R-parity Conserving Minimal SUSY $B − L$ Model

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Abstract

We propose a simple gauged $U(1)_{B-L}$ extension of the minimal supersymmetric Standard Model (MSSM), where R-parity is conserved as usual in the MSSM. The global $B − L$ (baryon number minus lepton number) symmetry in the MSSM is gauged and three MSSM gauge-singlet chiral multiplets with a unit $B − L$ charge are introduced, ensuring the model free from gauge and gravitational anomalies. We assign an odd R-parity for two of the new chiral multiplets and hence they are identified with the right-handed neutrino superfields, while an even R-parity is assigned to the other one (Φ). The scalar component of Φ plays the role of a Higgs field to break the $U(1)_{B-L}$ symmetry through its negative mass squared, which is radiatively generated by the renormalization group running of soft supersymmetry (SUSY) breaking parameters from a high energy. This radiative $U(1)_{B-L}$ symmetry breaking leads to its breaking scale being at the TeV naturally. Because of our novel R-parity assignment, three light neutrinos are Dirac particles with one massless state. Since R-parity is conserved, the lightest neutralino is a prime candidate of the dark matter as usual. In our model, the lightest eigenstate of the mixture of the $B − L$ gaugino and the fermionic component of Φ appears as a new dark matter candidate. We investigate phenomenology of this dark matter particle. We also discuss collider phenomenology of our model. In particular, the $B − L$ gauge boson (Z'), once discovered at the Large Hadron Collider, can be a probe to determine the number of (right-handed) Dirac neutrinos with its invisible decay width, in sharp contrast with the conventional $B − L$ extension of the SM or MSSM where the right-handed neutrinos are heavy Majorana particles and decay to the SM leptons.

1 Introduction

The $B - L$ (baryon number minus lepton number) is the unique anomaly-free global U(1)$_{B-L}$ symmetry in the Standard Model (SM). This symmetry is easily gauged, and the so-called minimal $B - L$ model [1]-[6] is a simple gauged $B - L$ extension of the SM, where three right-handed neutrinos and an SM gauge singlet Higgs field with two units of the $B - L$ charge are introduced. The three right-handed neutrinos are necessarily introduced to make the model free from all gauge and gravitational anomalies. Associated with a $B - L$ symmetry breaking by a Vacuum Expectation Value (VEV) of the $B - L$ Higgs field, the $B - L$ gauge field (Z' boson) and the right-handed neutrinos acquire their masses. After the electroweak symmetry breaking, tiny SM neutrino masses are generated via the seesaw mechanism [7]-[11].

Although the scale of the $B-L$ gauge symmetry breaking is arbitrary as long as phenomenological constraints are satisfied, a breaking at the TeV scale is probably the most interesting possibility in the view point of the Large Hadron Collider (LHC) experiments. However, mass squared corrections of the $B - L$ Higgs (any Higgs fields in 4-dimensional models, in general) are quadratically sensitive to the scale of a possible ultraviolet theory, and as a result the $B - L$ symmetry breaking scale is unstable against quantum corrections. As is well-known, supersymmetric (SUSY) extension is the most promising way to solve this vacuum instability. Very interestingly, SUSY extension of the minimal $B - L$ model offers a way to naturally realize the $B - L$ symmetry breaking at the TeV scale. With suitable inputs of soft SUSY breaking parameters at a high energy, their renormalization group (RG) evolutions drive the $B - L$ Higgs mass squared negative and therefore the $B - L$ gauge symmetry is radiatively broken [12, 13, 14]. Since the scale of the negative mass squared is controlled by the soft SUSY breaking parameters, the $B - L$ breaking scale lies at the TeV from naturalness.

SUSY extension opens a further possibility. As has been proposed in Ref. [15], it is not necessary to introduce the $B-L$ Higgs field, since the scalar partner of a right-handed neutrino can play the same role as the $B - L$ Higgs field in breaking the $B - L$ gauge symmetry. Hence, we can define the "minimal SUSY $B - L$ model" by a particle content, where only three right-handed neutrino chiral superfields are added to the particle content of the minimal SUSY SM (MSSM). It is interesting that such a particle content can be derived from heterotic strings [16, 17]. In Ref. [15], a negative soft mass squared of a right-handed sneutrino is assumed to break the $B - L$ gauge symmetry, so that the $B - L$ symmetry breaking occurs at the TeV scale. Associated with this symmetry breaking, R-parity is also spontaneously broken, and many interesting phenomenologies with the R-parity violation have been discussed [18, 19, 20, 21]. Through the non-zero VEV of the right-handed sneutrino, mixings between neutrinos, MSSM Higgsinos, MSSM neutralinos and $B - L$ gaugino are generated. Although the neutrino mass

matrix becomes very complicated, it has enough number of degrees of freedom to reproduce the neutrino oscillation data with a characteristic pattern of the mass spectrum [22, 23].

