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Signatures of Leptoquarks at the LHC and Right-handed Neutrinos

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Abstract

In this paper, we argue that an extension of the Standard Model with a single leptoquark and three right-handed neutrinos can explain the excess in the first-generation leptoquark search at the LHC. We also find that when the leptoquark has similarly sized couplings to all three generations, it produces additional signals which will soon be tested in the second and third generation leptoquark searches, as well as in decay channels consisting of two mixed flavor leptons and two jets. If the leptoquark only couples to the first generation, on the other hand, two of the right-handed neutrinos need to be fairly degenerate in mass with the leptoquark while the other right-handed neutrinos mass should be much lighter. This hierarchical structure could explain dark matter and the baryon asymmetry of the Universe. These simple models may be regarded as a benchmark models for explaining the excess, which can be tested in the next stage of the LHC running.

1 Introduction

Leptoquarks are particles that have both baryon number and lepton number, and appear in various beyond the standard model theories. For example, some grand unified theories (GUTs), such as SU(5) [1], $SU(4)_C \otimes SU(2)_L \otimes SU(2)_R$ [2], or SO(10) [3, 4] contain such particles. They are also found in technicolor models [5, 6] or other composite models [7]. Leptoquark searches, therefore, provide a powerful test for these theories beyond the Standard Model (SM).

Recently, the CMS collaboration announced that they observed an excess in the first-generation leptoquark search [8]. They analyzed the 8 TeV LHC data with the integrated luminosity of 19.6 fb^{-1}, and looked for first-generation leptoquarks in channels consisting of two electrons and at least two jets ($eejj$), or an electron, a neutrino and at least two jets ($e\nu jj$). An excess was found in both of these channels. However, this excess was only found after optimizing the event selection for leptoquarks with a mass of 650 GeV. The significance of the excess is estimated to be 2.4σ and 2.6σ in the $eejj$ and $e\nu jj$ channels respectively [8]. These excesses are, however, much smaller than those expected for a minimal extension of the SM with a leptoquark. In fact, the analysis carried out in Ref. [8] has excluded leptoquarks with masses less than 1005 (845) GeV if the branching fraction of the leptoquarks into an electron and a quark is equal to 1 (0.5). These constraints can be significantly relaxed, if the branching fraction to an electron and a jet are reduced. Actually, this suggests that leptoquarks have additional decay modes other than those with $eejj$ and $e\nu jj$ final states. Not surprisingly, leptoquarks may have a richer structure than is found in these naive models.

Stimulated by this observation, various interpretations of the excess have been proposed in the literature so far. For example, the authors in Ref. [9] introduce a coloron in addition to a leptoquark which could also explain the anomaly observed by the CMS collaboration in the searches for a right-handed W gauge boson plus a heavy neutrino [10]. See also Refs. [11, 12] for an explanation of both of these excesses. Other leptoquark models with a dark matter (DM) candidate are considered in Refs. [13, 14]. These models may also explain the excess in the two opposite-sign same-flavor leptons with greater than two jets and missing transverse energy [15] channel. In supersymmetric theories, the existence of the R-parity violating interactions may induce the observed excess; this possibility is discussed in Refs. [16–18].

In this paper, we study another, in fact quite simple, model which can explain the excess in the first-generation leptoquark searches. This model consists of adding a single leptoquark and three right-handed neutrinos to the SM. In contrast to previous work, we only consider renormalizable interactions. As will be seen below, this model can actually account for the observed excess. It turns out that when the leptoquark couples to all three generations, signals in the second and third generation leptoquark searches are expected to appear in the near future. Furthermore, decay modes containing a pair of mixed flavor leptons and two jets are also expected. If the leptoquark only couples to the first generation fermions, on the other hand, two of the right-handed neutrinos masses are required to be somewhat degenerate with the leptoquark mass. The remaining right-

Table 1: Quantum numbers of scalar leptoquarks and possible renormalizable interactions containing leptoquarks. We follow the notation in Ref. [19].

Leptoquarks	$\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$	Renormalizable couplings
S_0	$(\mathbf{3}, \mathbf{1}, -1/3)$	$S_0 Q_L^\dagger L_L^\dagger$, $S_0 u_R^\dagger e_R^\dagger$, $S_0 Q_L Q_L$, $S_0 u_R d_R$
$\widetilde{S}_0$	$(\mathbf{3}, \mathbf{1}, -4/3)$	$\widetilde{S}_0 d_R^\dagger e_R^\dagger$, $\widetilde{S}_0 u_R u_R$
S_1	$(\mathbf{3}, \mathbf{3}, -1/3)$	$S_1 Q_L^\dagger L_L^\dagger$, $S_1 Q_L Q_L$
$S_{1/2}^\dagger$	$(\mathbf{3}, \mathbf{2}, +7/6)$	$S_{1/2}^\dagger Q_L^\dagger e_R$, $S_{1/2}^\dagger u_R^\dagger L_L$
$\widetilde{S}_{1/2}^\dagger$	$(\mathbf{3}, \mathbf{2}, +1/6)$	$\widetilde{S}_{1/2}^\dagger d_R^\dagger L_L$

handed neutrino should be lighter than the electroweak scale. This hierarchical structure in the right-handed neutrino sector is quite interesting since the lightest right-handed neutrino can be a DM candidate while the other two could help explain the baryon asymmetry of the Universe (BAU). We will briefly discuss these possibilities.

2 Model

To begin with, let us describe our model with a 650 GeV leptoquark, which could account for the excess recently observed by the CMS collaboration [8]. A comprehensive list of leptoquarks[1] is found in Refs. [20, 21]. In this paper, we focus on scalar leptoquarks since massive vector particles require additional complexity in order to explain their masses, *i.e.*, the Higgs mechanism. We list scalar leptoquark models in Table 1. Among them, the first three types of leptoquarks cannot be assigned a definite baryon (B) and lepton (L) number such that the interactions of the leptoquarks conserve these charges [22], since they have both leptoquark and diquark couplings. In these cases, the tree-level exchange of leptoquarks induces proton decay [22–25], which is stringently constrained by experiments.[2] For this reason, we do not consider these possibilities in this paper. For the other two leptoquarks, $S_{1/2}^\dagger$ and $\widetilde{S}_{1/2}^\dagger$, there exist baryon-number violating dimension-five operators which are again problematic for proton decay. As discussed in Ref. [25], these operators can be forbidden by a $\mathbb{Z}_3$ symmetry under which each field transforms as $\psi \to \exp[2\pi i(B-L)/3]\psi$. This symmetry could be a remnant of the $\mathrm{U}(1)_{B-L}$ symmetry [26–28], which can be realized naturally in grand unified theories (GUTs).[3] Notice that this $\mathbb{Z}_3$ symmetry cannot suppress the tree-level proton decay for S_0, $\widetilde{S}_0$, and S_1, since

[1]For a review, see the "LEPTOQUARKS" section written by S. Rolli and M. Tanabashi in Ref. [19].

[2]In the case of $\widetilde{S}_0$, additional W-boson exchange is required for proton decay to occur, since the $\widetilde{S}_0 u_R u_R$ interaction should include either charm or top quark due to the antisymmetry in the color indices. The proton decay bound is still severe in this case.

[3]For instance, the vacuum expectation value (VEV) of a **672** of SO(10) spontaneously breaks the $\mathrm{U}(1)_{B-L}$ symmetry into the $\mathbb{Z}_3$ symmetry [29, 30].

the renormalizable interactions given in Table 1 conserve $B - L$. In what follows, we will assume that the leptoquarks $S^\dagger_{1/2}$ and $\widetilde{S}^\dagger_{1/2}$ do not lead to proton decay problems and focus on these two possibilities.

