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Neutrinos, $0\nu\beta\beta$ and the LHC

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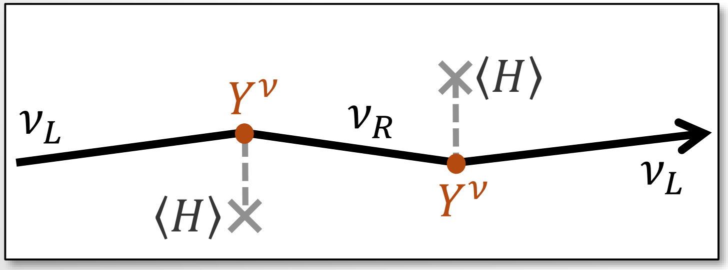
Collider Physics and the Cosmos | GGI Florence | Sep 2017

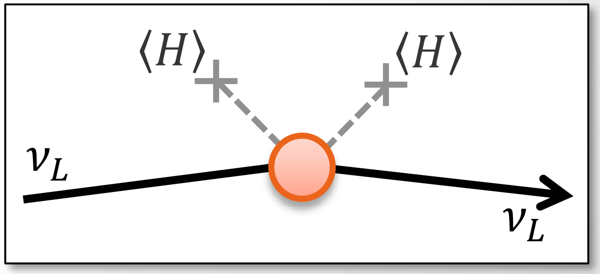
Dirac vs Majorana

- Two possibilities to define fermion 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

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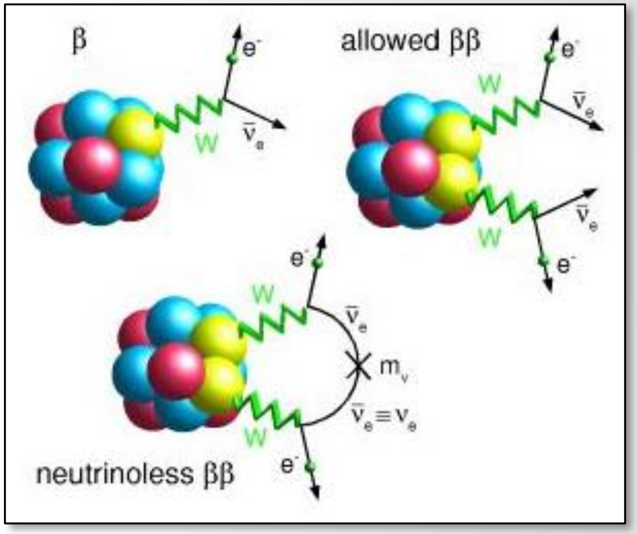
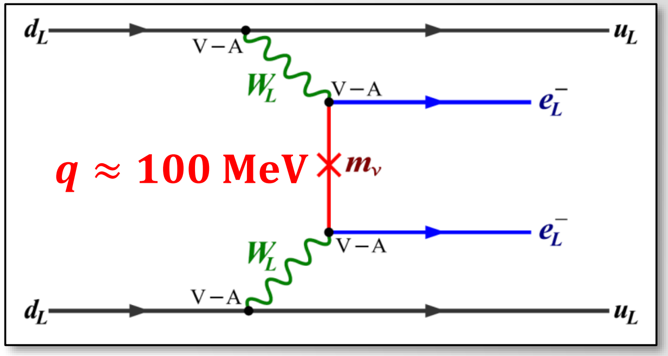
- Single beta decay
  $$(A, Z) \to (A, Z+1) + e^- + \bar{\nu}_e$$
- Allowed double beta ($2\nu\beta\beta$) decay
  $$(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e$$
- Neutrinoless double beta ($0\nu\beta\beta$) decay
  $$(A, Z) \to (A, Z+2) + 2e^-$$
  - Violation of lepton number
  - Mediated by Majorana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



$0\nu\beta\beta$

- Half-life

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



- Particle Physics

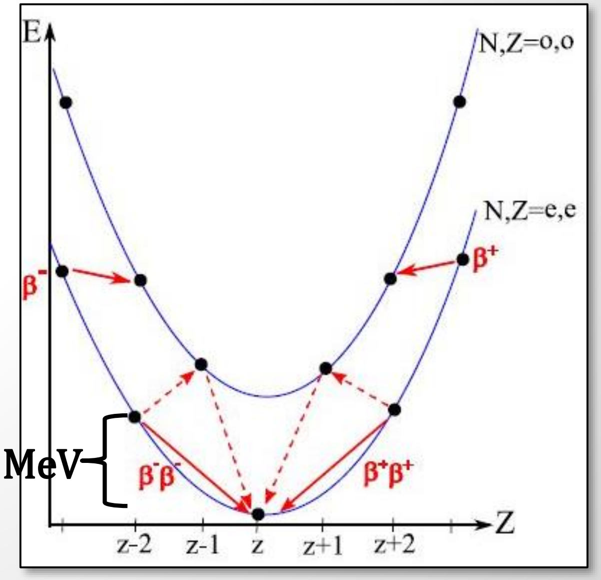
$$\mathcal{A}_{\mu\nu}^{lep} = \frac{1}{4}\sum_{i=1}^{3} U_{ei}^2 \gamma_\mu (1+\gamma_5) \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu (1-\gamma_5) \approx \frac{\gamma_\mu (1+\gamma_5)\gamma_\nu}{4q^2} \sum_{i=1}^{3} U_{ei}^2 m_{\nu_i} \rightarrow m_{\beta\beta}$$

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

$$T_{1/2}^{-1} \propto \frac{|m_{\beta\beta}|^2}{q^4} G_F^4 Q^5$$

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

$Q \approx 2-4$ MeV



Three Active Neutrinos

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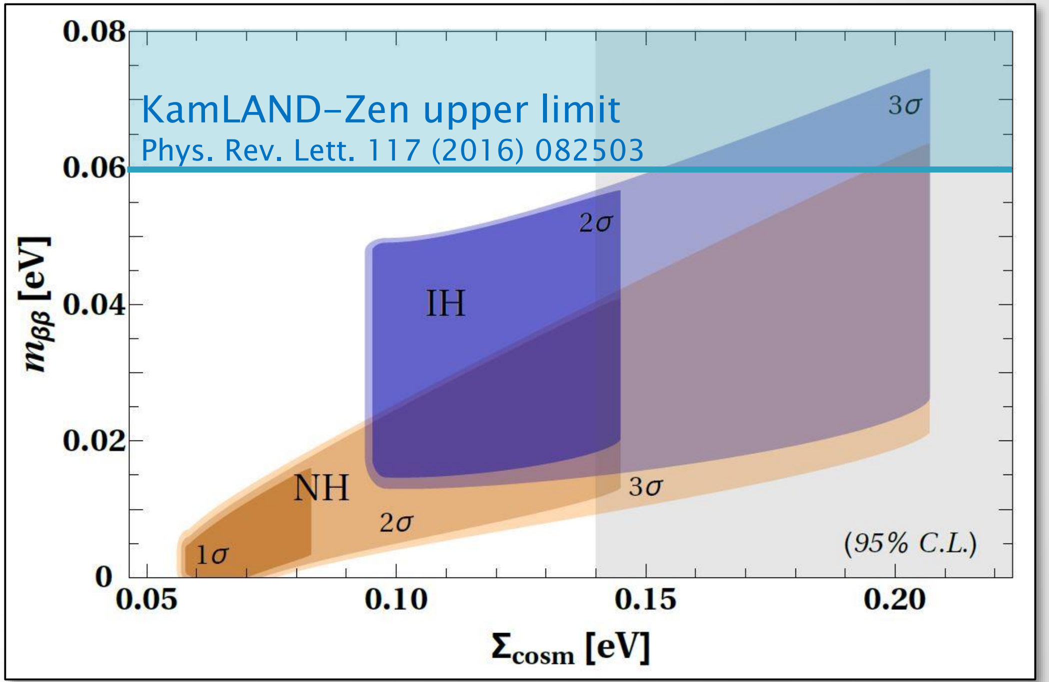
- Effective $0\nu\beta\beta$ Mass

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

- 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

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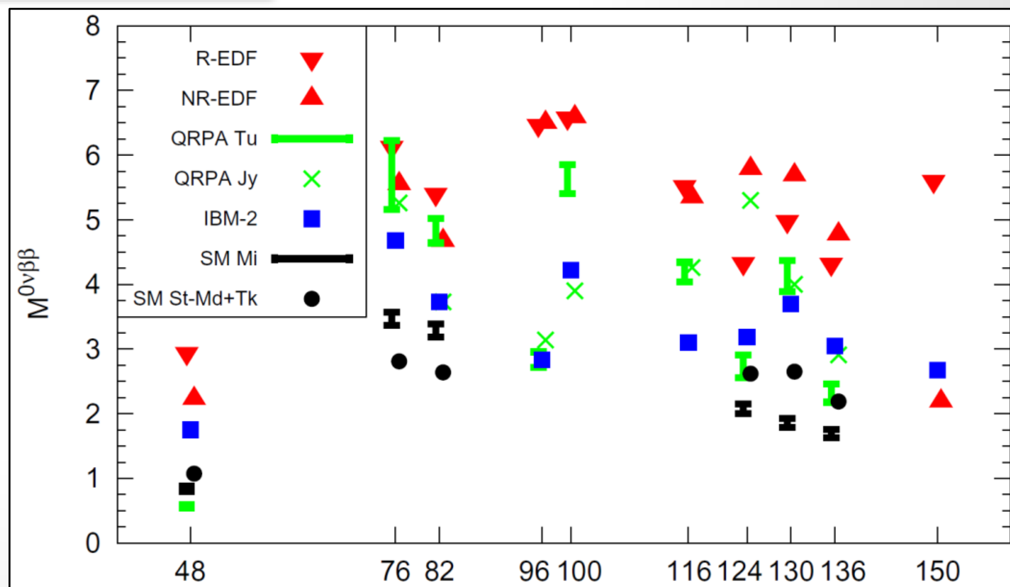
- Hadronic current

