Extended scalar sector of the EWν_R model

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Chakdar, Ghosh, Hung, Khan
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Chakdar, Ghosh, Hoang, Hung, Nandi,
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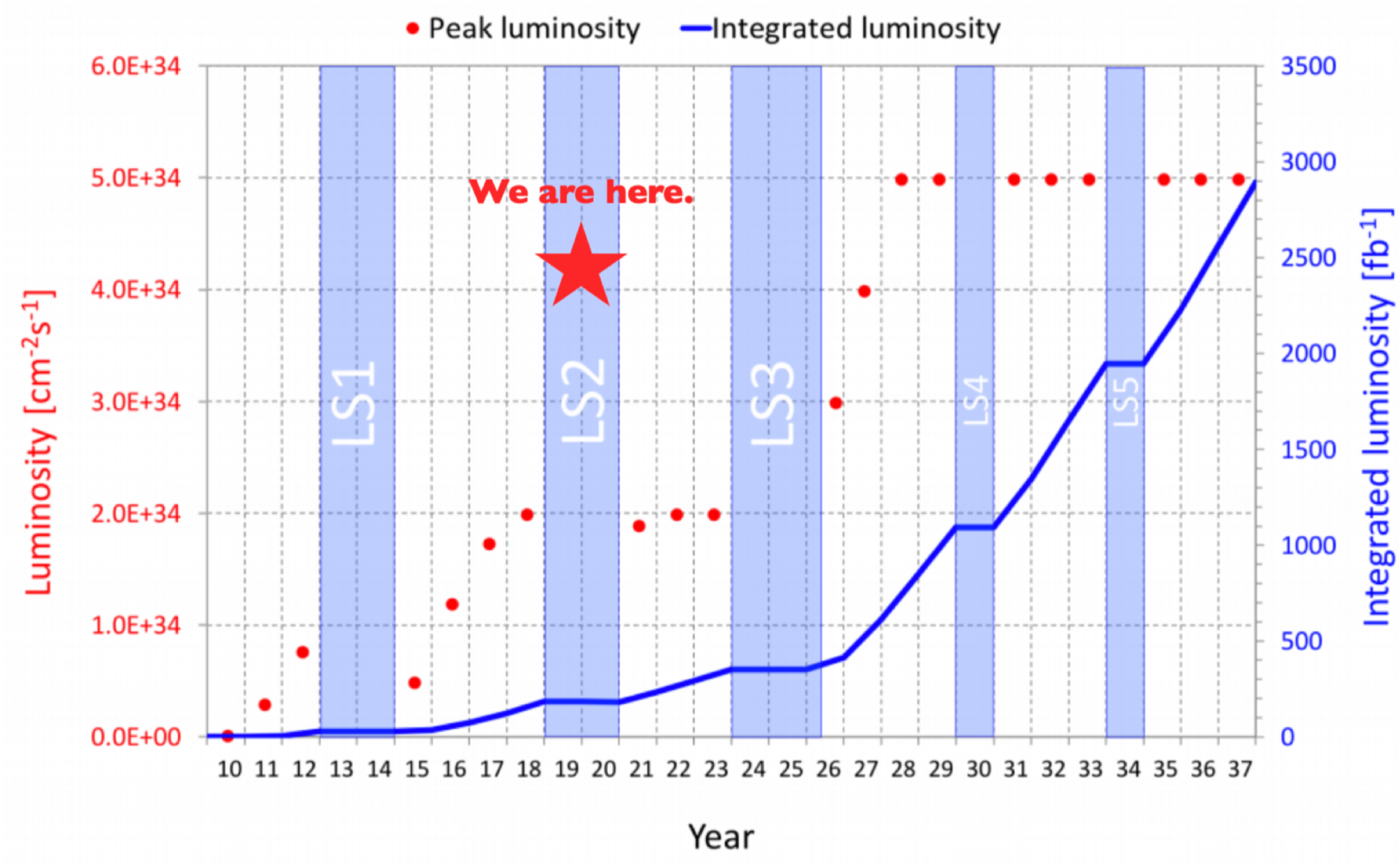
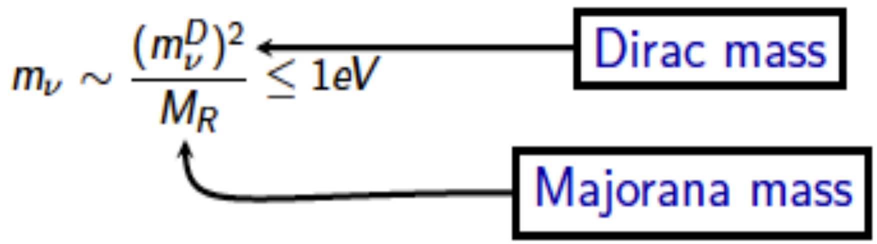
Post Higgs LHC: where are we?



