Confronting dark fermion with a doubly charged Higgs in the Left Right symmetric model

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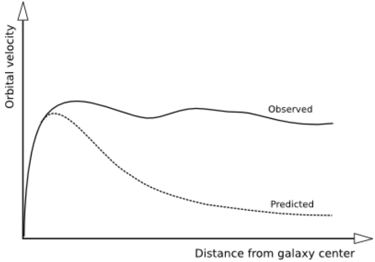
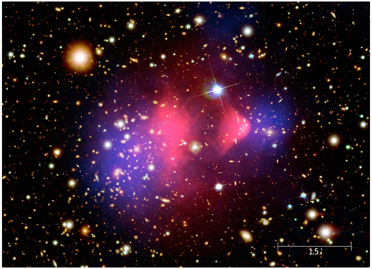
Plan of talk

- Motivation for Dark Matter
- Model and Particle contents
- Mass estimates of Dark Sector particles
- Dark Matter relic density and detection bounds
- Collider signatures of double charged Higgs
- Conclusion

- Rotational Curve of Galaxies
- Bullet Cluster's offset center of mass of baryonic matter





- Peculiar motion of clusters
- anisotropies of the Cosmic Microwave Background

- We introduced a $\mathcal{Z}_2$ symmetry with two vector like doublets $\psi_{1,2}$ in a standard MLRSM model, under which SM particles are even and Dark Sector Particles are odd , ensuring we have stable Dark Matter candidate.

Fermion Fields	$SU(3)_C$	$\otimes SU(2)_R$	$\otimes SU(2)_L$	$\otimes U(1)_{B-L}$	$\otimes \mathcal{Z}_2$
$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$	3	1	2	$\frac{1}{3}$	+
$Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$	3	2	1	$\frac{1}{3}$	+
$L_L = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_L$	1	1	2	-1	+
$L_R = \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}_R$	1	2	1	-1	+
$\psi_1 : \begin{pmatrix} \psi_1^0 \\ \psi_1^- \end{pmatrix}_L , \begin{pmatrix} \psi_1^0 \\ \psi_1^- \end{pmatrix}_R$	1	1	2	-1	-
$\psi_2 : \begin{pmatrix} \psi_2^0 \\ \psi_2^- \end{pmatrix}_L , \begin{pmatrix} \psi_2^0 \\ \psi_2^- \end{pmatrix}_R$	1	2	1	-1	-

Scalar Fields	$\underbrace{SU(3)_C \otimes SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L}}$				$\otimes \mathcal{Z}_2$
$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$	1	2	2	0	+
$\Delta_L = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}_L$	1	1	3	2	+
$\Delta_R = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}_R$	1	3	1	2	+

Gauge group is $\mathcal{G} \equiv SU(3)_C \otimes SU(2)_R \otimes SU(2)_L \otimes U(1)_{B-L} \otimes \mathcal{Z}_2$. Hypercharge $(B-L)$ of the field is obtained by using the relation : $Q = I_{3R} + I_{3L} + \frac{B-L}{2}$, where I_3 is the third component of isospin and Q is the electromagnetic charge.

- $SU(2)_R \otimes U(1)_{B-L} \xrightarrow{\langle \Delta_R \rangle} U(1)_Y$.
- $SU(2)_L \otimes U(1)_Y \xrightarrow{\langle \Phi \rangle} U(1)_Q$
- this Spontanious Symmetry Breaking is done by giving vev to the neutral components of scalars.

$$\langle \Phi \rangle = \begin{pmatrix} v_1 e^{i\alpha_1} & 0 \\ 0 & v_2 e^{i\alpha_2} \end{pmatrix}, \ \langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\beta_L} & 0 \end{pmatrix}, \ \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R e^{i\beta_R} & 0 \end{pmatrix}$$