As is often the case for a new scalar particle coupling to quarks and leptons, the addition of a leptoquark will, in general, cause flavor/CP problems. New interactions of a leptoquark with quarks and leptons may induce flavor-changing neutral currents (FCNC) and/or charged lepton flavor violation (CLFV), which are severely restricted by low-energy precision experiments. Furthermore, leptoquarks can also contribute to the electron and muon anomalous magnetic dipole moments, and the electric dipole moments of quarks and leptons; again the contribution should be small enough to be consistent with current experiments. For the existing constraints on leptoquarks from low-energy precision experiments, see Refs. [31–40]. These bounds are especially severe for leptoquarks which couple to both left- and right-handed quarks simultaneously, like $S^\dagger_{1/2}$ in Table 1 [31]. For this reason, $\widetilde{S}^\dagger_{1/2}$ is more promising. Although it may be possible to construct a viable model with $S^\dagger_{1/2}$, in this paper, we focus on $\widetilde{S}^\dagger_{1/2}$, and for brevity denote it by S in the following discussion.

As seen in Ref. [8], the CMS collaboration observed a slight excesses in both the $eejj$ and the $e\nu jj$ channels. It may seem problematic that we consider the $\widetilde{S}^\dagger_{1/2}$ leptoquark since it can only give rise to the $eejj$ or $\nu\nu jj$ modes and not $e\nu jj$ mode. Furthermore, the result in Ref. [8] indicates that leptoquarks have additional decay modes beyond those which produce the observed $eejj$ and $e\nu jj$ final states. This motivates us to consider the possibility that the leptoquarks couple to other particles that are singlet under $\mathrm{SU}(3)_C \otimes \mathrm{U}(1)_{\mathrm{EM}}$. With these additional couplings, it is possible to obtain the $e\nu jj$-like events from decays to this singlet particle which yields a missing transverse energy signal. In addition, these singlet particles allow us to hide the signature of leptoquarks if their masses are somewhat degenerate with the leptoquark mass, since the jets produced from the leptoquark decays become too soft to be detected. These additional hidden decay modes also result in a reduction of the branching fraction of the leptoquark to other states. Here, we will consider a singlet fermion which is coupled to the leptoquark through renormalizable interactions only.[4] The additional interactions of the leptoquarks are restricted by the SM gauge symmetries. The SM gauge symmetries indicate that these interactions should contain a quark field since leptoquarks are colored. The singlet fields should be fermionic in order to form a renormalizable Lorentz scalar from a leptoquark, a quark, and a singlet field. As we will see shortly, the leptoquark S actually has such an interaction with a singlet.[5]

The leptoquark S has $B = 1/3$ and $L = -1$ in order for the model to preserve B and L. Thus, unless the leptoquark coupling with the singlet violates lepton number,

[4]In Refs. [13, 14], on the other hand, leptoquarks are assumed to interact with a DM candidate through non-renormalizable interactions.

[5]Notice that $S^\dagger_{1/2}$ does not couple to singlet fields via renormalizable interactions. In this sense, $\widetilde{S}^\dagger_{1/2}$ is the only candidate for our considerations. However, it does still offer the possibility of hidden decays to other generations.

the singlet fermions should have $|L| = 1$. This charge assignment implies that these singlet fermions can be identified as right-handed neutrinos ν_R. Indeed the presence of right-handed neutrinos is well-motivated by the observation of neutrino oscillations, which indicates neutrinos are massive. Based on the above discussion, we consider an extension of the SM to which a leptoquark S and three right-handed neutrinos ν_{R_i} $(i = 1, 2, 3)$ are added.

The relevant interactions for our discussion are then given by:

$$\begin{aligned}\mathcal{L}_{\rm int} = &-\lambda_{ij}\epsilon_{\alpha\beta}(\overline{d_i})_a P_L (L_j)^\alpha S^{a\beta} - h_{ij}(\overline{Q_i})_{a\alpha} P_R \nu_j S^{a\alpha} \\ &- y_{ij}\epsilon_{\alpha\beta}\overline{\nu_i} P_L (L_j)^\alpha H^\beta - \frac{1}{2} M_i \overline{\nu_i^c} P_R \nu_i \quad + {\rm h.c}\ ,\end{aligned} \tag{1}$$

where i, j are the generation indices; a represents the color index; α, β are SU$(2)_L$ indices; c indicates the charge conjugation; $\epsilon_{\alpha\beta}$ is the antisymmetric tensor with $\epsilon_{12} = -\epsilon_{21} = +1$; $P_{L/R} \equiv (1 \mp \gamma_5)/2$. For later use, we write the SU$(2)_L$ components of the leptoquark $S^{a\alpha}$ as

$$S^a = \begin{pmatrix} S_u^a \\ S_d^a \end{pmatrix} . \tag{2}$$

The relative size of the neutrino Yukawa couplings y_{ij} and Majorana masses M_i are chosen such that the left-handed neutrinos have small masses consistent with the oscillation experiments. All of the interactions except for the Majorana mass terms conserve both baryon and lepton number, and thus do not induce rapid proton decay. The off-diagonal components of λ_{ij} are strongly restricted by flavor experiments, and thus we assume the new couplings introduced above are diagonal, *i.e.*, $\lambda_{ij} = \lambda_i \delta_{ij}$ and $h_{ij} = h_i \delta_{ij}$. Of course, this assumption can be relaxed within the experimental limits.

3 Leptoquark signature at LHC

At the LHC, leptoquarks are produced through gluon fusion and quark-antiquark annihilation. Their production cross sections are predominantly determined by the strong interactions, and the new coupling constants λ_i and h_i give only a negligible contribution to the leptoquark production since they are assumed to be very small. The reason for this will be clarified below. The NLO computation of the leptoquark pair production cross section is given in Ref. [41].

After being produced, S_u decays into the $d_R e_L^c$ or $u_L \nu_R^c$ final state, while S_d decays into the $d_R \nu_L^c$ or $d_L \nu_R^c$ channel. The partial decay widths of these decay modes are as follows:

$$\begin{aligned}\Gamma(S_u \to d_{Ri} e_{Li}^c) = \Gamma(S_d \to d_{Ri} \nu_{Li}^c) &= \frac{|\lambda_i|^2 M_{\rm LQ}}{16\pi}\ , \\ \Gamma(S_u \to u_{Li} \nu_{Ri}^c) = \Gamma(S_d \to d_{Li} \nu_{Ri}^c) &= \frac{|h_i|^2 M_{\rm LQ}}{16\pi}\left[1 - \frac{M_{R_i}^2}{M_{\rm LQ}^2}\right]^2\ ,\end{aligned} \tag{3}$$

where $M_{\rm LQ}$ and M_{R_i} are the masses of the leptoquark S and right-handed neutrinos, respectively. A pair production of S_u can yield both the $eejj$ and the $e\nu jj$ signals, while S_d gives $\nu\nu jj$ signals only. Since the first-generation leptoquark searches by the CMS collaboration only look for the former two signals, the production of S_d is irrelevant for our discussion.

