Lepton Flavour and Number Violation in Models with Left-Right Symmetry

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Overview

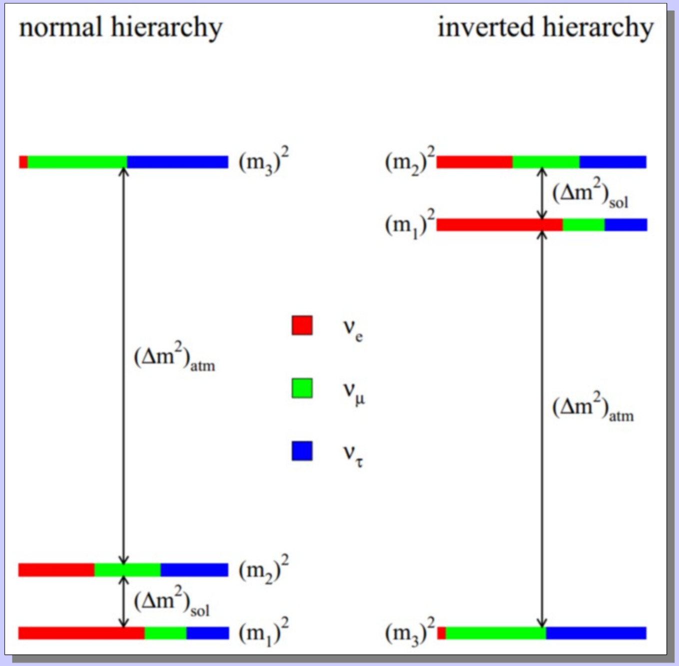
- **Neutrinos**
- **Neutrino Mass Generation**
  - Seesaw Mechanism
  - SUSY Seesaw
  - Left-Right Symmetry
- **Lepton Flavour Violation**
- **Lepton Number Violation**
- **Signals at the LHC**
- **Conclusions**

Neutrino Oscillations

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

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

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



De Gouvea '04

- **Solar neutrino oscillations**
  Large mixing
- **Atmospheric oscillations**
  ≈ Maximal mixing
- **Reactor and accelerator neutrinos**
  Antineutrino disappearance at Daya Bay (& Reno)

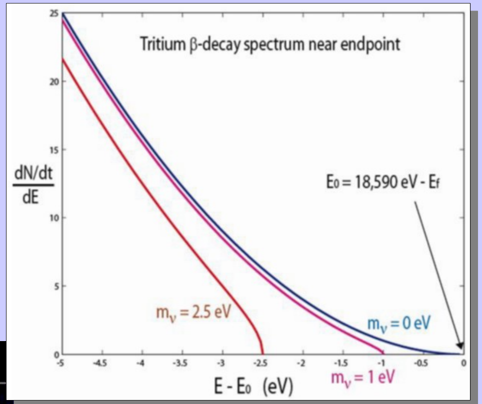
$$\sin^2(2\theta_{13}) = 0.092 \pm 0.021$$

Absolute Neutrino Mass

- **Energy endpoint in Beta decay**

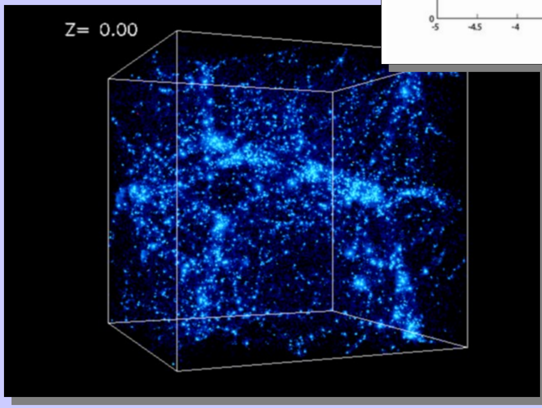
$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2 < (2.2\,eV)^2$$

Katrin: $m_\beta \approx 0.2$ eV



- **Impact on Large Scale Structure**

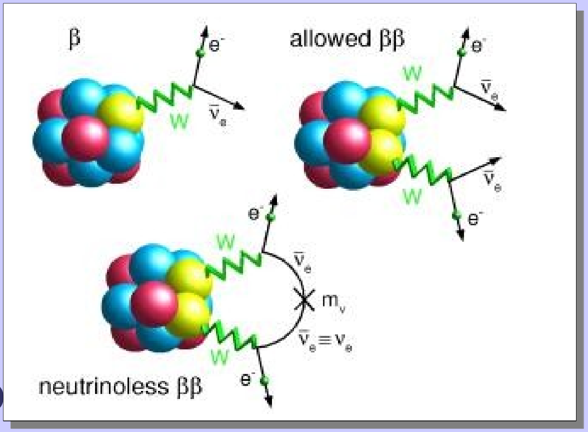
$$\Sigma = \sum_i m_i < 0.4 - 1\,\text{eV}$$

