Majorana dark matter in a new $B-L$ model

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FPCP 2018, UOH

July 17, 2018

Outline

Based on "Majorana Dark Matter in a new $B-L$ model", arXiv:[1710.05775].

Collaborators

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- SM fermion content is insufficient to cancel the triangle gauge anomalies.

$$\mathcal{A}^{\rm SM}\left[{\rm grav}^2 \times U(1)_{B-L}\right] = -3, \quad \mathcal{A}^{\rm SM}\left[U(1)^3_{B-L}\right] = -3.$$

- Possible solution is to add three neutral leptons each with $B-L$ charge -1.
- Three exotic fermions with $B-L$ charges -4, -4, +5

$$\begin{aligned}\mathcal{A}^{B-L}\left[U(1)^3_{B-L}\right] &= -3 + (+4)^3 + (+4)^3 + (-5)^3 = 0,\\ \mathcal{A}^{B-L}\left[{\rm grav}^2 \times U(1)_{B-L}\right] &= -3 + (+4) + (+4) + (-5) = 0.\end{aligned}$$

- Four exotic fermions : $\xi_L(4/3)$, $\eta_L(1/3)$, $\chi_{1R}(-2/3)$ and $\chi_{2R}(-2/3)$ is also a possible solution.

	Field	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$	Z_2
Fermions	$Q_L \equiv (u, d)^T_L$	$(\mathbf{2},\ 1/6)$	$1/3$	$+$
	u_R	$(\mathbf{1},\ 2/3)$	$1/3$	$+$
	d_R	$(\mathbf{1},\ -1/3)$	$1/3$	$+$
	$\ell_L \equiv (\nu,\ e)^T_L$	$(\mathbf{2},\ -1/2)$	-1	$+$
	e_R	$(\mathbf{1},\ -1)$	-1	$+$
	N_{1R}	$(\mathbf{1},\ 0)$	-4	$-$
	N_{2R}	$(\mathbf{1},\ 0)$	-4	$-$
	N_{3R}	$(\mathbf{1},\ 0)$	5	$-$
Scalars	H	$(\mathbf{2},\ 1/2)$	0	$+$
	ϕ_1	$(\mathbf{1},\ 0)$	-1	$+$
	ϕ_8	$(\mathbf{1},\ 0)$	8	$+$

Table : Fields and their charges of the proposed $U(1)_{B-L}$ model.

$$\begin{aligned}
\mathcal{L}_{\rm BL} \quad &= -\frac{1}{3}\, g_{\rm BL}\, \overline{Q}_L\, Z'_\mu \gamma^\mu Q_L - \frac{1}{3}\, g_{\rm BL}\, \overline{u}_R\, Z'_\mu \gamma^\mu u_R - \frac{1}{3}\, g_{\rm BL}\, \overline{d}_R\, Z'_\mu \gamma^\mu d_R \\
&+ g_{\rm BL}\, \overline{\ell}_L\, Z'_\mu \gamma^\mu \ell_L + g_{\rm BL}\, \overline{e}_R\, Z'_\mu \gamma^\mu e_R + i\, \overline{N}_{1R} \left(\partial\!\!\!/ + 4i\, g_{\rm BL}\, Z'_\mu \gamma^\mu\right) N_{1R} \\
&+ i\, \overline{N}_{2R} \left(\partial\!\!\!/ + 4i\, g_{\rm BL}\, Z'_\mu \gamma^\mu\right) N_{2R} + i\, \overline{N}_{3R} \left(\partial\!\!\!/ - 5i\, g_{\rm BL}\, Z'_\mu \gamma^\mu\right) N_{3R} \\
&- \frac{y_{\alpha\beta}}{2} \left(\sum_{\alpha,\beta=1,2} \overline{N^c_{\alpha R}} N_{\beta R} \phi_8 + h.c \right) - \frac{y_{\alpha 3}}{2} \left(\sum_{\alpha=1,2} \overline{N^c_{\alpha R}} N_{3R} \phi_1 + h.c \right) \\
&+ \left| \left(\partial_\mu + i\, g_{\rm BL}\, Z'_\mu\right) \phi_1 \right|^2 + \left| \left(\partial_\mu - 8\, i\, g_{\rm BL}\, Z'_\mu\right) \phi_8 \right|^2 \\
&- \frac{1}{4} F^{\mu\nu}_{Z'} F^{Z'}_{\mu\nu} - V\left(H, \phi_1, \phi_8\right) + \mathcal{L}_{\rm SM}\,, \qquad (1)
\end{aligned}$$

