Dilepton events with displaced vertices, double beta decay, and resonant leptogenesis with Type-II seesaw dominance, TeV scale $Z'$ and heavy neutrinos

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In a class of Type-II seesaw dominated $SO(10)$ models proposed recently with heavy neutrinos, extra $Z'$ boson, and resonant leptogenesis, at first we show that the lightest first generation sterile neutrino that mediates dominant contributions to neutrinoless double beta decay also generates the displaced vertex leading to verifiable like-sign di-electron as well as di-muon production events outside the LHC detectors having suppressed standard model back ground and missing energy. Resonant leptogenesis in this case is implemented by a pair of quasi-degenerate sterile neutrinos of the second and the third generations having masses of $\mathcal{O}(500)$ GeV. Then we predict a new alternative scenario where the models allow the second generation sterile neutrino mass to be $\mathcal{O}(10)$ GeV capable of mediating the dominant double beta decay as well as the displaced vertices for significantly improved number of like-sign dilepton events in different channels. Resonant leptogenesis in this alternative scenario is mediated by a pair of heavy quasi-degenerate sterile neutrino masses of the first and the third generations. In addition to QD type light neutrino mass hierarchy, we also show how these results are derived for the NH case. We also discuss $Z'$ production cross sections at $\sqrt{s} = 14$ TeV run-II of LHC and also at ILC. While the lepton flavour violating branching ratios are only few to four orders less than the current experimental bounds, proton lifetime predictions are accessible to ongoing Super K. or Hyper K. searches.

PACS numbers: 12.10.-g, 12.10.Kt, 14.80.-j

I. INTRODUCTION

The renormalisable standard model (SM) predicts the neutrinos to be massless whereas neutrino oscillation experiments prove them to be massive\footnote{The nonrenormalisable dim.5 operator scaled by the Planck mass gives too small a Majorana neutrino mass $\sim 10^{-5}$ eV\cite{1} to account for the oscillation data.}. Theoretically, these masses of the light neutrinos are predicted through various seesaw mechanisms\cite{2} such as Type-I, Type-II, Type-III, double seesaw, inverse seesaw\footnote{The nonrenormalisable dim.5 operator scaled by the Planck mass gives too small a Majorana neutrino mass $\sim 10^{-5}$ eV\cite{1} to account for the oscillation data.}, and radiative seesaw mechanisms in SM extensions. In a minimal left-right symmetric\cite{10,11} grand unified theory (GUT) like $SO(10)$\cite{12} where the origin of parity (P) violation in weak interaction is explained\cite{13}, a number of these seesaw mechanisms can be naturally embedded while answering the origin of the three gage couplings of the SM. With natural inclusion of right-handed (RH) neutrinos in its spinorial fermionic representation, the model can predict the Dirac neutrino masses or Yukawa couplings by fitting the charged fermion masses which play a crucial role in seesaw mechanisms, lepton flavour violations (LFVs), and lepton number violations (LNVs). The GUT model has also the potential to explain baryon asymmetry of the universe via leptogenesis through heavy RH neutrino decays\cite{14}. Although recently several attempts have been made to search for smoking gun signatures of TeV scale left-right gauge theory from available LHC measurements at $\sqrt{s} = 8$ TeV, no conclusion can be reached due to poor statistics of the available data and until different sources of standard model background events are clearly identified.

However it is possible that the associated intermediate scale of LR gauge theory in GUTs and the $W_R$ boson mass could be too large to be accessible to accelerator tests in near future and to manifest in ongoing experimental searches for $0\nu\beta\beta$ decay\cite{15,18}. Inspite of this, its neutral $Z'$ boson as a smoking gun signal of underlying high scale left-right gauge symmetry and the associated RH neutrinos could be near the TeV scale\cite{19,28}. Basically this scheme materialises in two-step breaking of the LR gauge theory,

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C (= G_{2213}, g_{2L} \neq g_{2R})$$

OR

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C (= G_{2213D}, g_{2L} = g_{2R})$$

$$\rightarrow SU(2)_L \times U(1)_R \times U(1)_{B-L} \times SU(3)_C (= G_{2113})$$

$$\rightarrow SM$$

Alternatively $G_{2113}$ can emerge from direct breaking of Pati-Salam gauge theory $SU(2)_L \times SU(2)_R \times SU(4)_C$ or a GUT like $SO(10)$, or $E_6$. In a recent paper\cite{28} we embedded this two-step symmetry breaking chain in two models originating from nonsupersymmetric (non-SUSY) $SO(10)$.
Model-I

\[ SO(10) \rightarrow G_{2213D} \rightarrow G_{2113} \rightarrow SM. \]  \hspace{1cm} (2)

Model-II

\[ SO(10) \rightarrow G_{2213} \rightarrow G_{2113} \rightarrow SM. \]  \hspace{1cm} (3)

In Model-I, the first step of symmetry breaking takes place by assigning the GUT-scale VEV to the neutral component of the Higgs submultiplet \((1, 1, 15) \subset 210_H \) of \( SO(10) \) under Pati-Salam gauge symmetry \( SU(2)_L \times SU(2)_R \times SU(4)_C \). As this neutral component carries D-Parity even quantum number \[29\], the GUT symmetry breaks without breaking D-Parity. In Model-II, the D-Parity itself breaks down at the GUT scale by assigning, in addition, the GUT scale VEV to the D-Parity odd singlet component \((1, 1, 1)_H \subset 210_H \). The second step of symmetry breaking in both models is implemented by assigning TeV scale VEV to the neutral component of the RH scalar triplet \( \Delta_R(1, 3, -2, 1) \) which generates the TeV scale \( Z' \)-boson and the RH neutrino masses. The Type-II seesaw dominance occurs in Model-I by the natural presence of the LH triplet \( \Delta_L(3, 1, -2, 1) \subset 126_H \) that acquires the desired induced VEV needed to drive the seesaw mechanism. Type-II seesaw contribution dominates by suppressing the linear seesaw term by appropriate fine-tuning of parameters. In Model-II the mass of the LH triplet \( \Delta_L(3, 1, -2, 1) \) is kept at the intermediate scale by fine-tuning of parameters to implement type-II seesaw dominance while the linear seesaw term is naturally suppressed in this case.

The \( W_R \) boson mass being \( > 10^8 \) GeV in both models, at first sight it appears that there are no additional contributions to the \( 0\nu\beta\beta \) decay other than the standard contributions due to light neutrinos though their NH, IH, or QD patterns of tiny Majorana masses and the well known structure of the PMNS mixing matrix. But the models of eq. (2) and eq. (3) have been specifically designed to include additional non-standard fermion singlets of three generations which acquire Majorana masses to mediate dominant contributions to the \( 0\nu\beta\beta \) decay irrespective of the hierarchy of light neutrino masses.

The other two of the sterile neutrinos being quasi-degenerate with masses around \( O(1) \) TeV have been shown [28] to mediate resonant leptogenesis [30] explaining baryon asymmetry of the Universe. These heavy Majorana neutrinos including the RH and sterile ones may also manifest in the production of like-sign dilepton signals at ATLAS or of the type observed at CMS detectors [31] provided adequate beam luminosity is reached.

Quite recently, as a very interesting and novel manifestation of Majorana type of RH neutrino that occurs in Type-I seesaw mechanism, it has been pointed out that if \( W_R \) boson is at the TeV scale and a RH neutrino mass needed for the seesaw is sufficiently light, it would mediate \( 0\nu\beta\beta \) decay while like-sign di-electron signals caused due to displaced vertices mediated by the RH neutrino mass in the range \( 1 - 80 \) GeV would provide more interesting model signatures through \( eejj \) events devoid of standard model back grounds [32, 33] without missing energy. Then these like-sign di-electron signals and \( 0\nu\beta\beta \) decay events would indicate the presence of the gauge theory at the TeV scale. Even if there is no \( W_R \) gauge boson at the TeV scale, this approach predicts the novel possibility of like-sign dilepton events outside the ATLAS or CMS detectors with suppressed SM background and missing energy in the channel \( eejj \) in the SM extension with a RH neutrino to accommodate Type-I seesaw. In such a Type-I seesaw model as the associated single RH neutrino is sufficiently light, it is difficult to implement TeV scale resonant leptogenesis for which two quasi-degenerate heavy masses of RH neutrinos of two other generations may be needed and this needs further investigation. Also such a single RH neutrino model may not adequately mediate inside detector events at CMS or ATLAS in the channels \( pp \rightarrow \mu\mu jjX \) or \( pp \rightarrow e\mu jjX \). In addition, the heavy-light neutrino mixings in this model can be any where bounded by the DELPHI [31] and the double beta decay experimental limits.