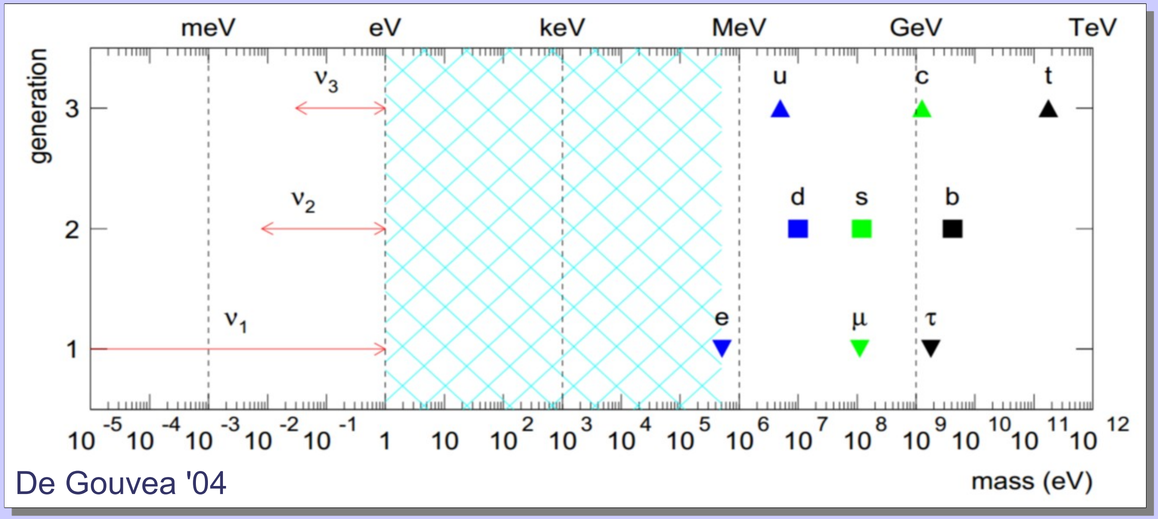


- **Neutrinoless Double Beta Decay**

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

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





De Gouvea '04

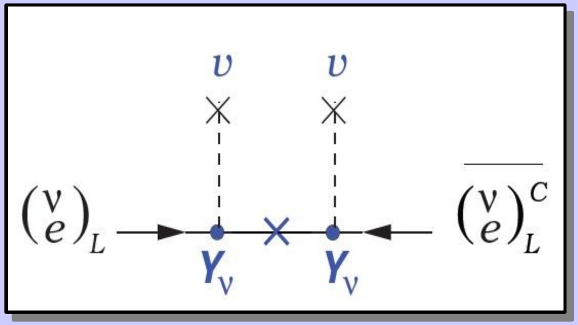
Seesaw Mechanism

- Add right-handed neutrinos to (MS)SM particle content, $M_R \approx 10^{14}$ GeV

$$W = W_{\text{MSSM}} - \frac{1}{2}\hat{\nu}_R^{cT} M_R \hat{\nu}_R^c + \hat{\nu}_R^{cT} Y_\nu \hat{L}\cdot\hat{H}_u$$

- Integrate out heavy right-handed neutrinos

$$\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}^T \quad \text{with} \quad m_D = Y_\nu \langle H_u^0\rangle \ll M_R$$

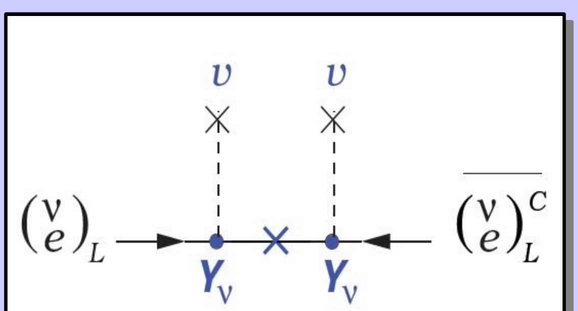


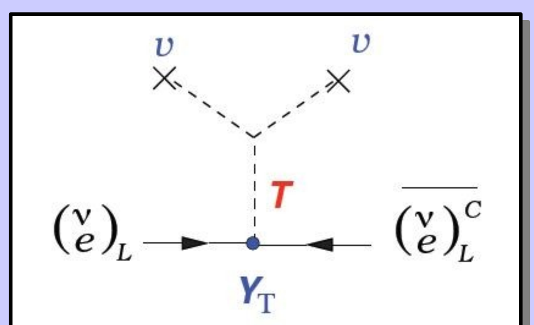
- Effective light neutrino mass matrix at low energies

