Neutrino Physics Course

Lecture XIX

5/7/2022

LMU

Summer 2022

Notation:

$$M_L \equiv M_{W_L} = M_W$$

$$M_R \equiv M_{W_R}$$

$$M_Z = M_{Z_L}$$

$$M_Z' \equiv M_{Z'} \equiv M_{Z_R}$$

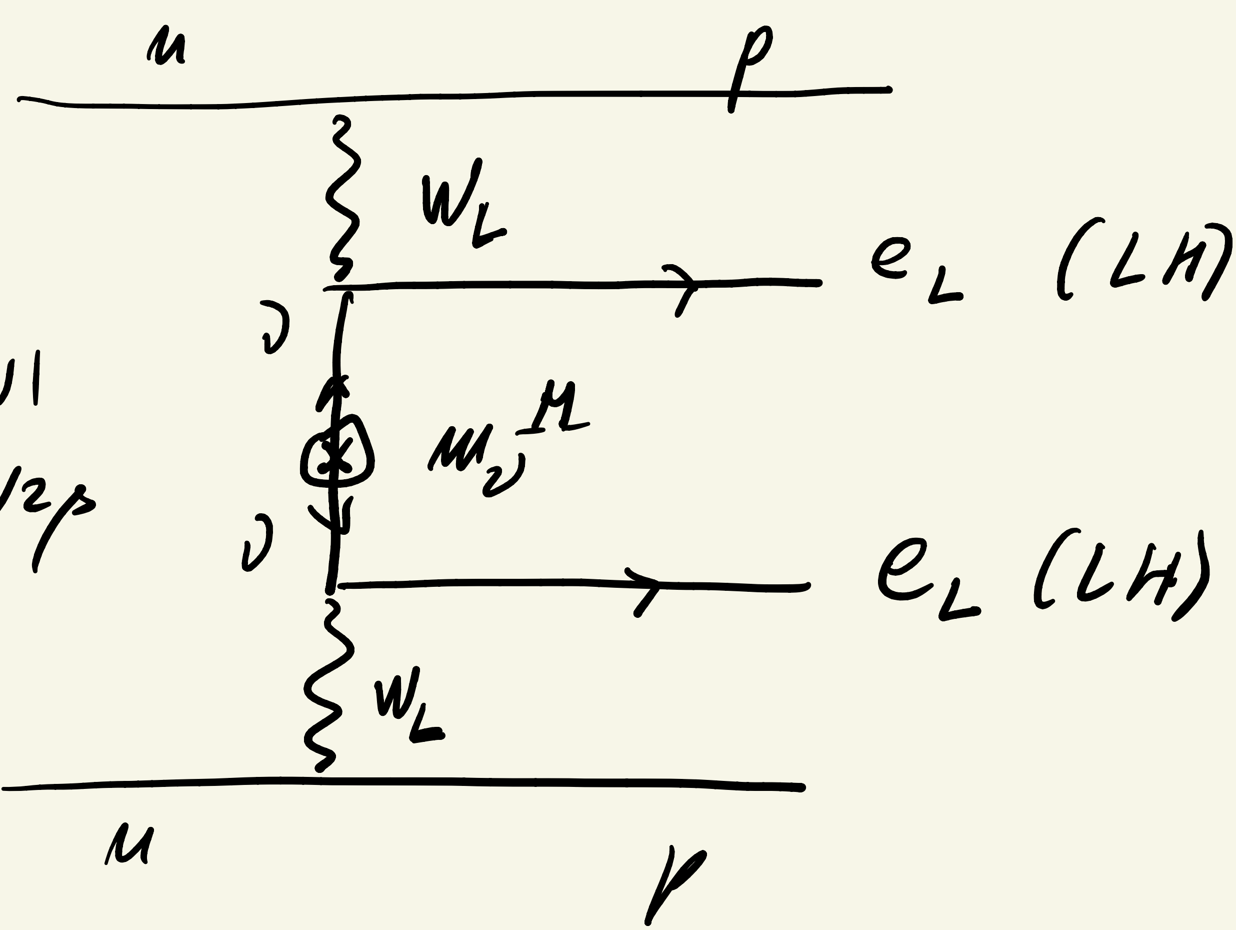
Majorana $\Rightarrow$ L N V

(Lepton Number Violation)