The purpose of this work is two fold:(i) In the first part we show that the two non-SUSY \( SO(10) \) models discussed recently [28], as indicated by eq. (2) and eq. (3), predict a rich structure of like-sign di-electron and di-muon events with displaced vertices outside the LHC detectors along with dominant contributions to double beta decay mediated by lighter masses of one of the three sterile neutrinos while TeV scale masses of Majorana neutrinos are available to mediate inside detector events like \( pp \rightarrow l^\pm l^\pm jjX \). In contrast to models along this line including those of ref. [32, 33] where heavy -light neutrino mixings are assumed under the DELPHI [34] and the double beta decay constraints , these mixings in our models are predicted from all charged fermion mass fit at the GUT scale and the LFV constraint. The Dirac neutrino mass matrix derived in this manner serves as important ingredient for predictions of LFV, LNV, and dilepton production events. In addition, our models provide a mechanism for resonant leptogenesis [30] mediated by TeV scale quasi-degenerate pair of sterile neutrinos. Two different cases have been identified. In the Case (a) discussed in this paper while the light sterile neutrino \( S_2 \) of first generation mediates dominant contribution to double beta decay and like-sign dilepton events with displaced vertices in the channels \( eejj, e\mu jj, \) and \( \mu\mu jj \), resonant leptogenesis is allowed to be mediated by heavy quasi-degenerate sterile neutrino pairs \( S_2 \) ans \( S_3 \) belonging to the second and the third generations, Identified as the alternative Case (b), dominant double beta decay and dilepton events with displaced vertices are mediated by the allowed lighter mass of \( S_2 \) while resonant leptogenesis is mediated by the heavy quasi-degenerate sterile neutrino pairs, \( S_1 \) and \( S_3 \). In addition to QD hierarchy of light neutrino masses, we also show how all these results hold in the presence of NH masses, a result which
might be important if the recent cosmological bound \[30\] is finally established. (ii) In the second part of this work we explore detection possibilities of the extra \(Z'\) boson predicted by these two models at the Large Hadron Collider (LHC) and the International Linear Collider (ILC). We also predict heavy RH Majorana neutrino production cross sections through the like-sign dilepton production at the LHC detectors in the \(W_L - W_L\) channel.

This paper is organized in the following manner. In sec.2 we provide a brief description of the model results investigated earlier. In sec.3 we discuss the neutrinoless double beta decay by sterile neutrino exchange. In sec.4 we discuss resonant leptogenesis in the cases where the first or the second generation sterile neutrino is light. In sec.5 we discuss decay width, half-life and displaced vertices. The heavy RH neutrino mediated dilepton production cross section in the \(W_L - W_L\) channel is discussed in sec.7 In sec.8 we discuss the neutrinoless double beta decay and leptogenesis with NH neutrinos. The \(Z'\) boson production cross section and its comparison with the standard \(Z\) boson cross section are discussed in sec.9. In sec.10 we summarize this work and draw conclusion.

II. TYPE-II SEESAW DOMINANCE IN \(SO(10)\)

Several interesting approaches have been made earlier to implement type-II seesaw dominance for neutrino masses in \(SO(10)\) \[37-39\]. As discussed below while giving a brief summary of common aspects of Model-I and Model-II \[28\] in non-SUSY \(SO(10)\) GUT relevant to the present work, we note that in both the models excellent gauge coupling unification has been achieved with proton lifetime predictions over a wider range of values in each model covering the experimentally accessible search limits \[35-40\] for \(p \rightarrow e^+ \pi^0\) mode.

A. Light and Heavy Neutrino Masses

The Yukawa Lagrangian of the two models \[28\] is given by

\[
L_{\text{Yuk}} = \sum_{i=1,2} Y_i^L \bar{\psi}_L \psi_R \Phi_i + f (\psi_R^c \psi_R \Delta_R + \psi_L^c \psi_L \Delta_L)
+ y_X (\bar{\psi}_R S \chi_R + \bar{\psi}_L S \chi_L)
+ \mu_S S S + \text{h.c.},
\]

(4)

where \(\mu_S\) represents the global lepton number violating mass term which is naturally and vanishingly small in the 't Hooft sense \[43\].

Using the VEVs of the Higgs fields and denoting \(M_N = f < \Delta_R > = f V_R, M = y_X < \chi_R > = y_X V_X\), \(M_D = Y_i < \Phi_i > + X\), where the origin of the term \(X\) has been discussed earlier \[28\], a \(9 \times 9\) neutral-fermion mass matrix has been obtained which, upon block diagonalisation, yields \(3 \times 3\) mass matrices each for the light neutrino (\(\nu_a\)), the right handed neutrino (\(N_a\)) and the sterile neutrino (\(S_a\)). Including the induced Type-II seesaw contribution in both the models, the following generalised form of the \(9 \times 9\) matrix has been obtained in the \((\nu, S, N)\) basis

\[
\mathcal{M} = \begin{pmatrix}
M^L + (M_D^T \mu_S M)^{-1} M^T_D
\end{pmatrix},
\]

(5)

where \(M^L\) = \(f v_L, v_L\) being the induced VEV of the neutral component in the LH triplet \(\Delta_L (3, 1, -2, 1) \subset \mathbb{126}_H\). On block diagonalisation under the extended seesaw constraint, \(M_N > M > M_D, \mu\), it has been shown that the Type-I seesaw term cancels out \[28, 41, 42\] and the generalised form of the light neutrino mass matrix is given by

\[
\mathcal{M}_\nu = f v_L + M_L M^{-1} M_N (M^T)^{-1} M^T_D
- [M_L M^T_D M^{-1} + M_D M^T_D M^{-1}] + (M_D/M) \mu_S (M_D/M)^T,
\]

(6)

Since the LH doublet \(\chi_L\) has vanishing VEV as explained in \[28\], the \(M_L\) term drops out and the Type-II seesaw dominance prevails in the limit of 't Hooft’s naturalness condition, \(\mu_S \rightarrow 0\) \[43\]

\[
\mathcal{M}_\nu \simeq f v_L.
\]

(7)

With Type-II seesaw dominated neutrino mass formula, the RH neutrino masses are also predicted in this scenario.

\[
M_N = f V_R M_\nu V_R^T / v_L.
\]

(8)

At first we will discuss the case when light neutrino masses are quasi-degenerate (QD), subsequently we will also show how our results are applicable for normally hierarchical (NH) case. As reported \[28\] with \(m_{\nu_1} = 0.2056\) eV, \(m_{\nu_2} = 0.2058\) eV and \(m_{\nu_3} = 0.2\) eV, and \(v_L = 0.5\) eV, the neutrino mass matrix, the Yukawa matrix \(f\), and the RH neutrino mass eigen values are

\[
m_{\nu} = \begin{pmatrix}
1.01 + 0.01i & 0.00055 + 0.01i & -0.009 + 0.1i \\
0.00055 + 0.01i & 1.01 + 0.008i & 0.01 + 0.105i \\
-0.009 + 0.1i & 0.01 + 0.1i & 0.9 - 0.02i
\end{pmatrix}
\]

(9)

\[
f = \begin{pmatrix}
2.02 + 0.02i & 0.0011 + 0.02i & -0.019 + 0.3i \\
0.0011 + 0.02i & 2.034 + 0.017i & 0.021 + 0.21i \\
-0.019 + 0.3i & 0.021 + 0.21i & 1.99 - 0.04i
\end{pmatrix}
\]

(10)
\[ |M_N| = \text{diag}(4.08, 4.03, 4.02) \text{ TeV}. \] \tag{11}

The mass matrix of the sterile neutrino is

\[ m_S = -M \frac{1}{M_N} M^T \] \tag{12}

where \( M \) is the \( N - S \) mixing mass term in the Yukawa Lagrangian of eq.\,[4].

