University College London

Looking for Lepton Number Violation

Frank Deppisch

f.deppisch@ucl.ac.uk

University College London

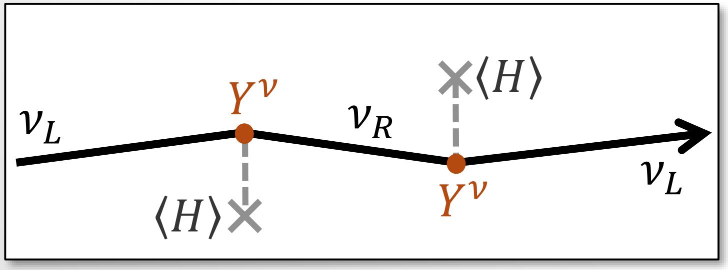
Portorož 2017 | 18-21 April 2017

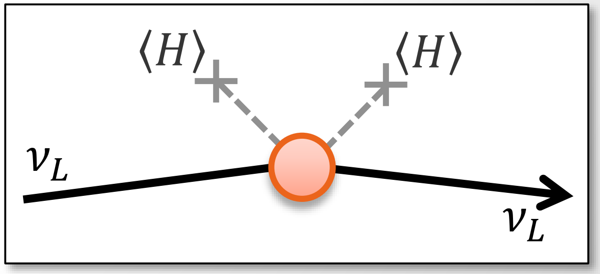
Dirac vs Majorana

- Two possibilities to define neutrino mass

Dirac mass analogous to other fermions but with ${}^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs

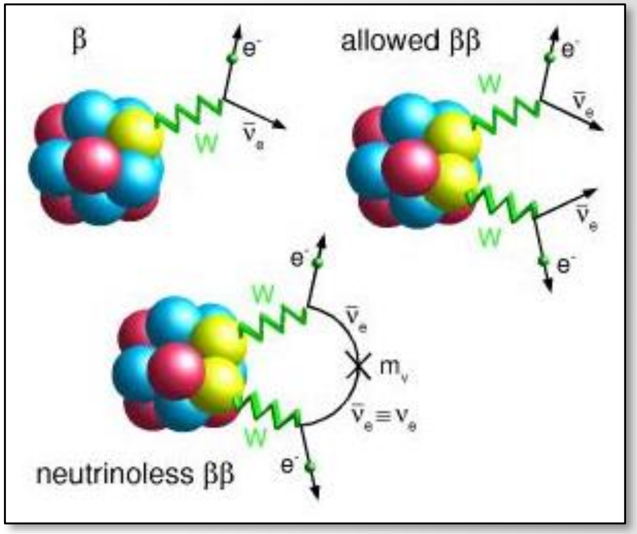
Majorana mass, using only a left-handed neutrino
→ Lepton number violation





Beta Decays

- Single beta decay
  $$(A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e$$
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A,Z) \rightarrow (A,Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana neutrinos
  - Variants
    - $0\nu\beta^+\beta^+$: $(A,Z) \rightarrow (A,Z-2) + 2e^+$
    - $0\nu\beta^+\mathrm{EC}$: $(A,Z) + e^- \rightarrow (A,Z-2) + e^+$
    - $0\nu\mathrm{ECEC}$: $(A,Z) + 2e^- \rightarrow (A,Z-2)$

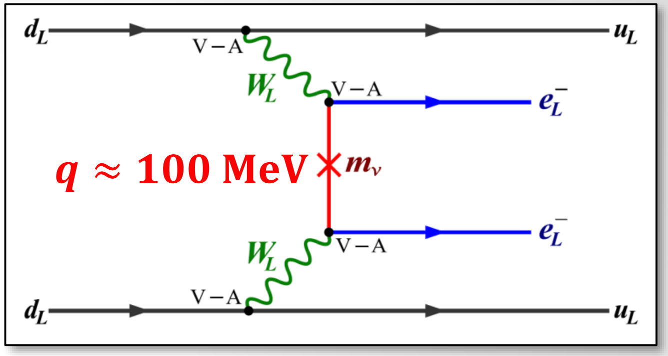


$0\nu\beta\beta$

University College London

- Half-life

$$T_{1/2}^{-1} = |m_{\beta\beta}|^2 G^{0\nu} |M^{0\nu}|^2$$



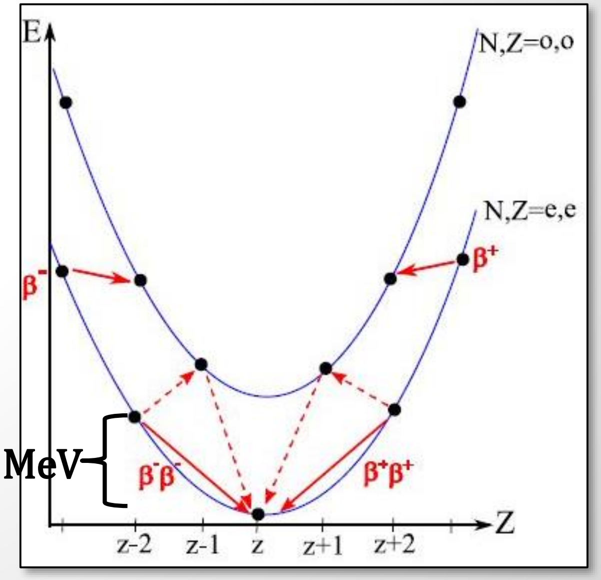
- Particle Physics

$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2\, \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu(1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2\, m_{\nu_i} \rightarrow m_{\beta\beta}$$

- Atomic Physics
  - Leptonic phase space $G^{0\nu}$
- Nuclear Physics
  - Nuclear transition matrix element $M^{0\nu}$

$$\frac{10^{25}\mathrm{yr}}{T_{1/2}} \approx \left(\frac{|m_{\beta\beta}|}{\mathrm{eV}}\right)^2$$

$Q \approx 2\text{–}4$ MeV



Three Active Neutrinos

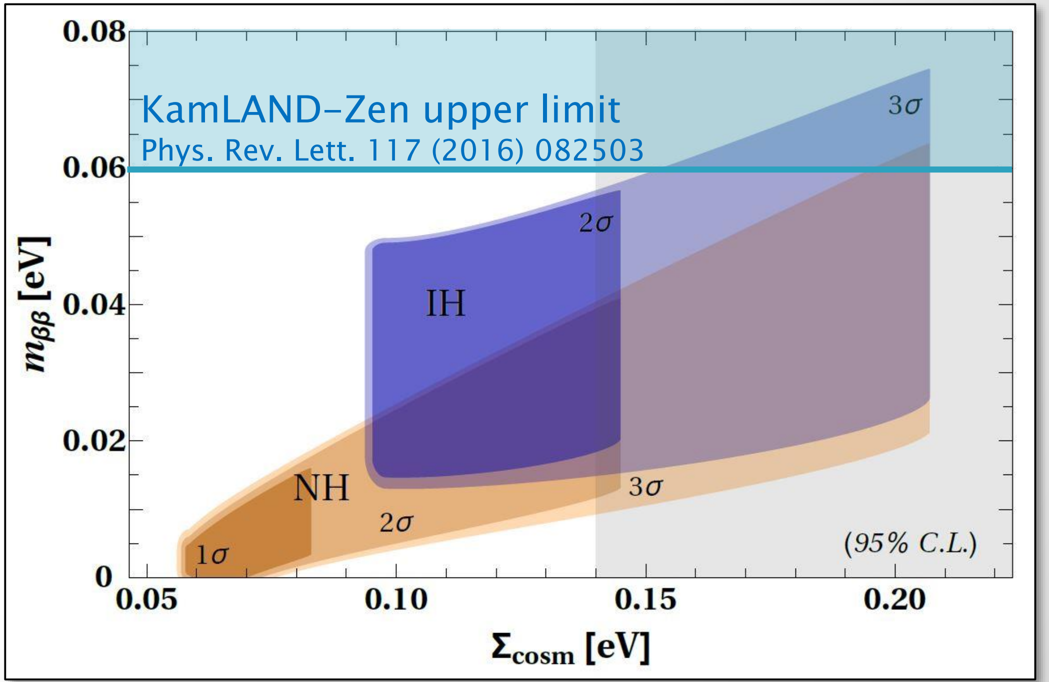
- Effective $0\nu\beta\beta$ Mass

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i(\phi_{13}-2\delta)}$$

- Degenerate Regime

$$|m_{\beta\beta}| = m_\nu \sqrt{1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\phi_{12}}{2}\right)}$$

