Singlet fermion Dark Matter within Left-Right Model

Sudhan Patra and Soumya Rao

Center of Excellence in Theoretical and Mathematical Sciences, Siksha ‘O’ Anusandhan University, Bhubaneswar-751030, India

ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia.

We discuss singlet fermion dark matter within a left-right symmetric model promoting baryon and lepton numbers as separate gauge symmetries. We add a simple Dirac fermionic dark matter singlet under $SU(2)_{L,R}$ with nonzero and equal baryon and lepton number which ensures electric charge neutrality. Such a dark matter candidate interacts with SM particles through the extra $Z_{B,L}$ gauge bosons. This can give rise to a dark matter particle of a few hundred GeV that couples to $\sim$ keV scale gauge bosons to give the correct relic density. This model thus accommodates TeV scale $Z_{B,L}$ gauge bosons and other low scale BSM particles, which can be easily probed at LHC.

I. INTRODUCTION

Standard Model (SM) has proven to be a highly successful theory in the history of particle physics accounting for forces and interactions between known fundamental particles up to current accelerator energy. However, one of the unexplained problems in SM is the existence of Dark matter (DM). There are many possible candidates for DM with the Weakly Interacting Massive Particle (WIMP) scenario being one of most well studied. The left-right symmetric model (LRSM) provides a framework for incorporating potential DM candidates in a beyond SM (BSM) scenario with the introduction of additional multiplets. We aim here to explore the possibility of studying DM phenomenology in a special class of LRSM where DM mass can be of the order of a few hundred GeV.

The range of DM mass in LRSM can be from $\sim$ keV to $\sim$ TeV. It is noted in refs. that the keV scale right handed neutrino can be a long-lived warm DM candidate. However, it is known that such a DM candidate is overabundant and needs a delicate production mechanism in early universe which is not very natural. Very recently a novel approach was taken to introduce stable TeV scale DM where stability of the DM is ensured either by the remnant discrete symmetry or accidentally via high dimensionality of DM multiplets forbidding tree-level decays. This approach involved DM candidates as fermionic triplets or quintuplets or scalar doublets and seven-plets. The detailed phenomenology of these DM candidates has been studied very recently in .

The higher $SU(2)_{L,R}$ dimensionality of stable dark matter in these models means that the constraints from PLANCK-WMAP and indirect detection push the DM mass beyond the reach of LHC. On the other hand if the DM particle is a singlet, it will be able to satisfy relic density bounds from PLANCK data as well as indirect detection constraints even at lower DM masses of a few hundred GeV. Motivated by the phenomenology of singlet DM we consider a simple LRSM where baryon and lepton numbers are separate local gauge symmetries . In this letter we study the framework in which the DM is a LR singlet with equal B and L charges thus ensuring its electric charge neutrality.

II. CONVENTIONAL LEFT-RIGHT MODELS

The prime goal here is to discuss conventional left-right symmetric model and demonstrate that why it is difficult to accommodate singlet dark matter. The basic gauge group of conventional left-right symmetric model is given by

$$G_{L,R} \equiv SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L},$$

where $B-L$ is the difference between baryon and lepton number. The electric charge is related to the 3rd component of isospin for $SU(2)_{L,R}$ gauge group and $B-L$ charge as

$$Q = T_{3L} + T_{3R} + \frac{B - L}{2}$$ (1)

The usual quarks and leptons belong to following representations

- $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = [2, 1, \frac{1}{3}]$, $q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} = [1, 2, \frac{1}{3}]$,
- $\ell_L = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} = [2, 1, -1]$, $\ell_R = \begin{pmatrix} \nu_R \\ \ell_R \end{pmatrix} = [1, 2, -1]$

The spontaneous breaking of left-right symmetric models is implemented with i) Scalar bidoublet $\Phi(2,2,0)$ plus doublets $H_L(2,1,-1) + H_R(1,2,-1)$, ii) Scalar bidoublet $\Phi(2,2,0)$ plus scalar triplets $\Delta_L(3,1,-2) + \Delta_R(1,3,-2)$. However, if we introduce a dark matter particle singlet

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*Electronic address: sudha.astro@gmail.com
†Electronic address: soumya.rao@adelaide.edu.au
‡Ref. studies the interesting signatures of these keV right handed neutrinos in neutrino mass searches.