The Dirac neutrino mass matrix plays crucial roles in predicting lepton flavour violating branching ratios, leptonic non-unitarity effects, lepton number violations, leading to heavy-light neutrino mixings which act as important ingredients in estimating the model predictions for di-lepton events at LHC as discussed below. In both our models this mass matrix has been determined by fitting the RG extrapolated values of charged fermion masses at the GUT scale \[44\] and extrapolating it back to the lower scale \( \mu \sim M_Z' \sim M_{10} \)

\[ M_D(\text{GeV}) = \begin{pmatrix}
0.014 & 0.04 - 0.01i & 0.109 - 0.3i \\
0.04 + 0.01i & 0.35 & 2.6 + 0.0007i \\
0.1 + 0.3i & 2.6 - 0.0007i & 79.20
\end{pmatrix}. \] \tag{13}

This procedure has been followed in a number of recent works in non-SUSY \( SO(10) \) with TeV scale \( Z' \) and RH Majorana neutrinos \[26\] and in SUSY \( SO(10) \) with TeV scale \( W_R \) but pseudo-Dirac neutrinos \[15\]. In the non-SUSY \( SO(10) \) model with TeV scale \( Z' \) and heavy RH pseudo-Dirac neutrinos, the corresponding matrix has been derived in ref.\,[23].

### B. Lepton Flavour Violations

In all conventional non-SUSY \( SO(10) \) GUTs with high scale Type-I or Type-II seesaw formula for neutrino masses, there are three generations of standard fermions in \( 16, (i = 1, 2, 3) \) and the RH neutrino masses are large which give negligible contribution to charged LFV decay amplitudes. In the case of non-SUSY \( SO(10) \) with inverse seesaw mechanism for neutrino masses, the three singlet fermions \( \nu_i \) with their mixing mass term \( M \) near the TeV scale and through their loop mediation make substantial contribution to LFV decay branching ratios accessible to ongoing experimental searches \[25\]. In the present non-SUSY \( SO(10) \) model, even though neutrino masses are governed by high scale type-II seesaw formula, the essential presence of singlet fermions \( S_i \) that implement the Type-II seesaw dominance by cancelling out the Type-I seesaw contribution give rise to experimentally observable LFV decay branching ratios through their \( N - S \) mixing mass terms in loop mediation. The heavier RH neutrinos in this model being in the range of \( \sim 0.1 - 1 \) TeV also contribute, but less significantly than the singlet neutrinos. The predicted branching ratios being only few to four orders less than the current experimental limits are verifiable by ongoing searches \[40\].

\[ BR(\mu \rightarrow e\gamma) = 6.43 \times 10^{-17}, \]

\[ BR(\tau \rightarrow e\gamma) = 8.0 \times 10^{-16}, \]

\[ BR(\tau \rightarrow \mu\gamma) = 2.41 \times 10^{-12}. \] \tag{14}

### III. HEAVY-LIGHT MIXING AND PREDICTIONS FOR NEW PHYSICS EFFECTS

In ref. \[28\] we have discussed how the lightest sterile neutrino of first generation gives rise to dominant double beta decay and the heavier quasi-degenerate pair of second and the third generation sterile neutrinos produce baryon asymmetry via resonant leptogenesis \[30\]. In this section we point out that, in addition to leptogenesis, the models have much wider impact on lepton number violating phenomena to be detectable by ongoing double beta decay experiments at low energies and like-sign dilepton production events at LHC via displaced vertices. In predicting the LFV branching ratios we have used the simplifying diagonal structure for \( M \),

\[ M = \text{diag.} (M_1, M_2, M_3), \] \tag{15}

which in combination with eq.\,[13] gives the elements of the \( \nu_1 - S \) mixing matrix

\[ \chi^{(LS)} = \begin{pmatrix}
M_{D,1}/M_1 & M_{D,2}/M_2 & M_{D,3}/M_3 \\
M_{D,1}/M_1 & M_{D,2}/M_2 & M_{D,3}/M_3 \\
M_{D,1}/M_1 & M_{D,2}/M_2 & M_{D,3}/M_3
\end{pmatrix}. \] \tag{16}

Only the physical manifestation of \( \chi^{(LS)}_{e_1} \) through new dominant prediction in double beta decay mediated by \( S_1 \) was discussed in \[28\]. But here we show that through this mixing element, \( S_1 \) would also be able to mediate displaced vertex for like-sign di-electron production events outside the LHC detector. Interestingly, because of the significant values of the element \( \chi^{(IS)}_{e_1} \), the sterile neutrino \( S_1 \) will also be able to mediate like-sign di-muon production events outside the LHC detector. Similarly, in an alternative scenario, the presence of the mixing matrix element \( \chi^{(IS)}_{\mu_2} \) would enable \( S_2 \) to mediate dominant double beta decay and displaced vertex for like-sign di-electron events outside the LHC detectors while through the presence of the sizeable element \( \chi^{(LS)}_{\mu_2} \), it would mediate like-sign di-muon signal events via displaced vertex outside the LHC detector. These are possible provided \( S_2 \) is sufficiently light. Although similar contributions due to the exchanges of other heavy Majorana neutrinos are possible, they are neglected as the corresponding masses are much heavier than \( \hat{m}_{S_1} \) or \( \hat{m}_{S_2} \). Details of applications of these possibilities have been discussed in the following sections. We categorize the mediation by light
in double beta decay and observable dilepton production events by displaced vertices as a second scenario, alternate to the first example where \( S_1 \) is light because the resonant leptogenesis constraint requires either \( S_2 \) and \( S_3 \) in the first case, or \( S_1 \) and \( S_3 \) in the second case are to be quasi-degenerate with mass \( \sim 500 \) GeV.

### A. Neutrinoless Double Beta Decay by Sterile Neutrino Exchange

As the \( W_R \) boson and the doubly charged Higgs bosons have masses \( > 10^9 \) GeV, they have negligible contributions to \( 0 \nu \beta \beta \) decay amplitude in these models. The Feynman diagram for sterile neutrino contribution to \( 0 \nu \beta \beta \) decay amplitude is shown in Fig. 1. Using suitable normalisations \[17,19\], the added contributions due to light-neutrinos, sterile neutrinos, and the heavy RH neutrinos in the \( W_L - W_L \) channel lead to the inverse half life

\[
\left[ T^{0\nu}_{1/2} \right]^{-1} \simeq G_{01} \left| \frac{M_{1\nu}}{m_e} \right|^2 \left| (m_{1\nu}^e + m_S^e + m_N^e) \right|^2,
\]

\[
= K_{0\nu} \left| (m_{1\nu}^e + m_S^e + m_N^e) \right|^2,
\]

where \( G_{01} = 0.686 \times 10^{-14} \text{yrs}^{-1}, M_{1\nu} = 2.58 - 6.64, \) and \( K_{0\nu} = 1.57 \times 10^{-23} \text{yrs}^{-1} \text{eV}^{-2} \). In eq. (17) the three effective mass parameters are

\[
m_{1\nu}^e = \sum_i (\nu_{ei})^2 m_{\nu_i},
\]

\[
m_S^e = \sum_i (\nu_{ei})^2 \frac{|p|}{m_{S_i}},
\]

\[
m_N^e = \sum_i (\nu_{ei})^2 \frac{|p|}{m_{N_i}},
\]

with

\[
m_{\text{eff}} = m_{1\nu}^e + m_S^e + m_N^e.
\]

Here \( m_{S_i} \) is the \( i \)-th eigen value of the \( S- \) fermion mass matrix \( m_S \), and the magnitude of neutrino virtuality momentum \(|p| = 120 \text{ MeV} - 200 \text{ MeV} \). The RH neutrinos being much heavier than \( m_{S_3} \) in the first case, or \( m_{S_2} \) in the second case, their contributions have been neglected. The variation of half-life with the first generation and second generation sterile neutrino mass is given in Fig. 2.