$$
\begin{aligned}
\mathcal{L}^{\rm DS} =& \overline{\psi_1}\Big[\, i\gamma^\mu\Big(\partial_\mu - ig_L\frac{\sigma^a}{2}W^a_{L\mu} - ig_{\rm BL}\frac{Y_{\rm BL}}{2}B_\mu\Big) - M_L\Big]\psi_1 \\
&+ \overline{\psi_2}\Big[\, i\gamma^\mu\Big(\partial_\mu - ig_R\frac{\sigma^a}{2}W^a_{R\mu} - ig_{\rm BL}\frac{Y_{\rm BL}}{2}B_\mu\Big) - M_R\Big]\psi_2 \\
&- \Big\{\Big(y_1\overline{\psi_1}\Phi\psi_2 + y_2\overline{\psi_1}\tilde{\Phi}\psi_2\Big) + h.c\Big\} \\
&- y_L\Big(\overline{\psi_1}\Delta_L^\dagger i\sigma_2\psi_1^c + h.c\Big) - y_R\Big(\overline{\psi_2}\Delta_R^\dagger i\sigma_2\psi_2^c + h.c\Big).
\end{aligned}
$$

$$
\psi_{(1,2)} = \psi_{(1,2)_L} + \psi_{(1,2)_R}
$$

$$\mathcal{L}^{\rm NDS}{\rm mass} = \frac{1}{2}\overline{X^c}\begin{pmatrix} y_L v_L\sqrt{2} & M_L & 0 & \frac{(y_1 v_1 + y_2 v_2)}{\sqrt{2}} \\ M_L & y_L v_L\sqrt{2} & \frac{(y_1 v_1 + y_2 v_2)}{\sqrt{2}} & 0 \\ 0 & \frac{(y_1 v_1 + y_2 v_2)}{\sqrt{2}} & y_R v_R\sqrt{2} & M_R \\ \frac{(y_1 v_1 + y_2 v_2)}{\sqrt{2}} & 0 & M_R & y_R v_R\sqrt{2} \end{pmatrix} X + h.c$$

$$= \frac{1}{2}\overline{X^c}\mathcal{M}_N X + h.c.$$

The eigen values of the above mass matrix $\mathcal{M}_N$ for neutral dark sector particles are given by

$$m^1_{\pm} = \frac{(y_L v_L + y_R v_R)\sqrt{2} - (M_L + M_R) \pm \left(\left(\frac{(y_L v_L - y_R v_R)}{\sqrt{2}} - (M_L - M_R)\right)^2 + 4\alpha^2\right)^{1/2}}{2}$$

$$m^2_{\pm} = \frac{(y_L v_L + y_R v_R)\sqrt{2} + (M_L + M_R) \pm \left(\left(\frac{(y_L v_L - y_R v_R)}{\sqrt{2}} + (M_L - M_R)\right)^2 + 4\alpha^2\right)^{1/2}}{2}$$

Here M_1 , M_2, M_3 and M_4 are the mass eigen values for the mass eigen states χ_1, χ_2, χ_3 and χ_4 respectivly. Here the lightest neutral state is assumed to be χ_1 $(M_1 < M_2 < M_3 < M_4)$ and it becomes the stable DM candidate. $\alpha = \frac{(y_1 v_1 + y_2 v_2)}{\sqrt{2}}$

$$\mathcal{L}^{\mathrm{CDS}}_{\mathrm{mass}} = \begin{pmatrix} \overline{\psi_1^-} & \overline{\psi_2^-} \end{pmatrix} \begin{pmatrix} M_L & \frac{v_1 y_2}{\sqrt{2}} \\ \frac{v_1 y_2}{\sqrt{2}} & M_R \end{pmatrix} \begin{pmatrix} \psi_1^- \\ \psi_2^- \end{pmatrix}$$

The mass eigen values of the charged dark sector particles are

$$M^{\pm}_{(1,2)} = \frac{1}{2}\left(M_L + M_R (\pm) \sqrt{(M_L - M_R)^2 + 2 v_1^2 y_2^2} \right)$$

- **Relic and Direct Search**

$\Omega_{DM} h^2 = 0.120 \pm 0.001$ at 90% CL.
The XENON 1T experiment puts a bound on the scattering cross-section of DM nucleon interaction.

- **Higgs invisible decay**

If dark matter's mass is below of half the mass of Higgs ,then Higgs can decay to dark matter via invisible decay

- **LEP Constraints**

LEP excludes charged fermions(Charged dark sector particles) below 100 GeV.

