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Dark matter in the classically conformal $B-L$ model

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Abstract

When the classically conformal invariance is imposed on the minimal gauged $B-L$ extended Standard Model (SM), the $B-L$ gauge symmetry is broken by the Coleman-Weinberg mechanism naturally at the TeV scale. Introducing a new Z_2 parity in the model, we investigate phenomenology of a right-handed neutrino dark matter whose stability is ensured by the parity. We find that the relic abundance of the dark matter particle can be consistent with the observations through annihilation processes enhanced by resonances of either the SM Higgs boson, the $B-L$ Higgs boson or the $B-L$ gauge boson (Z' boson). Therefore, the dark matter mass is close to half of one of these boson masses. Due to the classically conformal invariance and the $B-L$ gauge symmetry breaking via the Coleman-Weinberg mechanism, Higgs boson masses, Z' boson mass and the dark matter mass are all related, and we identify the mass region to be consistent with experimental results. We also calculate the spin-independent cross section of the dark matter particle off with nucleon and discuss implications for future direct dark matter search experiments.

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1 Introduction

The minimal gauged $B-L$ extended Standard Model (SM) is one of very attractive scenarios beyond the SM and has been receiving fare amount of attentions these days. The model is an elegant and simple extension of the SM, in which the right-handed neutrinos of three generations are necessarily introduced for the cancellation of the gauge and gravitational anomalies. In addition, the mass of right-handed neutrinos arises associated with the $\mathrm{U}(1)_{B-L}$ gauge symmetry breaking and the seesaw mechanism [1] for a natural generation of tiny neutrino masses is automatically implemented. The Large Hadron Collider (LHC) is currently exploring the TeV scale physics by collecting data very rapidly. In the view point of LHC physics it is the most desirable that the $B-L$ symmetry breaking scale lies at the TeV scale, so that the $B-L$ gauge boson (Z' boson) and the right-handed neutrinos can be discovered in the near future [2].

Recently, the minimal $B-L$ model with the classically conformal invariance has been proposed [3] and it has been shown [4] that the $B-L$ symmetry breaking in the model is naturally realized at the TeV scale when the $B-L$ gauge coupling constant is of the same order of the SM gauge coupling constants. Furthermore, one of cosmological aspects of the minimal $B-L$ model at the TeV scale, baryogenesis via leptogenesis, has been investigated with detailed numerical analysis. It has been shown [5] that the observed baryon asymmetry in the present universe can be reproduced via the resonant leptogenesis [6] with a suitable set of model parameters, which is also consistent with the neutrino oscillation data.

Towards the completion of phenomenology for the $B-L$ model at the TeV scale, we investigate, in this paper, another cosmological aspect, namely the dark matter issue. Among many possibilities, a very concise way to introduce a dark matter candidate in the minimal $B-L$ model has been proposed in Ref. [7], where a new Z_2 parity, instead of new particle(s) for the dark matter candidate, is introduced. Under the the parity, one right-handed neutrino is assigned as odd while all other particles are even. This parity assignment makes the Z_2-odd right-handed neutrino stable and hence the candidate for the (cold) dark matter. It has been found [7] that the observed relic abundance of the right-handed neutrino dark matter can be achieved through interactions with Higgs bosons. In this paper, we adopt this idea to the classically conformal $B-L$ extended model and investigate phenomenology of the right-handed neutrino dark matter. Although our analysis is quit analogous to those in Ref. [7], the classically conformal invariance imposed on the model plays the crucial role to severely constrain the parameter space of the model.

The paper is organized as follows. In the next section, we give a brief review on the classically conformal $B-L$ extended model (with Z_2 parity) and the natural realization of

	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$	$\mathrm{U}(1)_{B-L}$	Z_2
q_L^i	**3**	**2**	$+1/6$	$+1/3$	$+$
u_R^i	**3**	**1**	$+2/3$	$+1/3$	$+$
d_R^i	**3**	**1**	$-1/3$	$+1/3$	$+$
ℓ_L^i	**1**	**2**	$-1/2$	-1	$+$
ν_R^1	**1**	**1**	0	-1	$-$
ν_R^j	**1**	**1**	0	-1	$+$
e_R^i	**1**	**1**	-1	-1	$+$
H	**1**	**2**	$+1/2$	0	$+$
Φ	**1**	**1**	0	$+2$	$+$

