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The $eejj$ excess signal at the LHC and constraints on leptogenesis

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Abstract. We review the non-supersymmetric (Extended) Left-Right Symmetric Models (LRSM) and low energy E_6-based models to investigate if they can explain both the recently detected excess $eejj$ signal at CMS and leptogenesis. The $eejj$ excess can be explained from the decay of the right-handed gauge bosons (W_R) with mass $\sim$TeV in certain variants of the LRSM (with $g_L \neq g_R$). However such scenarios can not accommodate high-scale leptogenesis. Other attempts have been made to explain leptogenesis while keeping the W_R mass almost within the reach of the LHC by considering the resonant leptogenesis scenario in the context of the LRSM for relatively large Yukawa couplings. However, certain lepton number violating scattering processes involving the right-handed Higgs triplet and the right-handed neutrinos can stay in equilibrium till the electroweak phase transition and can washout the lepton asymmetry generated in the resonant leptogenesis scenario for mass range of W_R as indicated by the CMS excess signal. Thus in such a scenario one needs to invoke post-sphaleron baryogenesis to explain the observed baryon asymmetry of the universe. Next, we consider three effective low energy subgroups of the superstring inspired E_6 model having a number of additional exotic fermions which provides a rich phenomenology to be explored. We however find that these three effective low energy subgroups of E_6 too cannot explain both the $eejj$ excess signal and leptogenesis simultaneously.

Keywords: leptogenesis, baryon asymmetry, particle physics - cosmology connection

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Contents

1 Introduction

One of the most popular extensions of the Standard Model (SM) of particle physics is the Left-Right Symmetric Model (LRSM) [1–3]. The weak interactions of the LRSM are governed by the gauge group $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ where $B-L$ is the difference between baryon and lepton numbers. In such a model, the right-handed gauge bosons (W_R) decay in a manner very similar to their left-handed counterparts except that the left-handed neutrino (ν_L) gets replaced by its right-handed counterpart N_R. Now N_R may be a Dirac particle, decaying to a "proper-sign" lepton or a Majorana particle which can decay to either sign lepton. It can further decay via a virtual W_R emission or via mixing with ν_L giving a two lepton two jet signal.

The CMS Collaboration at the LHC at CERN has announced their results for the W_R search at a center of mass energy of $\sqrt{s} = 8\,\mathrm{TeV}$ and $19.7\mathrm{fb}^{-1}$ of integrated luminosity. Using the cuts $p_T > 60\,\mathrm{GeV}, |\eta| < 2.5 (p_T > 40\,\mathrm{GeV}, |\eta| < 2.5)$ for the leading (subleading) electron and selecting events with $m_{ee} > 200\,\mathrm{GeV}$ a total of 14 events were observed in the energy bin $1.8\,\mathrm{TeV} < M_{eejj} < 2.2\,\mathrm{TeV}$ compared to 4 events expected from the SM background giving a 2.8σ local excess in the $pp \to ee + 2j$ channel [4]. The excess of $eejj$ events has been explained to be due to W_R decay by embedding the LRSM in a class of SO(10) model in ref. [5] and by considering general flavour mixing in the LRSM in ref. [6]. Additional tests to study right-handed currents at LHC are proposed in ref. [7].

However confirmation of these excess events for the given range of the W_R mass has severe implications for the leptogenesis mechanism [8–10], which offers a very attractive possibility to explain the baryon asymmetry of the universe. The seesaw mechanism [11–15] which provides a natural solution to the smallness of neutrino masses, offers a mechanism for generating a lepton asymmetry (and hence a $B-L$ asymmetry) before the electroweak phase transition, which then gets converted to the baryon asymmetry of the universe via $B+L$ violating anomalous processes in equilibrium [8–10, 16]. The lepton asymmetry can be generated in two possible ways. One way is via the decay of right-handed Majorana neutrinos (N) which does not conserve lepton number [8–10]; another way is via the decay of very heavy Higgs triplet scalars with lepton number violating interactions [17–19]. In the conventional LRSM, the right-handed neutrinos interact with the $\mathrm{SU}(2)_R$ gauge bosons. By taking into account the effect of the scattering processes involving such interactions of W_R on the primordial lepton asymmetry of the universe, phenomenologically successful high-scale leptogenesis requires M_{W_R} to be very heavy for both the cases $M_N > M_{W_R}$ and $M_{W_R} > M_N$ [20]. Thus, an observed $1.8\,\text{TeV} < M_{W_R} < 2.2\,\text{TeV}$ implies that the decay of right-handed neutrinos can not generate the required lepton asymmetry of the universe. Furthermore, since the W_R interactions erase any primordial $B-L$ asymmetry, the observed baryon asymmetry of the universe must be generated at a scale lower than the $\mathrm{SU}(2)_R$ breaking scale. Attempts have been made to explain the required amount of lepton asymmetry in the context of resonant leptogenesis [21–28] while pushing the mass of W_R to as low as 3 TeV for relatively large Yukawa couplings [29, 30]. However, the presence of certain lepton number violating processes involving the doubly charged right-handed Higgs triplet and the right-handed neutrinos in the LRSM which stay in equilibrium close to the electroweak phase transition for M_{W_R} in the range of a few TeV will slowdown the leptogenesis above the electroweak phase transition [31]. Thus, the W_R mass is required to be quite high compared to the CMS signal range to have a successful resonant leptogenesis scenario. Similar arguments hold true even for the extended LRSM models which can be formed by extending the gauge group of the LRSM with additional U(1)'s. Next, we have considered generalized non-supersymmetric LRSM variants motivated by the low-energy subgroups of superstring inspired E_6 theories. These models are particularly interesting because in addition to having a gauge structure similar to the conventional LRSM, they also have a number of additional exotic fermions, thus providing a rich phenomenology to be explored. To this end, we examine these models to explore if the CMS excess signal can be explained while simultaneously allowing high-scale leptogenesis to generate the observed baryon asymmetry of the universe.

The outline of the article is as follows. In section 2, we first discuss the particle content and $B-L$ breaking scale of the Left-Right Symmetric Model. Then we argue that the $B-L$ breaking scale will be lower than the $\mathrm{SU}(2)_R$ breaking scale even in the extended LRSM. In section 3, We discuss how the CMS signal (if it is indeed due to W_R decay) rules out the possibility of high-scale leptogenesis. We also comment on certain lepton number violating processes involving the doubly charged right-handed Higgs triplet and right-handed neutrinos in (Extended) LRSM which stay in equilibrium close to the electroweak phase transition. These can rule out the possibility of TeV-scale resonant leptogenesis with the W_R mass in the few TeV range. In section 4, we first discuss the phenomenology of low energy subgroups of E_6 group. Then we show that though one of the subgroups allows high-scale leptogenesis, there does not exist any effective low energy subgroups of E_6 which can explain both the CMS $eejj$ excess as well as leptogenesis.[1] In section 5, we conclude with our results.

2 (Extended) Left Right Symmetric Model (LRSM)

In the LRSM the leptons and the quarks transform under the gauge group $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ as

$$\begin{aligned} l_L &= \begin{pmatrix} \nu \\ e \end{pmatrix}_L : (2,1,-1), & l_R &= \begin{pmatrix} N \\ e \end{pmatrix}_R : (1,2,-1), \\ Q_L &= \begin{pmatrix} u \\ d \end{pmatrix}_L : \left(2,1,\frac{1}{3}\right), & Q_R &=; \begin{pmatrix} u \\ d \end{pmatrix}_R : \left(1,2,\frac{1}{3}\right). \end{aligned} \tag{2.1}$$

[1] Since we consider non-supersymmetric LRSM, we assume that supersymmetry gets broken at a very high-scale in the low energy effective subgroups of E_6 and therefore supersymmetric particles are not really relevant for our analysis.

