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Quasi-Dirac neutrinos in the linear seesaw model

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Abstract. We implement a minimal linear seesaw model (LSM) for addressing the Quasi-Dirac (QD) behaviour of heavy neutrinos, focusing on the mass regime of $M_N \lesssim M_W$. Here we show that for relatively low neutrino masses, covering the few GeV range, the same-sign to opposite-sign dilepton ratio, $R_{\ell\ell}$, can be anywhere between 0 and 1, thus signaling a Quasi-Dirac regime. Particular values of $R_{\ell\ell}$ are controlled by the width of the QD neutrino and its mass splitting, the latter being equal to the light-neutrino mass m_ν in the LSM scenario. The current upper bound on m_{ν_1} together with the projected sensitivities of current and future $|U_{N\ell}|^2$ experimental measurements, set stringent constraints on our low-scale QD mass regime. Some experimental prospects of testing the model by LHC displaced vertex searches are also discussed.

1. Introduction

One of the most notorious evidence of Physics Beyond the Standard Model comes from the oscillatory behaviour of neutrinos, what in turn entails the existence of small neutrino masses. Among the rich variety of models addressing the generation of neutrino masses, the well-known seesaw mechanism can be considered as the most accepted framework, this involves extra heavy neutral fermions, denoted here as N_i ($i = 1, 2, \dots, n$, depending on the concrete seesaw realization). In most of these scenarios, the heavy neutrinos are Majorana fermions. However, in some seesaw scenarios, pairs of these Majorana neutrinos can reach smoothly their mass degeneracy limit, $\Delta M_N \to 0$. In this approximate degeneracy case, when ΔM_N is small but still finite (comparable to Γ_N), the LNV effects induced by its Majorana nature cancel only partially. These almost degenerate neutrinos are usually called *Quasi-Dirac* (QD) neutrinos. In the recent work in Ref. [1], we studied the framework of the minimal linear seesaw model, which naturally yields pairs of Quasi-Dirac right-handed neutrinos N and N' in a regime of masses below M_W.

2. Model setup

Besides the SM content, the minimal version of the LSM contains two different types of neutral $SU(2)$ singlet fermions (N, S) per generation. The corresponding Lagrangian contains, in addition to the kinetic sector, the following terms:

$$\mathcal{L}_Y = Y_D \overline{L} H^c N + Y_\epsilon \overline{L} H^c S + M_R \overline{N^c} S + \text{h.c.} \tag{1}$$

We do not show flavor indices to simplify the notation. In three generations, Y_D and Y_ϵ are 3×3 Yukawa matrices, with $Y_D \neq Y_\epsilon$, and M_R is a 3×3 diagonal matrix.

Working on the basis of Eq. (1), namely (ν_L^c, N, S), the texture of the neutrino mass (9×9) matrix, given in a 3×3 block notation, reads:

$$M_\nu = \begin{pmatrix} 0 & m_D & M_\epsilon \\ m_D^T & 0 & M_R \\ M_\epsilon^T & M_R^T & 0 \end{pmatrix}, \tag{2}$$

with $m_D = v_{SM} Y_D / \sqrt{2}$ and $M_\epsilon = v_{SM} Y_\epsilon / \sqrt{2}$. Bringing this 3×3 matrix into a block-diagonal form — through a diagonalization-like procedure considering $M_\epsilon \ll m_D < M_R$ — the non-diagonal mass matrix of the light neutrinos is given by

$$m_\nu = m_D M_R^{-1} M_\epsilon^T + M_\epsilon M_R^{T^{-1}} m_D^T = \frac{v^2}{2} (Y_D M_R^{-1} Y_\epsilon^T + Y_\epsilon M_R^{T^{-1}} Y_D^T). \tag{3}$$

This model naturally generates small light neutrino masses from the smallnes of the lepton-number violating term M_ϵ and the linear dependence on m_D, what precludes M_R from being extremely large.

An important feature of the LSM is the smallness of the mass splitting between both heavy neutrinos in each generation:

$$\Delta M_i \sim m_{\nu_i}, \tag{4}$$

this becomes crucial to study the Quasi-Dirac behaviour of pairs of heavy neutrinos in the linear seesaw model, as it is described in the next section.

3. Quasi-Dirac neutrinos

The Dirac-Majorana dichotomy present in the literature regarding the nature of neutrinos may be somehow misleading, since the Dirac case can be considered as a limiting case of a more general Majorana scenario presenting twice the neutrino content and degenerated masses, where all LNV sources of the model have vanished. Now, by reaching the Dirac limit in a continuous way — by gradually switching off the LNV mass terms — one enters an interesting, although narrow regime, usually defined as *Quasi-Dirac*.

