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Physics Letters B

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Singlet fermion dark matter within left-right model

Sudhanwa Patra^{a,*}, Soumya Rao^b^a Center of Excellence in Theoretical and Mathematical Sciences, Siksha 'O' Anusandhan University, Bhubaneswar, 751030, India^b ARC Centre of Excellence for Particle Physics at the Terascale, Department of Physics, University of Adelaide, Adelaide, SA 5005, Australia

ARTICLE INFO

Article history:

Received 18 January 2016

Received in revised form 26 May 2016

Accepted 30 May 2016

Available online 9 June 2016

Editor: G.F. Giudice

ABSTRACT

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 $Z_{B,\ell}$ gauge bosons. This can give rise to a dark matter particle of a few hundred GeV that couples to \sim TeV scale gauge bosons to give the correct relic density. This model thus accommodates TeV scale $Z_{B,\ell}$ gauge bosons and other low scale BSM particles, which can be easily probed at LHC.

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1. 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) [1–6] provides a framework for incorporating potential DM candidates in a beyond SM (BSM) scenario with the introduction of additional multiplets [7]. 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. [8,9] that the keV scale right handed neutrino can be a long-lived warm DM candidate.¹ 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 [7] 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

* Corresponding author.

E-mail addresses: sudha.astro@gmail.com (S. Patra), soumya.rao@adelaide.edu.au (S. Rao).¹ Ref. [10] studies the interesting signatures of these keV right handed neutrinos in neutrino mass searches.<http://dx.doi.org/10.1016/j.physletb.2016.05.098>0370-2693/© 2016 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

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 [11].

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 [12] 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.² 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.

2. 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 [1–6] is given by

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

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

² Gauge theories of baryons and leptons have been discussed in ref. [13].

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

The usual quarks and leptons belong to following representations

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

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

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 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.

3. 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 given by [14]

$$\mathcal{G}_{L,R}^{BL} \equiv SU(2)_L \times SU(2)_R \times U(1)_B \times U(1)_L$$

—omitting the $SU(3)_C$ structure for simplicity. The standard quarks and leptons transforming under this new class of left-right symmetric gauge group are

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

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

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

$$\mathcal{A}[SU(2)_L^2 \times U(1)_B] = 3/2,$$

$$\mathcal{A}[SU(2)_R^2 \times U(1)_B] = -3/2,$$

$$\mathcal{A}[SU(2)_L^2 \times U(1)_L] = 3/2,$$

$$\mathcal{A}[SU(2)_R^2 \times U(1)_L] = -3/2,$$

along with other vanishing gauge anomalies $\mathcal{A}[U(1)_{B(L)}^2 \times U(1)_{L(B)}]$, $\mathcal{A}[\text{gravity} \times U(1)_{L(B)}]$ and $\mathcal{A}[U(1)_{L(B)}^3]$. 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-quarks³ 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:

Table 1

Particle content of LR model where Baryon and Lepton number individually gauged. The baryon n_B and lepton charges n_L are same in order to ensure electromagnetic charge neutrality of the Dirac fermion $\chi = \chi_L \oplus \chi_R$.

	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
	ℓ_L	2	1	0	1
	ℓ_R	1	2	0	1
	Σ_L	3	1	-3/4	-3/4
	Σ_R	1	3	-3/4	-3/4
	(χ_L, χ_R)	1	1	n_B	n_L
Scalars	Φ	2	2	0	0
	Δ_L	3	1	0	-2
	Δ_R	1	3	0	-2
	S_{BL}	1	1	3/2	3/2

- A. $\Sigma_L \sim (1, 3, 1, -\frac{3}{4}, -\frac{3}{4})$, $\Sigma_R \sim (1, 1, 3, -\frac{3}{4}, -\frac{3}{4})$,
 B. $\Psi_L \sim (1, 2, 1, -n, -n)$, $\Psi_R \sim (1, 1, 2, -n, -n)$,
 C. $\Psi_L \sim (3, 2, 1, -\frac{n}{3}, -\frac{n}{3})$, $\Psi_R \sim (3, 1, 2, -\frac{n}{3}, -\frac{n}{3})$,
 D. $\Psi_L \sim (N, 2, 1, -\frac{n}{N}, -\frac{n}{N})$, $\Psi_R \sim (N, 1, 2, -\frac{n}{N}, -\frac{n}{N})$,

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, $q_L(2, 1, 1/3, 0)$, $q_R(1, 2, 1/3, 0)$ and leptons, $\ell_L(2, 1, 0, 1)$ 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 $SU(2)_{L,R}$ as $\chi(1, 1, n_B, n_L)$ 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, $\Delta_L \equiv (3_L, 1_R, 0_B, 2_L)$ and $\Delta_R(1_L, 3_R, 0_B, 2_L)$

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

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. 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 Φ with VEV $\langle \Phi \rangle = \text{diag}(v_1, v_2)$. The hierarchy between different VEVs is $v_L^2 \ll v^2 = v_1^2 + v_2^2 \ll v_R^2, v_{BL}$.