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

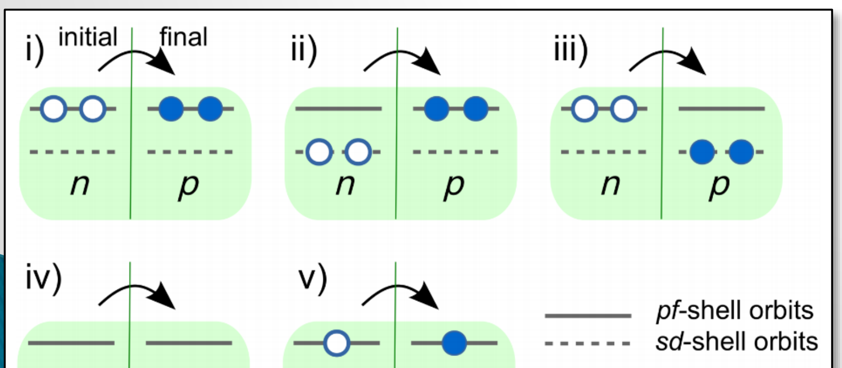
- Nuclear Matrix Element $M^{0\nu}$

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

  - Many-body problem
  - Factor 2 – 3 uncertainty between nuclear models



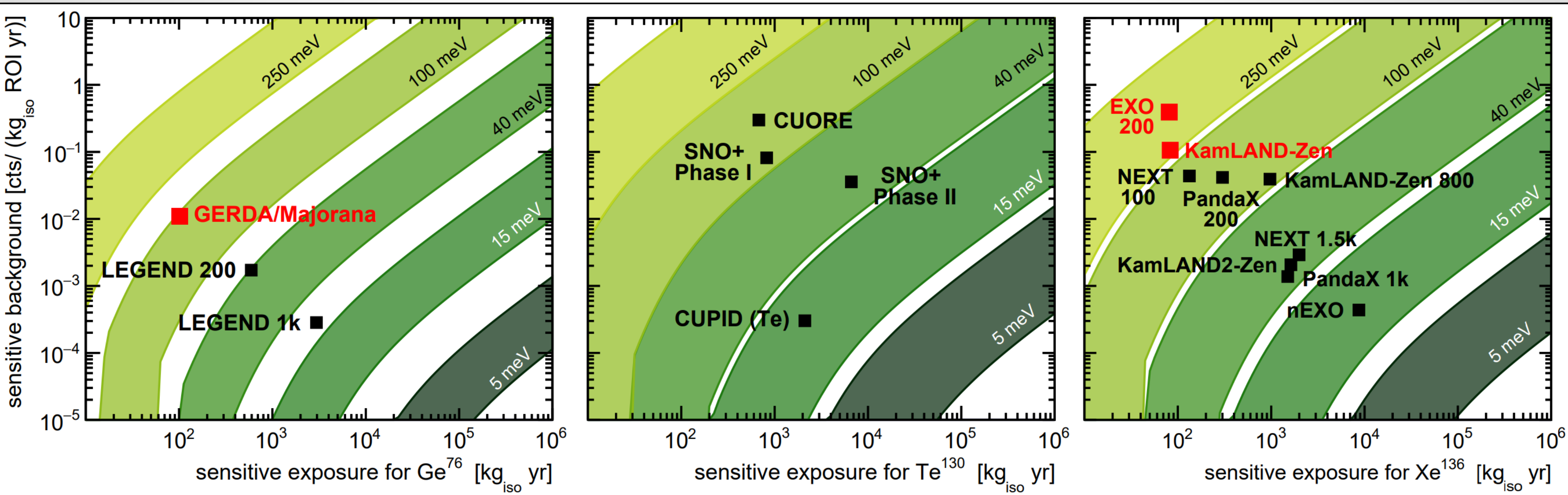
Menendez, arXiv:1605.05059



Iwata et al., Phys. Rev. Lett. 116, 112502

Three Active Neutrinos

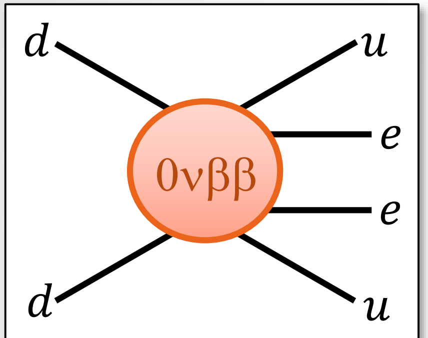
- Experimental Sensitivity



Agostini, Benato, Detwiler
arXiv:1705.02996

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

- Plethora of New Physics scenarios



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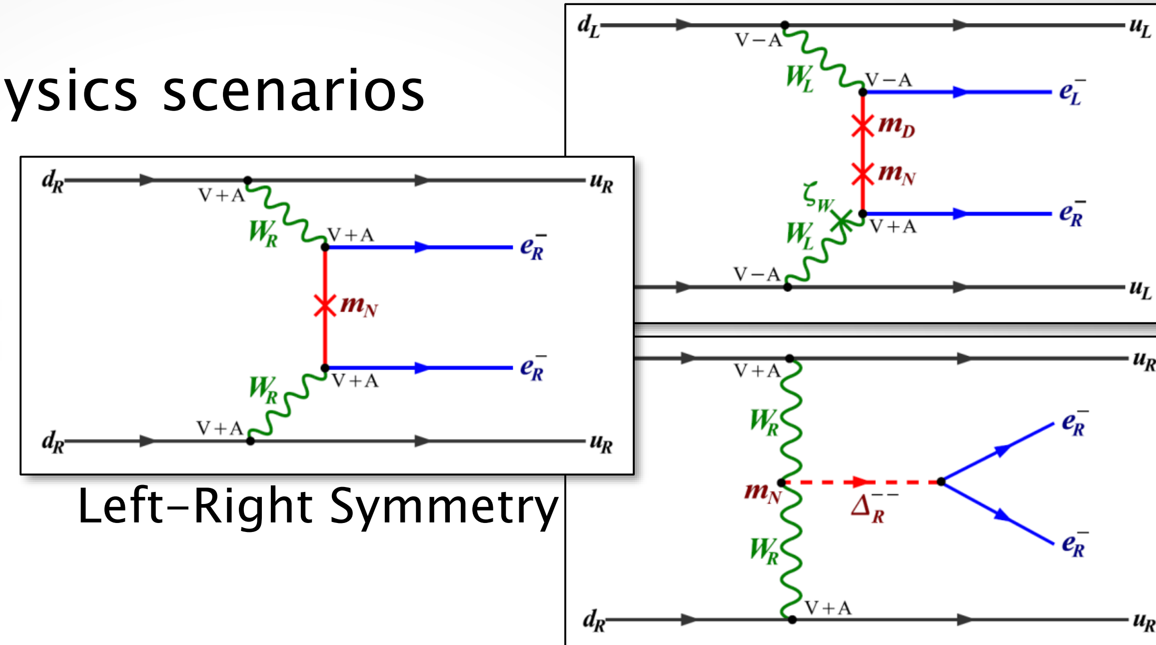
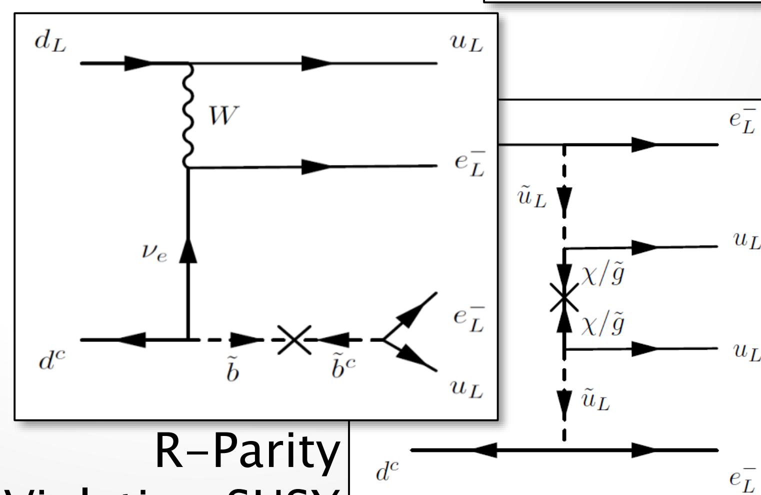
$$T_{1/2}^{-1} = \epsilon_{NP}^{2} G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^{2}$$



Left-Right Symmetry



R-Parity Violating SUSY

- Extra Dimensions
- Majorons
- Leptoquarks
- ...

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

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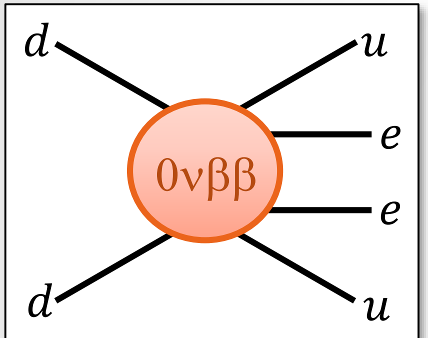

