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# SU(2)$_L\times$SU(2)$_R$ minimal dark matter with simplified Higgs sector

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We discuss the minimal dark matter models in the left-right symmetric extensions of the standard model (SM) where the simplified Higgs sector contains only SU(2)$_R$ doublet and SU(2)$_L\times$SU(2)$_R$ bidoublet. As a possible dark matter candidate, SU(2)$_R$ quintuplet fermions are considered in the framework of minimal dark matter where $B-L$ charges are taken as 0, 2 and 4. Then we show the analysis of dark matter phenomenology such as relic density and dark matter-nucleon scattering cross section. The collider physics of the model is also discussed.

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## 1. Introduction

The Standard Model (SM) has been successful to explain various experimental data for particle physics phenomena up to a few TeV scale. Still there are many mysterious issues which can not be described by the SM such that neutrino masses and mixings, nonbaryonic dark matter (DM), matter-antimatter asymmetry and so on. Thus it is interesting to explore an extension of the SM.

A left-right (LR) symmetric model is the one of the interesting extension of the gauge sector. In these models, the electroweak gauge symmetry is extended to $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ and the right-handed fermions form $\mathrm{SU}(2)_R$ doublets [1, 2, 3, 4, 5, 6]. The canonical structure of the LR model adopts the exact left-right symmetry with the Higgs sector as follows; $\mathrm{SU}(2)_L$ triplet $\Delta_L$, $\mathrm{SU}(2)_R$ triplet $\Delta_R$ and $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$ bidoublet $\phi$. The LR gauge symmetry is then spontaneously broken into $\mathrm{U}(1)_{em}$ by VEVs of $\Delta_R$ and $\phi$.

The exact LR symmetry can be loosened. The $\mathrm{SU}(2)_L$ and $\mathrm{SU}(2)_R$ gauge couplings could be different even at high energy scale and only VEVs of $\mathrm{SU}(2)_R$ doublet $H_R$ and a bidoublet $\phi$ can break the gauge symmetry. In fact, this simpler setup including $\mathrm{SU}(2)_L$ doublet Higgs has been discussed in Ref. [7] where the authors focused on he ATLAS 2 TeV diboson excess [8] where a moderate excess is also found by CMS [9, 10], in terms of 2 TeV $W'$ boson.

In the following, we review the minimal DM model based on the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ extension with simplified Higgs sector containing a bidoublet and $\mathrm{SU}(2)_R$ doublet [11]. Note that minimal DM in the exact left-right symmetric case is discussed in Ref. [12, 13], which provide qualitatively different phenomenology of DM compared to our model. We explore possible DM candidate and discuss DM phenomenology of our model.

## 2. The model

Here we recapitulate the model provided in Ref. [11] which is left-right extension of the SM applying the gauge symmetry $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ where $B$ and $L$ are baryon and lepton numbers respectively [1, 2, 3, 4, 5, 6]. The scalar contents are taken to be

$$H : (2, \bar{2}, 0), \quad H_R : (1, 2, 1) \tag{2.1}$$

where the numbers in parenthesis indicate the representations under the $\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ omitting SU(3) for simplicity. Note that we have loosened the exact left-right symmetry adopting more simplified choice of the scalar contents in order to break the gauge symmetry. The fermion contents of the model are also given by

$$q_L : (2, 1, 1/3), \quad q_R : (1, 2, 1/3), \quad \ell_L : (2, 1, -1), \quad \ell_R : (1, 2, -1), \quad S : (1, 1, 0). \tag{2.2}$$

Here Majorana fermion $S$ is introduced in order to induce inverse seesaw mechanism [14, 15, 16].

