Neutrino Physics Course

Lecture $\overline{\underline{XIII}}$

25/5/2021

LMU

Spring 2021

Effective theories $\longrightarrow$

UV completion (and back)

$$\boxed{B,\ L \text{ in SM} \to \text{BSM}}$$

$$\frac{G_F}{\sqrt{2}} J_\mu^w J_w^\mu \longleftarrow \frac{1}{q^2} J_\mu^{em} J^\mu_{em}$$

$$E \ll \Lambda_F \qquad G_F = \Lambda_F^{-2}$$

$\Rightarrow$ messenger = vector boson

- Effective theory of $\cancel{B}$

$$\frac{1}{\Lambda_B^2} (\underbrace{qqq}\, l) \leftarrow \text{lepton and NOT } \bar{e}$$

$$\boxed{B-L}$$

$\uparrow$ color singlet

$\Rightarrow \quad p \to e^c + \pi^0 \quad \not\to e + \pi^+ + \pi^+$

$n \to e^c + \pi^- \quad \not\to e + \pi^+$

$\Lambda_B \gg M_W \leftarrow$ only assumption

more: $\quad qqql \to qqsl$

~~NOT $q\text{-}q\bar{s}l$~~

$\Rightarrow \bar{s}$ is coming out of nucleon decay

$\cancel{n \to l + K^+}$ $(\cancel{B\text{-}L})$

$\to \ell^c + K^-$?

$K^- = \bar{u}\, s \Rightarrow \nu$ is out

$-2/3 \;\; -1/3 \;\; (-1)$

$\Downarrow$

$\boxed{n \not\to \text{kaon}}$ $\boxed{\text{two body}}$

exp'

$\boxed{\Lambda_B \lesssim M_W}$

$\boxed{\text{GUT}}$ $\boxed{1974,\ 1975}$

$\Downarrow$

new gauge boson: X

mediates proton decay

$d=6$ analysis 1979 Weinberg

$O_1 = (q\,l)\,(q\,q)$ ←

$O_2 = (q\,l)\,(u_R\,d_R)$

$O_3 = (q\,q)\,(u_R\,e_R)$

$O_4 = (u_R\,d_R)\,(u_R\,e_R)$ ← induced by scalar ✓

⇑

$(\psi_1\,\psi_2) \equiv \psi_1^T c\,\psi_2$

Lorentz

$$(D_1^F D_2^F) \equiv D_1^T i\sigma_2 C D_2$$

$$O_1 = \underbrace{(q_{L_\alpha}^T C i\sigma_2 q_{L_\beta})}_{\text{singlet}} \underbrace{(q_{L_\gamma}^T C i\sigma_2 l_L)}_{\text{singlet}} \epsilon_{\alpha\beta\gamma}$$

$$O_5 = \underbrace{q_L^T C i\sigma_2 \vec{\sigma} q_L}_{\boxed{\text{vector}}} \underbrace{(q_L^T C i\sigma_2 \vec{\sigma} l_L)}_{\boxed{\text{vector}}}$$

$$D_1^\dagger \vec{\sigma} D_2 = \vec{V}_1$$

$$D_1^T i\sigma_2 \vec{\sigma} D_2 = \vec{V}_2$$

$\Downarrow$

only 4 are independent

Abbott, Wise
'80s

$$O_2 = \underbrace{(q_L^T i\sigma_2 C q_L)}_{\ni} (u_R^T C e_R)$$

$$(u_L^T C d_L)(u_R^T C e_R)$$

$\Updownarrow$

$$(u^c)_L \equiv C \bar{u}_R^T$$

$$u_R \sim \overline{u_L^c}$$

$\Updownarrow$ $\Downarrow$

$$\boxed{(\overline{u^c_L}\gamma^\mu u_L)(\overline{e^c_L}\gamma^\mu d_L) \in O_2}$$

$\overline{\psi_{1L}}\psi_{2L} = 0$, $\overline{\psi_{1L}}\gamma^\mu\psi_{2L} =$ ~~Lorentz~~ vector

