{\alpha \alpha}$ ($\alpha = e, \mu, \tau$), could play a role similar to the terms of the standard MSW matter potential, or could be interpreted as the NSI induced mass squared difference, mimicking the ones that contain $\Delta m^2$, which could induce new resonance even if neutrinos were massless [18, 20]. On the other hand, off-diagonal NSI parameters, $\xi_{\alpha \beta}$ ($\alpha = \beta$) could play a role similar to the mixing angle. Even if there is no mixing in vacuum, the flavor transitions $\nu_\alpha \rightarrow \nu_\beta$ can occur in matter due to the presence of the off-diagonal NSI [18–20]. The complex phases of the off-diagonal elements $\xi_{\alpha \beta}$ could be a new source of CP violation, see e.g., [31, 64].

Currently, almost all the neutrino data are consistent with the standard three flavor scheme of massive and mixed neutrinos. Therefore, NSI, if they exist, is expected to manifest only as a subdominant effect. NSI in propagation has been constrained mainly by the oscillation data of solar and atmospheric neutrinos as well as neutrinos produced by accelerators. Reactor neutrinos do not constrain the propagation NSI because the matter effect is expected to be very small though they can constrain the detection NSI.

Roughly speaking, for a given neutrino energy, and the matter density, $\rho$, the impact of propagation NSI in neutrino oscillation (modification of the standard oscillation due to NSI) is essentially determined by the magnitude of the following dimensionless quantity,
3.3. NSI for atmospheric neutrinos

In this subsection we discuss the NSI effect for atmospheric neutrinos. The impact of NSI on atmospheric neutrinos have been considered by many authors, see e.g., [26, 29, 35, 41, 42, 44, 70].

Let us first consider the impact of NSI on the $\mu - e$ sector and assume that all the NSI parameters coupling to electron flavor neutrino, namely, $\varepsilon_{ee}$ are zero. In this scenario, $\varepsilon_{\mu e}$ and $\varepsilon_{\tau e}$ can be constrained mainly by the higher energy samples of the atmospheric neutrino data as will be seen below.

In the limit of $\Delta m_{32}^2 L/E \to 0$, with the constant matter density approximation, and ignoring $\theta_{13}$, the $\nu_\mu \to \nu_\mu$ survival probability is expressed as [32, 42]

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_e) \approx 1 - \sin^2 2\theta_{\text{eff}} \sin^2 \left[ \frac{\Delta_{31} L}{2} \right],$$

where

$$\sin^2 2\theta_{\text{eff}} \equiv \left[ \frac{\sin 2\theta_{13} \pm 2\eta_{\mu e}}{\xi} \right]^2,$$

$$\xi \equiv \sqrt{\sin^2 2\theta_{13} \pm 2\eta_{\mu e} + \left( \cos 2\theta_{13} + (\eta_{\mu e} - \eta_{\tau e}) \right)^2},$$

and the $+(−)$ sign in front of $\eta_{\mu e}$ corresponds to the normal (inverted) mass ordering. For anti-neutrino channel, the sign of $\eta_{\mu e}$ must be changed.

For the atmospheric neutrinos, the sensitivity to the NSI parameters can be estimated by studying the muon neutrino and anti-neutrino survival probabilities for different zenith angles, $\cos \theta_2$. Figure 1 shows the muon neutrino survival probabilities (for the normal mass ordering) for $\cos \theta_2 = -0.3$ (left panels), $-0.6$ (middle panels) and $-1$ (right panels) for the cases without NSI (by solid lines) and with NSI (by non-solid lines). For this calculation, the neutrino evolution equation (15) was solved numerically (without ignoring neither $\Delta m_{12}^2$ nor $\theta_{13}$) using the Earth matter density profile predicted in the Preliminary Reference Earth Model (PREM) model [106].