The gauge symmetry is broken when $H$ and $H_R$ develop non-zero vacuum expectation value(VEV). The VEVs of the scalar fields are assumed to be

$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \langle H_R \rangle = \begin{pmatrix} 0 \\ v_R/\sqrt{2} \end{pmatrix}. \tag{2.3}$$

After the spontaneous symmetry breaking of $\mathrm{SU(2)}_L\times\mathrm{SU(2)}_R\times\mathrm{U(1)}_{B-L}\to\mathrm{U(1)}_{em}$, electric charge $Q$ is given by

$$Q = T^3_L + T^3_R + \frac{1}{2}Q_{B-L} \tag{2.4}$$

where $T^3_{L(R)}$ and $Q_{B-L}$ are the diagonal generator of $\mathrm{SU(2)}_{L(R)}$ and the $B-L$ value for each field, respectively. In this model, we have gauge fields $W^\mu_{iL(R)}$ (i=1,2,3) and $X^\mu$ associated with $\mathrm{SU(2)}_{L(R)}$ and $\mathrm{U(1)}_{B-L}$ gauge symmetries. The mass eigenstate for charged and neutral gauge bosons are given by [17]

$$\begin{pmatrix} W^\pm_L \\ W^\pm_R \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} W^\pm \\ W'^\pm \end{pmatrix}, \tag{2.5}$$

$$\begin{pmatrix} W_{3L} \\ W_{3R} \\ X \end{pmatrix} = \begin{pmatrix} c_W c_X & c_W s_X & s_W \\ -s_W s_M c_X - c_M s_X & -s_W s_M s_X + c_M c_X & c_W s_M \\ -s_W c_M c_X + s_M s_X & -s_W c_M s_X - s_M c_X & c_W c_M \end{pmatrix} \begin{pmatrix} Z \\ Z' \\ A \end{pmatrix}, \tag{2.6}$$

where $W^\pm_{L(R)} = (W_{1L(R)} \mp W_{2L(R)})/\sqrt{2}$, $s_W(c_W) = \sin\theta_W(\cos\theta_W)$ with the Weinberg angle $\theta_W$, $s_M \equiv \sin\theta_M = g_{B-L}/\sqrt{g_R^2+g_{B-L}^2}$, $c_M \equiv \cos\theta_M = g_R/\sqrt{g_R^2+g_{B-L}^2}$, and $s_X(c_X) = \sin\theta_X(\cos\theta_X)$ is associated with mixing of massive neutral gauge bosons. The mixing angles $\xi$ and $\theta_X$ are assumed to be negligibly small and will be ignored in the following discussions. We obtain the relations among gauge couplings such that $g_R = e/(s_M c_W)$ and $g_{B-L} = e/(c_W c_M)$ where the $c_M$ and $s_M$ can be rewritten as

$$s_M = \tan\theta_W \left(\frac{g_R}{g_L}\right)^{-1}, \quad c_M = \left(\frac{g_R}{g_L}\right)^{-1} \sqrt{\left(\frac{g_R}{g_L}\right)^2 - \tan^2\theta_W}\,. \tag{2.7}$$

Note that the gauge coupling should satisfy $g_R/g_L > \tan\theta_W$ for consistency. Assuming $K \equiv \sqrt{k_1^2+k_2^2} \ll v_R$, the masses of new gauge bosons are approximately

$$m^2_{W'} \simeq \frac{1}{4} g_R^2 v_R^2 \left(1 + \frac{K^2}{v_R^2}\right), \tag{2.8}$$

$$m^2_{Z'} \simeq \frac{1}{4}(g_R^2 + g_{B-L}^2) v_R^2 \left(1 + \frac{K^2 c_M^2}{v_R^2}\right). \tag{2.9}$$

Thus we find the relation between $Z'$ and $W'$ masses as

$$\frac{m_{Z'}}{m_{W'}} \simeq \frac{g_R/g_L}{\sqrt{(g_R/g_L)^2 - \tan^2\theta_W}}\,. \tag{2.10}$$

In the model, we introduce a $\mathrm{SU(2)}_R$ quintuplet fermion as a candidate of DM based on the idea of minimal dark matter [18]. The quintuplet fermion does not have interaction leading its decay up to dimension-6 operator level and the lightest component can be stable in cosmological time-scale. Thus if the lightest component is neutral it can be a dark matter candidate.

