Like-sign dileptons with mirror type composite neutrinos at the HL-LHC

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Within a mirror type assignment for the excited composite fermions the neutrino mass term is built up from a Dirac mass, \( m_\nu \), which gives the mass of charged lepton component of the \( SU(2) \), right-handed, doublet, and a Majorana mass, \( m_L \), for the left-handed component (singlet) of the excited neutrino. The mass matrix is diagonalized leading to two Majorana mass eigenstates. The active neutrino field \( \nu_R^* \) is thus a superposition of the two mass eigenstates with mixing coefficients which depend on the ratio \( m_L/m_\nu \). We discuss the prospects of discovery of these physical states at the HL-LHC as compared with the previous searches of composite Majorana neutrinos at the LHC based on sequential type Majorana neutrinos.

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Introduction - A composite scenario [1–11], where at a sufficiently high energy scale \( \Lambda \) (compositeness scale) the standard model leptons and quarks show the effects of an internal substructure, has triggered considerable recent interest both from the theoretical [12–15] and experimental [16, 17] point of view. In particular, recent studies [18] have concentrated in searching for heavy composite Majorana neutrinos at the LHC. A recent CMS study has searched for a heavy composite Majorana neutrino (\( N \)), using 2.6 fb\(^{-1} \) data of the 2015 Run II at \( \sqrt{s} = 13 \) TeV [19, 20]. Heavy composite neutrino masses are excluded, at 95% CL, up to \( m_N = 4.60 \) TeV in the \( eeqq \) channel and \( m_N = 4.70 \) TeV in the \( \mu\mu qq \) channel for a value of \( \Lambda = m_N \).

We discuss here a variant of the model analyzed in [18, 20] taking up the scenario in which the excited fermions are organized with a mirror \( SU(2) \) structure relative to the SM fermions, i.e. the right-handed components form an \( SU(2) \) doublet while the left-handed components are singlets [21]. We construct a general Dirac-Majorana mass term appearing in the Lagrangian density of the model as:

\[
\mathcal{L}^{D+M} = -\frac{1}{2} m_L \bar{\nu}_L^\dagger (\nu_1^*)^c - m_\nu \bar{\nu}_L^R \nu_R^* + \text{h.c.} \tag{1}
\]

The Lagrangian mass term is easily diagonalized following standard procedures, obtaining two Majorana mass eigenstates, \( \nu_{1,2} \), with (positive) mass eigenvalues given by:

\[
m_{1,2} = \sqrt{m_\nu^2 + \left(\frac{m_L}{2}\right)^2} = \frac{m_L}{2} \tag{2}
\]

Interacting states can be written as a mixing of the mass eigenstate according to the relation:

\[
(\nu_L^1)^c = -i \cos \theta \nu_{1R} + \sin \theta \nu_{2R} \tag{3a}
\]

\[
\nu_R^* = i \sin \theta \nu_{1R} + \cos \theta \nu_{2R} \tag{3b}
\]

with the mixing angle \( \theta \) written in terms of the two masses of Dirac and Majorana:

\[
\theta = -\frac{1}{2} \arctg \left( \frac{2m_\nu}{m_L} \right). \tag{4}
\]

Now we take into account all the relevant effective couplings of these particles. In the usual mirror type model, we assume that the excited neutrino and the excited electron are grouped into left-handed singlets and a right-handed \( SU(2) \) doublet. The corresponding gauge mediated Lagrangian between the left-handed SM doublet and the right-handed excited doublet via the \( SU(2)_L \times U(1)_Y \)-
where \( L^T = (\nu_{\ell L}, \ell_L) \) is the ordinary \( SU(2)_L \) lepton doublet, \( g \) and \( g' \) are the \( SU(2)_L \) and \( U(1)_Y \) gauge couplings and \( W_{\mu \nu}, B_{\mu \nu} \) are the field strength for the \( SU(2)_L \) and \( U(1)_Y \) gauge fields; \( f \) and \( f' \) are dimensionless couplings usually set equal to unity. The relevant charged current (gauge) interaction of the excited (active) Majorana neutrino \( \nu_R^* \) is easily derived from Eq. 5:

