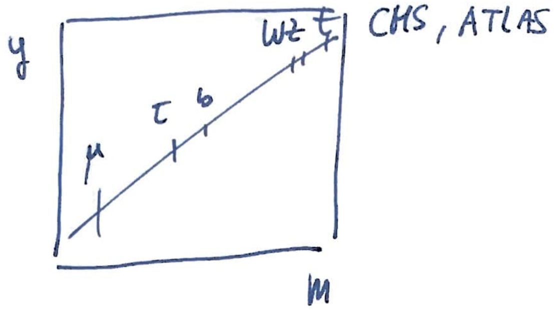
THEORY OF MASS ORIGIN

SM : $\mathcal{L}_Y = m_e \bar{l}_L \varphi l_R \Rightarrow \Gamma_{h\to f\bar{f}} \propto m_f^2$



But in the SM : $m_\nu = 0 \Rightarrow$ need New physics

THEORY OF NEUTRINO MASS

- Motivation(s) for BSM
  - Gravity, DM, SM aesthetics, global symmetries
  - NEUTRINO MASS = NEW PHYSICS
  - LNV, Dirac vs. Majorana, How to see it?

- In the SM with $m_\nu = 0$: $L_{e,\mu,\tau}$ and L are all conserved. We only have $L_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$ but no ν_R. So if we don't add non-renormalizable operators, neutrinos remain massless.

In the SM charged fermions

$$M_D \, \bar{\nu}_R \, \nu_L + h.c.$$

generic C matrix in family space

$$\| \qquad \text{with spinor indices explicit}$$

$$(\nu_R^c)^T \xrightarrow{\nearrow} M_D \, \nu^*_{R\dot{\alpha}} \, \nu_{L\beta} \, \delta^{\dot{\alpha}\beta} + h.c.$$

- However, for neutrinos, which are neutral, we can also write down the Majorana mass term

$$M_L \overline{\nu_L^c} \nu_L + h.c. = M_L \nu_L^T C \nu_L$$

$$\xrightarrow[\text{indices}]{\text{with spinor}} M_L \nu_{L\alpha} \nu_{L\beta} \varepsilon^{\alpha\beta} + h.c.$$

follows from the Pauli exclusion

$$\downarrow$$

here M_L is symmetric & $\mathbb{C}$ $\quad M_L^T = M_L$

- This Majorana mass term breaks any $U(1)$ because it looks like $\nu_L^{\textcircled{T}} \nu_L$, so we cannot give it to e.g. electron, it would break charge!

- However we can get $\nu_L^T C \nu_L$ from a gauge & Lorentz invariant operator(s). At the lowest order, this is the so-called Weinberg operator

$$\boxed{\mathcal{O}_W^{d=5} = \frac{\lambda}{M} (\ell H)(\ell H)}$$

- The $O_W^{d=5}$ is useful if no new physics states are reachable (we do experiments with $\sqrt{s} < M$), but if the states are accessible, we should consider the complete theory. = SEE-SAW

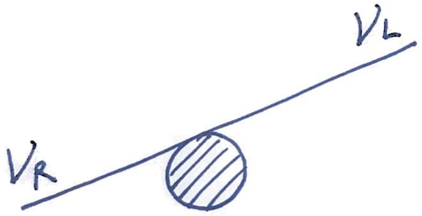
$$(\nu_L \quad \nu_R^c)\begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \xrightarrow{\text{DIAG.}} \begin{pmatrix} M_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

