Supersymmetric Modified Mirror Model

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Presented in 2nd IITB-Hiroshima Workshop

October 25, 2021

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Introduction

- Standard Model (SM) of particle physics is believed to be an established model which could explain many phenomena.
- The observation of Higgs particle by the ATLAS and CMS groups at the LHC is an important piece that make the SM a very solid theory for explaining many phenomena in the realm of elementary particles.
- However, many believe that the SM is not a complete theory, since there are several problems that have no answer in the SM, e.g. neutrino masses, particle-antiparticle asymmetry, dark matter, hierarchy problem, etc.
- Some models being proposed in order to solve these problems.

Introduction

- One of the promising model of the dark matter is the model with a mirror symmetry.
- The standard model (SM) particles (O-sector) have their parity-mirror partner that live in a mirror sector under hidden gauge group similar to the SM gauge group.
- Mirror model is a promising dark matter model since it can explain naturally why the dark matter energy density is of the same order as the baryonic energy density.
- All stable mirror sector (M-sector) particles basically can become the dark matter candidates.
- Some proposed mirror models[3]

[3] Foot, Lew, and Volkas 1991, Berezhiani 1996, Foot and Vagnozzi 2015

Introduction

- But just like the SM, the mirror model could not explain the hierarchy problem of the Higgs mass.
- The famous and aesthetic solution of this hierarchy problem of the Higgs mass is the supersymmetry (SUSY) model.
- We want to make a SUSY model of Modified Mirror Model (MMM). The detail will be explained later.

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MMM: Introduction

- MMM particle content are the ordinary particle, i.e. the SM particle content (plus additional right handed singlet neutrinos) plus their mirror partners.
- The Lagrangian of the model is invariant under the gauge group $SU(3)_1 \otimes SU(3)_2 \otimes SU(2)_L \otimes SU(2)_R \otimes U(1)_Y \otimes U(1)_X$ and Z_2-mirror symmetry that transform a left (or right) chiral ordinary particle into its right (or left) chiral mirror partner and vice versa.
- In this model there are 4 scalar particles, Higgs scalar and its mirror partner and a scalar (and its mirror partner) whose gauge quantum numbers are the same as the right handed electron (and its mirror partner).

MMM: Particle Content

Table 1: **Irreducible representation (irreps) and quantum number assignment for spinor particles**

O-particles	Irreps		M-particles	Irreps
$L_L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	$\mathbf{1},\mathbf{1},\mathbf{2},\mathbf{1},-1,0$		$L_R \equiv \begin{pmatrix} N \\ E \end{pmatrix}_R$	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{2},0,-1$
ν_R	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},0,0$		N_L	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},0,0$
e_R	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},-2,0$		E_L	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},0,-2$
$Q_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L$	$\mathbf{3},\mathbf{1},\mathbf{2},\mathbf{1},\frac{1}{3},0$		$Q_R \equiv \begin{pmatrix} U \\ D \end{pmatrix}_R$	$\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{2},0,\frac{1}{3}$
d_R	$\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1},-\frac{2}{3},0$		D_L	$\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{1},0,-\frac{2}{3}$
u_R	$\mathbf{3},\mathbf{1},\mathbf{1},\mathbf{1},\frac{4}{3},0$		U_L	$\mathbf{1},\mathbf{3},\mathbf{1},\mathbf{1},0,\frac{4}{3}$

MMM: Particle Content

Table 2: **Irreducible representation (irreps) and quantum number assignment for scalar particles**

O-particles	Irreps		M-particles	Irreps
$\chi_L \equiv \begin{pmatrix} \chi_\nu \\ \chi_e \end{pmatrix}$	**1**,**1**,**2**,**1**,-1,0		$\chi_R \equiv \begin{pmatrix} \chi_N \\ \chi_E \end{pmatrix}$	**1**,**1**,**1**,**2**,0,-1
ϕ_e	**1**,**1**,**1**,**1**,-2,0		ϕ_E	**1**,**1**,**1**,**1**,0,-2

