Neutrino BBSM Course

Lecture V

LMU

Spring 2020

It's neutrino, stupid

Lecture IV

- B and L violation

Majorana spinors

- EFT Effective Field Theory

$$\mathcal{H}_{eff}^{W} \simeq G_F \, J_W \, J^W$$

$G_F \sim \frac{1}{\Lambda^2}$; J_W: weak current

$$\mathcal{H}_{eff}^{QED} \simeq \frac{1}{q^2} J_{em} J^{em} \quad (\leftrightarrow 1/v)$$

dim. fields carry d of mass

$\underline{d = 4}$ $\mathcal{L}_0 = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$

$(\not{p} - m)\,\psi(p) = 0$

$E^2 - \vec{p}^2 = \boxed{p^2 = m^2}$

$\int \mathcal{L}\, d^4x = S;\ d[S] = 1 \quad (\hbar = 1)$

$\Rightarrow\ d[x] = 4 \qquad d[x] = d[m]^{-1}$

$\Rightarrow\ d(\bar{\psi}\psi) = 3 \Rightarrow d(\psi) = 3/2$

$J \sim \bar{\psi}\psi \Rightarrow d[JJ] = 6$

$\Rightarrow$ Eeffective H : d = 4

$$\boxed{G_F = \frac{1}{\Lambda^2} = 10^{-5}\,\mathrm{GeV}^{-2}}$$

$\boxed{\text{EFT for } \not{B}, \not{L}}$

p decay

$$p \to \nu + \pi^+$$

$$\to e + \pi^+ + \pi^+$$

$$\to e^c + \pi^0$$

$$n \to \nu + \pi^0$$

$$e + \pi^+$$

Weinberg '1979

$\boxed{qqql}$

r y b (red, yellow, blue)

$$\boxed{q = u, d \qquad l = e, \nu} \Big\} \boxed{\times \text{ gen}}$$

$\cdot\ q, q, q, l \longrightarrow LH$

$\Rightarrow \quad q_L\, q_L\, q_L\, l_L$

• $\underbrace{\text{Majorana mass term}}$

$u_L = \begin{pmatrix} \uparrow \\ \downarrow \end{pmatrix}$

$$\nu_L^T\, C\, \nu_L \longrightarrow \underbrace{u_L^T\, i\sigma_2\, u_L}_{|\uparrow\downarrow - \downarrow\uparrow\rangle}$$

$$\| $$

$$\begin{pmatrix} \nu_L \\ 0 \end{pmatrix}$$

$$\boxed{\nu_L \nu_L \approx \nu \nu}$$

$$\mathcal{H}_{eff}\,(\Delta B \neq 0) = G_x\,(q\,q\,q\,l)$$

$$B(\mathcal{H}_{eff}) = 3 \cdot \frac{1}{3} = 1$$

$$L(\text{- " -}) = 1 \quad \Longrightarrow$$

$$\boxed{(B-L)\,\mathcal{H}_{eff} = 0}$$

$$\mu \to e + \ldots - ?$$

$$G_x = \frac{1}{\Lambda_x^2}$$

$$\Longrightarrow \quad \Lambda_x \gtrsim \; ?$$

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

$$\boxed{(B+L)\,\mathcal{H}_{eff} = 2 \neq 0}$$

$$\tau_\mu \simeq 10^{-6}\,sec$$

$$\mathcal{H}_{eff}(\text{weak}) = G_F\, J\, \bar{J}$$

$$Q_{em}(\mathcal{H}^{w}_{eff}) = 0$$

- **B + L asymmetry**

$q\,q\,q\,l^c$????

Ex. Can you write Lorentz + em invariant such term?

NO

$q_L\, q_L\, q_L\, (\nu^c)_L$

$$\boxed{u_L\, d_L\, d_L\, (\nu^c)_L = \text{invariant}}$$

$\Delta(B+L) = 0$, $\Delta(B-L) \neq 0$

• $d=6$ $\not{B}, \not{L}$ operator
with only SM particles

$$\boxed{(\nu^c)_L = C\,\bar{\nu}_R^{\,T}}$$

never observed

ν_L = $\boxed{\text{neutrino}}$

$\downarrow$ weak int.

