TAE 2017 — Exercise sessions BSM 11 septiembre 2017

Minimal DM

① COMPLEX SCALAR DOUBLET

$X_{\gamma} = \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$, $\gamma = 1,2$, transforming in the fondamental, $X'_\delta = U_{\delta\gamma} X_\gamma$, $U = \exp\{ i \frac{\sigma^a}{2} a_a \}$, $a = 1,2,3$

- Case similar to 2HDM: X can replace H in analogues of the Yukawa terms.
- $$\mathcal{L}_{Yukawa} = -(Y_u)_{mn} (\bar{Q}_L)^{m\gamma\alpha} (H^c)_\gamma (u_R)_{n\alpha} - (Y_d)_{mn} (\bar{Q}_L)^{m\gamma\alpha} (H)_\gamma (d_R)_{n\alpha} - (Y_e)_{mn} (\bar{L}_L)^{m\gamma\alpha} (H)_\gamma (e_R)_{n\alpha} + h.c.$$

Y:		
$-\frac{1}{6}$	$-\frac{1}{2}$	$\frac{2}{3}$
$-\frac{1}{6}$	$\frac{1}{2}$	$-\frac{1}{3}$
$\frac{1}{2}$	$\frac{1}{2}$	-1

m,n: family index
$\gamma,\delta,\varepsilon,\varphi$: $SU(2)_L$ index
α: spinor (Lorentz) index

$H^c{}_\gamma = \varepsilon_{\gamma\gamma'} (H^*)^{\gamma'}$

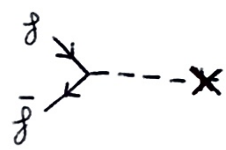
$\varepsilon_{\gamma\delta} = i\sigma^2{}_{\gamma\delta} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

The Yukawa's break explicitly the flavour symmetry of SM $U(3)^5$, $U(3)$ on each of Q_L^m, u_R^m, d_R^m, L_L^m, e_R^m.

- Replace H_γ with X_γ, assuming $Y(X) = Y(H) = \frac{1}{2}$ (otherwise, if $Y(X) = -\frac{1}{2}$, use X^c_γ)

$\boxed{d=4}$

$$\mathcal{L}_{\circ} \supset -(Y_u^X)_{mn} (\bar{Q}_L)^{m\gamma\alpha} (X^c)_\gamma (u_R)^n_\alpha - (Y_d^X)_{mn} (\bar{Q}_L)^{m\gamma\alpha} (X)_\gamma (d_R)^n_\alpha - (Y_e^X)_{mn} (\bar{L}_L)^{m\gamma\alpha} (X)_\gamma (e_R)^n_\alpha$$



- Unless $(Y^X_\cdot)_{mn} \propto (Y_\cdot)_{mn}$, there is a breaking of QUARK FLAVOUR / LEPTON FAMILY } NUMBER.

B, L are conserved.

(• In SUSY, 2HDM but H_u only couples to $\bar{Q}_L u_R$, H_d to $\bar{Q}_L d_R$ and $\bar{L}_L e_R$ due to holomorphy of W)

② MAJORANA FERMION TRIPLET

- Majorana: $\Psi = \begin{pmatrix} \psi_\alpha \\ \varepsilon^{\alpha\beta} \psi_\beta \end{pmatrix}$

- $X_{\gamma\delta}$, sym in γ and δ: irreps $\square\square$. $X_{12} = X_{21}$: $\begin{pmatrix} X^+ & \frac{1}{\sqrt{2}} X^0 \\ \frac{1}{\sqrt{2}} X^0 & X^- \end{pmatrix}$

(• Analogous to Wino in SUSY)

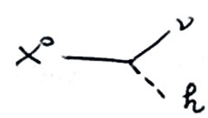
2×2, not $2 \times \bar{2}$ $\begin{pmatrix} \frac{W^3}{2} & \frac{W^+}{\sqrt{2}} \\ \frac{W^-}{\sqrt{2}} & -\frac{W^3}{2} \end{pmatrix}$ (traceless)

- Y can be 0, or 1, to give a neutral state. X Majorana, real, implies $Y = 0$.
- We must contract with 2 doublets, one of them a fermion $\longrightarrow$ can only choose L_L, otherwise the colour index of Q_L is not contracted (at $d=4$).

$\boxed{d=4}$

$$\mathcal{L} \supset c_m (\bar{L}_L)^{m\gamma\alpha} (X)_{\gamma\delta}{}^{\alpha} (H^*)^\delta$$

	Y	
$\frac{1}{2}$	0	$-\frac{1}{2}$



- Violation of LEPTON FAMILY NUMBER, and also of L.

($L(X) = 0$ since it must be real)

③ DIRAC FERMION FOURPLET

- $\square\square\square$ $\quad X_{\gamma\delta\varepsilon}$ completely simmetric, 4 ind. comp.: X_{111}, X_{112}, X_{122}, X_{222}.
- Y must be $\pm\frac{1}{2}$ or $\pm\frac{3}{2}$ to have a singlet. E.g.: $Y=+\frac{1}{2}$, $\begin{pmatrix} X^{++} \\ X^{+} \\ X^{0} \\ X^{-} \end{pmatrix}$ $\quad (Q=T^3+Y)$
- We need 3 doublet, one of them a fermion: $d \geq \frac{3}{2}+\frac{3}{2}+1+1=5$.