The neutral scalar particle and the scalar mirror partner of right handed electron acquire non zero vacuum expectation value (vev)

$$\langle \chi_L \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \upsilon_L \\ 0 \end{pmatrix}, \quad \langle \chi_R \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \upsilon_R \\ 0 \end{pmatrix},$$
$$\langle \phi_E \rangle = \upsilon_E, \quad \langle \upsilon_e \rangle = 0 \qquad (1)$$

MMM: Scalar Sector

- The most general scalar potential which is invariant under the gauge and Z_2-mirror transformation is

$$\begin{aligned} V_H = & - \mu_1^2 \left(|\chi_L|^2 + |\chi_R|^2\right) - \mu_2^2 \left(|\phi_e|^2 + |\phi_E|^2\right) + \lambda_1 \left(|\chi_L|^4 + |\chi_R|^4\right) \\ & + \lambda_2 \left(|\phi_e|^4 + |\phi_E|^4\right) + \alpha_1 |\chi_L|^2 |\chi_R|^2 + \alpha_2 |\phi_E|^2 |\phi_e|^2 \\ & + \alpha_3 \left(|\chi_L|^2 |\phi_E|^2 + |\chi_R|^2 |\phi_e|^2\right) + \alpha_4 \left(|\chi_L|^2 |\phi_e|^2 + |\chi_R|^2 |\phi_E|^2\right) \end{aligned} \tag{2}$$

  where μ_i's, λ_i's, and α_i's are the potential parameters.
- At high energy, there was a SSB which ϕ_E have non zero VEV, while ϕ_e remains with a zero VEV.
- At lower energy, there was another SSB which make χ_R and χ_L acquired non zero VEV, $\langle \chi_R \rangle \equiv \upsilon_R$ and $\langle \chi_L \rangle \equiv \upsilon_L$.
- After doing some calculation with assuming that $\alpha_3, \alpha_4 << 1$, we obtain relation between VEV of scalar particles, that is $\upsilon_E >> \upsilon_R, \upsilon_L$ and $\upsilon_R \neq \upsilon_L$.

MMM: Scalar Sector

- The scalar particle mass can be generated after χ_R and χ_L acquired VEV and given in tree level

$$m_{\phi_e}^2 = \frac{1}{2}\left(\alpha_3 \upsilon_R^2 + \alpha_4 \upsilon_L^2\right) \tag{3}$$

- The other three scalar particles will form mixing term $\mathbf{H}^T \mathbf{M}_h \mathbf{H}$ where $\mathbf{H} \equiv (h_E, h_R, h_L)^T$ and

$$M_h = \upsilon_R^2 \begin{pmatrix} \lambda_2/\eta^2 & \alpha_4/2\eta & \alpha_3\xi/2\eta \\ \alpha_4/2\eta & \lambda_1 & \alpha_1\xi/2 \\ \alpha_3\xi/2\eta & \alpha_1\xi/2 & \lambda_1\xi^2 \end{pmatrix} \tag{4}$$

where $\eta \equiv \upsilon_R/\upsilon_E$ and $\xi \equiv \upsilon_L/\upsilon_R$.

MMM: Scalar Sector

- Due to the measurement of Higgs mass (125 GeV), we can assume that there is no large mixing between Higgs and another scalar, and that $\upsilon_R > \upsilon_L$.
- We take λ's on the maximum (order of unity) and α's are small, the mass matrix (Eq.4) should have eigenvalues $m_{h_1} >> m_{h_2} > m_{h_3}$ for corresponding mass basis h_1, h_2, h_3.
- Moreover, h_E is dominated by h_1, h_R is dominated by h_2, and h_L is dominated by h_3, with small mixing between three of them.
- h_L is our O-Higgs, while h_R is the M-Higgs.

