Galactic Gamma Ray Excess and Dark Matter Phenomenology in a $U(1)_{B-L}$ Model

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Abstract

In this work, we have considered a gauged $U(1)_{B-L}$ extension of the Standard Model (SM) with three right handed neutrinos for anomaly cancellation and two additional SM singlet complex scalars with nontrivial B-L charges. One of these is used to spontaneously break the $U(1)_{B-L}$ gauge symmetry, leading to Majorana masses for the neutrinos through the standard Type I seesaw mechanism, while the other becomes the dark matter (DM) candidate in the model. We test the viability of the model to simultaneously explain the DM relic density observed in the CMB data as well as the Galactic Centre (GC) $\gamma$-ray excess seen by Fermi-LAT. We show that for DM masses in the range 40-55 GeV and for a wide range of $U(1)_{B-L}$ gauge boson masses, one can satisfy both these constraints if the additional neutral Higgs scalar has a mass around the resonance region. In studying the dark matter phenomenology and GC excess, we have taken into account theoretical as well as experimental constraints coming from vacuum stability condition, Planck bound on DM relic density, LHC and LUX and present allowed areas in the model parameter space consistent with all relevant data, calculate the predicted gamma ray flux from the GC and discuss the related phenomenology.

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I. INTRODUCTION

The presence of dark matter in the Universe is now well established. Its presence has been probed by its gravitational interaction with the visible world such as the rotation curve of spiral galaxies [1], gravitational lensing [2], and the phenomena of the Bullet cluster [3]. Meanwhile, the amount of dark matter present in the Universe has already been measured with an unprecedented accuracy by various satellite borne experiments like WMAP [4] and Planck [5]. The results of these experiments reveal that our Universe has more than 80% of its matter content in the form of dark matter while the remaining part is composed of known baryonic matter. However, the possible nature of the constituents of dark matter and their interactions with the Standard Model (SM) particles as well as with themselves still remains an enigma. As the Standard Model of particle physics does not have any fundamental particle which can play the role of a dark matter candidate, there exist many extensions of SM which can accommodate a single [6–16] or multicomponent dark matter scenarios [17–22]. Out of these different types of dark matter scenarios the most favourable one is the class of particles known as weakly interacting massive particle or WIMP [23, 24]. This class of dark matter particles were produced thermally at early stage of the Universe and maintained their thermal as well as chemical equilibrium through the interactions with other particles within the thermal plasma. As the Universe expanded and cooled down their rates began to decrease and eventually, when the annihilation rate of WIMP became less than the expansion rate of the Universe, WIMP decoupled from the thermal plasma and froze to a particular relic density.

Particle nature of WIMP can be explored mainly in two possible ways. First is the method of direct detection, where the information about WIMP mass and the nature of its interaction with SM particles can be obtained by measuring the recoil energy of the detector nuclei scattered by the WIMP. There are many ongoing dark matter direct detection experiments such as LUX [25, 26], XENON1T [27] and SuperCDMS [28]. However, none of them have observed yet any “real event” which is produced by the scattering of dark matter particles with the detector nuclei and have thus placed an upper bound on both the spin independent and spin dependent scattering cross sections of WIMP as a function of its mass. Another promising method is the indirect detection of dark matter, where the detection of annihilation products of gravitationally bound dark matter particles within the core of massive celestial objects like the Sun, galaxies, galaxy clusters and dwarf galaxies can provide viable information about the particle nature of dark matter. These annihilation products include high energy neutrinos, gamma-rays and charged cosmic rays (electrons, positrons, protons and antiprotons) [29]. Among these annihilation products gamma-rays and neutrinos play an important role as they propagate through these celestial objects unperturbed and thereby directly point towards their sources.

Recently, several groups have reported [30–40] an excess in gamma-ray flux in the energy range
1 – 3 GeV by analysing the Fermi-LAT publicly available data [41]. These analyses reveal that the observed gamma-ray flux originates from the inner few degrees around the centre of our Milky Way galaxy and the nature of this excess gamma-ray spectrum is compatible with that produced by the annihilation of WIMP dark matter in the Galactic Centre (GC) region. Although, there are astrophysical explanations of this anomalous gamma-ray excess in terms of unresolved point sources (e.g. millisecond pulsars) around the GC [42, 43], in this work we consider a dark matter explanation of the GC gamma-ray excess. In Ref. [40], the authors have shown that this observed gamma-ray flux can be well explained by an annihilating self-conjugate dark matter of mass around $48^{+6.4}_{-5.2}$ GeV with an annihilation cross section $\langle \sigma v \rangle_{\bar{b}b} = 1.75^{+0.28}_{-0.26} \times 10^{-26}$ cm$^3$/s for the $\bar{b}b$ annihilation channel. In this analysis they have used an NFW [44] dark matter halo profile with $\gamma = 1.26$ and local dark matter density $\rho_\odot = 0.4$ GeV/cm$^3$. Moreover, the authors of Ref. [40] have considered a region where galactic longitude and latitude vary in the range $|l| < 20^0$ and $2^0 < |b| < 20^0$ respectively as the region of interest (ROI) for their analysis. It is also mentioned in Ref. [40] that the uncertainties in the “astrophysical J factor”, due to our poor knowledge about DM halo profile parameters, can change the best fit DM annihilation cross section $\langle \sigma v \rangle_{\bar{b}b}$ by a multiplicative factor $A$ which varies in the range [0.17,5.3]. Various particle dark matter models explaining the Galactic Centre gamma-ray excess are available in Refs. [45–74].

In this work, we consider an extension of the SM where the gauge sector of SM is enhanced by a local $U(1)_{B-L}$ gauge group where B and L represent the baryon and lepton numbers respectively. In this model we have an extra neutral gauge boson $Z_{BL}$ as the model Lagrangian possesses an additional local $U(1)_{B-L}$ gauge invariance. In order to construct an anomaly free theory, the model needs three right handed neutrinos with $B - L$ charge equal to $-1$. Thus, $B - L$ extension of the SM is a well motivated beyond Standard Model (BSM) theory which can explain the origin of tiny neutrino masses through the type-I seesaw mechanism. Majorana mass terms of these three right handed neutrinos are generated in a gauge invariant way by introducing a SM gauge singlet scalar $\phi_H$ having $B - L$ charge $+2$. The $U(1)_{B-L}$ gauge symmetry breaks spontaneously when the scalar field $\phi_H$ gets a vacuum expectation value $v_{BL}$, thereby generating mass of the $B - L$ gauge boson $Z_{BL}$ and the right handed neutrinos. The mixing between the neutral components of $\phi_H$ and the SM Higgs doublet $\phi_h$ produces two physical scalars namely $h_1$ and $h_2$ where $h_1$ is identified as the SM-like Higgs boson with mass around 125.5 GeV. The $B - L$ extension of SM [75–78] has been explored before in the context of dark matter phenomenology [60, 79–86] and baryogenesis in the early Universe in Refs. [87–89]. In the present work we have introduced a complex scalar field $\phi_{DM}$ to the $U(1)_{B-L}$ extension of SM. This complex scalar field $\phi_{DM}$ is singlet under the SM gauge group while it transforms nontrivially under $U(1)_{B-L}$ gauge group. By choosing proper $B - L$ charge, this scalar field $\phi_{DM}$ can be made stable and hence it can play the role of a viable dark matter candidate. In this present work, we have considered the low mass region 40 GeV to 55 GeV of DM masses to explain the Fermi-LAT gamma-ray
excess from the Galactic Centre, whereas the high mass region has been studied in Ref. [85]. We have calculated the relic density of $\phi_{DM}$ by solving Boltzmann equation numerically. We have found that the gamma-ray flux produced from the annihilation of $\phi_{DM}$ and $\phi_{DM}^\dagger$ can reproduce the gamma-ray excess as observed by Fermi-LAT from the direction of GC. Moreover, in this work, we have taken into account all the possible existing theoretical as well as experimental constraints obtained from experiments like LHC, LEP, LUX, Planck.

The paper is arranged in the following way. In Section II we describe the model in detail and discuss the constraints on it from different experiment. In Section III we calculate the relic density in this model. In Section IV we show the variation of the relic density with different model parameters. In Section V we explain the Fermi-LAT gamma-ray excess. Finally in Section VI we conclude.

