Singlet-Triplet Fermionic Dark Matter and LHC Phenomenology

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Main Objectives

- Study of Dark Matter phenomenology.
- Direct and Indirect detection of dark matter.
- Collider signature by studying multi jet + missing energy observation.

Particle Contents of Our Model

Gauge Group	Baryon Fields $Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	Lepton Fields $L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N'	ρ	Scalar Fields ϕ_h	Δ
$SU(3)_c$	3	3	3	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	3	2	3
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	0	1/2	0
$\mathbb{Z}_2$	+	+	+	+	+	−	−	+	+

Table 1: Particles and their corresponding charges under SM gauge group

Model Description

The corresponding Lagrangian is given by,

$$\mathcal{L} = \mathcal{L}_{SM} + Tr\,[\bar{\rho}\, i\,\gamma^\mu D_\mu \rho] + \bar{N}'\, i\,\gamma^\mu D_\mu N' + Tr[(D_\mu \Delta)^\dagger (D^\mu \Delta)] - V(\phi_h, \Delta)$$
$$-Y_{\rho\Delta}\,(Tr[\bar{\rho}\,\Delta]\, N' + h.c.) - M_\rho\, Tr[\bar{\rho}^c \rho] - M_{N'}\, \bar{N}'^c N' \quad (1)$$

where the triplet fermion takes the following form,

$$\rho = \begin{pmatrix} \frac{\rho_0}{2} & \frac{\rho^+}{\sqrt{2}} \\ \frac{\rho^-}{\sqrt{2}} & -\frac{\rho_0}{2} \end{pmatrix}. \quad (2)$$

The complete form of the potential $V(\phi_h, \Omega)$ takes the following form,

$$V(\phi_h, \Delta) = -\mu_h^2 \phi_h^\dagger \phi_h + \frac{\lambda_h}{4}(\phi_h^\dagger \phi_h)^2 + \mu_\Delta^2 Tr[\Delta^\dagger \Delta] + \lambda_\Delta (\Delta^\dagger \Delta)^2 +$$
$$\lambda_1\,(\phi_h^\dagger \phi_h)\,\mathrm{Tr}\,[\Delta^\dagger \Delta] + \lambda_2\,\left(Tr[\Delta^\dagger \Delta]\right)^2 + \lambda_3\, Tr[(\Delta^\dagger \Delta)^2]$$
$$+\lambda_4\, \phi_h^\dagger \Delta \Delta^\dagger \phi_h + (\mu \phi_h^\dagger \Delta \phi_h + h.c.)\,. \quad (3)$$

After symmetry breaking neutral fermions mix and the mass eigenbasis becomes,

$$\rho_2^0 = \cos\beta\, \rho_0 + \sin\beta\, N'^c$$
$$\rho_1^0 = -\sin\beta\, \rho_0 + \cos\beta\, N'^c \quad (4)$$

In terms of $M_{\rho_1^0}$ and $M_{\rho_2^0}$, $Y_{\rho\Delta}$ takes the following form,

$$Y_{\rho\Delta} = \frac{(M_{\rho_2^0} - M_{\rho_1^0}) \sin 2\beta}{2\, v_\Delta},$$
$$= \frac{\Delta M_{21} \sin 2\beta}{2 v_\Delta} \quad (5)$$

where $\Delta M_{21} = (M_{\rho_2^0} - M_{\rho_1^0})$.

Constraints

Planck Limit

In this work we have used the following bound on the DM relic density,

$$0.1172 \leq \Omega h^2 \leq 0.1226 \;\text{ at } 68\% \text{ C.L.}\,, \quad (6)$$

Direct Detection

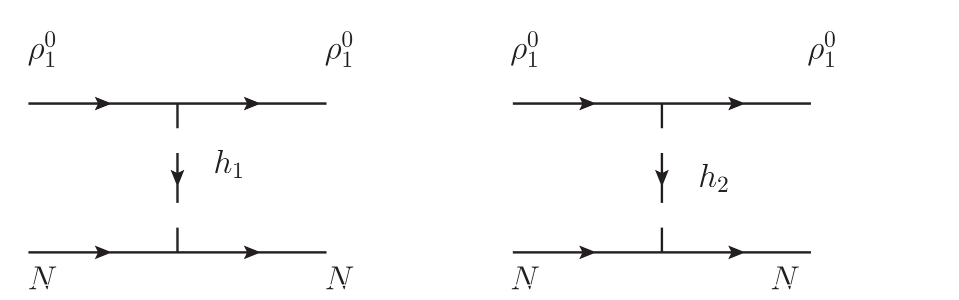


Figure 1: SI direct detection scattering processes between DM and nucleaon of the nucleus.