In these searches, the event selection for both $eejj$ and νejj signals is optimized for each leptoquark mass by imposing additional cuts beyond those referred to as the preselection cuts. A list of these cuts can be found in Ref. [8]. After all the cuts are imposed, the number of the lepto-quark events is estimated to be 125.85(58) and 37.22(37) in the $eejj$ and $e\nu jj$ channels, respectively, for $M_{\rm LQ} = 650$ GeV. Since the NLO production cross section for a 650 GeV leptoquark is determined to be 13.2 fb [41], the signal acceptances for the leptoquarks are 48.6% and 28.8% for $eejj$ and $e\nu jj$ [9] channels, respectively, for the integrated luminosity 19.6 fb^{-1}. On the other hand, 36 events are observed with $20.49 \pm 2.14({\rm stat}) \pm 2.45({\rm syst})$ events expected in the $eejj$, and in the $e\nu jj$ channel 18 events are detected with $7.54 \pm 1.20({\rm stat}) \pm 1.07({\rm syst})$ events expected. Therefore, to explain these excesses the branching fractions of the $S_u \to de^c$ and $S_u \to u\nu^c$ are required to be

$$\begin{aligned} {\rm BR}(S_u \to de^c) &\simeq 0.35 \ , \\ {\rm BR}(S_u \to u\nu^c) &\simeq 0.20 \ . \end{aligned} \tag{4}$$

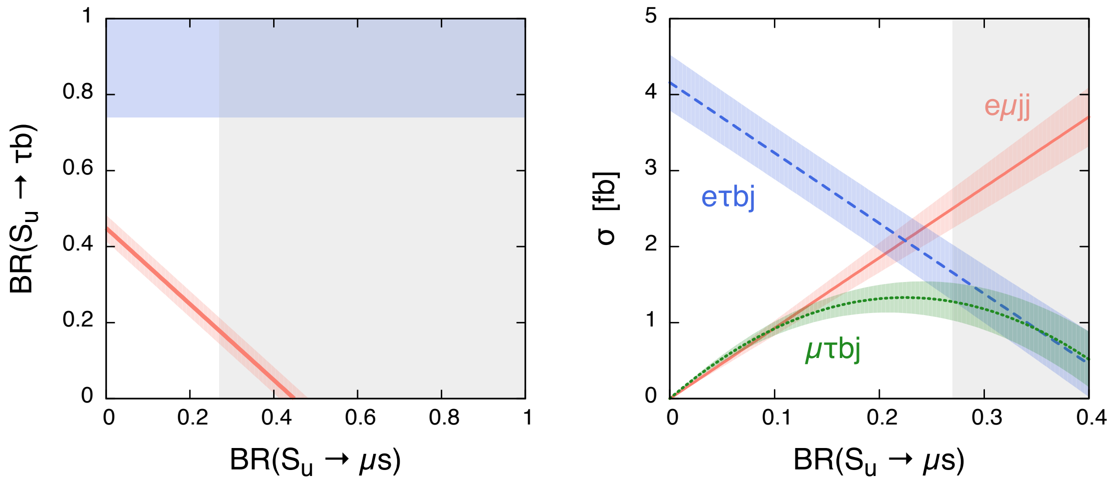
Clearly, the leptoquarks must have additional decay channels.

One of the most straightforward and simple explanations of the additional decay channels is that the leptoquark also decays into second and third generations quarks and leptons. We refer to this scenario as Model I in what follows.[6] For the assumption $M_{R_i} \ll M_{\rm LQ}$, the branching fractions of S_u are given by

$$\begin{aligned} {\rm BR}(S_u \to de^c) &= \frac{|\lambda_1|^2}{\sum_i |\lambda_i|^2 + \sum_i |h_i|^2} \ , \\ {\rm BR}(S_u \to u\nu^c) &= \frac{\sum_i |h_i|^2}{\sum_i |\lambda_i|^2 + \sum_i |h_i|^2} \ . \end{aligned} \tag{5}$$

Therefore, if we take the appropriate size for the couplings λ_2 and λ_3, we are able to explain the preferred branching fractions found in Eq. (4). The decay modes of the leptoquarks into the second and third generation quarks and leptons are restricted by searches for leptoquarks which couple to only the second or third generation quarks and leptons. For second generation leptoquarks, the CMS collaboration studied the final states consisting of two muons and at least two jets (the $\mu\mu jj$ channel) and one muon, and at least two jets, and missing transverse energy (the $\mu\nu jj$ channel) with the 8 TeV 19.6 fb^{-1} data [42]. The former channel leads to the constraint ${\rm BR}(S_u \to d\mu^c) \lesssim 0.27$ for a leptoquark of mass 650

[6] As already mentioned in footnote 5, $S^\dagger_{1/2}$ given in Table 1 may also explain the CMS excess in a similar manner, though this type of leptoquark in general suffers from severe low-energy experimental constraints.



(a) BR($S_u \to \mu s$) vs. BR($S_u \to \tau b$)

(b) $ll'jj$ channels

Figure 1: (a) Branching fractions to the second and third generations that can explain the excess in Ref [8] are plotted in a red solid line with the corresponding band showing the uncertainty coming from the experimental errors in the event rates. Right gray-shaded region is excluded by the second generation leptoquark search in the $\mu\mu jj$ channel [42], while the upper blue shaded region is disfavored by the third generation leptoquark search [43]. (b) Scattering cross sections for the $ll'jj$ modes as functions of BR($S_u \to \mu s$). Red solid, blue dashed, and green dotted lines show the cross sections of the $e\mu jj$, $e\tau bj$, and $\mu\tau bj$ modes, respectively, with the corresponding bands indicating the uncertainties from the error in the observed event rates. The gray shaded region in the right side is excluded by the second generation leptoquark search in the $\mu\mu jj$ channel [42]. The leptoquark mass is set to be 650 GeV.

GeV and the latter channel lead to BR$(S_u \to d\mu^c) \lesssim 0.64$ assuming BR$(S_u \to u\nu^c) = 0.20$ for the same leptoquark mass. They also searched for a third generation leptoquark with the 8 TeV 19.7 fb^{-1} data set, and found the bound on the branching fraction for a leptoquark decaying to a tau lepton and a bottom quark to be BR$(S_u \to \tau b) \lesssim 0.74$ [43]. The decay mode of a leptoquark to a top quark and a neutrino can in principle be constrained by the stop search, though the current constraint is still very weak [44, 45]. The ATLAS collaboration also searched for leptoquarks of these three generations with their 7 TeV data set [46–48], though currently their constraints are weaker than the CMS results. In Fig. 1(a), we show the preferred branching fractions to the second and third generations in a red solid line with the corresponding band representing the uncertainty coming from the experimental errors in event rates. Here, the right gray-shaded region is excluded by the second generation leptoquark search in the $\mu\mu jj$ channel [42], while the upper blue shaded region is disfavored by the third generation leptoquark search [43]. We find that to explain the excess in Ref. [8] the leptoquark must have a sizable branching fraction into the third generation fermions, $\mathrm{BR}(S_u \to \tau b) \gtrsim 0.2$. This rather large branching fraction may be probed in the upgraded LHC experiments. Note that since only the branching ratios are relevant to our discussion, the size of the new couplings can be small. Thus, we need not worry about non-perturbativity of the couplings nor the constraints coming from single leptoquark production at HERA experiments [49, 50] and the LHC experiments [51–53]. Because the leptoquarks can decay to second and third generation quarks and leptons, this model can be verified by searches for leptoquark with final states consisting of different flavors of charged leptons and two jets (the $ll'jj$ channels with $l \neq l'$, and $l', l = e, \mu, \tau$). In Fig. 1(b), we plot the scattering cross sections for these final states as functions of $\mathrm{BR}(S_u \to \mu s)$. Here, the red solid, blue dashed, and green dotted lines show the cross sections of the $e\mu jj$, $e\tau bj$, and $\mu\tau bj$ modes, respectively, with the corresponding bands indicating the uncertainties from the error in the observed event rates in Ref. [8]. Again, the gray shaded region on the right side is excluded by the second generation leptoquark searches in the $\mu\mu jj$ channel [42]. The leptoquark mass is set to be 650 GeV. This figure shows that the cross sections for the $ll'jj$ channels can be several fb, which are within the reach of the LHC experiments.