The Higgs sector of the LRSM consists of one bi-doublet Φ and two triplet $\Delta_{L,R}$ complex scalar fields with the transformations

$$\begin{aligned}
\Phi &= \begin{pmatrix} \Phi_1^0 & \Phi_1^+ \\ \Phi_2^- & \Phi_2^0 \end{pmatrix} : (2,2,0), \\
\Delta_L &= \begin{pmatrix} \frac{\Delta_L^+}{\sqrt{2}} & \Delta_L^{++} \\ \Delta_L^0 & -\frac{\Delta_L^+}{\sqrt{2}} \end{pmatrix}_L : (3,1,2), \\
\Delta_R &= \begin{pmatrix} \frac{\Delta_R^+}{\sqrt{2}} & \Delta_R^{++} \\ \Delta_R^0 & -\frac{\Delta_R^+}{\sqrt{2}} \end{pmatrix}_R : (1,3,2).
\end{aligned} \tag{2.2}$$

The left-right symmetry can be spontaneously broken to reproduce the Standard Model and the smallness of the neutrino masses can be taken care of by the see-saw mechanism. The symmetry breaking mechanism follows the scheme

$$\begin{aligned}
&\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \\
&\qquad\qquad\qquad\qquad \to \mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \\
&\qquad\qquad\qquad\qquad \to \mathrm{SU}(3)_C \times \mathrm{U}(1)_{EM}
\end{aligned} \tag{2.3}$$

Being aware of the above we now turn the table around and ask the question that if the CMS signal is indeed due to the decay of W_R corresponding to $\mathrm{SU}(2)_R$ breaking then can we conclusively say that (one of) the U(1)(s) in the left-right symmetric scheme (and its U(1) extensions) is necessarily $\mathrm{U}(1)_{B-L}$. If so then the next question is at what scale does it get broken. We start with an arbitrary U(1) (where we do not identify the U(1) charge with $B-L$) in the LRSM gauge group and then generalize the scheme to include more than one U(1). Consider the scheme $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X$, where the charge of the quark doublet under U(1) is assumed to be X_Q and that of the lepton pair is assumed to be X_l. Under $\mathrm{U}(1)_X$ the fields transform as

$$\begin{aligned}
l_L &:(2,1,X_l), & l_R &:(1,2,X_l), & & \\
Q_L &:(2,1,X_Q), & Q_R &:(1,2,X_Q), & & \\
\Phi &:(2,2,0), & \Delta_L &:(3,1,-2X_l), & \Delta_R &:(1,3,-2X_l).
\end{aligned} \tag{2.4}$$

Now we consider a scenario where in the first stage the right-handed triplet Δ_R acquires a Vacuum Expectation Value (VEV)

$$\langle \Delta_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \tag{2.5}$$

which breaks the $\mathrm{SU}(2)_R$ symmetry to give the right-handed neutrino a Majorana mass and to produce massive $W_R^\pm$, Z_R bosons. The next stage involves breaking the electroweak symmetry at some lower energy where the bi-doublet Higgs and left-handed Higgs triplet get VEVs giving mass to $W_L^\pm$ and Z_L gauge boson.[2] It turns out that in such a scheme X can

[2]Note that giving VEV to Δ_L is not necessary, however if such a scheme is allowed then left-handed fermions get both Majorana and Dirac masses.

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only be $B-L$ and the combination $\tau_L^3+\tau_R^3+\frac{1}{2}\mathbf{1}_{B-L}$ is the only unbroken generator satisfying the modified Gell- Mann-Nishijima formula

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}. \tag{2.6}$$

The $B-L$ symmetry can be violated either simultaneously or at a scale below the $\mathrm{SU}(2)_R$ breaking scale.

Next we consider the Extended LRSM such as $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X \times \mathrm{U}(1)_Z$, where we do not identify either X or Z with $B-L$. Then also we can argue that the $B-L$ breaking scale is lower than or equal to the $\mathrm{SU}(2)_R$ breaking scale. The argument goes as follows. We perform an SO(2) rotation on the gauge fields (A^X, A^Z) and choose a new basis $\mathrm{U}(1)'_X \times \mathrm{U}(1)'_Z$ such that the charge of Φ for one of the two groups, say $\mathrm{U}(1)'_X$, is zero. At this point we identify $\mathrm{U}(1)'_X$ with $B-L$. So the transformations of the Higgs fields are given by

$$\Phi : (2,2,0,Q_Z^{\Phi}), \Delta_L : (3,1,2,Q_Z^{\Delta_L}), \Delta_R : (1,3,2,Q_Z^{\Delta_R}). \tag{2.7}$$

So this reduces to the standard LRSM scenario if the additional $\mathrm{U}(1)'_Z$ breaks at a scale higher than the $\mathrm{SU}(2)_R$ breaking scale. This chain of arguments continue for any arbitrary number of U(1) extensions of the LRSM.

3 Constraints from leptogenesis

From section 2, it follows that $B-L$ gets broken either simultaneously with the $\mathrm{SU}(2)_R$ or else at a scale lower than the $\mathrm{SU}(2)_R$ breaking scale in the LRSM or any extension of the LRSM with arbitrary numbers of U(1)'s. The most stringent constraints on the W_R mass for successful high-scale leptogenesis come from the $\mathrm{SU}(2)_R$ interactions [20]. To have successful leptogenesis in the case $M_N > M_{W_R}$ the condition that the process

$$e_R^- + W_R^+ \to N_R \to e_R^+ + W_R^- \tag{3.1}$$

goes out of equilibrium translates into the condition

$$M_N \gtrsim 10^{16}\,\mathrm{GeV} \tag{3.2}$$

with $m_{W_R}/m_N \gtrsim 0.1$. Now for the case $M_{W_R} > M_N$ leptogenesis can happen either at $T \simeq M_N$ or at $T > M_{W_R}$ but at less than $B-L$ breaking scale. For $T \simeq M_N$, the condition that the scattering processes that maintain the equilibrium number density for N_R go out of equilibrium reduces to

$$M_{W_R} \gtrsim 2 \times 10^5\,\mathrm{GeV}(M_N/10^2\,\mathrm{GeV})^{3/4}. \tag{3.3}$$

For leptogenesis at $T > M_{W_R}$ the most relevant scattering process is

$$W_R^\pm + W_R^\pm \to e_R^\pm + e_R^\pm \tag{3.4}$$

through N_R exchange and the condition for this process to go out of equilibrium gives

$$M_{W_R} \gtrsim 3 \times 10^6\,\mathrm{GeV}(M_N/10^2\,\mathrm{GeV})^{2/3}. \tag{3.5}$$

Thus it follows that if the CMS excess is indeed a W_R signal with the mass of the W_R in the range $1.8\,\mathrm{TeV} < M_{W_R} < 2.2\,\mathrm{TeV}$ then for hierarchical neutrino masses ($M_{N_{3R}} \gg M_{N_{2R}} \gg$

$M_{N_{1R}} = m_N$) it is not possible to generate the required baryon asymmetry of the universe from high-scale leptogenesis.