The expression for the above direct detection process takes the following form,

$$\sigma_{SI} = \frac{\mu_{red}^2}{\pi}\left[\frac{M_N f_N}{v}\left(\frac{g_{\rho_1^0\rho_1^0 h_2}\sin\alpha}{M_{h_2}^2} - \frac{g_{\rho_1^0\rho_1^0 h_1}\cos\alpha}{M_{h_1}^2}\right)\right]^2 \quad (7)$$

$f_N = 0.3$, is the nucleon form factor while μ_{red} is the reduced mass,

$$\mu_{red} = \frac{M_N M_{\rho_1^0}}{M_N + M_{\rho_1^0}}, \quad (8)$$

The couplings in Eq. (7) $g_{\rho_1^0\rho_1^0 h_1}$ and $g_{\rho_1^0\rho_1^0 h_2}$ are given by,

$$g_{\rho_1^0\rho_1^0 h_1} = \frac{Y_{\rho\Delta}}{2}\sin 2\beta\, \sin\alpha\,,$$
$$g_{\rho_1^0\rho_1^0 h_2} = \frac{Y_{\rho\Delta}}{2}\sin 2\beta\, \cos\alpha\,, \quad (9)$$

Indirect Detection

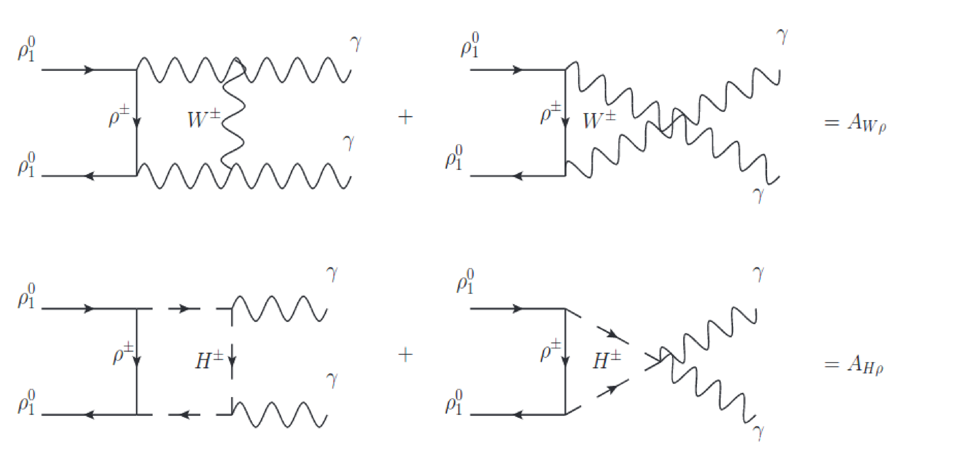


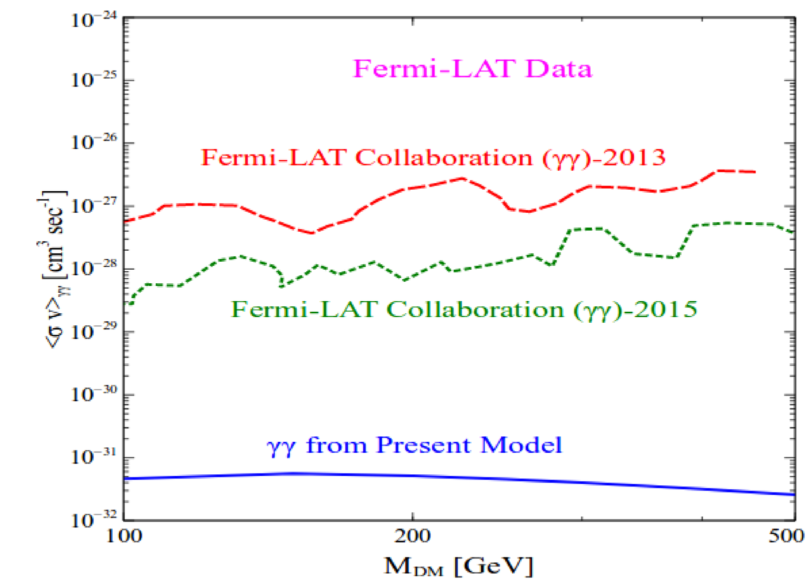
Figure 2: Feynman diagrams for Indirect detection