if $M_R \gg M_D \Rightarrow M_\nu \simeq - M_D^T M_R^{-1} M_D$

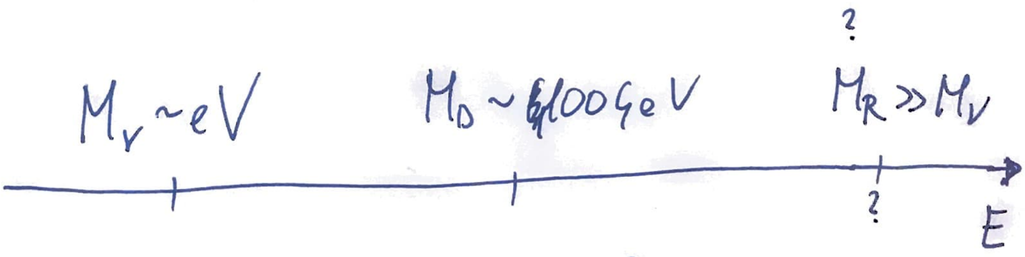
$M_N \simeq M_R$

$\Downarrow$

SEE-SAW : large $M_R \Rightarrow$ small M_ν



$M_R \gg M_\nu$



$y_D \leq O(1) \Rightarrow M_D \lesssim 500$ GeV

$M_R \gtrsim 10^{13 \div 15}$ GeV

} GUTs not observable

- strictly speaking, there's no lower bound on M_D so

$$M_D \in \underbrace{100\,\mathrm{eV} - 100\,\mathrm{GeV} - \mathrm{TeV} - 10^{15}\,\mathrm{GeV} \ldots}_{\text{observable at colliders}}$$

- Another way of getting the Weinberg operator is by introducing another Higgs boson = triplet Δ_L under $SU(2)_L$ with $Y = 2$

$$\mathcal{L}_{Y_\Delta} = Y_\Delta \, L_L^T \, \Delta_L \, L_L ,$$

$$\Delta_L = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \underset{\substack{\downarrow \\ \text{gets a small vev } v_\Delta}}{\Delta^0} & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$\Rightarrow \quad M_\nu = v_\Delta Y_\Delta$ ... a Majorana mass for ν_L

- the vev v_Δ comes from the Δ potential

$$m_\Delta^2 \Delta^2 + \mu_\Delta H \Delta H \Rightarrow v_\Delta \sim \underbrace{\frac{v^2}{m_\Delta^2}}_{\text{again see-saw}} \mu_\Delta$$

- If we combine the ν_R & Δ_L, we have a <u>mixed</u> seesaw type I + II

$$M_\nu = \begin{pmatrix} M_L & M_D^T \\ M_D & M_R \end{pmatrix} \xrightarrow{\text{diag.}} M_L - M_D^T M_R^{-1} M_D$$

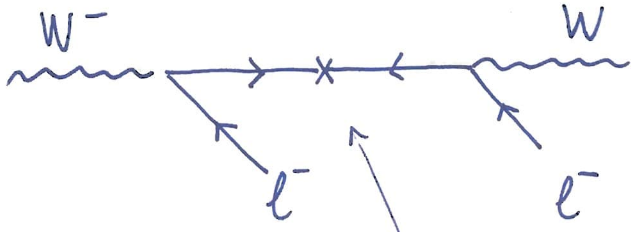
- We wrote M_ν, M_R, M_e in the flavor (gauge) basis. To get to the mass basis, we have to diagonalize these matrices

$$\left.\begin{aligned} M_e &= V_{eL}\, m_e\, V_{eR}^\dagger \\ M_\nu &= V_{\nu L}\, m_\nu\, V_{\nu R}^\dagger \end{aligned}\right\} \; V_{PMNS} = V_{eL}^\dagger V_{\nu L}$$

$\uparrow$

3 angles, 1 Dirac phase, 2 Majorana phases.

- Lepton number is broken

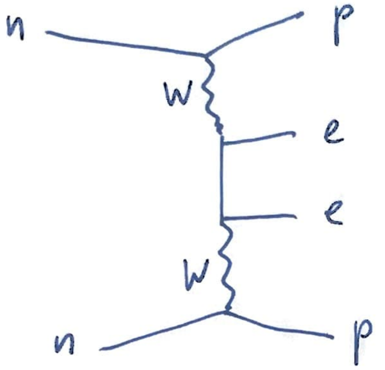


Majorana mass term $\nu_L^T C \nu_L$ breaks L by two units $\Delta L = 2$.

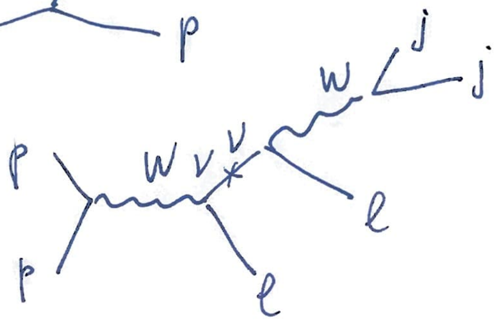
- LNV phenomenology

i) Nuclear process like β-decay $n \to p e \bar{\nu}_e$

$0\nu 2\beta$: neutrino-less double β decay



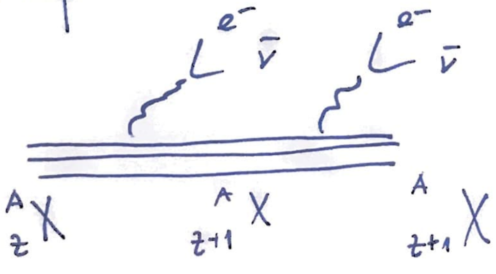
ii) At colliders



iii) LNV meson decays

$0\nu 2\beta$ in more detail

a) $2\nu 2\beta$: double beta decay (LNC)