Slide: Wang

EWν_R :Model and Framework

- Neutrino mass is the only evidence of NP so far!
- Neutrino (ν) masses → popular “Seesaw mechanism”
- In general Seesaw Mechanism:
  - $\nu_R \rightarrow SU(2)_L \times U(1)_Y$ singlet
  - RH neutrino mass at GUT scale! NOT directly testable at LHC



- 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?

Ref: P.Q Hung, PLB 649 (2007)

EW$\boldsymbol{\nu_R}$:Model and mirror fermions

SM + Mirror Fermions + extended scalar sector

Gauge Group : $SU(3)_c \times SU(2)_W \times U(1)_Y$

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \; e_R$$

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

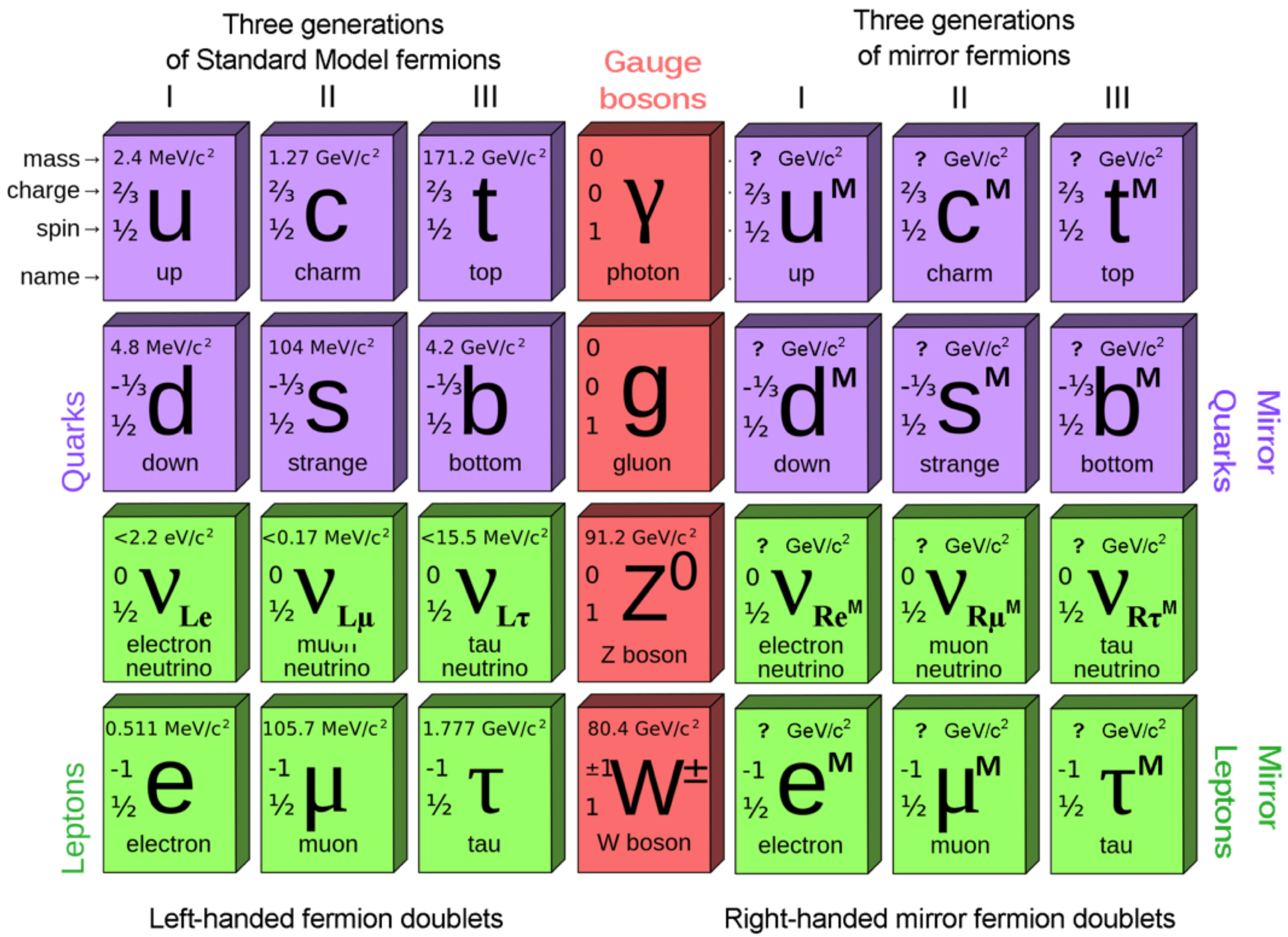
$$u_R \,, d_R$$

$$l_R^M = \begin{pmatrix} \nu_R^M \\ e_R^M \end{pmatrix} \; e_L^M$$

$$q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$$

$$u_L^M, d_L^M$$

Particle content of EWν_R model



- $\nu_R' s$ are non-sterile, RH doublets couples to the same W

Majorana and Dirac masses

Majorana

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