\[
\mathcal{L}_G = \frac{g f}{2 \Lambda} \bar{\nu}_R^* \sigma^{\mu \nu} \nu_L \partial_\mu W_\nu + h.c. \tag{6}
\]

and can be written out explicitly in terms of the Majorana mass eigenstates through Eq. (3b):

\[
\mathcal{L}_G = \frac{g f}{\sqrt{2 \Lambda}} \left(-i \sin \theta \nu_1 + \cos \theta \nu_2\right) \sigma^{\mu \lambda} \ell_L \partial_\mu W_\lambda + h.c. \tag{7}
\]

Contact interactions between ordinary and excited fermions may arise by constituent exchange if the fermions have common constituents, and/or by the exchange of the binding quanta of the new unknown interaction, whenever such binding quanta couple to the constituents of both particles [2, 21]. The dominant effect is expected to be given by the 6-dimension four-fermion interactions which scale with the inverse square of the compositeness scale \( \Lambda \):

\[
\mathcal{L}_{CI} = \frac{g_s^2}{\Lambda^2} \frac{1}{2} \bar{\nu}_\mu j_\mu^\nu, \tag{8a}
\]

\[
j_\mu = \eta_L \bar{f}_L \gamma_\mu f_L + \eta_L \bar{f}_L^* \gamma_\mu f_L + \eta_\mu \bar{f}_L^* \gamma_\mu f_L + h.c. + (L \to R) \tag{8b}
\]

where \( g_s^2 = 4 \pi \) and the \( \eta \) factors are usually set equal to unity. In this work the right-handed currents will be neglected for simplicity.

The single production \( qq' \to \nu^* \ell \) proceeds through flavour conserving but non-diagonal terms, in particular with currents like the third term in Eq. 8b which couple excited states with ordinary fermions:

\[
\mathcal{L}_{CI} = \frac{g_s^2}{\Lambda^2} \bar{q}_L \gamma^\mu q'_L \bar{\nu}_\mu \gamma_\mu \ell_L. \tag{9}
\]

The contact interactions in Eq. (9) can be written out explicitly in terms of the Majorana mass eigenstates \( \nu_i \) using Eq. (3b):

\[
\mathcal{L}_{CI} = \frac{g_s^2}{\Lambda^2} \bar{q}_L \gamma^\mu q'_L \left(-i \cos \theta \nu_1 + \sin \theta \nu_2\right) \gamma_\mu \ell_L. \tag{10}
\]

The model needs to be implemented in a Monte Carlo generator to extract predictions. Here we have obtained the Feynman rules of the model thanks to the Mathematica package FeynRules [24]. The MC simulation samples and the numerical computations are then mostly obtained with Madgraph [25], complementing the results with a validation obtained with the tree-level simulator CalcHEP [26].

**Probe at the HL-LHC -** In the compositeness framework discussed above, the heavy Majorana neutrino could trigger processes with Lepton Number Violation (LNV). In particular, the production of a heavy neutrino \( \nu^* \) in association with a charged lepton could be followed by the subsequent decay of the neutrino to a like-sign lepton plus two jets coming from the hadronization of the quarks in the detector. It is important to emphasize that, in this version of the model, the mediator acts as a mixture of the two mass eigenstates. The whole process results in the like-sign dileptons and dijets signature, that is the golden channel for LNV searches in hadron collider experiments. This is shown diagrammatically in Fig. 3. Here we focus on the two-positrons final state, because of the higher-luminosity of the partons involved in this channel in proton-proton collisions with respect to the
shows the behaviour of the production cross section for the two mass eigenstates \( pp \rightarrow e^+ \nu_{1,2} \) for two different Majorana mass values, \( m_L = 50, 500 \) GeV. (Right-panel) Cross section for the like-sign dileptons signature, \( pp \rightarrow e^+e^+ qq \) at the HL-LHC \( \sqrt{s} = 14 \) TeV.

