Prospect of singlet scalar DM candidate in the EW scale-ν_R model

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Model and Framework

Neutrino mass is the only evidence of BSM Physics so far!

- Neutrino (ν) masses → popular "Seesaw mechanism"
- In general Seesaw Mechanism:
  $\nu_R \to SU(2)_L \times U(1)_Y$ singlet
- RH neutrino mass at GUT scale! NOT directly testable at LHC

$$m_\nu \sim \frac{(m_\nu^D)^2}{M_R} \leq 1eV$$

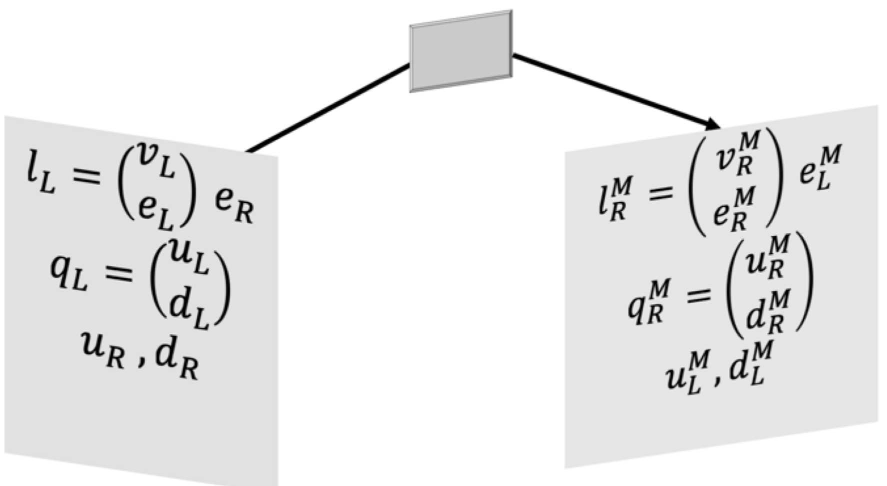
Dirac mass

Majorana mass

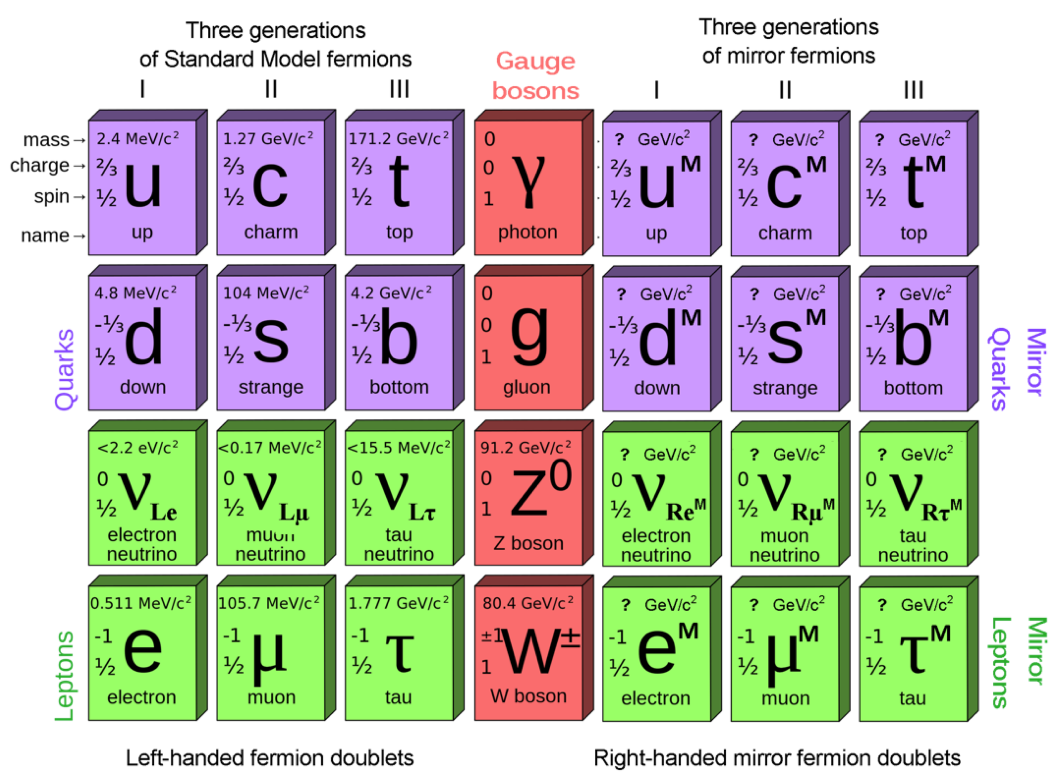
- Stand scenes: L-R : $m_D \sim \Lambda_{EW}$, $M_R \sim M_{WR}$, GUT: $M_R \sim \Lambda_{GUT}$
  ν_R's are Sterile in standard scenarios
- What if $M_R \sim \Lambda_{EW}$? Can ν_R 's be non-sterile?