Table 1: Particle contents: In addition to the SM particles, three right-handed neutrinos, ν_R^1 and ν_R^j ($j = 2, 3$), and a complex scalar Φ are introduced. Under the global Z_2 parity, ν_R^1 is assigned to be odd, while the other particles are even. $i = 1, 2, 3$ is the generation index.

the $B - L$ symmetry breaking at the TeV scale. In Sec. 3, we analyze the relic abundance of the right-handed neutrino dark matter and identify the parameter region for reproducing the observed dark matter abundance. We also calculate the spin-independent scattering cross section between the dark matter particle and nucleon in Sec 4. The last section is devoted for summary.

2 The classically conformal $B - L$ extended SM

The minimal $B-L$ extended SM is based on the gauge group $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L}$. As has been discussed above, we introduce a global Z_2 parity in the model, and the particle contents are listed in Table 1. The three right-handed neutrinos ($\nu_R^k (k = 1, 2, 3)$) are necessarily introduced to cancel all the gauge and gravitational anomalies. Only the ν_R^1 is assigned to be odd under the Z_2 parity. The SM singlet scalar field (Φ) works to break the $\mathrm{U}(1)_{B-L}$ gauge symmetry by its vacuum expectation value (VEV), $\langle \Phi \rangle = v_{B-L}/\sqrt{2}$. Once the $B - L$ gauge symmetry is broken, the Z' boson acquires mass,

$$m_{Z'} = 2 g_{B-L} v_{B-L}, \tag{1}$$

where g_{B-L} is the $B-L$ gauge coupling constant. The LEP experiment has set the lower bound on the $B - L$ symmetry breaking scale as $v_{B-L} \gtrsim 3$ TeV [8]. Recent LHC results for Z' boson search with 1.1 fb^{-1} [9] excluded the $B - L$ Z' gauge boson mass $m_{Z'} \lesssim 1.5$ TeV [10] when the $B - L$ coupling is not too small. We see that the LEP bound is more severe than the LHC bound for $m_{Z'} \gtrsim 1.5$ TeV.

The Lagrangian relevant for the seesaw mechanism is given by

$$\mathcal{L} \supset -y_D^{ij}\overline{\nu_R^i}H\ell_L^j - \frac{1}{2}y_N^k\Phi\overline{\nu_R^{kc}}\nu_R^k + \text{h.c.}, \tag{2}$$

where without loss of generality, we work on the basis in which the second term is diagonalized and $y_N^k(k=1,2,3)$ is real and positive. The first term gives the neutrino Dirac mass matrix after the electroweak symmetry breaking. Note that because of Z_2 parity, ν_R^1 has no coupling with the lepton doublets and the neutrino Dirac mass matrix is 2 by 3. The right-handed neutrino Majorana masses are generated through the second term associated with the $B-L$ gauge symmetry breaking ($m_{N_i} = \frac{y_N^i}{\sqrt{2}}v_{B-L}$).

The $B-L$ symmetry breaking scale is determined by parameters in the (effective) Higgs potential and in general we can take any scale for it as long as the experimental constraints are satisfied. It has been pointed out in [3, 4] if we impose the classically conformal symmetry on the minimal $B-L$ model, the $B-L$ symmetry breaking is naturally realized at the TeV scale. Thus, the mass scale of all new particles are at the TeV scale or smaller.

Under the hypothesis of the classically conformal invariance of the model, the classical scalar potential is given by

$$V(H,\Phi) = \lambda_H \left(H^\dagger H\right)^2 + \lambda\left(\Phi^\dagger\Phi\right)^2 - \lambda'\left(\Phi^\dagger\Phi\right)\left(H^\dagger H\right). \tag{3}$$