- Uncertainty from unknown Majorana phases
- Accidental cancellation for NH possible



Dell'Oro, Marcocci, Viel, Vissani,
Adv.High Energy Phys. (2016) 2162659

Nuclear Matrix Elements

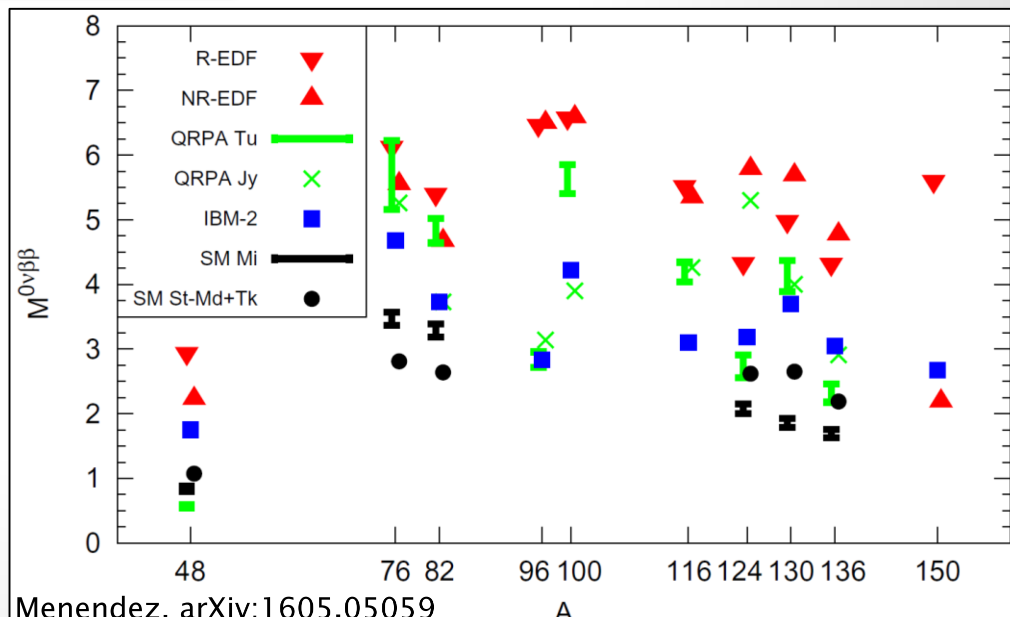
- Hadronic current

$$J^{\mu}(q) = g_V \gamma^{\mu} - g_A \gamma^{\mu}\gamma^5 + \frac{i g_M}{2 m_N}\sigma^{\mu\nu} q_{\nu} - g_P \gamma^5 q^{\mu}$$

- Nuclear Matrix Element $M^{0\nu}$

$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_A^2}{g_V^2} M_F + M_T \right)$$

  - Dependence on isotope and operator
  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models



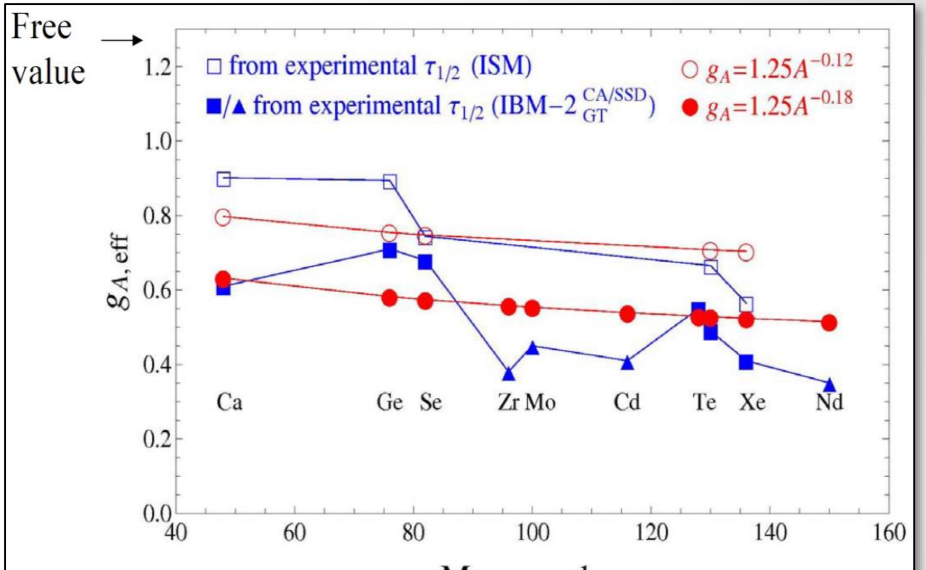
Menendez, arXiv:1605.05059

Quenching of g_A?

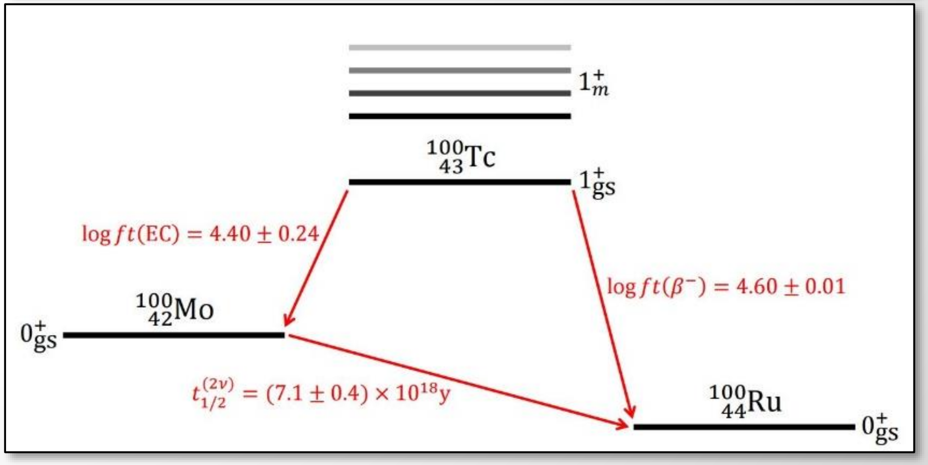
- Nuclear matrix element

$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_A^2}{g_V^2} M_F + M_T \right)$$

- Axial-vector coupling g_A
  - Free nucleon: $g_A \approx 1.27$
  - Comparison of β and $2\nu\beta\beta$ decay with theory: $g_A \approx 0.6\text{–}0.8$
  - If applicable to $0\nu\beta\beta$, strong reduction of sensitivity
  - Genuine effect or short-coming of models?