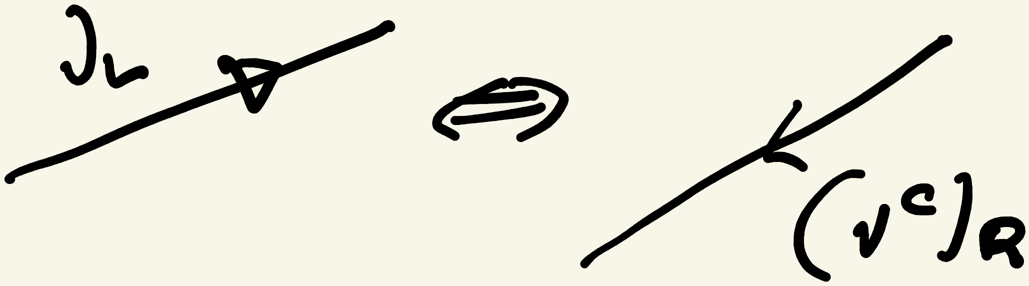
e_L

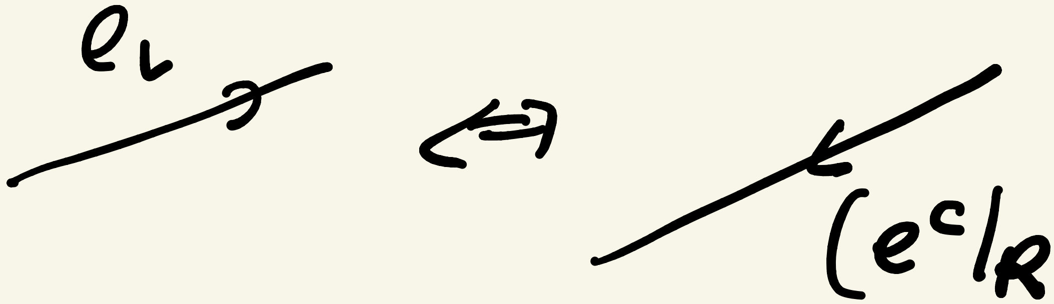
$\boxed{L(\nu^c) = -1}$

$$\nu_M = \nu_L + \underbrace{C\,\bar{\nu}_L^{\,T}}_{RH} = (\nu^c)_R$$

ν = neutrino $\therefore$ $L(\nu) = 1$

$$(\nu^c)_R = C\,\bar{\nu}_L^{\,T}$$





Q. $\Downarrow$?

$$J_\mu^W = \bar{\nu}_L \gamma^\mu e_L \qquad \bar{J}_\mu^W = \bar{e}_L \gamma_\mu \nu_L$$