$$V(H,\phi_1,\phi_8) = \mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \mu_1^2 \phi_1^\dagger \phi_1 + \lambda_1 (\phi_1^\dagger \phi_1)^2 + \mu_8^2 \phi_8^\dagger \phi_8 + \lambda_8 (\phi_8^\dagger \phi_8)^2 + \lambda_{H1} (H^\dagger H)(\phi_1^\dagger \phi_1) + \lambda_{H8} (H^\dagger H)(\phi_8^\dagger \phi_8) + \lambda_{18} (\phi_1^\dagger \phi_1)(\phi_8^\dagger \phi_8). \quad (2)$$

$$H^0 = \frac{1}{\sqrt{2}}(v+h) + \frac{i}{\sqrt{2}} A^0 ,$$
$$\phi_1^0 = \frac{1}{\sqrt{2}}(v_1+h_1) + \frac{i}{\sqrt{2}} A_1 ,$$
$$\phi_8^0 = \frac{1}{\sqrt{2}}(v_8+h_8) + \frac{i}{\sqrt{2}} A_8 , \quad (3)$$

where $\langle H \rangle = (0, v/\sqrt{2})^T$, $\langle \phi_1 \rangle = v_1/\sqrt{2}$, and $\langle \phi_8 \rangle = v_8/\sqrt{2}$.

- $M_{Z'} = g_{\rm BL}\sqrt{v_1^2 + 64 v_8^2}$
- Exotic fermion mass matrix

$$M_R = \frac{1}{\sqrt{2}}\begin{pmatrix} y_{11}v_8 & y_{12}v_8 & y_{13}v_1 \\ y_{12}v_8 & y_{22}v_8 & y_{23}v_1 \\ y_{13}v_1 & y_{23}v_1 & 0 \end{pmatrix}$$

$$M_{D\alpha} = (U^T M_R U)_\alpha \text{ and } N_{D\alpha} = U^\dagger_{\alpha\beta} N_\beta .$$

- CP-even

$$M_E^2 = \begin{pmatrix} 2\lambda_H v^2 & \lambda_{H1} v v_1 & \lambda_{H8} v v_8 \\ \lambda_{H1} v v_1 & 2\lambda_1 v_1^2 & \lambda_{18} v_1 v_8 \\ \lambda_{H8} v v_8 & \lambda_{18} v_1 v_8 & 2\lambda_8 v_8^2 \end{pmatrix} . \tag{4}$$

- CP-odd

$$A_{\rm G} = -\frac{8v_8}{\sqrt{v_1^2+64v_8^2}}A_8 + \frac{v_1}{\sqrt{v_1^2+64v_8^2}}A_1 \quad \text{(eaten up by } Z'\text{)},$$

$$A_{\rm NG} = \frac{v_1}{\sqrt{v_1^2+64v_8^2}}A_8 + \frac{8v_8}{\sqrt{v_1^2+64v_8^2}}A_1 \quad \text{(remains as NG)}.$$

- It can give rise to an additional decay channel contributing to the invisible width of SM Higgs, given as

$$\Gamma(H_1 \to A_{\rm NG}A_{\rm NG}) \simeq \frac{M_{H_1}^3 \sin^2\beta}{32\pi v_1^2}\,, \tag{5}$$

where β denotes the mixing between H and ϕ_1. The invisible branching ratio of Higgs is given as

$$\mathrm{Br}_{\rm inv} = \frac{\Gamma(H_1 \to A_{\rm NG}A_{\rm NG})}{\Gamma(H_1 \to A_{\rm NG}A_{\rm NG}) + \cos^2\beta\ \Gamma_{\rm SM}^{\rm Higgs}}. \tag{6}$$

Using the constraint, $\mathrm{Br}_{\mathrm{inv}} \simeq 20\%$ [1] , $\Gamma_{\mathrm{SM}}^{\mathrm{Higgs}} \simeq 4$ MeV, we obtain the upper limit on the mixing angle as

$$|\tan\beta| \leq 2.2 \times 10^{-4} \times \left(\frac{v_1}{\mathrm{GeV}}\right). \quad (7)$$

If the NG stays in thermal equilibrium with ordinary matter until muon annihilation, then it mimics as fractional cosmic neutrinos contributing nearly 0.39 to the effective number of neutrino species to give $N_{\mathrm{eff}} = 3.36^{+0.68}_{-0.64}$ at 95% C.L [2], a remarkable agreement with Planck data.

