Neutrino Physics Course

Lecture XXIV

18/7/2023

LMU

Summer 2023

LNV and LFV @ High and Low E

Lepton Flavor Violation

$\boxed{\text{Lepton Number Violation}}$

text-book example

$0\nu 2\beta$

$$d + d \to u + u + e + e$$

$$\tau_{0\nu 2\beta} \gtrsim 10^{26}\,\text{yr} \qquad (1)$$

• <u>effective point of view</u>

$$\frac{1}{\Lambda^5}\,\bar{u}\,\bar{u}\,\bar{e}\,\bar{e}\,d\,d \qquad (d=9)$$

$(1) \Rightarrow \quad \Lambda \gtrsim 3\ \text{TeV}$

$SU(2)_L \times U(1) \times SU(3)_c$ inv.

(i) $\underline{f_R = (u, d, e)_R}$ (all RH)

$$d_R d_R \longrightarrow d_R^T\, C\, d_R$$

$$C = i\sigma_2\gamma_0 = \begin{pmatrix} i\sigma_2 & 0 \\ 0 & -i\sigma_2 \end{pmatrix}$$

$\bar{e}\,\bar{e} \to \overline{e_R}\,\overline{e_R}$ (not Lorentz inv.)

reminder: $\psi \to \Lambda \psi$

$(\bar{\psi} \not\to \Lambda \bar{\psi})$

$\psi^c \to \Lambda \psi^c \qquad \psi^c = C\bar{\psi}^T$

$(e^c)_L^T\, C\, (e^c)_L$ (Lorentz inv.)

$(u^c)_L^T\, C\, (u^c)_L$ — " —

$\Downarrow$

$$\underbrace{O_1 = \frac{1}{\Lambda_5} (e^c)_L^T \, c \, (e^c)_L \, (u^c)_L^T \, c \, (u^c)_L \times d_R^T \, c \, d_R}_{\text{made of only RH fermions}}$$

($\Leftrightarrow$ LH anti – " –)

- <u>some mixture</u>: d_R, e_L, u_L

$$dd \longrightarrow d_R^T C d_R$$

Q. $\underbrace{e_L, u_L}$ $\longleftarrow$ SU(2) inv.

$$\ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L , \quad q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

SU(2) inv.

$$l_L^T \, i\sigma_2 \, C \, q_L = \text{(inv.)}, \text{ Lorentz}$$

$$\Updownarrow$$

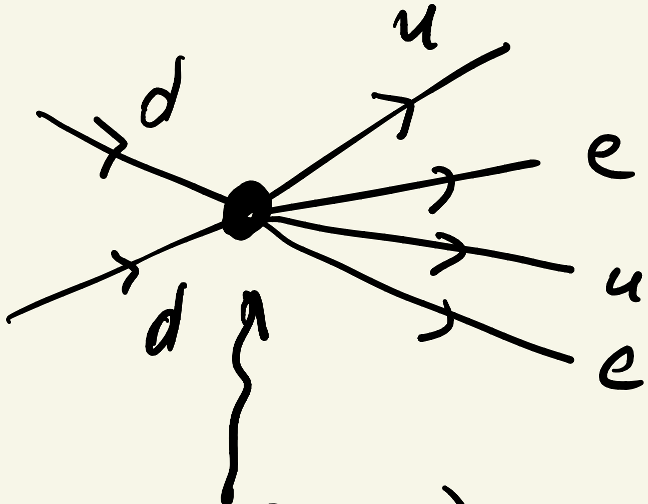
$$(l^c)_R^T \, i\sigma_2 \, C \, (q^c)_R$$