Solution:

- SM + Mirror Fermions + extended scalar sector
  Gauge Group : $SU(3)_c \times SU(2)_W \times U(1)_Y$



Particle Content



Majorana

$$\mathcal{L}_M = g_M (l_R^{M,T}\sigma_2)(i\tau_2\tilde{\chi}) l_R^M + h.c.$$

$$\tilde{\chi}\ (3, \frac{Y}{2}=1)$$

$$M_R = g_M v_M; < \chi^0 >= v_M \sim \Lambda_{EW}$$

$$\tilde{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}}\chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}}\chi^+ \end{pmatrix}$$

Dirac

$$\mathcal{L}_S = g_{Sl}\bar{l}_L \phi_S l_R^M + h.c.$$

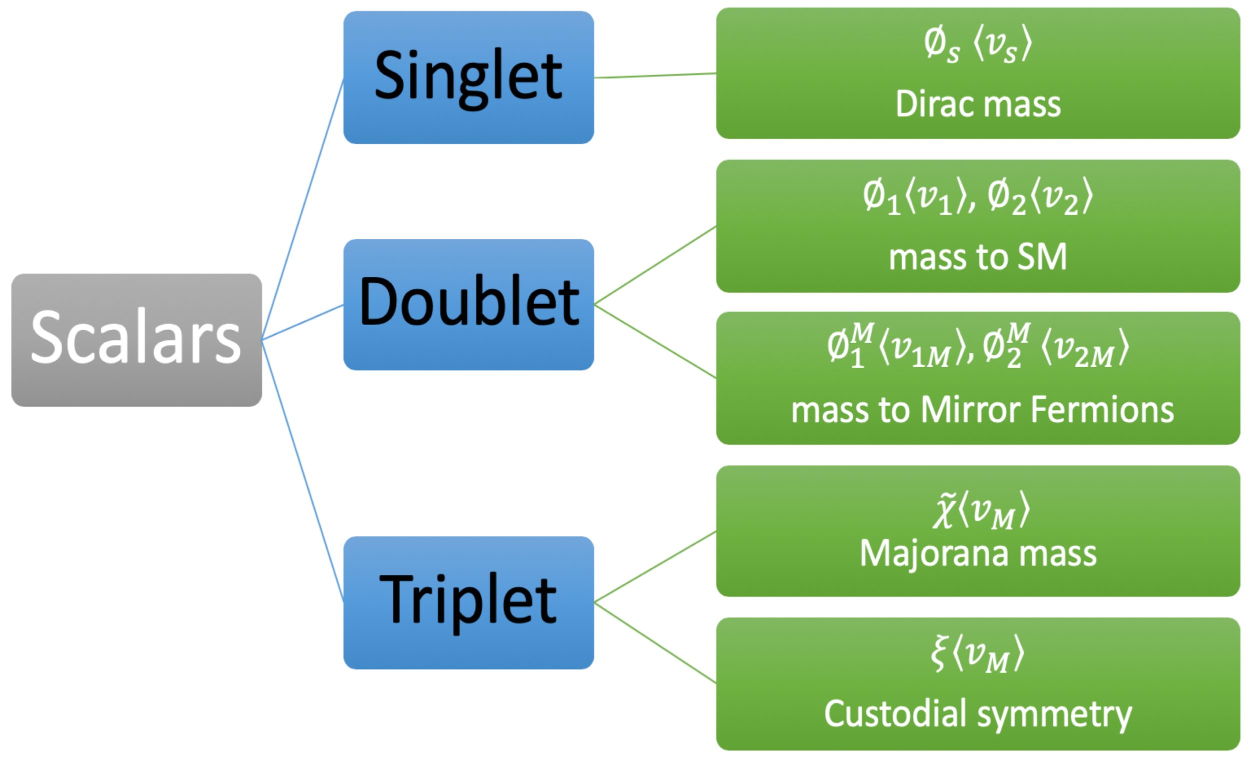
$$\phi_S\ (1, \frac{Y}{2}=0)$$

$$m_\nu^D = g_{Sl} v_S \quad \text{where} \quad < \phi_S >= v_S$$

$$m_\nu \leq 1eV \quad \Rightarrow \quad v_S \sim 10^{5-6} eV \text{ with } g_{Sl} \sim \mathcal{O}(1)$$

$$\text{or} \quad v_S \sim \Lambda_{EW} \text{ with } g_{Sl} \sim \mathcal{O}(10^{-6})$$