- <u>low E</u>

$(0\nu 2\beta)$

$A^{(\nu)}_{0\nu 2\beta}$



$\Downarrow$ GERDA

$\tau_\beta \gtrsim 10^{26}\ \mathrm{yr} \Rightarrow m_\nu^M \le 0.3\ \mathrm{eV}$

Q. $0\nu 2\beta \longrightarrow$ probe of m_ν^M ?

A. NO

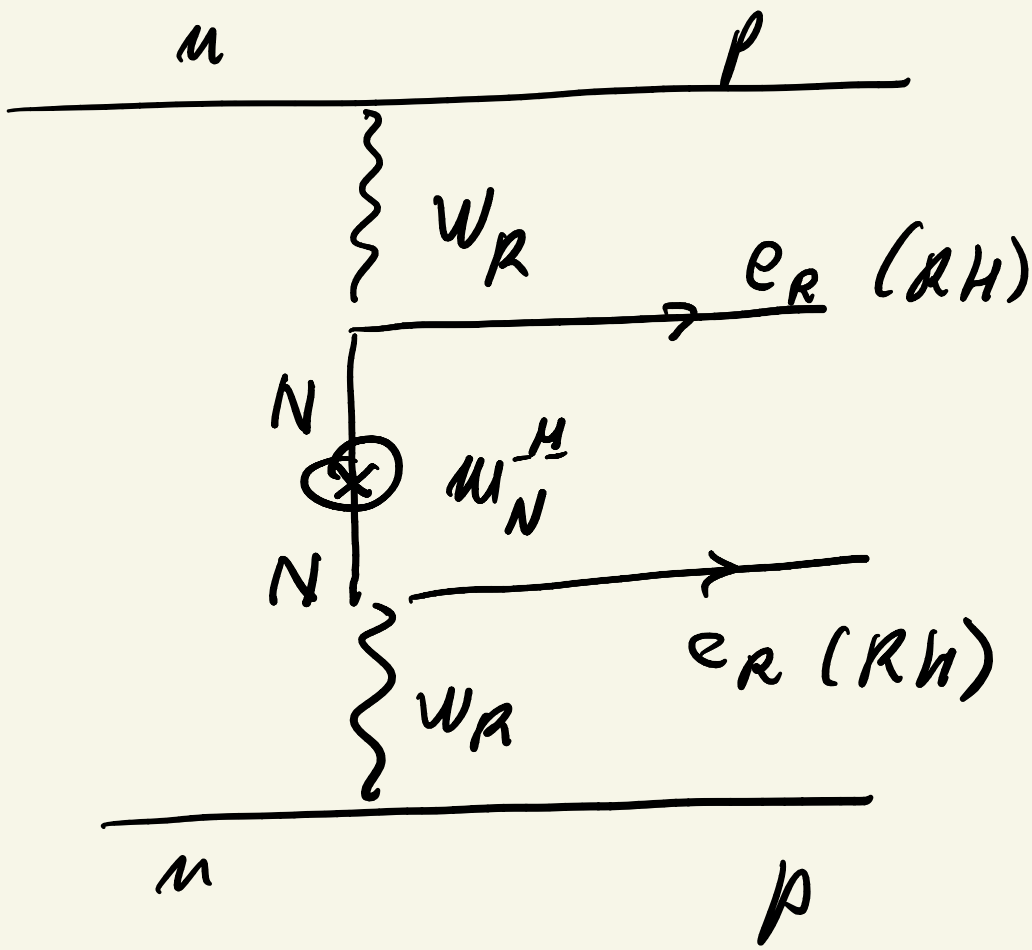
Imagine $e = e_R$ (RH)

