Probing Lepton Number Violation in Double Beta Decay and at the LHC

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in collaboration with
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MPIK Theorie Seminar
MPIK Heidelberg, 21 January 2013

Overview

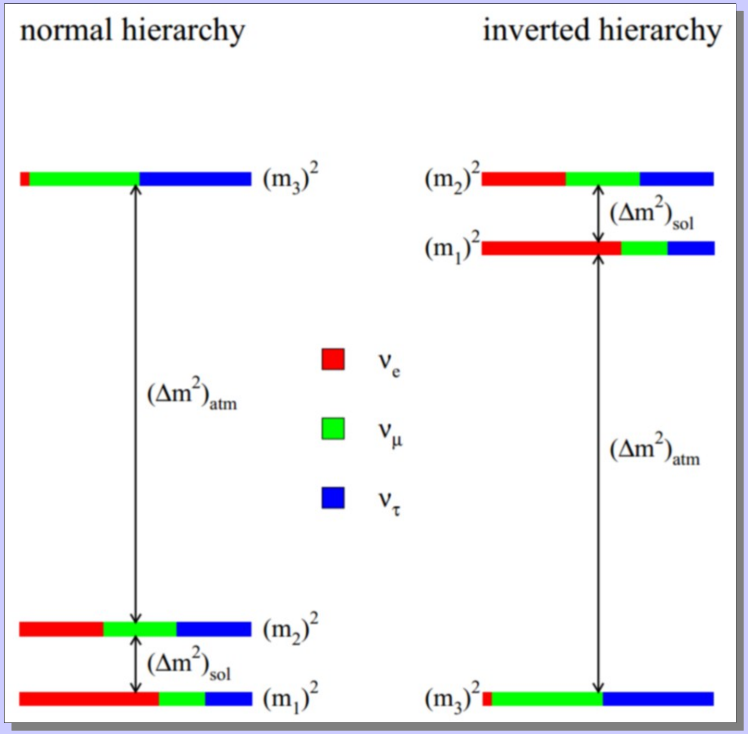
- Neutrinos
  - Oscillations
  - Absolute Mass
- Neutrinoless Double Beta Decay
  - Light Neutrino Exchange
  - New Physics Mechanisms
- Neutrino Mass Models
  - Effective Mass and Seesaw
  - Minimal Left-Right Symmetry
- LFV and LNV at the LHC
- Conclusion

Neutrino Oscillations

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

$$\nu_i = \sum_\alpha U_{i\alpha} \nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)} \nu_i$$

$$\Rightarrow P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(1.27 \frac{\Delta m^2}{\text{eV}^2} \frac{L/\text{km}}{E/\text{GeV}}\right)$$



- **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: $m_\beta \; {}^{5}_{8} \; 0.2$ eV

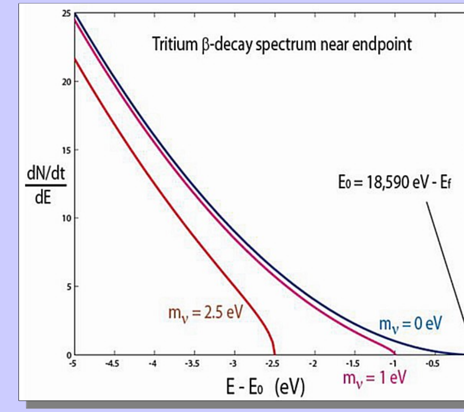
- **Impact on Large Scale Structure**

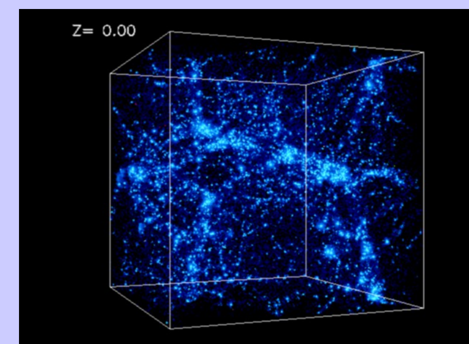
$$\Sigma = \sum_i m_i < 0.4 - 1\,\mathrm{eV}$$

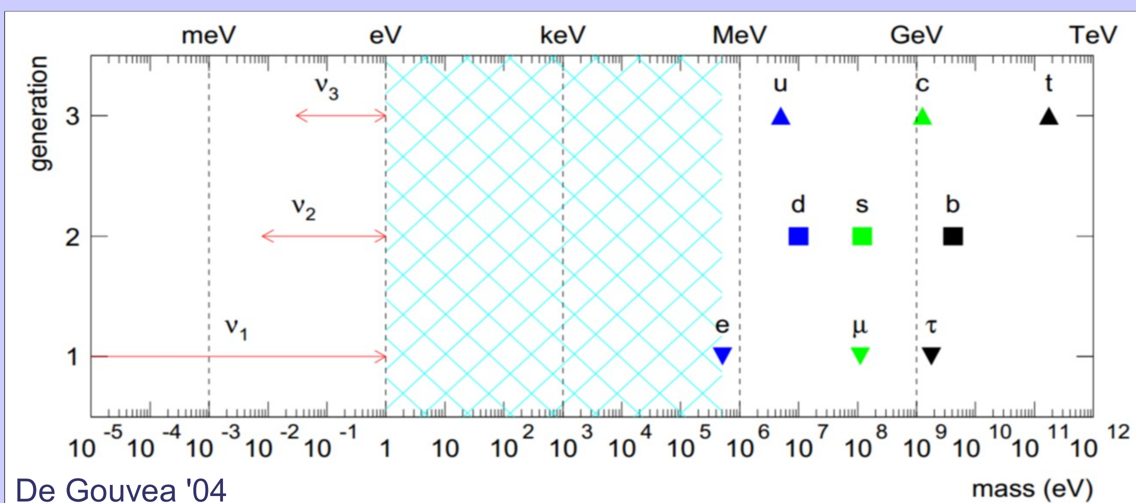
- **Neutrinoless Double Beta Decay**

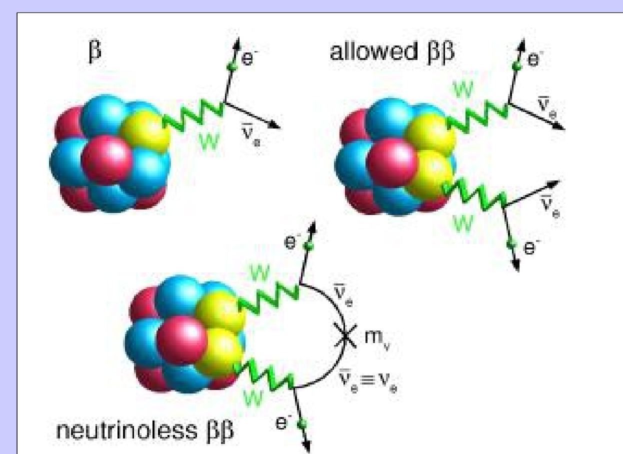
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_{\nu_i}\right| < 0.2 - 2.0\,\mathrm{eV}$$

Future Experiments:
$m_{\beta\beta} \; {}^{5}_{8} \; 0.01$ eV



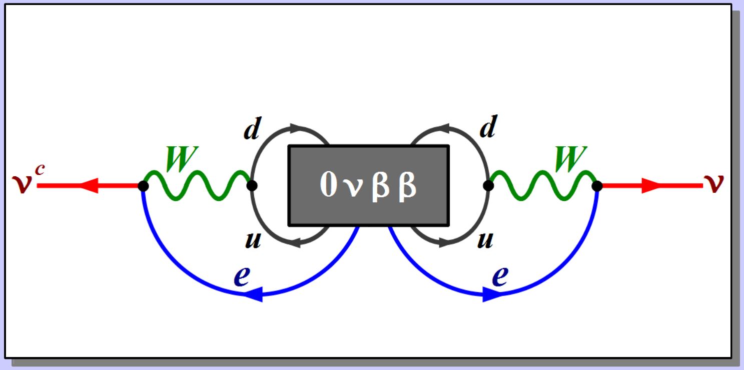






Neutrinoless Double Beta Decay

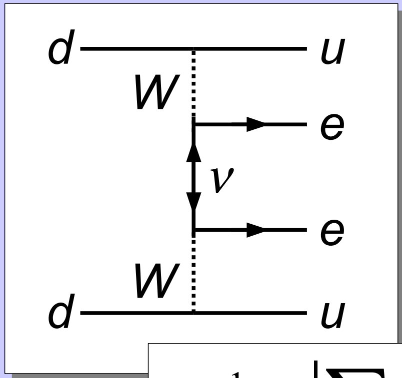
- **Process: $(A, Z) \to (A, Z+2) + 2e^-$**
- **Uncontroversial detection of 0νββ of utmost importance**
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles (Schechter, Valle '82)



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

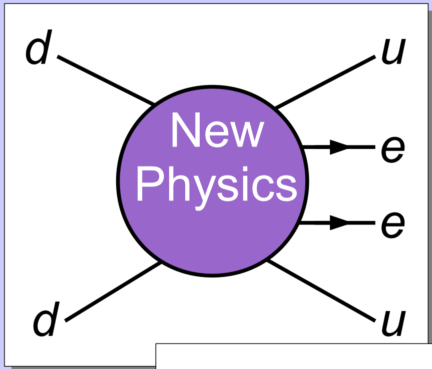
- **Which mechanism triggers the decay?**

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

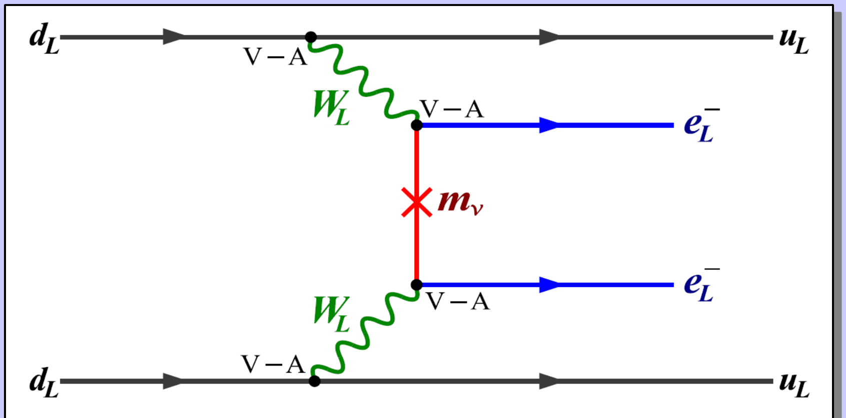


$$\bar{u}\,\bar{u}\,\bar{e}\,\bar{e}\,d\,d\,/\,M^5$$

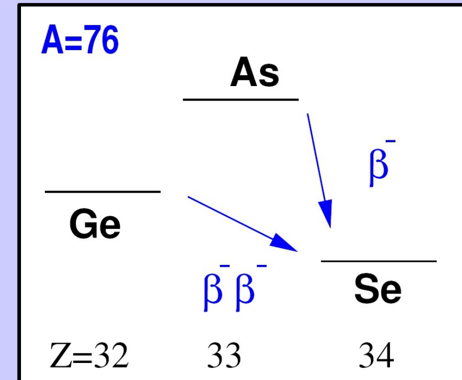
$$T_{1/2}^{-1} \approx 10^{25}\ \mathrm{y} \to M \approx 1\ \mathrm{TeV}$$