We present here the Lagrangian for the present model as

$$\mathcal{L}_{LR}^{BL} = \mathcal{L}_{\text{scalar}} + \mathcal{L}_{\text{Kin.}}^{\text{gauge}} + \mathcal{L}_{\text{Kin.}}^{\text{fermion}} + \mathcal{L}_{\text{Yuk.}} \quad (2)$$

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

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].

$$\begin{aligned} \mathcal{L}_{\text{scalar}} = & \text{Tr}[(\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi)] + \text{Tr}[(\mathcal{D}_\mu \Delta_L)^\dagger (\mathcal{D}^\mu \Delta_L)] \\ & + \text{Tr}[(\mathcal{D}_\mu \Delta_R)^\dagger (\mathcal{D}^\mu \Delta_R)] + (\mathcal{D}_\mu S_{BL})^\dagger (\mathcal{D}^\mu S_{BL}) \\ & - \mathcal{V}(\Phi, \Delta_L, \Delta_R, S_{BL}) \end{aligned} \quad (3)$$

where $\mathcal{V}(\Phi, \Delta_L, \Delta_R, S_{BL})$ is the scalar potential and \mathcal{D}_μ 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

$$\begin{aligned} \mathcal{L}_{\text{Kin.}}^{\text{gauge}} = & -\frac{1}{4} W_{\mu\nu L} W^{\mu\nu L} - \frac{1}{4} W_{\mu\nu R} W^{\mu\nu R} \\ & - \frac{1}{4} Z_{\mu\nu}^B Z^{\mu\nu, B} - \frac{1}{4} Z_{\mu\nu}^\ell Z^{\mu\nu, \ell} \end{aligned} \quad (4)$$

while that for fermions by

$$\begin{aligned} \mathcal{L}_{\text{Kin.}}^{\text{fermion}} = & i\bar{q}_L \gamma^\mu \mathcal{D}_\mu q_L + i\bar{q}_R \gamma^\mu \mathcal{D}_\mu q_R + i\bar{\ell}_L \gamma^\mu \mathcal{D}_\mu \ell_L \\ & + i\bar{\ell}_R \gamma^\mu \mathcal{D}_\mu \ell_R + i\bar{\Sigma}_L \gamma^\mu \mathcal{D}_\mu \Sigma_L + i\bar{\Sigma}_R \gamma^\mu \mathcal{D}_\mu \Sigma_R \end{aligned} \quad (5)$$

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

$$\begin{aligned} \mathcal{D}_\mu^\Psi \Psi = & \left[\partial_\mu - i g_L \tau^a W_{\mu L}^a - i g_R \tau^a W_{\mu R}^a \right. \\ & \left. - i g_B B^\Psi Z_\mu^B - i g_\ell \ell^\Psi Z_\mu^\ell \right] \Psi \end{aligned} \quad (6)$$

The Yukawa structure of the present framework is

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} = & Y_q \bar{q}_L \Phi q_R + \tilde{Y}_q \bar{q}_L \tilde{\Phi} q_R \\ & + Y_\ell \bar{\ell}_L \Phi \ell_R + \tilde{Y}_\ell \bar{\ell}_L \tilde{\Phi} \ell_R \\ & + [f_L (\bar{\ell}_L)^c (i\tau_2) \Delta_L \ell_L + f_R (\bar{\ell}_R)^c (i\tau_2) \Delta_R \ell_R] \\ & + \lambda_\Sigma \left(\Sigma_L^T C \Sigma_L + \Sigma_R^T C \Sigma_R \right) S_{BL} \\ & + M_\chi \bar{\chi} \chi + \text{h.c.} \end{aligned} \quad (7)$$

3.1. Gauge boson mass

In the present framework the mass matrix of the weak gauge bosons ($W_\mu^{3L}, W_\mu^{3R}, Z_\mu^\ell, Z_\mu^B$), is given by

$$\begin{pmatrix} \frac{1}{4} g_L^2 (v^2) & -\frac{1}{4} g_L g_R (v^2) & 0 & 0 \\ -\frac{1}{4} g_L g_R (v^2) & \frac{1}{4} g_R^2 (v^2 + 4v_R^2) & 2g_R g_\ell v_R^2 & 0 \\ 0 & 2g_R g_\ell v_R^2 & \frac{9}{4} g_\ell^2 v_{BL}^2 + 4g_\ell^2 v_R^2 & \frac{9}{4} g_B g_\ell v_{BL}^2 \\ 0 & 0 & \frac{9}{4} g_B g_\ell v_{BL}^2 & \frac{9}{4} g_B^2 v_{BL}^2 \end{pmatrix}$$

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.

