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Recap

m_ν from $\bar{L}\,\tilde{\Phi}\,N_R$ (Dirac mass m_D)

(−) huge suppression for all generations

Solution: $\frac{1}{2} M_R\, \overline{N_R^c}\, N_R$ with new energy scale M_R

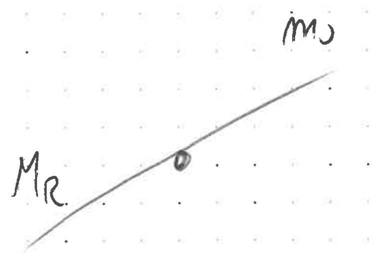
after EWSB: $m_\nu = m_D^2/M_R$ in $\mathcal{L} = \frac{1}{2} m_\nu\, \bar{\nu}_L\, \nu_L^c$

mixing of light „active" states with heavy „steriles"

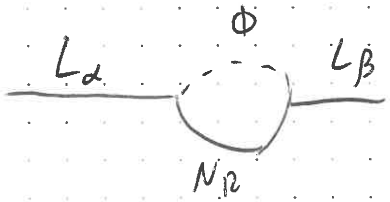
$\nu_{phys} = \cos\Theta\ \nu_L + \sin\Theta\ N_R^c$; $\Theta \simeq \frac{m_D}{M_R} = \sqrt{\frac{m_D^2}{M_R^2}} = \sqrt{\frac{m_\nu}{M_R}}$

for $m_D \sim m_{top}$: $M_R \sim 10^{15}$ GeV $\quad \Theta \simeq 10^{-12}$

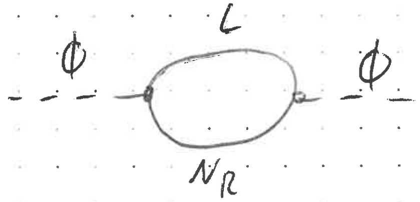
$m_D \sim m_e$: $M_R \sim$ TeV $\quad \Theta \sim 10^{-6}$



How to test seesaw? vertex $\frac{1}{v} m_D \bar{L} \tilde{\Phi} N_R$

1) 

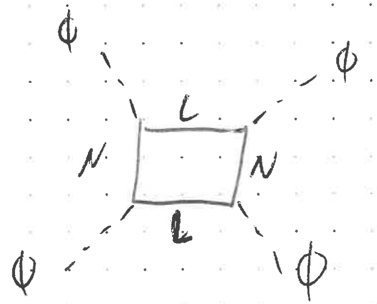
lepton flavor violation

2) a) 

$$\delta m_h^2 = \frac{m_D^2}{v^2 16\pi^2} M_R^2 = \frac{m_D M_R^3}{16\pi^2 v^2}$$

$\Rightarrow M_R \lesssim 10^7$ GeV from $\delta m_h^2 \leq$ observed Higgs mass

„naturalness"

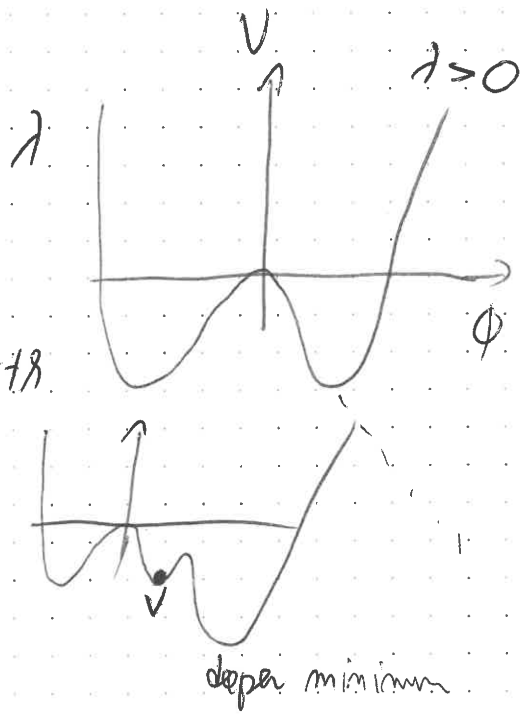
b) 