$$= \overline{(\nu^c)_R}\, \gamma_\mu (e^c)_R$$

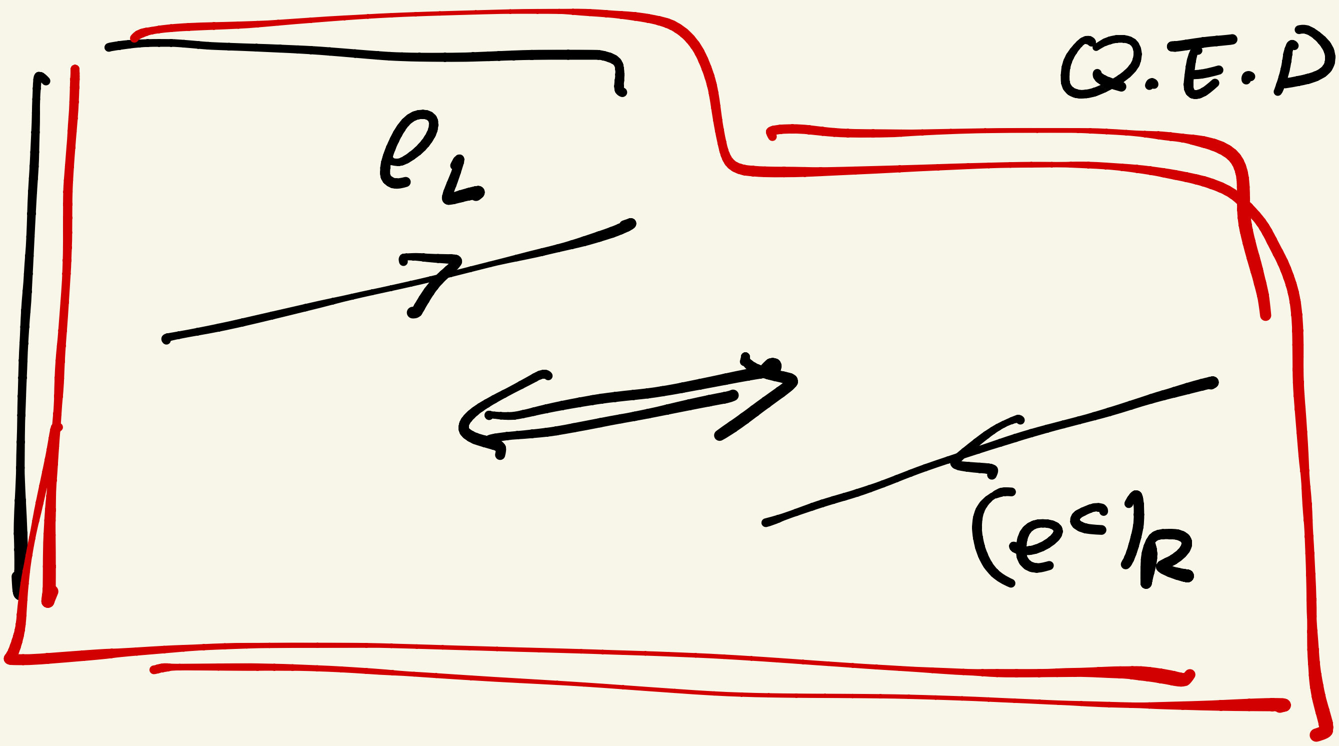
$\boxed{\text{A. YES}}$

Proof: $(e^c)_R = C\,\bar{e}_L^{\,T}$

$$\overline{(\nu^c)_R}\,\gamma_\mu (e^c)_R = \dots C\,\bar{e}_L^{\,T}$$

$$= \bar{e}_L \dots \dots \nu_L$$

Q.E.D.



- $\cancel{\nu_L \leftrightarrow \nu_R}$ (massive)

