Quintuplet Minimal Dark Matter in Left-Right Symmetric Model

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Outline

- Left-right Symmetry
- Quintuplet LR Model
- Dark Matter
- Phenomenology of Heavy Scalar
- Conclusion

Left-right Symmetry

- Gauge group extended to

$$SU(3)_c \times SU(2)_R \times SU(2)_L \times U(1)_{B-L}$$

- Quarks and leptons are all doublets.
- Origin of Parity violation as a spontaneously broken symmetry.
- Solve the strong CP problem.
- Minimal model can naturally generate light neutrino mass.

Quintuplet LR Model

- Quarks and leptons

$$Q_L(3,1,2,1/3)=\begin{pmatrix}u_L\\ d_L\end{pmatrix};\ Q_R(3,2,1,1/3)=\begin{pmatrix}u_R\\ d_R\end{pmatrix};\ l_L(3,1,2,-1)=\begin{pmatrix}v_L\\ e_L\end{pmatrix};$$

$$l_R(3,2,1,-1)=\begin{pmatrix}v_R\\ e_R\end{pmatrix};\ N(1,1,1,0).$$

- Dark Matter

$$\chi(1,5,1,4)=\begin{pmatrix}\chi^{4+} & \chi^{3+} & \chi^{2+} & \chi^{+} & \chi^{0}\end{pmatrix}^T.$$

- Scalar

$$H_R(1,2,1,1)=\begin{pmatrix}H_R^{\ +}\\ H_R^{\ 0}\end{pmatrix};\ \Phi(1,2,2,0)=\begin{pmatrix}\phi_1^0 & \phi_2^+\\ \phi_1^- & \phi_2^0\end{pmatrix};\ S(1,1,1,0).$$

- Electric Charge $Q = I_{3R} + I_{3L} + (B-L)/2$.
- Scalar doublet H_R required for symmetry breaking.
- Bidoublet Φ is needed for quark and lepton mass generation.
- Fermion singlets *N* needed for light neutrino masses.
- Quintuplet χ provides the dark matter candidate and produces unique collider signatures.
- Singlet *S* gives DM mass and helps getting the correct dark matter relic density.

- The non-zero vacuum expectation values

$$\langle \phi_1^0 \rangle = \mathrm{v}_1, \ \langle \phi_2^0 \rangle = \mathrm{v}_2, \ \langle H_R^0 \rangle = \mathrm{v}_R, \langle S \rangle = \mathrm{v}_S.$$

- Symmetry breaking pattern

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\mathrm{v}_R} SU(2)_L \times U(1)_Y \xrightarrow{\mathrm{v}_1, \mathrm{v}_2} U(1)_{EM}$$

- Yukawa Lagrangian

$$\mathcal{L}_Y = Y^q \overline{Q}_L \Phi Q_R + \widetilde{Y}^q \overline{Q}_L \widetilde{\Phi} Q_R + Y^l \bar{l}_L \Phi l_R + \widetilde{Y}^l \bar{l}_L \widetilde{\Phi} l_R + f_R \bar{l}_R \widetilde{H}_R N + \frac{\mu_N}{2} N N + H.C.$$

- Quark and lepton masses

$$M_u = Y^q v_1 + \widetilde{Y}^q v_2, \quad M_d = Y^q v_2 + \widetilde{Y}^q v_1, \quad M_l = Y^l v_2 + \widetilde{Y}^l v_1$$

- Neutrino mass matrix is 3×3, light neutrino mass generated via inverse seesaw mechanism.

- Gauge boson masses

$$M_{W_R}^2 = \frac{1}{2} g_R^2 \left(v_R^2 + v^2\right), \quad M_{Z_R}^2 = \frac{1}{2}\left(g_R^2 + g_{B-L}^2\right)\left[v_R^2 + \frac{g_R^2 v^2}{\left(g_R^2 + g_{B-L}^2\right)}\right]$$