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

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

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

Dirac

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

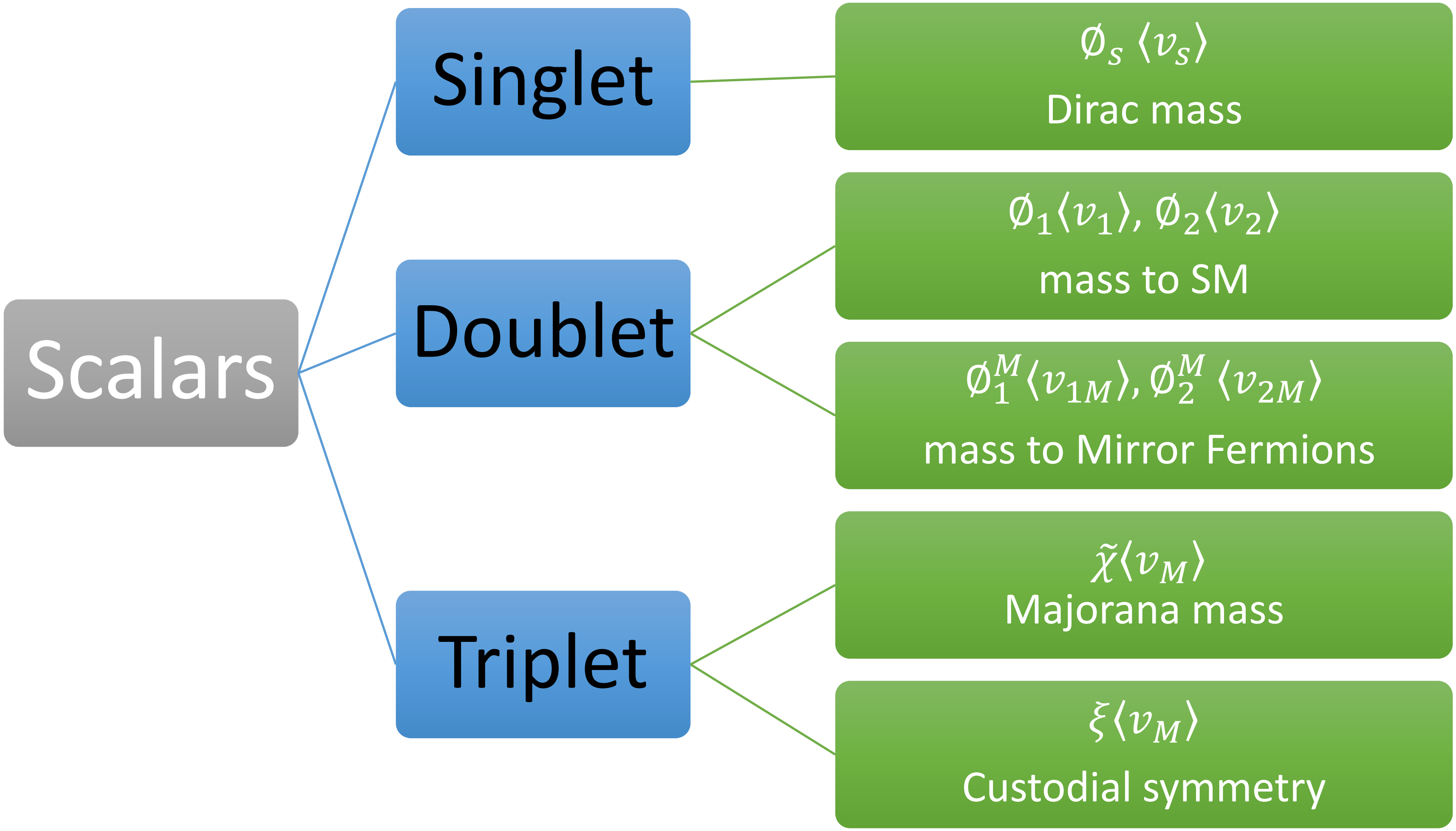
$$\phi_S\ (1,\ \frac{Y}{2} = 0)$$

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

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

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

Complete Scalar Sector



Scalar Sector Custodial symmetry

- $\rho = {M_W^2}/{M_Z^2 \cos^2\theta_W}$ = 1 (custodial global symmetry SU(2))
- $v_M \sim O\,(\Lambda_{EW}) \rightarrow$ A "large" triplet vev would spoil $\rho = 1$ at Tree level
- To restore the Custodial symmetry, a triplet Higgs scalar $\xi = (3, \frac{Y}{2} = 0)$ is added such that

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

- The potential has a global $SU(2)_L \times SU(2)_R$ symmetry $\rightarrow SU(2)_D$
- Rich Higgs sector!
- The nature of EW symmetry breaking is intrinsically linked to the Majorana mass of the non-sterile RH neutrino

