Neutrinos and Collider Physics

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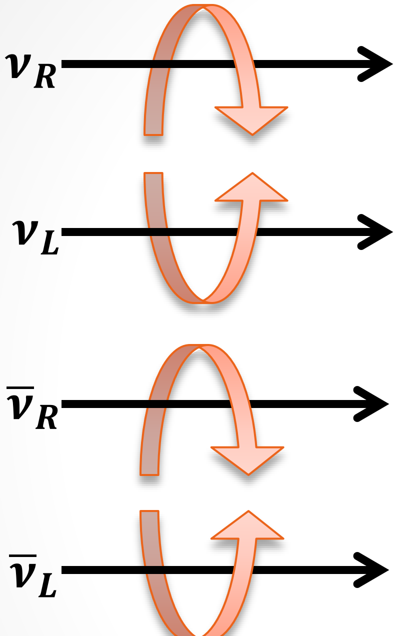
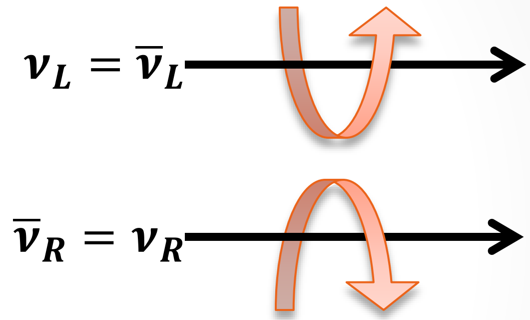
University College London

“Matter to the Deepest” | Ustroń | 13-18/09/2015

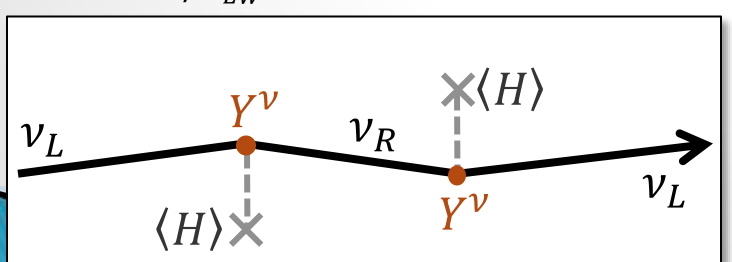
Dirac vs Majorana

- Two possibilities to define fermion mass

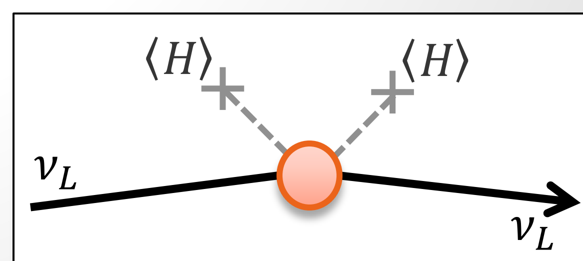




Dirac mass analogous to other fermions but with $m_\nu / \Lambda_{EW} \approx 10^{-12}$ couplings to Higgs



Majorana mass, using only a left-handed neutrino → Lepton Number Violation



Neutrinoless Double Beta Decay

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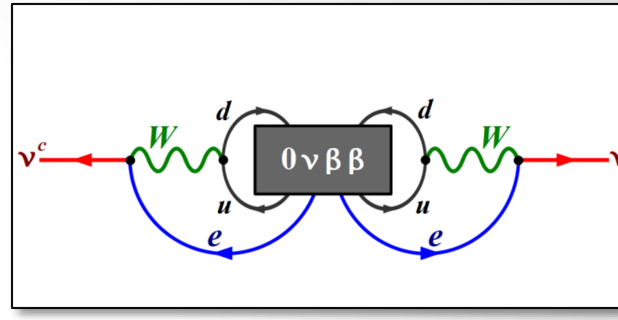
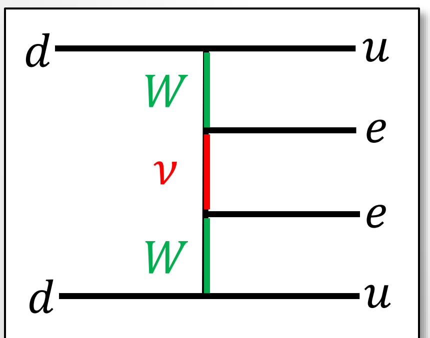
- Process $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- Uncontroversial detection of $0\nu\beta\beta$ of utmost importance
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles (Schechter & Valle '82)



$$\delta m_\nu \approx \frac{1}{(16\pi^2)^4} \frac{\text{MeV}^5}{M_W^4} \approx 10^{-23}\,\text{eV}$$

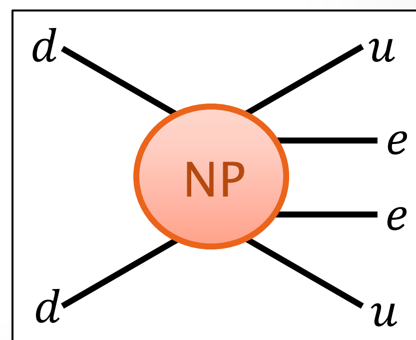
- Which mechanism triggers the decay?

Light Neutrino Exchange



$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\ \text{yr} \rightarrow m_{\beta\beta} \approx 0.1\ \text{eV}$$

General Effective Operator



$$\frac{\bar{u}\bar{u}\bar{e}\bar{e}dd}{M_{LNV}^5}$$

$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\ \text{yr} \rightarrow M_{LNV} \approx 1\ \text{TeV}$$

New Physics Contributions to $0\nu\beta\beta$

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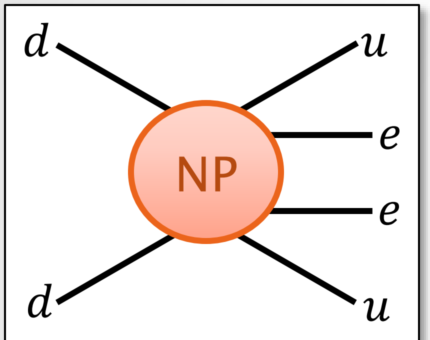
- Plethora of New Physics scenarios



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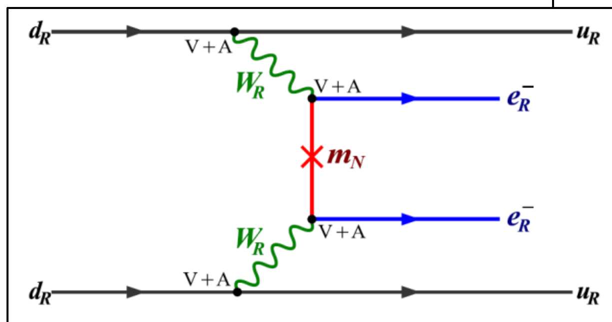
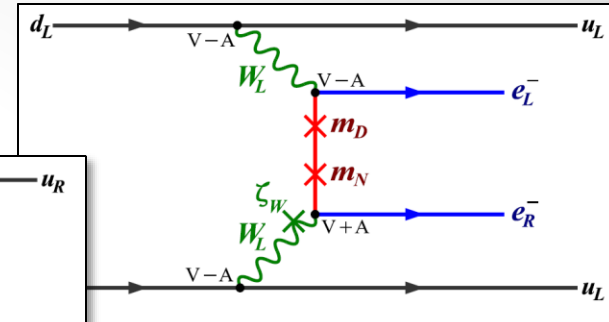
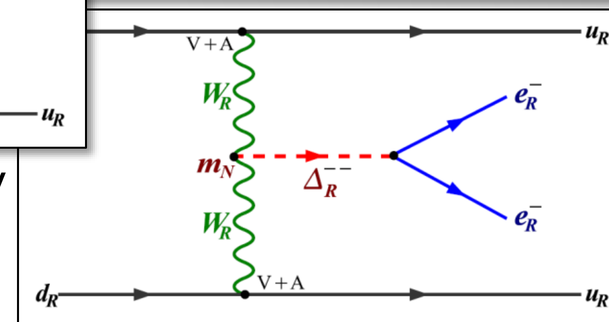
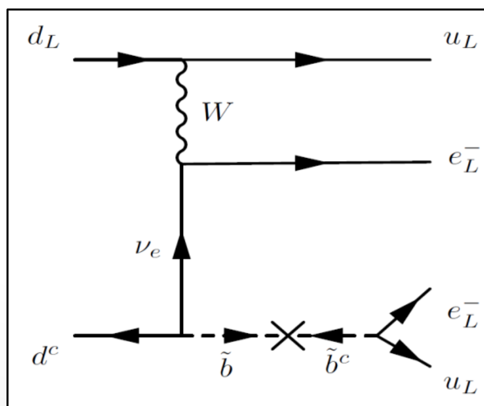
$$\Gamma = T_{1/2}^{-1} = \epsilon_{NP}^2 G_{NP}^{0\nu} \left| M_{NP}^{0\nu} \right|^2$$

