Neutrinoless double beta decay and Lepton Flavor Violation

Vincenzo Cirigliano

Caltech

DPF 2004, Riverside, August 30 2004

Outline

- Introduction: the role of $0\nu\beta\beta$ in neutrino physics
- Link between Lepton Number Violation (LNV) and Lepton Flavor Violation (LFV) in muon decays: useful 'diagnostic tool' to reveal $0\nu\beta\beta$ mechanism
- Illustrations:
  - RPV SUSY
  - Left-Right symmetric models
- Conclusion

Based on hep-ph/0406199, with A. Kurylov, M.J. Ramsey-Musolf, P. Vogel

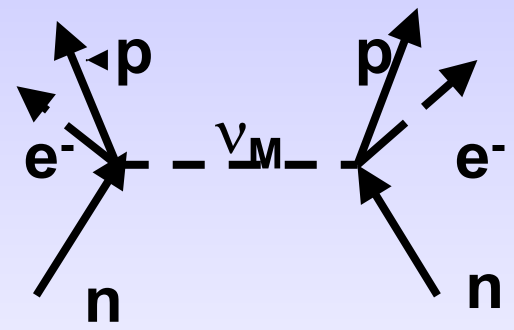
Outstanding questions in neutrino physics

- Charge conjugation properties (Dirac or Majorana?)
- Absolute mass scale in the spectrum

$0\nu\beta\beta$ $[(Z,A) \rightarrow (Z+2,A) + 2\, e^-]$ ***can help address both issues***

1. Observation of $\Delta L=2$ transition $\Rightarrow$ ν are Majorana particles

2. **If light ν exchange is the dominant mechanism $\Rightarrow$ access to mass scale**



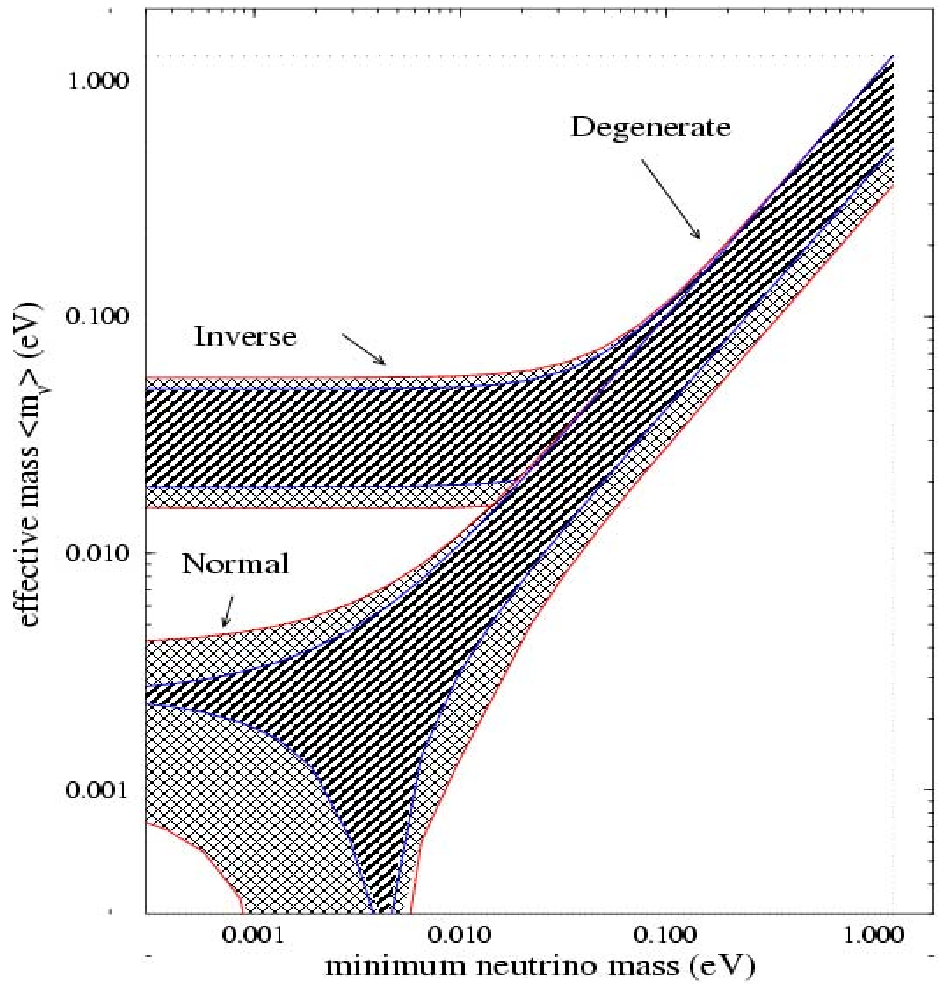
$$\Gamma_{0\nu\beta\beta} = G_{PS}\, |M_{nucl}|^2\, m_{\beta\beta}^2 \qquad m_{\beta\beta} = |\sum_i U_{ei}^2\, m_{\nu_i}|$$