- Scalar potential is given as

$$\begin{aligned} V_H \supset\; & -\mu_1^2 \,\mathrm{Tr}\left[\Phi^\dagger \Phi\right] - \mu_2^2 \,\mathrm{Tr}\left[\widetilde{\Phi}\Phi^\dagger + H.C.\right] - \mu_R^2 H_R^\dagger H_R - \frac{\mu_S^2}{2} S^2 + \lambda_1 \left[\mathrm{Tr}\left(\Phi^\dagger\Phi\right)\right]^2 + \lambda_4 \mathrm{Tr}\left(\Phi^\dagger\Phi\right) \mathrm{Tr}\left[\widetilde{\Phi}\Phi^\dagger + H.C.\right] \\ & + \lambda_2 \left[\left\{\mathrm{Tr}\left(\widetilde{\Phi}\Phi^\dagger\right)\right\}^2 + H.C.\right] + \lambda_3 \mathrm{Tr}\left(\widetilde{\Phi}\Phi^\dagger\right) \mathrm{Tr}\left(\widetilde{\Phi}^\dagger \Phi\right) + \alpha_3 \mu_3 S \mathrm{Tr}\left(\Phi^\dagger\Phi\right) + \alpha_4 \mu_4 S \mathrm{Tr}\left[\widetilde{\Phi}\Phi^\dagger + H.C.