Neutrino Physics Course

Lecture XXIII

14/7/2023

LMU

Summer 2023

$d = 5$ LNV interaction (II)

1979 Weinberg

neutrino mass

$$\frac{1}{\Lambda_{new}} \nu \nu \phi_0 \phi_0 \longrightarrow \frac{1}{\Lambda_{new}} \ell \ell \phi \phi$$

$$\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$$

$$\phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

$\Delta L \neq 0$ motivation

$\ell \ell \leftarrow$ at least two

$$l^T i\sigma_2 C\, l = 0$$

$$\underbrace{l\, l\ \ \phi\, \phi}_{\substack{\Delta Y = 0 \\ \Delta T_3 = 0}}$$

$$(\mathrm{I})\quad \frac{\overbrace{(l^T i\sigma_2\, \phi)}^{S}\; C\; \overbrace{(\phi^T i\sigma_2\, l)}^{S\, =\, \text{Singlet}}}{\Lambda_{new}}$$

$$(\mathrm{III})\quad (l^T i\sigma_2 \vec{\sigma}\, \phi)\, C\, (\phi^T i\sigma_2 \vec{\sigma}\, l) / \Lambda_{new}$$

$$\underbrace{\qquad\qquad\qquad\qquad}_{\vec{V}\,(T)} \qquad \underbrace{\qquad\qquad\qquad\qquad}_{\vec{V}\,(T)}$$

|| ||

vector triplet

$$S = \ell^T i\sigma_2 \phi \quad = \text{fermion}$$

$$\vec{V} = \ell^T i\sigma_2 \vec{\sigma} \phi \quad = \text{—"—}$$

$$(\mathrm{II}) \; \underline{\left(\ell^T C\, i\sigma_2 \vec{\sigma}\, \ell\right)\left(\phi^T i\sigma_2 \vec{\sigma} \phi\right)}$$

Λ_{new}

$\vec{V}$

$$\ell^T \text{---} i\sigma_2 \vec{\sigma}\, \ell \quad = \text{scalar}$$

$$\phi^T i\sigma_2 \vec{\sigma}\phi = -''-$$

$$\rightarrow \phi_{m} = \begin{pmatrix} 0 \\ \phi_0 \end{pmatrix} \Rightarrow$$

$$(\mathrm{II}) \longrightarrow \# \frac{\nu^T c \nu \phi_0 \phi_0}{\Lambda_{new}}$$

$$\Downarrow$$

$$\boxed{\mathrm{I}, \mathrm{II}, \mathrm{III} = \text{equal} \quad \text{(proportional to each other)}}$$

$$\uparrow$$

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In the general $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

$\underline{\overline{I}} \sim \underline{\overline{II}} \sim \underline{\overline{III}} \quad \alpha$

$$\Big(\nu_L^T C \nu_L \;\; \phi_0 \phi_0 \, , \;\; \nu_L^T C e_L \;\; \phi_0 \phi^+ , \;\; e_L^T C e_L \;\; \phi^+ \phi^+ \Big) \frac{1}{\Lambda_{new}}$$

$\Big\downarrow$ dust settles

$$\nu_L \;\; \nu_L \;\; \frac{v_{SM}^2}{\Lambda_{new}} \iff \nu = \text{Majorana}$$

$$\mathcal{L}_{int} = \frac{\nu \nu \phi_0 \phi_0}{\Lambda_{new}}$$

$\phi_0 = h + \cancel{v}$

$$\frac{\nu \nu v_{SM} h}{\Lambda_{new}} \qquad\qquad \frac{\nu \nu v_{SM}^2}{\Lambda_{new}}$$

$$\Updownarrow \qquad\qquad\qquad \Downarrow$$

$$\bar{f} f \frac{m_f}{v_{SM}} h \qquad\qquad \boxed{m_\nu = \frac{v_{SM}^2}{\Lambda_{new}}} \quad (*)$$

