Neutrino Physics Course

Lecture VIII

19/5/2023

LMU

Spring 2023

Parity and Higgs-Weinberg mechanism in SM

- $G_{SM} = SU(2)_L \times U(1)$
- matter = fermions

$\rightarrow q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad u_R, d_R$

$\rightarrow l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \qquad e_R$

- Higgs rep.

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (Y=1)$$

$$\mathcal{M}_0 = \{ \Phi_0 \,\therefore\, V = V_{min} \}$$

$$= \left\{ \Phi_0 = \begin{pmatrix} 0 \\ v \end{pmatrix} \right\} \therefore$$

$$\boxed{\begin{aligned} Q_{em}\, \Phi_0 &= \Phi_0 \\ Q_{em} &= T_3 + \frac{Y}{2} \end{aligned}}$$

$$\Downarrow$$

$$M_A = 0 \quad (\text{photon})$$

$$(\text{exp. } M_A \leq 10^{-15}\, eV)$$

$$\boxed{M_W = \frac{g}{2} v}, \quad \boxed{M_Z \cos\theta_W = M_W}$$

physical renorm. dependent

- $\Phi_{un} = \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

(Goldstone) Higgs - Weinberg boson

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

def. value of λ

- fermion mass

$$Y: \quad -1/3 \quad 1 \quad -2/3$$

$$\mathcal{L}_Y^{(d)} = \bar{q}_L Y_d \Phi \, d_R + h.c.$$

$$\Big\downarrow SU(2)$$

$$\bar{q}_L U^+ U \Phi d_R = inv.$$

(down)

$$\boxed{\mathcal{L}_Y^{(d)} = (\bar{u}_L \; \bar{d}_L) \, Y_d \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + h.c.}$$

$$= \bar{d}_L d_R Y_d (v+h) + h.c.$$

$$= Y_d v \, \bar{d} d \left(1 + \frac{h}{v}\right)$$

$$\Downarrow$$

$$\boxed{m_d = Y_d v}$$

Higgs coupling $y_d h \bar{d} d$

$$\boxed{y_d = \frac{m_d}{v} = \frac{g}{2}\frac{m_d}{M_W}}$$

$$\Gamma(h \to d\bar{d}) = \frac{y_d^2}{8\pi} m_h$$

$$(m_h \gg m_d)$$

125 GeV 5 MeV

$\Downarrow$

$$\boxed{\Gamma(h \to d\bar{d}) = \left(\frac{g}{2}\,\frac{m_d}{M_W}\right)^2 m_h}$$

1st $\quad u, d$

2nd $\quad c, s$

3rd $\quad \boxed{t, b}$ ← Higgs mirror

$\boxed{W, Z}$

• (up)

$\qquad -1/3 \qquad -1 \quad 4/3$

$$\mathcal{L}_Y^{(u)} = \bar{Q}_L\, \epsilon\, Y_u\, \Phi^* u_R$$

$\quad\uparrow \qquad\qquad \uparrow$

anti-doublet

$$\epsilon_{12} = -\varepsilon_{21} = 1$$

$$\varepsilon_{11} = \varepsilon_{22} = 0$$

$$= \overline{q_L}\, i\sigma_2\, y_u\, \Phi^* u_R$$

$$\to \overline{q_L}\, U^+ i\sigma_2\, U^* y_u\, \Phi^* u_R$$

$$= \overline{q_L}\, U^+ U\, i\sigma_2\, y_u\, \Phi^* u_R$$

$$U = e^{i\,\sigma_i/2\,\theta_i}$$

$$\Downarrow$$

$$U^* = e^{-i\,\sigma_i^*/2\,\theta_i}$$

$$= e^{-i\left(\theta_1 \frac{\sigma_1}{2} - \frac{\sigma_2}{2}\theta_2 + \frac{\sigma_3}{2}\theta_3\right)}$$