(Maria Goepert-Mayer)

b) $0\nu 2\beta$:

@ 1loop

$Q \sim 3$ MeV , $p_\nu \sim 100$ MeV

$\Gamma_{0\nu\beta\beta} = G(Q)\,|\mathcal{M}|^2$

- decay rate $\Gamma_{0\nu 2\beta} = \underbrace{G(Q)}_{\text{phase space}} \times \underbrace{|\mathcal{M}|^2}_{\text{amplitude squared}}$

- The amplitude can be calculated (estimated) as

$$\mathcal{M} = 8 G_F^2 \int d^4x\, d^4y\, J^{\mu}_{had}\, J^{\nu}_{had}\, L_{\mu\nu}(x,y)$$

$$L_{\mu\nu} = \bar{e}\, \gamma_\mu \underset{\substack{\| \\ P_L \text{ projector}}}{L} \left[\frac{\not p + M_\nu}{p^2 - M_\nu^2} \right] \gamma_\nu \underset{\substack{\Downarrow \\ \text{the } (e_L)^c \text{ is} \\ \text{right-handed}}}{\underbrace{P_R e^c}}$$

now : $P_L \not p \gamma P_R = 0$

only $P_L M_\nu \gamma_\nu P_R$ remains , $L_{\mu\nu} \propto M_\nu$.

also $p^2 \gg M_\nu$

$$L_{\mu\nu} \propto M_\nu^{ee} \frac{1}{p^2} .$$

$\Downarrow$

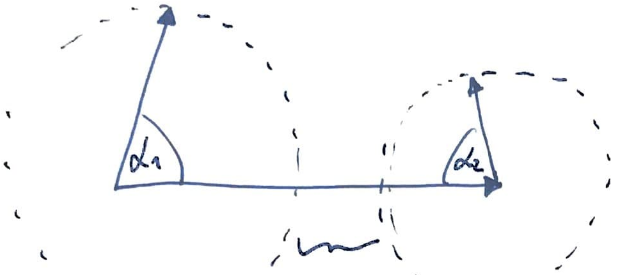
$0\nu 2\beta$ measures the e-e element of M_ν

$$M_\nu^{ee} = \sum \underbrace{U_{ei}^2}_{\text{PMNS}} m_i = m_1 |U_{e1}|^2 + m_2 |U_{e2}^{\cancel{2}}| e^{i\alpha_1} + m_3 |U_{e3}|^2 e^{i\alpha_2}$$

* depends on $\theta_{12,23,13}$, δ and $\boxed{\alpha_1, \alpha_2}$

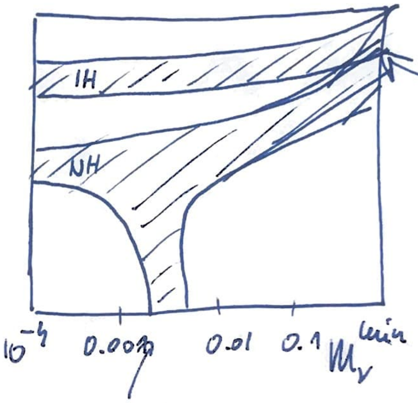
* sensitive to Maj. phases !!

GEOMETRIC PICTURE of M_ν^{ee}



can lead to cancellations in NH (not IH)

