$\mathbf{SU(2)_L}{\times}\mathbf{SU(2)_R}$ minimal dark matter with $\mathbf{2}\mathbf{~TeV}$ W'

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Abstract

We construct the minimal dark matter models in the left-right symmetric extensions of the standard model (SM), where the gauge symmetry $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ is broken into its subgroup $SU(3)_C \times U(1)_{em}$ by nonzero VEVs of a $SU(2)_R$ doublet H_R and a $SU(2)_L \times$ $SU(2)_R$ bidoublet H. A possible candidate of dark matter is explored in the framework of minimal dark matter considering $SU(2)_{L,R}$ multiplet scalar bosons and fermions. Then we focus on $SU(2)_R$ quintuplet fermions with $B-L$ charges 0, 2 and 4 as the minimal dark matter candidates and investigate phenomenology of them. We show that the dark matter in the model can provide observed relic density with $2 \text{ TeV } W'$ boson which is motivated by the ATLAS diboson excess and CMS eejj excess. The possible mass of dark matter is predicted for each $B - L$ charge. We then estimate the scattering cross section of dark matter with nucleon and production cross section of charged components in the quintuplets at the LHC.

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I. INTRODUCTION

The Standard Model (SM) based on $SU(3) \times SU(2)_L \times U(1)_Y$ has been very successful in describing particle physics phenomena from low energy to ∼ (a few) TeV. Still it suffers from a number of phenomenological drawbacks such as neutrino masses and mixings, nonbaryonic dark matter (DM) and matter-antimatter asymmetry as well as cosmological inflation, not even mentioning theoretical puzzles such as fine tuning of Higgs mass, the origin of flavor and generation, and strong CP problem, etc.. There are a number of different extensions of the SM, based on which problem it aims to solve.

One interesting gauge extension of the SM would be left-right (LR) symmetric models, where the right-handed fermions form $SU(2)_R$ doublets, similarly to the left-handed (LH) fermions forming $SU(2)_L$ doublets [\[1](#page-10-0)[–6\]](#page-10-1). In this case one can enjoy a possibility that the left-right symmetry is completely restored in high energy scale if we assume $g_L = g_R$ and similar assumptions for Yukawa couplings. Also strong CP problem [\[7,](#page-10-2) [8](#page-10-3)], neutrino masses and mixings, and lepton number violation [\[9](#page-10-4)[–15\]](#page-10-5) can be addressed as well from different viewpoints.

The canonical version of the LR model is to assume the exact left-right symmetry with the following Higgs sector, SU(2)_L triplet Δ_L , SU(2)_R triplet Δ_R and SU(2)_L × SU(2)_R bidoublet ϕ . Then, the LR symmetry is assumed to be spontaneously broken into $U(1)_{em}$ by nonzero VEVs of Δ_R and ϕ . This setup has been studied extensively, including flavor physics [\[9](#page-10-4)[–19](#page-11-0)], minimal DM [\[20\]](#page-11-1) and right-handed neutrino DM [\[21](#page-11-2), [22\]](#page-11-3).

However the assumption of exact LR symmetry may be a too strong and constraining assumption. In principle, the $SU(2)_L$ and $SU(2)_R$ gauge couplings could be different even at high energy scales. Moreover one can achieve the necessary gauge symmetry breaking with nonzero VEVs of $SU(2)_R$ doublet H_R instead of triplet Δ_R and a bidoublet ϕ , which is much simpler than the canonical LR models. We also note that inverse seesaw mechanism can be applied introducing gauge singlet fermions [\[23](#page-11-4)[–25\]](#page-11-5).

In fact, this simpler setup including $SU(2)_L$ doublet Higgs has been studied recently [\[26\]](#page-11-6), mainly motivated by the ATLAS 2 TeV diboson excess [\[27](#page-11-7)] where a moderate excess is also found by CMS [\[28](#page-11-8), [29](#page-11-9)]. The 2 TeV W' boson from $SU(2)_R$ is a possible explanation of the excess, which is also discussed in the canonical LR models [\[19](#page-11-0), [20,](#page-11-1) [30](#page-11-10)[–37](#page-11-11)]. Although one has to await more data accumulation at LHC Run 2, it is interesting to ask oneself what kind of new physics may explain this tantalizing ATLAS 2 TeV diboson excess, if it is a real signature of physics beyond the SM. Furthermore, there is also some excess in the *eejj* channel of the CMS search [\[38\]](#page-11-12), which could be also discussed as a potential signal of W' decaying into electron and right-handed neutrinos [\[26,](#page-11-6) [37](#page-11-11), [39](#page-11-13)[–41\]](#page-11-14).