$\eta_{\mu \mu} = \frac{\varepsilon_{\mu e} \Delta_{ij} V_i}{\Delta_{ij}} \approx 0.1 \times \varepsilon_{\mu e} \left[ \frac{E}{\text{GeV}} \right] \left[ \frac{2.4 \times 10^{-3} \text{ eV}^2}{\Delta m_{ij}^2} \right] \left[ \frac{\rho}{\text{g cm}^{-3}} \right]$ (16)
Note that, by comparing the upper and lower panels, the dependence on the sign of NSI parameters for neutrinos and anti-neutrinos are opposite. Note also that, with a good approximation, the survival probabilities are invariant under the simultaneous transformation 
\[ \Delta_{31} \rightarrow -\Delta_{31} \text{ and } \epsilon_{3\mu} \rightarrow -\epsilon_{3\mu}. \]
In the limit of the 2 flavor approximation, what is relevant is only the relative sign of these quantities. As can be seen from figure 1, the impact of NSI is small for lower energies, for \( E \lesssim 5 \text{ GeV} \), even for the case where neutrino pass through the center of the Earth. On the other hand, the impact of NSI for energy \( E \gtrsim 10 \text{ GeV} \), could be quite large for the NSI parameters considered in figure 1 and it is expected that these values could be disfavored or excluded.

Here we quote the bounds on these NSI parameters obtained by the Super-Kamiokande collaboration (2007),
\[ |\epsilon_{3\mu}| < 1.1 \times 10^{-2} \text{ and } -4.9 \times 10^{-2} < \epsilon_{3\tau} - \epsilon_{3\mu} < 4.9 \times 10^{-2} \text{ at 90% CL}. \]
More recently, by using the IceCube-79 and DeepCore data, authors of (2008) obtained somewhat better bounds, \[ |\epsilon_{3\tau}| \lesssim 6 \times 10^{-3} \text{ and } |\epsilon_{3\tau} - \epsilon_{3\mu}| \lesssim 3 \times 10^{-2} \text{ at 90% CL}. \]

For the \( \nu_e - \nu_e \) sector, besides the probability for \( \nu_e \rightarrow \nu_{\mu} \), it is also useful to consider the \( \nu_{\mu} \rightarrow \nu_e \) case. The computation of these probabilities, shown in figure 2, was done in an analogous way to the case shown in figure 1. For this computation different NSI parameters have been considered: \( \epsilon_{ee}, \epsilon_{e\mu}, \text{ and } \epsilon_{e\tau} \). It is important to notice that, in this case, the \( \epsilon_{e\tau} \) parameters, could play a role similar to \( \theta_{13} \). Therefore, there is some impact on the \( \nu_{\mu} \rightarrow \nu_e \) channel as it is possible to see in the lower panels of figure 2.

When \( \epsilon_{ee}, \epsilon_{e\tau}, \text{ and } \epsilon_{e\tau} \) are assumed to be simultaneously nonzero, it is known (2007) that the allowed combinations of the NSI parameters are approximately given by the parabolic relation,
\[ \epsilon_{e\tau} \sim \frac{3 |\epsilon_{e\tau}|^2}{1 + 3|\epsilon_{ee}|}. \]

This feature can be also confirmed in figures 8 and 9 in (2007) which show the constraints on these NSI parameters obtained by the Super-Kamiokande atmospheric neutrino data. It is also pointed out in (2004) that atmospheric neutrino data alone can not essentially constrain \( \epsilon_{ee} \) parameter. Therefore, in general one can obtain the allowed regions of \( \epsilon_{ee} \) and \( \epsilon_{e\tau} \) for given values of \( \epsilon_{ee} \) as done in (2004, 2007). For example, from figure 9 of (2007), we see that for \( \sin^2 \theta_{23} = 0.5 \), for \( \epsilon_{ee} = -0.5 \), 0, and 0.5, \( \epsilon_{e\tau} \lesssim 0.08, 0.11 \) and 0.18, respectively, at 90% CL.