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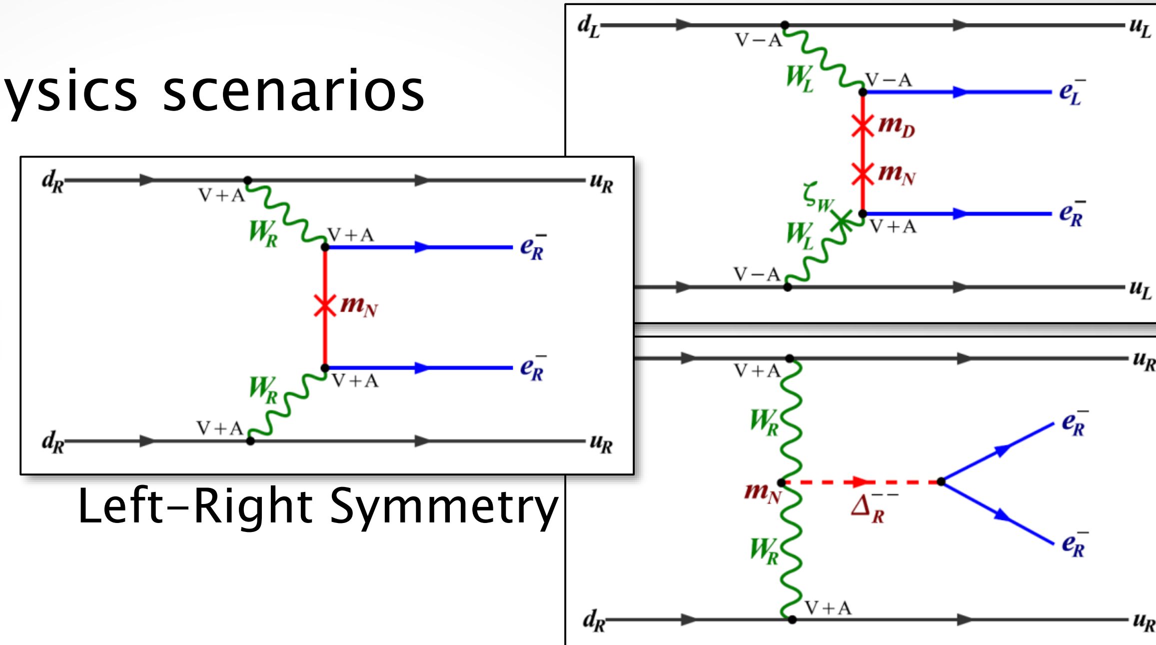
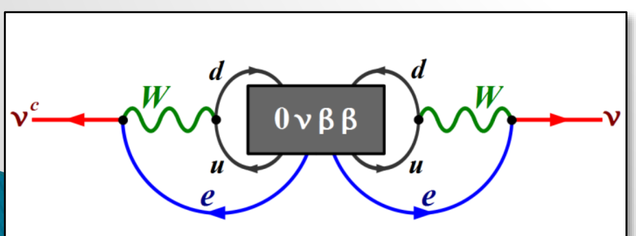
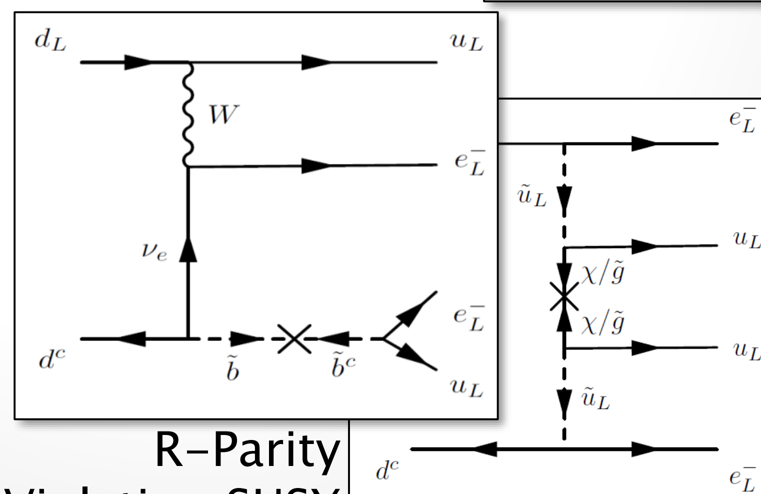


Left–Right Symmetry

- Neutrinos still Majorana





R–Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

…

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

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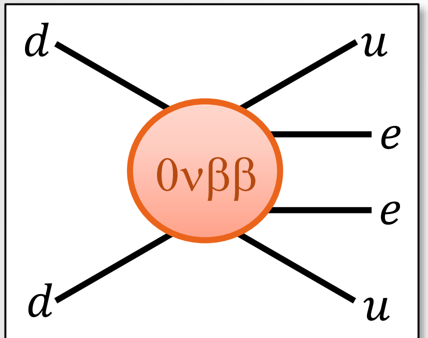
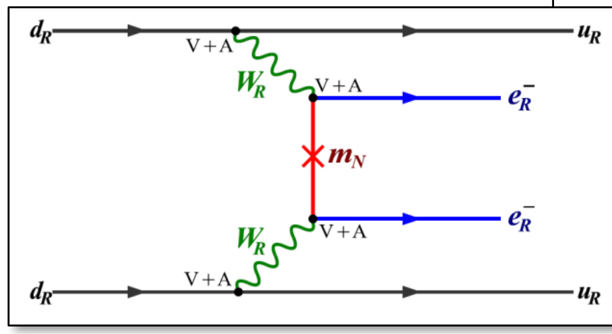
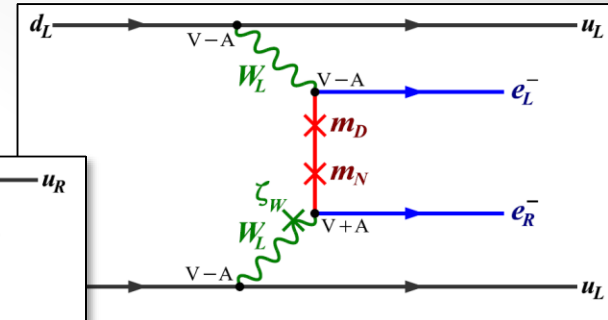
- Examples in Left-Right Symmetry







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

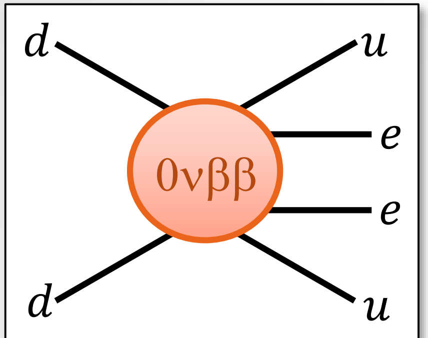
$$\epsilon_3^{RRz} = \sum_{i=1}^{3} V_{ei}^2 \frac{m_p}{m_N} \frac{m_W^4}{m_{W_R}^4} \approx \frac{10^{-8}}{(\Lambda/1\ \mathrm{TeV})^5}$$

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

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

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

- Examples in Left-Right Symmetry



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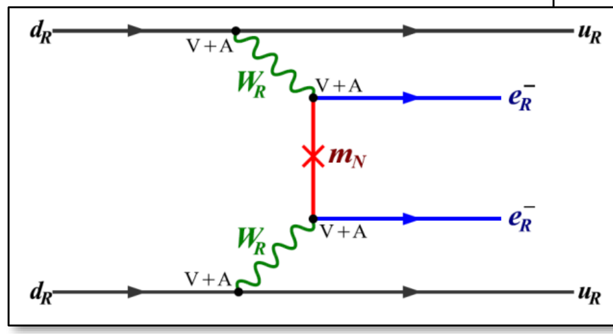

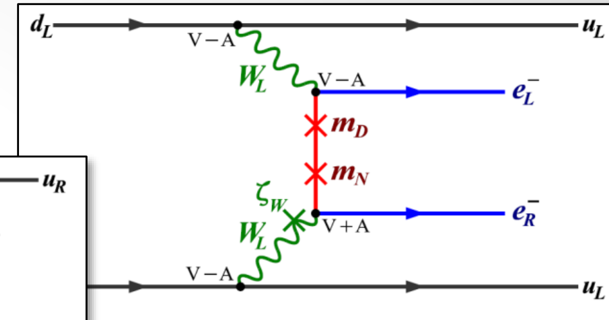

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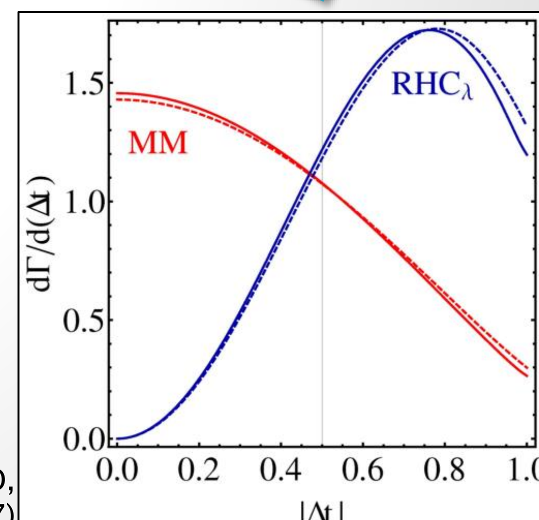
Modified angular and energy distribution of emitted electrons
(Doi et al. '83; Ali et al. '06)

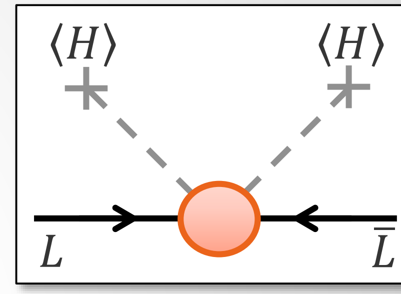


FFD, SuperNEMO, Eur.Phys.J. C70 (2010) 927)

Effective Mass and Seesaw

- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

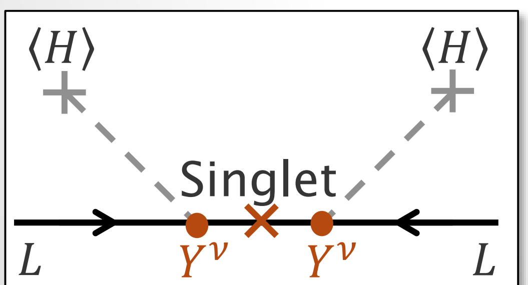
$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right) \xrightarrow[\langle H \rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$



- Seesaw Mechanism
  - Sterile neutrino mass scale unknown

$$m_\nu \approx 0.1\ \text{eV}\left(\frac{Y_\nu \langle H \rangle}{100\ \text{GeV}}\right)^2 \left(\frac{10^{14}\ \text{GeV}}{M_N}\right)$$

Seesaw I



$M_N \approx 10^{14}$ GeV	Naïve Seesaw, GUTs
$\gtrsim 10^9$ GeV	Thermal Leptogenesis
$\approx 10^2$ GeV	Resonant Leptogenesis, LHC
≈ 1 keV	Dark Matter Candidate
≈ 1 eV	Oscillations, Cosmology, $0\nu\beta\beta$