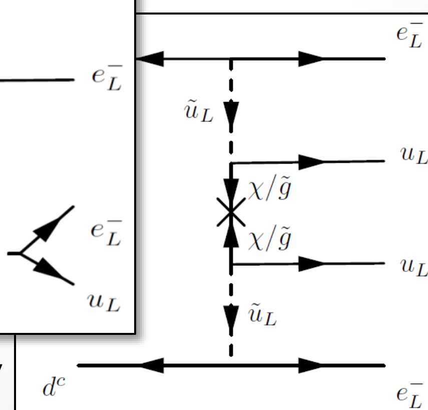






Left-Right Symmetry





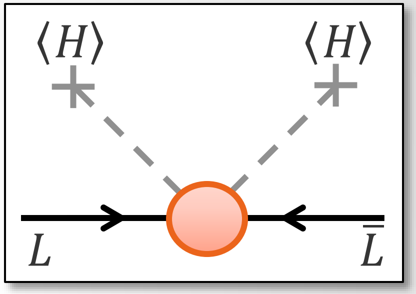
R-Parity Violating SUSY

Extra Dimensions
Majorons
Leptoquarks
…

Effective Mass and Seesaw

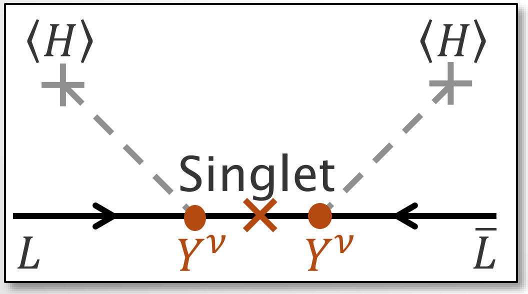
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

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

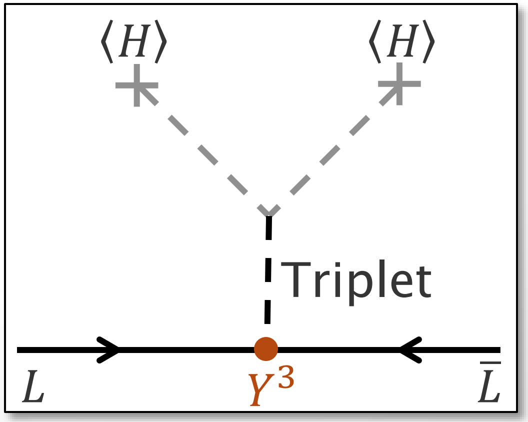


- Seesaw Mechanisms
  - Three possible mediators at tree level

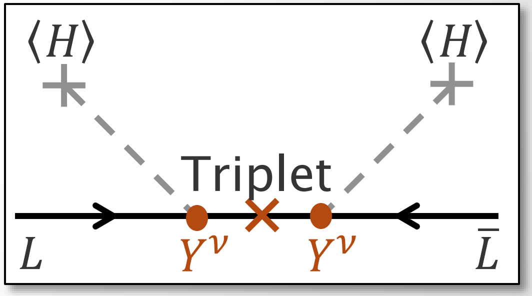
Seesaw I



Seesaw II



Seesaw III



Effective Mass and Seesaw

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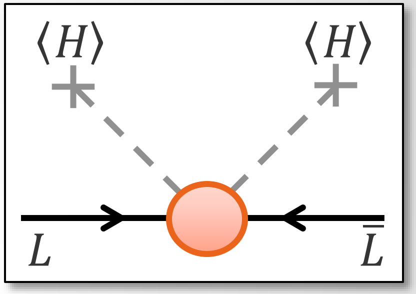
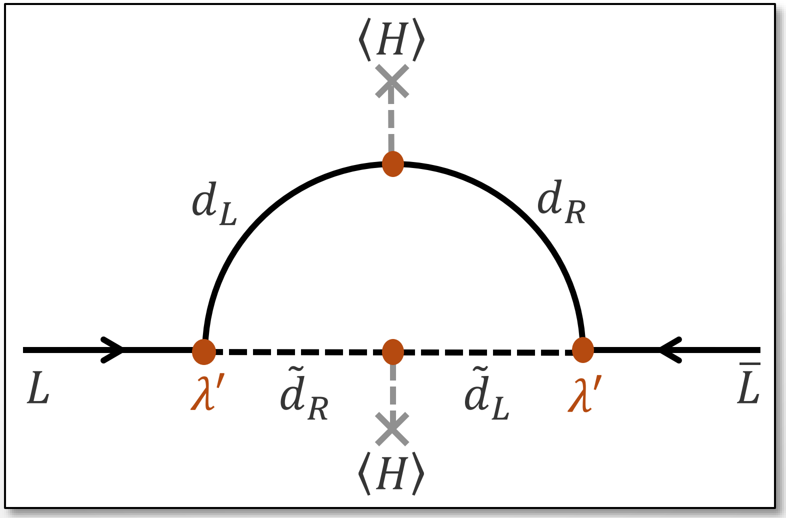


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. R-Parity Violating SUSY



Heavy Sterile Neutrinos
Low Scale Singlet Seesaw Models

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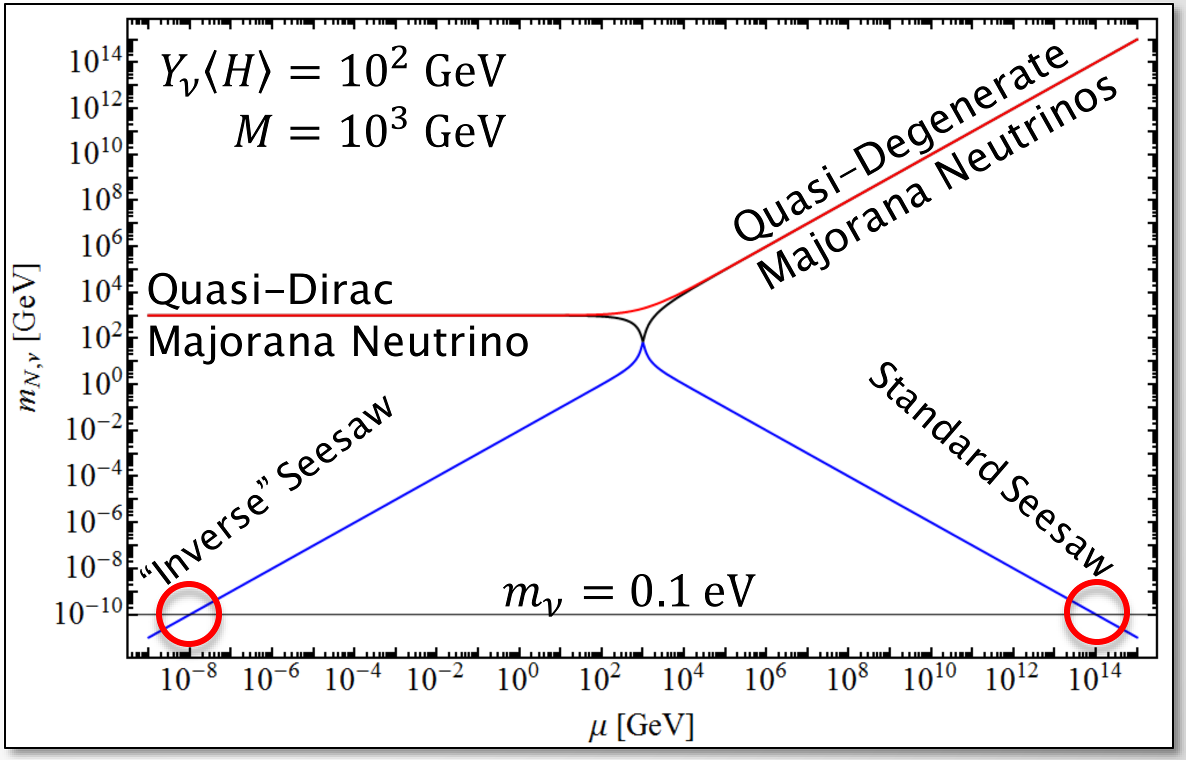
- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings

$$Y_\nu \approx 10^{-6}\sqrt{M_N/\mathrm{TeV}}$$

  - "Bent" Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

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

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



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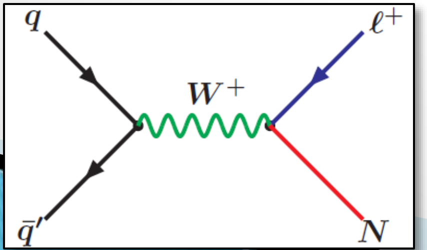
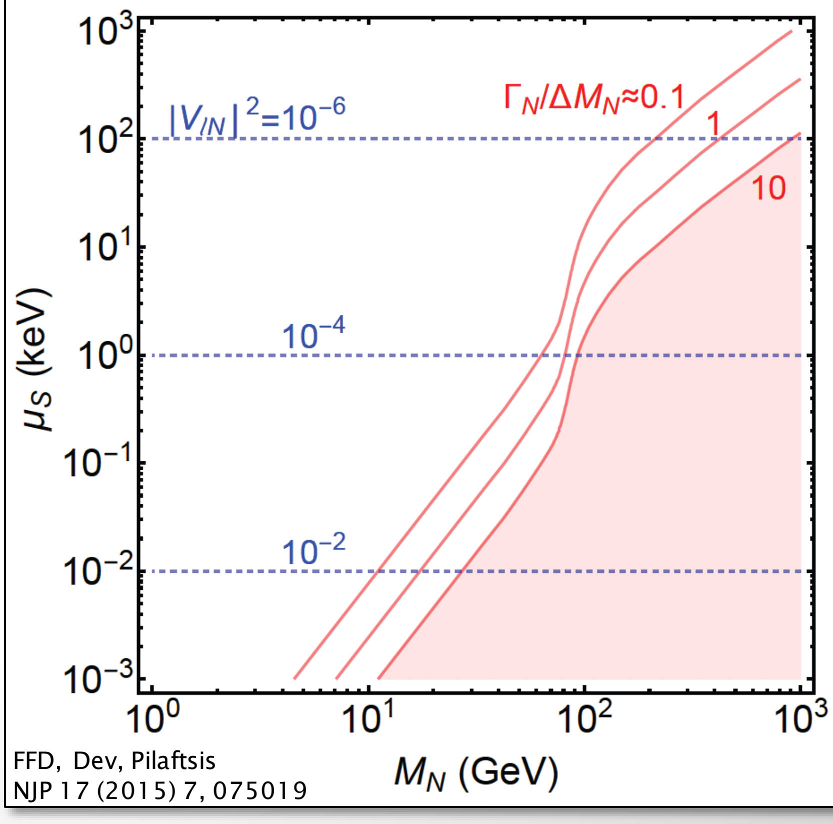
$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

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

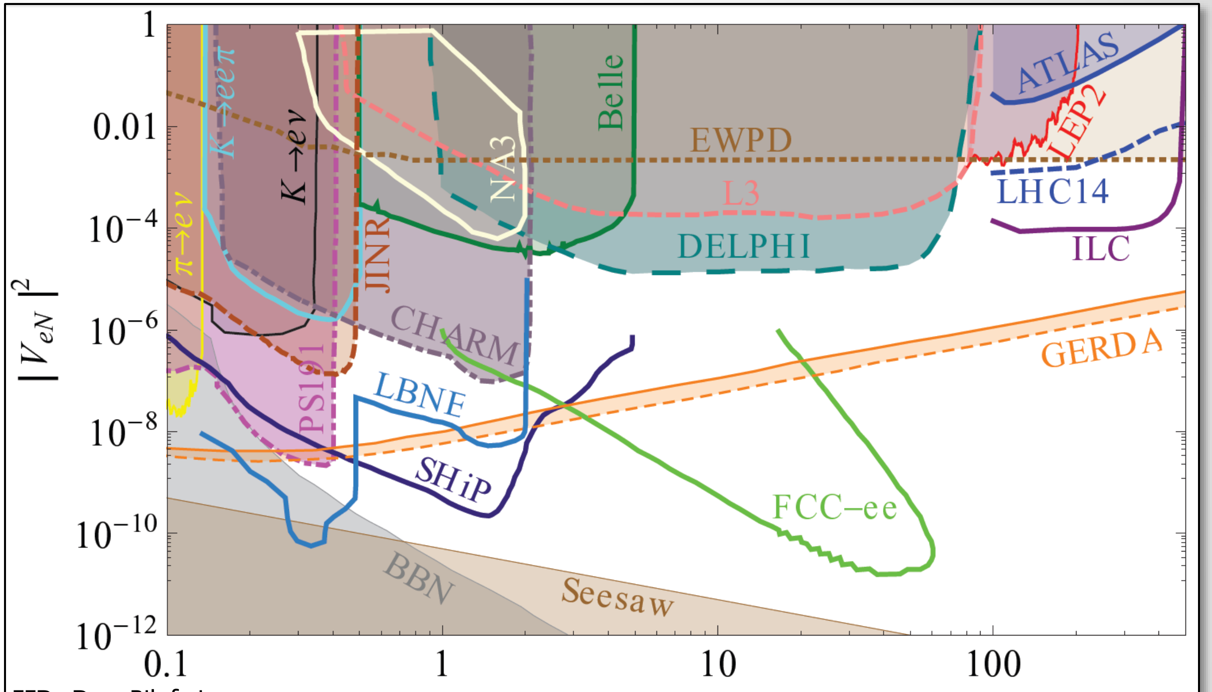




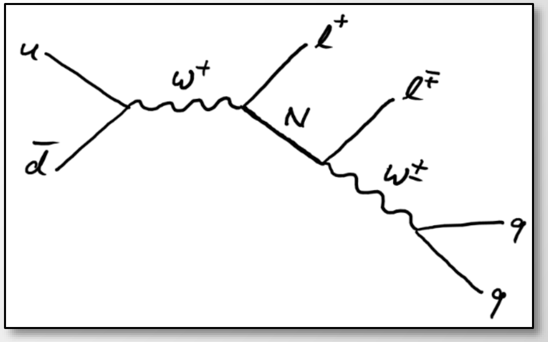
FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019