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2 Gauge theories of baryons and leptons has been discussed in ref.
under $SU(2)_{L,R}$ and charged under $U(1)_{B-L}$ — looking at electric charge formula—it is found that there is no way to find a electrically neutral stable dark matter candidate. This gives us strong motivation to consider alternative class of left-right symmetric model which can accommodate singlet dark matter discussed in following section.

### III. THE PRESENT MODEL FRAMEWORK

We go beyond the conventional left-right symmetric models and construct a very simple model of left-right theory accommodating singlet dark matter. The basic gauge group of left-right theory where individual baryon and lepton number promoted as local gauge symmetry is $SU(3)_C$ structure for simplicity. The standard quarks and leptons transforming under this new class of left-right symmetric gauge group are

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \equiv [2, 1, 1/3, 0], \quad q_R = \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv [1, 2, -1/3, 0],$$

$$\ell_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \equiv [2, 1, 0, 1], \quad \ell_R = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \equiv [1, 2, 0, 1].$$

It is known that additional $U(1)$ gauge groups introduces extra gauge anomalies to the theory which needs to be canceled. These gauge anomalies in case of extra $U(1)_B$ and $U(1)_L$ gauge groups are

$$A\left[U(1)_B^2 \times U(1)_L\right] = 3/2,$$

$$A\left[U(1)_B^2 \times U(1)_L\right] = -3/2,$$

$$A\left[U(1)_B \times U(1)_L\right] = 3/2,$$

$$A\left[U(1)_B \times U(1)_L\right] = -3/2,$$

along with other vanishing gauge anomalies

$$A\left[U(1)^2_{B(L)} \times U(1)^2_{L(B)}\right], \quad A\left[\text{gravity} \times U(1)^2_{B(L)}\right] \quad \text{and} \quad A\left[U(1)^2_{B(L)}\right].$$

Moreover it is already pointed out in ref. [14] that there are various ways to construct a anomaly free left-right symmetric model with gauging baryon and lepton numbers by adding extra pair of lepto-quarks $^3$ transforming under the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_B \times U(1)_L$ as follows:

| Field  | $SU(2)_L$ | $SU(2)_R$ | $U(1)_B$ | $U(1)_L$ |
|--------|-----------|-----------|-----------|-----------|
| Fermions $q_L$ | 2 | 1 | 1/3 | 0 |
| $q_R$ | 1 | 2 | 1/3 | 0 |
| $\ell_L$ | 2 | 1 | 0 | 1 |
| $\ell_R$ | 1 | 2 | 0 | 1 |
| $\Sigma_L$ | 3 | 1 | -3/4 | -3/4 |
| $\Sigma_R$ | 1 | 3 | -3/4 | -3/4 |
| $(\chi_L, \chi_R)$ | 1 | 1 | $n_B$ | $n_L$ |
| Scalars $\Phi$ | 2 | 2 | 0 | 0 |
| $\Delta_L$ | 3 | 1 | 0 | -2 |
| $\Delta_R$ | 1 | 3 | 0 | -2 |
| $S_{BL}$ | 1 | 1 | 3/2 | 3/2 |

### IV. ANOMALY CANCELLATION

where $n$ is the number of fermion generation and $N$ is the dimension of these lepto-quarks under $SU(3)_C$ gauge group.