In this paper, we propose the minimal SUSY $B - L$ model with an R-parity conservation. The particle content is the same as the one of the minimal SUSY $B - L$ model discussed above, while we assign an even R-parity to one right-handed neutrino chiral superfield (Φ) and an odd R-parity to the other two right-handed neutrino chiral superfields. The R-parity assignment for the MSSM fields is as usual. Because of this parity assignment and the gauge symmetry, the chiral superfield Φ has no Dirac Yukawa coupling with the lepton doublet fields. In fact, it does not appear in the renormalizable superpotential. We consider the case that the $B - L$ symmetry breaking is driven by a VEV of the R-parity even right-handed sneutrino. Phenomenological consequences in this model are very different from those of the conventional minimal SUSY $B - L$ model. As usual in the MSSM, R-parity is conserved and hence the lightest neutralino is a candidate of the dark matter. In addition to the lightest neutralino in the MSSM, the model offers a new candidate for the dark matter, namely, a linear combination of the fermion component of Φ and the $B - L$ gaugino. Since Φ has no Dirac Yukawa coupling, no Majorana mass term is generated in the SM neutrino sector, and as a result, the SM neutrinos are Dirac particles. With only the two right-handed neutrinos involved in the Dirac Yukawa couplings, the Dirac neutrino mass matrix leads to three mass eigenstates, one massless chiral neutrino and two Dirac neutrinos. A general 2-by-3 Dirac mass matrix includes a number of free parameters enough to reproduce the neutrino oscillation data. This Dirac nature of the SM neutrinos are quite distinctive from those in the usual $B - L$ model, where the right-handed neutrinos are heavy Majorana particles and the mass eigenstates different from the light SM neutrinos. If the Z' boson is discovered at the LHC, this difference could be tested through its decay products and the decay width measurements.

This paper is organized as follows. In the next section, we define our minimal SUSY $B - L$ model with a novel R-parity assignment. Then, we introduce the superpotential and soft SUSY breaking terms relevant for our discussion. In Sec. 3, we discuss a way to radiatively break the $B - L$ gauge symmetry, while keeping R-parity manifest. Focusing on the $B - L$ sector, for simplicity, we perform a numerical analysis for the RG evolutions of the soft SUSY breaking masses of the right-handed sneutrinos, and show that the $B - L$ gauge symmetry is radiatively broken at the TeV scale by a VEV of the scalar component of Φ. In Sec. 4, we consider a new dark matter candidate which is a linear combination of the scalar component of Φ and the $B - L$ gaugino. We show a parameter set which can reproduce the observed dark matter relic density. In Sec. 5, we also briefly discuss an implication of the Dirac neutrinos to the LHC phenomenology through the Z' boson production. The last section is devoted for conclusions

chiral superfield	SU(3)$_c$	SU(2)$_L$	U(1)$_Y$	U(1)$_{B-L}$	R-parity
Q^i	**3**	**2**	$+1/6$	$+1/3$	$-$
U_i^c	**3***	**1**	$-2/3$	$-1/3$	$-$
D_i^c	**3***	**1**	$+1/3$	$-1/3$	$-$
L_i	**1**	**2**	$-1/2$	-1	$-$
Φ	**1**	**1**	0	$+1$	$+$
$N_{1,2}^c$	**1**	**1**	0	$+1$	$-$
E_i^c	**1**	**1**	-1	$+1$	$-$
H_u	**1**	**2**	$+1/2$	0	$+$
H_d	**1**	**2**	$-1/2$	0	$+$

Table 1: Particle content of the minimal SUSY $B-L$ model with a conserved R-parity. In addition to the MSSM particles, three right-handed neutrino superfields (Φ and $N_{1,2}^c$) are introduced. We assign an even R-parity for Φ. $i = 1, 2, 3$ is the generation index.

and discussions.

2   Minimal SUSY $B-L$ model with a conserved R-parity

The minimal SUSY $B-L$ model is based on the gauge group of SU(3)$_c$×SU(2)$_L$×U(1)$_Y$×U(1)$_{B-L}$. In addition to the MSSM particle content, we introduce three chiral superfields which are singlets under the SM gauge groups and have a unit $B-L$ charge. The new fields are identified as the right-handed neutrino chiral superfields, and their existence is essential to make the model free from all gauge and gravitational anomalies. Unlikely to direct supersymmetrization of the minimal $B-L$ model, the $B-L$ Higgs superfields are not included in the particle content. The key of our proposal is that we assign an even R-parity to one right-handed neutrino chiral superfield, in contrast with the minimal SUSY $B-L$ model proposed in Ref. [15], where all the right-handed neutrino superfields are R-parity odd as usual. The particle content is listed in Table 1.

