Neutrino Physics Course

Lecture XXIII

29/6/2021

LMU

Summer 2021

LR Theory : physics

- ~~P~~ spontaneously

$$W_L^{\pm} \longleftrightarrow W_R^{\pm}$$

$\not{P}$ violation through chirality

(SPS) 1983

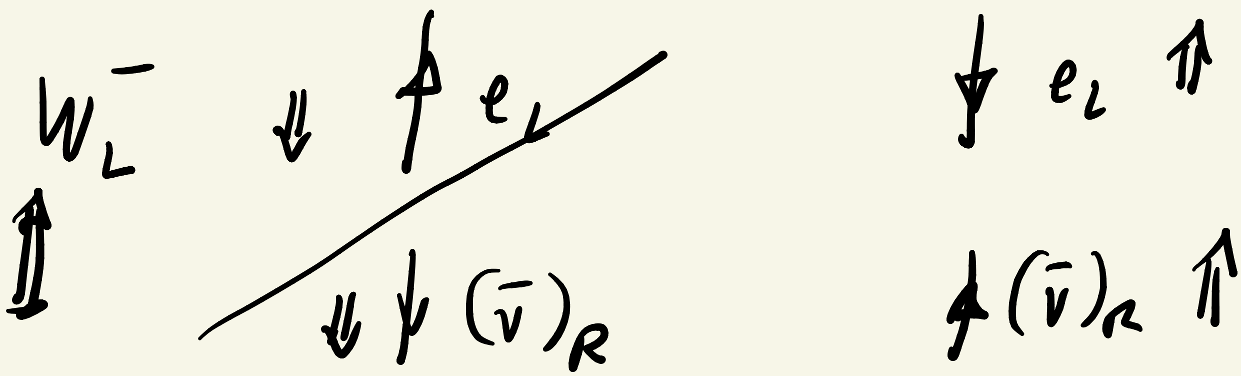
$$W_L^- \longrightarrow e_L^- + \bar{\nu}_L \equiv e_L + (\bar{\nu})_R$$

$$\underset{(\bar{u})_R}{\overset{\Rightarrow}{\longrightarrow}} \qquad \underset{d_L}{\overset{\Rightarrow}{\longleftarrow}} \qquad W_L \text{ at rest } \Uparrow$$

$$S_z^W = +1$$

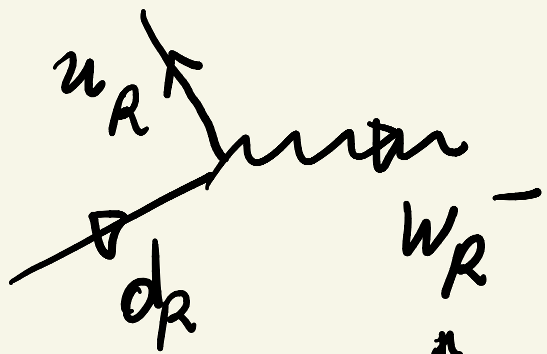
$$w_f = 0 \Rightarrow \boxed{\begin{aligned} h\, f_L &= -\tfrac{1}{2}\, f_L \\ h\, f_R &= +\tfrac{1}{2}\, f_R \end{aligned}}$$

$$\Downarrow$$

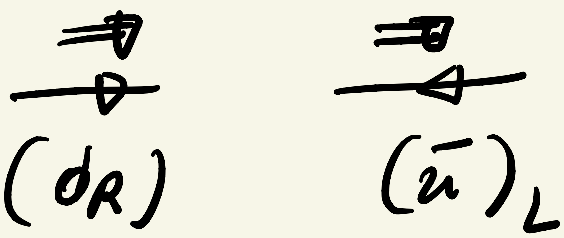


$$\boxed{\frac{d\Gamma(W)}{d\Omega} \propto (1-\cos\theta)^2 \qquad \Uparrow}$$

$\boxed{LHC}$



polarized



$$S_z^{(W_R)} = +1$$

$$W_R^- \longrightarrow e_R + (\bar{N})_L$$

$$m_N \ll M_{W_R} \Rightarrow m_N \simeq 0$$

$$\frac{d\Gamma}{d\Omega}(W_R^-) \propto (1+\cos\theta)^2$$

We will know the "chirality"

of W_R $\Leftrightarrow$

LHC sees a W'