$$\max\left\{2|U_{ei}^2|m_{\nu_i} - m_{\beta\beta}^{\mathrm{MAX}}\,,\,0\right\} \leq m_{\beta\beta} \leq \sum_i |U_{ei}^2|\; m_{\nu_i}$$

Based on LMA oscillation parameters. Cross-hatched region ⇔ 1σ errors

Stripes region ⇔unknown Majorana phases

By determining $m_{\beta\beta}$ one can deduce the neutrino mass pattern



R.D. McKeown and P.Vogel

Mechanism(s) generating $0\nu\beta\beta$

(i) Light ν exchange

[Single electron spectra/polarization discriminate the two]

→ Helicity flip ($\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$) $A_L \sim G_F^2 \frac{m_{\beta\beta}}{\bar{k}^2}$

→ Helicity non-flip (R-currents, …)

(ii) Heavy particle exchange → $A_H \sim G_F^2 \frac{M_W^4}{\Lambda^5}$

$\frac{A_H}{A_L} \sim \frac{M_W^4 \bar{k}^2}{\Lambda^5 m_{\beta\beta}}$ is O(1) for $m_{\beta\beta} \sim 0.1 - 0.5\,\mathrm{eV}$, $\Lambda \sim 1\,\mathrm{TeV}$, $\bar{k} \sim 50\,\mathrm{MeV}$

- TeV scale LNV could contribute to $0\nu\beta\beta$ at the sensitivity-level of future experiments

Need extra 'handle' to decide $0\nu\beta\beta$ mechanism:
LFV phenomenology provides one !

Linking LNV to LFV   I

$$B_{\mu\to e\gamma} = \frac{\Gamma(\mu\to e\gamma)}{\Gamma(\mu\to e\nu_\mu\bar{\nu}_e)}$$

$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A)\to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A)\to \nu_\mu + (Z-1,A))}$$

- SM extensions with low ($\sim$ TeV) scale LNV $\Rightarrow$**

RPV SUSY
LRSM
…

$$\mathcal{R} = \frac{B_{\mu\to e}}{B_{\mu\to e\gamma}} >> 10^{-2}$$

- SM extensions with high (GUT) scale LNV $[\Gamma_{0\nu\beta\beta}\sim m^2_{\beta\beta}]\Rightarrow$

SUSY GUT
SUSY SEE-SAW
…

$$\mathcal{R}\sim O(\alpha/\pi)\sim 10^{-3} - 10^{-2}$$

**** In absence of special symmetries or hierarchies in Yukawa-like couplings. Important caveat!**

Linking LNV to LFV II

- Projected experimental sensitivities: MECO $\rightarrow$ $B_{\mu\to e} \sim 10^{-16}$
  MEG $\rightarrow$ $B_{\mu\to e\gamma} \sim 10^{-14}$

- Simple criteria** based on ratio $\mathcal{R} = \dfrac{B_{\mu\to e}}{B_{\mu\to e\gamma}}$

1. $\mathcal{R} \sim 10^{-2}$ $\rightarrow$ $\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$

2. $\mathcal{R} >> 10^{-2}$ $\rightarrow$ $\Gamma_{0\nu\beta\beta} \sim \ ?$ (Need more input to discriminate)

