

Neutrino Physics

Course

Lecture X

3/6/2021

LMU

Summer 2022



Left-Right Symmetric Model (LRSM)

- Imagine LR sym. world: \textcircled{P}

$$e_L \equiv \begin{pmatrix} u \\ d \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} u \\ d \end{pmatrix}_R \equiv e_R$$

$$l_L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}_L \longleftrightarrow \begin{pmatrix} \nu \\ e \end{pmatrix}_R \equiv l_R$$

$$\Rightarrow \boxed{m_\nu \neq 0}$$

but

$$(f = 2, l)$$

$$\mathcal{L}_Y = \bar{f}_L (-M_f + Y_T T) f_R + \text{h.c.}$$

$$f_{L,R} \rightarrow U f_{L,R}$$

$\hookrightarrow SU(2)$

$$\Rightarrow T \rightarrow U T U^\dagger$$

$\rightarrow \uparrow$
adjoint scalar
(triplet)

$$T = T^\dagger, \quad T, T = 0$$

$$V_T \equiv \langle T \rangle \neq 0$$

$$\Rightarrow M_z = 0, M_W = g V_T$$

all hell breaks loose!

What if P = conserved?

$$\begin{array}{c} \Downarrow \\ \mathfrak{g} \equiv \mathfrak{g}_L = \mathfrak{g}_R \\ G_{LR} = SU(2)_L \times SU(2)_R \quad ? \\ \uparrow \qquad \qquad \qquad \uparrow \\ \Downarrow \quad \text{NOT enough} \end{array}$$

$$Q_{em} = T_{3L} + T_{3R} \quad ?$$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L$$

||

$$\begin{pmatrix} u \\ d \end{pmatrix}_R$$

matter

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

||

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_R$$

NO

masses

\vec{W}_L

\vec{W}_R

$$M_{W_R} \gg M_{W_L}$$

Again:

$$Q = T_{3L} + T_{3R} \quad ?$$

all multiplets (same)

→ same prediction

⇓

- $Q_u = Q_d, \quad Q_e = Q_d$

- $Q = \pm 1/2$

⇑

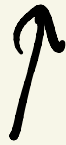
$$\bar{T}_L f_R = \bar{T}_R f_L = 0$$

$$T_{3L} f_L = T_{3R} f_R = \pm 1/2$$



$$Q = T_{3L} + T_{3R} + \frac{Y'}{2}$$

better: $\frac{Y'}{2} = Q - T_{3L} - T_{3R}$



exp

theory



group group

$$G_{LR} = SU(2)_L \times SU(2)_R \times \frac{U(1)}{Z}$$
$$\mathcal{G} \equiv \mathcal{G}_L = \mathcal{G}_R \quad \bar{\mathcal{G}}$$

$$\# \text{ of g. b.} = 3 \quad + \quad 3 \quad + \quad 1$$

$$\qquad\qquad (L) \qquad\qquad (R) \qquad\qquad (1)$$



$$W_L^+, W_L^-, Z_L \quad + \quad W_R^+, W_R^-, Z_R$$

$$\qquad\qquad\qquad (z) \qquad\qquad\qquad (z')$$

$$+$$

$$A \text{ (photon)}$$



$$\underbrace{M_{WA} \simeq M_{ZR}}_{M_A} \gg \underbrace{M_{WL} \simeq M_{ZL}}_{M_L \equiv M_W}$$

Pati, Selam 1974

Holapata, G.S. - 1975



modem: 1979



$w_1 \neq 0$

CURSE '70s

Higgsing

(i) S-M Higgs ϕ (doublet)

= where?



$$\mathcal{L}_Y = \bar{f}_L \gamma \Phi f_R + h.c.$$

$$f_L \rightarrow U_L f_L, \quad f_R \rightarrow U_R f_R$$

$$\left(\begin{array}{l} U_L = e^{i\vec{\theta}_L \cdot \vec{T}}, \quad U_R = e^{i\vec{\theta}_R \cdot \vec{T}} \\ \vec{T} \equiv \vec{\sigma}/2 \end{array} \right)$$



$$\Phi \rightarrow U_L \Phi U_R^\dagger$$



$\Phi = \text{matrix}$

(bi-doublet)