We propose an anomaly free left-right symmetric model promoting baryon and lepton numbers as separate gauge symmetries. In addition to the usual quarks, $q_L(2, 1, 1/3, 0)$, $q_R(2, 1, 2/3, 0)$ and leptons, $\ell_L(1, 2, 0, 1)$ and $\ell_R(1, 2, 0, 1)$ we include extra lepto-quarks $\Sigma_L(3, 1, -3/4, -3/4)$ and $\Sigma_R(1, 3, -3/4, -3/4)$ for anomaly cancellation. The role of these lepto-baryons $\Sigma_{L,R}$ is to generate neutrino mass via type-III seesaw mechanism which has been pointed out in [15]. Instead in this letter we intend to discuss stable cold dark matter which can not only satisfy relic density consistent with PLANCK data and indirect detection constraints but can also give novel collider possibility. This can be easily incorporated by introducing a dark matter candidate which is a fermionic singlet under $SU(2)_L$ as $\chi_L(1, 1, n_B, n_L)\equiv \chi_L$ with the electrically charge neutral condition of DM impose equal value of $n_B$ and $n_L$. This singlet dark matter can be applicable to other scenarios also. The Higgs sector of the model consists of a bidoublet $\Phi \equiv (2_L, 2_R, 0_B, 0_L)$ and two triplet scalars, $\Delta_L \equiv (3_L, 1_R, 0_B, 0_L, 0_B)$ and $\Delta_R \equiv (3_R, 1_L, 0_B, 0_L, 0_L)$

$$\Delta_{L,R} \equiv \begin{pmatrix} \delta_{L,R}^+ / \sqrt{2} \\ \delta_{L,R}^- / \sqrt{2} \end{pmatrix}, \quad \Phi \equiv \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}.$$

along with singlet scalar $S_{BL}(1_L, 1_R, 3/2_B, 3/2_L)$. The spectrum is presented in Table[1].

At the first stage the symmetry is broken down to LR gauge group via $S_{BL}$ by breaking baryon and lepton number symmetries while preserving $B - L$. This singlet scalar also gives a Majorana mass term to fermion triplet once it takes a non-zero VEV. The second stage of symmetry breaking can be done via Higgs triplets.

\[3\] A viable model of left right theories promoting B and L as gauge symmetries and its connection to neutrino mass via type III seesaw has been studied in [15].
These triplets are needed for giving Majorana masses to neutrinos via respective VEVs of these Higgs triplets \( \langle \Delta_{L,R} \rangle = v_{L,R} \). Lastly, the electroweak symmetry is broken by standard Higgs doublet belonging to a bi-doublet \( \Phi \) with VEV \( \langle \Phi \rangle = \text{diag}(v_1, v_2) \). The hierarchy between different VEVs is \( v_L^2 \ll v_R^2 = v_1^2 + v_2^2 \ll v_B^2, v_{BL}^2 \).

We present here the Lagrangian for the present model as

\[
\mathcal{L}_{LR}^\text{BL} = \mathcal{L}^\text{scalar} + \mathcal{L}^\text{gauge}_{\text{Kin.}} + \mathcal{L}^\text{fermion}_{\text{Kin.}} + \mathcal{L}^\text{Yuk.}
\]

(2)

The different parts of the Lagrangian can then be written as follows. Firstly, the scalar Lagrangian is written as

\[
\mathcal{L}^\text{scalar} = \text{Tr}((D_\mu \Phi)^\dagger (D^\mu \Phi)) + \text{Tr}((D_\mu \Delta_L)^\dagger (D^\mu \Delta_L)) + \text{Tr}((D_\mu \Delta_R)^\dagger (D^\mu \Delta_R)) - \text{V}(\Phi, \Delta_L, \Delta_R, S_{BL})
\]

(3)

where \( \text{V}(\Phi, \Delta_L, \Delta_R, S_{BL}) \) is the scalar potential and \( D_\mu \) is the covariant derivative for respective scalars.