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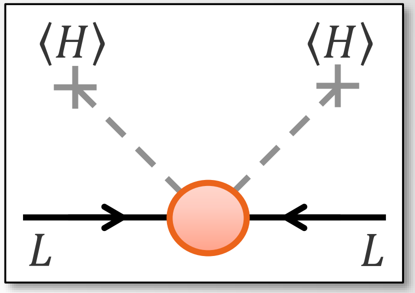
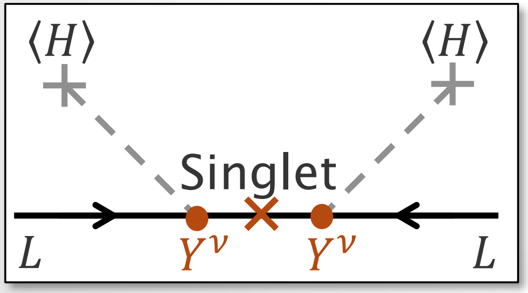
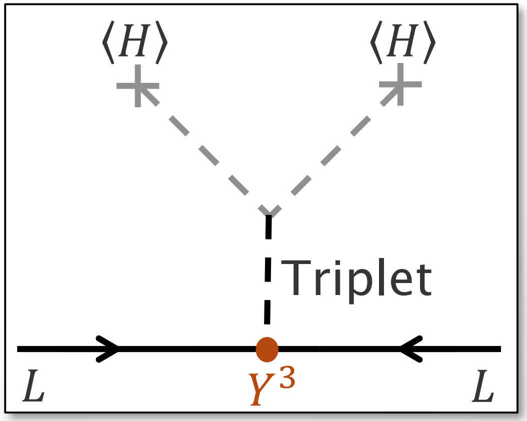


- Seesaw Mechanisms
  - Three possible mediators at tree level

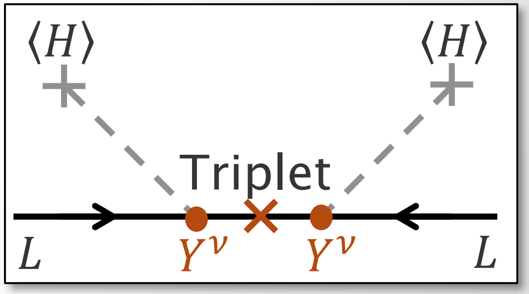
Seesaw I



Seesaw II



Seesaw III



Effective Mass and Seesaw

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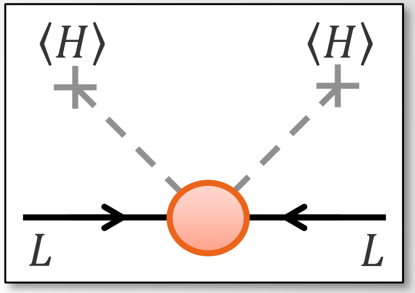
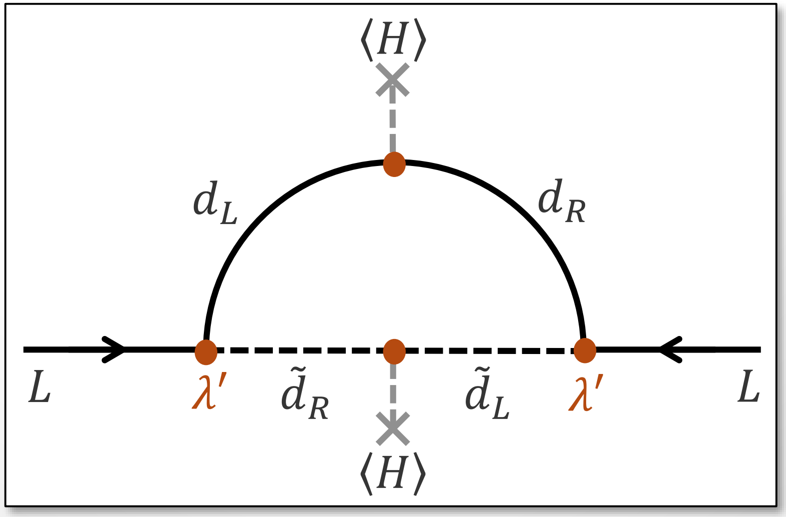


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. R-Parity Violating SUSY



Heavy Sterile Neutrinos

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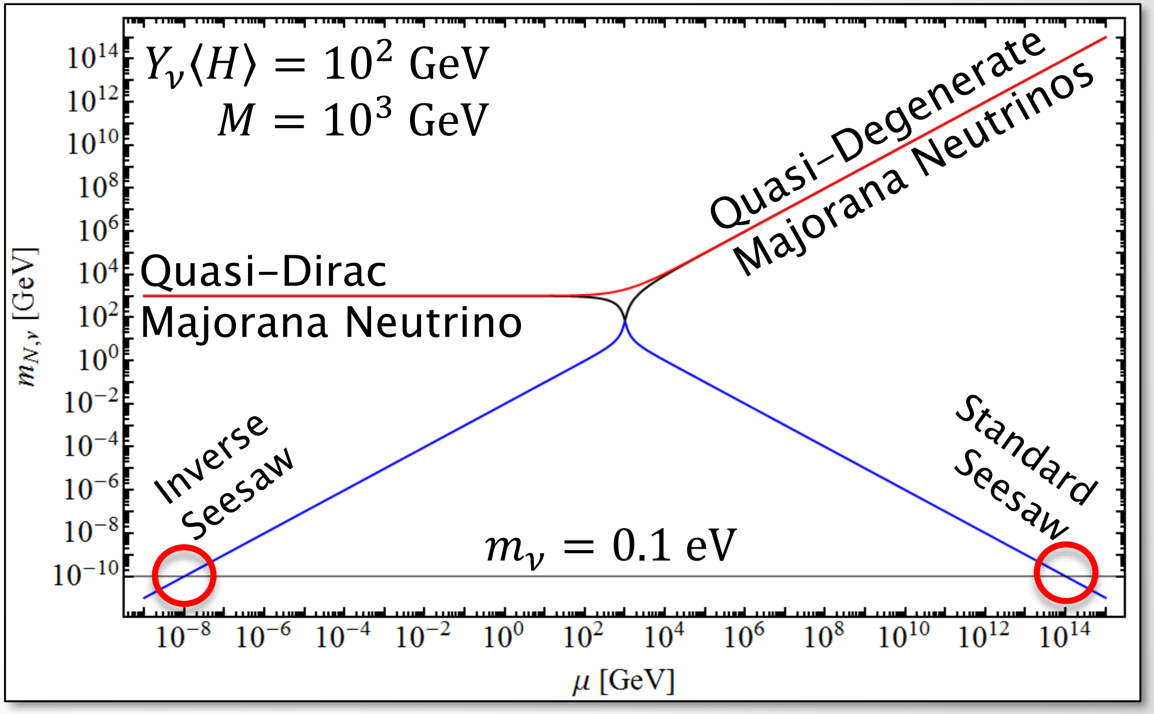
- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$
  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$\begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

    - Large Yukawa couplings $\approx 10^{-2}$
    - Quasi-Dirac heavy neutrino

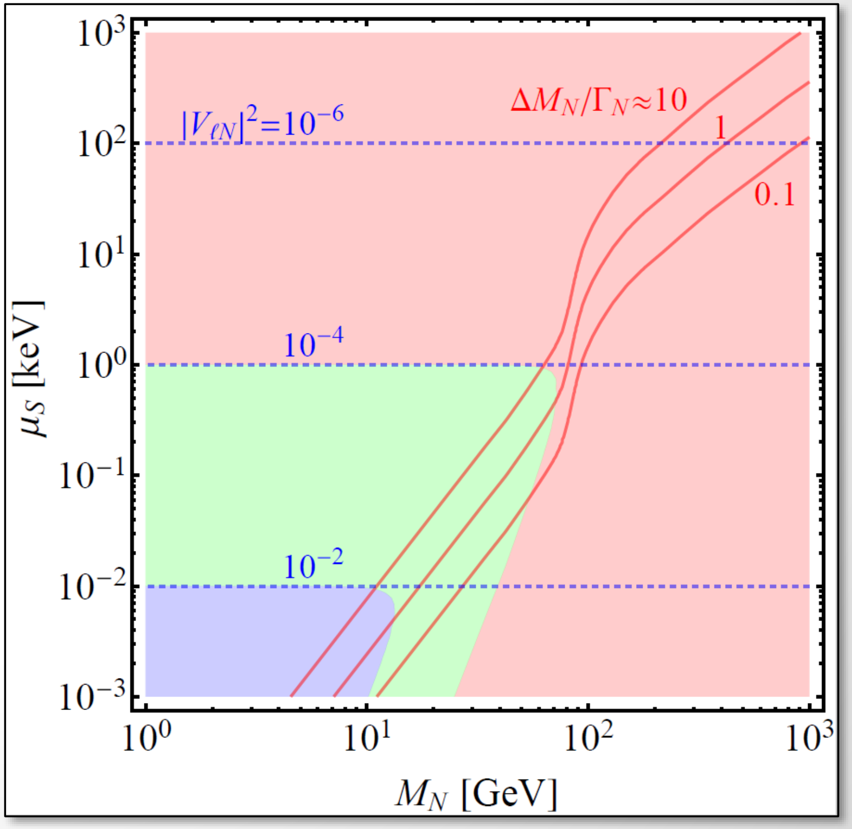


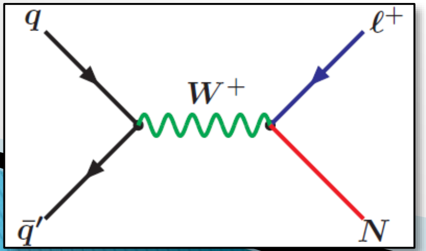
Heavy Sterile Neutrinos
Low Scale Singlet Seesaw Models

- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings $Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$
  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

$$\begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

    - LNV in resonant N production suppressed by $\frac{\Delta m_N}{\Gamma_N} \approx \frac{\mu}{\Gamma_N}$