In this letter we construct a minimal dark matter model in the $SU(2)_L\times SU(2)_R\times$ $U(1)_{B-L}$ extension where the gauge symmetry is broken down to $U(1)_{em}$ by nonzero VEV's of a bidoublet H and a $SU(2)_R$ doublet H_R [\[51](#page-12-0)]. We shall explore the possible candidates of DM introducing $SU(2)_{L,R}$ multiplet scalar bosons and fermions based on the idea of minimal DM [\[42](#page-11-15)]. Then the $SU(2)_R$ quintuplet fermions with $B - L = 0$, 2 and 4 are investigated as candidates of minimal DM of $SU(2)_R$ multiplet. We show that properties of the minimal DM such as the mass splitting within the multiplet are different from that in the canonical LR models [\[20](#page-11-1)]. The allowed DM mass range is then different in two cases, and so is the resulting phenomenology. Particularly we find that our minimal DM can be accommodated with 2 TeV W' where the relic density tends to be smaller than observed value in the canonical LR model for the parameter region in which a neutral component of $SU(2)_R$ multiplet is the lightest one because of different mass splitting pattern. The mass values of DM are predicted for $m_{W'} = 2$ TeV. We then estimate DM-nucleon scattering cross section for DM direct detection and production cross section of charged components in the DM multiplet at the LHC Run 2.

II. THE MODEL

Let us consider a left-right extension of the SM applying the gauge symmetry $\text{SU}(3)\times \text{SU}(2)_L\times \text{SU}(2)_R\times \text{U}(1)_{B-L}$ where B and L are baryon and lepton numbers respectively [\[1](#page-10-0)[–6](#page-10-1)]. The scalar contents are taken to be

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

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

$$
q_L: (2, 1, 1/3), q_R: (1, 2, 1/3), \ell_L: (2, 1, -1), \ell_R: (1, 2, -1), S: (1, 1, 0), (2)
$$

where Majorana fermion S is introduced to lead inverse seesaw mechanism $[23-25]$.

The gauge symmetry is broken by non-zero vacuum expectation value of H and H_R . We assume the VEVs of the scalar fields are developed such that

$$
\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} k_1 & 0 \\ 0 & k_2 \end{pmatrix}, \ \langle H_R \rangle = \begin{pmatrix} 0 \\ v_R / \sqrt{2} \end{pmatrix} . \tag{3}
$$

The gauge symmetry is then broken as $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \rightarrow U(1)_{em}$ where the electric charge Q is given by

$$
Q = T_L^3 + T_R^3 + \frac{1}{2} Q_{B-L}
$$
\n(4)

where $T_{L(R)}^3$ and Q_{B-L} denote the diagonal generator of $SU(2)_{L(R)}$ and the $B-L$ value of a field respectively. After spontaneous symmetry breaking, we obtain the mass terms of the gauge bosons such that

$$
L_M = (W_L^{+\mu}, W_R^{+\mu}) \tilde{M}_W^2 \begin{pmatrix} W_{L\mu}^- \\ W_{R\mu}^- \end{pmatrix} + \frac{1}{2} (W_L^{3\mu}, W_R^{3\mu}, X^{\mu}) \tilde{M}_0^2 \begin{pmatrix} W_{L\mu}^3 \\ W_{R\mu}^3 \\ X_{\mu} \end{pmatrix},
$$
(5)

where $W_{L,R}^{\pm \mu} = (W_{L,R}^{1\mu} \mp iW_{L,R}^{2\mu})/\sqrt{2}$. The mass matrices are given by

$$
\tilde{M}_W^2 = \frac{1}{4} \begin{pmatrix} g_L^2 K^2 & -2g_L g_R k_1 k_2 \\ -2g_L g_R k_1 k_2 & g_R^2 (K^2 + v_R^2) \end{pmatrix}, \ \tilde{M}_0^2 = \begin{pmatrix} \frac{g_L^2}{4} K^2 & -\frac{g_L g_R}{4} K^2 & 0 \\ -\frac{g_L g_R}{4} K^2 & \frac{g_R^2}{4} (K^2 + v_R^2) & \frac{g_R g_B - L}{4} v_R^2 \\ 0 & \frac{g_R g_B - L}{4} v_R^2 & \frac{g_B^2 - L}{4} v_R^2 \end{pmatrix} \tag{6}
$$

