

Probing the origin - and
nature - of neutrino mass

Lecture III

18/8/2023

Fermilab



Neutrinos at colliders

SSB of $P \Rightarrow \exists \nu_R$

$$N_L = C \bar{\nu}_R^T \quad (RSM)$$



$$H_N \propto M_{-R} (-M_{\nu_R})$$



$$\left[M_\nu = - M_D^T \frac{1}{M_N} M_0 \right]$$

—(see saw)

$\Sigma M : H_R \rightarrow \emptyset \Rightarrow H_N \rightarrow \emptyset$

$\Rightarrow H_V \rightarrow \emptyset$

Seesaw ($\exists N$)



Prog:

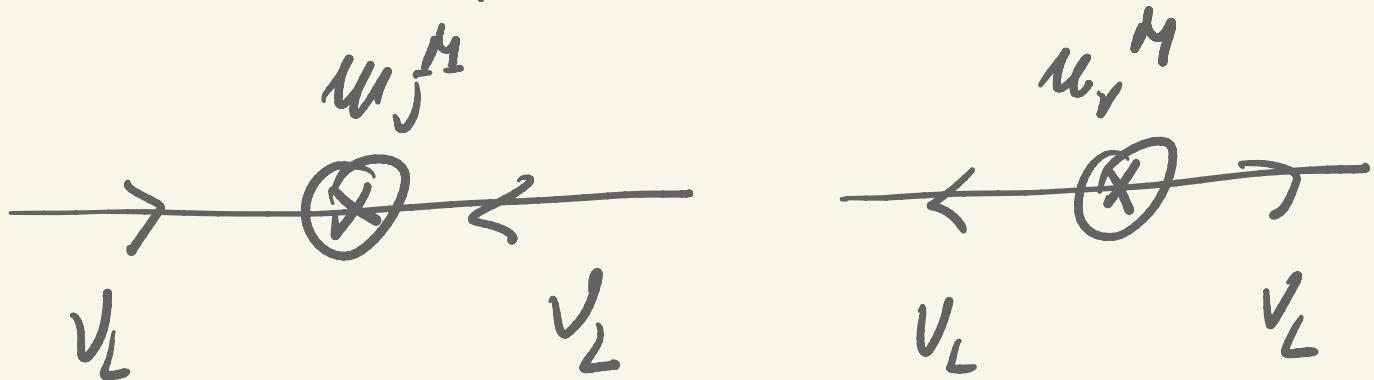
1) $m_\delta \sim m_e$