- **FCNC constraints**

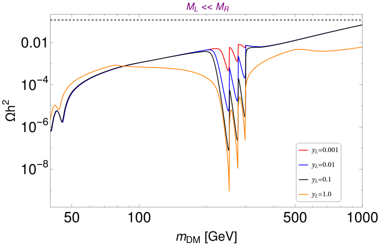
The flavour changing neutral current (FCNC) puts a strong lower bound on heavy neutral scalars $M_{H,A} > 15\,TeV$. Using approximate expression of heavy neutral scalar ,

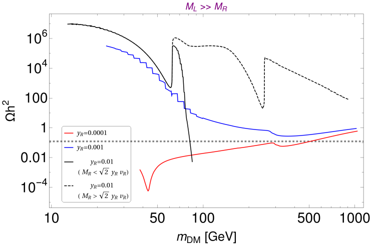
$$\frac{1}{2}\alpha_3\left(\frac{v_R}{\mathrm{TeV}}\right)^2 \gtrsim \left(\frac{15}{\mathrm{TeV}}\right)^2 \quad (1)$$

The neutral dark sector particle with lowest mass (χ_1) is the DM candidate which freezes out when ($n\sigma v << \mathcal{H}$).

$(\chi_1\chi_1 \leftrightarrow SMSM)$, $(\chi_1\chi_i \leftrightarrow SMSM)$, $(\chi_1\chi_i^{\pm} \leftrightarrow SMSM)$, $(\chi_i\chi_j \leftrightarrow SMSM)$, $(\chi_i^{\pm}\chi_j^{\pm} \leftrightarrow SMSM)$

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} = -\langle\sigma v\rangle_{eff}\left(n_{DM}^2 - n_{eq}^2\right)$$

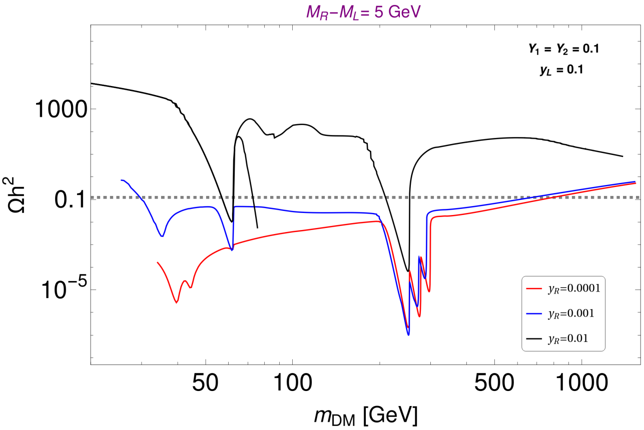


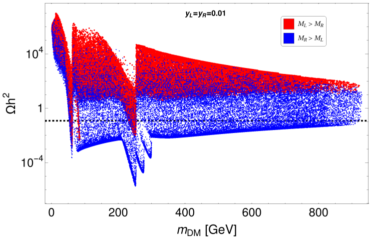


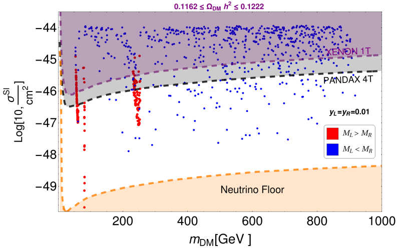
$$\chi_1 \simeq -\frac{i}{\sqrt{2}}(\psi_1 - \psi_1^c) \quad \text{of mass} \quad M_1 = M_{L/R} - \sqrt{2}\; v_{L/R}\; y_{L/R}\; (\equiv m_{\rm DM})$$

$$\chi_2 \simeq \frac{1}{\sqrt{2}}(\psi_1 + \psi_1^c) \quad \text{of mass} \quad M_2 = M_{L/R} + \sqrt{2}\; v_{L/R}\; y_{L/R}$$

$$\chi_1^{\pm} \simeq \psi_1^{\pm} \quad \text{of mass} \quad M_1^{\pm} = M_{L/R},$$