Cross section for the above processes,

$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{\alpha_{EM}^2 M_{\rho_1^0}^2}{16\pi^3}|A|^2$$

where

$$A_{W_\rho} = -2C_1^2\left[2I_3^a(M_W) + 2(M_{\rho^\pm}^2 + M_W^2 - M_{\rho_1^0}^2)I_4^a + 2M_{\rho^\pm}^2 I_4^b + 3M_{\rho^\pm}^2 I_4^c + I_3^b(M_W, M_{\rho^\pm})\right]$$
$$+8C_1^2 M_{\rho^\pm} M_{\rho_1^0}(I_4^b + I_4^c),$$
$$A_{H_\rho} = C_2^2\left[2M_{\rho^\pm}^2 I_4^b + M_{\rho^\pm}^2 I_4^c + I_3^b(M_{H^\pm}, M_{\rho_1^0})\right]$$



Invisible decay width of Higgs

In the present model the Higgs decay width to invisible states ρ_1^0 (since in the present work $M_{\rho_2^0} > \frac{M_{h_1}}{2}$, hence Higgs can not decay to ρ_2^0) is given by,

$$\Gamma_{h_1 \to \rho_1^0 \rho_1^0} = \frac{M_{h_1} g^2_{\rho_1^0\rho_1^0 h_1}}{16\pi}\left(1 - \frac{4M^2_{\rho_1^0}}{M^2_{h_1}}\right)^{3/2}, \quad (10)$$

where $g_{\rho_1^0\rho_1^0 h_1}$ is given in Eq. (9). In order to satisfy the LHC limit, the model parameters have to satisfy the following constraint

$$\frac{\Gamma_{h_1 \to \rho_1^0\rho_1^0}}{\Gamma_{h_1}^{Total}} \leq 34\% \text{ at } 95\% \text{ C.L.} \quad (11)$$

In determining the relic density and SI direct detection, we have written down the model in **Feynrules** to generate the model files and we have implemented the model files in **micrOMEGAS**.

Results

Relevant Diagrams

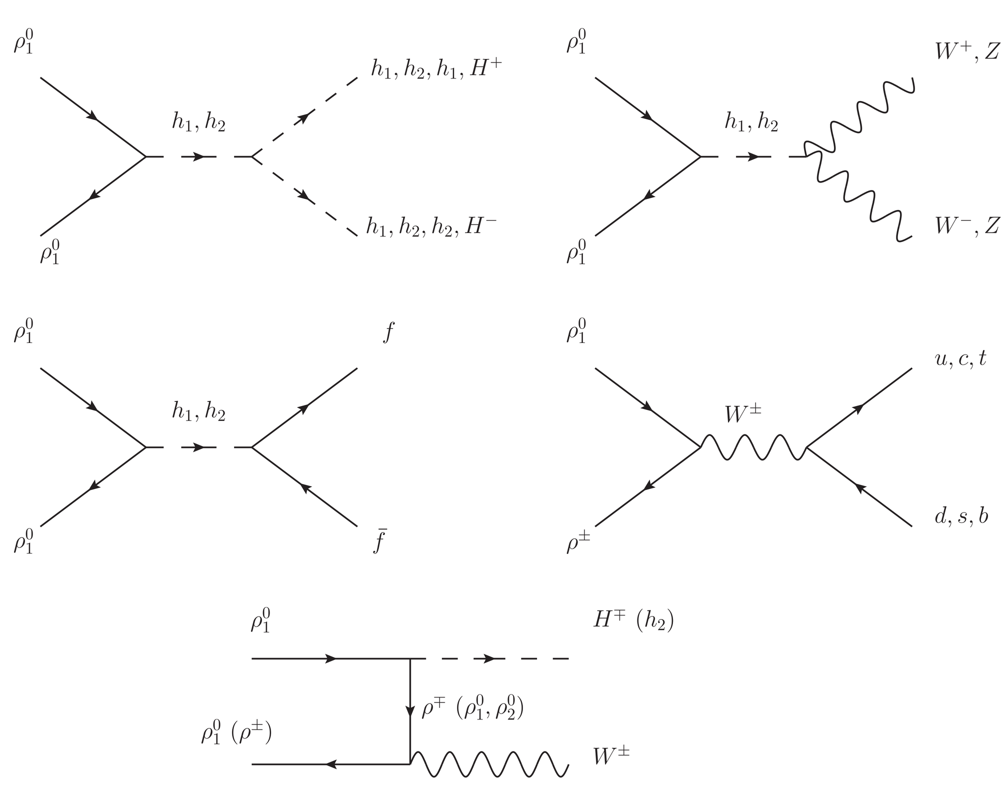


Figure 3: Annihilation and Co-annihilation processes which contribute to the DM relic density.