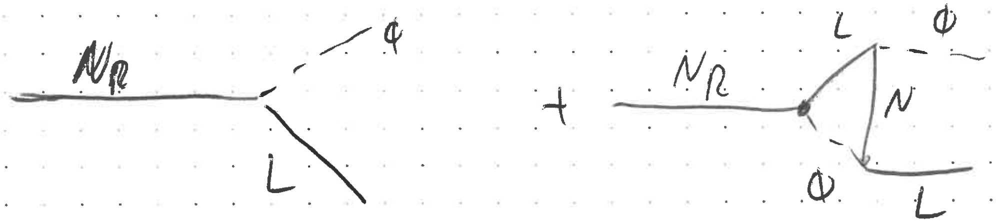
~~[illegible]~~ running of λ

$$\dot{\lambda} = -C \frac{m_D^4}{v^2}$$

λ becomes smaller with increasing energy

„vacuum stability"



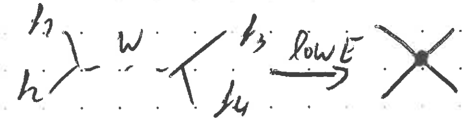
3) 

may create more matter than antimatter if m_D is complex

"leptogenesis"

Model-independently "Effective Theories"

write terms constructed out of SM fields with dimension > 4

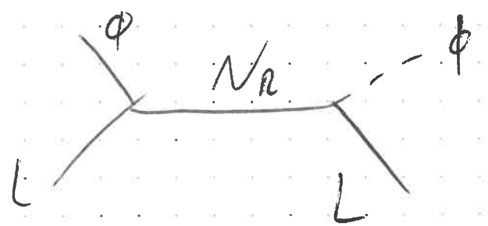
($\leftrightarrow$ Fermi $G_F\, \bar{f}_1 \gamma^\mu f_2\, \bar{f}_3 \gamma_\mu f_4$ 

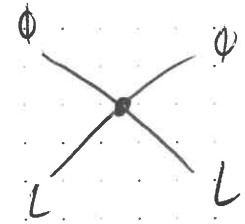
)

there is only one term of dim 5

$$\mathcal{L} = \frac{1}{\Lambda} \frac{1}{2} y\, \bar{L}\, \tilde{\Phi}\, \tilde{\Phi}^T L^c \xrightarrow{EWSB} \frac{1}{2} y \frac{v^2}{\Lambda} \bar{\nu}_L \nu_L^c$$

Weinberg operator

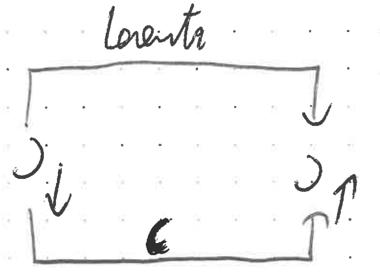


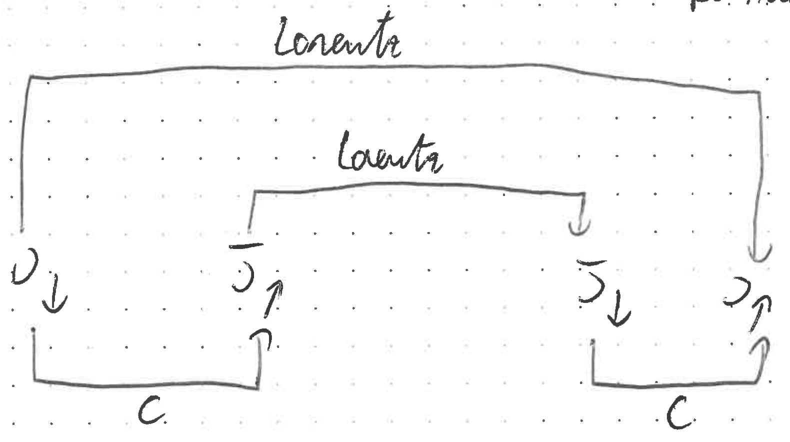


$M_R = \Lambda$

How to distinguish Dirac from Majorana ?

