BBSM Neutrino Course

Lecture XXIV

LMU
Spring 2020

MLRSM - symmetry Breaking

MLRSM = Minimal Left-Right Symmetric Model

$$\boxed{\text{"Decoupling"}}$$

heavy scales effects go as $\frac{1}{M_H^2}$ ← heavy

$\Downarrow$

$$\boxed{\Delta_L, \ \Delta_R}$$

$$\Rightarrow \langle \Delta_L \rangle = 0, \quad \langle \Delta_R \rangle \neq 0$$

$$\rho_1 \left(\mathrm{Tr}\, \Delta_L^\dagger \Delta_L + \mathrm{Tr}\, \Delta_R^\dagger \Delta_R \right)^2$$

$$+ \left(\rho_3 - 2\rho_1 \right) \mathrm{Tr}\, \Delta_L^\dagger \Delta_L \, \mathrm{Tr}\, \Delta_R^\dagger \Delta_R$$

$$\Downarrow$$

$$\boxed{\rho_3 - 2\rho_1 > 0}$$

$$\boxed{\text{look at } \Delta_R}$$

$$\boxed{\rho_1 , \quad \rho_2} \qquad \rho_2 > 0 \Rightarrow \nabla$$

$$\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$$

$$\Downarrow$$

$$\boxed{m_{\Delta_L} = (\rho_3 - 2\rho_1)\, v_R^2 \quad > 0}$$

$M_{W_R} = \frac{g}{2} v_R$ $\qquad$ $M_{W_L} = M_W = \frac{g}{2} v$

$$\boxed{\Delta m^2_{\Delta_L} \simeq O(v^2)}$$

$$\boxed{m_{\delta_R^{++}} = \rho_2 v_R^2}$$

$\rho_2 > 0$

δ_R^+ — eaten by W_R^+

$$\boxed{\rho_3 = 2\rho_1,\ \rho_2 = 0}$$

$$\Downarrow$$

$$\boxed{m_{\Delta_L} = 0;\quad m_{\delta_R^{++}} = 0}$$

$$\boxed{V = f\left(\mathrm{Tr}\,\Delta_L^\dagger \Delta_L + \mathrm{Tr}\,\Delta_R^\dagger \Delta_R\right)\ (1)}$$

$$\Downarrow$$

symmetry in this limit?

$\boxed{\Delta_R}$

$\rho_2 = 0 \Rightarrow V = f(\mathrm{Tr}\,\Delta_R^\dagger \Delta_R)$

$m_{\delta_R^{++}} = 0$ $\qquad\qquad\Downarrow$

$$SO(6)$$

$$\frac{6\cdot 5}{2} - \frac{5\cdot 4}{2} = 5 \quad \big\downarrow \ 5 \text{ broken gen.}$$

$$SO(5)$$

$$\Downarrow$$

5 NG bosons:

$$\boxed{\underbrace{\delta_R^+,\ \delta_R^-,\ \mathrm{Im}\,\delta_R^0}_{3 \text{ eaten}} + \delta_R^{++}}$$

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in (1) $\Longrightarrow$ $\boxed{\text{symmetry} = SO(12)}$

$$SO(12) \xrightarrow[v_R \neq 0]{} SO(11)$$

$$\frac{12 \cdot 11}{2} - \frac{11 \cdot 10}{2} = 11 \text{ broken gen.}$$

$\Downarrow$

11 NG bosons:

$$\underbrace{\Delta_L \ (=6) + 5 \text{ fields in } \Delta_R}_{\boxed{\text{massless}}}$$

$\boxed{\rho_2 \neq 0}$ $\boxed{\rho_3 = 2\rho_1}$

$\boxed{m_{\delta_R^{++}} = \rho_2 v_R^2}$ $\boxed{m_{\Delta_L} = 0}$

$\Downarrow$

$$\boxed{\text{mass of } \Delta_L \Leftarrow \rho_2 \text{ does not enter}}$$

$$\mathrm{Tr}\langle \Delta_R \Delta_R^\dagger \rangle = v_R^2$$

$$\Downarrow$$

$$\boxed{\begin{array}{l} \alpha_1 v_R^2 \; \mathrm{Tr}\, \Phi^\dagger \Phi \\ \longrightarrow \text{just redefines } \mu_\phi^2 \end{array}}$$