$\Rightarrow m_\nu \propto m_e \quad m_e/m_\nu \ll m_e$

2) $m_\nu^H V_L^\top \subset V_L + \text{h.c.}$

c

Hejona



$$\Delta L = 2$$

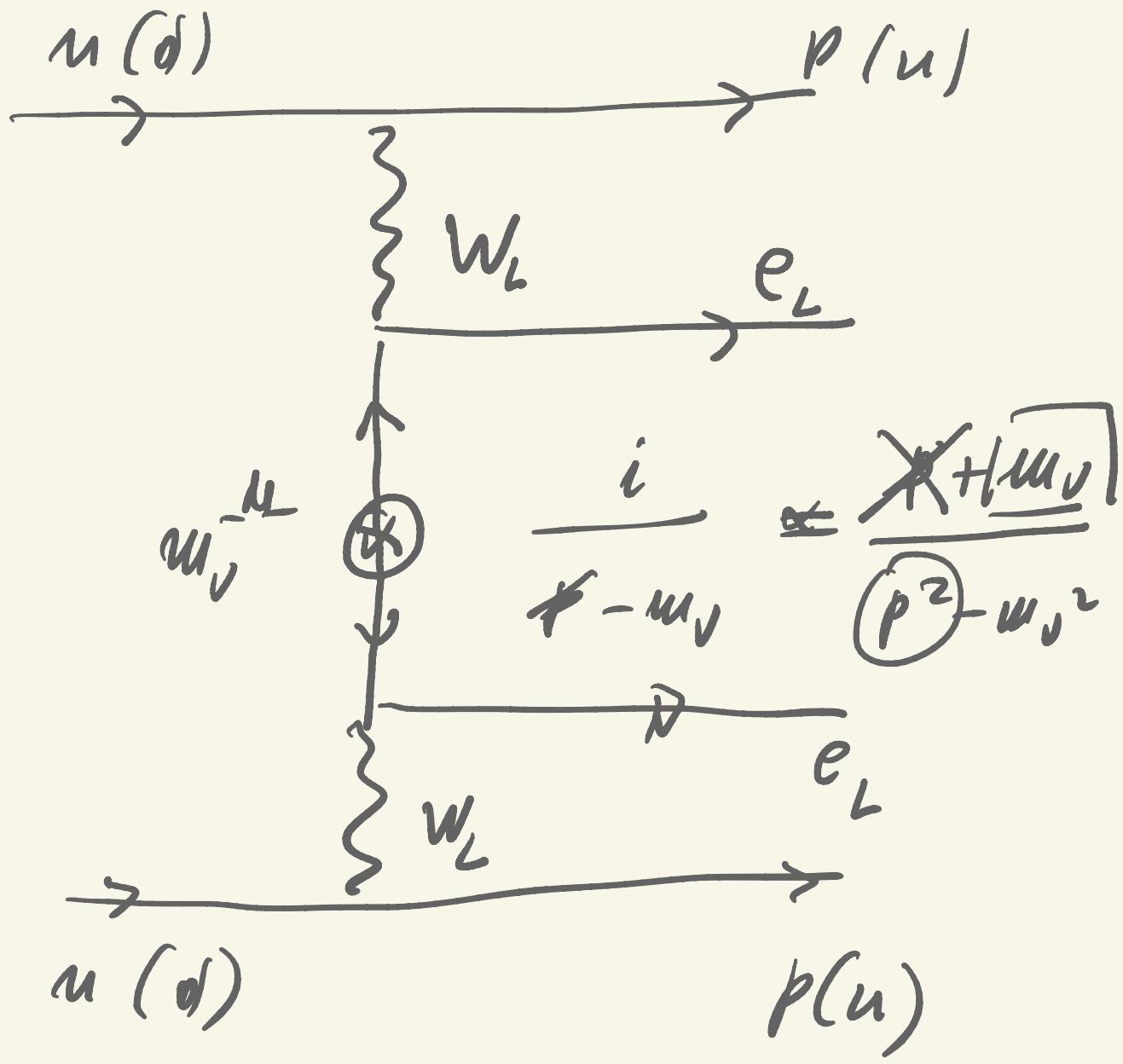
$$\Delta L = 2$$



$$0 \vee 2\beta = \text{low } E$$

$$(\Delta L = 2)$$

}



$$A_{\text{ov}2p} \propto \frac{\mu_L^M}{p^2}, p \approx \text{looked}$$

$$I_{\text{ov}2p} \approx 10^{26} \text{ A} \quad (\text{GERDA})$$

$$\Rightarrow \mu_L^M \leq 1 \text{ eV}$$

$Ov2\rho$ = probe of

↳ Majorana mass?

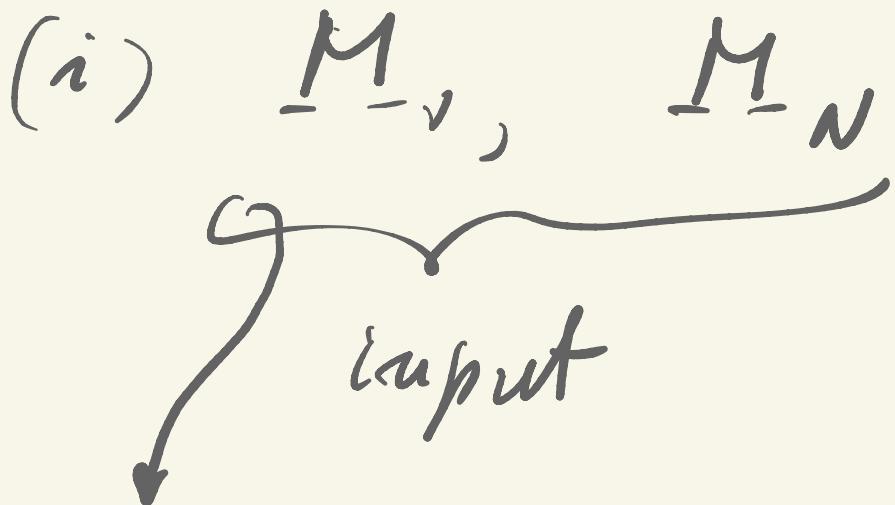
[NO]

