# Lepton Number Violation in Neutrinoless Double Beta Decay and at the LHC

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# Dirac vs. Majorana Neutrinos

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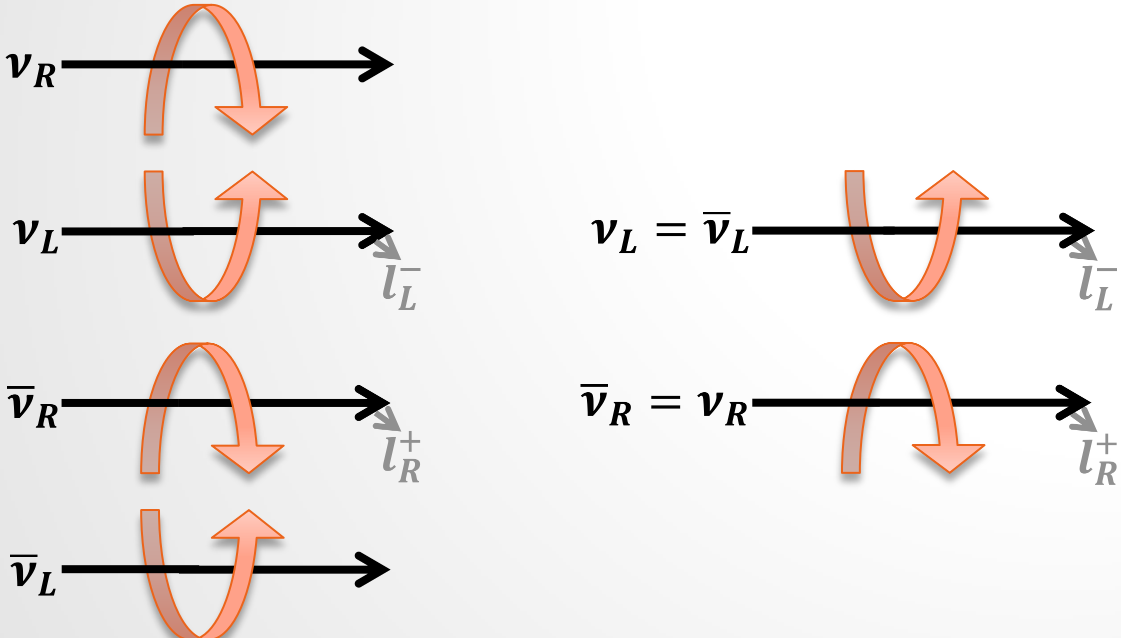
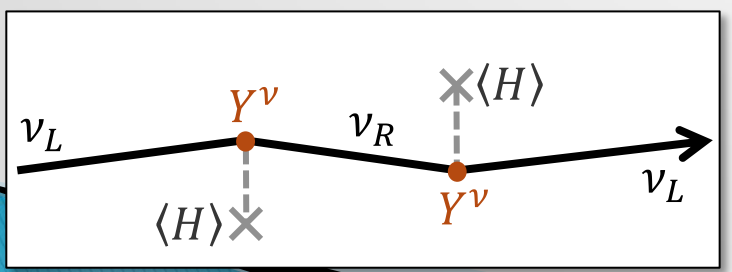
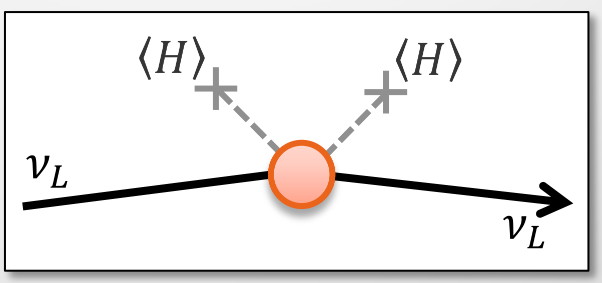
- Two possibilities to define Fermion mass




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

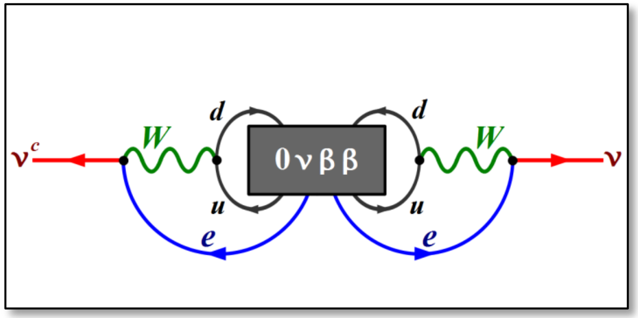



Majorana mass, using only a left-handed neutrino → Lepton Number Violation



# Neutrinoless Double Beta Decay

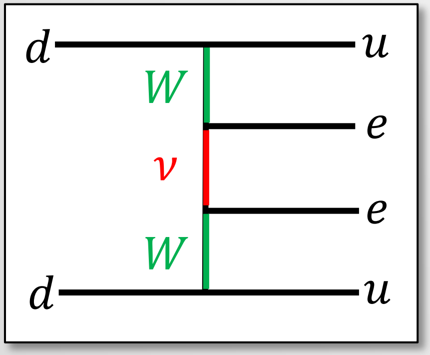
- Process $(A, Z) \to (A, Z+2) + 2e^-$
- Uncontroversial detection of $0\nu\beta\beta$ of utmost importance
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles
    (Schechter & Valle '82)




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

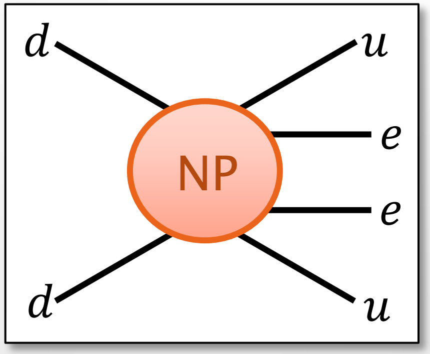
- Which mechanism triggers the decay?