Light Neutrino Exchange

- **Standard Mass Mechanism**



Heidelberg-Moscow
$T_{1/2}(^{76}Ge) \geq 1.9 \times 10^{25}$ y
$m_\nu \lesssim (0.3 - 0.6)$ eV



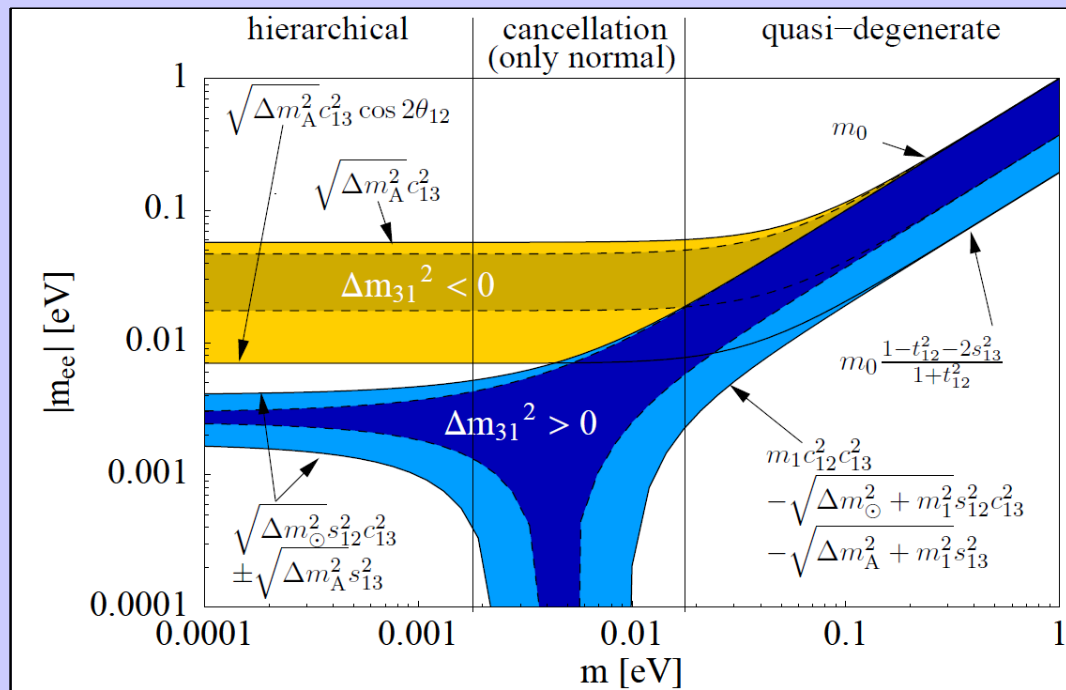
- **Decay Rate**

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

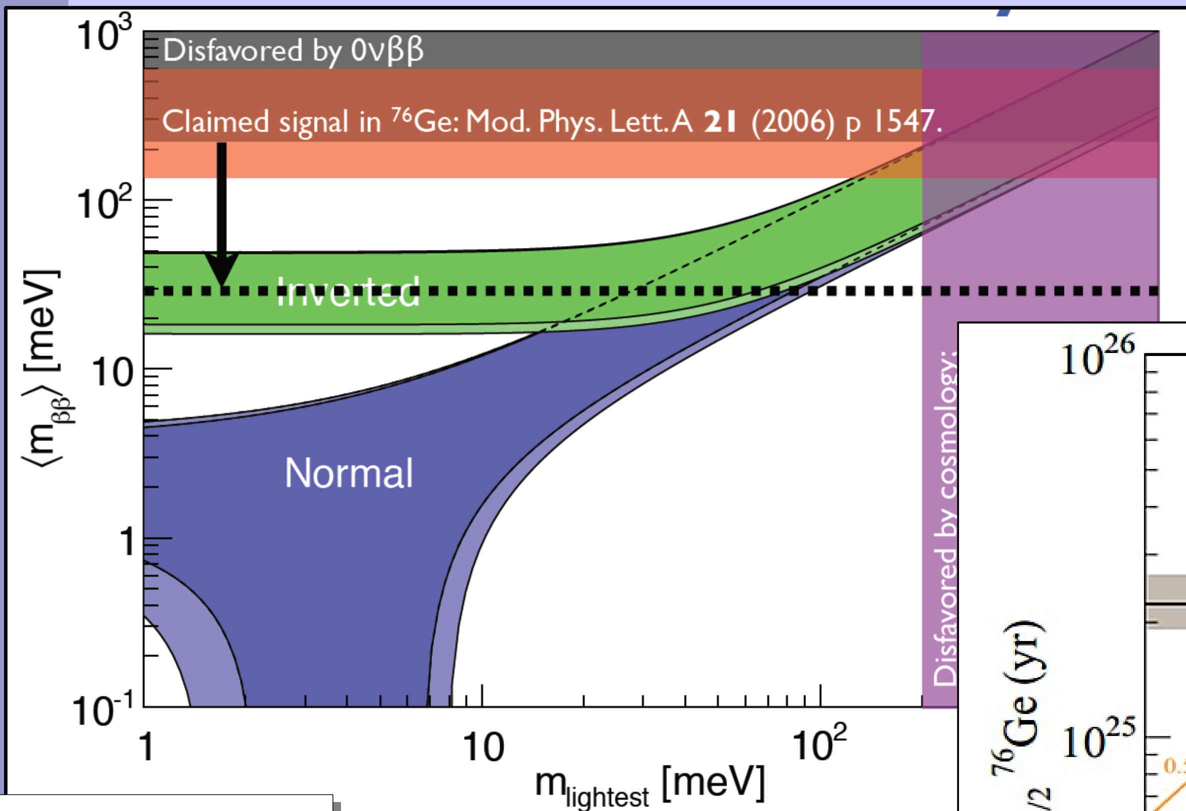
- **Effective Mass**

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

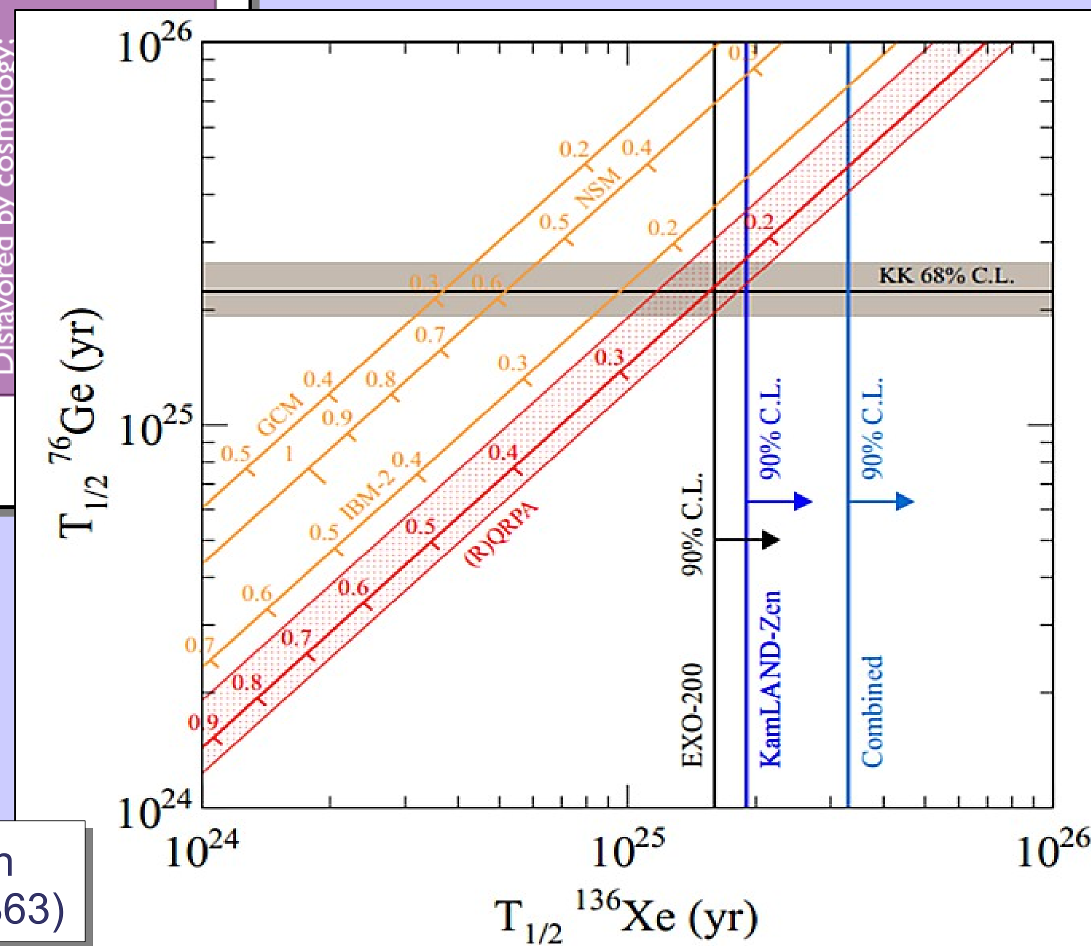
Lindner, Merle, Rodejohann (2005)



Experimental Situation



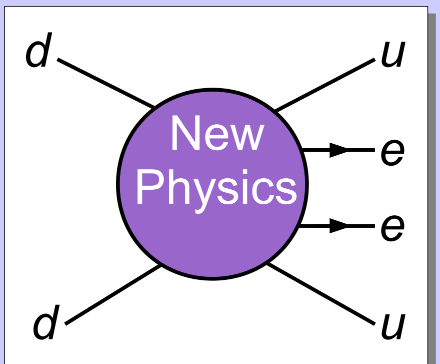
Detwiler (2012)



KamLAND-Zen (arXiv:1211.3863)