$$(SM \text{ Higgs: } \phi \rightarrow U \phi$$

$$T_i \phi = \frac{\sigma_i}{2} \phi$$
$$U = e^{i T_i \theta_i} = 1 + i T_i \theta_i + \dots$$

$$\bar{\Phi} \rightarrow U_L \bar{\Phi} U_R^\dagger$$

$$U_L = 1 + i \bar{\theta}_L \cdot \vec{T} + \dots$$

$$U_R = 1 + i \bar{\theta}_R \cdot \vec{T} + \dots$$

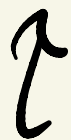
$$\hat{T} \bar{\Phi} = \vec{\sigma} \cdot \bar{\Phi} - \bar{\Phi} \vec{\sigma} \cdot \bar{\Phi}$$

- $Q = T_{3L} + T_{3R} + \frac{Y}{2}$
 $\bar{Y} = ?$

$$f_L : T_{3A} f_L = 0$$

$$\begin{aligned} \bar{Y} f_L &= \underbrace{(Q - T_{3L})}_{Y'} f_L \\ &= Y' f_L \end{aligned}$$

$$\Rightarrow \bar{Y} f_L = Y' f_L$$



SM hypercharge

$$\therefore Y' l_L = (-1) l_L$$

$$Y' e_L = \frac{1}{3} e_L$$

$$\Rightarrow \boxed{Y' = B - L}$$



$$B q = \frac{1}{3} q, \quad L q = 0$$

$$B l = 0, \quad L l = l$$

$$L \leftrightarrow R$$

$$\bar{Y} f_R = (B - L) f_R$$

$$\bar{Y} = B - L \quad \text{on } L \text{ and } R$$

essentially the global
symmetry of SM

↓
gauge symmetry in LR

↓

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$L_Y = \bar{f}_L \gamma \bar{\Phi} f_R + h.c.$$

$$Q \cdot (B-L) \bar{\Phi} = ?$$

$$A \cdot (B-L) \bar{\Phi} = 0$$

⇓

$$Q \bar{\Phi} = T_{3L} \bar{\Phi} - \bar{\Phi} T_{3R}$$

$$= \left(\frac{\sigma_3}{2} \bar{\Phi} - \bar{\Phi} \frac{\sigma_3}{2} \right)$$

$$Q \equiv Q_{em}$$

$$\Phi = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

$$Qa = 0, \quad Qd = 0$$

$$Qc = -c, \quad Qb = +1$$

$$\left[\Phi = \begin{pmatrix} \varphi_0 & \varphi^+ \\ \varphi^- & -\varphi_0^* \end{pmatrix} \right] \text{ (minimal)}$$

S.M. Higgs

$$\phi_G = \begin{pmatrix} \varphi^+ \\ \varphi_0 \end{pmatrix}$$

$$\left(\begin{pmatrix} \varphi_0 \\ \varphi^- \end{pmatrix} \right) = \phi_D$$

$$\left(\begin{array}{l} \tilde{\phi}_G \\ \phi_G \end{array} \right) = i\tau_2 \phi^* = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} \varphi^- \\ \varphi_0^* \end{pmatrix}$$

$$= \begin{pmatrix} \phi_0^* \\ -\varphi^- \end{pmatrix}$$

$$\tilde{\phi}_0 \equiv i\sigma_2 \phi_0^* = \begin{pmatrix} \varphi^+ \\ -\varphi_0^* \end{pmatrix}$$

$$\Rightarrow \bar{\Phi}^+ = \begin{pmatrix} \varphi_0^* & \varphi^+ \\ \varphi^- & -\varphi_0 \end{pmatrix}$$

$$\bar{\Phi} = \begin{pmatrix} \varphi_0 & \varphi^+ \\ \varphi^- & -\varphi_0^* \end{pmatrix} \leftarrow$$

$$T, \bar{\Phi}^+ \Phi = (|\varphi_0|^2 + \varphi^+ \varphi^-) 2$$

$$= 2 \phi^+ \phi$$



$$\phi^\dagger \phi = \text{SM invariant}$$

$$V_{SM} = f(\phi^\dagger \phi) = f(\tau_r \bar{\Phi}^\dagger \Phi)$$

$$\bar{\Phi} \rightarrow U_L \bar{\Phi} U_R^\dagger$$

$$\underbrace{\hspace{10em}}_{\text{SU}(2)_L \times \text{SU}(2)_R}$$

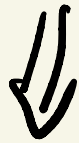
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?