$\Downarrow$

NOT through m_ν^M

Mohapatra, G.S. '79

$\boxed{\text{LRSM}}$ $\boxed{\text{if } L \Rightarrow R}$



$$A^{(N)}_{0\nu 2\beta}$$

$$\left(G_F \propto \frac{1}{M_L^2} \right)$$

$$\Downarrow \sim \left(\frac{M_L}{M_L}\right)^4$$

$$A^{(\nu)}_{0\nu2\beta} \simeq G_F^2 \frac{m_\nu}{\cancel{m_\nu^2}-k^2} \leftarrow k \simeq 100\,\mathrm{MeV}$$

$$A^{(N)}_{0\nu2\beta} \simeq G_F^2 \left(\frac{M_L}{M_R}\right)^4 \frac{m_N}{\cancel{k^2}-m_N^2}$$

$$M_R \to \infty \Rightarrow A^{(N)}_{0\nu2\beta} \to 0$$

- $$A^{(\nu)}_{0\nu2\beta} \simeq G_F^2 \frac{m_\nu}{10^{-2}\,\mathrm{GeV}^2}$$

$$\simeq G_F^2\, 10^{-8}/\mathrm{GeV}\,, \quad m_\nu \simeq 1/10\,\mathrm{eV}$$

$\simeq G_F^2 \, 10^{-9}/\text{GeV}, \quad m_\nu \simeq 1/100 \, \text{eV}$

- LHC: $M_R \gtrsim 5 \, \text{TeV} \quad (\simeq)$

$$\Downarrow$$

$$A_{0\nu 2\beta}^{(N)} \simeq G_F^2 \, 10^{-7} \frac{1}{m_N}$$

$$\simeq G_F^2 \, 10^{-8}, \quad m_N \simeq 10 \, \text{GeV}$$

$$\simeq G_F^2 \, 10^{-9}, \quad m_N \simeq 100 \, \text{GeV}$$

$$\simeq G_F^2 \, 10^{-10}, \quad m_N \simeq \text{TeV}$$

$$\Downarrow$$

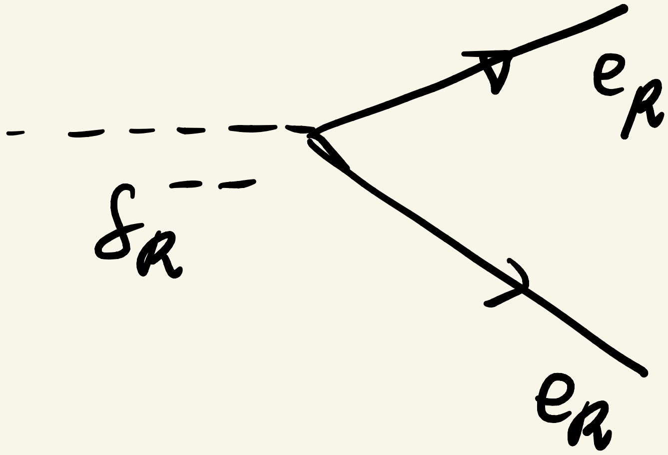
- if $0\nu 2\beta$ "Tomorrow"
  and
- if $e = e_R$ (RH)

$\Downarrow$ natural candidates

$$\boxed{\begin{array}{c} M_R \leq 10\,\text{TeV} \\ \\ \text{LHC} \longrightarrow \text{next collider} \end{array}}$$

$\Delta_R \longrightarrow \delta_R^{++} \ (\delta_R^{--})$

$\Delta_L \longrightarrow \delta_L^{++} \ (\delta_L^{--})$



- if $e = e_L$ (both electrons)