From Fig. 2 we find that that the first (second) generation sterile neutrino saturates the current experimental bounds at \( m_{S_1} \sim 1 \) (\( m_{S_2} \sim 2 - 3 \) GeV). For larger values of these mass eigen values the predicted half-life increases but for very large values of these masses the curves would asymptotically approach the horizontal lines as happens in the case of QD mass hierarchy of light neutrinos when all other contributions are neglected.

### IV. Two Alternative Cases for Resonant Leptogenesis

The CP-asymmetry formula for the resonant leptogenesis is \[28\]

\[
\varepsilon_{S_k} = \sum_j \frac{\text{Im}[y_i y_j^* y_{kj}]}{|y_i y_j y_{kj}|} R,
\]

\[
R = \frac{(m_{S_1}^2 - m_{S_2}^2) m_{S_3} \Gamma_{S_1}}{(m_{S_1}^2 - m_{S_2}^2)^2 + m_{S_3}^2 \Gamma_{S_3}^2},
\]

where \( y = (M/M_N)h, \ h = M_D/V_{ek} \) and \( V_{ek} \simeq 174 \) GeV. In order to estimate lepton asymmetry caused by the decay of heavy sterile fermions \( S_k (k = 1, 2, 3) \) via
their mixing with the heavier RH neutrinos, the corresponding Feynmann diagrams at the tree and one-loop levels, including the vertex and self energy diagrams, are shown in Fig. 3.

FIG. 3. Tree and one-loop diagrams for the $S_k$ decay contributing to the CP-asymmetry. All fermion-Higgs couplings in the diagrams are of the form $V h$ where $h = N - l - \Phi$, Yukawa coupling and $V \approx M/M_N$.

The fermion-Higgs coupling in all the diagrams is $V h$ instead of the standard Higgs-Yukawa coupling $h = M_D/V_{wek}$ where $V \approx M/M_N$, $M_D$ is given in eq. (13), and $V_{wek} \approx 174$ GeV. Denoting the mass eigen value of a sterile neutrino by $\hat{m}_{S_k}(k = 1, 2, 3)$, for computation of baryon asymmetry $Y_B$ of the Universe with a washout factor $K_k$, we utilise the ansatz (30):

$$Y_B \approx \frac{\varepsilon_{S_k}}{200 K_k},$$

$$K_k = \frac{\Gamma_{S_k}}{H(\hat{m}_{S_k})},$$

where $H(\hat{m}_{S_k})$ being the Hubble parameter at temperature $\hat{m}_{S_k}$. Defining

$$\delta_i = \frac{|\hat{m}_{S_k} - \hat{m}_{S_j}|}{\Gamma_{S_i}} (i \neq j),$$

the depleted washout factor is [50]

$$K_i^{\text{eff}} \approx \delta_i^2 K_i.$$  

Here we discuss two cases for the sterile neutrino contribution towards leptogenesis and baryon asymmetry: (a) $\hat{m}_{S_1}$ is light, $\hat{m}_{S_2}$ and $\hat{m}_{S_3}$ are quasi-degenerate; (b) $\hat{m}_{S_2}$ is light, $\hat{m}_{S_1}$ and $\hat{m}_{S_3}$ are quasi-degenerate.

Case (a). $\hat{m}_{S_1}$ light, $\hat{m}_{S_2}$ and $\hat{m}_{S_3}$ heavy and quasi-degenerate.

Using an allowed interesting region of the parameter space $M \approx \text{diag.}(3200, 146, 3200)$ GeV, eq. (10), eq. (12), $V_R = 10^4$ GeV, and $M_N = f_{V_R}$ we get

$$\hat{m}_{S_1} = \text{diag.}(1.0, 595.864, 595.864) \text{GeV}. \quad (26)$$

leading to $K_2 = 2.7 \times 10^7$. Using $(\hat{m}_{S_2} - \hat{m}_{S_3}) \approx 2 \times 10^{-7}$ GeV, we obtain

$$\varepsilon_{S_2} = 0.824, \quad Y_B = 1.5 \times 10^{-10}. \quad (27)$$

Case (b). $\hat{m}_{S_2}$ light, $\hat{m}_{S_1}$ and $\hat{m}_{S_3}$ heavy and quasi-degenerate.

Choosing another allowed region of the parameter space $M \approx \text{diag.}(500, 567, 1.0, 500, 567) \text{GeV}$, similarly we get

$$\hat{m}_{S_1} = \text{diag.}(500.567, 1.0, 500.567) \text{GeV}. \quad (28)$$

leading to $K_1 = 4 \times 10^6$. using $(\hat{m}_{S_1} - \hat{m}_{S_3}) \approx 7 \times 10^{-5}$ GeV, we obtain

$$\varepsilon_{S_1} = 0.682, \quad Y_B = 4 \times 10^{-10}. \quad (29)$$

In Case (a) with $\hat{m}_{S_1} \sim \mathcal{O}(1)$ GeV, the lightest sterile neutrino acts as the most dominant source of $0\nu\beta\beta$ decay whereas the heavy quasi-degenerate pair of sterile neutrinos $S_2$ and $S_3$ mediate resonant leptogenesis. Similarly in the alternative scenario of Case (b) with $\hat{m}_{S_2} \sim \mathcal{O}(1)$ GeV, the second generation light sterile neutrino acts as the mediator of dominant double beta decay while the heavy quasi-degenerate pair of the first and the third generation sterile neutrinos mediate resonant leptogenesis. Because of the resonant leptogenesis constraint, we note that either Case (a) or Case (b) is permitted, but not both.

| $m_{s_1}$ (GeV) | $m_{s_2}$ (GeV) | $m_{s_3}$ (GeV) | Baryon asymmetry | $T_{1/2}^{\nu\beta\beta}$ (10^{25} \text{yrs.}) |
|-----------------|-----------------|-----------------|------------------|-------------------------|
| 1               | 500             | 500             | $3.73 \times 10^{-10}$ | 2.72               |
| 10              | 500             | 500             | $3.5 \times 10^{-10}$ | 16.01             |
| 500             | 1               | 500             | $4.2 \times 10^{-10}$ | 0.0494             |
| 500             | 3               | 500             | $4.1 \times 10^{-10}$ | 2.19               |

TABLE I. Predictions for baryon asymmetry and double-beta decay half-life as a function of sterile neutrino masses.

Our predictions for the double beta decay half-life and the baryon asymmetry in Case (a) and Case (b) are presented in Table I. It is clear that for smaller mass eigen values of sterile neutrinos in Case (a) or Case (b), it is possible to saturate current experimental limit on the double-beta decay half-life while explaining the right order of magnitude of the baryon asymmetry. Thus, in addition to the Case (a) found in ref. [28], we have shown another possible alternative scenario as Case (b).