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

- **Plethora of New Physics Scenarios**



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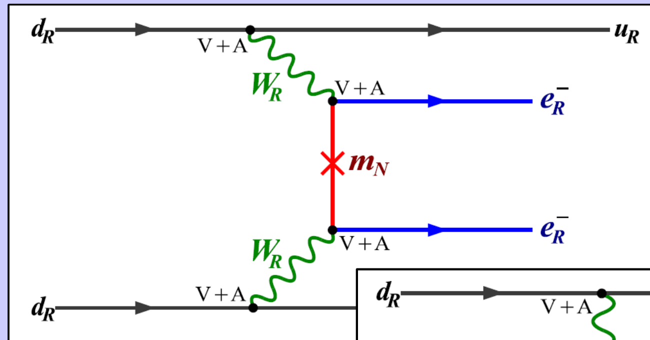
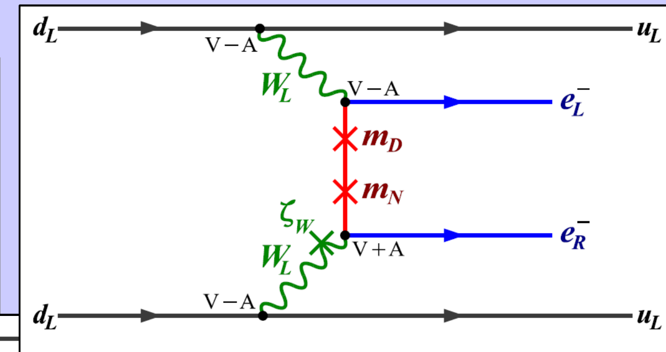
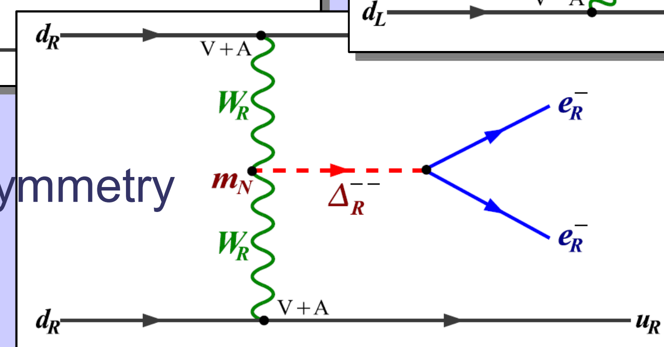






Left-Right Symmetry

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

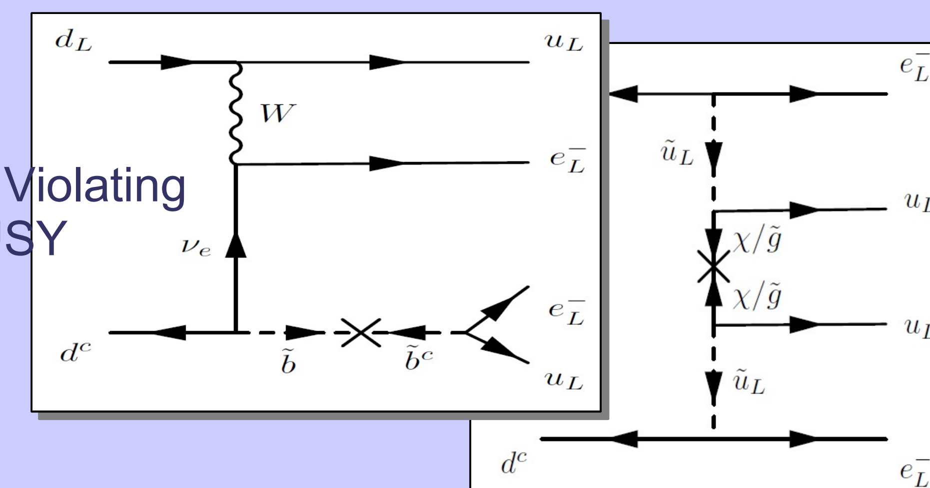
Extra Dimensions

Majorons

Leptoquarks

...

R-Parity Violating SUSY



Effective Mass and Seesaw Mechanism

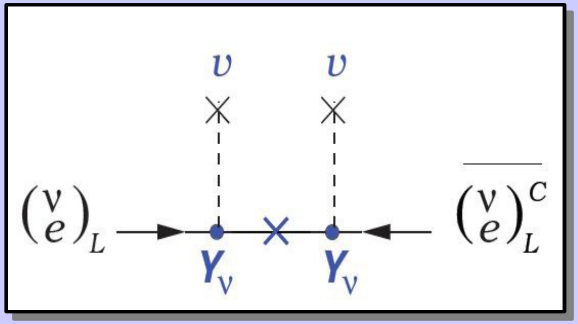
- **Effective operator for Majorana neutrino mass**

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

Unique dim-5 Operator

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

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



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

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

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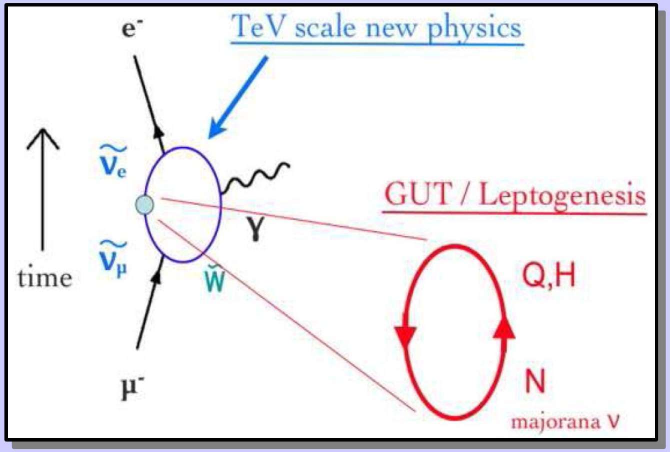
- **Possible Solutions**
  - **SUSY Seesaw**
    Testable LFV effects from sleptons



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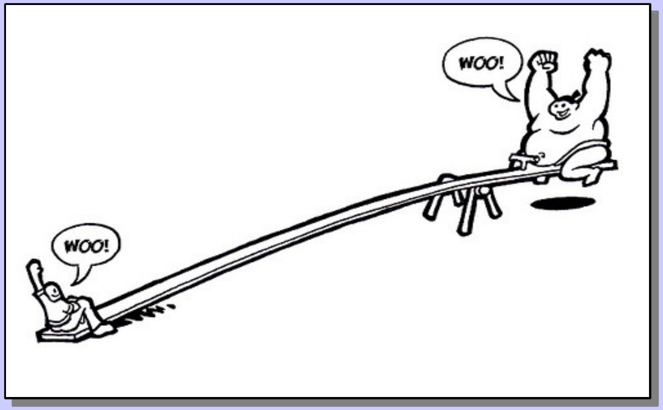
  - **“Bent” Seesaw mechanisms**
    LNV at low scale allows low mass of right-handed neutrinos



Problems of Seesaw Mechanism

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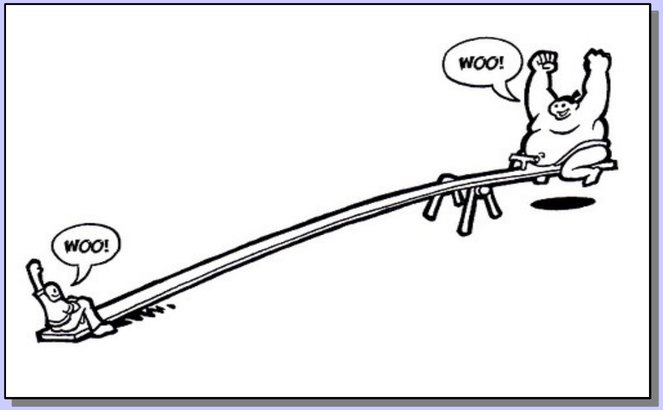
  - **Left-Right symmetric models**
    Right-handed neutrinos couple with gauge strength to charged leptons



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

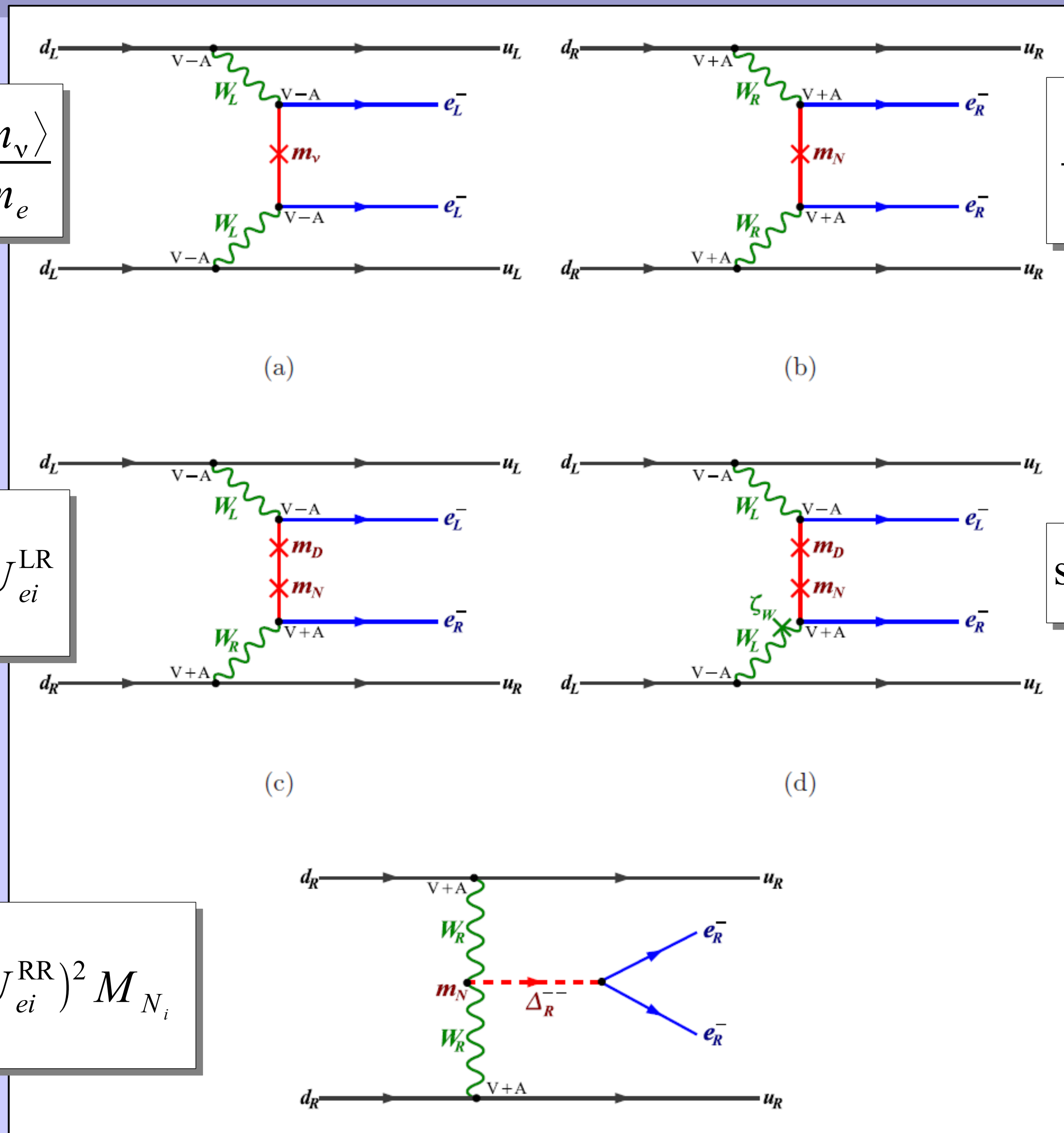
$$J^{\mu-}_{W_L} \approx \frac{g_L}{\sqrt{2}} U_{\ell i}\bar{\nu}_i\gamma^\mu \ell_L,$$

$$J^{\mu-}_{W_R} \approx \frac{g_R}{\sqrt{2}} V_{\ell i}\bar{N}_i\gamma^\mu \ell_R,$$