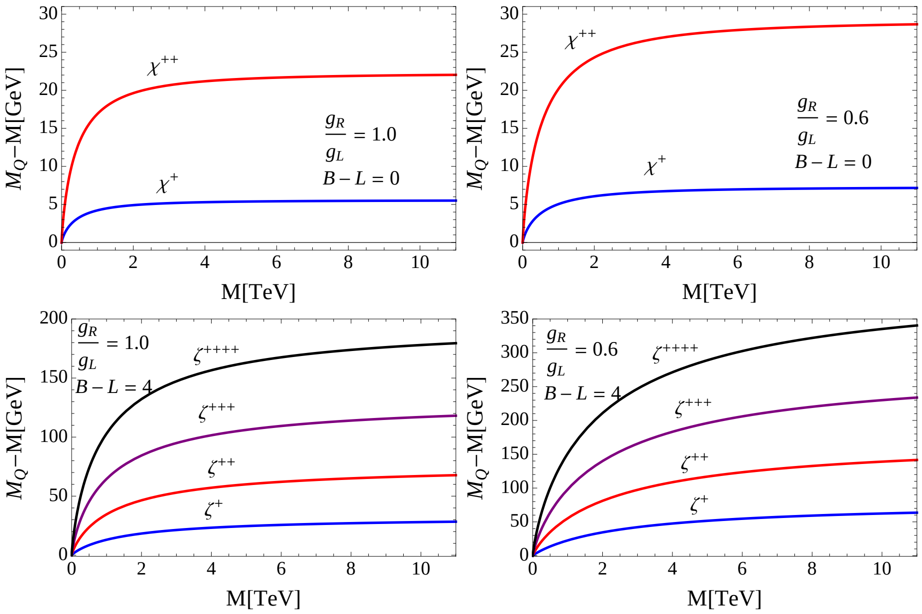


**Figure 1:** Mass difference between neutral and charged components of SU(2)$_R$ quintuplet where $B-L = \{0,4\}$ and $g_R/g_L = \{1, 0.6\}$.

## 3. Dark matter phenomenology

In our analysis, we focus on SU(2)$_R$ quintuplets $\Psi^{Q_{B-L}}$ whose electrically neutral component provides a DM candidate. To obtain neutral component, possible values of $Q_{B-L}$ are 0, 2 and 4. The corresponding multiplets are denoted as

$$\Psi^0 = (\chi^{++}, \chi^{+}, \chi^{0}, \chi^{-}\chi^{--})^T, \quad \Psi^2 = (\eta^{+++}, \eta^{++}, \eta_1^{+}, \eta^{0}, \eta_2^{-})^T,$$
$$\Psi^4 = (\zeta^{++++}, \zeta^{+++}, \zeta^{++}, \zeta^{+}, \zeta^{0})^T. \tag{3.1}$$

where subscripts "+" etc. indicate electric charge of each component, and $\chi^0$ is Majorana fermion while the others are Dirac fermion.

For a component $\psi^Q$ ($\psi = \chi, \eta, \zeta$), gauge interactions associated with mass eigenstates of the gauge bosons can be written by

$$L \supset -s_W s_M g_R Q \bar{\psi}^Q Z^\mu \gamma_\mu \psi^Q + c_M g_R \left( Q - \frac{Q_{B-L}}{2c_M^2} \right) \bar{\psi}^Q Z'^\mu \gamma_\mu \psi^Q$$
$$+ c_W s_M g_R Q \bar{\psi}^Q A^\mu \gamma_\mu \psi^Q + \frac{g_R}{\sqrt{2}} (c_{2m} \bar{\psi}^{Q+1} W'^{+\mu} \gamma_\mu \psi^Q + h.c.), \tag{3.2}$$

where $c_{2m} = \sqrt{(2+m+1)(2-m)}$ with $m = Q - Q_{B-L}/2$.