V. DECAY WIDTH, HALF-LIFE, AND DISPLACED LENGTHS OF STERILE NEUTRINOS

When the RH Majorana neutrino is near the TeV scale with shorter lifetime and path length, it is expected...
to mediate like-sign dilepton events inside the LHC detectors [51][53]. But when the mass of the Majorana type sterile neutrino is $O(1)$ GeV having its naturally small mixing with active light neutrinos, its half life is longer resulting in its path lengths extending to regions outside the LHC detectors. This is expected to cause the dilepton signal events to be observed via displaced vertices outside the detectors. As already explained, because of the $SO(10)$ model predictions of heavy-light mixing matrix elements $\mathcal{V}_{ci}, \mathcal{V}_{ii}$ ($i = 1, 2$), either $S_1$ or $S_2$ is capable of mediating the displaced vertices resulting in the like-sign dilepton events $eejj, \mu\mujj$, and $e\mujj$ without missing energy and with almost negligible SM background provided that the signal strength is strong enough under different cut conditions [32]. The Feynman diagram for the production of like-sign dileptons along with two jets in the $W_L - W_L$ channel is given in Fig. 4. The contribution of sterile neutrino to neutrino-less double beta decay is shown in Fig. 4. As already clarified the double beta decay occurs even without missing energy and with almost negligible $e\mujj$ because of the existence of $\mathcal{V}_{ci}$ or $\mathcal{V}_{ii}$ [51–53]. But when the mass of the Majorana $S_0$ type sterile neutrino is $O(1)$ GeV having its naturally small mixing with active light neutrinos, its half life is being sufficiently light, $\Gamma_{S_0} \sim O(10)$ GeV and two other heavy and quasi-degenerate mass eigen values, it would be interesting to explore the outcome of the Case (b) along with the Case (b) for dilepton production with displaced vertices.

![Feynman diagram](image)

**FIG. 4.** The Feynman diagram for like-sign dilepton production process $t^\pm t^\pm jj$ in the $W_L - W_L$ channel in the $pp$ collision process at LHC

At LHC the sterile neutrino mediated cross section can be expressed in terms of heavy-light mixing [53]

$$\sigma(pp \to S^\pm \to t^\pm t^\pm jj) = (2 - \delta_{1122})S_{1122}\sigma_0(S)$$

$$S_{1122} = \frac{|V_{1s}|^2 V_{2s}^* V_{2s}^*|^2}{\sum_{l=e, \mu} |V_{ls}|^2}$$ (30)

where $l = e$ or $\mu$ and $\sigma_0(S)$ is the bare cross section arising out of the exchange of the sterile neutrino $S$. If the second lepton is produced outside the LHC detector within a path length $L$ defined by eq. (35) given below, the number of events within the displaced length limit is estimated through the formula [32]

$$N = L \times \sigma(pp \to S_l^\pm \to t^\pm jj) \times PN$$

$$PN = e^{-d_1/L} - e^{-d_2/L}$$ (31) (32)

In the Type-I seesaw based RH sterile neutrino case [32], using the DELPHI bound [34] and double beta constraint on LH and RH neutrino mixing, a correlation between sterile neutrino mass and allowed values of mixings has been derived under different cut conditions [55] such that approximately $3 - 5$ like-sign dilepton events in the $t^\pm t^\pm jj$ channel can be detected outside the LHC detectors with luminosity $L = 300$ fb$^{-1}$. Keeping the transverse momentum cut of the first electron at $p_T^e > 30$ GeV, the allowed region sensitive to mixings has been identified under the momentum cut conditions for the second electron for $p_T^2 > 7, 30, 35$, and, $45$ GeV with rapidity cut $|\eta| < 2.5$. Also keeping $p_T^2 > 7$ GeV, the allowed region has been investigated under the jet momentum cut conditions $p_T > 10, 15$, and $20$ GeV for $p_T^2 > 30$ GeV and $|\eta| < 2.5$. It turns out that $3 - 5$ events of $e\mujj$ might be barely possible in the double beta decay mixing region with $|V_{ls}|^2 \sim 10^{-7} - 10^{-8}$ provided a lower value of the second lepton momentum cut is imposed and the luminosity is large enough, $L = 3000$ fb$^{-1}$. However for larger values of mixings displaced vertices can be observed for lower luminosity like $L = 300$ fb$^{-1}$. For the RH sterile neutrino mass in the range $2 - 80$ GeV, subject to different cut conditions, the assumed values of modulus square of mixings sensitive for displaced vertex search have been found to be constrained to the region $10^{-5}$ to $10^{-7}$.

In our Model-I and Model-II, the heavy light mixings as well as the sterile neutrino masses are predicted by the underlying mechanism in $SO(10)$. We investigate how these model predictions are accommodated in the almost model-independent approach of ref. [32]. We also predict the number of events that can be produced through displaced vertices in other channels like $e\mujj, \mu\mujj$, and $e\taujj$. The decay width of the $i$th light sterile neutrino ($i = 1$ or $2$) of these two models in Case (a) or Case (b) as discussed above is

$$\Gamma_{s_i} = \frac{3G_F^2}{32\pi^3} m_{s_i}^5 \sum_l |V_{ls}|^2$$ (33)

where $G_F =$ Fermi coupling constant and $V_{ls}$ is the light neutrino- sterile neutrino mixing matrix.

Coexistig with sterile neutrinos $S_1, S_2, S_3$ in Model-I and Model-II, the heavy RH neutrinos of three generations with masses at the $\sim TeV$ scale are assumed to predict negligible new contributions to double beta decay and also to displaced vertices outside the LHC detectors, ATLAS or CMS. In contrast, one of the sterile neutrinos being sufficiently light, $S_1$ in Case (a) or $S_2$ in Case (b) in each of the two models (Model-I and Model-II), is
expected to provide quite effective mediation for these two processes. With the value $G_{01} = 0.686 \times 10^{-14} \text{yr}^{-1}$, the nuclear matrix element $M_N = 233 - 412$, $m_p =$ proton mass defined through eq. (17), the half-life of the $i$-th sterile neutrino of mass eigen value $\tilde{m}_{si}$ is

$$T_{1/2}^{-1} = G_{01} (M_N m_p)^2 V_{ls}^4 \tilde{m}_{si}^{-2}$$  \hspace{1cm} (34)$$

leading to the displaced length of the first generation sterile neutrino $S_1$ in case (a) or the second generation sterile neutrino $S_2$ in Case (b)

$$L = 487.5 \tilde{\gamma}_i \left( \frac{\text{GeV}}{\tilde{m}_{si}} \right)^{5} 10^{-7} \left| V_{ls} \right|^2$$ \hspace{1cm} (35)

where $\tilde{\gamma}_i = \frac{E_i}{\tilde{m}_{si}}$, $E_i$ being the average energy of the sterile neutrino $S_i$.

From DELPHI [34] the mixing limit is $\sim 10^{-5}$ and from the neutrino-less double beta $(0\nu\beta\beta)$ decay the upper limit (lower limit) of mixing is $10^{-7}(10^{-8})$. Our model is different from other models in that the heavy-light mixings, be it with RH neutrinos or sterile neutrinos, are determined from the fermion mass fits at the SO(10) GUT scale and the LFV constraint on $M_1 (i = 1, 2, 3)$ [28]. As already noted, the Dirac neutrino mass matrix in eq. (13) that is basic to heavy-light mixing has been determined by fitting the RG extrapolated values of charged fermion masses at the GUT scale and running the matrix elements to the TeV scale using the top-down approach. Then the $\nu - N$ mixing matrix is $M_D^{MN}$ whereas the $\nu - S$ mixing matrix is $M_D^{MS}$.

The model-independent analysis of the type given in ref. [32] using the formula of eq. (35) is shown in Fig. 5. The mass of the sterile neutrino in the range $1 - 80$ GeV, corresponds to the displaced length of the order of $(0.001 - 1) \text{m}$ and the displaced vertex search is sensitive in the pink coloured shadow region given of Fig. 5 [28].

An important point shown in this work is that the heavy-light mixings predicted by our Model-I and Model-II based on SO(10), either in Case (a) or Case (b) of each model, are found to be in the sensitive region of the model-independent search [32]. In the following section we predict signal events of dilepton production due to displaced vertices in various channels.

FIG. 5. Constraints on active-sterile neutrino mixings including DELPHI and neutrinoless double beta decay limits. The lower-most solid line of the pink colored shadow region having upward concavity corresponds to $L=1 \text{m}$ and the upper-most line corresponds to $L=0.001 \text{m}$ where the displaced vertex search at LHC is expected to be sensitive. The dashed lines correspond to different $p_T$ cuts: $p_T^X > 40 \text{ GeV}$, $p_T^X > 7 \text{ GeV}$, $p_T^X > 40 \text{ GeV}$, $p_T^X > 45 \text{ GeV}$ and $|\eta^i| < 2.5$ with luminosity $300 \text{fb}^{-1}$. The two lower solid curves with positive slopes indicate the double beta decay limits.