The possibility of generating the required lepton asymmetry with a considerably low value of the W_R mass has been discussed in the context of the resonant leptogenesis scenario [21–28]. It has also been pointed out that successful low-scale leptogenesis with a quasi-degenerate right-handed neutrinos mass spectrum requires an absolute lower bound of 18 TeV on the W_R mass [29]. Recently it was shown that just the right amount of lepton asymmetry can be produced even for a substantially low value of the W_R mass ($M_{W_R} > 3$ TeV) [30] by considering relatively large Yukawa couplings. However there are certain lepton number violating processes which are ignored in the aforementioned analysis. In particular, below the left-right symmetry breaking scale, the lepton number violating scattering processes $e_R^{\pm} W_R^{\mp} \to e_R^{\mp} W_R^{\pm}$ and $e_R^{\pm} e_R^{\pm} \to W_R^{\pm} W_R^{\pm}$ mediated via doubly charged right-handed Higgs triplet scalars and the right-handed neutrinos will be very rapid in washing out the lepton asymmetry till the temperature drops below the mass of W_R. At a temperature below the W_R mass scale the latter process becomes doubly phase space suppressed. However, in spite of being singly Boltzmann suppressed, the former process stays in equilibrium till a temperature near the electroweak phase transition temperature for W_R mass in the TeV range and continues to wash out lepton asymmetry[3] [31]. Therefore, the lower limit on M_{W_R} for successful resonant leptogenesis will go up beyond the CMS excess range. In such a scenario, a post-sphaleron baryogenesis mechanism is required to explain the observed baryon asymmetry of the universe.

At this point, a natural question to ask is whether there exist other models with gauge extensions of the standard model gauge group which can get around the above constraints to provide a successful leptogenesis scenario while being able to accommodate the CMS excess. Below we consider extensions of the Standard Model motivated by the superstring inspired E_6 model to explore if the CMS excess signals can be compatible with high-scale leptogenesis.

4 E_6-subgroups involving heavy right-handed gauge bosons

In this section we explore three effective low energy subgroups of the superstring inspired E_6 model which involve additional exotic fermions leading to a rich gauge boson phenomenology. We have already discussed the possibility of producing both the $eejj$ and $e\not{p}_T jj$ signals and having sucessful high-scale leptogenesis in the context of low energy subgroups of E_6 in ref. [32] by involving supersymmetric particles. In this letter we assume that supersymmetry gets broken at a very high scale and that supersymmetric partners do not play any role in the following analysis.

Under one of the maximal subgroups of E_6 given by $\mathrm{SU}(3)_C \times \mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$, the fundamental 27 representation reduces to

$$27 = (3, 3, 1) + (3^*, 1, 3^*) + (1, 3^*, 3) \tag{4.1}$$

where $(u, d, h) : (3, 3, 1)$ and $(h^c, d^c, u^c) : (3^*, 1, 3^*)$ and $(1, 3^*, 3)$ corresponds to the leptons. The exotic quark h carries a charge $-\frac{1}{3}$. The other exotic particles are the charge conjugate of h, a right-handed neutrino N^c, two lepton isodoublets (ν_E, E), (E^c, N_E^c) and n. The

[3] Compared to the other gauge scattering processes without any external W_R these processes are suppressed by a factor $\exp(-M_{N_R}/M_{W_R})$, and thus, for a scenario where $M_{N_R} \sim M_{W_R}$ these scattering processes are particularly very important.

assignment of the first family is given by

$$\begin{pmatrix} u \\ d \\ h \end{pmatrix} + \begin{pmatrix} u^c & d^c & h^c \end{pmatrix} + \begin{pmatrix} E^c & \nu & \nu_E \\ N_E^c & e & E \\ e^c & N^c & n \end{pmatrix}, \tag{4.2}$$

where $\mathrm{SU}(3)_L$ operates vertically and $\mathrm{SU}(3)_R$ operates horizontally. The $\mathrm{SU}(3)_{R,L}$ further decompose to $\mathrm{SU}(2) \times \mathrm{U}(1)$. There are three different choices for the decomposition of $\mathrm{SU}(3)_R$ corresponding to three directions of symmetry breaking, which are the familiar T, U, V isospins of SU(3). Below we use the subscript (R) to correspond to these three choices of breaking. These three choices result in three different kinds of heavy right-handed gauge bosons.

4.1 Case 1

The $\mathrm{SU}(2)_R$ doublet is (d^c, u^c) as in the LRSM and $Q = T_{3L} + \frac{1}{2}Y_L + T_{3R} + \frac{1}{2}Y_R$. Note that $Y_L + Y_R = (B-L)/2$ holds for all the SM particles and one can extend this as a definition for the new fermions belonging to the fundamental representation of E_6 to have invariant Yukawa interactions with the SM particles which ensures that all Yukawa and gauge interactions conserve $B-L$.The transformation of the fields under the subgroup $G = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ is given by

$$\begin{aligned}
(u,d)_L &: \left(3,2,1,\frac{1}{6}\right), & (d^c,u^c)_L &: \left(\bar{3},1,2,-\frac{1}{6}\right), \\
(\nu_e,e)_L &: \left(1,2,1,-\frac{1}{2}\right), & (e^c,N^c)_L &: \left(1,1,2,\frac{1}{2}\right), \\
h_L &: \left(3,1,1,-\frac{1}{3}\right), & h_L^c &: \left(\bar{3},1,1,\frac{1}{3}\right), \\
\begin{pmatrix} \nu_E & E^c \\ E & N_E^c \end{pmatrix}_L &: (1,2,2,0), & n_L &: (1,1,1,0).
\end{aligned} \tag{4.3}$$

If ν_e combines with N^c to form the Dirac neutrino then the mass of the $W_R^\pm$ gets constrained from polarized μ^+ decay [33]. There will also be a charged current mixing matrix for the quarks in the right-handed sector. Using a form similar to the Kobayashi- Maskawa matrix the $K_L - K_S$ mass difference can constrain the $W_R^\pm$ mass [34–36]. In ref. [37] it was pointed out that a calculation of the mixing matrix for the right-handed quark sector shows that the difference between left and right mixing angles is very small. Kaon decay and neutron electric dipole moment can also give further constraints on the W_R mass [36, 38]. We have already discussed some of the phenomenological details of the W_R decay in connection with the LRSM. Those hold good for this scenario, however one can have more complicated decay modes of W_R in the presence of the new exotic fermions.

With the assignment given in eq. (4.3), among the five neutral fermions only ν_e and N^c carry nonzero $B-L$. Thus the only source of $B-L$ violation is the Majorana mass of N^c which also ensures the small neutrino masses. In order to have successful leptogenesis the decay rate of the Majorana neutrino N must satisfy the out-of-equilibrium condition, namely,

$$\Gamma_N < H(T = m_N). \tag{4.4}$$

This translates into the condition that the Majorana mass of N_R must be many orders of magnitude greater than the TeV scale. On the other hand, the quantum number assignments of N^c as given in eq. (4.3) imply that it transforms at low energies. This can result in lepton-number violating interactions involving W_R. The associated lepton-number violating scattering processes can wash out the asymmetry produced by leptogenesis at high scale. Therefore successful leptogenesis can not be obtained in this conventional left-right model. Thus we focus below on the two variants where the $\mathrm{SU}(2)_R$ breaking scale can be much lower ($\sim$ TeV range) independent of the $\mathrm{U}(1)_{B-L}$ breaking scale.

