Probing Lepton Number Violation on Three Frontiers

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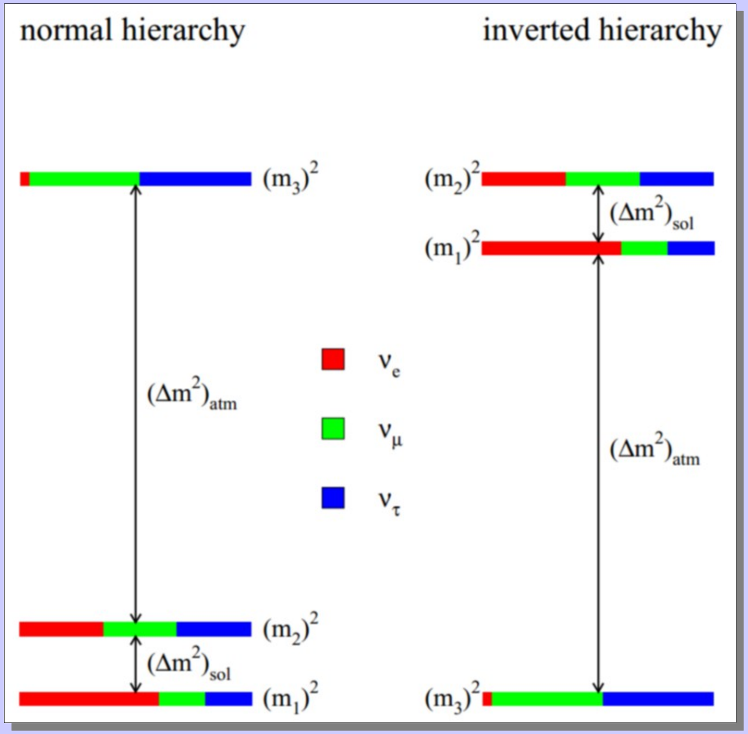
Overview

- Neutrinos
  - Oscillations
  - Absolute Mass
- Neutrinoless Double Beta Decay
  - Light Neutrino Exchange
  - New Physics Mechanisms
  - In Combination with Cosmology
- Neutrino Mass Models
  - Effective Mass and Seesaw
  - Minimal Left-Right Symmetry
- LFV and LNV at the LHC
- Conclusion

Neutrino Oscillations

- **Neutrino interaction states different from mass eigenstates**
  Neutrino flavour can change through propagation

$$\nu_i = \sum_\alpha U_{i\alpha}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i$$
$$\Rightarrow P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$



- **Solar neutrino oscillations**
  Large mixing
- **Atmospheric oscillations**
  ≈ Maximal mixing
- **Reactor and accelerator neutrinos**

$$\sin^2(2\theta_{13}) = 0.092 \pm 0.021$$

- **Experimental unknowns and anomalies**
  CP violation? Sign of Δm_{23}? Sterile Neutrinos?

Absolute Neutrino Mass

- **Energy endpoint in Beta decay**

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 < (2.2\,\mathrm{eV})^2$$

Katrin: $m_\beta \approx 0.2$ eV

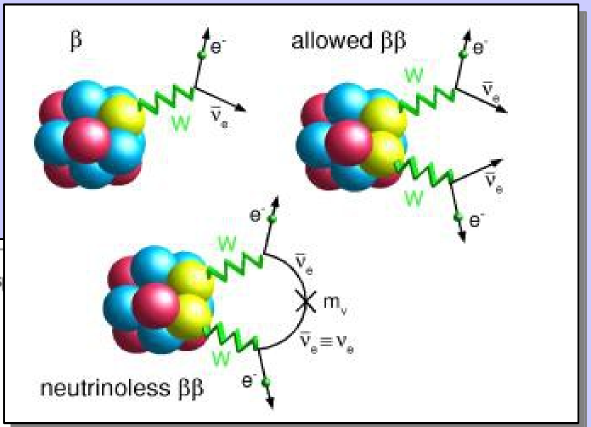
- **Impact on Large Scale Structure**

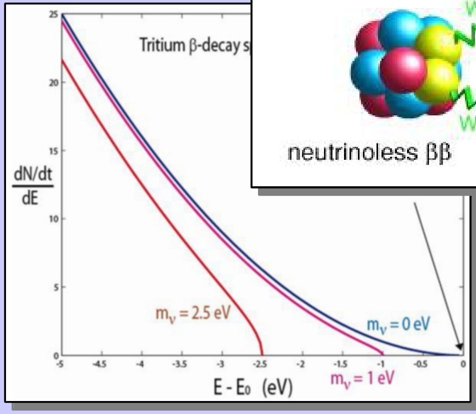
$$\Sigma = \sum_i m_i < 0.3 - 1\,\mathrm{eV}$$

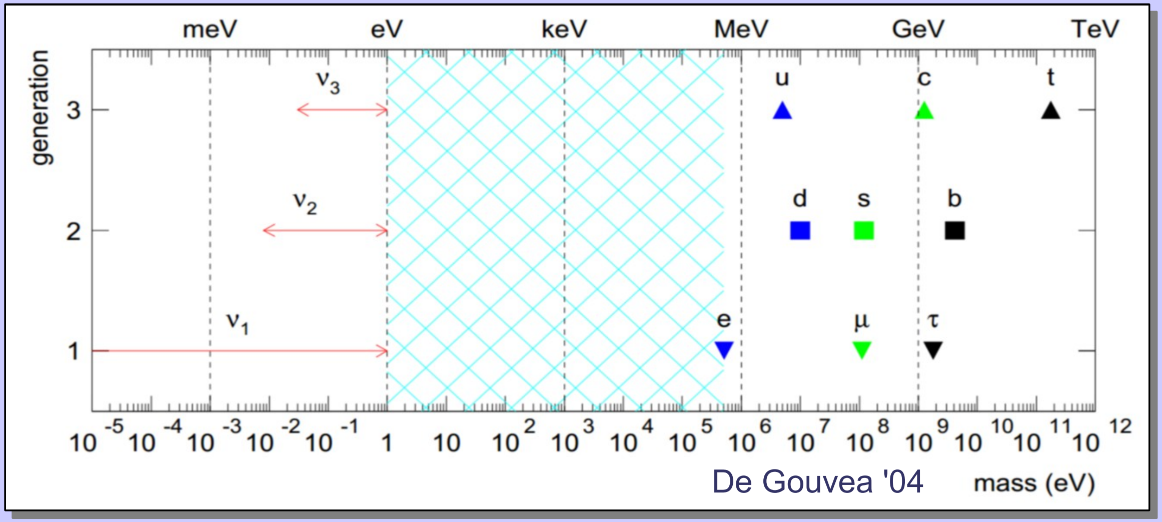
- **Neutrinoless Double Beta Decay**

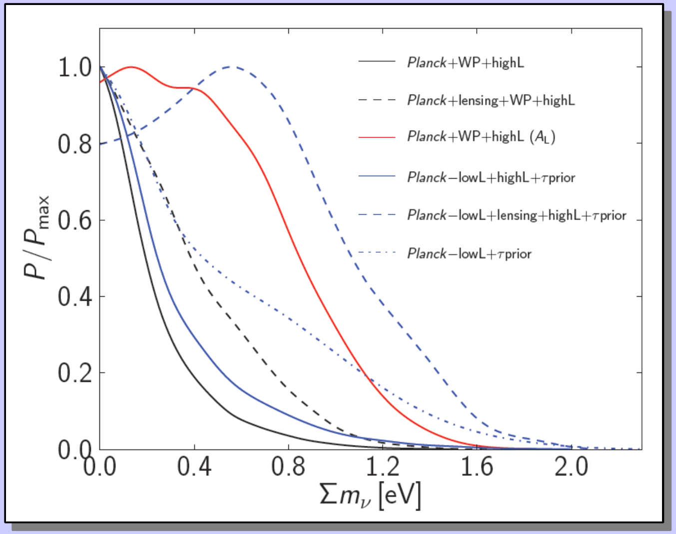
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_{\nu_i}\right| < 0.2 - 2.0\,\mathrm{eV}$$

