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Left-right symmetric models and long baseline neutrino experiments

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The Standard Model has been the most successful theory in the history of particle physics, but it fails to account for many important questions, such as the origin of neutrino mass. The so-called left-right symmetric models provide an easy answer to these issues by adding a simple extension to the Standard Model gauge group, but it implies the existence of heavy right-handed neutrinos and additional Higgs particles. In this work we discuss how the left-right symmetry group would affect neutrino oscillations taking place in long baseline neutrino oscillation experiments in the form of sterile neutrinos and non-standard neutrino interactions, using the Deep Underground Neutrino Experiment as our example.

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1. Introduction

The celebrated discovery of neutrino oscillations proved that the Standard Model (SM) gauge group $\mathrm{SU(2)_L \times U(1)}_Y$ is not able to describe all particle physics phenomena, as it cannot explain the origin of neutrino mass. The existence of neutrino oscillations is therefore a direct indication of physics beyond the SM.

The present neutrino oscillation experiments indicate that the neutrino masses m_1, m_2 and m_3 correspond to the two squared mass differences $\Delta m_{21}^2 = m_2^2 - m_1^2 \approx 7.5 \times 10^{-5}\,\mathrm{eV}^2$ and $|\Delta m_{31}^2| = |m_3^2 - m_1^2| \approx 2.5 \times 10^{-3}\,\mathrm{eV}^2$. From these results it is obvious that there must be at least two neutrino masses that are different from zero. Thus far experiments have not yet determined neither the magnitude nor the ordering of the neutrino masses. At the same time, it is unknown why the neutrino masses are light as compared with the other massive particles.

One popular method to tackle the lightness problem is the so-called seesaw mechanism, where the suppression of neutrino masses follows from the existence of a new mass scale much higher than the electroweak scale $\mathscr{O}(10^2)$ GeV. In Type I seesaw models the neutrino masses are generated by heavy right-handed neutrinos, whereas in Type II seesaw models a set of new scalars $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$ is added to the SM particle content. In both types of models, the SM particle content is extended with new particles, leading to potentially testable phenomena at the current and future particle physics experiments.

In this proceeding, we focus on the so called left-right symmetric models, where Type I and II seesaw models occur naturally. In this class of models, the SM gauge group is extended to $\mathrm{SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)}_{B-L}$. In addition to explaining the small neutrino masses via a Type I+II seesaw mechanism, the advantages of the left-right symmetric models include the spontaneous breaking of the CP symmetry. Left-right symmetric models have been studied vastly in the literature, and its signatures of have been sought in e.g. high-energy proton-proton collision experiments. In this work, we investigate the prospects of probing scalar triplets of the left-right symmetric models in long baseline neutrino experiments.

2. The left-right symmetry

While SM is very successful in describing the interactions at the electroweak scale, in addition to the emergence of neutrino masses, it does not explain the origin of parity violation. Both of these mysteries are mitigated in left-right symmetric models (LRSM), which assume the fundamental interactions are parity symmetric at high energies. This requires a larger particle content, consisting of right-handed neutrinos and gauge bosons and an extended scalar sector. In addition, LRSM can be thought of as an intermediate step between SM and SO(10) grand unified theory, which has a built-in automatic $B-L$ gauge symmetry and right-handed neutrinos.

The electroweak part of LRSM has the gauge group $G = \mathrm{SU(2)}_L \times \mathrm{SU(2)}_R \times \mathrm{U(1)}_{B-L}$, where the generator of U(1) group exhibits anomaly-free quantum number $B-L$. The electric charge operator is given by

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2} \tag{2.1}$$

In addition to gauge transformations, LRSM is invariant under the parity transformation $L \leftrightarrow R$.