4. Dark matter in LRSM

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

$$\mathcal{L}_{DM} = i\bar{\chi} \gamma^\mu \mathcal{D}_\mu \chi - M \bar{\chi} \chi + \frac{1}{2} M_{Z_1}^2 Z_{1\mu} Z_1^\mu + \frac{1}{2} M_{Z_2}^2 Z_{2\mu} Z_2^\mu \quad (8)$$

where $\mathcal{D}_\mu \chi = (\partial_\mu + i g_B n_B Z_{B\mu} + i g_\ell n_\ell Z_{\ell\mu}) \chi$. Here we denote weak gauge bosons by Z_ℓ and Z_B while the mass eigenstates are

Table 2

Benchmark points satisfying constraints from relic density, indirect signals of DM and collider physics.

Benchmark point	M_χ	M_{Z_B}	g_B	n_B	Ωh^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

denoted by $Z_{1,2}$. Here Z_B, Z_ℓ 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 $\bar{\chi}\chi$ annihilation channels through Z boson mediated processes can be neglected. Thus, the only relevant annihilation channels for $\bar{\chi}\chi$ 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,

$$-g_B n_B^f \bar{f} \gamma^\mu f Z_{B\mu} - g_\ell n_\ell^f \bar{f} \gamma^\mu f Z_{\ell\mu}, \quad (9)$$

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

Now, the expression for the DM relic density is given by [16]

$$\Omega_{DM} h^2 = \frac{2.14 \times 10^9 \text{ GeV}^{-1}}{J(x_f) \sqrt{g_*} M_{\text{Pl}}}, \quad (10)$$

with $J(x_f)$ written as

$$J(x_f) = \int_{x_f}^{\infty} \frac{\langle \sigma v \rangle (x)}{x^2} dx. \quad (11)$$

Here $\langle \sigma v \rangle$ is the thermally averaged DM annihilation cross section. The analytical expression for the DM annihilation cross section through an intermediate $Z_{B,\ell}$ state is given by [17]

$$\begin{aligned} \sigma(\bar{\chi}\chi \rightarrow Z_{B,\ell}^* \rightarrow \bar{f}f) = & \frac{N_c^f n_B^f{}^2 g_B^4 n_B^f{}^2}{12\pi s} \\ & \frac{\sqrt{s - 4m_f^2} (s + 2m_\chi^2) (s + 2m_f^2)}{\sqrt{s - 4m_\chi^2} \left((s - M_{Z_B}^2)^2 + M_{Z_B}^2 \Gamma_{Z_B}^2 \right)} \end{aligned} \quad (12)$$

Now in order to study the DM phenomenology we look at four specific benchmark points which are listed in Table 2 according to the parameters M_χ, M_{Z_B}, g_B and n_B . Although the current framework includes two neutral gauge bosons $Z_{B,\ell}$ 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 Ωh^2 lies within 5σ limit of the PLANCK value 0.1199 ± 0.0022 [12]. In each of the four benchmark points we chose $M_{Z_B}/g_B \gtrsim 6 \text{ TeV}$ 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 constrain Z' mass to be $\gtrsim 2 \text{ TeV}$ [22,23]. 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 [18] and Fermi-LAT [19] put constraints in the