Fermi

$$\underbrace{\overline{u_L}\gamma^\mu d_L}\ \overline{e_L}\gamma^\mu \nu_L$$

$$W^+_\mu(\overline{u_L}\gamma^\mu d_L + \overline{\nu_L}\gamma^\mu e_L)$$

$$\boxed{X_\mu\left[\overline{u^c_L}\gamma^\mu u_L + \overline{d_L}\gamma^\mu e^c_L\right]}$$

$Q_X = -4/3$, color

χ and neutrino mass

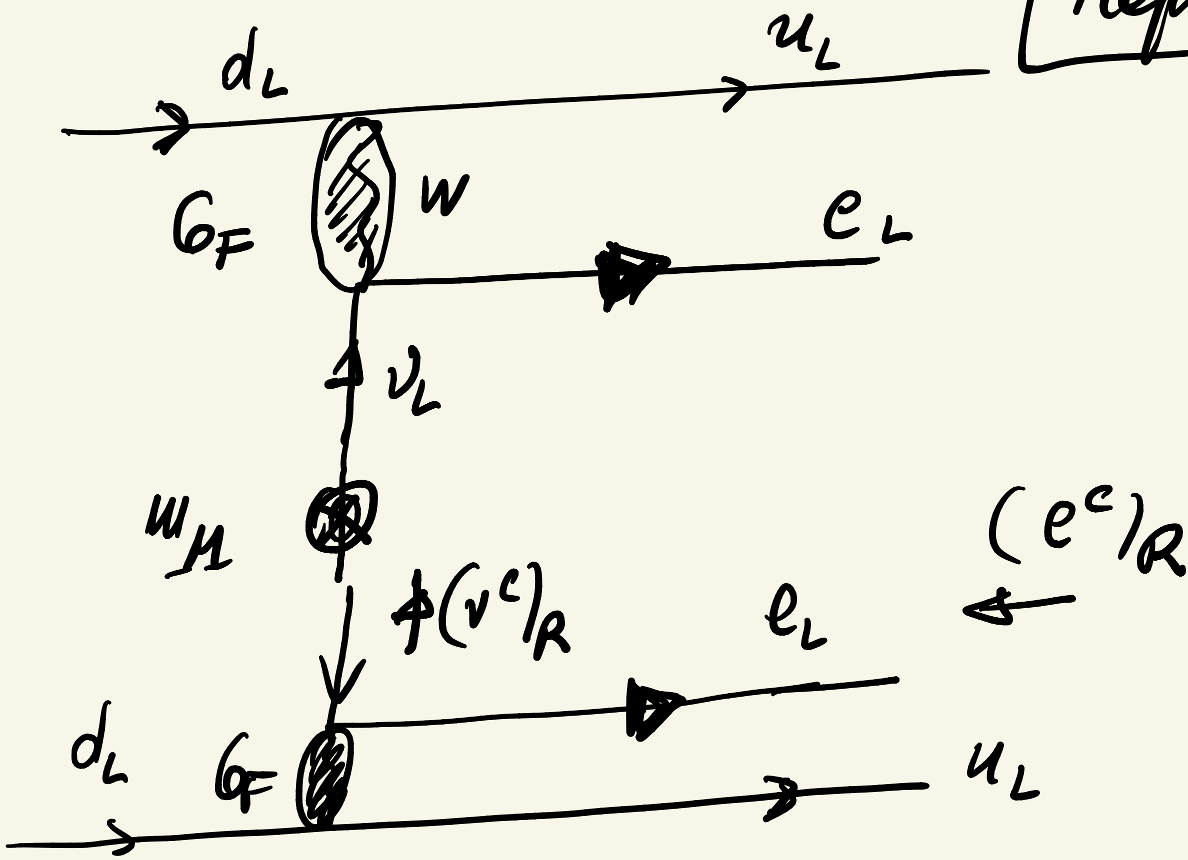
$$\nu_L^T C \nu_L = \text{Majorana mass}$$

$$\Delta L = 2 \qquad + \nu_L^{\dagger} C^{\dagger} \nu_L^{*}$$

$\Downarrow$

$\boxed{0\nu 2\beta}$

$\boxed{\nu^c = \nu}$ Majorana



$$\bar{e}_L \gamma^\mu (\not{k} + m_\nu) \gamma^\nu e_R^c \quad \frac{1}{k^2 - m_\nu^2}$$