$$i\sigma_2 \, U^* = e^{i\left(\theta_1 \frac{\sigma_1}{2} + \frac{\sigma_2}{2}\theta_2 + \frac{\sigma_3}{2}\theta_3\right)} i\sigma_2$$

$$\bar{q}_L \, U^\dagger i\sigma_2 \, U^* \, \Phi^* u_R =$$

$$= \bar{q}_L \, i\sigma_2 \, U^\dagger \, U \, \Phi^* u_R = \text{inv.}$$

$$\Downarrow$$

$$\mathcal{L}_Y^{(u)} = \left(\bar{u}_L \;\; \bar{d}_L\right) y_u \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ v+h \end{pmatrix} u_R$$

$$+ h.c.$$

$$= \left(\bar{u}_L u_R + \bar{u}_R u_L\right) y_u \left(v + h\right)$$

$$\Downarrow$$

$$\boxed{m_\mu = y_\mu v}$$

$$\boxed{y_\mu = \frac{g}{2}\frac{m_\mu}{M_W}}$$

$$\Downarrow$$

$$\boxed{\Gamma(h \to \bar{\mu}\mu) = \frac{g}{2}\left(\frac{m_\mu}{M_W}\right)^2 m_h}$$

$$+1 \quad +1 \quad -2 = 0$$

- $\mathcal{L}_Y^{(e)} = \overline{l_L}\, y_e\, \Phi\, e_R + h.c.$

$$\Downarrow$$

$$\boxed{m_e = y_e v}$$

$$\Downarrow$$

$$\boxed{\begin{gathered} m_f = y_f v \\ y_f = \frac{g}{2}\frac{m_f}{M_W} \end{gathered}}$$

$$\boxed{\text{Dynamical theory of the origin of mass}}$$

- neutrino

Is it massive?

(a) $\not\exists\, \nu_R \Rightarrow m_D^{(\nu)} = 0$

(b) $\nu_L^T C \nu_L \quad (m_\nu^{(M)})$?

allowed ?

$T_3 : \frac{1}{2} + \frac{1}{2} = 1 \leftarrow$ triplet

· compare

not U(1) inv.

$e_L^T C \nu_L \Leftarrow l_L^T i\sigma_2 C l_L$

$T_3 : -\frac{1}{2} + \frac{1}{2} = 0$

SU(2) inv.

$\Downarrow$ SM

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

only incompleteness of SM

Experiment.

