8.701

Introduction to Nuclear and Particle Physics

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8. Neutrinos

8.2 Neutrino Mass

Neutrino Masses

Mass terms can be constructed in different ways by introducing sterile neutrinos

$$-\mathcal{L}_{M_\nu} = M_{D\,ij}\bar{\nu}_{si}\nu_{Lj} + \frac{1}{2}M_{N\,ij}\bar{\nu}_{si}\nu^c_{sj} + \text{h.c.}$$

The first **“Dirac”** terms is generated after spontaneous electroweak symmetry breaking from Yukawa interactions as we have seen for charged leptons

$$Y^\nu_{ij}\bar{\nu}_{si}\tilde{\phi}^\dagger L_{Lj} \Rightarrow M_{D\,ij} = Y^\nu_{ij}\frac{v}{\sqrt{2}}$$

It conserved lepton number but breaks lepton flavour number symmetries.

Dirac Neutrinos

Identify sterile neutrinos as right-handed component of four-spinor neutrino field

$$-\mathcal{L}_{M_\nu} = \sum_{k=1}^{3} m_k \bar{\nu}_{Dk} \nu_{Dk}$$

$$\nu_{Dk} = (V^{\nu\dagger} \vec{\nu}_L)_k + (V_R^{\nu\dagger} \vec{\nu}_s)_k$$

Weak-doublet components

$$\nu_{Li} = P_L \sum_{j=1}^{3} V_{ij}^{\nu} \nu_{Dj} \,. \qquad i = 1, 2, 3$$

Neutrino Masses

$$-\mathcal{L}_{M_\nu} = M_{D\,ij}\bar{\nu}_{si}\nu_{Lj} + \frac{1}{2}M_{N\,ij}\bar{\nu}_{si}\nu^c_{sj} + \text{h.c.}$$

2nd term is a **“Majorana”** mass term.

It is a singlet of the SM gauge group and can appear as a bare mass term

It involved two neutrino (right-handed) fields and breaks lepton number.

Rewrite $$-\mathcal{L}_{M_\nu} = \frac{1}{2}(\overline{\vec{\nu}^c_L}, \overline{\vec{\nu}_s}) \begin{pmatrix} 0 & M_D^T \\ M_D & M_N \end{pmatrix} \begin{pmatrix} \vec{\nu}_L \\ \vec{\nu}^c_s \end{pmatrix} + \text{h.c.} \equiv \overline{\vec{\nu}^c} M_\nu \vec{\nu} + \text{h.c.}$$

See-saw Mechanism

If the mass eigenstate of M_N are much higher than the EW scale, the diagonalization of M_ν leads to three light neutrinos ν_l and potentially numerous heavy neutrinos N.

$$-\mathcal{L}_{M_\nu} = \frac{1}{2}\bar{\nu}_l M^l \nu_l + \frac{1}{2}\bar{N} M^h N\,,$$

$$M^l \simeq -V_l^T M_D^T M_N^{-1} M_D V_l, \qquad M^h \simeq V_h^T M_N V_h\,,$$

$$V^\nu \simeq \begin{bmatrix} \left(1 - \frac{1}{2} M_D^\dagger M_N^{*-}{}^1 M_N^{-1} M_D\right) V_l & M_D^\dagger M_N^{*-1} V_h \\ -M_N^{-1} M_D V_l & \left(1 - \frac{1}{2} M_N{}^{-1} M_D M_D^\dagger M_N^{*-1}\right) V_h \end{bmatrix}$$

Mass of heavier states proportional to M_N while light state to $M_N{}^{-1}$

Light sterile neutrinos

If the scale of some eigenvalues of MN are night higher than the EW scale, the low energy spectrum contains additional light states with large admixture of sterile components, i.e. more than 3 light neutrinos. Both light and heavy neutrinos are Majorana particles.

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