$\downarrow$

probe chirality

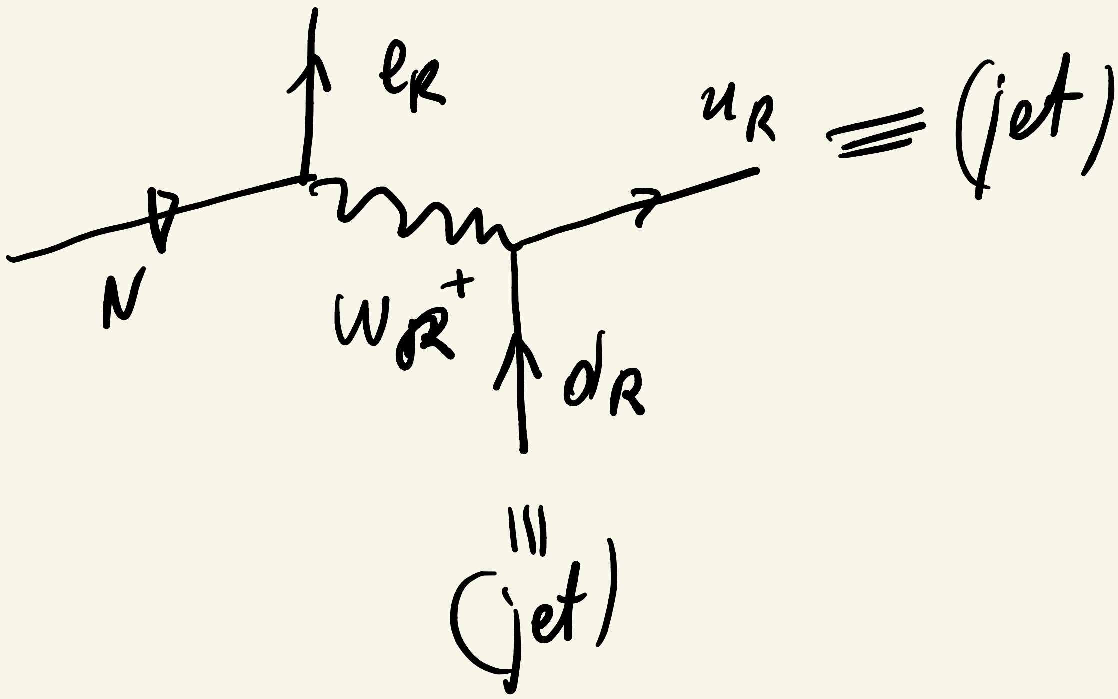
$\Rightarrow$ doable (trivial when

$m_N \ll M_{W_R}$)

$\Downarrow$

$N =$ Majorana

- $N \xrightarrow[W_R]{} e_R + j_1 + j_2$ 50%



$$\longrightarrow \left\{ \left(\overline{e_R} \right) = \left(\bar{e} \right)_L \right] + \bar{u}_R + d_R \right\}$$

50%

$\boxed{\text{check Majorality}}$

• $\mathcal{M}_\nu = - M_D^T \frac{1}{\mathcal{M}_N} M_D$

$\Uparrow$

$$\begin{array}{c} \nu \\ N \end{array} \begin{pmatrix} 0 & \mathcal{M}_D^T \\ M_D & M_N \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & \theta^+ \\ -\theta & 1 \end{pmatrix} \quad (\theta \ll 1)$$

$$\begin{pmatrix} \nu \\ N \end{pmatrix} \rightarrow U \begin{pmatrix} \nu \\ N \end{pmatrix}$$

$$\boxed{\theta = \frac{1}{M_N} \mathcal{M}_D} \quad (\ll 1)$$

$$\nu \to \nu + \theta^+ N$$

$$N \to -\theta \nu + N$$

$$\Downarrow$$

$$\bar{\nu}_L \gamma^\mu e_L W^+_{\mu L} \to \bar{\nu}_L \gamma^\mu e_L W^+_{\mu L}$$

$$\underbrace{+ \bar{N}_L \theta \gamma^\mu e_L W^+_{\mu L}}_{\text{NOT a way to produce}}$$