Heavy Sterile Neutrinos
Experimental Searches

- 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

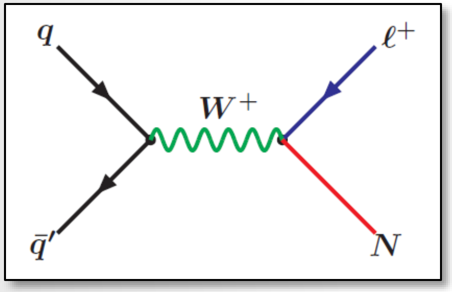


FFD, Dev, Pilaftsis
arXiv:1502.06541

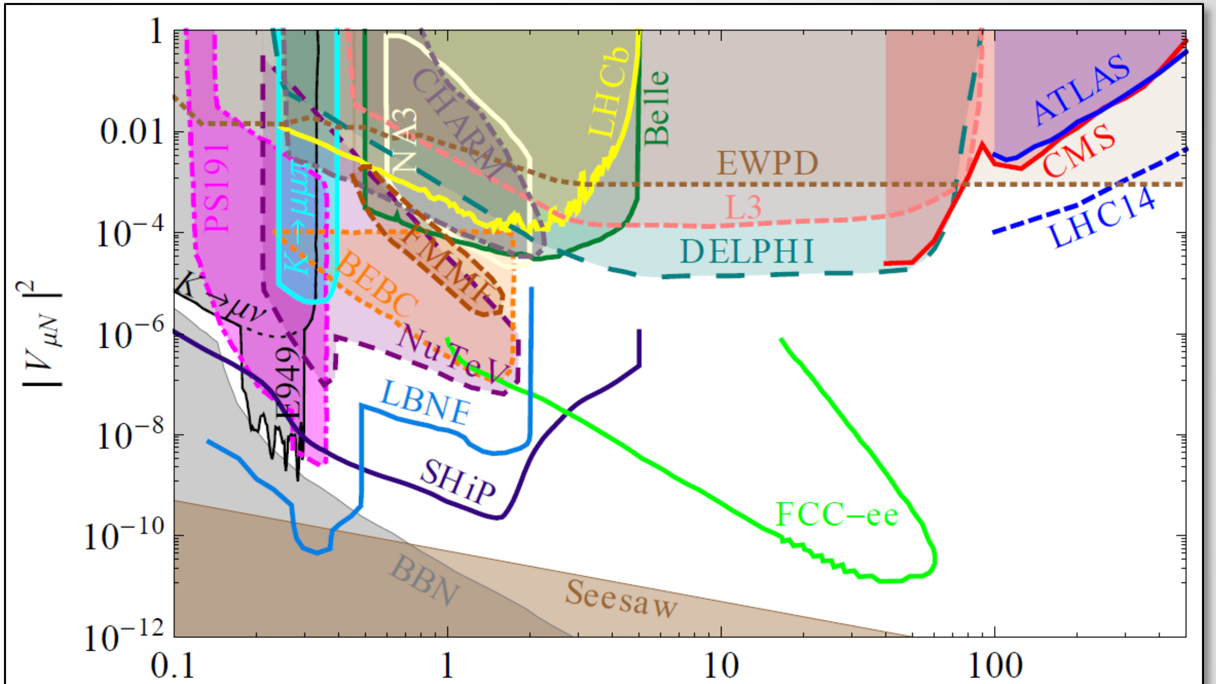


Heavy Sterile Neutrinos
Experimental Searches

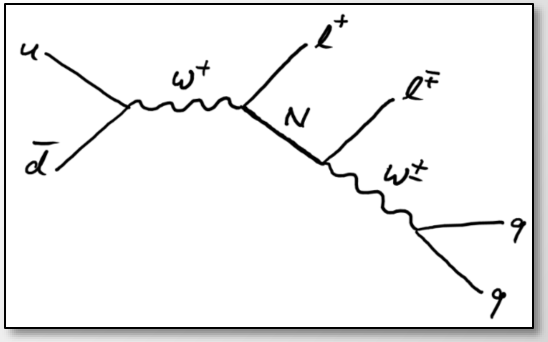
- Constraints on coupling to leptons $|V_{lN}|$
- LEP2, ILC
  $e^+e^- \to N\nu,\ N \to eW, \nu Z, \nu H$
- LHC (ATLAS, CMS, LHC14)
  - Drell-Yan Production



  - 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



Heavy Sterile Neutrinos
Experimental Searches

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- Constraints on coupling to leptons $|V_{lN}|$
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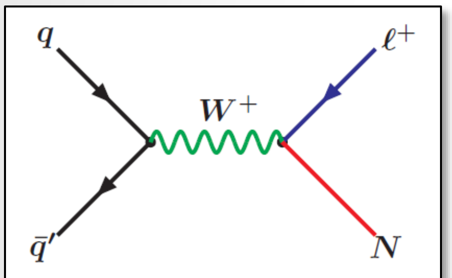

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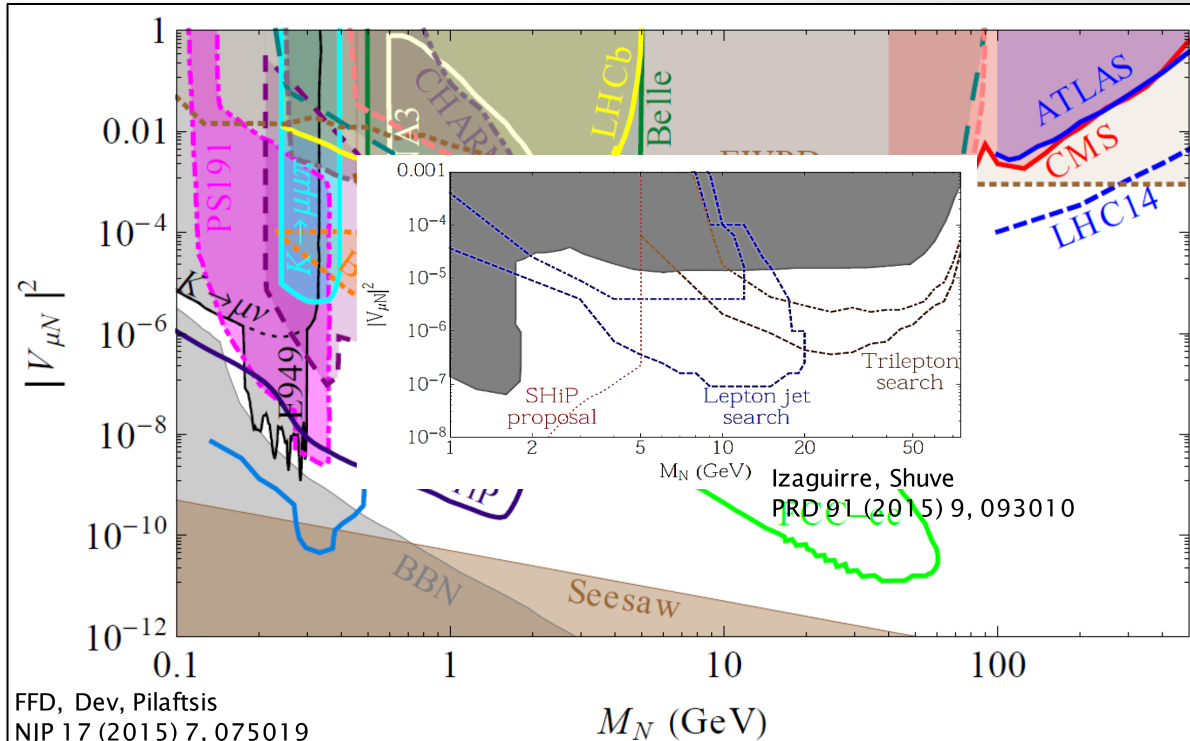
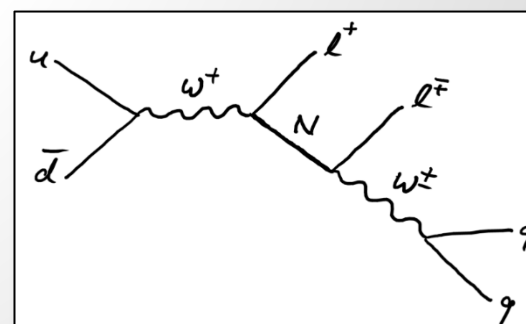


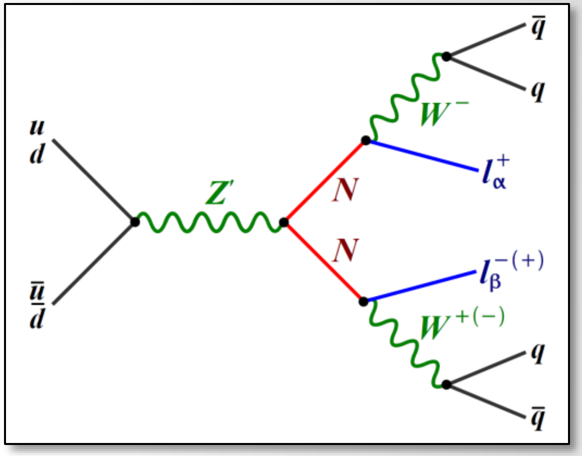
FFD, Dev, Pilaftsis
NJP 17 (2015) 7, 075019

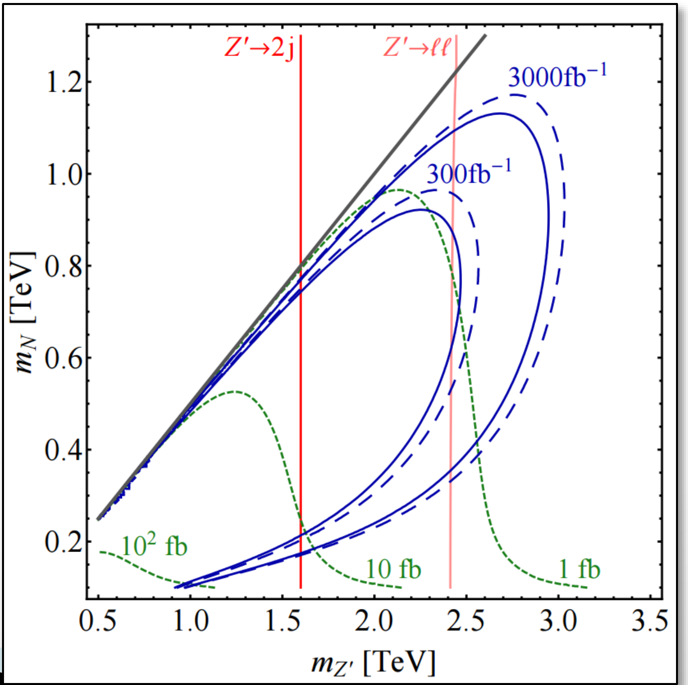
Izaguirre, Shuve
PRD 91 (2015) 9, 093010