The scalar potential

$$
\begin{aligned}
V =\ & \lambda_{1a}\Big[Tr\Phi_1^\dagger\Phi_1 - v_1^2\Big]^2 + \lambda_{2a}\Big[Tr\Phi_{1M}^\dagger\Phi_{1M} - v_{1M}^2\Big]^2 + \lambda_{1b}\Big[Tr\Phi_2^\dagger\Phi_2 \\
& - v_2^2\Big]^2 + \lambda_{2b}\Big[Tr\Phi_{2M}^\dagger\Phi_{2M} - v_{2M}^2\Big]^2 + \lambda_3\Big[Tr\chi^\dagger\chi - 3v_M^2\Big]^2 \\
& + \lambda_s\Big[\Phi_s^\dagger\Phi_s - v_s^2\Big]^2 + \lambda_4\Big[Tr\Phi_1^\dagger\Phi_1 - v_1^2 + Tr\Phi_{1M}^\dagger\Phi_{1M} - v_{1M}^2 \\
& + Tr\Phi_2^\dagger\Phi_2 - v_2^2 + Tr\Phi_{2M}^\dagger\Phi_{2M} - v_{2M}^2 + Tr\chi^\dagger\chi - 3v_M^2 + \Phi_s^\dagger\Phi_s - v_s^2\Big]^2 \\
& + \lambda_{5a}\Big[(Tr\Phi_1^\dagger\Phi_1)(Tr\chi^\dagger\chi) - 2(Tr\Phi_1^\dagger\frac{\tau^a}{2}\Phi_1\frac{\tau^b}{2})(Tr\chi^\dagger T^a\chi T^b)\Big] \\
& + \lambda_{6a}\Big[(Tr\Phi_{1M}^\dagger\Phi_{1M})(Tr\chi^\dagger\chi) - 2(Tr\Phi_{1M}^\dagger\frac{\tau^a}{2}\Phi_{1M}\frac{\tau^b}{2})(Tr\chi^\dagger T^a\chi T^b)\Big] \\
& + \lambda_{5b}\Big[(Tr\Phi_2^\dagger\Phi_2)(Tr\chi^\dagger\chi) - 2(Tr\Phi_2^\dagger\frac{\tau^a}{2}\Phi_2\frac{\tau^b}{2})(Tr\chi^\dagger T^a\chi T^b)\Big] \\
& + \lambda_{6b}\Big[(Tr\Phi_{2M}^\dagger\Phi_{2M})(Tr\chi^\dagger\chi) - 2(Tr\Phi_{2M}^\dagger\frac{\tau^a}{2}\Phi_{2M}\frac{\tau^b}{2})(Tr\chi^\dagger T^a\chi T^b)\Big] \\
& + \lambda_{5c}\Big[\{\Phi_s^2(Tr\Phi_1^\dagger\Phi_{1M} + Tr\Phi_1^\dagger\Phi_{2M} + Tr\Phi_2^\dagger\Phi_{1M} + Tr\Phi_2^\dagger\Phi_{2M}) + h.c.\} \\