$$= \bar{e} R \gamma^\mu (\not{k} + m_\nu) \gamma^\nu R e^c \quad - \text{''} -$$

$$= \bar{e} \gamma^\mu (\not{k} R + m L) \gamma^\nu R e^c \quad - \text{''} -$$

$$\boxed{\begin{aligned} \overline{e_L} \gamma^\mu &= (e_L^+) \gamma^0 = (L e)^+ \gamma^0 \\ &= e^+ L \gamma^0 = \bar{e} R \end{aligned}}$$

$$= \left[\cancel{\bar{e} \gamma^\mu \not{k} \gamma^\nu L R e^c} + \bar{e} \gamma^\mu \gamma^\nu m_\nu R R e^c \right] \frac{1}{k^2 - m_\nu^2}$$

$$= \bar{e} \gamma^\mu \gamma^\nu R e^c \frac{m_\nu}{k^2} \quad \checkmark$$

$\boxed{\text{both } e = e_L}$ $\Leftrightarrow$ SM + Majorana ν

$e_L + e^c_R$

out in

$$\mathcal{H}_{eff}^{0\nu2\beta} = \frac{1}{\Lambda_L^5}\Big[\underbrace{(\bar{e}\bar{e})(\bar{u}\bar{u})(dd)}_{d=9} + (ee)(uu)\bar{d}\bar{d}\Big]$$

Q. How to know that $0\nu2\beta$ is <u>not</u> due to m_ν?

all we need : e_R in $\mathcal{H}_{eff}^{0\nu2\beta}$!

• $\underbrace{\mathcal{O}^{0\nu 2\beta} \text{ with } e_R}$ $\qquad (\bar{d}_R \bar{d}_R)$

$$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \parallel$$

$$(e_R^T C e_R)(u_R^T C u_R)(d_L^{c\,T} C d_L^c)$$

$$d_L^c \equiv C \bar{d}_R^T$$

$$\boxed{L \leftrightarrow R}$$

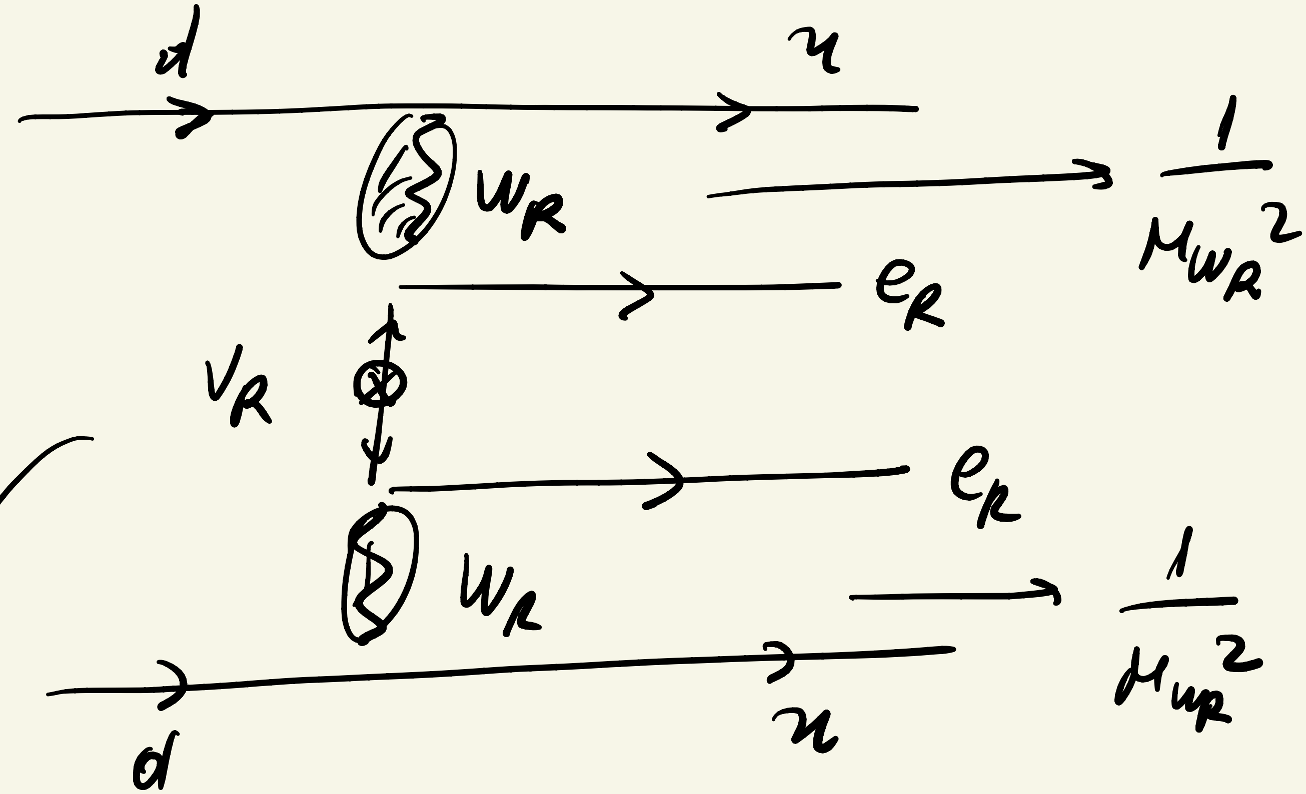
$$SM + \nu_M \Rightarrow (e_L e_L)(u_L u_L)(d_R^c d_R^c)$$