4.2 Case 2

Another choice for the $\mathrm{SU}(2)_{(R)}$ doublet is (h^c, u^c), first pointed out in ref. [39]. The relevant charge equation is given by $Q = T_{3L} + \frac{1}{2}Y_L + T'_{3R} + \frac{1}{2}Y'_R$, where

$$T'_{3R} = \frac{1}{2}T_{3R} + \frac{3}{2}Y_R, \quad Y'_R = \frac{1}{2}T_{3R} - \frac{1}{2}Y_R, \tag{4.5}$$

and we have $T'_{3R} + Y'_R = T_{3R} + Y_R$. Note that for interactions involving only the Standard Model particles and gauge bosons (left-handed) the schemes of Case 1 and Case 2 are indistinguishable. In this scenario, often referred to as the Alternative Left Right Symmetric Model (ALRSM) in the literature, the assignments of fields transforming under the subgroup $G = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_{R'} \times \mathrm{U}(1)_{Y'}$ are given as

$$\begin{aligned}
&(u,d)_L : \left(3,2,1,\frac{1}{6}\right), && (h^c,u^c)_L : \left(\bar{3},1,2,-\frac{1}{6}\right),\\
&(\nu_E,E)_L : (1,2,1,-\frac{1}{2}), && (e^c,n)_L : \left(1,1,2,\frac{1}{2}\right),\\
&h_L : \left(3,1,1,-\frac{1}{3}\right), && d^c_L : \left(\bar{3},1,1,\frac{1}{3}\right),\\
&\begin{pmatrix}\nu_e & E^c\\ e & N^c_E\end{pmatrix}_L :(1,2,2,0), && N^c_L : (1,1,1,0),
\end{aligned} \tag{4.6}$$

and $Y' = Y_L + Y'_R$. Here also ν_e can pair off with N^c to form a Dirac neutrino, but now N^c has a trivial transformation under $\mathrm{SU}(2)_{R'}$ thus allowing high-scale leptogenesis. Two different assignments for N^c are possible determining whether ν_e is massless or massive. For the case where N^c has the assignments $B = 0$, $L = 0$ an exactly massless ν_e is possible, while in the other case N^c is assigned $B = 0$, $L = -1$ leading to a tiny mass of ν_e via the seesaw mechanism. In this scenario, e is coupled to n via the right-handed charged current, but n being presumably much heavier than the electron, polarized μ^+ decay cannot constrain the mass of $W^{\pm}_{R'}$ in contrast to Case 1. Furthermore $W^{\pm}_{R'}$ does not couple to d and s quarks. Consequently, there is no constraint on the mass of $W^{\pm}_{R'}$ from the $K_L - K_S$ mass difference in this case. So this model can allow a much lighter $W^{\pm}_{R'}$ as compared to Case 1. However in this model $D^0 - \bar{D}^0$ mixing can be induced through the $W_{R'}$ coupling of the c and u quarks to the exotic leptoquark h [40]. The relevant box diagrams are shown in figure 1. The amplitude of this mixing induced by these exotic box diagrams can give constraint on the $\mathrm{SU}(2)_{R'}$ breaking scale in this model.

The interesting point to note here is that in contrast to Case 1 where all the gauge bosons have the assignments $B = 0$ and $L = 0$, in this case $W^-_{R'}$ carries a leptonic charge $L = 1$. In this model the coupling of the $W_{R'}$ to the fermions reads

$$\mathcal{L} = \frac{1}{\sqrt{2}} g_R W^{\mu}_{R'} (\bar{h}^c \gamma_\mu u^c_L + \bar{E}^c \gamma_\mu \nu_L + \bar{e}^c \gamma_\mu n_L + \bar{N}^c_E \gamma_\mu e_L) + \text{h.c.} \tag{4.7}$$

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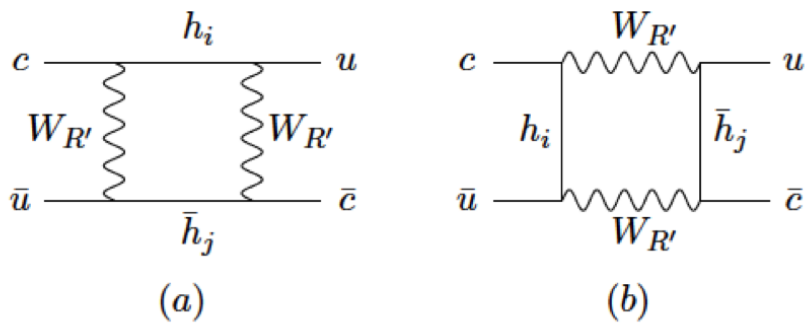

Figure 1. Box diagrams that can contribute to $D^0 - \bar{D}^0$ mixing.

So the $W_{R'}$ is coupled to h_L^c and n field, in contrast to the coupling with the d_L^c and N^c in the conventional LRSM.

The quantum numbers of $W_{R'}$ imply that the usual $u\bar{d}$ scattering in hadronic colliders can not produce $W_{R'}$. Furthermore $2M_{W_R} > M_{Z'}$ forbids the pair production of $W_{R'}$ via the decay of the heavy Z'. The process which can yield a large cross section for $W_{R'}$ production is the associated production of $W_{R'}$ and leptoquark h via the process $g + u \to h + W_{R'}^+$ [41]. The relevant diagrams are shown in figure 2. The differential cross section of this process is given by

$$\frac{d\hat{\sigma}}{dt} = \frac{1}{16\pi\hat{s}^2}|\bar{\mathcal{M}}_{R'}|^2, \tag{4.8}$$

with the spin and color averaged partonic amplitude given by [42]

$$\begin{aligned}|\bar{\mathcal{M}}_{R'}|^2 = \frac{4\pi G_F M_{W_{R'}}^2}{3\sqrt{2}}\,\alpha_s\Bigg[&-\left(\frac{t'}{\hat{s}}+\frac{\hat{s}}{t'}\right)\left(2+\frac{M_h^2}{M_{W_{R'}}^2}\right)-2\frac{M_h^2}{M_{W_{R'}}^2}\\ &+2\left(2M_{W_{R'}}^2-M_h^2-\frac{M_h^4}{M_{W_{R'}}^2}\right)\left(\frac{1}{\hat{s}}+\frac{1}{t'}\right)\\ &+\frac{2}{\hat{s}t'}\left(-\frac{M_h^6}{M_{W_{R'}}^2}+3M_h^2M_{W_{R'}}^2-2M_{W_{R'}}^4\right)\\ &+2\frac{M_h^2}{t'^2}\left(2M_{W_{R'}}^2-M_h^2-\frac{M_h^4}{M_{W_{R'}}^2}\right)\Bigg],\end{aligned} \tag{4.9}$$

where $\hat{s}$, t are the Mandelstam variables, $t' = t - M_h^2$, and M_h ($M_{W_{R'}}$) is the mass of h ($W_{R'}$). The partonic cross section of the process can be obtained by integrating the differential cross section over t' between the limits

$$t'_{1,2} = -\frac{1}{2}\left(\hat{s}+M_h^2-M_{W_{R'}}^2\right) \pm \frac{1}{2}\left[\left(\hat{s}-M_h^2-M_{W_{R'}}^2\right)^2-4M_h^2M_{W_{R'}}^2\right]^{1/2}. \tag{4.10}$$

The total hadronic cross section is obtained by convoluting the partonic cross section with the parton distribution functions

$$\sigma \sim \int_0^1 dx_1dx_2[u^p(x_1)g^p(x_2)+g^p(x_1)u^p(x_2)]\hat{\sigma}(x_1x_2s), \tag{4.11}$$

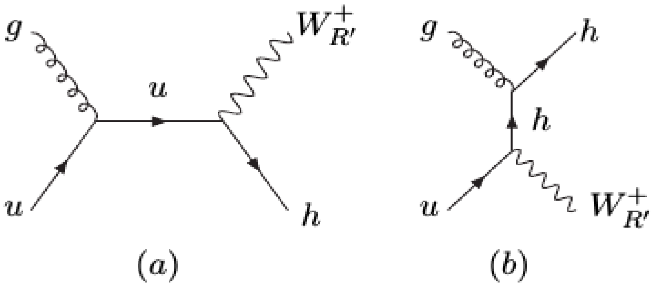

Figure 2. s- and t-channel Feynman diagrams for $g + u \to h + W^+_{R'}$.