$$N_M = N_L + C \bar{N}_L^T \equiv N$$

$$\Downarrow$$

$$N \to e_L + W_L^+$$

$$(\bar{e})_R + W_L^-$$

$$\therefore \quad \Gamma(N \to eW) \propto |\Theta|^2$$

$$\Theta \equiv \frac{1}{\underline{M}_N} \underline{M}_D$$

- $\underline{M}_N \equiv V_R \, m_N \, V_R^T$ $\boxed{LHC}$

$$\underline{M}_\nu \equiv V_L^* \, m_\nu \, V_L^+$$

oscillations, $0\nu2\beta$
(low E)

$$W_R^- \longrightarrow N_i + e_R^j$$

$i = 1, 2, 3 \quad (e, \mu, \tau)$

$\boxed{\text{measure } \nu_R}$

$\boxed{M_N, \ M_\nu}$ (measurable)

$\Downarrow$

$$M_D = f(M_\nu, M_N)$$

$\Downarrow$

$$\Theta = \frac{1}{M_N} M_D$$

$$\bullet \quad LR = C \vee P$$

$$f_L \to \cdots f_R^{*} \qquad\qquad f_L \to f_R$$

$$P: \quad Y_\Phi = Y_\Phi^{\dagger}$$

$$C: \quad Y_\Phi = Y_\Phi^{T}$$

$$\boxed{C: \quad M_D^{T} = M}$$

$$\Downarrow$$

$$M_D = i \; M_N \sqrt{1/M_N \, M_\nu} \quad \leftarrow$$

$$M_D^T = i\left(\sqrt{1/M_N\, M_\nu}\right)^T M_N^T$$

$$= i\sqrt{\left(1/M_N\, M_\nu\right)^T}\; M_N^T$$

$$= i\sqrt{M_\nu^T \left(1/M_N\right)^T}\; M_N^T$$

$$M_\nu = M_\nu^T, \quad M_N = M_N^T$$

Majorana

$$\Rightarrow \boxed{\begin{aligned} M_D^T &= i\sqrt{M_\nu M_N^{-1}}\; M_N \\ M_D &= i\; M_N \sqrt{M_N^{-1} M_\nu} \end{aligned}}$$

$M_\nu, \; M_N$ = arbitrary

$\Rightarrow M_N^{-1} M_\nu$ = arbitrary

$\Rightarrow \sqrt{M_N^{-1} M_\nu}$ = arbitrary $\equiv A$

$$M_N = M_N^T \equiv S$$

$$M_D = i S A$$

$$M_D^T = i A^T S$$

(???)

$S = \sigma_3, \quad A = \sigma_1$

$SA = \sigma_3 \sigma_1$

$$A^T S = \sigma_1 \sigma_3 \neq \sigma_3 \sigma_1 = S A$$

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

$$= i\, M_N \sqrt{1/M_N \, M_\nu}\;\, 1/M_N \; M_N$$

Theorem

$$L \equiv A \sqrt{B}\, A^{-1} = \sqrt{A B A^{-1}} \equiv R$$

Check $\quad L^2 = R^2 \; \checkmark$

$$\Downarrow$$

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

$$= i\sqrt{M_\nu \, 1/M_N} \, M_N = M_D^T$$

$\Leftrightarrow$ <u>Leeruw</u> !

$$M_D = i\sqrt{M_N} \, O \sqrt{M_\nu}^{-1}$$

$$O O^T = O^T O = 1$$

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

$$\boxed{O = \sqrt{M_N} \sqrt{1/M_N \, M_\nu} \sqrt{1/M_\nu}}$$

$$[M_N, M_\nu] = 0 \Rightarrow O = 1$$

$$\boxed{\text{Summary}}$$

$$N \to e_R + j_1 + j_2 \quad \{M_N\}$$

$$\to W_L^+ + e_L$$

predicted

$$\theta = \frac{1}{M_N} M_\nu$$

$M_{W_R} \simeq 100\, M_{W_L}$, $m_N \simeq \text{TeV}$

$\simeq 8\,\text{TeV}$, $m_\nu = 0.1\,\text{eV}$

$$\Rightarrow \frac{\Gamma(N \to W e_L)}{\Gamma(N \to e_R jj)} \simeq 10^{-3}$$

$\boxed{\underline{LHC:} \quad m_N, \; v_R}$

$\Downarrow$

$\boxed{\text{low energy predictions}}$

$\boxed{C}$

$$\mathcal{L}_y^{\Delta} = \ell_L^T C \, i\sigma_2 \, \Delta_L \, Y_\Delta \, \ell_L + \ell_R^T C \, i\sigma_2 \, \Delta_R \, Y_\Delta^* \, \ell_R + h.c.$$