Neutrinoless Double Beta Decay in the LRSM

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

$$\frac{M^4_{W_L}}{M^4_{W_R}} \sum_i \frac{(U^{\mathrm{RR}}_{ei})^2}{M_{N_i}}$$



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

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

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

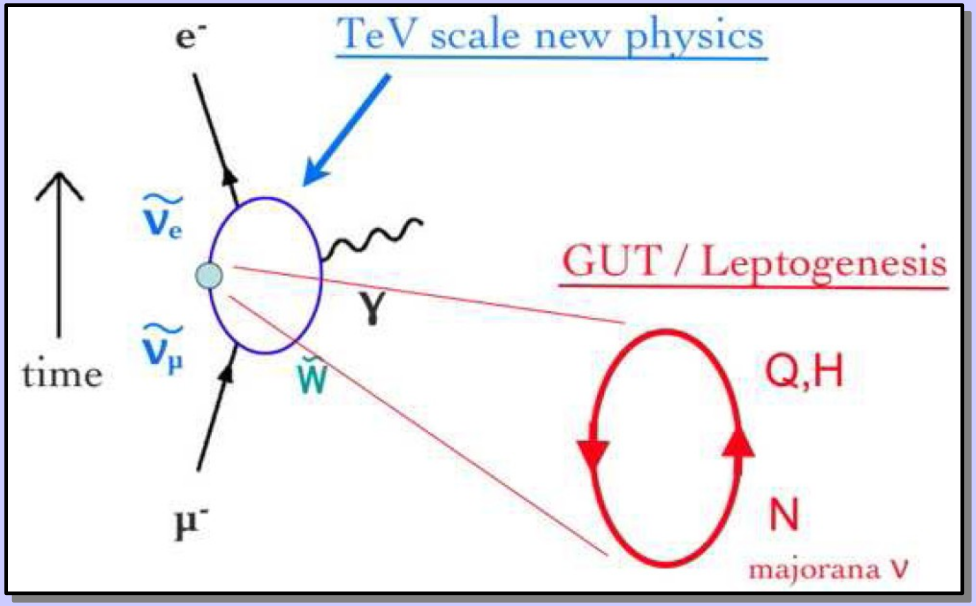
Charged Lepton Flavour Violation

- **Lepton flavour practically conserved in the Standard Model**

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W} \right|^2 \approx 10^{-54}$$

LFV is clear sign for BSM physics

- **Flavour violation in quark and neutrino sector**
  Strong case to look for charged LFV
- **LFV can shed light on**
  - Grand Unification models
  - Flavour symmetries
  - Origin of flavour



Rare LFV Processes

- **Mediated by right-handed neutrinos and doubly charged Higgs bosons**

$$\mathrm{BR}(\mu \to e\gamma) \approx 2 \times 10^{-9} \sin^2(2\phi) \left(\frac{\Delta m_{12}^2}{m_{W_R}^2}\right)^2 \left(\frac{2\ \mathrm{TeV}}{m_{W_R}}\right)^4 ,$$

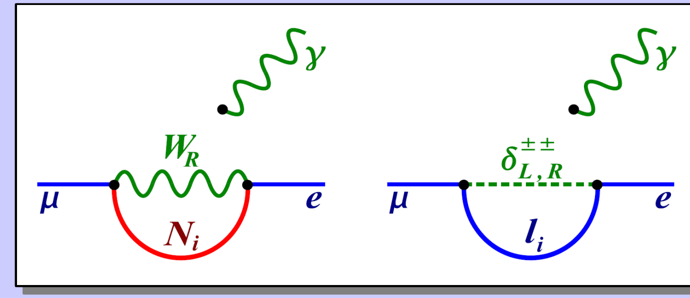
- ***μ*-e conversion in nuclei enhanced via box diagrams**

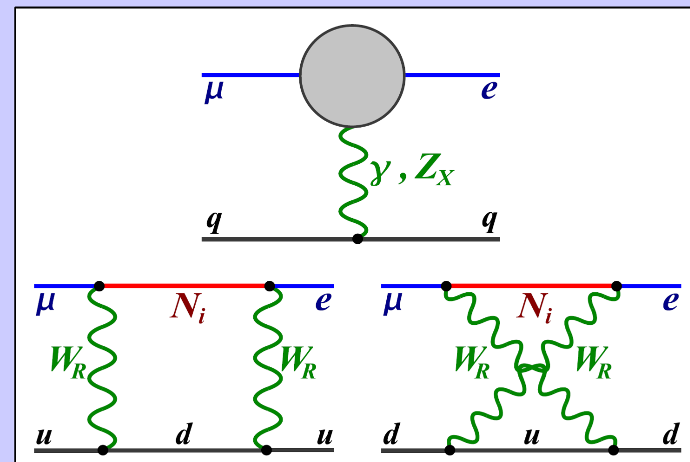
$$R(\mu \to e) \approx Br(\mu \to e\gamma)$$

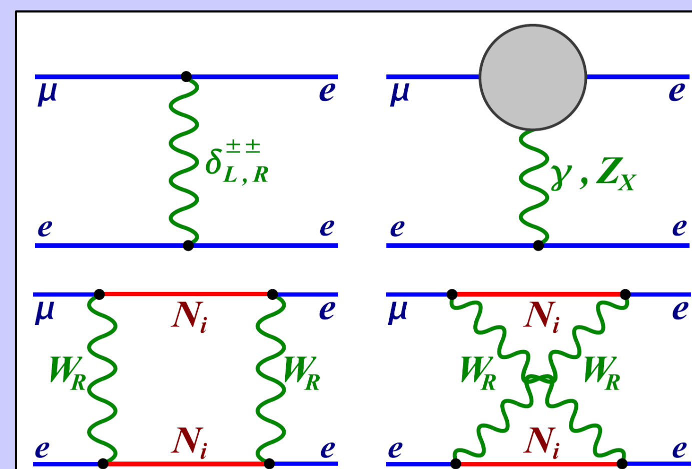
- ***μ* → eee strongly enhanced due to tree level contribution**

$$Br(\mu \to eee) \approx 10^2 \times R(\mu \to e)$$

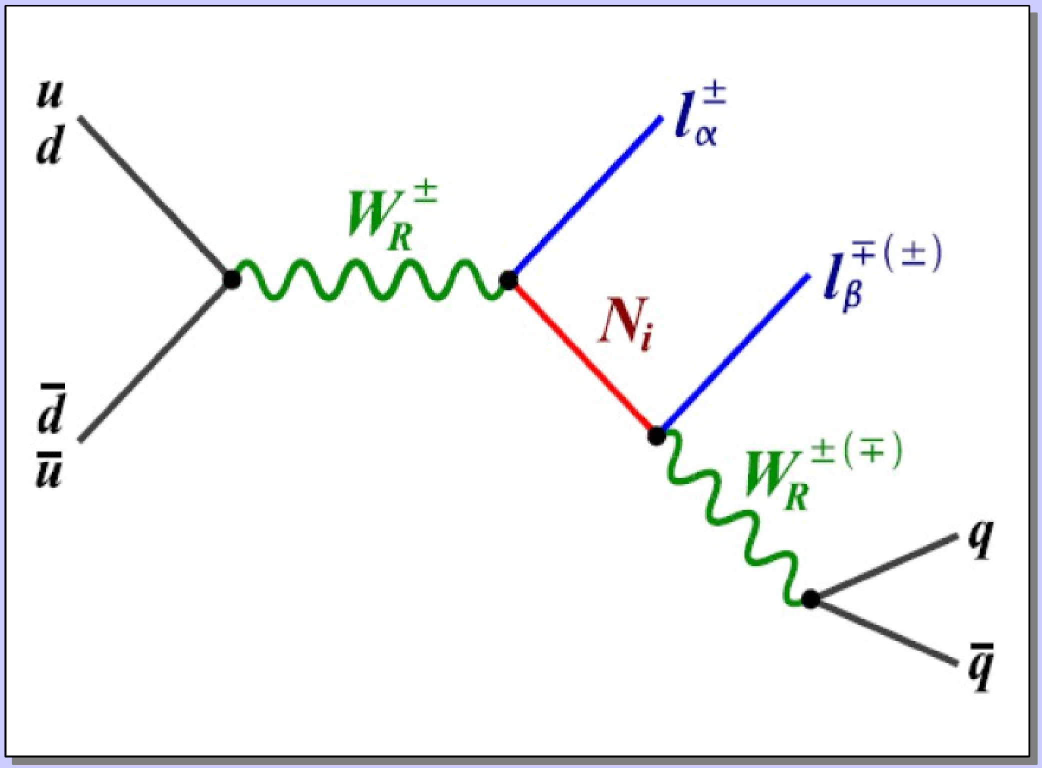
- **BSM Flavour Problem**
  Small mixing and / or mass differences required

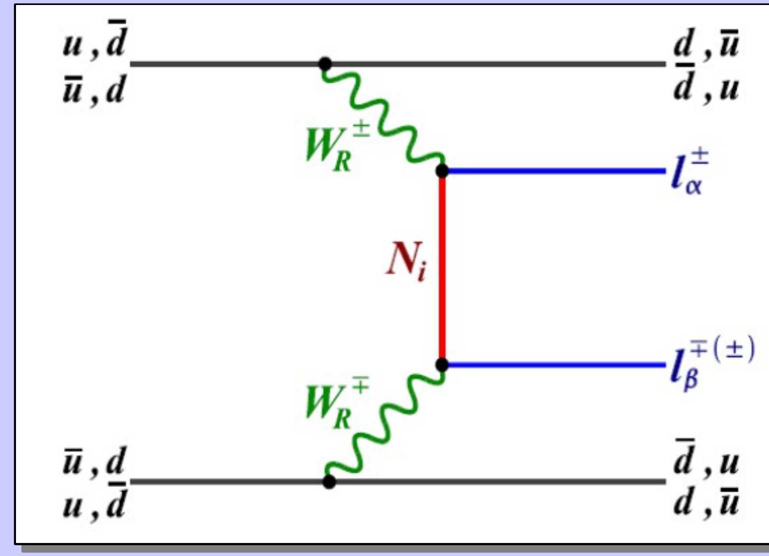


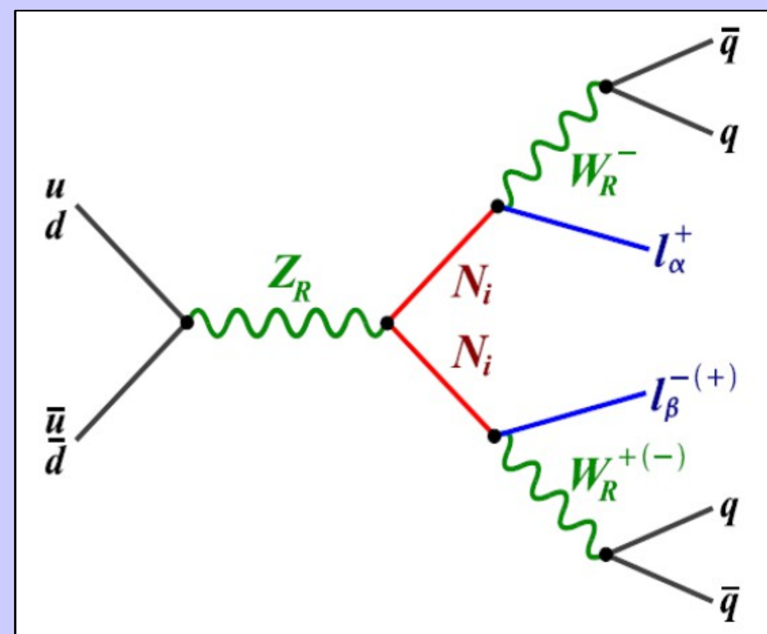




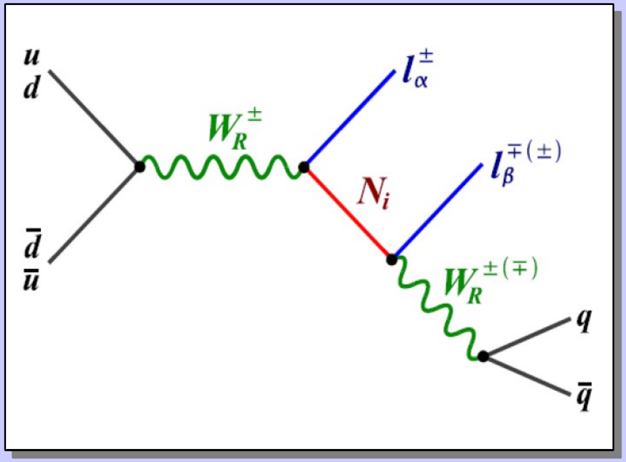
Right-handed Neutrino Production at the LHC