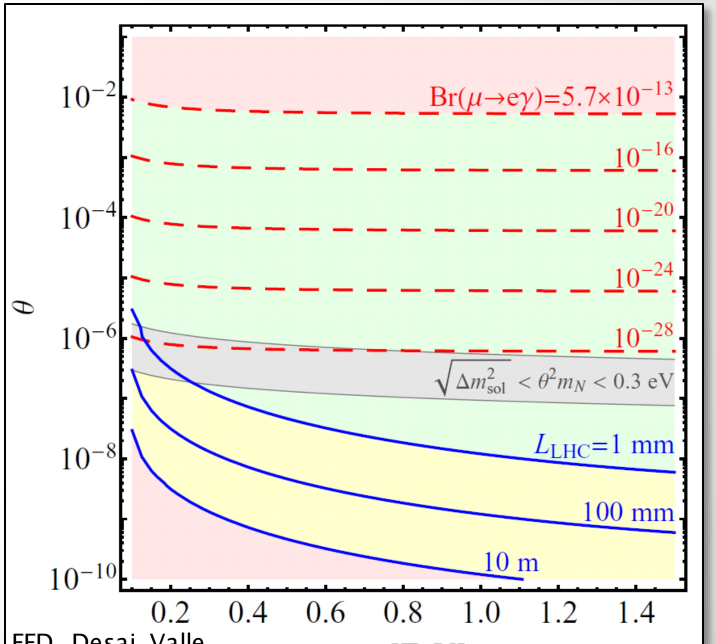


Extended Gauge Sectors
Additional U(1)

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







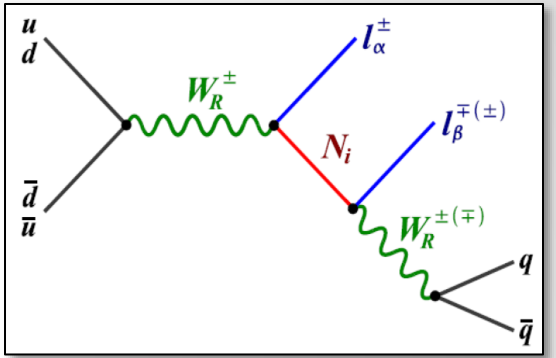
FFD, Desai, Valle
PRD 89, 051302

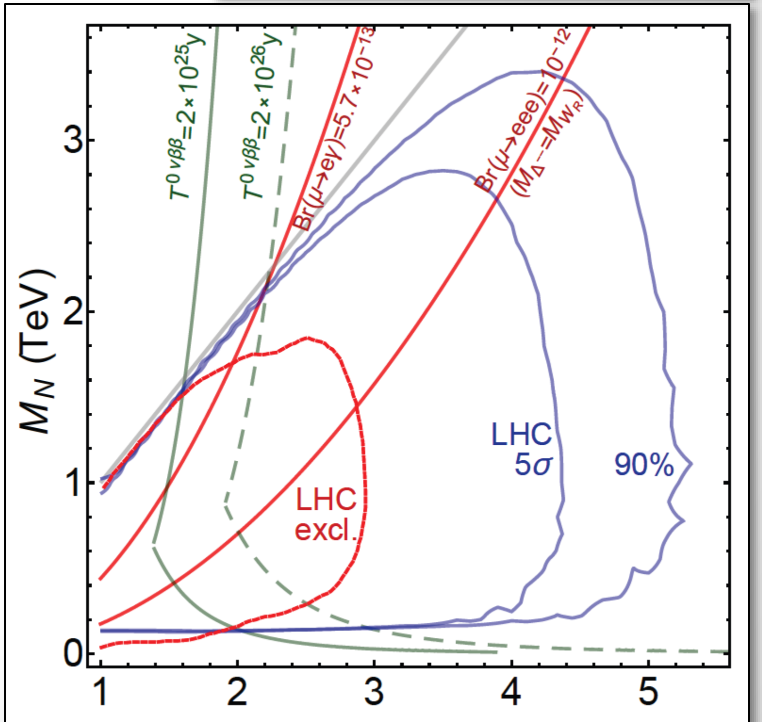
Extended Gauge Sectors
Left-Right Symmetric Models

- Extension of the Standard Model
  (Mohapatra, Senjanovic '75)

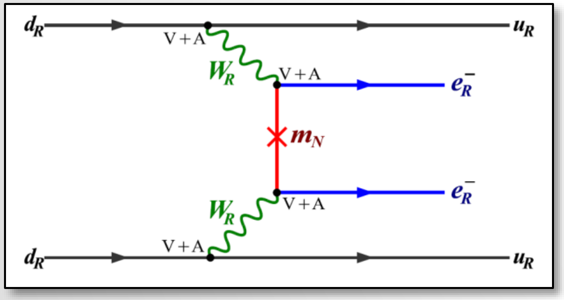
$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

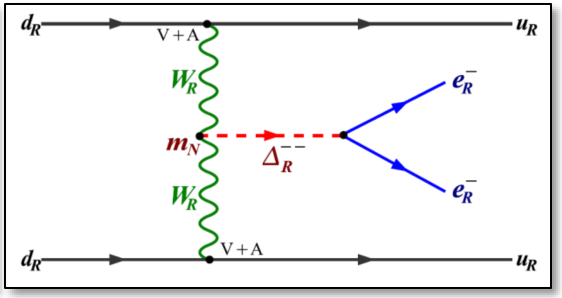
- Production of heavy neutrinos with gauge coupling strengths via right-handed charged current
  (Keung, Senjanovic '83)
- Complementarity to $0\nu\nu\beta$ and charged LFV

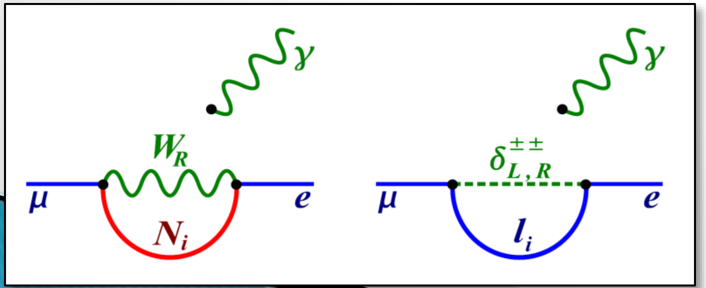




Das, FFD, Kittel, Valle
PRD 86 (2012) 055006







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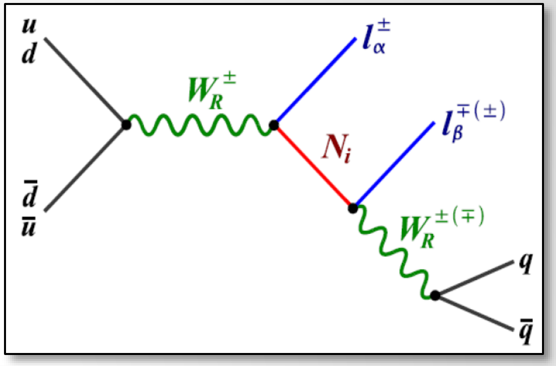
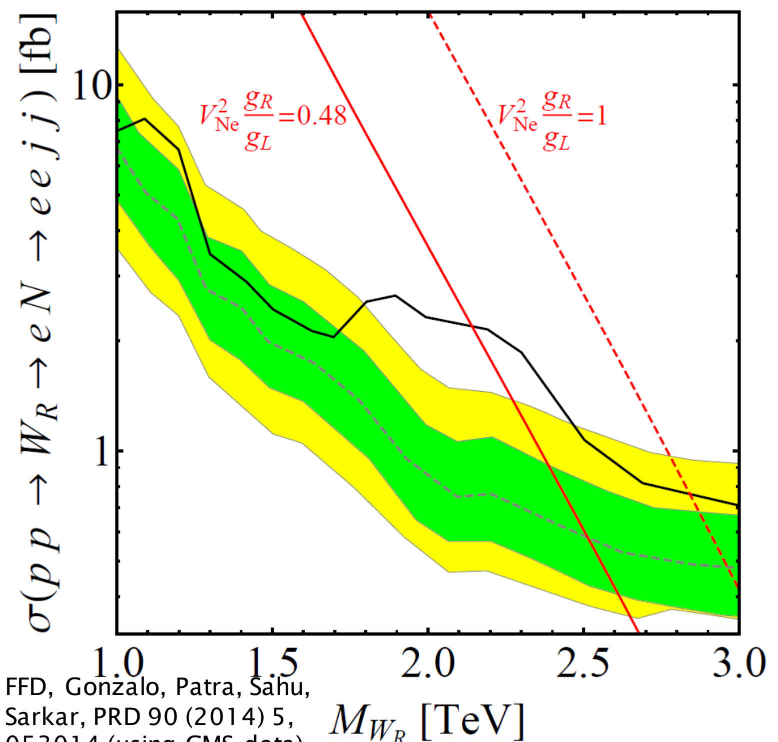
$$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