Future: $m_{\beta\beta} \approx 0.01$ eV



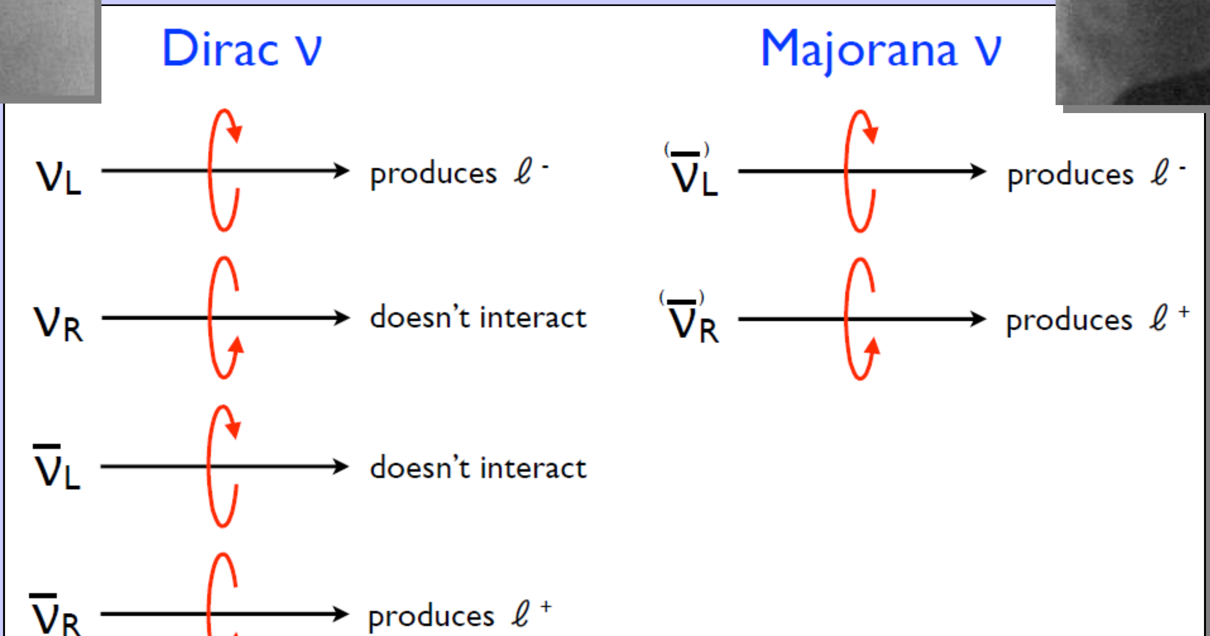




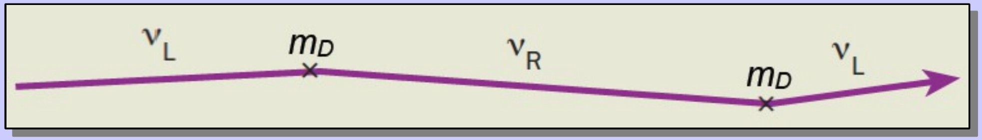


Dirac vs Majorana

Two possibilities to define mass



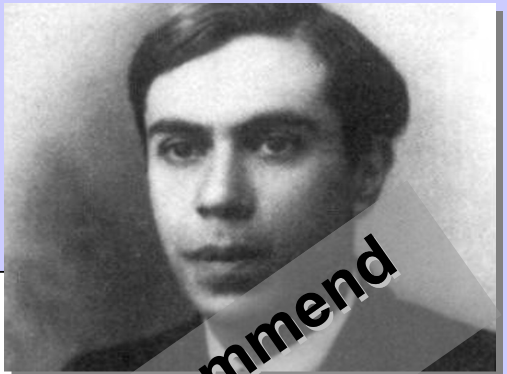
Detwiler '12



Dirac mass, analogous to other fermions (but with tiny coupling to Higgs)

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

Dirac vs Majorana



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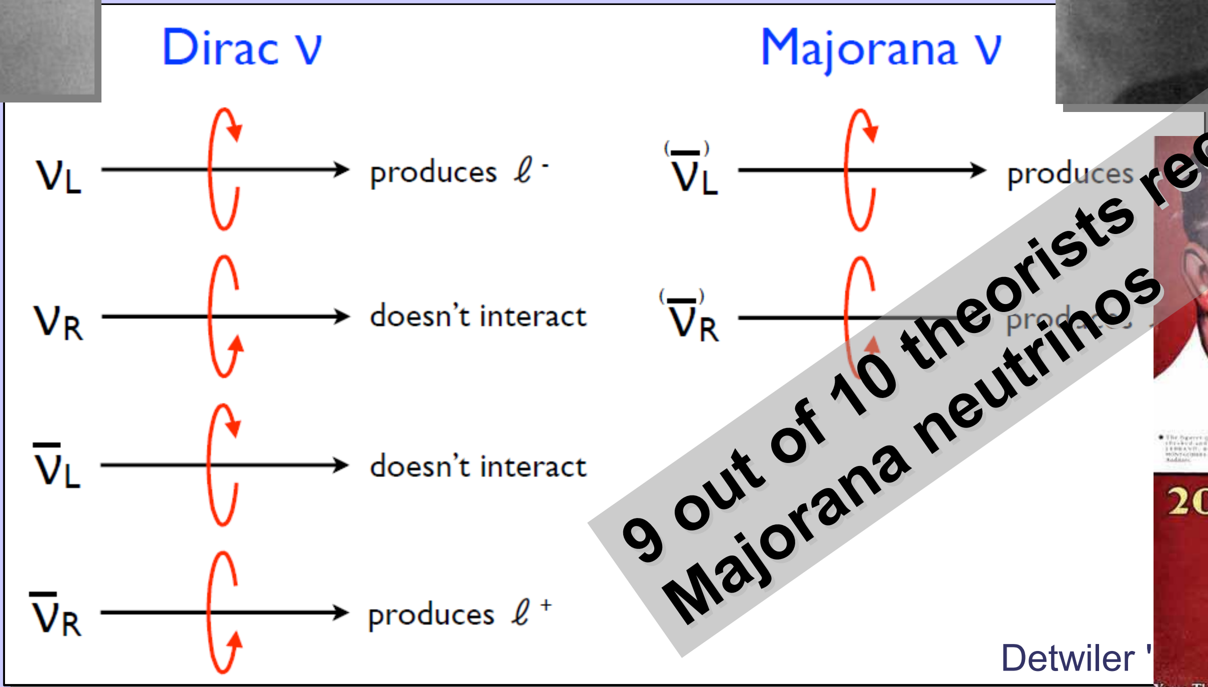

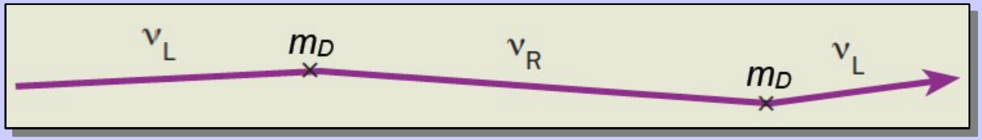

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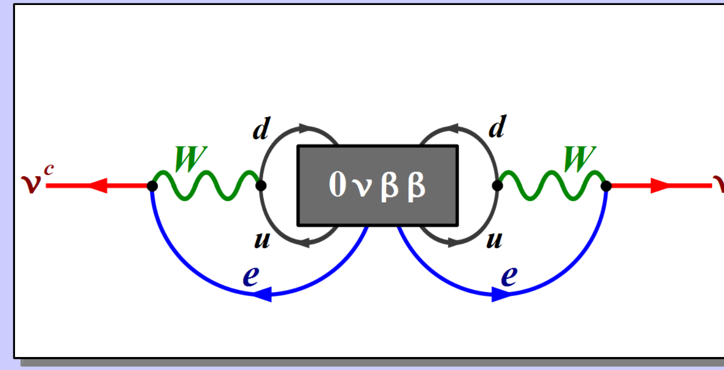
Neutrinoless Double Beta Decay

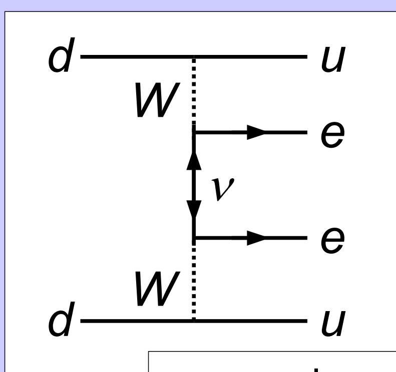
- **Process: $(A, Z) \to (A, Z{+}2) + 2e^-$**
- **Uncontroversial detection of $0\nu\beta\beta$ of utmost importance**
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles (Schechter, Valle '82)



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

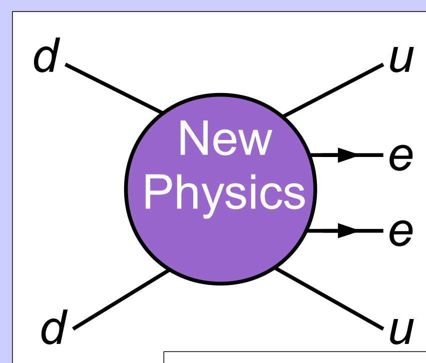
- **Which mechanism triggers the decay?**

Light Neutrino Exchange
(LH Current, Mass Mechanism)



$$T_{1/2}^{-1} \propto \left| \sum_i U_{ei}^2 m_{\nu_i} \right|$$

General Effective Operator

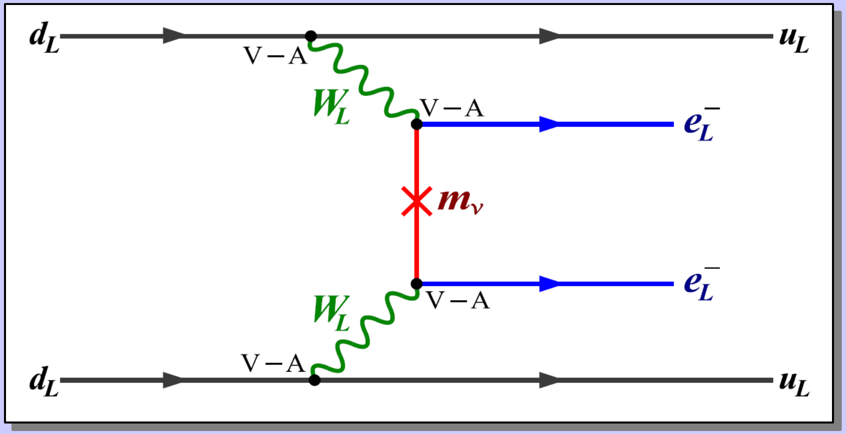


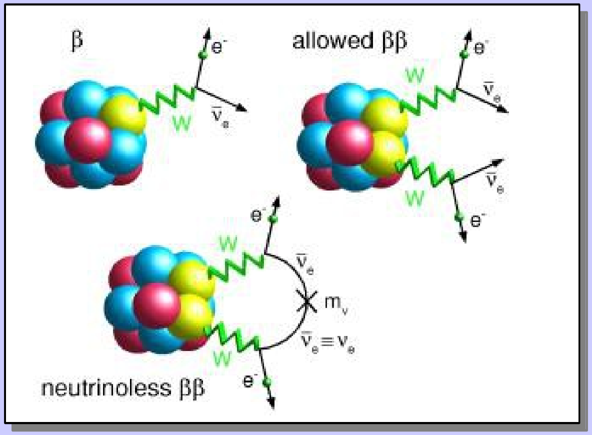
$$T_{1/2}^{-1} \approx 10^{25}\ \mathrm{y} \to M \approx 1\ \mathrm{TeV}$$

