Singlet-Triplet Fermionic Dark Matter and LHC Phenomenology

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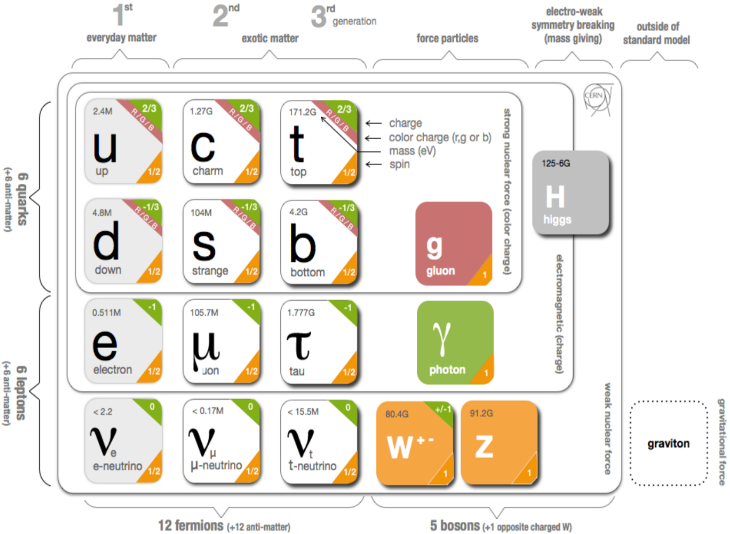
Strategy in DM Study

Will focus on the following points,

- Satisfying Relic Density bound
  (**FeynRules** $\rightarrow$ **MicrOMEGAs**).
- DM direct detection.
- DM indirect detection.
- DM collider signature
  (**FeynRules** $\rightarrow$ **MadGraph** $\rightarrow$ **PYTHIA** $\rightarrow$ **Delphes**).

Standard Model Particles



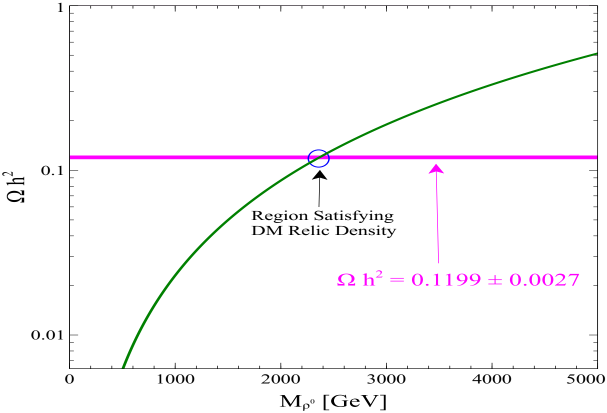
- Need to extend the SM.
- Introduce a triplet fermion,

Gauge Group	Baryon Fields			Lepton Fields			Scalar Fields
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	ρ	ϕ_h
$SU(3)_c$	3	3	3	1	1	1	1
$SU(2)_L$	2	1	1	2	1	3	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1	0	1/2
$\mathbb{Z}_2$	+	+	+	+	+	−	+

where

$$\rho = \begin{pmatrix} \frac{\rho_0}{2} & \frac{\rho^+}{\sqrt{2}} \\ \frac{\rho^-}{\sqrt{2}} & -\frac{\rho_0}{2} \end{pmatrix} . \qquad (1)$$

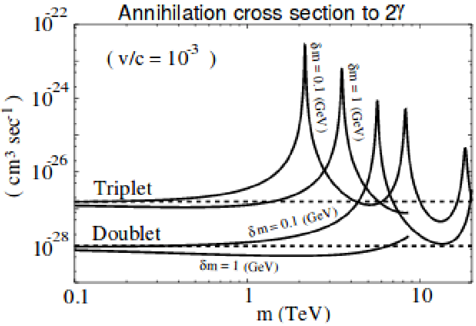
Relic Density



- ♠ Relic density satisfies around 2.3 TeV.
- ♠ This simplest model has few drawbacks which are as follows.

Drawbacks

J. Hisano et. al. [PRD 05]



- Sommerfeld enhancement after 1 TeV mass.

Cont...