& - 2\,\Phi_s^\dagger\Phi_s(Tr\Phi_1^\dagger\Phi_{1M} + Tr\Phi_1^\dagger\Phi_{2M} + Tr\Phi_2^\dagger\Phi_{1M} + Tr\Phi_2^\dagger\Phi_{2M})\Big] \\
& + \lambda_{7a}\Big[(Tr\Phi_1^\dagger\Phi_1)(Tr\Phi_{1M}^\dagger\Phi_{1M}) - (Tr\Phi_1^\dagger\Phi_{1M})(Tr\Phi_{1M}^\dagger\Phi_1)\Big] \\
& + \lambda_{7b}\Big[(Tr\Phi_2^\dagger\Phi_2)(Tr\Phi_{2M}^\dagger\Phi_{2M}) - (Tr\Phi_2^\dagger\Phi_{2M})(Tr\Phi_{2M}^\dagger\Phi_2)\Big] \\
& + \lambda_{7ab}\Big[(Tr\Phi_1^\dagger\Phi_1)(Tr\Phi_2^\dagger\Phi_2) - (Tr\Phi_1^\dagger\Phi_2)(Tr\Phi_2^\dagger\Phi_1)\Big] \\
& + \lambda_{7Mab}\Big[(Tr\Phi_{1M}^\dagger\Phi_{1M})(Tr\Phi_{2M}^\dagger\Phi_{2M}) - (Tr\Phi_{1M}^\dagger\Phi_{2M})(Tr\Phi_{2M}^\dagger\Phi_{1M})\Big] \\
& + \lambda_{7aMb}\Big[(Tr\Phi_1^\dagger\Phi_1)(Tr\Phi_{2M}^\dagger\Phi_{2M}) - (Tr\Phi_1^\dagger\Phi_{2M})(Tr\Phi_{2M}^\dagger\Phi_1)\Big] \\
& + \lambda_{7abM}\Big[(Tr\Phi_2^\dagger\Phi_2)(Tr\Phi_{1M}^\dagger\Phi_{1M}) - (Tr\Phi_2^\dagger\Phi_{1M})(Tr\Phi_{1M}^\dagger\Phi_2)\Big] \\
& + \lambda_8\Big[Tr\chi^\dagger\chi\chi^\dagger\chi - (Tr\chi^\dagger\chi)^2\Big],
\end{aligned}
$$

Transformations:

$\Phi_{1,2} \to e^{-2i\alpha_{\rm SM}}\,\Phi_{1,2}$, $\Phi_{1M,2M} \to e^{2i\alpha_{\rm MF}}\,\Phi_{1M,2M}$

$\tilde{\chi} \to e^{-2i\alpha_{\rm MF}}\,\tilde{\chi}$, $\xi \to \xi$, $\Phi_s \to e^{-i(\alpha_{\rm SM}+\alpha_{\rm MF})}\,\Phi_s$

The blue $\lambda_{5/6}$'s terms break explicitly the $U(1)_{SM} \times U(1)_{MF}$ symmetry

Blue terms help to get exact minimization of the scalar potential and non-zero mass for the singlet-type complex scalar field.