$\downarrow$ instead, go back to a theory

$$\Downarrow$$

$$\boxed{LRSM}$$

effective

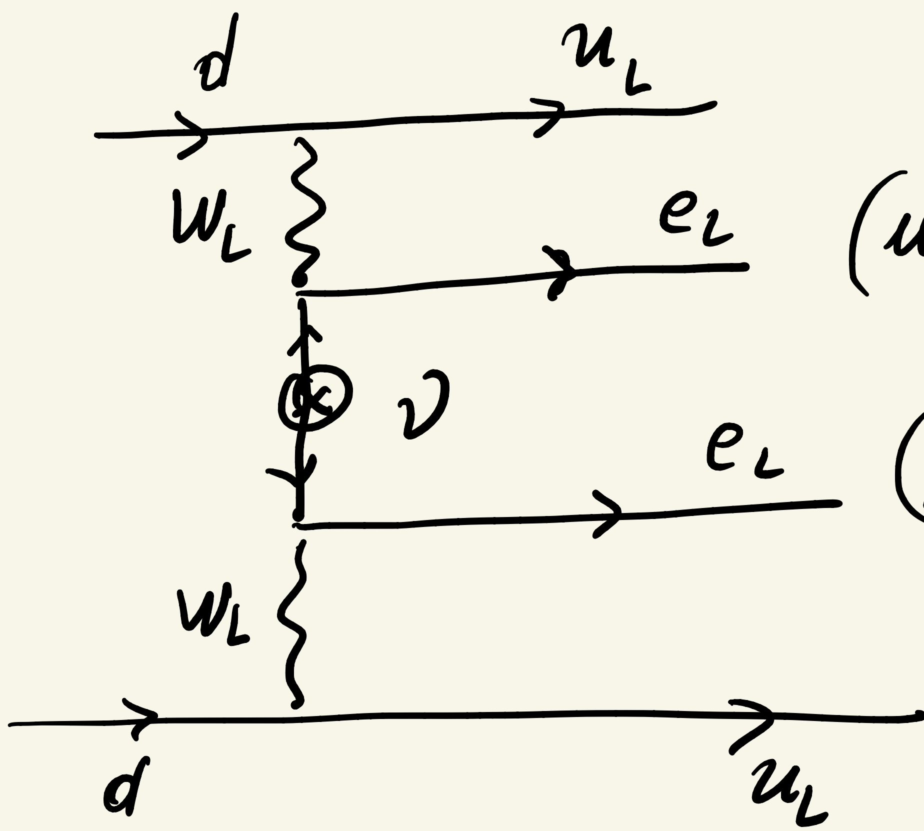


$(1/\Lambda_5)$

fundamental (UV completion)