Since there is no mass term in the Higgs potential, the symmetry should be broken radiatively through the Coleman-Weinberg (CW) mechanism [11]. Assuming a small λ', in which case the SM Higgs sector and the $B-L$ Higgs sector are approximately decoupled, the renormalization group (RG) improved effective potential for the $B-L$ sector gives the stationary condition [3],

$$\alpha_\lambda \simeq -\frac{6}{\pi}\left(\alpha_{B-L}^2 - \frac{1}{96}\sum_i\left(\alpha_N^i\right)^2\right), \tag{4}$$

where $\alpha_\lambda = \lambda/(4\pi)$, $\alpha_{B-L} = g_{B-L}^2/(4\pi)$ and $\alpha_N^i = \left(y_N^i\right)^2/(4\pi)$ are the RG running coupling evaluated at v_{B-L}. The mass of the SM singlet Higgs is given by

$$m_\phi^2 \simeq -16\pi\alpha_\lambda v_{B-L}^2 \simeq \frac{6}{\pi}\left(\alpha_{B-L} - \frac{1}{96}\frac{\sum_i(\alpha_N^i)^2}{\alpha_{B-L}}\right)m_{Z'}^2 \simeq \frac{6}{\pi}\alpha_{B-L}m_{Z'}^2 \tag{5}$$

Note that the $B-L$ symmetry breaking via the CW mechanism leads to the mass relation between the SM singlet Higgs and Z' boson.

Once v_{B-L} is generated, the SM Higgs doublet acquires a mass squared, $-\lambda' v_{B-L}^2$, so that the electroweak symmetry is broken for $\lambda' > 0$. The SM Higgs boson mass is given by

$$m_h^2 = \lambda' v_{B-L}^2 = 2\lambda_H v^2, \tag{6}$$

with $v = 246$ GeV, and the scalar mass matrix is found to be

$$\mathcal{M} = \begin{pmatrix} m_h^2 & -m_h^2 \left(\frac{v}{v_{B-L}}\right) \\ -m_h^2 \left(\frac{v}{v_{B-L}}\right) & m_\phi^2 \end{pmatrix}. \tag{7}$$

Thus the mixing angle to diagonalize the mass matrix is given by

$$\tan 2\theta = \frac{2m_h^2(v/v_{B-L})}{m_h^2 - 96\alpha_{B-L}^2 v_{B-L}^2}. \tag{8}$$

Using Eqs.(1) and (5), the mass matrix and the mixing angle are functions of three independent parameters, m_h, α_{B-L} and $m_{Z'}$. Except for the special case, $m_h^2 \simeq 96\alpha_{B-L}^2 v_{B-L}^2$, the mixing angle is always small because of the suppression by v/v_{B-L} with $v = 246$ GeV and $v_{B-L} \gtrsim 3$ TeV. Thus, one mass eigenstate is the SM-like Higgs boson while the other is the SM singlet-like Higgs boson.

There are theoretical constraints on α_{B-L} and $m_{Z'}$. First we require that the $B-L$ gauge coupling does not blow up below the Planck scale (M_{Pl}). Second, the Higgs boson mass can receive big quantum corrections at two loop diagrams involving top quark and Z' boson such as [3]

$$\Delta m_h^2 = \frac{8\alpha_{B-L} m_t^2 m_{Z'}^2}{(4\pi)^3 v^2} \log \frac{M_{Pl}^2}{m_{Z'}^2}. \tag{9}$$

Here we have used the Planck scale for the cutoff of the loop integral. In the naturalness point of view, this corrections should not exceed the electroweak scale and we obtain a stringent bound on Z' boson mass by imposing $\Delta m_h^2 \leq v/\sqrt{2}$, for example[1]. The allowed parameter region is depicted in Fig. 1. The upper region $\alpha \gtrsim 0.015$ is excluded by the condition of the $B-L$ gauge coupling blow-up. The left of the solid line (in blue) is excluded by the LEP experiment, $v_{B-L} \gtrsim 3$ TeV. The upper-right side of the solid line (in red) is disfavored by the naturalness condition of the electroweak scale. The future search reach of the Z' boson mass is also shown on the figure. The left of the dashed line can be explored in 5-σ significance at the LHC with $\sqrt{s}$=14 TeV and an integrated luminosity 100 fb^{-1} [12]. The left of the dotted line can be explored at the International Linear Collider with $\sqrt{s}$=1 TeV, assuming 1% accuracy [12]. The figure indicates that if the $B-L$ gauge coupling is of the same order as the SM gauge couplings, Z' boson mass appears around a few TeV.