MMM: Gauge Sector

The Lagrangian of interaction between gauge-scalar after SSB is

$$\begin{aligned}\mathcal{L}_g &\supset \frac{1}{4}\upsilon_L^2 g^2 W^+_{L\mu} W_L^{-\mu} + \frac{1}{4}\upsilon_R^2 g^2 W^+_{R\mu} W_R^{-\mu} + \frac{1}{8}\mathcal{W}_L^T \mathbb{M}_L \mathcal{W}_L \\ &+ \frac{1}{8}\mathcal{W}_R^T \mathbb{M}_R \mathcal{W}_R \end{aligned} \tag{5}$$

where $\mathcal{W}_L = \left(W^3_{L\mu}, B_{Y\mu}\right)^T$, $\mathcal{W}_R = \left(W^3_{R\mu}, B_{X\mu}\right)^T$ and

$$W^{\pm}_{R\mu} = \frac{\left(W^1_{R\mu} \mp i W^2_{R_\mu}\right)}{\sqrt{2}}; \qquad W^{\pm}_{L\mu} = \frac{\left(W^1_{L\mu} \mp i W^2_{L_\mu}\right)}{\sqrt{2}} \tag{6}$$

MMM: Gauge Sector

$\mathbb{M}_L$ is similar with SM, while $\mathbb{M}_R$ is

$$\mathbb{M}_R = \begin{pmatrix} g^2\upsilon_R^2 & -gg'\upsilon_R^2 \\ -gg'\upsilon_R^2 & g'^2(\upsilon_R^2 + 4\upsilon_E^2) \end{pmatrix} \tag{7}$$

Mass matrix in Eq. 7 can be diagonalized using $\mathcal{W}_R = \mathbf{S}_R \mathcal{W}'_R$, where $\mathcal{W}'_R = (Z_R^\mu, D^\mu)^T$ is the mass basis, and

$$\mathbf{S}_R = \begin{pmatrix} \frac{x\eta^2}{c_+} & \frac{x\eta^2}{c} \\ -\frac{a+b}{c_+} & \frac{b-a}{c_-} \end{pmatrix} \tag{8}$$

with $x = g'/g \equiv \tan\theta_W$ and

$$a = \frac{1}{2}((x^2-1)\eta^2 + 4x^2); \quad b = \sqrt{a^2 + \eta^4 x^2};$$
$$c_+ = \sqrt{2b(b+a)}; \quad c_- = \sqrt{2b(b-a)} \tag{9}$$

MMM: Gauge Sector

- The gauge boson mass eigenvalues in the M-sector are

$$m_{W_R} = \frac{g\upsilon_R}{2}; \quad m_{Z_R} = \frac{g\upsilon_R}{2}\sqrt{1 + \frac{\eta^2 x^2}{b - a}} \tag{10}$$

$$m_D = \frac{g\upsilon_R}{2}\sqrt{1 - \frac{\eta^2 x^2}{b + a}} \tag{11}$$

- The D^μ s the gauge field of M-electromagnetic interaction, i.e. the M-photon.
- For the case when $\eta << 1(\upsilon_E >> \upsilon_R)$, $m_D \to g\upsilon_R/2$ and $m_{Z_R} \to g'\upsilon_E$.
- So at the lower energy, the M-electromagnetic interaction become as weak as the M-weak interaction, while the M-weak interaction is ξ^4 times weaker than the O-weak interaction.

MMM: Yukawa Interactions

- The most general Yukawa interaction which invariant under the gauge and Z_2 mirror symmetry is (suppressing the generation index)