basic

A_ν

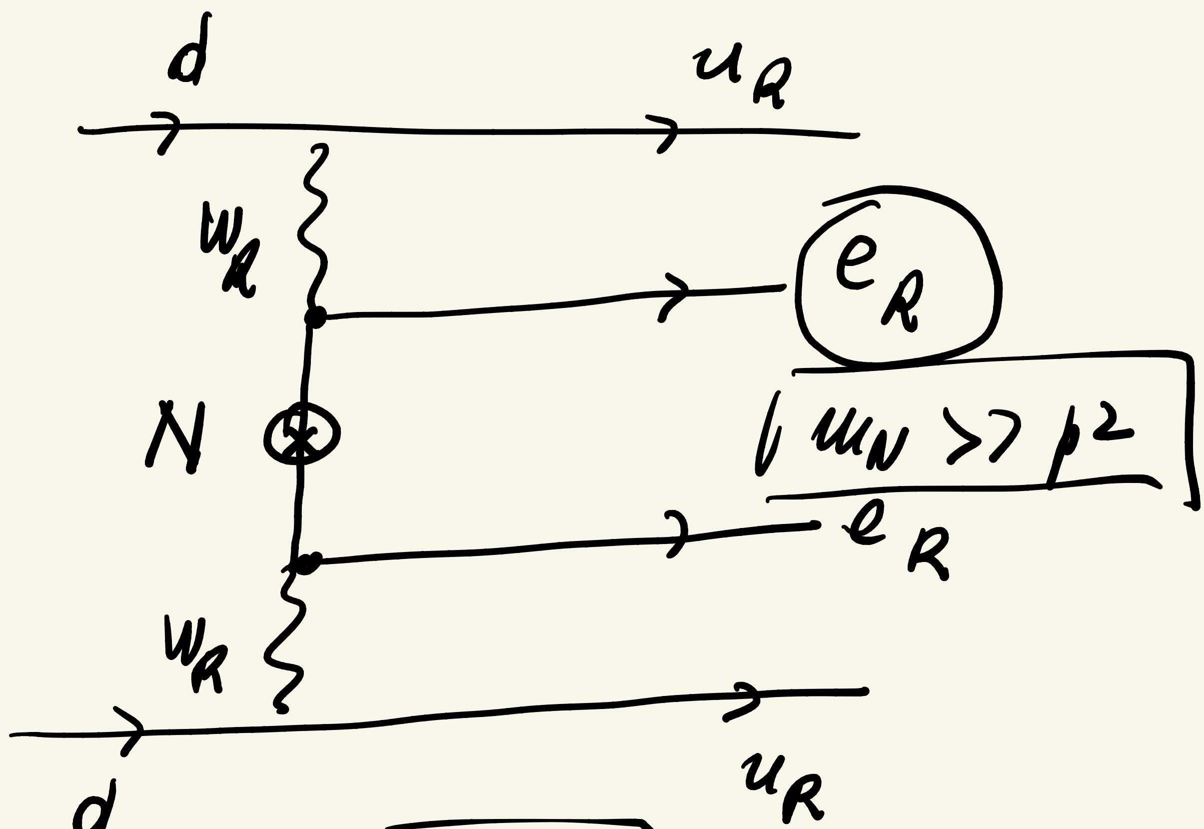


$(w_0 << p)$

$(p \simeq 100\,\mathrm{MeV})$

new

A_N



$$\boxed{\Delta L = 2}$$

$$\Downarrow$$

$$A_\nu \propto \frac{1}{M_{W_L}^4} \frac{m_\nu}{p^2} \left\{ \frac{\cancel{\not p} + m_\nu}{p^2 - \cancel{m_\nu^2}} \right.$$

$$A_N \propto \frac{1}{M_{W_R}^4} \frac{m_N}{m_N^2} = \frac{1}{M_{W_R}^4} \frac{1}{m_N}$$

$$A_\nu \simeq G_F^2 \frac{m_\nu}{p^2}$$

$$A_N \simeq G_F^2 \left(\frac{M_L}{M_R}\right)^4 \frac{1}{m_N}$$

$$\Downarrow$$

$$\boxed{A_N / A_\nu \simeq (M_L/M_R)^4 \frac{p^2}{m_\nu m_N}}$$

$$\boxed{\begin{aligned} m_N &= Y_\Delta v_R \\ &\# \\ M_R &= g\, v_R \end{aligned}}$$