[1]This argument is applicable to any new physics which couples with the SM Higgs doublet. In other words, under the hypothesis of the classically conformal invariance of the model we implicitly assume that none of new physics beyond our $B-L$ model takes place at a scale much higher than the TeV scale, except quantum gravity at the Planck scale.

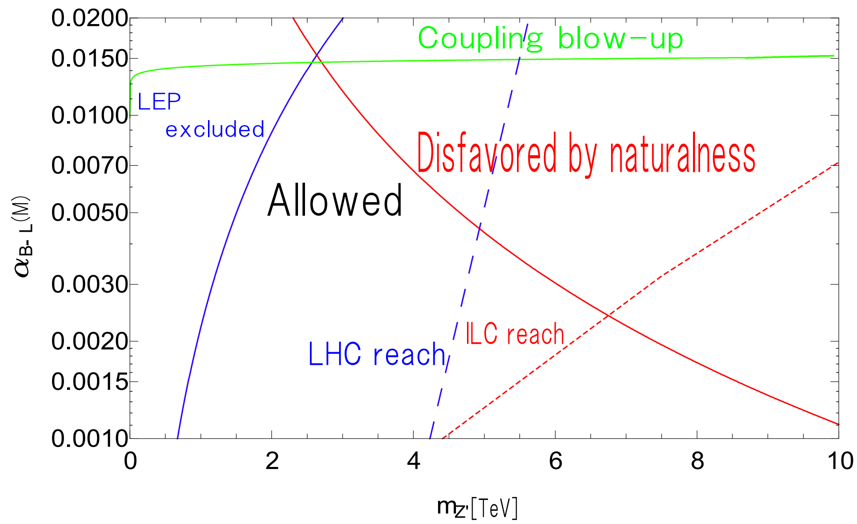

Figure 1: The allowed parameter region is drawn [4]. The upper region of the almost straight line (in green) is rejected by a requirement that the $B-L$ gauge coupling does not diverge up to the Planck scale. The upper-right side of the solid line (in red) is disfavored by the naturalness condition of the electroweak scale. The left of the solid line (in blue) has been already excluded by the LEP experiment, $v_{B-L} \gtrsim 3$ TeV. Recent LHC results for Z' boson search excluded the region $m_{Z'} \lesssim 1.5$ TeV [10]. The left of the dashed line can be explored in 5-σ significance at the LHC with $\sqrt{s}$=14 TeV and an integrated luminosity 100 fb^{-1}. The left of the dotted line can be explored at the ILC with $\sqrt{s}$=1 TeV, assuming 1% accuracy.

3 Relic density of right-handed neutrino dark matter

The Z_2-odd right-handed neutrino is stable and the dark matter candidate. In this section, we estimate its relic abundance and identify the model parameters to be consistent with the current observations. The dark matter particles annihilate into the SM particles through interactions with the Z' boson and the Higgs bosons. In practice, the annihilation processes are dominated by the s-channel mediated by the $B-L$ gauge boson and the Higgs bosons. All the general formulas of the annihilation cross sections necessary for our analysis are listed in Appendices of Ref. [7].

The Boltzmann equation of the right-handed neutrino dark matter is given by

$$\frac{dY_{N_1}}{dz} = -\frac{z\langle\sigma v\rangle s}{H(m_{N_1})}\left(Y_{N_1}^2 - Y_{N_1}^{eq2}\right), \tag{10}$$

where Y_{N_1} is the yield (the ratio of the number density to the entropy density s) of the right-handed neutrino dark matter, $Y_{N_1}^{eq}$ is the yield in thermal equilibrium, temperature of the universe is normalized by the mass of the right-handed neutrino $z = m_{N_1}/T$, $H(m_{N_1})$ is the Hubble parameter at $T = m_{N_1}$, and $\langle\sigma v\rangle$ is the thermal averaged product of the annihilation