Light Neutrino Exchange




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

General Effective Operator




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

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

# New Physics Contributions

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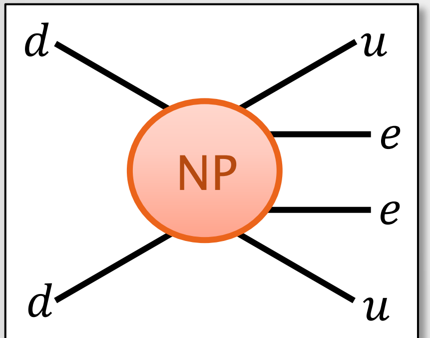
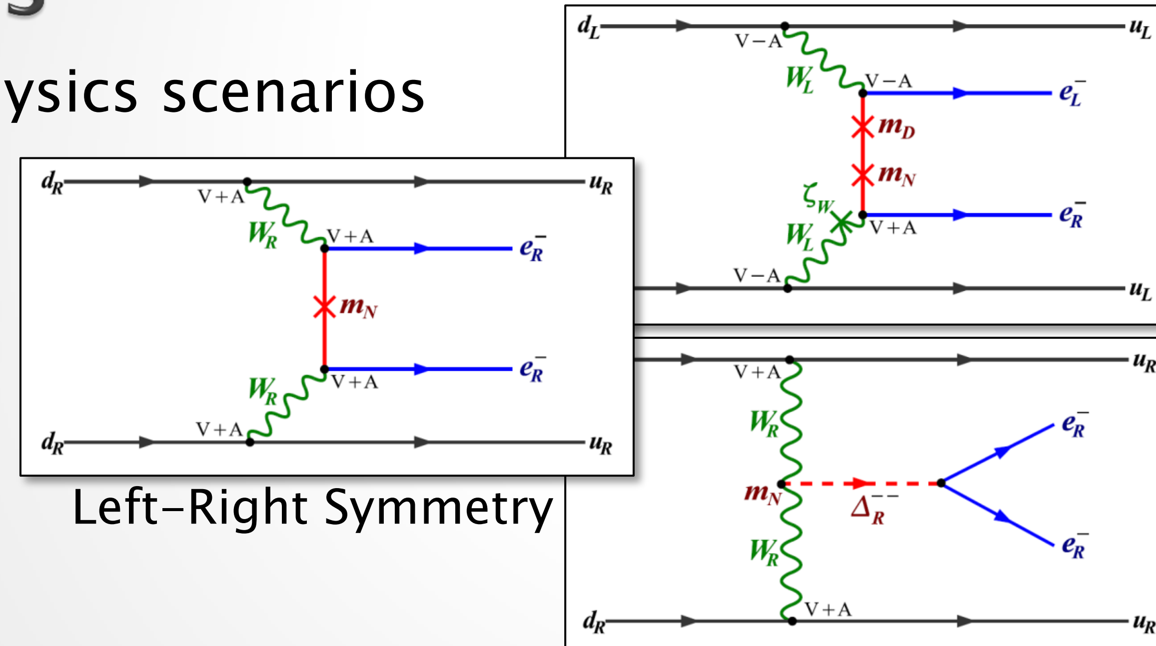
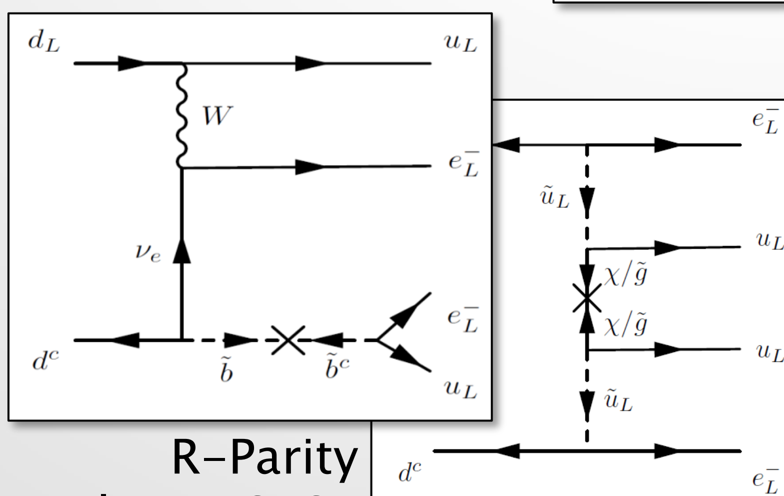
- Plethora of New Physics scenarios




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




Left-Right Symmetry




R-Parity Violating SUSY

Extra Dimensions

Majorons

Leptoquarks

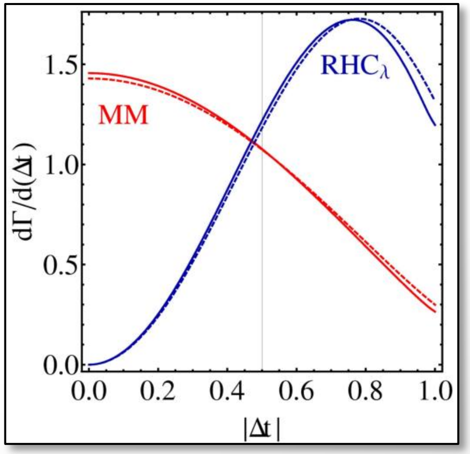
…

# Disentangling New Physics Contributions

- Angular and energy distribution of emitted electrons
  (Doi et al. '83; Ali et al. '06; Arnold et al. '10; FFD, Jackson, Nasteva, Söldner-Rembold '10)