$$\updownarrow$$

$$(W_L \text{ exchange } \nu_L) \qquad G_F^2 \cdot \frac{m_\nu}{k^2 - m_\nu^2}$$

$$\Downarrow$$

$$(W_R \text{ exchange } \nu_R)$$



$$N \equiv \nu_R \qquad \boxed{m_N \gtrsim M_W}$$

$$\Rightarrow \; G_F^2 \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \frac{m_N}{\cancel{k^2} - m_N^2}$$

$$= G_F^2 \left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \frac{1}{m_N}$$

$$\Rightarrow \; M_{W_R} \simeq \text{few TeV}$$

$$\left| \; m_N \; : \; 100 \text{ GeV} - \text{TeV} \; \right|$$

$$\Leftrightarrow \frac{1}{\Lambda_L^5} (uu)(ee)(\bar{d}\bar{d})$$

$$\Updownarrow$$

$$G_F^2 \frac{m_\nu}{h^2} \qquad - \,\text{''}\, - \qquad (h = 100 \text{ MeV})$$

$$\|$$

$$10^{-10} \frac{10^{-10}}{10^{-2}} = 10^{-18} \text{ GeV}^{-5}$$

$$\Downarrow$$

$$\Lambda_L^5 \simeq 10^{18} \text{ GeV}^5$$

$$\Rightarrow \boxed{\Lambda_L \simeq 3 \text{ TeV}}$$

· <u>comment</u>

$\cancel{B}$ $\dfrac{1}{\Lambda_B^2}(qqq\ell) \Rightarrow \Lambda_B \gtrsim 10^{15}\,\text{GeV}$

$\Longleftrightarrow \tau_p \gtrsim 10^{34}\,\text{yr}$

$$\frac{1}{\Lambda_B^2} = \frac{\epsilon^2}{\Lambda_B'^2} \qquad (\epsilon \ll 1)$$

$$\Rightarrow \boxed{\Lambda_B' = \varepsilon \Lambda_B}$$

$g = O(1) \Leftarrow$ gauge theory

$$\frac{1}{\Lambda_B^2} = \frac{g^2}{M_X^2} \Rightarrow M_X \simeq \Lambda_B$$

Neutrino mass

$\boxed{d=5}$

$$\mathcal{H}_{eff}^{\Delta L=2} = \frac{1}{\Lambda_{weinberg}} (l\, l)(\Phi\, \Phi)$$