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The right-handed fermions ν_{Ri} and ℓ_{Ri} form SU(2)$_R$ doublets $L_{Ri} = \binom{\nu_{Ri}}{\ell_{Ri}} \sim (\mathbf{1},\mathbf{2},-1)$. To break the LRSM gauge group G to SM electroweak gauge group, one has to introduce left- and right-handed leptophilic scalar triplets $\Delta_L \sim (\mathbf{3},\mathbf{1},2)$ and $\Delta_R \sim (\mathbf{1},\mathbf{3},2)$, respectively. This is the minimal LRSM field content. The Yukawa Lagrangian relevant to neutrino oscillations is

$$\mathscr{L} = \sum_{i,j=1}^{3} h_{ij}\overline{L}_{Li}\phi L_{Rj} + \tilde{h}_{ij}\overline{L}_{Li}\tilde{\phi}L_{Rj} + Y_{ij}(L_{Li}^T C^{-1}\sigma_2\Delta_L L_L + L_{Ri}^T C^{-1}\tau_2\Delta_R L_{Rj}) + \text{h.c.} \tag{2.2}$$

where the SM Higgs fields are presented as a bidoublet ϕ, and $\tilde{\phi} \equiv \sigma_2\phi^*\sigma_2$, with $\phi,\tilde{\phi} \sim (\mathbf{2},\mathbf{2},0)$. These terms generate light neutrino masses via Type I+II seesaw mechanism (see Fig. 1). Similarly the scalar triplet are 2×2-matrices, defined

$$\Delta_L = \sum_{i=1}^{3} \frac{1}{\sqrt{2}}\sigma_i\Delta_{Li}, \qquad \Delta_R = \sum_{i=1}^{3} \frac{1}{\sqrt{2}}\sigma_i\Delta_{Ri}. \tag{2.3}$$

The scalar sectors gain the following vacuum expectation values:

$$\langle\Delta_L\rangle = \begin{pmatrix} 0 & 0 \\ v_L & 0 \end{pmatrix}, \qquad \langle\Delta_R\rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}, \qquad \langle\phi\rangle = \begin{pmatrix} k & 0 \\ 0 & k' \end{pmatrix}, \tag{2.4}$$

where $k^2 + k'^2 = 2v^2$. Let us denote $\phi_1 \equiv \phi$ and $\phi_2 \equiv \tilde{\phi}$. The scalar potential of LRSM contains mixed $\Delta_L\Delta_R\phi$ terms

$$\sum_{i,j=1}^{2} \gamma_{ij}\text{Tr}(\Delta_L^\dagger\phi_i\Delta_R\phi_j^\dagger) + \text{h.c.}, \tag{2.5}$$

and assuming that right-handed scalar triplet is much more massive that Δ_L and SM Higgs, we may integrate out the right-handed scalar, leaving a effective trilinear term (H is the SM Higgs doublet)

$$\mathscr{L}_{HH\Delta_L} = \lambda_\phi H^T i\sigma_2\Delta_L^\dagger H. \tag{2.6}$$

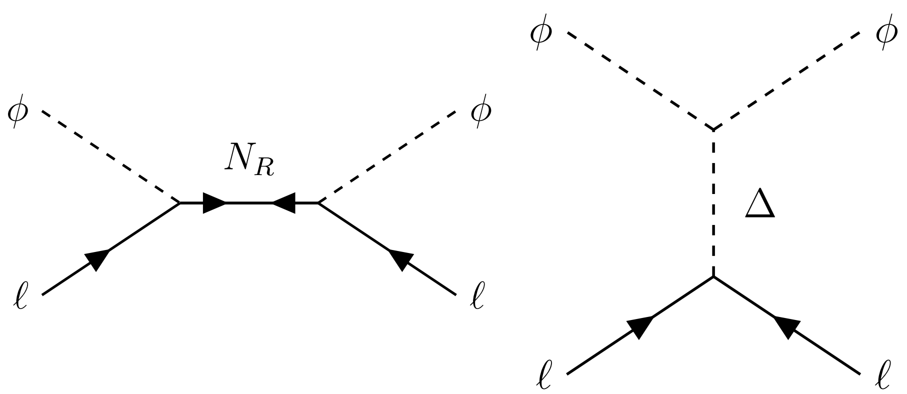

Figure 1: Tree-level generation of neutrino masses in Type I (left) and Type II (right) seesaw mechanisms, both of which are present in left-right symmetric models. In Type I neutrino masses originate from interactions with the right-handed neutrinos N_R and in Type II in the scalar triplet Δ.