Iachello '16

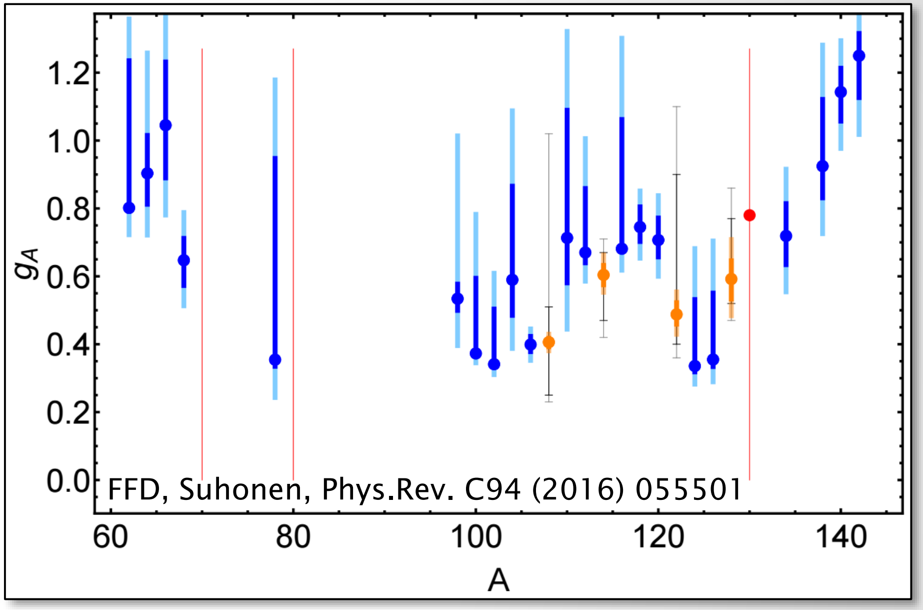


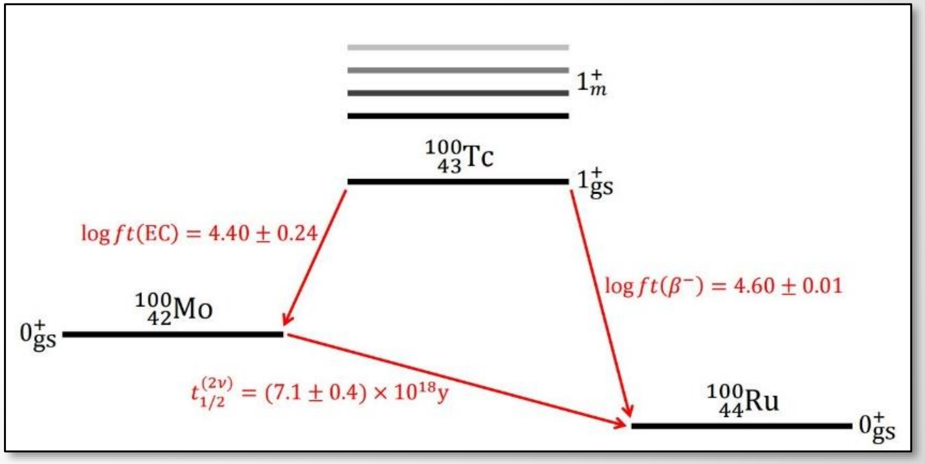
Quenching of g_A?

- Nuclear matrix element

$$M^{0\nu} = g_A^2 \left(M_{GT} - \frac{g_A^2}{g_V^2} M_F + M_T \right)$$

- Axial-vector coupling g_A
  - Free nucleon: $g_A \approx 1.27$
  - Comparison of β and $2\nu\beta\beta$ decay with theory: $g_A \approx 0.6 - 0.8$
  - If applicable to $0\nu\beta\beta$, strong reduction of sensitivity
  - Genuine effect or short-coming of models?



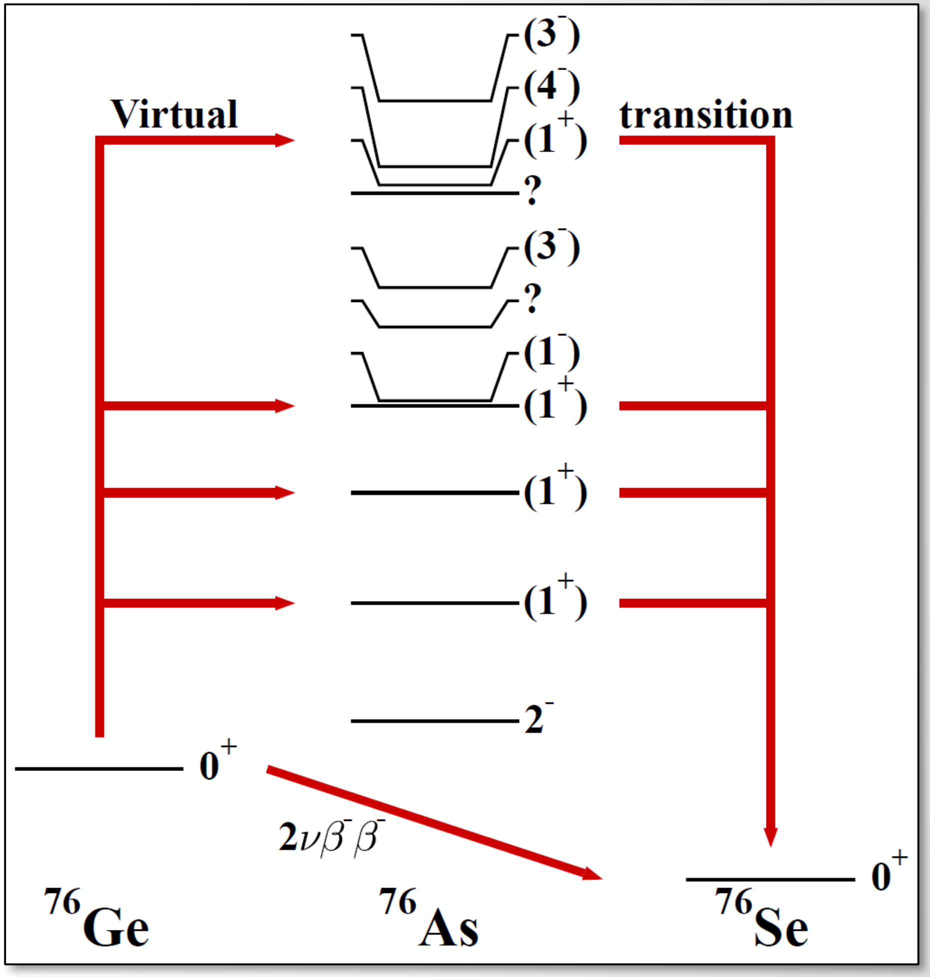


Quenching of g_A?

- Single beta / EC / $2\nu\beta\beta$ analysis relevant for $0\nu\beta\beta$?

Unclear!

- Processes different at nucleon level
- Probing different transitions
- Incorporate more experimental information
  - Higher, forbidden beta decays
  - Charge exchange reactions
  - Muon capture

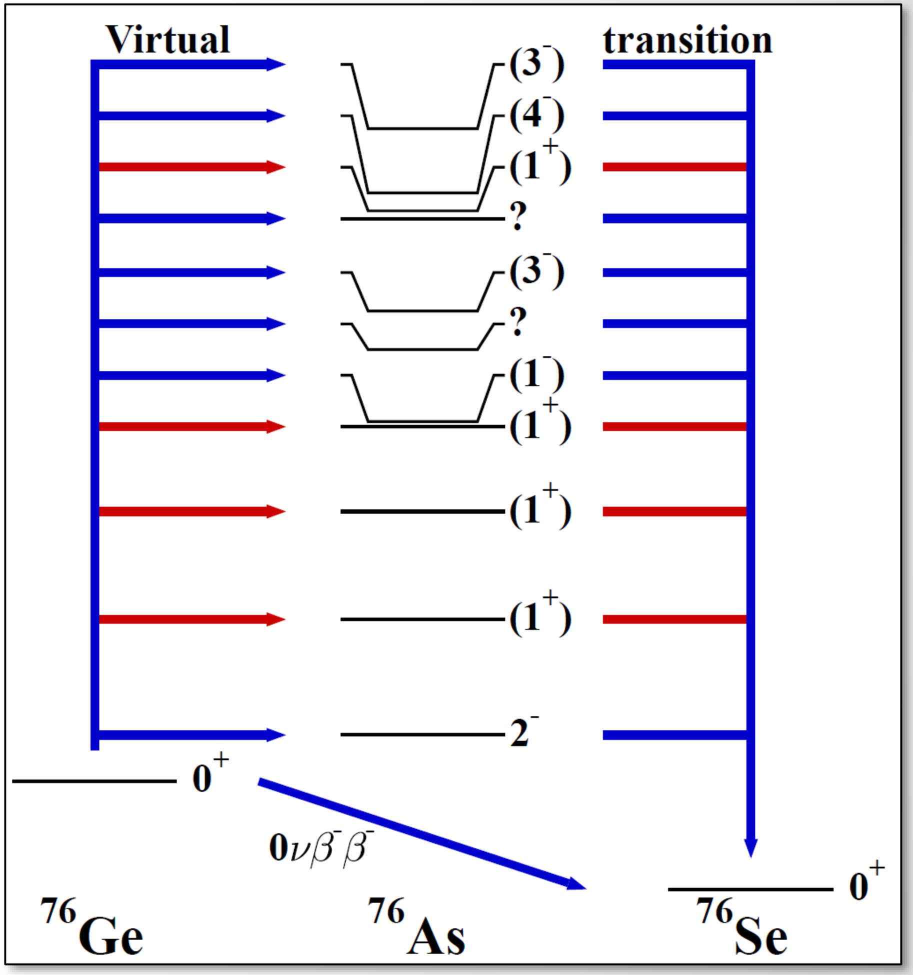


Quenching of g_A?

