Fermion Singlet Dark Matter in Scotogenic $B - L$ Model

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Introduction

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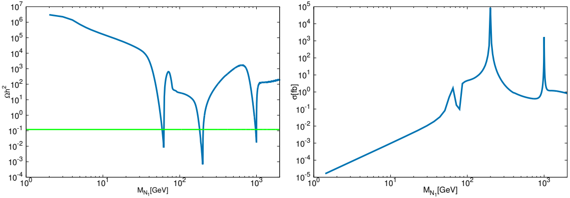

$M_{h_1} = 125$ GeV, $M_{h_2} = 400$ GeV, $M_{Z_{B-L}} = 2$ TeV, $\sin\gamma = 0.1$

- To bring more allowed parameter space for dark matter mass we need more cross-section by having extra channels.

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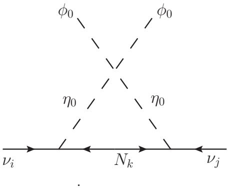

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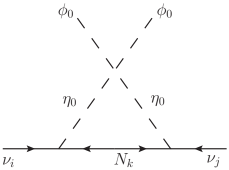

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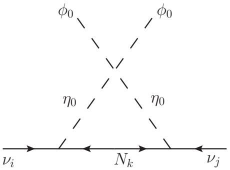

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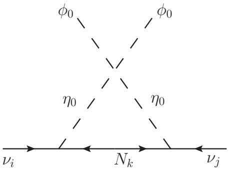

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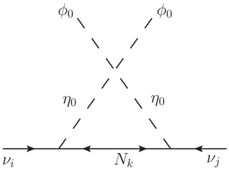

- Dark matter-lightest particle running in the loop can be a dark matter candidate
- Calling as 'scotogenic' dark matter
- We can show that the high mass scale is reduced
- We can probe this in forthcoming experiments

Fermion Singlet Dark Matter in Scotogenic $B - L$ Model

- By combining these ideas we studied extra channel contributions on relic density
- And also studied the allowed parameter space from neutrino, direct detection and collider experiments.

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Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_{B-L}$	Z_2
N_R	1	1	0	-1	-
η	1	2	$\frac{1}{2}$	0	-
χ	1	1	0	2	$+$

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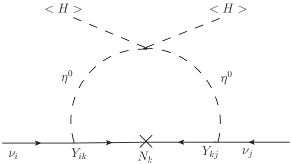
$$\mathcal{L}_Y = \sum_{j,k=1}^{3} -y_{jk}\overline{\ell}_{jL}N_{kR}\,\tilde{\eta} - \lambda_{jk}\overline{(N_{jR})^c}\,N_{kR}\,\chi + h.c - V(H,\chi,\eta)$$

Where

$$\begin{aligned} V(H,\chi,\eta) = & -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 \\ & -\mu_\chi^2 \chi^\dagger\chi + \lambda_\chi(\chi^\dagger\chi)^2 + \mu_\eta^2\eta^\dagger\eta + \lambda_\eta(\eta^\dagger\eta)^2 \\ & +\lambda_{H\chi}(H^\dagger H)(\chi^\dagger\chi) + \lambda_{H\eta}(H^\dagger H)(\eta^\dagger\eta) + \lambda_{\chi\eta}(\chi^\dagger\chi)(\eta^\dagger\eta) \\ & +\lambda_1(\eta^\dagger H)(H^\dagger\eta) + \frac{\lambda_2}{2}\left[(H^\dagger\eta)^2 + h.c.\right] \end{aligned}$$

Radiative Neutrino Mass



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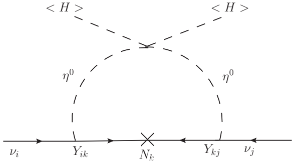

$$(m_\nu)_{ij} = \sum_k \frac{y_{ik} y_{kj} M_k}{32\pi^2} \left[\frac{M_{\eta R}^2}{M_{\eta R}^2 - M_k^2} \log\left(\frac{M_{\eta R}^2}{M_k^2}\right) - \frac{M_{\eta I}^2}{M_{\eta I}^2 - M_k^2} \log\left(\frac{M_{\eta I}^2}{M_k^2}\right)\right]$$