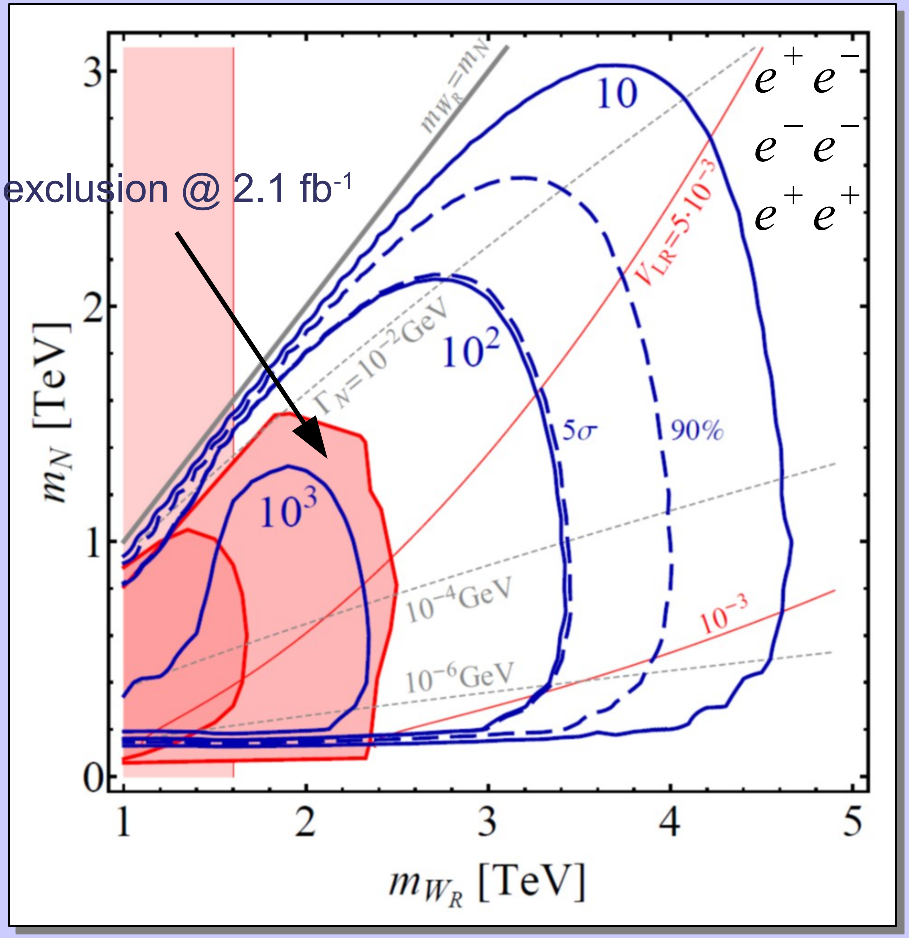
Single Neutrino Production
Sensitivity Reach



- **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

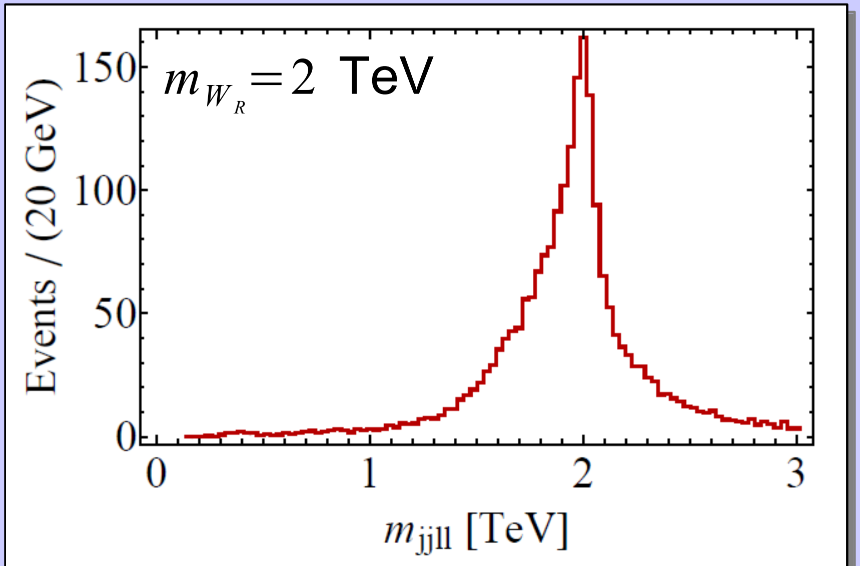
ATLAS exclusion @ 2.1 fb^{-1}

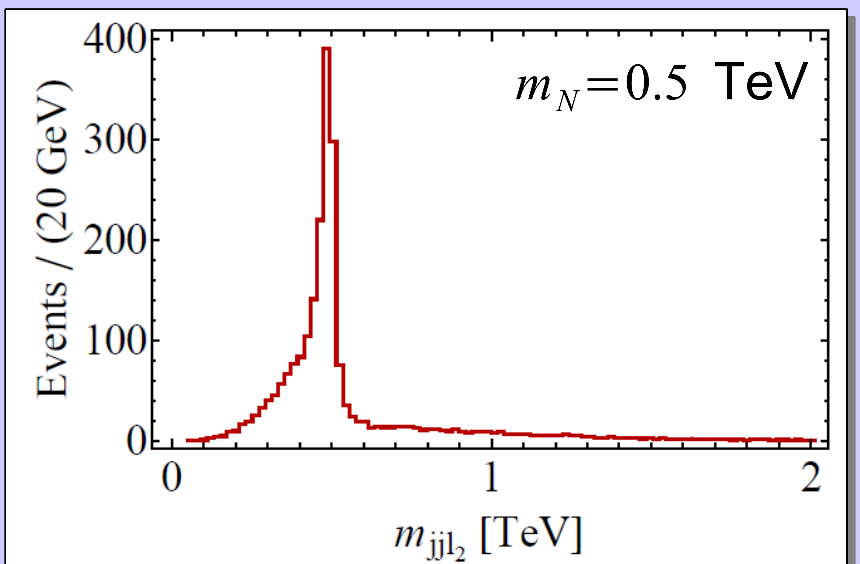


Opposite Sign + Same Sign Leptons
LHC reach @ 14 TeV, 30 fb^{-1}

Single Neutrino Production
Sensitivity Reach

- **Reconstruction of W_R and N**





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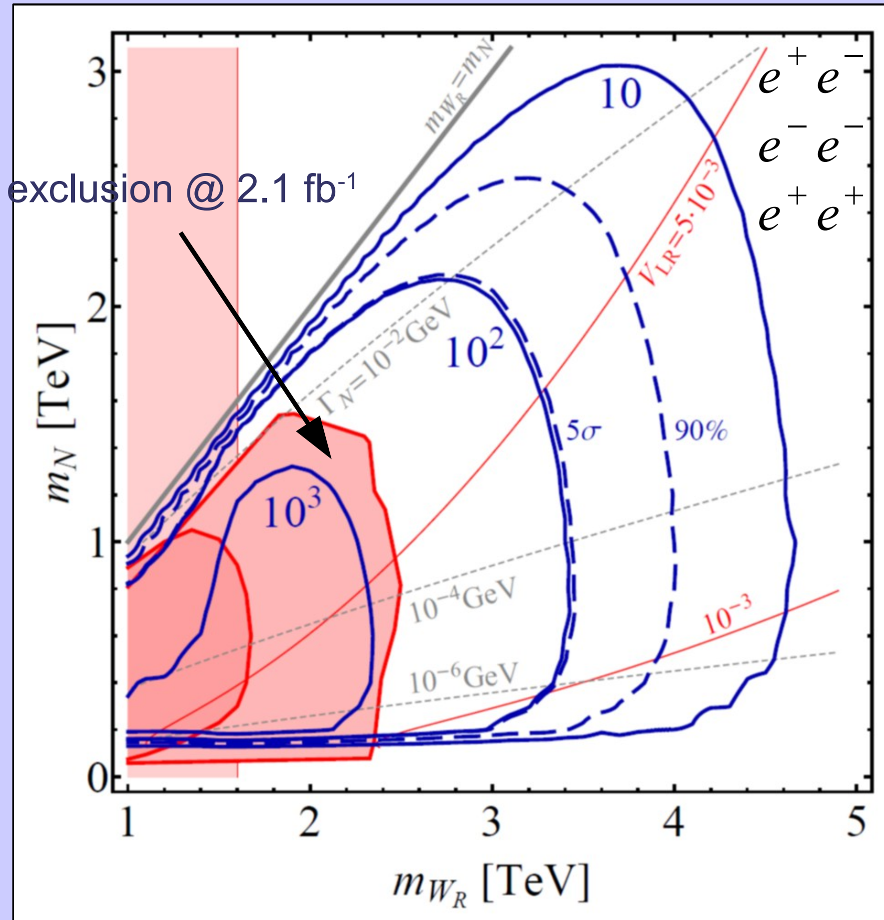