where s is the squared hadronic center of mass energy, $\hat{s} = x_1 x_2 s$, and u^p, g^p are the parton distribution functions relative to the proton. A quantitative benchmark for the same is given in refs. [41] and [42]. To give a quantitative estimate, for $M_h \sim 1\,\text{TeV}$ and $M_{W_{R'}} \sim 2.1\,\text{TeV}$ the cross section at the LHC for the process $pp \to W^+_{R'} h$ is about $\sigma \sim 0.2$ pb at $\sqrt{s} = 14\,\text{TeV}$ and is about $\sigma \sim 0.02$ pb at $\sqrt{s} = 8\,\text{TeV}$, where we have used the parton distribution functions given in ref. [43] for the numerical estimations. Note however that the production cross section of $\sigma(W^+_{R'} h)$ is always substantially larger compared to $\sigma(W^-_{R'} \bar{h})(\sim 10^{-3}$ pb at $\sqrt{s} = 14\,\text{TeV}$ and $\sim 5 \times 10^{-4}$ pb at $\sqrt{s} = 8\,\text{TeV}$, for $M_h \sim 1\,\text{TeV}$ and $W^-_{R'} \sim 2.1\,\text{TeV})$. This is due to the fact that u distribution function in a proton beam is larger than the $\bar{u}$ distribution function. The decay modes of the $W_{R'}$ can be obtained by using eq. (4.7).

$$W_{R'} \to \bar{h}^c u^c,\ \bar{E}^c \nu,\ \bar{e}^c n_L,\ \bar{N}^c_E e. \tag{4.12}$$

To keep our discussion fairly general and model independent we only consider the decay modes (of the new exotic particles) mediated by light and heavy gauge bosons (and ignore the decay modes involving Higgs couplings). Examining all the further decay channels of the exotic particles coming from the decay modes of $W_{R'}$ listed above immediately shows that the $W_{R'}$ decay can not give rise to the $ee+2j$ signal in contrast to Case 1. Thus, this scenario has an appealing feature of allowing high-scale leptogenesis. However, a two electron and two jet signal can not be produced from $W_{R'}$ decay.

4.3 Case 3

A third way of selecting the $\text{SU}(2)_{(R)}$ doublet is (h^c, d^c) [44] and the relevant charge equation is given by $Q = T_{3L} + \frac{1}{2} Y_L + \frac{1}{2} Y_N$, where the $\text{SU}(2)_{(R)}$ does not contribute to the electric charge equation and we will represent it by $\text{SU}(2)_N$. Once the $\text{SU}(2)_N$ gets broken, the gauge bosons $W^\pm_N$ and Z_N become massive. The superscript $\pm$ corresponds to the $\text{SU}(2)_N$ charge. The fields transform under the subgroup $G = \text{SU}(3)_c \times \text{SU}(2)_L \times \text{SU}(2)_N \times \text{U}(1)_Y$ as

$$\begin{aligned}
(u,d)_L &: \left(3,2,1,\frac{1}{6}\right), & (h^c,d^c)_L &: \left(\bar{3},1,2,\frac{1}{3}\right),\\
(E^c,N^c_E)_L &: \left(1,2,1,\frac{1}{2}\right), & (N^c,n)_L &: (1,1,2,0),\\
h_L &: \left(3,1,1,-\frac{1}{3}\right), & u^c_L &: \left(\bar{3},1,1,-\frac{2}{3}\right),\\
\begin{pmatrix}\nu_e & \nu_E\\ e & E\end{pmatrix}_L &: \left(1,2,2,-\frac{1}{2}\right), & e^c_L &: (1,1,1,1).
\end{aligned} \tag{4.13}$$

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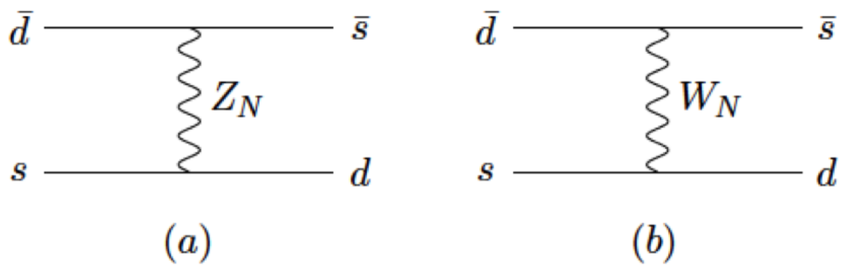

Figure 3. Tree level flavor changing neutral current processes in presence of mixing between six quarks (d, s, b and $h_i, i = 1, 2, 3$).

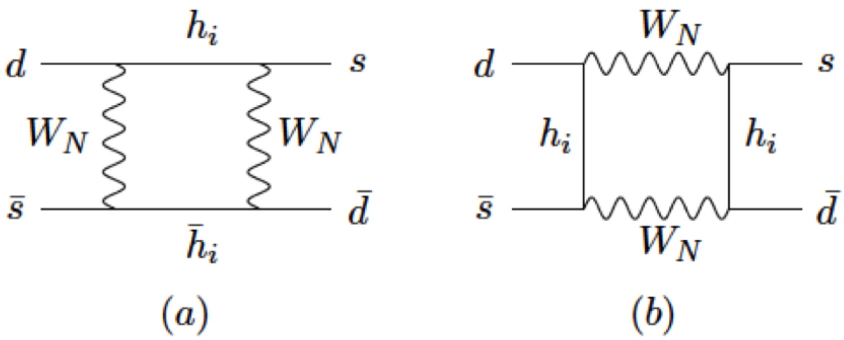

Figure 4. Box diagrams contributing to $\bar{d}s - \bar{s}d$ mixing if only exotic $h_i, i = 1, 2, 3$ mix, and $\bar{s}_L$ and $\bar{d}_L$ have same T_{3N} eigenvalues.

Similar to case 2, in this scenario also W_N has nonzero leptonic charge and zero baryonic charge. Note that in this case W_N and Z_N can induce $K^0 - \bar{K}^0$ mixing. Mixing between six quarks (three generations) forming SU$(2)_N$ doublets

$$\begin{pmatrix} \bar{h}_1 \\ \bar{d} \end{pmatrix} \quad \begin{pmatrix} \bar{h}_2 \\ \bar{s} \end{pmatrix} \quad \begin{pmatrix} \bar{h}_3 \\ \bar{b} \end{pmatrix} \tag{4.14}$$

can lead to the tree level Flavor Changing Neutral Current (FCNC) processes shown in figure 3 and in such a scenario one can get constraints on the W_N mass from the $K_L - K_S$ mass difference [44]. In the absence of mixing of $\bar{d}$ and $\bar{s}$ with exotic $\bar{h}_i$, one can still have a tree level contribution to the kaon mixing. If opposite T_{3N} quantum numbers are assigned to $\bar{d}_L$ and $\bar{s}_L$ and if they mix then the diagrams shown in figure 3 are still possible [44]. On the other hand if only the exotic $\bar{h}_i$ mix and we assign same T_{3N} to $\bar{d}_L$ and $\bar{s}_L$ then the box diagrams shown in figure 4 result [44]. Likewise in the leptonic sector considering SU$(2)_N$ doublets

$$\begin{pmatrix} E \\ e \end{pmatrix} \quad \begin{pmatrix} M \\ \mu \end{pmatrix} \quad \begin{pmatrix} T \\ \tau \end{pmatrix}, \tag{4.15}$$

even if mixing between the ordinary and exotic fermions is absent, the process $\mu \to e\gamma$ can be possible if mixing between the exotic fermions is present [44] as shown in figure 5. The coupling of the W_N to the fermions reads

$$\mathcal{L} = \frac{1}{\sqrt{2}} g_R W_N^\mu (\bar{h}\gamma_\mu d_R + \bar{e}\gamma_\mu E_L + \bar{\nu}\gamma_\mu (\nu_E)_L + \bar{N}^c \gamma_\mu n_L) + \text{h.c.} \tag{4.16}$$