$Ov2\rho$: $e = e_R$

\Rightarrow New Physics (NP)

$Ov2\rho$ = probe of NP?

Cons:



- $\cdot \underline{M}_{\nu} = V_L^* u_{\nu} V_L^+$

||
disregard (u_1, u_2, u_3) ,

low $E \leftarrow$ oscillations

- $\cdot \underline{M}_N = V_R u_N V_R^T$

$\uparrow \quad (M_N = M_R^*)$

$V_R, M_N \leftarrow LHC$

$$M_v = - M_D^T \frac{1}{M_N} M_D \quad (1)$$

$$M_D = i \sqrt{M_N} \begin{pmatrix} O & \sqrt{M_J} \end{pmatrix}$$

↓
Complex

$$M_D^T = i \sqrt{M_J} \begin{pmatrix} O^T & \sqrt{M_N} \end{pmatrix}$$

↓ Casas, Ibarra

~2000

$$H_\nu = -i \sqrt{\mu_\nu} O^T \sqrt{\mu_N} \frac{1}{\sqrt{\mu_N}}$$

$$i \sqrt{\mu_N} O \sqrt{\mu_\nu}$$

$$= + \sqrt{\mu_\nu} O^T O \sqrt{\mu_\nu}$$

$$\boxed{i \text{if } O^T O = 1}$$

$$\Rightarrow H_\nu = \sqrt{\mu_\nu} \sqrt{\mu_\nu} w$$

2×2

$$O = \begin{pmatrix} \cosh x & i \sinh x \\ i \sinh x & -\cosh x \end{pmatrix}$$

$$0 \rightarrow \infty \iff x \rightarrow \infty$$

Jeedom cannot determine M_0

$$\binom{v}{N} \rightarrow -U \binom{v}{N}$$

$$U = \begin{pmatrix} 1 & \theta^+ \\ -\theta^- & 1 \end{pmatrix}$$

$$\therefore \theta = \frac{1}{M_N} M_D \ll 1$$

$$\mathcal{V} \rightarrow \mathcal{V} + \theta^+ N$$

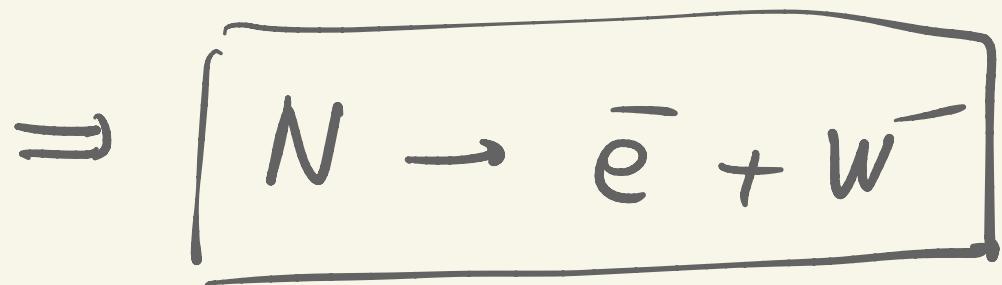
$$\Rightarrow \bar{\nu}_L \gamma^\mu e_L W_\mu^+ \rightarrow \dots$$

