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Neutrino Theory & Phenomenology

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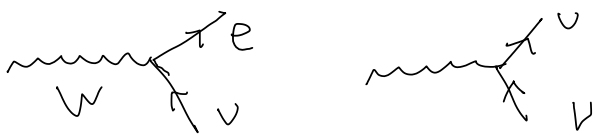
Quarks $u\ c\ t$
$d\ s\ b$

Leptons $e\ \mu\ \tau$
$\nu_e\ \nu_\mu\ \nu_\tau$

1. Neutrino Masses

1.1 Neutrinos in the SM

$$\mathcal{L} \supset \sum_{\alpha=e,\mu,\tau} \overline{\nu_{\alpha L}}\, i\partial \nu_{\alpha L} + \frac{g}{\sqrt{2}}\left(W^{\mu +}\, \overline{\nu_{\alpha L}}\, \gamma_\mu\, e_{\alpha L} + \text{h.c.}\right) + \frac{g}{2\cos\theta_W} Z^\mu\, \overline{\nu_{\alpha L}}\, \gamma_\mu\, \nu_{\alpha L}\Big]$$



1.2 Dirac Masses

In the SM, only LH ν

$$\nu_L = \frac{1-\gamma^5}{2}\nu = \begin{pmatrix} \chi_1 \\ \chi_2 \\ 0 \\ 0 \end{pmatrix}$$

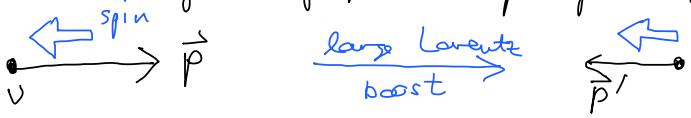
Dirac masses → make also lower components physical

$$\nu_R = \frac{1+\gamma^5}{2}\nu = \begin{pmatrix} 0 \\ 0 \\ \chi_3 \\ \chi_4 \end{pmatrix}$$

↳ $\mathcal{L}_m \supset \sum_{\alpha,\beta} m_{\alpha\beta}\, \bar{\nu}_{\alpha L}\, \nu_{\beta R}$

$m_{\alpha\beta}$: general complex 3×3 matrix $= Y_{\alpha\beta}\langle H\rangle$

Now 4 degrees of freedom per flavour



1.3 Majorana Masses

Mass terms couple LH and RH fields

The antiparticle of ν_L is a RH field

Could ν_R be identical to the anti-ν_L?

More formally: charge conjugation

$$\hat{C}: \psi \longrightarrow \psi^c \equiv -i\gamma^2\gamma^0\bar{\psi}^T$$

Effect on chirality

$(\psi^\dagger\gamma^0)^T = \gamma^0\psi^*$

$$\begin{aligned}\gamma^5\psi^c &= \gamma^5(-i\gamma^2\gamma^0)\bar{\psi}^T \\ &= +i\gamma^2\gamma^5\psi^* \\ &= -(\gamma^5\psi)^c\end{aligned}$$

$\hat{C}$ flips chirality → transforms LH particles into their RH antiparticles (and vice-versa)

Identify $\nu_R \equiv (\nu_L)^c$

In 4-component: $\nu_L = \begin{pmatrix}\chi_1\\ \chi_2\\ 0\\ 0\end{pmatrix} = \begin{pmatrix}\chi\\ 0\end{pmatrix}$

$$(\nu_L)^c = -i\begin{pmatrix}0 & \sigma^2\\ -\sigma^2 & 0\end{pmatrix}\begin{pmatrix}\chi^*\\ 0\end{pmatrix} = \begin{pmatrix}0\\ i\sigma^2\chi^*\end{pmatrix}$$

Majorana spinor:

$$\nu = \nu_L + (\nu_L)^c = \begin{pmatrix}\chi\\ i\sigma^2\chi^*\end{pmatrix}$$

Majorana spinor has 4 non-zero components, but only 2 dof

Note: $\nu^c = \nu$

A new type of mass term:

$$\mathcal{L} \supset \frac{1}{2}\sum_{\alpha,\beta} m_{\alpha\beta}\, \overline{(\nu_{L\alpha})^c}\, \nu_{L\beta} + \text{h.c.}$$

$m_{\alpha\beta}$: symmetric complex 3×3 matrix

Problem:

- why is m_{ν_i} so small?
- how to obtain this from an SU(2)-invariant theory?

