Neutrino Physics Course

Lecture XXVIII

16/7/2021

Last lecture

LMU

Summer 2021

LR Theory · Last Words

Last ?

Theory ! $M_R \equiv M_{W_R} \gtrsim 2.5\ TeV$

'80s

$\boxed{\bullet \text{ gauge theory}}$

$\longrightarrow$ gauge int.

W_R^+, W_R^-, Z_R

$M_{Z_R} \simeq \sqrt{3}\, M_{W_R}$, $\theta_W \simeq 30^\circ$

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

$\Rightarrow M_{Z_R} \gtrsim 8$ TeV (theory)

Last (not least)

$\boxed{\text{Higgs sector}}$

$\Delta_L, \quad \Delta_R$: $\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$

$M_{W_R} = g v_R$

Φ = bi-doublet

$\Phi = (\tilde{\phi}_1 \;\; \phi_2)$

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

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

→ SM Higgs doublet, iff

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

$$\phi \equiv h$$

$$\phi' \equiv H$$

$$\Rightarrow \frac{1}{\cos 2\beta} H^0 \, \bar{d}_L V_L^+ m_u V_R d_R + h.c.$$

$$d_{L,R} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{L,R}$$

$$\Phi = \begin{pmatrix} v_1 & 0 \\ 0 & v_2 e^{-ia} \end{pmatrix}$$

$$\tan\beta \equiv v_2/v_1$$

$$\Rightarrow \boxed{m_H \gtrsim 10\ \text{TeV}}$$

$\boxed{\text{origin?}}$

$\boxed{\cdot \text{ explicit: } \tan\beta = 0}$

$$\Delta_R \rightarrow U_R \Delta_R U_R^\dagger$$

$$\Delta_L \longrightarrow U_L \Delta_L U_L^\dagger$$

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

$$\mathcal{L}_Y = \bar{q}_L^0 \left(y_1 \Phi + y_2 \tilde{\Phi} \right) q_R^0 + h.c. \quad (*)$$

$$q_{L,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{L,R}$$

$$q_{L,R} \to U_{L,R}\, q_{L,R}$$

Assume: $\langle \Phi \rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix}$

$$\langle \phi_2 \rangle = 0, \quad \langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

real by $U(1)_Y$

$$\Rightarrow \begin{array}{ll} M_u = y_1 v & (m_t) \\ M_d = y_2 v & (m_b) \end{array}$$

$$m_t \gg m_b \Rightarrow y_1 \gg y_2$$

$$\Rightarrow \begin{array}{ll} \phi_1 = h & (\text{SM Higgs}) \\ \phi_2 \equiv H & (\text{new} = \text{heavy, scalar doublet;} \neq \text{Higgs}) \end{array}$$

$$\Downarrow$$

$$M_u = U_{Lu}\, m_u\, U_{Ru}^{+} \qquad (M_u = Y_1 v)$$

$$M_d = U_{Ld}\, m_d\, U_{Rd}^{+} \qquad (M_d = Y_2 v)$$

$$\Downarrow$$

$$\Phi = (\tilde{\phi}_1 \;\; \phi_2)$$

$$\circledast$$

$$\mathcal{L}_y^d = \bar{d}_L^0 \left(Y_1 \phi_2^0 + Y_2 \phi_1^{0*} \right) d_R^0$$

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

$$\mathcal{L}_y^d = \bar{d}_L^0 \left(\frac{M_u}{v} \phi_2^0 + \frac{M_d}{v} \phi_1^{0*} \right) d_R^0$$

$$= \bar{d}_L V_{Ld}^{+} \frac{M_u}{v} H^0 V_{Rd} d_R \; +$$

$$+ \bar{d}_L V_{Ld}^{+} \frac{M_d}{v} V_{Rd} h^0 d_R$$

$$= h \, \bar{d}_L \frac{m_d}{v} d_R \quad (\leftarrow \quad SM) \; +$$

$$H^0 \bar{d}_L \underbrace{U_{Ld}^{+} U_{Lu}}_{V_L^{+}} \frac{m_u}{v} \underbrace{U_{Ru}^{+} U_{Rd}}_{V_R} d_R$$

$$\mathcal{L}_y^{(d)} = \mathcal{L}_y^{(d)}(SM) \; +$$

$$+ H^0 \, \bar{d}_L \, V_L^\dagger \frac{m_u}{v} V_R \, d_R + h.c.$$

$$\tan\beta = 0 \Rightarrow \cos\beta = 1$$

$$\Rightarrow \cos^2\beta = 1$$

$$\boxed{= g \, H^0 \, \bar{d}_L \, V_L^\dagger \left(\frac{m_u}{M_W}\right) V_L \, d_R + h.c.}$$