3. Implications on long baseline neutrino experiments

In this work, we estimate the phenomenological implications of the triplet scalar and heavy right-handed neutrino fields in long baseline neutrino experiments. Specifically, we calculate the experimental sensitivities for the future neutrino oscillation facilities to measure the properties of the triplet Higgs bosons Δ in presence of the heavy right handed neutrinos N_i, where $i = 1,2,3$.

We study the triplet in the limit where the mass of the triplet scalars M_Δ is assumed to be the same for Δ^0, Δ^+ and Δ^{++}, and the momenta of the processes are negligible with respect to the triplet mass. In this limit, the amplitudes of the relevant processes are described by the following effective Lagrangians [1]:

$$\mathscr{L}_\nu^m = \frac{Y_{\alpha\beta}\,\lambda_\phi\,v^2}{M_\Delta^2}\,\left(\overline{\nu_{\alpha R}^C}\,\nu_{\beta L}\right) = -\frac{1}{2}\,(m_\nu)_{\alpha\beta}\,\overline{\nu_{\alpha R}^C}\,\nu_{\beta L}, \tag{3.1}$$

$$\mathscr{L}_{\rm NSI} = \frac{Y_{\sigma\beta}\,Y_{\alpha\rho}^\dagger}{M_\Delta^2}\,\left(\overline{\nu_{\alpha L}}\,\gamma_\mu\,\nu_{\beta L}\right)\,\left(\overline{\ell_{\rho L}}\,\gamma^\mu\,\ell_{\sigma L}\right), \tag{3.2}$$

where m_ν is the mass matrix that represents the left-handed neutrinos, λ_ϕ is the trilinear coupling strength from Eq. (2.6), and v is the vacuum expectation value of the SM scalar Higgs field ϕ. The Yukawa couplings are contained in the matrix Y.

The NSI term of the effective Lagrangian in Eq. (3.2) describes the non-standard neutrino interactions (NSI) with leptons. These interactions arise from couplings with the scalar triplet Δ. In neutrino oscillations taking place in long baseline experiments the effective NSI Lagrangian can also be written as

$$\mathscr{L}_{\rm NSI} = -2\sqrt{2}G_F\,\varepsilon_{\alpha\beta}^{ff'C}(\overline{\nu}_{\alpha L}\gamma^\mu\nu_{\beta L})(\overline{f}\gamma_\mu P_C f'), \tag{3.3}$$

where P_C refers to the chiral projection operators P_L and P_R, G_F is the Fermi coupling constant, f and f' are fermions of any type, and $\varepsilon_{\alpha\beta}^{ff'C}$ $(\alpha,\beta = e,\mu,\tau)$ are the NSI parameters to describe the strength of the NSI couplings.

The NSI effects that emerge in neutrino propagation in matter are derived by solving the Yukawa coupling $Y_{\alpha\beta}$ from the Majorana mass term in Eq. (3.1), inserting it to Eq. (3.2), and comparing the result with Eq. (3.3). This yields the following expression:

$$\varepsilon_{\alpha\beta}^{\rho\sigma} = -\frac{M_\Delta^2}{8\sqrt{2}\,G_F\,v^4\,\lambda_\phi^2}\,(m_\nu)_{\sigma\beta}\,(m_\nu^\dagger)_{\alpha\rho}, \tag{3.4}$$

where α,β,ρ and σ are flavor indices. The expression (3.4) indicates the larger the ratio $M_\Delta^2/\lambda_\phi^2$ the stronger are the NSI of the light neutrinos. Conversely, stricter bounds on $\varepsilon_{\alpha\beta}^{\rho\sigma}$ also mean more stringent constraints on $M_\Delta^2/\lambda_\phi^2$.