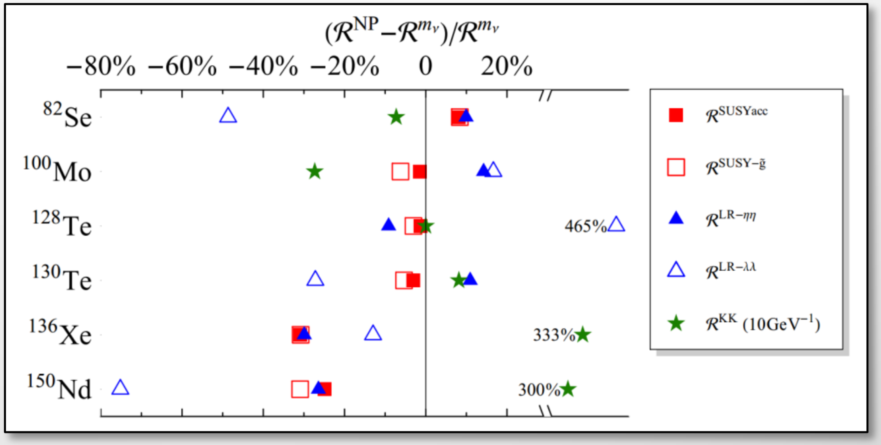
$$\frac{d\Gamma}{dE_{e_1} dE_{e_2} d\cos\theta} = \frac{\Gamma}{2}\left(1 - k\left(E_{e_1}, E_{e_2}\right)\cos\theta\right), \qquad -1 < k < 1$$

  - Linear in $\cos\theta$
  - $k(E_{e_1}, E_{e_2})$ depends on $0\nu\beta\beta$ mechanism

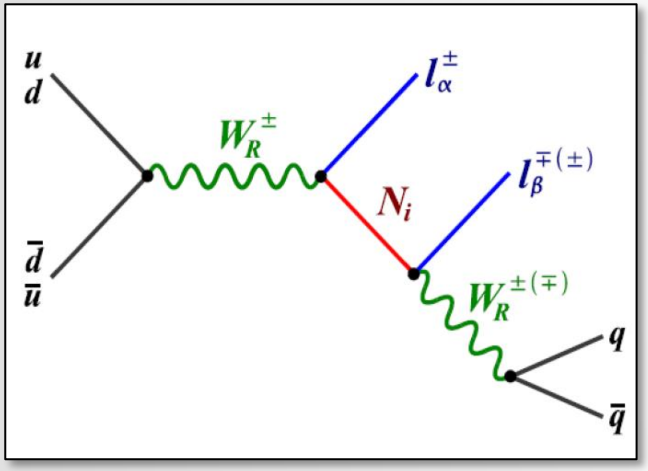



- Comparison of $0\nu\beta\beta$ in multiple isotopes
  (FFD, Päs PRL 2007)
  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics (if one mechanism dominates)

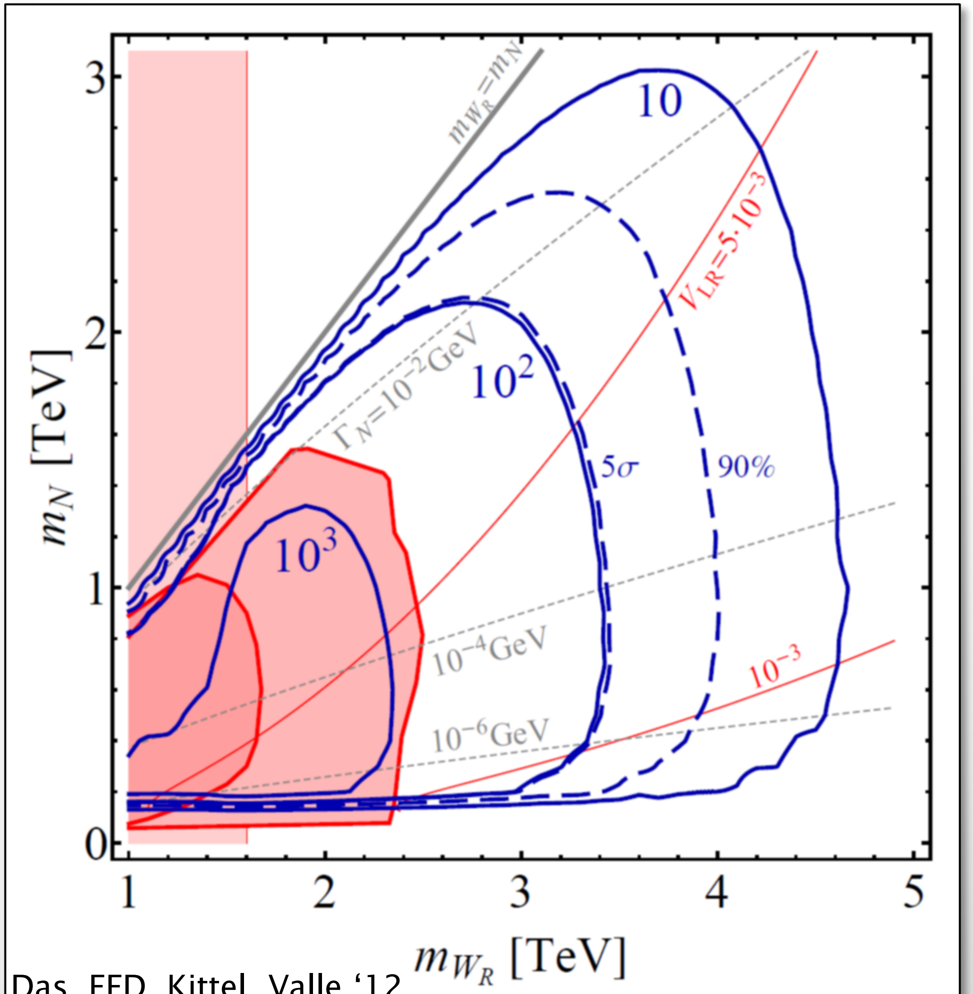
$$\frac{T_{1/2}(X)}{T_{1/2}(Y)} = \frac{G(Y)|M(Y)|^2}{G(X)|M(X)|^2}$$