$\Downarrow$ <u>but</u>

$$\boxed{\alpha_3 \, \mathrm{Tr} \, \Phi^\dagger \Phi \, \Delta_R \Delta_R^\dagger}$$

$$\Downarrow$$

$$\alpha_3 \, \mathrm{Tr} \, \Phi^\dagger \Phi \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \begin{pmatrix} 0 & v_R \\ 0 & 0 \end{pmatrix}$$

$$= \alpha_3 \, \mathrm{Tr} \, \Phi^\dagger \Phi \begin{pmatrix} 0 & 0 \\ 0 & \boxed{v_R^2} \end{pmatrix} \qquad (2)$$

$$\boxed{\Phi = \begin{pmatrix} \varphi_1^0 & \varphi_2^+ \\ \varphi_1^- & -\varphi_2^{0*} \end{pmatrix}} \quad \downarrow SU(2)_L$$

$$\xrightarrow{SU(2)_R}$$

$$\Phi = \underbrace{\left(\phi_1 \, , \, \tilde{\phi}_2 \right)}_{\text{doublets under } SU(2)_L}$$

$\Downarrow$

$$\boxed{\Rightarrow \; \underbrace{\alpha_3 (\phi_2^\dagger \phi_2) V_R^2} \quad \text{splits the two doublets}}$$

after $SU(2)_R$ breaking

$$\boxed{\begin{aligned} &(-\mu_\phi^2 + \alpha_1 V_R^2)\,\phi_1^\dagger \phi_1 \\ &(-\mu_\phi^2 + \alpha_1 V_R^2 + \alpha_3 V_R^2)\,\phi_2^\dagger \phi_2 \end{aligned}} \quad (3)$$

$\Downarrow$ $\boxed{V_R \gtrsim 10\,\mathrm{TeV}}$

ϕ_2 (doublet) $= \begin{pmatrix} \varphi_2^0 \\ \varphi_2^- \end{pmatrix}$

$\to$ gets a large mass

$\Downarrow$

$$\boxed{\phi_1 = \phi_{WS} \quad \text{SM doublet}}$$

$$\phi_1 = \phi_{WS} = \begin{pmatrix} \cancel{\phi^+ = G_W^+} \\ v + h + i\,\cancel{G_Z} \end{pmatrix}$$

$$\boxed{m_h = \sqrt{2\lambda}\, v}$$

$$\boxed{\mu_\phi^2 \simeq \alpha_1 V_R^2} \Longrightarrow \boxed{\begin{matrix} m_{\phi_1} \simeq 0 \\ (v \ll V_R) \end{matrix}}$$

$\Downarrow$

$$\boxed{\text{Fine - Tuning (FT)}}$$

Pseudo - Goldstone boson

Anselm, - - -

Berezhiani, Dvali

'80s

- $\underbrace{\langle \bar{q}_L q_R \rangle}_{\text{doublet}} \neq 0 \; (= \Lambda^3_{QCD})$

$$\Downarrow$$

$$\boxed{\begin{aligned} \Lambda_{QCD} &\simeq 200\,\text{MeV} \\ &\simeq 10^{-3}\,M_W \end{aligned}}$$

Weinberg
Susskind 70's

$$\boxed{\underbrace{\langle \bar{Q}_L Q_R \rangle = \Lambda_W^3}_{\text{Techni - Color}}}$$