Heavy Sterile Neutrinos

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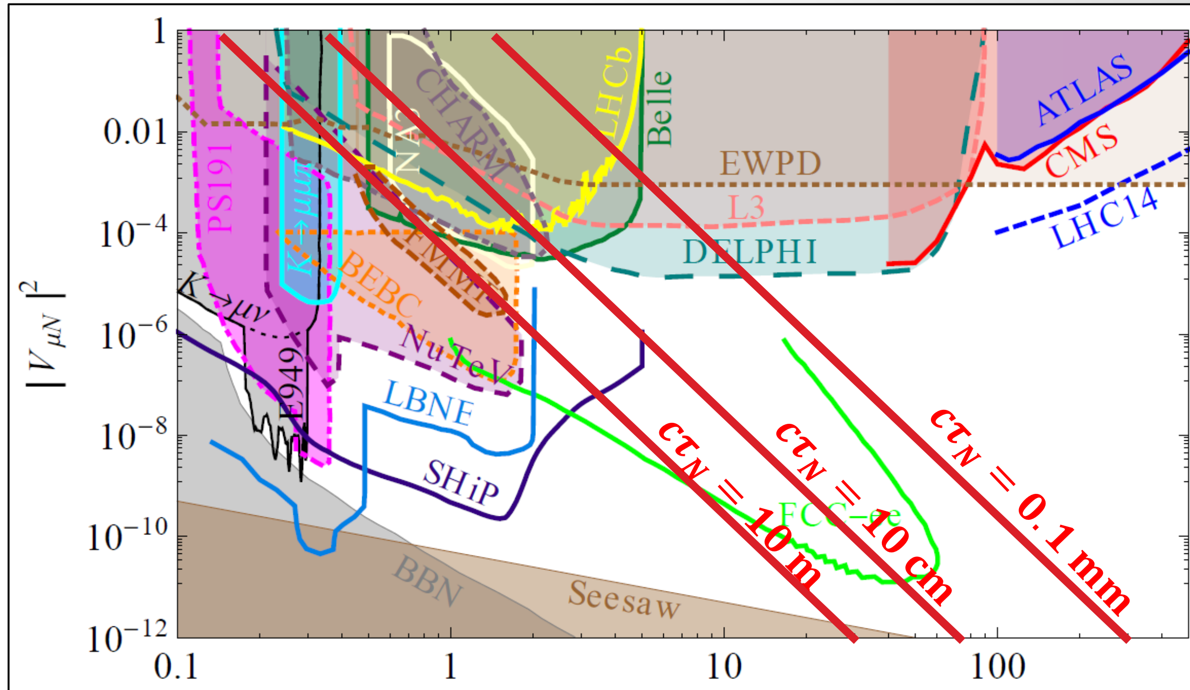
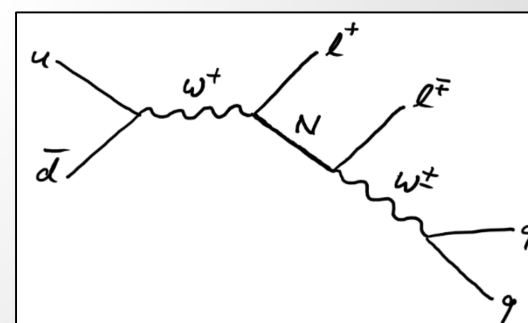
- Constraints on coupling to leptons $|V_{lN}|$
- Neutrinoless Double Beta Decay
  - GERDA
  - stringent for pure Majorana N
- Peak Searches in Meson Decays
  - $\pi, K \to e\nu$
  - Belle
- Beam Dump Experiments
  - e.g. PS191, CHARM
  - LBNE
- LNV Meson Decays
  - $K \to ee\pi$
  - SHiP
- Z Decays
  - LEP: L3, Delphi
  - FCC-ee
- Electroweak Precision Tests
  - EWPD: Fit of electroweak precision observables, lepton universality observables



FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019



Heavy Sterile Neutrinos

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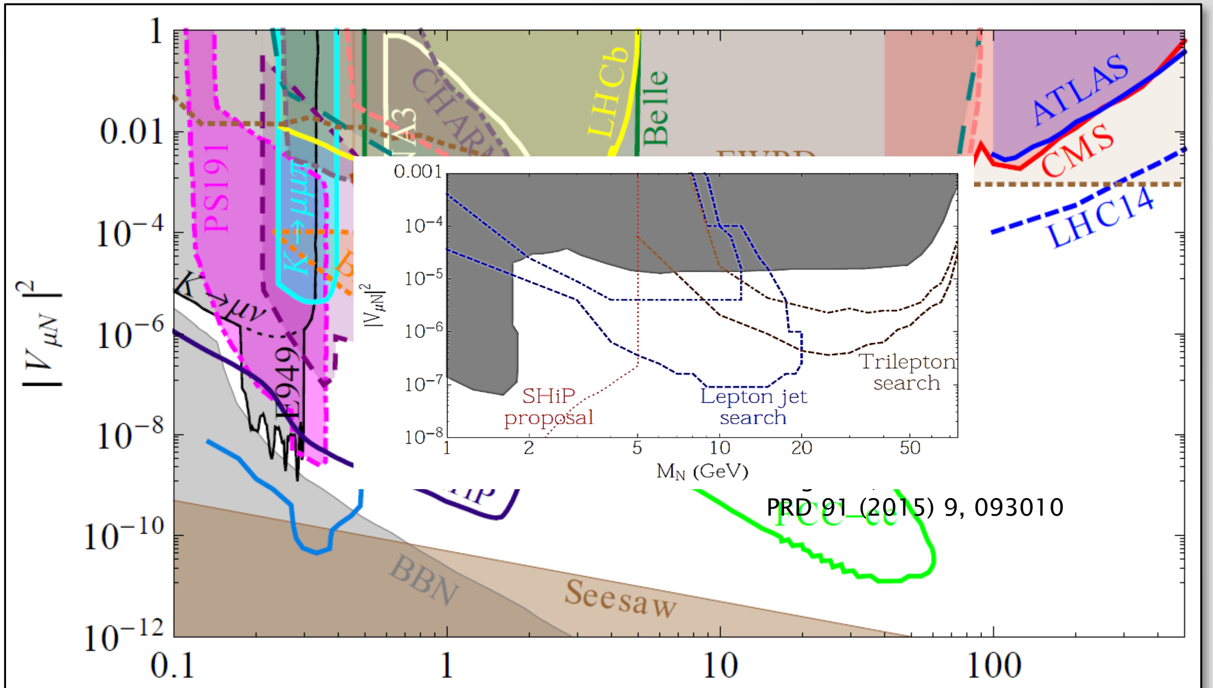
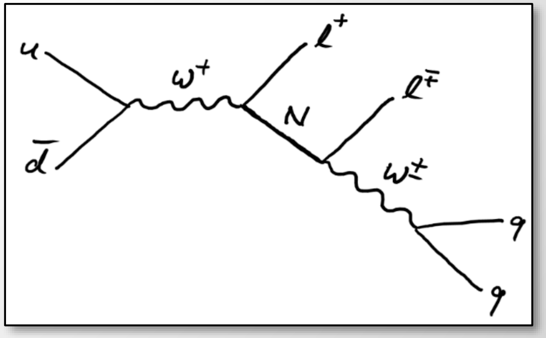
- Constraints on coupling to leptons $|V_{lN}|$
- LEP2, ILC
  $e^+e^- \to N\nu,\ N \to eW, \nu Z, \nu H$
- LHC (ATLAS, CMS, LHC14)
  - Drell-Yan Production
  - Majorana N
    - Same-sign dilepton signal
  - (Quasi-)Dirac N
    - Trilepton signal
  - Modified searches for
    - Lighter neutrinos
    - Long-lived neutrinos



FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019

PRD 91 (2015) 9, 093010



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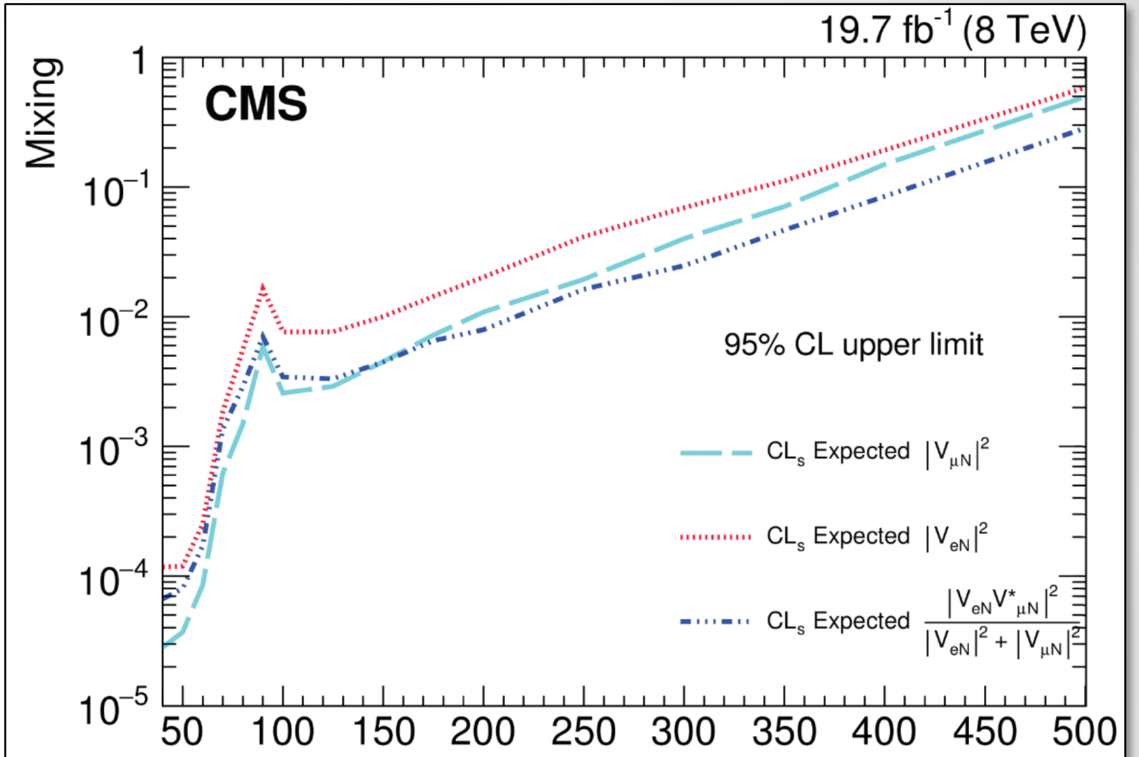
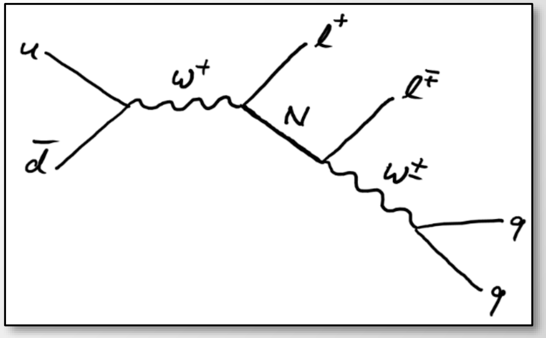


CMS, JHEP 04 (2016) 169



Extended Gauge Sectors
Additional U(1)