- This DM is ruled out by the HESS and Fermi-LAT data.
- ~ 2 TeV DM is difficult to detect at LHC.
- No tree level DD processes exist.

Way Out

- **One way out :** Introduce a Singlet fermion and a triplet scalar.

- Complete particles list are as follows,

Gauge Group	Baryon Fields			Lepton Fields				Scalar Fields	
	$Q_L^i = (u_L^i, d_L^i)^T$	u_R^i	d_R^i	$L_L^i = (\nu_L^i, e_L^i)^T$	e_R^i	N'	ρ	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
$\mathbb{Z}_2$	+	+	+	+	+	−	−	+	+

- All the above drawbacks are solved.

Lagrangian

Present model Lagrangian,

$$\begin{aligned}\mathcal{L} \quad &= \quad \mathcal{L}_{SM} + Tr\left[\bar{\rho}\, i\,\gamma^{\mu} D_{\mu}\,\rho\right] + \bar{N'}\, i\,\gamma^{\mu} D_{\mu} N' + Tr[(D_{\mu}\Delta)^{\dagger}(D^{\mu}\Delta)] - V(\phi_h, \Delta) \\ &\quad - Y_{\rho\Delta}\,(Tr[\bar{\rho}\,\Delta]\, N' + h.c.) - M_{\rho}\; Tr[\bar{\rho^{c}}\,\rho] - M_{N'}\; \bar{N'^{c}} N' \qquad (2)\end{aligned}$$

where triplet fermion,

$$\rho = \begin{pmatrix} \frac{\rho_0}{2} & \frac{\rho^{+}}{\sqrt{2}} \\ \frac{\rho^{-}}{\sqrt{2}} & -\frac{\rho_0}{2} \end{pmatrix} . \qquad (3)$$

Potential $V(\phi_h, \Omega)$ is,

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

Mass Eigenstates

- ϕ_h will take vev spontaneously, and simultaneously the triplet scalar Δ will get induced *vev*,

$$\mu_h^2 > 0, \quad \mu_\Delta^2 > 0, \quad \lambda_h > 0 \text{ and } \lambda_\Delta > 0\,.$$

- **After symmetry breaking**, there will be **mixing** between the **two neutral scalars**, **two charged scalars**, and **two neutral fermions**.
- Therefore, we need to introduce mass basis in the following way,
  Neutral Higgs:

$$\begin{aligned} h_1 &= \cos\alpha\, H + \sin\alpha\, \Delta_0 \\ h_2 &= -\sin\alpha\, H + \cos\alpha\, \Delta_0 \end{aligned}$$

Charged Higgs:

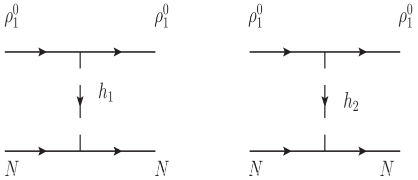
$$\begin{aligned} G^\pm &= \cos\delta\, \phi^\pm + \sin\delta\, \Delta^\pm \\ H^\pm &= -\sin\delta\, \phi^\pm + \cos\delta\, \Delta^\pm \end{aligned} \tag{5}$$

Fermions:

$$\begin{aligned} \rho_2^0 &= \cos\beta\, \rho_0 + \sin\beta\, N'^c \\ \rho_1^0 &= -\sin\beta\, \rho_0 + \cos\beta\, N'^c \end{aligned} \tag{6}$$

Constraints Used in DM Study

SI direct detection cross section



DD cross section for the above diagrams,

$$\sigma_{SI} = \frac{\mu_{red}^2}{\pi} \left[\frac{M_N f_N}{v} \frac{\Delta M_{21} \sin^2 2\beta \sin 2\alpha}{4 v_\Delta} \left(\frac{1}{M_{h_2}^2} - \frac{1}{M_{h_1}^2} \right) \right]^2$$