Here we discuss the mass splitting between charged components and the neutral component in a given multiplet. The mass splitting can be obtained by calculating radiative correction where the

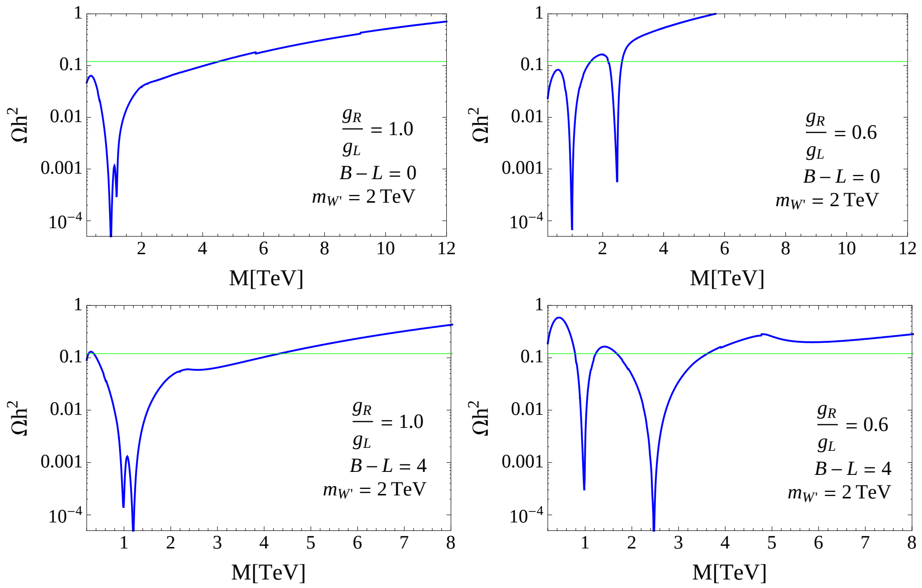


**Figure 2:** Relic density $\Omega h^2$ for SU(2)$_R$ quintuplet DM (fermion) with $B-L=0$ and 4 where the left(right) panel shows $g_R/g_L = 1.0(0.6)$.

gauge bosons propagate inside loop diagrams. The formula of the mass splitting can be written by

$$M_Q - M_0 \simeq \frac{g_R^2}{(4\pi)^2} M[Q(Q-Q_{B-L})f(r_{W'}) - c_M^2 Q\{Q - Q_{B-L}/c_M^2\}f(r_{Z'}) \\ - s_W^2 s_M^2 Q^2 f(r_Z) - c_W^2 s_M^2 Q^2 f(r_\gamma)] \tag{3.3}$$

where $Q$ is electric charge, $r_X = m_X/M$ and $f(r) \equiv 2\int_0^1 dx(1+x)\log[x^2+(1-x)r^2]$. In Fig. 1, we show the mass difference $M_Q - M$ for $m_{W'} = 2$ TeV and $g_R/g_L = 1.0(0.6)$ where $M_Q$ and $M$ are masses of component with charge $Q$ and DM. We find that $M_Q - M$ is always positive for $Q_{B-L} = 0$, which is qualitatively different from Ref. [12] where the $M_Q - M$ becomes negative when DM mass $M$ is larger than ∼1.8(4.5) TeV for $m_{W'} = 2(5)$ TeV. This difference is understood from mass relation between $m_{Z'}$ and $m_{W'}$; the ratio $m_{Z'}/m_{W'}$ is smaller in our case when the same $g_R/g_L$ value is applied. For the $Q_{B-L} = 2$ multiplet, the second singly charged component $\eta_2^-$ becomes the lightest component for $M \gtrsim 1(0.6)$ TeV. We find that the light relic density can not be obtained when the neutral component is lightest and we omit the figure for the $Q_{B-L}$ case. The $Q_{B-L} = 4$ multiplet also induce positive $M_Q - M$ for all $M$ value and the mass splitting is larger than the case of $Q_{B-L} = 0$.

