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$$-m_D \overline{\nu_L} \nu_R - m_D \overline{\nu_R} \nu_L$$

$$\overline{\nu_R^c} \, \nu_L^c$$

$-m_D \overline{\nu_L} \nu_R$

$$= -\nu_R^T C^\dagger C \overline{\nu_L}^T$$

$-\frac{1}{2} m_D \overline{\nu_L} \nu_R$ $\quad$ $-\frac{1}{2} m_D \overline{\nu_R^c} \nu_L^c$

$$= -\nu_R^T \overline{\nu_L}^T$$

$$= + \overline{\nu_L} \nu_R$$

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$$m_l = \frac{m_D^2}{m_R} \sim \frac{\mathrm{GeV}^{\cancel{2}} \times \mathrm{GeV}}{10^{10}\,\mathrm{GeV}} \sim \underline{\underline{0.1\ \mathrm{eV}}}$$

$$m_R \uparrow \;\Rightarrow\; m_l \downarrow$$

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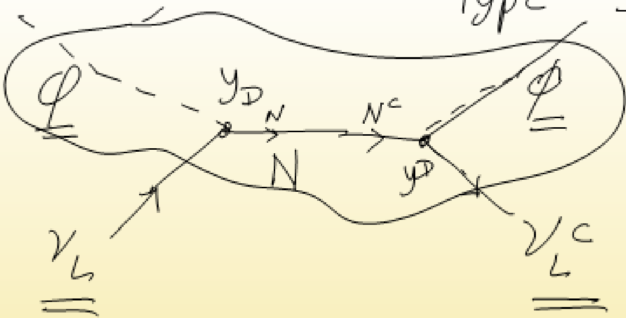
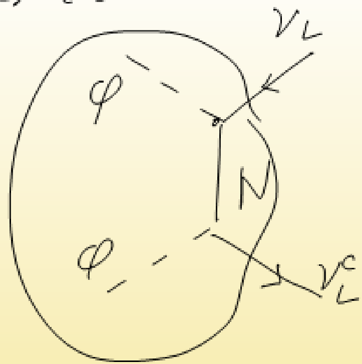
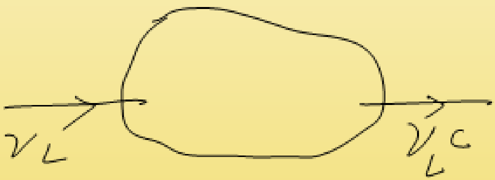
Type-I seesaw





$$\equiv$$



$$\overline{\nu_L^c}\,\Phi \quad y_D \frac{1}{\not{p}-m_N} y_D \quad \Phi^T \cancel{\Phi}\,\nu_L$$

 $\dfrac{y_D^2}{M_N}\,\underbrace{\overline{\nu_L^c}\,\Phi\,\Phi^T\nu_L}$

Amp:  $\overline{\nu_L^c}\,\nu_L$

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$$\mathcal{L}_{eff} \sim \square\, y_D^2 \cdot \frac{\ell \ell \Phi \Phi}{M}$$

$$K_5\, \ell \ell \Phi \Phi \; : \quad K_{abcd} \left(\overline{\ell_L^c}\right)_a \left(\ell_L\right)_b \left(\phi\right)_c \left(\phi\right)_d$$

depends on a, b, c, d

depends on Feynman rules (model)

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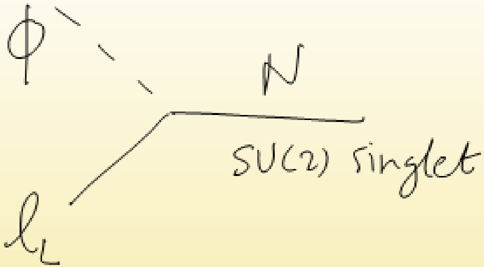
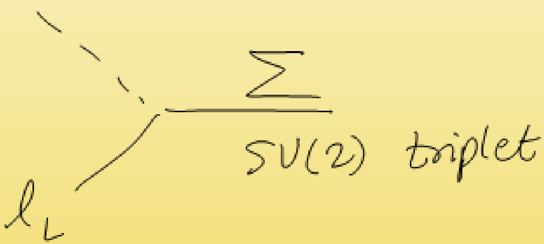
Type-III seesaw