\right] \\ & + \alpha_5 \mu_5 S H_R^\dagger H_R + \frac{\beta_1}{2} S^2 \mathrm{Tr}\left(\Phi^\dagger\Phi\right) + \frac{\beta_2}{2} S^2 \mathrm{Tr}\left[\widetilde{\Phi}\Phi^\dagger + H.C.\right] + \frac{\beta_3}{2} S^2 H_R^\dagger H_R + \rho_1 H_R^\dagger H_R \mathrm{Tr}\left[\Phi^\dagger\Phi\right] \\ & + \rho_2 H_R^\dagger H_R \mathrm{Tr}\left[\widetilde{\Phi}\Phi^\dagger + H.C.\right] + \rho_3 H_R^\dagger \Phi^\dagger \Phi H_R + \lambda_R \left(H_R^\dagger H_R\right)^2 + A_S \mu_S S^3 + \frac{\lambda_S}{4} S^4 \end{aligned}$$

Dark Matter

- Neutral Component of χ is the Dark matter candidate.
- No extra symmetry is needed to stabilize the DM.
- Terms leading to DM decay is of mass dimension 6 or higher.
- Charged fields produce exotic collider signals.
- Mass term for DM field

$$L_{\chi} \supset \lambda_{\chi} S \bar{\chi} \chi$$

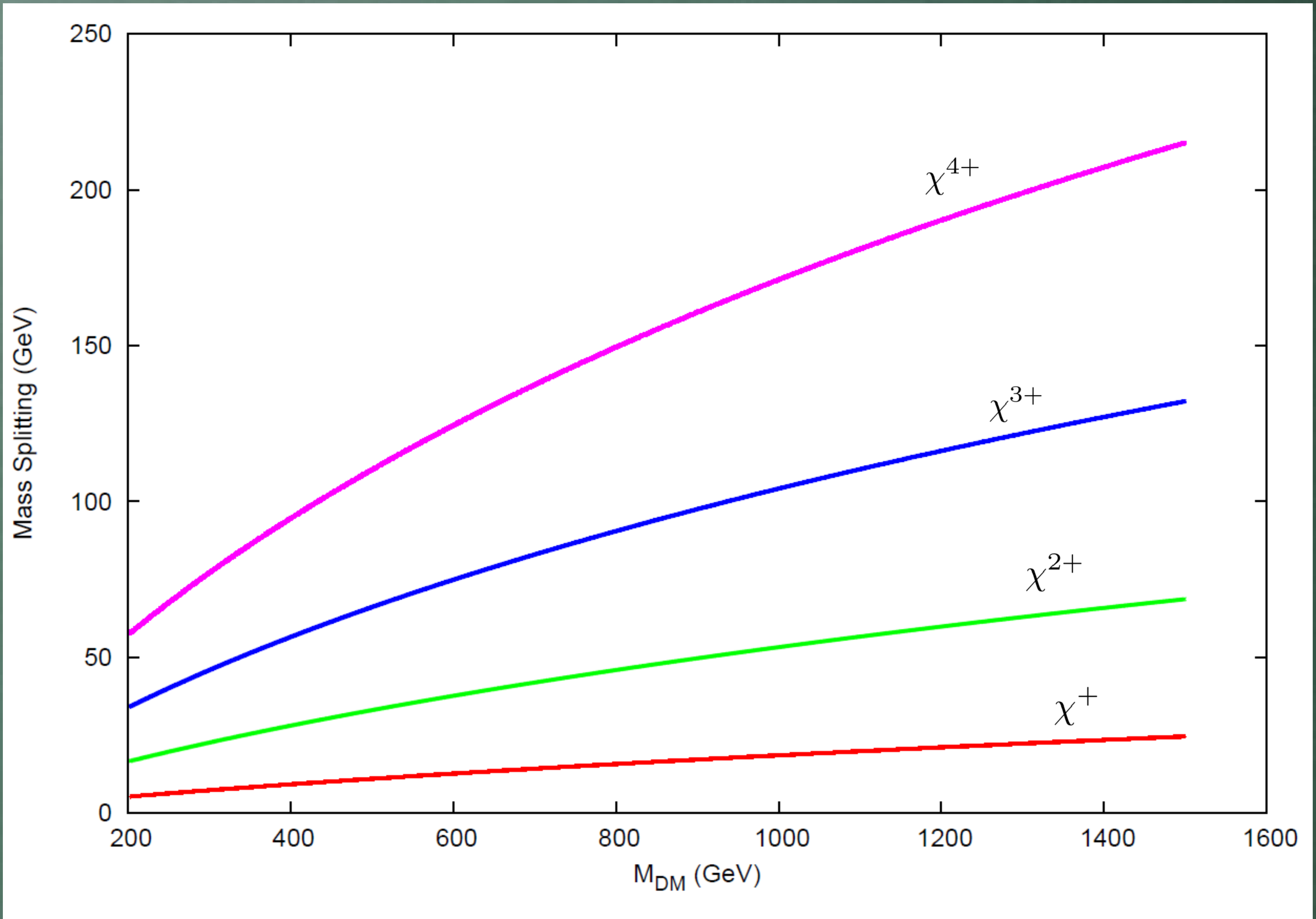
- At tree level all the fields in χ are equal in mass.