In this work we interested in the NSI couplings with electrons, which are parametrized as $\varepsilon_{\alpha\beta}^m = \varepsilon_{\alpha\beta}^{ee}$, where $\alpha,\beta = e,\mu,\tau$. In the literature, these are often referred to as the matter NSI parameters.

The only background in probing the NSI effects caused by the scalar triplets is the presence of heavy right-handed neutrinos. In left-right symmetric models the heavy right-handed neutrino fields give rise to three heavy neutrinos neutrinos with masses close to the electroweak scale. These neutrinos are too heavy to be kinematically accessible in neutrino oscillation experiments, but they do affect the oscillation of light neutrinos by making their mixing matrix non-unitary. There are several methods to parametrize the low energy effects of the non-unitarity, but in this work we choose the parametrization which was introduced in Ref. [2]. In this framework, mixing between the light neutrinos is described with the non-unitary mixing matrix $N = N^{\rm NP}U$, where U is the conventional unitary 3×3 matrix and $N^{\rm NP}$ is the triangular matrix

$$N^{\rm NP} = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix}. \tag{3.5}$$

Here $\alpha_{\ell\ell'}$ parametrize the deviations from unitarity, and since these deviations are known to be small, one has $\alpha_{\ell\ell} \ll 1$ and $|\alpha_{\ell\ell'}| \ll 1$.

The parametrizations used for the triplet non-standard interactions in Eq. (3.4) and the non-unitarity of the mixing matrix in Eq. (3.5) do correlate to some extent. In the leading order, the two low energy parametrizations are related as follows [2]:

$$\begin{aligned} &\varepsilon^m_{ee} = -\alpha_{ee} && \varepsilon^m_{\mu\mu} = \alpha_{\mu\mu} && \varepsilon^m_{\tau\tau} = \alpha_{\tau\tau} \\ &\varepsilon^m_{e\mu} = \frac{1}{2}\alpha^*_{\mu e} && \varepsilon^m_{e\tau} = \frac{1}{2}\alpha^*_{\tau e} && \varepsilon^m_{\mu\tau} = \frac{1}{2}\alpha^*_{\tau\mu}. \end{aligned} \tag{3.6}$$

The non-unitarity of the light neutrino mixing matrix and the matter NSI effects have both been studied in the literature. The prospects of constraining the matter NSI parameters in DUNE were studied in detail in Ref. [3] and the present experimental constraints on the non-unitarity parameters are presented in Ref. [2].

4. Numerical studies

In this section we calculate the available parameter values which DUNE will be sensitive to regarding the triplet mass M_Δ and the trilinear coupling strength λ_ϕ. We begin by estimating the upper bound for the ratio $M_\Delta/|\lambda_\phi|$ which DUNE can constrain in case no signal of matter NSI is found.

First, we rewrite Eq. (3.4) into the following forms:

$$\frac{M_\Delta^2}{\lambda_\phi^2} = -\frac{8\sqrt{2}G_F\, v^4\, \varepsilon^m_{\alpha\beta}}{(m_\nu)_{e\beta}(m_\nu^\dagger)_{\alpha e}}, \tag{4.1}$$

$$\frac{M_\Delta^2}{\lambda_\phi^2} = -\frac{8\sqrt{2}G_F\, v^4\, (\varepsilon^m_{\alpha\beta} - \varepsilon^m_{\alpha'\beta'})}{(m_\nu)_{e\beta}\,(m_\nu^\dagger)_{\alpha e} - (m_\nu)_{e\beta'}\,(m_\nu^\dagger)_{\alpha' e}}, \tag{4.2}$$

where $\varepsilon^m_{\alpha\beta} = \varepsilon^{ee}_{\alpha\beta}$ and $\varepsilon^m_{\alpha'\beta'} = \varepsilon^{ee}_{\alpha'\beta'}$ for $\alpha, \beta, \alpha', \beta' = e, \mu, \tau$.