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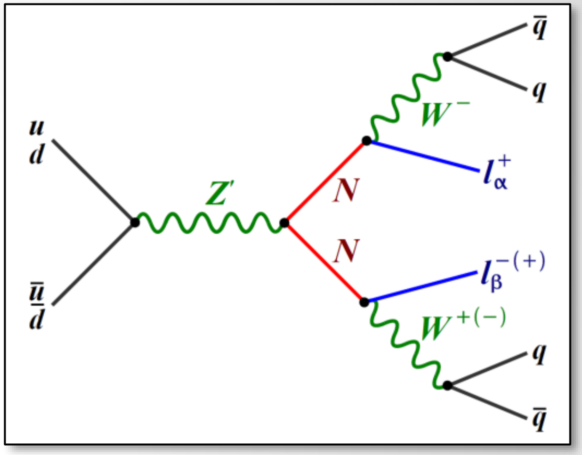
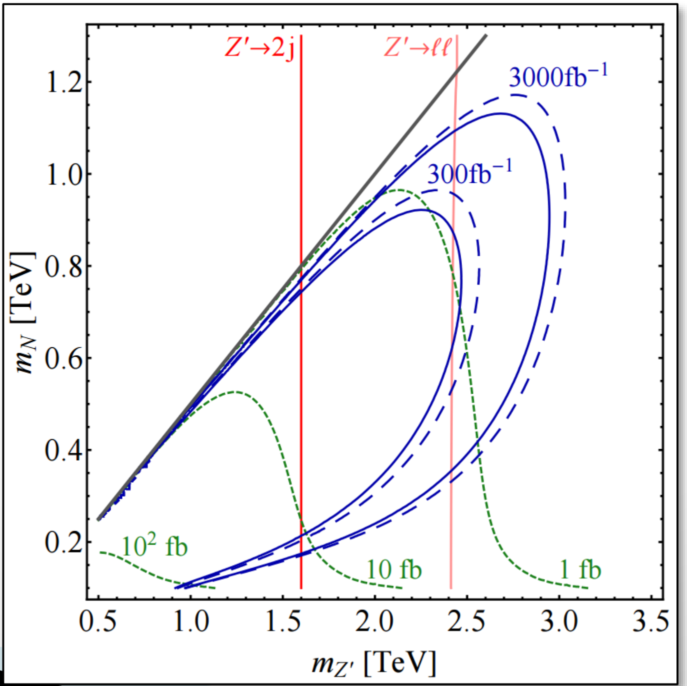
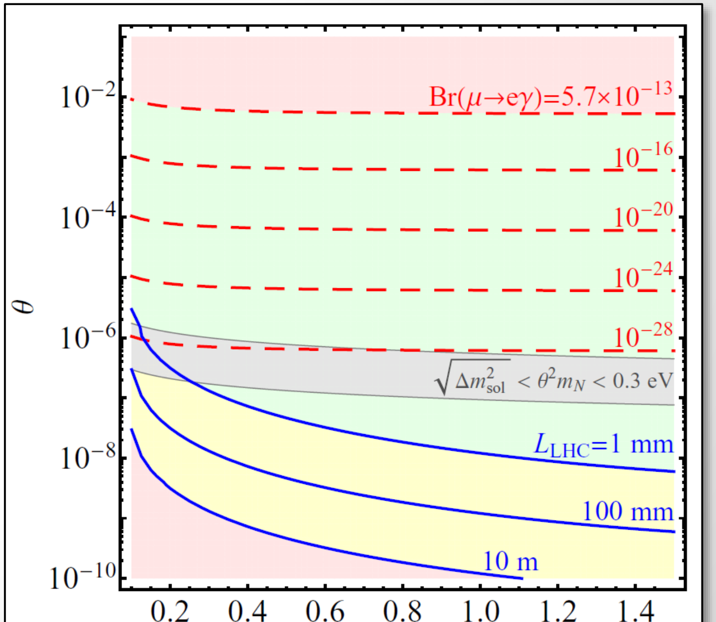
- Production at LHC via Z' portal
- Ability to measure small couplings via displaced vertices
- N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$







FFD, Desai, Valle
PRD 89, 051302

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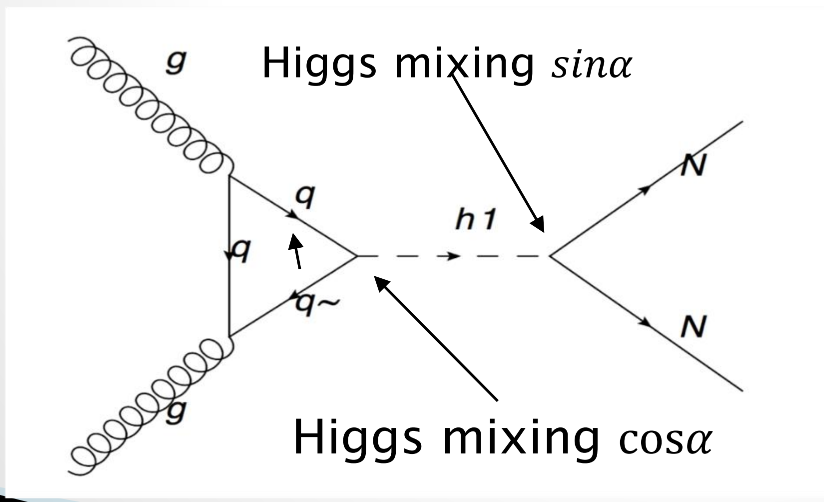
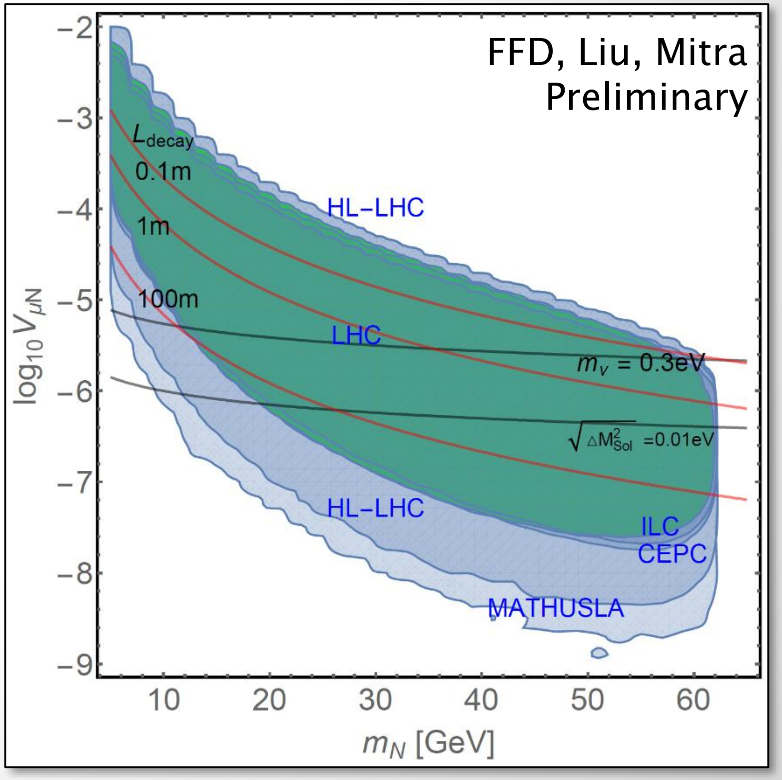
- N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$



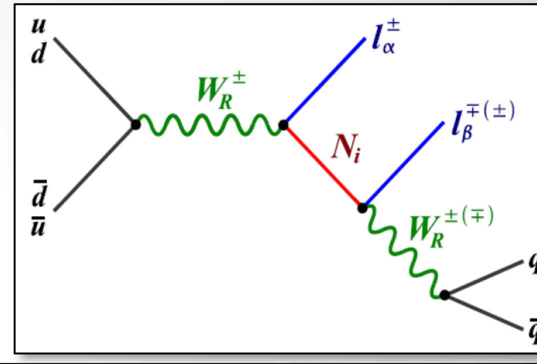


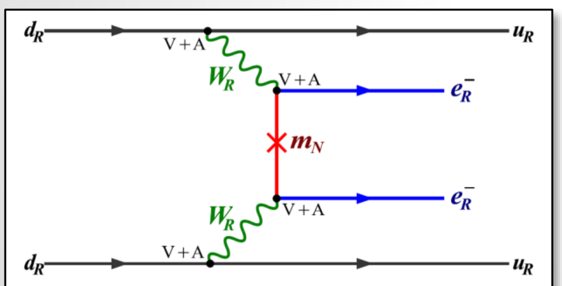
Extended Gauge Sectors

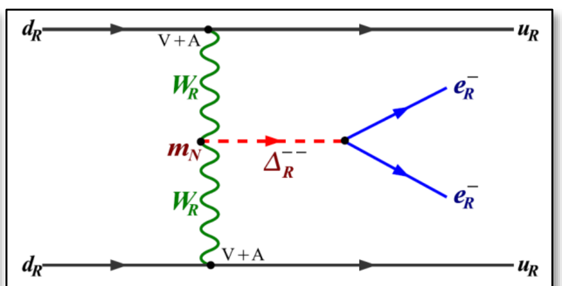
- Left-Right Symmetric models
  (Mohapatra, Senjanovic '75)

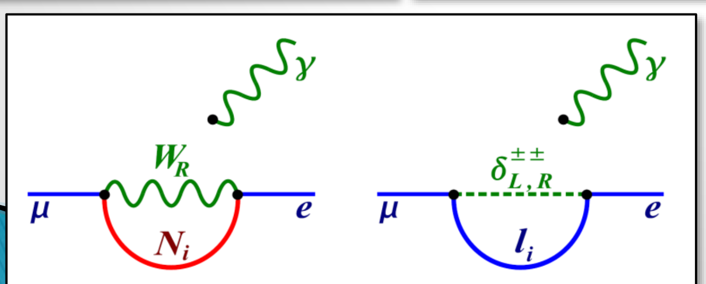
$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