1. G. Belanger et.al, Phys.Lett. B723 (2013) 340-347.
2. S. Weinberg, PRL 110 (2013) no. 24, 241301.

For simplicity, we consider

$$M_R = \begin{pmatrix} x & a & b \\ a & x & b \\ b & b & 0 \end{pmatrix}, \tag{8}$$

which can be obtained by assuming the Yukawa couplings to satisfy the relations $y_{11} \approx y_{22}$ and $y_{13} \approx y_{23}$ along with $v_1 \approx v_8$. The above mass matrix can be diagonalized using the unitary matrix as $(U_1\cdot)^T \cdot M_R \cdot (U_1\cdot)$.

$$M^{\rm diag} = \begin{pmatrix} x-a & 0 & 0 \\ 0 & \frac{1}{2}\left(-(x+a)+\sqrt{8b^2+(x+a)^2}\right) & 0 \\ 0 & 0 & \frac{1}{2}\left((x+a)+\sqrt{8b^2+(x+a)^2}\right) \end{pmatrix}. \tag{9}$$

Possible annihilation channels in scalar portal :

$N_{D1}N_{D1} \to f\bar{f}, W^+W^-, ZZ, A_{\rm NG}A_{\rm NG}, H_iH_j$

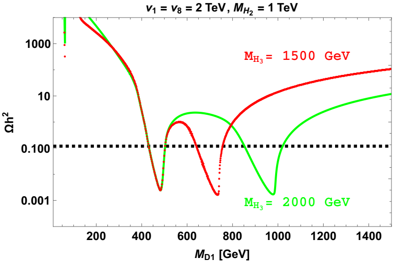
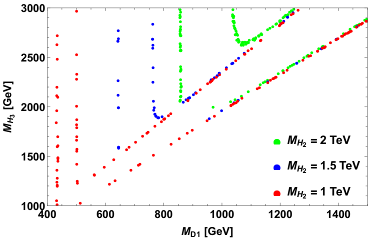
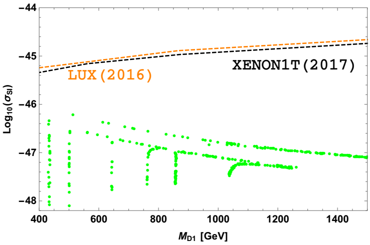


Figure : Scalar-portal relic abundance as a function of DM mass M_{D1} for two specific mass values of the physical scalar H_3. The horizontal dashed lines represent the 3σ value of the current relic density.





Parameters	Range
$v_{1,8}$ [GeV]	2000
M_{H_2} [GeV]	1000 − 2000
M_{H_3} [GeV]	M_{H_2} − 3000
β	0.01 − 0.001

* XENON Collaboration, E. Aprile et.al, PRL 119 (2017) no.18, 181301.

* LUX Collaboration, D.S. Akerib et.al, Phys. Rev. Lett. 118, 021303

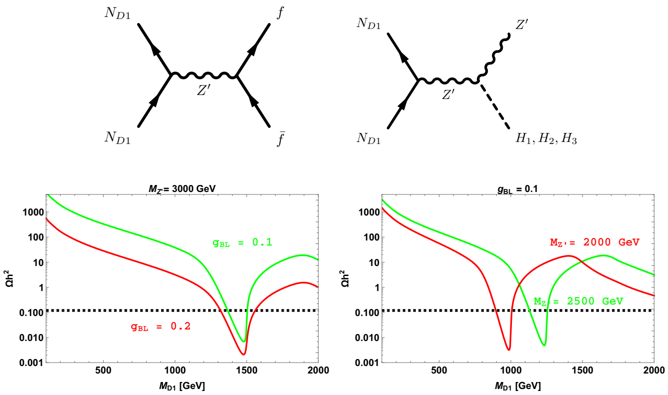
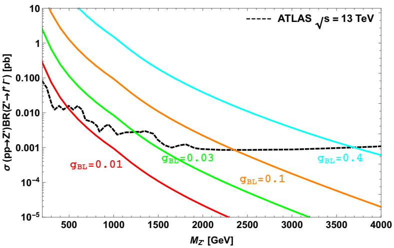
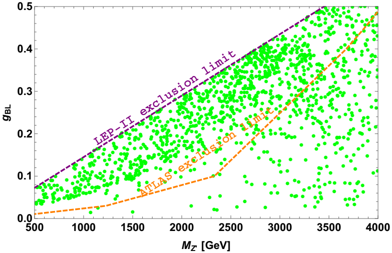