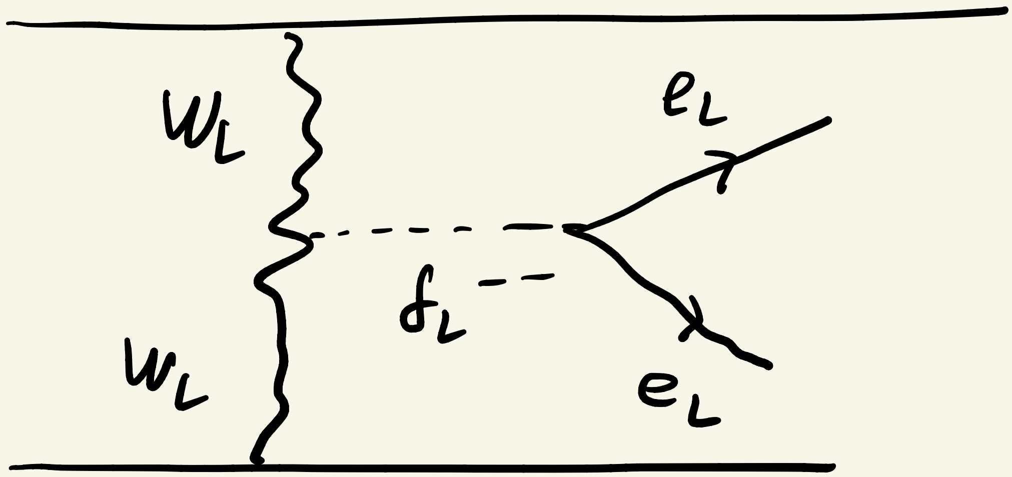
$\Downarrow$

m_ν^M is a "natural" explanation

<u>but</u>

NOT only

e.g. $\boxed{\delta_L^{--} \longrightarrow e_L + e_L}$

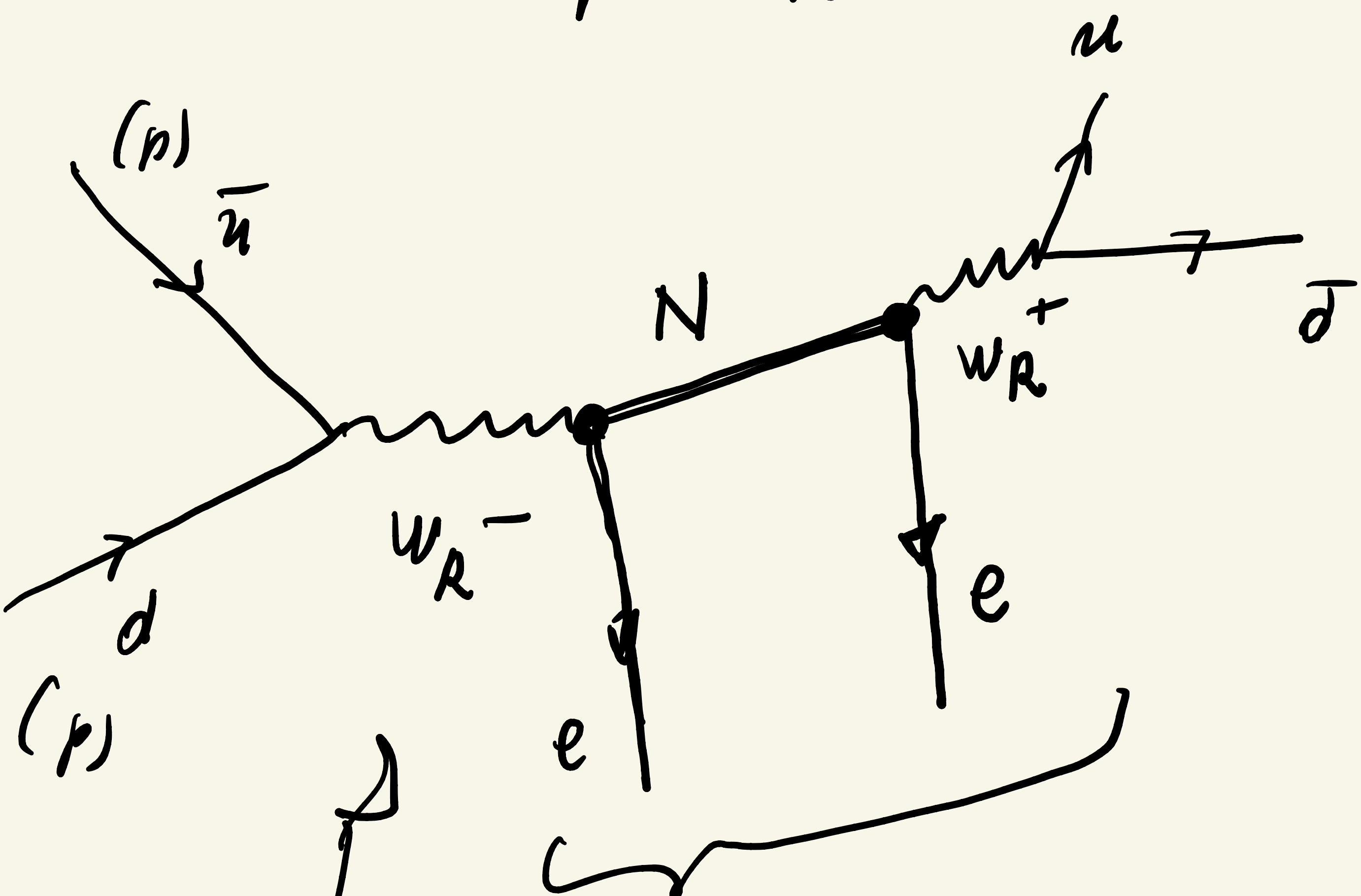


in LRSM this is suppressed

$\Rightarrow$ it is sub-dominant

- if $e = e_R$

I look for W_R



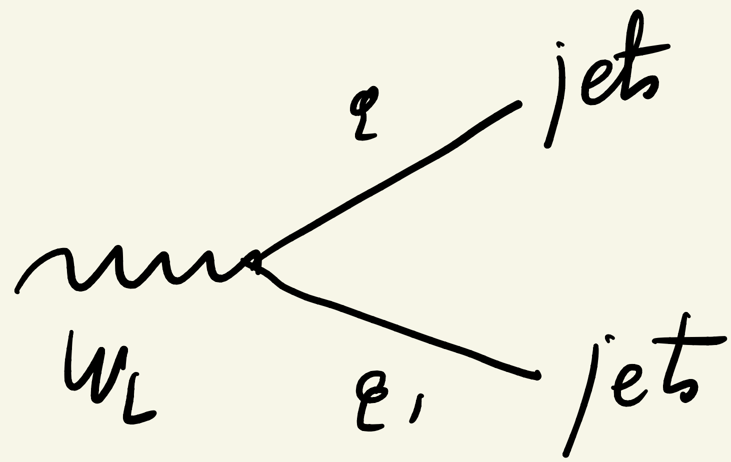
$\Delta L = 2$

measure M_R, M_N

$\Uparrow$

measure E_i, p_i (outgoing particles)

e.g.



LHC: $M_{W_R} \simeq 5.5$ TeV

$m_N \simeq 100$ GeV

int. $\simeq$?

$\Downarrow$

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

$\boxed{\text{Tello 2012 PhD thesis}}$

Experiment

- $0\nu 2\beta$ at low E

  many : NEMO, GERDA, EXO, Majorana, ZENO, ...

- KS process (LNV at colliders) at high E

ATLAS, CMS

$$\boxed{M_{W_R} \gtrsim 5\,\mathrm{TeV}}$$

SEESAW

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