$$\begin{aligned}\mathcal{L}_{yuk} \supset & -G_e(\bar{L}_L\chi_L^c e_R + \bar{L}_R\chi_R^c E_L) - G_\nu(\bar{L}_L\chi_L\nu_R + \bar{L}_R\chi_R N_L) \\ - & G_d(\bar{Q}_L\chi_L^c d_R + \bar{Q}_R\chi_R^c D_L) - G_u(\bar{Q}_L\chi_L u_R + \bar{Q}_R\chi_R U_L) \\ - & G_{\nu e}(\bar{e}_R\phi_e N_L + \bar{E}_L\phi_E\nu_R) - G'_{\nu e}(\bar{e}_R\phi_e\nu_R^c - \bar{E}_L\phi_E N_L^c) \\ - & G'_\nu(\bar{L}_L\chi_L N_L^c - \bar{L}_R\chi_R\nu_R^c) - M_m(\bar{\nu}_R^c\nu_R - \bar{N}_L^c N_L) - M_d\bar{N}_L\nu_R + h.c\end{aligned} \tag{12}$$

where the couplings G's and the M's above are 3×3 matrices to account for three generations.

- After χ_L and χ_R acquired VEV, the Lagrangian for generating the quark mass is

$$\mathcal{L}_{quark} \supset -G_d(\upsilon_L\bar{d}_L d_R + \upsilon_R\bar{D}_R D_L) - G_u(\upsilon_L\bar{u}_L u_R + \upsilon_R\bar{U}_R U_L) + h.c \tag{13}$$

and the O-quark and M-quark mass are as follow

$$M_u = G_u\upsilon_L;\, M_d = G_d\upsilon_L;\, M_U = G_u\upsilon_R;\, M_D = G_d\upsilon_D \tag{14}$$

MMM: Yukawa Interactions

- Lagrangian for the lepton sector is

$$\begin{aligned}\mathcal{L}_{lep} \supset \quad & - \quad G_e(\upsilon_L \bar{e}_L e_R + \upsilon_R \bar{E}_R E_L) - G_\nu(\upsilon_L \bar{\nu}_L \nu_R + \upsilon_R \bar{N}_R N_L) \\ & - \quad G'_\nu(\upsilon_L \bar{\nu}_L N_L^c - \upsilon_R \bar{N}_R \nu_R^c) - G_{\nu e} \upsilon_E \bar{E}_L \nu_R + G'_{\nu e} \upsilon_E \bar{E}_L N_L^c \\ & - \quad M_d \bar{N}_L \nu_R - M_m(\bar{\nu}_R^c \nu_R - \bar{N}_L^c N_L) + h.c \qquad (15)\end{aligned}$$

  and the O-charge lepton mass is $M_e = G_e \upsilon_L$

- While the O-neutrinos, the M-neutrinos and the M-charged leptons are mixing even in one generation. For detail, please read Satriawan 2017.

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SMMM: Introduction

Different from Minimal Supersymmetric Standard Model (MSSM), in this SUSY extension of MMM:

- Using $U(1)_R$ instead of discrete R-parity with we follow Riva, Biggio, and Pomarol 2013 for the R-charge assignment.
- Making the first generation of sneutrino (SUSY partner of neutrino) acquire VEV and plays role as Higgs particle to give mass to particle $\rightarrow$ no Higgs superfield.
- Non zero VEV of the first generation of mirror selectron in order to give mass to the mirror photon.

Therefore this SUSY extension model of MMM do not contain Higgsinos, free from the μ-problem, and the gaugino will have Dirac mass instead of Majorana mass.

SMMM: The Model

Table 3: O-sector chiral superfield of the SMMM and charge assignment under MMM gauge group and the $U(1)_R$ symmetry.