At the LHC, a common observable used to look for Majorana neutrinos is the same-sign (SS) to opposite-sign (OS) dilepton ratio in $\ell\ell jj$ events with no missing p_T, which is called here $R_{\ell\ell}$. Lepton number violating processes — mediated by Majorana neutrinos — lead to these events with same-sign pairs of leptons, while opposite-sign pairs are produced via lepton number conserving processes mediated by both Dirac and Majorana neutrinos.

We would like to stress the fact that prompt searches of these charged leptonic signals are background dominated, while the displaced vertex (DV) events are background free. Therefore, a more favorable measurement of $R_{\ell\ell}$ through $\ell\ell jj$ signals involves the detection of "displaced dileptons" plus jets.

The ratio of SS over OS events can be expressed as [2]:

$$R_{\ell\ell} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2}. \tag{5}$$

This expression leads to the two limiting Majorana and Dirac scenarios for $R_{\ell\ell} \to 1$ when $\Gamma \ll \Delta M$, and $R_{\ell\ell} \to 0$ when $\Delta M \ll \Gamma$, respectively. For Quasi-Dirac neutrinos, the ratio $R_{\ell\ell}$ can take any value between 0 and 1; as we approach $R_{\ell\ell} \to 0$, the LNV effects are more and more suppressed. Considering the estimate for the mass splitting in Eq. (4), it is readily seen that the QD behaviour in the linear seesaw model is determined by the light-neutrino masses and the heavy-neutrino decay width.

Finally, in order to characterize this QD regime, we computed the total decay width of the first heavy neutrino [3], focusing on the $M_{N_1} \lesssim 2.5$ GeV regime, where QCD is non-perturbative. For the hadronization of the quark currents in this regime (see Ref. [4]), we made use of Chiral Perturbation Theory [5] and Resonance Chiral Theory [6].

4. Parametrization

We intended to cover in the most general way the parameter space of the linear seesaw, focusing on the regions where current and near-future experiments aim to explore.

For this purpose, we took the master parametrization described in Ref. [7], which allows to fit any Majorana neutrino mass model and automatically reproduce current experimental data. For the case of the linear seesaw, the Yukawa couplings of Eq. (3) are parametrized as:

$$\begin{aligned} Y_D^T &= \left(\frac{M_R}{v_{\rm SM}}\right)^{1/2} W T \left(\frac{\hat{m}_\nu}{v_{\rm SM}}\right)^{1/2} U^\dagger_{\ell\nu}, \\ Y_\epsilon^T &= \left(\frac{M_R}{v_{\rm SM}}\right)^{1/2} W^* B \left(\frac{\hat{m}_\nu}{v_{\rm SM}}\right)^{1/2} U^\dagger_{\ell\nu}, \end{aligned} \tag{6}$$

where $v_{\rm SM}$ is the Higgs vacuum expectation value, $B = (T^T)^{-1}(I - K)$, and $U_{\ell\nu}$ is the neutrino (PMNS) mixing matrix. In Eq. (6) W encloses all possible rotations in the Yukawa parameter space, while T and K contain the scaling of the different components of the Yukawa couplings. For our analysis we considered two special cases:

Scenario a: we set $W = U_{\ell\nu}$, $T = f \times (v_{SM}/\hat{m}_\nu)^{1/2}$ and $K = 0$, in such a way that one of the Yukawa matrices becomes diagonal. Here f is just a scale factor parametrizing the magnitude of the Yukawas. However, we conveniently redefine $f = \alpha 10^{-1}/f'$ with $\alpha = (246)^{-1/2}$. Notice that f' is such that Y_ϵ and Y_D are proportional and inversely proportional to f', respectively.

Scenario b: we take a specially simple choice $W = I$, $T = g \times I$ and $K = 0$, such that $Y_D = g^2 Y_\epsilon$. Note that this parametrization leaves $Y_D Y_\epsilon^T$ constant and, in consequence, the neutrino mass unchanged for any value of g. For $g = 1$, both Yukawa matrices become equal $Y_D = Y_\epsilon$ and the traditional seesaw scenario is recovered.

A different choice in the parametrization structure either explores the same region or falls into non-testable or excluded regions.