With the additional \( U(1)_{B,L} \) gauge groups, the Lagrangian for kinetic terms for gauge bosons is given by

\[
\mathcal{L}^\text{gauge}_{\text{Kin.}} = -\frac{1}{4} W_{\mu\nu L} W^{\mu\nu L} - \frac{1}{4} W_{\mu\nu R} W^{\mu\nu R} - \frac{1}{4} Z_{\mu\nu}^B Z^{\mu\nu B} - \frac{1}{4} Z_{\mu\nu}^F Z^{\mu\nu F}
\]

(4)

while that for fermions as

\[
\mathcal{L}^\text{fermion}_{\text{Kin.}} = \overline{i} \tau^a \gamma_{\mu} D_\mu q + \overline{i} \tau^a \gamma_{\mu} D_\nu q R + \overline{i} \tau^a \gamma_{\mu} D_\nu l L + \overline{i} \tau^a \gamma_{\mu} D_\nu l R + i \overline{\sigma} \gamma_{\mu} \gamma_5 \sigma v \nonumber
\]

(5)

Now we can define the respective covariant derivatives, in general, as

\[
D_\mu \Psi = \partial_\mu - i g_\nu \tau^a W_{\mu L}^a - i g_\nu \tau^a W_{\mu R}^a - i g_\nu \ell^a Z_{\mu L}^a - i g_\nu \ell^a Z_{\mu R}^a
\]

(6)

The Yukawa structure of the present framework is

\[
\mathcal{L}^\text{Yuk.} = Y_\Phi \overline{q}_{L} \Phi \Psi_R + \overline{Y}_\Phi \Psi \Phi_R + \overline{\lambda}_l \overline{\ell}\Phi \ell_R + (f_L (\ell_L) (i \tau_2) D_{\mu L} \ell_L + f_R (\ell_R) (i \tau_2) D_{\mu R} \ell_R)
\]

(7)

\[ + \lambda_\Sigma (\Sigma_L^\dagger C \Sigma_L + \Sigma_R^\dagger C \Sigma_R) S_{BL} + M_{\chi} \chi + \text{h.c.} \]

A. Gauge Boson Mass

In the present framework the mass matrix of the weak gauge bosons \((W_{\mu L}^a, W_{\mu R}^a, Z_{\mu L}^a, Z_{\mu R}^a)\), is given by

\[
\begin{pmatrix}
\frac{1}{2} g L^2 (v_1^2) & - \frac{1}{2} g L \bar{g}_R (v_1^2) & 0 & 0 \\
- \frac{1}{2} g L \bar{g}_R (v_1^2) & \frac{1}{2} g L^2 (v_2^2 + 4 v_R^2) & \frac{2}{9} g g \bar{g}_B v_R^2 & 0 \\
0 & \frac{2}{9} g g \bar{g}_B v_R^2 & \frac{1}{2} g L^2 (v_L^2 + 4 v_R^2) & \frac{2}{9} g g \bar{g}_B v_R^2 \\
0 & 0 & \frac{2}{9} g g \bar{g}_B v_R^2 & \frac{1}{2} g L^2 (v_1^2 + v_2^2) + \frac{1}{2} g g \bar{g}_B v_R^2
\end{pmatrix}
\]

where \( v^2 = v_1^2 + v_2^2 = 174 \text{ GeV}^2 \). The complete diagonalization gives one massless photon \( A \), SM neutral gauge boson \( Z \) and heavy neutral gauge boson \( Z_{1,2} \).

We now present a discussion of the dark matter phenomenology where we look at constraints from direct and indirect detection experiments and collider physics.

IV. DARK MATTER IN LRSM

We introduce the DM singlet fermion through the following Lagrangian term,

\[
\mathcal{L}^\text{DM} = i \chi \gamma^\mu D_\mu \chi - M \chi \chi + \frac{1}{2} M_{Z_{1,2}}^2 Z_{1,2} \chi^\dagger \chi + \frac{1}{2} M_{Z_2}^2 Z_2 \chi^\dagger \chi + \frac{1}{2} M_{Z_1}^2 Z_1 \chi^\dagger \chi
\]