$$l^T c\, i\sigma_2\, l = 0$$

$$\left(\frac{1}{\Lambda_{weinberg}} (l^T i\sigma_2 \Phi)\, c\, (\Phi^T i\sigma_2\, l) \right.$$

$$\Phi_{un} = \begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad M_W = \frac{g}{2} v$$

$$\Rightarrow \quad m_\nu = \frac{v^2}{\Lambda} = \frac{4}{g^2} \frac{M_W^2}{\Lambda}$$

$$\Downarrow$$

$$\boxed{m_\nu \le 10^{-1}\,\mathrm{eV} \Rightarrow \Lambda \ge 10^{14}\,\mathrm{GeV}}$$

$$\frac{1}{\Lambda_{\text{Weinberg}}} = \frac{\varepsilon}{\Lambda'} \quad ??$$

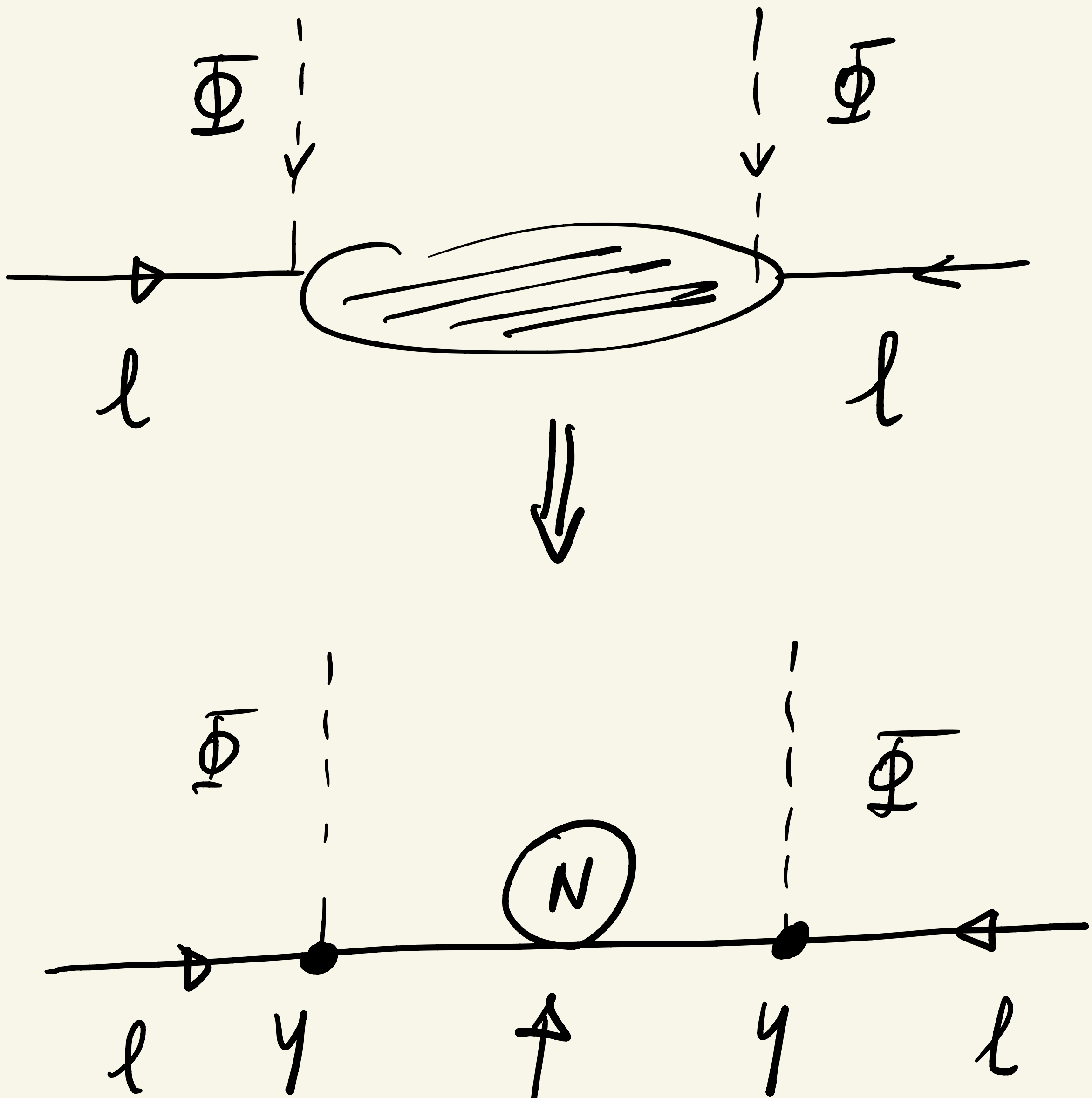
$$\frac{1}{\Lambda_{\text{Weinberg}}} \underbrace{(\overset{\frac{1}{2}}{\ell}\ \overset{0}{\Phi})}(\Phi \ell) \Leftrightarrow \frac{1}{\Lambda_F^2} J^\mu_W \bar{J}_\mu{}^W$$