(f = charged fermion)

$$\Leftrightarrow \quad y_f = m_f / v_{SM}$$

$$\Downarrow$$

$$\Gamma(h \to f\bar{f}) \propto \frac{m_f^2}{v_{SM}^2}\, m_h$$

$$\Updownarrow \quad \text{analogy with } \nu$$

$$\nu\, \nu\, \frac{v_{SM}}{\Lambda_{new}}\, h$$

$$\Rightarrow \quad y_\nu = \frac{v_{SM}}{\Lambda_{new}}$$

but: $$m_\nu / v_{SM} = \frac{v_{SM}}{\Lambda_{new}} \quad (*)$$

$$\Downarrow$$

$$\boxed{y_\nu = \frac{m_\nu}{v_{SM}}}$$

$$\Rightarrow \Gamma(h \to \nu\nu) \propto \frac{m_\nu^2}{v_{SM}^2} m_h$$

$$m_\nu < 1\,\text{eV}$$

$$v_{SM} \simeq 100\,\text{GeV} \simeq 10^{11}\,\text{eV}$$

$$\Rightarrow \quad Br(h \to \nu\nu) \equiv \frac{\Gamma(h \to \nu\nu)}{\Gamma_{total}}$$

$$\boxed{Br(h \to \nu\nu) \leq 10^{-22}}$$

$$\boxed{\begin{array}{l}d=5 \text{ implies (by itself)} \\ \text{no new physics} \\ \quad (\text{except for } \Delta L = 2)\end{array}}$$

(I) $\Longleftrightarrow$ Type I seesaw

(II) $\Longleftrightarrow$ –"– II –"–

(III) $\Longleftrightarrow$ –"– III –"–

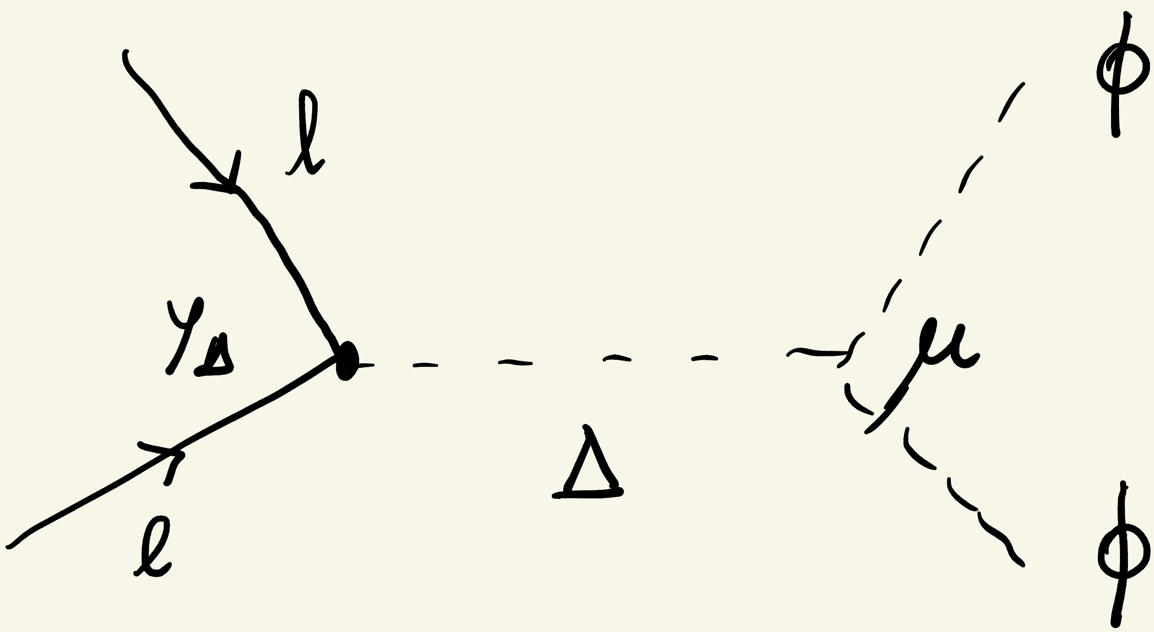
Example

Type II seesaw

SU(2)$_L$ triplet

$$Y_\Delta \, \ell \, \Delta \, \ell \; + \mu \, \phi \, \Delta^* \phi$$

$$Y(\Delta) = 2$$



$$\Downarrow$$

$$\mathcal{L}_{eff} = Y_\Delta \mu \; \ell \ell \frac{1}{k^2 - m_\Delta^2} \phi \phi$$