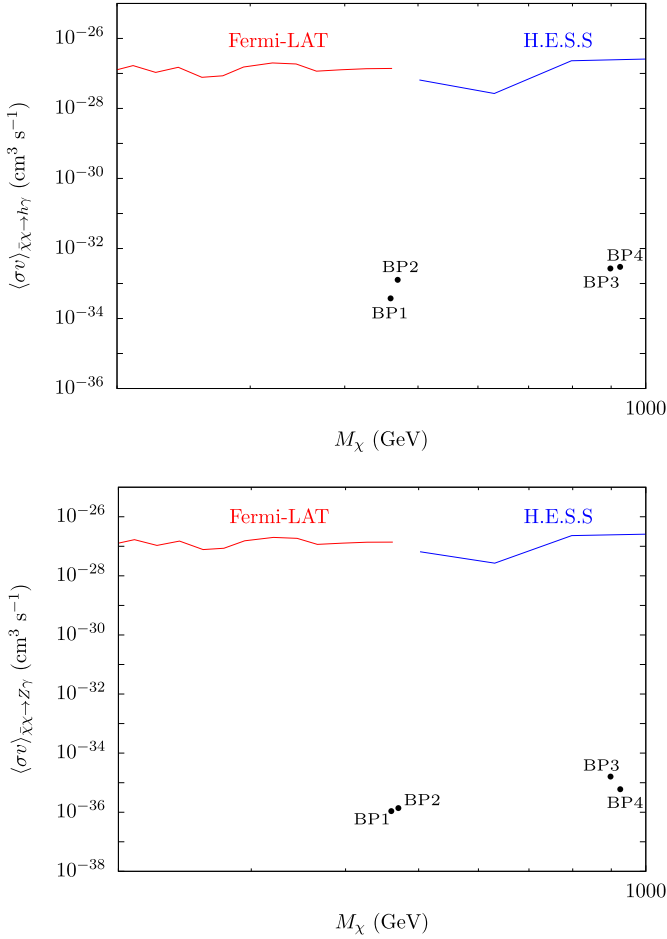


Fig. 1. Gamma ray signal from the processes $\bar{\chi}\chi \rightarrow h\gamma$ (top panel) and $\bar{\chi}\chi \rightarrow Z\gamma$ (bottom panel) along with the observed data from HESS [18] and Fermi-LAT [19] for the benchmark points listed in Table 2.

current framework of LRSM model where gamma ray line signal can be generated from the following process

$$\bar{\chi}\chi \rightarrow Z_B^* \rightarrow \gamma\gamma, h\gamma, Z\gamma \quad (13)$$

$$\bar{\chi}\chi \rightarrow Z_\ell^* \rightarrow \gamma\gamma, h\gamma, Z\gamma. \quad (14)$$

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 [17]. 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 HESS [18] and Fermi-LAT [19] 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 [17]. 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

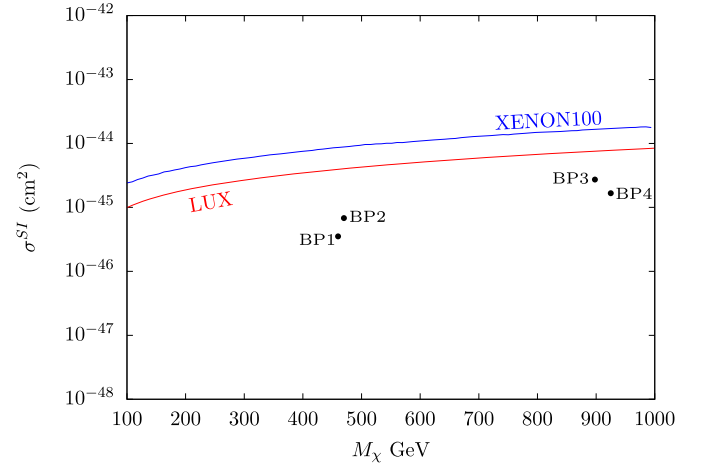


Fig. 2. Spin independent cross section from DM scattering off nucleons along with limits from LUX [20] and XENON100 [21] for the benchmark points listed in Table 2.

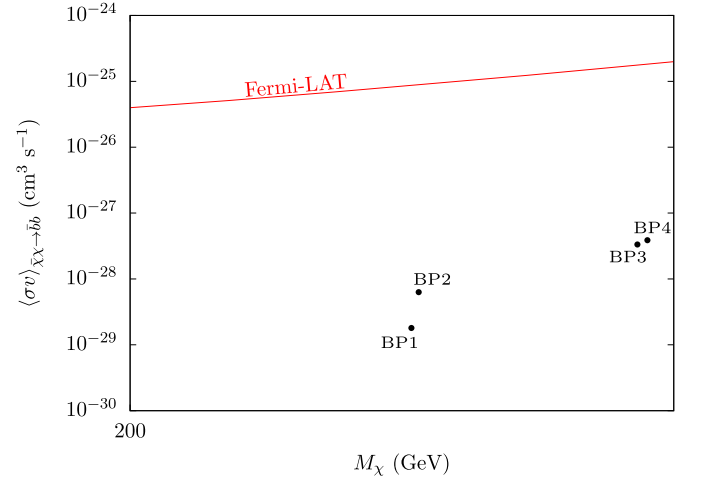


Fig. 3. The DM annihilation rate for $\bar{b}b$ channel for the benchmark points shown in Table 2. Also shown in red is the Fermi-LAT constraint from dwarf spheroidal galaxies on the $\bar{b}b$ annihilation rate.

by Fermi-LAT [24] is also satisfied as shown in Fig. 3 where the annihilation rate for $\bar{b}b$ 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.

5. 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 its 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 $\bar{b}b$ 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.

Acknowledgements

Both the authors acknowledge the warm hospitality provided by the organisers during the WHEPP XIV workshop held in IIT Kanpur, India, between 4th–13th December, 2015, during which this work was completed. The work of SP is partially supported by the Department of Science and Technology, Govt. of India under the financial grant SB/S2/HEP-011/2013.

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