$\nu_L \leftarrow (\nu^c)_R$

- $m_M \nu_L^T C \nu_L + m_M \nu_L^\dagger C^\dagger \nu_L^*$

$$\| $$

$$\overline{(\nu^c)_R}\, \nu_L \qquad (\nu^c)_R = C \bar{\nu}_L^T$$

COURSE ON ν

$\nu_L \longleftrightarrow \nu_R$

boring

$\nu_L \longleftrightarrow (\nu^c)_R$

Pandora's box

- $\tau_p > 10^{34}$ yr

swimming pool = protons

$$\boxed{\Lambda_X \ggg M_W \simeq 100\,\mathrm{GeV}}$$

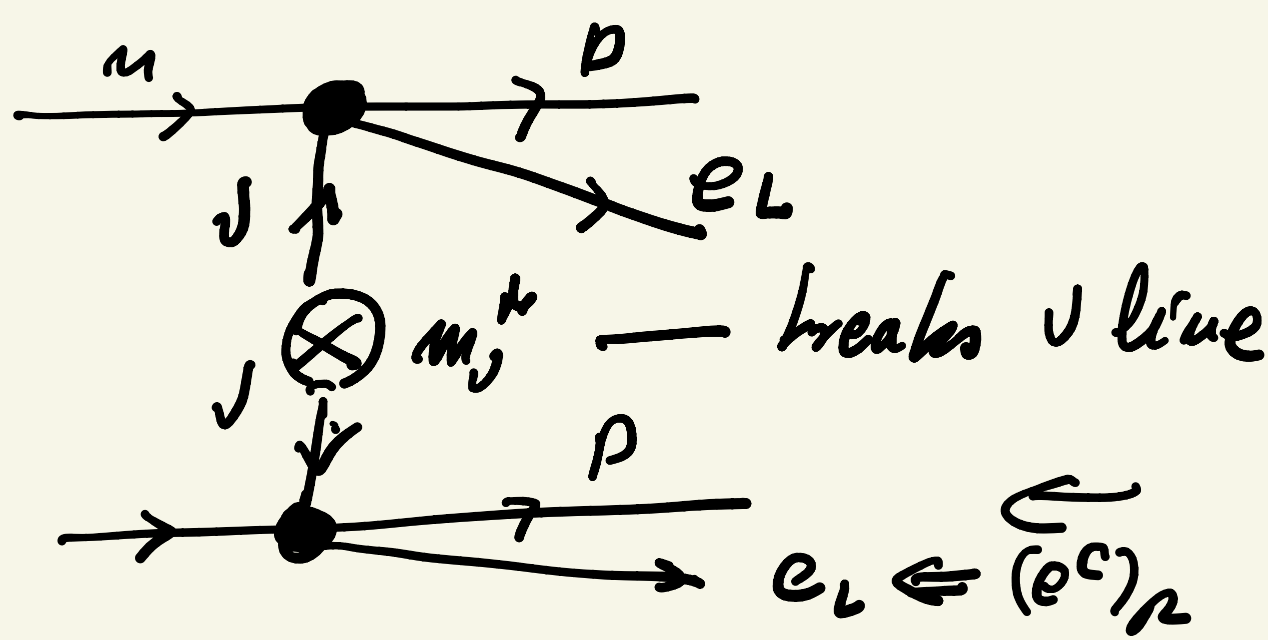
p decay is science fiction
$\longleftrightarrow$ direct LHC

- $\nu_M = \nu_L + C\bar{\nu}_L{}^T \Leftarrow$

$$m_M\, \nu_L{}^T C\, \nu_L$$

$\Downarrow$

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



$$A_\nu \propto G_F^2 \frac{m_\nu \cancel{\mp \not p}}{p^2 - \cancel{m_\nu^2}} \qquad \boxed{m_\nu \leq 1 eV}$$

$$\boxed{Ge \to Se + 2e}$$

$p \sim 100\ MeV$

$$\nu_M \Rightarrow \boxed{S(\nu_M) = \frac{i}{\not p - m_M}}$$

$$\mathcal{L}_M = i \bar\Psi_M \gamma^\mu \partial_\mu \psi_M - m_M \bar\Psi_M \Psi_M$$

$$\psi_M = \psi_L + C \bar\Psi_L^T$$

$$e_L \Longleftrightarrow (e^c)_R$$

$$\boxed{\bar e_L \gamma^\mu \nu_L \equiv \overline{(\nu_c)}_R \gamma_\mu (e^c)_R}$$

$$\bar e_L^T$$

$$A^{(\nu)}_{0\nu 2\beta} \simeq G_F^2\, \bar{e}\,\gamma_\mu L\, \frac{\not p + m_\nu}{p^2 - \cancel{m_\nu^2}}\, \gamma_\nu R\, e^c$$

$$\simeq G_F^2\, \bar{e}\,\gamma_\mu\, \frac{\not p R + m_\nu^\mu L}{p^2}\, \gamma_\nu R\, e^c$$

$$= G_F^2\, \bar{e}\,\gamma^\mu\, \frac{\cancel{\not p\,\gamma_\nu L\cdot R} + m_\nu^\mu \gamma_\nu R^2}{p^2}\, e^c$$

$$= G_F^2\, \bar{e}\,\gamma_\mu \gamma_\nu\, e^c\, \frac{m_\nu^\mu}{p^2}$$

$$\boxed{A^{(\nu)}_{0\nu 2\beta} \simeq G_F^2\, \frac{m_\nu^\mu}{p^2}} \quad \boxed{\times \text{ nuclear}}$$

