Neutrino Physics Course

Lecture XIV

17/6/2022

LMU

Summer 2022

SSB of LRSM (3)

- New Particles:

(i) $W_R^\pm$, Z' (Z_R) gauge bosons

$M_{W_R} \gtrsim 5$ TeV (LHC)

$M_{Z'} \gtrsim 2$ TeV (?) (")

Theory: $\boxed{M_{Z'} \simeq 1.7\, M_{W_R}}$

(ii) N (RH) neutrino

$m_N \gtrsim$? stay tuned

(iii) scalars: $(\delta_L^0, \delta_L^+, \delta_L^{++})$

Δ_L : $\boxed{m_\Delta \gtrsim 400-500\ \text{GeV}}$

h_R : $m_h > ?$ $\quad \boxed{m_h^2 \simeq 2\rho_1 v_R^2 \quad (\rho_1 = ?)}$

δ_R^{++}

$m_{\delta_R^{++}} \gtrsim 400-500\ \text{GeV}$

$$\boxed{m^2_{\delta_R^{++}} \simeq \rho_2 v_R^2}$$

$\cancel{\delta_R^+}$ (eaten by W_R^+)

$$G \xrightarrow[M_G]{} SM$$

examples: (a) $G = G_{LR} \Rightarrow M_G = M_R$

$M_R \gtrsim 5\,\mathrm{TeV}$

(b) $G = SU(5) \Rightarrow M_G \simeq 10^{16}\,\mathrm{GeV}$

$$m_{h_G}^2 = 2 \rho_G M_G^2$$

$$\rho_G = ?$$

$$m_{h_G} = ?$$

$$\Downarrow \boxed{\text{MORE}}$$

$$\Phi = (\phi_1, \tilde{\phi}_2)$$

$$= \begin{pmatrix} \varphi_1^0 & \varphi_2^+ \\ \varphi_1^- & -\varphi_2^{0*} \end{pmatrix}$$

$$\phi_i \equiv \begin{pmatrix} \varphi_i^- \\ \varphi_i^0 \end{pmatrix} \qquad \tilde{\phi}_i = i\sigma_2 \phi_i^*$$

$i = 1,2$

$$G_{LR} \xrightarrow[\langle \Delta_R \rangle]{} G_{SM}$$

$SU(2)_L \times U(1)$

$\Downarrow$

$$\langle \Phi \rangle = \begin{pmatrix} v_1 & v_2 \sin\theta \\ 0 & v_2 \cos\theta \end{pmatrix}$$

$\Rightarrow \quad \theta = 0$ in order to

guarantee $Q_{em} \langle \Phi \rangle = 0$

$$\Downarrow$$

$$\phi_i \quad \therefore \quad \langle \phi_i \rangle = \begin{pmatrix} v_i \\ 0 \end{pmatrix}$$

$$\Downarrow$$

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

$$\phi' = (v_2 \phi_1 - v_1 \phi_2) N \qquad N = \frac{1}{\sqrt{v_1^2 + v_2^2}}$$

$$\Downarrow$$

$$\langle \phi' \rangle = 0, \quad \langle \phi \rangle = \sqrt{v_1^2 + v_2^2} \equiv v$$

- if $m_{\phi'} \gg m_\phi$

$(m_\phi \lesssim v) \leftarrow$ Higgs

$\boxed{\text{SSB with } \Phi}$

$\boxed{\mathrm{Tr}\, \Phi^\dagger \Phi,\ \det \Phi,\ \det \Phi^\dagger}$

$$\boxed{\begin{aligned} V_\Phi = &- \mu^2 \,\mathrm{Tr}\, \Phi^\dagger \Phi - \nu^2 \underbrace{(\det \Phi + h.c.)}_{\text{ok}} \\ &+ \frac{\lambda_1}{4} (\mathrm{Tr}\, \Phi^\dagger \Phi)^2 + \frac{\lambda_2}{4} \det \Phi (\det \Phi)^* \\ &+ \frac{\lambda_3}{4} \underbrace{\left[(\det \Phi)^2 + h.c. \right]}_{\text{ok}} + \frac{\lambda_4}{4} \mathrm{Tr}\, \Phi^\dagger \Phi (\det \Phi + h.c.) \end{aligned}}$$

$$\mathcal{L}_Y = \bar{f}_L (Y \Phi + \tilde{Y} \tilde{\Phi}) f_R + h.c.$$

$$\tilde{\Phi} = i\sigma_2 \Phi^* i\sigma_2$$

$$G_{LR} = SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$$(f = q, \ell)$$

