Neutrino Physics

Lecture XI

2/6/2023

LMU

Summer 2023

LR theory: Higgs sector

LR symmetric Model = LRSM

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

- $q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \begin{pmatrix} u \\ d \end{pmatrix}_R = q_R$

  $\ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad \begin{pmatrix} \nu \\ e \end{pmatrix}_R = \ell_R$

- Higgs

$$\phi_{SM} \subseteq \Phi$$

$$\phi_{SM} \to U_L \phi_{SM} \qquad \boxed{\Phi \to U_L \Phi U_R^+}$$

bi-doublet

$$\mathcal{L}_Y = \bar{q}_L Y_q \Phi q_R + h.c.$$

$$+ \bar{l}_L Y_e \Phi l_R + \text{-}\|\text{-}$$

$q_L \to U_L q_L \qquad q_R \to U_R q_R$

$l_L \to \text{-}\|\text{-} \; l_L \qquad l_R \to U_R l_R$

$\Downarrow$

$$\Phi = \underbrace{(\tilde{\phi}_1, \ \phi_2)}_{\text{SM doublets}}$$

$$\phi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

$$\tilde{\phi} \equiv i\sigma_2 \, \phi^* \equiv \begin{pmatrix} \varphi_0^* \\ -\varphi^- \end{pmatrix}$$

$$(\phi, \tilde{\phi}) \longrightarrow U_L (\phi, \tilde{\phi})$$

$$\Updownarrow$$

$$\Phi = \begin{pmatrix} \phi_1^{0*} & \phi_2^+ \\ -\phi_1^- & \phi_2^0 \end{pmatrix}$$

$$\mathcal{L}_Y = \begin{pmatrix} \bar{u}_L & \bar{d}_L \end{pmatrix} \begin{pmatrix} \phi_1^{0*} & \phi_2^{+} \\ -\phi_1^{-} & \phi_2^{0} \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$= \bar{u}_L \phi_1^{0*} u_R + \bar{u}_L \phi_2^{+} d_R +$$

$$- \bar{d}_L \phi_1^{-} u_R + \bar{d}_L \phi_2^{0} d_R$$

$\boxed{\text{Is this all ?}}$

Reminder SM

$$\mathcal{L}_Y^{SM} = \bar{q}_L Y_d \phi d_R + \bar{q}_L Y_u \tilde{\phi} u_R + h.c.$$

$\Uparrow$

if $\exists\ \phi \Longrightarrow \exists\ \tilde{\phi} \propto \phi^*$

LR

$$\boxed{\begin{aligned} \text{if } \exists\ \Phi \Rightarrow \tilde{\Phi} &= i\sigma_2\, \Phi^* (-i\sigma_2) \\ &= \sigma_2\, \Phi^*\, \sigma_2 \\ &\propto \Phi^* \end{aligned}}$$

$\Downarrow$ important

$$\boxed{\begin{aligned}\mathcal{L}_Y^{(LR)} &= \bar{q}_L \left(Y_q \Phi + \tilde{Y}_q \tilde{\Phi} \right) q_R \\ &+ \bar{l}_L \left(Y_l \Phi + \tilde{Y}_l \tilde{\Phi} \right) l_R + h.c.\end{aligned}}$$

$\updownarrow$ enology with SM

$$Y_q, \tilde{Y}_q \longleftrightarrow Y_u, Y_d$$

$$\boxed{\text{LRSM = equally predictive as SM}}$$

$$\boxed{\begin{array}{l} G_{LR} \longrightarrow G_{SM} \longrightarrow U(1)_{em} \\ M_R = \langle \text{new Higgs} \rangle \qquad \langle \Phi \rangle \cong M_W \\ \quad = M_{new} \end{array}}$$

SM:

$$M_W^2 = \left(\frac{g}{2}\right)^2 \langle\phi\rangle^2$$

$$M_Z^2 = \frac{g^2+g'^2}{4} \langle\phi\rangle^2 = \frac{M_W^2}{\cos^2\theta_W}$$