Opposite Sign + Same Sign Leptons
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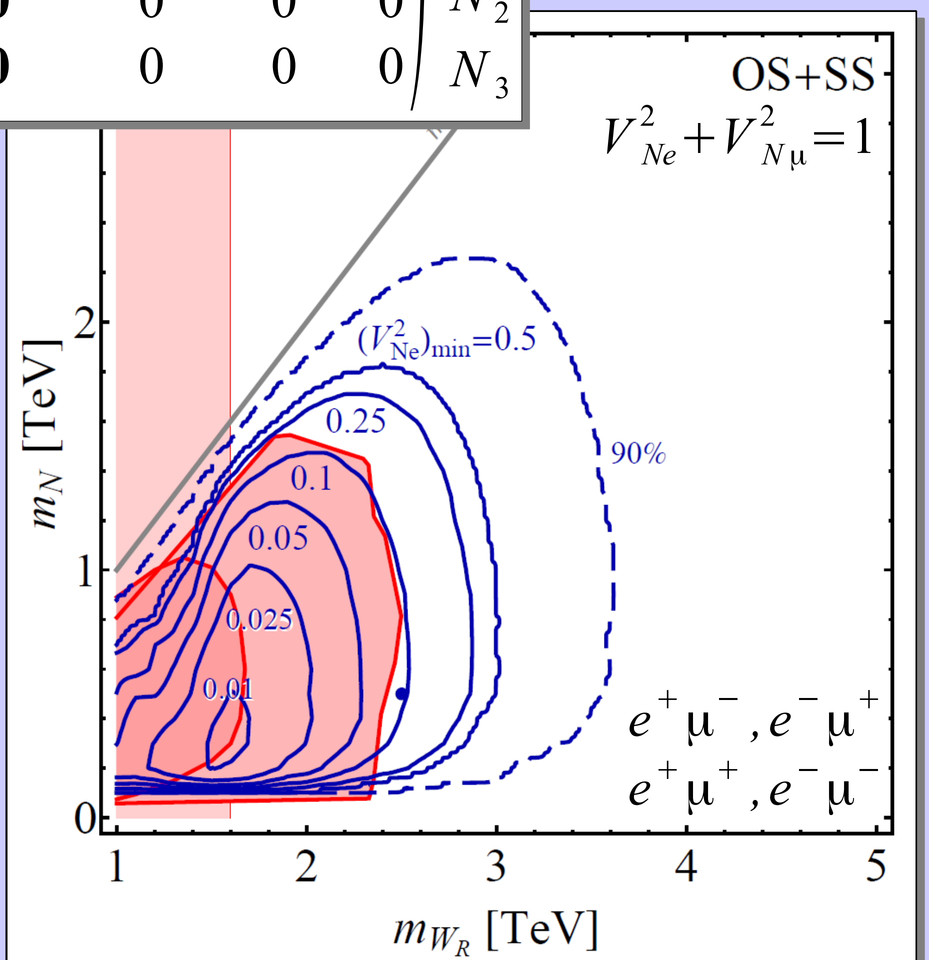
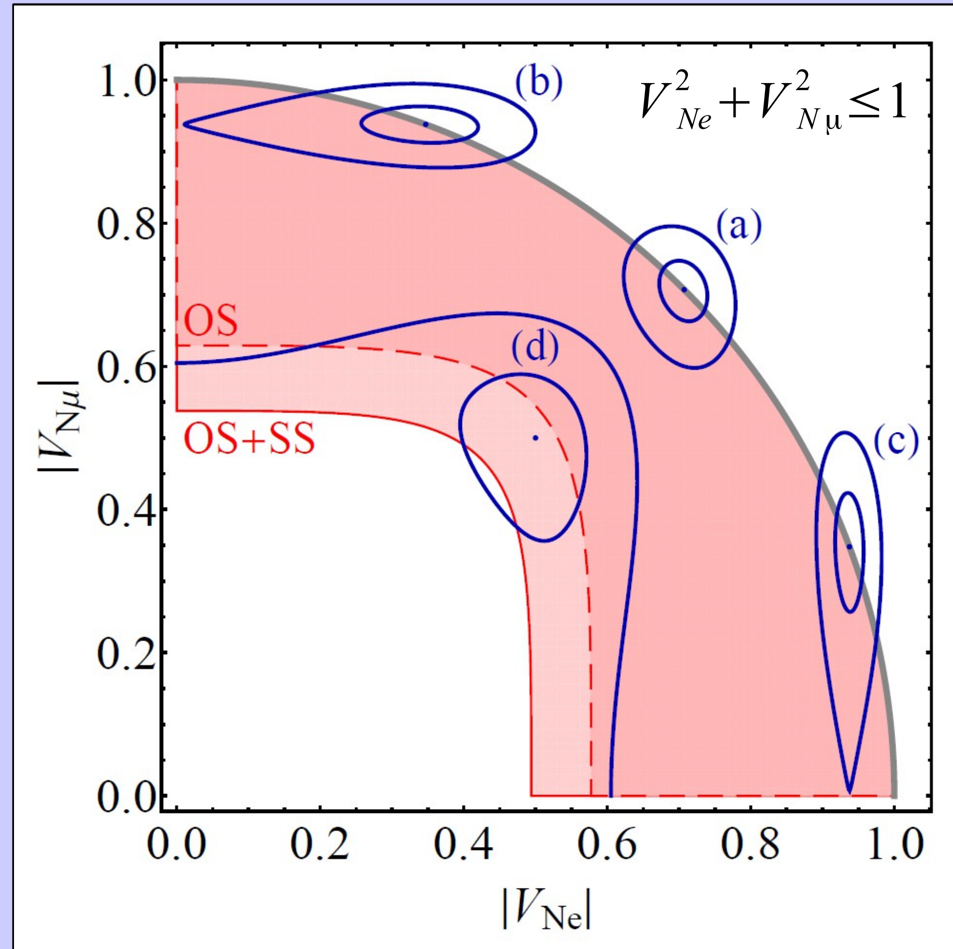
Single Neutrino Production

General e-μ Mixing

$$\begin{array}{c} \\ \\ \\ \\ \\ \end{array}\begin{array}{cccc} l_{jL} & e_R & \mu_R & \tau_R \end{array}$$

$$\begin{pmatrix} \boldsymbol{U}_{\mathbf{PMNS}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & V_{Ne} & V_{N\mu} & 0 \\ \mathbf{0} & 0 & 0 & 0 \\ \mathbf{0} & 0 & 0 & 0 \end{pmatrix} \begin{matrix} \nu_i \\ N_1 \\ N_2 \\ N_3 \end{matrix}$$





$m_{W_R}=2.5$ TeV, $m_N=0.5$ TeV

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

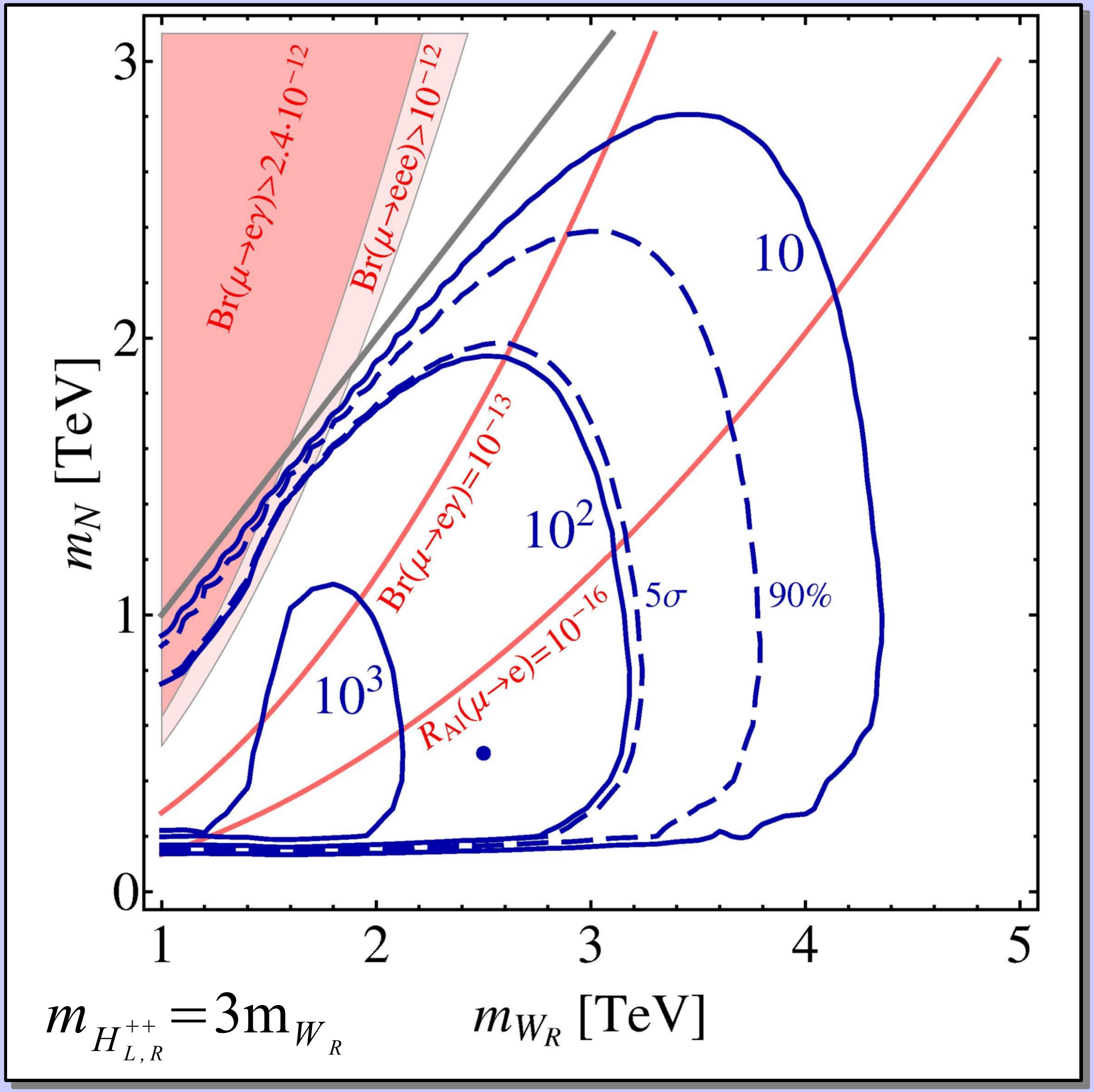
Two Neutrino Oscillations
Maximal Lepton Flavour Violation