$$\underset{(k \to 0)}{\propto} Y_\Delta \mu \; \ell \ell \frac{1}{m_\Delta^2} \phi \phi$$

$$\mathcal{L}_{eff}^{(d=5)} \text{(Weinberg)} = \ell \ell \phi \phi \frac{1}{\Lambda_{new}}$$

iff $\dfrac{1}{\Lambda_{new}} = \dfrac{m_\Delta^2}{Y_\Delta \mu}$

Type I seesaw

$$\frac{1}{\Lambda_{new}} = \frac{m_N}{y_D^2}$$

(here $d=5$ language is better)

$\Lambda_{new} = ?$

Information ???

$\Downarrow$ $d=5$

$$m_\nu = \frac{v_{SM}^2}{\Lambda_{new}} \qquad m_\nu < 10^{-9}\,\text{GeV}$$

$$\Rightarrow \quad \Lambda_{new} = \frac{v_{SM}^2}{m_\nu}$$

$$\Lambda_{new} \gtrsim \frac{10^4}{10^{-9}}\,\text{GeV}$$

$$\boxed{\Lambda_{new} \gtrsim 10^{13}\,\text{GeV}}$$

$\boxed{\underline{\text{Cheat}}}$

$$\mathcal{L}_{eff} = \frac{\ell\ell\ \phi\phi}{\Lambda'_{new}}\, g_{eff}$$

$$\Downarrow$$

$$\frac{1}{\Lambda_{new}} = \frac{g_{eff}}{\Lambda_{new}'}$$

$$\boxed{\Lambda_{new}' = \Lambda_{new}\, g_{eff}}$$

<u>Type I seesaw</u> ! $g_{eff} = y_D^2$

$$m_D \simeq m_e \Leftrightarrow y_D \cong y_e$$

$$y_e \simeq 10^{-5} \; !!!$$

$$\Rightarrow \boxed{\Lambda_{new}' = 10^{-10}\,\Lambda_{new} = 10^{3}\,\mathrm{GeV}}$$

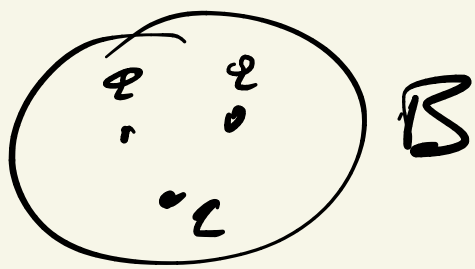
$d=5$ eff $\rightarrow$ seesaw $=$ UV completion

$\bar{U}\bar{V}$ = Ultra Violet

- $\Delta L \neq 0 \qquad \ell\ell\phi\phi/\Lambda$

- $\Delta B \neq 0$

$$B_q = \frac{1}{3}$$



$\cancel{q_\alpha q_\beta}$

$$3_c \times 3_c = 6_c + 3_c^*$$

(S) (A)

quarks conf.

$$\cancel{\bar{q}\, e \ (B=0)}$$

$$\varepsilon_{\alpha\beta\gamma}\, q_\alpha q_\beta q_\gamma = \text{color singlet}$$

$$\Downarrow$$

$$\Delta B \neq 0 \ ! \qquad \underbrace{q\ q\ q\ \ l}_{s = \ 1/2\ \ 1/2\ \ 1/2\ \ 1/2} = 0$$

Lorentz inv.

$SU(2) \times U(1)$ inv.

$$\Rightarrow \mathcal{L}_{eff}(\Delta B \neq 0) = \frac{q q q\, l}{\Lambda_{new}^2}$$

$$(\Lambda_{new} \gg M_W)$$

$\boxed{\text{p-roton decays}}$

$\boxed{\text{G.S. 2009}}$

$\Rightarrow$ <u>prediction</u>

$$\cancel{p \to K^0 e^+}$$

$$\cancel{n \to K^0 \nu}$$

$$\tau_p \gtrsim 10^{34}\,\text{yr} \Rightarrow \boxed{\Lambda_{new} > 10^{15}\,\text{GeV}}$$