We estimate thermal relic density of DM using `micrOMEGAs 4.1.5` [19] to solve the Boltzmann equation by implementing relevant interactions in Eq. (3.2) inducing (co)annihilation processes of DM. The estimated relic density is shown by blue lines in Fig. 2 for $Q_{B-L} = 0$ and 4 with $m_{W'} = 2$ TeV; the left(right) panels correspond to $g_R/g_L = 1.0(0.6)$. These estimation are compared to the value measured by Planck [20], $\Omega h^2 = 0.1199 \pm 0.0027$, which is indicated by green horizontal line in the plots. For $M \sim m_{W'}/2$ and $M \sim m_{Z'}/2$, we see resonant effect where (co)annihilation cross sections become large decreasing relic density. The relic density tends to larger for smaller $g_R/g_L$ since the (co)annihilation cross section is suppressed by following effects: (1) the heavier $Z'$ for the smaller value of $g_R/g_L$, and (2) the gauge coupling $g_R$ is smaller compared with $g_L$. We also find that $Q_{B-L} = 4$ multiplet provides larger relic density than $Q_{B-L} = 0$ multiplet since (a) DM is Dirac fermion for $Q_{B-L} = 4$ (b) larger mass splitting suppress the coannihilation process. The masses of DM providing observed relic density are summarized in third column of Table. 1. We note that SU(2)$_R$ quintuplet can provide observed relic density with $m_{W'} = 2$ TeV. Furthermore, when we apply $g_R/g_L = 0.6$ the required mass of DM can be as light as $\mathscr{O}(1)$ TeV which is light compared to SU(2)$_L$ quintuplet in MDM model [21].

For $Q_{B-L} \neq 0$ multiplets, DM can interact with nucleon through $Z'$ boson exchange. We obtain the DM-$Z'$ coupling from Eq. (3.2) where $Z'$ couples to right-handed $u$- and $d$-type quark currents with couplings $c_M g_R(2/3-1/(6c_M^2))$ and $c_M g_R(-1/3-1/(6c_M^2))$ respectively. Then DM-nucleon scattering cross section is estimated for $\zeta^0$ to investigate constraint from DM direct detection experiment. The spin independent elastic scattering cross section of DM and nucleon $N$ is given by

$$\sigma_{\zeta^0 N} \simeq \frac{4g_R^2 g_{NNZ'}^2}{\pi c_M^2} \frac{1}{m_{Z'}^4} \frac{m_N^2 M^2}{(m_N+M)^2} \tag{3.4}$$

where $g_{ppZ'} = c_M g_R(1/2-1/(4c_M^2))$, $g_{nnZ'} = -g_R/(4c_M)$ and $m_N$ is nucleon mass. The cross section is almost independent of DM mass since our DM is much heavier than nucleon. We find that the cross sections averaged by nucleon, $(\sigma_{\zeta^0 p} + \sigma_{\zeta^0 n})/2$, are estimated as $6.8 \times 10^{-44}$cm$^2$ and $1.1 \times 10^{-44}$cm$^2$ for $g_R/g_L = 1.0$ and 0.6 respectively. These values are compared to current constraint given by LUX experiment [22] where we listed the upper limits in seventh column of Table. 1 for each DM mass. Thus the cases of $g_R/g_L = 1.0$ and of $g_R/g_L = 0.6$ with $M \lesssim 1$TeV are excluded unless there is a cancellation mechanism to suppress DM-Nucleon scattering while that of $g_R/g_L = 0.6$ with $M \gtrsim 1$ TeV are allowed. Interestingly, the scattering cross sections for proton and neutron are evidently different as summarized in sixth column of Table. 1. For the case of

**Table 1:** DM mass with observed relic density $\Omega h^2 = 0.1199$, mass difference $M_Q - M$, cross section for $pp \to \psi^Q \psi^{Q'}$ at 13(14) TeV where $\psi^Q \psi^{Q'}$ includes all possible combination including charged component, $\sigma_{\rm DM-N}$ denotes a DM-nucleon scattering cross section where the value outside(inside) bracket is for proton(neutron), and $\sigma_{\rm Lux}$ is current limit by Lux [22].