$M_R - M_L = 5$ GeV
$Y_1 = Y_2 = 0.1$
$y_L = 0.1$
1000
0.1
10^{-5}
Ωh^2
50
100
500
1000
m_{DM} [GeV]
y_R=0.0001
y_R=0.001
y_R=0.01



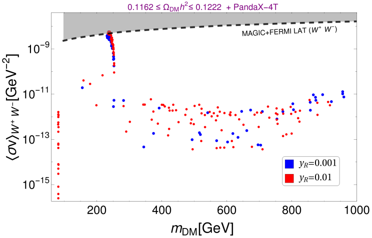


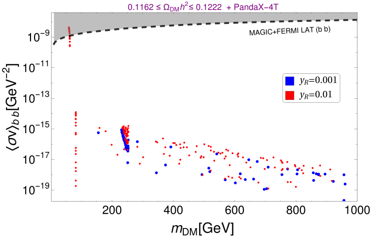
We perform a numerical scan over the following region :

$$M_L : \{100 - 1000\} \text{ GeV} \qquad M_R : \{100 - 1000\} \text{ GeV}$$

$$Y \equiv Y_1 = Y_2 : \{0.01 - 0.20\} \qquad y \equiv y_L = y_R : \{0.001,\ 0.01\}$$

Dark Matter Phenomenology : Relic Density + Direct + Indirect Detection

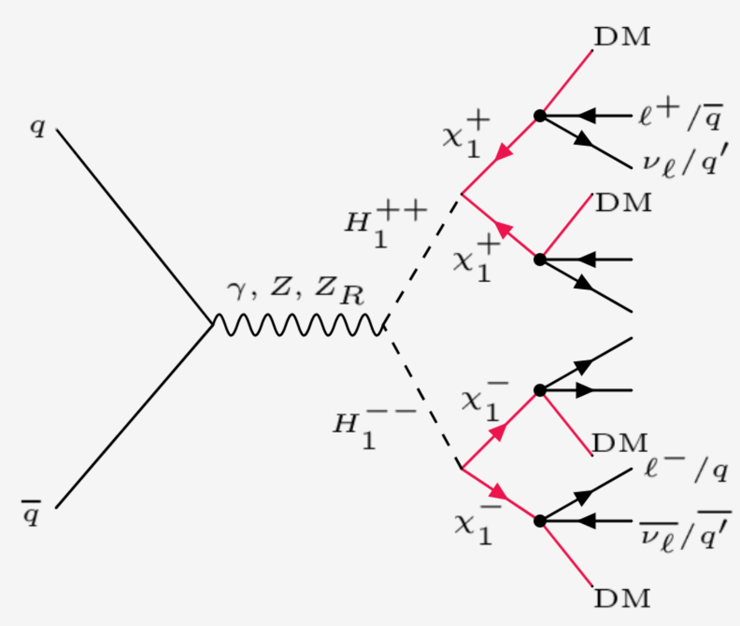




Benchmarks for collider studies

	BPC1	BPC2	BPC3
$\left(M_{H_R^{\pm\pm}},\ M_{H_L^{\pm\pm}},\ v_R\right)$	$(889.2,\ 300.3,\ 30\times10^3)$	$(1000,\ 280,\ 30\times10^3)$	$(800,\ 300,\ 30\times10^3)$
DM Inputs Mass(GeV)	$M_L = 150 \quad M_R = 150$ $Y_1 = Y_2 = 4\times10^{-2}$ $y_R = 2.06\times10^{-3} \quad y_L = 0.6$	$M_L = 142 \quad M_R = 142$ $Y_1 = Y_2 = 4\times10^{-2}$ $y_R = 2.08\times10^{-3} \quad y_L = 2.0$	$M_L = 120 \quad M_R = 210$ $Y_1 = 0.036 \ Y_2 = 0.06$ $y_R = 0.028 \ y_L = 0.6$
Dark Particles Mass(GeV)	$M_1 = 62.044,\ M_2 = 149.708,$ $M_3 = 150.291,\ M_4 = 237.955$ $M_1^{\pm} = 143.035,\ M_2^{\pm} = 156.964$	$M_1 = 61.118,\ M_2 = 147.735,$ $M_3 = 152.264,\ M_4 = 238.811$ $M_1^{\pm} = 143.035,\ M_2^{\pm} = 156.964$	$M_1 = 89.8,\ M_2 = 120.4,$ $M_3 = 120.6,\ M_4 = 328.9$ $M_1^{\pm} = 118.8,\ M_2^{\pm} = 211.1$
Relic Density, Direct Detection, Indirect Detection	$\Omega_{\rm DM}h^2 = 0.107$ $\sigma_n^{\rm SI} = 4.92\times10^{-48}\ {\rm cm}^2$ $\langle\sigma v\rangle_{\mu\mu} = 1.61\times10^{-13}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\tau\tau} = 4.54\times10^{-11}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\rm bb} = 7.50\times10^{-10}\ {\rm GeV}^{-2}$	$\Omega_{\rm DM}h^2 = 0.1150$ $\sigma_n^{\rm SI} = 1.46\times10^{-48}\ {\rm cm}^2$ $\langle\sigma v\rangle_{\rm WW} = 1.19\times10^{-12}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\mu\mu} = 4.38\times10^{-21}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\tau\tau} = 1.24\times10^{-18}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\rm