Here, we note that although we have assumed $M_{R_i} \ll M_{\mathrm{LQ}}$ in this analysis, some or all of the right-handed neutrinos can have masses of $\mathcal{O}(100)$ GeV without modifying the results too much. This freedom is important when we discuss the possibility of right-handed neutrino DM, as will be seen in Sec. 4.

Next, we consider the case where the leptoquark only couples to the first generation fermions, *i.e.*, $\lambda_2 = \lambda_3 = 0$. This scenario we call Model II. For this case, to realize the branching fractions in Eq. (4), we need to hide some of the decays into the right-handed neutrinos. To accomplish this, we assume that some of the right-handed neutrinos are degenerate in mass with the leptoquark. This makes the decays of the leptoquark to the degenerate right-handed neutrinos invisible since jets in this decay process become too soft to be detected. For example, the first generation leptoquark searches in Ref. [8] require that the leading jet should have a transverse momentum larger than 125 GeV. Thus if the mass difference between the leptoquark and right-handed neutrinos are less than ~ 100 GeV, the jet from the decay of the leptoquark evades the selection. From Eq. (4), we see that the invisible decays to right-handed neutrinos should have a branching ratio of about 0.45, which is twice as large as the visible neutrino branching ratio $\mathrm{BR}(S_u \to u\nu^c)$. This observation is inline with two of the three right-handed neutrinos being somewhat degenerate in mass with the leptoquark. In this case, each branching ratio is given by

$$\mathrm{BR}(S_u \to d e^c) = \frac{|\lambda_1|^2}{|\lambda_1|^2 + \sum_i |h_i|^2 \left[1 - \frac{M_{R_i}^2}{M_{\rm LQ}^2}\right]^2} ,$$

$$\mathrm{BR}(S_u \to u \nu^c) = \frac{|h_1|^2}{|\lambda_1|^2 + \sum_i |h_i|^2 \left[1 - \frac{M_{R_i}^2}{M_{\rm LQ}^2}\right]^2} ,$$

$$\mathrm{BR}(\text{invisible}) = \sum_{j=2,3} \frac{|h_j|^2}{|\lambda_1|^2 + \sum_i |h_i|^2 \left[1 - \frac{M_{R_i}^2}{M_{\rm LQ}^2}\right]^2} \left[1 - \frac{M_{R_j}^2}{M_{\rm LQ}^2}\right]^2 , \quad (6)$$

where we have assumed $M_{R_1} \ll M_{R_2}, M_{R_3}$. This gives $|h_1| \simeq 0.76|\lambda_1|$. Moreover, if $|h_2| = |h_3| = h$ and $M_{\rm LQ} - M_{R_2} = M_{\rm LQ} - M_{R_3} = 100$ GeV, then $h \simeq 2.8|\lambda_1|$. At present, the coupling λ_1 is a free parameters. However, this prediction for the relation among the couplings can be important when the lightest right-handed neutrino is the dominant component of DM in the Universe, as we will discuss in the next section. Also, λ_1 will be constrained in this case.

Finally, we consider constraints on these models from the dijet plus missing transverse energy ($jj + \not{E}_T$) searches. After being produced, 100% (4%) of S_d (S_u) pairs decay into two quarks and two neutrinos giving the $jj + \not{E}_T$ events in detector. For a 650 GeV leptoquark decaying to $jj + \not{E}_T$, the current upper limit on the cross section is about a few $\times 10$ fb [54, 55],[7] which is larger than the leptoquark production cross section. If some of the right-handed neutrinos have similar masses to that of the leptoquark, then the constraints are significantly relaxed. Anyways, we expect that the LHC run II experiments can observe events in this mode. This is a powerful consistency check of our models.

4 Right-handed neutrino DM and baryon asymmetry of the Universe

In the previous section, it was found that the CMS measurement can be explained by a leptoquark by adjusting the branching fractions (couplings) of the leptoquark. However, the upper bound on the couplings is independent of the CMS signal and a rather weak upper bound on the couplings is placed by HERA [49, 50] and CMS [51–53] single produced leptoquark searches. In fact, order one couplings are still allowed. The lower bound on the couplings of the leptoquark come from requiring that the leptoquark decay be prompt. This amounts to having a decay length shorter than about 1 mm. If the decay length is longer than 1 mm, then the constraint from searches for displaced vertices can be severe

[7] The ATLAS limit given in Ref. [55] only shows the results obtained for a combined 2–6 jets plus missing energy search. This makes it rather difficult to ascertain the constraints on the production cross section for this mode alone.

[56]. The total decay width for the leptoquark discussed above is

$$\Gamma_S = \Gamma_{S_u} = \Gamma_{S_d} \simeq \sum_i \left[|\lambda_i|^2 + |h_i|^2 \left(1 - \frac{M_{R_i}^2}{M_{\rm LQ}^2} \right) \right] \frac{M_{\rm LQ}}{16\pi} = \frac{|\lambda_1|^2}{{\rm BR}(S_u \to d e^c)} \frac{M_{\rm LQ}}{16\pi} \;, \quad (7)$$

for both Model I and II. Then, we find the decay length to be

$$c\Gamma_S^{-1} \simeq 1 \text{ mm} \times \left(\frac{650 \text{ GeV}}{M_{\rm LQ}} \right) \times \left(\frac{7.3 \times 10^{-8}}{\lambda_1} \right)^2 \;. \quad (8)$$

As can be seen from this expression, if the couplings are smaller than 10^{-7} their decays can no longer be considered prompt. Finally, we find that the allowed range for the leptoquark couplings is $10^{-7} \lesssim \lambda_1 \lesssim 1$, and are basically unrestricted by collider searches.[8]

The size of the leptoquark couplings λ_i and h_i, however, becomes important once we consider the phenomenology of right-handed neutrinos. Right-handed neutrinos may play a significant role in both particle physics and cosmology since they explain not only small neutrino masses via the seesaw mechanism [61], but also DM and the baryon asymmetry of the Universe. Indeed, it has been proposed that an extension of the SM with three right-handed neutrinos can account for all of these phenomena. This scenario [62] is called the ν Minimal Standard Model (νMSM).[9] It is therefore quite interesting to see if adding a leptoquark still gives a model which affords a DM candidate and can generate the desired baryon asymmetry. We will see that the range for the leptoquark couplings will be drastically reduced by the above requirements.

4.1 Vanishing Leptoquark Couplings

As a warm up, let us first consider the limit of vanishing h_i and λ_i. In this limit, the model considered in this article is exactly that of the νMSM [62], for which DM and baryogenesis can be explained. Later, we will discuss the effects the leptoquark couplings have on the phenomenology of these models. As we will see below, these couplings can drastically alter the situation. In the νMSM, the lightest right-handed is assumed to have a mass of $\mathcal{O}(10)$ keV and to be the DM of the Universe. The masses of the other two heavy right-handed neutrinos are quasi-degenerate and are of $\mathcal{O}(0.1$–$100)$ GeV in order to generate the baryon asymmetry. Both DM production and baryogenesis are non-equilibrium processes. For this to be the case, it is assumed that no right-handed

[8] Low-energy precision measurements, on the other hand, give fairly strong constraints on the leptoquark couplings. For example, measurements of the parity-violating transition in cesium atoms [57, 58] restrict the first-generation leptoquark couplings so that $|\lambda_1| \leq 0.22$ [52] for a 650 GeV leptoquark. The $Q_{\rm weak}$ experiment [59], which determines the weak charge of the proton by measuring the parity-violating asymmetry in elastic electron-proton scattering, gives a similar constraint on this coupling. The most severe constraint for Model I comes from $K_L \to \mu^- e^+$ decays. In fact, the constraint on the leptoquark couplings is $|\lambda_2 \lambda_1^*| < 0.9 \times 10^{-5}$ [52, 60]. As we will see, however, these are not the strongest constraints on the couplings of our model.