$$\langle \Phi \rangle \in \mathbb{R} \; + \; Y_{1,2} = Y_{1,2}^\dagger$$

$$\Rightarrow M_u = M_u^\dagger, \; M_d = M_d^\dagger$$

$$\Rightarrow \begin{array}{l} U_{Lu} = V_{Ru} \\ U_{Ld} = V_{Rd} \end{array} \rightarrow V_L = V_R$$

$$\mathcal{L}_H^{(d)}(\Delta S \neq 0) = H^0 g \frac{m_c}{M_W} \bar{d} s \sin\theta_c \cos\theta_c + h.c.$$

$$\Downarrow$$

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

Higgs potential

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

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

$$\Rightarrow \quad \Phi^\dagger \Phi \to U_R \Phi^\dagger \Phi U_R^\dagger \quad (*)$$

$$\Delta_R \to U_R \Delta_R U_R^\dagger \quad (*)$$

$$\Delta_R^\dagger \to U_R \Delta_R^\dagger U_R^\dagger \quad (*)$$

$$\Downarrow$$

$$V_H = \dots + \lambda \,\mathrm{Tr}\, \Delta_R^\dagger \Phi^\dagger \Phi \Delta_R + \dots$$

$$\to \lambda \,\mathrm{Tr}\, U_R \Delta_R^\dagger U_R^\dagger U_R \Phi^\dagger \Phi U_R^\dagger U_R \Delta_R U_R^\dagger$$

$$= \boxed{\lambda \,\mathrm{Tr}\, \Delta_R^\dagger \Phi^\dagger \Phi \Delta_R} \Leftarrow$$

(did not write: $\mathrm{Tr}\, \Delta_R^\dagger \Delta_R \left(\mathrm{Tr}\, \Phi^\dagger \Phi\right)$)

need to split h from H

(ϕ_1 tran ϕ_2)

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

$\hookrightarrow \lambda \, Tr \, \langle \Delta_R^+ \rangle \, \Phi^+ \Phi \, \langle \Delta_R \rangle$

$$= \lambda \, Tr \, v_R^2 \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} (\Phi^+ \Phi) \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$= \lambda \, Tr \, v_R^2 \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} (\Phi^+ \Phi)$$

$$= \lambda \, Tr \, v_R^2 \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} (\Phi^+ \Phi)$$

$$= \lambda \, v_R^2 (\Phi^+ \Phi)_{22}$$

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

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

$$\Downarrow$$

$$(\Phi^\dagger \Phi)_{22} = \phi_2^{-}\phi_2^{+} + |\phi_2^{0}|^2$$

$$\equiv \phi_2^\dagger \phi_2 \equiv H^\dagger H$$

$$\phi_2 \equiv \begin{pmatrix} \phi_2^{+} \\ \phi_2^{0} \end{pmatrix}$$

$$\Downarrow$$

λ term: $\boxed{\lambda v_R^2 H^+ H}$

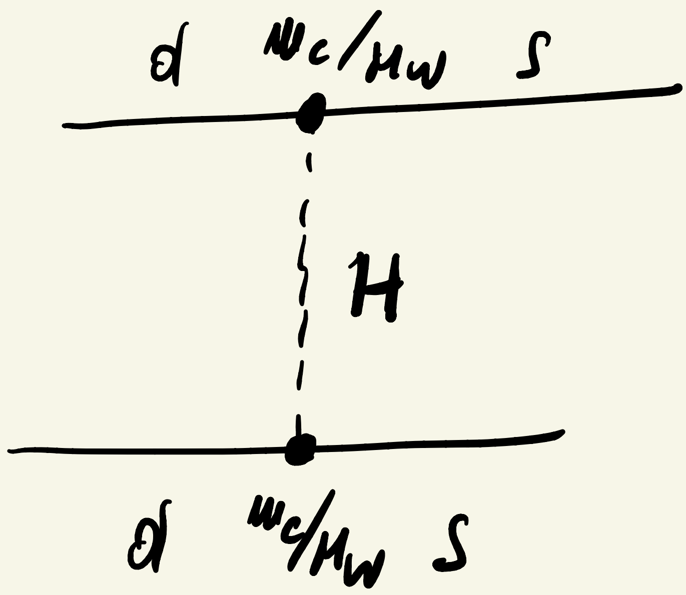
no such term for h

$$M_{W_R} = g v_R \gtrsim 5 \text{ TeV}$$

$$\boxed{v_R \gtrsim 10 \text{ TeV}}$$

$$M_d - M_d^+ \propto \varepsilon (M_u \cdots)$$

$$\boxed{\varepsilon = \tan\beta \sin\alpha} \boxed{\ll 1}$$



$\boxed{\Delta S = 2}$ $\boxed{\text{small}}$

$$\Rightarrow \boxed{\frac{\Delta m_K}{m_K} \simeq 10^{-14}} \quad (m_c \leq 2\,\text{GeV})$$