### 3.4. NSI for accelerator neutrinos

So far the bounds on propagation NSI from accelerator neutrinos mainly come from the \( \nu_{\mu} \rightarrow \nu_{\mu} \) and \( \nu_{\mu} \rightarrow \nu_{\tau} \) channels. For these channels, at first approximation, the relevant NSI parameters are \( \epsilon_{e\mu}, \epsilon_{\mu\mu}, \text{ and } \epsilon_{e\tau} \). The \( \nu_{\mu} \rightarrow \nu_{\tau} \) and \( \nu_{\mu} \rightarrow \nu_{\mu} \) survival probabilities as a function of neutrino energy for the MINOS baseline, \( L = 730 \text{ km} \), are shown in figure 3. The computations were done without the presence of NSI (solid lines) and with
$\epsilon_{\mu\tau} = \pm 0.1$ (dotted and dashed lines). As it is possible to see from figure 3 the impact of NSI for $\nu$ and $\bar{\nu}$ channels are opposite.

The bounds obtained by the MINOS collaboration [109], translated to the notation used in this review, can be stated as $-0.067 < \epsilon_{\mu\tau} < 0.023$ at 90% CL.

### 3.5. NSI for solar neutrinos

The most updated analysis of solar neutrinos in the context of the propagation NSI comes from [74]. For solar neutrinos, under the so-called one mass scale dominance approximation, $|\Delta m^2_{31}| \to \infty$, the neutrino evolution can be effectively reduced to that of the 2 flavorsystem [110], as follows,

$$i \frac{d}{dr} \begin{bmatrix} \nu'_\alpha \\ \nu'_\beta \\ \nu'_\gamma \end{bmatrix} = \left\{ U_{\beta\alpha} \begin{bmatrix} 0 & 0 \\ 0 & \Delta_{21} \end{bmatrix} U_{\beta\alpha}^\dagger + \sum_f V_f \begin{bmatrix} \epsilon^2_{Df} - \epsilon^2_{Nf} \\ \epsilon^2_{Df} \end{bmatrix} \begin{bmatrix} \nu_{\alpha f} \\ \nu_{\beta f} \end{bmatrix} \right\} \begin{bmatrix} \nu'_\alpha \\ \nu'_\beta \end{bmatrix},$$

(21)

where

$$\begin{bmatrix} \nu'_\alpha \\ \nu'_\beta \\ \nu'_\gamma \end{bmatrix} = \begin{bmatrix} \alpha_{12} & s_{12} & 0 \\ -s_{12} & \alpha_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_\alpha \\ \nu_\beta \\ \nu_\gamma \end{bmatrix} = \begin{bmatrix} \epsilon_D & \epsilon_N \\ \epsilon_N & -\epsilon_D \end{bmatrix} \begin{bmatrix} \nu_\alpha \\ \nu_\beta \end{bmatrix},$$

(22)

with $\nu'_\gamma$ being decoupled from the system [110], and diagonal $\epsilon_D$ and off-diagonal $\epsilon_N$ NSI parameters are related to $\epsilon_{\alpha\beta}$ as [74],

$$\epsilon_D = c_{13} s_{13} \text{Re} \left[ e^{i\delta_{\nu}} (s_{23} \epsilon_{\mu\tau} + c_{23} \epsilon_{\mu\tau}) \right] - \left( 1 + s_{13}^2 \right) c_{23} \text{Re} \left( \epsilon_{\mu\tau} \right)$$

$$- \frac{\epsilon_3^2}{2} \left( \epsilon_{\mu\tau} - \epsilon_{\mu\mu} \right) + \frac{s_{23}^2 - s_{13}^2 c_{23}^2}{2} (\epsilon_{\tau\tau} - \epsilon_{\mu\tau}),$$

$$\epsilon_N = c_{13} \left( s_{23} \epsilon_{\mu\tau} - s_{23} \epsilon_{\mu\tau} \right) + s_{13} e^{i\delta_{\nu}} s_{23} \epsilon_{\mu\tau} - c_{13}^2 \epsilon_{\mu\tau} + c_{23} s_{23} \left( \epsilon_{\tau\tau} - \epsilon_{\mu\tau} \right).$$

(23)

In this approximation, the survival probability is given as

$$P(\nu_\alpha \to \nu_\beta) = s_{13}^2 + c_{13}^2 P_{23}(\nu'_\alpha \to \nu'_\beta),$$

(24)

where $P_{23}(\nu'_\alpha \to \nu'_\beta)$ is calculated for the effective 2 flavor system described by (21). According to [74], the bounds on these parameters are $-0.25 < \epsilon_D < -0.02$ and $-0.14 < \epsilon_N < 0.12$ at 90% CL assuming NSI with $d$-quark.