where $K^2 = k_1^2 + k_2^2$ and $g_{L,R}$ and g_{B-L} are gauge couplings of $SU(2)_{L,R}$ and $U(1)_{B-L}$. The mass matrices are diagonalized by the orthogonal transformation [\[43\]](#page-11-16)

$$
\begin{pmatrix} W_L^{\pm} \\ W_R^{\pm} \end{pmatrix} = \begin{pmatrix} \cos \xi & \sin \xi \\ -\sin \xi & \cos \xi \end{pmatrix} \begin{pmatrix} W^{\pm} \\ W'^{\pm} \end{pmatrix},\tag{7}
$$

$$
\begin{pmatrix}\nW_{3L} \\
W_{3R} \\
X\n\end{pmatrix} = \begin{pmatrix}\nc_{W}c_{X} & c_{W}s_{X} & s_{W} \\
-s_{W}s_{M}c_{X} - c_{M}s_{X} & -s_{W}s_{M}s_{X} + c_{M}c_{X} & c_{W}s_{M} \\
-s_{W}c_{M}c_{X} + s_{M}s_{X} & -s_{W}c_{M}s_{X} - s_{M}c_{X} & c_{W}c_{M}\n\end{pmatrix}\n\begin{pmatrix}\nZ \\
Z' \\
A\n\end{pmatrix},
$$
\n(8)

where $s_W(c_W) = \sin \theta_W(\cos \theta_W)$ with the Weinberg angle θ_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 ξ and θ_X are assumed to be very small and will be ignored in the following analysis of dark matter phenomenology. The gauge couplings satisfy the relations $g_R = e/(s_M c_W)$ and $g_{B-L} = e/(c_W c_M)$. The c_M and s_M can be rewritten as

$$
s_M = \tan \theta_W \left(\frac{g_R}{g_L}\right)^{-1}, \quad c_M = \left(\frac{g_R}{g_L}\right)^{-1} \sqrt{\left(\frac{g_R}{g_L}\right)^2 - \tan^2 \theta_W},\tag{9}
$$

where the gauge coupling should satisfy $g_R/g_L > \tan \theta_W$ for consistency. Assuming $K \ll v_R$, the mass eigenvalues of new gauge bosons are approximately given by

$$
m_{W'}^2 \simeq \frac{1}{4} g_R^2 v_R^2 \left(1 + \frac{K^2}{v_R^2} \right),\tag{10}
$$

$$
m_{Z'}^2 \simeq \frac{1}{4} (g_R^2 + g_{B-L}^2) v_R^2 \left(1 + \frac{K^2 c_M^2}{v_R^2} \right). \tag{11}
$$

Thus the mass relation of heavier gauge bosons are approximately

$$
\frac{m_{Z'}}{m_{W'}} \simeq \frac{g_R/g_L}{\sqrt{(g_R/g_L)^2 - \tan^2 \theta_W}} \ . \tag{12}
$$

Fig. [1](#page-4-0) shows the $m_{Z'}$ as a function of g_R/g_L with $m_{W'} = 2$ TeV where $m_{Z'}/m_{W'} \sim 1.2$ for $g_L = g_R$. We note that extra factor of $\sqrt{2}$ appear in the numerator of RHS when an $SU(2)_R$ triplet develops VEV instead of doublet.

The left-right related W' boson with $m_{W'} \sim 2$ TeV would explain the diboson excess observed in the ATLAS experiment [\[27\]](#page-11-7) where the W' is produced as $\bar{q}'q \to W'$ and decays into $WZ(\rightarrow jj)$ at the LHC [\[19,](#page-11-0) [20,](#page-11-1) [26,](#page-11-6) [30](#page-11-10)[–37](#page-11-11), [44](#page-11-17)]. Furthermore 2 TeV W' also can be an explanation of $eejj$ excess in the CMS search [\[38\]](#page-11-12) when W' decays electron and right-handed neutrino [\[26,](#page-11-6) [37,](#page-11-11) [39](#page-11-13)[–41](#page-11-14)]. It is also indicated that coupling relation of $g_R < g_L$ is suitable to explain these excesses [\[26](#page-11-6), [37](#page-11-11), [39](#page-11-13)]. Motivated by these possibility, we fix the mass of W' as 2 TeV and consider two different cases, $g_R/g_L = 1.0$ and $g_R/g_L = 0.6$ in following analyses.