$\Downarrow$

$N_L = C \bar{\nu}_R^{\,T}$

$$\underline{M}_{\nu_R} = Y_\Delta^* \, v_R$$

$\Downarrow$

$$\boxed{M_N = Y_\Delta \, v_R}$$

$$\underset{(L)}{\Delta_R} = \begin{pmatrix} \delta^+ & \delta^{++} \\ \delta^0 & -\delta^+ \end{pmatrix}_{\underset{(L)}{R}}$$

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

$$= e_R^T C \, \frac{M_N^*}{v_R} \, e_R \, \delta_R^{++}$$

$$\boxed{m_{++} \gtrsim 400 \text{ GeV}}$$

$$\Big\downarrow \delta_R^{++}$$

$$\boxed{\text{direct access to } M_N}$$

$$\Downarrow$$

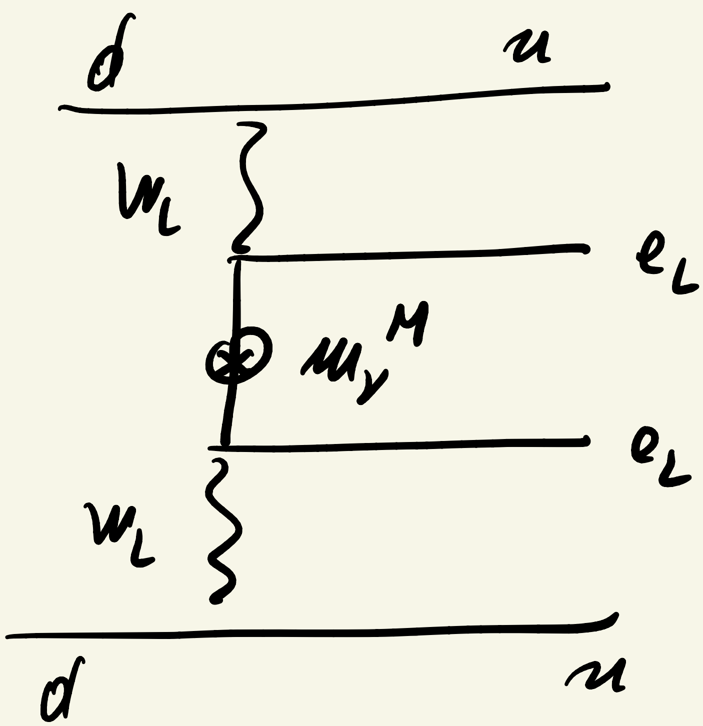
$$\boxed{\text{Low energy experiments}}$$