[9] For a review, see Ref. [63].

neutrinos are generated during reheating. After reheating, the right-handed neutrinos are generated by various scatterings of the thermal bath. Since the oscillations among different generations of right-handed neutrinos can be a non-equilibrium process which violates lepton number, a lepton asymmetry is generated in the right-handed neutrinos among the different generations. The lepton sector includes extra CP phases and thus offers new sources for CP-violation, which is required to produce a baryon asymmetry. The asymmetry in the right-handed neutrinos is converted to an asymmetry in the left-handed neutrinos via oscillations. This asymmetry is then converted to a baryon asymmetry via the sphaleron [64]. Importantly, the right-handed neutrinos do not reach equilibrium until after electroweak symmetry breaking, when the sphaleron shuts off, preventing the generated asymmetry in the right-handed neutrinos, and thus in the left-handed neutrinos, from being washed out. Because the sphaleron process is inert when the right-handed neutrinos reach equilibrium, the baryon asymmetry is preserved.

The production mode for the right-handed neutrinos is predominantly through the scattering $t\bar{t} \to h^* \to \nu_L N$ for the νMSM, where N, t and h denote right-handed neutrinos, top quark and the Higgs boson, respectively. When the temperature T is much higher than the masses of the particles participating in the scattering process, this scattering leads to a production rate of

$$\Gamma_N = n_{\rm EQ} \langle \sigma_{t\bar{t}\to\nu N}\ v \rangle \simeq 10^{-3} |y_{ij}|^2 T\ , \tag{9}$$

where $i \neq 1$, $n_{\rm EQ}$ indicates the number density of a massless particle and $\langle \sigma_{t\bar{t}\to\nu N} v \rangle$ is the thermally averaged scattering cross section times relative velocities. In the νMSM, the Yukawa couplings of the neutrinos with the Higgs are quite small in order to explain small neutrino masses. For the heavier neutrinos they are of order $y_{ij} \lesssim 10^{-7}$ when $i \neq 1$ while $y_{ij} \lesssim 10^{-11}$ for $i = 1$.[10] The heavier right-handed neutrinos will then come into equilibrium much earlier than the lightest right-handed neutrino. They will come into equilibrium when $\Gamma_N \sim H$ (H is the Hubble expansion rate) which gives

$$T_{\rm EQ} \simeq 10^{-3} |y_{ij}|^2 \frac{M_P}{1.66 g_*^{1/2}} \sim \left(\frac{|y_{ij}|}{10^{-7}} \right)^2 \times \mathcal{O}(10)\ \text{GeV}\ , \tag{10}$$

where $T_{\rm EQ}$ is the temperature at which the heavier neutrinos come into the thermal equilibrium; $M_P = 1.22 \times 10^{19}$ GeV is the Planck mass; g_* is the effective degrees of freedom for relativistic particles in thermal bath. A more detailed calculation shows that to ensure right-handed neutrinos are out of thermal equilibrium before sphaleron process shuts off, the Yukawa couplings should be smaller than 2×10^{-7} [62], and thus the heavier right-handed neutrino masses should be $M_{R_{2,3}} \lesssim 20$ GeV. Furthermore, this scenario means that the largest asymmetry in the right-handed neutrinos, and likewise in the left-handed neutrinos, is produced just before the sphaleron shuts off. This larger asymmetry

[10] In the presence of the leptoquark S, the Yukawa coupling can also be induced at the loop level since the leptoquark couples to both left- and right-handed neutrinos. This contribution is potentially dangerous since it could generate Yukawa couplings which are too large. However, it turns out that this contribution is smaller than that from seesaw for the scenarios discussed below, *i.e.*, leptoquark Yukawa couplings $\mathcal{O}(10^{-4})$.

can then offset the small mixing of the right- and left-handed neutrinos and produce the needed baryon asymmetry.

DM in the νMSM is the lightest right-handed neutrino. It is well-known that a sterile neutrino with a mass of $\mathcal{O}(10)$ keV is a good warm DM candidate [65, 66]. The Yukawa couplings of the lightest right-handed neutrino, if it is DM, needs to be sufficiently small so that its lifetime is longer than the age of the Universe. The dominant decay mode of the right-handed neutrino is the $N \to 3\nu$ channel. By evaluating the decay rate, one finds that an $\mathcal{O}(10)$ keV right-handed neutrino naturally realizes a lifetime much longer than the age of the Universe. As it turns out, however, this is not the most severe restriction on the couplings of the lightest right-handed neutrino if it is DM. Its couplings are more severely constrained by searches for diffuse X/γ rays [67–70]. If the the decay width is too large, it will produce diffuse X/γ rays which can be detected. To avoid these constraints, the lifetime needs to be longer than about 10^{28} s which gives

$$\tau_{N_1\to\gamma\nu} = \Gamma^{-1}_{N_1\to\gamma\nu} = \left(\frac{9\alpha G_F^2}{1024\pi^4}\sin^2(2\theta_1)M_{R_1}^5\right)^{-1} \simeq 10^{28}\text{s}\left(\frac{6.0\times10^{-24}}{\sum_i|y_{i1}|^2}\right)\left(\frac{M_{R_1}}{\text{keV}}\right)^3 , \quad (11)$$

with

$$\theta_1^2 = \sum_i \frac{v^2|y_{i1}|^2}{M_{R_1}^2} , \quad (12)$$

where α is the fine-structure constant; G_F is the Fermi constant; $v \simeq 246$ GeV is the Higgs VEV; N_1 denotes the lightest right-handed neutrino DM. As can be seen from these expressions, the decay is facilitated by a mixing of the left- and right-handed neutrinos and a W boson loop. By inhibiting the oscillations between the right- and left-handed neutrinos, this decay mode can be drastically suppressed. Suppressing oscillation amounts to taking smaller values of y_{ij}.

Because the Yukawa couplings for the lightest right-handed neutrino is extremely small, its production from top scatterings is suppressed and therefore not enough DM is produced. This problem can be alleviated if a large asymmetry is generated in the left-handed neutrinos which persists to scales below electroweak symmetry breaking [71]. This large asymmetry in the left-handed neutrinos can be produced via neutrino oscillation of the two heavier right-handed neutrinos as they freeze out or from resonantly enhanced decays [72]. For the oscillation production mechanism, the asymmetry is produce via mixing among the right-handed neutrinos. When the mass scale associated with mixing of the right-handed neutrinos, *i.e.*, differences of right-handed neutrino masses, are similar in size to the Hubble parameter, an asymmetry develops among the different species of the right-handed neutrinos. This asymmetry is then converted to an asymmetry in the left-handed neutrinos via mixing between the right and left-handed neutrinos. Since this oscillation occurs after freeze out of the right-handed neutrinos, the left-handed neutrinos do not oscillate back to the heavier neutrinos. A similar mechanism is used to produce the baryon asymmetry as the right-handed neutrinos are being generated by scatterings of the thermal bath before equilibrium has been reached [62, 73]. However, the production of the baryon asymmetry must occur at a temperature above $\mathcal{O}(100)$ GeV before the sphaleron shuts off. Where as, the asymmetry needed for DM production is produced below the scale where the sphaleron shuts off. If the asymmetry in the left-handed neutrinos is produced via decays, the masses of the right-handed neutrinos still need to be degenerate in order to enhance the CP violating parameter and produce a large enough asymmetry in the left-handed neutrinos [74]. Once this asymmetry in the left-handed neutrinos is produced, the thermal effects associated with this non-zero chemical potential alter the neutrino mass matrix and so alter the mixing relations between the left- and right-handed neutrinos, like the MSW effect [75]. In fact, for some temperature the mixing becomes of order one. If the temperature of the Universe for which the mixing is order one is still greater than the mass of the lightest right-handed neutrino, the left-handed neutrinos can be converted into the lightest right-handed neutrino giving a sufficient density to account for DM.