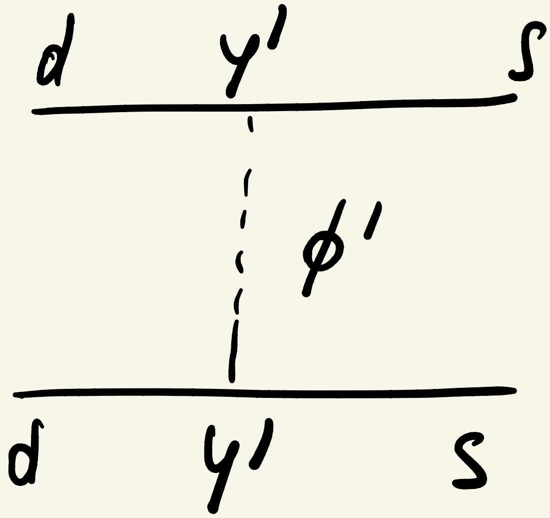
general

$\phi_1, \phi_2 \Rightarrow$

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

$\Rightarrow Y_{\phi'} =$ arbitrary

$\Downarrow$



$$\propto \left(\frac{y'^2}{m_{\phi'}^2} \right)$$

0 ?

$$\boxed{m_{\phi'} = \text{anything}}$$

bottom line

$$m_H \gtrsim 10\ \text{TeV} \Leftrightarrow y' = Y_H = \frac{m_c}{M_W}\theta_c$$

$$\Downarrow$$

$$LR = SM + O\left(M_W / M_R \right)$$

$\boxed{\text{Message}}$

LR $\Longleftrightarrow$ $\cancel{P}$ spont. broken

- $\exists\ \nu_R \Longrightarrow m_\nu \neq 0 \quad (N \propto \nu_R^*)$
- Higgs $\Longrightarrow$ seesaw mechanism

$$M_\nu = - M_D^T \frac{1}{M_N} M_D$$

- $P \longrightarrow M_D = f(M_N, M_\nu)$
- $N =$ Majorana

$$\Leftrightarrow \quad N \to e + W^+$$

$$\bar{e} + W^-$$

$$\therefore \quad \Gamma(e) = \Gamma(\bar{e})$$

$$\boxed{\text{Direct probe of Majoranity}}$$

- $0\nu2\beta \longleftrightarrow N$ at LHC

$\boxed{\text{CP violation vs beauty}}$

early '70s

$\boxed{\text{2 generations}}$

$\Downarrow$

CP conservation

$$V_L = O_c = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

$\boxed{\text{NO phase}}$

$\Downarrow$

(a)

3 gen. SM

(b)

LR

Mohapatra,
Pati
2 generations

$$V_L = \begin{pmatrix} \theta_1, \theta_2, \theta_3, \\ \delta \end{pmatrix}$$

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

$$\Phi \longrightarrow V_L \, \Phi \, V_R^{\dagger} \quad (\text{bi-doublet})$$

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

Tello thesis

$$\boxed{\varepsilon \simeq \tan\beta \sin\alpha}$$

$$\Rightarrow \quad M_\ell \neq M_\ell^{\dagger}$$

$$M_\ell - M_\ell^{\dagger} \propto \varepsilon .$$

$$\boxed{V_R \neq V_L}$$

$$V_L = O_\ell \Rightarrow$$

$$V_R = \begin{pmatrix} \cos\theta_R & -e^{i\delta}\sin\theta_R \\ e^{-i\delta}\sin\theta_R & \cos\theta_R \end{pmatrix}$$

$\boxed{\cancel{CP}} \Downarrow \boxed{\text{through } W_R}$

$$\boxed{\varepsilon_{\cancel{CP}} \simeq \left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sin\delta}$$

$\Uparrow$

CP conserving weak int. (WI)

$\propto G_F \; (\sim 1/M_{W_L}^2)$

CP violating weak int. (WI)

$\propto 1/M_{W_R}^2$

$$\varepsilon_{\not{CP}} = \frac{\text{CP violating WI}}{\text{CP conserving WI}}$$

$$\Downarrow$$

$$\varepsilon_{\not{CP}} \cong \left(\frac{M_L}{M_R}\right)^2 \sin\delta \sim 10^{-3}$$

$$\sin\delta \leq 1$$

$$\boxed{\Rightarrow M_R^2 \leq 10^3 M_L^2}$$

$$\Downarrow$$

$$\boxed{M_A \leq 2.5\ \text{TeV}}$$

ε_{CP} = small $\Leftrightarrow$

maximal P violation

~~Berlioz~~ Huxley

"Tragedy of science =

many beautiful theories killed

by ugly facts of nature."

Predictivity

Theory (well-defined structure)

$\downarrow$

vacuum (ground state)

$\downarrow$

compute physical processes