$$\tau_U \simeq 10^{10}\,\text{yr}$$

~ 1950 Maurice Goldhaber

$$\boxed{\tau_p \gtrsim 10^{18}\ \mathrm{yr}}$$

"feel it in my bones"

$$\boxed{\text{what is a "good" } \Delta L \neq 0 \text{ operator?}}$$

- $\underline{d=5}$ — $\ell \ell \phi \phi$

— "no good" ! m_ν = Majorana

• $\Delta L = 2$ low energy process

• $e \to \nu + \gamma$

$\Delta Q \neq 0$

$$\boxed{\tau_e \gtrsim 10^{26}\,yr}$$

• $\boxed{0\nu 2\beta}$

$u + u \to p + p + e + e$

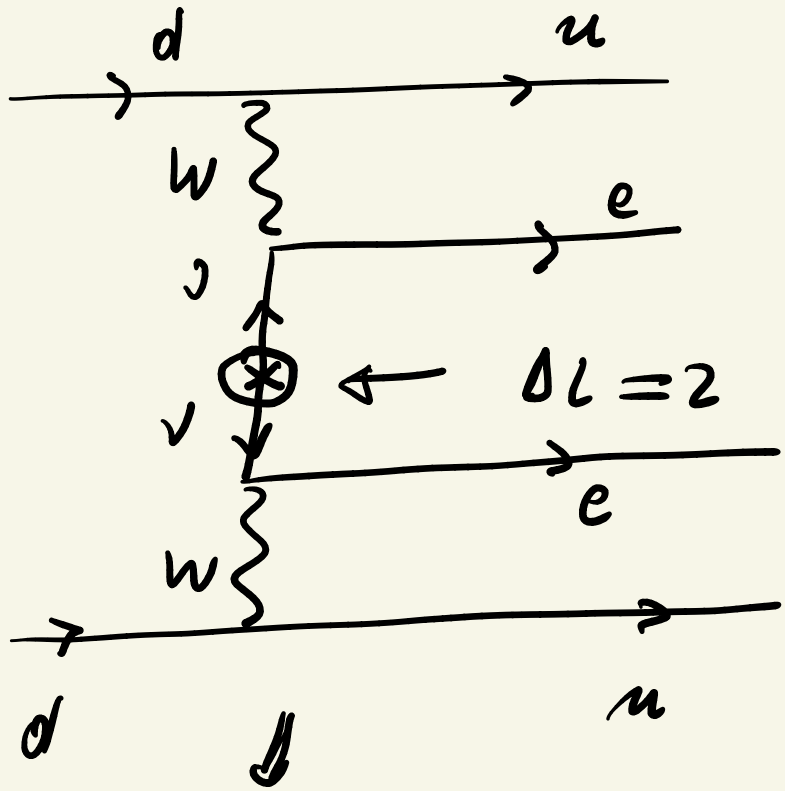
$\Updownarrow$

$d + d \to u + u + e + e$

6 fermions $(\mathcal{O}_f = 3/2)$

$$\mathcal{L}_{int}(d=9) = \frac{\bar{e}\bar{e}\,\bar{u}\bar{u}\,dd}{\Lambda_{new}^{5}}$$

$$\boxed{\begin{array}{c} \Delta L = 2 \\ \Delta B = 0 \end{array}}$$



$$\boxed{G_F \simeq 10^{-5}\,\text{GeV}^{-2}}$$

$$\bar{u}\bar{u}\;\bar{e}\bar{e}\;dd \quad G_F^{2}\,\frac{m_\nu}{p^{2}}$$

$(p \simeq 100$ GeV$)$

$$\frac{1}{\Lambda_{new}^5} \lesssim \frac{10^{-10}\ 10^{-10}}{10^{-2}}\ \text{GeV}^{-5}$$

$$\lesssim 10^{-18}\ \text{GeV}^{-5}$$

$$\boxed{\Lambda_{new} \gtrsim 3 \times 10^3\ \text{GeV}}$$

$$\Uparrow$$

$$\boxed{\text{LHC ??}}$$

$$\frac{\bar{u}\bar{u}\, d d\, \bar{e}\bar{e}}{\Lambda_{new}^5}\ y_{eff}$$

perturbability ✓

$$(y_{eff} \leq O(1))$$