- Single beta / EC / $2\nu\beta\beta$ analysis relevant for $0\nu\beta\beta$?

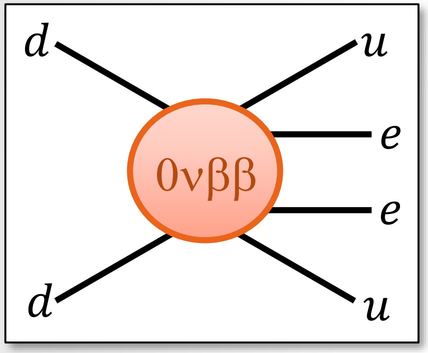
Unclear!

- Processes different at nucleon level
- Probing different transitions
- Incorporate more experimental information
  - Higher, forbidden beta decays
  - Charge exchange reactions
  - Muon capture



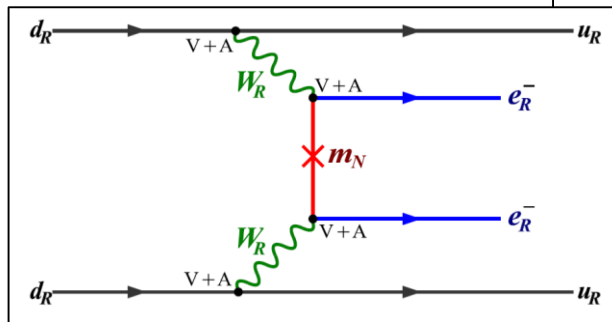
New Physics and $0\nu\beta\beta$

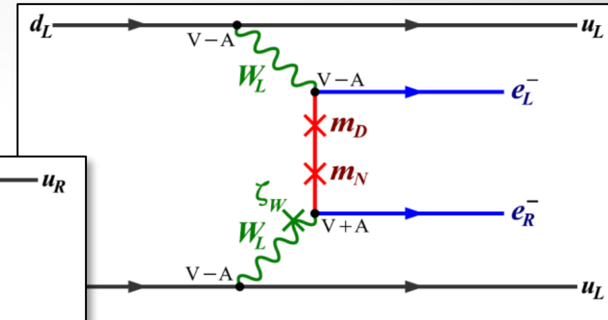
- Plethora of New Physics scenarios

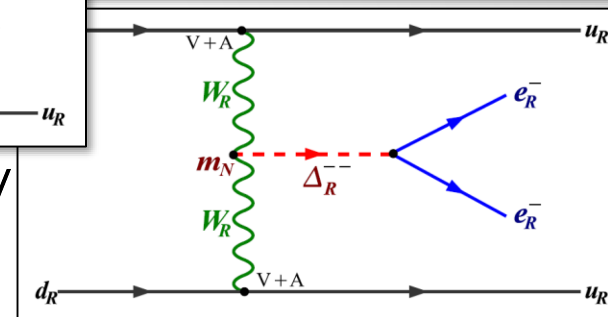


=

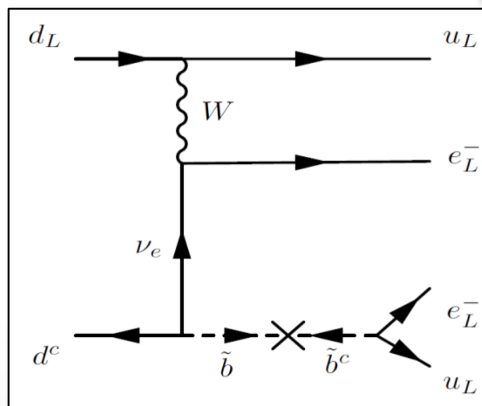
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