# LNV at the LHC




- Heavy Neutrino Production in Left-Right Symmetry
- Monte Carlo Simulation (PROTOS)
- Main background $t\bar{t}$, $Z$ + jets (Pythia, Alpgen)
- Fast Detector Simulation (AcerDET)




LHC reach @ 14 TeV, 30 $\mathrm{fb}^{-1}$
Opposite + Same Sign Leptons

# LNV at the LHC

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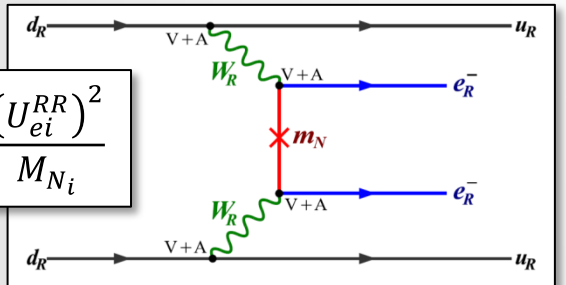
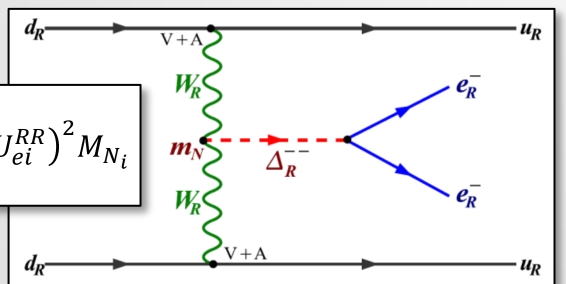
- Contributions to $0\nu\beta\beta$
  - Heavy Neutrinos

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \sum_i \frac{\left(U_{ei}^{RR}\right)^2}{M_{N_i}}$$

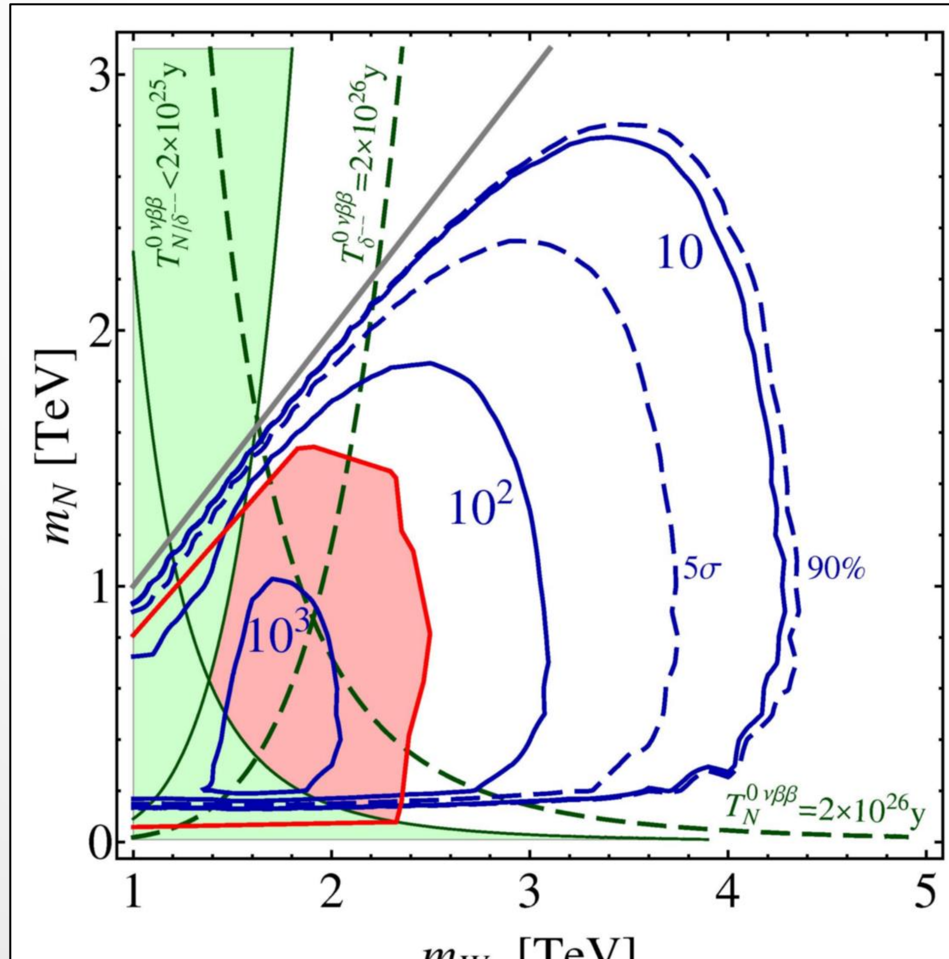



  - Triplet R-Higgs

$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \frac{m_p}{M^2_{\Delta_R^{--}}} \sum_i \left(U_{ei}^{RR}\right)^2 M_{N_i}$$