Dark Matter Phenomenology

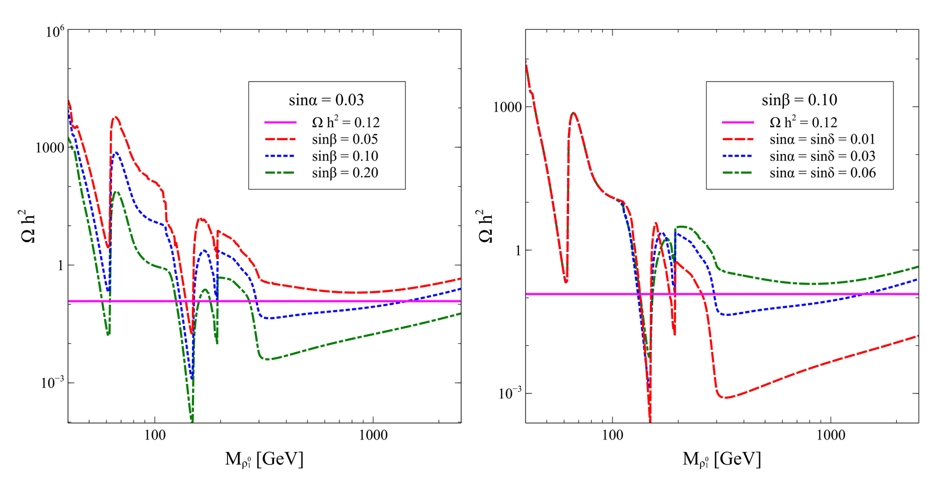


Figure 4: Variation of DM relic density with DM mass.

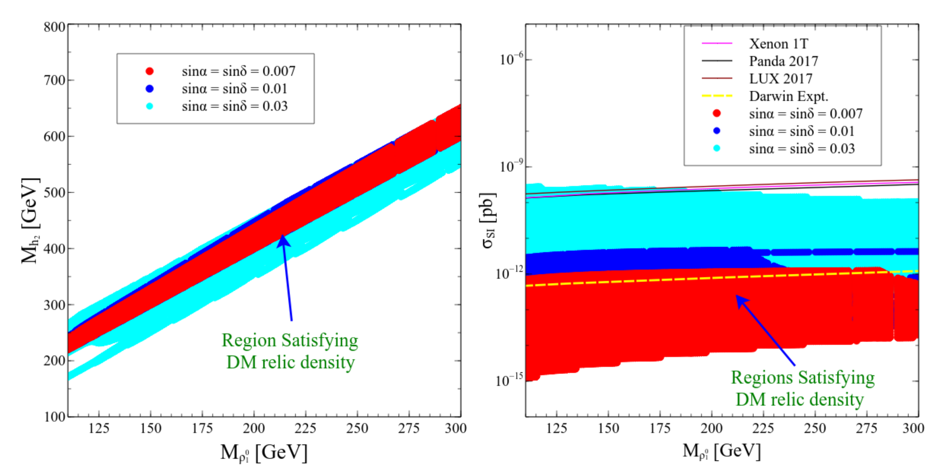


Figure 5: Allowed regions after satisfying the DM relic density bound.

LHC phenomenology

We have considered the following production channels associated with upto two additional jets at the parton level.

$$pp \to XY$$
$$pp \to XYj$$
$$pp \to XYjj \quad (12)$$

where {X Y} indicates any of the three pairs, $\{\rho_2^0\,\rho^+\}$, $\{\rho_2^0\,\rho^-\}$ and $\{\rho^+\,\rho^-\}$. After that showering has been done using Pythia. Finally, we have studied the following signal for the present model at the 13 TeV run of LHC,