DM Results

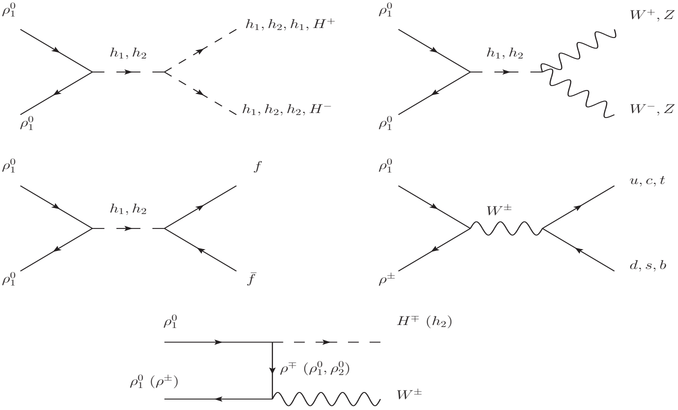
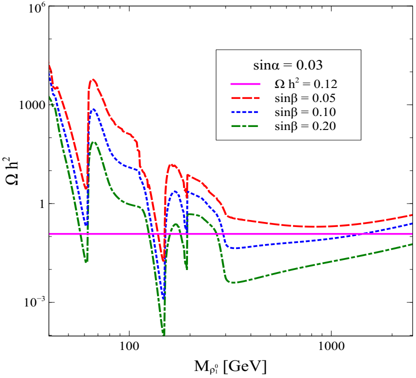


Figure: Feynman diagrams which take part in DM phenomenology

DM Results



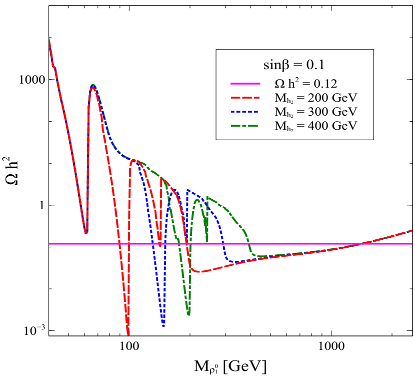


Figure: BSM Higgs mass, $M_{h_2} = 300$ GeV, $\sin\delta = \sin\alpha = 0.03$ and $\Delta M_{12} = 50$ GeV.

DM Results

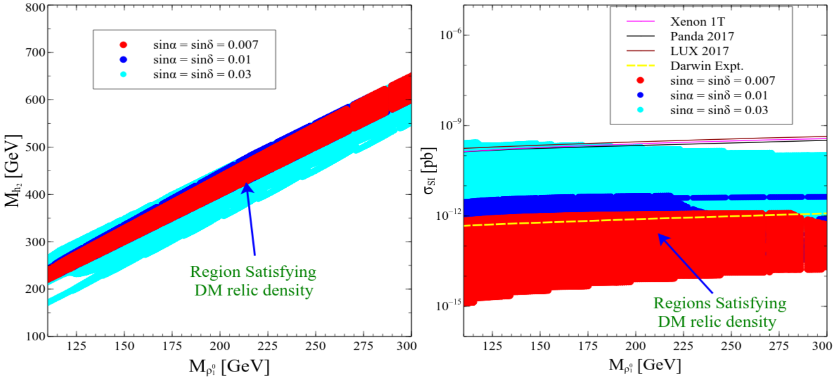


Figure: $M_{\rho_1^0}$, M_{h_2} and $\sin\beta$ three parameters have been varied for scatter plots.

Indirect Detection

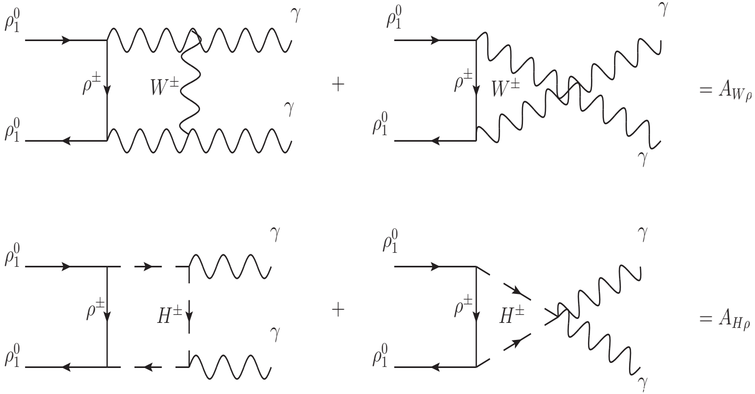
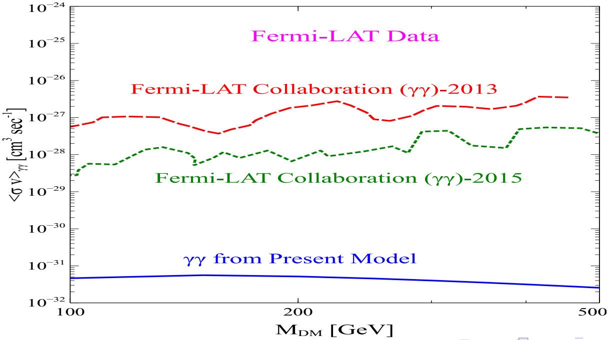