  - LR-Mixing neglected



Das, FFD, Kittel, Valle '12

LHC reach @ 14 TeV, 30 $\text{fb}^{-1}$
Same Sign Leptons

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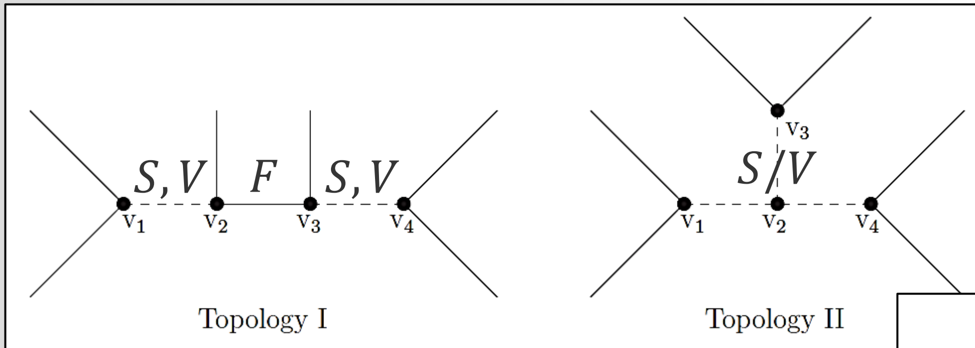
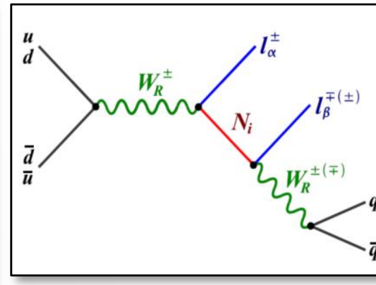
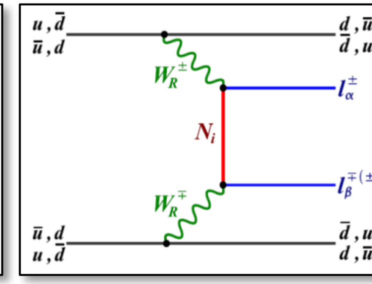
# General UV Completion

(Helo, Kovalenko, Hirsch, Pas '13)

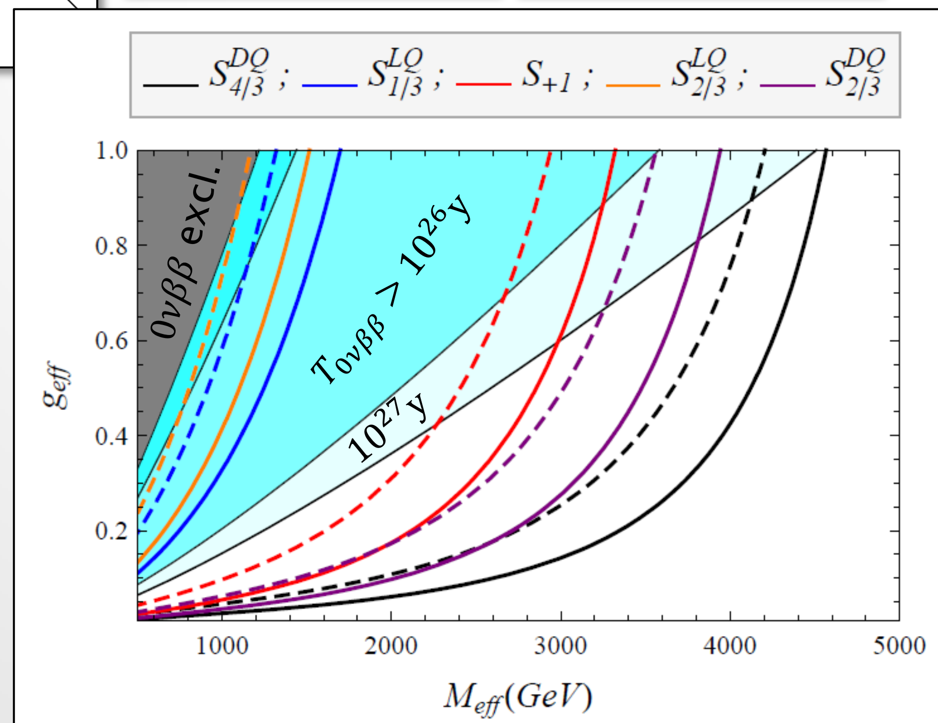
- Generic Tree-level Topologies for $0\nu\beta\beta$ 9-dim Operator