(8)

where \( D_\mu \chi \) is \( (\partial_\mu + ig B_{\mu B} Z_{B\mu} + ig n_{1Z} Z_{1\mu}) \chi \). Here we denote weak gauge bosons by \( Z_{1,2} \) and \( Z \) while the mass eigenstates are denoted by \( Z_{1,2} \). Here \( Z_{B}, Z_{1,2} \) can be written in terms of an admixture of mass eigenstates of all neutral gauge bosons in the theory. Assuming mixing between SM neutral gauge boson \( Z \) and other heavy gauge bosons \( Z_{1,2} \) to be small \((< 10^{-3})\), the \( \chi \) annihilation channels through \( Z \) boson mediated processes can be neglected. Thus, the only relevant annihilation channels for \( \chi \) are coming from \( Z_{1,2} \) mediated diagrams. The interactions of DM with SM particles which contribute to the relic density are described by the following lagrangian term,

\[
- g_B n_B^f \gamma^\mu f Z_{B\mu} - g_n^f \gamma^\mu f Z_{1\mu}
\]

(9)

where \( g_B, g_n \) are gauge coupling for \( U(1)_{B,L} \) gauge groups while \( n_B^f, n_n^f \) are baryon and lepton charges for usual fermions including quarks and leptons.

Now, the expression for the DM relic density is given by

\[
\Omega_{DM} h^2 = \frac{2.14 \times 10^9 \text{GeV}^{-1}}{J(x_f) \sqrt{x_f}} M_{Pl}
\]

(10)

with \( J(x_f) \) written as

\[
J(x_f) = \int_x^\infty \frac{(\sigma v)(x)}{x^2} dx
\]

(11)

Here \( (\sigma v) \) is the thermally averaged DM annihilation cross section. The analytical expression for the DM annihilation cross section through an intermediate \( Z_{B,L} \) state is given by

\[
\sigma \propto \frac{N_{B}^f n_B^f g_B^4 n_n^f}{12 \pi \sqrt{8}} \sqrt{s - 4 m_{Z}^2 \left( s + 2 m_1^2 \right) \left( s + 2 m_2^2 \right)}
\]

\[
\left\{ \left( s - M_{Z_{2B}}^2 \right)^2 + M_{Z_2}^2 \Gamma_{Z_2}^2 \right\}
\]

(12)

Now in order to study the DM phenomenology we look at four specific benchmark points which are listed in Table [II] according to the parameters \( M_{\chi}, M_{Z_{2B}}, g_B \) and

\[
\begin{pmatrix}
\frac{1}{2} g L^2 (v_1^2) & - \frac{1}{2} g L \bar{g}_R (v_1^2) & 0 & 0 \\
- \frac{1}{2} g L \bar{g}_R (v_1^2) & \frac{1}{2} g L^2 (v_2^2 + 4 v_R^2) & \frac{2}{9} g g \bar{g}_B v_R^2 & 0 \\
0 & \frac{2}{9} g g \bar{g}_B v_R^2 & \frac{1}{2} g L^2 (v_L^2 + 4 v_R^2) & \frac{2}{9} g g \bar{g}_B v_R^2 \\
0 & 0 & \frac{2}{9} g g \bar{g}_B v_R^2 & \frac{1}{2} g L^2 (v_1^2 + v_2^2) + \frac{1}{2} g g \bar{g}_B v_R^2
\end{pmatrix}
\]
TABLE II: Benchmark points satisfying constraints from relic density, indirect signals of DM and collider physics.

| Benchmark point | $M_\chi$ (GeV) | $M_{Z_B}$ (GeV) | $g_B$ | $n_B$ | $\Omega h^2$ |
|-----------------|----------------|----------------|-------|-------|--------------|
| BP1             | 460            | 1000           | 0.03  | 2.0   | 0.1093       |
| BP2             | 470            | 1000           | 0.1   | 0.25  | 0.1169       |
| BP3             | 898            | 2000           | 0.1   | 2.0   | 0.1101       |
| BP4             | 925            | 2000           | 0.25  | 0.25  | 0.1104       |

