


Neutrino Physics Course

Lecture XII

21/5/2021

LMU

Spring 2021



B end L in SM end

Beyond

Summary of SM

$$m_f = g_f v \Leftrightarrow g_f h \bar{f} f$$

$$\Rightarrow g_f = \frac{g}{2} \frac{m_f}{M_W}$$

\Downarrow

$$\Gamma(h \rightarrow f \bar{f}) \propto m_f^2$$

$SM \Rightarrow m_\nu = 0$

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

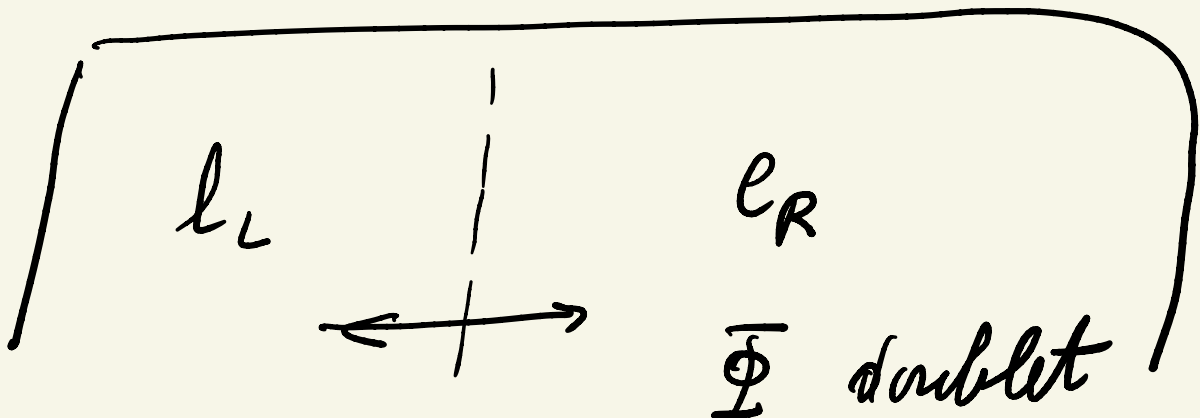
$$\Rightarrow \textcircled{1} \cancel{\bar{V}_L \nu_R + \bar{V}_R \nu_L} \Leftrightarrow \bar{A} \nu_R$$

$$\textcircled{2} \nu_L^T C \nu_L \mu_H \quad ?$$

\uparrow Lorentz invariant

not allowed! ~~SO(2)_L~~, ~~U(1)~~

$$\boxed{\mathcal{I} \text{ maximal}} \Leftrightarrow \bar{A} \nu_R$$



Imaginary P symmetry

$$W_\mu^+ \left[\bar{\nu}_L \gamma^\mu e_L + \bar{\nu}_R \gamma^\mu e_R \right]$$

$$W_\mu^+ \left[\bar{\nu}_L \gamma^\mu d_L + \bar{\nu}_R \gamma^\mu e_R \right]$$

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

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

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

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

$$\nu_L \leftrightarrow \nu_R$$

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

$$SU(2)_{LR} : \begin{array}{l} \bar{q}_L M_e q_R = m\nu_e \\ \bar{l}_L M_e l_R = m\nu_e \end{array}$$

$$\Rightarrow \begin{array}{l} m_u = m_d \\ m_\nu = m_e \end{array}$$

What Higgs to use?

A mess!

$$\text{if: } \nu_L^T C \nu_L \Rightarrow 0\nu 2\nu$$

Neutrinoless double beta

$$\Delta L = 2$$

Baryon and lepton numbers

$$W [\bar{e} e + \bar{l} l] \Rightarrow \Delta B = 0 = \Delta L$$

$$Z, A \quad - \parallel - \quad \quad \quad - \parallel -$$

$$h \quad \bar{f} f \quad \quad \quad - - H -$$



$$\left(M_A = 0 \Leftrightarrow \frac{dQ}{dt} = 0 \right)$$

B and L are conserved

$$\Delta B \neq 0$$

p decay

$$\tau_p \approx 10^{34} \text{ yr}$$

$$(T_{\mu} \approx 10^{-6} \text{ sec})$$

$$\Delta L \neq 0$$

OUZP

$$T_{\text{OZP}} \geq 10^{25} \text{ yr}$$



1979 Weinberg

Wilczek, Zee

B S M $\Delta B \neq 0 \neq \Delta L$

(Beyond Standard Model)

→ unreachable

Feyn

WI



effective theory



$$d = 6$$

lowest dimension

BS4

$$\Lambda \gg M_W$$

$$H_{\text{eff}} = H_{\text{eff}}(\text{leading}) + O(M_W/\Lambda)$$

↓

smallest dimension

$$\Delta B \neq 0$$

proton decay

||

3 quarks

$$\Rightarrow N_q \geq 3$$

$$H_{\text{eff}}^{\Delta B} = O^{\Delta B} = \underbrace{q q q}_{(s+0)} \downarrow \text{add } (???)$$

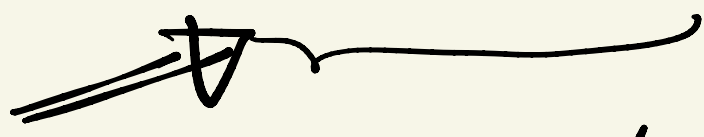
$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

u_R, d_R

↓
1 fermion!!