$\overbrace{+\bar{N}_L \partial^\mu \theta e_L W_\mu^+}$
 $+ \bar{e}_L \gamma^\mu \theta^+ N W_\mu^-$

$$N \rightarrow e + W^+ (\theta)$$

$$\begin{matrix} N^c \\ \Downarrow \\ N \end{matrix} \rightarrow \bar{e} + W^- (\theta)$$

$$N = N_L + C \bar{N_L}^T (N^c)$$



$$(ii) \quad \sigma(N) \propto \theta^2 \propto \frac{\mu_b^2}{\mu_N^2} \propto \frac{\mu_J}{\mu_N}$$

$$\mu_N \approx \mu_W \approx 100 \text{ keV}$$

$\sigma(N) \propto 10^{-11} \dots !!!$



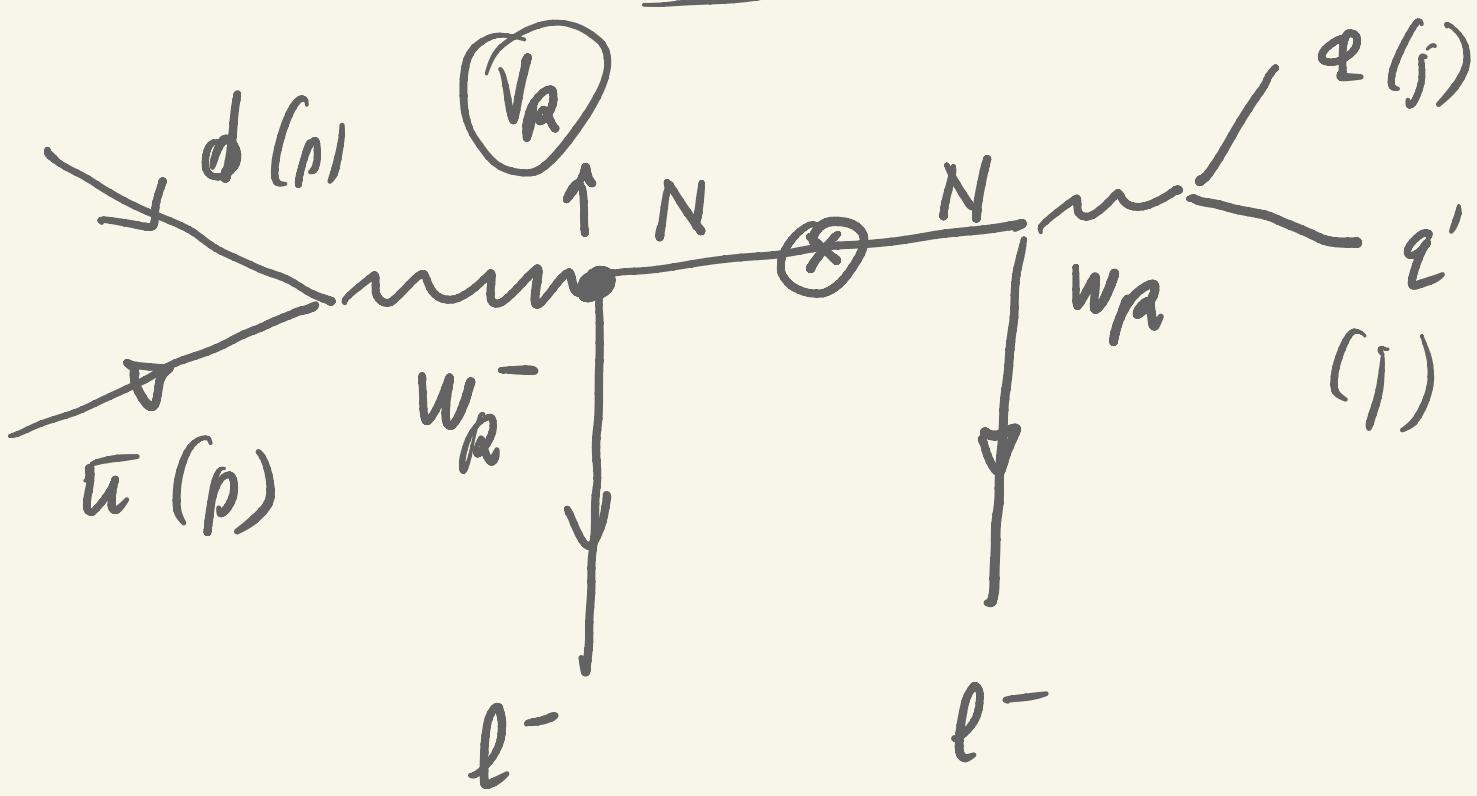
(ii) LRSM

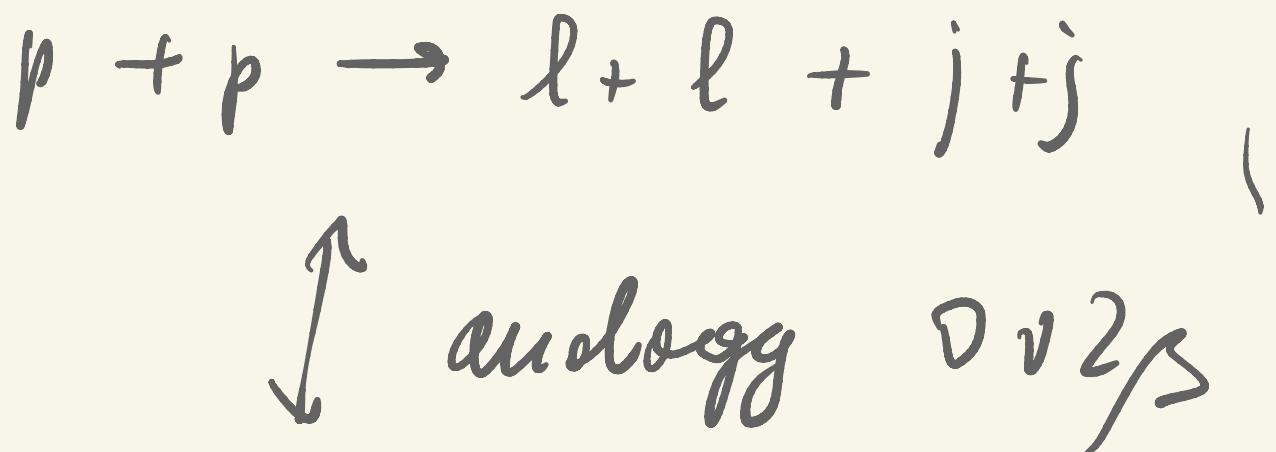
(w) $w_L \longleftrightarrow w_R \therefore$

$\bar{N}_R \delta^\mu e_R w_{\mu R}^+$ Production
at N

ks

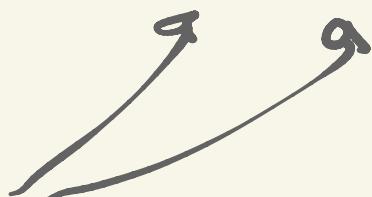
[Keung, G.S. 1983]