From the expressions in Eqs. (4.1) and (4.2) we calculate the upper limits for $M_\Delta^2/\lambda_\phi^2$ from the known 90% CL bounds for $|\varepsilon^m_{\alpha\beta}|$ and $|\varepsilon^m_{\alpha\beta} - \varepsilon^m_{\alpha'\beta'}|$. The elements of the light neutrino mass matrix m_ν are obtained from the equation

$$(m_\nu)^2 = U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + A \begin{pmatrix} 1+\varepsilon^m_{ee} - \varepsilon^m_{\mu\mu} & \varepsilon^m_{e\mu} & \varepsilon^m_{e\tau} \\ \varepsilon^{m*}_{e\mu} & 0 & \varepsilon^m_{\mu\tau} \\ \varepsilon^{m*}_{e\tau} & \varepsilon^{m*}_{\mu\tau} & \varepsilon^m_{\tau\tau} - \varepsilon^m_{\mu\mu} \end{pmatrix}, \tag{4.3}$$

where U is the PMNS neutrino mixing matrix.

We maximize the denominators of (Eq. 4.1) and (4.2) by varying all relevant oscillation parameters within their current experimental limits. Using the current experimental limits and the DUNE sensitivities available for $|\varepsilon^m_{ee} - \varepsilon^m_{\mu\mu}|$, $|\varepsilon^m_{\tau\tau} - \varepsilon^m_{\mu\mu}|$, $|\varepsilon^m_{e\mu}|$, $|\varepsilon^m_{e\tau}|$ and $|\varepsilon^m_{\mu\tau}|$, one can obtain upper bounds for $M_\Delta/|\lambda_\phi|$. See Ref. [4] for more details.

The presence of heavy right-handed neutrinos may cause similar deviations from the standard three neutrino oscillations as the matter NSI originating from interactions with the scalar triplet. The parameter values for which the non-unitarity due to the heavy right-handed neutrinos can be identified by converting the present experimental constraints for the non-unitarity parameters [2] into matter NSI parameters by using the relations in Eq. (3.6).

The results are presented in Fig. 2. The white region shows the parameter values which can be excluded by 90% confidence level with the present experimental data (see Ref. [3]). When the DUNE bounds are taken into account, the yellow region is excluded. The blue region represents the parameter values for which the non-unitarity caused by the heavy right-handed neutrinos can be mistaken as matter NSI from the scalar triplet. The green region shows the values which can not be probed by DUNE and are distinguishable from the non-unitarity effect. The dashed, dot-dashed and dotted lines show where these 90% CL contours would be if interted hierarchy was assumed.

Finally, we calculate which parameter values are allowed for λ_ϕ when the present experimental limits for M_Δ are taken into account. It is known from collider experiments that there are lower limits for the triplet mass M_Δ. We approximate this as a constraint $M_\Delta \gtrsim 750\,\mathrm{GeV}$ and obtain the lower bounds for λ_ϕ. See Ref. [4] for more details. The results are presented in Fig. 3.

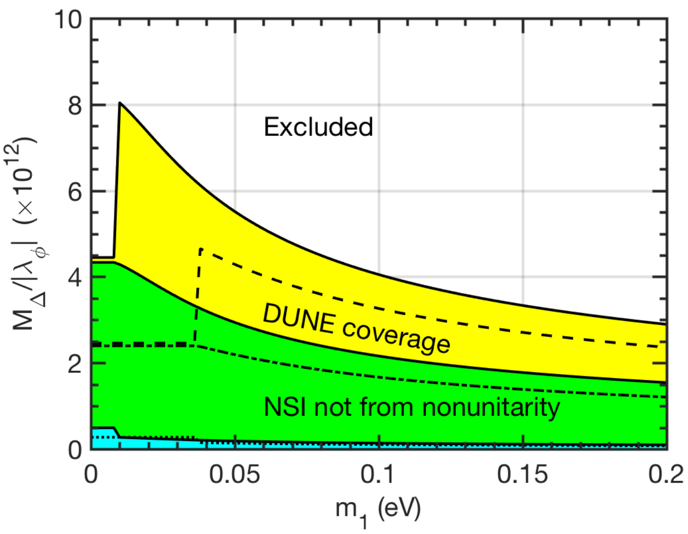

Figure 2: The allowed values of $M_\Delta/|\lambda_\phi|$ at 90% CL, shown as function of the absolute neutrino mass scale. When the normal hierarchy is assumed, the yellow, green and blue regions correspond to the allowed values for the present experimental limits, DUNE sensitivities, and the non-unitarity ambiguity, respectively. The dashed, dot-dashed and dotted lines show the 90% CL contours for inverted hierarchy. See Ref. [4] for more details.