bb} = 1.98\times10^{-17}\ {\rm GeV}^{-2}$	$\Omega_{\rm DM}h^2 = 0.0973$ $\sigma_n^{\rm SI} = 6.687\times10^{-47}\ {\rm cm}^2$ $\langle\sigma v\rangle_{\mu\mu} = 4.46\times10^{-18}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\tau\tau} = 1.26\times10^{-15}\ {\rm GeV}^{-2}$ $\langle\sigma v\rangle_{\rm bb} = 1.07\times10^{-14}\ {\rm GeV}^{-2}$
Neutrino sector ($m_\nu = 0.1$ eV)	$M_{Dii} = 5\times10^{-5}$ GeV $M_{Di\neq j} = 0$ $Y_{\Delta Rii} = 5.892\times10^{-4}\ Y_{\Delta Ri\neq j} = 0$ $M_N = 25$ GeV; $V_{\ell N} \simeq 10^{-6}$	$M_{Dii} = 5\times10^{-5}$ GeV $M_{Di\neq j} = 0$ $Y_{\Delta Rii} = 5.892\times10^{-4}\ Y_{\Delta Ri\neq j} = 0$ $M_N = 25$ GeV; $V_{\ell N} \simeq 10^{-6}$	$M_{Dii} = 1\times10^{-4}$ GeV $M_{Di\neq j} = 0$ $Y_{\Delta Rii} = 2.357\times10^{-3}\ Y_{\Delta Ri\neq j} = 0$ $M_N = 100$ GeV; $V_{\ell N} \simeq 10^{-6}$
Doubly charged Scalar	$\Gamma(H_L^{\pm\pm}) = 1.228\times10^{-1}$ GeV ${\rm Br}(H_L^{\pm\pm}\to\chi_1^{\pm}\ \chi_1^{\pm}) \simeq 98.67\%$ ${\rm Br}(H_L^{\pm\pm}\to\chi_1^{\pm}\chi_2^{\pm}) \simeq 0.659\%$ ${\rm Br}(H_L^{\pm\pm}\to WW) \simeq 0.665\%$	$\Gamma(H_L^{\pm\pm}) = 7.571\times10^{-2}$ GeV ${\rm Br}(H_L^{\pm\pm}\to\chi_1^{\pm}\ \chi_1^{\pm}) \simeq 99.08\%$ ${\rm Br}(H_L^{\pm\pm}\to WW) \simeq 0.9195\%$	$\Gamma(H_L^{\pm\pm}) = 3.835$ GeV ${\rm Br}(H_L^{\pm\pm}\to\chi_1^{\pm}\ \chi_1^{\pm})\simeq 99.9\%$
Dark charged Fermion	$\Gamma(\chi_1^{\pm}) = 4.005\times10^{-6}$ GeV ${\rm Br}(\chi_1^{\pm}\to\chi_1 W^{\pm})\simeq 100\%$	$\Gamma(\chi_1^{\pm}) = 1.462\times10^{-5}$ GeV ${\rm Br}(\chi_1^{\pm}\to\chi_1 W^{\pm})\simeq 100\%$	$\Gamma(\chi_1^{\pm}) = 9.39\times10^{-7}$ GeV ${\rm Br}(\chi_1^{+}\to\chi_1 u_i \bar{d}_j')\simeq 66.6\%$ ${\rm Br}(\chi_1^{+}\to\chi_1\ell^{+}\nu_\ell(\ell = e,\mu))\simeq 22.2\%$ ${\rm Br}(\chi_1^{+}\to\chi_1\ell^{+}\nu_\ell(\ell = \tau))\simeq 11.1\%$
Cross-section $\sqrt{s} = 14$ TeV (LHC)	$\sigma(pp\to H_L^{++}H_L^{--}) = 13.953$ fb	$\sigma(pp\to H_L^{++}H_L^{--}) = 16.58$ fb	$\sigma(pp\to H_L^{++}H_L^{--}) = 13.9$ fb $\sigma(e^+e^-\to H_L^{++}H_L^{--}) = 58.22$ fb (ILC: $\sqrt{s} = 1$ TeV)