4.2 Non-Vanishing Leptoquark Couplings

For non-zero values of h_{ij} and y_{ij}, things change drastically since they couple the neutrinos with SM fields. These additional couplings provide additional scattering processes which can generate the right-handed neutrinos. The most important process among them is the leptoquark-gluon scattering, $gS \to Q_L N$, which gives a production rate of order

$$\Gamma_N = n_{\rm EQ} \langle \sigma_{gS \to Q_L N} v \rangle \sim 10^{-2} \alpha_s |h_{ij}|^2 T \ . \tag{13}$$

The equilibrium temperature for the right-handed neutrinos is then

$$T_{\rm EQ} \sim 10^{-2} \alpha_s |h_{ij}|^2 \frac{M_P}{1.66 g_*^{1/2}} \sim 10 \times \left(\frac{|h_{ij}|}{10^{-7}} \right)^2 \ {\rm GeV} \ . \tag{14}$$

If the couplings are taken as small as are allowed by the prompt decay limit, we could get a situation similar to the νMSM for baryogenesis. Although this may work, it does significantly restrict the parameter space of the model.

However, this production mechanism is very problematic for DM in Model II. Since the LHC measurements require the coupling of each right-handed neutrino to be of similar size, the amount of the lightest right-handed neutrino produced will be similar to the other right-handed neutrinos. This corresponds to a near thermal abundance for lightest right-handed neutrino, which will, in general, be too much DM.[11] Since its decay modes become severely inhibited for energies below the leptoquark mass, the right-handed neutrinos produced will stick around and over close the Universe.

Below, we will discuss how the lightest right-handed neutrino could still be DM in this scenario. However, first we discuss constraints on the couplings of the lightest right-handed neutrino to leptoquarks if it is indeed DM. These additional couplings will give additional contributions to $\Gamma_{N_1 \to \nu\gamma}$. Because the interaction of the leptoquark with the

[11] In Model I, it may be possible to suppress production of the lightest right-handed neutrino by taking $h_1 \ll h_{2,3}$.

neutrinos are vector like, this decay has a contribution coming from a loop involving a leptoquark and a quark [76]. A lifetime of the lightest right-handed neutrino of order 10^{28} s, again required by constraint coming from diffuse X/γ rays [69, 70], requires parameters of order [76][12]

$$\Gamma^{-1}_{N_1\to\nu_L\gamma} \simeq \left(\frac{10^{-4}}{\lambda_1}\right)^2 \left(\frac{10^{-4}}{h_1}\right)^2 \left(\frac{M_{\rm LQ}}{650\ \text{GeV}}\right)^5 \left(\frac{4\ \text{keV}}{M_{R_1}}\right)^3 \times 10^{28}\ \text{s}\ . \tag{15}$$

Fortunately, these couplings are much larger than those needed for prompt decay of the right-handed neutrinos. If the couplings lie right at the upper edge allowed by this constraint, the leptoquarks with right-handed neutrino DM could explain the 3.5 keV line observed in X-ray spectra [77].

As can be seen from the previous paragraph, the constraints on the couplings of right-handed neutrino DM to the leptoquark is not so severe. The problems for producing the right-handed neutrino DM arise from thermal processes for $T \gtrsim M_{\rm LQ}$. Below this temperature the leptoquarks decouple from the thermal bath and have little effect on the cosmology. One way to circumvent this problem is, therefore, to have a very low reheat temperature. If the reheat temperature T_R is smaller than the leptoquark mass, the production of the lightest right-handed neutrinos from $Sg \to NQ$ will be Boltzmann suppressed. This allows us to take larger values of λ and h while keeping right-handed neutrinos from being over produced by the thermal bath. For larger values of h and λ, the scattering process $\bar{L}d \to \bar{Q}N$ will become important. Through this process, the right-handed neutrino DM can be non-thermally produced. This is the same as the non-thermal equilibrium DM scenario discussed in Refs. [30, 78]. In this scenario, the right-handed neutrino DM is only weakly coupled to the thermal bath. This is due to the small couplings λ and h and because the mediator of this process, the leptoquark, has a mass somewhat larger than the reheating temperature. The lightest right-handed neutrinos are then produced by scatterings of the thermal bath. Because of the small couplings and large leptoquark mass, the right-handed neutrinos never reach thermal equilibrium. However, for particular values of the couplings, leptoquark mass, and reheat temperature enough of the lightest right-handed neutrinos can be produced to account for DM.

If the right-handed neutrinos come into equilibrium, they will over close the Universe and could cause problems for galaxy formation [65]. The right-handed neutrinos will come into equilibrium when the production rate is equal to the Hubble parameter. To guarantee that the lightest right-handed neutrino never comes into equilibrium, we calculate the production cross sections for $T < T_R < M_{\rm LQ}$ to leading order

$$\langle \sigma_{d\bar{L}\to QN_1}\, v\rangle = \sum_i \langle \sigma_{d_i\bar{L}_i\to QN_1}\, v\rangle \simeq \frac{3}{2\pi} N_C N_w \sum_i |\lambda_i h_1|^2 \frac{T^2}{M^4_{\rm LQ}}\ , \tag{16}$$

where $N_C = 3$ is the $SU(3)_C$ color factor and $N_w = 2$ is for the doublet factor of $SU(2)_L$. The right-handed neutrino DM is not in thermal equilibrium if the production rate is

[12]This constraint on the couplings is more mild than that found in Ref. [76]. This is due to the lightest right-handed neutrino only coupling to the down-type quarks.

much smaller than the Hubble expansion rate. This condition, $\langle\sigma_{QN_1\to d\bar{L}}v\rangle n_N^{\rm EQ} < H$, is always satisfied if

$$\sum_i |\lambda_i h_i|^2 < 1.5\times 10^{-14}\left(\frac{g_*}{100}\right)^{\frac{1}{2}}\left(\frac{M_{\rm LQ}}{650\ {\rm GeV}}\right)\ , \tag{17}$$

where we have used the inequality $T < T_R < M_{\rm LQ}$. As can be seen, if $\lambda_i \simeq h_i \simeq \lambda$ for $\lambda_i, h_i \neq 0$, then $\lambda < 3.5\times 10^{-4}$ satisfies this condition. For this case, the right-handed neutrino DM cannot come into equilibrium after reheating.