The gauge and parity invariant superpotential which is added to the MSSM one is only the neutrino Dirac Yukawa coupling as

$$W_{BL} = \sum_{i=1}^{2} \sum_{j=1}^{3} y_D^{ij} N_i^c L_j H_u. \tag{1}$$

Note that the Yukawa coupling for Φ is forbidden by the parity, and Φ has no direct coupling with the MSSM fields. After the electroweak symmetry breaking, the neutrino Dirac mass matrix is generated. Since this is a 2-by-3 matrix, one neutrino remains massless. Therefore, we have one massless neutrino and two Dirac neutrinos in the model. The 2-by-3 Dirac mass

matrix has a sufficient number of free parameters to reproduce the neutrino oscillation data. Although we have introduced the special parity assignment, this may be unnecessary in the practical point of view. Without the parity assignment, the superpotential in Eq. (1) can include

$$W_{BL} \supset \sum_{j=1}^{3} y_D^j \Phi L_j H_u, \tag{2}$$

which are unique direct couplings between Φ and the MSSM fields. Let us now take a limit $y_D^j \to 0$, which switch off the direct communication of Φ with the lepton and Higgs doublets. In this sense, our parity assignment can be regarded as a result of symmetry enhancement caused by this limit. Since the neutrinos are Dirac particles, the Dirac Yukawa coupling constants must be extremely small in order to reproduce the observed neutrino mass scale. We will discuss a possibility to naturally realize such small parameters in the last section.

Next, we introduce soft SUSY breaking terms for the fields in the $B - L$ sector:

$$\mathcal{L}_{\text{soft}} = -\left(\frac{1}{2}M_{BL}\lambda_{BL}\lambda_{BL} + h.c.\right) - \left(\sum_{i=1}^{2} m_{\tilde{N}_i^c}^2 |\tilde{N}_i^c|^2 + m_\phi^2 |\phi|^2\right), \tag{3}$$

where λ_{BL} is the $B - L$ gaugino and $\tilde{N}_i^c$ and ϕ are scalar components of N_i^c and Φ, respectively. Since the Dirac Yukawa couplings are very small, we omit terms relevant to the couplings. In the next section, we analyze the RG evolutions of the soft SUSY breaking masses and find that m_ϕ^2 is driven to be negative and the U(1)$_{B-L}$ symmetry is radiatively broken. Although we do not assume the grand unification of our model, we take $M_U = 2 \times 10^{16}$ GeV as a reference scale at which the boundary conditions for the soft masses are given.

3   Radiative $B - L$ symmetry breaking

It is well-known that the electroweak symmetry breaking in the MSSM is triggered by radiative corrections which drive soft mass squared of the up-type Higgs doublet negative. Because of this radiative symmetry breaking, the electroweak symmetry breaking scale is controlled by the soft SUSY breaking mass scale and the SUSY breaking scale at the TeV naturally results in the right electroweak scale of $\mathcal{O}(100 \text{ GeV})$. Similarly to the MSSM, a radiative $B - L$ symmetry breaking occurs by the RG evolution of soft SUSY breaking parameters from a high energy to low energies. However, the mechanism that drives m_ϕ^2 negative is different from the one in the MSSM where the large top Yukawa coupling plays a crucial role.

To make our discussion simple, we consider the RG equations only for the $B - L$ sector.[1]

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[1] See Refs. [24, 25] for more elaborate analysis and parameter scans to identify parameter regions which are consistent with current experimental results.
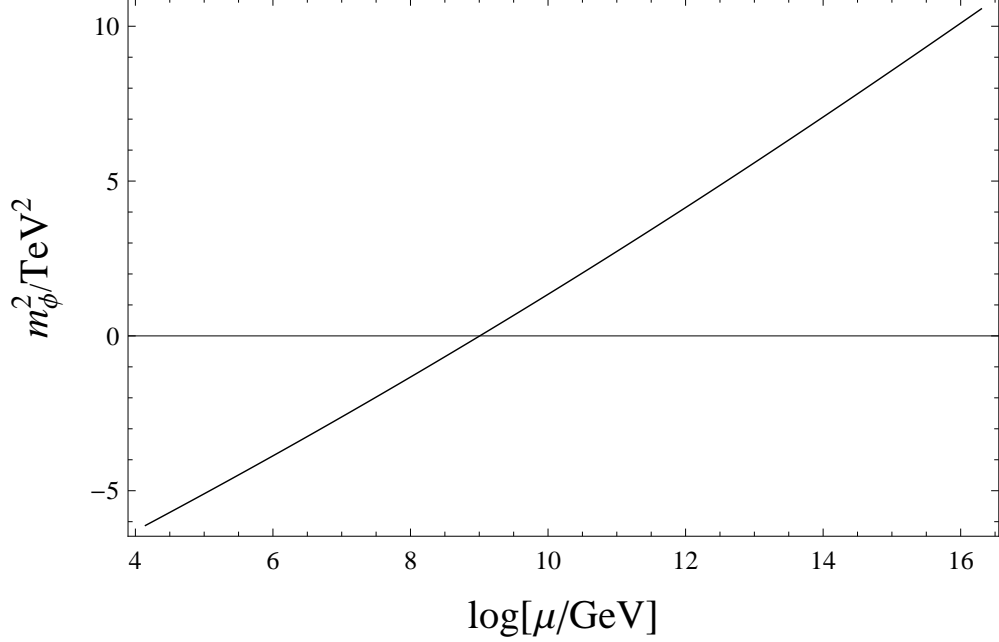
Figure 1: The RG evolution of the soft SUSY breaking mass m_ϕ^2 from M_U to low energies.