3. Non observation $\rightarrow$ $\Gamma_{0\nu\beta\beta} \sim m_{\beta\beta}^2$

$$B_i \sim \left(\frac{\Lambda_{\rm weak}}{\Lambda_{\rm LFV}}\right)^4$$

Effective theory description I

$$\mathcal{L}_{0\nu\beta\beta} = \sum_i \frac{\tilde{c}_i}{\Lambda^5} \tilde{O}_i$$

$$\mathcal{L}_{\rm LFV} = \sum_i \frac{c_i}{\Lambda^2} O_i$$

Operators (omitting L $\leftrightarrow$ R)

$$\tilde{O}_i = \bar{q}\Gamma_1 q \ \bar{q}\Gamma_2 q \ \bar{e}\Gamma_3 e^c$$

$$O_{\sigma L} = \frac{e}{(4\pi)^2} \overline{\ell_{iL}} \sigma_{\mu\nu} i \not{D} \ell_{jL} F^{\mu\nu} + \text{h.c.}$$

$$O_{\ell L} = \overline{\ell_{iL}} \ell^c_{jL} \overline{\ell^c_{kL}} \ell_{mL}$$

$$O_{\ell q} = \overline{\ell_i} \Gamma_\ell \ell_j \overline{q} \Gamma_q q$$

- $O_{\sigma L}$ arises at loop level
- $O_{\ell L}$, $O_{\ell q}$ may arise at tree level
- Leading terms in c_i are nominally of order (Yukawa)^2

Effective theory description II

$$\mathcal{R} = \frac{\Phi}{48\pi^2}\,\frac{\left| e^2\,\eta_1\,c_{\sigma L} \;+\; e^2\left(\eta_2\,c_{\ell L} \;+\; \eta_3\,c_{\ell q}\right)\log\dfrac{\Lambda^2}{m_\mu^2} \;+\; \eta_4\,(4\pi)^2\,c_{\ell q} \;+\ldots\right|^2}{e^2\left(|c_{\sigma L}|^2 + |c_{\sigma R}|^2\right)}$$

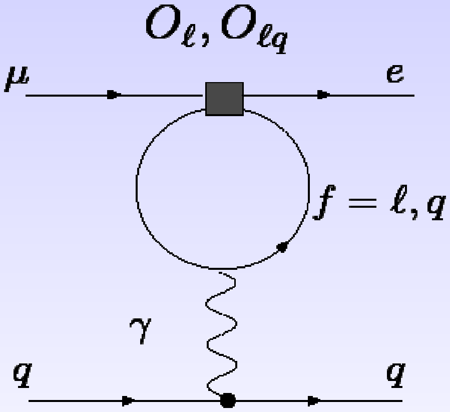
- Phase space + overlap integrals: $\Phi = \dfrac{Z\,F_p^2(m_\mu^2)}{g_V^2 + 3g_A^2} \sim O(1)$ for light nuclei

- η_n are coefficients of O(1)

- Origin of large logs:

  one loop operator mixing

  [Raidal-Santamaria '97]



Effective theory description III

$$\mathcal{R} = \frac{\Phi}{48\pi^2} \frac{\left| e^2\, \eta_1\, c_{\sigma L} \;+\; e^2 \Big(\eta_2\, c_{\ell L} \;+\; \eta_3\, c_{\ell q}\Big) \log \dfrac{\Lambda^2}{m_\mu^2} \;+\; \eta_4\, (4\pi)^2\, c_{\ell q} \;+\; \ldots \right|^2}{e^2 \Big(|c_{\sigma L}|^2 + |c_{\sigma R}|^2 \Big)}$$

(i) No tree level $c_{\ell L}$, $c_{\ell q}$ $\Rightarrow$ $\mathcal{R} \sim \dfrac{\Phi\, \eta_1^2\, \alpha}{12\pi} \sim 10^{-3} - 10^{-2}$

(ii) Tree level $c_{\ell L}$, $c_{\ell q}$ * $\Rightarrow$ log enhancement and $\mathcal{R} \sim O(1)$

(iii) Tree level $c_{\ell q}$ ** $\Rightarrow$ $\mathcal{R} \gg 1$

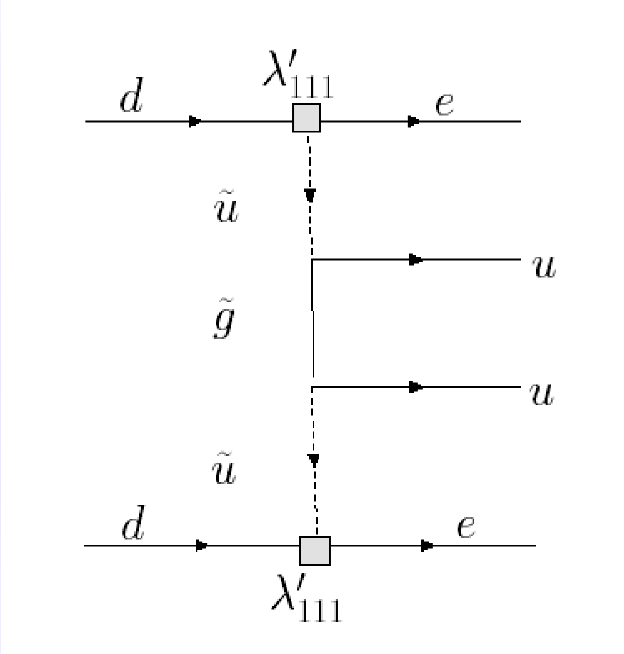
Need to show that in models with low scale LNV
O_l and/or O_{lq} are generated at tree level.
No general proof, but two illustrations