Superfield	spin 0	spin 1/2	Gauge group reps.	$U(1)_R$
$\hat{L}_1$	$(\tilde{\nu}_L, \tilde{e}_L)_1$	$(\nu_L, e_L)_1$	**1**,**1**,**2**,**1**,-1,0	0
$\hat{L}_{2,3}$	$(\tilde{\nu}_L, \tilde{e}_L)_{2,3}$	$(\nu_L, e_L)_{2,3}$	**1**,**1**,**2**,**1**,-1,0	$1-L$
$\hat{e}^c_1$	$\tilde{e}^\dagger_{R_1}$	$e^\dagger_{R_1}$	**1**,**1**,**1**,**1**,2,0	2
$\hat{e}^c_{2,3}$	$\tilde{e}^\dagger_{R_{2,3}}$	$e^\dagger_{R_{2,3}}$	**1**,**1**,**1**,**1**,2,0	$1+L$
$\hat{\nu}^c_1$	$\tilde{\nu}^\dagger_{R_1}$	$\nu^\dagger_{R_1}$	**1**,**1**,**1**,**1**,0,0	2
$\hat{\nu}^c_{2,3}$	$\tilde{\nu}^\dagger_{R_{2,3}}$	$\nu^\dagger_{R_{2,3}}$	**1**,**1**,**1**,**1**,0,0	$1+L$
$\hat{d}^c_i$	$\tilde{d}^\dagger_{Ri}$	$d^\dagger_{Ri}$	**3***,**1**,**1**,**1**, 2/3,0	$1-B$
$\hat{q}_i$	$(\tilde{u}, \tilde{d})_{Li}$	$(u, d)_{Li}$	**3**,**1**,**2**,**1**, 1/3,0	$1+B$
$\hat{u}^c_i$	$\tilde{u}^*_{Ri}$	$u^\dagger_{Ri}$	**3***,**1**,**1**,**1**,-4/3,0	$1-B$
$\hat{\Phi}_S$	S	$\tilde{S}$	**1**,**1**,**1**,**1**, 0,0	0
$\hat{\Phi}_T$	T	$\tilde{T}$	**1**,**1**,**3**,**1**, 0,0	0
$\hat{\Phi}_O$	O	$\tilde{O}$	**8**,**1**,**1**,**1**, 0,0	0

SMMM: The Model

Table 4: M-sector chiral superfield of the SMMM and charge assignment under MMM gauge group and the $U(1)_R$ symmetry.

Superfield	spin 0	spin 1/2	Gauge group reps.	$U(1)_R$
$\hat{R}_1$	$(N_R, E_R)_1$	$(N_R, E_R)_1$	**1**,**1**,**1**,**2**,0,-1	0
$\hat{R}_{2,3}$	$(\tilde{N}_R, \tilde{E}_R)_{2,3}$	$(N_R, E_R)_{2,3}$	**1**,**1**,**1**,**2**,0,-1	$L-1$
$\hat{E}_1$	$\tilde{E}^\dagger_{L_1}$	$E^\dagger_{L_1}$	**1**,**1**,**1**,**1**,0,2	-2
$\hat{E}_{2,3}$	$\tilde{E}^\dagger_{L_{2,3}}$	$E^\dagger_{L_{2,3}}$	**1**,**1**,**1**,**1**,0,2	$-1-L$
$\hat{N}_1$	$\tilde{N}^\dagger_{L_1}$	$N^\dagger_{L_1}$	**1**,**1**,**1**,**1**,0,0	-2
$\hat{N}_{2,3}$	$\tilde{N}^\dagger_{L_{2,3}}$	$N^\dagger_{L_{2,3}}$	**1**,**1**,**1**,**1**,0,0	$-1-L$
$\hat{D}_i$	$\tilde{D}^\dagger_{Li}$	$D^\dagger_{Li}$	**3***,**1**,**1**,**1**,0, 2/3	$B-1$
$\hat{Q}_i$	$(\tilde{U}, \tilde{D})_{Ri}$	$(U, D)_{Ri}$	**3**,**1**,**1**,**2**, 0,1/3	$-1-B$
$\hat{U}^c_i$	$\tilde{U}^\dagger_{Li}$	$U^\dagger_{Li}$	**3***,**1**,**1**,**1**,0,-4/3	$B-1$
$\hat{\Phi}_{S'}$	S'	$\tilde{S}'$	**1**,**1**,**1**,**1**, 0,0	0
$\hat{\Phi}_{T'}$	T'	$\tilde{T}'$	**1**,**1**,**1**,**3**, 0,0	0
$\hat{\Phi}_{O'}$	O'	$\tilde{O}'$	**1**,**8**,**1**,**1**, 0,0	0

SMMM: The Model

Table 5: O-sector vector superfield of the SMMM and charge assignment under MMM gauge group and the $U(1)_R$ symmetry.