LR: $\phi_1 \quad \phi_2 \qquad (i = 1,2)$

$$\mathcal{L}_\Phi = \frac{1}{2}(D_\mu \phi_i)^+ (D^\mu \phi)_i + \cdots$$

$$\Downarrow$$

$$M_W^2 = \frac{g^2}{4}\left[\langle\phi_1\rangle^2 + \langle\phi_2\rangle^2\right]$$

$$M_Z^2 = \frac{g^2+g'^2}{4}\left[\quad -\|- \quad\right] = \frac{M_W^2}{\cos^2\theta_W}$$

$$\boxed{\mu^2 = \lambda v^2}$$

<u>SM</u>

$$V = \frac{\lambda}{4}\left(\phi^\dagger\phi - v^2\right)^2$$

$$= -\frac{\mu^2}{2}\,\phi^\dagger\phi + \frac{\lambda}{4}\,|\phi^\dagger\phi|^2 + \text{const.}$$

<u>LR</u>

$$V = -\frac{\mu^2}{2}\,\mathrm{Tr}\,\Phi^\dagger\Phi + \cdots$$

$$/ \quad \Phi \to U_L\,\Phi\,U_R^\dagger$$

$$\Phi^\dagger \to U_R \Phi^\dagger U_L^\dagger$$

$$\Downarrow$$

$$\Phi^\dagger \Phi \to U_R \Phi^\dagger \Phi U_R^\dagger$$

$$= -\frac{\mu^2}{2} \left(\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2 \right) + \cdots$$

$$\Downarrow$$

$$\langle \phi_1^0 \rangle = v_1, \quad \langle \phi_2^0 \rangle = v_2$$

$$\boxed{v^2 = v_1^2 + v_2^2 = v_{SM}^2}$$

$$\Downarrow$$

$$\boxed{M_W^2 = \frac{g^2}{4} v^2 = M_Z^2 \cos^2\theta_W}$$

true for any # of

SM doublets (Higgs)

$$M_W = \frac{g}{2} v \qquad v = \sqrt{v_1^2 + v_2^2}$$

$$\Downarrow$$

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

heavy $= m_h \propto M_{new} = M_R$

light $= m_e \ll M_W$

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exp. (LHC)

$$\Downarrow$$

$$M_R \gg M_W = 80\,\text{GeV}$$

$$(M_R > 4\,\text{TeV})$$

New Higgs ?

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

$$\Big\downarrow \; \langle \text{new Higgs} \rangle$$

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

$$Q_{em} = T_{3L} + \frac{Y}{2}$$

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

$$\Downarrow$$

new Higgs =

$$\Delta_L \quad + \quad \Delta_R$$

$LR = P$ sym.

$\therefore$

$$\underbrace{\langle \Delta_L \rangle = 0\,, \quad \langle \Delta_R \rangle = M_R}_{\not{P} \text{ spont.}}$$

Pati, Salam '74
(LR?)

Mohapatra, Pati '74

$$(\Delta_L, \ \Delta_R \in R)$$

$$\Downarrow$$

$$V = -\frac{\mu^2}{2} \left(\Delta_L^2 + \Delta_R^2 \right)$$

$$+ \frac{\lambda}{4} \left(\Delta_L^4 + \Delta_R^4 \right)$$

$$+ \frac{\lambda'}{2} \Delta_L^2 \Delta_R^2$$

$$= -\frac{\mu^2}{2} \left(\Delta_L^2 + \Delta_R^2 \right) + \frac{\lambda}{4} \left(\Delta_L^2 + \Delta_R^2 \right)^2$$
$$+ \frac{\lambda' - \lambda}{2} \Delta_L^2 \Delta_R^2$$

- $\lambda' = \lambda$ (not physical) $\boxed{\mu^2 > 0}$

Hint: $\ominus \mu^2 \Rightarrow$ SSB

$\Downarrow$

$\underbrace{\Delta^2 \equiv \Delta_L^2 + \Delta_R^2}$ $\Rightarrow$ $\langle \Delta \rangle^2 = \mu^2/\lambda$