$$\phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} = \begin{pmatrix} R_1 + iR_2 \\ R_3 + iR_4 \end{pmatrix}$$

$$i=1, \dots, 4 \therefore R_i \in \mathbb{R}$$

$$\phi^\dagger \phi = R_1^2 + R_2^2 + R_3^2 + R_4^2$$

$$SO(4)$$



$$SU(2) \times SU(2) = SO(4)$$

$$d = 1 + 1 = 2$$

$$r = 2$$

$$\# \text{ glu.} = 3 + 3 = 6$$

$$\frac{4 \cdot 3}{2} = 6$$

$$\mathcal{L}_Y = \bar{f}_L \gamma \Phi f_R + \text{h.c.}$$

↓ $\langle \Phi \rangle$

masses

$$\underline{\text{but:}} \quad \langle \bar{\Phi} \rangle = \begin{pmatrix} v & 0 \\ 0 & -v \end{pmatrix}$$

\Downarrow

$$\mathcal{L}_{\text{mass}} = (\bar{u}_L \quad \bar{d}_L) \gamma \begin{pmatrix} u & 0 \\ 0 & -u \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}^+ + \text{h.c.}$$

$$= (\bar{u}_L u_R - \bar{d}_L d_R) \gamma u + \text{h.c.}$$

\Downarrow

$$\boxed{M_u = -u_d}$$

BAD

\Downarrow

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

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

$$= \begin{pmatrix} \tilde{\phi}_2 & \phi_2 \\ & \end{pmatrix}_G$$

\Downarrow

$$\mathcal{L}_Y = \bar{P}_L \gamma \Phi P_R + h.c.$$

$$\langle \Phi \rangle = \begin{pmatrix} v_1 & 0 \\ 0 & -v_2 \end{pmatrix}$$

\Downarrow

$$\underline{M}_u = Y u^c; \quad M_d = -Y d^c \quad (1)$$

BAD $M_u \propto M_d$

SM

$$\underline{M}_u = Y u^c; \quad M_d = Y d^c$$

good

• From (1) \Rightarrow $M_u \propto M_d$

$$m_u \approx 3 \text{ MeV}$$

$$m_d \approx 5 \text{ MeV}$$

$$m_c \approx 1.5 \text{ GeV}$$

$$m_s \approx 100 \text{ MeV}$$

$$m_t \approx 175 \text{ GeV}$$

$$m_b \approx 5 \text{ GeV}$$

$$\textcircled{+} \quad V_{CKM} = U_u^\dagger U_d \neq \mathbb{1}!$$

$$M_q \rightarrow U_{Lq} M_q U_{Rq}^\dagger = m_q$$

but: if $M_u \propto M_d$

\Downarrow

$$U_u = U_d \Rightarrow V_{CKM} = \mathbb{1}$$

\textcircled{SM}

$\textcircled{Y_d \neq Y_u}$

$$\mathcal{L}_Y^e = \bar{e}_L Y_d \phi_G^R +$$

$$+ \bar{e}_L Y_u i \sigma_2 \underbrace{\phi_G^*}_{\tilde{\phi}_G} \nu_R + \text{h.c.}$$



because \therefore if $e \Rightarrow \bar{e}$

• if $\phi \Rightarrow \tilde{\phi}$



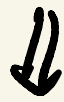
if $\Phi \Rightarrow \tilde{\Phi}$!

• $\phi \rightarrow \cup \phi, \tilde{\phi} \rightarrow \cup \tilde{\phi}$



SM

$$\tilde{\phi} = i\gamma_2 \phi^*$$



$$\tilde{\Phi} = \sigma_2 \Phi^* \sigma_2 \quad \therefore$$

$$\Phi \rightarrow U_L \Phi U_R \Rightarrow$$

$$\tilde{\Phi} \rightarrow U_L \tilde{\Phi} U_R$$

PROVE!