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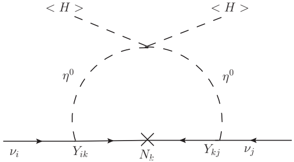

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A typical choice of Yukawa couplings,

$$\begin{aligned}
y_{e1} &= 0.00001, y_{e2} = 0.621, y_{e3} = 0.0001, \\
y_{\mu_1} &= 0.00001, y_{\mu_2} = 1.15, y_{\mu_3} = 0.485, \\
y_{\tau_1} &= 0.045, y_{\tau_2} = 0.3, y_{\tau_3} = 0.765. \\
M_{N_1} &= 99\mathrm{GeV}, M_{N_2} = 10^4\mathrm{GeV}, M_{N_3} = 10^3\mathrm{GeV}, \\
M_{\eta R} &= 106.00000001\mathrm{GeV}, M_{\eta_I} = 106\mathrm{GeV}.
\end{aligned}$$

Relic Density of N_1 in Scotogenic $B-L$ model

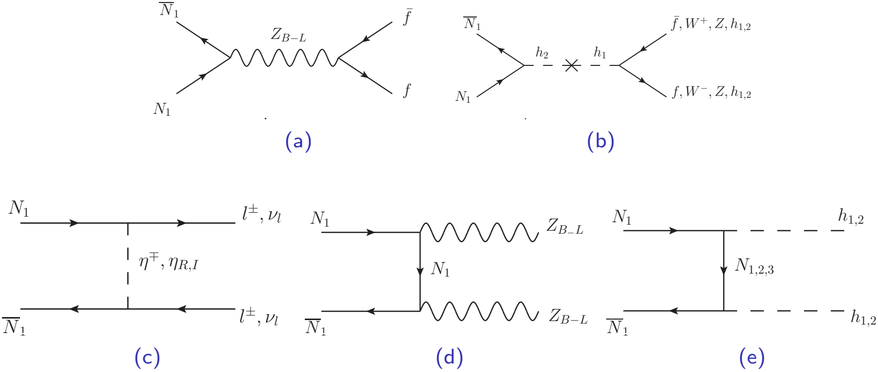

Figure: DM annihilation channels.

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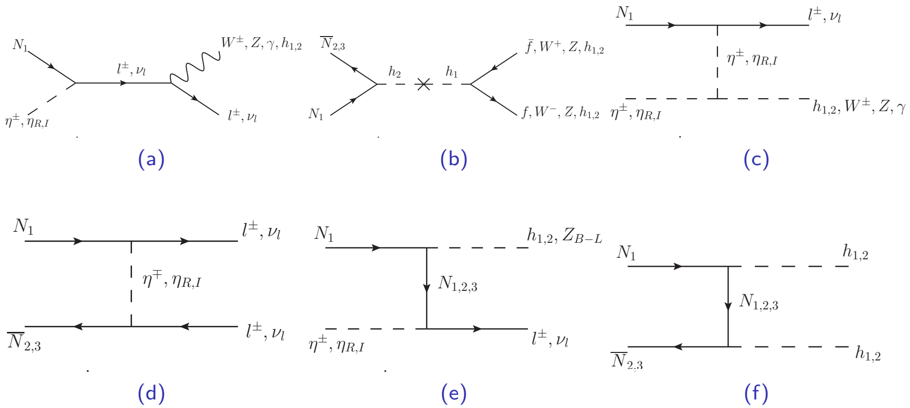

Figure: DM co-annihilation channels.

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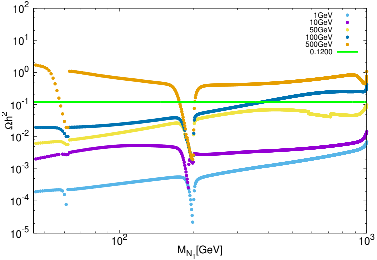

$$\delta M = M_{\eta_R,\eta_I,\eta^{\pm}} - M_{N_1}$$
$$M_{N_2} = 1010 \text{ GeV}, \; M_{N_3} = 1020 \text{ GeV},$$
$$M_{h_1} = 125 \text{ GeV}, \; M_{h_2} = 400 \text{ GeV},$$
$$M_{Z_{B-L}} = 2 \text{ TeV}, \; \sin\gamma = 0.1$$