$$(B-L)\, f_L = (B-L)\, f_R$$

$$\Downarrow$$

$$\boxed{(B-L)\, \Phi = 0}$$

$$V_{\Phi,\Delta} = \alpha_1 \, Tr\, \Phi^\dagger \Phi \left(Tr\, \Delta_L^\dagger \Delta_L + L \leftrightarrow R \right)$$

$$+ \left(\alpha_2 \det \Phi + h.c. \right) \left(\quad - \, {}'' - \quad \right)$$

$$+ \alpha_3 \, Tr \left(\Delta_L \Delta_L^\dagger \, \Phi \Phi^\dagger + \Delta_R \Delta_R^\dagger \, \Phi^\dagger \Phi \right)$$

$$\Delta_L \to U_L \, \Delta_L \, U_L^\dagger \qquad \Phi \to U_L \, \Phi \, U_R^\dagger$$

$$\Delta_R \to U_R \, \Delta_R \, U_R^\dagger \qquad \Phi^\dagger \to U_R \, \Phi^\dagger U_L^\dagger$$

$$\Rightarrow \quad \Phi \Phi^+ \longrightarrow U_L \, \Phi \Phi^+ U_L^+$$

$$\Phi^+ \Phi \longrightarrow U_R \, \Phi^+ \Phi \, U_R^+$$

$$? \left(\mathrm{Tr} \; \Delta_L \Delta_L^+ \tilde{\Phi} \Phi^+ + L \leftrightarrow R \right)$$

but: $\underbrace{\Phi^+ \tilde{\Phi}}_{\text{trivial}} = \frac{1}{2} \mathrm{Tr} \; \Phi^+ \tilde{\Phi} \; \mathbb{1}$

$$\mathrm{Tr} \; \Phi^+ \tilde{\Phi} = ? \det \Phi^+$$

PROVE!

$\Rightarrow$ (included in α_2)

$$\boxed{\alpha_3 \longrightarrow \alpha_3' \; \mathrm{Tr} \; \Delta_L \Delta_L^+ \tilde{\Phi} \tilde{\Phi}^+ \quad ?}$$

$$\Uparrow$$

$$\Phi^\dagger \Phi + \tilde{\Phi}^\dagger \tilde{\Phi} \propto (\mathrm{Tr}\, \Phi^\dagger \Phi)\, \mathbb{1}$$

$$\Rightarrow \tilde{\Phi}^\dagger \tilde{\Phi} = (\mathrm{Tr}\, \Phi^\dagger \Phi)\, \mathbb{1} - \Phi^\dagger \Phi$$

not new

$\Rightarrow$ α_3' is NOT a new term!

$$\alpha_3' = f(\alpha_3, \alpha_1)$$

but

$$\Delta_L \to \langle \Delta_L \rangle = 0$$

$$\Delta_R \to \langle \Delta_R \rangle = v_R$$

$V_{\Phi\Delta}$ $\searrow$ $\Downarrow$

$$\alpha_1 v_R^2 \, \mathrm{Tr}\, \Phi^\dagger \Phi \qquad (\sim \mu^2)$$

$$+ \alpha_2 v_R^2 (\det \Phi + h.c.) \qquad (\sim v^2)$$

$$+ \alpha_3 \, \mathrm{Tr} \langle \Delta_R \Delta_R^\dagger \rangle \Phi^\dagger \Phi$$

$$\|$$

$$\alpha_3 v_R^2 \, \mathrm{Tr} \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \Phi^\dagger \Phi$$

$$= \alpha_3 v_R^2 \, \mathrm{Tr} \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \Phi^\dagger \Phi$$

$$= \alpha_3 v_R^2 (\Phi^\dagger \Phi)_{22}$$

$$\Phi = \begin{pmatrix} \varphi_1^0 & \varphi_2^+ \\ \varphi_1^- & -\varphi_2^{0*} \end{pmatrix}, \quad \Phi^\dagger = \begin{pmatrix} \varphi_1^{0*} & \varphi_1^+ \\ \varphi_2^- & -\varphi_2^0 \end{pmatrix}$$

$$\Downarrow$$

$$\boxed{\begin{aligned}(\Phi^+\Phi)_{22} &= \varphi_2^-\varphi_2^+ + |\varphi_2^0|^2 \\ &= \phi_2^+\phi_2\end{aligned}}$$

$$\boxed{\begin{aligned}\phi &= (v_1\phi_1 + v_2\phi_2)N \\ \phi' &= (v_2\phi_1 - v_1\phi_2)N\end{aligned}}$$

$$\langle\phi\rangle = v \equiv \sqrt{v_1^2+v_2^2}$$

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

<u>limit</u>: $v_2 = 0$

$$\Downarrow$$

$$\boxed{\begin{gathered}\phi = \phi_1, \quad \phi' = \phi_2 \\ v_1 \equiv v\end{gathered}}$$

$\Downarrow$ to be shown

$$\boxed{m_{\phi'} = m_{\phi_2} \gg M_W}$$

$\Downarrow$ from $V_{\Phi\Delta}$

$$\boxed{\alpha_3 \, v_R^2 \, \phi_2^\dagger \phi_2 = \alpha_3 \, v_R^2 \, \phi'^\dagger \phi'}$$

ϕ' gets naturally heavy!