Scalar Sector

- Physical scalars can be groped 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 → $H_3^{\pm}, H_3^0, \quad H'^{\pm}_3, H'^0_3, H_M^{\pm}, H_M^0, H'^{\pm}_M, H'^0_M$
- Real Singlet → $H_1^0, H'^0_1, H^0_{1M}, H'^0_{1M}, \ H^{10}, H_1^{s0}$
- Complex Singlet → A_s^0
- Singlet States:

$$\widetilde{H}_s^0 = \phi_1^{0r}, \ H_2^0 = \phi_2^{0r}, \ H_{1M}^0 = \phi_{1M}^{0r}, \ H_{2M}^0 = \phi_{2M}^{0r},$$

$$H_S^0 = \phi_s^{0r}, \ H_1^{0'} = \sqrt{\frac{2}{3}}\chi^{0r} + \sqrt{\frac{1}{3}}\zeta^0, \quad \text{and} \ \boxed{A_s^0 = i\phi_s^{0i}}$$

- VEV's satisfy: $v_{\mathrm{SM}} = \sqrt{v_1^2 + v_{1M}^2 + v_2^2 + v_{2M}^2 + 8v_M^2} \equiv 246.221^2 \ \mathrm{GeV}^2$

Masses of the scalars

- At tree level, the mass of the complex singlet scalar $A_S^0 = i\phi_S^{0i}$

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

- In gen, $\widetilde{H}_S^0$, H_2^0, H_{1M}^0, H_{2M}^0, H_S^0 and $H_1^{0\prime}$ can mix:

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

- We denote the 6 mass eigenstates by $\widetilde{H_s}$, $\widetilde{H}$, $\widetilde{H}'$, $\widetilde{H}''$, $\widetilde{H}'''$, $\widetilde{H}''''$
- $\widetilde{H_s}$ $\rightarrow$ lightest, singlet DM, next heavier ones are $\widetilde{H}'$, $\widetilde{H}''$, $\widetilde{H}'''$, with heaviest state $\widetilde{H}''''$ and $\widetilde{H}$ being the 125 GeV Higgs

BP's and BR's: Scalar Sector masses

	Benchmark Points															Masses of the scalar fields (GeV)								
	VEV of the scalar fields (GeV)						Scalar quartic couplings λ's																	
	v_1	v_2	v_{1M}	v_{2M}	v_M	v_s	λ_{1a}	λ_{1b}	λ_{2a}	λ_{2b}	λ_3	λ_4	λ_5	λ_8	λ_s	$M_{\widetilde{H}''''}$	$M_{\widetilde{H}'''}$	$M_{\widetilde{H}''}$	$M_{\widetilde{H}'}$	$M_{\widetilde{H}}$	$M_{\widetilde{H}_s}$	m_5	$m_{3,H^\pm,H_3^0}$	$m_{3,\text{All others}}$
BP-1 $0.65\%\ \phi_1,\ 99.1\%\ (\chi,\xi)$	39.37	145	95	95	50	10^{-7}	6.0	6.0	6.0	6.0	.087	0.2	5.0	5.0	0.1	1022.27	679.172	658.179	277.488	125.291	10^{-6}	953.61	550.567	711.511
BP-2 $18.88\%\ \phi_1,\ 81.11\%\ (\chi,\xi)$	90.4145	120	95	95	50	10^{-7}	0.27	9.0	9.0	9.0	0.24	0.04	5.0	5.0	0.1	1020.54	809.661	806.102	146.706	124.43	10^{-6}	953.61	550.567	711.511
BP-3 $10.54\%\ \phi_1,\ 89.54\%\ (\chi,\xi)$	90.4145	120	95	95	50	10^{-7}	0.242	9.0	9.0	9.0	0.262	0.00068	5.0	5.0	0.1	1018.27	806.163	806.102	126.037	125.484	10^{-6}	953.61	550.567	711.511