$$\bar{u}\,\bar{u}\,\bar{e}\,\bar{e}\,d\,d\,/\,M^5$$

Light Neutrino Exchange

- **Standard Mass Mechanism**





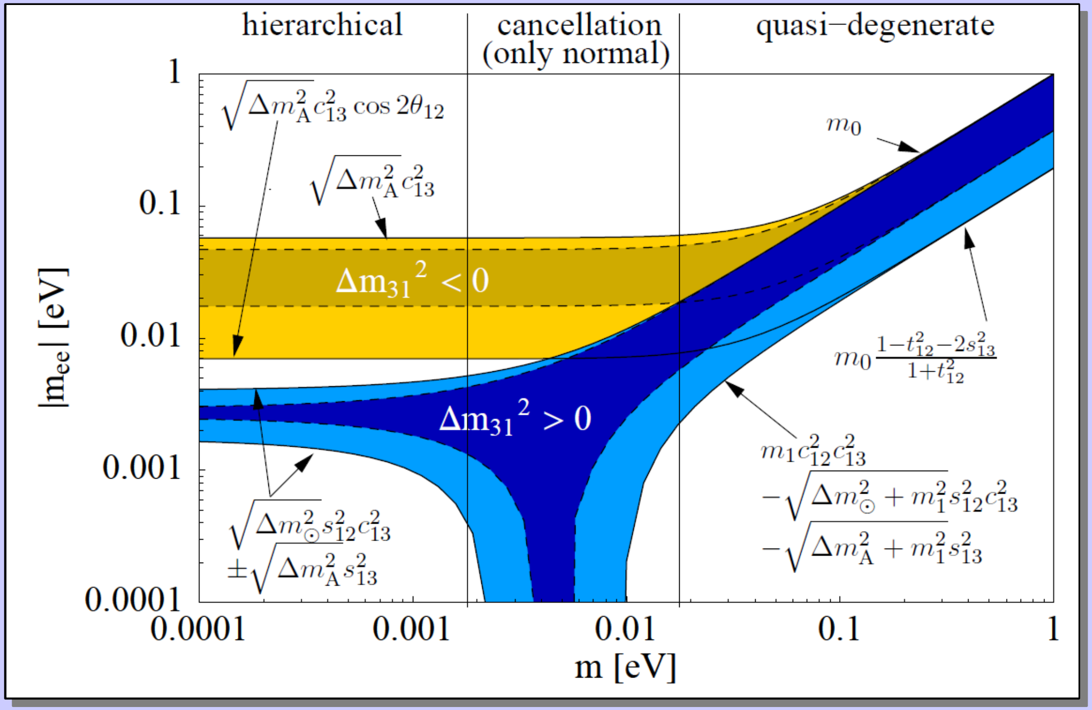
- **Decay Rate**

$$\Gamma = T_{1/2}^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G^{0\nu} \left| M^{0\nu} \right|^2$$

- **Effective Mass**

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| \equiv (m_\nu)_{ee}$$

Lindner, Merle, Rodejohann (2005)

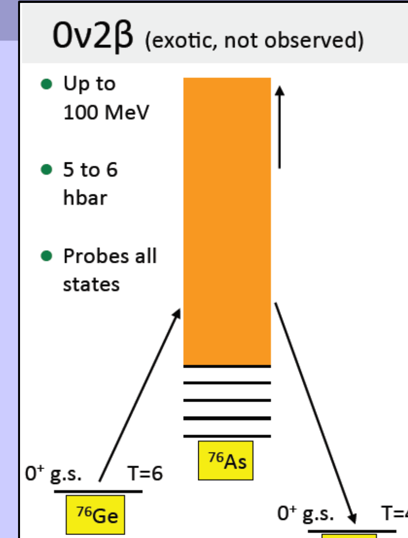


Nuclear Matrix Elements

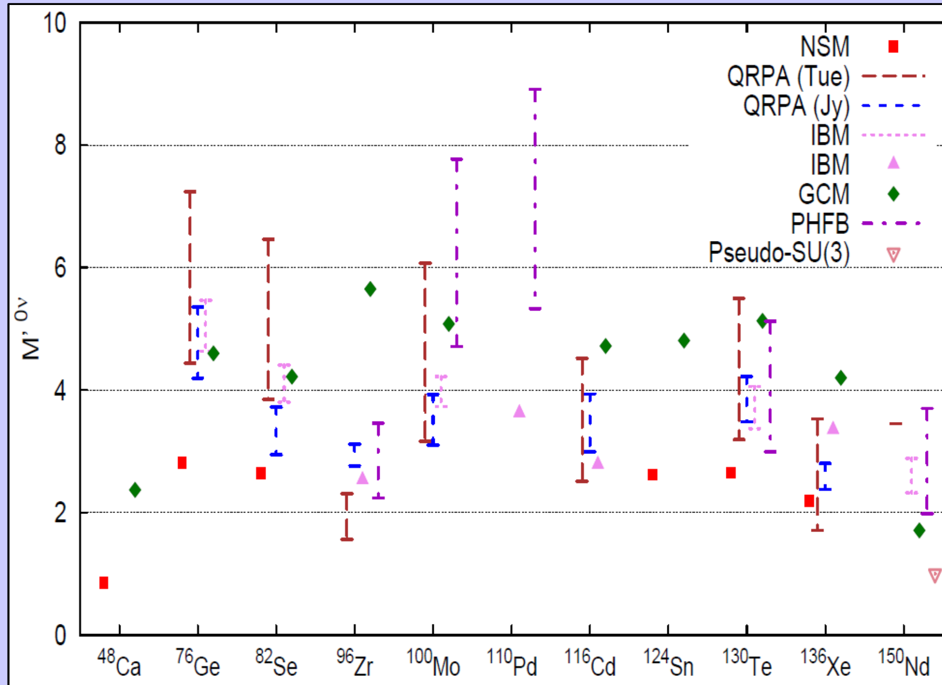
- **Decay Rate**

$$\Gamma = T_{1/2}^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G^{0\nu} \left| M^{0\nu} \right|^2$$

- **Requires calculation of matrix element of the nuclear transition via intermediate state**
- **Many-body problem not solvable from first principle**
- **Factor 2 – 3 uncertainty between different nuclear models**
  - Shell Models
  - QRPA
  - IBM
- **Important to search for $0\nu\beta\beta$ in several isotopes**

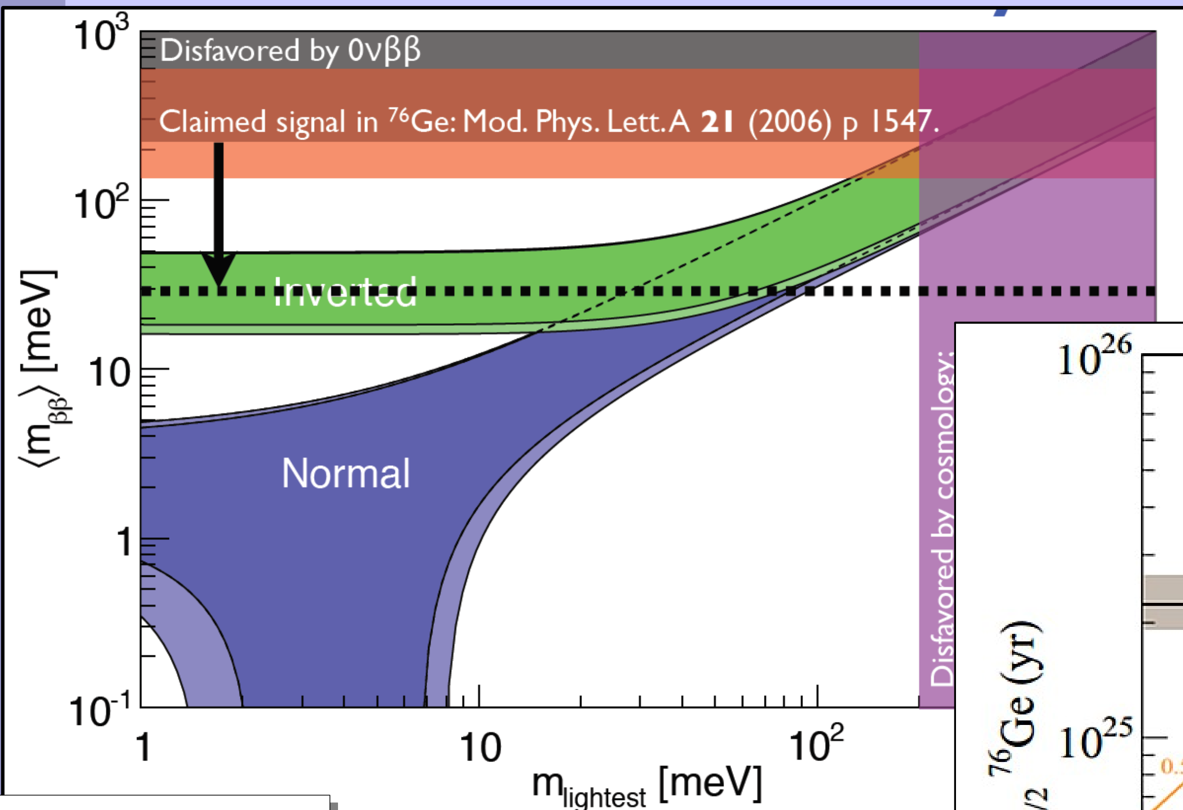


Kay (2011)