Figure : Variation of relic abundance Ωh^2 with the mass of DM with $(M_{H_2}, M_{H_3}) = (1, 1.5)$ TeV. Left panel depicts the variation for fixed Z' mass and varying $B - L$ gauge coupling g_{BL}. The right panel displays the behavior for constant coupling g_{BL} and varying mediator mass.





* ATLAS-CONF-2015-070.

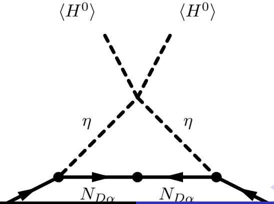
* ALEPH, DELPHI, L3, OPAL and LEP Electroweak Collaborations, Phys.Rept. 532 (2013) 119-244.

Field	$SU(2)_L \times U(1)_Y$	$U(1)_{B-L}$	Z_2
η	$(\mathbf{2}, 1/2)$	-3	-1

Interaction term to generate light neutrino mass at one loop level is

$$\sum_{\alpha=1,2} Y_{i\alpha} \overline{(\ell_L)}_i \tilde{\eta} N_{\alpha R}. \tag{10}$$

$$\begin{aligned} V' &= V(H, \phi_1, \phi_8) + \mu_\eta(\eta^\dagger \eta) + \lambda_\eta (\eta^\dagger \eta)^2 + \lambda'_{H\eta}(H^\dagger \eta)(\eta^\dagger H) \\ &+ \frac{\lambda''_{H\eta}}{2}\left[(H^\dagger \eta)^2 + \mathrm{h.c.}\right] + (\eta^\dagger \eta)\left[\lambda_{H\eta}(H^\dagger H) + \lambda_{\eta 1}(\phi_1^\dagger \phi_1) + \lambda_{\eta 8}(\phi_8^\dagger \phi_8)\right]. \end{aligned}$$



The masses of real and imaginary components of the inert doublet η are

$$M_{S,A}^2 = \mu_\eta^2 + \frac{\lambda_{\eta 1}}{2} v_1^2 + \frac{\lambda_{\eta 8}}{2} v_8^2 + \left(\lambda_{H\eta} + \lambda'_{H\eta} \pm \lambda''_{H\eta}\right) \frac{v^2}{2},$$

Assuming $m_0^2 = (M_S^2 + M_A^2)/2$ is much greater than $M_S^2 - M_A^2 = \lambda''_{H\eta} v^2$, then

$$(\mathcal{M}_\nu)_{ij} = \frac{\lambda''_{H\eta} v^2}{16\pi^2} \sum_{\alpha=1}^{3} \frac{Y_{i\alpha} Y_{j\alpha} M_{D\alpha}}{m_0^2 - M_{D\alpha}^2} \left[1 - \frac{M_{D\alpha}^2}{m_0^2 - M_{D\alpha}^2} \ln \frac{m_0^2}{M_{D\alpha}^2}\right]. \qquad (11)$$

Here $M_{D\alpha} = (U^T M_R U)_\alpha$ and $N_{D\alpha} = U^\dagger_{\alpha\beta} N_\beta$. With a sample parameter space, $(Y, \lambda''_{H\eta}) \sim (10^{-2}, 10^{-5})$ and $(m_0, M_{D\alpha}) \sim (2, 0.5)$ TeV, one can have $m_\nu \sim 10^{-11}$ GeV.

- We have explored a $B-L$ gauge extension of SM with three exotic fermions with $B-L$ charges $-4, -4, +5$ to avoid the triangle gauge anomalies.
- We have the studied the fermion DM phenomenology in the scalar and gauge portal scenario.
- We have discussed the mechanism of generating light neutrino mass by adding an inert doublet with $B-L$ charge -3.
- A massless physical Goldstone plays a role in DM relic density.
- Finally, the $B-L$ gauge extensions are simple to work, with minimal particle content and parameters.

Thank you