NOT
Lorentz
invariant

$u_R \quad d_R \quad d_R$



$SU(2)_L$ Huplet

$U(1)$ - 1 -

quark or lepton?



possible:

$u_R \quad u_R \quad d_R$

$u_R \quad u_R \quad u_R$

Lepton!!!



Color

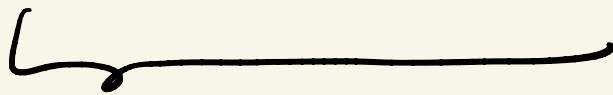
~~??~~

?? \rightarrow color

$$\epsilon_{\alpha\beta\gamma} \psi^\alpha \psi^\beta \psi^\gamma = \text{color invariant}$$



$$\psi \psi \psi \ell$$



Color invariant

Lorentz invariant

Charge invariant

$SU(2)$ -11-

$d=6$ 4 fermion

$$J_{\text{eff}}^{\Delta B \neq 0} = \frac{1}{\Lambda_B^2} \psi \psi \psi \ell$$



$$\Rightarrow p \rightarrow e^+ + \pi^0 (\gamma, h^0)$$

$$\tau_p \approx 10^{34} \text{ yr}$$

$$\mathcal{L}_{\text{eff}}^{\Delta B \neq 0} = \frac{1}{M_W^2} (\bar{e} \nu_e) (\bar{\nu}_\mu \mu)$$

$$\mu \rightarrow e + \bar{\nu}_e + \nu_\mu$$

$$m_\mu = 100 \text{ MeV}$$

$$m_e = 0.5 \text{ MeV}$$

$$\tau_\mu \approx 10^{-6} \text{ sec}$$

large penguin approach:

$$\Gamma_\mu \approx \frac{1}{M_W^4} m_\mu^5$$

$$\Gamma_p \approx \frac{1}{\Lambda_B^4} m_p^5$$

$$\left(\tau = \frac{1}{\Gamma} \right)$$



$$\tau_p / \tau_\mu \approx \left(\frac{\Lambda_B}{M_W} \right)^4 \left(\frac{m_\mu}{m_p} \right)^5 = 10^{-5} \left(\frac{\Lambda_B}{M_W} \right)^4$$

$$\tau_p = 10^{-11} \text{ sec} \left(\frac{\Lambda_B}{M_W} \right)^4 \approx 10^{41} \text{ sec}$$

$$\left(\Lambda_B / M_W \right)^4 \approx 10^{52}$$

$$\Rightarrow \Lambda_B \approx 10^{15} \text{ GeV}$$

$$\bullet \kappa_{\text{eff}}^{\Delta B \neq 0} \equiv \frac{1}{\Lambda_B^2} \mathcal{O}^{\Delta B \neq 0} = \frac{1}{\Lambda_B^2} \underbrace{99 \text{ e l}}$$

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

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

SU(2) inv. (i) $q_L^T C i \sigma_2 q_L \propto u_L^T C d_L$

\uparrow \uparrow
 Lorentz Hylet \quad SU(2) Hylet

(ii) $q_L^T C i \sigma_2 l_L \propto (u_L^T C e_L - d_L^T C \nu_L)$

(iii) $u_R^T C u_R, u_R^T C d_R, d_R^T C d_R$
 $u_R^T C e_R, d_R^T C e_R$

\Downarrow

$$O_1 = (q_L^{\alpha T} C i \sigma_2 q_L^{\beta}) (q_L^{\gamma T} C i \sigma_2 l_L^{\delta}) \epsilon_{\alpha\beta\gamma\delta}$$

$$Y: \quad \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + -1 = 0$$

$$= (u_L^T C d_L) (u_L^T C e_L - d_L^T C \nu_L)$$

↓

u u d e

⏟

neutral

↓

(u d d v)

⏟

neutral

$$O_2 = (u_L^T c d_L) (u_R^T c e_R)$$

$$O_3 = (u_L^T c e_L - d_L^T c v_L) \frac{u_R^T c u_R}{\boxed{u_R^T c d_R}} - \cancel{d_R^T c d_R}$$

(e e)