$$(M_R/M_L)^2 \gtrsim 10^6 , \quad p = 100\,\mathrm{MeV}$$

$$\boxed{A_N / A_\nu \gtrsim 1, \text{ iff } m_N \lesssim 100\ \text{GeV}}$$

$\Downarrow$

$$\boxed{M_R \lesssim 10-20\ \text{TeV}}$$

In order for A_N visible at experiment

LHC $\longrightarrow$ M_R up to 6-7 TeV

- if $0\nu 2\beta$ is seen tomorrow and $e = e_R$

$\Downarrow$

$M_R \lesssim 20$ TeV

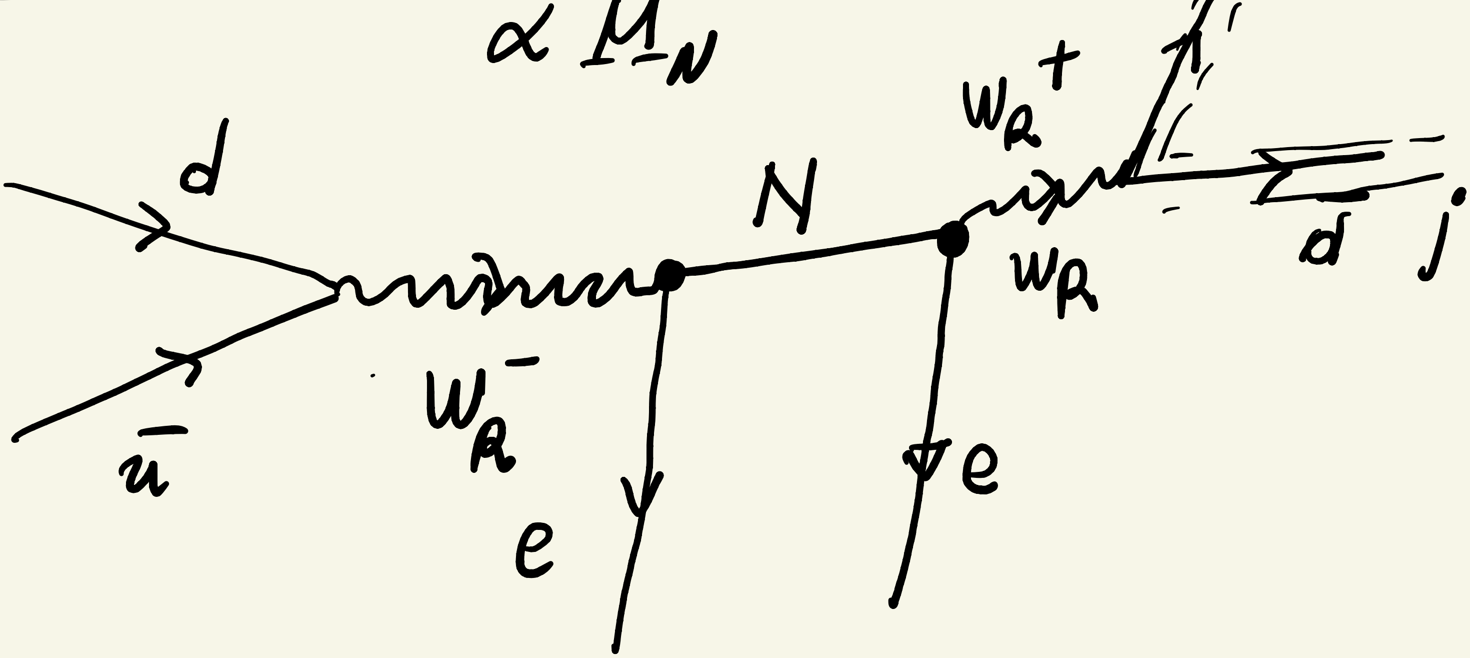
$\Rightarrow$ new collider

$\Downarrow$

in $0\nu 2\beta \Rightarrow$ it is imperative to measure chirality

Connection with LHC ?

$\boxed{\text{LHC}}$



KS process =

= collider analogy of $0\nu 2\beta$

$$\boxed{p + p\,(\bar{p}) \to e + e + j + j}$$

$\Delta L = 2$

LRSM = self-contained, predictive

- KS = rich physics

(i) $N \to e_R + j + j$

$N \to (e^c)_L + j' + j'$

$\Downarrow$

verify Majorana

(ii) through $\Theta_{\nu N}$ $\Rightarrow$

$$\left.\begin{array}{l} N \to e_L + W_L^+ \\ N \to (e^c)_R + W_L^- \end{array}\right\} \propto M_D$$

$$M_N = V_R \, m_N \, V_R^T$$

$$m_N = \mathrm{diag}\,(m_N^1, m_N^2, \ldots)$$

$$\boxed{\text{US} \longrightarrow V_R,\ m_N}$$

$\uparrow$

by looking at

$ee,\ e\mu,\ e\tau$

$\mu\tau,\ \mu\mu,\ \tau\tau$

$\Downarrow$

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

double checks:

$$N \to e_L + W^+$$

$$\Gamma(-\parallel-) \propto |M_D|^2$$

$$\boxed{M_D = i\, M_N \sqrt{1/m_N\, M_\nu}}$$

(iii) measure LF: ee,

μe

$\vdots$

$\Downarrow$

v_R, m_N

$\downarrow$

LFV @ low E

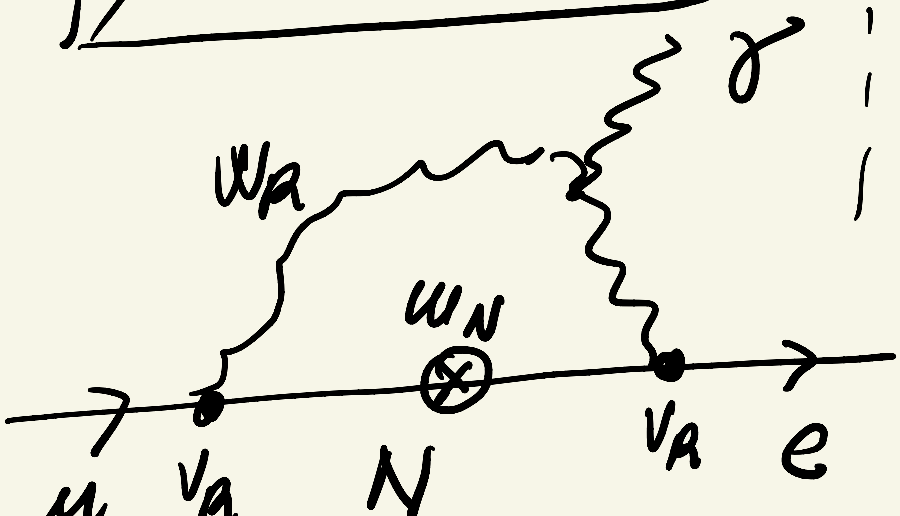
ν in muon decay

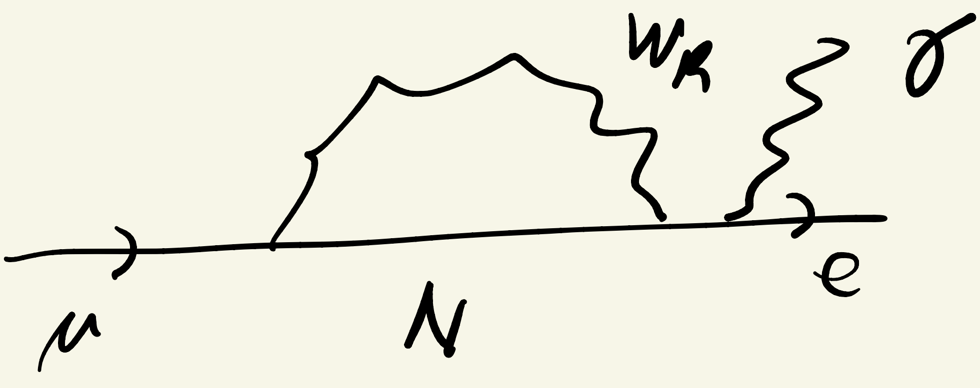
$$\underbrace{\mu \to e + \bar{\nu}_e + \nu_\mu}$$

LFC (not LFV)

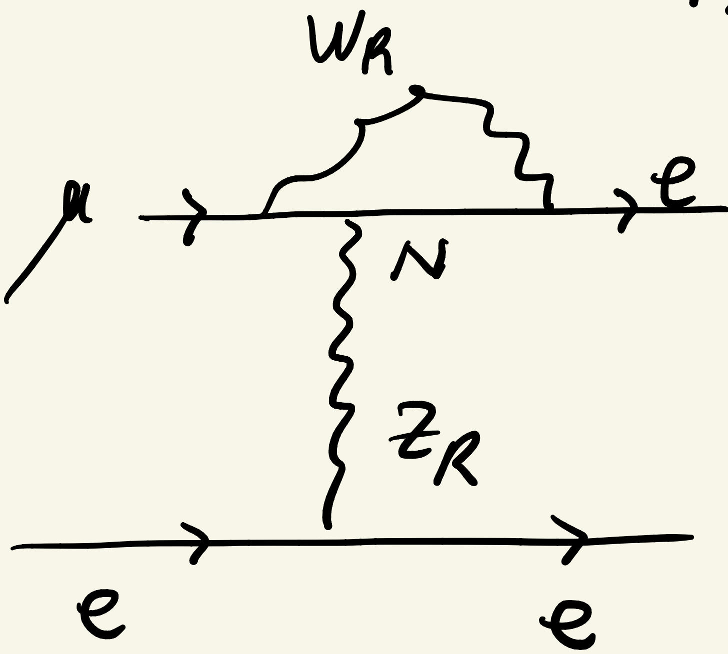
(a) $\boxed{\mu \to e + \gamma}$, $\tau \to e + \gamma$