FIG. 3. The like-sign dileptons and dijets signature mediated by the heavy composite Majorana neutrino.

negatively charged case. Fig.2 shows the behaviour of the production cross section for the two mass eigenstates and for the full LNV process for different model scenarios. It is worth to notice that in the limit \( m_L \rightarrow 0 \) the cross-section of the like-sign dileptons and dijets process goes to zero, as the process becomes essentially mediated by Dirac neutrinos. This is confirmed by the behaviour of the signal cross section with respect to the parameter \( m_L \) as shown in Fig. 4.

In order to study the potentiality of a successful detection of this kind of particle, LHE samples coming from the MC generators are interfaced with the Fast-Simulation framework Delphes [27], considering a CMS Phase-2 [28] parametrization without considering any pileup effect. Hence, the potential for discovery at HL-LHC in the three-dimensional parameter space \((\Lambda, m_L, m_\tau)\) can briefly discussed.

Standard Model processes that could mimic the detection of a LNV signal in this rather clean signature are mainly the triple W boson production, \( pp \rightarrow W^+W^+W^- \), and the top quark pair production \( pp \rightarrow t\bar{t} \), the former being the dominant background source. Since the kinematic features of the final state reconstructed objects are similar to those of Ref. [18], we lower the background contribution by imposing two cuts on the leading lepton \((p_T(e_1) > 110 \) GeV\) and on the second-leading lepton \((p_T(e_1) > 35 \) GeV\). This particular signal region allows an efficiency in selecting signal around the 80\%, while beating the background sources with efficiency of 0.00044\% for the \( t\bar{t} \) and of 0.0034\% for the \( W^+W^+W^- \).

The statistical significance is defined by the relation

\[
S = \frac{L\sigma_{\text{sig}}\epsilon_{\text{sig}}}{\sqrt{L\sigma_{\text{bkg}}\epsilon_{\text{bkg}}}} \tag{11}
\]

where \( \epsilon_{\text{sig}}, \epsilon_{\text{bkg}} \) are respectively the cumulative efficiencies of the signal and the background due to the selection.

Figure 5 shows the 5-\( \sigma \) contours in the \((\Lambda, m_\tau)\) for two benchmark choices of the lepton number violating parameter \( m_L = 50, 500 \) GeV.

Another interesting feature of this version of the model
We have studied the charge asymmetry

$$A = \frac{\sigma_{e^+ e^- jj} - \sigma_{e^+ e^+ jj}}{\sigma_{e^+ e^- jj} + \sigma_{e^+ e^+ jj}}$$

(12)

for a fixed value of the scale $\Lambda$. We expect that the compositeness scale does not play a crucial role in the asymmetry because when taking the ratio in Eq. 12 it will essentially cancel out. In addition it should also not play a significant role in the yields of the like sign versus the opposite sign. As shown in Fig. 6, the asymmetry depends both on the Majorana mass $m_L$ and on the Dirac mass $m_*$ without reaching the $A = 0$, that would correspond to a process mediated by a single Majorana neutrino.

As the Dirac mass reaches higher values, we see that the like-sign channel is suppressed ($A = 1$), being the magnitude of the suppression dependent on the parameter $m_L$.

Conclusions - We have presented a mechanism of lepton number violation within a mirror type model compositeness scenario. The mirror type case is realized when the left components of the excited states are singlets while the right components are active doublets which do participate to gauge transition interactions with SM fermions. We therefore introduce a left-handed Majorana neutrino singlet of mass $m_L$ while the right-handed component belongs to a doublet and has a Dirac mass $m_*$. This situation is exactly specular to the one encountered in typical see-saw models where the sterile neutrino is the right-handed component and the active one is the left-handed component. Diagonalization of the mass matrix gives two Majorana mass eigenstates whose phenomenology at the HL-LHC is presented. We provide the 5-$\sigma$ contour curves of the statistical significance, for two different values of the Majorana mass $m_L = 50, 500$ GeV, of the like-sign dileptons and dijet signature giving indications about the discovery potential at the CMS Phase-2 detector. We have additionally shown that the charge asymmetry is a potential observable that could allow to distinguish between different values of $m_L$ in the regime of high values of the Dirac mass ($m_* \in [2500, 5000]$ GeV for $\Lambda = 10$ TeV).

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