- Vissani '02 plot
- An observation
  1) LNV
  2) Measure of absolute mass



here they are degenerate NH ~ IH

Cancellation in NH

The hard part : nuclear matrix elements NMEs $M^{0\nu}$

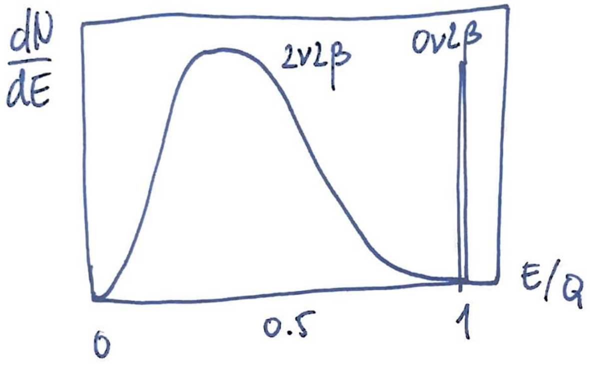
review by Engel-Mendez 1610.06548

- uncertain by few - 10 - 100 - 1000 %, depending on the nucleus A,

- How do we measure $0\nu 2\beta$

→ need a nucleus where β-decay is <u>forbidden</u>.

→ there are isotopes that are like that (use the Weizsäcker semi-empirical) (Ge, Mo, Xe, Cd, Nd, Ca)



* $2\nu 2\beta$ spectrum is continuous, goes all the way to the endpoint of the spectrum.

* $0\nu 2\beta$ has a peak at $E = Q$, a monochromatic line that stands out also

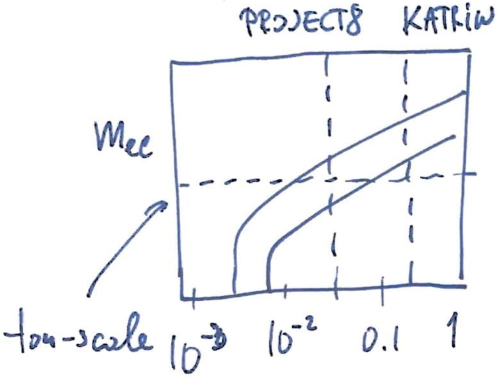
$$\tau_{0\nu 2\beta} < 10^{25-26} \text{ yrs} = \text{HUGE lifetime!}$$

$$10^{15} \times \tau_{\text{UNIVERSE}}$$

* To have sensitivity to such long lifetimes, one needs a huge sample (N_A × tons of material) with a very good control of the backgrounds

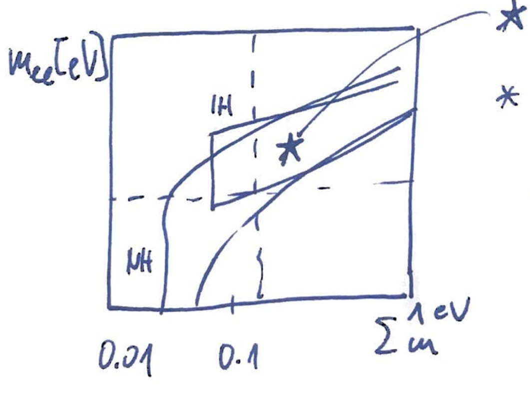
- There are two other types of experiments that are sensitive to the overall mass scale (unlike oscillations)

A) Endpoint kinematics in β decay (Tritium)



B) COSMOLOGY from large structure formation $\propto \sum m_\nu$

$$\sum m_i \lesssim 0.12\,\text{eV} \quad (\text{Planck})$$



* $0\nu 2\beta$ observation here

* may lead to tensions with Cosmology

- There is room for New Physics to trigger a signal in $0\nu 2\beta$ experiments. (from UV theories that give Majorana mass to neutrinos)

Let's look at operators that can give a

0ν2β signal

$$\mathcal{O}^{d=9}_{NP} = \frac{\lambda}{\Lambda^5}\, n n p p e e \Rightarrow A^{NP}_{0\nu} = \frac{\lambda}{\Lambda^5}$$

- we should compare to $A^{m_\nu}_{0\nu} = G_F^2 \frac{m_\nu}{p^2}$

for $\lambda \sim G_F^2 M_W^4 \Rightarrow \boxed{\Lambda \sim \text{TeV}}$ within the reach of colliders

- 0ν2β = WINDOW TO NEW PHYSICS @ TeV scales.

CAN WE TEST these LNV mediators also @ colliders?

↳ Need a theory to look for mediators.

Which theory? What should guide the construction of a UV theory of m_ν?

i) QUANTUM NUMBERS IN THE SM are ad-hoc in

$SU(2)_L \times U(1)_Y$

This simplifies with VERY SYMMETRIC

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \Rightarrow Y = T_{3R} + \frac{B-L}{2}$$

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

- This happens in a Left-Right symmetric model

$$\underbrace{SO(3,1)}_{\text{Lorentz space-time}} \times \underbrace{SU(3)_c}_{\text{color}} \times \underbrace{SU(2)_L \times SU(2)_R \times U(1)_{B-L}}_{\substack{\text{E-W symmetry now restored} \\ \text{at high scales}}}$$

- B-L is anomaly free but needs the $\boxed{\nu_R}$!