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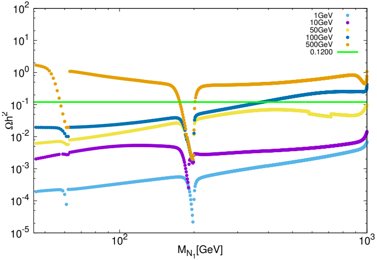

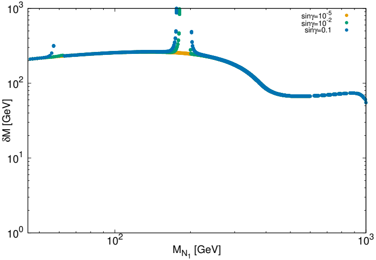

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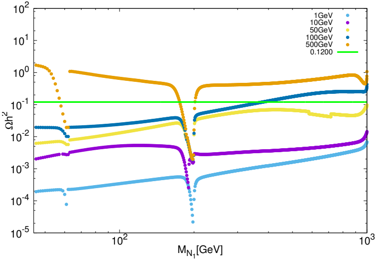

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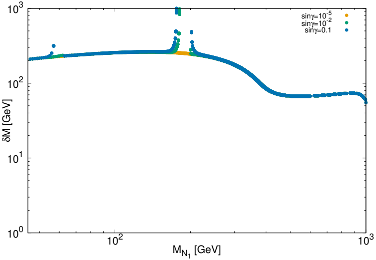

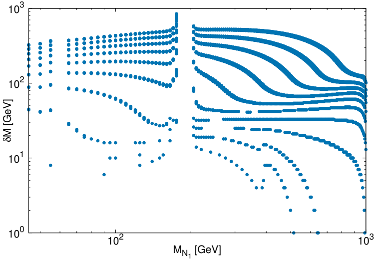

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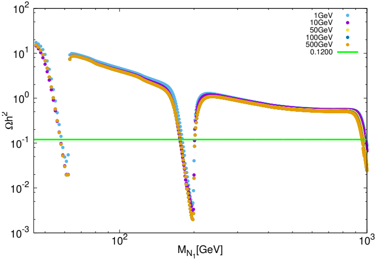

$\delta M = M_{N_{2,3}} - M_{N_1} = 1, 10, 50, 100, 500$ GeV
$M_{\eta^\pm} = 1030$ GeV,
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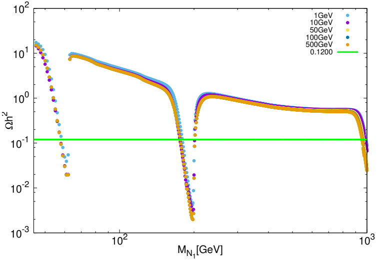

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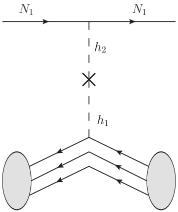
- The mass-splitting between $\delta M = M_{\eta_R,\eta_I,\eta^\pm} - M_{N_1}$ is more effetive than the mass-splitting between $\delta M = M_{N_{2,3}} - M_{N_1}$.

Direct Detection of Dark Matter



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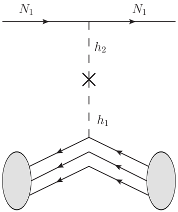

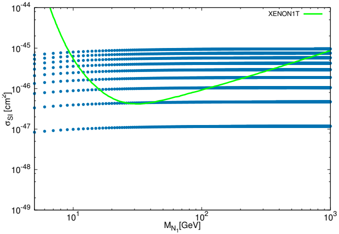

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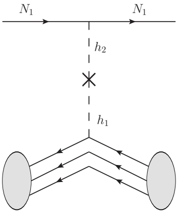