II. MODEL

In the present work, we have considered “pure” $U(1)_{B-L}$ extension of the Standard Model (SM) of elementary particles where the SM gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$ is enhanced by an additional local $U(1)_{B-L}$ gauge symmetry where B and L represent the baryon and lepton numbers, respectively. Therefore, all the SM (quarks and leptons) fields transform nontrivially under this $U(1)_{B-L}$ gauge group. Besides the SM fields, we have to introduce three right handed neutrinos ($N_i$, $i = 1$ to 3) such that the present model becomes anomaly free. Further, in addition to the usual SM Higgs doublet $\phi_h$, the scalar sector of the SM is also extended by adding two SM gauge singlet complex scalar fields, namely $\phi_H$, $\phi_{DM}$ both of which possess nonzero $U(1)_{B-L}$ charge. $U(1)_{B-L}$ gauge symmetry breaks spontaneously when the scalar field $\phi_H$ gets a nonzero vacuum expectation value (VEV) $v_{BL}$. Consequently, we have one extra neutral massive gauge field $Z_{BL}$ in the model. Moreover, after spontaneous breaking of $U(1)_{B-L}$ symmetry, the Majorana mass terms for the three right handed neutrinos can be generated in a gauge invariant way by choosing a suitable $U(1)_{B-L}$ charge +2 of the scalar field $\phi_H$. Also, if the value of the relevant model parameters are such that the VEV of $\phi_{DM}$ is zero then the complex scalar field $\phi_{DM}$ can be made stable by giving an appropriate $B - L$ to it. Under such circumstances $\phi_{DM}$ can be a viable dark matter candidate. The $U(1)_{B-L}$ charges as well as the SM gauge charges of all the fields present in the model are given in a tabular form (see Table I).
Table I: Particle content and their corresponding charges under various symmetry groups.

| Gauge Group | Baryon Fields | Lepton Fields | Scalar Fields |
|-------------|---------------|---------------|---------------|
| $SU(2)_L$   | $Q_L^i = (u_L^i, d_L^i)^T$ | $L_L^i = (e_L^i, \nu_L^i)^T$ | $\phi_h$ |
| $U(1)_Y$    | 2 1 1         | 2 1 1         | $\phi_H$ |
| $U(1)_{B-L}$| 1/3 1/3 1/3   | -1 -1 -1      | $\phi_{DM}$ |

The Lagrangian of the present model including the SM Lagrangian $\mathcal{L}_{SM}$ is as follows

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{DM} + (D_\mu \phi_H)\dagger (D^\mu \phi_H) - \frac{1}{4} F_{BL\mu\nu} F_{BL}^{\mu\nu} + \frac{i}{2} \bar{N}_i \gamma^\mu D_\mu N_i - V(\phi_h, \phi_H)$$

$$- \sum_{i=1}^3 \frac{1}{2} \lambda_{N_i} \phi_H \bar{N}_i^c N_i - \sum_{i,j=1}^3 y_{ij} \bar{L}_i \phi_h N_j + h.c.,$$

with $\bar{\phi}_h = i \sigma_2 \phi_h^\ast$, while $\mathcal{L}_{DM}$ represents the dark sector Lagrangian whose expression is given by

$$\mathcal{L}_{DM} = (D_\mu \phi_{DM})\dagger (D^\mu \phi_{DM}) - \mu_{DM}^2 \phi_{DM} \phi_{DM} - \lambda_{DH} (\phi_{DM}^\dagger \phi_{DM})(\phi_h^\dagger \phi_h)$$

$$- \lambda_{DH} (\phi_{DM}^\dagger \phi_{DM})(\phi_h^\dagger \phi_h) - \lambda_{DM} (\phi_{DM}^\dagger \phi_{DM})^2,$$

and the self interactions of $\phi_H$ and its mutual interaction with the SM Higgs doublet $\phi_h$ are described by $V(\phi_h, \phi_H)$ which can be written as

$$V(\phi_h, \phi_H) = \mu_H^2 \phi_H^\dagger \phi_H + \lambda_H (\phi_H^\dagger \phi_H)^2 + \lambda_{HH} (\phi_h^\dagger \phi_h)(\phi_h^\dagger \phi_H).$$

In Eq. (1), $F_{BL\mu\nu} = \partial_\mu Z_{BL\nu} - \partial_\nu Z_{BL\mu}$ is the field strength tensor of the $U(1)_{B-L}$ gauge field $Z_{BL}$. Covariant derivative appearing in Eqs. (1, 2) is defined as

$$D_\mu \psi = (\partial_\mu + ig_{BL} Q_{BL}(\psi) Z_{BL\mu}) \psi,$$

where $\psi = \phi_H, \phi_{DM}, N_i$ and $Q_{BL}(\psi)$ is the corresponding $U(1)_{B-L}$ gauge charge which is given in Table II. In general, the Majorana mass matrix for the three right handed neutrinos, obtained after spontaneous breaking of $B-L$ symmetry, will contain off diagonal terms. However these off diagonal terms can be easily removed by changing the basis and therefore, we have considered the diagonal Majorana mass matrix for the three right handed neutrinos (or the right handed neutrinos $N_i$’s are in mass basis).

After spontaneous breaking of $U(1)_{B-L}$ symmetry the scalar fields $\phi_h$ and $\phi_H$ in unitary gauge take the following form

$$\phi_h = \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad \phi_H = \begin{pmatrix} v_{BL} + H_{BL} \end{pmatrix} \sqrt{2}.$$
where $v = 246$ GeV is the VEV of $\phi_h$, which breaks the electroweak symmetry to a $U(1)$ symmetry ($U(1)_{em}$). On the other hand the VEV of $\phi_H$, $v_{BL}$, is responsible for the breaking of $B - L$ gauge symmetry of the Lagrangian and thereby generates masses for the three right handed neutrinos as well as the gauge boson $Z_{BL}$,

$$M_{N_i} = \frac{\lambda_{N_i}}{\sqrt{2}} v_{BL},$$
$$M_{Z_{BL}} = 2 g_{BL} v_{BL}. \quad (6)$$

In Eq. (5) $H$ and $H_{BL}$ are two neutral scalar fields of $\phi_h$ and $\phi_H$ respectively. There is also mixing between $H$ and $H_{BL}$ through the term $\lambda_{hH}$ (see Eq. (3)). As a result, the mass matrix of $H$ and $H_{BL}$ contains off diagonal elements which are proportional to $\lambda_{hH}$, $v$ and $V_{BL}$. Hence, $H$ and $H_{BL}$ are not representing any physical field. The scalar mass matrix with respect to the basis $(H, H_{BL})$ is given by

$$M^2_{scalar} = \begin{pmatrix} 2\lambda_h v^2 & \lambda_h v v_{BL} \\ \lambda_h v v_{BL} & 2\lambda_{h} v^2_{BL} \end{pmatrix}. \quad (7)$$

In order to obtain the physical states we have to diagonalise the real symmetric matrix $M^2_{scalar}$ (Eq. (7)) by an orthogonal matrix. The physical fields or the mass eigenstates which are linearly related to $H$ and $H_{BL}$, can be obtained through the following relations

$$h_1 = H \cos \alpha + H_{BL} \sin \alpha, \quad h_2 = -H \sin \alpha + H_{BL} \cos \alpha, \quad (8)$$

where the scalar field $h_1$ is identified as the SM like Higgs boson and $h_2$ is the extra Higgs boson in the model, while $\alpha$ is the mixing angle between $H$ and $H_{BL}$ given as

$$\tan 2\alpha = \frac{\lambda_h v v_{BL}}{\lambda_h v^2 - \lambda_{h} v^2_{BL}}. \quad (9)$$

We will see later that from LHC results, the allowed values of the mixing angle $\alpha$ are extremely small. The expressions of masses of the three physical scalar fields $h_1$, $h_2$ and $\phi_{DM}$ are

$$M^2_{h_1} = \lambda_h v^2 + \lambda_{h} v^2_{BL} + \sqrt{(\lambda_h v^2 - \lambda_{h} v^2_{BL})^2 + (\lambda_h v v_{BL})^2},$$
$$M^2_{h_2} = \lambda_h v^2 + \lambda_{h} v^2_{BL} - \sqrt{(\lambda_h v^2 - \lambda_{h} v^2_{BL})^2 + (\lambda_h v v_{BL})^2},$$
$$M^2_{DM} = \mu_{DM}^2 + \frac{\lambda_{Dh} v^2}{2} + \frac{\lambda_{DH} v^2_{BL}}{2}. \quad (10)$$

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1 In present model we have taken all the coupling constants and VEVs as real.
Since $h_1$ is the SM like Higgs boson therefore we have taken $M_{h_1} = 125.5$ GeV.

In this model, besides the SM parameters, we have twelve unknown independent parameters, namely the masses of $h_2$, $\phi_{DM}$, $Z_{BL}$, $N_i$, $U(1)_{B-L}$ gauge coupling $g_{BL}$, $B-L$ charge ($n_{BL}$) of dark matter ($\phi_{DM}$), scalar mixing angle $\alpha$ and three quartic couplings $\lambda_{DH}$, $\lambda_{Dh}$, $\lambda_{DM}$. In terms of these independent parameters, the couplings appearing in the Lagrangian (Eqs. (1-3)) can be expressed as

$$
\lambda_H = \frac{M_{h_1}^2 + M_{h_2}^2 + (M_{h_2}^2 - M_{h_1}^2)\cos 2\alpha}{4v_{BL}^2},
$$

$$
\lambda_h = \frac{M_{h_1}^2 + M_{h_2}^2 + (M_{h_1}^2 - M_{h_2}^2)\cos 2\alpha}{4v^2},
$$

$$
\lambda_{hH} = \frac{(M_{h_1}^2 - M_{h_2}^2)\cos \alpha \sin \alpha}{v v_{BL}},
$$

$$
\mu_{\phi_h}^2 = -\frac{(M_{h_1}^2 + M_{h_2}^2)v + (M_{h_1}^2 - M_{h_2}^2)(v \cos 2\alpha + v_{BL} \sin 2\alpha)}{4v},
$$

$$
\mu_{\phi_H}^2 = -\frac{(M_{h_1}^2 + M_{h_2}^2)v_{BL} + (M_{h_1}^2 - M_{h_2}^2)(v_{BL} \cos 2\alpha - v \sin 2\alpha)}{4v_{BL}},
$$

where $\mu_{\phi_h}^2$ and $\mu_{\phi_H}^2$ are the quadratic self coupling of the SM Higgs doublet $\phi_h$ and the extra Higgs singlet $\phi_H$ respectively. Moreover, the model parameters are subjected to satisfy certain conditions arising from theoretical constraints as well as relevant experimental results. These constraints are briefly discussed below.