$\Uparrow$

not clear who gets a vev

- $\boxed{\underbrace{\lambda' - \lambda > 0}}$

$(\lambda' - \lambda)\, \Delta_L^2 \Delta_R^2 \geq 0$

$\Downarrow$

min $\rightarrow$ $\langle \Delta_L \rangle = 0$, $\langle \Delta_R \rangle \neq 0$

- $\underbrace{\lambda' - \lambda < 0}$

$(\lambda' - \lambda)\, \Delta_L^2 \Delta_R^2 \leq 0$

$\Downarrow$

$\langle \Delta_L \rangle \neq 0 \neq \langle \Delta_R \rangle$

$(\langle \Delta_L \rangle = \langle \Delta_R \rangle)$

- $$\left.\frac{\partial^2 V}{\partial \Delta_L^2}\right|_{\langle \Delta_L \rangle = 0} = -\mu^2 \leftarrow \text{maximum}$$

$$\Downarrow$$

$$\boxed{\begin{gathered}\langle \Delta_L \rangle = 0 \,, \langle \Delta_R \rangle = 0 \\ \text{is a maximum}\end{gathered}}$$

NOT physical

$$\Downarrow$$

$$\boxed{\lambda' - \lambda > 0}$$

we live here

$\Downarrow$ minimum of V

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

$\therefore$ $\cancel{P}$ spont.

$$\boxed{(\lambda' - \lambda)\langle \Delta_L^2 \rangle, \langle \Delta_R^2 \rangle = 0}$$

minimizes V

$\Updownarrow$

all $m^2 > 0 \Leftrightarrow$ minimum

at the $\langle \Delta_L \rangle = 0, \ \langle \Delta_R \rangle \neq 0$

$\boxed{\text{Prove}}$

<u>Reminder</u>

$$V_{SM} = \frac{\lambda}{4}\left(\phi^{+}\phi - v^{2}\right)^{2}$$

$\underbrace{\lambda > 0, \quad -}_{\text{we live here}}$

We established $\cancel{P}$:

$$0 = \langle \Delta_L \rangle \ , \quad \langle \Delta_R \rangle = \underline{M}_R$$

<u>but</u> Mohapatra, Senjanović '75

who are these guys?

doublets ?

triplets ?

- <u>original choice</u>

$$\underbrace{\Delta_L \longleftrightarrow \Delta_R}_{\underbrace{\text{doublets}}} \ , \quad B-L = 1$$

$\Uparrow$

$$\boxed{\underline{\text{no}} \text{ coupling to } f}$$

$$\cancel{\bar{f}_L \Delta_L f_R} \qquad \cancel{\bar{f}_L \Delta_R f_R}$$

$$\cancel{f_L \Delta_L f_L} \qquad - - - -$$

"s" $= \frac{1}{2}$ $\qquad \Downarrow$

"s" $= \frac{1}{2}, \frac{3}{2} \neq 0$

$\Downarrow$

only $\bar{\Phi} \longrightarrow f$

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

$$\Downarrow$$

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

<u>but:</u> $m_\nu \leq 10^{-9} m_t$!

why? How?

- However, ν_R could be Majorana???

SM

$$\underbrace{\nu_R^T\, C\, \nu_R}$$

$SU(2)_L$ inv. ; $U_Y(1)$ inv.

$$Q_{em} = T_{3L} + \frac{Y}{2}$$

$$\boxed{T_{3L}\, \nu_R = 0} \Rightarrow \boxed{Y \nu_R = 0}$$

$$\Uparrow$$

$$Q_{em}\, \nu_R = 0$$

$$\Downarrow$$

LR $\boxed{m_{\nu_R} \propto M_R}$

$$\Downarrow$$

SM at "low" $(E \ll M_R)$ E

Visible universe

stars $(u, d, e) \rightarrow 10^{80}$

photons $\rightarrow 10^{90}$

neutrinos $\rightarrow 10^{90}$

$\boxed{????}$

Why $n_B \ll n_\gamma$?

$\uparrow$

genesis $\begin{cases} \text{baryo} \\ \text{lepto} \end{cases}$

SM

$h \to \gamma\gamma$ discovey 4/7/2012

$h \to \gamma Z$

excess ? $\rightsquigarrow$ 3σ

discovey ! 5σ