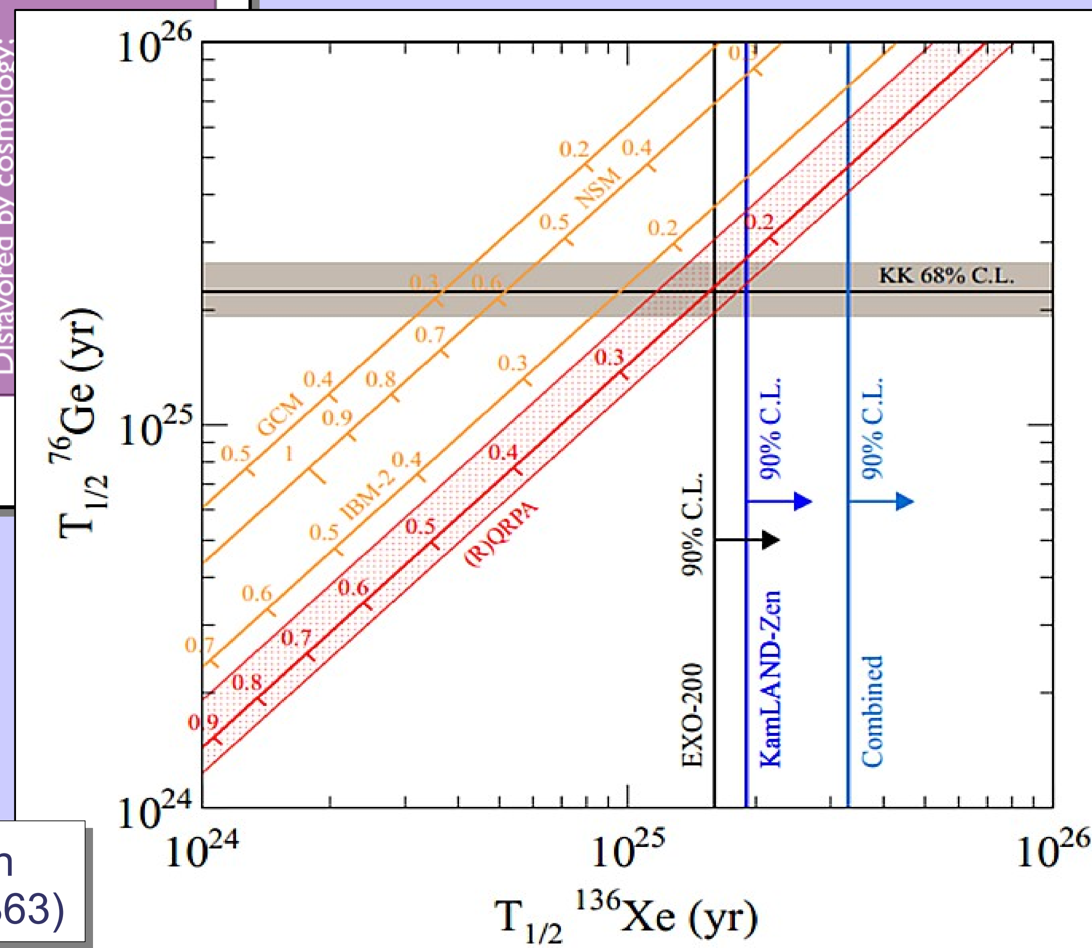


Rodejohann (2012)

Experimental Situation



Detwiler (2012)



KamLAND-Zen (arXiv:1211.3863)

Combining 0νββ and Cosmology

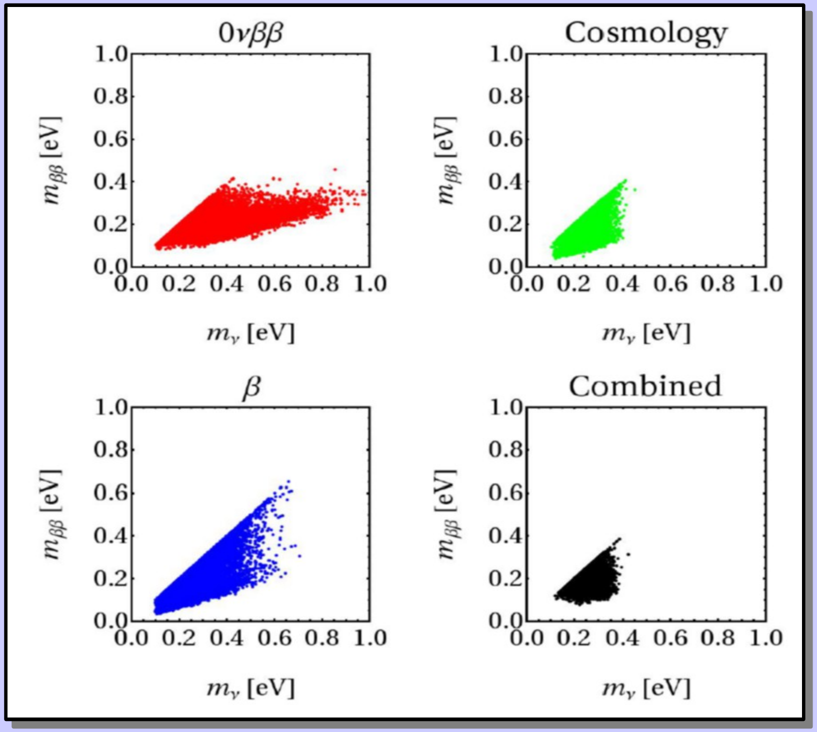
J. Auger, FFD, O. Lahav, I. Sadeh, D. Waters, Work in Progress

- **Effective 0νββ Observable**

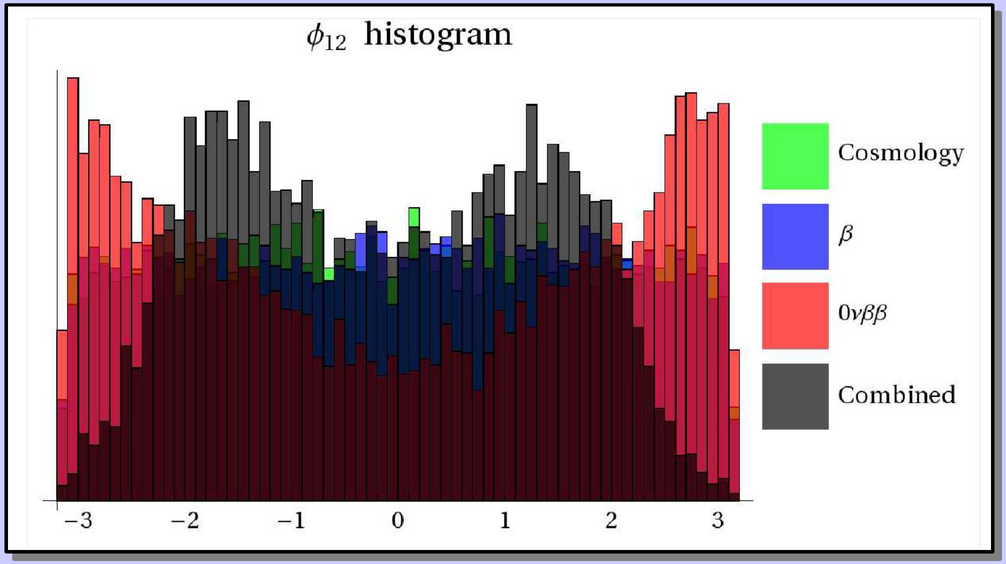
$$m_{\beta\beta} \equiv (m_\nu)_{ee} = \left|\sum_i U_{ei}^2 m_{\nu_i}\right| = \left|m_{\nu_1}|V_{e1}|^2 + m_{\nu_2}|V_{e2}|^2 e^{2i\phi_{12}} + m_{\nu_3}|V_{e3}|^2 e^{2i\phi_{23}}\right|$$

$$\approx m_1\sqrt{1-\sin^2(2\theta_{12})\sin^2(\phi_{12})} \quad \text{quasi-deg. neutrinos}$$

- **Interplay of mass probes**

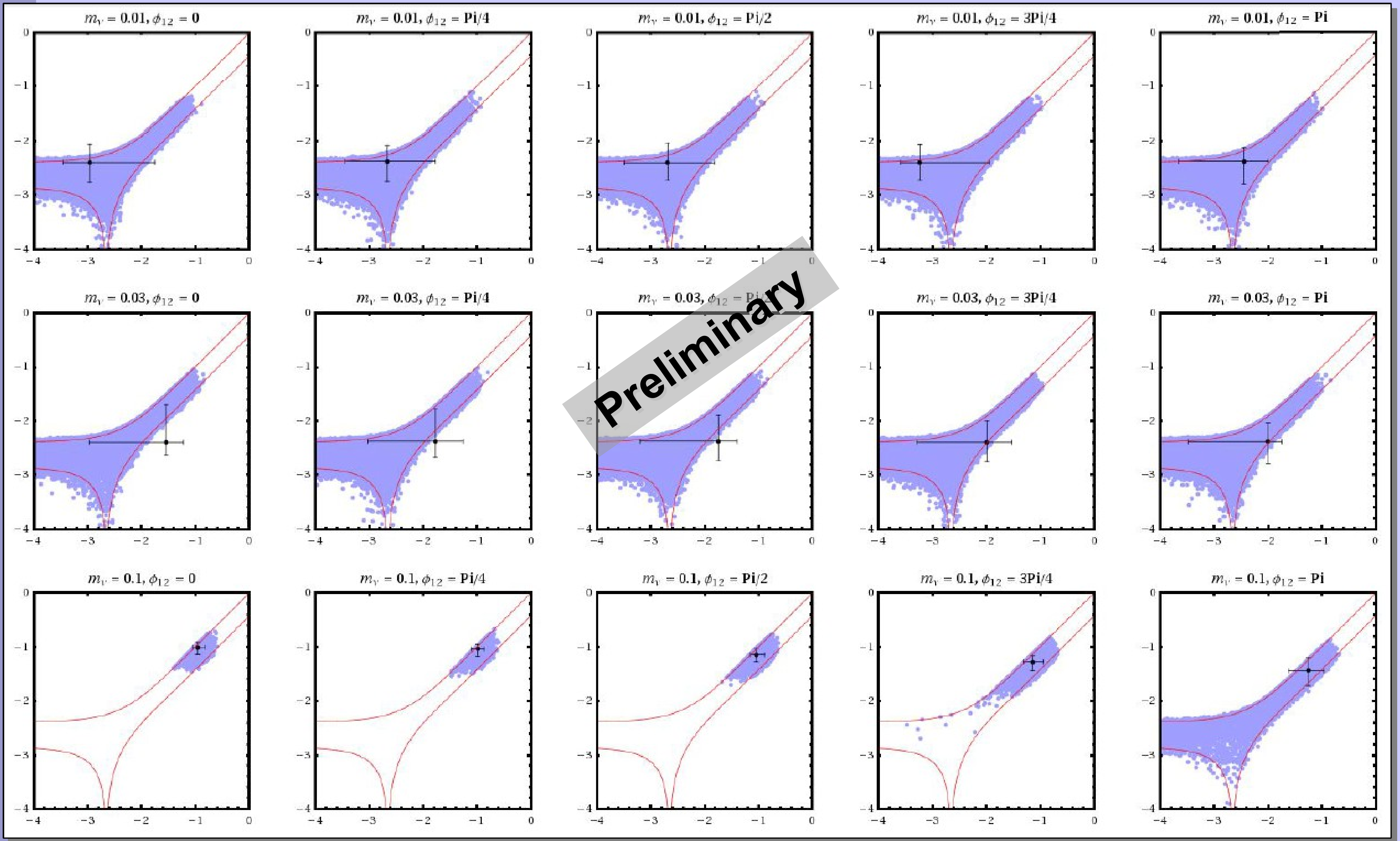


Simulation of observables incl. NME and expected exp. uncertainties with $m_{\nu_1} = 0.25\ \text{eV}, \phi_{12} = \pi/2$