input ?

NO

input: $M_\nu \leftarrow$ low E

(oscillations,

KATRIN, $0\nu 2\beta$, ...)

$M_N \leftarrow$ high E (LHC)

$\Downarrow$

$$\boxed{M_D \overset{?}{=} f(M_\nu, M_N)}$$

$$\Theta_{\nu N} = \frac{1}{M_N} M_D \quad (\text{def. } \Theta)$$

$\uparrow$ input $\quad (\Theta \ll 1)$

$\Downarrow$

$$N \longrightarrow \ell W^+ \quad (\propto \theta)$$

$\Updownarrow$ analogy

$$m_f = y_f v \Longrightarrow y_f = \frac{g}{2}\frac{m_f}{M_W}$$

$$m_f \longrightarrow y_f \Rightarrow \Gamma(h \to f\bar{f}) \propto y_f^2$$

$\Downarrow$ for seesaw

I need M_D

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

$$\Downarrow$$

$$M_D = i \sqrt{M_N}\; O \sqrt{M_\nu}$$

$$(M_\nu = M_\nu^T) \Downarrow (M_N = M_N^T)$$

$$M_\nu = (-1)(-)\sqrt{M_\nu}\; O^T \underbrace{\sqrt{M_N} \frac{1}{M_N} \sqrt{M_N}}_{1} O \sqrt{M_\nu}$$