- **Two neutrinos exchanged with maximal mixing and 1% mass splitting**

$$\begin{matrix} & l_{jL} & e_R & \mu_R & \tau_R & \\ \end{matrix}$$
$$\begin{pmatrix} \mathbf{U_{PMNS}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \cos\phi & \sin\phi & 0 \\ \mathbf{0} & -\sin\phi & \cos\phi & 0 \\ \mathbf{0} & 0 & 0 & 0 \end{pmatrix} \begin{matrix} \nu_i \\ N_1 \\ N_2 \\ N_3 \end{matrix}$$

$$\phi = \pi/4$$

- **Correlation with low energy LFV processes**



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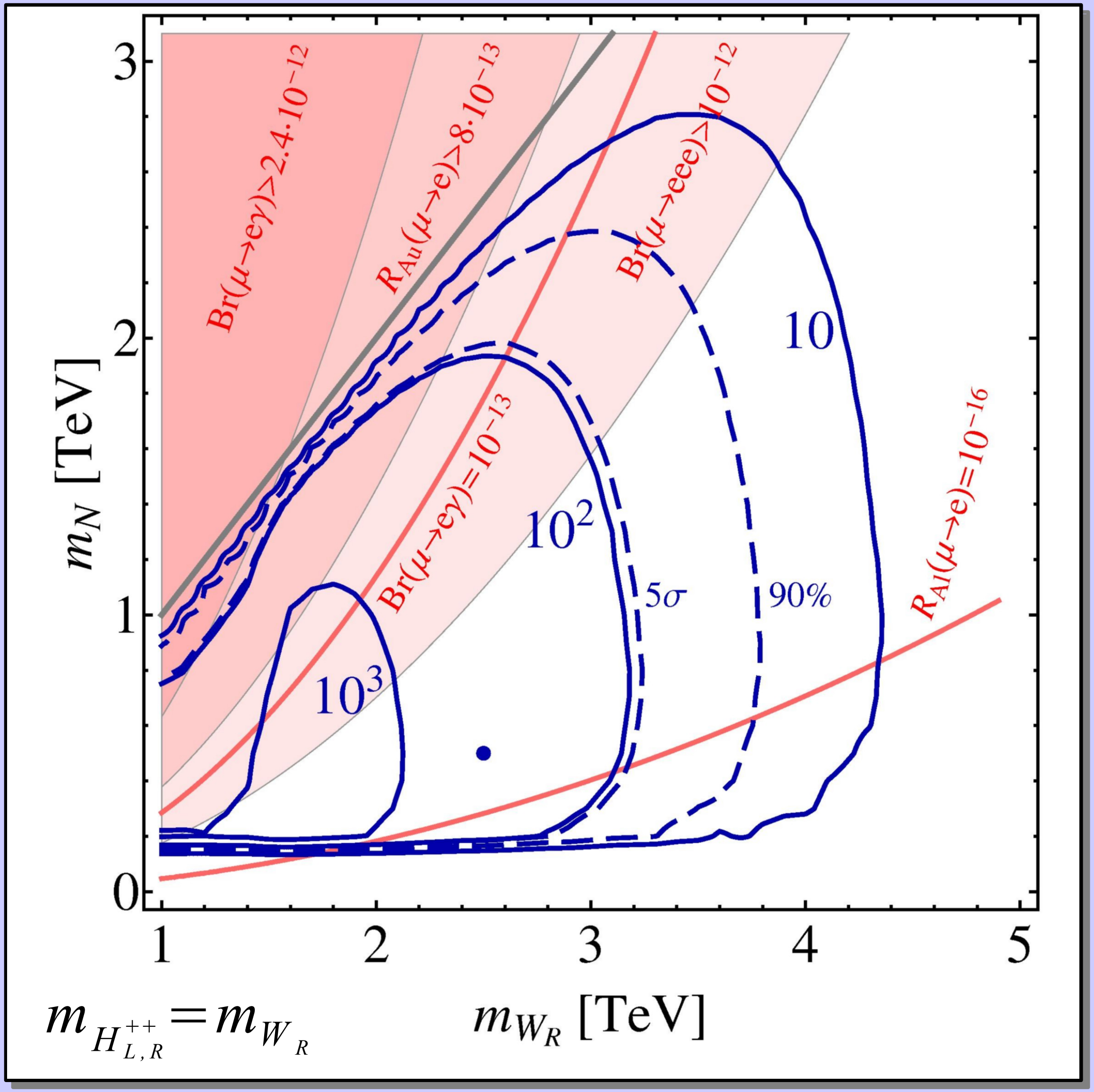
(columns: l_{jL}, e_R, μ_R, τ_R)

$$\phi = \pi/4$$

- **Correlation with low energy LFV processes**



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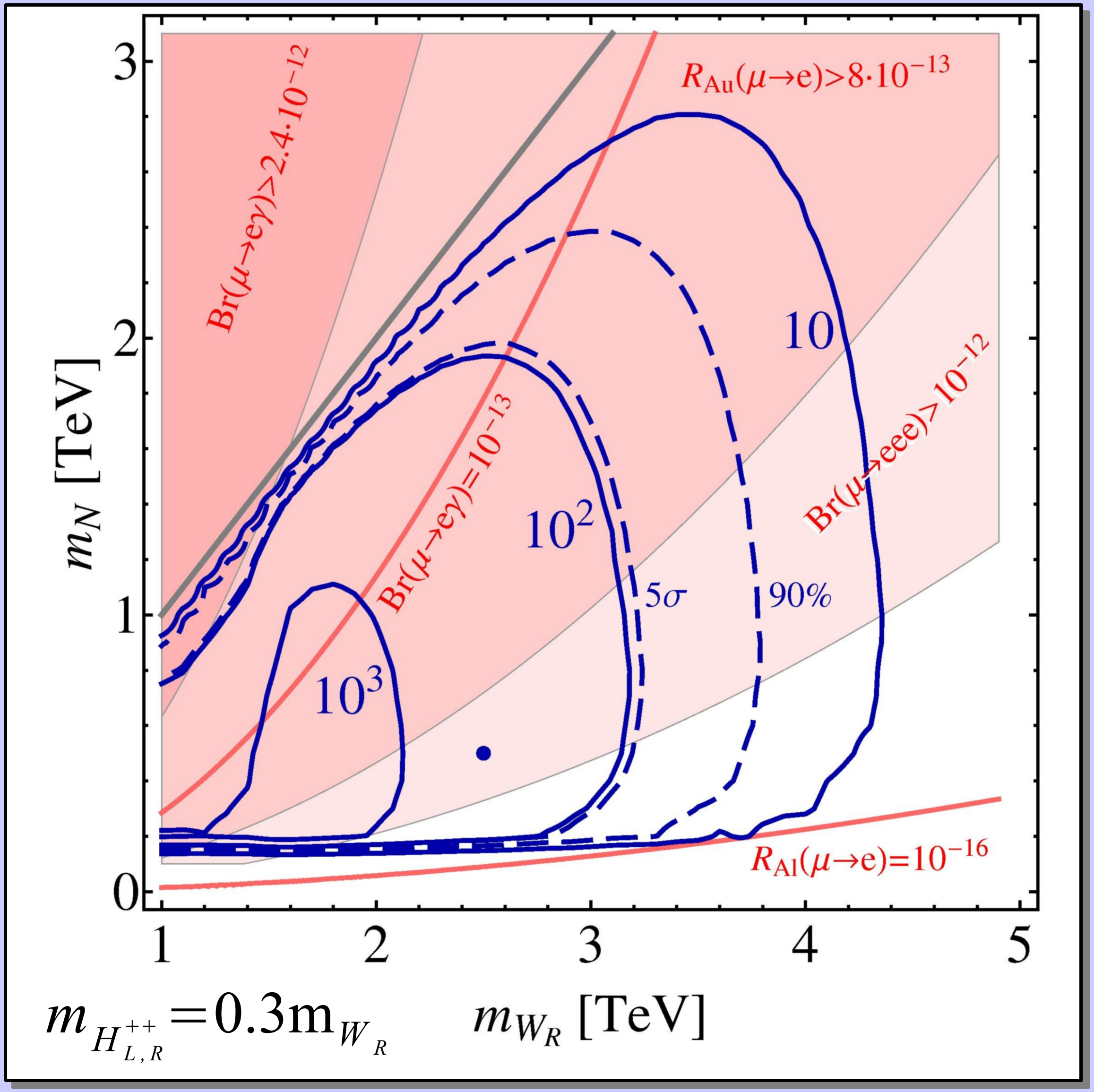
$$
\begin{array}{c}
\begin{array}{cccc} l_{jL} & e_R & \mu_R & \tau_R \end{array} \\
\begin{pmatrix}
\boldsymbol{U}_{\mathbf{PMNS}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\
\mathbf{0} & \cos\phi & \sin\phi & 0 \\
\mathbf{0} & -\sin\phi & \cos\phi & 0 \\
\mathbf{0} & 0 & 0 & 0
\end{pmatrix}
\begin{array}{c} \nu_i \\ N_1 \\ N_2 \\ N_3 \end{array}
\end{array}
$$

$$\phi = \pi/4$$

- **Correlation with low energy LFV processes**



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

Two Neutrino Oscillations
Mixing Angle and Mass Difference

- **Two neutrinos exchanged with mixing angle ϕ and mass diff. Δm_N**

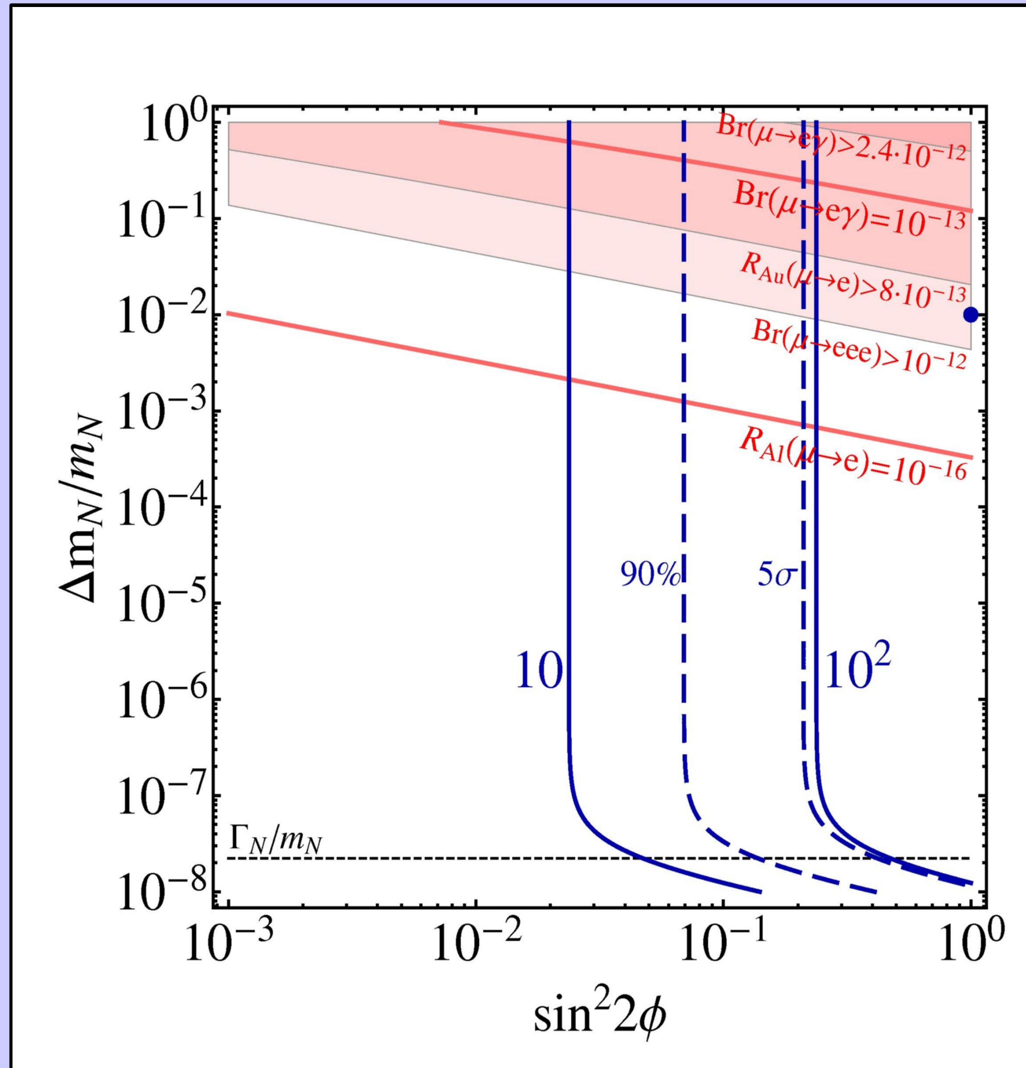
$$\begin{array}{c} \\ \nu_i \\ N_1 \\ N_2 \\ N_3 \end{array}
\begin{array}{cccc} l_{jL} & e_R & \mu_R & \tau_R \\ \end{array}$$