In table 2 we show the summary of the bounds on the propagation NSI.

### 4. NSI phenomenology in detection

Several experiments have been devoted specifically to measure with precision the neutrino interaction with quarks and leptons. They are performed at very short baselines, avoiding effects coming from the standard...
oscillation. These measurements allow us to test the validity of the interactions described by the Standard Model, and, therefore, they could be a basis to search for new physics beyond SM.

For non-oscillation experiments, NSI can be constrained by comparing the measured cross sections with that predicted by SM for the interaction of the neutrinos with the corresponding target. Most of these experiments record fewer events than oscillation experiments. On the other hand, they are independent of the mixing parameters; therefore, the cross section measurements, in general, do not suffer from the uncertainties of the oscillation parameters. Moreover, non-oscillation experiments are sensitive to axial couplings, a coupling that is absent in propagation NSI effects.

Here we will review different experiments that constrain NSI through detection. We will start by considering the neutrino interactions with electrons and, afterwards, we will review its interactions with quarks.

We will illustrate the phenomenology involved in this type of experiment by considering the specific case of the electron anti-neutrino scattering off electrons. In this case, the differential cross section, including the corrections coming from the Lagrangian shown in equation (1), will be given by

$$
\frac{d\sigma}{dT_e} = \frac{2G_F^2 m_e}{\pi} \left[ \left( g_R + \varepsilon^R_{ee} \right)^2 
+ \sum_{\alpha \neq e} |g_\alpha|^2 + \left( \varepsilon^L_{\alpha e} + \sum_{\alpha \neq e} |\varepsilon^L_{\alpha e}| \right)^2 \right] \left[ 1 - \frac{T_e}{E_e} \right]^2 
- \left( \varepsilon^L_{ee} + \varepsilon^R_{ee} \right) \left( \varepsilon^L_{ee} + \varepsilon^R_{ee} \right) \sum_{\alpha \neq e} |\varepsilon^L_{\alpha e}| |\varepsilon^R_{\alpha e}| m_e E_e. \right]
$$

(26)

Here, $m_e$ is the electron mass, $T_e \equiv E_e - m_e$ (with $E_e$ being the total electron energy) stands for the electron recoil energy, and $E_e$ is the anti-neutrino energy. The Standard Model couplings, at tree level, are defined as $g_L = 1/2 + \sin^2 \theta_W$ and $g_R = \sin^2 \theta_W$. We can see from this expression that flavor changing NSI parameters ($\varepsilon_{\mu e}^{LR}$ and $\varepsilon_{\tau e}^{LR}$) will only give quadratic corrections while the flavor diagonal ones could give linear corrections.

This is illustrated in figure 4, where we show the differential cross section for anti-neutrino electron scattering, $\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$, averaged over a typical anti-neutrino reactor spectrum [111, 112]. The plot is given in terms of the electron recoil energy, $T_e$, for an energy window relevant for an anti-neutrino detector such as TEXONO [113, 114]. In the plot, the prediction for the SM cross section is shown, as well as that for the NSI one. For both flavor changing and flavor conserving NSI, the same negative value of the parameters are used; this illustrates how flavor diagonal NSIs have more impact on detection signals than flavor changing parameters.

The NSI parameters for this reaction can be constrained by considering, for example, the data from the TEXONO collaboration, which use $\bar{\nu}_e e$ scattering as the detection signal. We have updated the analysis reported by the TEXONO collaboration [113], including the new predicted spectrum [111, 112] and radiative corrections [115] in order to obtain new constraints for these parameters. We have also combined the results of this analysis with the constraints coming from the $\nu_e e$ scattering measurements reported by the LSND collaboration [116]. By combining these two experiments we can obtain stronger bounds both on left and right NSI parameters, taking advantage of the different chirality of both neutrino experiments. The result of this new analysis is shown in figure 5 for the diagonal parameters $\varepsilon_{\mu e}^{LR}$, and is also shown in table 3 along with other current constraints.