$\Downarrow$

BSM with 55 doublets

54 become heavy

1 light $\Longleftrightarrow$ FT

$\Downarrow$

$$V = -\mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2$$

$\Downarrow$

- $\mu^2 > 0$ why??? $\Rightarrow$ SB

- $\lambda > 0$ (bounded)

$$\boxed{\begin{array}{l} m_h = \sqrt{\lambda}\, v \\ \lambda h^4 \end{array}}$$

$\Updownarrow$

$SU(5)$, $SO(10)$

Φ_H (heavy)

study separately

$$\boxed{V = -\mu_\phi^2 \phi^+\phi + \lambda(\phi^+\phi)^2}$$

$$+ \frac{g^4}{64\pi^2}(\phi^+\phi)^2 \ln \frac{\phi^+\phi}{\mu_\phi^2} \quad (4)$$

$g^4 \sim \lambda$

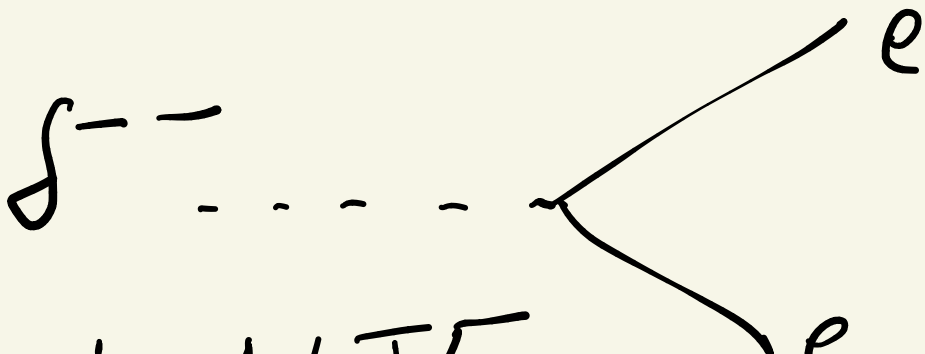
NOT OUR WORLD

$$M_{W_R} \gtrsim 4\ \text{TeV}$$

$$m_{\delta^{++}_{L,R}} \gtrsim 400\ \text{GeV}$$

$$\boxed{\begin{array}{l} h = \text{SM Higgs} \\ h' = \mathrm{Re}\,\delta_R^0 \;\therefore\; m_{h'} = ?? \end{array}}$$

$$\boxed{m_{h'} \simeq \sqrt{\rho}\, v_R \; = \; ?}$$



LNV

"

$$\boxed{\text{Lepton Number Violation}}$$

$$\boxed{SM}$$

$$m_h = \sqrt{\lambda}\, v$$

$$\boxed{\alpha_{gauge} = \frac{g^2}{4\pi} \lesssim 1} \quad \boxed{\text{pert.}}$$

$$\to \quad \lambda \lesssim 4\pi \quad \text{pert.}$$

$$\boxed{m_h \lesssim 800\,\text{GeV}}$$

$\phi_1, \ \phi_2$ = SM doublets
in Φ

$\langle \phi_i \rangle = v_i$

$$\Rightarrow \quad \phi = (v_1 \phi_1 + v_2 \phi_2) N$$

$$\phi' = (v_2 \phi_1 - v_1 \phi_2) N$$

$$\langle \phi \rangle = (v_1^2 + v_2^2) N \qquad N \equiv \frac{1}{\sqrt{v_1^2 + v_2^2}}$$

$$\langle \phi' \rangle = 0$$

$$\Downarrow$$

$\phi = \phi_{SM}$; $\boxed{\phi' = \text{new heavy scalar}}$

$$\Downarrow$$

ϕ' — flavor violation

$$m_{\phi'} = \sqrt{\alpha_3}\; v_R$$

$$\alpha_3 \le 4\pi$$

$$\boxed{M_{W_R} \text{ bigger} = \text{safer}}$$

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t', b' ?