Extended Scalar sector



- Two doublets in each sector, coupling to up and down components
- $\rho = M_W^2 / M_Z^2 \cos^2\theta_W = 1$ (custodial global symmetry SU(2))
- $v_M \sim O(\Lambda_{EW}) \to$ A "large" triplet vev spoils $\rho = 1$ at Tree level
- To restore the Custodial symmetry, a triplet Higgs scalar $\xi = (3, \frac{Y}{2} = 0)$ is added to the scalar sector such that

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

- The Higgs potential has a global $SU(2)_L \times SU(2)_R$ symmetry → $SU(2)_D$
- The nature of EW symmetry breaking is intrinsically linked to Majorana mass of the non-sterile RH ν
- Physical scalars are grouped into Custodial $SU(2)_D$ states:
  18 physical scalars grouped 5 + 3 + 3 + 3 + 3 + 1
  Quintet → $H_5^{\pm\pm}, H_5^\pm, H_5^0$
  Triplet → $H_3^\pm, H_3^0, \ H_3'^\pm, H_3'^0, H_M^\pm, H_M^0, H_M'^\pm, H_M'^0$
  Real Singlet → $H_1^0, H_1'^0, H_{1M}^0, H_{1M}'^0, \ H^{10}, H_1^{s0}$
  Complex Singlet → A_s^0

Singlet States:

$$\widetilde{H}_s^0 = \phi_1^{0r},\ H_2^0 = \phi_2^{0r},\ H_{1M}^0 = \phi_{1M}^{0r},\ H_{2M}^0 = \phi_{2M}^{0r},$$
$$H_S^0 = \phi_s^{0r},\ H_1^{0'} = \sqrt{\frac{2}{3}}\chi^{0r} + \sqrt{\frac{1}{3}}\zeta^0, \text{ and } A_s^0 = i\phi_s^{0i}$$

Vev's satisfy:

$$v_{SM} = \sqrt{v_1^2 + v_{1M}^2 + v_2^2 + v_{2M}^2 + 8v_M^2} \equiv 246.221^2 \text{ GeV}^2$$

Singlet Scalar

- $A_s^0 = i\phi_s^{0i}$, the complex singlet is investigated to be DM candidate in this analysis
- At tree level, the mass of the complex singlet scalar $A_s^0 = i\phi_s^{0i}$ is given by

$$M_{A_s^0}^2 = 8\,\lambda_{5c}\,(v_1 + v_2)(v_{1M} + v_{2M}).$$

- In gen, $\widetilde{H}_s^0, H_2^0, H_{1M}^0, H_{2M}^0, H_s^0$ and H_1^{0r} components can mix through

$$\mathcal{M}_{Singlet}^{real} = v_{SM}^2 \begin{pmatrix}
8(\lambda_{1a}+\lambda_4)s_1^2 & 8\lambda_4 s_1 s_2 & 8\lambda_4 s_1 s_m & 8\lambda_4 s_1 s_{2m} & 8\lambda_{4a}\frac{v_s s_1}{v_{SM}} & 2\sqrt{6}\lambda_4 s_1 s_m \\
8\lambda_4 s_1 s_2 & 8(\lambda_{1b}+\lambda_4)s_2^2 & 8\lambda_4 s_2 s_m & 8\lambda_4 s_2 s_{2m} & 8\lambda_{4a}\frac{v_s s_2}{v_{SM}} & 2\sqrt{6}\lambda_4 s_2 s_m \\
8\lambda_4 s_1 s_m & 8\lambda_4 s_2 s_m & 8(\lambda_{2a}+\lambda_4)s_m^2 & 8\lambda_4 s_m s_{2m} & 8\lambda_{4a}\frac{v_s s_m}{v_{SM}} & 2\sqrt{6}\lambda_4 s_m^2 \\
8\lambda_4 s_1 s_{2m} & 8\lambda_4 s_2 s_{2m} & 8\lambda_4 s_m s_{2m} & 8(\lambda_{2b}+\lambda_4)s_{2m}^2 & 8\lambda_{4a}\frac{v_s s_{2m}}{v_{SM}} & 2\sqrt{6}\lambda_4 s_m s_{2m} \\
8\lambda_{4a}\frac{v_s s_1}{v_{SM}} & 8\lambda_{4a}\frac{v_s s_2}{v_{SM}} & 8\lambda_{4a}\frac{v_s s_m}{v_{SM}} & 8\lambda_{4a}\frac{v_s s_{2m}}{v_{SM}} & 8(\lambda_{4a}+\lambda_s)\frac{v_s^2}{v_{SM}^2} & 2\sqrt{6}\lambda_{4a}\frac{v_s s_m}{v_{SM}} \\
2\sqrt{6}\lambda_4 s_1 s_m & 2\sqrt{6}\lambda_4 s_2 s_m & 2\sqrt{6}\lambda_4 s_m^2 & 2\sqrt{6}\lambda_4 s_m s_{2m} & 2\sqrt{6}\lambda_{4a}\frac{v_s s_m}{v_{SM}} & 3(\lambda_3+\lambda_4)s_m^2
\end{pmatrix}$$