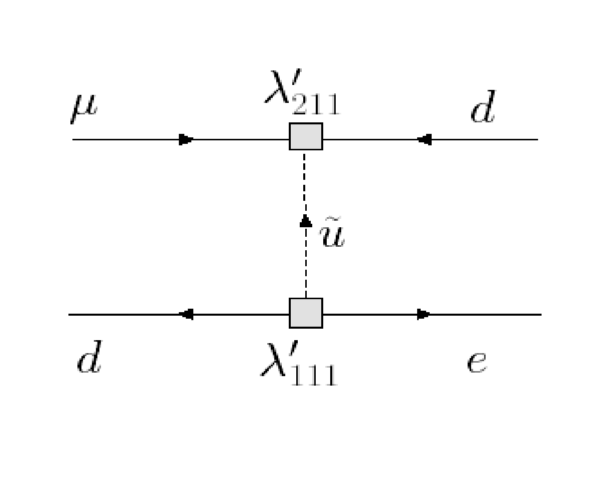
Illustration I: RPV SUSY [R = $(-1)^{3(B-L) + 2s}$]

$$W_{RPV} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k + \mu'_i L_i H_u$$

Illustration I: RPV SUSY $[R = (-1)^{3(B-L)+2s}]$

$$W_{RPV} = \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \lambda''_{ijk} U^c_i D^c_j D^c_k + \mu'_i L_i H_u$$





$$\frac{c_\ell}{\Lambda^2} \sim \frac{\lambda_{i11}\lambda^*_{i21}}{m^2_{\tilde{\nu}_i}}, \frac{\lambda^*_{i11}\lambda_{i12}}{m^2_{\tilde{\nu}_i}}$$

$$\frac{c_{\ell q}}{\Lambda^2} \sim \frac{\lambda'^*_{11i}\lambda'_{21i}}{m^2_{\tilde{d}_i}}, \frac{\lambda'^*_{1i1}\lambda'_{2i1}}{m^2_{\tilde{u}_i}}$$

$$\frac{c_\sigma}{\Lambda^2} \sim \frac{\lambda\lambda^*}{m^2_{\tilde{\ell}}}, \frac{\lambda'\lambda'^*}{m^2_{\tilde{q}}}$$

$$\frac{\tilde{c}_i}{\Lambda^5} \sim \frac{\pi\alpha_s}{m_{\tilde{g}}}\frac{\lambda'^2_{111}}{m^4_{\tilde{f}}}; \frac{\pi\alpha_2}{m_\chi}\frac{\lambda'^2_{111}}{m^4_{\tilde{f}}}$$

[deGouvea-Lola-Tobe '00]

Illustration II: Left-Right Symmetric Model

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B\text{-}L} \;\Rightarrow\; SU(2)_L \otimes U(1)_Y \;\Rightarrow\; U(1)_{EM}$$

$$\mathcal{L}_Y^{\text{lept}} = -\overline{L_L}^{\,i} \left(y_D^{ij}\, \Phi + \tilde{y}_D^{ij}\, \tilde{\Phi} \right) L_R^j - \overline{(L_L)^c}^{\,i}\, y_M^{ij}\, \tilde{\Delta}_L\, L_L^j - \overline{(L_R)^c}^{\,i}\, y_M^{ij}\, \tilde{\Delta}_R\, L_R^j$$