$$\boxed{\begin{array}{l} m_{t'} = y_{t'} v \\ y_{t'}^2 \le 4\pi \text{ pert.} \end{array}}$$

$$\mathcal{L}_Y(\Delta) = l_L^T C\, i\sigma_2\, \Delta_L\, Y_{\Delta_L} l_L$$

$$+ l_R^T C\, i\sigma_2\, \Delta_R\, Y_{\Delta_R}\, l_R + \text{h.c.}$$

$$\Downarrow$$

$$\boxed{\nu_R^T C\, \nu_R\, Y_{\Delta_R}\, \nu_R}$$

$$e_R^T Y_{\Delta_R}\, e_R\, \delta_R^{++}$$

$$\| $$

$$\underline{M}_N \qquad \boxed{N = \nu_R^*}$$

$$\underline{M}_{\nu_R}^*$$

$$\left[\, \delta_R^{-+} \longrightarrow l_i\, l_j\, (\underline{M}_N^{ij}) \,\right]$$

$$\mu^2 \phi^+\phi + \alpha \underbrace{\langle H^+H \rangle}_{\text{new}} \phi^+\phi$$

$$\boxed{\mu_{eff}^2 = \mu^2 + \alpha v_H^2}$$

$$\boxed{\text{large} + \text{large} = \text{small}}$$

loops $\frac{g^2}{16\pi^2}$

$$\boxed{\beta \, Tr \, \Phi \Delta_R \Phi^+ \Delta_L^+} \quad (5)$$

..

$$\boxed{\langle \Delta_L \rangle = 0\,, \quad \langle \Delta_R \rangle \neq 0}$$

(5) $\boxed{\text{! term on symm. breaking}}$

$$\rho\, T_1 \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix} \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \begin{pmatrix} v_1 & 0 \\ 0 & v_2 \end{pmatrix} \begin{pmatrix} 0 & v_L \\ 0 & 0 \end{pmatrix}$$

$$= \rho\, T_1 \begin{pmatrix} 0 & 0 \\ v_2 v_R & 0 \end{pmatrix} \begin{pmatrix} 0 & v_1 v_L \\ 0 & 0 \end{pmatrix}$$

$$= \boxed{\rho\, v_1 v_2 v_R v_L} \longleftarrow \text{"tadpole" for } v_L$$

$$\Downarrow \quad v_L = \langle \delta_L^0 \rangle$$

$$\boxed{\beta v_1 v_2 v_R \delta_L^0} + \underbrace{m_{\Delta_L}^2}_{= v_R^2} \delta_L^{0\,2}$$

$$\frac{\partial V}{\partial \delta_L^0} = \underbrace{\beta v_1 v_2 v_R}_{\neq 0} + v_R^2 \delta_L^0 = 0$$

$$\Downarrow$$

$$\boxed{\langle \delta_L^0 \rangle = v_L \simeq \beta \frac{v_1 v_2}{v_R}}$$

$$\Downarrow$$

$$\boxed{m_{\nu_L} = Y_{\Delta_L} v_L = Y_{\Delta_L} \beta \frac{v_1 v_2}{v_R}}$$

$v_1 \sim v_2 \sim v \sim M_W$; $v_R \sim M_{W_R}$

$$\boxed{\Rightarrow m_{\nu_L} \simeq y_{\Delta_L}\, \beta\, \frac{M_W^2}{M_{W_R}} \quad (6)}$$

$\Downarrow$

$\boxed{\beta \ll 1}$

Is this natural?

Loops?