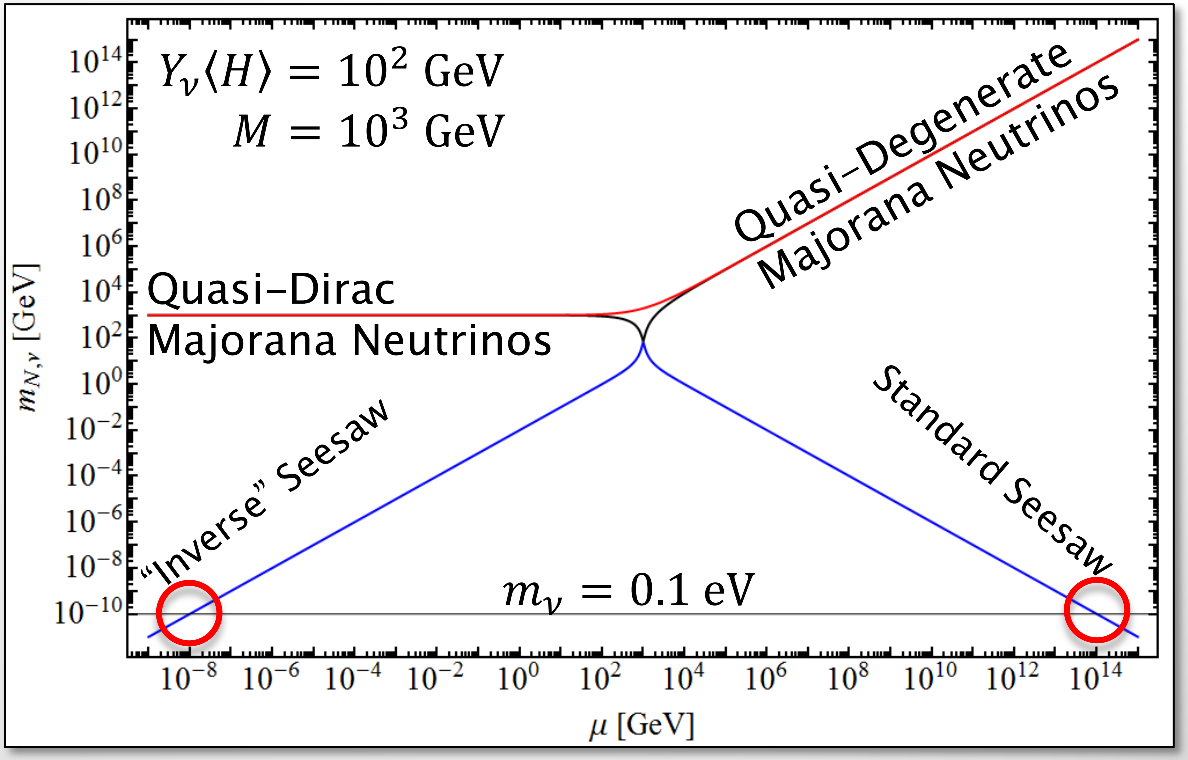

- Sensitivity Comparison between $0\nu\beta\beta$ and LHC
  - LHC with $14\,\mathrm{TeV}, 300\,\mathrm{fb}^{-1}$
  - Heavy Resonance
  - LHC generally more sensitive if heavy particles can be produced on-shell
- Important to look at non-resonant diagrams



# Small Yukawas vs "Bent" Seesaw

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

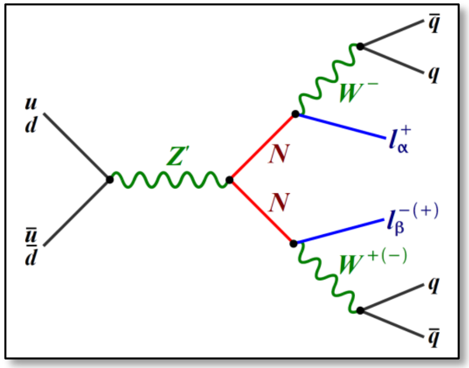
$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$