$$pp \to nj + \not{E}_T, (n \geq 2) \quad (13)$$

Production Cross section

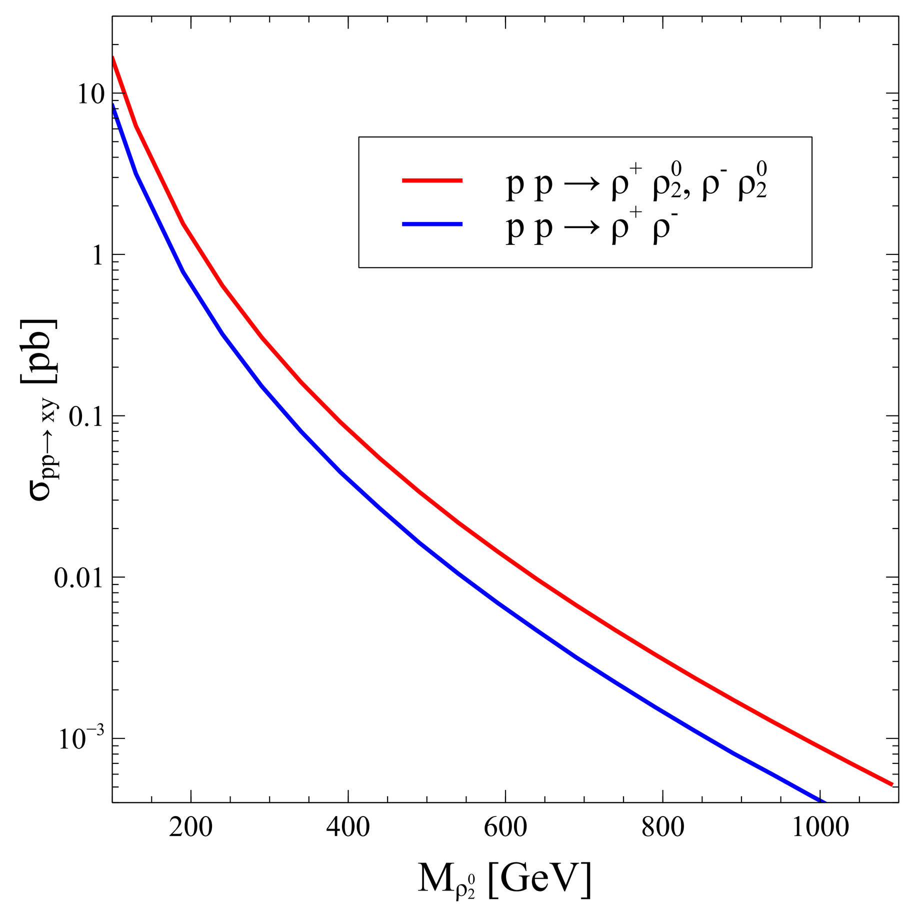


Figure 6: Production cross section at LHC.

Benchmark Points

Parameters	$M_{\rho_1^0}$ [GeV]	$M_{\rho_2^0}$ [GeV]	M_{ρ^+} [GeV]	M_{h_2} [GeV]	$M_{H^\pm}$ [GeV]	σ_{SI} [pb]	Ωh^2
BP1	87.6	128.0	128.2	195.5	195.5	2.1×10^{-12}	0.1207
BP2	132.0	172.0	172.2	300.0	300.0	4.1×10^{-12}	0.1208
BP3	171.1	211.0	211.2	400.0	400.0	4.8×10^{-12}	0.1197
BP4	86.7	200.0	200.2	194.1	194.1	1.8×10^{-11}	0.1186
BP5	119.0	230.0	230.2	280.0	280.0	2.9×10^{-11}	0.1195

Statistical Significance

In order to compute statistical significance ($\mathcal{S}$) of our signal for the different benchmark points over the SM background we have used

$$\mathcal{S} = \sqrt{2 \times \left[(s+b)\ln\left(1 + \frac{s}{b}\right) - s\right]}. \quad (14)$$

where s is the number of signal events and b that of the total SM background contribution.

Signal at 13 TeV		Statitical Significance ($\mathcal{S}$)	Required Luminosity $\mathcal{L}$ (fb^{-1})
BP	DM mass [GeV]	$\mathcal{L}$ = 100 fb^{-1}	$\mathcal{S} = 3\sigma$
BP1	87.6	3.5	74.4
BP2	132.0	2.0	223.0
BP3	171.1	1.3	545.3
BP4	86.7	1.8	282.3
BP5	119.0	1.4	473.9

Conclusions

- For pure triplet type DM relic density is satisfied around DM mass 2.3 TeV. After taking mixing with the singlet fermion, the relic density can be satisfied for DM mass ∼ 100 GeV.
- This model can be tested in near future by different type of DD experiments like Darwin, Xenon-1T.
- The model can also be tested at the 13 TeV run of LHC.

References

[1] S. Choubey, S. Khan, M. Mitra and S. Mondal, Eur. Phys. J. C **78**, no. 4, 302 (2018) [arXiv:1711.08888 [hep-ph]].

[2] E. Ma and D. Suematsu, Mod. Phys. Lett. A **24**, 583 (2009) [arXiv:0809.0942 [hep-ph]].

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[4] G. Aad *et al.* [ATLAS Collaboration], JHEP **1409**, 176 (2014) [arXiv:1405.7875 [hep-ex]].