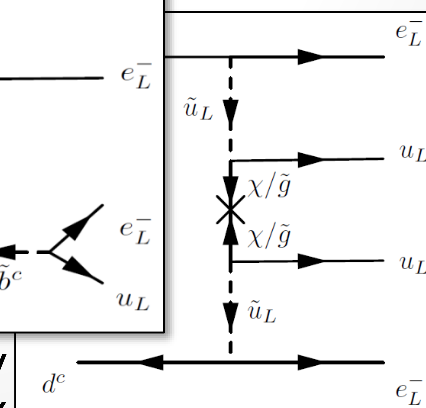






Left-Right Symmetry



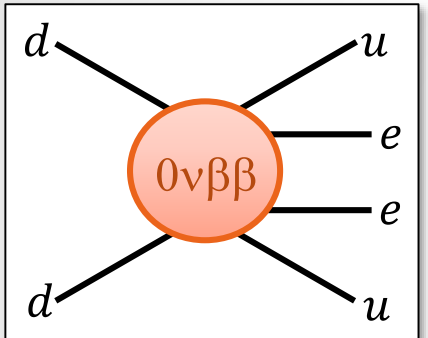


R-Parity
Violating SUSY

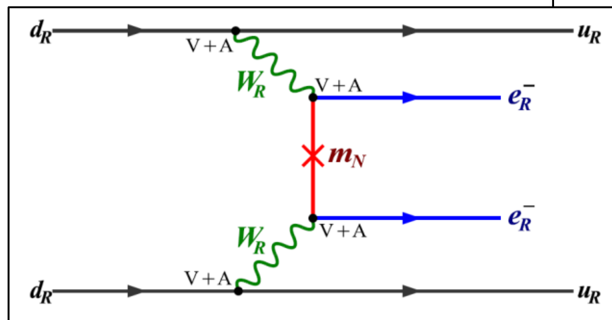
Extra Dimensions
Majorons
Leptoquarks
…

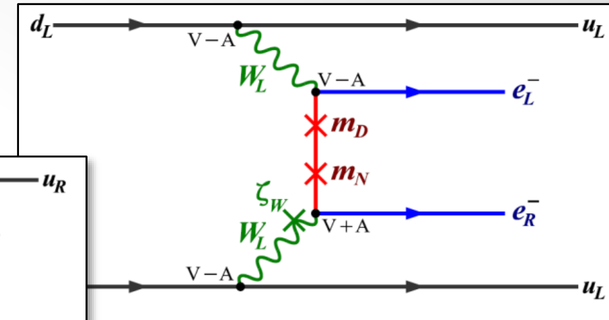
New Physics and $0\nu\beta\beta$

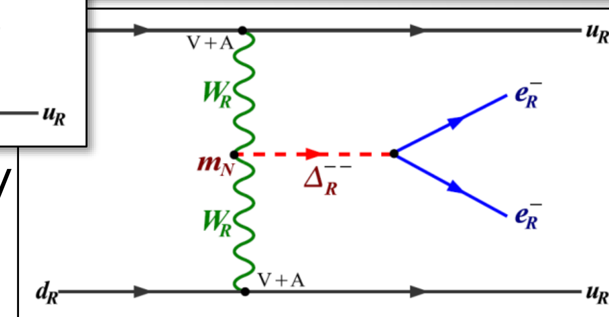
- Plethora of New Physics scenarios



=



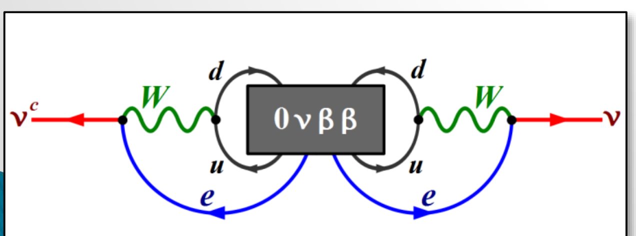


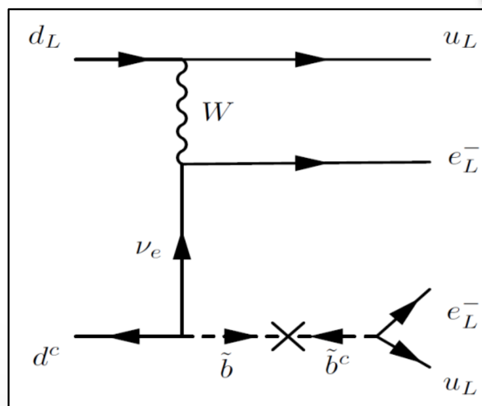


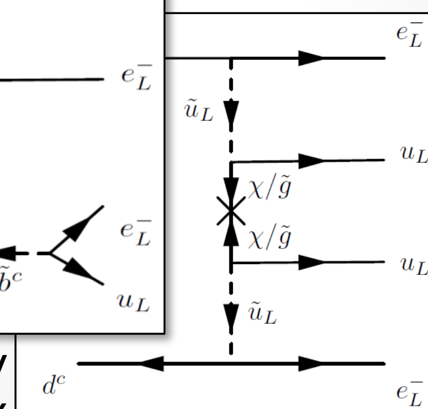
Left-Right Symmetry

$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$

- Neutrinos still Majorana





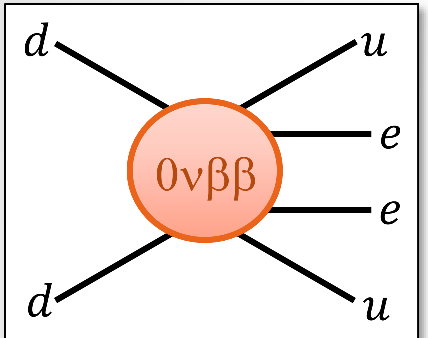


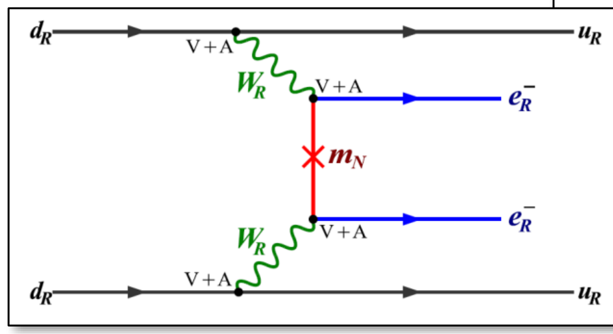
R-Parity Violating SUSY

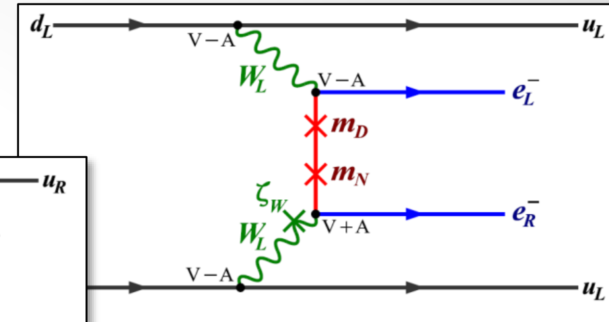
- Extra Dimensions
- Majorons
- Leptoquarks
- ...

New Physics and $0\nu\beta\beta$

- Examples in Left-Right Symmetry







$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \text{TeV})^5}$$

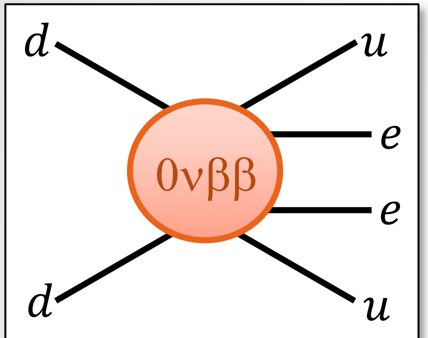
$$\epsilon_{V-A}^{V+A} = \sum_{i=1}^{3} U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/10\ \text{TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale

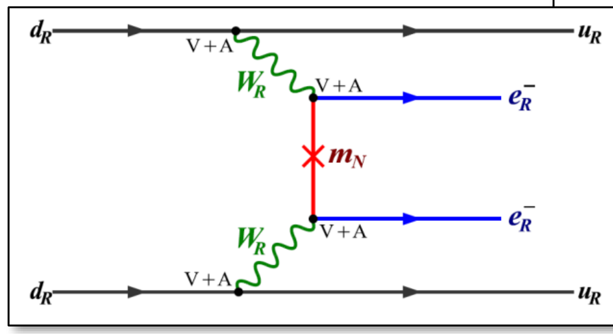
New Physics and $0\nu\beta\beta$

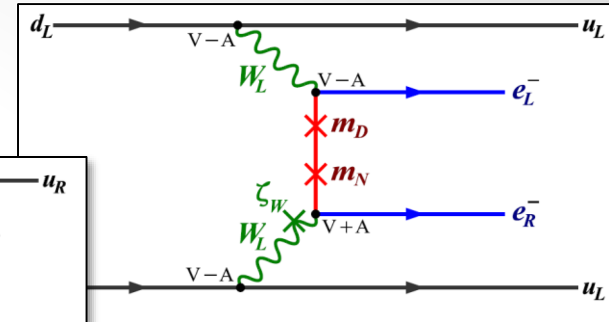
University College London

- Examples in Left-Right Symmetry



=





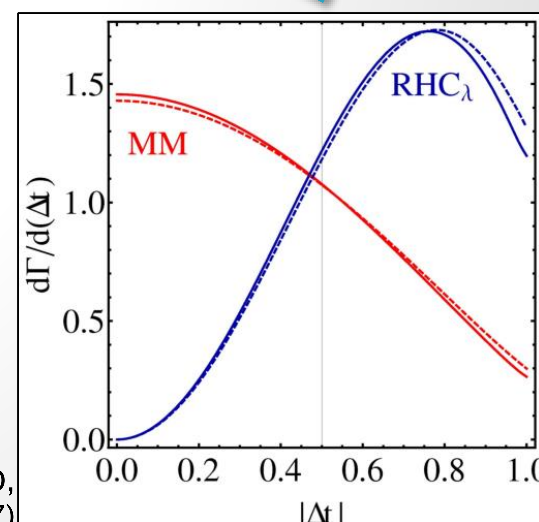
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\text{ TeV})^5}$$

$$\epsilon_{V-A}^{V+A} = \sum_i U_{ei} W_{ei} \tan\zeta_W \approx \frac{10^{-9}}{(\Lambda/1\text{ TeV})^3}$$

- $0\nu\beta\beta$ probes the TeV scale

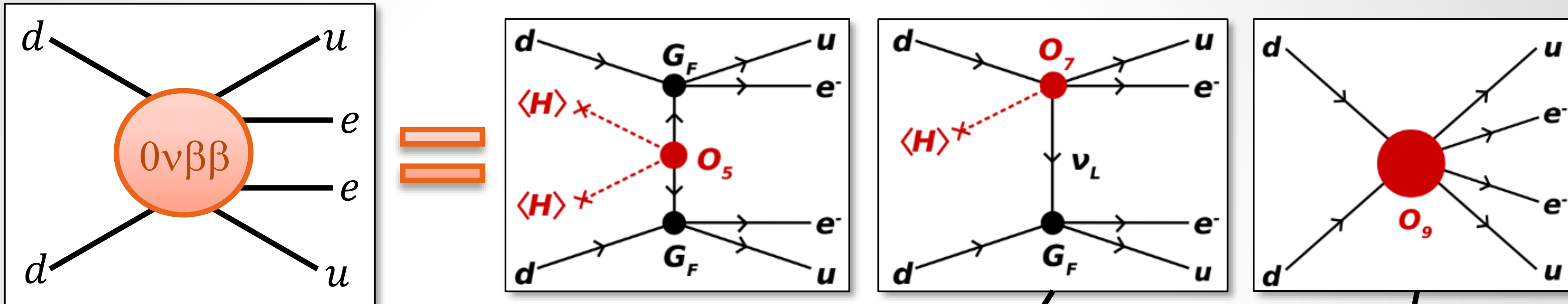
Modified angular and energy distribution of emitted electrons
(Doi et al. '83; Ali et al. '06)