Dirac has 4 degrees of freedom ; Majorana has two (helicity ↑↓ particle or anti-particle)



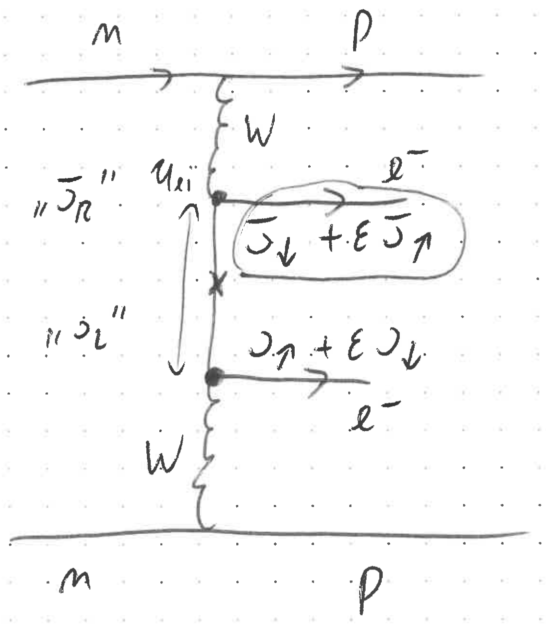


$\nu_M = (\nu_\downarrow , \nu_\uparrow)$

$\nu_D = (\nu_\uparrow , \nu_\downarrow , \bar{\nu}_\uparrow , \bar{\nu}_\downarrow)$

In SM, observable difference between D and M always suppressed:
ν are highly relativistic and helicity $\neq$ chirality

E.g. $\quad u_\downarrow = u_L^{(m=0)} + \frac{m}{2E} u_R^{(m=0)} \quad \Rightarrow P_R u_\downarrow \propto m/E$



"neutrinoless double beta decay" ($0\nu\beta\beta$)

$$(A, Z) \longrightarrow (A, Z+2) + 2e^-$$

$\varepsilon \sim \frac{m_i}{E}$

works if $\nu = \bar\nu$: absorb $\nu_\uparrow$ from upper vertex in lower vertex

rate suppressed by $\left(\frac{m}{E}\right)^2$

(example SM: $\nu_L = \nu_\uparrow + \varepsilon\,\nu_\downarrow$: antineutrino rate $\propto \varepsilon^2$)

Avogadro beats $\left(\frac{m}{E}\right)^2$ suppression!

E.g. ${}^{76}Ge \longrightarrow {}^{76}Se + 2e^-$: $T_{1/2} \gtrsim 10^{26}$ yrs

$$\Gamma(0\nu\beta\beta) \propto \frac{|U_{ei}^2\, m_i|^2}{E^2} \quad \text{with } E^2 \sim q^2 = \left(\frac{1}{fm}\right)^2 \sim (100\,\text{MeV})^2$$

with $\left|\sum U_{ei}^2\, m_i\right| = m_{ee}$ effective mass to be precise: $\Gamma(0\nu\beta\beta) = G(Q,Z)\,|\underbrace{M(A,Z)}_{\text{nuclear matrix element}}|^2\, m_{ee}^2$

$G(Q,Z)$: phase space factor

nuclear matrix element (factor 2-3 uncertainty)

m_{ee}^2: particle physics

Technical details: Majorana nature leads to new propagators!

usual propagator: $\langle 0|T\{\psi(x)\bar\psi(y)\}|0\rangle = S(x-y)$

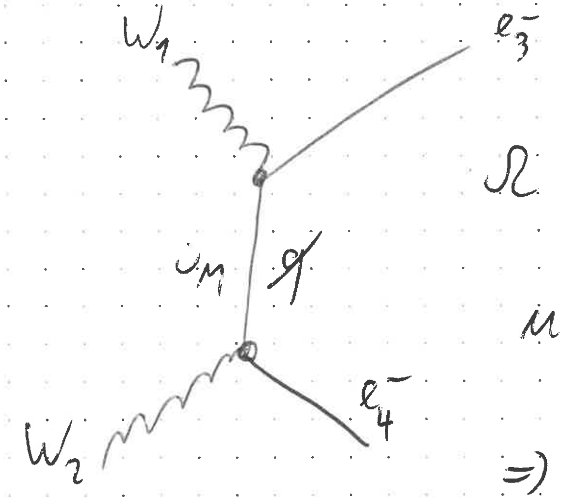
$$= -i\int \frac{d^4p}{(2\pi)^4}\,\frac{\not p + m}{p^2-m^2-i\varepsilon}\,e^{-ip(x-y)}$$