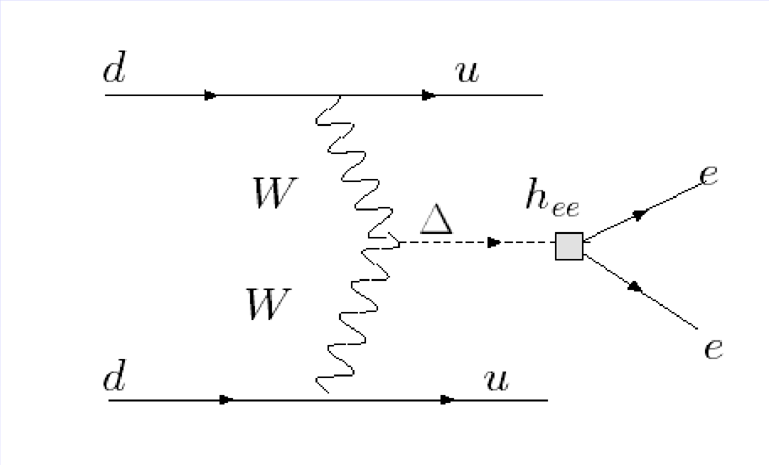
$$\Rightarrow \quad \mathcal{L}_{\delta^{\pm\pm}_{L,R}} = \frac{g}{2} \left[\delta^{++}_{L,R}\, \overline{l^c} \left(h\, P_{L,R} \right) l + \delta^{--}_{L,R}\, \overline{l} \left(h^\dagger\, P_{R,L} \right) l^c \right]$$

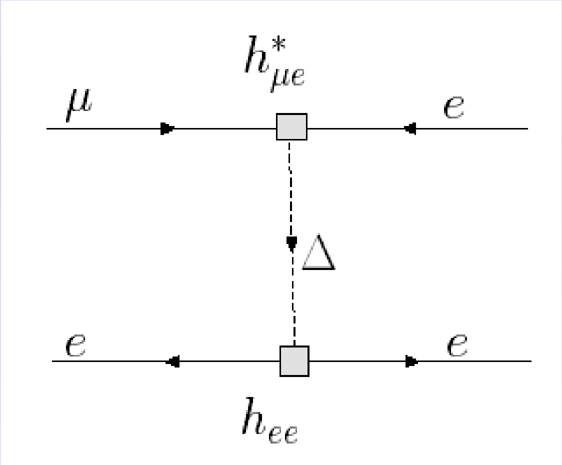
Illustration II: Left-Right Symmetric Model

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \Rightarrow SU(2)_L \otimes U(1)_Y \Rightarrow U(1)_{EM}$$

$$\mathcal{L}_Y^{\rm lept} = -\overline{L_L}^i \left(y_D^{ij}\,\Phi + \tilde{y}_D^{ij}\,\tilde{\Phi}\right) L_R^j - \overline{(L_L)^c}^i\, y_M^{ij}\,\tilde{\Delta}_L\, L_L^j - \overline{(L_R)^c}^i\, y_M^{ij}\,\tilde{\Delta}_R\, L_R^j$$

$$\Rightarrow \quad \mathcal{L}_{\delta^{\pm\pm}_{L,R}} = \frac{g}{2}\left[\delta^{++}_{L,R}\,\overline{l^c}\,(h\,P_{L,R})\,l + \delta^{--}_{L,R}\,\overline{l}\left(h^\dagger\,P_{R,L}\right) l^c\right]$$





$$\frac{\tilde{c}_i}{\Lambda^5} \sim \frac{g_2^4}{M_{W_R}^4}\frac{1}{M_{\nu_R}} \; ; \; \frac{g_2^3}{M_{W_R}^3}\frac{h_{ee}}{M_\Delta^2}$$

$$\frac{c_\ell}{\Lambda^2} \sim \frac{h_{\mu i} h_{ie}^*}{m_\Delta^2} \qquad \frac{c_\sigma}{\Lambda^2} \sim \frac{(h^\dagger h)_{e\mu}}{M_{W_R}^2}$$

Conclusions

- The ratio $\mathcal{R} = \frac{B_{\mu\to e}}{B_{\mu\to e\gamma}}$ provides insight about $0\nu\beta\beta$ mechanism and possibility to access ν mass scale

- Low scale LNV $\Rightarrow$* $\mathcal{R} >> 10^{-2}$

- Simple criteria:
  - if $\mathcal{R} \sim 10^{-2}$ $\Rightarrow$ $\Gamma_{0\nu\beta\beta} \sim m^2_{\beta\beta}$
  - if $\mathcal{R} >> 10^{-2}$, TeV scale LNV is possible

  More expt./th. input needed to decide $0\nu\beta\beta$ mechanism