VI. MODEL PREDICTION OF DILEPTON SIGNAL EVENTS WITH DISPLACED VERTICES

In this section we estimate the number of signal events that may appear outside the LHC detectors using the heavy-light neutrino mixings and the sterile neutrino masses predicted in our Model-I and Model-II in Case (a) and Case (b). In earlier analyses with the single RH neutrino as sterile neutrino, like-sign dilepton events have been investigated mostly in the $eejj$ channel [32] for various assumed values of mixings satisfying experimental constraints from DELPHI and double-beta decay experimental limits. In the present work the, because of the available predictions on two interesting possible cases for double beta decay and resonant leptogenesis caused by the lighter masses of the sterile neutrino $S_1$ or $S_2$, we are able to predict like-sign dilepton events for $eejj$, $\mu\mu jj$, $\epsilon\epsilon jj$, and $\epsilon\tau jj$ channels as shown in Table. II Table. III Table. IV Table. V Table. VI Table. VII and Table. VIII for the respective cases as functions of sterile neutrino masses, luminosities, and cut conditions. As clarified through our analytic formulas in eq. (12) and eq. (16), the sterile neutrino mass eigen value can be increased or decreased by keeping $M_1$ or $M_2$ fixed over limited range of values while decreasing or increasing $M_N$ that depends upon the ratio of two VEVs, $\frac{\text{V}_2}{\text{V}_1}$. Since our sterile neutrino-light neutrino mixings are inversely proportional to $M_i$, this ratio has been also utilised to have the desired values of mixings for larger values of sterile neutrino masses.

We conclude that dilepton events through displaced vertices are possible in various channels with suppressed SM back ground events and also with vanishing missing
TABLE II. Prediction of like sign dielectron events via displaced vertices in the $eejj$ channel as a function of sterile neutrino mass $\tilde{m}_{e_1}$.

| Cut Condition | $\tilde{m}_{e_1}$ (GeV) | $V_{R/V_L}$ | $L(300)$ ($fb^{-1}$) | $L(3000)$ ($fb^{-1}$) |
|---------------|----------------|-------------|------------------|------------------|
| $P_T^{e_1} \geq 35 GeV$ | 1.2 | $2 \times 10^{13}$ | 0.5 | 5 |
| $P_T^{e_1} \geq 30 GeV$ | 6 | $10^{14}$ | 0.5 | 5 |

TABLE III. Prediction of like sign dimuon events via displaced vertices in the $\mu\mu jj$ channel as a function of sterile neutrino mass $\tilde{m}_{\mu_1}$.

| Cut Condition | $\tilde{m}_{\mu_1}$ (GeV) | $V_{R/V_L}$ | $L(50)$ ($fb^{-1}$) | $L(300)$ ($fb^{-1}$) |
|---------------|----------------|-------------|------------------|------------------|
| $P_T^{\mu_1} \geq 35 GeV$ | 1.2 | $2 \times 10^{13}$ | 2.67 | 16 |
| $P_T^{\mu_1} \geq 30 GeV$ | 6 | $10^{14}$ | 2 | 9 |

TABLE IV. Prediction of like sign dimuon events via displaced vertices in the $\mu\mu jj$ channel as a function of sterile neutrino mass $\tilde{m}_{\mu_2}$.

| Cut Condition | $\tilde{m}_{e_1}$ (GeV) | $V_{R/V_L}$ | $L(300)$ ($fb^{-1}$) | $L(3000)$ ($fb^{-1}$) |
|---------------|----------------|-------------|------------------|------------------|
| $P_T^{e_1} \geq 35 GeV$ | 1.2 | $2 \times 10^{13}$ | 0.51 | 5.1 |
| $P_T^{e_1} \geq 30 GeV$ | 6 | $10^{14}$ | 0.51 | 5.1 |

TABLE V. Prediction of like sign dielectron events via displaced vertices in the $e\mu jj$ channel as a function of sterile neutrino mass $\tilde{m}_{e_2}$.

| Cut Condition | $\tilde{m}_{e_2}$ (GeV) | $V_{R/V_L}$ | $L(300)$ ($fb^{-1}$) | $L(3000)$ ($fb^{-1}$) |
|---------------|----------------|-------------|------------------|------------------|
| $P_T^{e_2} \geq 35 GeV$ | 1.2 | $2 \times 10^{13}$ | 0.3 | 3.26 |
| $P_T^{e_2} \geq 30 GeV$ | 6 | $10^{14}$ | 0.3 | 3.26 |

TABLE VI. Prediction of electron-muon events via displaced vertices in the $e\mu jj$ channel as a function of sterile neutrino mass $\tilde{m}_{e_1}$.

| Cut Condition | $\tilde{m}_{e_2}$ (GeV) | $V_{R/V_L}$ | $L(300)$ ($fb^{-1}$) | $L(3000)$ ($fb^{-1}$) |
|---------------|----------------|-------------|------------------|------------------|
| $P_T^{e_2} \geq 35 GeV$ | 1.2 | $2 \times 10^{13}$ | 0.58 | 6 |
| $P_T^{e_2} \geq 30 GeV$ | 6 | $10^{14}$ | 0.5 | 6 |

energy. This serves as an interesting prediction based upon Type-II seesaw dominant SO(10) GUTs.

VII. DILEPTON SIGNATURE BY HEAVY RH NEUTRINO EXCHANGE

After discussing the manifestation of sterile neutrinos in Model-I and Model-II through various physical processes like double beta decay, dilepton signals with displaced vertices, and resonant leptogenesis, in this section we investigate if the TeV scale RH neutrinos present in both the models may manifest at the LHC, particularly, through the like-sign dilepton production events that may materialise inside the ATLAS or the CMS detectors. Since the $W_R$ boson mass is quite heavy, $M_{W_R} > 10^8$ GeV, only the $W_L-W_L$ channel is dominant for the process $pp \rightarrow l^{\pm}l^{\pm}X$ where $l = e, \mu$. The heavy RH Majorana neutrino exchange cross section is given by \cite{53}

$$\sigma(pp \rightarrow Nl^{\pm} \rightarrow l^{\pm}jj) = \sigma_{prod}(pp \rightarrow W_L \rightarrow Nl^{\pm}) \times BR(N \rightarrow l^{\pm}jj)$$

where the production cross section $\sigma_{prod}$ is estimated by using patron level distribution function CTEQ6L \cite{57}.

The branching ratio is estimated using

$$BR(N \rightarrow l^{\pm}jj) = \frac{\Gamma(N \rightarrow l^{\pm}jj)}{\Gamma_{tot}^N} \times BR(W \rightarrow jj)$$

with $BR(W \rightarrow jj) = 0.676$. The total width is calculated by sum of all the partial widths.
The heavy-light neutrino mixing plays a crucial role in calculating the signal cross section. In our model the heavy-light neutrino mixing matrix for heavy RH neutrinos is \( \frac{M_D}{M_N} \), where \( M_D \) is the Dirac neutrino mass matrix and \( M_N \) is the RH neutrino mass matrix. An interesting aspect of the models is that both the matrices, \( M_D \) and \( M_N \), are already predicted by TeV scale gauge symmetry breaking, the neutrino oscillation data, and charged fermion mass fits at the GUT scale.