$$\langle 0|T\{\psi(x)\,\psi(y)\}|0\rangle = -S(x-y)\,C$$

$$\langle 0|T\{\bar\psi(x)\,\bar\psi(y)\}|0\rangle = C^{-1}\,S(x-y)$$

$\leftrightarrow$ production of two particles or antiparticles on mass dependence:

comes from $\mathcal{L} = \frac{-g}{2\sqrt{2}} \, \bar{e} \gamma^\mu (1-\gamma_5) \nu_M W_\mu$



$\mathcal{M} \propto \overline{e_3} \gamma_\mu (1-\gamma_5) \nu \quad \overline{e_4} \gamma_\nu (1-\gamma_5) \nu$

use identity $\quad \bar{e} \gamma_\mu (1-\gamma_5) \nu = -\overline{\nu^c} \gamma_\mu (1+\gamma_5) e^c$

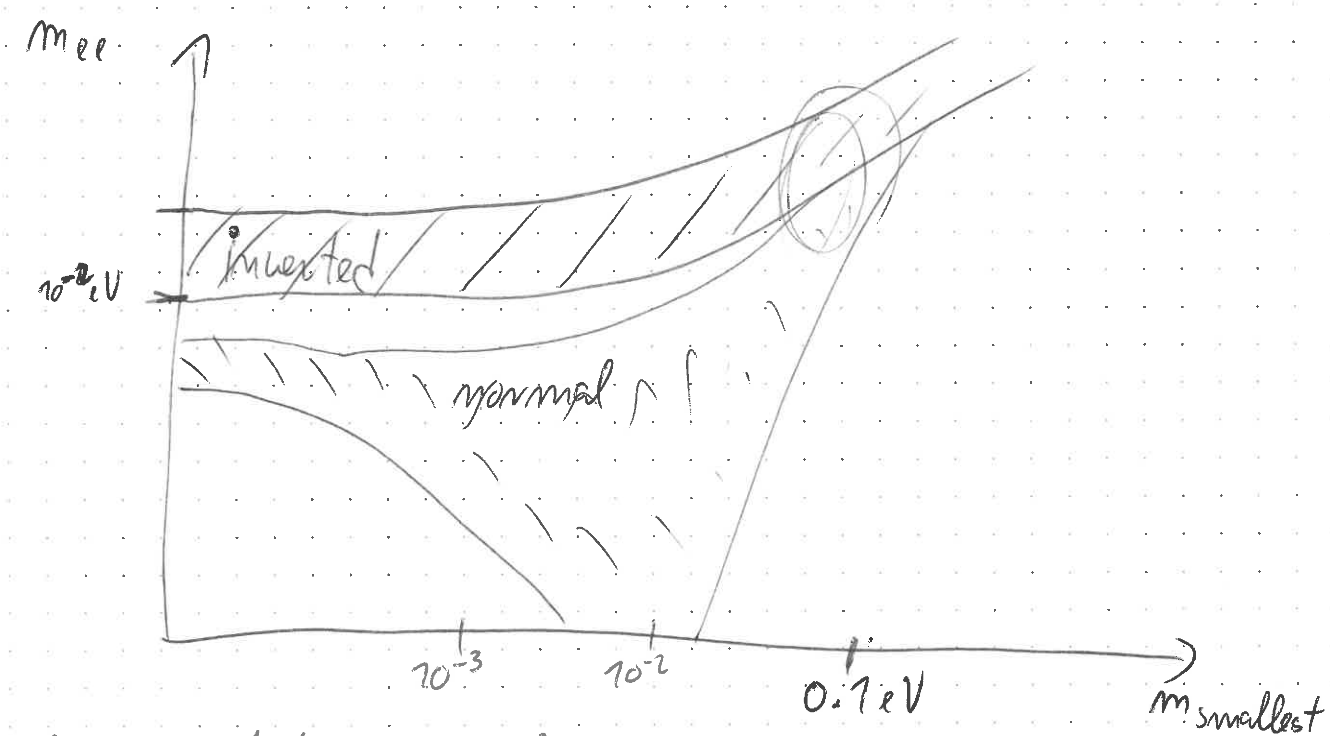
$\Rightarrow \mathcal{M} \propto \overline{e_3} \gamma_\mu (1-\gamma_5) \underbrace{\nu \overline{\nu^c}}_{\text{propagator}} \gamma_\nu (1+\gamma_5) e_4^c$

