Fundamental question: are the neutrinos Dirac or Majorana-type fermions?
- A Dirac fermion consists of a pair of mass degenerate Majorana fermions
- Electric charge conservation forces charged fermion to be Dirac type
- As a neutral fermion, a neutrino can be Dirac, Majorana or the mixed type
- Easiest way to confirm neutrino as Majorana fermion
- Direct evidence of lepton number violation
- Provide information about the absolute neutrino mass
  ⇒ 20 experiments proposed (2 operating, 4 under construction)

Minimal extension of SM – exchange of three light Majorana neutrinos
- Long-distance contribution dominated
- Critical to control the uncertainty of nuclear matrix elements
  ⇒ Lattice QCD interplays with \(\chi EFT\)

Light-neutrino exchange in 0ν2β decay
- \(\Delta l = 1\) effective Lagrangian for \(\beta\) decay
  \[ \mathcal{L}_{\text{eff}}^{0\nu2\beta} = 2 \sqrt{2} G_F V_{ud} \langle \bar{u} \gamma_{\nu} d \rangle \langle \bar{\nu}_e \gamma_{\nu} \nu_e \rangle \]
- \(\Delta l = 2\) effective Hamiltonian for 2β decay
  \[ \mathcal{H}_{\text{eff}}^{0\nu2\beta} = \frac{1}{21} \int d^4x \mathcal{L}_{\text{eff}}^{0\nu2\beta}(x) \bar{\nu}_e \gamma_{\nu} \nu_e \]
- Neutrino flavor eigenstate mixes with three mass eigenstates
  \[ \bar{\nu}_e \rightarrow \sum_k \bar{\nu}_k \]

Assume that 0ν2β is mediated by exchange of light Majorana neutrinos
\[
\bar{\nu}_e \rightarrow \sum_k \bar{\nu}_k \rightarrow \sum_k m_k U_{ek} \bar{\nu}_{eL}
\]

0ν2β decay amplitude is proportional to the absolute neutrino mass

Decay amplitude
- Decays of 4
  \[ A = \langle f, e^+_1, e^-_2 | \mathcal{H}_{\text{eff}}^{0\nu2\beta} | i \rangle \]
  is given by
  \[ A \propto \int \frac{d^4q}{(2\pi)^4} \sum_{n} \left[ \frac{\langle f | \bar{u}_{eL} | n \rangle \langle n | \bar{u}_{eL} | i \rangle}{\sqrt{m_{eL}}} \right] \tilde{U}(\tilde{p}_2) \gamma_{\nu} \tilde{U}(\tilde{p}_1) \]
- A can be split into two parts: \(A \propto A_1 + A_2\)
  \[ A_1 = \int \frac{d^4q}{(2\pi)^4} \sum_{n} \left[ \frac{\langle f | \bar{u}_{eL} | n \rangle \langle n | \bar{u}_{eL} | i \rangle}{\sqrt{m_{eL}}} \right] \tilde{U}(\tilde{p}_2) \gamma_{\nu} \tilde{U}(\tilde{p}_1) \]
  \[ A_2 = \int \frac{d^4q}{(2\pi)^4} \sum_{n} \left[ \frac{\langle f | \bar{u}_{eL} | n \rangle \langle n | \bar{u}_{eL} | i \rangle}{\sqrt{m_{eL}}} \right] \tilde{U}(\tilde{p}_2) \gamma_{\nu} \tilde{U}(\tilde{p}_1) \]

Here, \(A_2\) may be suppressed by a factor of
\[
\frac{|E_{\nu} - E_{\bar{\nu}}|}{|E_{\nu} + |q| + E_{\bar{\nu}} - E_2|} \approx \frac{1}{E_2} \sim 1 \text{ MeV and } E_2 \sim 40 \text{ MeV}
\]

Thus one can focus on the dominant contribution \(-A_1\)