$$\left(\text{from } M_N = V_R \, m_N \, V_R^T \right)$$

(i) $\Delta L = 2$ $\quad (\Leftrightarrow \Delta(B-L)=2)$

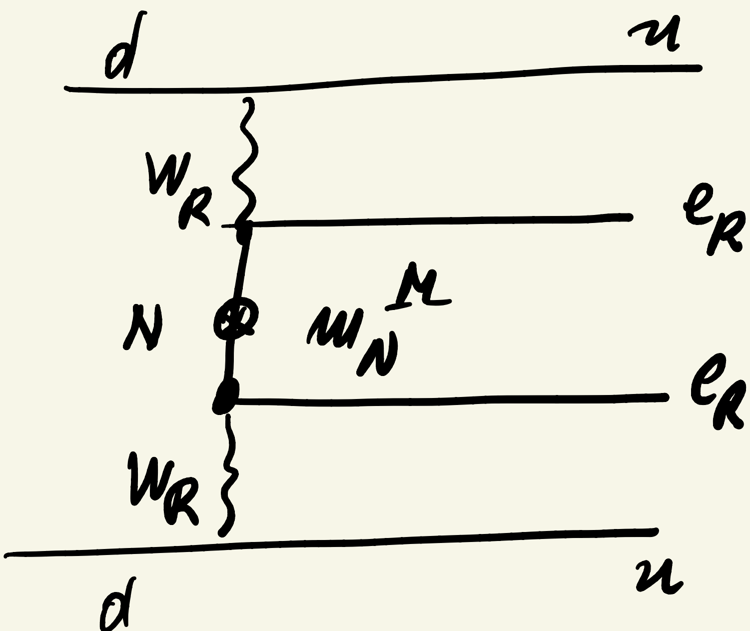
$\Delta B = 0$

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



$$A_\nu \propto G_F^2 \frac{m_\nu^M}{p^2 - \cancel{m_\nu^2}}$$

$p \simeq 100$ MeV – GeV



$M_L \equiv M_{W_L}$

$M_R \equiv M_{W_R}$

$$A_N \propto G_F^2 \left(\frac{M_L}{M_R}\right)^4 \frac{m_N^M}{\cancel{p^2} - m_N^2}$$

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

$\uparrow m_N^{?}, \; v_R$ ie

$$A_\nu \simeq G_F^2 \frac{10^{-10}}{(10^{-2}-1)} \text{GeV}^{-1} \simeq G_F^2 (10^{-8}-10^{-10}) \text{GeV}^{-1}$$

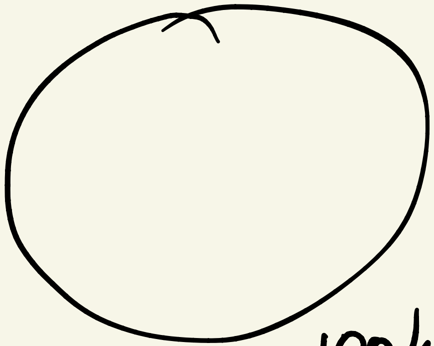
$$A_N^{(LHC)} \gtrsim G_F^2 \, 10^{-8} \cdot 10^{-2} \, \text{GeV}^{-1} \quad (m_N = 100 \, \text{GeV})$$

$$M_R \simeq 8 \, \text{TeV}$$

Low E : $0\nu 2\beta$

$e_R \Rightarrow W_R$ exchange

$\Rightarrow M_{W_R} \lesssim 10$ TeV



next (LHC)'

100km

$\boxed{\ell_R \text{ in } 0\nu 2\beta \Rightarrow W_R \text{ at LHC}'}$

ii) $\boxed{\text{LFV} \quad \text{lepton Flavor Violation}}$

(a) $\mu \to e + \gamma$

$\mu \to e + Z^* \to e + \cancel{\nu + \bar{\nu}}$

$+ e + \bar{e}$

(b) $\mu \to e + e + \bar{e}$

(c) $\tau \to e + e + \bar{e}$

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

$e + \mu + \bar{\mu}$

. - - - -

$\boxed{\underline{SM} + \text{massive } \nu}$ ←

• quarks ← BFV

↔ V_{CKM} (W boson)

• lepton ← LFV

↔ V_{PMNS} (W boson)

$\boxed{LFV}$ $\left\{ \begin{array}{l} \nu_e \to \nu_\mu \\ \nu_\mu \to \nu_\tau \end{array} \right.$?

$\{ \nu_e \to \nu_\tau \}$

$$\frac{g}{\sqrt{2}} \left(\bar{\nu}_1 \; \bar{\nu}_2 \; \bar{\nu}_3 \right)_L \bar{V}_{PMNS} \, \gamma^\mu \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}_L W_\mu^+$$