Lorentz : fermion $(s = 1/2)$

$SU(2)_L$: singlet

color : singlet

Q_{em} : zero



SU(2) singlet

$Q_{em} = 0$

called ν_R : RH "neutrino"

ν_R $\quad\Big|\quad \boxed{N_L \equiv C\bar{\nu}_R^T \equiv (\nu^c)_L}$

$$\Rightarrow \boxed{\frac{1}{\Lambda_{weakly}} = \frac{y^2}{\cancel{R} - m_N} \sim \frac{y^2}{m_N}}$$

$$\boxed{\Lambda_{weakly} = \frac{m_N}{y^2}}$$

$$y_e \simeq \frac{m_e}{m_W} \simeq 10^{-5}$$

$$y = y_e \simeq 10^{-5}$$

$$\Rightarrow \boxed{m_N = 10^{-10}\Lambda_{weakly} \simeq 10^{4}\,\text{GeV}}$$

$$\boxed{\text{Nexchange} = \text{see saw mechanism}}$$

$$\mathcal{L}_y = y \underbrace{l_L^T i\sigma_2 \Phi C N_L}_{\checkmark} + h.c.$$

$$l_L^T i\sigma_2 \Phi = SU(2) \text{ singlet}$$

$$\boxed{= y(-) N_L^T C^T (i\sigma_2)^T \Phi\, l_L} + h.c.$$

$$= -y\, \overline{\nu_R} \underbrace{C^T C^T}_{(-1)} (-i\sigma_2) \Phi\, l_L + h.c.$$

$$\overset{?}{=} -y\, \overline{\nu_R}\, i\sigma_2 \Phi\, l_L + h.c.$$

Dirac type Yukawa

$$\boxed{y = y_D}$$

$$\boxed{SU(2)\times U(1)}$$

$$\mathcal{L}_y = y\, l_L^T\, i\sigma_2\, \Phi\, C\, N_L +$$

$$\underbrace{+ N_L^T C N_L \frac{m_N}{2}}_{\substack{\text{Lorentz, } SU(2)\times U(1)\times SU(3) \\ \text{invariant}}} + h.c.$$

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

$$\mathcal{L}_y = y\, l_L^T\, i\sigma_2 \begin{pmatrix} 0 \\ v+h \end{pmatrix} C N_L + \cdots$$

$$= y\, \nu_L^T C N_L (v+h) + \frac{m_N}{2} N_L^T C N_L + h.c.$$

$\Rightarrow$ mass terms: $\qquad C^T = -C$

$$\frac{1}{2} v y \left[\nu_L^T C N_L + N_L^T (-) C^T \nu_L \right] + \frac{m_N}{2} N_L^T C N_L$$

$$+ h.c.$$

$$= \frac{1}{2} \left\{ \left[N_L^T C \nu_L m_D + m_D^T \nu_L^T C N_L \right] + \right.$$

$$+ m_N N_L^T C N_L + h.c.$$

$$\Downarrow$$

$$\boxed{\begin{array}{c|cc} & & \\ \nu_L & 0 & m_D \\ N_L & m_D & m_N \end{array}}$$

$\Downarrow$ diagonalise

$\boxed{m_N \gg m_D}$

heavy neutral lepton

masses and states