- Mass degeneracy lifted by loop corrections

$$
\begin{aligned}
M_{\chi^i} - M_{\chi^0} &= \frac{g_R^2}{(4\pi)^2} M_{\chi^0} \Bigg[Q_{\chi^i} \left(Q_{\chi^i} - Q_{B-L} \right) f(r_{W_R}) - Q_{\chi^i} \left(\frac{g_Y^2}{g_{B-L}^2} Q_{\chi^i} - Q_{B-L} \right) f(r_{Z_R}) \\
&\quad - \frac{g_Y^2}{g_R^2} Q_{\chi^i}^2 \left\{ s_W^2 f(r_Z) + c_W^2 f(r_\gamma) \right\} \Bigg],
\end{aligned}
$$

where $r_x = m_x / M_{\chi^0}$, Q is the electric charge and

$$f(r) = 2\int_0^1 dx(1+x)\log[x^2 + (1-x)r^2]$$



Mass Splitting (GeV)
M_{DM} (GeV)
0
50
100
150
200
250
200
400
600
800
1000
1200
1400
1600
χ^{4+}
χ^{3+}
χ^{2+}
χ^{+}

- Couplings relevant for relic density calculations

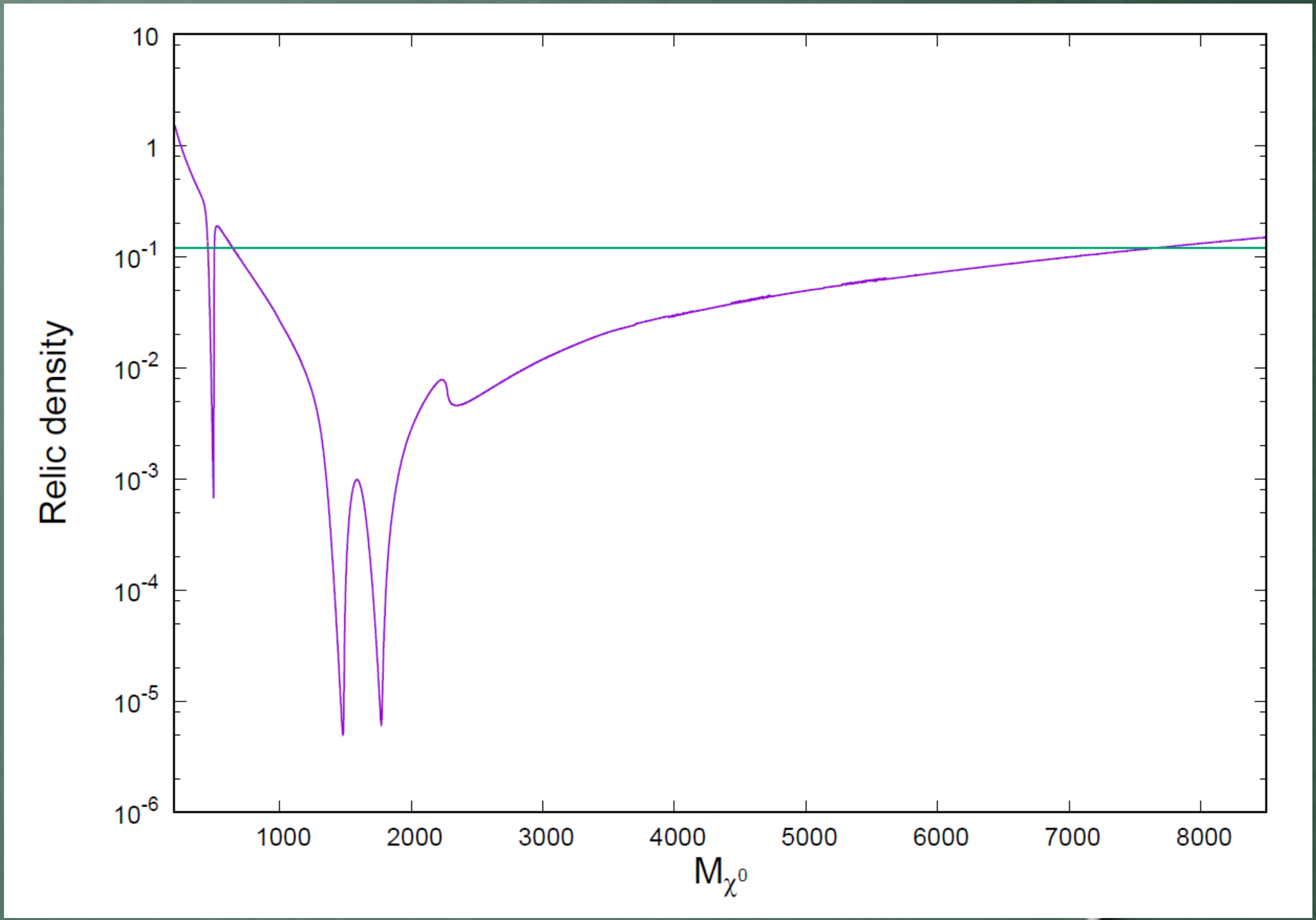
χ with gauge bosons and heavy singlet scalar

+

Heavy scalar coupling with light SM-like Higgs

$$L \supset - g_Y s_W Q_{\chi^i} \overline{\chi}^i Z^\mu \gamma_\mu \chi^i + \sqrt{g_R^2 - g_Y^2}\left[Q_{\chi^i} - \frac{g_R^2 Q_{B-L}}{2\left(g_R^2 - g_Y^2\right)}\right] \overline{\chi}^i Z_R^\mu \gamma_\mu \chi^i$$
$$+ \; e Q_{\chi^i} \overline{\chi}^i A^\mu \gamma_\mu \chi^i + \frac{g_R}{\sqrt{2}}\left(c_{2m} \overline{\chi}^{i+1} W_R^{-\mu} \gamma_\mu \chi^i + h.c.\right) + \alpha_3 \mu_3 H_1 h h + \lambda_\chi \overline{\chi} \chi H_1$$