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

$$\simeq 10^{-18}\, \mathrm{GeV}^{-5}$$

$m_\nu^\mu \simeq 10^{-1}\, \mathrm{eV}$

exp

$p \simeq 10^{-1}\, \mathrm{GeV}$

$\underline{0\nu 2\beta}$ $\quad \underbrace{\bar{p}\bar{p}}\,\underbrace{uu\,ee}$ $(\bar{u}\bar{u}\,dd\,ee)$

$$d = 6 \times \tfrac{3}{2} = 9$$

$$\boxed{d\,(H_{eff}) = 4}$$

$\Rightarrow \dfrac{1}{\Lambda_5}$ $(\bar{u}\bar{u}\,dd\,ee) \sim (uu\,dd\,ee)$

$\hookrightarrow$ new scale

New Physics $\leftarrow$ 1959 Goldhaber Feinberg

$\hookrightarrow 0\nu 2\beta$

$\Downarrow$

$\boxed{0\nu 2\beta \text{ is seen in } 2022}$

m_ν^M

$\Updownarrow$

$\boxed{\text{weak int.}}$

$\Downarrow$

$\cancel{\bar{e}_L \bar{e}_L = (e_L)(e^c)_R}$

New Physics

if $\ell = \ell_R$ in $0\nu 2\beta$

<u>Exp</u> is sensitive to

$$\boxed{\Lambda^{-5} \simeq 10^{-18}\,\mathrm{GeV}^{-5}}$$

$$\boxed{\Lambda \simeq 3\,\mathrm{TeV} \; !!!}$$

Neutrino oscillations

ATM | **SOLAR**

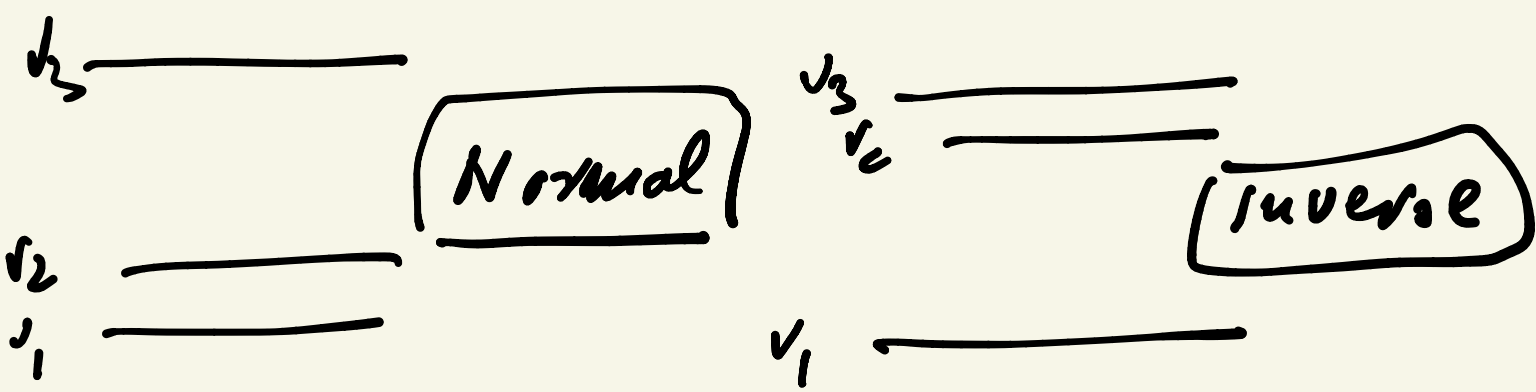
$\Delta m_A^2 \simeq 10^{-3}\, eV^2$ | $\Delta m_\odot^2 \simeq 10^{-4}\, eV^2$

$\theta_A \simeq 45^\circ$ | $\theta_\odot \simeq 30^\circ$

$$e \longleftrightarrow \nu_e = \nu_1 \cos\theta_\odot + \nu_2 \sin\theta_\odot$$

$$\mu \longleftrightarrow \nu_\mu = -\nu_1 \sin\theta_\odot + \nu_2 \cos\theta_\odot$$