TABLE I: BPs obtained fitting for Higgs mass at 125 GeV in conjunction with other heavier scalars

	Benchmark Points and Branching of SM-like Higgs							
	$\Gamma^{\text{Total}}_{\text{SM-likeHiggs}}$ (MeV)	Branching of SM-like Higgs						
		$Br(\widetilde{H} \to b\bar{b})$	$Br(\widetilde{H} \to \tau\bar{\tau})$	$Br(\widetilde{H} \to WW^*)$	$Br(\widetilde{H} \to ZZ^*)$	$Br(\widetilde{H} \to \gamma\gamma)$	$Br(\widetilde{H} \to \widetilde{H}_s\widetilde{H}_s, A_s^0 A_s^0)$	$Br(\widetilde{H} \to \text{Other BSM})$
SM	~ 4.0	$5.66\,\text{E}^{-01}$	$6.21\,\text{E}^{-02}$	$2.26\,\text{E}^{-01}$	$2.81\,\text{E}^{-02}$	$2.28\,\text{E}^{-03}$	–	–
BP-1	~ 4.0	$1.53\,\text{E}^{-01}$	$\sim 1.0\,\text{E}^{-04}$	$\sim 1.0\,\text{E}^{-06}$	$\sim 1.0\,\text{E}^{-06}$	$\sim 1.0\,\text{E}^{-06}$	$8.47\,\text{E}^{-01}$	–
BP-2	~ 4.0	$7.09\,\text{E}^{-01}$	$\sim 1.0\,\text{E}^{-04}$	$\sim 1.0\,\text{E}^{-06}$	$\sim 1.0\,\text{E}^{-06}$	$\sim 1.0\,\text{E}^{-06}$	$2.90\,\text{E}^{-01}$	–
BP-3	~ 2.8	$9.8\,\text{E}^{-01}$	$\sim 1.0\,\text{E}^{-04}$	$\sim 1.0\,\text{E}^{-06}$	$\sim 1.0\,\text{E}^{-06}$	$\sim 1.0\,\text{E}^{-06}$	$2.90\,\text{E}^{-07}$	–

TABLE II: 125 GeV Higgs BR's corresponding to the BP's shown in Table I

Singlet DM Prospect and *LLP* signals

- $A_S^0 = i\emptyset_S^{0i}$ is investigated to be a feasible DM candidate
- M_R are in EW Scale (~ 250 GeV) and from lepton sector ($\mu \rightarrow e\gamma$, μ to e conversion) bounds on the coupling $g_{sl} < 10^{-4}$
- The singlet connecting SM to Mirror world can be light (~KeV scale) DM candidate!
- As a result of g_{sl} being constrained, lightest mirror fermions are *LLPs (*Decay length can be substantially LARGE, mm-> cm range)
- Typical decay lengths >> Hadronization length~ $O(fermi)$
- Formation of QCD bound states: Mirror mesons $\bar{q}^M q^M$ and hybrid mesons $\bar{q}^M q$ get formed first before decay
- Collider searches of DM promising through the *Lifetime* frontier due to the possibility of large displaced vertex ($e_R^M \rightarrow e + \varphi$)

Take-Home message

- EWν_R scenario links neutrino, DM and LLP's
- Framework has Majorana masses and mirror fermions having masses within the reach of the current colliders
- We analyze the complete scalar sector spectrum which includes heavier triplets, doublets and singlet Higgs states in conjunction with the 125-GeV LHC data
- Model contains distinguished Long-lived particle (*LLP*) signals with large displaced vertices (mm-cm) in quark and lepton sectors
- The case of whether neutrinos are of a Dirac or Majorana nature can be settled if like-sign dilepton signals are discovered at displaced vertices at LHC
- Also investigating the prospect of the light singlet scalar fulfilling the role of the light DM candidate in this framework

Thank You!