Superfield	spin 0	spin 1/2	Gauge group reps.	$U(1)_R$
$\hat{W}_3^\alpha$	$\tilde{g}$	g	$\mathbf{8},\mathbf{1},\mathbf{1},\mathbf{1},0,0$	1
$\hat{W}_2^\alpha$	$\tilde{W}^\pm$ $\tilde{W}^0$	$W^\pm$ W^0	$\mathbf{1},\mathbf{1},\mathbf{3},\mathbf{1},0,0$	1
$\hat{W}_1^\alpha$	$\tilde{B}^0$	B^0	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},0,0$	1

Table 6: M-sector vector superfield of the SMMM and charge assignment under MMM gauge group and the $U(1)_R$ symmetry.

Superfield	spin 0	spin 1/2	Gauge group reps.	$U(1)_R$
$\hat{W}_3^{\alpha\prime}$	$\tilde{g}'$	g'	$\mathbf{1},\mathbf{8},\mathbf{1},\mathbf{1},0,0$	-1
$\hat{W}_2^{\alpha\prime}$	$\tilde{W}'^\pm$ $\tilde{W}'^0$	$W'^\pm$ W'^0	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{3},0,0$	-1
$\hat{W}_1^{\alpha\prime}$	$\tilde{B}'^0$	B'^0	$\mathbf{1},\mathbf{1},\mathbf{1},\mathbf{1},0,0$	-1

Superpotential

The most general superpotential in O-sector is

$$W = -(y_d)_{ij}\hat{d}^c_i\hat{q}_j\hat{L}_1 - y_2\hat{e}^c_2\hat{L}_2\hat{L}_1 - y_3\hat{e}^c_3\hat{L}_3\hat{L}_1 + \eta\hat{S}\hat{\nu}^c + \kappa\hat{S}\hat{S}\hat{\nu}^c + \rho\hat{\nu}^c \quad (16)$$

The most general superpotential in M-sector is

$$W' = -(y_d)_{ij}\hat{D}^c_i\hat{Q}_j\hat{R}_1 - y_2\hat{E}^c_2\hat{R}_2\hat{R}_1 - y_3\hat{E}^c_3\hat{R}_3\hat{R}_1 + \eta\hat{S}'\hat{N}^c + \kappa\hat{S}'\hat{S}'\hat{N}^c + \rho\hat{N}^c \quad (17)$$

In the superpotential above, we do not write the $SU(2)$ indices. The SU(2) field can be contracted by antisymmetric tensor $\epsilon^{\alpha\beta}$. For example:

$$W(d) = -(y_d)_{ij}\hat{d}^c_i\hat{q}_j\hat{L}_1 = -(y_d)_{ij}\hat{d}^c_i\hat{q}_{j\alpha}\epsilon^{\alpha\beta}\hat{L}_{1\beta} \quad (18)$$

SMMM: Fermion Mass

- The O and M sector fermion mass can be generated from superpotential after $\tilde{\nu}_{L1}$ (which is $\tilde{\nu}_{eL}$) and $\tilde{N}_{R1}$ acquired non-zero VEV $\langle\tilde{\nu}_{L1}\rangle = \upsilon_L$ and $\left\langle \tilde{N}_{R1} \right\rangle = \upsilon_R$ respectively.