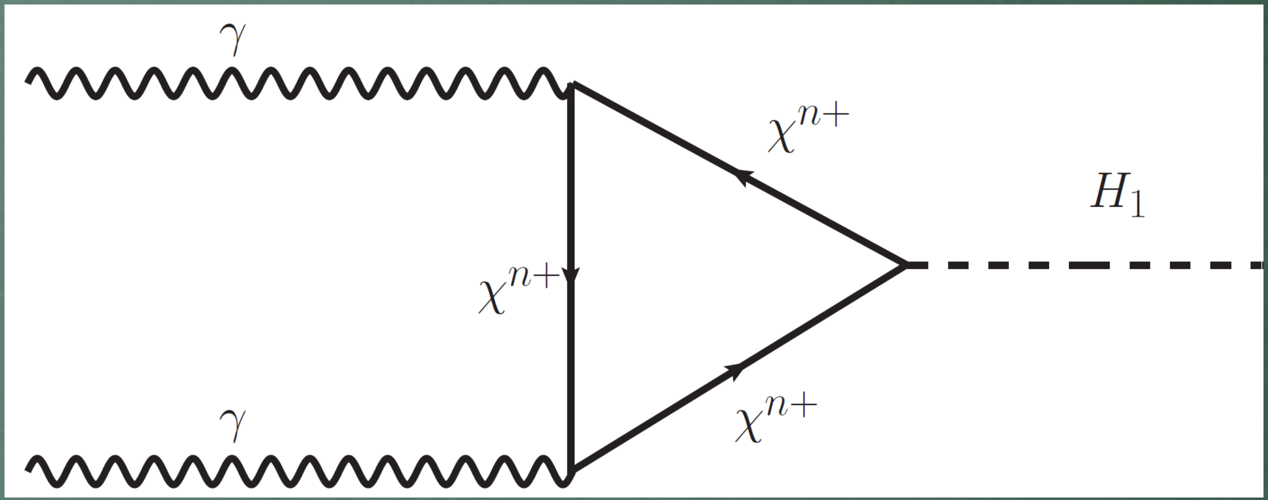
where $c_{2m} = \sqrt{(2+m+1)(2-m)}$ with $m = Q - Q_{B-L}/2$.



$M_{H_1} = 1$ TeV, $M_{W_R} = 3$ TeV, $M_{Z_R} = 3.6$ TeV, $\alpha_3\mu_3 = 0.5\text{v}_{EW}$, $\lambda_\chi = 0.5$

Phenomenology of Heavy Scalar

- Primary production channel for the heavy scalar is through photon fusion.



- Same process can give rise to a diphoton excess which may be observed at the LHC.

- Heavy H_1 can decay into $hh, \gamma\gamma, \gamma Z, ZZ, \chi^i \overline{\chi}^i$.

$$\Gamma_{hh} = \frac{\alpha_3^2 \mu_3^2}{8\pi m_{H_1}} \left(1 - \frac{4m_h^2}{m_{H_1}^2}\right)^{\frac{1}{2}},$$

$$\Gamma_{\chi^i\bar{\chi}^i} = \frac{\lambda_\chi^2}{8\pi} m_{H_1} \left(1 - \frac{4M_{\chi^i}^2}{m_{H_1}^2}\right)^{\frac{3}{2}},$$