$\tau \to \mu + \gamma$





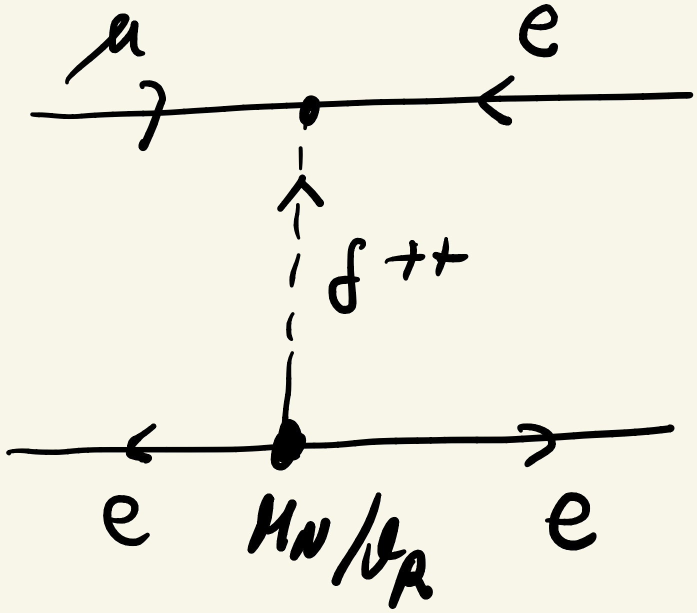
(b) $\mu \to e + \underbrace{e + \bar{e}}_{2f,\ Q_{em} = 0}$



but

$$\Delta_{L,R} = \begin{pmatrix} \delta^{+} & \delta^{++} \\ \delta^{0} & -\delta^{+} \end{pmatrix}_{L,R}$$

$\delta^{++} e e, \quad \delta^{++} e \mu \ \ldots$



$$\mathcal{L}_Y = l_L^T C\, i\sigma_2\, Y_\Delta\, C\, \Delta_L\, l_L$$

$$\Vert$$

$$\underbrace{+\, l_R^T C\, i\sigma_2\, Y_\Delta\, C\, \Delta_R\, l_R}$$

$$\Longrightarrow \boxed{\nu_R^T C\, Y_\Delta\, \nu_R^T\, \delta_{0,R} + e_R^T C\, Y_\Delta\, e_R\, \delta_R^{++}}$$

$$\Downarrow$$

$$M_{\nu_R} = Y_\Delta v_R = M_N^*$$

$$(N = C\bar{\nu}_R^T)$$

$$\Rightarrow \boxed{\delta^{++} e_R^T C \frac{M_N^*}{v_R} e_R}$$ Higgs mechanism

$\Downarrow$

decay det. by

$$M_N = V_R m_N V_R^T$$

$$\boxed{\begin{aligned} &B(\mu \to e\gamma) \leq 10^{-12} - 10^{-13} \\ &B(\mu \to e e \bar{e}) \leq 10^{-12} - 10^{-13} \end{aligned}}$$

$\hookrightarrow \tau \to \mu \bar{\mu} \mu$

$\to \mu e \bar{\mu}$

$\to \mu e \bar{e}$

$\to e \mu \bar{\mu}$

Tello, PhD thesis 2012

Origin of neutrino mass

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

Higgs

$$M_N = y_\Delta v_R$$

$\downarrow$ Higgs origin

$$\boxed{e_R\, \delta^{++}\, M_N^*\, e_R}$$

$$N \to e + W^+ \quad (M_D)$$

Higgs origin

analogy $\updownarrow$

$$h \to f \bar{f} \quad (m_f)$$

SM $\quad \Gamma(h \to f\bar{f})$

$\propto m_f^{\,2} \quad \leftarrow$ today

$\Updownarrow$ predictive

LRSM

$\Gamma(N \to eW) \propto$

$\propto M_D^2 \propto M_N M_\nu$

tomorrow?