FFD, SuperNEMO, Eur.Phys.J. C70 (2010) 927)

New Physics and $0\nu\beta\beta$

- Effective Operators



$$T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

Long-range

Isotope	$\lvert\epsilon_{V-A}^{V+A}\rvert$	$\lvert\epsilon_{V+A}^{V+A}\rvert$	$\lvert\epsilon_{S-P}^{S+P}\rvert$	$\lvert\epsilon_{S+P}^{S+P}\rvert$	$\lvert\epsilon_{TL}^{TR}\rvert$	$\lvert\epsilon_{TR}^{TR}\rvert$
^{76}Ge	$3.5 \cdot 10^{-9}$	$6.2 \cdot 10^{-7}$	$1.1 \cdot 10^{-8}$	$1.1 \cdot 10^{-8}$	$6.7 \cdot 10^{-10}$	$1.1 \cdot 10^{-9}$
^{136}Xe	$2.8 \cdot 10^{-9}$	$5.6 \cdot 10^{-7}$	$6.8 \cdot 10^{-9}$	$6.8 \cdot 10^{-9}$	$4.8 \cdot 10^{-10}$	$8.1 \cdot 10^{-10}$

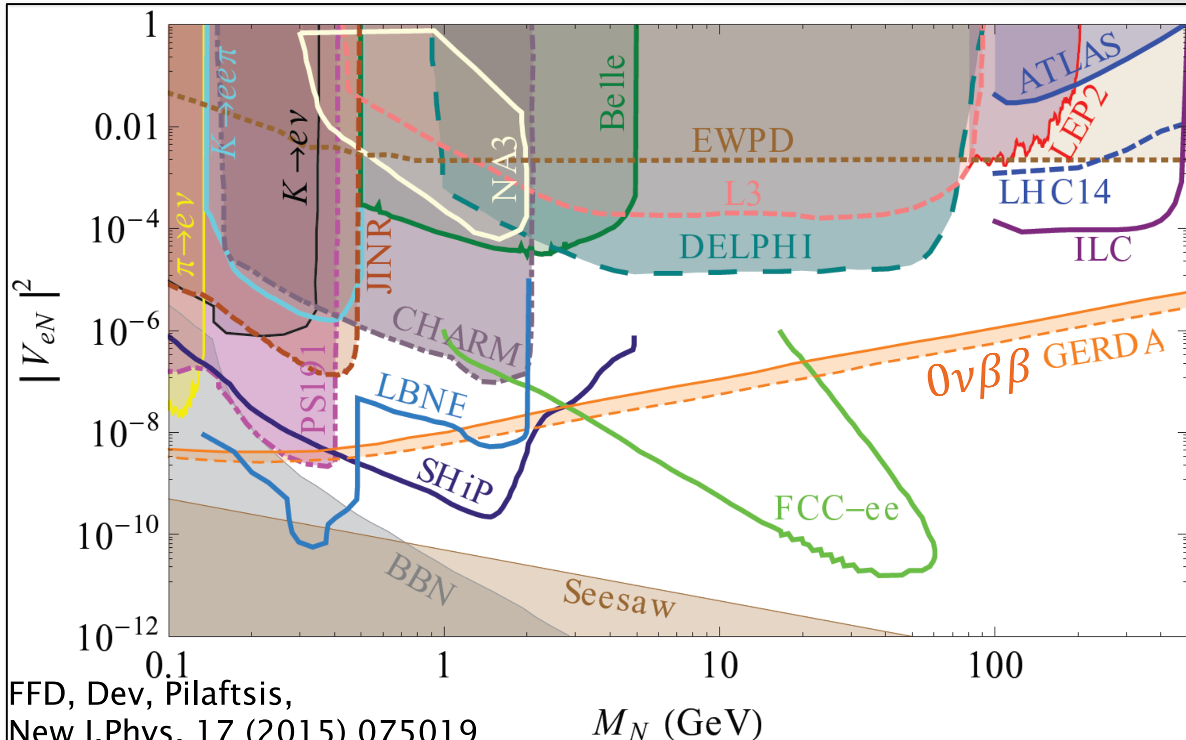
Short-range

FFD, Päs, Hirsch,
J.Phys. G39 (2012) 124007

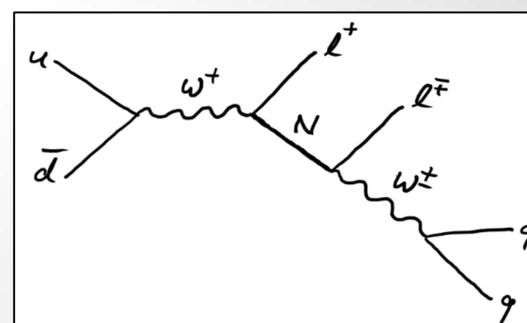
^{A}X	$\lvert\epsilon_1\rvert$	$\lvert\epsilon_2\rvert$	$\lvert\epsilon_3^{LLz(RRz)}\rvert$	$\lvert\epsilon_3^{LRz(RLz)}\rvert$	$\lvert\epsilon_4\rvert$	$\lvert\epsilon_5\rvert$
^{76}Ge	$3.2 \cdot 10^{-7}$	$1.8 \cdot 10^{-9}$	$2.2 \cdot 10^{-8}$	$1.4 \cdot 10^{-8}$	$1.5 \cdot 10^{-8}$	$1.5 \cdot 10^{-7}$
^{136}Xe	$2.6 \cdot 10^{-7}$	$1.4 \cdot 10^{-9}$	$1.1 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$	$1.2 \cdot 10^{-8}$	$1.2 \cdot 10^{-7}$

Heavy Neutrinos

- $0\nu\beta\beta$
  - stringent for pure Majorana N
- Peak Searches in Meson Decays
  - $\pi, K \to e\nu$; Belle
- Beam Dump Experiments
  - e.g. PS191; CHARM; LBNE
- LNV Meson Decays
  - $K \to ee\pi$; SHiP
- Z Decays
  - LEP: L3, Delphi; FCC-ee
- Electroweak Precision Tests (EWPD)
  - Fit of electroweak precision observables, lepton universality observables