ν_1, ν_2 — physical state



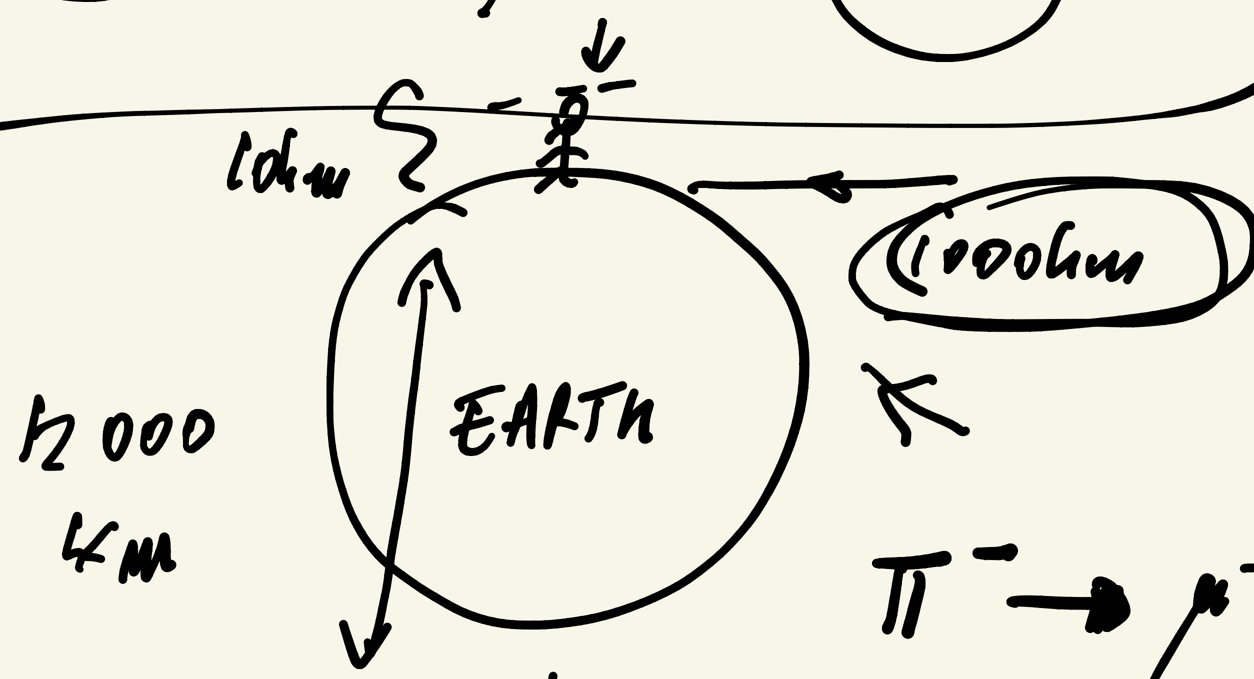
$0\nu 2\beta \longleftrightarrow$ INVERSE

NORMAL $\Longrightarrow$ $0\nu 2\beta$ is due to NP

JUNO exp

SUN $\quad \nu_e \longleftrightarrow \nu_\mu$

ATM $\quad \nu_\mu \longleftrightarrow \nu_\tau$



$\pi^- \longrightarrow \mu^- \bar{\nu}_\mu$

$\qquad\qquad e^- \bar{\nu}_e$

$m_\pi \simeq 150\,\text{MeV}$

$m_e \simeq \text{MeV}, \; m_\mu \simeq 100\,\text{MeV}$

$$\boxed{\text{Weak} \Leftrightarrow LH}$$

π^- · sitting — ℓ_L lepton ← ⇒ — $\bar{\nu}_e$ R → ⇒ — $\vec{z}$

$$\left.\begin{array}{l} S_\pi = 0 \\ L_\pi = 0 \end{array}\right\} J_z = 0$$

$$h(\psi_L) = -1/2$$
$$h(\psi_R) = +1/2$$

$$\boxed{\begin{array}{c} \text{if } m_e = 0 \\ \Downarrow \\ \text{NO } \pi \\ \text{decay} \end{array}}$$

$m_e \ll m_\mu$

$$\frac{\Gamma(\pi^- \to e\bar{\nu}_e)}{\Gamma(\pi^- \to \mu\bar{\nu}_\mu)} \propto \left(\frac{m_e}{m_\mu}\right)^2 \simeq 10^{-4}$$

$$\boxed{\pi^- \longrightarrow \bar{\nu}_\mu + \mu}$$

$$\bar{\nu}_\mu + p \longrightarrow \bar{\mu} + n$$

$$\boxed{L_{osc} \simeq 1000\,km}$$

ν long baseline South

Fermilab Dakota

800km