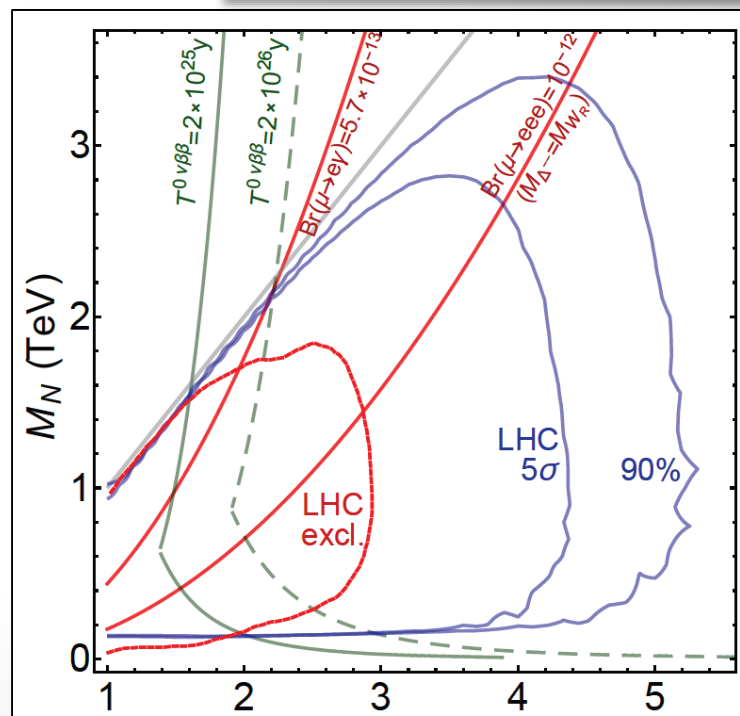
- Heavy neutrino production via right-handed charged current
  (Keung, Senjanovic '83)
- Complementarity with $0\nu\nu\beta$ and charged LFV







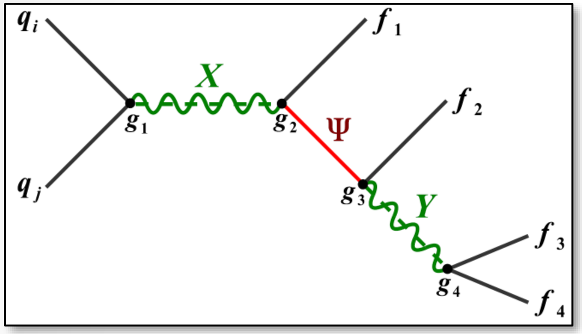


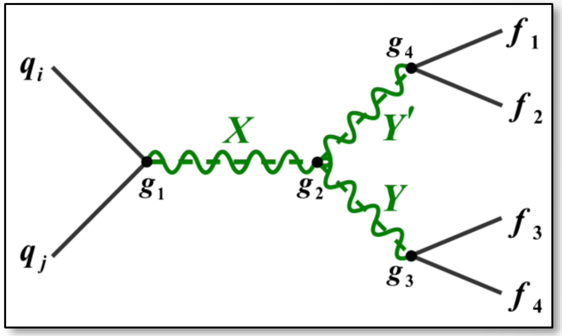


Das, FFD, Kittel, Valle
PRD 86 (2012) 055006

$0\nu\beta\beta$ vs LHC

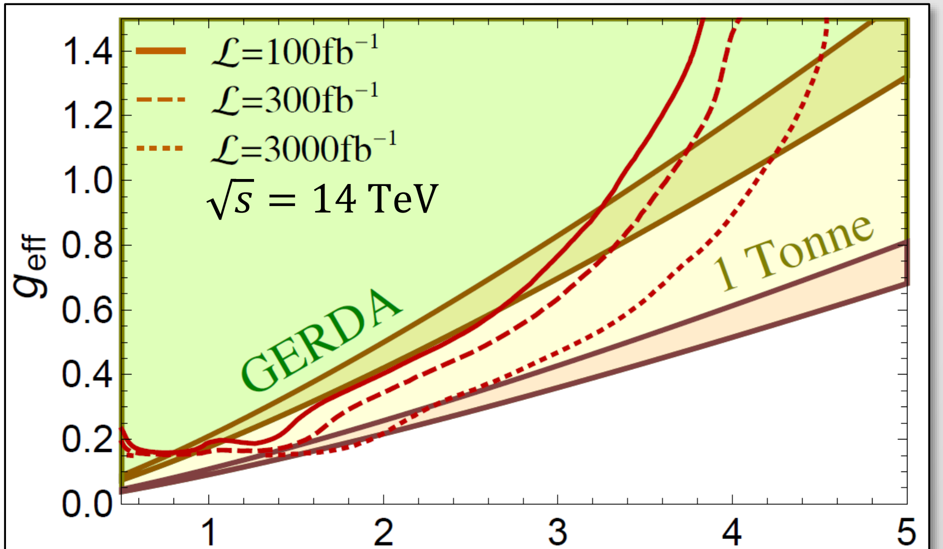
- Generic Tree-level Topologies for $0\nu\beta\beta$ 9-dim Operator





- Comparison between $0\nu\beta\beta$ and LHC
  - Heavy resonance @ LHC
  - Wilson running and pion contributions for $0\nu\beta\beta$
  - Comparable sensitivity

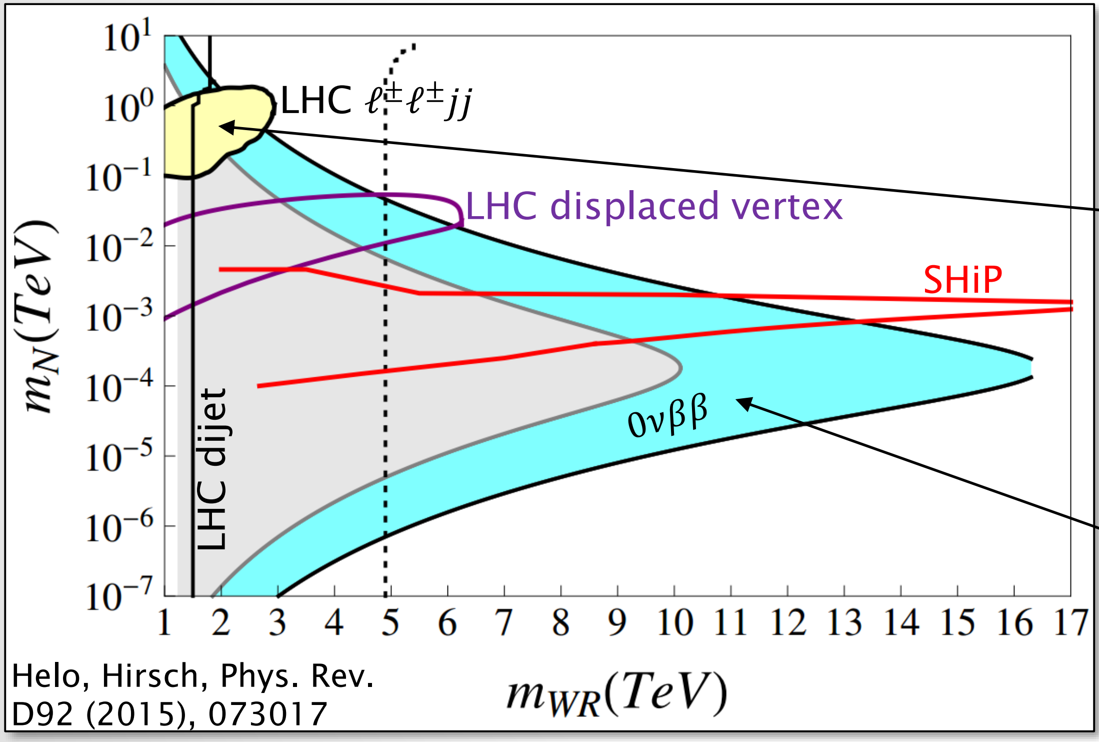
Mahajan, Phys.Rev.Lett. 112 (2013) 031804; Helo, Hirsch, Kovalenko, Päs, Phys.Rev. D88 (2013) 073011; Gonzalez, Hirsch, Kovalenko, Phys.Rev. D93 (2016), 013017;
Peng, Ramsey-Musolf, Winslow, Phys.Rev. D93 (2016) 093002

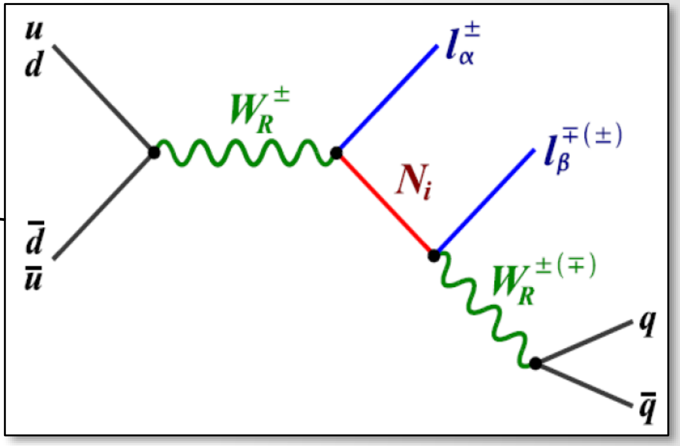


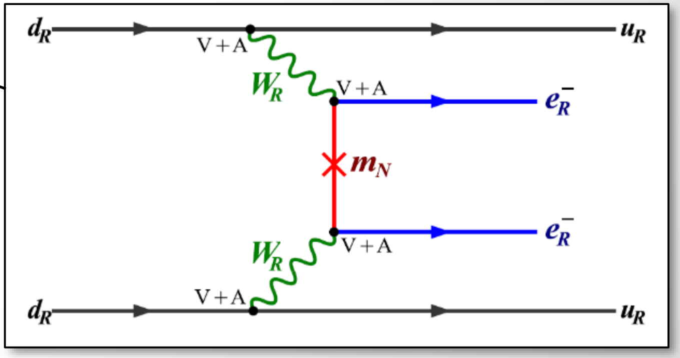
Peng, Ramsey-Musolf, Winslow '16

$0\nu\beta\beta$ vs LHC

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



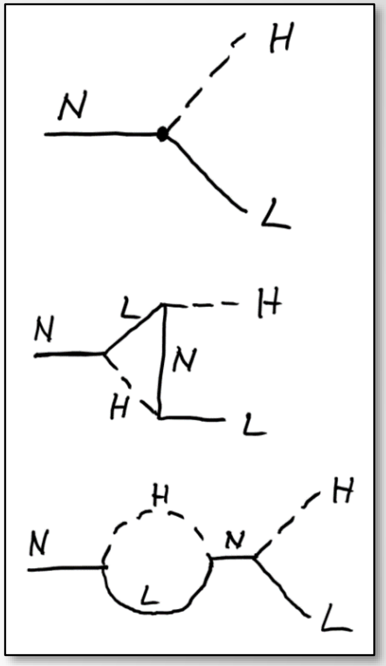




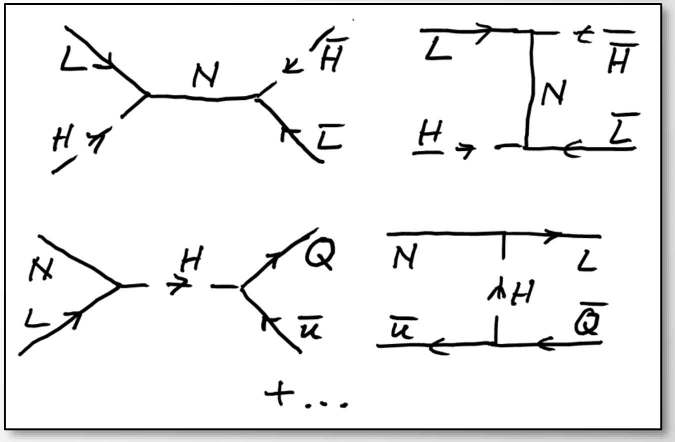
Baryon Asymmetry Generation and Washout

- 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

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



- Other possible scenarios
  - For us only important: $(B - L)$ asymmetry generated above LHC scale