- **Vacuum Stability**: In our model we choose the ground state $(\phi_h, \phi_H, \phi_{DM}) = (v, v_{BL}, 0)$. This requires the following constrains on the quadratic self couplings of the scalar fields,

$$
\mu_{\phi_h}^2 < 0, \quad \mu_{\phi_H}^2 < 0 \quad \text{and} \quad \mu_{DM}^2 > 0.
$$

Also in order to obtained a stable ground state (vacuum), the quartic couplings, appearing in the Lagrangian, need to satisfy the following conditions

$$
\lambda_h \geq 0, \quad \lambda_H \geq 0, \quad \lambda_{DM} \geq 0, \quad \lambda_{hH} \geq 0, \quad \lambda_{Dh} \geq 0, \quad \lambda_{DH} \geq 0,
$$

$$
\sqrt{\lambda_{hH} + 2\sqrt{\lambda_h \lambda_H}} \sqrt{\lambda_{Dh} + 2\sqrt{\lambda_h \lambda_{DM}}} \sqrt{\lambda_{DH} + 2\sqrt{\lambda_H \lambda_{DM}}} + 2\sqrt{\lambda_h \lambda_{hH} \lambda_{DM} + \lambda_{hH} \lambda_{Dh} \lambda_{DM} + \lambda_{Dh} \lambda_{DH} \lambda_h} \geq 0.
$$

- **Planck Limit**: The relic density $\Omega_{DM}h^2$ of the dark matter particle $\phi_{DM}$ at the present epoch should lie within the range reported by the satellite borne experiment Planck [5],
which is

$$0.1172 \leq \Omega_{DM} h^2 \leq 0.1226 \quad \text{at } 68\% \text{ C.L.} \quad (14)$$

- **Stability of dark matter:** We give a $U(1)_{B-L}$ charge to the dark matter candidate ($\phi_{DM}$) in such a way so that all possible decay terms are forbidden by the invariance of $U(1)_{B-L}$ gauge symmetry which therefore ensures the stability of $\phi_{DM}$. In general, the possible decay terms of $\phi_{DM}$ are like $\phi_{DM} \bar{f}^p f^q H$ (where $p + q \leq 3$ and $p$, $q$ are integer can vary from 0 to 3) and $\phi_{DM} \bar{f'}^f$, where $f$ is $N_i$ and $f' = N_i^c$. From Table I one can see that the B – L charges of $\phi_h$ and $\phi_H$ are 0 and +2 respectively. Therefore if we take $n_{BL} \neq -2q$ then we can not write the term $\phi_{DM} \bar{f}^p f^q H$, as it will violate the $U(1)_{B-L}$ gauge symmetry. In addition, in our case, we have varied dark matter mass from 40 GeV to 55 GeV and $M_{DM} < M_{h_1}, M_{h_2}$ as a result any decay modes of $\phi_{DM}$ to these scalar bosons are kinematically forbidden. Moreover, due to the presence of $\phi_{DM} \bar{N}_i^c N_i$ term, the dark matter candidate can also decay into two Majorana type right handed neutrinos in the final state, if the kinematical condition ($M_{DM} > 2M_{N_i}, i = 1$ to 3) is satisfied, which can also destroy its stability. To get rid of this decay term we can not choose $n_{BL} = +2$ as the combination $\bar{N}_i^c N_i$ has B – L charge $-2$. Therefore, in order to avoid all the above mentioned decay terms (due to renormalizability of the Lagrangian we have considered operators only upto dimension 4) we need $n_{BL} \neq \pm 2q$ where $q$ is any integer between 0 and 3.

- **LEP bound:** Since the SM fermions are charged under the gauge group $U(1)_{B-L}$, therefore LHC should find some footprint of the B – L gauge boson $Z_{BL}$ as it can directly interact with all the SM fermions. The nondetection of any signature of $Z_{BL}$ puts a severe constraint on its mass ($M_{Z_{BL}}$) and B – L gauge coupling ($g_{BL}$). From LEP experiment the ratio $\frac{M_{Z_{BL}}}{g_{BL}}$ is bounded from below by the following condition \[90, 91\]

$$\frac{M_{Z_{BL}}}{g_{BL}} \gtrsim 6 - 7 \text{ TeV}.$$ \hspace{1cm} (15)

- **LUX limit:** In this model, the complex scalar field $\phi_{DM}$ is our dark matter candidate. Therefore, both $\phi_{DM}$ and its antiparticle can elastically scatter off the detector nuclei

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2 Since $\phi_{DM}$ is singlet under SM gauge group therefore a term like $\phi_{DM} \bar{f} f$ with $f$ being any Standard Model fermion is forbidden.

3 which is required to explain Fermi-LAT gamma excess \[40\], see section \[\text{V}\] for more detailed discussion.

4 Recent bounds on the mass and gauge coupling of $Z_{BL}$ from ATLAS collaboration are given in Ref. \[92\].
through the exchange of neutral scalars $h_1$, $h_2$ and $U(1)_{B-L}$ gauge boson $Z_{BL}$. Moreover, due to the presence of vector boson ($Z_{BL}$) mediator, the elastic scattering cross sections for the dark matter and its antiparticle are different. If we take the number densities of the dark matter and its antiparticle to be equal at the present epoch (which is true if the species has negligible chemical potential [23]), then we have to multiply the elastic scattering cross sections of dark matter and its antiparticle by a factor $1/2$ while comparing these scattering cross sections, obtained from the present model, with the experimental upper limits reported by the direct detection experiment LUX [25, 26]. The reason behind this is the exclusion regions in $\sigma_{SI} - M_{DM}$ plane reported by different dark matter direct detection experiments are computed assuming the existence of only one type of dark matter particle (and also self-conjugate) in the Universe. Although our model too has only one kind of dark matter candidate, however, it has a different antiparticle and they do not possess equal interaction strengths with the detector nuclei. Feynman diagrams for the elastic scattering of both $\phi_{DM}$ and $\phi_{DM}^\dagger$ with the nucleon ($N$) are shown in Fig. 1. These processes are mediated through the exchange of $h_1$, $h_2$ and $Z_{BL}$. The expressions of spin independent scattering cross sections off the nucleon ($N$) for both $\phi_{DM}$ and $\phi_{DM}^\dagger$ are given by

$$\sigma_{\phi_{DM}^\dagger} = \frac{\mu^2}{4\pi} \left[ \frac{M_N f_N \cos \alpha}{M_{DM} v} \left( \frac{\tan \alpha g_{\phi_{DM}\phi_{DM}^\dagger h_2}}{M_{h_2}^2} - \frac{g_{\phi_{DM}\phi_{DM}^\dagger h_1}}{M_{h_1}^2} \right) - \left( \frac{2 n_{BL} g_{BL}^2 f_{Z_{BL}}}{3 m_{Z_{BL}}^2} \right) \right]^2,$$

where $g_{\phi_{DM}\phi_{DM}^\dagger h_i}$ is the vertex factor for a vertex involving fields $\phi_{DM} \phi_{DM}^\dagger h_i$ ($i = 1, 2$) and its expression is given in Table I. The reduced mass between nucleon $N$ (proton or
neutron) and DM particle is denoted by $\mu$. Moreover, the nuclear form factor for the scalar mediated processes is $f_N \sim 0.3$ \footnote{N $\bar{N}$ $Z_{BL}$ coupling $g_{N N z_{BL}} = \sum_{q=u,d} f_N^q \times g_{q \bar{q} z_{BL}}$ \footnote{We have considered the central value of the combined signal strength of the SM Higgs boson reported by the CMS collaboration [95].} with $g_{q \bar{q} z_{BL}} = -\frac{g_{q \bar{q} z_{BL}}}{3}$ is the coupling for the vertex containing fields $q \bar{q} Z_{BL}$ (see Table II). Now for proton (neutron) $f_{p_q}^u = 2$, $f_{p_q}^d = 1$ ($f_{n_q}^u = 1$, $f_{n_q}^d = 2$) \footnote{see the expression of $g_{\phi_D M} \phi_{DM} Z_{BL}$ in Table II}. Therefore, for both the nucleon $N$ (and $p$) the coupling $g_{N N z_{BL}} = f_{z_{BL}} \times g_{q \bar{q} z_{BL}}$ with $f_{z_{BL}} = \sum_{q=u,d} f_{N_q}^N = 3$. Thus in this model form factors of proton and neutron are same for $Z_{BL}$ mediated diagram.} while that for $Z_{BL}$ mediated diagram is $f_{Z_{BL}} = 3.0$. \footnote{We have considered the central value of the combined signal strength of the SM Higgs boson reported by the CMS collaboration [95].} From the expression of spin independent scattering cross section it is seen that although, the elastic scattering cross sections of $\phi_{DM}$ and $\phi_{DM}^\dagger$ with $N$ are identical when the scattering processes are mediated through the scalar bosons only, however, if we include the $Z_{BL}$ mediated diagram then the elastic scattering cross sections for both $\phi_{DM}$ and $\phi_{DM}^\dagger$ become different from each other. It is due to the fact that the momentum dependent vertex factors for the vertices $\phi_{DM} \phi_{DM} Z_{BL}$ and $\phi_{DM}^\dagger \phi_{DM}^\dagger Z_{BL}$ are differ by a -ve sign (due to the change in sign of momentum while go from particle to anti particle scenario) from each other which results in a difference between $\sigma_{\phi_{DM}}$ and $\sigma_{\phi_{DM}^\dagger}$ arising from the interaction terms between $Z_{BL}$ and scalar bosons mediated diagrams. If $\sigma_{SI}^{exp}$ represents the upper limit of the spin independent scattering cross section reported by the LUX experiment for a particular dark matter mass then for a viable dark matter model both $\sigma_{\phi_{DM}}$ and $\sigma_{\phi_{DM}^\dagger}$ must satisfy the following condition