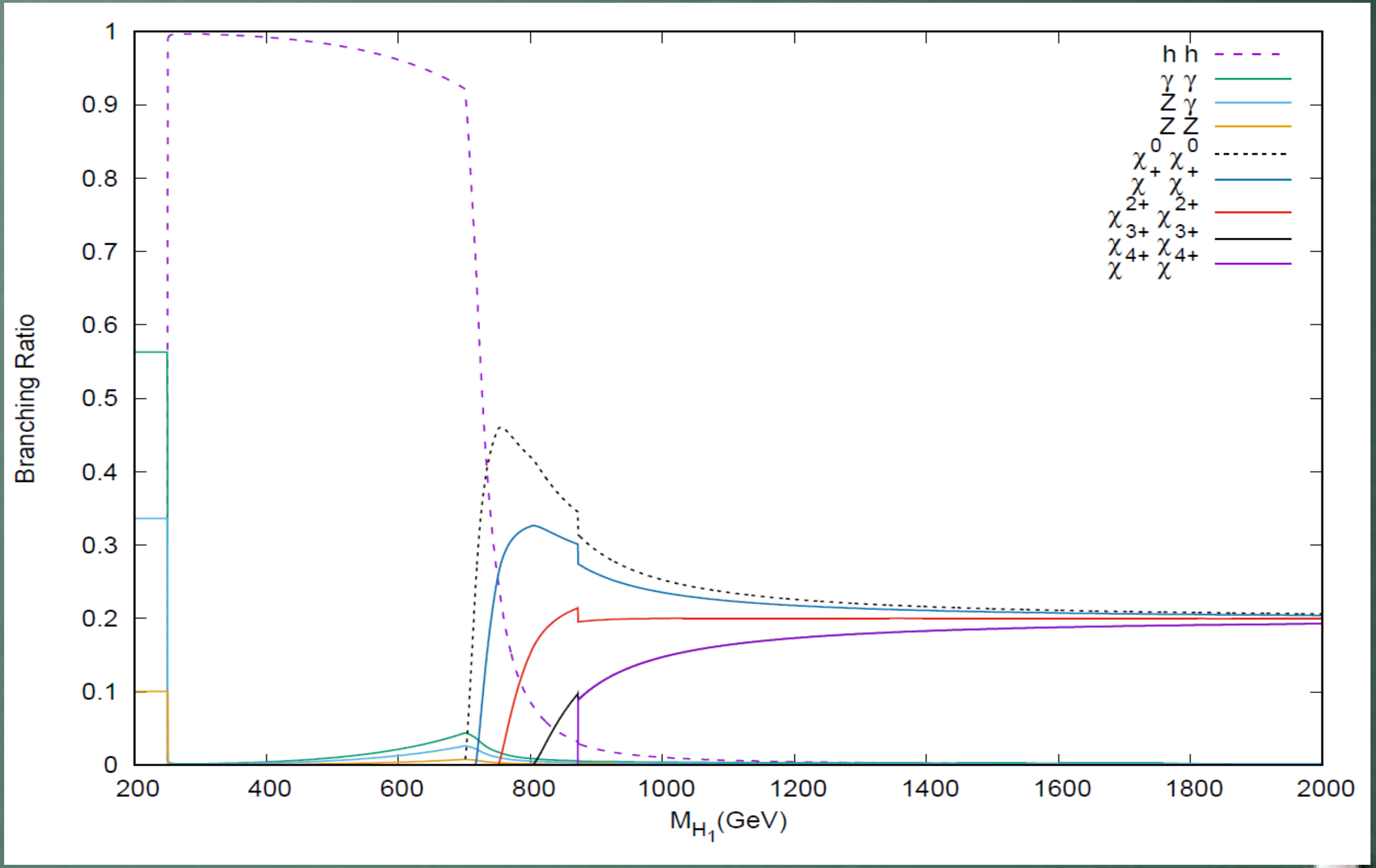
$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 m_{H_1}^3 \lambda_\chi^2}{256\pi^3} \left| \sum_{\chi^i} \frac{Q_{\chi^i}^2}{M_{\chi^i}} A_{\frac{1}{2}} \left(\frac{m_{H_1}^2}{4M_{\chi^i}^2}\right) \right|^2,$$

$$\Gamma_{Z\gamma} = \frac{\alpha^2 m_{H_1}^3 \lambda_\chi^2}{128\pi^3} \tan^2\theta_W \left| \sum_{\chi^i} \frac{Q_{\chi^i}^2}{M_{\chi^i}} A_{\frac{1}{2}} \left(\frac{m_{H_1}^2}{4M_{\chi^i}^2}\right) \right|^2,$$

$$\Gamma_{ZZ} = \frac{\alpha^2 m_{H_1}^3 \lambda_\chi^2}{256\pi^3} \tan^4\theta_W \left| \sum_{\chi^i} \frac{Q_{\chi^i}^2}{M_{\chi^i}} A_{\frac{1}{2}} \left(\frac{m_{H_1}^2}{4M_{\chi^i}^2}\right) \right|^2,$$