Previous works involving the neutrino scattering off electrons obtained constraints from a combined analysis of reactor neutrino experiments. There are different experiments that involve an electron (anti)neutrino...
Figure 4. Averaged differential cross section for the electron anti-neutrino scattering off electrons for the SM case (black solid line), for a flavor changing NSI (blue dashed line), and for a flavor conserving NSI (green dashed dotted line). The reactor anti-neutrino flux has been considered in order to integrate the anti-neutrino cross section over the appropriate neutrino energy range.

Figure 5. Allowed region, at 90% CL, for diagonal NSI parameters, $\varepsilon _{ee}^{R}$, from a combined analysis of TEXONO reactor anti-neutrino and LSND neutrino electron scattering off electrons.

| Table 3. Constraints on the detection NSI couplings at 90% C.L for the interaction of neutrinos with electrons |
|----------------------------------------------------------|
| One parameter | Two parameter |
|----------------|----------------|
| $\varepsilon _{ee}^{R}$ | ($-0.021, 0.052$) $[^{[60]}]$ | ($-0.02, 0.09$) $[^{[68]}]$ | ($-0.036, 0.063$) $[^{[60]}]$ |
| $\varepsilon _{\mu e}^{R}$ | ($-0.07, 0.08$) $[^{[122]}]$ | ($-0.08, 0.09$) $[^{[123]}]$ | ($-0.10, 0.09$) $[^{[123]}]$ |
| $\varepsilon _{e\mu}^{R}$ | ($-0.03, 0.03$) $[^{[40]}]$ | ($-0.03, 0.03$) $[^{[54]}]$ | ($-0.033, 0.055$) $[^{[54]}]$ |
| $\varepsilon _{ee}^{R}$ | ($-0.03, 0.03$) $[^{[40]}]$ | ($-0.03, 0.03$) $[^{[54]}]$ | ($-0.040, 0.053$) $[^{[54]}]$ |
| $\varepsilon _{ee}^{L}$ | ($-0.16, 0.11$) $[^{[60]}]$ | ($-0.46, 0.24$) $[^{[54]}]$ | ($-0.51, 0.34$) $[^{[68]}]$ |
| $\varepsilon _{e\mu}^{L}$ | ($-0.25, 0.45$) $[^{[54]}]$ | ($-0.35, 0.50$) $[^{[68]}]$ | ($-0.4, 0.6$) $[^{[54]}]$ |
| $\varepsilon _{e\mu}^{R}$ | ($-0.13, 0.13$) $[^{[54]}]$ | ($-0.13, 0.13$) $[^{[54]}]$ | ($-0.16, 0.11$) $[^{[60]}]$ |
| $\varepsilon _{ee}^{R}$ | ($-0.19, 0.19$) $[^{[122]}]$ | ($-0.13, 0.13$) $[^{[54]}]$ | ($-0.53, 0.53$) $[^{[35]}]$ |
| $\varepsilon _{ee}^{L}$ | ($-0.4, 0.4$) $[^{[40]}]$ | ($-0.33, 0.33$) $[^{[54]}]$ | ($-0.53, 0.53$) $[^{[35]}]$ |
| $\varepsilon _{e\mu}^{R}$ | ($-0.28, -0.05$) and $[^{[54]}]$ | ($0.05, 0.28$) $[^{[54]}]$ | ($-0.53, 0.53$) $[^{[35]}]$ |
| $\varepsilon _{e\mu}^{L}$ | ($-0.19, 0.19$) $[^{[122]}]$ | ($-0.13, 0.13$) $[^{[54]}]$ | ($-0.53, 0.53$) $[^{[35]}]$ |

flux, such as reactor neutrinos (TEXONO $[^{[113]}]$, MUNU $[^{[117]}]$, Rovno $[^{[118]}]$, Krasnoyarsk $[^{[119]}]$, Irvine $[^{[120]}]$) and accelerator neutrinos (LSND $[^{[116]}]$ and LAMPF $[^{121}]$).