$$\sigma_{\phi_{DM}} + \sigma_{\phi_{DM}^\dagger} < 2\sigma_{SI}^{exp} , \tag{17}$$

\[ \bullet \] \textbf{LHC constraints:}

\begin{itemize}
  \item \textbf{Signal Strength of SM-like Higgs:} The signal strength of $h_1$ for a particular decay channel $h_1 \rightarrow X \bar{X}$ ($X$ is any SM particle such as gauge boson, quark or lepton) is defined as

$$R_{X \bar{X}} = \frac{\sigma BR(h_1 \rightarrow X \bar{X})}{[\sigma BR(h \rightarrow X \bar{X})]_{SM}} , \tag{18}$$

where $\sigma$ and $BR(h_1 \rightarrow X \bar{X})$ are the production cross section of $h_1$ and its branching ratio for $X \bar{X}$ decay channel. In the denominator of the above equation $[\sigma BR(h \rightarrow X \bar{X})]_{SM}$ represent the same quantities for the SM Higgs boson ($h$). If the neutral boson $h_1$ is similar to the SM Higgs boson then according to LHC result the signal strength ratio $R_{X \bar{X}}$ should be $> 0.8$ \footnote{We have considered the central value of the combined signal strength of the SM Higgs boson reported by the CMS collaboration [95].}. We will see later, in Fig. 3 (Section IV) that the above condition will impose severe constrain on the allowed values of scalar mixing angle $\alpha$.}

\end{itemize}
**Invisible decay width of Higgs boson:** In the present model, the SM like Higgs boson $h_1$ can decay into a pair of $\phi_{DM}$ and $\phi^\dagger_{DM}$ if the kinematical condition $M_{h_1} \geq 2M_{DM}$ is satisfied. Such decay channel is known as the invisible decay model of $h_1$. The expression of partial decay width of $h_1$ into $\phi_{DM}\phi^\dagger_{DM}$ final state is

$$\Gamma_{h_1\rightarrow \phi_{DM}\phi^\dagger_{DM}} = \frac{g_{h_1\phi_{DM}\phi^\dagger_{DM}}^2}{16\pi M_{h_1}} \sqrt{1 - \frac{4M^2_{DM}}{M^2_{h_1}}},$$

(19)

where $g_{h_1\phi_{DM}\phi^\dagger_{DM}}$ is the vertex factor for the vertex involving $h_1\phi_{DM}\phi^\dagger_{DM}$. Throughout this work we have considered the partial width of this invisible decay channel of $h_1$ to be less than 20% \cite{96, 97} of its total decay width.

**Fermi-LAT gamma excess from Galactic Centre:** In order to explain the Fermi-LAT observed gamma-ray excess from the Galactic Centre using a self-conjugate annihilating dark matter, one needs a dark matter particle of mass $48.7^{+6.4}_{-5.2}$ GeV \cite{40}. If we assume an NFW halo profile with $\gamma = 1.26$, $\rho_\odot = 0.4$ GeV/cm$^3$, $r_\odot = 8.5$ kpc and $r_s = 20$ kpc then the annihilation cross section of dark matter particle for the $b\bar{b}$ annihilation channel should lie in the range $\langle \sigma v \rangle_{bb} \sim 1.75^{+0.28}_{-0.26} \times 10^{-26}$ cm$^3$/s \cite{40}. However, if we take into account the uncertainties of DM halo profile parameters (mentioned above) then the quantity $\langle \sigma v \rangle_{bb}$ can vary in the range $\mathcal{A} \times 1.75^{+0.28}_{-0.26} \times 10^{-26}$ cm$^3$/s with $\mathcal{A} = [0.17, 5.3]$ \cite{40}. We will discuss about the Fermi-LAT gamma-ray excess elaborately in Section V where we will see that the required value of $\langle \sigma v \rangle_{bb}$ for a non-self-conjugate DM (which is true for the present model) is different from a dark matter candidate whose particles and antiparticles are same.
III. RELIC DENSITY

The evolution of total number density ($n$) of both $\phi_{DM}$ and $\phi_{DM}^\dagger$ is governed by the Boltzmann equation which is given by [23]

$$\frac{dn}{dt} + 3nH = -\frac{1}{2} \langle \sigma v \rangle (n^2 - (n_{eq}^2))^2,$$  

(20)

where $H$ is the Hubble parameter and $n_{eq}$ is the equilibrium number density of both $\phi_{DM}$ and $\phi_{DM}^\dagger$. $\sigma$ is the annihilation cross section for the channel $\phi_{DM}\phi_{DM}^\dagger \rightarrow f\bar{f}$, where $f$ is any SM fermion except top quark $^8$. Tree level Feynman diagrams for the process $\phi_{DM}\phi_{DM}^\dagger \rightarrow f\bar{f}$ mediated through the exchange of $h_1$, $h_2$ and $Z_{BL}$ are given in Fig. 2. The expression of $\sigma$ is as follows,

$$\sigma = \frac{3}{8\pi s} \sqrt{\frac{s - 4m_f^2}{s - 4M_{DM}^2}} \left\{ A^2 (s - 4m_f^2) \left| \frac{g_{h_1\phi_{DM}\phi_{DM}^\dagger}}{(s - M_{h_1}^2) + i\Gamma_{h_1}M_{h_1}} - \frac{\tan\alpha g_{h_2\phi_{DM}\phi_{DM}^\dagger}}{(s - M_{h_2}^2) + i\Gamma_{h_2}M_{h_2}} \right|^2 \right. \\
+ \left. \frac{2}{9} \frac{g_{BLh_{BL}^2}}{(s - M_{Z_{BL}}^2 + (\Gamma_{Z_{BL}}M_{Z_{BL}})^2)(s - 4M_{DM}^2) + 2m_f^2} \right\},$$  

(21)

where $\Gamma_i$ is the total decay width of the particle $i$ ($i = h_1, h_2, Z_{BL}$), $m_f$ is the mass of the SM fermion $f$ and $\sqrt{s}$ is centre of mass energy. $g_{i\phi_{DM}\phi_{DM}^\dagger}$ is the vertex factor for the vertex involving the fields $i\phi_{DM}\phi_{DM}^\dagger$ ($i = h_1, h_2$) and its expression is given in Table II. Moreover the quantity $A = \frac{m_f}{v} \cos\alpha$, with $\alpha$ is the scalar mixing angle, is the coupling for the vertex $f\bar{f}h_1$ (see Table II). In Eq. (20), $\langle \sigma v \rangle$ represents the thermal average of the product between annihilation cross section $\sigma$ and the relative velocity $v$ of the annihilating particles. Extra 1/2 factor appearing before $\langle \sigma v \rangle$ is due to non-self-conjugate nature of $\phi_{DM}$ [23]. Thermal averaged annihilation cross section $\langle \sigma v \rangle$ can be defined in terms of annihilation cross section $\sigma$ and modified Bessel functions ($K_1$, $K_2$) as [23]

$$\langle \sigma v \rangle = \frac{1}{8M_{DM}^4TK_2^2\left(\frac{M_{DM}}{T}\right)} \int_{4M_{DM}^2}^{\infty} \sigma (s - 4M_{DM}^2) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T}\right) \, ds,$$  

(22)

where $T$ is the temperature of the Universe. Now, we define two dimensionless variables $Y$ and $x$ as follows

$$Y = \frac{n}{s}, \quad x = \frac{M_{DM}}{T}$$

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$^8$ In order to explain Fermi-LAT $\gamma$-ray excess we need $M_{DM}$ in the range $48.7_{-6.0}^{+6.4}$ GeV [40] and thus other annihilation channels of $\phi_{DM}$ ($\phi_{DM}\phi_{DM}^\dagger \rightarrow W^+W^-, ZZ, Z_{BL}Z_{BL}, t\bar{t}, h_1h_1$ etc.) are not kinematically allowed.
with $s$ is the entropy density of the Universe while $Y$ is called the total comoving number density of both $\phi_{DM}$ and $\phi_{DM}^\dagger$. In terms of these two variables the Boltzmann equation, given in Eq. (20), can be written as

$$\frac{dY}{dx} = -\left(\frac{45G}{\pi}\right)^{\frac{1}{2}} \frac{M_{DM}}{x^2} \sqrt{g_*} \frac{1}{2} \langle \sigma v \rangle \left( Y^2 - (Y_{eq})^2 \right),$$

where $G$ is the Newton’s gravitational constant and $g_*$ is a function of effective degrees of freedom related to both energy and entropy densities of the Universe [23]. Now, one can find the value of the total comoving number density ($Y$) at the present temperature ($T_0 \sim 10^{-13} \text{ GeV}$) by solving the first order differential equation. The estimated value of $Y(T_0)$ is then used to compute the total relic abundance of both $\phi_{DM}$ and $\phi_{DM}^\dagger$ at the present epoch through the following equation [98]

$$\Omega_{DM}h^2 = 2.755 \times 10^8 \left( \frac{M_{DM}}{\text{GeV}} \right) Y(T_0).$$

**IV. RESULTS**

In this section we have shown how the relic density of DM varies with various model parameters namely $\alpha$, $g_{BL}$, $n_{BL}$, $M_{h_2}$, $M_{DM}$, $M_{Z_{BL}}$, $\lambda_{Dh}$, $\lambda_{DH}$. In order to compute the DM relic density, we have solved the Boltzmann equation (Eq. (23)) numerically using the micrOMEGAs [99] package while the information of the present model is supplied to micrOMEGAs through the LanHEP [100] package. All the constraints on the model parameters, listed in Section II, are also taken into account in the numerical calculations.