RG equations relevant for our discussion are

$$16\pi^2 \mu \frac{dM_{BL}}{d\mu} = 32 g_{BL}^2 M_{BL}, \tag{4}$$

$$16\pi^2 \mu \frac{dm_{\tilde{N}_i^c}^2}{d\mu} = -8 g_{BL}^2 M_{BL}^2 + 2 g_{BL}^2 \left(\sum_{j=1}^{2} m_{\tilde{N}_j^c}^2 + m_\phi^2 \right), \tag{5}$$

$$16\pi^2 \mu \frac{dm_\phi^2}{d\mu} = -8 g_{BL}^2 M_{BL}^2 + 2 g_{BL}^2 \left(\sum_{j=1}^{2} m_{\tilde{N}_j^c}^2 + m_\phi^2 \right), \tag{6}$$

where the $B - L$ gauge coupling obeys

$$16\pi^2 \mu \frac{dg_{BL}}{d\mu} = 16 g_{BL}^3. \tag{7}$$

In Eq. (5) the contributions from very small Dirac Yukawa couplings are omitted. In fact, the second term in the right-hand side of Eq. (6), which originates from the D-term interaction, plays an essential role to drive m_ϕ^2 negative. Since squarks and sleptons have $B - L$ charges, their soft squared masses also appear in the RG equations, but we have omitted them, for simplicity, by assuming they are much smaller than $m_{\tilde{N}_i^c}^2$ and m_ϕ^2.

To illustrate the radiative $B - L$ symmetry breaking, we numerically solve the above RG equations from $M_U = 2 \times 10^{16}$ GeV to low energy, choosing the following boundary conditions.

$$g_{BL} = 0.311, \quad M_{BL} = 8.13 \text{ TeV}, \quad m_{\tilde{N}_1^c} = m_{\tilde{N}_2^c} = 20.0 \text{ TeV}, \quad m_\phi = 3.25 \text{ TeV}. \tag{8}$$

Fig. 1 shows the RG evolution of m_ϕ^2. The mass squared of ϕ becomes negative at low energies as shown in this figure, while the other squared masses remain positive. The mass squared hierarchy $m_{\tilde{N}_i^c} \gg m_\phi^2$ is crucial to drive $m_\phi^2 < 0$.

We now analyze the scalar potential with the soft SUSY breaking parameters obtained from the RG evolutions. We choose the VEV of ϕ as $v_{BL} = \sqrt{2}\langle\phi\rangle = 14$ TeV as a reference, at which the solutions of the RG equations are evaluated as follows:

$$g_{BL} = 0.250, \quad M_{BL} = 5.25 \text{ TeV}, \quad m_{\tilde{N}_1^c} = m_{\tilde{N}_2^c} = 19.6 \text{ TeV}, \quad |m_\phi| = 2.47 \text{ TeV}. \tag{9}$$

The scalar potential is given by

$$V = m_{\tilde{N}_1^c}^2 |\tilde{N}_1^c|^2 + m_{\tilde{N}_2^c}^2 |\tilde{N}_2^c|^2 + m_\phi^2 |\phi|^2 + \frac{g_{BL}^2}{2}\left(|\tilde{N}_1^c|^2 + |\tilde{N}_2^c|^2 + |\phi|^2\right)^2. \tag{10}$$

Solving the stationary conditions, we find (in units of TeV)

$$\langle\tilde{N}_1^c\rangle = \langle\tilde{N}_2^c\rangle = 0, \quad \langle\phi\rangle = \frac{\sqrt{-2m_\phi^2}}{g_{BL}} \simeq \frac{14}{\sqrt{2}}. \tag{11}$$

This result is consistent with our choice of $v_{BL} = 14$ TeV in evaluating the running soft masses.

In our parameter choice, the Z' boson mass is given by

$$m_{Z'} = g_{BL} v_{BL} = 3.5 \text{ TeV}. \tag{12}$$

The ATLAS and CMS collaborations at the LHC Run-2 have been searching for the Z' boson resonance with the dilepton final state and have recently reported their results which are consistent with the SM expectaions [26, 27]. In Ref. [28], the ATLAS and CMS search results are interpreted to a constraint on the Z' boson in the minimal $B - L$ model, where an upper bound of the the $B - L$ gauge coupling as a function of Z' boson mass has been obtained. We refer the results in Ref. [28] such that $g_{BL} \leq 0.328$ and 0.350 for $m_{Z'} = 3.5$ TeV from the ATLAS and CMS results, respectively.[2] Our parameter choice of $g_{BL} = 0.250$ for $m_{Z'} = 3.5$ TeV is consistent with the recent LHC Run-2 results.

4 Right-handed neutrino dark matter

As we showed in the previous section, the $B - L$ gauge symmetry is radiatively broken by the RG effects on the soft SUSY breaking masses. Since the breaking occurs by the VEV of R-parity even scalar field ϕ, R-parity is still manifest, by which the stability of the lightest R-parity odd

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[2] It is also shown in Ref. [28] that the ATLAS bound at the LHC Run-2 is more severe than the bound obtained from the LEP2 data [29] for $m_{Z'} \leq 4.3$ TeV.

particle is ensured. Thus, as usual in the MSSM, the lightest neutralino is a candidate of the dark matter. In addition to the MSSM neutralinos, a new dark matter candidate arises in our model, namely, the fermion component of Φ (ψ). We can call ψ the R-parity odd right-handed neutrino. In this section, we study phenomenology of the right-handed neutrino dark matter.