In the case of vanilla seesaw model investigated in [53], the heavy-light neutrino mixing is \( V_{HN}^2 = m_\nu/M_N \) which is quite small and gives rise to a cross section \( \sigma(pp \to \mu\mu jj X) \approx 10^{-16} \text{ pb} \) in the \( W_L - W_L \) channel for exchanged heavy RH neutrino mass \( \approx 100 \text{ GeV} \). On the other hand if the heavy-light mixing is assumed to be as large as \( V_{HN}^2 = 3 \times 10^{-3} \) [53], the cross section is also large leading to \( \sigma(pp \to \mu\mu jj X) \sim 6 \times 10^{-2} \text{ pb} \). However we do not assume any such large mixings here. In our type-II seesaw dominant models where all the heavy-light neutrino mixings are predicted, the estimated value of dimuon signal cross section in the \( W_L - W_L \) channel turns out to be \( \approx 5 \times 10^{-4} (2 \times 10^{-5}) \text{ pb} \) for the mass of \( M_{N_1} = 100(200) \text{ GeV} \) resulting in nearly 24(12) events for beam luminosity \( \mathcal{L} = 300 \text{ fb}^{-1} \) after including the cuts [54]. This result is shown in fig. (6). Thus if the RH neutrino masses are within \( M_N \leq 300 \text{ GeV} \), they are detectable at LHC run-II at \( \sqrt{s} = 14 \text{ TeV} \) for projected beam luminosity \( \mathcal{L} = 3000 \text{ fb}^{-1} \), although the RH neutrino masses \( M_{N_1} \leq 200 \text{ GeV} \) are detectable with beam luminosity \( \mathcal{L} = 300 \text{ fb}^{-1} \). In these models the larger values of RH neutrino masses, \( M_{N_1} > 500 \text{ GeV} \), are likely to escape detection at LHC through like-sign dilepton production signals. These conclusions remain valid after imposing the various cut conditions applicable to the \( pp \to l^\pm l^\pm jj X \) channels [53, 54]. In the case of \( M_{N_2} \) we have similar conclusion.

\[
\Gamma(N \to l^\pm W) = \frac{g^2 |V_{\nu l}|^2 M_N^3}{64\pi} \left(1 - \frac{M_W^2}{M_N^2}\right)^2 \times (1 + \frac{2M_W^2}{M_N^2}), \quad (37)
\]

\[
\Gamma(N \to \nu_i Z) = \frac{g^2 |V_{\nu l}|^2 M_N^3}{128\pi \cos^2\theta_W} \left(1 - \frac{M_Z^2}{M_N^2}\right)^2 \times (1 + \frac{2M_Z^2}{M_N^2}), \quad (38)
\]

\[
\Gamma(N \to \nu_i h) = \frac{g^2 |V_{\nu l}|^2 M_N^3}{128\pi} \left(1 - \frac{M_h^2}{M_N^2}\right)^2 \quad (39)
\]

FIG. 6. The signal cross section of the heavy RH neutrino as a function of its mass for dimuon at LHC with \( \sqrt{s} = 14 \text{ TeV} \).

VIII. DOUBLE BETA DECAY, DISPLACED VERTICES, AND LEPTOGENESIS WITH NH NEUTRINOS

In ref. [28], we have already shown how dominant double beta decay rate occurs for normally hierarchical (NH), invertedly hierarchical (IH), and quasi-degenerate (QD) mass patterns of light and active neutrinos due to the exchange of lightest sterile neutrino \( S_1 \). But our applications as given above for dominant double beta decay along with displaced vertices and resonant leptogenesis have been confined only to the QD pattern of light neutrino masses. On the otherhand if the recent cosmological limit [36] is ultimately confirmed by laboratory experiments, neutrino masses could be NH type. It would be interesting to investigate if the results derived so far are also applicable to NH case. For this purpose we note that in the NH case the new contribution to \( 0\nu\beta\beta \) half-life by \( S_1 \) saturates the experimental bound for \( m_{S_1} = 2.5 \pm 0.5 \text{ GeV} \) as shown in fig. (7). Such a mass certainly mediates like-sign dilepton events with displaced vertices in the \( eejj \) and \( \mu\mu jj \) channels as discussed above. To complete the application to resonant leptogenesis we search for parameter values in \( M = \text{diag.}(M_1, M_2, M_3) \) to find solutions for quasi-degenerate pair of masses \( m_{S_2} \) and \( m_{S_3} \) near TeV scale so that the ansatz given above and in ref. [28] goes through to explain baryon asymmetry of the universe.

We choose an interesting region of the parameter space \( M \approx \text{diag.}(38.27, 752.1, 1219.0) \text{ GeV} \). Then using the RH neutrino mass matrix \( M_N \) derived in ref. [28] in the NH case and eq. (41), we get

\[
\hat{m}_{S_1} = \text{diag.}(2.8, 1348.86.., 1348.86...) \text{ GeV}. \quad (40)
\]

containing the desired mass patterns. Using the formula for resonant leptogenesis, we get \( K_1 = 2 \times 10^{12} \), using \( (\hat{m}_{S_2} - \hat{m}_{S_3}) \approx 0.001 \text{ GeV} \), we obtain

\[
\bar{\varepsilon}_{S_2} = 0.013, \quad Y_B = 7.4 \times 10^{-10}. \quad (41)
\]

The values of \( \hat{m}_{S_1} \) upto \( \mathcal{O}(10) \text{ GeV} \) are easily obtained while satisfying the required constraints for resonant leptogenesis. With the value of \( S_1 \) mass given in eq. (40)
we have verified that the double beta decay lifetime is predicted with a value close to the current experimental limit.

Thus we have shown that for NH pattern of light neutrino masses that favours the recent cosmological bound \cite{36}, a light sterile neutrino mass \( m_{\nu_4} \lesssim 100 \text{ GeV} \) allowed within the allowed parameter space.

\[ \text{FIG. 7. The half-life of the neutrinoless double beta decay as a function of sterile neutrino mass.} \]

IX. Z' DETECTION AT COLLIDERS

One important and interesting feature of this paper is the prediction of of extra neutral Z' boson at the TeV scale accessible for detection at LHC, International Linear Collider [ILC], and future collider experiments. In this section we estimate relevant cross sections which may help in identifying the Z'-boson signals.

A. Cross section of Z' boson

In this section we discuss the possible signatures of the Z' boson at LHC and ILC experiment through opposite sign dilepton production cross sections. We also discuss possible signature of Z' boson through the production of W^+W^- pairs for different values of Z - Z' mixings at LHC. In the dilepton channel we compare our estimated Z' production cross section with those obtained by CMS experiment \cite{56} in the channel \( pp \to Z'X \to l^+l^-X \) where \( l = e, \mu \).

The resonant production cross section for the opposite sign dilepton production via Z' boson resonance is \cite{22,23}

\[
\sigma(pp \to Z' \to f \bar{f}) = \frac{\pi}{48S} \left[ C_u w_u(S, M_{Z'_L}) + C_d w_d(S, M_{Z'_L}) \right],
\]

(42)

where the coefficients \( C_u \) and \( C_d \) are

\[
c_{u,d} = g^2_z (z_u^2 + z_d^2) Br(t^+l^-).
\]

(43)

Here \( w_{u(d)} \) \cite{22} is related to the parton luminosities \( \frac{d\sigma_{u(d)}}{dM_{Z'_L}} \) and \( \frac{d\sigma_{l\bar{l}X}}{dM_{Z'_L}} \). Therefore they depend only upon the collider energy and the Z' mass.

The production cross section in the channel \( pp \to Z'X \to l^+l^-X \) as a function of invariant dilepton mass (or the Z'- mass) is shown in Fig.8

This result suggests that at \( \sqrt{S} = 14 \text{ TeV} \) the number of Z' production events could be large in the region of \( M_{Z'} \sim 1 \text{ TeV} \) even for \( 30 \text{ fb}^{-1} \) beam luminosity, but to get sizeable number of events in the region of \( M_{Z'} \sim 2 - 3 \text{ TeV} \), the beam luminosity has to increase beyond several 1000 fb^{-1}.

\[ \text{FIG. 8. The signal cross section of the Z' boson as a function of its mass in the production channel pp \to Z'X \to l^+l^-X} \]

The international linear collider (ILC) is expected to provide a rigorous experimental verification of various Z’ models as far as their predicted masses are concerned. In our model, the variation of the predicted annihilation cross section via Z’ resonance with center of mass energy of the colliding lepton beams is given in Fig.9. To estimate this cross section we have used the total decay width of Z' boson as the sum of decay widths of Z' into quarks and leptons \cite{22}.

\[
\Gamma_{Z'} = \frac{g^2}{48\pi} \left[ 9(g_W^2 + g_A^2) + 9(g_W^2 + g_A^2) + 3(g_W^2 + g_A^2) + 3(g_W^2 + g_A^2) \right]
\]

(44)
The signal cross section is found to be 70 pb at the center of mass energy $\sqrt{s} = 2800$ GeV which corresponds to the $Z'$ mass. Therefore its presence can be easily detected even for as low a luminosity as $\mathcal{O}(1)$ pb$^{-1}$.