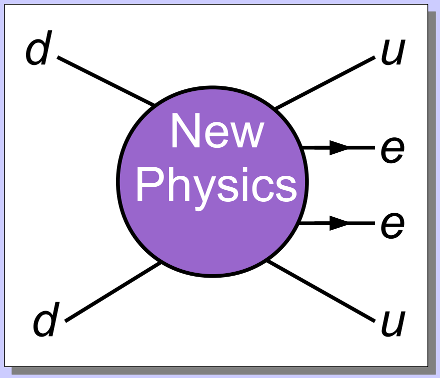
Combining $0\nu\beta\beta$ and Cosmology

J. Auger, FFD, O. Lahav, I. Sadeh, D. Waters, Work in Progress



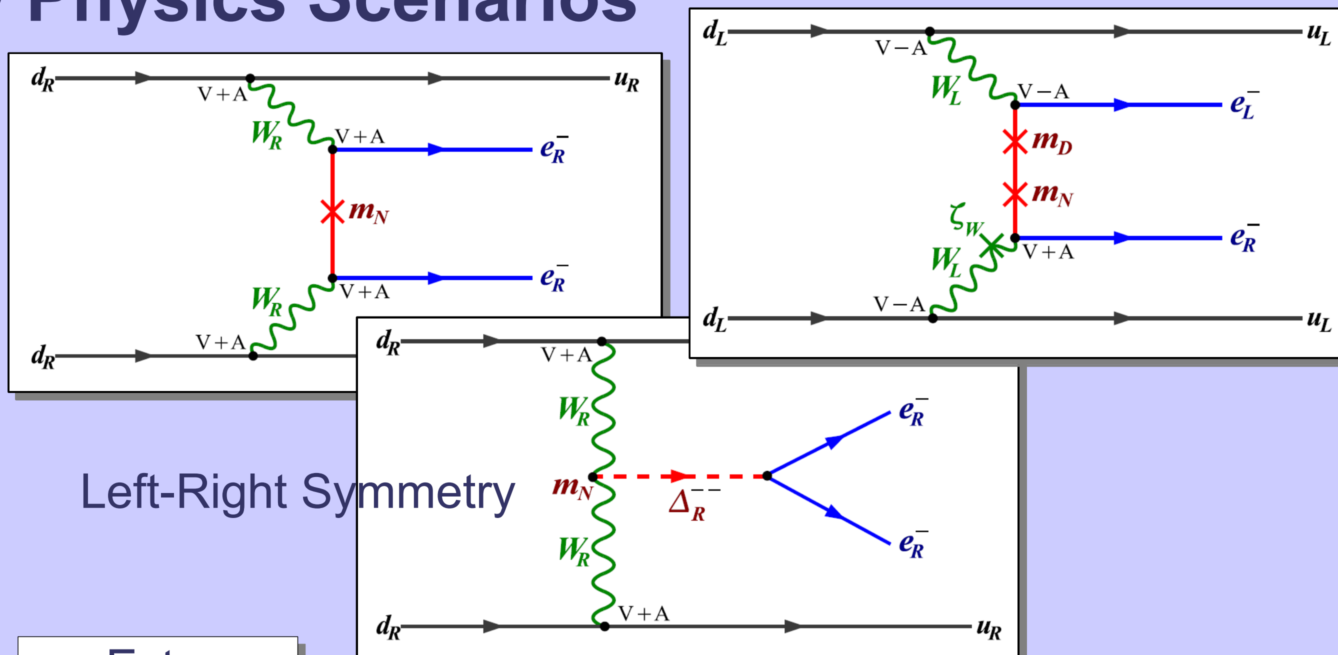
New Physics Contributions to 0νββ

- **Plethora of New Physics Scenarios**



$$=$$

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



Left-Right Symmetry

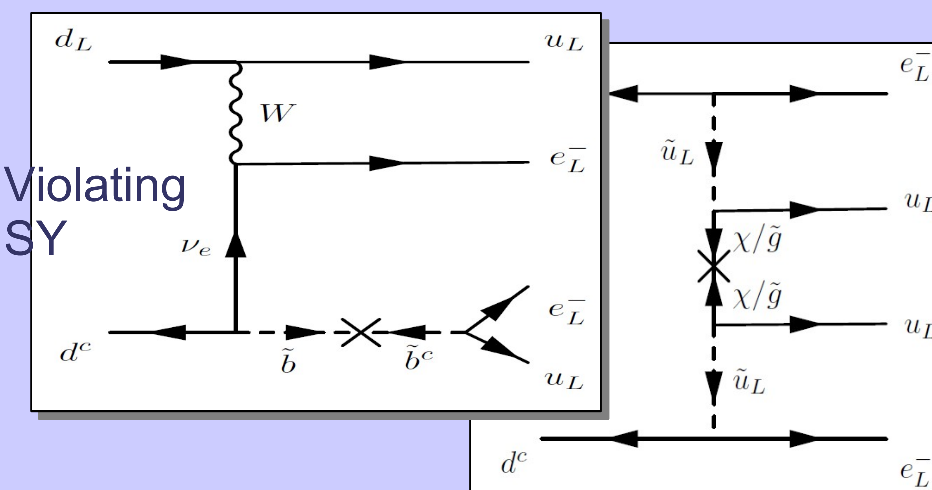
Extra Dimensions

Majorons

Leptoquarks

...

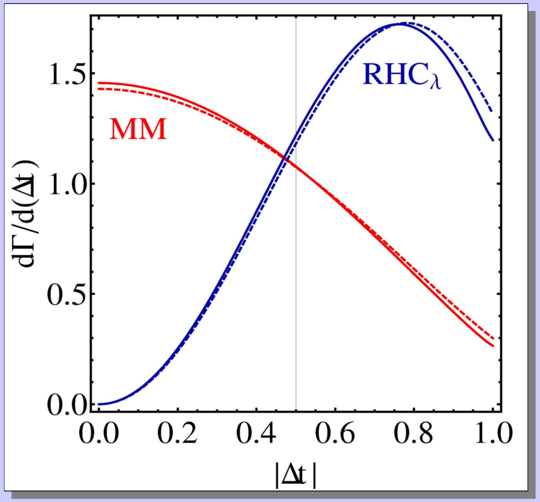
R-Parity Violating SUSY



Disentangling New Physics Scenarios

- **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)

$$\frac{d\Gamma}{dE_1\, dE_2\, d\cos\theta} = \frac{\Gamma}{2}\left(1 - k(E_1, E_2)\cos\theta\right) \qquad -1 < k < 1$$



  - Linear in $\cos\theta$
  - $k(E_1, E_2)$ depends on $0\nu\beta\beta$ mechanism

- **Comparison of $0\nu\beta\beta$ in multiple isotopes**
  (FFD, Päs PRL 2007)

$$\frac{T_{1/2}({}^A\mathrm{X})}{T_{1/2}({}^B\mathrm{Y})} = \frac{G({}^B\mathrm{Y})\left|M({}^B\mathrm{Y})\right|^2}{G({}^A\mathrm{X})\left|M({}^A\mathrm{X})\right|^2}$$

  - Depends on $0\nu\beta\beta$ mechanism
  - Independent of details of new physics (if one mechanism dominates)

Effective Mass and Seesaw Mechanism

- **Effective operator for Majorana neutrino mass**

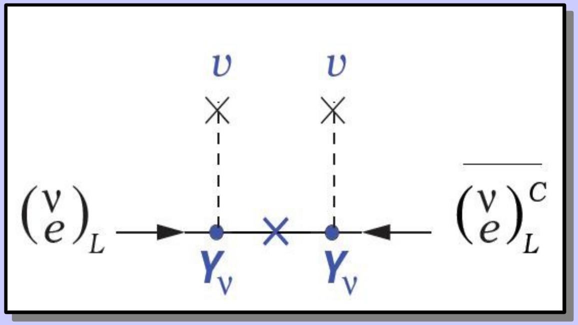
$$L = \frac{1}{2}\frac{h_{ij}}{\Lambda_{\text{LNV}}}\left(\overline{L_i^c}\cdot\tilde{H}\right)\left(\tilde{H}^T\cdot L_j\right) \rightarrow \frac{1}{2}(m_\nu)_{ij}\overline{\nu_i^c}\nu_j$$

Unique dim-5 Operator

- **Seesaw Mechanism**

  Add right-handed neutrinos to the Standard Model particle content, $M \approx 10^{14}$ GeV

$$L = L_{\text{SM}} - \frac{1}{2}\bar{\nu}_R M \nu_R^c + \bar{\nu}_R Y_\nu L\cdot H_u$$



- **Light neutrino mass matrix at low energies**

$$m_\nu = m_D^T M^{-1} m_D \text{ for } m_D \ll M_R \qquad m_\nu \approx 0.1\text{eV}\left(\frac{m_D}{100\,\text{GeV}}\right)^2\left(\frac{M}{10^{14}\,\text{GeV}}\right)^{-1}$$

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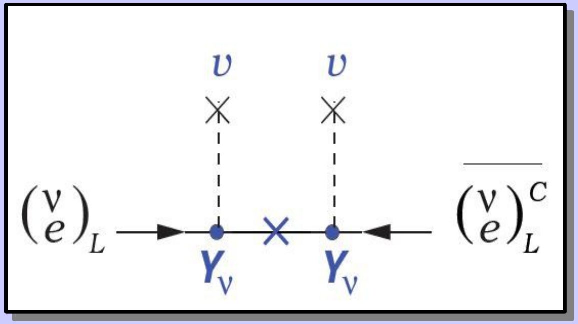
Unique dim-5 Operator