To accommodate minimal dark matter (DM) within our model, we consider a new fermion or scalar $SU(2)_{L,R}$ multiplet. If a multiplet does not have interaction leading its decay up to dimension-6 operator level the lightest component can be stable in cosmological time-scale by the same idea as Minimal Dark Matter (MDM) model [\[42\]](#page-11-15). In Tables. [I,](#page-5-0) we summarize possible interactions for decay of $SU(2)_{L,R}$ multiplet scalar(fermion) $\Phi_{L,R}(\Psi_{L,R})$ up to

FIG. 1: Mass of heavy neutral gauge boson Z' as a function of g_R/g_L with $m_{W'} = 2 \text{ TeV}$.

quintuplet. We find that scalar $SU(2)_L$ quintuplet with non-zero Q_{B-L} does not have an operator less than dimension 6 while scalar $SU(2)_R$ quintuplet have dimension 5 operator. On the other hand, fermion $SU(2)_L$ quadruplet with $Q_{B-L} = 3$ and both fermion $SU(2)_L$ and $SU(2)_R$ quintuplet do not have operator less than dimension 6. Note, however, that a DM with $Y \neq 0$ are excluded by DM direct detection due to large DM-nucleron scattering cross section via Z-exchange unless some other mechanism suppress the cross section. Therefore we shall focus on the fermion $SU(2)_R$ quintuplet for our study of minimal DM since $SU(2)_L$ quintuplet is same as discussed in MDM model in the canonical LR model [\[20](#page-11-1)].

III. DM PHENOMENOLOGY

In this paper we focus on $SU(2)_R$ quintuplets $\Psi^{Q_{B-L}}$ whose electrically neutral component provides a DM candidate. Possible values of Q_{B-L} are 0, 2 and 4, where the corresponding multiplets can be written as

$$
\Psi^{0} = (\chi^{++}, \chi^{+}, \chi^{0}, \chi^{-}\chi^{--})^{T}, \quad \Psi^{2} = (\eta^{+++}, \eta^{++}, \eta^{+}_{1}, \eta^{0}, \eta^{-}_{2})^{T}, \n\Psi^{4} = (\zeta^{++++}, \zeta^{+++}, \zeta^{++}, \zeta^{+}, \zeta^{0})^{T}.
$$
\n(13)

where subscripts "+" etc. denote electric charge of the components and χ^0 is Majorana fermion while the others are Dirac fermion. We note that $Q_{B-L} = 0$ multiplet is discussed in the exact left-right symmetric case in Ref. [\[20](#page-11-1)].

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

$$
L \supset -s_W s_M g_R Q \bar{\psi}^Q Z^{\mu} \gamma_{\mu} \psi^Q + c_M g_R \left(Q - \frac{Q_{B-L}}{2c_M^2} \right) \bar{\psi}^Q Z^{\prime \mu} \gamma_{\mu} \psi^Q + c_W s_M g_R Q \bar{\psi}^Q A^{\mu} \gamma_{\mu} \psi^Q + \frac{g_R}{\sqrt{2}} (c_{2m} \bar{\psi}^{Q+1} W^{\prime + \mu} \gamma_{\mu} \psi^Q + h.c.),
$$
\n(14)

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

A. Mass splitting

The mass splitting between charged components and the neutral component in a given multiplet can be obtained by calculating radiative correction where the gauge bosons propagate inside loop diagrams. We then find the formula of the mass splitting as

$$
M_Q - M_0 \simeq \frac{g_R^2}{(4\pi)^2} M [Q(Q - Q_{B-L}) f(r_{W'}) - c_M^2 Q \{Q - Q_{B-L}/c_M^2\} f(r_{Z'}) - s_W^2 s_M^2 Q^2 f(r_Z) - c_W^2 s_M^2 Q^2 f(r_\gamma)]
$$
\n(15)