$$\overline{l_L^c}\, l_L\, \phi\phi$$

$$\boxed{\frac{K_{abcd}}{M_\Sigma}}\ \overline{l_L^c}\, l_L\, v^2$$

Want a term

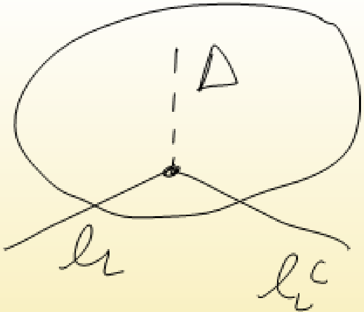
$$\underbrace{\bar{l}_L \, l_L^c}_{(2,1)\times(2,1)} \Delta \longrightarrow \mathcal{L}$$

$$\longrightarrow (1,2)$$

$$\underbrace{(3,2)\;(3,-2)}_{(1,0)} \longrightarrow \mathcal{L}$$

Type-II seesaw

$$l_L \, l_L^c \, \Delta$$



$y\langle\varphi\rangle \bar{q}_L q_R$

$\Delta : (3,-2)$

$$\boxed{f\langle\Delta_0\rangle \bar{l}_L l_L^c}$$

$$Q = T_3 + \frac{Y}{2}$$

$$0 = +1 \quad -1$$

$$-1 = 0 \quad -1$$

$$-2 = -1 \quad -1$$

$$\begin{pmatrix} \Delta_0 \\ \Delta_- \\ \Delta_{--} \end{pmatrix} \leftarrow \text{Higgs triplet}$$

Δ_0 gets v.e.v. $\langle\Delta^0\rangle$

$$m_\nu = f\langle\Delta_0\rangle$$

$$m_e \sim f\langle\Delta_0\rangle$$

$$\underbrace{\overset{\varphi}{(2,1)}\quad\overset{\varphi}{(2,1)}}_{(3,\,2)}$$

$$\underbrace{\mu\,\Phi\,\Phi\,\Delta}_{(3,\,-2)}$$

$$\boxed{\frac{f\mu}{M_\Delta^2}}\ \boxed{\ell\ell\varphi\varphi} \longrightarrow \frac{\kappa_5}{M}\,\ell\ell\varphi\varphi$$

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Seesaw :

$$\mathcal{L}_{eff} \sim \frac{\kappa_5}{M} \, l l \phi \phi$$

$$\kappa_5 \, l l \phi \phi$$

Mass :

$$\bar{l} \cdot \square \, \bar{\nu}_L \nu_L^c$$

Type I

$m_R \sim \text{TeV}$

$$\Gamma(\ell\varphi \to N) \propto y_D^2$$

$$m_\nu = \frac{m_D^2}{m_N} = \frac{y_D^2 v^2}{2 m_N}$$

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$$m_\nu = \frac{y_D^2 v^2}{2 m_N}$$

$$y_D^2 = \frac{2 m_\nu m_N}{v^2} \sim \frac{2 \times 0.1 \times 10^{12}}{10^{22}}$$

$$\sim 10^{-11}$$

$$m_N \ \text{TeV} \Rightarrow y_D^2 \sim 10^{-11}$$

$$\Gamma(\ell \phi \to N) \sim 10^{-11}$$

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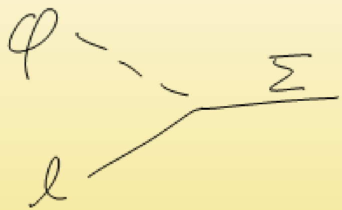
$$y_D^2 = \frac{2\, m_\nu\, m_N}{v^2} \sim \frac{2 \times 0.1 \times 10^{19}}{10^{22}}$$

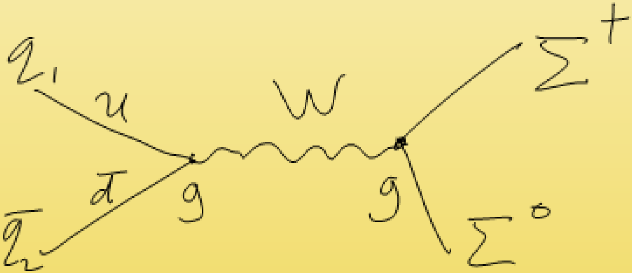
$$\longrightarrow 10^{-4}$$

Type III

$$M_\Sigma = TeV \longrightarrow y_D^2 \sim 10^{-11}$$



$\longrightarrow$ unobservable



$$\Gamma(u\bar{d} \to W \to \Sigma^+\Sigma)$$
$$\sim g^2$$