$\Rightarrow$ at $d=4$ all SM accidental symmetries are conserved.

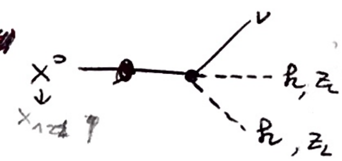
$\boxed{d=5}$

$Y(X)=-\frac{1}{2}$: $\quad \dfrac{c_m}{\Lambda_X}\,(\bar{L}_L)^{m\gamma\alpha}\,X^{\alpha}_{\gamma\delta\varepsilon}\,H_{\delta'}\,(H^*)^{\varepsilon}\,\varepsilon^{\delta\delta'}$

Y: $\quad \frac{1}{2} \quad -\frac{1}{2} \quad \frac{1}{2} \quad -\frac{1}{2}$

$Y(X)=-\frac{3}{2}$: $\quad \dfrac{c_m}{\Lambda_X}\,(\bar{L}_L)^{m\gamma\alpha}\,X^{\alpha}_{\gamma\delta\varepsilon}\,H_{\delta'}\,H_{\varepsilon'}\,\varepsilon^{\delta\delta'}\,\varepsilon^{\varepsilon\varepsilon'}$

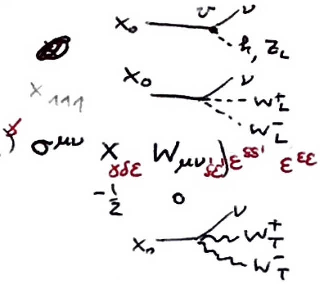
$\quad \frac{1}{2} \quad -\frac{3}{2} \quad \frac{1}{2} \quad \frac{1}{2}$



(• Violation at $d=5$ of lepton family, and L)

- The decay width will be $\Gamma_{X_0} \sim \dfrac{1}{8\pi}\dfrac{m_X^3}{\Lambda_X^2}$

(or $Y=\frac{1}{2}$: $(\bar{L}_L)^{\gamma}\,\sigma^{\mu\nu}\,X_{\gamma\delta\varepsilon}\,W_{\mu\nu\,\delta'\varepsilon'}\,\varepsilon^{\delta\delta'}\,\varepsilon^{\varepsilon\varepsilon'}$
$\quad \frac{1}{2} \quad -\frac{1}{2} \quad 0$



Let's say decay time $\geq \dfrac{1}{\Gamma_{X_0}} > 150$ Gyr $= 7\cdot 10^{45}$ TeV^{-1}

$$\Rightarrow \Lambda_X > \left(\tau_{Uni}\cdot\frac{m_X^3}{8\pi}\right)^{1/2} = 1.6\cdot 10^{25}\ \text{GeV}\left(\frac{m_X}{10\ \text{TeV}}\right)^{3/2}$$

Already $\Lambda_X = M_P$ would give a too large Γ_X!

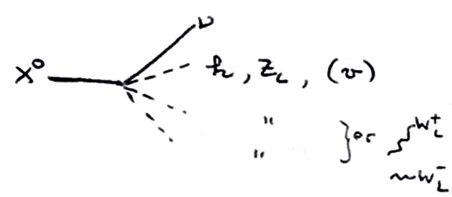
④ MAJORANA FERMION QUINTUPLET

$\square\square\square\square$ $\quad X_{\gamma\delta\varepsilon\varphi}$, completely symmetric.

- Need 1 L_L, and $2H+1H$ or $1\,W_{\mu\nu}+1H$ $\rightarrow$ $\boxed{d=6}$.
- Y must be integer: for $Y=0$, for example,

$Y(X)=0$: $\quad \dfrac{c_m}{\Lambda_X^2}\,(\bar{L}_L)^{m\gamma\alpha}\,X^{\alpha}_{\gamma\delta\varepsilon\varphi}\,\underbrace{H_{\delta'}\,H^{*\varepsilon}}_{\text{can replace with } \sigma_{\mu\nu}\,\dots\,W^{\mu\nu}_{\delta\varepsilon}\,\varepsilon^{\delta\delta'}\,\varepsilon^{\varepsilon\varepsilon'}}\,H^{*\varphi}\,\varepsilon^{\delta\delta'}$

Y: $\quad \frac{1}{2} \quad 0 \quad \frac{1}{2} \quad -\frac{1}{2} \quad -\frac{1}{2}$



- Decay is more suppressed, $\Gamma_X \propto \dfrac{m_X^5}{\Lambda_X^4}\dfrac{1}{8\pi}$

$\rightarrow \Lambda_X > 2.2\cdot 10^{15}$ GeV $\left(\dfrac{m_X}{10\ \text{TeV}}\right)^{5/4}$ $\quad$ (γ-ray bounds give $1.6\cdot 10^{16}$ GeV, i.e. $\tau_X > 10^5\,\tau_{Uni}$!)

Candidate	SM accidental sym at d=4: quark flavour	B	lepton family	L	$\mathbb{Z}_2$ at d=4	$\mathbb{Z}_2$ at d=5
complex scalar 2	✗	✓	✗	✓	✗	✗
Maj. fermion 3	✓	✓	✗	✗	✗	✗
Dirac fermion 4	✓	✓	✓	✓	✓	✗
Maj. fermion 5	✓	✓	✓	✓	✓	✓