In the left panel (right panel) of Fig. 3 we plot the variation of DM relic density $\Omega h^2$ with the scalar mixing angle $\alpha$ for three different values of $\lambda_{DH} = -0.005$ ($\lambda_{Dh} = 0.008$) (green dashed line), $-0.0104$ (0.001) (red solid line) and $-0.015$ (0.004) (blue dashed-dotted line) while the values of other parameters are kept fixed at $g_{BL} = 0.01$, $M_{DM} = 52.0$ GeV, $M_{h_2} = 102.8$ GeV, $M_{Z_{BL}} = 104.1$ GeV, $\lambda_{Dh} = 0.001$ ($\lambda_{DH} = -0.0104$) and $n_{BL} = 0.15$. In this plot, magenta dotted line represents the central value of DM relic density as reported by the Planck collaboration ($\Omega h^2 = 0.1199$). From the Table II we see that the $Z_{BL}$ mediated diagram is independent of the mixing angle $\alpha$, so its contribution does not depend on $\alpha$. On the other hand the two Higgs scalars $h_1, h_2$ mediated diagrams are dependent on the mixing angle $\alpha$. It is seen from Fig. 3 that the dark matter relic density is practically independent of the mixing angle $\alpha$ when $\alpha$ becomes too small ($\alpha < 3 \times 10^{-3}$). This can be explained as follows, in this region $\sin \alpha \sim 0$ and the $h_2$ mediated diagram does not contribute since the $l\bar{l}h_2$ vertex is suppressed and it is mostly
the $Z_{BL}$ and $h_1$ mediated diagrams that contribute. For very small $\alpha$, even the $h_1$ mediated diagram is independent of $\alpha$ since $\cos \alpha \sim 1$, making $\Omega h^2$ constant with $\alpha$. We also note from left (right) panel of Fig. 3 that in this region, $\Omega h^2$ has no dependence on $\lambda_{DH}$ ($\lambda_{Dh}$). This again can be explained using the fact that here only the $h_1$ mediated diagram (in addition to the $Z_{BL}$ mediated diagram which is anyway independent of $\alpha$, $\lambda_{DH}$ and $\lambda_{Dh}$) contributes and Table II reveals that for small $\alpha$ we have impact of only $\lambda_{Dh}$ on $\Omega h^2$.

On the other hand if we start increasing the mixing $\alpha$ after the value ($\alpha > 3 \times 10^{-3}$), the scalars $h_1$ and $h_2$ both start contributing along with $B - L$ gauge boson $Z_{BL}$ in the DM annihilation process, which enhances $\langle \sigma v \rangle_{b\bar{b}}$. Therefore the relic density which is approximately inverse of $\langle \sigma v \rangle_{b\bar{b}}$ decreases with increase of mixing angle $\alpha$. Again we notice from Table II that the cos $\alpha$ dependent term in the vertex $\phi_{DM} \phi_{DM}^\dagger h_1$ and the sin $\alpha$ dependent term in the vertex $\phi_{DM} \phi_{DM}^\dagger h_2$ is proportional to $\lambda_{DH}$. This makes the relic density decrease with increasing $\lambda_{DH}$ for larger values of $\alpha$, as is evident from the left panel of Fig. 3. Likewise the right panel shows the dependence of

| Vertex | Vertex Factor |
|--------|---------------|
| $a b c$ | $g_{abc}$ |
| $q \bar{q} h_1$ | $-\frac{M_q}{v} \cos \alpha$ |
| $q \bar{q} h_2$ | $\frac{M_q}{v} \sin \alpha$ |
| $q \bar{q} Z_{BL}$ | $-\frac{g_{BL}}{v} \gamma^\mu$ |
| $l \bar{l} h_1$ | $-\frac{M_l}{v} \cos \alpha$ |
| $l \bar{l} h_2$ | $\frac{M_l}{v} \sin \alpha$ |
| $l \bar{l} Z_{BL}$ | $g_{BL} \gamma^\mu$ |
| $\phi_{DM} \phi_{DM}^\dagger h_1$ | $\frac{1}{2 g_{BL}} (2 g_{BL} v \lambda_{Dh} \cos \alpha + M_{Z_{BL}} \lambda_{DH} \sin \alpha)$ |
| $\phi_{DM} \phi_{DM}^\dagger h_2$ | $\frac{1}{2 g_{BL}} (2 g_{BL} v \lambda_{Dh} \sin \alpha - M_{Z_{BL}} \lambda_{DH} \cos \alpha)$ |
| $\phi_{DM} \phi_{DM}^\dagger Z_{BL}$ | $n_{BL} g_{BL} (p_2 - p_1)^\mu$ |
| $\phi_{DM} \phi_{DM}^\dagger h_1 h_1$ | $-(\lambda_{Dh} \cos^2 \alpha + \lambda_{DH} \sin^2 \alpha)$ |
| $\phi_{DM} \phi_{DM}^\dagger h_2 h_2$ | $-(\lambda_{Dh} \sin^2 \alpha + \lambda_{DH} \cos^2 \alpha)$ |
| $\phi_{DM} \phi_{DM}^\dagger Z_{BL} Z_{BL}$ | $\sin \alpha \cos \alpha (\lambda_{Dh} - \lambda_{DH})$ |
| $\phi_{DM} \phi_{DM}^\dagger Z_{BL} h_1 h_2$ | $2 g_{BL}^2 n_{BL}^2$ |
| $\phi_{DM} \phi_{DM}^\dagger \phi_{DM} \phi_{DM}^\dagger$ | $-4 \lambda_{DM}$ |

Table II: All possible vertex factors related to dark matter annihilation for the present model.
Region excluded only by LHC
Region excluded by LHC and LUX

n = 0.15
λ\text{DH} = -0.005
λ\text{DH} = -0.0104
λ\text{DH} = -0.015
Ω h^2 = 0.1199

Figure 3: Left (Right) panel: Variation of relic density Ω h^2 with mixing angle α for n_{BL} = 0.15 and three different values of λ_{DH} (λ_{Dh}) while other parameters value have been kept fixed at \( g_{BL} = 0.01, M_{DM} = 52.0 \text{ GeV}, M_{h_2} = 102.8 \text{ GeV}, M_{Z_{BL}} = 104.1 \text{ GeV}, \lambda_{Dh} = 0.001 (\lambda_{DH} = -0.0104). \)

the relic density on \( \lambda_{Dh} \) which comes from the first term of the \( \phi_{DM}\phi_{DM}^\dagger h_1 \) vertex. This explains the decrease of the relic density with \( \lambda_{Dh} \). In this figure, we have also shown the excluded region for mixing angle α from LUX and LHC experiment. The crossed region is excluded by both LUX and LHC experiment, whereas the forward lines is only excluded by LHC experiment.

Left panel of Fig. 4 represents the variation of Ω h^2 with \( U(1)_{B-L} \) gauge coupling \( g_{BL} \) for three different chosen values of \( \lambda_{DH} \). Here green dashed-dotted line is for \( \lambda_{DH} = -0.015 \), red solid line is for \( \lambda_{DH} = -0.0104 \) whereas the plot for \( \lambda_{DH} = -0.015 \) is shown by blue dashed line. Like the previous figures here also, the central value of Planck limit on DM relic density is indicated by magenta dotted line. It is seen from the left panel of Fig. 4 that initially the relic density increases with \( g_{BL} \) and attains a maximum value at \( g_{BL} \sim 0.01 \), thereafter it starts decreasing with \( g_{BL} \).

The initial rise of Ω h^2, for low \( g_{BL} \), is due to s channel process of \( \phi_{DM}\phi_{DM}^\dagger \rightarrow f\bar{f}, \) mediated by \( h_1 \) and \( h_2 \). In this case, the relevant couplings (\( \phi_{DM}\phi_{DM}^\dagger h_i, i = 1, 2 \)) are inversely proportional to \( g_{BL} \) (see Table I). However, as \( g_{BL} \) becomes large (\( g_{BL} \gtrsim 0.01 \)), the other s channel process mediated by B – L gauge boson starts dominating over the scalar exchange processes. From Table II one can easily see that the coupling \( \phi_{DM}\phi_{DM}^\dagger Z_{BL} \) is proportional to \( g_{BL} \), which makes \( \langle \sigma v \rangle_{ff} \) (via \( Z_{BL} \) exchange) proportional to fourth power of \( g_{BL} \). The dominance of s channel \( Z_{BL} \) exchange annihilation process over the scalar mediated ones is indicated by the fact that in this region (higher value of \( g_{BL}, g_{BL} \gtrsim 0.01 \)) \( \Omega h^2 \) (or \( \langle \sigma v \rangle_{ff} \)) does not depend on the coupling

\( f\bar{f}Z_{BL} \) coupling is also proportional to \( g_{BL} \).
Figure 4: Left (Right) panel: Variation of relic density $\Omega h^2$ with $g_{BL}$ ($M_{h_2}$) for $n_{BL} = 0.15$ and three different values of $\lambda_{DH}$ ($\alpha$) while other parameters value have been kept fixed at $M_{DM} = 52.0$ GeV, $M_{Z_{BL}} = 104.1$ GeV, $M_{h_2} = 102.8$ GeV, $\lambda_{Dh} = 0.001$, $\alpha = 0.045$ ($\lambda_{DH} = -0.0104$). For discussion about the two marked regions see text below of this figure.