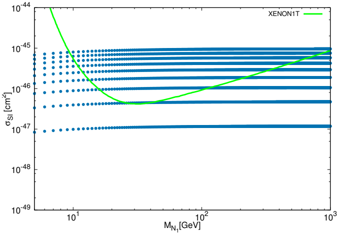

- Spin-independent elastic scattering cross-section of DM per nucleon

$$\sigma_{SI}^{h_1 h_2} = \frac{{\mu_r}^2}{\pi A^2}\left(\frac{\lambda_{11}\sin 2\gamma}{2\sqrt{2}}\right)^2\left[\frac{1}{M_{h_2^2}}-\frac{1}{M_{h_1^2}}\right]^2$$
$$\times \quad [Z(\frac{m_p}{v})(f_{Tu}^p+f_{Td}^p+f_{Ts}^p+\frac{2}{9}f_{TG}^p)+(A-Z)(\frac{m_n}{v})(f_{Tu}^n+f_{Td}^n+f_{Ts}^n+\frac{2}{9}f_{TG}^n)]^2$$

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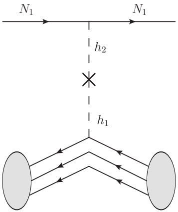

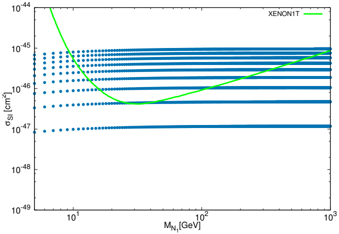

$\lambda_{11} \sin 2\gamma \geq 0.2.$

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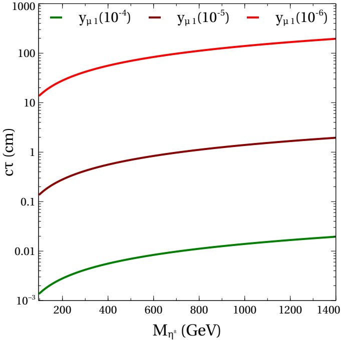
$$\times \quad [Z(\frac{m_p}{v})(f_{Tu}^p + f_{Td}^p + f_{Ts}^p + \frac{2}{9}f_{TG}^p) + (A-Z)(\frac{m_n}{v})(f_{Tu}^n + f_{Td}^n + f_{Ts}^n + \frac{2}{9}f_{TG}^n)]^2$$

Collider Signature

- $\eta^{\pm}$ can be next to LSP.
- If the mass splitting between $M_{\eta^{\pm}}$ and M_{N_1} is small.

The displaced Vertex signature:

$$\Gamma_{\eta^{\pm}\to N_1\mu} = \frac{y_{\mu_1}^2\left(m_{\eta^{\pm}}^2 - (m_{N_1}+m_{\mu})^2\right)}{8m_{\eta^{\pm}}\pi}\sqrt{1-\left(\frac{m_{N_1}-m_{\mu}}{m_{\eta}^{\pm}}\right)^2}\sqrt{1-\left(\frac{m_{N_1}+m_{\mu}}{m_{\eta}^{\pm}}\right)^2}$$

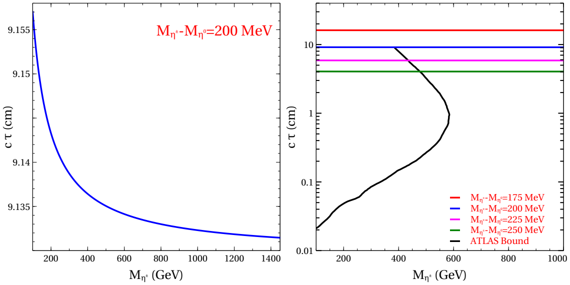


Collider Signature

- If the mass splitting between $M_{\eta^\pm}$ and M_{η^0} is of order of 100 MeV.

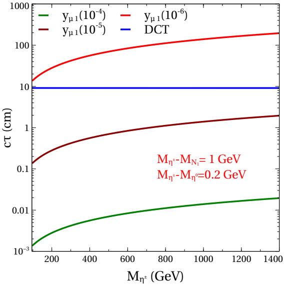
The disappearing charged track signature:

$$\Gamma_{\eta^\pm \to \eta^0 \pi} = \frac{f_\pi^2 g^4}{m_W^4} \frac{\left(m_{\eta^\pm}^2 - m_{\eta^0}^2\right)^2}{512 m_{\eta^\pm} \pi} \sqrt{1 - \left(\frac{m_{\eta^0} - m_\pi}{m_\eta^\pm}\right)^2} \sqrt{1 - \left(\frac{m_{\eta^0} + m_\pi}{m_\eta^\pm}\right)^2}$$



Collider Signature

- The comparison between the leptonic decay mode and pionic decay mode for different values of Yukawa couplings.