- 6 mass eigenstates are denoted by $\widetilde{H}_s, \widetilde{H}, \widetilde{H}', \widetilde{H}'', \widetilde{H}''', \widetilde{H}''''$
- $\widetilde{H}_s$ → lightest (DM), next heavier ones are $\widetilde{H}', \widetilde{H}'', \widetilde{H}'''$, with heaviest state $\widetilde{H}''''$ and $\widetilde{H}$ → 125 GeV

- Yukawa part of the Lagrangian is given by:

$$\mathcal{L}_y = g_l\,\overline{\psi}_L\,\Phi_1\,l_R + g_l^M\,\overline{\psi}_R^M\,\Phi_{M1}\,l_R^M + g_{Sl}\,\overline{\psi}_L\,\psi_R^M\,\Phi_s + g_M\,\psi_R^{M,T}\,iC\sigma_2\,\tilde{\chi}\,\psi_R^M$$
$$+ g_d\,\overline{Q}_L\,\Phi_1\,d_R + g_d^M\,\overline{Q}_R^M\,\Phi_{M1}\,d_R^M - g_u\,\overline{Q}_L\,i\sigma_2\,\Phi_2\,u_R - g_u^M\,\overline{Q}_R^M\,i\sigma_2\,\Phi_{M2}\,u_R^M$$
$$+ g_{Sd}\,\overline{d}_R d_L^M\,\Phi_s + g_{Sq}\,\overline{Q}_L Q_R^M\,\Phi_s + g_{Su}\,\overline{u}_R u_R^M\,\Phi_s + \text{ h.c}$$

Benchmark Points and experimental data

	Benchmark Points and Branching of SM-like Higgs								$\frac{\sigma_{pph,our}}{\sigma_{pph,SM}}$ Ratio of
	$\Gamma_{\text{SM-likeHiggs}}^{\text{Total}}$	Branching of SM-like Higgs							Production
	(MeV)	$Br(\widetilde{H} \to b\bar{b})$	$Br(\widetilde{H} \to \tau\bar{\tau})$	$Br(\widetilde{H} \to WW^*)$	$Br(\widetilde{H} \to ZZ^*)$	$Br(\widetilde{H} \to \gamma\gamma)$	$Br(\widetilde{H} \to \widetilde{H}_s\widetilde{H}_s, A_s^0 A_s^0)$	$Br(\widetilde{H} \to \text{Other BSM})$	Cross-section
SM	~ 4.0	5.66 E^{-01}	6.21 E^{-02}	2.26 E^{-01}	2.81 E^{-02}	2.28 E^{-03}	–	–	1
BP-3	5.481	6.912 E^{-01}	$\sim$ 8.561 E^{-02}	19.825 E^{-01}	$\sim$ 2.46 E^{-02}	$\sim$ 1.96 E^{-03}	$<$ 1 E^{-06}	$<$ 1 E^{-06}	1.38

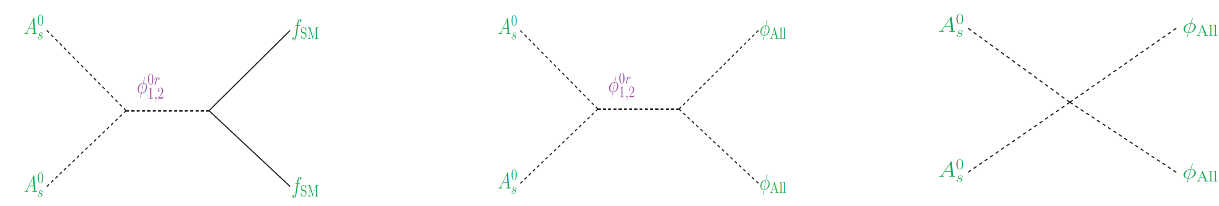
TABLE I: Branching Ratios for SM-like Higgs ($m_H \sim 125$ GeV) decaying through various SM and BSM channels for a model Benchmark Point