$$M_\nu = + \sqrt{M_\nu}\; O^T O \sqrt{M_\nu} = M_\nu$$

$$\text{iff } (O^T O = 1)$$

$\uparrow$ ambiguity
(Casas-Ibarra)

$$\begin{cases} O \in \mathbb{C} \text{ in general} \\ O^T O = 1 \end{cases}$$

- $O \in \mathbb{R}$, $O^T O = 1$

  $\Rightarrow |O_{ij}| \leq 1$

- $O \in \mathbb{C}$, $O^T O = 1$

$$O = \begin{pmatrix} \mathrm{ch}\,\alpha & i\,\mathrm{sh}\,\alpha \\ i\,\mathrm{sh}\,\alpha & \mathrm{ch}\,\alpha \end{pmatrix}$$

$$O_{ij} \to \infty \; !!\; ??$$

See saw: $M_D \ll M_N$

$$\Updownarrow$$

$$M_\nu \ll M_D$$

$$\Downarrow$$

$\Theta \ll 1 \leftarrow$ but in SM

you produce N through

$\Theta \Rightarrow$ "never" produce N

at colliders

"$0 \to \infty$" $\Rightarrow$ $M_D \simeq M_N$

$\Rightarrow \Theta \simeq O(1)$

I can produce N !!

Opposite!

Good theory $\Rightarrow$ compute

M_D from M_ν, M_N

$$\boxed{\text{LRSM}: \quad M_D = f(M_\nu, M_N) \quad \text{predicted}}$$

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

<u>SM</u>

$$\mathcal{L}_Y = \bar{q}_L \, Y_d \, \Phi \, d_R + h.c.$$

$$M_d = Y_d \langle \Phi \rangle$$

$\uparrow$ arbitrary

$$\Rightarrow \quad M_d = \text{arbitrary}$$

$$\Rightarrow M_u, \; M_e, \; M_D \; \text{arbitrary}$$

LRSM

$$\mathcal{L}_Y = \bar{q}_L \, Y \, \Phi \, q_R + \bar{q}_R \, Y^\dagger \, \Phi^\dagger q_L$$

$$P: \quad q_L \longleftrightarrow q_R \qquad \Phi \longleftrightarrow \Phi^\dagger$$

$$q_L \to U_L \, q_L$$
$$q_R \to U_R \, q_R$$

$$\Phi \to U_L \, \Phi \, U_R^\dagger$$
$$\Phi^\dagger \to U_R \, \Phi^\dagger U_L^\dagger$$

$$\Downarrow$$

$$\boxed{Y = Y^\dagger}$$

$$\Rightarrow \quad \boxed{M = M^\dagger}$$

$$\Downarrow$$

$$\boxed{M_D^{+} = M_D}$$ (Tello, G.S. \ 2016-2020)

$$\Downarrow$$

$$M_D = f(M_D, M_N)$$

- simpler case: $M_D \in \mathbb{R}$

$$\Downarrow$$

$$\boxed{M_D = M_D^{T}} \Leftarrow (LR = C)$$

always true

PROVE!

$$\Downarrow$$

Nemevšek, Tello, G.S. 2012

$$\underline{M}_\nu = - M_D^T \frac{1}{\underline{M}_N} \underline{M}_D$$

$$\Downarrow$$

$$M_\nu = - M_D \frac{1}{\underline{M}_N} \underline{M}_D \Big/ \frac{1}{M_N} \text{ (LHS)}$$

$$\frac{1}{\underline{M}_N} \underline{M}_\nu = - \frac{1}{M_N} \underline{M}_D \frac{1}{M_N} \underline{M}_D$$

$$= - \left(\frac{1}{\underline{M}_N} \underline{M}_D \right)^2$$

$$\Downarrow$$

$$\frac{1}{\underline{M}_N} \underline{M}_D = i \sqrt{\frac{1}{M_N} \underline{M}_\nu} \Big/ M_N \text{ (LHS)}$$