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

+ h.c.

$$LRSM: \quad Y, \tilde{Y}$$

$$SM: \quad Y_u, Y_d$$

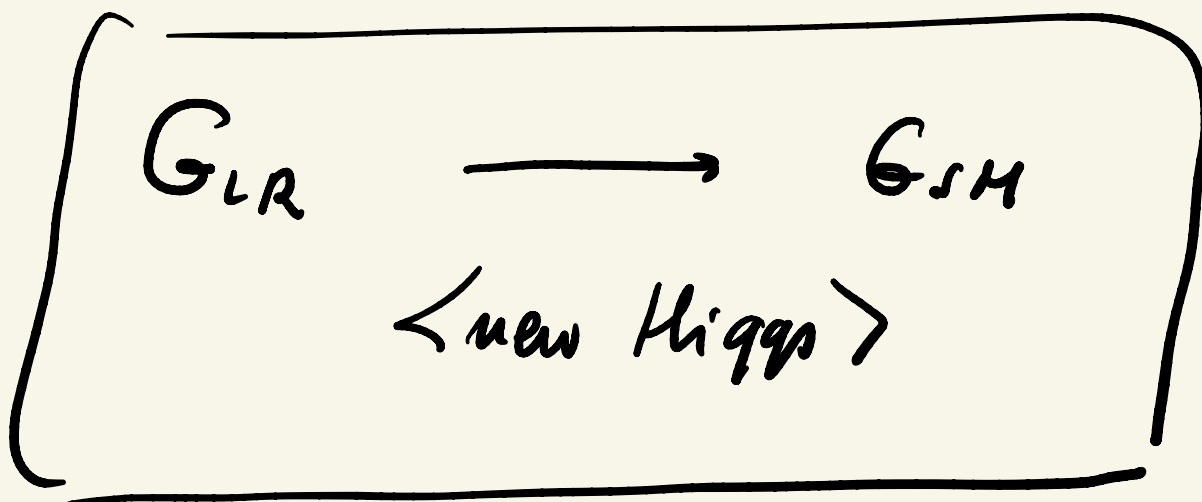
Summary!

- $\phi \subseteq \Phi \quad (\Phi \rightarrow U_L \Phi U_R^\dagger)$

some Yukawa predictions

- $Q = T_{3L} + T_{3R} + \frac{B-L}{2}$

but:



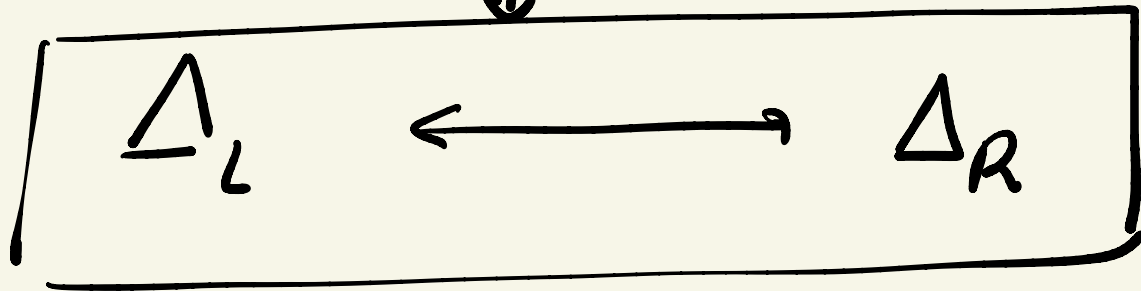
$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

<new Higgs> \longrightarrow $SU(2)_L \times U(1)_Y$

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

↓ (new Higgs)

$$U(1)_Y$$



∴

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

$$M_R \gg M_L (M_W)$$

at M_R ignore $\overline{\Phi}$

- $SU(2)_L \times U(1) \xrightarrow{Y} U(1)_{em}$
 $\langle \Phi \rangle$

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

$$\langle \phi_i \rangle = v_i$$



$$M_{W_L}^2 = \frac{g^2}{4} (v_1^2 + v_2^2)$$

CP ?

$$V_{CKM} \in C \Rightarrow CP$$

//

$$U_L^\dagger U_{cd} \Leftarrow M \rightarrow \text{diag.}$$

↑

$$\frac{4}{f} = \left(\frac{y}{f} \right)^2$$

Source of $\frac{4}{f}$