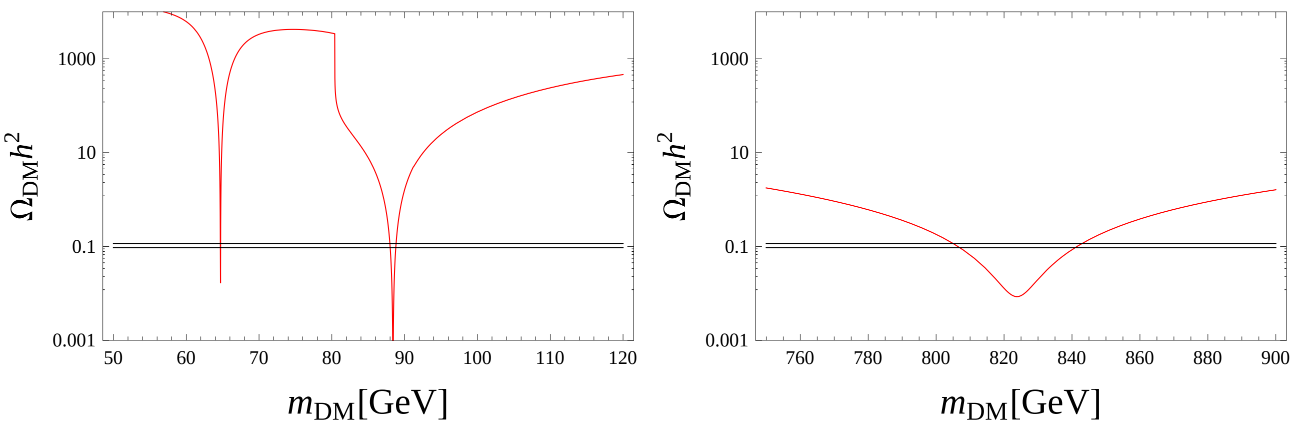

Figure 2: The thermal relic density of the right-handed neutrino dark matter as a function of its mass. The left panel corresponds to the Higgs resonance regions while the right panel to the Z' resonance region.

cross section and the relative velocity. The density parameter of the dark matter particle is written as

$$\Omega_{DM}h^2 = \frac{m_{N_1} s_0 Y_{N_1}(\infty)}{\rho_c/h^2}, \tag{11}$$

where $Y_{N_1}(\infty)$ is the asymptotic value of the yield, $s_0 = 2890\text{cm}^{-3}$ is the entropy density of the present universe, and $\rho_c/h^2 = 1.05 \times 10^{-5}\text{GeV cm}^{-3}$ is the critical density. The thermal relic abundance of the dark matter is approximately given by

$$\Omega_{DM}h^2 = 1.1 \times 10^9 \frac{m_{N_1}/T_d}{\sqrt{g_*} M_{Pl} \langle \sigma v \rangle}, \tag{12}$$

where g_* is the total number of relativistic degrees of freedom, and T_d is the decoupling temperature.

There are six free parameters involved in our analysis: $m_h, \alpha_{B-L}, m_{z'}, m_{N_1}, m_{N_2}, m_{N_3}$. For simplicity, we fix three of them as follows:

$$m_h = 130 \text{ GeV}, \quad m_{N_2} = m_{N_3} = 2 \text{ TeV}. \tag{13}$$

Note that finely degenerate masses for the two Z_2-even right-handed neutrinos are necessary for the successful baryogenesis via resonant leptogenesis [6]. Then, we have only three free parameters left, namely, α_{B-L}, $m_{Z'}$ and $m_{N_1} = m_{DM}$ being the dark matter mass. As we have discussed in the previous section, α_{B-L} and $m_{Z'}$ are constrained as depicted in Fig. 1. In the following analysis, we show our results along three lines in Fig. 1: the "LEP line" due to the constraint $v_{B-L} = 3$, the "Naturalness line" and the "LHC line" corresponding to the LHC search reach. Along these lines, α_{B-L} is given as a function of $m_{Z'}$, so that we show our results in terms of only two free parameters, $m_{Z'}$ and m_{DM}.