$\lambda_{DH}$. We show by the hatched region the values of $g_{BL}$ excluded by LEP.

In the right panel of Fig. 4 we show the variation of $\Omega h^2$ with the mass of the non-standard Higgs boson $h_2$ for three different values of its mixing angle with SM Higgs, namely $\alpha = 0.045, 0.05, 0.055$. From this plot, it is seen that for all the chosen values of $\alpha$ the relic density satisfies the Planck limit only near the resonance region when $M_{DM} \sim M_{h_2}/2$. The figure shows that in this region $\Omega h^2$ becomes practically independent of $\alpha$. We see that there are two sets of values of $M_{h_2}$ for which the model can predict the correct dark matter relic density. Of these two regions which are marked in the figure, one of them with $M_{h_2} \sim 100$ GeV produces $\langle \sigma v \rangle_{\bar{b}b} \sim 10^{-26}$ cm$^3$/s, thus can explain the Fermi-LAT gamma-ray excess [40]. Whereas the other region labelled as “Region can’t explain Fermi-LAT $\gamma$ excess” ($M_{h_2} \sim 120$ GeV) produces $\langle \sigma v \rangle_{\bar{b}b} \sim 10^{-29}$ cm$^3$/s (see Fig. 9 also).

Variation of $\Omega h^2$ with the mass of $B-L$ gauge boson is shown in left panel of Fig. 5. In this figure three different plots are computed for three different values of $B-L$ gauge coupling ($g_{BL}$). Here, red solid line is for $g_{BL} = 0.01$ while $g_{BL} = 0.0108$ and 0.0104 are represented by green dashed line and blue dashed-dotted line, respectively. This figure is drawn for fixed values of other parameters, namely, $\alpha = 0.045$, $M_{DM} = 52.0$ GeV, $M_{h_2} = 102.8$ GeV, $\lambda_{Dh} = 0.001$, $\lambda_{DH} = -0.0104$, $n_{BL} = 0.15$. From this plot it is seen that for a fixed value of $M_{Z_{BL}}$, DM relic density increases with $g_{BL}$, which is consistent with the plot in left panel of Fig. 4 (cf. red line in the left panel of Fig. 4 where the maxima of $\Omega h^2$ occurs for $g_{BL} \gtrsim 0.015$). The presence of
Figure 5: Left panel: Variation of relic density $\Omega h^2$ with the mass of $Z_{BL}$ for three different values of $g_{BL}$. Right panel: Variation of DM relic density with its $B-\bar{L}$ gauge charge $n_{BL}$ for three different values of $\alpha$. Both the plots are drawn for $M_{DM} = 52.0$ GeV, $M_{h_2} = 102.8$ GeV, $\lambda_{Dh} = 0.001$, $\lambda_{ Dh} = -0.0104$.

Resonance due to $Z_{BL}$ (when $\sqrt{s} \simeq M_{Z_{BL}}$) is also seen from this figure and like the previous case for $h_2$ here also the Planck limit is satisfied only near the resonance. However, the resonance due to $Z_{BL}$ is not as sharp as it is due to $h_2$ because in this region of parameter space the decay width of $Z_{BL}$ is nearly two orders of magnitude larger than that of $h_2$. Here in the left panel the shaded region is not allowed by the LEP bound on $Z_{BL}$. Right panel of Fig. 5 describes the variation of $\Omega h^2$ with the $B-\bar{L}$ gauge charge ($n_{BL}$) for three different values of neutral scalar mixing angle namely $\alpha = 0.04$ (blue dashed-dotted line), 0.045 (red solid line) and 0.05 (green dashed line), respectively. From this figure it is seen that as the $B-\bar{L}$ charge of the DM candidate $\phi_{DM}$ decreases, its relic density increases sharply and eventually the DM relic density saturates after a certain value of $n_{BL} < \sim 0.1$. A possible explanation of this nature of $\Omega h^2$ could be as follows. For large value of $n_{BL}$ ($n_{BL} \sim 1$) the maximum contribution to DM annihilation cross section comes from $B-\bar{L}$ gauge boson mediated channel as the cross section for this channel is directly proportional to $n_{BL}^2$. Hence $\langle \sigma v \rangle_{ff}$ becomes practically independent of the mixing angle $\alpha$. However as $n_{BL}$ decreases from unity the scalar mediated s channel processes become significant and consequently after a certain value of $n_{BL}$ ($n_{BL} \lesssim 0.1$) the annihilation cross section $\langle \sigma v \rangle_{ff}$ becomes nearly insensitive to $n_{BL}$ and depends strongly on the mixing angle $\alpha$. In the right panel, we have given upper bound on the DM charge $n_{BL}$, which we get from LUX limit on spin independent direct detection cross section.

Variation of $\Omega h^2$ with dark matter mass for two different values of $n_{BL}$ are shown in Fig. 6. In this figure, the left panel is for $n_{BL} = 0.15$ while the right panel is for $n_{BL} = 0.2$. In each
Figure 6: Left (Right) panel: Variation of relic density $\Omega h^2$ with mass of $\phi_{DM}$ for $n_{BL} = 0.15$ ($n_{BL} = 0.20$) and three different value of $\lambda_{DH}$ while other parameters value have been kept fixed at $\alpha = 0.045$, $g_{BL} = 0.01$, $M_{h_2} = 102.8$ GeV, $M_{Z_{BL}} = 104.1$ GeV, $\lambda_{Dh} = 0.001$.

panel the three different lines represent the variation of $\Omega h^2$ with $n_{BL}$ for three chosen values of $\lambda_{DH} = -0.005, -0.0104$ and $-0.015$ respectively. From both panels of Fig. 6 it is seen that there are two resonance regions where the first one is for the non-standard Higgs boson $h_2$ ($M_{h_2} \sim 104$ GeV) while the second one corresponds to the SM Higgs boson of mass 125.5 GeV. In both panels the DM relic density satisfies the Planck limit (indicated by the magenta dotted line) only near the resonance regions. In both the panel of Fig. 6 we have shown allowed region of DM mass for explaining Fermi-LAT gamma-ray excess from GC.

We finally show the variation of $\Omega h^2$ with two remaining model parameters $\lambda_{Dh}$ and $\lambda_{DH}$ in left and right panel of Fig. 7 respectively. In each panel we have shown the variation of $\Omega h^2$ for three different values of mixing angle $\alpha$ namely $\alpha = 0.045, 0.05$ and $0.055$. From the left panel of Fig. 7 it is seen that for small value of the parameter $\lambda_{Dh}$ ($\lambda_{Dh} < 0.03$) relic density remains unaffected with respect to the change in value of $\lambda_{Dh}$ as in this region DM annihilation cross section is controlled by the coupling $\lambda_{DH}$ which is considered to be $|\lambda_{DH}| \sim 0.01$. Also from Table II we see that when $\lambda_{DH} \gg \lambda_{Dh}$, the couplings $g_{h_1\phi_{DM}\phi_{DM}^\ast} \propto \sin \alpha$ and $g_{h_2\phi_{DM}\phi_{DM}^\ast} \propto \cos \alpha$. However, the term within the modulus in Eq. (21) is proportional to $\sin^2 \alpha$. Therefore, inspite of being small in value, the variation of $\alpha$ produces a significant change in $\sigma$ and hence in relic density. Similarly, using Eq. (21) and Table II one can easily see that for higher value of $\lambda_{Dh}$ (when $\lambda_{DH} \ll \lambda_{Dh}$), the scalar mediated term in $\sigma$ (term within modulus in Eq. (21)) mainly depends on $\cos \alpha$ and $\lambda_{Dh}$. Consequently, for the higher value of $\lambda_{Dh}$, there is no observable change in relic density with respect to $\alpha$ and it decreases with the increase of $\lambda_{Dh}$. In right
Figure 7: Left (Right) panel: Variation of relic density $\Omega h^2$ with $\lambda_{Dh}$ ($\lambda_{DH}$) for $n_{BL} = 0.15$ and three different values of mixing angle $\alpha$ while other relevant parameters value have been kept fixed at $M_{DM} = 52.0$ GeV, $M_{h_2} = 102.8$ GeV, $M_{Z_{BL}} = 104.1$ GeV, $\lambda_{DH} = -0.0104$ ($\lambda_{Dh} = 0.001$).