$\propto \gamma_\mu (1-\gamma_5) (\not{q} + m) \gamma_\nu (1+\gamma_5)$

$= \gamma_\mu (1-\gamma_5) m \gamma_\nu$

effective mass: $m_{ee} = \left| \sum U_{ei}^2 m_i \right|$ coherent sum

$= \left| \sum |U_{ei}|^2 e^{i\phi_i} m_i \right|$ (two new phases for Majorana neutrinos... mass term $\nu\nu^T$...)



(m_1 for normal, m_3 inver...)

1) inverted: m_{ee} always $\neq 0$

2) normal: m_{ee} can be zero ...

$T_{1/2} \gtrsim 10^{26}$ yrs $\Rightarrow m_{ee} \lesssim 0.2$ eV $\Rightarrow m_{smallest} \lesssim 0.6$ eV

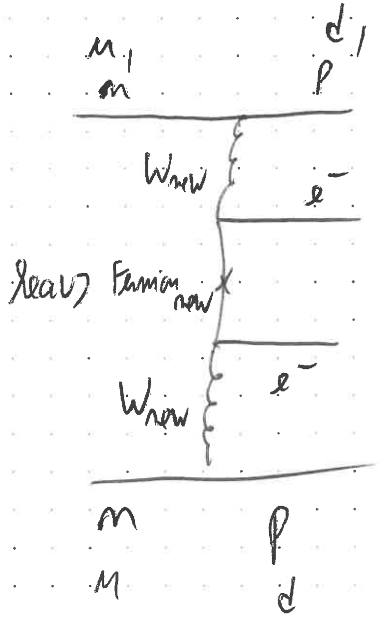
vs. cosmology: $\sum m_i \lesssim 0.5$ eV $\Rightarrow m_{smallest} \lesssim 0.15$ eV

$m_\beta \lesssim 0.8$ eV

$m_{smallest} \lesssim 0.8$ eV

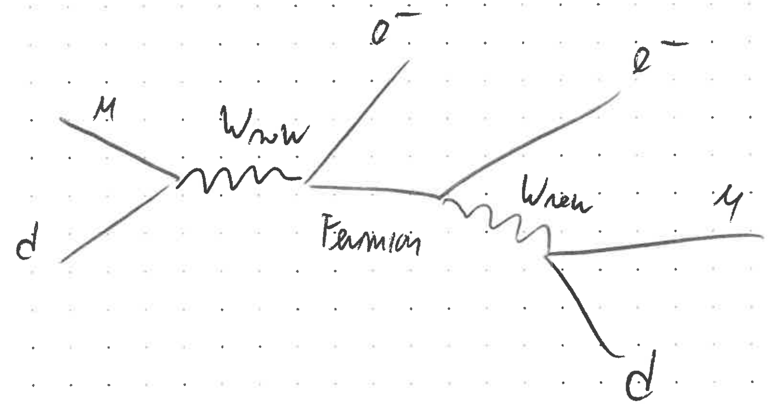
New physics in $0\nu\beta\beta$

standard $\mathcal{A} \simeq G_F^2 \frac{m_{ee}}{q^2} \sim 7 \cdot 10^{-18} \left(\frac{m_{ee}}{0.5\,eV}\right) \; GeV^{-5} \lesssim (TeV)^{-5}$



$\mathcal{A} \sim \frac{c}{M_{new}^5}$

$T_{1/2}(TeV) = T_{1/2}(eV)$



$pp \to 2e^- + 2j$

Black - Box - Theorem