$$\Downarrow$$

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

$$\left(\sqrt{\mathbb{1}_2} = \text{ambiguity} \right)$$

$M_\nu / M_N = \mathbb{1}\, c$ – pathology

$\boxed{O = \,?}$ Compute

$$M_D = i \sqrt{M_N}\; O \sqrt{M_\nu}$$

$$\Rightarrow \boxed{O = \text{fixed}}$$

$$y_D = \frac{m_D}{v_{SM}} = \frac{i\, m_N}{v}\sqrt{1/m_N \cdot m_\nu}$$

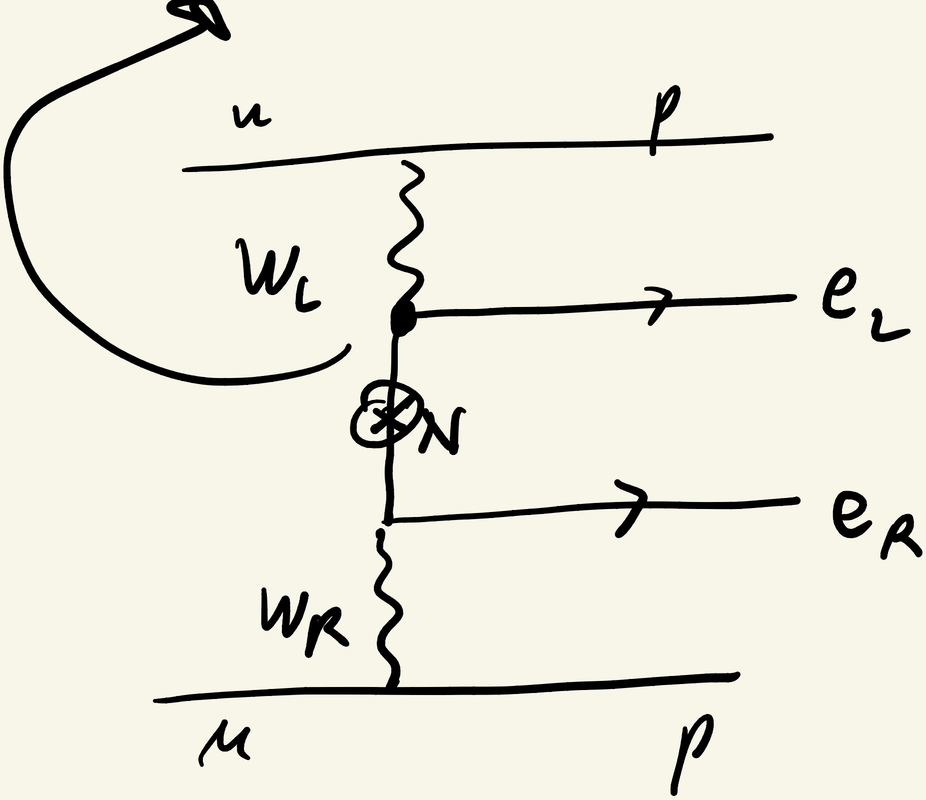
compute decays:

$$\left.\begin{aligned} N &\to e\,W^+ \\ &\quad\; \nu\, Z \\ &\quad\; \nu\, h \end{aligned}\right\}$$

$\Longleftrightarrow$ SM picture

$$\Gamma(h \to f\bar{f}) \propto y_f^{\,2}$$

$\Theta_{\nu N} \neq 0 \quad N \leftrightarrow W_L$



if $m_N \leq 100$ MeV ?

2β

the rest of the course

$\boxed{m_N \gtrsim 1\text{–}10 \text{ GeV}}$

$\boxed{SM}$ $$M_f = U_L^{+} m_f V_R$$

$$\Rightarrow V_{CKM} = U_{Lu}^{+} U_{Ld}$$

$\boxed{LR}$ $$V_R = V_L \Leftrightarrow M_f = M_f^{+}$$

$$\Downarrow$$

$$\boxed{V_{CKM}(R) = V_{CKM}(L)}$$