1.4 Seesaw Mechanism

Augment SM with 3 RH neutrinos, N_R
(singlets under the SM gauge group)

For illustration, consider 1 LH ν_L, 1 RH N_R field

$$\mathcal{L} \supset -m_D \bar{\nu}_L N_R - \frac{1}{2} m_M \overline{(N_R)^c} N_R + \text{h.c.}$$

m_D: from Higgs mechanism, $O(m_H)$; m_M: can be very large

Write $n = \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$

$$\hookrightarrow \mathcal{L} \supset -\frac{1}{2} \overline{n^c} M n + \text{h.c.}$$

$$M = \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix}$$

$$= -\frac{1}{2} \left(\overline{(\nu_L)^c} \; \overline{N_R} \right) \begin{pmatrix} 0 & m_D \\ m_D & m_M \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^c \end{pmatrix}$$

Diagonalize M, assuming $m_D \ll m_M$

eigenvalues: $\sim m_M$, $\sim -\frac{m_D^2}{m_M}$ (can be absorbed into rephasing of ν_L')

eigenvectors:

$$N_R' \sim N_R + O\left(\frac{m_D}{m_M}\right) \nu_L^c$$

$$\nu_L' \sim \nu_L + O\left(\frac{m_D}{m_M}\right) N_R^c$$

Effective low-E Lagrangian

$$\mathcal{L} \supset -\frac{1}{2} \frac{m_D^2}{m_M} \overline{(\nu_L')^c} \nu_L'$$

with $m_D \sim 100$ GeV and $m_M \sim 10^{14}$ GeV

$\hookrightarrow m_\nu \equiv \frac{m_D^2}{m_M} \sim 0.1$ eV

1.5 Measuring ν masses

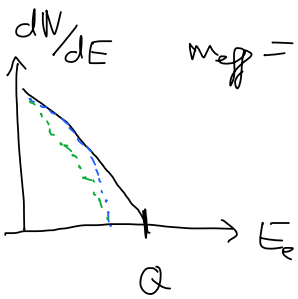
1.5.1 Kinematic measurements

β-decay $^3H \to {}^3He + e^- + \bar{\nu}_e$

$$E_{max}^e = Q - m_\nu$$

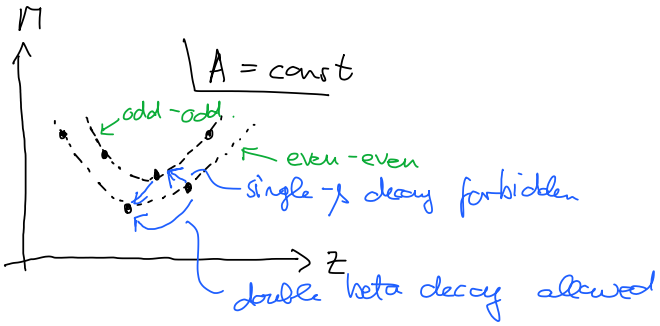
$Q = m_H - m_{He}$

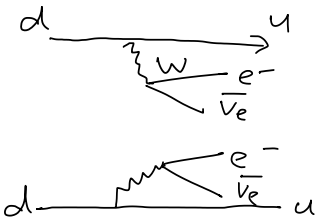
Measure e^- spectrum, look at endpoint



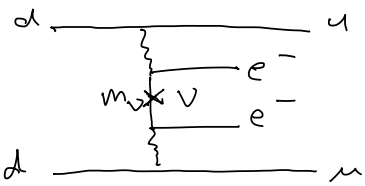
$$m_{eff} = \sum_i |M_{ei}|^2 m_i$$

1.5.3 Neutrinoless double beta decay





For Majorana neutrinos



$\sim m_\nu$

By measuring $0\nu2\beta$ decay rate,
we can measure Majorana ν masses

[Note: large nuclear matrix element uncertainties need to be taken into account]