Signal Strength	Benchmark Points and Signal strength of SM-like Higgs				
	$\mu_{b\bar{b}}$	$\mu_{\tau\bar{\tau}}$	μ_{WW}	μ_{ZZ}	$\mu_{\gamma\gamma}$
$\mu_{\text{Best-Fit}}$ (CERN-EP-2018-263)	$2.51^{+2.43}_{-2.01}$	$1.05^{+0.53}_{-0.47}$	$1.35^{+0.35}_{-0.21}$	$1.22^{+0.23}_{-0.21}$	$1.16^{+0.21}_{-0.18}$
$\mu_{\text{BP}-3}$	1.70	1.91	1.214	1.211	1.19

TABLE II: Signal Strengths for the Higgs-like Boson for the benchmark point examined in Table I

Dark Matter

- The pseudo singlet scalar is the DM candidate (Mev-GeV mass range)
- The main contribution to the DM effective annihilation cross-section comes from annihilation channel $A_s^0\ A_s^0$ → SM SM, (diagrams below)



- Relic density related to annihilation cross-section and decay lifetime

$$\Omega h^2 \simeq \frac{9.62 \times 10^{-28}\,[\text{cm}^3\text{sec}^{-1}]}{\langle \sigma v \rangle}\, Exp\left(-\sum_i \frac{t_U}{\tau_{i,DM}}\right)$$

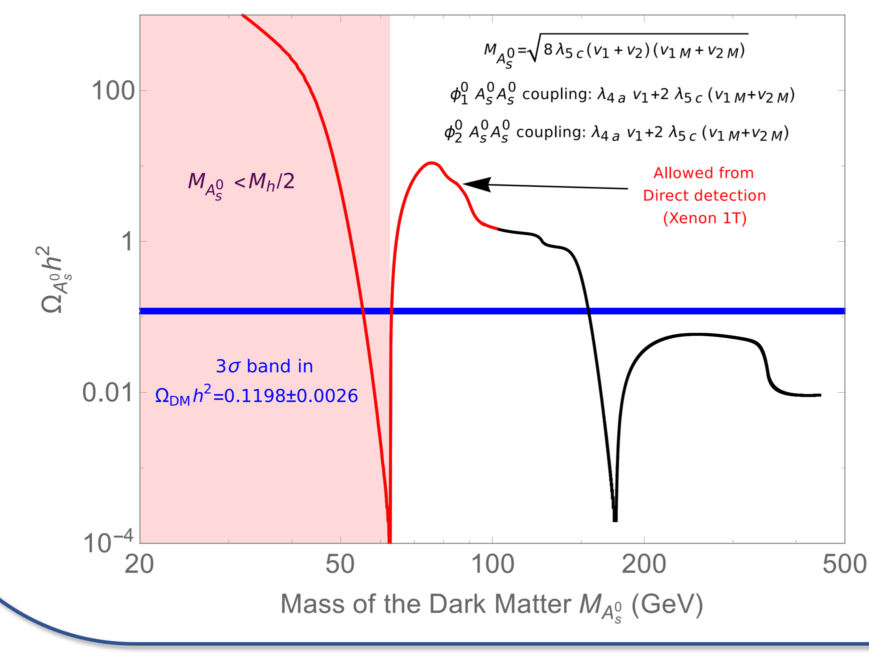


Fig: Plot shows variation of relic density (Ωh^2) vs Dark matter mass. The red line signifies bounds coming from the recent direct detection xenon 1T data. The blue band corresponds to allowed relic density region at 3σ. From this plot the allowed parameter space belonging to this particular BP corresponds to 55-65 GeV mass range.

Summary

- Framework has Majorana and new mirror fermion masses within the reach of the current colliders
- Complete scalar sector spectrum including heavier triplets, doublets and singlet Higgs states in conjunction with the current 125-GeV LHC data is analyzed
- Prospect of the singlet scalar fulfilling the role of the DM candidate is investigated wrt the current bounds
- EWν_R scenario links neutrino mass, DM studies and Long-lived Particles (*LLP*) searches at the Collider

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