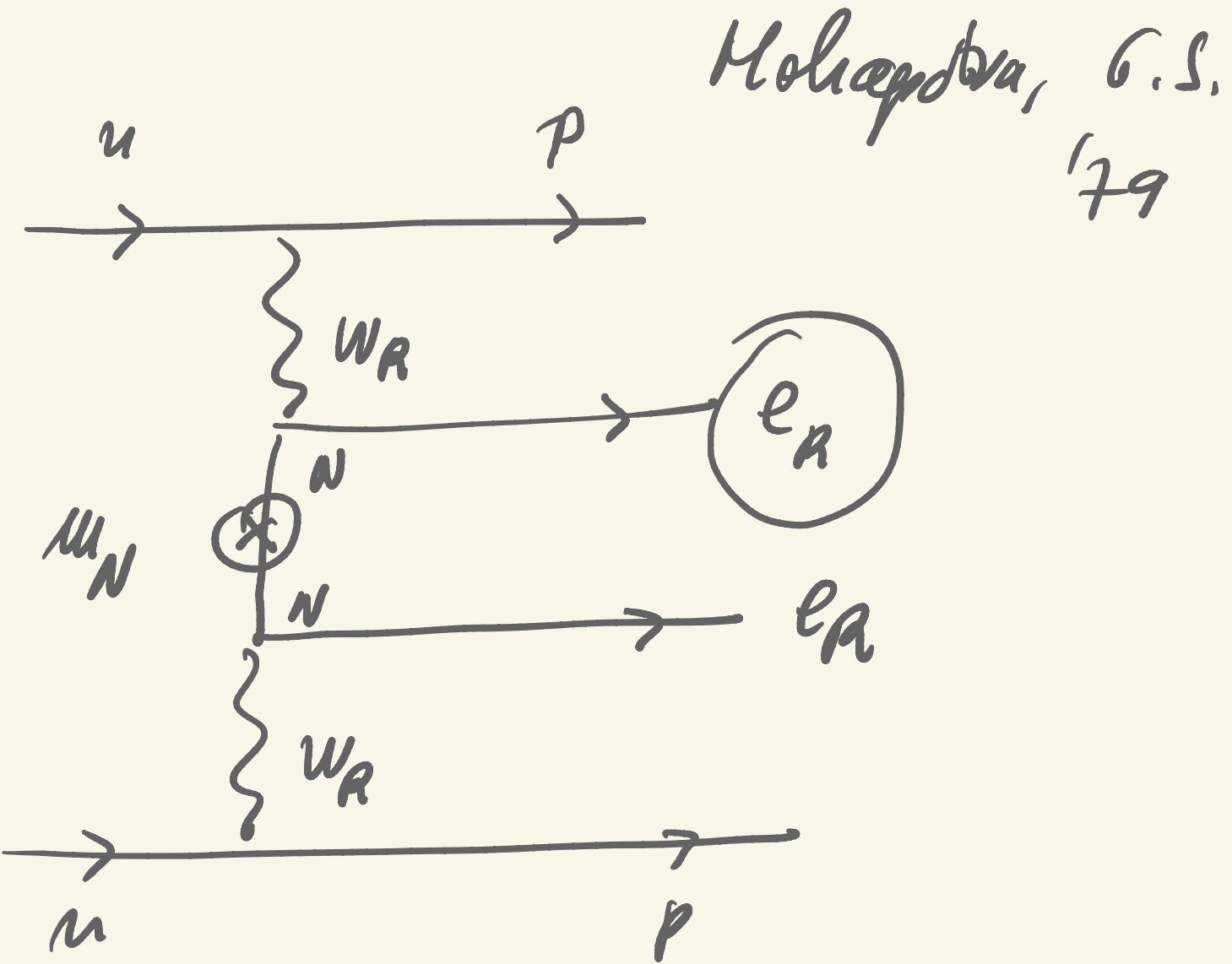
LHC (next collider)

$$\rightarrow M_N = V_R \quad u_N \quad V_R^T$$



measure both





if $e = e_R \Rightarrow$

imply (w_R, N)