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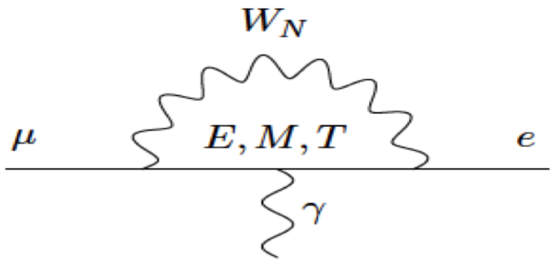

Figure 5. Loop diagrams involving exotic fermions (mixing among themselves) and W_N leading to $\mu \to e\gamma$.

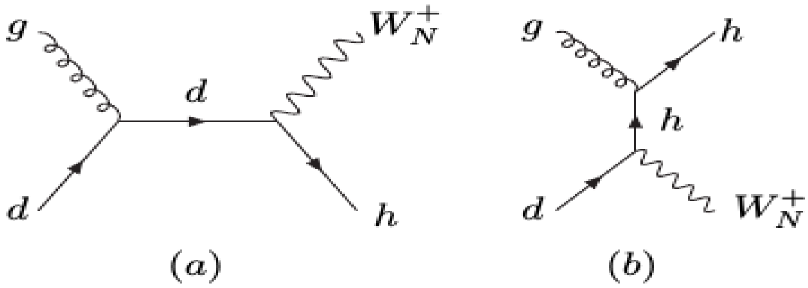

Figure 6. s- and t-channel Feynman diagrams for $g + d \to h + W_N^+$.

Following similar arguments as in Case 2, one can not produce W_N via the usual Drell-Yan mechanism or from the decay of heavy Z_N. The process $g + d \to h + W_N$ can yield a large cross section for W_N production via the diagrams shown in figure 6 [45]. The invariant amplitude squared averaged over partonic spin and color is given by [42, 45]

$$|\bar{\mathcal{M}}_N|^2 = \frac{4\pi G_F M_{W_N}^2}{3\sqrt{2}}\,\alpha_s\Bigg[-\left(\frac{t'}{s}+\frac{s}{t'}\right)\left(2+\frac{M_h^2}{M_{W_N}^2}\right)-2\frac{M_h^2}{M_{W_N}^2} +2\left(2M_{W_N}^2 - M_h^2 - \frac{M_h^4}{M_{W_N}^2}\right)\left(\frac{1}{s}+\frac{1}{t'}\right) +\frac{2}{st'}\left(-\frac{M_h^6}{M_{W_N}^2}+3M_h^2M_{W_N}^2-2M_{W_N}^4\right)\Bigg], \tag{4.17}$$

where $t' = t - M_h^2$, and M_h (M_{W_N}) is the mass of h (W_N). The partonic cross section of the process can be obtained by integrating over t' between the limits

$$t'_{1,2} = -\frac{1}{2}\left(\hat{s} + M_h^2 - M_{W_N}^2\right) \pm \frac{1}{2}\left[\left(\hat{s} - M_h^2 - M_{W_N}^2\right)^2 - 4M_h^2M_{W_N}^2\right]^{1/2}. \tag{4.18}$$

A comparison of eq. (4.17) with eq. (4.9) reveals that the production cross sections for W_N and $W_{R'}$ are similar, particularly if $M_h \sim M_W$. A detailed account of the above W_N production cross section is given in refs. [42, 45], both of which find the cross section to be substantially large. To give a quantitative order of magnitude estimate, for $M_h = 1\,\text{TeV}$ and $M_{W_N} \sim 2.1\,\text{TeV}$ the cross section at the LHC for the process $pp \to W_N^+ h$ is about $\sigma \sim 0.05$ pb at $\sqrt{s} = 14\,\text{TeV}$ and $\sigma \sim 0.005$ pb at $\sqrt{s} = 8\,\text{TeV}$. In this case also the production cross

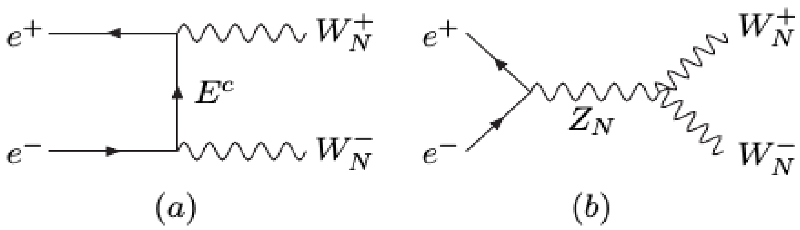

Figure 7. $t-$ and $s-$channel Feynman diagrams for $e^+e^- \to W_N^+ W_N^-$.

sections $\sigma(W_N^+) > \sigma(W_N^-)$, due to the fact that d-quark distribution function in a proton beam is larger than the $\bar{d}$-quark distribution function.

Pair production of W_N can take place via the process $e^+e^- \to W_N^+ W_N^-$ [45]. The relevant diagrams are shown in figure 7. This process is particularly sensitive to the underlying gauge structure and cancellations between the given amplitudes. Thus it can serve as a probe for the non-abelian $\mathrm{SU}(2)_N$ gauge theory. Under the approximation that $M_{Z_N} \sim M_{W_N}$, the differential cross section for this process is given by [45]

$$\frac{d\sigma}{dz} = \frac{G_F^2 M_{W_N}^4}{8\pi s}\beta\left(F_1 + \frac{1}{8}F_2\frac{s^2}{(s-M_{Z_N}^2)^2 + M_{Z_N}^2\Gamma_{Z_N}^2} - \frac{1}{2}F_3\frac{s(s-M_{Z_N}^2)}{(s-M_{Z_N}^2)^2 + M_{Z_N}^2\Gamma_{Z_N}^2}\right), \tag{4.19}$$

where $\beta \equiv (1 - 4M_{W_N}^2/s)^{1/2}$ and the F_i's are given by

$$\begin{aligned} F_1 &\equiv r^2\left[2y + \frac{1}{2}(1-z^2)\beta^2\left\{(y/x)^2 + \frac{1}{4}y^2\right\}\right], \\ F_2 &\equiv \beta^2[16y + (1-z^2)(y^2 - 4y + 12)], \\ F_3 &\equiv r\left[16(1+X^{-1}) + \gamma y\beta^2 + \frac{1}{2}\beta^2(1-z^2)(y^2 - 2y - 4y/x)\right], \end{aligned} \tag{4.20}$$

with

$$y \equiv s/M_{Z_N}^2, \quad x \equiv t/M_{Z_N}^2, \quad r \equiv \frac{t}{t - M_{Z_N}^2}, \tag{4.21}$$

and $t = M_{Z_N}^2 - \frac{1}{2}s(1-\beta z)$. In ref. [45] the total cross section for the process $e^+e^- \to W_N^+ W_N^-$ is estimated as a function of M_{W_N} and M_E for $\sqrt{s} = 1\,\mathrm{TeV}$. To have a quantitative order of magnitude estimate, for $\sqrt{s} = 1\,\mathrm{TeV}$, $M_E \sim 1.0\,\mathrm{TeV}$ and $M_{W_N} \sim 350\,\mathrm{GeV}$ the total cross section for the process $e^+e^- \to W_N^+ W_N^-$ is about 1 pb. For $M_{W_N} \lesssim 270\,\mathrm{GeV}$ or so, the production cross section increases substantially with increasing M_E, while for $M_{W_N} \gtrsim 370\,\mathrm{GeV}$ or so the production cross section decreases with increasing M_E.