where Q is electric charge, $r_X = m_X/M$ and $f(r) \equiv 2 \int_0^1 dx (1+x) \log[x^2 + (1-x)r^2]$. We note that $Q_{B-L} = 0$ provides same formula as in Ref. [\[20\]](#page-11-1). Fig. [2](#page-6-0) shows 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 of DM respectively. We find that the mass splitting $M_Q - M$ is always positive for $Q_{B-L} = 0$ which is qualitatively different from Ref. [\[20\]](#page-11-1) where the $M_Q - M$ becomes negative when DM mass M is larger than \sim 1.8(4.5) TeV for $m_{W'} = 2(5)$ TeV. This difference comes from mass relation between $m_{Z'}$ and $m_{W'}$; $m_{Z'}/m_{W'}$ is smaller in our case when the same g_R/g_L value is applied. For the multiplet with $Q_{B-L} = 2$, the second singly charged component η_2^- becomes lighter than the neutral component for $M \gtrsim 1(0.6)$ TeV. The $Q_{B-L} = 4$ multiplet also provides positive $M_Q - M$ for all M value where the mass splitting is larger than the case of $Q_{B-L} = 0$.

TABLE I: Interactions leading to DM decay for scalar(fermion) $SU(2)_{L,R}$ multiplet where "Reps." correspond to representation under $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, Y_{DM} is hypercharge of DM, $H =$ $(i\sigma_L^2)H^T(i\sigma_R^2)$ with $\sigma_{L(R)}^2$ being the second Pauli matrix acting on $SU(2)_{L(R)}$ representation space, and $\tilde{H}_R = (i\sigma_R^2)H_R^*$. The Lorentz indices are suppressed.

Reps.	Interaction	Y_{DM}	Reps.	Interaction	Y_{DM}
	$SU(2)_R$ multiplet scalar Φ_R	$SU(2)_R$ multiplet fermion Ψ_R			
(1,2,1)	$\Phi_R H_R^{\dagger}$	θ	(1,2,1)	$\bar{\Psi}_R \ell_R^c H^{\dagger} H$	θ
(1,3,0)	$\Phi_R H_R H_R$	$\overline{0}$	(1,3,0)	$\bar{\Psi}_R \ell_R H_R$	θ
(1,3,2)	$\Phi_R \tilde{H}_R \tilde{H}_R$	$\overline{0}$	(1,3,2)	$\bar{\Psi}_R \ell_R^c H_R$	Ω
(1,4,1)	$\Phi_R \tilde{H}_R \tilde{H}_R H_R$	$\overline{0}$	(1,4,1)	$\bar{\Psi}_R \ell_R^c H_R H_R$	θ
(1,4,3)	$\Phi_R H_R H_R H_R$	θ	(1,4,3)	$\bar{\Psi}_R \ell_R^c H_R H_R$	0
(1,5,0)	$\Phi_R \tilde{H}_R \tilde{H}_R H_R H_R$	θ	(1,5,0)	dim > 5	$\left(\right)$
(1,5,2)	$\Phi_R H_R H_R H_R H_R$	θ	(1,5,2)	dim > 5	0
(1,5,4)	$\Phi_R H_R H_R H_R H_R$	θ	(1,5,4)	dim > 5	θ
	$SU(2)_L$ multiplet scalar Φ_L			$SU(2)_L$ multiplet fermion Ψ_L	
(2,1,1)	$\Phi_L H_R^\dagger \tilde{H}$	1/2	(2,1,1)	$\bar{\Psi}_L \ell_L^c H^{\dagger} H$	1/2
(3,1,0)	$\Phi_L H H$	Ω	(3,1,0)	$\Psi_L \ell_L H H_R$	Ω
(3,1,2)	$\Phi_L \bar{\ell}_L^c \ell_L$	1	(3,1,2)	$\bar{\Psi}_L \ell_L^c HH_R$	$\overline{0}$
(4,1,1)	$\Phi_L H H H H_R$	1/2	(4,1,1)	$\bar{\Psi}_L \ell^c_L H \ddot{H}$	1/2
(4,1,3)	$\Phi_L \bar{\ell}_L^c \ell_L H H_R$	3/2	(4,1,3)	dim > 5	3/2
(5,1,0)	$\Phi_L(H\tilde{H})(H\tilde{H})$	$\overline{0}$	(5,1,0)	dim > 5	0
(5,1,2)	dim > 5	1	(5,1,2)	dim > 5	1
(5,1,4)	dim > 5	2	(5,1,4)	dim > 5	$\overline{2}$