After reheating, the number density for the right-handed neutrinos is effectively zero. Since the number density is effectively zero, the annihilation rate of the right-handed neutrinos is negligible. The Boltzmann's equation for generating DM can be simplified to include only the production part [30, 78]

$$\frac{dY_N(x)}{dx} = \sqrt{\frac{\pi}{45}}\frac{g_s}{\sqrt{g_\rho}}M_P M_{N_1}\frac{\langle\sigma_{d\bar{L}\to QN_1}\ v\rangle}{x^2}Y_{\rm EQ}^2\ , \tag{18}$$

where $x = M_{R_1}/T$, $Y_N = n_N/s$, and $Y_{\rm EQ} = n_{\rm EQ}/s$; n_N is the number density of the lightest right-handed neutrino DM; s is the entropy of the Universe; g_s and g_ρ are the effective degrees of freedom for entropy and energy density respectively; $\langle\sigma_{d\bar{L}\to QN_1}\ v\rangle$ is as above. By integrating the above equation, we obtain the required reheat temperature,

$$T_R \simeq 400\left(\frac{\Omega_{\rm DM}h^2}{0.12}\right)^{\frac{1}{3}}\left(\frac{g_*}{100}\right)^{\frac{1}{2}}\left(\frac{M_{\rm LQ}}{650\ {\rm GeV}}\right)^{\frac{4}{3}}\left(\frac{10\ {\rm keV}}{M_{R_1}}\right)^{\frac{1}{3}}\left(\frac{2}{N_G}\right)^{\frac{1}{3}}\left(\frac{10^{-8}}{\lambda h}\right)^{\frac{2}{3}}\ {\rm GeV}\ , \tag{19}$$

where we set $g_s = g_\rho = g_*$. N_G is the number of generations participating in the production process, which is model dependent. $\Omega_{\rm DM}h^2$ is the present DM density parameter. This reheat temperature falls exactly where is needed for N_1 to be a good DM candidate. Namely, it is just below the leptoquark mass so that the leptoquark interactions are suppressed. Furthermore, it is above the sphaleron process which means the non-equilibrium dynamics could generate a baryon asymmetry via the lepton asymmetry induced by oscillations in the heavier right-handed neutrinos, as discussed above. This scenario is more plausible for Model I, where we may take the heavier right-handed neutrino masses to be $\mathcal{O}(1$–$10)$ GeV. The baryon asymmetry may also be generated through decays after the right-handed neutrinos freeze out. Again, the asymmetry in the left-handed neutrinos is converted to the baryon asymmetry through the sphaleron process. Since the constraints from diffuse X/γ rays only pertain to the lightest right-handed neutrino, the leptoquark couplings could also be adjusted to increase or decrease the baryon asymmetry as needed.

To determine the precise relic density of the right-handed neutrino DM and the baryon asymmetry in our models, it is necessary to numerically solve a set of coupled Boltzmann equations with thermal effects adequately taken into account. This calculation is necessary to determine the leptoquark couplings with better accuracy. In particular, a more detailed computation is needed to determine if these models can explain the 3.5 keV X-ray line excess [77]. This analysis will be left for future work.

5 Gauge coupling unification

It is widely known that the SM is not compatible with the minimal SU(5) Grand Unified Theory (GUT) [1]. Firstly, the SM gauge couplings approach each other but never unify sufficiently [79]. Secondly, the GUT scale is predicted to be too low to evade the current proton decay constraints. Therefore, the simplest SU(5) GUT is ruled out.

Since the leptoquark S is charged under the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge interactions, it can affect the running of the SM gauge couplings. Thus, the presence of the leptoquark may solve the problems mentioned above and revive the minimal SU(5). Indeed, the leptoquark we consider can be embedded in a **10**, **15**, **40**, ... of SU(5). This allows us to construct a GUT model where S is a component of an irreducible representation of SU(5).

At the two-loop level, the running of the SM gauge coupling constants g_a $(a = 1, 2, 3)$ are given by

$$\mu \frac{dg_a}{d\mu} = \frac{1}{16\pi^2} b_a^{(1)} g_a^3 + \frac{g_a^3}{(16\pi^2)^2} \left[\sum_{b=1}^{3} b_{ab}^{(2)} g_b^2 - \sum_{k=u,d,e} c_{ak} \, \mathrm{Tr}(f_k^\dagger f_k) \right] , \tag{20}$$

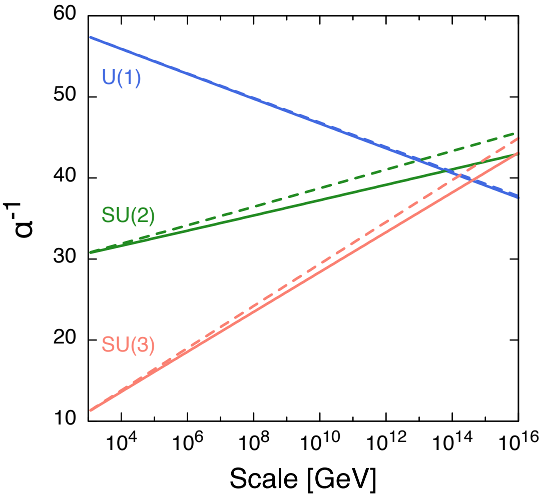
where $g_1 \equiv \sqrt{5/3} g'$ and f_k $(k = u, d, e)$ denotes the Yukawa matrices of the SM fermions. The coefficients $b_a^{(1)}$, $b_{ab}^{(2)}$, and c_{ak} in the SM are given in Ref. [80]. The change in the coefficient of the beta-function from S is found to be

$$\Delta b^{(1)} = \begin{pmatrix} 1/30 \\ 1/2 \\ 1/3 \end{pmatrix} , \qquad \Delta b^{(2)} = \begin{pmatrix} 1/150 & 3/10 & 8/15 \\ 1/10 & 13/2 & 8 \\ 1/15 & 3 & 22/3 \end{pmatrix} . \tag{21}$$

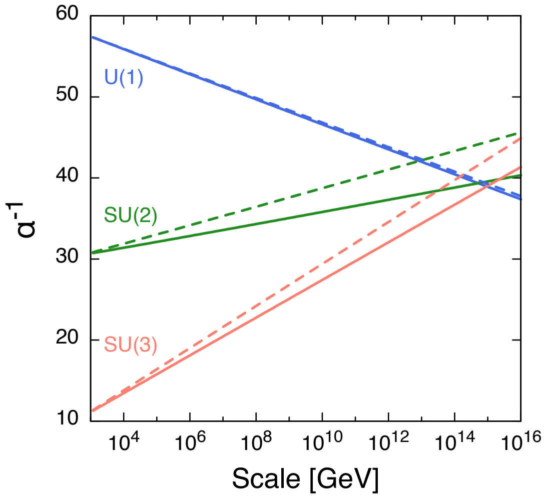
Here, we neglect the effects of the leptoquark Yukawa couplings since they are assumed to be very small.

In Fig. 2(a), we plot the running of the SM gauge couplings with a leptoquark S in solid lines. The blue, green, red lines show α_a^{-1} $(a = 1, 2, 3)$, respectively, with $\alpha_a \equiv g_a^2/(4\pi)$. The dashed lines show the running due to SM fields alone. In this computation, we use the two-loop renormalization group equations given above. However, we have not included threshold corrections at the GUT scale since they are dependent on a unknown mass spectrum. From this figure, we see that although the presence of a leptoquark improves gauge coupling unification, the deviation is still sizable and the unification scale is still rather low.