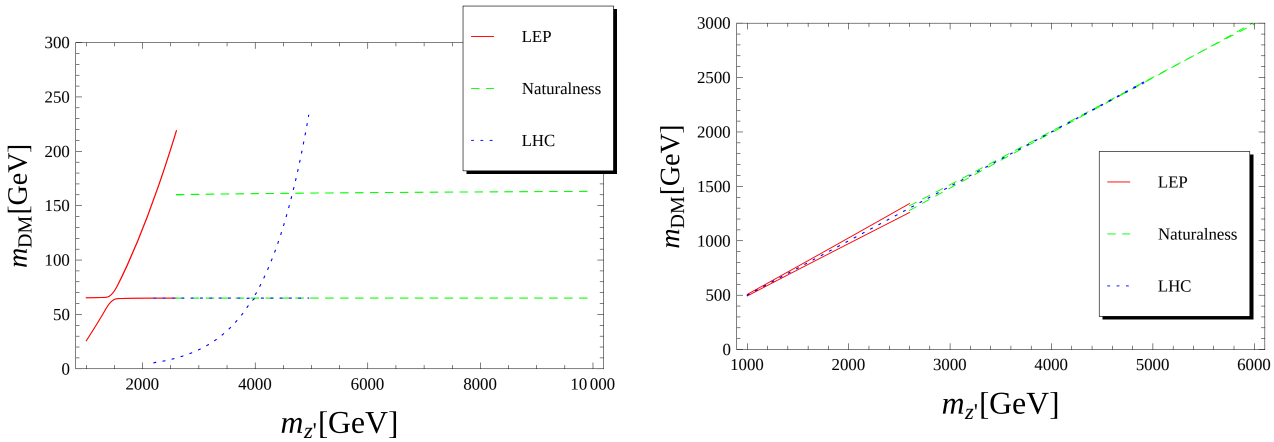

Figure 3: The dark matter mass as a function of Z' boson mass. The left panel shows the results when the dark matter mass is close to half of Higgs masses, while the right panel corresponds to the case with the dark matter mass being close to half of the Z' boson mass. The solid, dashed and dotted lines correspond to the LEP, Naturalness and LHC lines, respectively.

Fig. 2 shows the resultant relic density $\Omega_{DM}h^2$ as a function of the dark matter mass for fixed values of $\alpha_{B-L} = 0.006$ and $m_{Z'} = 1.65$ TeV (on the LEP line), along with the observed values at 2-σ level [13]

$$\Omega_{DM}^{obs}h^2 = 0.1120 \pm 0.0056. \tag{14}$$

We find that the observed relic abundance can be achieved only if the dark matter mass is very close to the resonance point of the s-channel annihilation process mediated by either the SM-like Higgs boson, the SM singlet-like Higgs boson or the Z' boson.

Along the three lines, we determine the dark matter mass by comparing it with the observed relic abundance. The results are shown in Fig. 3 as a function of the Z' boson mass. The left panel shows the solution when the dark matter mass is close to the Higgs resonance points, while to the Z' boson resonance point in the right panel. The solid, dashed and dotted lines correspond to the LEP, Naturalness and LHC lines, respectively. As can be seen in Fig. 2, there are two solutions corresponding to each the resonance point, but they are well-overlapped and not distinguishable for most of lines in Fig. 3. Along the Naturalness line in the left panel, Higgs boson masses are almost constant as can be understood from Eqs. (5) and (9).

4 Direct detection of dark matter

A variety of experiments are underway and also planned to detect a dark matter particle directly or indirectly, through the elastic scattering of dark matter particle off with nuclei. The right-handed neutrino dark matter in our model couples with quarks in two ways. One is through

Higgs bosons, the other is via Z' boson exchange. Because of its Majorana nature, the dark matter particle has the axial vector coupling with the Z' boson, while the quarks have the vector coupling. As a result, there is no contribution from the Z' boson exchange in the non-relativistic limit. Therefore, we consider only the spin-independent elastic scattering process via Higgs boson exchange.