- This can be further unified in $SU(3)_c \times U(1)_{B-L} \to SU(4)_c$

- Or even further in $SO(10)$.

<u>PARITY</u> $\psi = \begin{pmatrix} \chi_L \\ \chi_R \end{pmatrix}$, $\gamma_0 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = 1 \otimes \sigma_1$

- does not commute with Lorentz ($K_i = \sigma_i \otimes \sigma_3$)

- the only way to restore parity is to exchange

  $\chi_L \leftrightarrow \chi_R$ and also $W_L \leftrightarrow W_R$

- Of course we don't see W_R, so we need the scale of breaking to be high.

- The L-R scale is broken spontaneously, with an extended Higgs mechanism. w. $\phi = (2_L, 2_R, 0)$

  + extra Higgses.

- The minimal LR model : $\underline{SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-}}$

Fermions : $L_{L,R}$, $Q_{L,R}$

Gauge bosons : G_μ^a , $W_{L\mu}^a$, $W_{R\mu}^a$

Scalars (Higgs) : $\phi = (2_L, 2_R)$, $\Delta_L = (3_L, 1)$

$\Delta_R = (1, 3_R)$

ϕ ↖ bidoublet

Δ_L, Δ_R ↓ two triplets

- Neutrinos get Majorana masses from couplings to the triplets.

$$M_N = y_\Delta \langle \Delta_R \rangle , \quad M_L = y_\Delta \langle \Delta_L \rangle$$

$$M_D = y_D v$$

- The mass spectrum is $M_{W_L} \sim 80\,\text{GeV}$, $M_Z \sim 90\,\text{GeV}$

$$\underbrace{M_{W_R} \sim g v_R \, , \quad M_Z \simeq \sqrt{3}\, g v_R}_{\text{can be around the TeV scale}}$$

- The implication of parity (or charge conjugation) is that $M_D = M_D^\dagger$ (P-parity) or $M_D = M_D^T$ (C-parity)

- This fixes $V_R^{CKM} \simeq V_L^{CKM}$ and $M_D = M_N \sqrt{\frac{v_L}{v_R} - \frac{1}{M_N} M_\nu}$

— UNG - F26 — Dirac is no longer free

- The new W_R interactions

$$\mathcal{L}_{W_R} = \frac{g}{\sqrt{2}}\,\bar{\ell}_R\,\gamma^\mu W_{R\mu}\, V_{RPMNS}\,\nu_R$$

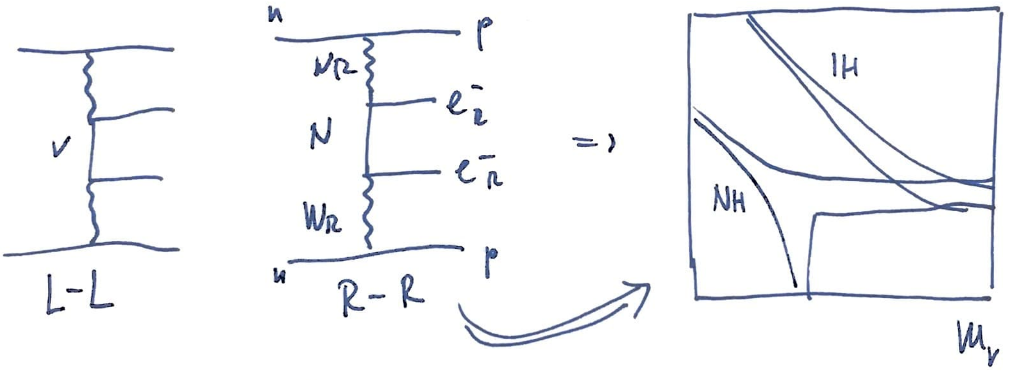
$$+\ \frac{g}{\sqrt{2}}\,\underset{\overset{\|}{\bar{u}_R}}{\bar{q}_R}\,\gamma^\mu W_{R\mu}\, V_{RCKM}\, d_R$$