- We will show how to generate fermion mass, e.g. down type quark. We write Eq. 18 in terms of its scalar component fields

$$W(\tilde{d}) = -(y_d)_{ij}(\tilde{d}_R^{\dagger})_i \left((\tilde{u}_L)_j \tilde{e}_L - (\tilde{d}_L)_j \tilde{\nu}_{eL}\right) \tag{19}$$

- The down type quark mass can be obtain after $\langle\tilde{\nu}_{eL}\rangle = \upsilon_L$ and using equation:

$$-\frac{1}{2}\frac{\partial^2 W(\varphi)}{\partial\varphi_i \partial\varphi_j}\psi_i\psi_j + h.c. = -\frac{1}{2}\upsilon_L (y_d)_{ij}(d_R^{\dagger})_i d_{L_j} + h.c \tag{20}$$

- Thus we have mass matrix in flavor space $m_{d_{ij}} = \upsilon_L (y_d)_{ij}$, which we have to diagonalize to obtain the mass of three down-type quark and for M-sector $m_{D_{ij}} = \upsilon_R (y_d)_{ij}$

SMMM: Fermion Mass

- The second and third generation of both sector electron can be generated from the second and third term of superpotential

$$m_{e_2} = \upsilon_L y_2; \quad m_{e_3} = \upsilon_L y_3; \quad m_{E_2} = \upsilon_R y_2; \quad m_{E_3} = \upsilon_R y_3 \tag{21}$$

- The up-type quark mass can be originated as supersymmetry breaking effects. Introducing spurion superfield $\hat{X} = x + \theta^2 F_X$ which has properties:

$$\langle F_X \rangle \neq 0; \quad R[\hat{X}] = R[x] = 2; \quad R[F_X] = 0 \tag{22}$$

- Therefore, we can write

$$\int d^4\theta \omega_{ij} \frac{\hat{X}^\dagger}{M} \frac{\hat{u}_i^c \hat{q}_j \hat{L}_1^\dagger}{\Lambda} = \int d^2\theta (y_u)_{ij} \hat{u}_i^c \hat{q}_j \hat{L}_1^\dagger \tag{23}$$

where ω_{ij} is dimesionless coupling and $(y_u)_{ij} \equiv \omega \langle F_X \rangle / M\Lambda$ is Yukawa coupling matrix of up-type quark.

SMMM: Fermion Mass

- Therefore, the up-type quark mass for both sector are

$$m_{u_{ij}} = (\omega)_{ij} \frac{\upsilon_L \langle F_X \rangle}{M\Lambda} \quad m_{U_{ij}} = (\omega)_{ij} \frac{\upsilon_R \langle F_X \rangle}{M\Lambda} \tag{24}$$

where M is the scale at which the supersymmetry-breaking effects are mediated, while Λ is the scale at which the higher-dimensional operator (Eq.23) is generated.

- The electron of both sectors can be generated by operator (Grant and Kakushadze 1999)

$$\int d^4\theta \mathbf{y}_3 \frac{\hat{X}^\dagger \hat{X}}{M^2} \frac{\hat{L}_1 D^\alpha \hat{L}_1 D_\alpha \hat{e}_1^c}{\Lambda^2} = \int d^2\theta y_e \hat{L}_1 \hat{L}_1 \hat{e}_1^c \tag{25}$$

Then the electron mass of both sectors are

$$m_{e_1} = y_3 \frac{\upsilon_L \langle F_X \rangle^2}{M^2 \Lambda^2}; \quad m_{E_1} = y_3 \frac{\upsilon_R \langle F_X \rangle^2}{M^2 \Lambda^2} \tag{26}$$

SMMM: Soft SUSY Breaking

- $U(1)_R$ symmetry prevent gaugino have Majorana mass. The Dirac mass term of gaugino are constructed from a spurion superfield $\hat{J}'_\alpha = \lambda'_\alpha + \theta_\alpha D'$ with D-type supersymmetry breaking which has properties

$$\langle D' \rangle \neq 0; \quad R[\hat{J}'_\alpha] = R[\lambda'_\alpha] = 1; \quad R[D'] = 0 \tag{27}$$

- The Lagrangian containing the Dirac gaugino mass is

$$\mathcal{L}^D_{\text{gaugino}} = \int d^2\theta \frac{\hat{J}'_\alpha}{M} \left[\sqrt{2}\eta_1 \hat{W}_1^\alpha \hat{S} + 2\sqrt{2}\eta_2 \mathrm{Tr}(\hat{W}_2^\alpha \hat{T}) + 2\sqrt{2}\eta_3 \mathrm{Tr}(\hat{W}_3^\alpha \hat{O}) \right] \tag{28}$$

The mass of Dirac gaugino $M_{D_i} = \eta_i \frac{\langle D' \rangle}{M}$.