diagonal

$$V_L^+ \cdots$$

$$M_\nu = V_L^* m_N V_L^+$$

- $\mu \to e\gamma$ $\quad BR(\mu \to e\gamma) = ?$

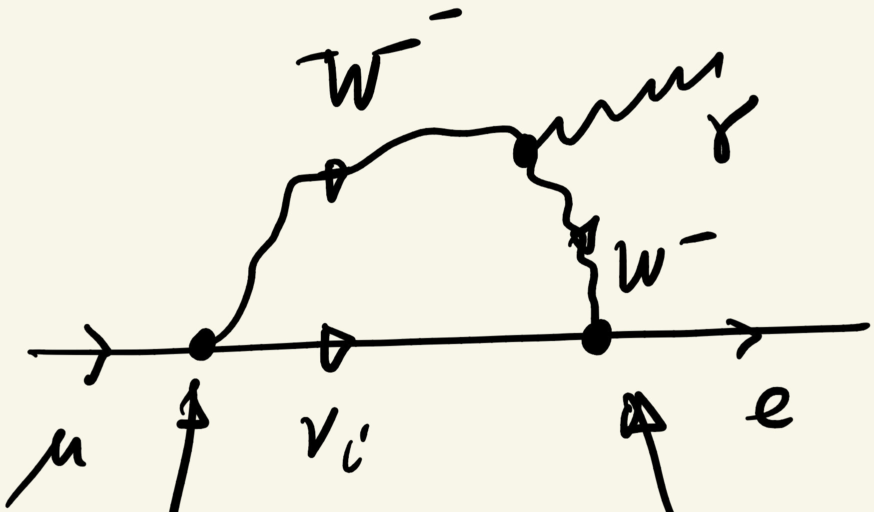
$$BR(\mu \to e\gamma) \equiv \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to \text{all})}$$

w_L

$$\cong \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e + \bar{\nu}_e + \nu_\mu)}$$

w_L

tree level



$(V_{PMNS})_{i\mu}$ $\qquad$ $(V^{+}_{PMNS})_{ei}$

$$BR(\mu \to e\gamma) \simeq \left(\frac{\text{loop}}{\text{tree}}\right) \cdot \sin^2 2\theta \cdot \left(\frac{\Delta m_\nu^2}{M_W^2}\right)^2$$

$(\sin^2\theta \cos^2\theta)$

2 generations :

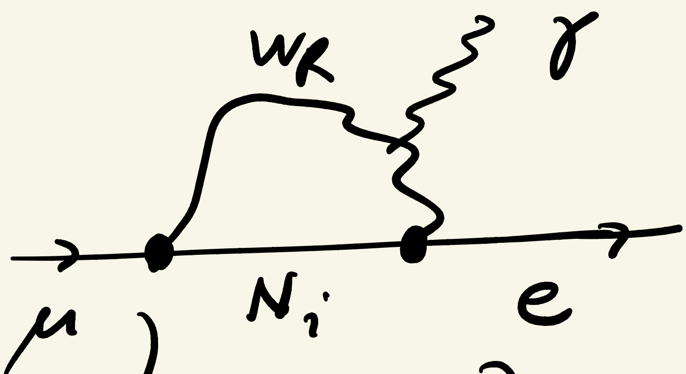
$$V_{PMNS} = \begin{pmatrix} \cos\theta_\ell & \sin\theta_\ell \\ -\sin\theta_\ell & \cos\theta_\ell \end{pmatrix}$$

$$\Delta m_\nu^2 \simeq 10^{-3}\,\mathrm{eV}^2 \simeq 10^{-21}\,\mathrm{GeV}^2$$

$$BR(\mu \to e\gamma) \simeq \frac{\alpha}{4\pi} \sin^2 2\theta \left(\frac{10^{-21}}{10^4}\right)^2$$

$$\lesssim 10^{-50} \;!!!$$

$\boxed{W_R,\quad N}$ <u>LFV?</u>



$(V_R^\dagger)_{ie}$

$(V_R)_{i\mu}$ ---

$$\Downarrow$$

$$V_R = \begin{pmatrix} \cos\theta_R & \sin\theta_R \\ -\sin\theta_R & \cos\theta_R \end{pmatrix}$$

$$BR(\mu \to e\gamma) \simeq \frac{\alpha}{4\pi} \sin^2 2\overset{\overset{LHC}{\downarrow}}{\theta_R} \left(\frac{\overset{\overset{LHC}{\downarrow}}{\Delta m_N^2}}{M_{W_R}^2}\right)^2 \cdot$$

$$\left(\frac{M_{W_L}^2}{M_{W_R}^2}\right)^2 \qquad M_{W_R} \simeq 100\, M_{W_L}$$

$$\simeq 10^{-8} \cdot 10^{-2} \left(\frac{\Delta m_N^2}{M_{W_R}^2}\right)^2 \leq 10^{-13}$$

feasible!

<u>exp:</u> $10^{-15} - 10^{-16}$

LNV $\leftrightarrow$ LFV

PhD Thesis Tello '2012