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back to LFV

$\delta_R^{++} \, e_R^T C \, \boxed{Y_\Delta} \, e_R$

$\parallel$

$\delta_L^{++} \; e_L^T \, C \, \boxed{Y_\Delta} \, e_L$

$\Rightarrow$ δ_L decays measure

$Y_\Delta \propto M_N^*$

additional test

- Probe of Higgs origin of M_N

$\Downarrow$

LR Sdy

$$\ell_R Y_\Delta \Delta \ell_R \to \nu_R Y_\Delta \nu_R \delta_R^0$$

$$+ e_R^T Y_\Delta e_R \delta_R^{++}$$

$$\langle \delta_R^0 \rangle = v_R \leftarrow \text{Higgs}$$

$$\Downarrow$$

$$M_N^* \propto Y_\Delta$$

$$\updownarrow$$

Sdy

$$\bar{\ell} Y_e \phi e_R \Rightarrow \bar{e}_L \varphi_0 Y_e e_R$$

$$\Rightarrow m_e = Y_e \langle \varphi_0 \rangle$$

$$\Downarrow$$

$$y_e = \frac{m_e}{\langle \varphi_0 \rangle}$$

$$\to \Gamma(h \to e\bar{e}) \propto m_e^2$$

$$\Downarrow$$

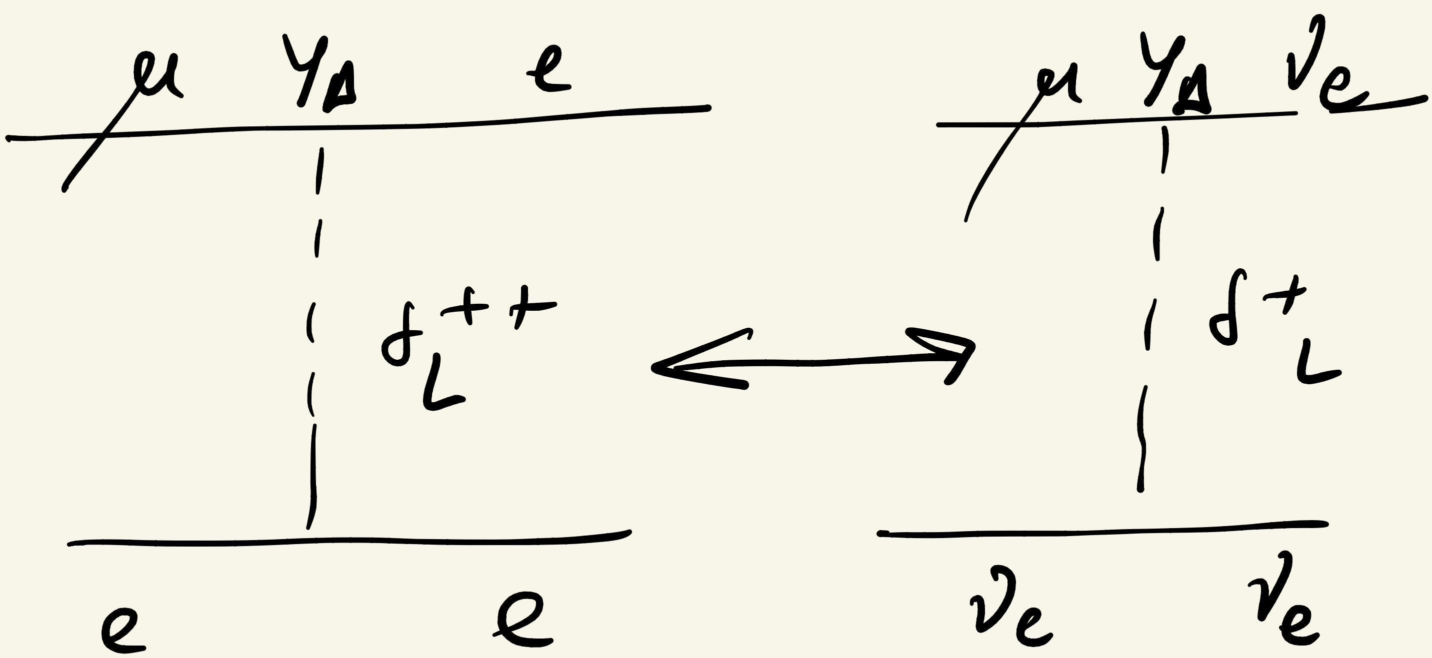
$$\left.\begin{array}{l} 0\nu 2\beta \\ \\ \mu \to e\gamma,\ \mu \to 3e \\ \\ \text{LHC} \end{array}\right\} \text{same time scale}$$

$\downarrow$ LFV

$$\boxed{\mu \to e + e + \bar{e}} \quad \text{(LFV)}$$

$$\mu \to e + \underbrace{\nu_e + \bar{\nu}_e}_{\text{hard to detect}} \quad \text{(LFV)}$$

$$\boxed{\mu \to e\gamma} \quad \text{easy to observe}$$



$$m_{\delta_L^{++}} \gtrsim 800\ \text{GeV (LHC)}$$

$$\Rightarrow m_{\delta_L^+} \simeq m_{\delta_L^{++}} \gtrsim 100\ \text{GeV}$$

$$\Downarrow$$

$$\boxed{\Gamma(\mu \to 3e) \simeq \Gamma(\mu \to e\nu\nu)}$$