- **Seesaw Mechanism**
- **Sterile Neutrino Mass Scale Unknown**
  - $\approx 10^{14}$ GeV: Naive Seesaw, GUTs
  - $>10^{9}$ GeV: Thermal Leptogenesis
  - $\approx 10^{2}$ GeV: Resonant Leptogenesis, Production at LHC
  - $\approx$ 1 keV: Dark Matter Candidate
  - $\approx$ 1 eV: Oscillation, Cosmology, (Double) Beta Decay



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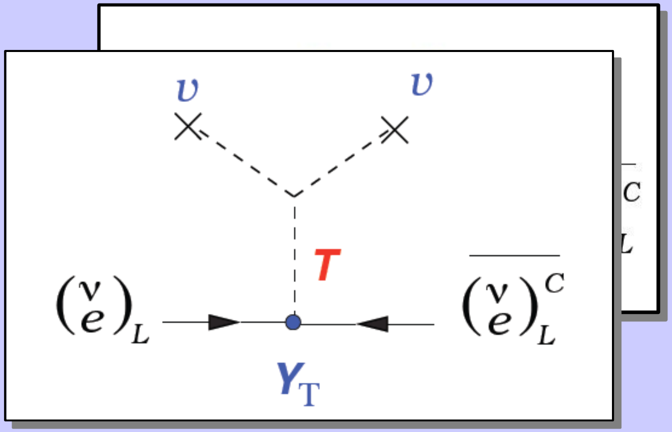
Unique dim-5 Operator

- **Seesaw Mechanism**
- **Three possible mediators at tree level**



Seesaw II

Effective Mass and Seesaw Mechanism

- **Effective operator for Majorana neutrino mass**

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Unique dim-5 Operator

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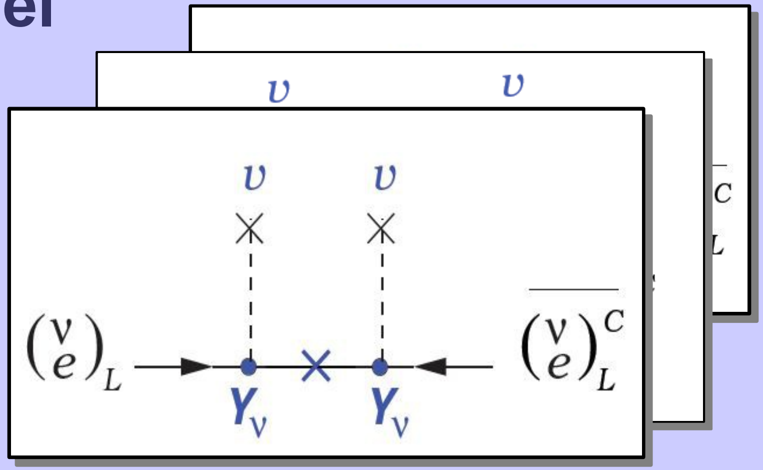

Seesaw III

Effective Mass and Loops

- **Effective operator for Majorana neutrino mass**

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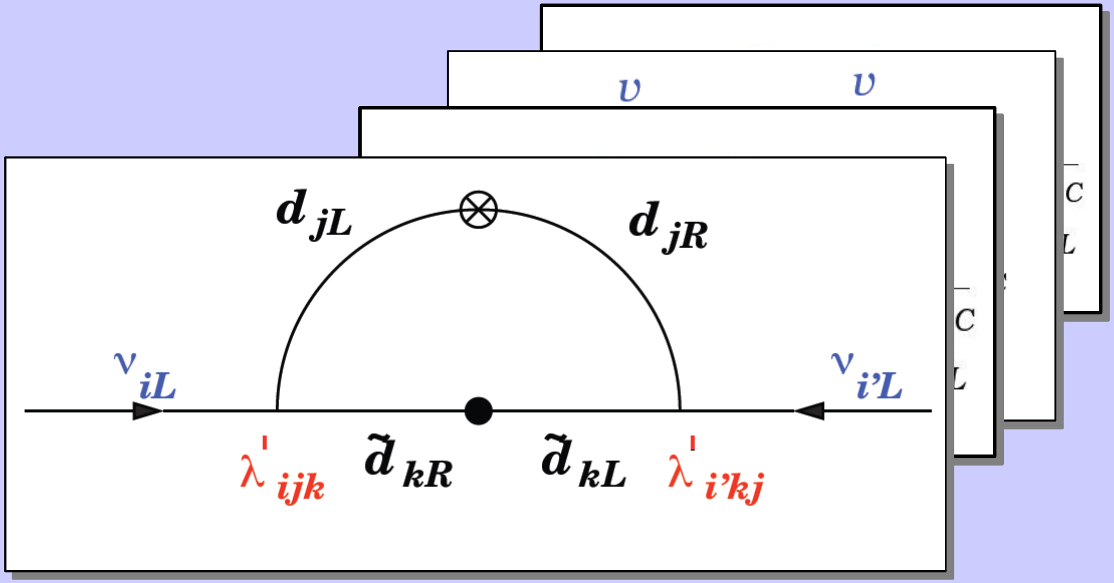
Unique dim-5 Operator

- **Radiative Generation via Loops**
  Alternative to Seesaw Mechanism



R-Parity Violating SUSY

Problems of Seesaw Mechanism

- **Introduces high energy scale**
- **Right-handed neutrinos are singlets**
  Couple only via small mixture with active neutrinos
- **Mechanism not testable with low energy observables**

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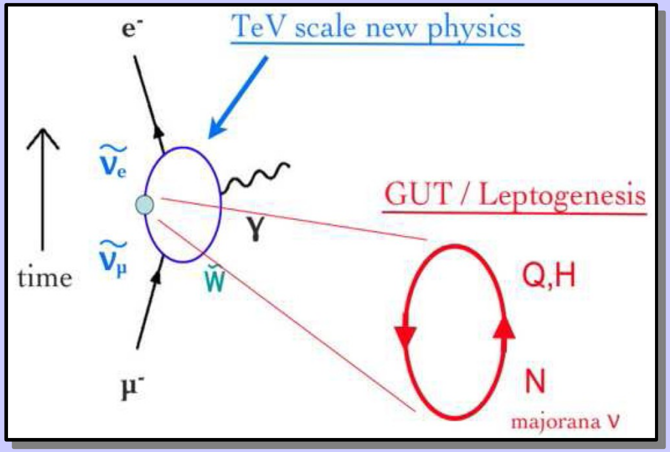
- **Possible Solutions**
  - **SUSY Seesaw**
    Testable LFV effects from sleptons



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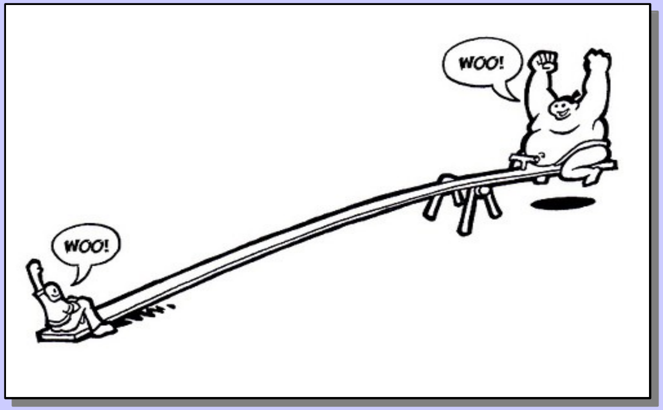
  - **“Bent” Seesaw mechanisms**
    LNV at low scale allows low mass of right-handed neutrinos



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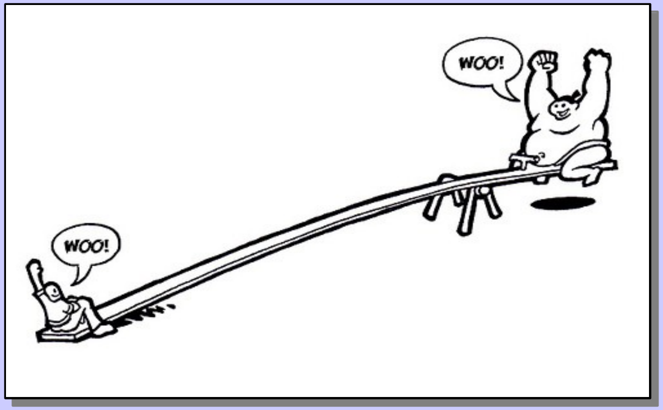
  - **Left-Right symmetric models**
    Right-handed neutrinos couple with gauge strength to charged leptons



Minimal Left-Right Symmetrical Model

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

  Pati & Salam '74
  Mohapatra & Senjanovic '75

- **Higgs Sector:**
  Bidoublet (EW Breaking) + Left-handed Triplet + Right-handed Triplet (Breaking Lepton Number + Parity + $\mathrm{SU}(2)_R$)

- **Generate N_i + W_R + Z_R masses** $M_{N_i}\approx M_{W_R}\approx M_{Z_R}\approx <\Delta_R>\approx 0.5-5\ \mathrm{TeV}$

- **General Seesaw II Mechanism** $M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix},$

- **Charged current weak interactions**

$$J^{\mu-}_{W_1} = \frac{g_L}{\sqrt{2}}\left(\bar\nu_i U^{LL}_{\ell i} + \bar N^c_i U^{LR}_{\ell i}\right)\gamma^\mu \ell_L + \frac{g_R}{\sqrt{2}}\sin\zeta_W\left(\bar\nu_i U^{RL}_{\ell i} + \bar N_i U^{RR}_{\ell i}\right)\gamma^\mu \ell_R,$$
$$J^{\mu-}_{W_2} = -\frac{g_L}{\sqrt{2}}\sin\zeta_W\left(\bar\nu_i U^{LL}_{\ell i} + \bar N_i U^{LR}_{\ell i}\right)\gamma^\mu \ell_L + \frac{g_R}{\sqrt{2}}\left(\bar N_i U^{RR}_{\ell i} + \bar\nu^c_i U^{RL}_{\ell i}\right)\gamma^\mu \ell_R,$$