$$\begin{pmatrix} \mathbf{U_{PMNS}} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \cos\phi & \sin\phi & 0 \\ \mathbf{0} & -\sin\phi & \cos\phi & 0 \\ \mathbf{0} & 0 & 0 & 0 \end{pmatrix} \begin{matrix} \nu_i \\ N_1 \\ N_2 \\ N_3 \end{matrix}$$

suppressed as $\Delta m_N^2/(m_N \Gamma_N)$

- **Correlation with low energy LFV processes**

suppressed as $\Delta m_N^2/m_{W_R}^2$



$m_{W_R}=2.5$ TeV , $m_N=0.5$ TeV

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

Single Neutrino Production
Unitary e–μ–τ Mixing

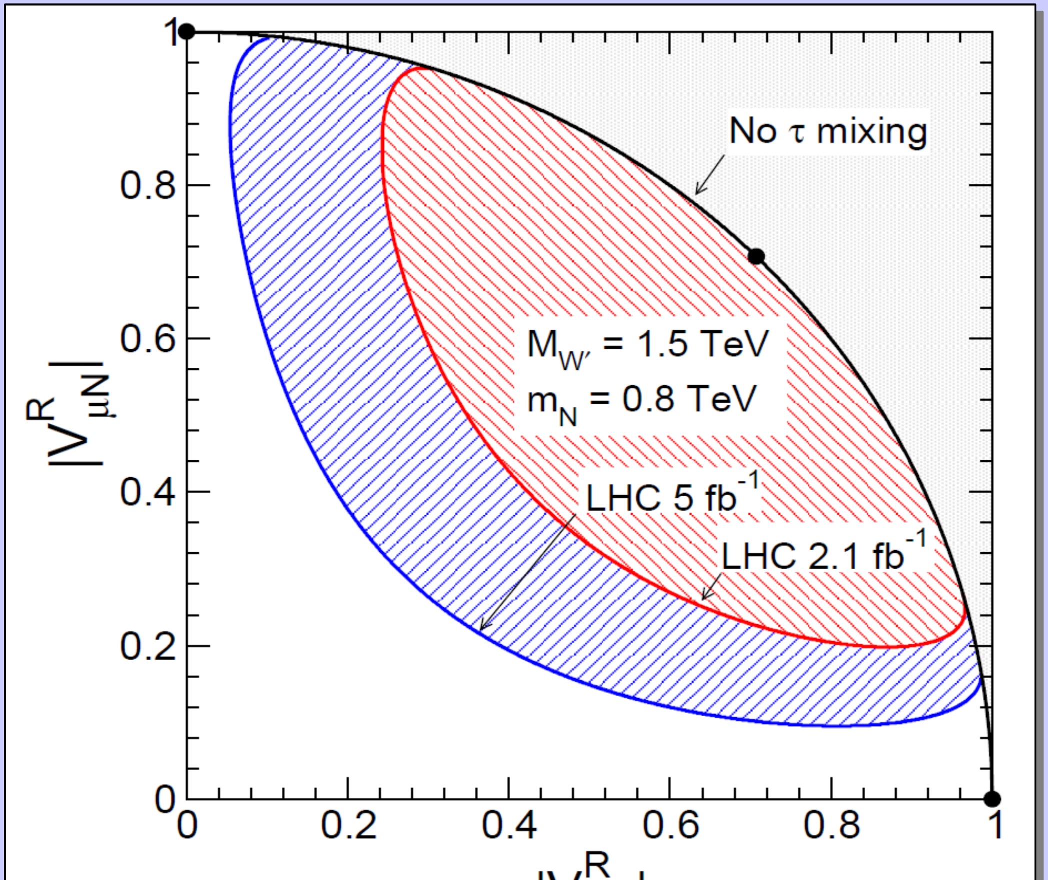
- **Including coupling to taus**

$$\begin{array}{c|cccc|c} & l_{jL} & e_R & \mu_R & \tau_R & \\ & \mathbf{U_{PMNS}} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \nu_i \\ & \mathbf{0} & V_{Ne} & V_{N\mu} & V_{N\tau} & N_1 \\ & \mathbf{0} & 0 & 0 & 0 & N_2 \\ & \mathbf{0} & 0 & 0 & 0 & N_3 \end{array}$$

- **Tau reconstruction efficiency reduced by**

$$Br(\tau \to e(\mu)\nu\bar{\nu}) \approx 1/3$$

  - **Highly boosted secondary leptons**
  - **No cut on missing p_T**



$V^2_{Ne} + V^2_{N\mu} + V^2_{N\tau} = 1$

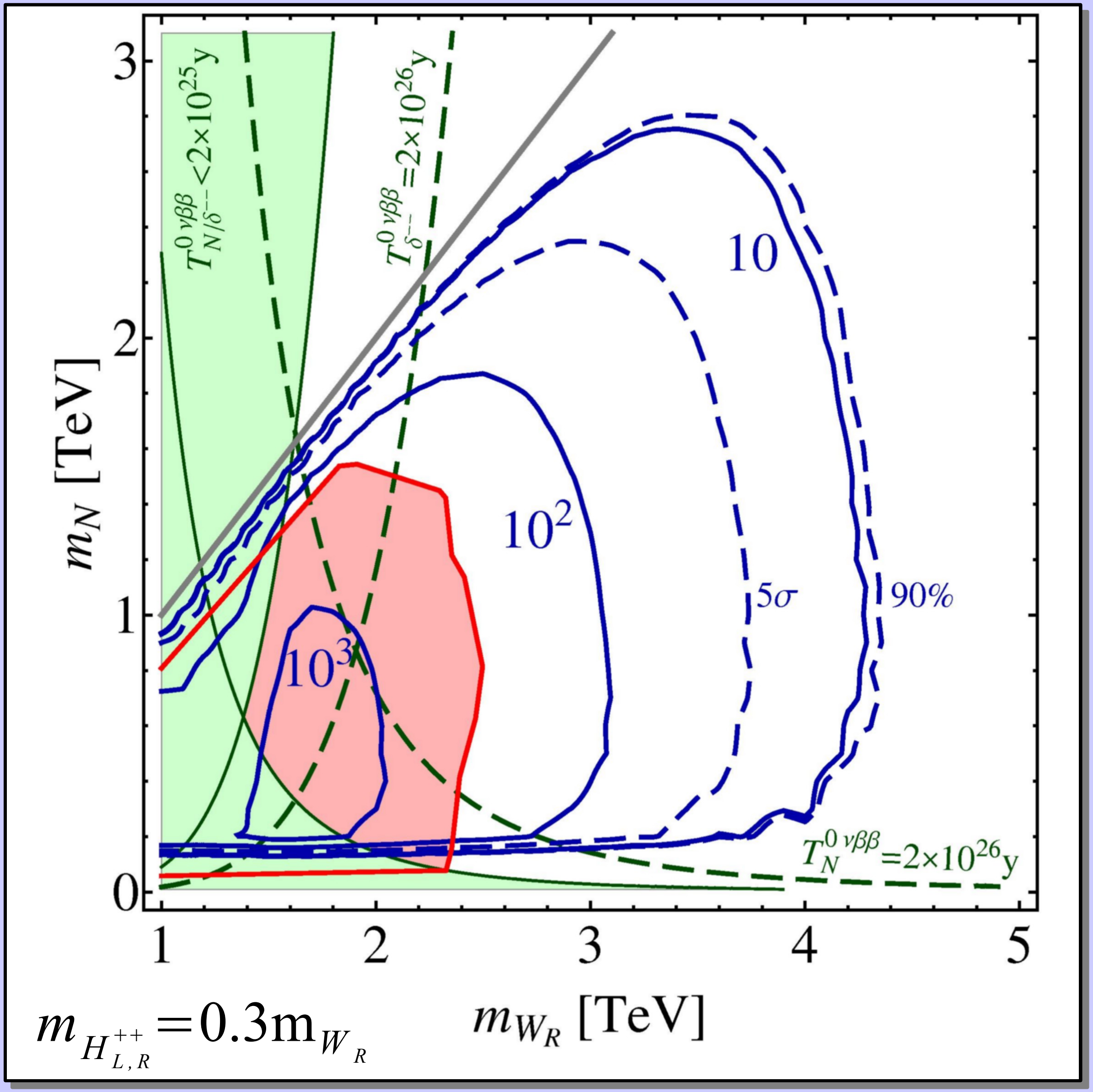
Comparison to 0νββ

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

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

- **and heavy neutrinos**

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



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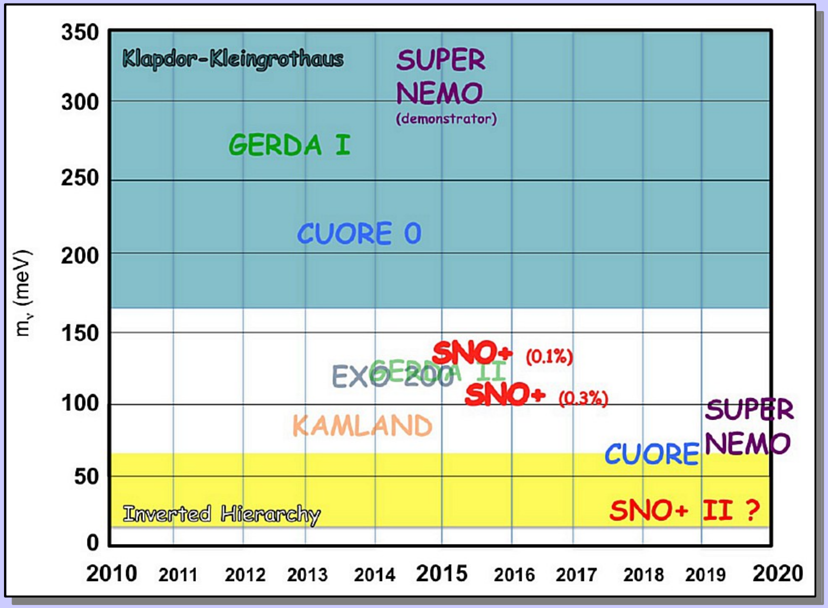
Lefeuvre (2011)



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

Lefeuvre (2011)