gauge $\quad g, g'$

$\downarrow$

g, e

$$\boxed{e = g \sin\theta_W}$$

$\uparrow$

$$\frac{g}{\cos\theta_W} Z_\mu \, j^\mu_Z$$

$$j^\mu_Z = \bar{f} \gamma^\mu \left[T_3 - Q \sin^2\theta_W \right]$$

$$\frac{e}{\sin\theta_W \cos\theta_W}$$

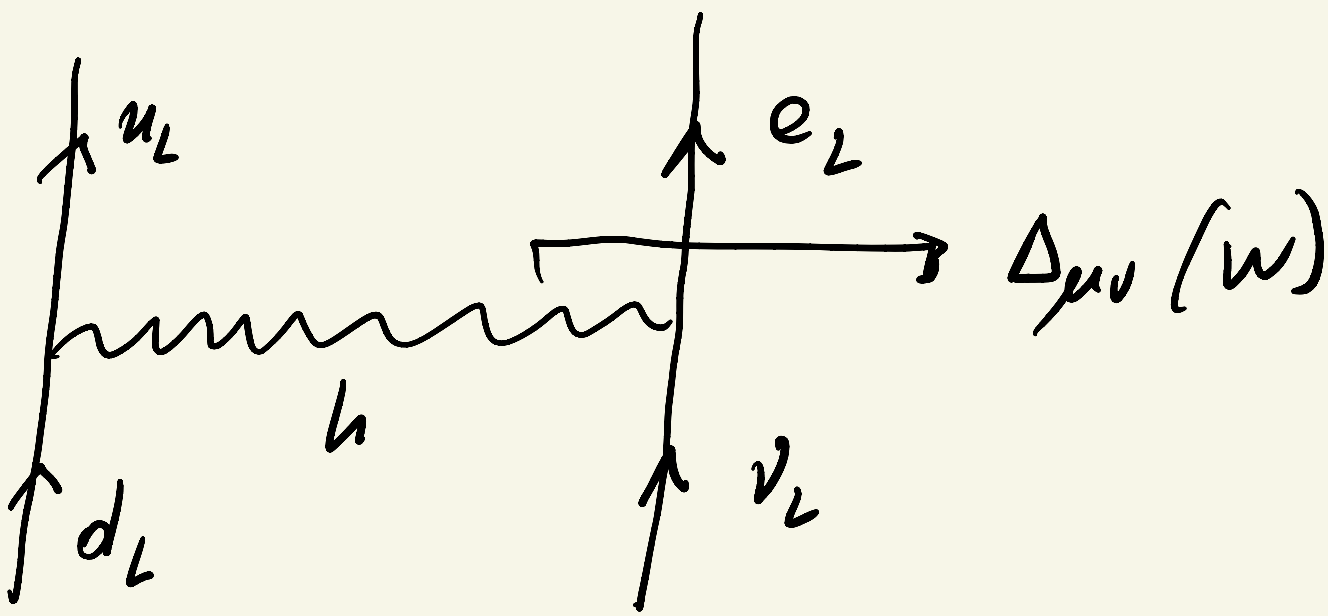
θ_W exp

central parameter in SM

$$\boxed{\theta_W \simeq 30^\circ}$$

$$\frac{g}{\sqrt{2}} W^{+}_{\mu} j^{\mu}_{W} + h.c.$$

$$j^{\mu}_{W} = \bar{u}_L \gamma^{\mu} d_L + \bar{\nu}_L \gamma^{\mu} e_L$$



$$d \rightarrow u + e + \bar{\nu}$$

$$H_{eff} = \left(\frac{g}{\sqrt{2}}\right)^2 j^{\mu}_{W} \; \Delta_{\mu\nu}(W) \, \bar{j}^{\nu}_{W}$$

$$= \left(\frac{g}{\sqrt{2}}\right)^2 j^\mu_W \, \frac{g_{\mu\nu} \cancel{- \frac{k_\mu k_\nu}{M_W^2}}}{k^2 - M_W^2} \, \bar{j}^\nu_W$$

$$\Nearrow$$

limit: $\quad k \ll M_W$

$$= \frac{g^2}{2} \frac{1}{M_W^2} \, j^\mu_W \, \bar{j}_\mu^W$$

$$= \frac{4 G_F}{\sqrt{2}} \quad -\!\!\shortparallel\!\!- \quad (\text{Fermi})$$

$$\Downarrow$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8 M_W^2} = \frac{e^2}{8 (M_W \sin\theta_W)^2} \qquad e^2 \simeq 1/10$$

$10^{-5}\,\mathrm{GeV}^{-2}$

$$\boxed{M_W \sin\theta_W \simeq 40\,\mathrm{GeV}}$$

$\Downarrow$ exp (θ_W)

$$\boxed{M_W = 80\,\mathrm{GeV}}$$

$\Downarrow$

- $m_f \Rightarrow$ check the Higgs origin

$\Uparrow$

$$y_f = \frac{g}{2}\,\frac{m_f}{M_W}$$

- M_W, M_Z $\Rightarrow$

$$h \to W^+ W^{-*}$$
$$\to Z Z^*$$

$$\boxed{\begin{array}{c}\text{Summary:}\\ W, Z, t, b, \tau \\ \uparrow \\ \text{Higgs}\end{array}}$$