Although the current framework includes two neutral gauge bosons $Z_{B,L}$ in addition to the SM ones, we choose $Z_B$ to be the mediator for DM interactions with SM particles while the other extra gauge boson is chosen to be super heavy and hence does not give any observable signal. We choose the benchmark points such that the relic density $\Omega h^2$ lies within $5\sigma$ limit of the PLANCK value $0.1199 \pm 0.0022$\cite{Planck18}. In each of the four benchmark points we chose $M_{Z_B}/g_B \gtrsim 6$ TeV in accordance with the LEP limit on $Z'$. Here we note that much more stringent constraints on $Z'$ have recently been analysed using the LHC data on dilepton searches which constrains $Z'$ mass to be $\gtrsim 2$ TeV \cite{Aad12,Baum13}. However, these limits are for conventional cases of LRSM which are not strictly applicable to the scenario of LRSM considered here in which the gauge couplings corresponding to $U(1)_B$, $U(1)_L$ gauge groups are free parameters.

Recent limits from searches for monochromatic gamma ray emission from HESS \cite{Aharonian09} and Fermi-LAT \cite{Ackermann13} put constraints in the current framework of LRSM model where gamma ray line signal can be generated from the following process

$$\chi\chi \rightarrow Z_B^* \rightarrow \gamma\gamma, h\gamma, Z\gamma$$  \hspace{1cm} (13)

$$\chi\chi \rightarrow Z_L^* \rightarrow \gamma\gamma, h\gamma, Z\gamma.$$  \hspace{1cm} (14)

In the present scenario gamma ray line signatures can be observed from processes with final states $h\gamma$ and $Z\gamma$ while $\gamma\gamma$ is absent as it only occurs for axial couplings of DM to $Z_B$\cite{Jiang14}. The gamma ray line produced in this way could be seen distinctly in experiments since most of the astrophysical sources produce continuum spectra. We plot the DM signal from the $h\gamma$ and $Z\gamma$ channels along with the observed data from the gamma ray line searches of H.E.S.S\cite{Aharonian09} and Fermi-LAT\cite{Ackermann13} as shown in Fig.1. We use the Einasto profile of DM density distribution in order to compare with the experimental data and the analytical expressions for one loop cross section from \cite{Jiang14}. We see that the DM signal for the four benchmark points chosen is well below the observed data, this is because higher values of DM coupling to $Z_B$ would conflict with the direct detection limits whose results are shown in Fig. 2. In order to reduce the direct detection scattering cross section the coupling of DM to $Z_B$ needs to be decreased and this in turn results in an overabundance of relic density. In order to achieve the correct relic density the annihilation rate of DM needs to be increased and this is done through increasing the mass of the $Z_B$ such that it gets closer to the resonance value of $\sim 2M_\chi$. In addition we also see that the constraint from dwarf spheroidal galaxies by Fermi-LAT \cite{Abazajian13} is also satisfied as is shown in Fig. 3 where the annihilation rate for $bb$ is plotted for the benchmark points which satisfy relic density. In conclusion we see that the constraints from direct detection are the strongest on the DM mass range below 1 TeV which we have chosen in our benchmark points.
V. CONCLUSION

We have shown that a singlet stable dark matter naturally arises within LRSM where baryon and lepton numbers are promoted to separate gauge symmetries. We point out that the electric charge neutrality condition for DM forces it’s charges under $U(1)_{B,l}$ gauge groups to be equal. We then proceed to study the DM phenomenology in such a scenario. We present benchmark points that satisfy constraints from direct as well as indirect detection experiments while being consistent with the relic density observation. In particular we look at constraints from gamma ray line searches by Fermi-LAT and HESS as well as limits on $bb$ cross section from observations on dwarf spheroidal galaxies by Fermi-LAT and direct detection limits from LUX and XENON100. We find that for DM mass range below 1 TeV the strongest constraints come from direct detection experiments. And finally, we note that this formalism can also be applied to singlet scalar DM which we plan to pursue in future work.

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