The spin-independent dark matter-proton cross section is given by

$$\sigma_{SI}^{(p)} = \frac{4}{\pi}\left(\frac{m_p m_N}{m_p + m_N}\right)^2 f_p^2, \tag{15}$$

with the hadronic matrix element

$$\frac{f_p}{m_p} = \sum_{q=u,d,s} f_{Tq}\frac{\alpha_q}{m_q} + \frac{2}{27} f_{TG} \sum_{q=c,b,t} \frac{\alpha_q}{m_q}, \tag{16}$$

and the effective vertex

$$\alpha_q = -\frac{y_N^1 y_q}{4} \sin 2\theta \left(\frac{1}{M_H^2} - \frac{1}{M_\Phi^2}\right), \tag{17}$$

where m_q is a mass of a quark with a Yukawa coupling y_q, and $M_H(M_\Phi)$ is the mass eigenvalue of the SM-like (SM singlet-like) Higgs boson. The parameter f_{Tq} has recently been evaluated accurately by the lattice QCD simulation using the overlap fermion formulation. The result of the simulation has shown that $f_{Tu} + f_{Td} \simeq 0.056$ and $|f_{Ts}| \leq 0.08$ [14]. On the other hand, the parameter f_{TG} is obtained by f_{Tq} through the trace anomaly, $1 = f_{Tu} + f_{Td} + f_{Ts} + f_{TG}$ [15]. For conservative analysis, we take $f_{Ts} = 0$.

The results for the spin-independent cross sections are depicted in Fig. 4. The top-left (top-right) panel shows the cross sections along the LEP, Naturalness and LHC lines for the case with $m_{DM} \sim M_H/2$ ($m_{DM} \sim M_\Phi/2$). The resultant cross section is found to be far below the current limits reported by XENON100 [16]: $\sigma_{SI} \lesssim 10^{-8} - 10^{-7}$ pb, for a dark matter mass of 100 GeV$-$1 TeV. The result for the case with $m_{DM} \sim m_{Z'}/2$ is depicted in the bottom panel. The cross section found in this case is relatively higher but yet below the current limit. The cross section is enhanced around $m_{Z'} = 4$ TeV where the mixing angle becomes maximum. In future experiments such as XENON1T [17] the search limit can be as low as $\sigma_{SI} = 10^{-11} - 10^{-10}$ pb and the region $m_{Z'} \lesssim 3$ TeV in the bottom panel can be tested.

5 Summary

Gauged $B - L$ extension of the Standard Model is a very simple and elegant way to account for the mass and flavor mixing of neutrinos. Three right-handed neutrinos are introduced

