Quasi-Dirac neutrinos in the linear seesaw model

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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.

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1. Introduction

Neutrino oscillation experiments have found overwhelming evidence for the existence of non vanishing –albeit small– neutrino masses , thus showing the existence of Physics Beyond the Standard Model. The most widely accepted mechanism to generate small neutrino masses is the well-known seesaw mechanism, which involves extra heavy neutral fermions, denoted here as N_i ($i = 1, 2, \ldots, n$, depending on the model). In most of these scenarios, the heavy neutrinos are Majorana fermions. However, there are seesaw scenarios where pairs of these Majorana neutrinos approach smoothly their mass degeneracy limit, $\Delta M_N \to 0$. These almost degenerate Majorana 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. Considering the basis (ν_L^c, N, S), the texture of the neutrino mass (9×9) matrix, given in a 3×3 block notation, reads:

$$M_\nu = \begin{pmatrix} 0 & m_D & M_\epsilon \\ m_D^T & 0 & M_R \\ M_\epsilon^T & M_R^T & 0 \end{pmatrix}, \tag{1}$$

where $m_D = v_{SM} Y_D / \sqrt{2}$ and $M_\epsilon = v_{SM} Y_\epsilon / \sqrt{2}$, with Y_D and Y_ϵ 3×3 Yukawa matrices and M_R being a 3×3 diagonal matrix. 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

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

The smallness of the lepton-number violating term M_ϵ, together with the linearity on m_D, generates small m_ν masses for the light neutrinos, without requiring M_R to be extremely large.

An important feature of the LSM is that the mass splitting between the two heavy neutrinos within each generation is very small:

$$\Delta M_i \sim m_{\nu_i}, \tag{3}$$

This is crucial in order 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 usual Dirac-Majorana dichotomy regarding the nature of neutrinos is somehow misleading, since the Dirac case can be considered as a limiting case of a more general Majorana scenario with twice the neutrino content and degenerated masses, where all LNV sources of the model have vanished.

An observable that is commonly used at the LHC 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 we call $R_{\ell\ell}$. The production of these events with a pair of leptons of the same sign, are expected to occur only through lepton number violating processes mediated by Majorana neutrinos, while opposite-sign pair of leptons are produced via lepton number conserving processes mediated by both Dirac and Majorana neutrinos.

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

$$R_{\ell\ell} = \frac{\Delta M^2}{2\Gamma^2 + \Delta M^2} \, .\tag{4}$$

Note that $R_{\ell\ell} \to 1$ if $\Gamma \ll \Delta M$, while $R_{\ell\ell} \to 0$ if $\Delta M \ll \Gamma$. These two scenarios correspond to the limiting Majorana and Dirac cases, respectively. In models with 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. Using the estimate for the mass splitting from Eq. (3), it follows that the window of $R_{\ell\ell}$ values compatible with QD neutrinos is determined, in the linear seesaw model, by the light-neutrino masses and the heavy-neutrino decay width.

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. [3] for the concrete case of the linear seesaw, which allows to fit any Majorana neutrino mass model and automatically reproduce current experimental data.

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 are needed. This is illustrated in Fig. 1, which shows the regions in the m_{ν_1}-M_{N_1} plane that belong 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 $10 \text{ GeV} \lesssim M_{N_1} \lesssim 20 \text{ GeV}$ 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.

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

We analyzed the $|U_{N_1\ell}|^2 - M_{N_1}$ region and identified the zones in the parameter space where some current experiments could have sensitivity; the prospects of future experiments were also considered. The numerical analysis was based on the systematic diagonalization of the 9×9 mass matrix of the neutral states M_ν (see Eq. (1))
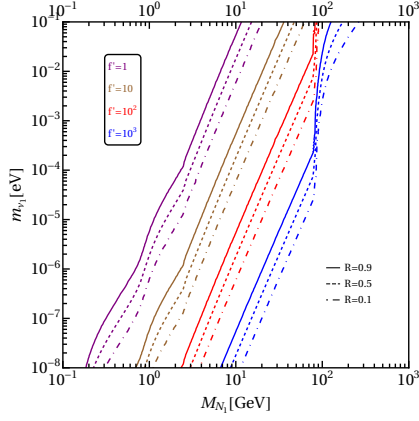
Figure 1: $m_{\nu_1} - M_{N_1}$ lines corresponding to a specific value of $R_{\ell\ell}$ and f'.
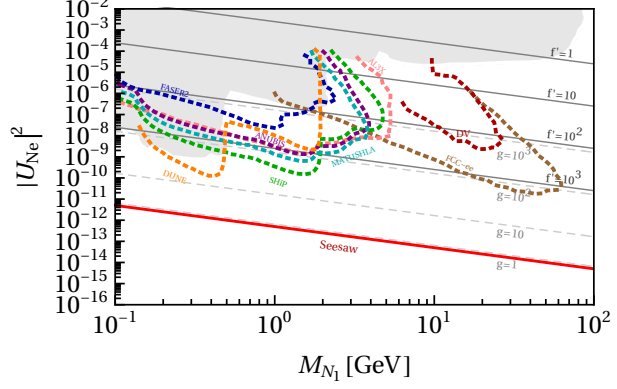
Figure 2: Active-sterile neutrino mixing $|U_{N_1e}|^2$ versus the neutrino mass M_{N_1}, for different values of the parameters f' and g.

$$M_\nu = U\hat{M}_\nu U^T \,, \tag{5}$$

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, while Y_D is independent of the light neutrino masses. Then the mixing U_{N_1e} does not depend on m_{ν_1}.

- *Scenario b*: light neutrino masses enter separately all Y_ϵ and Y_D entries, an explicit dependence on m_{ν_1} is then expected. This results in a less constrained scenario.

- *Scenario a and b*: if there is some appreciable hierarchy between the Yukawas Y_ϵ and Y_D, the predicted mixing falls into the range testable by present and near-future experiments.

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.

Acknowledgements

References

[1] C. Arbeláez, C. Dib, K. Monsálvez-Pozo and I. Schmidt, *Quasi-Dirac neutrinos in the linear seesaw model*, *JHEP* (2021) 154 [2104.08023].

[2] G. Anamiati, M. Hirsch and E. Nardi, *Quasi-Dirac neutrinos at the LHC*, *JHEP* **10** (2016) 010 [1607.05641].

[3] I. Cordero-Carrión, M. Hirsch and A. Vicente, *Master Majorana neutrino mass parametrization*, *Phys. Rev. D* **99** (2019) 075019 [1812.03896].