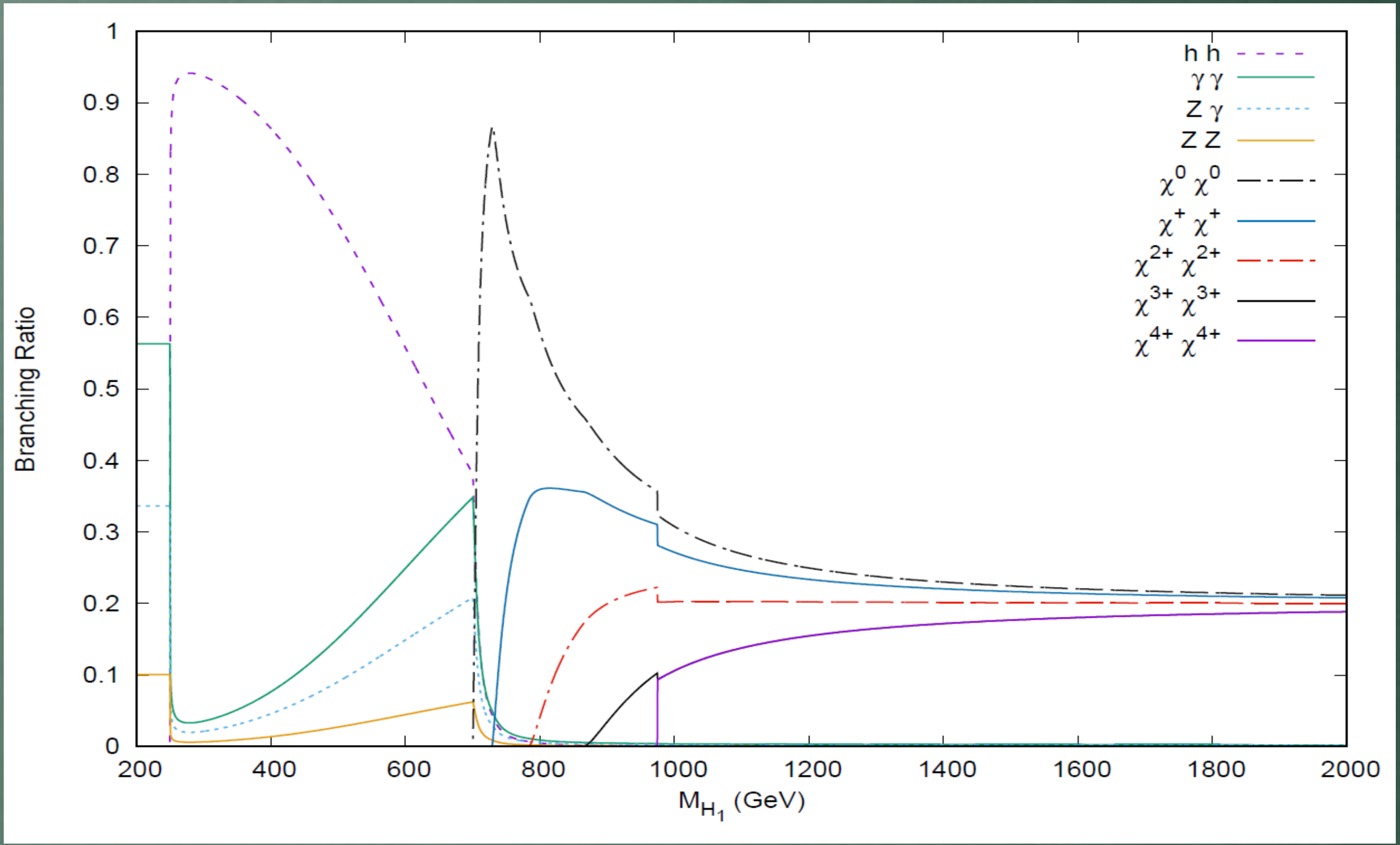
where, $A_{1/2}(\tau) = 2\tau^{-2}\left[\tau + (\tau - 1) f(\tau)\right],$ with

$$f(\tau) = \begin{cases} \arcsin^2\sqrt{\tau} & \tau \le 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2 & \tau > 1 \end{cases}$$



$$M_{\chi^0} = 350 \text{ GeV}, \ \alpha_3\mu_3 = 0.5\mathrm{v}_{EW}, \ \lambda_\chi = 0.5$$

Lower values for α_3 and higher values of λ_χ can produce a more pronounced diphoton peak.



$$M_{\chi^0} = 350 \text{ GeV},\ \alpha_3\mu_3 = 0.1\mathrm{v}_{EW},\ \lambda_\chi = 1.0$$

The Singlet scalar has very interesting collider signals

Diphoton excess or multi-lepton final states.

Conclusion

- Study a minimal DM model in LR scenario with a quintuplet DM candidate.
- DM particle is stable without the need to introduce any extra symmetry.
- Extra singlet scalar provides the DM mass and helps in getting the correct relic density.
- This heavy scalar can have unique signals (Diphoton, multi-lepton final states) which may be studied at the colliders.