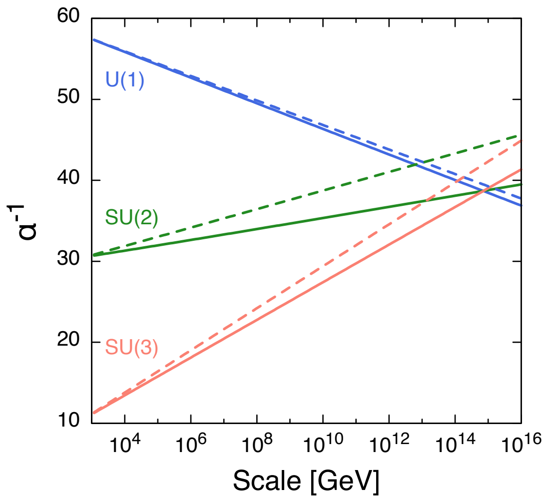
The situation is drastically improved, however, if there is an additional leptoquark around the TeV scale. A leptoquark with a mass of $\mathcal{O}(1)$ TeV can easily evade the current LHC bounds. In Fig. 2(b), we show the gauge coupling running for this case. We



(a) One leptoquark



(b) Two leptoquarks



(c) Two leptoquarks and one additional Higgs

Figure 2: The running of the gauge couplings with (a) one leptoquark, (b) two leptoquarks or (c) two leptoquarks plus one additional Higgs doublet added to the SM are shown in solid lines. The SM running is shown in dashed lines for comparison.

also show the case where two leptoquarks and a Higgs doublet[13] are added to the SM in

[13]The contribution of a Higgs doublet to the beta-function coefficients is given by

$$\Delta b^{(1)} = \begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix}, \qquad \Delta b^{(2)} = \begin{pmatrix} 9/50 & 3/10 & 0 \\ 9/10 & 13/6 & 0 \\ 0 & 0 & 0 \end{pmatrix}. \tag{22}$$

Fig. 2(c). This situation was already noticed in Ref. [81]. As can be clearly seen, gauge coupling unification in these two cases is far more precise. Accordingly, an extension of the SM with leptoquarks provides an alternative and promising framework for an SU(5) GUT without supersymmetry.

In the above cases, the unification scale is predicted to be $\sim 7 \times 10^{14}$ GeV, which is still too low if one considers the bound from proton decay. In the non-supersymmetric GUTs, proton decay is induced by the exchange of the heavy SU(5) gauge bosons. The dominant decay channel is then $p \to e^+\pi^0$ mode. The present experimental limit on this channel is $\tau(p \to e^+\pi^0) > 1.4 \times 10^{34}$ years [82]. To evade this constraint, we need to assume that the heavy gauge boson mass M_X is $\gtrsim 3 \times 10^{15}$ GeV, which is much heavier than the unification scale found above. With this disparity between scales, we expect sizable threshold corrections at the GUT scale and thus the gauge couplings do not need to precisely unify [83]. In this sense, all of the models in Fig. 2 can be compatible with the SU(5) GUT framework and thus quite promising. Anyways, all of these scenarios give a relatively light SU(5) gauge boson, and thus future proton decay experiments should detect proton decay in the $p \to e^+\pi^0$ mode. This is a distinct prediction of these models compared with the SUSY SU(5) GUT scenario. In the SUSY GUTs, the dominant decay channel is generically the $p \to K^+\bar{\nu}$ channel [84]. Additionally, since proton decay in our scenario occurs via the gauge interactions, the various decay modes are related by CKM matrix elements. Thus, this model will give specific prediction for ratios such as $\mathrm{BR}(p \to e^+K^0)/\mathrm{BR}(p \to e^+\pi^0)$. As a consequence of this, the leptoquark extension of the SM discussed in this paper offers a simple way to achieve an SU(5) GUT model [81, 85] which can be tested in proton decay experiments in the near future.

6 BAU and DM From Additional Leptoquarks

As was seen in the previous section, having two light leptoquarks can be motivated by grand unification. If we now include an additional leptoquark in the model discussed above, we find additional freedoms for generating the baryon asymmetry. In fact, the gauge symmetries allow the operator

$$V_{\not{B}} = q_{ijk} S_i S_j S_k H \ , \tag{23}$$

where $i, j, k = 1, 2$. Although this operator breaks the discrete $B - L$ discussed above, it may still give acceptably small proton decay because the proton decay operators are induced at two-loop level and the couplings between the leptoquark and the SM particles are extremely small. Another possible way to prevent proton decay would be to give the second leptoquark a different charge under $B - L$ of $1/3$. With this symmetry the above operator would still be allowed under the discreet $B - L$, but the second leptoquark would be forbidden from coupling to the SM particles alleviating proton decay.

This operator can be relevant for generating the baryon asymmetry. Since the leptoquarks are scalars, it is possible that during inflation one of the leptoquarks obtains a large VEV. After inflation, the VEV of the leptoquark will eventually return to zero. However, since the couplings q_{ijk} can violate CP, the relaxation can generate angular momentum in the leptoquark fields [86]. This angular momentum violates baryon number and lepton number. The baryon number stored in the leptoquark angular momentum generates a baryon asymmetry in the quarks as the VEV decays. If conditions are right, this could be how the baryon asymmetry was generated. The lepton number stored in the VEV leads to the production of right-handed neutrinos when the VEV of the leptoquark decays. This could be a non-thermal means of producing the lightest right-handed neutrino. If the density is large enough, it could be DM.

7 Conclusion

There are several unexplained signals lurking at the LHC. One particularly interesting signal is the excess in both $eejj$ and $e\nu jj$ found in the CMS first generation leptoquark searches [8]. The signals found in these searches rely on the leptoquark having some decay paths which are hidden so the branching fraction that produce the $eejj$ and $e\nu jj$ are sufficiently small. If we assume the leptoquark has SM charges $(\mathbf{3}, \mathbf{2}, 1/6)$ in the basis $\mathrm{SU}(3)_C \otimes \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$, it will have the interactions $S\bar{d}L$ and $S\bar{Q}\nu_R$ with generation indices suppressed. For this model, the simplest way of explaining the hidden decays is to assume that the leptoquark couples to all three generations. Since the current searches for leptoquarks focus on leptoquarks that couple to each generation individually, the hidden decay modes could merely be decays to other generations. If this is the case, events with mixed generation leptons like τejj should be seen at the upgraded LHC.

On the other hand, if right-handed neutrinos are lighter than the leptoquark, they could decay to right-handed neutrinos. If the two heavier right-handed neutrinos are somewhat degenerate in mass with the leptoquark, these decay modes would be excluded because the jets produced in this event would be too soft.

For each of these scenarios, the lightest right-handed neutrino is a viable DM candidate if its couplings to the leptoquarks are small enough that its life time is longer than the age of the Universe. If the coupling of the right-handed neutrinos to the leptoquarks are small enough, this model looks very similar to the νMSM [63] with similar production modes for the DM and baryon asymmetry. However, if these couplings are on the larger end of the allow range and the reheat temperature of the Universe is small enough, the lightest right-handed neutrino DM can be a non-equilibrium thermal DM candidate [30, 78].

With the leptoquark couplings small, the width of the leptoquark is also small. Thus, we expect a narrow peak in the invariant mass distribution constructed from a quark and a lepton final state. Since the statistics are low for this signal, we currently cannot conclude whether the excesses observed in the CMS experiment is actually peaked or not. Future LHC experiments with more data will be able to confirm or exclude this prediction.

The quality of the gauge coupling unification in the SM is made more precise by the addition of a leptoquark. It is even better with two leptoquarks and an additional Higgs multiplet. Since proton decay in these SM extension is governed by interaction with the heavy gauge bosons, the relative sizes of the different decay modes is determined by the CKM matrix elements. Since the mass of the heavy gauge bosons also tends to be relatively light, these models make fairly precise predictions for proton decay experiments.

The additional leptoquarks also give other possibilities for producing the baryon asymmetry of the Universe. They allow for an Affleck-Dine [86] like production of the baryon asymmetry.

Note Added: As we were about to post, we noticed the following paper [87] which also discusses an interpretation of the CMS excess [8] in terms of leptoquarks. However, this model is quite different from our model. They consider the leptoquark S_0 instead of $\widetilde{S}^{\dagger}_{1/2}$ which we consider. They also consider non-diagonal Yukawa couplings. The diagonality of our couplings is advantageous because it does not have difficulty with rare meson decays.

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