The scalar particle can be obtain by soft-SUSY breaking term as follow

$$\begin{aligned}\mathcal{L}^{\rm mass}_{\rm scalar} = & -m^2_{\tilde{q}_i}\tilde{q}^\dagger_i\tilde{q}_i - m^2_{\tilde{L}}\tilde{L}^\dagger_{23}\tilde{L}_{23} - m^2_{\tilde{\chi}_L}\tilde{\chi}^\dagger_L\tilde{\chi}_L - m^2_{\tilde{\phi}_e}\tilde{\phi}^\dagger_e\tilde{\phi}_e - m^2_{\tilde{e}}\tilde{e}^{c\dagger}\tilde{e}^c \\ & - m^2_{\tilde{d}}\tilde{d}^{c\dagger}\tilde{d}^c - m^2_{\tilde{u}}\tilde{u}^{c\dagger}\tilde{u}^c - m^2_{\tilde{\nu}}\tilde{\nu}^{c\dagger}\tilde{\nu}^c - m^2_S S^\dagger S - 2m^2_T \mathrm{Tr}(T^\dagger T) \\ & - 2m^2_O \mathrm{Tr}(O^\dagger O) - m^2_{\tilde{Q}_i}\tilde{Q}^\dagger_i\tilde{Q}_i - m^2_{\tilde{R}}\tilde{R}^\dagger_{23}\tilde{R}_{23} - m^2_{\tilde{\chi}_L}\tilde{\chi}^\dagger_R\tilde{\chi}_R - m^2_{\tilde{\phi}_E}\tilde{\phi}^\dagger_E\tilde{\phi}_E \\ & - m^2_{\tilde{E}}\tilde{E}^{c\dagger}\tilde{E}^c - m^2_{\tilde{D}}\tilde{D}^{c\dagger}\tilde{D}^c - m^2_{\tilde{U}}\tilde{U}^{c\dagger}\tilde{U}^c - m^2_{\tilde{N}}\tilde{N}^{c\dagger}\tilde{N}^c - m^2_{S'}S^{\dagger\prime}S' \\ & - 2m^{2\prime}_T \mathrm{Tr}(T'^\dagger T') - 2m^{2\prime}_O \mathrm{Tr}(O'^\dagger O') \qquad (29)\end{aligned}$$

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- In this model there is no MSSM Higgs superfield $(\hat{H}_u, \hat{H}_d) \rightarrow$ no Higgsinos $\rightarrow$ O-sector particles are smaller than MSSM.
- The first generation sneutrino $\tilde{\nu}_{eL}$ acquired VEV and plays the SM Higgs role to give SM fermion masses.
- The first generation mirror selectron $(\tilde{E}_{L_1})$ also acquired VEV in order to generate Mirror Photon mass.

- Dirac gaugino is an interesting dark matter candidate (Belanger et al. 2009).

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Summary

- In the O-sector this model have smaller particle number than MSSM.
- First generation sneutrino $\tilde{\nu}_{eL}$ acquired VEV and plays the SM Higgs role to give SM fermion masses.
- The charge scalar particle is natural in SUSY.
- $U(1)_R$ symmetry implies that gaugino has Dirac masses and it can be the dark matter candidate.

What's Next

- Neutrino mass
- The other dark matter candidate
- Cosmological constraint
- Quark sector
- Scalar sector

Thank you

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