FIG. 2: Mass difference between neutral and charged components of right-handed quintuplet where $B - L = \{0, 2, 4\}$ and $g_R/g_L = \{1, 0.6\}.$

B. Relic density

Thermal relic density of DM is numerically calculated using micrOMEGAs 4.1.5 [\[45\]](#page-11-18) to solve the Boltzmann equation by implementing relevant interactions providing (co)annihilation processes of DM. Here the (co)annihilation processes of DM are induced by gauge interactions in Eq. [\(14\)](#page-4-1). We show the estimated relic density by blue lines in Fig. [3](#page-7-0) for $Q_{B-L} = 0$ and 4 with $m_{W'} = 2$ TeV where the left(right) panels correspond to $g_R/g_L = 1.0(0.6)$. It is compared to the value measured by Planck [\[46\]](#page-11-19), $\Omega h^2 = 0.1199 \pm 0.0027$, indicated by green horizontal line in the plots. Note that the case of $Q_{B-L} = 2$ is not shown in Fig. [3](#page-7-0) since it can not provide observed relic density in the region of M where the neutral component is the lightest. The plots show the resonance effects around $M \sim m_{W'}/2$ and $M \sim m_{Z'}/2$ where (co)annihilation cross sections become large decreasing relic density. We find that the relic density tends to larger for smaller g_R/g_L since the (co)annihilation cross section is suppressed by following effects: (*i*) the heavier Z' for the smaller g_R/g_L , and (ii) the smaller coupling constant g_R compared with g_L . Also $Q_{B-L} = 4$ 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 effect. The masses of DM giving observed relic density are summarized in third column of Table. [II](#page-8-0) for

FIG. 3: Relic density Ωh^2 for fermionic $SU(2)_R$ quintuplet DM with $B - L = 0$ and 4 where the left(right) panel shows $g_R/g_L = 1.0(0.6)$.

each case. We note that $SU(2)_R$ quintuplet can provide observed relic density with $m_{W'} = 2$ TeV unlike the case of the exact left-right symmetric model in Ref. [\[20](#page-11-1)] due to different mass splitting relations. Furthermore, when we apply $g_R/g_L = 0.6$ the required mass of DM can be as light as $\mathcal{O}(1)$ TeV which is light compared to $SU(2)_L$ quintuplet in MDM model [\[47\]](#page-11-20).

C. DM nucleon scattering cross section

For the multiplet with $Q_{B-L} \neq 0$, DM can interact with nucleon by exchanging Z' boson. The DM-Z' coupling is obtained from Eq. (14) while 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. We then estimate DM-nucleon scattering cross section for ζ^0 to investigate constraint from DM direct detection experiment. The spin independent elastic scattering cross section of DM and nucleon N can be calculated as

$$
\sigma_{\zeta^0 N} \simeq \frac{4g_R^2 g_{NNZ'}^2}{\pi c_M^2} \frac{1}{m_{Z'}^4} \frac{m_N^2 M^2}{(m_N + M)^2} \tag{16}
$$

where m_N is nucleon mass, $g_{ppZ'} = c_M g_R(1/2 - 1/(4c_M^2))$ and $g_{nnZ'} = -g_R/(4c_M)$. Since our DM is much heavier than nucleon the cross section is almost independent of DM mass. We then find that the values of cross section averaged by nucleon $(\sigma_{\zeta^0 p} + \sigma_{\zeta^0 n})/2$ are 6.8 \times 10^{-44} cm² and 1.1×10^{-44} cm² for $g_R/g_L = 1.0$ and 0.6 respectively. These cross sections are compared to current constraint given by LUX experiment [\[48](#page-11-21)] where the upper limits are given in seventh column of Table. [II](#page-8-0) 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 some cancellation mechanism work 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 significantly different which are summarized in sixth column of Table. [II.](#page-8-0) For the case of $Q_{B-L} = 0$, DM interacts with nucleon at one-loop level exchanging W' boson and the scattering cross section is much smaller than the current constraint.