- Production of heavy neutrinos with gauge coupling strengths via right-handed charged current
  (Keung, Senjanovic '83)
- Complementarity to $0\nu\nu\beta$ and charged LFV
- 2.8σ hint for excess at CMS
  - Not compatible with minimal LR symmetry $g_R = g_L$
  - Only one 1 out of 14 events is LNV
  - Only ee, no $\mu\mu$
  - No clear discrete excess in $m_{lqq}^2 = m_N^2$
- No excess at ATLAS
  - Search only for SS leptons

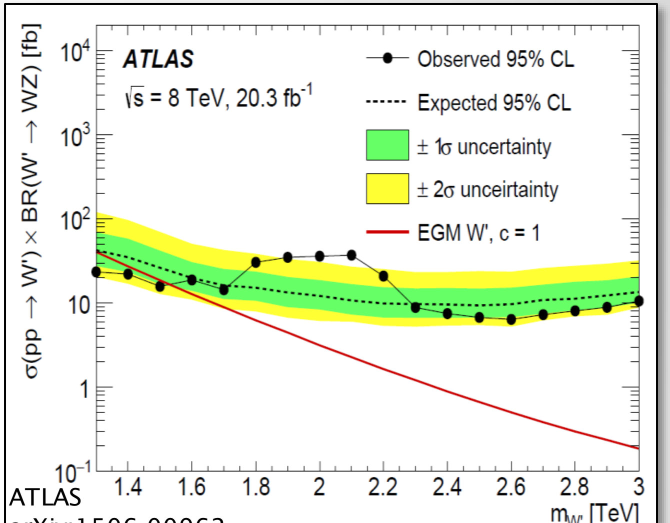




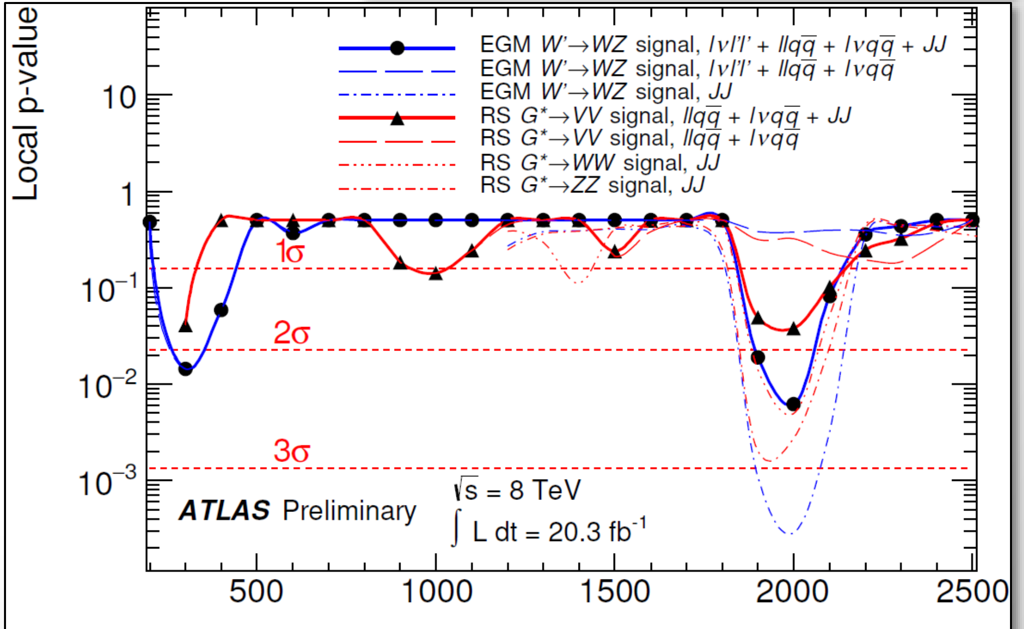
FFD, Gonzalo, Patra, Sahu, Sarkar, PRD 90 (2014) 5, 053014 (using CMS data)

Extended Gauge Sectors
Excesses @ 2 TeV

- Excesses in other resonant searches around 2 TeV
  - WW, ZZ or WZ
    - up to 3.4σ @ ATLAS (hadronic)
    - no excess in (semi-)leptonic channels
  - HW
    - 2σ @ CMS (leptonic)
    - tension with hadronic channel
  - jj
    - small excesses @ ATLAS and CMS (1.5σ,1.9σ)
    - tension with tb channel



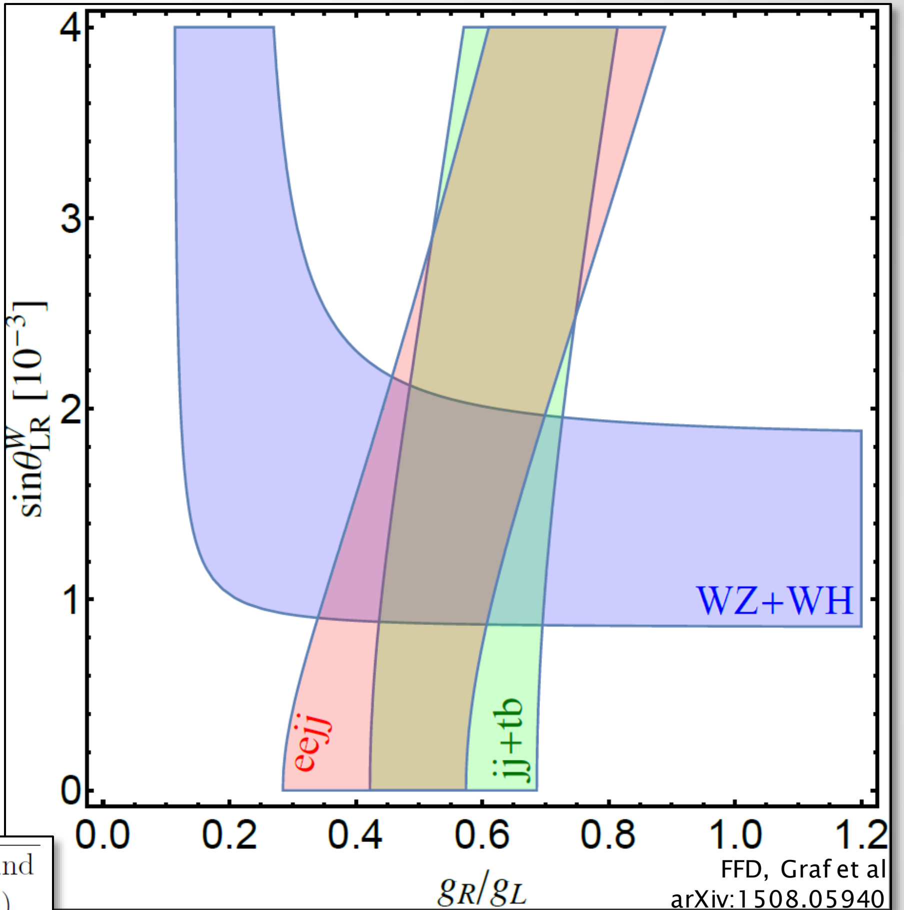
ATLAS arXiv:1506.00962



ATLAS-CONF-2015-045

Extended Gauge Sectors Excesses @ 2 TeV

- Combined interpretation in effective LR model
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to WZ)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to WH)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to jj)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to Ne) \times \mathrm{Br}(N \to ejj) = 0.66 \pm 0.4$ fb
- Model parameters
  - $M_{W_R} = 1.9$ TeV
  - $M_N = 1.6$ TeV
  - g_R/g_L: Ratio of $\mathrm{SU(2)_{R/L}}$ couplings
  - $\sin\theta_W$: $W - W_R$ mixing angle
  - $\sin\theta_N = 0$: $\nu - N$ mixing angle