A scenario of the parity-odd right-handed Majorana neutrino dark matter was first proposed in [30] in the context of the non-SUSY minimal $B - L$ model, where a Z_2 parity is introduced and an odd parity is assigned to one right-handed neutrino while the other fields are all parity-even. Because of the Z_2-parity conservation, the parity-odd right-handed neutrino becomes stable and hence the dark matter candidate. Phenomenology of this dark matter has been investigated in [30, 31, 32]. Recently, in terms of the complementarity to the LHC physics, the right-handed neutrino dark matter has been investigated in detail [28]. Supersymmetric version of the minimal $B - L$ model with the right-handed neutrino dark matter has been proposed in [14].

Our dark matter scenario that we will investigate in this section shares similar properties with the scenario discussed in [14]. However, there is a crucial difference that ψ has no Majorana mass by its own, but it acquires a Majorana mass through a mixing with the $B - L$ gaugino (λ_{BL}). After the U(1)$_{B-L}$ symmetry breaking, a mass matrix for ψ and λ_{BL} is generated to be

$$M_\chi = \begin{pmatrix} 0 & m_{Z'} \\ m_{Z'} & M_{BL} \end{pmatrix}. \tag{13}$$

The mass matrix is diagonalized as

$$\begin{pmatrix} \psi \\ \lambda_{BL} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \chi_\ell \\ \chi_h \end{pmatrix} \tag{14}$$

with $\tan 2\theta = 2m_{Z'}/M_{BL}$. Let us assume that the lighter mass eigenstate (χ_ℓ) is the lightest neutralino. Since ψ and λ_{BL} are the SM gauge singlets, possible annihilation processes of the dark matter are very limited. Furthermore, given a small $B - L$ gauge coupling and the Majorana nature of the dark matter particle, the annihilation process via sfermion exchanges is not efficient. We find that a pair of dark matter particles can annihilate efficiently only if the dark matter mass is close to half of the Z' boson mass and the Z' boson resonance in the s-channel annihilation process enhances the cross section. Let us set $M_{BL} \simeq (3/2)m_{Z'}$, so that the lightest mass eigenvalue is found to be $m_{DM} \simeq m_{Z'}/2$ and $\cos^2\theta \simeq 0.8$. Our parameter choice in the previous section is suitable for this setup, $M_{BL} = (3/2)m_{Z'} = 5.25$ TeV for $m_{Z'} = 3.5$ TeV.

Let us now calculate the dark matter relic abundance by integrating the Boltzmann equation given by

$$\frac{dY}{dx} = -\frac{s\langle\sigma v\rangle}{xH(m_{DM})}\left(Y^2 - Y_{EQ}^2\right), \tag{15}$$

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where temperature of the universe is normalized by the mass of the right-handed neutrino $x = m_{DM}/T$, $H(m_{DM})$ is the Hubble parameter at $T = m_{DM}$, Y is the yield (the ratio of the dark matter number density to the entropy density s) of the dark matter particle, Y_{EQ} is the yield of the dark matter particle in thermal equilibrium, and $\langle \sigma v \rangle$ is the thermal average of the dark matter annihilation cross section times relative velocity. Explicit formulas of the quantities involved in the Boltzmann equation are as follows:

$$s = \frac{2\pi^2}{45} g_\star \frac{m_{DM}^3}{x^3},$$

$$H(m_{DM}) = \sqrt{\frac{4\pi^3}{45} g_\star} \frac{m_{DM}^2}{M_{Pl}},$$

$$sY_{EQ} = \frac{g_{DM}}{2\pi^2} \frac{m_{DM}^3}{x} K_2(x), \tag{16}$$

where $M_{Pl} = 1.22 \times 10^{19}$ GeV is the Planck mass, $g_{DM} = 2$ is the number of degrees of freedom for the Majorana dark matter particle, $g_\star$ is the effective total number of degrees of freedom for particles in thermal equilibrium (in the following analysis, we use $g_\star = 106.75$ for the SM particles), and K_2 is the modified Bessel function of the second kind. In our scenario, a pair of dark matter annihilates into the SM particles dominantly through the Z' boson exchange in the s-channel. The thermal average of the annihilation cross section is given by

$$\langle \sigma v \rangle = (sY_{EQ})^{-2} \frac{m_{DM}}{64\pi^4 x} \int_{4m_{DM}^2}^{\infty} ds \, \hat{\sigma}(s) \sqrt{s} K_1 \left(\frac{x\sqrt{s}}{m_{DM}} \right), \tag{17}$$

where the reduced cross section is defined as $\hat{\sigma}(s) = 2(s - 4m_{DM}^2)\sigma(s)$ with the total annihilation cross section $\sigma(s)$, and K_1 is the modified Bessel function of the first kind. The total cross section of the dark matter annihilation process $\chi_\ell \chi_\ell \to Z' \to f\bar{f}$ (f denotes the SM fermions plus two right-handed neutrinos) is calculated as