In the left panel of Fig. 7 we have shown the variation of $\Omega h^2$ with $\lambda_{DH}$. It is seen from this figure that, the behaviour of DM relic density with respect to the coupling $\lambda_{DH}$ is same as it is with $\lambda_{Dh}$ i.e. initially for small value of $\lambda_{DH}$ relic density remains unchanged and therefore after a certain value of $\lambda_{DH}$ (when $\lambda_{DH} > \lambda_{Dh}$, $\lambda_{Dh} \sim 10^{-3}$) relic density falls gradually with the increase of $\lambda_{DH}$. However, by comparing both the plots in Fig. 7 one finds that with respect to $\alpha$ the behaviour of $\Omega h^2$ Vs $\lambda_{DH}$ curve is exactly opposite to the curve $\Omega h^2$ Vs $\lambda_{Dh}$ (shown in the left panel) which can be easily understood from Table II and Eq. (21). In both the panel we have shown allowed regions for the coupling constant $\lambda_{Dh}$ and $\lambda_{DH}$ respectively. The crossed regions are excluded by both LHC and LUX, whereas for left panel the backward line region is excluded by LUX and for right panel the forward line region is excluded by LHC.

In the left panel of Fig. 8 we show how the average value of spin independent scattering cross section $\frac{1}{2}(\sigma_{\phi_{DM}} + \sigma_{\phi_{DM}^\dagger})$ of $\phi_{DM}$ and $\phi_{DM}^\dagger$ with the detector nuclei varies as a function of dark matter mass for $n_{BL} = 0.15$. While computing this plot, we have varied the mass of B – L gauge boson in range of $2M_{DM}^{\pm 70}$ GeV for a particular value of DM mass ($M_{DM}$) since the relic density is satisfied only near the respective resonance regions of $Z_{BL}$ and $h_2$ where $M_{h_2}, M_{Z_{BL}} \sim 2M_{DM}$ (see Figs. 4, 5). The other relevant parameters are kept fixed at $\alpha = 0.045, g_{BL} = 0.01$, $\lambda_{Dh} = -0.0104$, $\lambda_{DH} = 0.001$. The experimental upper limits on the DM spin independent scattering cross section with the detector nuclei is also shown by blue dashed line. Here all the points within the red and green patches satisfy all the necessary constraints namely Planck limit on relic density, LHC bounds on invisible decay width and signal strength of SM-like...
Figure 8: Left panel: Spin independent cross section \( \sigma_{SI} \) between and dark matter particle (\( \phi_{DM} \)) and the detector nucleon for \( n_{BL} = 0.15 \). Blue dashed lines in this panel represent upper limit on \( \sigma_{SI} \) reported by LUX collaboration. Right panel: Allowed regions in \( M_{DM} - M_{h_2} \) plane which satisfy the observed relic density, Fermi-LAT gamma-ray excess \( \langle \sigma v \rangle_{\bar{b}b} \sim 10^{-26} \text{ cm}^3/\text{s} \) for red coloured region only) and LHC constraints listed in Section II.

Higgs boson (\( h_1 \)), lower limit on \( \frac{M_{Z_{BL}}}{g_{BL}} \) from LEP and also the vacuum stability conditions. From this plot it is seen that although the dark matter mass between 40 GeV to 55 GeV satisfies all the constraints mentioned above, the lower mass region between 40 GeV to 45 GeV has already been excluded by the upper limit on spin independent scattering cross section reported by the LUX collaboration. Therefore in this model with the considered ranges of model parameters, dark matter mass of 45 GeV to 55 GeV is still allowed by all possible experimental as well as theoretical constraints. This allowed region can be tested in near future by the upcoming “ton-scale” direct detection experiments like XENON 1T.

As we have seen earlier in Fig. 4 (right panel), that for two values of \( M_{h_2} \) Planck’s relic density central value is satisfied. If we consider the higher value of \( M_{h_2} \) (\( M_{h_2} \sim 120 \) GeV) then the annihilation cross section for the channel \( \phi_{DM}\phi_{DM}^\dagger \rightarrow \bar{b}b \) comes in around \( \langle \sigma v \rangle_{\bar{b}b} \sim 10^{-29} \text{ cm}^3/\text{s} \), which cannot explain Fermi-LAT gamma excess. On the other hand the lower value of \( M_{h_2} \) (\( M_{h_2} \sim 100 \) GeV) produces \( \langle \sigma v \rangle_{\bar{b}b} \) in the right ballpark value of \( 10^{-26} \text{ cm}^3/\text{s} \) which is required to explain the Fermi-LAT gamma excess. To find the allowed region which can satisfy all the constraints as mentioned in Section II we have varied \( M_{h_2} \) and \( M_{Z_{BL}} \) in the ranges \( 2 M_{DM}^{+25}_{-10} \) GeV and \( 2 M_{DM}^{+70}_{-30} \) GeV respectively. The allowed region in \( M_{DM} - M_{h_2} \) plane is shown in the right panel of Fig. 8. In this plot red coloured region around \( \sim 2 \times M_{DM} \) corresponds to the lower value of \( M_{h_2} \) which can explain the Fermi-LAT \( \gamma \)-ray excess while the higher allowed value
of $M_{h_2}$ is indicated by green coloured patch which is unable to explain the GC $\gamma$-ray excess. As we have discussed above, here also the region corresponds to dark matter mass of 40 GeV to 45 GeV is ruled out by the results of LUX direct detection experiment. The region beyond the dark matter mass of 45 GeV satisfies all the constraints listed in Section II.

Figure 9: Allowed region in $M_{h_2}$-$\alpha$ plane satisfied by various experimental constraints considered in this work. Other relevant parameters are kept fixed at $\lambda_{Dh} = 0.001$, $\lambda_{DH} = -0.0104$, $M_{Z_{BL}} = 104.1$ GeV and $g_{BL} = 0.01$. Here, green coloured region satisfies all the constraints except Fermi-LAT bound on dark matter annihilation cross section into $b\bar{b}$ final state while the values of $\alpha$ and $M_{h_2}$ lying within the red coloured patch are allowed by all the experimental constraints listed in Section II. The region in $\lambda_{DH} - g_{BL}$ plane which satisfies simultaneously the results of Planck, LUX, LHC, LEP and Fermi-LAT experiments is shown by a red coloured patch in the left panel of Fig. 10. While computing this plot we have varied the mass of the extra neutral gauge boson $Z_{BL}$ in the range of 50 GeV to 1050 GeV and the values of other relevant parameters are kept fixed at $M_{DM} = 52$ GeV, $M_{h_2} = 102.8$ GeV, $\alpha = 0.045$, $\lambda_{Dh} = 0.001$ and $n_{BL} = 0.15$. From this figure it is evident that $g_{BL} \lesssim 0.1$ and $|\lambda_{DH}| \lesssim 0.011$ are allowed for $50$ GeV $\leq M_{Z_{BL}} \leq 1050$ GeV. On the other hand from the right panel of Fig. 10 one can see that all the considered range of $M_{Z_{BL}}$ ($50$ GeV $\leq M_{Z_{BL}} \leq 1050$ GeV), except the extreme right region with $g_{BL}$ lies between 0.01 to 0.1 (LEP excluded region), is allowed with respect to the variation of $U(1)_{B-L}$ gauge coupling constant $g_{BL}$. 
Figure 10: Left panel (Right panel): Allowed region in $g_{BL}$-$\lambda_{DH}$ ($g_{BL}$-$M_{Z_{BL}}$) plane satisfied by all the experimental constraints considered in this work. Other relevant parameters are kept fixed at $\lambda_{Dh} = 0.001$, $\alpha = 0.045$, $M_{DM} = 52$ GeV and $M_{h_2} = 102.8$ GeV.

V. GAMMA-RAY FLUX

In this present model the pair annihilation of $\phi_{DM}\phi^\dagger_{DM}$ produces $b$ and $\bar{b}$ at the final state$^{10}$. Therefore, these $b$ quarks undergo hadronisation processes and produce $\gamma$-rays. The differential gamma-ray flux from the pair annihilation of $\phi_{DM}$ and $\phi^\dagger_{DM}$ at the Galactic Centre region is given by

$$
\frac{d\Phi_{\gamma}}{d\Omega dE} = \frac{1}{2\pi} \frac{r_\odot}{8} \left( \frac{\rho_\odot}{M_{DM}} \right)^2 \bar{J} \langle \sigma v \rangle_{bb} \frac{dN_{b\gamma}}{dE},
$$

(25)

where $r_\odot = 8.5$ kpc is the distance of solar system from the centre of our Milky way galaxy and dark matter density near the solar neighbourhood is denoted by $\rho_\odot$ which is taken to be 0.4 GeV/cm$^3$. Similar to Eqs. (20, 23), here also the half factor appearing in the expression of the differential gamma-ray flux is due the non-self-conjugate nature of $\phi_{DM}$. Moreover, $\frac{dN_{b\gamma}}{dE}$ is the spectrum of produced gamma-rays from the hadronisation processes of $b$ quarks and we have adopted the numerical values of $\frac{dN_{b\gamma}}{dE}$ for different values of photon energy from ref. [101]. Annihilation cross section for the channel $\phi_{DM}\phi^\dagger_{DM} \rightarrow b\bar{b}$ which acts as the seed mechanism for the Galactic Centre gamma-excess, is denoted by $\langle \sigma v \rangle_{bb}$. Further, $\bar{J}$ is the averaged of

$^{10}$ One can extrapolate this work and can explain the Fermi-LAT gamma-ray excess by studying different channels such as $\tau^+\tau^-$, $W^+W^-$, $q\bar{q}$ and $h_1h_1$. 