Feynman Diagram



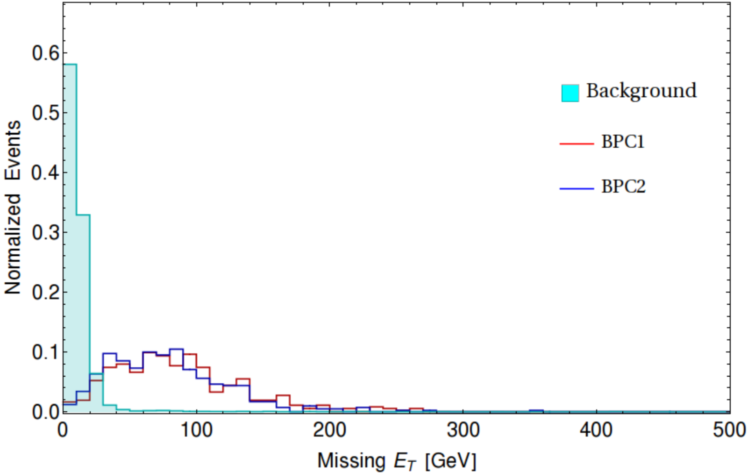
Signal and backgrounds :

- Signal will appear when all four W bosons produced in the cascade decay of the pair of double charged Higgs, decays leptonically.
- The dominant background are SM sub-processes producing $t\bar{t}Z$, ZZ and VVV. Additional sources $t\bar{t}$ and WZ.

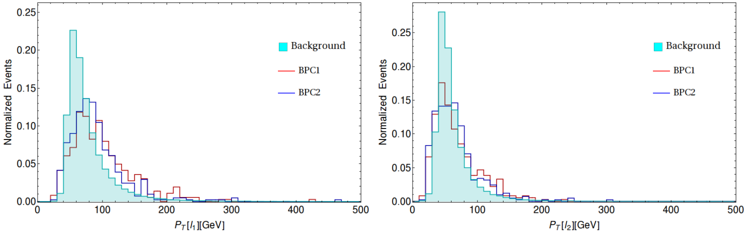
Selection cuts :

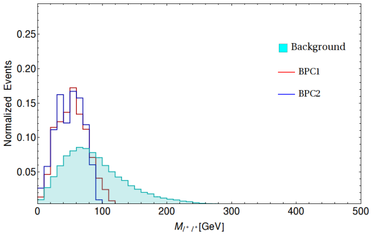
- $p_{T_l} > 10$ GeV and $|\eta_l| < 2.5$.
- We demand a hadronically quite environment by putting veto on events with light jets and b jets with $p_{T_{b/j}} > 40$ GeV and $|\eta_{b/j}| < 2.5$. This helps in suppressing a significant part of the background coming from $t\,\bar{t}(Z)$ production.