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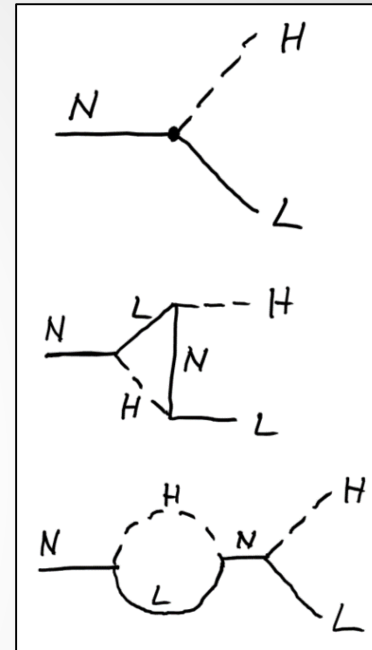
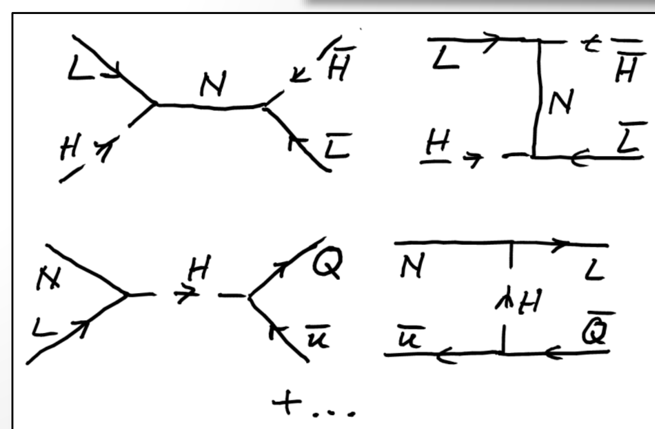
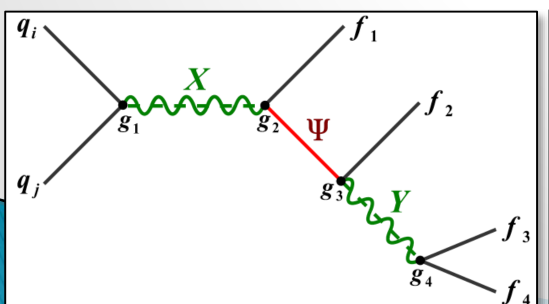
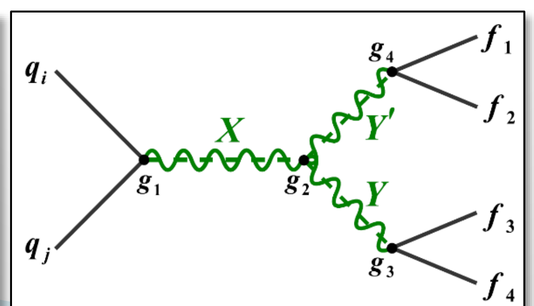


- What if we observe lepton number violating processes at the LHC (or in $0\nu\beta\beta$)?







Induced Washout

University College London

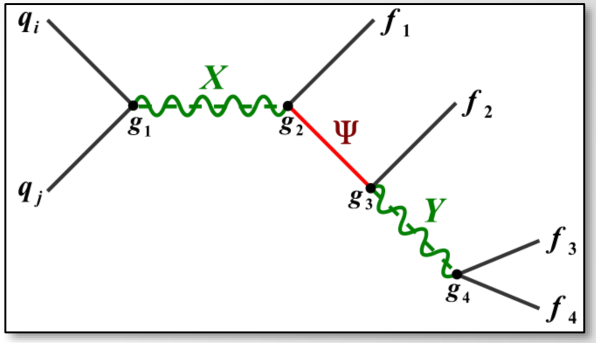
- Compare LHC cross section with lepton number asymmetry washout

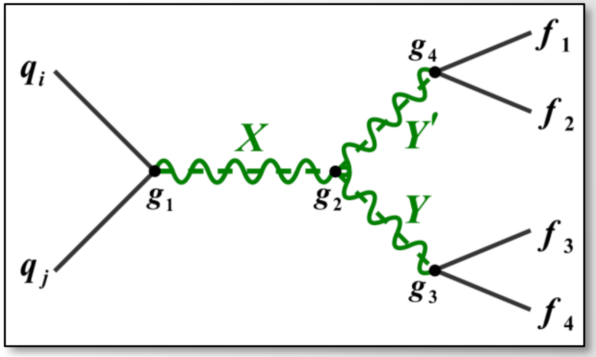
$$\frac{\Gamma_W}{H} > 3 \times 10^{-3} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\, \sigma_{\mathrm{LHC}})$$

  - Lower limit on total washout rate
    - Neglecting other washout processes

$$\log_{10} \frac{\Gamma_W}{H} > 7 + 0.6 \left(\frac{M_X}{\mathrm{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}$$

  - Observation of LNV @ LHC corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - Excludes Leptogenesis models that generate asymmetry above M_X





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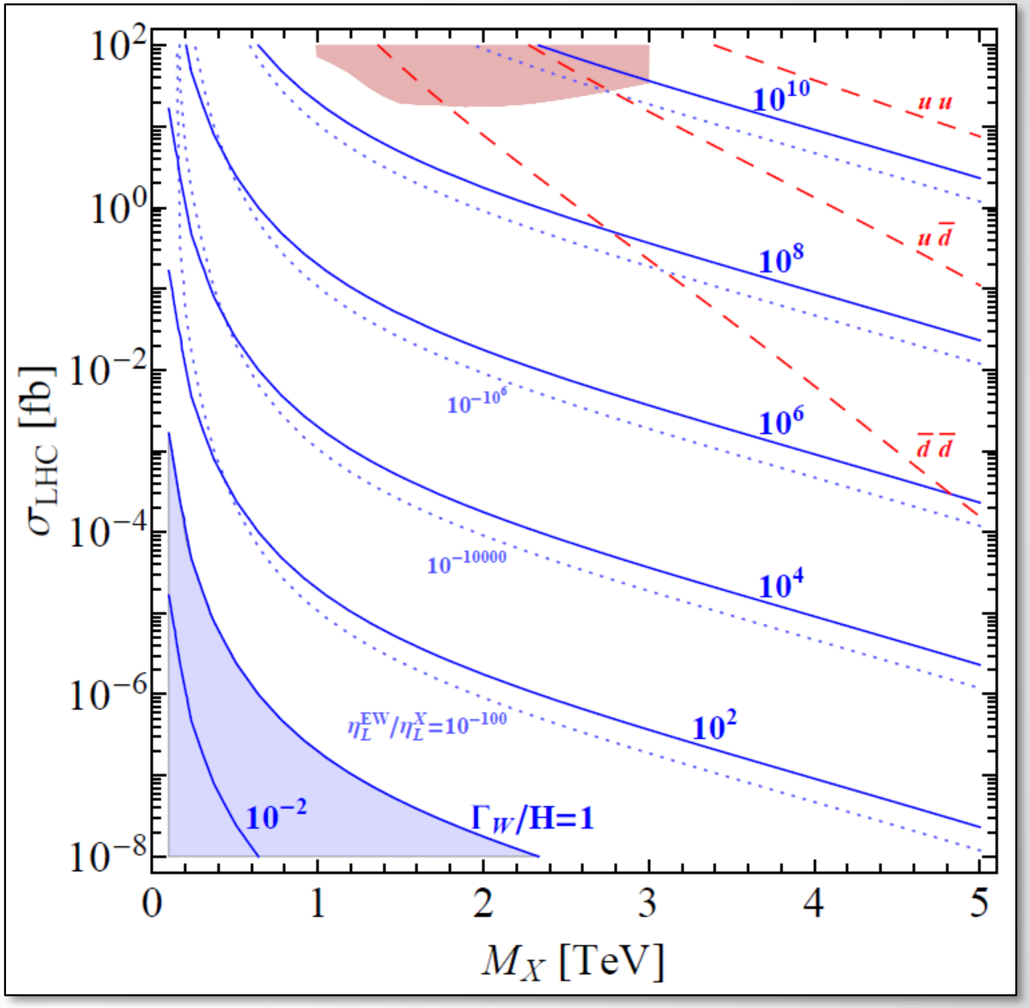

Conclusion

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- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Neutrino masses need BSM physics, but at what scale?
- **Neutrino physics is BSM physics**
  - Neutrino mass models can be searched for at LHC
  - Wide range of scenarios and signatures
- **Observation of LNV processes**
  - Likely pinpoints the origin of neutrino mass generation
  - Can falsify high scale baryogenesis scenarios
- **Important information for model selection, e.g.**
  - Observation of $0\nu\beta\beta$
  - Observation of LNV @ LHC

  } LNV @ TeV Scale
  Disfavours high-scale seesaw

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University College London

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  } Improved confidence in standard $0\nu\beta\beta$ mechanism