$$\sigma(s) = \frac{5}{4\pi} g_{BL}^4 \cos^2 \theta \frac{\sqrt{s(s - 4m_{DM}^2)}}{(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2}, \tag{18}$$

where all final state fermion masses have been neglected. The total decay width of Z' boson is given by

$$\Gamma_{Z'} = \frac{g_{BL}^2}{24\pi} m_{Z'} \left[15 + \cos^2 \theta \left(1 - \frac{4m_{DM}^2}{m_{Z'}^2} \right)^{\frac{3}{2}} \theta \left(\frac{m_{Z'}^2}{m_{DM}^2} - 4 \right) \right]. \tag{19}$$

Here, we have assumed that all sparticles have mass larger than $m_{Z'}/2$.

Now we solve the Boltzmann equation numerically, and find the asymptotic value of the yield $Y(\infty)$. The dark matter relic density is evaluated as

$$\Omega_{DM} h^2 = \frac{m_{DM} s_0 Y(\infty)}{\rho_c/h^2}, \tag{20}$$
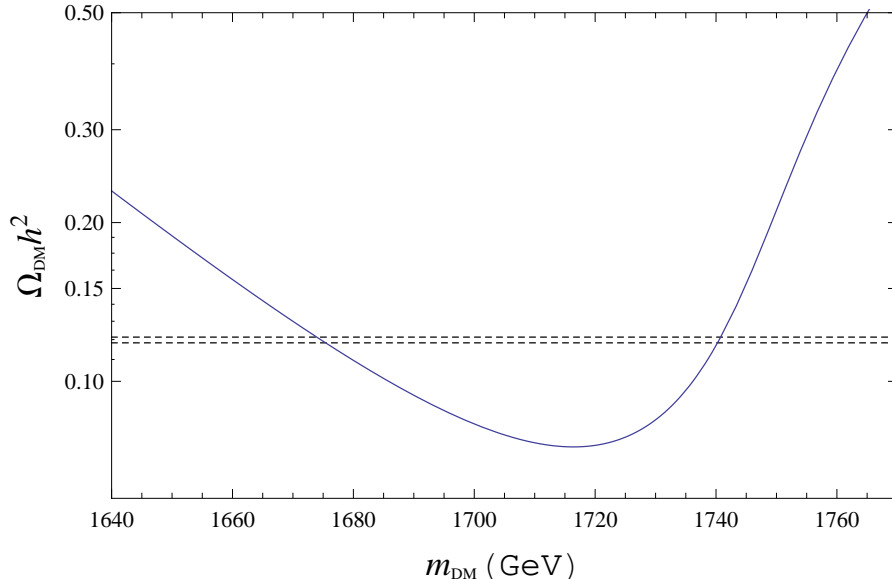
Figure 2: The relic abundance of the dark matter particle as a function of the dark matter mass (m_{DM}) for $g_{BL} = 0.250$, $m_{Z'} = 3.5$ TeV and $\cos^2\theta = 0.8$. The two horizontal lines denote the range of the observed dark matter relic density, $0.1183 \leq \Omega_{DM}h^2 \leq 0.1213$ [33].

where $s_0 = 2890$ cm^{-3} is the entropy density of the present universe, and $\rho_c/h^2 = 1.05 \times 10^{-5}$ GeV/cm^3 is the critical density. In our analysis, only three parameters, namely g_{BL}, $m_{Z'}$ and m_{DM}, are involved.[3] As mentioned above, a sufficiently large annihilation cross section is achieved only if $m_{DM} \simeq m_{Z'}/2$. Thus, we focus on the dark matter mass in this region and in this case $\cos^2\theta \simeq 0.8$. For $g_{BL} = 0.250$, $m_{Z'} = 3.5$ TeV and $\cos^2\theta = 0.8$, Fig. 2 shows the resultant dark matter relic abundance as a function of the dark matter mass m_{DM}, along with the bound $0.1183 \leq \Omega_{DM}h^2 \leq 0.1213$ (65% limit) from the Planck satellite experiment [33] (two horizontal dashed lines). We have confirmed that only if the dark matter mass is close to half of the Z' boson mass, the observed relic abundance can be reproduced.

5 Implication of Dirac neutrino to LHC physics

Because of our R-parity assignment, the SM neutrinos are Dirac particles in our model. This is quite distinct from usual $B - L$ extension of the SM, where right-handed neutrinos are heavy Majorana states. Since the right-handed neutrinos are singlet under the SM gauge groups and the Dirac Yukawa coupling constants are very small in both Dirac and Majorana cases, the right-handed neutrinos can communicate with the SM particles only through Z' boson

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[3] The mixing angle θ is determined once $m_{Z'}$ and m_{DM} are fixed.

exchange. As we mentioned above, the search for Z' boson resonance is underway at the LHC Run-2. Once discovered at the LHC, the Z' boson will allows us to investigate physics of the right-handed neutrinos through precise measurements of Z' boson properties. In this section we consider an implication of the Dirac neutrinos to LHC physics.