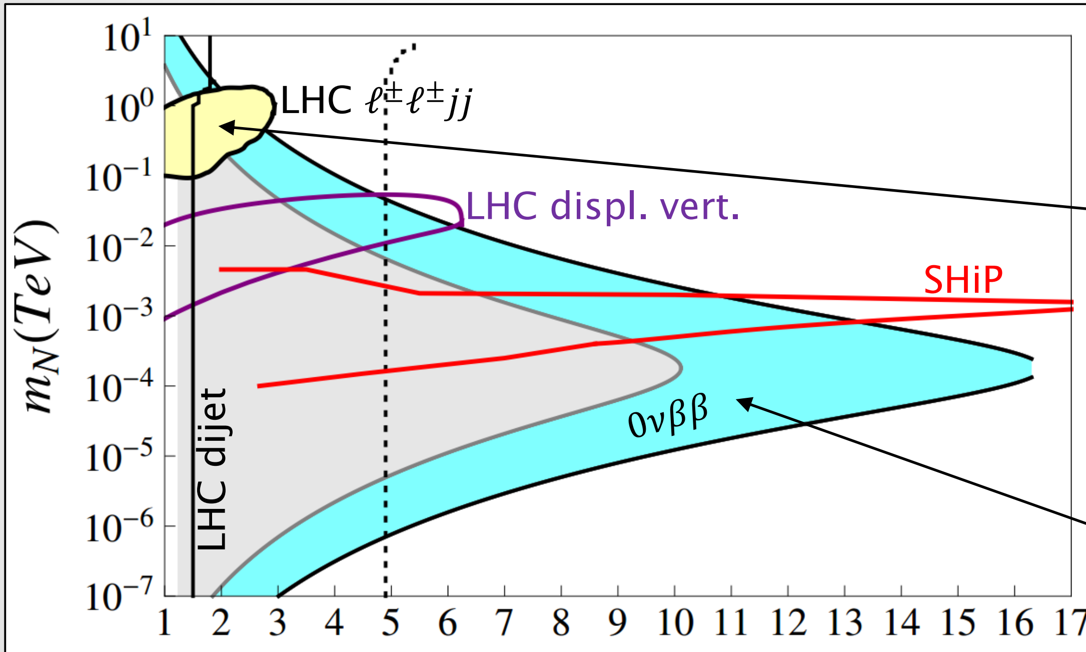


FFD, Dev, Pilaftsis, New J.Phys. 17 (2015) 075019

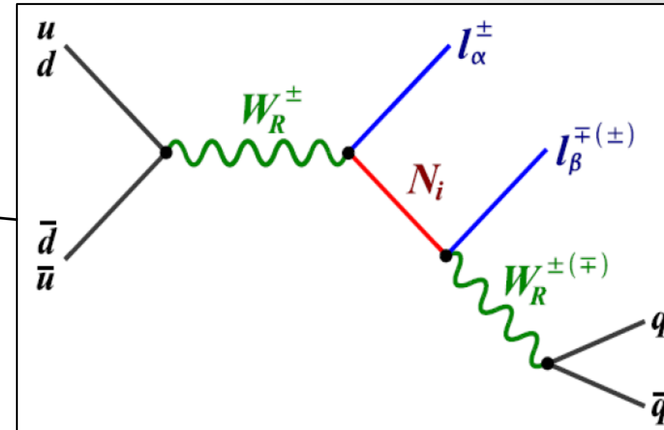


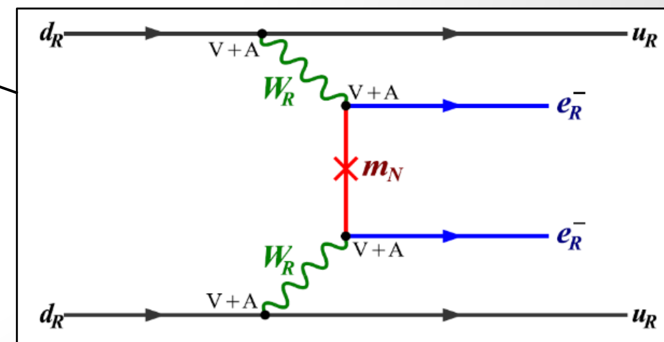
$0\nu\beta\beta$ vs LHC

- Example of Left-Right Symmetry
  (Mohapatra, Senjanovic '75)



Helo, Hirsch, Phys.Rev. D92 (2015), 073017



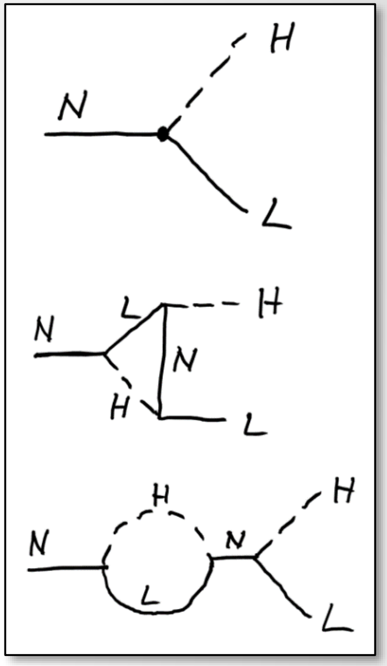


University College London

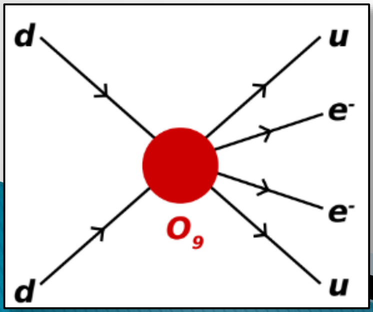
Baryon Asymmetry Generation and Washout

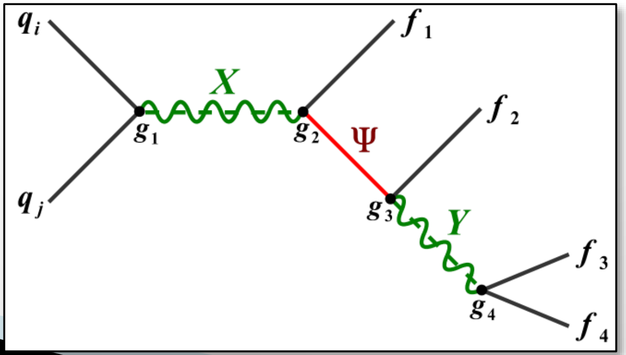
- Classic Example: High-Scale Leptogenesis
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\ \mathrm{GeV}$
    - Observed asymmetry

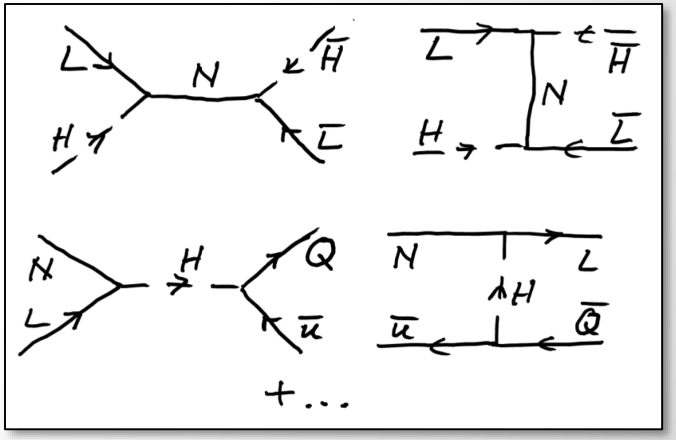
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



- What if we observe lepton number violating processes in $0\nu\nu\beta$ or at the LHC?





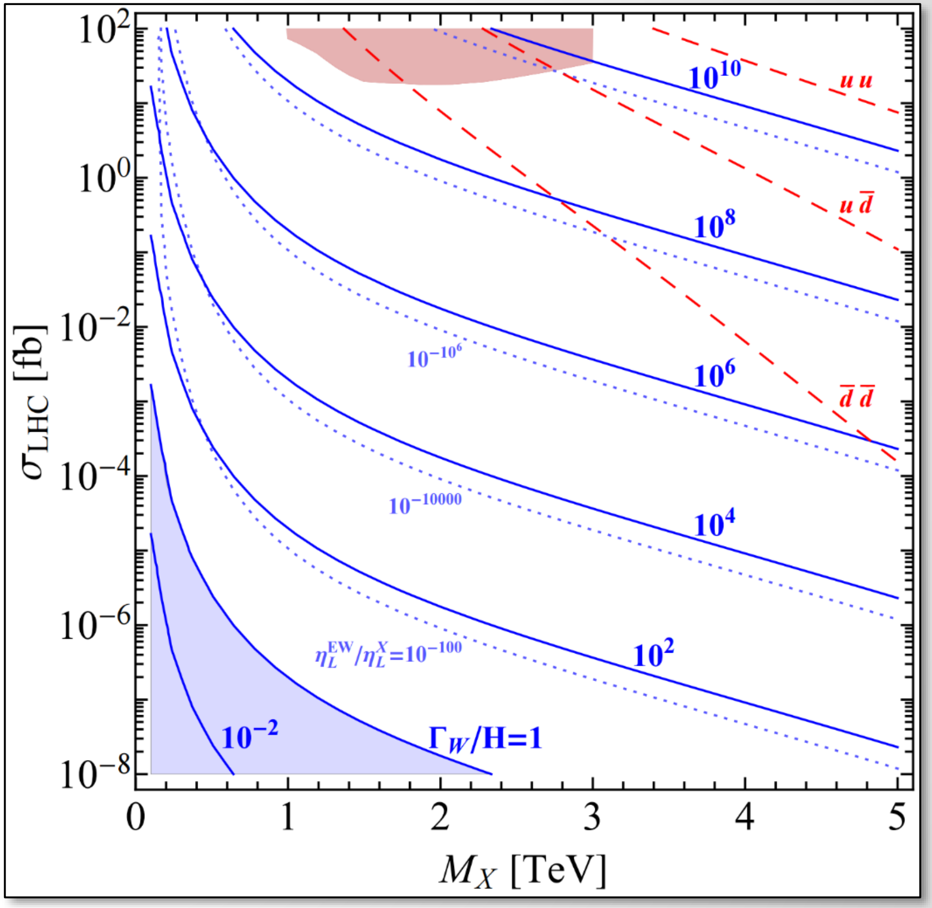


Baryon Asymmetry
Lepton Asymmetry Washout

- Compare $0\nu\beta\beta$ rate / LHC cross section with lepton number washout in the early Universe
  FFD, Harz, Hirsch, Phys.Rev.Lett. 112 (2014) 221601
  FFD, Harz, Hirsch, Huang, Päs, Phys.Rev. D92 (2015) 036005