| $B-L$ | $g_R/g_R$ | $m_{DM}$[TeV] | $\Delta M$[GeV] | $\sigma_{\psi^Q\psi^{Q'}}$[fb] | $\sigma_{\rm DM-N}$[cm$^2$] | $\sigma_{\rm Lux}$[cm$^2$] |
|---|---|---|---|---|---|---|
| 0 | 1 | 4.54 | 5.34 | $\ll 10^{-2}$ | $\ll 10^{-45}$ | $\sim 57. \times 10^{-45}$ |
| 0 | 0.6 | 1.61 | 5.79 | 0.11(0.18) | $\ll 10^{-45}$ | $\sim 18. \times 10^{-45}$ |
| | | 2.18 | 6.18 | 0.034(0.069) | $\ll 10^{-45}$ | $\sim 26. \times 10^{-45}$ |
| | | 2.64 | 6.39 | $\ll 10^{-2}$ | $\ll 10^{-45}$ | $\sim 30. \times 10^{-45}$ |
| 4 | 1 | 0.244 | 5.07 | 2010(2380) | $1.9(12.) \times 10^{-44}$ | $\sim 3.1 \times 10^{-45}$ |
| | | 0.356 | 6.71 | 1420(1740) | $1.9(12.) \times 10^{-44}$ | $\sim 4.3 \times 10^{-45}$ |
| | | 4.32 | 23.7 | $\ll 10^{-2}$ | $1.9(12.) \times 10^{-44}$ | $\sim 52. \times 10^{-45}$ |
| 4 | 0.6 | 0.785 | 19.1 | 371.(460) | $6.8(15.) \times 10^{-45}$ | $\sim 8.9 \times 10^{-45}$ |
| | | 1.23 | 25.9 | 1.44(2.05) | $6.8(15.) \times 10^{-45}$ | $\sim 14. \times 10^{-45}$ |
| | | 1.66 | 31.1 | 0.173(0.298) | $6.8(15.) \times 10^{-45}$ | $\sim 19. \times 10^{-45}$ |
| | | 3.62 | 45.7 | $\ll 10^{-2}$ | $6.8(15.) \times 10^{-45}$ | $\sim 45. \times 10^{-45}$ |



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$Q_{B-L} = 0$, DM interacts with nucleon at one-loop level exchanging $W'$ boson providing scattering cross section much smaller than the current constraint.

The scalar particles in SU(2)$_R$ quintuplet can be produced at the LHC such that $pp \to V \to \bar{\psi}^Q \psi^{Q'}$ where $V$ can be $\gamma$, $Z$, $W'$ or $Z'$ according to interactions in Eq. (3.2). Here we focus on the production processes which include charged components; $pp \to \bar{\psi}^Q \psi^Q$, $pp \to \bar{\psi}^Q \psi^{Q\pm1}$, and $pp \to \bar{\psi}^\pm \psi^0$ where $\psi = \chi, \eta$ and $Q \neq 0$. The production cross section is numerically calculated by CalcHEP [23] utilizing the code with `CTEQ6L` PDF [24] for $\sqrt{s} = 13$ and 14 TeV. In 5th column of Table. 1, we listed the production cross sections for each DM masses providing right relic density where all production modes are summed over. We can obtain cross sections which can be larger than 0.1 fb for $M \lesssim 2$ TeV which would be within reach of the LHC.

The decay patterns of charged scalars are given by $\psi^Q \to \psi^{Q\mp1} M^\pm (M^\pm = \pi^\pm, K^\pm, \text{etc.})$ and $\chi^Q \to \chi^{Q\mp1} \bar{q}' q$ where off-shell $W'$ converts into $M^\pm$ and light quarks $\bar{q}' q$ assuming heavy right-handed neutrinos. In our case, $\psi^Q \to \psi^{Q\mp1} \bar{q}' q$ provide dominant contribution of decay width which is given by

$$\Gamma(\psi^Q \to \psi^{Q-1} \bar{q}' q) \simeq N_c c_{2m}^2 \frac{g_R^4}{120\pi^3} \frac{\Delta M^5}{m_{W'}^4} \tag{3.5}$$

where $Q$ is taken to be positive here. We find that the lifetime of the charged components are less than $1\text{cm}/c$. Thus they would decay within the non-detector region and the signal of quintuplet production is "jets + missing $E_T$" in our case.