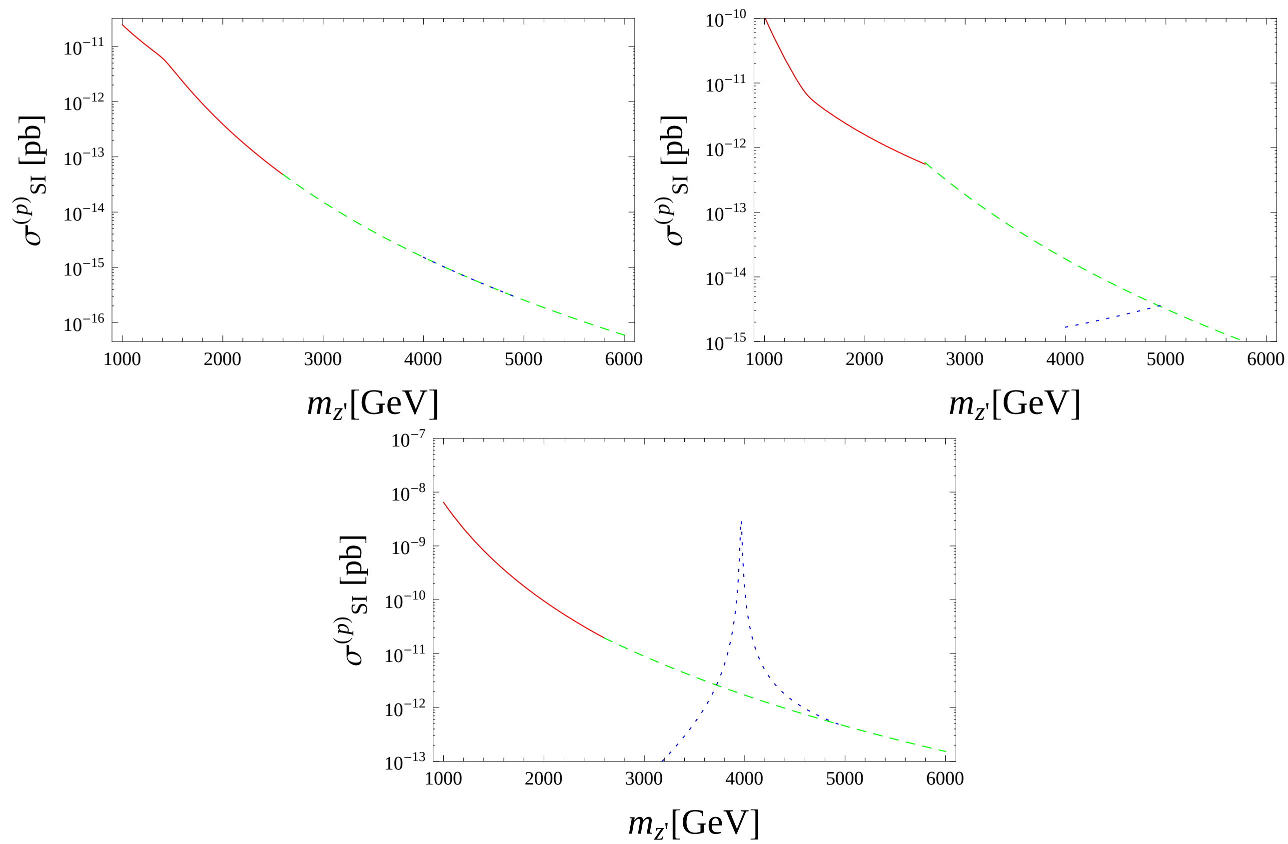

Figure 4: The spin-independent cross sections as a function of Z' boson mass. The top-left panel shows the case of $m_{DM} \sim M_H/2$, the top-right panel is for the case of $M_{DM} \sim M_\Phi/2$, and the case for $M_{DM} \sim m_{Z'}/2$ is shown in the bottom panel. The (red) solid lines, the (green) dashed lines and the (blue) dotted lines correspond to the LEP line, Naturalness line and LHC line, respectively.

to make the model free from the gauge and gravitational anomalies. Associated with the $B - L$ gauge symmetry breaking, the right-handed neutrinos acquire the Majorana mass, and after the electroweak symmetry breaking the light neutrino masses are generated through the seesaw mechanism. The scale of the $B - L$ gauge symmetry breaking is arbitrary as long as phenomenological constraints are satisfied.

We have introduced the classically conformal invariance of the model, which forbids the mass terms for the Standard Model Higgs doublets and the SM singlet $B - L$ Higgs field. In this system, the $B - L$ gauge symmetry is radiatively broken via the CW mechanism, which triggers the electroweak symmetry breaking by generating the negative mass squared for the SM Higgs doublet. The naturalness argument constrains the model parameter space and we find the $B - L$ symmetry breaking scale to be the TeV scale if the $B - L$ gauge coupling is of the same order of the SM gauge couplings. Therefore, all new particles in the model, Z' gauge boson, right-handed neutrinos and $B-L$ Higgs boson, have masses around TeV or smaller and they can be discovered at the LHC.

We have investigated cosmological aspects of the model, in particular, the dark matter issue. We have introduced a Z_2 parity under which one right-handed neutrino is odd and the other particles are even. In this way, the Z_2-odd right-handed neutrino becomes the candidate for the dark matter, without introducing any new particles into the model. Through the seesaw mechanism, the other two right-handed neutrinos play the role of realizing the observed neutrino oscillation data. In this concise setup, we have calculated the relic abundance of the dark matter. It has been found that the observed abundance can be reproduced through the annihilation processes of the dark matter particles enhanced by resonances of either the SM Higgs boson, $B-L$ Higgs boson or Z' gauge boson. As a result, the dark matter masses are almost fixed to be half of the mass of either resonant states.

The classically conformal invariance and the $B-L$ symmetry breaking via the CW mechanism lead to a relation between model parameters, namely, Higgs boson masses, Z' boson mass and the dark matter mass are all related. We have identified the mass region to be consistent with the experimental constraints. We have also calculated the spin-independent cross section of the dark matter elastic scattering off with nuclei. The resultant cross section is found to be consistent with the current limit by the direct dark matter detection experiments. The parameter region can be tested in part by the future experiments.

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