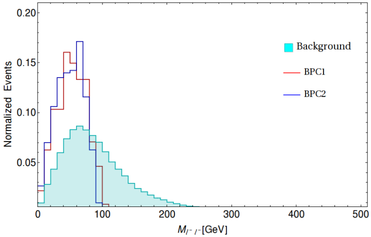
$4\ell + \not{E}_T$ signature

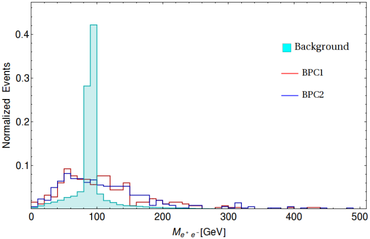


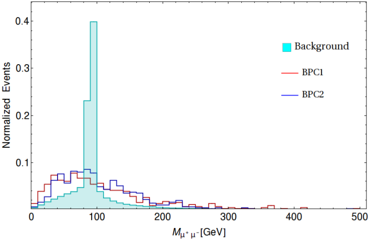
$4\ell + \not{E}_T$ signature




Normalized Events
0.25
0.20
0.15
0.10
0.05
0
100
200
300
400
500
$M_{l^+l^+}$[GeV]
Background
BPC1
BPC2


Normalized Events
0.20
0.15
0.10
0.05
0
100
200
300
400
500
$M_{l^-l^-}$[GeV]
Background
BPC1
BPC2


Normalized Events
0.1
0.2
0.3
0.4
0
100
200
300
400
500
$M_{e^+e^-}$[GeV]
Background
BPC1
BPC2


Normalized Events
0.1
0.2
0.3
0.4
0
100
200
300
400
500
$M_{\mu^+\mu^-}$[GeV]
Background
BPC1
BPC2

$4\ell + \not{E}_T$ signature results at 3000 fb^{-1}

Cuts (GeV)	$\not{E}_T < 30$	$82 < M_{e^+e^-} < 100$	$82 < M_{\mu^+\mu^-} < 100$	$p_T[l_2] < 30$	$M_{l_i^+ l_j^+} > 110$	$M_{l_i^- l_j^-} > 110$
BPC1	15.4	13.6	10.4	9.5	9.4	9.3
BPC2	18.2	15.9	11.4	10.2	9.9	9.9
Background	687.7	381.0	53.0	20.0	8.5	1.0

Benchmark	Signal	Background	Significance
BPC1	9.4	1.0	5.50
BPC2	9.9	1.0	5.75

$3\ell + 2j + \not{E}_T$ signature results at 1000 fb^{-1}

Cuts (GeV)	$\not{E}_T < 30$	$75 < M_{e^+e^-} < 100$	$80 < M_{\mu^+\mu^-} < 100$	$M_{l^\pm j_1 j_2} > 130$	SetA: $M_{l_i^+ l_j^+} > 100$ SetB: $M_{l_i^- l_j^-} > 90$	SetA: $65 < M_{j_1 j_2} < 90$ SetB: $60 < M_{j_1 j_2} < 90$
BPC1	28.5	26.3	23.0	7.5	7.0	5.5
BPC2	31.9	29.6	25.7	9.2	9.1	6.5
Background	40395	26293	3974	56.7	24.1	1.7

Benchmark	Signal	Background	Significance
BPC1	5.5	1.7	3.13
BPC2	6.5	1.7	3.59

- This model contains Dark matter candidate in a Left Right symmetric construction.
- A wide range of mass $(70 - 900 Gev)$ is available for DM.
- In this model we have different mechanisms for producing dark matter with different gauge properties $(SU(2)_{L/R})$ which provides different parameter regions satisfying direct and indirect detection bounds.
- We studied collider signatures of double charged Higgs, whose lower bound on mass can be reduced below 400 GeV under the construction of this model at luminosity of 3000 fb^{-1} at LHC(14 TeV) .
- We also studied a benchmark point with the $3\ell + 2j + \not{E}_T$ signal where double charged Higgs decays through off-shell W Boson to dark fermions which has very low sensitivity at LHC but can have higher significance (4.8σ) at ILC(1 TeV).