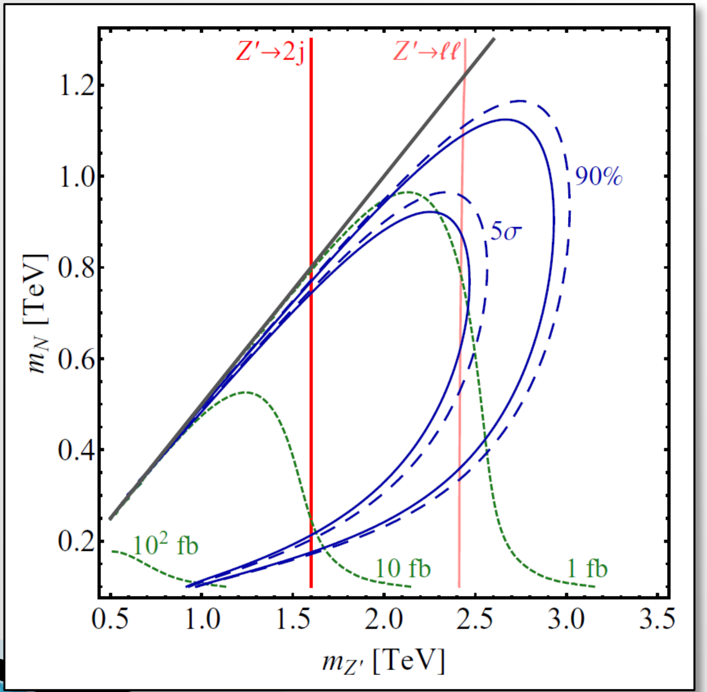


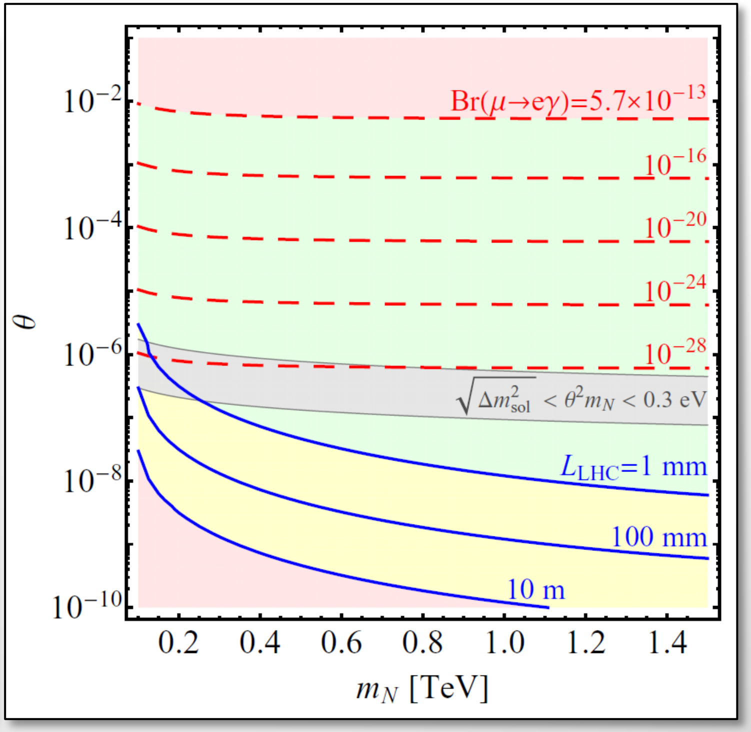
# Probing Small Yukawa Couplings

(FFD, Desai, Valle, Phys. Rev. D89 051302)

- Heavy neutrino $N$ production via $Z'$
  - $N$ can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$
  - LHC cross section is independent of $\theta$ (until displaced vertices occur)
  - Observable LFV at the LHC for very small $\theta$



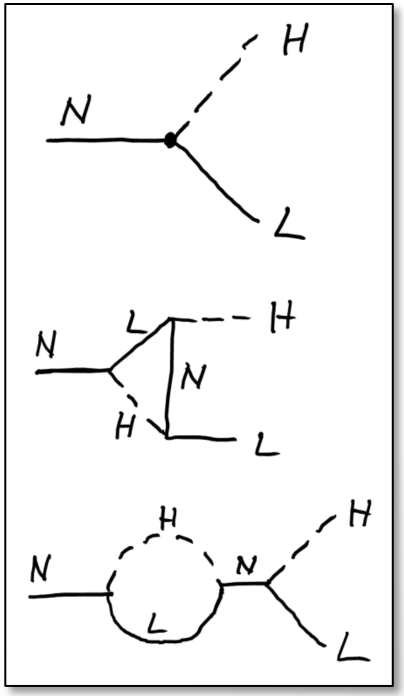



# Falsifying Leptogenesis at the LHC

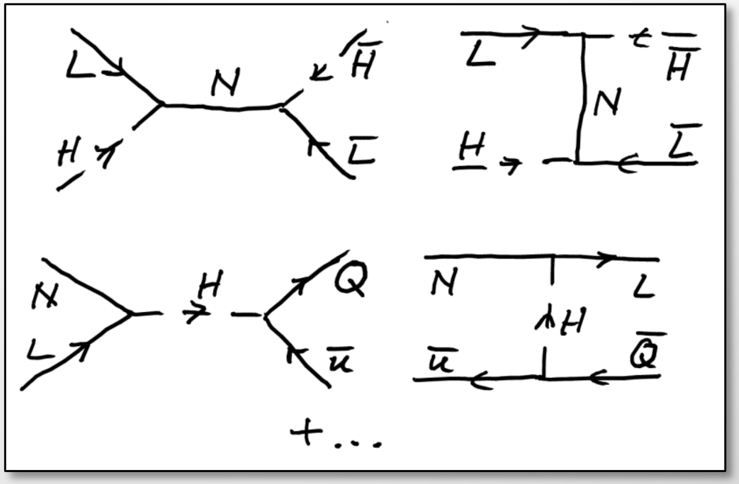
(FFD, Harz, Hirsch, Phys. Rev. Lett. 112, 221601)

- Classic Leptogenesis Scenario
  - Heavy Majorana Neutrino Decays
  - Competition with LNV washout processes
  - Net lepton number asymmetry
  - Conversion to baryon asymmetry
    - 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: Lepton number asymmetry generated above LHC scale
- What is the effect on Leptogenesis models if we observe LNV @ LHC?



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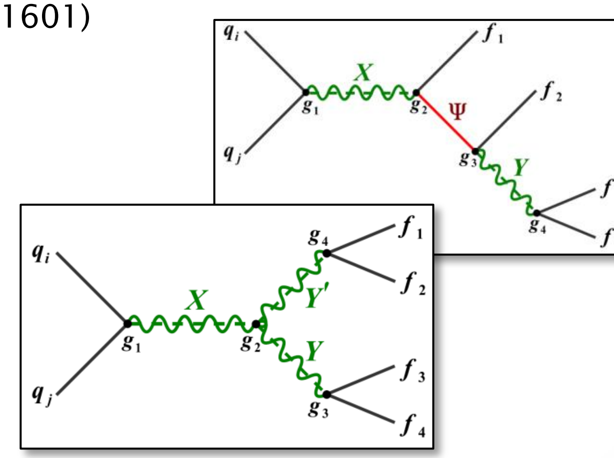