The decay modes of the W_N can be obtained from eq. (4.16) as

$$W_N \to \bar{h}d,\ \bar{e}E,\ \bar{\nu}\nu_E,\ \bar{N}^c n_L. \tag{4.22}$$

Like in Case 2, an inspection of all the further decays of the exotic particles for the decay modes of W_N listed above tells us that an $ee+2j$ signal can not be obtained from the decay of W_N. Moreover from the assignments of eq. (4.13) it follows that N^c transforms as a doublet under $\mathrm{SU}(2)_N$ and hence for low-energy $\mathrm{SU}(2)_N$ breaking, following the same logic as in Case 1, the possibility of successful leptogenesis is ruled out.

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5 Conclusions

We have reviewed the non-supersymmetric versions of the (Extended) Left-Right Symmetric Model and the models appearing as the low-energy subgroups of the superstring motivated E_6 group which can have low-scale $\mathrm{SU}(2)_{(R)}$ breaking. Our aim was to examine if a signal like the CMS $eejj$ excess can be explained from these models while allowing leptogenesis.

In the LRSM and any extension of it with multiple U(1)'s, for hierarchical neutrino masses ($M_{N_{3R}} \gg M_{N_{2R}} \gg M_{N_{1R}} = m_N$) the possibility of generating the required baryon asymmetry of the universe from high-scale leptogenesis is ruled out if the W_R mass lies in the TeV range as indicated by the CMS events. Recently, it was shown that the required lepton asymmetry can be produced even for a substantially low value of the W_R mass ($M_{W_R} > 3\,\mathrm{TeV}$) [30] by considering relatively large Yukawa couplings in the context of resonant leptogenesis. However we have mentioned that certain lepton-number violating scattering processes involving the doubly charged Higgs triplet and right-handed neutrinos can wash out the lepton asymmetry below the $B - L$ breaking scale till the electroweak phase transition thus ruling out the possibility of resonant leptogenesis for the mass range of W_R as indicated by the CMS excess signal. Therefore we have then considered low energy subgroups of the superstring motivated E_6 group involving new exotic fermions and a low-energy $\mathrm{SU}(2)_{(R)}$ gauge sector. Amongst all low energy subgroups considered in the analysis there is only one choice of $\mathrm{SU}(2)_{(R)}$ which allows high-scale leptogenesis. However, this particular choice cannot account for the excess signal seen at CMS. So this together with our consideration of high-scale and TeV-scale resonant leptogenesis for the LRSM and its extensions implies that a pre-electroweak phase transition leptogenesis scenario can not generate the baryon asymmetry in the non-supersymmetric models under consideration. Thus one needs to look for post-sphaleron mechanisms to explain the observed baryon asymmetry of the universe. To this end, possibilities like neutron-antineutron oscillations can be explored [46, 47].

Note added. After our paper was posted online, ref. [48] appeared, where the authors of ref. [30] have updated their limit on W_R mass for a successful TeV-scale resonant leptogenesis from $M_{W_R} > 3\,\mathrm{TeV}$ to $13.1\,\mathrm{TeV}$ after a more careful analysis. In addition to the gauge scattering processes such as $N_R e_R \to \bar{u}_R d_R$, $N_R \bar{u}_R \to e_R d_R$, $N_R d_R \to e_R u_R$ and $N_R N_R \to e_R \bar{e}_R$; the lepton number violating scattering processes mediated via doubly charged right-handed Higgs triplet were taken into consideration in ref. [48] following our claim in this paper. In this ref. only the right-handed Higgs triplet channel was considered and for a particular texture of type-I seesaw model with relatively small M_{N_R} it was found to have a small contribution, as expected for a large M_{W_R}/M_{N_R} (the lepton number violating scattering processes with external W_R is suppressed by a factor of $e^{-m_{W_R}/m_{N_R}}$ in comparison to the processes with no external W_R). However the other gauge scattering processes in that scenario are strong enough to give a lower bound of 13.1 TeV on the W_R mass. We have given a more detailed account of the scattering processes involving external W_R including triplet Higgs channel, right handed neutrinos and their interference in ref. [31].

References

[1] J.C. Pati and A. Salam, *Lepton number as the fourth color*, *Phys. Rev.* **D 10** (1974) 275 [*Erratum ibid.* **D 11** (1975) 703] [INSPIRE].

JCAP09(2015)035

[2] R.N. Mohapatra and J.C. Pati, *A natural left-right symmetry*, *Phys. Rev.* **D 11** (1975) 2558 [INSPIRE].

[3] G. Senjanović and R.N. Mohapatra, *Exact left-right symmetry and spontaneous violation of parity*, *Phys. Rev.* **D 12** (1975) 1502 [INSPIRE].

[4] CMS collaboration, *Search for heavy neutrinos and* W *bosons with right-handed couplings in proton-proton collisions at* $\sqrt{s} = 8\,TeV$, *Eur. Phys. J.* **C 74** (2014) 3149 [arXiv:1407.3683] [INSPIRE].

[5] F.F. Deppisch, T.E. Gonzalo, S. Patra, N. Sahu and U. Sarkar, *Signal of right-handed charged gauge bosons at the LHC?*, *Phys. Rev.* **D 90** (2014) 053014 [arXiv:1407.5384] [INSPIRE].

[6] J.A. Aguilar-Saavedra and F.R. Joaquim, *Closer look at the possible CMS signal of a new gauge boson*, *Phys. Rev.* **D 90** (2014) 115010 [arXiv:1408.2456] [INSPIRE].

[7] M. Heikinheimo, M. Raidal and C. Spethmann, *Testing right-handed currents at the LHC*, *Eur. Phys. J.* **C 74** (2014) 3107 [arXiv:1407.6908] [INSPIRE].

[8] M. Fukugita and T. Yanagida, *Baryogenesis without grand unification*, *Phys. Lett.* **B 174** (1986) 45 [INSPIRE].

[9] S. Davidson, E. Nardi and Y. Nir, *Leptogenesis*, *Phys. Rept.* **466** (2008) 105 [arXiv:0802.2962] [INSPIRE].

[10] C.S. Fong, E. Nardi and A. Riotto, *Leptogenesis in the universe*, *Adv. High Energy Phys.* **2012** (2012) 158303 [arXiv:1301.3062] [INSPIRE].

[11] P. Minkowski, $\mu \to e\gamma$ *at a rate of one out of* 10^9 *muon decays?*, *Phys. Lett.* **B 67** (1977) 421 [INSPIRE].

[12] M. Gell-Mann, P. Ramond and R. Slansky, *Complex spinors and unified theories*, *Conf. Proc.* **C 790927** (1979) 315 [arXiv:1306.4669] [INSPIRE].

[13] T. Yanagida, *Horizontal symmetry and masses of neutrinos*, *Conf. Proc.* **C 7902131** (1979) 95.

[14] R.N. Mohapatra and G. Senjanović, *Neutrino mass and spontaneous parity violation*, *Phys. Rev. Lett.* **44** (1980) 912 [INSPIRE].

[15] R.N. Mohapatra and G. Senjanović, *Neutrino masses and mixings in gauge models with spontaneous parity violation*, *Phys. Rev.* **D 23** (1981) 165 [INSPIRE].