We show in table 3 the summary of the constraints from these analysis. We prefer to show in this table results obtained by different research groups since the analysis may have different assumptions that can be important in the interpretation of the parameters. These results consider either one or two parameters at a time, while all
other parameters equal to zero; in some cases, especially for flavor diagonal couplings, the correlation between these two parameters is important.

We also show in table 3 the constraints obtained from muon (anti)neutrino fluxes, based on the results coming from the CHARMII experiments [124]. Although there is no manmade tau neutrino sources, it is possible to constrain these interactions if one considers the LEP measurements of the process $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ where tau neutrinos appear as part of this inclusive reaction, or to consider the solar neutrino flux that also includes a tau neutrino component [60]; such constraints are also shown in table 3.

In order to get constraints on the NSI of neutrinos with $d$ type quarks, it is necessary to study experiments such as CHARM, CDHS [125, 126] and, more recently, by NuTeV [127]. They have measured the cross section for the scattering of electron and muon neutrinos off quarks. For the case of NuTeV, there have been a long discussion about a discrepancy of the measured cross section with the SM prediction. After the revaluation of the predicted sea contributions from the $c$ quark, it has been possible to solve this puzzle [128, 129]; currently NSI suggested by the NuTeV experiment are considered as consistent with zero.

Table 4 shows the summary of the constraints for the $d$ quark NSI coming from these experiments. Constraints coming from charge lepton flavor conversion, such as $\mu \rightarrow e\gamma$ or $\mu \rightarrow e\nu\nu$, have not been considered here. They always involve, at some level, a one loop dressing of the neutrino vertex; therefore, they will always be model dependent. The readers interested in such constraints can see, for example, those reported in [65, 130].

5. Future Prospects

There are several experimental proposals that plan to improve the current knowledge of neutrino properties. Therefore, there is plenty of room to improve the sensitivity to NSI in the near future. Some of these experimental set-ups are discussed below, showing the future perspectives for different types of experiments.

Again, the discussion is divided into propagation and detection NSI.

It is important to notice that, besides the need for more restrictive bounds on NSI parameters, it is also necessary to solve the possible confusion between standard and non-standard parameters. As has been stated in the past [36], it is possible to have a confusion in neutrino oscillation experiments between NSI parameters and standard mixing angles, especially $\theta_{13}$; recently, this subject has been discussed in the context of solar [131] and reactor neutrinos [78, 79]. The significant progress in improving the precision on $\theta_{13}$ will strongly restrict this possibility in the near future.

Another important topic in this direction is that of the robustness of the solar neutrino data against NSI. It might be possible that large NSI effects give rise to a dark-LMA solution without contradicting any current experimental result [132]. This solution has persisted as a plausible picture [63, 74], and could be generated through an extra $U(1)'$ gauge symmetry [133]. A recent study on the future combined data of JUNO [134], RENO-50 [135] and NOvA [136] has discussed the perspectives to exclude this solution [137].

5.1. Perspectives for NSI in propagation

Different experimental set-ups (proposed to increase the precision for the determination of the neutrino oscillations parameters) have been considered in recent years. The need for a better knowledge of the Kobayashi-Maskawa type CP phase in the lepton sector as well as the mass ordering is certainly a major motivation for these proposals. Currently ongoing experiments such as T2K and NOvA may improve somewhat the current bounds.
on some NSI parameters but probably not so much, especially for that coming from the $\nu_e (\bar{\nu}_e)$ appearance mode due to relatively small statistics.

Hyper-Kamiokande [138–140] is an interesting proposal that expects to improve the sensitivity to NSI, by using the atmospheric neutrino data [141–143]; their expectations for the normal hierarchy case are particularly appealing. the LBNE [144] and LBNO [145] proposals, the expected sensitivity to NSI is also encouraging, especially for the flavor changing case of $\epsilon_{\mu e}$ and $\epsilon_{\mu\tau}$ [146].