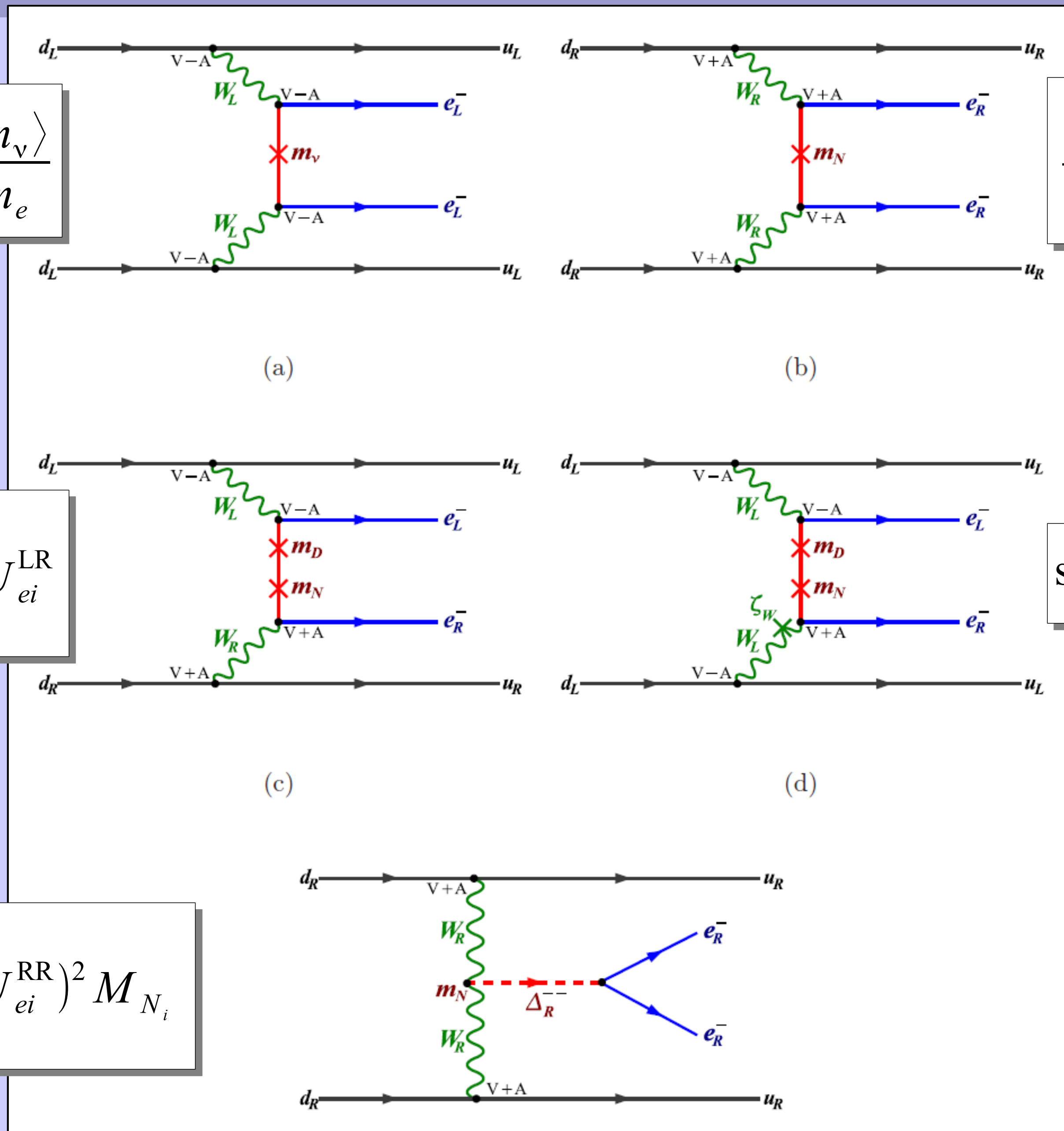
Neglect any Left-Right mixing

$$J^{\mu-}_{W_L} \approx \frac{g_L}{\sqrt{2}} U_{\ell i}\bar\nu_i\gamma^\mu\ell_L,$$
$$J^{\mu-}_{W_R} \approx \frac{g_R}{\sqrt{2}} V_{\ell i}\bar N_i\gamma^\mu\ell_R,$$

Neutrinoless Double Beta Decay in the LRSM

$$\sum_i \left(U_{ei}^{\mathrm{LL}}\right)^2 \frac{m_{\nu_i}}{m_e} = \frac{\langle m_\nu \rangle}{m_e}$$

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

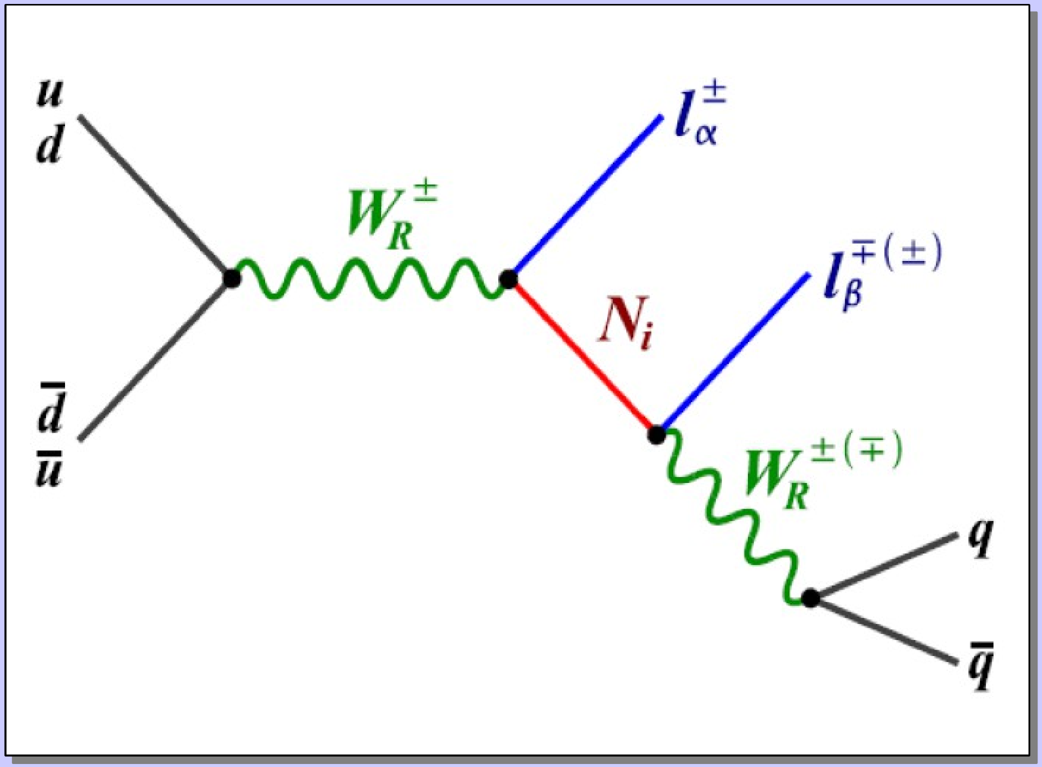


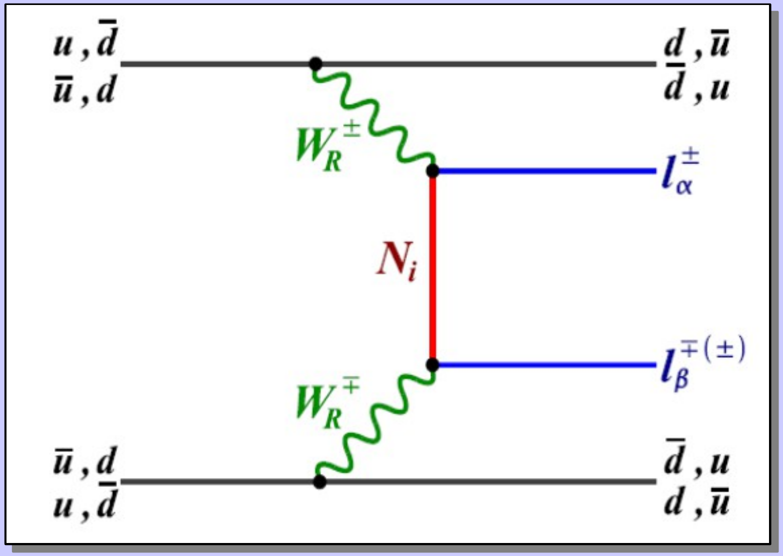
$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sum_i U_{ei}^{\mathrm{LL}} U_{ei}^{\mathrm{LR}}$$

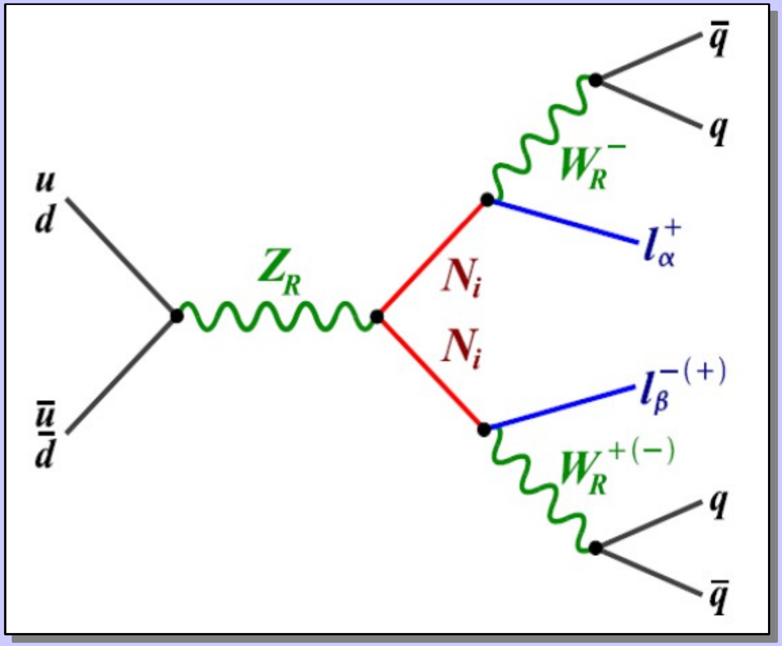
$$\sin^2\zeta \sum_i U_{ei}^{\mathrm{LL}} U_{ei}^{\mathrm{LR}}$$