5. Results

5.1. Dilepton ratio in the LSM

The Quasi-Dirac regime $0 < R_{\ell\ell} < 1$ occurs when $\Delta M \sim \Gamma$. Since $\Delta M \sim m_\nu$ and $\Gamma(M_N)$ grows quite fast with M_N, for smaller values of m_{ν_1}, smaller values of M_N lead to the QD behaviour. This is illustrated in Fig. 1, which shows the regions in the m_{ν_1}-M_{N_1} plane that pertain to the QD regime. As expected, for each specific m_{ν_1}, there is a relatively narrow window of M_{N_1} values such that $0 < R_{\ell\ell} < 1$. For example, if $m_{\nu_1} = 10^{-5}$ eV, then values of 10 GeV $\lesssim M_{N_1} \lesssim 20$ GeV are needed in order to obtain a $R_{\ell\ell}$ value within the QD regime. Unlike the inverse seesaw model [2], where values of $R_{\ell\ell} < 1$ are still obtained for larger values of M_{N_1}, here the current upper bound for the light neutrino mass $m_{\nu_1} \lesssim 0.1$ eV and a $f' = 100$ sets $R_{\ell\ell} = 0$ for values of $M_{N_1} \gtrsim 100$ GeV.

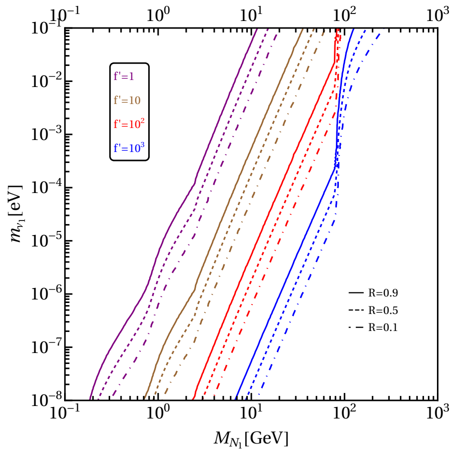

Figure 1. $m_{\nu_1} - M_{N_1}$ lines corresponding to a specific value of $R_{\ell\ell}$ and f'.

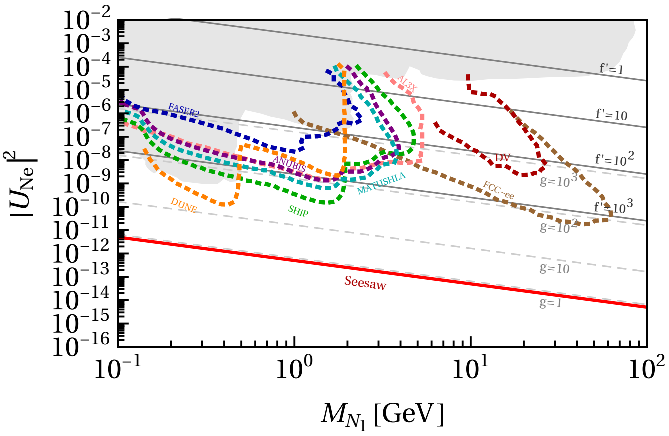

Figure 2. Active-sterile neutrino mixing $|U_{N_1 e}|^2$ versus the neutrino mass M_{N_1}, for different values of the parameters f' and g.

5.2. Heavy to light neutrino mixing $U_{N\ell}$

We analyzed the $|U_{N_1\ell}|^2 - M_{N_1}$ region and studied the sensitivity of some current and future experiments to the interesting zones of the parameter space. The numerical analysis was based on the systematic diagonalization of the 9×9 mass matrix of the neutral states M_ν (see Eq. (2))

$$M_\nu = U \hat{M}_\nu U^T \,, \tag{7}$$

with U containing the PMNS mixing matrix and the heavy-light neutrino mixing elements $U_{N_1\ell}$ as well.

We present the results in Fig. 2. Some of our findings are summarized as follows:

- *Scenario a*: all neutrino masses m_{ν_1} enter all Y_ϵ entries, being Y_D independent of the light neutrino masses. Then the mixing $U_{N_1 e}$ does not depend on m_{ν_1}.
- *Scenario b*: light neutrino masses enter separately all Y_ϵ and Y_D entries, so that there is an explicit dependence on m_{ν_1}. This results in a less constrained scenario.
- *Scenario a and b*: if the Yukawas Y_ϵ and Y_D present an appreciable hierarchy, current and near-future experiments will be able to test the predicted mixing region.

The bounds on the mixing themselves can place already stringent constraints into the QD regime, which can be found by studying the interplay between Figures 1 and 2. We also studied the bounds steming from the lepton-flavour violating $\mu \to e\gamma$ and the LNV neutrinoless double beta decay processes, and concluded that these are not competitive as compared to the ones given in Fig. 2.

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