Figure: Feynman diagrams contributing in $\gamma\gamma$ final state.

Indirect Detection

CS times velocity is, [L. Bergstrom et. al., NPB 97; Z. Bern et. al, PLB 97]

$$\langle \sigma v \rangle_{\gamma\gamma} = \frac{\alpha_{EM}^2 M_{\rho_1^0}^2}{16\pi^3} |A_{W\rho} + A_{H\rho}|^2 \,. \tag{7}$$



Collider Part

Signal Production :

$$\begin{aligned} p\,p &\rightarrow X\,Y \\ p\,p &\rightarrow X\,Y\,j \\ p\,p &\rightarrow X\,Y\,j\,j \end{aligned}$$

Signal-I:

$$\{\mathrm{X\ Y}\} = \{\rho_2^0\ \rho^+\},\ \{\rho_2^0\ \rho^-\}$$

Signal-II:

$$\{\mathrm{X\ Y}\} = \{\rho^+\ \rho^-\}$$

Showering by Pythia $\rightarrow$ looked for the signal,

$$\not{E}_T + n\,j, \textbf{ where n} \geq \mathbf{2}$$

Collider Part

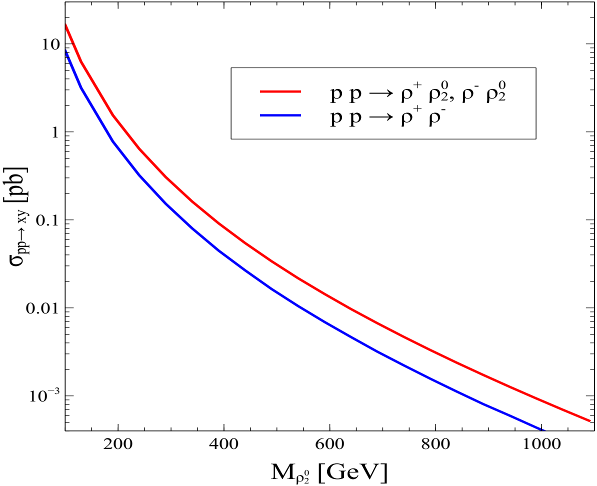


Figure: Production cross section

Collider Part

Bencmark 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	$2.1\ \times 10^{-12}$	0.1207
BP2	132.0	172.0	172.2	300.0	300.0	$4.1\ \times 10^{-12}$	0.1208
BP3	171.1	211.0	211.2	400.0	400.0	$4.8\ \times 10^{-12}$	0.1197
BP4	86.7	200.0	200.2	194.1	194.1	$1.8\ \times 10^{-11}$	0.1186
BP5	119.0	230.0	230.2	280.0	280.0	$2.9\ \times 10^{-11}$	0.1195

Statistical Significance ($\mathcal{S}$)

We have used following formula in determining $\mathcal{S}$,

$$\mathcal{S} = \sqrt{2 \times \left[(s+b)\ln\left(1+\frac{s}{b}\right) - s\right]} \tag{8}$$

$\mathcal{S}$ **for different BPs** :

Signal at 13 TeV		Statitical Significance ($\mathcal{S}$)	Required Luminosity $\mathcal{L}$ (fb^{-1})
BP	DM mass [GeV]	$\mathcal{L} = 100\ \text{fb}^{-1}$	$\mathcal{S} = 3\sigma$
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

Conclusion

- ☺ By introducing singlet fermion, we have overcome the drawbacks of pure triplet fermions.
- ☺ The lighest among the two neutral fermions becomes a viable DM candidate.
- ☺ DM can be tested in different on going DD experiments like Xenon-1T, LUX.
- ☺ Fermi-LAT and HESS can detect the DM indirectly by detecting gamma-rays signal in future.
- ☺ This model can also be tested at collider by searching multi-jet + $\not{E}_T$ signal.