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

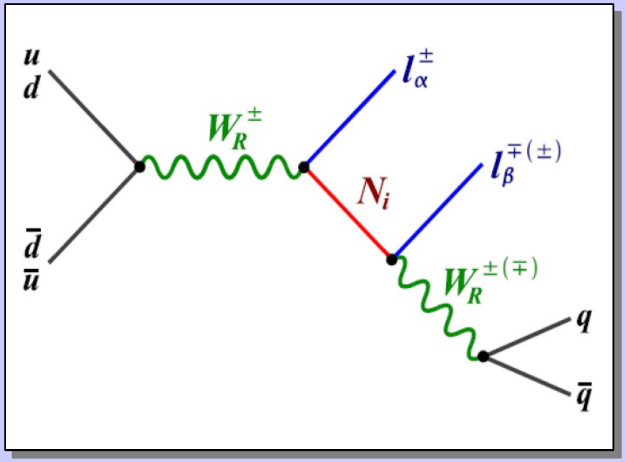
Right-handed Neutrino Production at the LHC







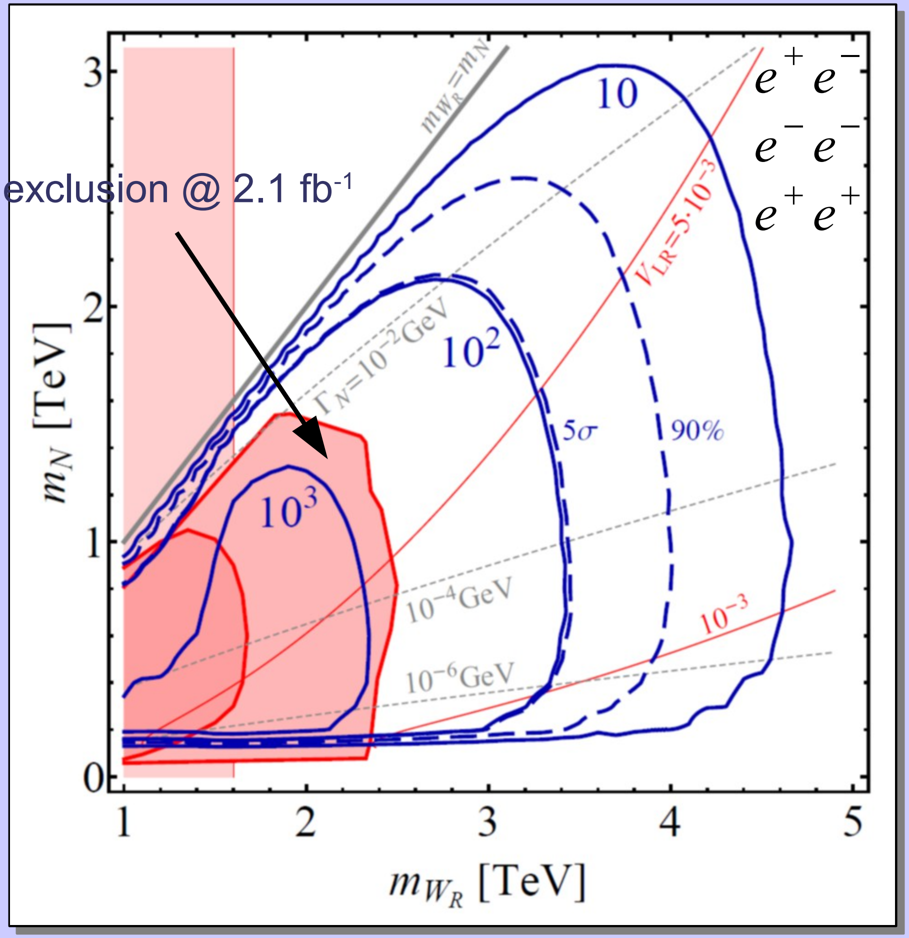
Single Neutrino Production



- **Monte Carlo Simulation (PROTOS)**
- **Background ttbar, Z + jets**
  (Pythia, Alpgen)
- **Fast Detector Simulation**
  (AcerDET)
- **Selection Criteria**

number of jets	$N_j \geq 2$
number of isolated leptons	$N_\ell = 2$
invariant dilepton mass	$m_{\ell\ell} > 300$ GeV
total invariant mass	$m_{\ell\ell jj} > 1.5$ TeV

ATLAS exclusion @ 2.1 fb^{-1}



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

Comparison to 0νββ

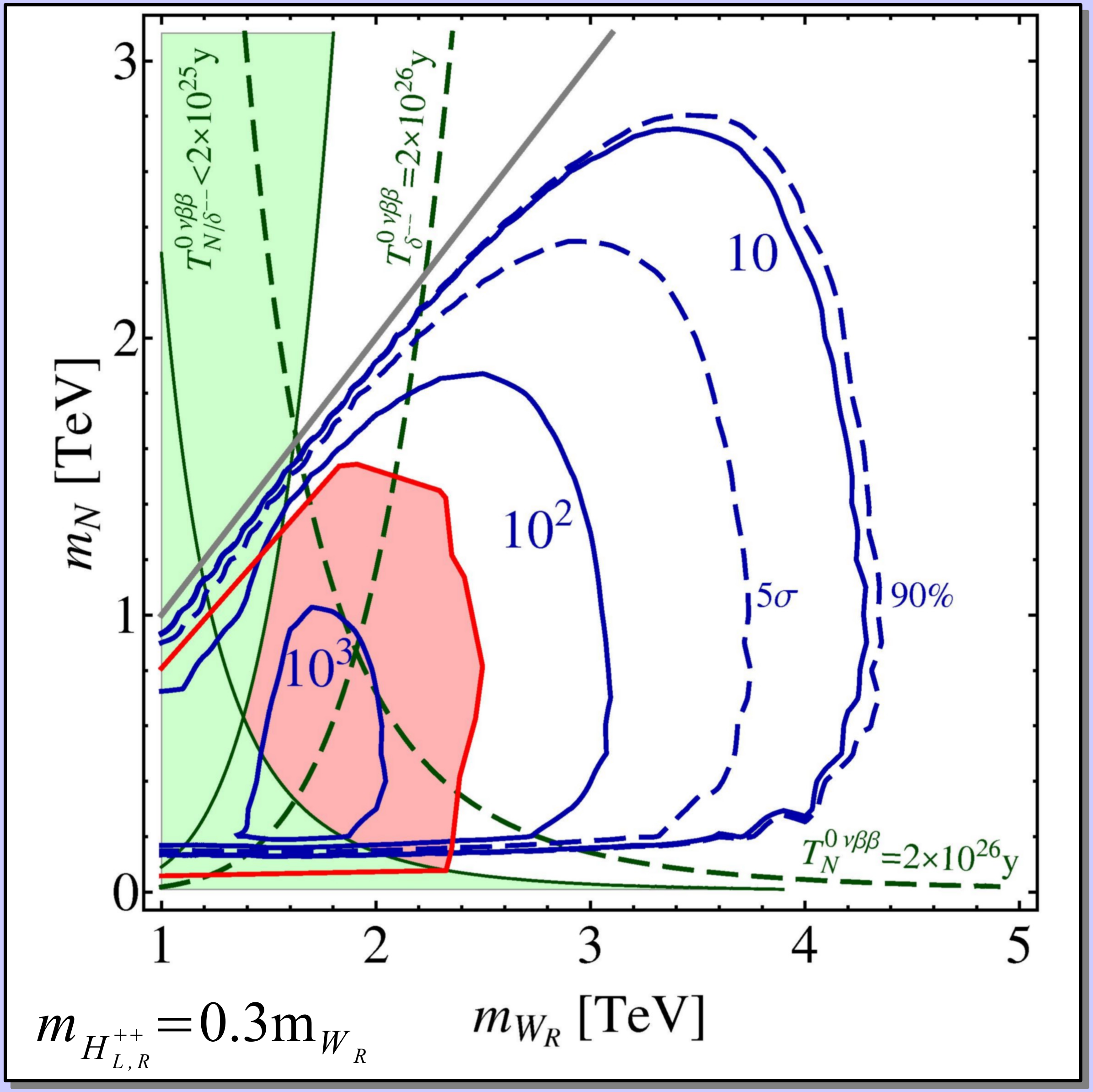
- **Consider contributions to 0νββ from triplet Higgs**

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

- **and heavy neutrinos**

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

LHC reach @ 14 TeV, 30 fb^{-1}



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    Only 5-dim operator from LNV
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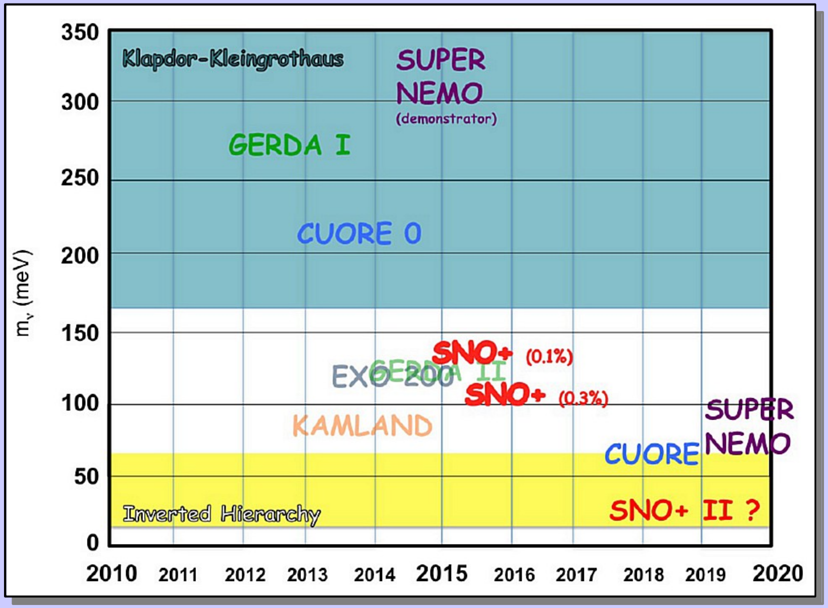
Lefeuvre (2011)



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- **Rich phenomenology in models of neutrino mass generation**
  - Cosmological Observations
  - Charged lepton flavour violation
  - LFV and LNV processes at the LHC
  - Connection to Leptogenesis?

Lefeuvre (2011)