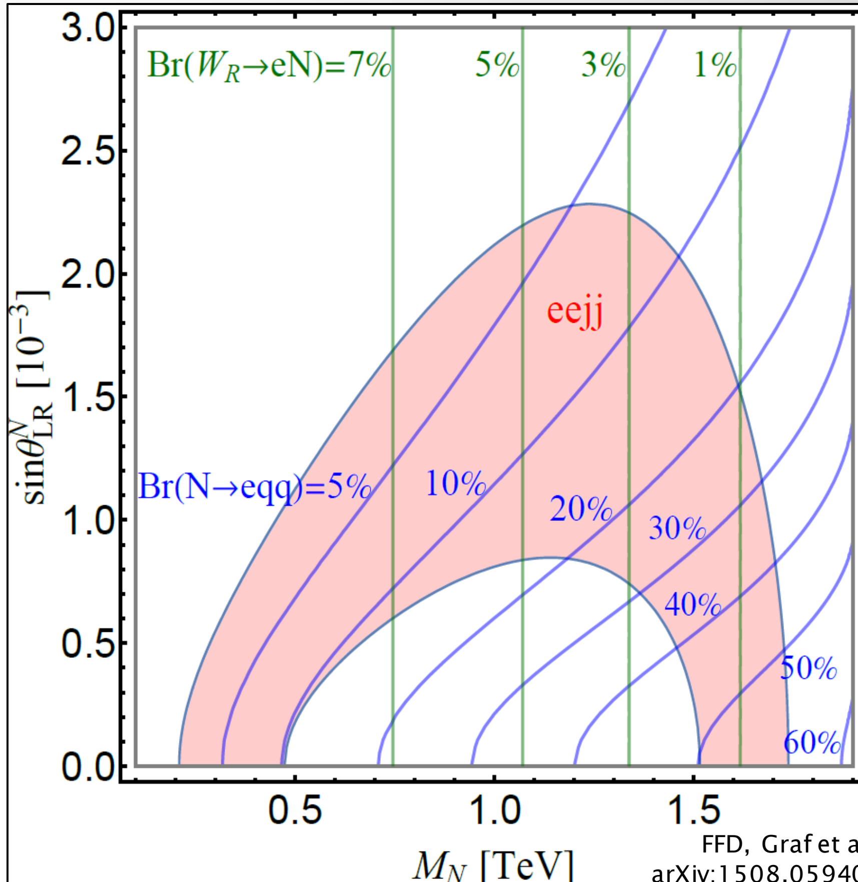


Process	Fitted cross section [fb]	Upper bound (90% CL)
$pp \to X \to WZ^1$	$5.9^{+5.3}_{-3.5}$	13.7
$pp \to X \to ZZ^1$	$5.5^{+5.1}_{-3.7}$	12.8
$pp \to X \to WH$	$4.5^{+6.2}_{-3.9}$	17.0
$pp \to X \to jj$	91^{+53}_{-45}	170
$pp \to X \to tb$	0^{+11}_{-0}	38
$pp \to X \to tb$ (without ATLAS $bb\ell\nu$ [13])	0^{+39}_{-0}	60

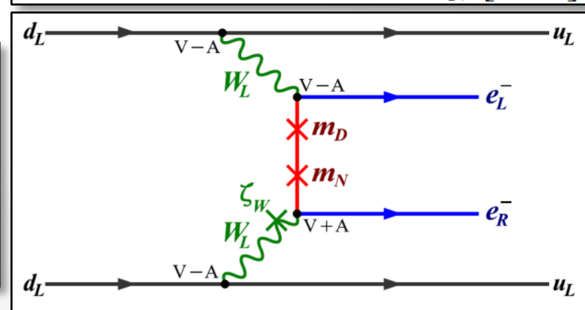
Brehmer, Hewett, Kopp, Rizzo, Tattersall, arXiv:1507.00013

Extended Gauge Sectors
Excesses @ 2 TeV

- Combined interpretation in effective LR model
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to WZ)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to WH)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to jj)$
  - $\sigma(pp \to W_R) \times \mathrm{Br}(W_R \to Ne) \times \mathrm{Br}(N \to ejj) = 0.66 \pm 0.4$ fb
- Model parameters
  - $M_{W_R} = 1.9$ TeV
  - M_N: Heavy neutrino mass
  - $g_R/g_L = 0.57$
  - $\sin\theta_W = 1.5 \times 10^{-3}$
  - $\sin\theta_N = 0$: $\nu - N$ mixing angle
- Consequence for $0\nu\beta\beta$



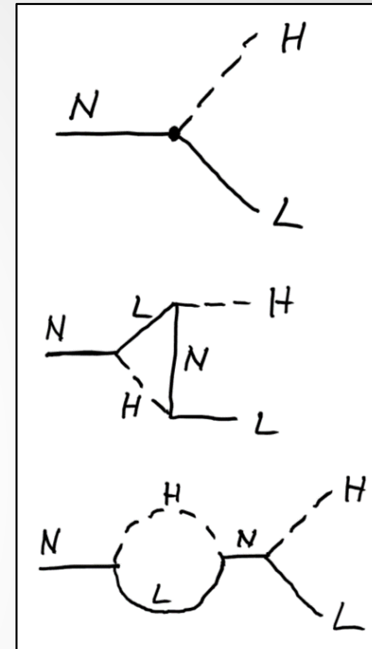
$$\frac{3\times 10^{25}\ \mathrm{y}}{T_\lambda^{0\nu}} \approx \left(\frac{g_R/g_L}{0.6}\right)^4 \left(\frac{\langle\theta\rangle^{0\nu}}{10^{-3.0}}\right)^2 \left(\frac{2\ \mathrm{TeV}}{M_{W_R}}\right)^4,$$
$$\frac{3\times 10^{25}\ \mathrm{y}}{T_\eta^{0\nu}} \approx \left(\frac{g_R/g_L}{0.6}\right)^2 \left(\frac{\langle\theta\rangle^{0\nu}}{10^{-5.3}}\right)^2 \left(\frac{|\sin\theta^W_{LR}|}{10^{-3}}\right)^2.$$



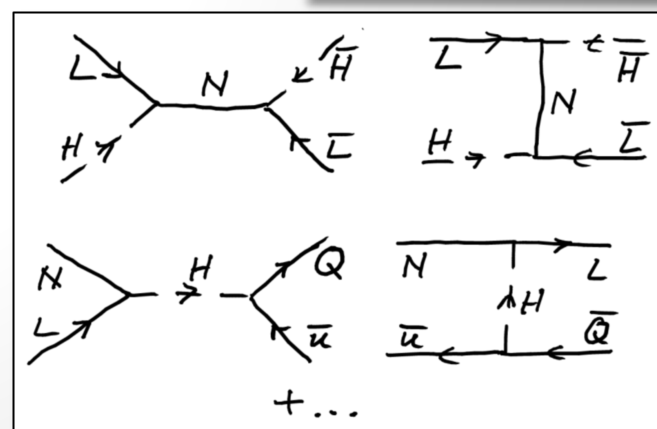
Baryon Asymmetry
Leptogenesis

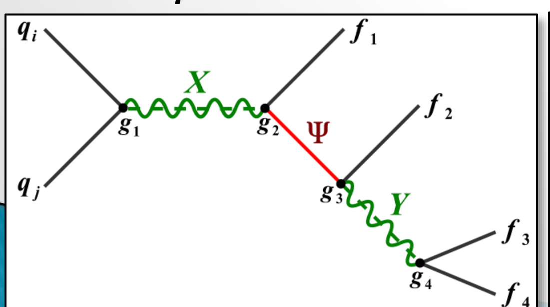
- Classic Scenario
  - Generation via heavy neutrino decays
  - Competition with LNV washout processes
  - Conversion to baryon asymmetry
    - EW sphaleron processes at $T \approx 100\,\mathrm{GeV}$
    - Observed asymmetry

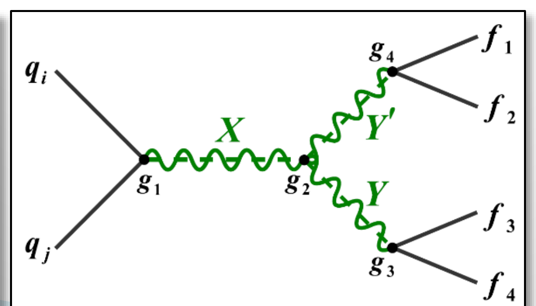
$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.20 \pm 0.15) \times 10^{-10}$$