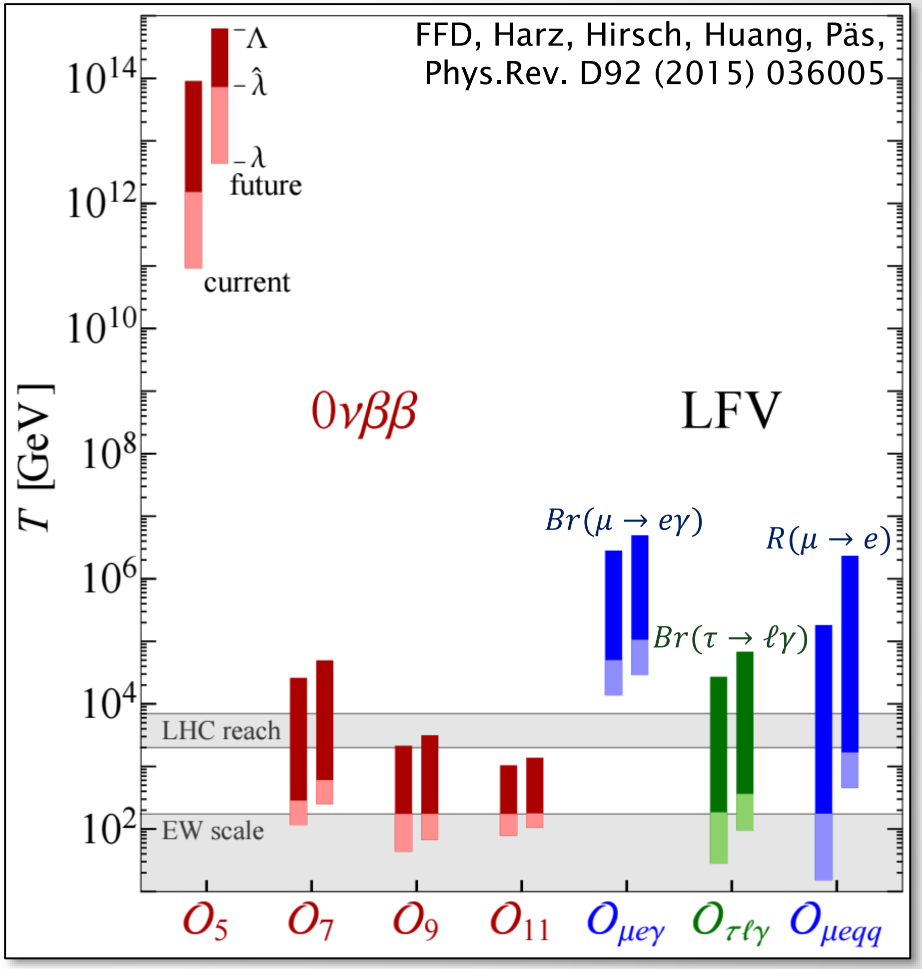
$$\frac{\Gamma_W}{H} > 3 \times 10^{-3} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\,\sigma_{\text{LHC}})$$

- Observation of LNV corresponds to highly effective washout $\Gamma_W/H \gg 1$



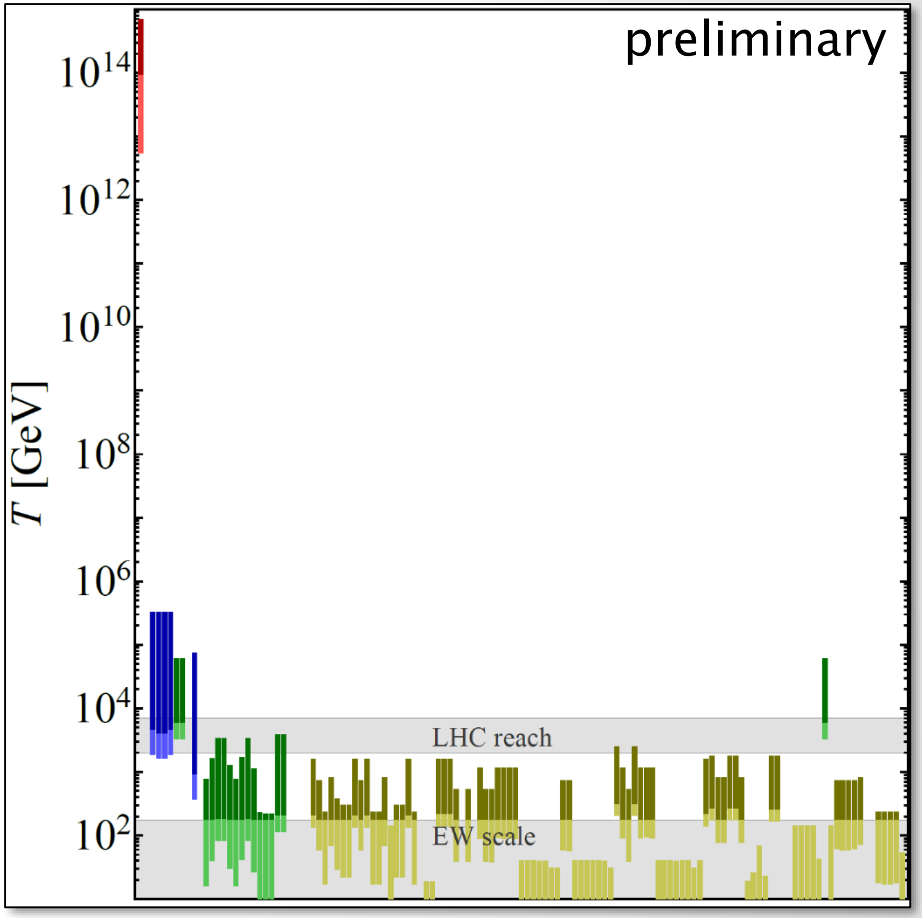
Baryon Asymmetry
Lepton Asymmetry Washout

- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LN(F)V
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**



Baryon Asymmetry
Lepton Asymmetry Washout

- Temperature ranges of strong equilibration
  - **Assumes observation of corresponding process!**
- Observation of LN(F)V
  - gives information at what temperatures operators are in equilibrium
  - **can falsify high-scale baryogenesis scenarios**



Conclusion

University College London

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Natural suppression of charged LFV?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - New LNV physics at the LHC scale?
  - Standard Mass Mechanism?
    - 5-dim operator from LNV at GUT scale
  - Impact on baryon asymmetry in the Universe
  - Challenging Physics: concerted effort between theory/experiment in nuclear/particle physics
- **Importance of probing LNV around the TeV scale**
  - Mechanism of neutrino mass generation?
  - Other probes, e.g.
    - LNV Higgs decays [Maiezza, Nemevšek, Nesti, Phys.Rev.Lett. 115 (2015) 081802]
    - $\mu^- \to e^+$ conversion in nuclei [Geib, Merle, Zuber, Phys.Lett. B764 (2017) 157]