Thank you

Back UP Slides

Selection Cuts

Basic Cuts (A0) :

- Leptons are selected with $p_T^l > 10$ GeV and the pseudorapidity $|\eta^\ell| < 2.5$, where $\ell = e, \mu$.
- We used $p_T^\gamma > 10$ GeV and psudorapidity $|\eta^\gamma| < 2.5$ as the basic cuts for photon.
- We have chosen the jets which satisfy $p_T^j > 40$ GeV and $|\eta^j| < 2.5$.
- We have considered the azimuthal separation between all reconstructed jets and missing energy must be greater than 0.2 i.e. $\Delta\phi(jet, \not{\vec{E}}_T) > 0.2$.

Selection Cuts

A1: We have imposed a lepton and photon veto in the final state.

A2: p_T requirements on the hardest and second hardest jets: $p_T^{j_1} > 130$ GeV and $p_T^{j_2} > 80$ GeV.

A3: In order to minimise *QCD* multi-jet, we have ensured that the $\vec{\not{E}}_T$ and the jets are well separated, i.e., $\Delta\phi(j_i, \vec{\not{E}}_T) > 0.4$ where i $= 1$, 2. For all the other jets, $\Delta\phi(j, \vec{\not{E}}_T) > 0.2$.

A4: We demand a hard cut on the effective mass variable, $M_{Eff} > 800$ GeV, where $M_{Eff} = \sum_i |\vec{p}^{\,j}_{T_i}| + \sum_i |\vec{p}^{\,\ell}_{T_i}| + \not{E}_T$.

A5: We put the bound on the missing enrgy $\not{E}_T > 160$ GeV.

Cut-flow table for BKG

BKG Contribution after applying cuts :

SM Backgrounds at 13 TeV		Effective Cross section after applying cuts (pb)				
Channels	Cross-section (pb)	A0 + A1	A2	A3	A4	A5
$Z + \leq 4$ jets	5.7×10^4	5.5×10^3	361.90	241.60	11.40	2.20
$W^\pm + \leq 4$ jets	1.9×10^5	9.1×10^3	783.20	504.00	18.90	1.50
QCD ($\leq$ 4 jets)	2.0×10^8	1.5×10^7	3.5×10^5	2.4×10^5	2.5×10^3	-
$t\bar{t} + \leq 2$ jets	722.94	493.73	171.46	120.63	13.89	1.94
$W^\pm Z + \leq 2$ jets	51.10	19.66	5.37	3.59	0.50	0.12
$ZZ + \leq 2$ jets	13.71	4.99	0.80	0.53	0.06	0.02
Total Backgrounds						5.78

Cut-flow table for Signal-I

Signal-I Contribution after applying cuts :

Signal at 13 TeV		Effective Cross section after applying cuts (fb)				
BP	Cross-section (pb)	$A0 + A1$	A2	A3	A4	A5
BP1	6.757	1005.05	175.08	138.45	22.02	19.15
BP2	2.279	385.22	69.16	56.51	11.87	10.85
BP3	1.052	189.71	34.63	29.19	7.36	6.82
BP4	1.296	1047.86	145.67	116.94	14.19	9.82
BP5	0.760	616.00	89.60	72.63	9.80	7.40

Cut-flow table for Signal-II

Signal-II Contribution after applying cuts :

Signal at 13 TeV		Effective Cross section after applying cuts (fb)				
BP	Cross-section (pb)	$A0 + A1$	A2	A3	A4	A5
BP1	3.419	2639.30	74.36	59.18	8.54	7.31
BP2	1.156	880.60	28.77	23.87	4.95	4.43
BP3	0.532	402.24	14.80	12.62	3.18	2.95
BP4	0.652	446.80	63.99	45.54	5.72	3.76
BP5	0.380	258.55	34.40	28.07	3.99	3.08