When the right-handed neutrinos are heavy Majorana particles as in the minimal $B - L$ model, a pair of right-handed Majorana neutrinos, if kinematically allowed, can be produced through Z' boson decays at the LHC. The produced right-handed neutrino subsequently decays to weak gauge bosons/Higgs boson plus leptons. Because of the Majorana nature of the right-handed neutrino, the final states include same-sign leptons. This is a characteristic signature from the lepton number violation, and we expect a high possibility to detect such final states with less SM background. For a detailed studies, see, for example, Ref. [34].

The Majorana neutrinos are heavy and can be produced only if they are kinematically allowed, while the Dirac neutrinos in our model are always included in the Z' boson decay products. However, they cannot be detected just like the usual SM neutrinos produced at colliders. This process may remind us of the neutrino production at the LEP through the resonant production of the Z boson. It was a great success of the LEP experiment that the precise measurement of the Z boson decay width and the production cross section at energies around the Z boson peak has determined the number of the SM neutrinos to be three [35]. We notice that the Z' production is quite analogous to the Z production at the LEP. Although the right-handed neutrinos produced by the Z' boson are completely undetectable, the total Z' boson decay width carries the information of the invisible decay width. A precise measurement of the Z' boson cross section at the LHC may reveal the existence of the right-handed Dirac neutrinos. To illustrate this idea, we calculate in the following the differential cross section for the process with the dilepton final states, $pp \rightarrow \ell^+\ell^-$ with $\ell = e, \mu$ mediated by photon, Z boson and Z' boson at the LHC with a collider energy $\sqrt{s} = 14$ TeV.

The differential cross section with respect to the final state dilepton invariant mass M_{ll} is described as

$$
\begin{aligned}
\frac{d\sigma(pp \rightarrow \ell^+\ell^- X)}{dM_{ll}} &= \sum_{a,b} \int_{-1}^{1} d\cos\theta \int_{\frac{M_{ll}^2}{E_{\mathrm{CMS}}^2}}^{1} dx_1 \frac{2M_{ll}}{x_1 E_{\mathrm{CMS}}^2} \\
&\times f_a(x_1, Q^2) f_b\left(\frac{M_{ll}^2}{x_1 E_{\mathrm{CMS}}^2}, Q^2\right) \frac{d\sigma(\bar{q}q \rightarrow \ell^+\ell^-)}{d\cos\theta},
\end{aligned} \tag{21}
$$

where $E_{\mathrm{CMS}} = 14$ TeV is the center-of-mass energy of the LHC. In our numerical analysis, we employ CTEQ5M [36] for the parton distribution functions (f_a) with the factorization scale $Q = m_{Z'}$. Reader may refer Appendix in Ref. [37] for the helicity amplitudes to calculate $d\sigma(\bar{q}q \rightarrow \ell^+\ell^-)/d\cos\theta$. For the Z' boson mediated process, we consider two cases, $N(\nu_R) = 0$
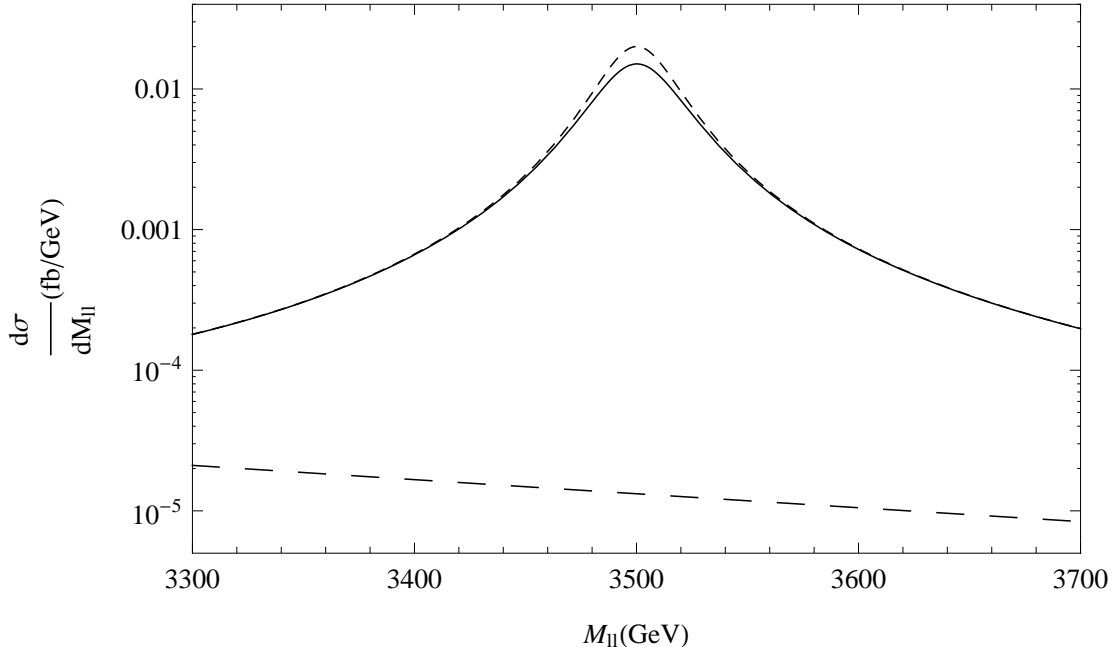
Figure 3: The differential cross section for $pp \to e^+e^-X + \mu^+\mu^-X$ at the 14 TeV LHC for $m_{Z'} = 3.5$ TeV and $g_{BL} = 0.250$. The solid and dashed curves correspond to the results for $N(\nu_R) = 2$ and 0, respectively. The horizontal long-dashed line represents the SM cross section, which is negligible compared with the Z' boson mediated process.