$m_{\phi'} \propto v_R$

$$\boxed{\text{Physics of } \phi \text{ and } \phi'}$$

$$\mathcal{L}_Y = \bar{f}_L \left(y\, \bar{\Phi} + \tilde{y}\, \tilde{\bar{\Phi}} \right) f_R + h.c.$$

$$\rightarrow \bar{f}_L \left(y \begin{pmatrix} \phi_1^0 & 0 \\ 0 & -\phi_2^{0*} \end{pmatrix} + \tilde{y} \begin{pmatrix} \phi_2^0 & 0 \\ 0 & -\phi_1^{0*} \end{pmatrix} \right) f_R$$

$$+ h.c.$$

$$\downarrow$$

$$= \bar{u}_L^0 \left(y\, \phi_1^0 + \tilde{y}\, \phi_2^0 \right) u_R^0 +$$

$$+ \bar{d}_L^0 \left(y\, \phi_2^{0*} + \tilde{y}\, \phi_1^{0*} \right) d_R^0 \, (-) + h.c.$$

$$f = \begin{pmatrix} u \\ d \end{pmatrix} \quad \text{(quarks)}$$

$$\Downarrow \quad \langle \phi_1^0 \rangle = v_1 \equiv v$$

$$\langle \phi_2^0 \rangle = v_2 = 0$$

$$\Rightarrow \boxed{M_u = y v, \quad M_d = -\tilde{y} v}$$

$$\bar{u}_L^0 M_u u_R^0 + \bar{d}_L^0 M_d d_R^0$$

non-diagonal

$$u^0_{L,R} \to U_{L,R} u_{L,R} \qquad U^\dagger_{L,R} U_{L,R} = 1$$

$$d^0_{L,R} \to D_{L,R} d_{L,R} \qquad D^\dagger_{L,R} D_{L,R} = 1$$

$$\Rightarrow \boxed{V_{CKM} = V_L = U_L^\dagger D_L}$$

$$\Leftrightarrow \boxed{M_u = U_L\, m_u\, U_R^+}$$

$$\bar{u}_L^0\, M_u\, u_R^0 = \bar{u}_L\, m_u\, u_R$$

$$\bar{d}_L^0\, M_d\, d_R^0 = \bar{d}_L\, m_d\, d_R$$

$$\boxed{M_d = D_L\, m_d\, D_R^+}$$

$$m_u = \mathrm{diag}\,(m_u, m_c, m_t)$$

$$m_d = \mathrm{diag}\,(m_d, m_s, m_b)$$

$$\Downarrow \qquad \begin{aligned} \phi &\equiv \phi_1 \\ \phi' &\equiv \phi_2 \end{aligned}$$

$$\phi^0 = \phi_1^0 = v + h$$

$$\phi^{0'} = \phi_2^0 = H$$

(1)
$$-h\, \bar{d}_L^0\, \tilde{y}\, d_R^0 = +h\, \bar{d}_L^0\, \frac{M_d}{v}\, d_R^0 + h.c.$$

$$\underbrace{= h\, \bar{d}_L \frac{m_d}{v} d_R + h.c.}_{\text{SM Higgs coupling}}$$

$\Longleftrightarrow$ FLAVOR diagonal

$\Longleftrightarrow$ $\boxed{\text{conserves FLAVOR}}$

(ii)

$$H\, \bar{d}_L^0\, y\, d_R^0 + h.c. =$$

$$= H\, \bar{d}_L D_L^\dagger \frac{M_u}{v} D_R\, d_R + h.c.$$

$$= H\, \bar{d}_L D_L^\dagger U_L \frac{m_u}{v} U_R^\dagger D_R\, d_R + h.c.$$

$$\downarrow$$

$$H\, \bar{d}_L \underbrace{V_{CKM}^{+}(L)\, \frac{m_u}{v}\, V_{CKM}(R)}_{\text{FLAVOR VIOLATION}} d_R + h.c.$$