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





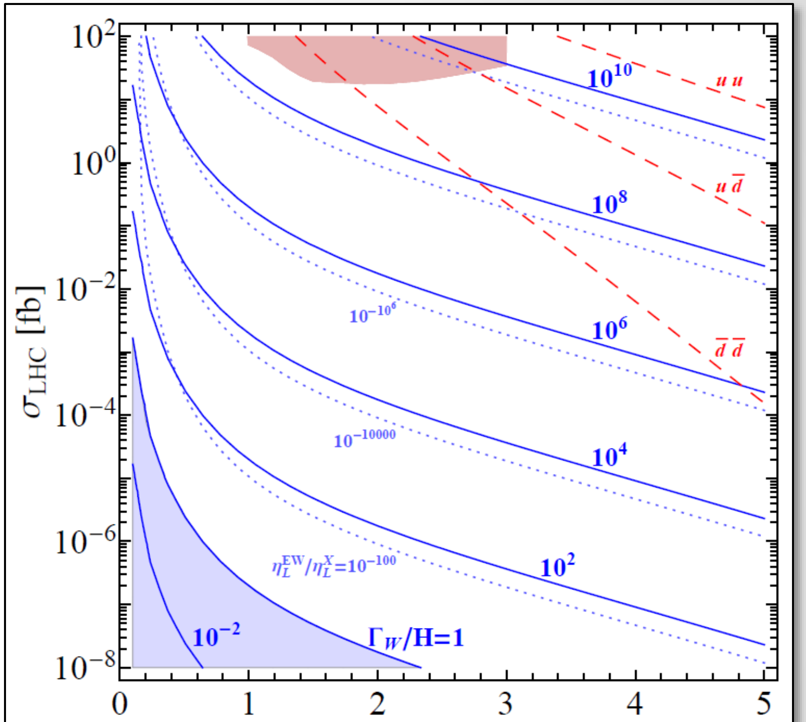


Baryon Asymmetry Constraint on High-scale Baryogenesis

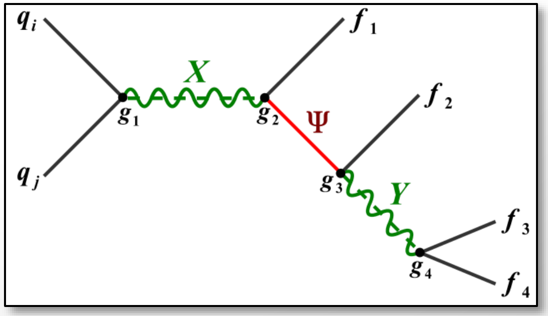
- Compare LHC cross section with lepton number asymmetry washout

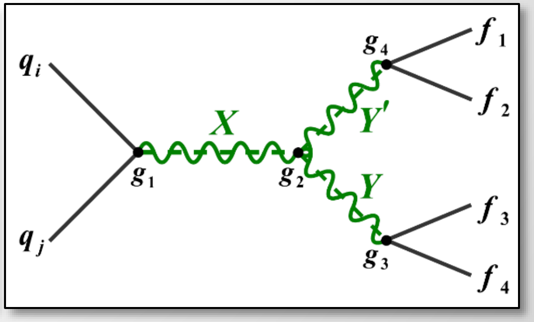
$$\frac{\Gamma_W}{H} > 3\times10^{-3}\,\frac{M_{Pl}M_X^3}{T^4}\,\frac{K_1(M_X/T)}{f_{q_1q_2}(M_X/\sqrt{s})}\times(s\,\sigma_{\mathrm{LHC}})$$

  - Lower limit on total washout rate
  - Observation of LNV @ LHC corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - Excludes baryogenesis models that generate asymmetry above M_X



FFD, Harz, Hirsch
PRL 112 (2014) 221601





Baryon Asymmetry Synergy with $0\nu\beta\beta$ and LFV

- LNV effective operators are of mass dimensions 5, 7, 9, 11, …
- $0\nu\beta\beta$ sensitive to operators at scales

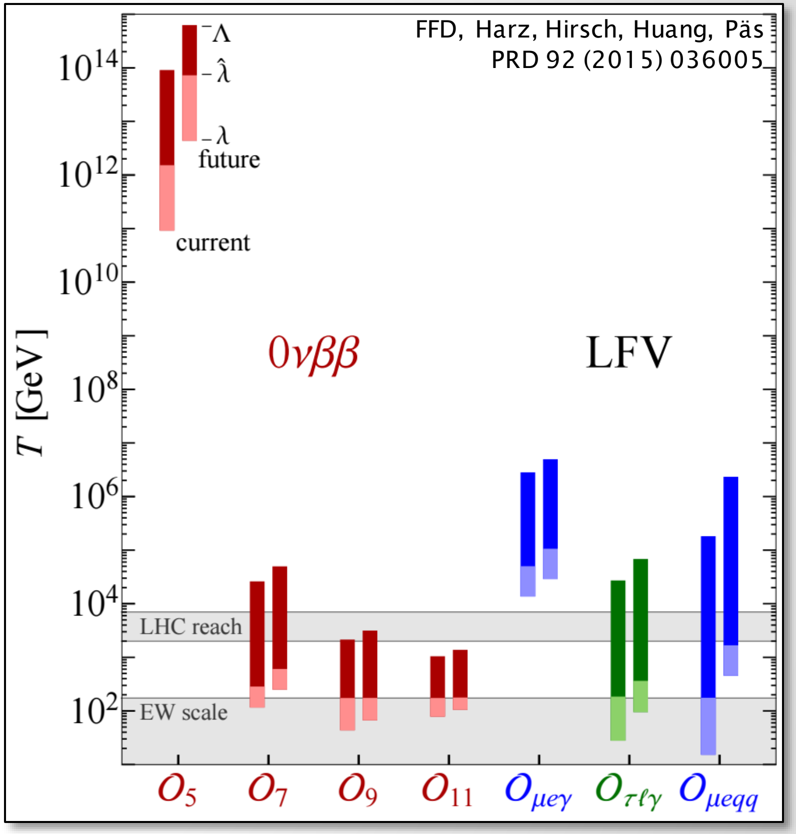
$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\mathrm{yr} \rightarrow m_\nu \approx 0.1\,\mathrm{eV} \rightarrow \Lambda_5 \approx 10^{14}\,\mathrm{GeV}$$

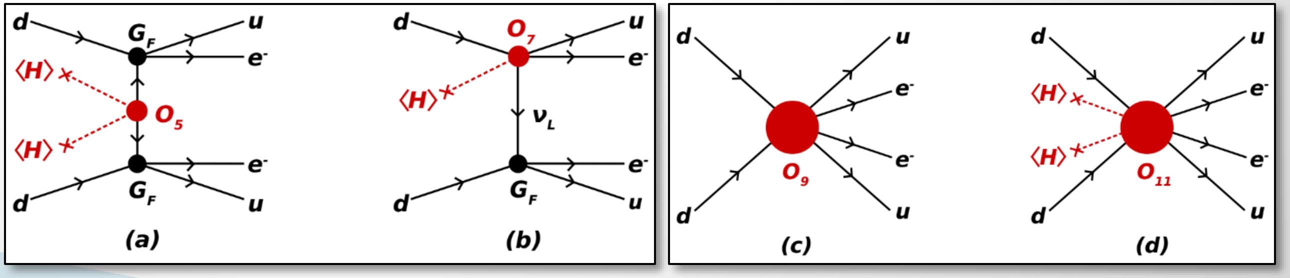
$$T_{1/2}^{0\nu\beta\beta} \approx 10^{25}\mathrm{yr} \rightarrow \Lambda_9 \approx 1\,\mathrm{TeV}$$

- Observation of LNV and LFV would
  - give information at what temperatures operators are in equilibrium

$$\left(\frac{\Lambda_D}{c_D \Lambda_{Pl}}\right)^{1/(2D-9)} \Lambda_D = \lambda_D < T < \Lambda_D$$

  - can provide strong constraint on baryogenesis models and falsify high-scale scenarios





Conclusion

University College London

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Mechanism of neutrino mass generation? At what scale?
- **Neutrino physics is BSM physics**
  - Seesaw I – Sterile neutrinos
  - Seesaw II – Scalar triplet
    - $pp \to W^* \to H^{++}W^-$, $H^{++} \to l^+l^+$, $m_{H^{++}} > 500$ GeV
  - Seesaw III – Fermion triplet
    - $pp \to W^* \to \Sigma^+\Sigma^0$, $m_\Sigma > 250$ GeV
  - Extended gauge sectors
  - Supersymmetry
    - SUSY Seesaw / R-Parity violating SUSY (loop-mediated neutrino masses)
- **LHC probes neutrino mass models at TeV scale**
  - Strong synergy with $0\nu\beta\beta$
    - LHC can deep-probe anatomy of $0\nu\beta\beta$ LNV operators
  - Lepton Number Violation as smoking gun
    - Can falsify high-scale baryogenesis
    - BUT: LNV not necessarily predicted