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“astrophysical J factor” over a solid angle $\Delta \Omega$. The value of solid angle $\Delta \Omega$ around the Galactic Centre depends on the choice of a particular region of interest (ROI). In the present work we have adopted the same ROI as considered by Calore et al. [40] which is $|l| < 20^0$ and $2^0 < |b| < 20^0$ with $l$ and $b$ are the galactic longitude and latitude respectively. Therefore, the expression of $\bar{J}$ is given by

$$\bar{J} = \frac{4}{\Delta \Omega} \int \int \, db \, dl \cos b \, J(b, l) ,$$

with

$$J(l, b) = \int_{l.o.s.} \frac{ds}{r_\odot} \left( \frac{\rho(r)}{\rho_\odot} \right)^2 ,$$

and

$$\Delta \Omega = 4 \int dl \int db \cos b ,$$

where the integration of Eq. (27) is performed along the line of sight (l.o.s) distance $s$ which can be defined using Eq. (29). In the definition of “astrophysical J factor” (Eq. (27)), $\rho(r)$ represents the variation of dark matter density with respect to the distance $r$ from the Galactic Centre, which is also known as the density profile of dark matter. As the actual form of the density profile is still unknown to us there are many approximate dark matter density profiles available in the literature such as NFW profile [44], Einasto profile [102], Isothermal profile [103], Moore profile [104]. Therefore, as in ref. [40], in this work also, we have used NFW halo profile with $\gamma = 1.26$, $r_s = 20$ kpc. Using Eqs. (26-29) and a NFW dark matter halo profile we have found the value of $\bar{J} = 57.47$ for the above mentioned ROI ($|l| < 20^0$ and $2^0 < |b| < 20^0$). However, due to our poor knowledge about the halo profile parameters ($\rho_\odot$, $\gamma$, $r_s$) the value of $\bar{J}$ may vary from its canonical value $\bar{J} = 57.47$ obtained for $\gamma = 1.26$, $r_s = 20$, $\rho_\odot = 0.4$ GeV/cm$^3$. Now in order to include such uncertainties into the value of $\bar{J}$, which exist within the values of DM density profile parameters, we have redefined $\bar{J}$ in the following way

$$\bar{J} = A \bar{J}_{\text{canonical}} ,$$

where $\bar{J}_{\text{canonical}} = 57.47$, i.e. the value of $\bar{J}$ for $\gamma = 1.26$, $r_s = 20$, $\rho_\odot = 0.4$ GeV/cm$^3$ and the quantity $A$ can vary in the range 0.19 to 5.3 [40]. Therefore, the values of $\bar{J}$ and $J_{\text{canonical}}$ coincide when $A = 1$.

Using Eqs. (25-30), we have computed the $\gamma$-ray flux due to the pair annihilation of $\phi_{DM} \phi_{DM}^\dagger$ into $b \bar{b}$ final state and it is plotted in Fig. 11. In this plot, Fermi-LAT observed gamma-ray
flux from the direction of Galactic Centre is denoted by black triangle shaped points with the black vertical lines represent the uncorrelated statistical errors while the correlated systematics are described by yellow coloured boxes. The red solid line denotes the gamma-ray flux which is computed for an annihilating non-self-conjugate dark matter particle of mass $M_{DM} = 52$ GeV using the present model. We have found that the gamma-flux obtained from the present model agrees well with the flux observed by Fermi-LAT if the product of $\mathcal{A}\langle\sigma v\rangle_{b\bar{b}} = 4.7 \times 10^{-26}$ cm$^3$/s. Therefore, if we use the canonical values of the halo profile parameters (when $\mathcal{A} = 1$ and $\bar{J} = 57.47$) then in order to reproduced Fermi-LAT observed gamma-ray flux from the pair annihilation of a non-self-conjugate dark matter of mass 52 GeV its annihilation cross section for the $b\bar{b}$ channel must be $4.7 \times 10^{-26}$ cm$^3$/s. For the other values of $\mathcal{A}$ which are not equal to unity, the quantity $\langle\sigma v\rangle_{b\bar{b}}$ will be scaled accordingly.

![Figure 11: Gamma-ray flux produced from dark matter annihilation at the Galactic Centre.](image)

Three allowed values of $\langle\sigma v\rangle_{b\bar{b}}$ that we have obtained from the present model for $M_{DM} = 52$ GeV, which are also satisfying all the constrains listed in Section II, are given in Table III.
VI. SUMMARY AND CONCLUSION

Existence of neutrino masses and dark matter in the Universe are two of the main observational evidences for physics beyond the Standard Model. If the Galactic Centre gamma ray excess reported by the Fermi-LAT data is indeed due to DM annihilation, then we need our beyond SM physics to be able to explain this excess along with the observed DM relic density as well as neutrino masses and mixing. In this work we showed that the gauged $U(1)\text{B} - \text{L}$ extension of the Standard Model, which can very naturally explain lepton number violation and hence the existence of small Majorana neutrino masses, can also be extended to explain the relic DM density and the Fermi-LAT gamma ray excess, without conflicting with any existing theoretical or observational constraint.

Since $U(1)\text{B} - \text{L}$ symmetry that we impose is local, there is an additional gauge boson $Z_{BL}$ in this model. Three right handed neutrinos also have to included in the model to make it anomaly free. In order to break the $U(1)\text{B} - \text{L}$ symmetry spontaneously, one introduces an extra SM singlet scalar $\phi_H$ which carries a nontrivial B−L charge. The B−L charge of this scalar can be arranged in such a way that the right handed neutrinos pick up Majorana masses when $\phi_H$ gets a VEV, breaking the $U(1)\text{B} - \text{L}$ symmetry spontaneously. As a result the $Z_{BL}$ gauge boson also becomes massive. This extra neutral gauge boson has been searched for at collider experiments which put a stringent bound on the combination of the new $U(1)\text{B} - \text{L}$ gauge coupling and the mass of $Z_{BL}$. We extended this gauged $U(1)\text{B} - \text{L}$ model further by adding another complex SM scalar $\phi_{DM}$ which is charged under $U(1)\text{B} - \text{L}$ and arranged its $U(1)\text{B} - \text{L}$ charge in such a way that all decays of $\phi_{DM}$ are forbidden making it a stable DM candidate.

We next studied the viability of this model in simultaneously explaining the relic DM density of the Universe as well as the GC gamma ray excess through the annihilation of $\phi_{DM}$ and $\phi_{DM}^+$ into the $b\bar{b}$ channel, mediated by $h_1$, $h_2$ and $Z_{BL}$, where $h_1$ and $h_2$ are the two neutral scalars in our model, of which we identified $h_1$ as the SM-like Higgs with its mass fixed at 125.5 GeV. There are 12 unknown new parameters in this model. We imposed constraints coming from vacuum stability, LEP bound on $M_{Z_{BL}}/g_{BL}$, LHC bounds on signal strength of the SM-like Higgs and

| $M_{DM}$ [GeV] | $n_{BL}$ | $M_{h_2}$ [GeV] | $M_{Z_{BL}}$ [GeV] | $\Omega h^2$ | $<\sigma v>_{\phi}$ [cm$^3$s$^{-1}$] | $A$ |
|----------------|---------|-----------------|-------------------|-------------|-----------------|-----|
| 52.0           | 0.15    | 103.3           | 77.1              | 0.1208      | $7.005 \times 10^{-26}$ | 0.67 |
|                |         | 102.8           | 104.2             | 0.1191      | $4.545 \times 10^{-26}$ | 1.03 |
|                |         | 101.4           | 168.6             | 0.1199      | $2.853 \times 10^{-26}$ | 1.65 |

Table III: Allowed values of <$\sigma v>_{\phi}$ and $A$ for three randomly chosen benchmark points $M_{h_2}$ and $M_{Z_{BL}}$. The values of other relevant parameters are $g_{BL} = 0.01$, $\alpha = 0.045$, $\lambda_{DH} = -0.0104$ and $\lambda_{Db} = 0.001$. 
invisible decay width of the SM-like Higgs, and found the regions of the model parameter space which can simultaneously explain the observed DM relic density as well as the Fermi-LAT GC gamma ray excess and at the same time evaded the bounds from the direct detection experiments such as LUX. We showed that for DM masses in the range 40-55 GeV and for a wide range of $U(1)_{B-L}$ gauge boson masses, one can satisfy all these constraints if the additional neutral Higgs scalar has a mass around the resonance region. We presented allowed areas in the model parameter space consistent with all relevant data, calculated the predicted gamma ray flux from the GC and discussed the related phenomenology.

In conclusion, the observation of neutrino masses and dark matter are the two main observational evidences of physics beyond the Standard Model. The small neutrino masses can be explained in terms of lepton number violation and the gauged $U(1)_{B-L}$ extension of the Standard Model can very easily accommodate the type-I seesaw mechanism since it must have three additional right-handed neutrinos for anomaly cancellation and light Majorana neutrino masses are generated through this seesaw mechanism when the $U(1)_{B-L}$ is broken spontaneously. We propose an extension of this model by adding a complex scalar field $\phi_{DM}$ that acts as the dark matter candidate and make it stable by arranging suitably its $U(1)_{B-L}$ charge. We showed that both the relic abundance and the Galactic Centre gamma ray excess could be explained in this model. Thus this model can simultaneously explain neutrino masses, the dark matter relic density of the Universe and the GC gamma ray excess, while simultaneously satisfying all other collider and direct detection constraints. This model should be testable at the next-generation XENON1T experiment.

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