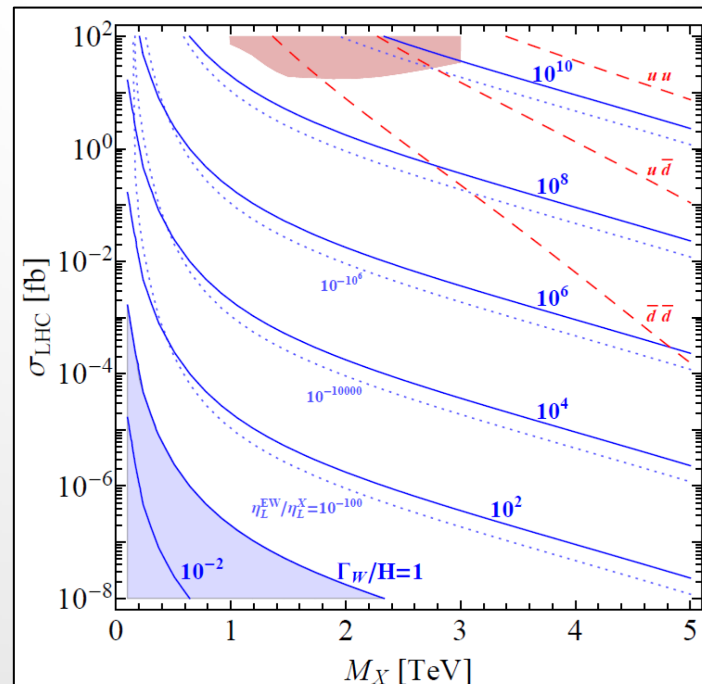

- Compare LHC cross section with lepton number asymmetry washout

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

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

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

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



# Falsifying Leptogenesis at the LHC (FFD, Harz, Hirsch, Phys. Rev. Lett. 112, 221601)

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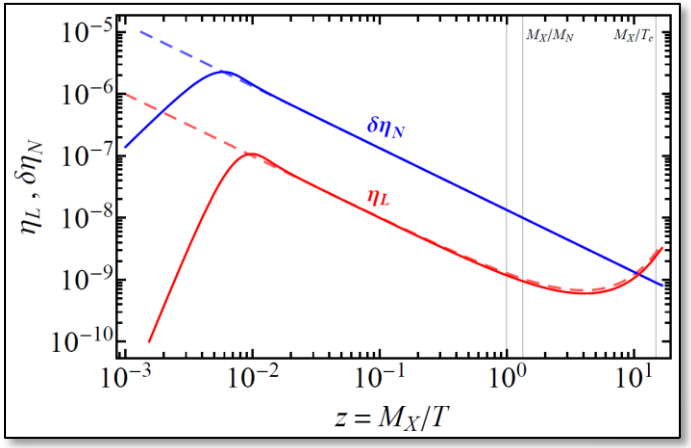
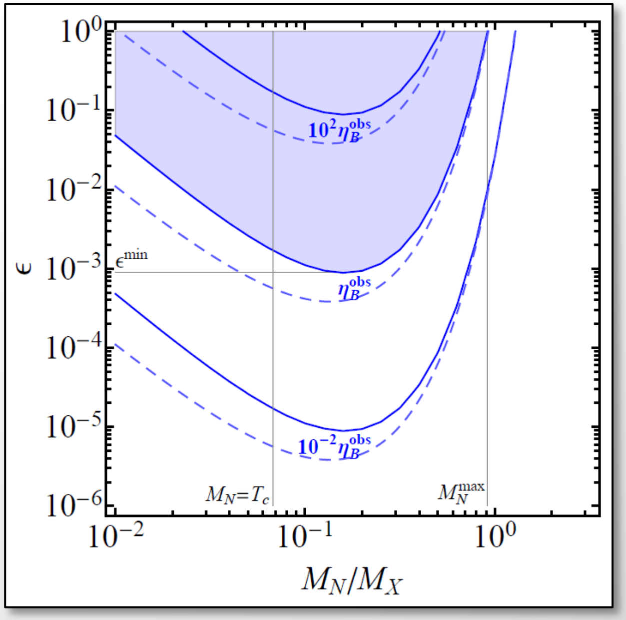
- Classic Leptogenesis with one heavy neutrino $N$, neglecting flavour
  - Upper limit on baryon asymmetry

$$\log_{10}\left|\frac{\eta_B}{\eta_B^{\mathrm{obs}}}\right| < 2.4\frac{M_X}{\mathrm{TeV}}\left(1-\frac{4}{3}\frac{M_N}{M_X}\right)+\log_{10}\left[|\epsilon|\left(\frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}\right)^{-1}\left(\frac{4}{3}\frac{M_N}{M_X}\right)^2\right]$$

  - LNV is observed at LHC
    - → High scale Leptogenesis ($M_N > M_X$) is not viable
    - → Strong limit on CP asymmetry $\epsilon$ for low scale Leptogenesis ($M_{EW} < M_N < M_X$)
- Caveat
  - Asymmetry can be present in one lepton generation only
    - Falsification requires observation of LNV in all flavours (or observation of low energy LFV such as $\tau \to e\gamma$)



# Conclusion

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- **Neutrinos much lighter than other fermions**
  - Mechanism of neutrino mass generation?
  - Dirac or Majorana? Lepton Number Violation?
- **$0\nu\beta\beta$ is crucial probe for BSM physics**
  - New LNV physics at the TeV scale?
  - Standard Mass Mechanism?
    - 5-dim operator from LNV at GUT scale

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

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

- **Strong Synergy with LHC searches**
  - LHC can deep-probe anatomy of $0\nu\beta\beta$ LNV operators
  - Observation of LNV would strongly constrain Leptogenesis
  - → Important information for model selection, e.g.
    - Observation of $0\nu\beta\beta$
    - No Observation of LNV @ LHC

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

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    - "Compatible" Observation of LNV @ LHC

    } LNV @ TeV Scale<br>Disfavours high-scale seesaw

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