Sym. Breaking = SB

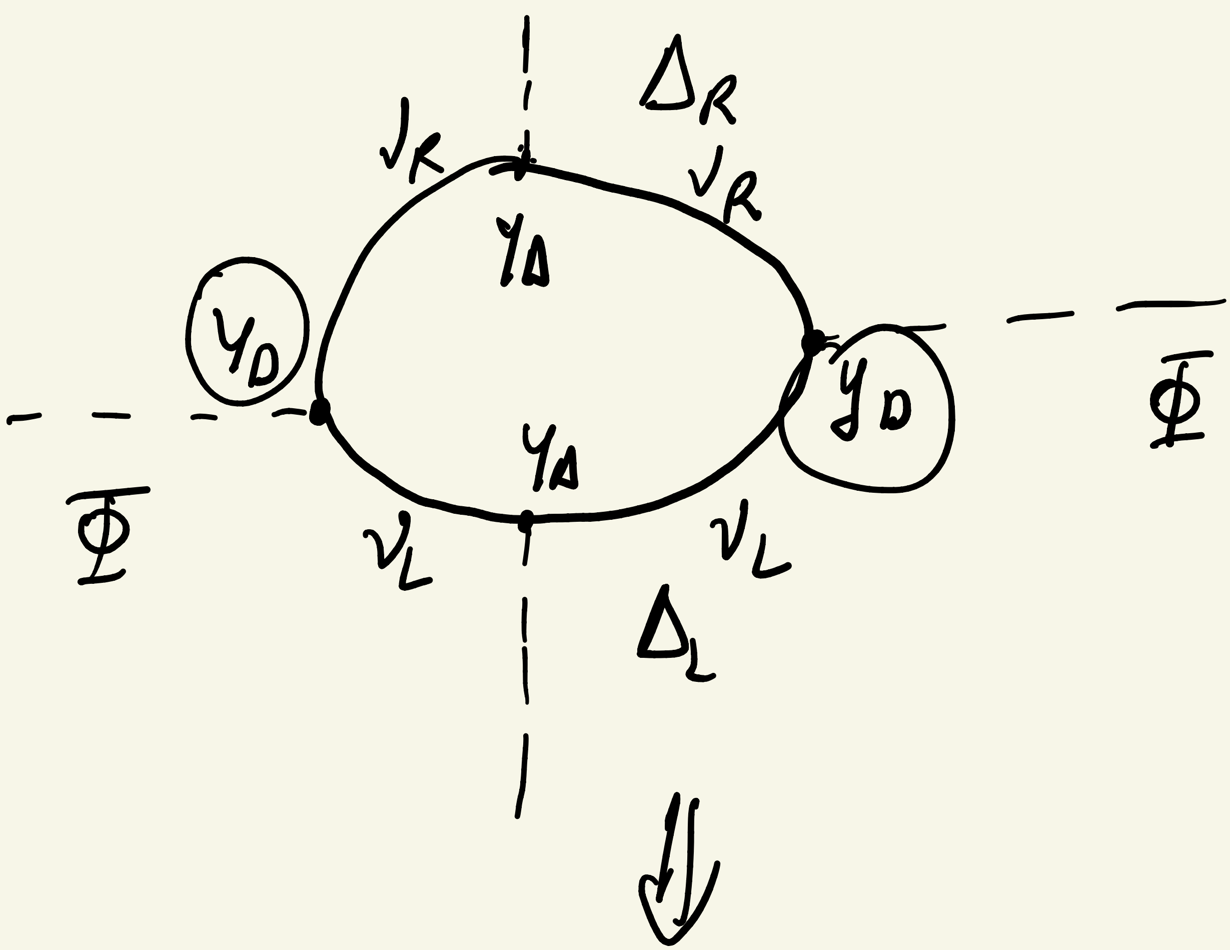
- $M_W = 0 \ (v_i = 0) \Rightarrow v_L = 0,\ v_R \neq 0$

- $M_W \neq 0 \Rightarrow$

$$\langle \Delta_L \rangle \sim \beta \langle \phi_{SM} \rangle \frac{\langle \phi_{SM} \rangle}{\boxed{M_H = M_{W_R}}}$$

triplet = doublet × doublet

$\boxed{\beta \text{ is not small?}}$



$$\boxed{\beta \simeq \frac{1}{16\pi^2} Y_D^2 \, y_\Delta^2}$$

$$\boxed{\beta = 0} \Rightarrow M_\nu = \frac{M_D^2}{M_N}$$

$$M_D = \sqrt{M_N M_\nu}$$

$$\boxed{M_N = 100\,\text{GeV}} \Rightarrow M_D = \sqrt{10^{-10}\,\text{GeV} \cdot 100\,\text{GeV}}$$