$$\Rightarrow \boxed{M_{w_R} \approx 10 \text{ TeV}}$$

Nemirovich, Nest, Tello,

G. S. 2011

LHC: $M_{W_R} \gtrsim 4 \text{ TeV}$

future: $M_{W_R} \sim 6-7 \text{ TeV}$

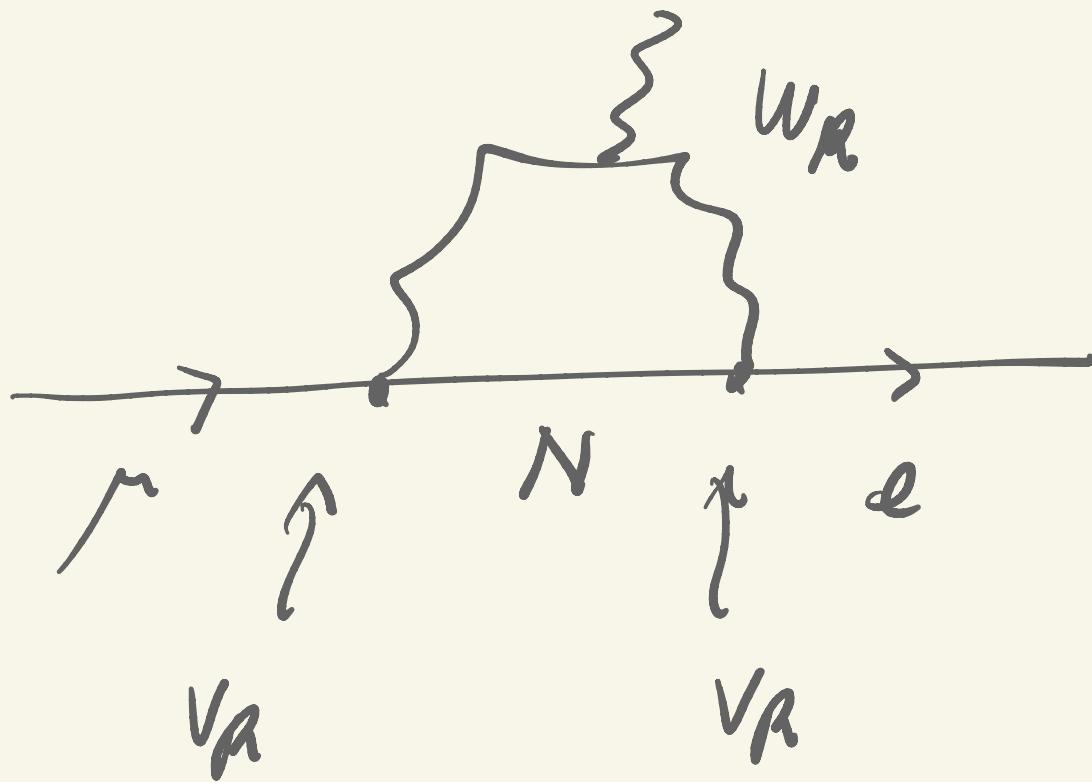
Tello 2012

PhD thesis

$(W_R, N) \rightarrow L F \bar{V}$

(Lepton Flavor Violation)

$\mu \rightarrow e \gamma$



$$Br(\mu \rightarrow e \gamma) \lesssim 10^{-12}$$

$\rightarrow M_{\text{up}} \simeq 100 \text{ TeV}$

upper limit

(i) $\boxed{\text{det. of } M_D}$

$$\overline{\nu}_R M_D \nu_L + \overline{\nu}_L M_D^+ \nu_R$$

$\underbrace{\hspace{10em}}$

Dvac mass term

• P.: $\nu_L \leftrightarrow \nu_R$ Tello, 6.S
2015-2020

$\Rightarrow \boxed{M_D = M_D^+}$

$$\cdot C : \nu_L \longleftrightarrow i\Omega_2 \nu_R^*$$

$$\Rightarrow \boxed{M_D = M_D^T}$$

Nemec Šeh, Tello, G.S.

2012

Example

$$C : M_D = M_D^T$$

$$\Rightarrow \frac{1}{M_N} M_V = - \frac{1}{M_N} M_D \frac{1}{M_N} M_D$$



$$\frac{1}{M_N} M_\nu = - \left(\frac{1}{M_N} M_D \right)^2$$



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



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



$$\left(\theta = \frac{1}{M_N} M_D \right)$$

$$\theta = i \sqrt{\frac{1}{\mu_N} \mu_V}$$

$$N \rightarrow e + W^+ (\theta) \quad \left. \right]^{1/2}$$

$$\rightarrow e^c + W^- (\theta) \quad \left. \right]^{1/2}$$

a

Majority of N

short

- $N \varrho$ hadron colliders:

(a) "Majority" $\begin{pmatrix} e \\ \bar{e} \end{pmatrix}$

(b) $M_N = V_R \mu_N V_R^T$



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



see saw

not a theory of mass

effective $d = 5$

operator analysis

Weinberg 1979

$$(J^T c v) \frac{\phi^2}{\lambda_{new}}$$

• $m_N \not> m_D$???

$m_N < m_D$

↓

$A_{ov2\beta} \propto m_N^{!!}$