- <u>important:</u>

$$\mathcal{L}_Y = \overline{f_L}\,(Y \Phi + \dots)\, f_R + \overline{f_R}\,(Y^{+} \Phi^{+} + \dots)\, f_L$$

$$P: \quad f_L \longleftrightarrow f_R$$

$$(\Phi \to U_L \Phi U_R^{+}) \quad \Phi \Longleftrightarrow \Phi^{+} \quad (\Phi^{+} \to U_R \Phi^{+} U_L^{+})$$

$$\Downarrow$$

$$\boxed{\psi = \psi^+, \quad \tilde{\psi} = \tilde{\psi}^+}$$

$$\Downarrow$$

$$M_u = \psi \vartheta \quad , \quad -M_d = \tilde{\psi} \vartheta$$

$$\Downarrow$$

$$\boxed{M_u = M_u^+, \quad M_d = M_d^+}$$

$$\Downarrow$$

$$\boxed{V_L = V_R, \quad D_L = D_R}$$

$$\Downarrow$$

$$\boxed{V_L \ (\text{сим}) = V_R}$$

$\Downarrow$

$$\boxed{H\, \bar{d}_L\, V^{+}_{CKM}\, \frac{m_u}{v}\, V_{CKM}\, d_R + \text{h.c.}}$$

predicted FV

Flavor Violation

$\Downarrow$

from the absence of such FV

$\Downarrow$

$$\boxed{m_H > 10\ \text{TeV}}$$

$$\Downarrow$$

H is NOT a low energy (SM) Higgs boson

$$\Downarrow$$

bottom line:

h = SM Higgs

$$+ \text{ effects } \left(\frac{m_h}{m_H}\right)^2 \leq \left(\frac{100\ \text{GeV}}{10\ \text{TeV}}\right)^2 \simeq 10^{-4}$$

$$H = \phi^{0\prime} \; (\phi_2^0)$$

$m_n > 10$ TeV $\Rightarrow$ $\phi^{+\prime}$ must be heavy

$$\Rightarrow \boxed{m_{\phi'} \gtrsim 10 \text{ TeV}}$$

$$\Updownarrow$$

$$\boxed{\phi' = \text{degenerate} \equiv H \quad \text{heavy scalar doublet}}$$

Summary

$$\Phi = \begin{pmatrix} \phi_1 & \tilde{\phi}_2 \end{pmatrix} =$$

$$= \begin{pmatrix} \phi & \tilde{\phi}' \end{pmatrix}$$

limit $v_2 = 0$

SM doublet
(Higgs)

heavy scalar doublet

$$\phi = \begin{pmatrix} h+v \\ 0 \end{pmatrix}$$

↳ rest gets eaten

H

· $v_2 = 0$ limit $\nearrow$

· $v_2 \neq 0 \Rightarrow$ $\boxed{\begin{array}{l} \phi = (\phi_1 v_1 + \phi_2 v_2)N \\ \phi' \perp \phi \end{array}}$

SM Higgs

H

$\boxed{\text{Rest as before}}$

$$\boxed{\begin{array}{l} \cdot\ m_H^2 = \alpha_3 v_R^2 \\ \Leftrightarrow \alpha_3 > 0 \end{array}}$$

SM

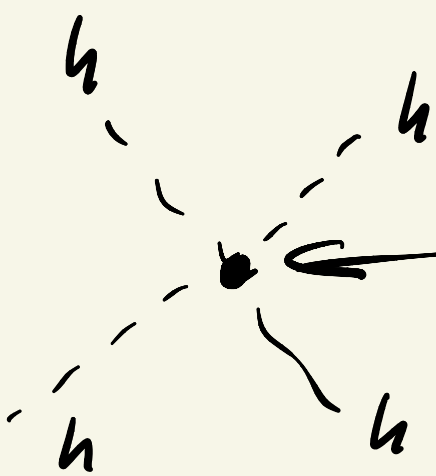
$$m_h^2 = 2\lambda v^2$$

$$M_W = \frac{g}{2} v$$

$$\Downarrow$$

$$v = \frac{2M_W}{g} \simeq ?$$

$$\lambda = \frac{m_h^2}{2v^2} = \frac{m_h^2 g^2}{4M_W^2}$$



λ (stay tuned)

$\Downarrow$ by analogy

$$m_H^2 = \alpha_3 v_R^2 = \alpha_3 \frac{M_{W_R}^2}{g^2}$$

$$\Downarrow$$

$$\boxed{\alpha_3 = \frac{m_H^2 g^2}{M_{W_R}^2}}$$