$c, \mu \leftarrow$ getting there

- <u>fermions</u>

$$y_f = g/2 \, \frac{m_f}{m_W}$$

$$\Downarrow$$

$$\Gamma(h \to f\bar{f}) = \left(\frac{g}{2} \frac{m_f}{m_W}\right)^2 m_h$$

probe! g

+

small deviations

BSM

QED

$(g_\mu - 2) = \cdot\cdot(\cdot 10^{-10})$

magnetic moment of muon

$\boxed{\text{Experiment} = \text{machines}}$

- W, Z in 1983 @ CERN

hadron	lepton
$p + p \, (q + \bar{q})$	$e + \bar{e}$
$p + \bar{p} \, (q + \bar{q})$	

$$p = (u\,u\,d) + \underset{(q\,\bar{q})}{\text{clouds}}$$

$$r_c = \frac{\hbar}{m_p} \leftarrow \text{compton wave-length}$$

$$\boxed{d_p \sim r_c\,(p)}$$

Given: $m_G \simeq 80$ kg

$$r_c(G) = \frac{1}{m_G} \qquad (\hbar = 1)$$

$$\ll r_G$$

?

machine = fixed E

LHC : $E \simeq 14$ TeV $\quad l = 27$ km

(p+p) $\quad E_p \simeq 7$ TeV

$$E_e = \text{free} \; (\leq E_p)$$

$\uparrow$

$p + p(\bar{p})$ = discovery machines

$\boxed{\text{hadron}}$

$\boxed{\text{lepton}}$ $e + \bar{e}$ (LEP)

$\boxed{E \simeq 200 \text{ GeV}}$ $l = 27$ km

$\boxed{\text{high precision test}}$

- 1983 W, Z (rough)

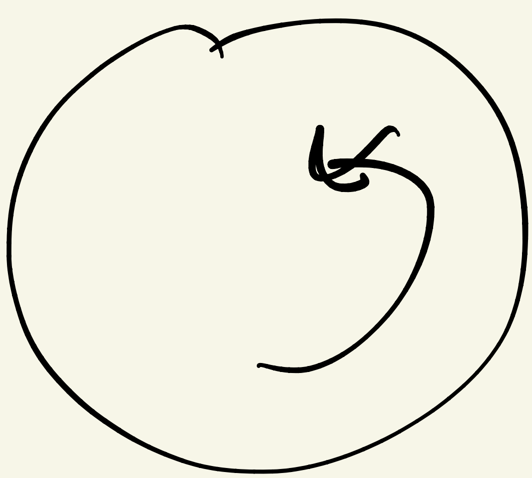
$p + \bar{p}$ $(E \simeq 100 \text{ GeV})$

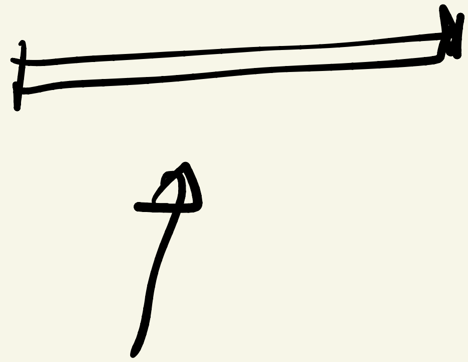
LEP (SM test)

$\Gamma_W = 2$ GeV $(\simeq \Gamma_Z)$

$M_W \simeq 80$ GeV $\quad M_Z = 90$ GeV

$\lesssim (1\%)$





length

radiation energy loss

$$\propto \frac{1}{m^4}$$

$\boxed{\text{LEP}}$ 205 GeV $= E$

$$e + \bar{e} \longrightarrow Z + h \quad (E \gtrsim 215\,\text{GeV})$$

Z: 90 GeV, h: 125 GeV

$Y_e\, \bar{e} e h \quad \mathcal{J}$ — h directly

$\downarrow$ problem

$$y_e = \frac{g}{2}\frac{m_e}{m_W} \simeq \left(\frac{\text{MeV}}{100\,\text{GeV}}\right)$$

$$\sigma \propto y_e^2 \propto 10^{-10} \;!!!$$

$$(\simeq 0)$$