- because of parity restoration $V_{RCKM} \simeq V_{LCKM}$

$$\Downarrow$$

flavor is fixed

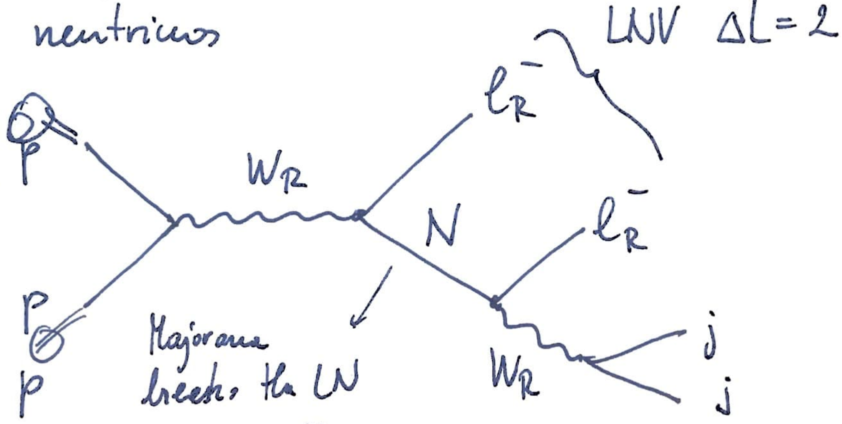
- With <u>new</u> interactions, we get more pheno, in particular we get new sources of $0\nu 2\beta$.



light Majorana neutrinos

heavy Majorana neutrinos

- LHC connection



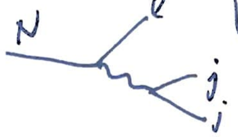
Keung, Senjanović, '83

- The LHC signal $pp \to \bar{\ell}\bar{\ell} jj$ would signal

  i) breaking of lepton number

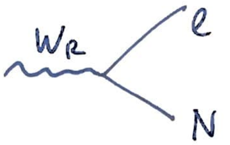
  ii) measure the flavor V_{RPMNS}

  iii) measure $m_N = m^{inv}_{\ell jjj}$



$\Big\}\ m^{inv}_{\ell qq} = m_N$

$M_{W_R} = m^{inv}_{\ell\ell jj}$



$\Big\}\ m^{inv}_{\ell N} \cong M_{W_R}$

- LHC reach is ~ 6 - 6.5 TeV

-> future colliders @ $\sqrt{s} = 30, 100$ TeV go to $M_{W_R} \sim 30$ TeV!

- It is also possible to determine whether W_R is really right-handed (polarizations)

FLAVOR CONSTRAINTS

- New physics constrained in $\underbrace{K^0 - \bar{K}^0}$, $B - \bar{B}$ measurement

  $M_{W_R} \gtrsim 1.6$ TeV '82

  $M_H >$ few TeV

- New limits: $M_{W_R} > 3$-4 TeV

  ↳ in the future B-mesons will dominate the bounds.

  $\Rightarrow M_{W_R} \gtrsim 8$ TeV!

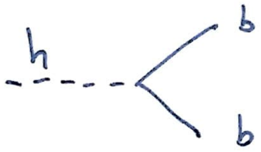
How do we test the neutrino mass generation?

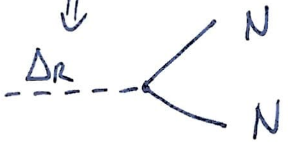
Higgs mechanism for neutrinos?

$\langle \phi \rangle = \begin{pmatrix} v & 0 \\ 0 & 0 \end{pmatrix}$ $\langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix}$

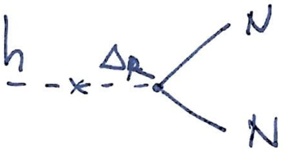
$h \to b\bar{b}$ in the SM $\Delta_R^0 \to NN$

$\Downarrow$





- h and Δ_R also mix, so



↳

a new, exotic decay that violates lepton number.

the reach of $M_{W_R} \gtrsim 7$ TeV @ the LHC.

BOUNDS from CP violation

- strong CP parameter $\bar{\Theta}$ is calculable $M_{W_R} \gtrsim 30$ TeV
- if an axion relaxation is present $M_{W_R} \gtrsim 10$ TeV

$$\underbrace{\text{NEW COLLIDERS} \qquad 0\nu 2\beta \qquad \text{B-mesons}}_{\boxed{\text{FUTURE}}}$$