D. Implication to collider physics

The components in $SU(2)_R$ quintuplet can be produced at the LHC through gauge interactions $pp \to V \to \bar{\psi}^Q \dot{\psi}^Q$ where V can be γ , Z, W' or Z' according to interactions in Eq. [\(14\)](#page-4-1). Since DM just appears as missing transverse energy E_T we consider production processes which include charged components; $pp \to \bar{\psi}^Q \psi^Q$, $pp \to \bar{\psi}^Q \psi^{Q \pm 1}$, and $pp \to \bar{\psi}^{\pm} \psi^0$ where $\psi = \chi, \eta$ and $Q \neq 0$. Here we estimate the production cross section numerically by CalcHEP [\[49\]](#page-11-22) utilizing the code with CTEQ6L PDF [\[50](#page-12-1)] for $\sqrt{s} = 13$ and 14 TeV. We show the production cross sections in 5th column of Table. [II](#page-8-0) where all production modes are summed over. The cross section can be larger than 0.1 fb for $M \leq 2$ TeV which would be within reach of the LHC.

The charged components can decay as $\psi^Q \to \psi^{Q \mp 1} M^{\pm} (M^{\pm} = \pi^{\pm}, K^{\pm}, \text{etc.})$ and $\chi^Q \to \pi^{\pm}$. $\chi^{Q \mp 1} \bar{q}' q$ where off-shell W' converts into M^{\pm} and light quarks $\bar{q}' q$ assuming heavy righthanded neutrinos. Since the mass splittings are $\Delta M > 5$ GeV in our case, $\psi^Q \to \psi^{Q \mp 1} \bar{q}' q$ provide dominant contribution of decay width which is given by

$$
\Gamma(\psi^Q \to \psi^{Q-1} \bar{q}'q) \simeq N_c c_{2m}^2 \frac{g_R^4}{120\pi^3} \frac{\Delta M^5}{m_{W'}^4} \tag{17}
$$

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

Here we briefly discuss the diboson excess in our model. Calculating with CalcHEP, the production cross section for $pp \to W'$ is given as $\sigma(pp \to W') \simeq 220 (g_R/g_L)^2$ fb for $m_{W'} = 2$

TABLE II: DM mass giving 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, σ_{DM-N} denotes a DM-nucleon scattering cross section where the value outside(inside) bracket is for proton(neutron), and σ_{Lux} is current limit by Lux [\[48](#page-11-21)].

$B-L$	g_R/g_R	$m_{DM}[\text{TeV}]$	ΔM [GeV]	$\sigma_{\psi^Q\psi^{Q'}}$ [fb]	$\sigma_{DM-N}[\text{cm}^2]$	$\sigma_{\text{Lux}}[\text{cm}^2]$
$\overline{0}$	-1	4.54	5.34	$\ll 10^{-2}$	$\ll 10^{-45}$	$\sim 57. \times 10^{-45}$
$\overline{0}$	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	$\ll 10^{-2}$	$\ll 10^{-45}$	$\sim 30. \times 10^{-45}$
$\overline{4}$	$\mathbf{1}$	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	$\ll 10^{-2}$	$1.9(12.) \times 10^{-44}$	$\sim 52. \times 10^{-45}$
$\overline{4}$	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	$\ll 10^{-2}$	$6.8(15.) \times 10^{-45}$	$\sim 45. \times 10^{-45}$

TeV, which is similar to other $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ models [\[19,](#page-11-0) [20,](#page-11-1) [26,](#page-11-6) [30](#page-11-10)[–37,](#page-11-11) [44\]](#page-11-17). On the other hand the branching fraction for $W' \to WZ$ would be different since we have additional $SU(2)_R$ quintuplet fermion. The W' can decay into quintuplet states where the partial width is given by

$$
\Gamma\left(W' \to \sum_{i,j} \bar{\psi}_i \psi_j\right) = \left(\sum_{ij} C_{ij}^2\right) \frac{g_R^2}{12\pi} m_{W'} \left(1 + \frac{2M^2}{m_{W'}^2}\right) \sqrt{1 - \frac{4M^2}{m_{W'}^2}}
$$
(18)

where ψ_i represents a component in quintuplet, and

$$
\sum_{ij} C_{ij}^2 = \begin{cases} (\sqrt{2})^2 + \frac{1}{2}(\sqrt{3})^2 &= \frac{7}{2} \quad \text{for } B - L = 0 \quad \text{quintuplet,} \\ (\sqrt{2})^2 + (\sqrt{3})^2 + (\sqrt{3})^2 + (\sqrt{2})^2 &= 10 \quad \text{for } B - L = 4 \quad \text{quintuplet,} \end{cases}
$$