## 4. Summary

We have reviewed a DM model with SU(2)$_L$×SU(2)$_R$×U(1)$_{B-L}$ gauge symmetry where the Higgs sector is simplified compared to exact LR symmetric case. The Higgs sector contains an SU(2)$_R$ doublet and an SU(2)$_L$×SU(2)$_R$ bidoublet and their VEVs break the gauge symmetry. Then we introduced a new fermion which is SU(2)$_R$ quintuplet as DM candidate based on the idea of minimal dark matter.

As a new candidate of DM, we focused on SU(2)$_R$ quintuplet with $B-L = 0$, 2 and 4, and discussed phenomenology of the DM. We investigated mass splitting between neutral and charged components, relic density of DM, and DM-nucleon scattering cross section. Then we have shown that $B-L = 0$ and 4 cases provide DM which can satisfy experimental constraints while $B-L = 2$ case is not suitable since charged particle tends to stable particle. The collider physics is also discussed and we obtain 0.1 fb to 2.1 fb production cross section for charged components when we obtain right DM relic density.

## References

[1] R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 2558 (1975).

[2] J. C. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974) [Phys. Rev. D **11**, 703 (1975)].

[3] G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975).

[4] G. Senjanovic, Nucl. Phys. B **153**, 334 (1979).

[5] R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).

[6] R. N. Mohapatra and G. Senjanovic, Phys. Rev. D **23**, 165 (1981).

[7] F. F. Deppisch, L. Graf, S. Kulkarni, S. Patra, W. Rodejohann, N. Sahu and U. Sarkar, arXiv:1508.05940 [hep-ph].

[8] G. Aad *et al.* [ATLAS Collaboration], arXiv:1506.00962 [hep-ex].

[9] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1408**, 173 (2014) [arXiv:1405.1994 [hep-ex]].

[10] V. Khachatryan *et al.* [CMS Collaboration], JHEP **1408**, 174 (2014) [arXiv:1405.3447 [hep-ex]].

[11] P. Ko and T. Nomura, Phys. Lett. B **753**, 612 (2016) [arXiv:1510.07872 [hep-ph]].

[12] J. Heeck and S. Patra, Phys. Rev. Lett. **115**, no. 12, 121804 (2015) [arXiv:1507.01584 [hep-ph]].

[13] C. Garcia-Cely and J. Heeck, JCAP **1603**, 021 (2016) [arXiv:1512.03332 [hep-ph]].

[14] D. Wyler and L. Wolfenstein, Nucl. Phys. B **218**, 205 (1983).

[15] R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D **34**, 1642 (1986).

[16] M. C. Gonzalez-Garcia and J. W. F. Valle, Phys. Lett. B **216**, 360 (1989).

[17] P. Duka, J. Gluza and M. Zralek, Annals Phys. **280**, 336 (2000) [hep-ph/9910279].

[18] M. Cirelli, N. Fornengo and A. Strumia, Nucl. Phys. B **753**, 178 (2006) [hep-ph/0512090].

[19] G. Belanger, F. Boudjema, A. Pukhov and A. Semenov, arXiv:1407.6129 [hep-ph].

[20] P. A. R. Ade *et al.* [Planck Collaboration], Astron. Astrophys. **571**, A15 (2014) [arXiv:1303.5075 [astro-ph.CO]].

[21] M. Cirelli, A. Strumia and M. Tamburini, Nucl. Phys. B **787**, 152 (2007) [arXiv:0706.4071 [hep-ph]].

[22] D. S. Akerib *et al.* [LUX Collaboration], Phys. Rev. Lett. **112**, 091303 (2014) [arXiv:1310.8214 [astro-ph.CO]].

[23] A. Belyaev, N. D. Christensen and A. Pukhov, Comput. Phys. Commun. **184**, 1729 (2013) [arXiv:1207.6082 [hep-ph]].

[24] P. M. Nadolsky, H. L. Lai, Q. H. Cao, J. Huston, J. Pumplin, D. Stump, W. K. Tung and C.-P. Yuan, Phys. Rev. D **78**, 013004 (2008) [arXiv:0802.0007 [hep-ph]].