and $N(\nu_R) = 2$, where $N(\nu_R)$ is the number of right-handed (Dirac) neutrinos. For our case with $N(\nu_R) = 2$, the total Z' boson decay width is given in Eq. (19), while the number 15 in the bracket must be replaced to 12 for $N(\nu_R) = 0$.

Fig. 3 shows the differential cross section for $pp \to e^+e^-X + \mu^+\mu^-X$ for $m_{Z'} = 3.5$ TeV and $g_{BL} = 0.250$, along with the SM cross section mediated by the Z-boson and photon (horizontal long-dashed line). The solid and dashed curves correspond to the results for $N(\nu_R) = 2$ and 0, respectively. The dependence of the total decay width on the number of right-handed neutrinos reflects the resultant cross sections. When we choose a kinematical region for the invariant mass in the range, $M_{Z'} - 100 \leq M_{ll}(\text{GeV}) \leq M_{Z'} + 100$, for example, the signal events of 892 and 1049 for $N(\nu_R) = 2$ and 0, respectively, would be observed with the prospective integrated luminosity of 1000/fb at the High-Luminosity LHC. The difference between $N(\nu_R) = 2$ and 0 are distinguishable with a $4 - 5\sigma$ significance.

6 Conclusions and discussions

We have proposed a simple gauged $U(1)_{B-L}$ extension of the MSSM, where R-parity is conserved as usual in the MSSM. The global $B - L$ symmetry in the MSSM is gauged and three right-handed neutrino chiral multiplets are introduced, which make the model free from all gauge and gravitational anomalies. No $B - L$ Higgs field is introduced. We assign an even R-parity to one right-handed neutrino superfield Φ, while the other two right-handed neutrino superfields are odd as usual. The scalar component of Φ plays a role of the $B - L$ Higgs field to beak the $U(1)_{B-L}$ gauge symmetry through its negative mass squared which is radiatively generated by the RG evolution of soft SUSY breaking parameters. Therefore, the scale of the $U(1)_{B-L}$ symmetry breaking is controlled by the SUSY breaking parameters and naturally be at the TeV scale. We have shown that this radiative symmetry breaking actually occurs with a suitable choice of model parameters. Because of our novel R-parity assignment, three light neutrinos are Dirac particles with one massless state. Since R-parity is conserved, the lightest neutralino is a prime candidate of the dark matter of the universe. Depending on its mass, the lighter Majorana mass eigenstate (χ_ℓ) of a mixture of the $B - L$ gaugino and the fermionic component of Φ (R-parity odd right-handed neutrino) appears as a new dark matter candidate. Assuming χ_ℓ is the lightest R-parity odd particle, we have calculated the dark matter relic abundance. When the mass of χ_ℓ is close to half of the Z' boson mass, the pair annihilation cross section of the dark matter particle is enhanced through the Z' boson resonance in the s-channel process and the observed dark matter relic abundance is reproduced. We have also discussed LHC phenomenology for the Dirac neutrinos. The Z' boson, once discovered at the LHC, will be a novel probe of the Dirac nature of the light neutrinos since its invisible decay processes include the final states with one massless (left-handed) neutrino and two Dirac neutrinos, in sharp contrast with the conventional $B - L$ extension of the SM or MSSM, where the right-handed neutrinos are heavy Majorana particles and decay to the weak gauge bosons/Higgs boson plus leptons. If the Z' boson is discovered, the High-Luminosity LHC may reveal the existence of the right-handed neutrino with a precise measurement of the total decay width of Z' boson.

Since the neutrinos are Dirac particles in our model, their Dirac Yukawa coupling must be extremely small. It is an important issue how to naturally realize such a small Yukawa coupling, or a huge hierarchy between the neutrino Yukawa coupling and those of the other SM fermions, in a reasonable theoretical framework. In addition, the mass squared hierarchy between ϕ and the other right-handed sneutrinos is crucial to achieve the radiative $B - L$ gauge symmetry breaking. Realizing this hierarchy in a natural way is an additional issue. In order to solve these hierarchy problems, we may extend the model to the brane-world framework with 5-dimensional warped space-time [38]. Arranging the bulk mass parameters for the bulk

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hypermultiplets corresponding to matter and Higgs fields in the minimal SUSY $B - L$ model, we can obtain large hierarchy among parameters in 4-dimensional effective theory with mildly hierarchical model parameters in the original 5-dimensional theory. This direction is worth investigating [39].

Acknowledgments

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