The CMS collaboration [56] has also measured the cross section ratio $\sigma(pp \rightarrow Z' \rightarrow l^+l^-X)/\sigma(pp \rightarrow Z \rightarrow l^+l^-X)$ as shown in Fig. 10 as function of the $Z'$ mass $M_{Z'}$. Our prediction using $l = \ell$ is shown by almost a slanted linear curve with falling value of the ratio with increasing value of $M_{Z'}$. From this Fig. 10 we find that in our model the lower limit of the $Z'$ mass is predicted to be $M_{Z'} \sim 2.8$ TeV.

In summary we find that the two $SO(10)$ models proposed recently to predict TeV scale $Z'$ and RH neutrinos with charged lepton flavor violating branching ratios only few to four orders smaller than the experimental upper bounds make dominant contributions to neutrinoless double beta decay mediated by light sterile neutrino mass of the first or the second generation. Although only the first generation sterile neutrino was shown to mediate the double beta decay process in ref. [28], here we have found that each of the first or the second generation sterile neutrino mass is allowed to be in the range of $\sim 1 - 10$ GeV and has the capability investigated [23]. In this paper we estimate the variation of differential cross section with respect to the invariant mass $M$ of the produced $W^+W^-$ pair for different $Z - Z'$ mixings. The corresponding differential cross section for the process $pp \rightarrow W^+W^- + X$ averaged over quark colors can be obtained by [23]

$$
\frac{d\hat{\sigma}(Z')}{d\cos\theta} = \frac{\pi\alpha^2\cot^2\theta_w}{48} \frac{\beta_{\nu_{2f}}^2 (\nu_{2f})}{M_{\ell}^2} \left( \frac{\hat{s}}{M_{\ell}^2} \right) + \frac{\hat{s}}{M_{\ell}^2} \sin^2\theta + \frac{\hat{s}}{M_{\ell}^2} \left( 4 - \sin^2\theta + 12\sin^2\theta \right)
$$

In our model for invariant mass 2.3 TeV, the mixings are $1.2 \times 10^{-3}$, $0.9 \times 10^{-3}$, and $0.7 \times 10^{-3}$ at invariant mass values of 2.3 TeV, 3.5 TeV, and 4 TeV, respectively. The distribution curves are shown in fig. 11 for these three sets of values. Our predicted results give the value of $\frac{d\sigma}{ds} = 0.52$ (fb/GeV) for $M_{Z'} = 3.5$ TeV. The predicted values of the peak positions at 2.3 TeV and 4 TeV can also provide a test of the models if such a $Z'$ is present in nature.

X. SUMMARY AND CONCLUSION

In summary we find that the two $SO(10)$ models proposed recently to predict TeV scale $Z'$ and RH neutrinos with charged lepton flavor violating branching ratios only few to four orders smaller than the experimental upper bounds make dominant contributions to neutrinoless double beta decay mediated by light sterile neutrino mass of the first or the second generation. Although only the first generation sterile neutrino was shown to mediate the double beta decay process in ref. [28], here we have found that each of the first or the second generation sterile neutrino mass is allowed to be in the range of $\sim 1 - 10$ GeV and has the capability.
to make dominant contributions to double beta decay while mediating displaced vertices for like-sign dilepton signals of the type eejj, eµjj, and µµjj outside the LHC detectors with drastically suppressed standard model backgrounds and without missing energy. The predicted values of heavy light mixings in Model-I and Model-II of non-SUSY SO(10) theory are found to overlap with regions of the parameter space identified in the model-independent approach under different cut conditions. For the eejj process to be visible with the heavy-light mixings compatible with double-beta decay bound, a low momentum cut of the second electron is necessary. Significant number of events in the eτjj and µµjj channels are predicted with luminosity L = (50 – 300) fb⁻¹ which will either testify or falsify these models. With the first generation sterile neutrino mediating the double beta decay and the displaced vertices for eejj and µµjj events, both the SO(10) models explain the right order of the baryon asymmetry of the universe through resonant leptogenesis mediated by the heavy quasi-degenerate pair of the second and third generation sterile neutrinos having mass ∼ 500 GeV. In the second alternative scenario where dominant double beta decay and di-electron and di-muon production through displaced vertices are mediated by the second sterile neutrino mass of ∼ 10 GeV, the resonant leptogenesis to explain the baryon asymmetry is implemented by the quasi-degenerate pair of heavy sterile neutrinos of mass ∼ 500 GeV belonging to the first and the third generations. These predictions with displaced vertices are easier to verify as the number of signal events are produced outside the detectors having suppressed back grounds in the l±l±jj channels without missing energy.

In this work we have also shown how the dominant double beta decay, resonant leptogenesis, observable like-sign dilepton production via displaced vertices along with non-unitarity effects and experimentally accessible proton lifetime are possible in the two models in the presence of NH pattern of light neutrino masses consistent with the recent cosmological bound.

We have discussed two aspects of resonant Z' production at the LHC in the lepton pair ℓ⁺ℓ⁻ production and W⁺W⁻ pair production channels. While in the former case detection of Z' with mass M_{Z'} ≥ 2.5 TeV would require beam luminosity > 1000 fb⁻¹, in the latter case it may easier to identify the peak structure even for reasonable luminosities. At ILC the Z' boson would manifests most prominently by direct detection of its resonant peak at the predicted mass value. Finally we conclude that the two TeV scale Z' models proposed recently with Type-II see-saw dominance are quite effective in predicting like-sign dilepton events via displaced vertices while explaining neutrino oscillation data and baryon asymmetry of the universe with predictions of significant leptonic non-unitarity effects, and LFV and LNV decays accessible to ongoing searches. Earlier it was noted that the proton lifetime predictions are also accessible to experimental searches. These models have high degree of falsifiability through a number of experimental observables they predict.

ACKNOWLEDGMENT

M. K. P. thanks the Science and Engineering Research Board, Department of Science and Technology, Government of India for grant of research project SB/S2/HEP-011/2013. B.P.N. thanks Siksha ‘O’ Anusandhan University for a research fellowship.

[1] S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979).
[2] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[3] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[4] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[5] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[6] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[7] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[8] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[9] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
[10] R. Foot, H. Lew, X. G. He, G. C. Joshi, Z. Phys. C 44, 441 (1989).
Phys. Rev. Lett. B 50, 1427 (1983).

[52] F. del Aguila, J. A. Aguilar-Saavedra, Nucl. Phys. B 813 (2009) 22; F. del Aguila, J. A. Aguilar-Saavedra, Phys. Lett. B 672 (2009) 158.

[53] C.Y. Chen, P. S. B. Dev, R. N. Mohapatra, Phys. Rev. D 88, 033014 (2013).

[54] Anupama Atre, Tao Han, Silvia Pascoli, Bin Zhang, J. High Energy Phys.0905, 030 (2009), arXiv:1401.1412 [hep-ph].

[55] ATLAS Collaboration, JINST 8, 07015 (2013).

[56] E. Accomando, A. Belyaev, J. Fiaschi, S. Moretti, K. Mimasu, C. Shepherd-Themistocleous, arxiv:1503.02672.

[57] J.Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky, and W. K. Tung, JHEP 07, 012 (2002).