[16] V.A. Kuzmin, V.A. Rubakov and M.E. Shaposhnikov, *On the anomalous electroweak baryon number nonconservation in the early universe*, *Phys. Lett.* **B 155** (1985) 36 [INSPIRE].

[17] E. Ma and U. Sarkar, *Neutrino masses and leptogenesis with heavy Higgs triplets*, *Phys. Rev. Lett.* **80** (1998) 5716 [hep-ph/9802445] [INSPIRE].

[18] G. Lazarides and Q. Shafi, *R symmetry in minimal supersymmetry standard model and beyond with several consequences*, *Phys. Rev.* **D 58** (1998) 071702 [hep-ph/9803397] [INSPIRE].

[19] T. Hambye, E. Ma and U. Sarkar, *Supersymmetric triplet Higgs model of neutrino masses and leptogenesis*, *Nucl. Phys.* **B 602** (2001) 23 [hep-ph/0011192] [INSPIRE].

[20] E. Ma, S. Sarkar and U. Sarkar, *Scale of* $\mathrm{SU}(2)(R)$ *symmetry breaking and leptogenesis*, *Phys. Lett.* **B 458** (1999) 73 [hep-ph/9812276] [INSPIRE].

[21] M. Flanz, E.A. Paschos and U. Sarkar, *Baryogenesis from a lepton asymmetric universe*, *Phys. Lett.* **B 345** (1995) 248 [*Erratum ibid.* **B 382** (1996) 447] [hep-ph/9411366] [INSPIRE].

[22] M. Flanz, E.A. Paschos, U. Sarkar and J. Weiss, *Baryogenesis through mixing of heavy Majorana neutrinos*, *Phys. Lett.* **B 389** (1996) 693 [hep-ph/9607310] [INSPIRE].

[23] A. Pilaftsis, *CP violation and baryogenesis due to heavy Majorana neutrinos*, *Phys. Rev.* **D 56** (1997) 5431 [hep-ph/9707235] [INSPIRE].

JCAP09(2015)035

[24] E. Roulet, L. Covi and F. Vissani, *On the CP asymmetries in Majorana neutrino decays*, Phys. Lett. **B 424** (1998) 101 [hep-ph/9712468] [INSPIRE].

[25] W. Buchmüller and M. Plümacher, *CP asymmetry in Majorana neutrino decays*, Phys. Lett. **B 431** (1998) 354 [hep-ph/9710460] [INSPIRE].

[26] M. Flanz and E.A. Paschos, *Further considerations on the CP asymmetry in heavy Majorana neutrino decays*, Phys. Rev. **D 58** (1998) 113009 [hep-ph/9805427] [INSPIRE].

[27] T. Hambye, J. March-Russell and S.M. West, *TeV scale resonant leptogenesis from supersymmetry breaking*, JHEP **07** (2004) 070 [hep-ph/0403183] [INSPIRE].

[28] A. Pilaftsis and T.E.J. Underwood, *Resonant leptogenesis*, Nucl. Phys. **B 692** (2004) 303 [hep-ph/0309342] [INSPIRE].

[29] J.-M. Frere, T. Hambye and G. Vertongen, *Is leptogenesis falsifiable at LHC?*, JHEP **01** (2009) 051 [arXiv:0806.0841] [INSPIRE].

[30] P.S. Bhupal Dev, C.-H. Lee and R.N. Mohapatra, *Leptogenesis constraints on the mass of right-handed gauge bosons*, Phys. Rev. **D 90** (2014) 095012 [arXiv:1408.2820] [INSPIRE].

[31] M. Dhuria, C. Hati, R. Rangarajan and U. Sarkar, *Falsifying leptogenesis for a TeV scale $W_R^\pm$ at the LHC*, Phys. Rev. **D 92** (2015) 031701 [arXiv:1503.07198] [INSPIRE].

[32] M. Dhuria, C. Hati, R. Rangarajan and U. Sarkar, *Explaining the CMS eejj and $e\not{p}_T jj$ excess and leptogenesis in superstring inspired E_6 models*, Phys. Rev. **D 91** (2015) 055010 [arXiv:1501.04815] [INSPIRE].

[33] TWIST collaboration, J.F. Bueno et al., *Precise measurement of parity violation in polarized muon decay*, Phys. Rev. **D 84** (2011) 032005 [arXiv:1104.3632] [INSPIRE].

[34] G. Beall, M. Bander and A. Soni, *Constraint on the mass scale of a left-right symmetric electroweak theory from the $K(L)K(S)$ mass difference*, Phys. Rev. Lett. **48** (1982) 848 [INSPIRE].

[35] A. Maiezza, M. Nemevšek, F. Nesti and G. Senjanović, *Left-right symmetry at LHC*, Phys. Rev. **D 82** (2010) 055022 [arXiv:1005.5160] [INSPIRE].

[36] Y. Zhang, H. An, X. Ji and R.N. Mohapatra, *General CP-violation in minimal left-right symmetric model and constraints on the right-handed scale*, Nucl. Phys. **B 802** (2008) 247 [arXiv:0712.4218] [INSPIRE].

[37] G. Senjanović and V. Tello, *Right handed quark mixing in left-right symmetric theory*, Phys. Rev. Lett. **114** (2015) 071801 [arXiv:1408.3835] [INSPIRE].

[38] G. Ecker, W. Grimus and H. Neufeld, *The neutron electric dipole moment in left-right symmetric gauge models*, Nucl. Phys. **B 229** (1983) 421 [INSPIRE].

[39] E. Ma, *Particle dichotomy and left-right decomposition of E_6 superstring models*, Phys. Rev. **D 36** (1987) 274 [INSPIRE].

[40] E. Ma, *D^0-$\bar{D}^0$ mixing in the new left-right model*, Mod. Phys. Lett. **A 3** (1988) 319 [INSPIRE].

[41] J.F. Gunion et al., *Signatures for a new supersymmetric left-right gauge model from superstrings*, Int. J. Mod. Phys. **A 2** (1987) 1199 [INSPIRE].

[42] F. Aversa, S. Bellucci, M. Greco and P. Chiappetta, *Production of $W(R)$ and $W(I)$ bosons from superstring inspired E_6 models at hadron colliders*, Phys. Lett. **B 254** (1991) 478 [INSPIRE].

[43] M. Diemoz, F. Ferroni, E. Longo and G. Martinelli, *Parton densities from deep inelastic scattering to hadronic processes at super collider energies*, Z. Phys. **C 39** (1988) 21 [INSPIRE].

[44] D. London and J.L. Rosner, *Extra gauge bosons in E_6*, Phys. Rev. **D 34** (1986) 1530 [INSPIRE].

[45] T.G. Rizzo, *Production of flavor changing gauge bosons from E_6 at e^+e^- hadron colliders*, Phys. Rev. **D 38** (1988) 71 [INSPIRE].

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[46] R.N. Mohapatra and R.E. Marshak, *Local B-L symmetry of electroweak interactions, Majorana neutrinos and neutron oscillations*, *Phys. Rev. Lett.* **44** (1980) 1316 [*Erratum ibid.* **44** (1980) 1643] [INSPIRE].

[47] D.G. Phillips, II et al., *Neutron-antineutron oscillations: theoretical status and experimental prospects*, submitted to *Phys. Rept.*, arXiv:1410.1100 [INSPIRE].

[48] P.S. Bhupal Dev, C.-H. Lee and R.N. Mohapatra, *TeV scale lepton number violation and baryogenesis*, *J. Phys. Conf. Ser.* **631** (2015) 012007 [arXiv:1503.04970] [INSPIRE].

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