Conclusion

- By extending the SM with $U(1)_{B-L} \times Z_2$ symmetry, we studied co-annihilation effects on relic density
- and the corresponding parameter space allowed from netrino, direct detection experiments.
- We studied interesting collider signatures, displaced vertex signature and disappearing charged track signature.

Thank You

M_{N_1} (GeV)	$M_{\eta^\pm}$, $M_{\eta^{0R}}$, $M_{\eta^{0I}}$ (GeV)	$\sigma_{p\,p \to \eta^+\eta^-}$ (pb)
100	105, 120, 120	0.189
200	205, 220, 220	1.65×10^{-2}
300	305, 320, 320	3.46×10^{-3}
400	405, 420, 420	1.04×10^{-3}
500	505, 520, 520	3.817×10^{-4}
600	605, 620, 620	1.593×10^{-4}
700	705, 720, 720	7.286×10^{-5}
800	805, 820, 820	3.568×10^{-5}
900	905, 920, 920	1.828×10^{-5}
1000	1005, 1020, 1020	9.794×10^{-6}

Table: Production cross sections of $\eta^+\eta^-$ from $p\,p$ collisions at $\sqrt{s} = 14$ TeV LHC. Here we have kept fixed the mass splittings as $M_{\eta^\pm} - M_{N_1}$=5 GeV and $M_{\eta^{0R}} - M_{\eta^\pm}$=$M_{\eta^{0I}} - M_{\eta^\pm}$=15 GeV

M_{N_1} (GeV)	$M_{\eta^\pm}$, $M_{\eta^{0R}}$, $M_{\eta^{0I}}$ (GeV)	$\sigma_{p\,p \to \eta^+\eta^-}$ (pb)
100	101, 120, 120	0.2176
200	201, 220, 220	1.782×10^{-2}
300	301, 320, 320	3.65×10^{-3}
400	401, 420, 420	1.087×10^{-3}
500	501, 520, 520	3.957×10^{-4}
600	601, 620, 620	1.647×10^{-4}
700	701, 720, 720	7.523×10^{-5}
800	801, 820, 820	3.656×10^{-5}
900	901, 920, 920	1.879×10^{-5}
1000	1001, 1020, 1020	1.004×10^{-5}

Table: Production cross sections of $\eta^+\eta^-$ from $p\,p$ collisions at $\sqrt{s} = 14$ TeV LHC. Here we have kept fixed the mass splittings as $M_{\eta^\pm} - M_{N_1}$=1 GeV and $M_{\eta^{0R}} - M_{\eta^\pm}$=$M_{\eta^{0I}} - M_{\eta^\pm}$=19 GeV

M_{N_1} (GeV)	$M_{\eta^\pm}$, $M_{\eta^{0R}}$, $M_{\eta^{0I}}$ (GeV)	$\sigma_{p\,p \to \eta^+ \eta^0}$ (pb)
100	101.2, 101, 101.2	0.2473
200	201.2, 201, 201.2	2.057×10^{-2}
300	301.2, 301, 301.2	4.359×10^{-3}
400	401.2, 401, 401.2	1.341×10^{-3}
500	501.2, 501, 501.2	5.001×10^{-4}
600	601.2, 601, 601.2	2.141×10^{-4}
700	701.2, 701, 701.2	9.938×10^{-5}
800	801.2, 801, 801.2	4.91×10^{-5}
900	901.2, 901, 901.2	2.546×10^{-5}
1000	1001.2, 1001, 1001.2	1.367×10^{-5}

Table: Production cross sections of $\eta^{\pm}\eta^{0}$ from $p\,p$ collisions at $\sqrt{s} = 14$ TeV LHC. Here we have kept fixed the mass splittings as $M_{\eta^{0R}} - M_{N_1}$=1 GeV and $M_{\eta^\pm} - M_{\eta^{0R}}$=$M_{\eta^{0I}} - M_{\eta^{0R}}$=200 MeV