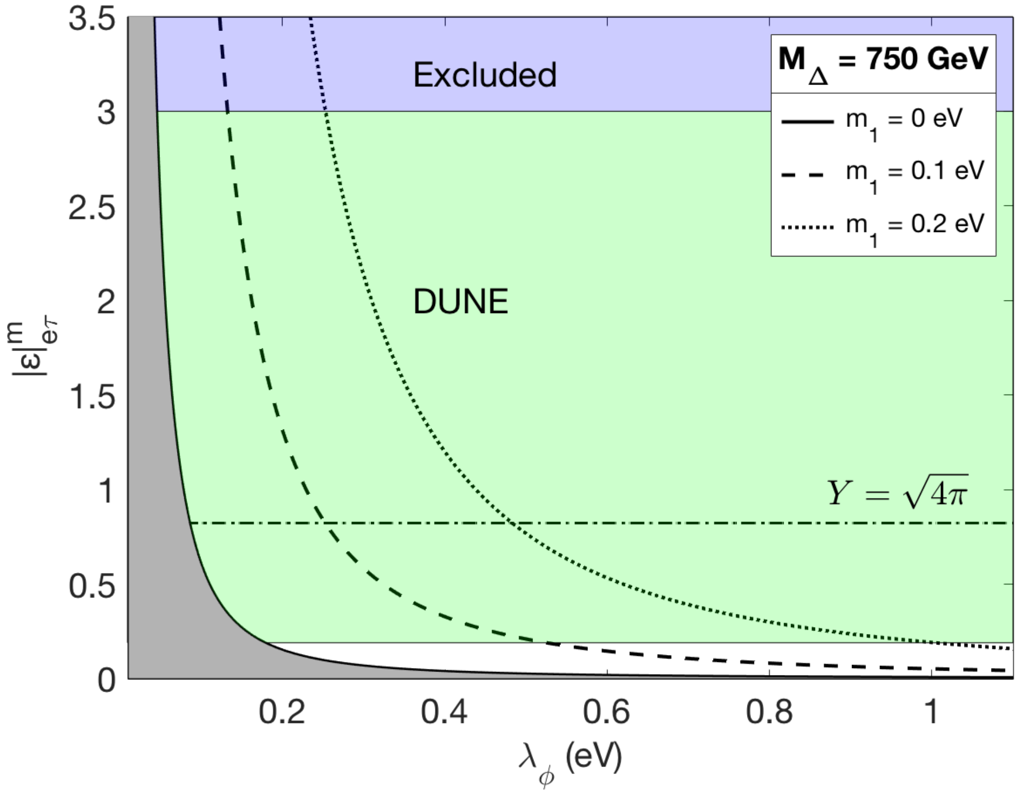

Figure 3: The allowed values of $|\varepsilon^m_{e\tau}|$ and λ_ϕ in $(\lambda_\phi, |\varepsilon^m_{e\tau}|)$-plane. The blue region is excluded by the present experimental limits, whereas the green region shows the parameter values which are available in DUNE. When $M_\Delta \gtrsim 750\,\mathrm{GeV}$, everything below each m_1 contour is excluded. The contours are shown for m_1 =0, 0.1 and 0.2 eV. The dot-dashed line shows the $\varepsilon^m_{e\tau}$ values which correspond to the Yukawa couplings $Y_{\alpha\beta} = \sqrt{4\pi}$, where $\alpha, \beta = e, \mu, \tau$. See Ref. [4] for more details.

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