where $1/2$ factor appears in second term of LHS for B-L=0 since the neutral component is Majorana fermion. We assumed all the components ψ_i have the common mass M, ignoring mass difference in the quintuplet for simplicity. The other partial decay widths are given by

$$
\Gamma\left(W' \to \sum \bar{q}q'\right) = \frac{3g_R^2}{16\pi} m_{W'}
$$
\n
$$
\Gamma(W' \to WZ) = \Gamma(W' \to Wh) = \frac{g_L^2}{192\pi} \sin^2 \xi \frac{m_W^5}{m_W^4}
$$
\n(19)

where $\sum \bar{q}q'$ indicates sum of possible combinations of SM quarks, ξ is the W-W' mixing angle in Eq.[\(7\)](#page-3-0) and all the quark masses are omitted. We find that branching fraction of $W' \to \sum_{i,j} \bar{\psi}_i \psi_j$ is dominant when $2M < m_{W'}$. In this case a value of sin ξ should be larger than the value in a left-right model without extra multiplet in order to obtain $\sigma(pp \to W')BR(W' \to WZ) \sim 10$ fb for explaining the diboson excess; $\sin \xi \sim 3(2) \times 10^{-3}$ and $\sim 5(3) \times 10^{-3}$ are required for the cases of $B - L = 0$ and 4 with $2M < m_{W'}$ and $g_R/g_R = 1.0(0.6)$ while $\sin \xi \sim 2(1) \times 10^{-3}$ is required for $2M > m_{W'}$ and $g_R/g_R = 1.0(0.6)$ as the other left-right models.

IV. SUMMARY AND DISCUSSION

We have studied a DM model with $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ gauge symmetry where the 2 TeV W′ boson from the extended gauge symmetry is a potential explanation of diboson excess in ATLAS and eejj excess in CMS. The gauge symmetry is broken by VEVs of $SU(2)_R$ doublet and $SU(2)_{L,R}$ bi-doublet scalar field where the scalar sector is simplified loosening the exact left-right exchange symmetry. Then we have classified a new fermion and scalar $SU(2)_{L,R}$ multiplet which can be stable in cosmological timescale based on the idea of minimal dark matter.

As a new candidate of DM, we focused on three fermion $SU(2)_R$ quintuplets with $B-L =$ 0, 2 and 4. We investigated mass splitting between neutral and charged components of the quintuplets, relic density of DM, and DM-nucleon scattering for each multiplets adopting $m_{W'} = 2 \text{ TeV}$. For the mass splitting of $B-L = 0$ quintuplet, we find that neutral component is always lightest where it is qualitatively different from the exact left-right symmetric case. We have also shown that the neutral component is always the lightest for $B - L = 4$ while a charged component in $B - L = 2$ quintuplet becomes the lightest when DM mass is

 $M \gtrsim 1.0(0.6)$ TeV for $g_R/g_L = 1.0(0.6)$. The observed relic density can be obtained for the $B - L = 0$ and 4 quintuplets but the $B - L = 2$ quintuplet give smaller relic density in the region where neutral component is the lightest. Furthermore the investigation of DM-nucleon scattering for $B - L = 4$ excludes cases of $g_R/g_L = 1.0$ and $g_R/g_L = 0.6$ with $M \lesssim 1$ TeV since the scattering cross section via Z' exchange is larger than current limit. Thus the values of DM mass are predicted to be $4.5(1.6, 2.2, 2.6)$ TeV for $B - L = 0$ with $g_R/g_L = 1.0(0.6)$ and $\{1.2, 1.7, 3.6\}$ TeV for $B - L = 4$ with $g_R/g_L = 0.6$ respectively. We then show that charged components can be produced at the LHC 13 and 14 TeV with total cross section around 0.1 to 2.1 fb when DM mass is relatively light as 1.2 to 1.7 TeV. The charged components predominantly decay into an other charged (neutral) component with 1-unit charge difference and light quarks, which lead the signal of the quintuplet production as jets plus missing E_T . Further analysis of the signal is left as future work.

Acknowledgments We are grateful to Ayon Patra for discussions on the left-right symmetric models. This work is supported in part by National Research Foundation of Korea (NRF) Research Grant NRF-2015R1A2A1A05001869, and by SRC program of NRF Grant No. 20120001176 funded by MEST through Korea Neutrino Research Center at Seoul National University (PK).

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