⏟

$Q_{ew} = -1/3$

$$O_4 = (u_R^T c u_R) (d_R^T c e_R)$$

(symbolic) $\boxed{f f \equiv f^T c f}$

(iσ₂)

$$O_1 = (\bar{q}_L q_L) (\bar{q}_L l_L) \leftarrow q \bar{q} q l$$

$$O_2 = (\bar{q}_L q_L) (\bar{u}_R e_R) \leftarrow q \bar{q} q l$$

$$O_3 = (\bar{q}_L l_L) (\bar{u}_R d_R) \leftarrow q \bar{q} q l$$

$$O_4 = (\bar{u}_R u_R) (\bar{d}_R e_R) \leftarrow \frac{(\bar{u}d)(\bar{u}e)?}{\boxed{\text{not new}}} \\ (\bar{q}q q l)$$

$$\left[(\bar{l})_R \equiv (l^c)_R \equiv C \bar{l}_L^T \leftarrow \text{doublet} \right]$$

$$\text{all } O \sim \underbrace{q \bar{q} q l}$$

$$\frac{q \bar{q} q \bar{l}}{\quad}$$

$$\Delta B = 1 = \Delta L \Rightarrow \boxed{\Delta(B-L) = 0}$$

$$\Rightarrow \boxed{p \rightarrow e^+ + \text{boson}} \\ \not\rightarrow e + \text{boson}$$

exp. $p \rightarrow e + \pi^+ + \pi^+$

↓

$\Lambda_B \rightarrow M_W$

$$\Delta L \neq 0 \quad (\Delta B \neq 0)$$

$$H_{\text{eff}}^{\Delta L \neq 0} = \sum_L C_L \bar{l}_L \gamma_5 l_L (\text{boson})$$

↑ ↘ |

lorentz

SU(2)

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

$$\left[(d=5 \quad \Delta L \neq 0) \right]$$

$$H_{\text{eff}}^{\Delta L \neq 0} = \underbrace{\left(l_L^T C i \sigma_2 l_L \right)}_{\text{lorentz}} \underbrace{\left(\bar{\Phi}^T i \sigma_2 \Phi \right)}_{\text{SU(2)}} \left(\frac{1}{\Delta_L} \right)$$

$$y = -2$$

$$Q = T_3 + \frac{Y}{2} \Rightarrow 0 = \frac{1}{2} - \frac{1}{2} = 0$$

but: $\bar{\Phi}^T i \sigma_2 \Phi = 0 = \phi^u \phi^d - \phi^d \phi^u = 0$

$$l^T C i \sigma_2 l = 0$$

$$\left. \begin{array}{l} q \\ l \end{array} \quad \begin{array}{l} q q \\ q l \end{array} \right\} \text{pairs}$$

$$\begin{array}{c}
 l \\
 \bar{\Phi}
 \end{array}
 \quad
 \begin{array}{c}
 ll, \bar{\Phi}\bar{\Phi} \\
 \textcircled{ll\bar{\Phi}} \\
 \Downarrow
 \end{array}$$

$$\mathcal{H}_{\text{eff}}^{\Delta L \neq 0} = \frac{1}{\Lambda^2} \underbrace{(l_L^\top i\sigma_2 \bar{\Phi})}_{\neq 0} G \underbrace{(\bar{\Phi}^\top i\sigma_2 l)}_{\neq 0}$$

+ (two other ways) ???

\Rightarrow all equivalent!

$$\bullet \quad l = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \bar{\Phi}_{\text{un}} = \begin{pmatrix} 0 \\ \nu + h \end{pmatrix}$$



$$\Rightarrow \mathcal{L}_{\text{eff}} = \frac{1}{\Lambda_L} (\nu_L^T C \nu_L) (\nu + h)^2$$

$$= \frac{1}{\Lambda_L} (\nu_L^T C \nu_L) (\nu^2 + 2\nu h + h^2)$$

\uparrow \uparrow
 (a) (b)

$$(a) \Rightarrow m_\nu^M = \frac{\nu^2}{\Lambda_L} = \nu \left(\frac{\nu}{\Lambda_L} \right)$$

$$m_e = y_e \nu$$

$$\Rightarrow \Lambda_L \gg \nu$$

$$\begin{aligned} \nu &\approx 100 \text{ GeV} \\ m_\nu &\leq \frac{1}{10} \text{ eV} \end{aligned} \Rightarrow \Lambda_L \approx \frac{10^4}{10^{-10}} \text{ GeV}$$

$$\Lambda_L \approx 10^{14} \text{ GeV}$$

Probe of neutrino mass
= hopeless

$$(5) \quad \frac{v}{\Lambda_L} \nu_L^T C \nu_L h \equiv g_\nu h \nu_L^T C \nu_L$$

$$g_\nu = \frac{v}{\Lambda_L} \approx \frac{100}{10^{14}} \approx 10^{-12}$$

$$B(h \rightarrow \nu\nu) \approx 10^{-24} \quad (\text{tragic})$$

⇓ summarize

• $d=6$ $\Delta B \neq 0 \Leftrightarrow p$ decay

• $d=5$ $\Delta L \neq 0 \Leftrightarrow$ neutrino mass parameter

• $O_{V2\beta}$ $\Delta L=2$ process
($d+d \rightarrow u+u+e+e$)
 $u+u \rightarrow p+p+e+e$

6 fermion

$$\mathcal{H}_{\text{eff}}^{O_{V2\beta}} = \frac{1}{\Lambda_{O_{V2\beta}}^5} \underbrace{\bar{u}\bar{u}\bar{e}\bar{e}dd}_{d=9}$$

$$\Gamma_{O_{V2\beta}} \approx 10^{25} \text{ yr}^{-1}$$

$$\Lambda_{O_{V2\beta}} \approx 3 \text{ TeV}$$