$$M_D \simeq 10^{-4}\,\text{GeV} = Y_D \, v_{SM}$$

$$v_{SM} = 100\,\text{GeV}$$

$$\Rightarrow \boxed{Y_D \simeq 10^{-6}}$$

$$\boxed{\Rightarrow \beta \ll 10^{-12}}$$

$$\Downarrow$$

$$\boxed{SM}$$

$$\Phi = D$$

$$\boxed{\mu D D T} \Rightarrow \boxed{\langle T \rangle \neq 0}$$

$$+ \, m_T T^2 \quad \boxed{m_T \gg M_W}$$

$$\Downarrow$$

$$m_Z^2 = (g^2 + g'^2)\left(v_{SM}^2 + 2 \langle T \rangle^2\right)$$

$$m_W^2 = g^2\left(v_{SM}^2 + \langle T \rangle^2\right)$$

$$\rho \equiv \frac{m_Z^2 \cos^2\theta_W}{m_W^2} = 1 + \frac{\langle T \rangle^2}{v_{SM}^2}$$

$\tan\theta_W = g'/g$

deviation from SM

$$M_N = Y_\Delta v_R$$

$$\boxed{Y_\Delta \simeq g \frac{M_N}{M_{W_R}}}$$

$$\boxed{g_\Delta^2/4\pi \leq 1}$$ (*)

$m_e \simeq M_W$

$m_e = \frac{y_e}{g} M_W$

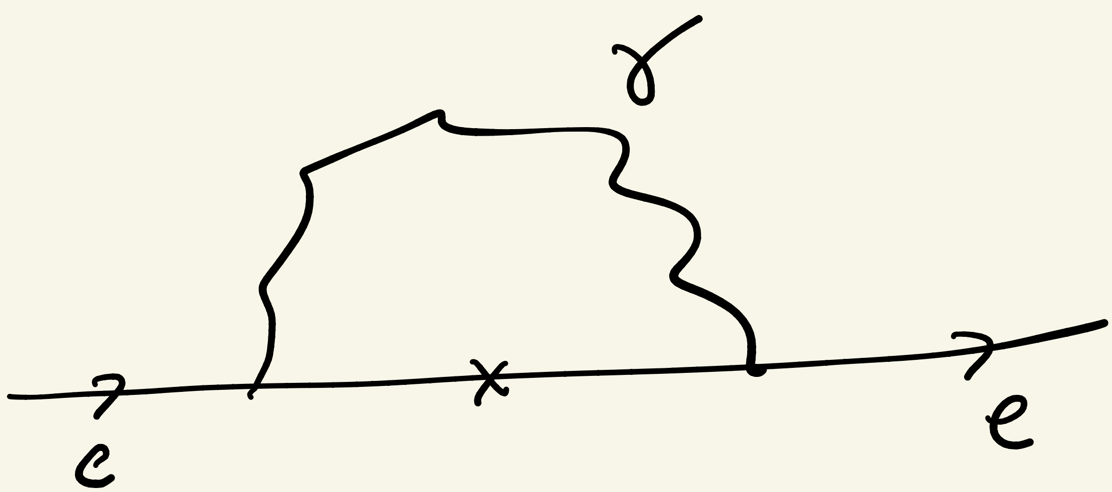
$y_e \cong 10^{-5}$

$$\boxed{m_e = ?}$$

$$\boxed{\Gamma(h \to e\bar{e}) \propto m_e^2}$$

- $y_\Delta \leq \sqrt{4\pi}$ pert.

$$\boxed{M_W = \frac{y_\Delta}{8} M_{UR} \leq \frac{\sqrt{4\pi}}{8} M_{UR}}$$



$$m_e^{(1)} = m_e^{(0)} \left[1 + \frac{\alpha}{4\pi} \ln \frac{\Lambda}{m_e} \right]$$

$$m_e^{(0)} = 0 \Rightarrow \underbrace{e_L \to e_L,\ e_R \to -e_R}_{\text{protects } m_e \text{ to all orders}}$$

$$\alpha\, \phi^\dagger \phi \underbrace{H^* H}_{\text{heavy}}$$

$$\Big\downarrow \text{vacuum}$$

$$M_H^2$$

$$\boxed{\alpha\, \phi^\dagger \phi\, M_H^2}$$