Finally, important constraints are expected from the IceCube Deep Core and PINGU experiments. These are extensions of the IceCube experiment focused on a lower energy range. In this case, the expectations to constrain the flavor changing NSI parameter $\epsilon_{\mu\tau}$ could reach the one percent level. For the flavor diagonal case, it might be possible to obtain information about the elusive parameter $\epsilon_{ee}$ [108, 147, 148].

5.2. Perspectives for NSI in detection

The future neutrino oscillation experiments will also be sensitive to the NSI parameters through a detection effect. For instance, for the case of the proposed JUNO [134] and RENO-50 [135] an improvement to the constraints on $\epsilon_{\mu\mu}$ and $\epsilon_{\mu\tau}$ is expected [77].

For the case of the interaction of electron neutrinos with electrons, both ISODAR [149] and LENA [150] proposals could give complementary information if both proposals are done in the future. In the case of ISODAR, it is proposed to use an intense anti-neutrino $^6$Li source, with an anti-neutrino energy ranging up to 14 MeV, in combination with the KamLAND liquid scintillator [149]. The LENA proposal plans to use a neutrino Chromium source, providing a monochromatic neutrino flux of energy, $E_{\nu} = 0.747$ MeV, located at the top of a 100 kTon liquid scintillator cylindrical detector [150]. These are not the only proposals for neutrino electron scattering, but they illustrate the future potential of this experiments.

The use of either a neutrino or anti-neutrino source leads to a better determination of the left or right-handed couplings, respectively. Therefore, if both neutrino and anti-neutrino experiments are done in the future, there could be a good room for the improvement of the NSI parameters.

We illustrate this by showing, in figure 6, the expected sensitivity for the case of a neutrino artificial source in combination with the proposed LENA detector as has already been calculated in [151], where an expected total number of $1.9 \times 10^5$ neutrino events and a 5% systematic error was considered. The case of an anti-neutrino source is also shown in figure 6. In this last case the analysis developed in [149] has been closely followed. The expected result from the combined analysis of both future experiments is shown by the region filled by the magenta color. We show in the same figure one of the current constraints on NSI, coming from the solar neutrino analysis [60]. It is possible to see that there is room for improving these constraints by almost one order of magnitude, especially if both experiments are realized.

Regarding the NSI of neutrinos with quarks, there are several proposals that could improve current bounds. An interesting proposal is that of neutrino coherent scattering off nuclei [152]. After seminal works on the construction of these type of detectors [153, 154], there was a renewed interest in the previous decade [155, 156]. At the same time, the sensitivity to NSI parameters and new physics searches was also noted [49, 157]. Different experimental set-ups have already been considered, either using a reactor anti-neutrino flux [156], and spallation source [158–160, 166], beta beams [161, 162], or pion decay [163–165]. These experiments could have an excellent sensitivity to the NSI. In particular, the TEXONO proposal has been studied in the past, using either
a $^{76}$Ge or $^{28}$Si as a detector; an improvement of even one order of magnitude could be achieved in this case [157]. Other possible nuclei have also been studied [130] such as $^{48}$Ti and $^{27}$Al.

6. Conclusions

Neutrino experiments have shown the existence of a new sector beyond the Standard Model because of the experimental evidences of nonzero neutrino masses that is already part of the current knowledge on particle physics. The mass and mixing of lepton sector turned out to be non-trivial, very different from that of the quark sector. While our knowledge on neutrino properties is continuously improving, the theoretical explanation of the neutrino mixing and the neutrino mass pattern is still an open question.

In this context, possible presence of the non-standard interaction of neutrinos and its impact was discussed in this brief review from a phenomenological point of view, describing the current status on the search for new physics coming from NSI.

So far there is no experimental evidence or indication of the presence of NSI and there exist only the constraints, which are summarized in tables 2, 3 and 4 where we show the lower and upper bounds of the NSI parameters. Ongoing as well as proposed near future neutrino experiments are expected to improve considerably the NSI bounds or may indicate the presence of NSI.

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