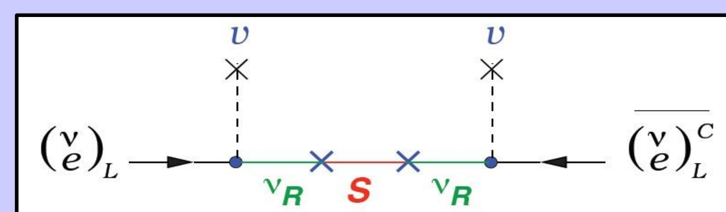
$$m_\nu = m_D^T M^{-1} m_D \;\text{ for }\; m_D \ll M_R \qquad m_\nu \approx 0.1\,\text{eV}\left(\frac{m_D}{100\,\text{GeV}}\right)^2\left(\frac{M_R}{10^{14}\,\text{GeV}}\right)^{-1}$$

Seesaw Mechanisms

Seesaw I	Seesaw II	Inverse Seesaw
$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, e_i^c, \nu_i^c$	$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, e_i^c, \nu_i^c$	$\begin{pmatrix} \nu_i \\ e_i \end{pmatrix}, e_i^c, \nu_i^c, S_i$
$\begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix}$	$\begin{pmatrix} m_{LL} & m_D^T \\ m_D & M_R \end{pmatrix}$	$\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix}$
$m_D \ll M_R \Rightarrow$ $m_\nu = m_D^T M^{-1} m_D$	$m_D \ll M_R \Rightarrow$ $m_\nu = m_{LL} - m_D^T M^{-1} m_D$	$\mu, m_D \ll M_R \Rightarrow$ $m_\nu = m_D^T M_R^{T-1} \mu M_R^{-1} m_D$

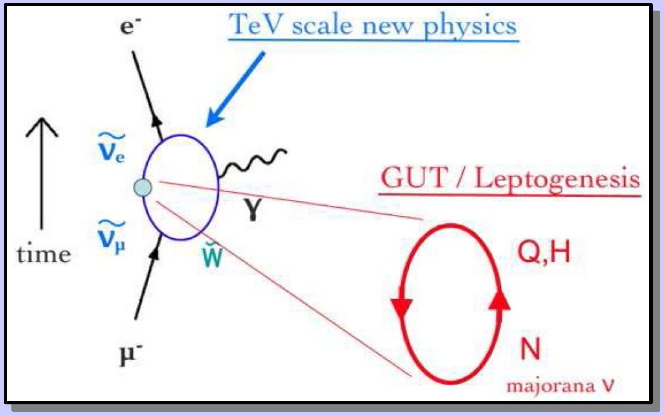


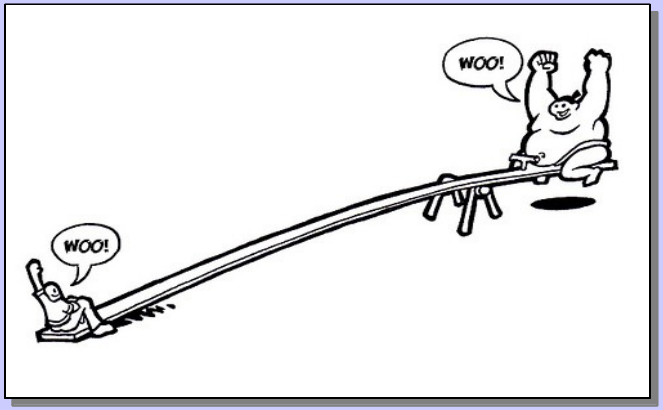




Problems of Seesaw Mechanism

- **Introduces high energy scale**
- **Right-handed neutrinos are singlets**
  Couple only via small mixture with active neutrinos
- **Mechanism not testable with low energy observables**
- **Possible Solutions**
  - **SUSY Seesaw**
    Testable LFV effects on sleptons
  - **Bended Seesaw mechanisms**
    LNV at low scale allows low mass right-handed neutrinos
  - **Left-Right symmetry models**
    Right-handed neutrinos couple with gauge strength to charged leptons





Minimal Left-Right Symmetrical Model

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

  Pati & Salam '74
  Mohapatra & Senjanovic '75

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

- **Generating r.h. Neutrino + WR + ZR masses**

$$M_{N_i}\approx M_{W_R}\approx M_{Z_R}\approx <\Delta_R>$$

- **Charged current weak interactions**

$$J_W^{\mu-} = \frac{g_L}{\sqrt{2}}\left(\bar{\nu}U_{LL}+\bar{N}^c U_{LR}\right)\gamma^\mu e_L + \frac{g_R}{\sqrt{2}}\sin\zeta_W\left(\bar{\nu}U_{RL}+\bar{N}U_{RR}\right)\gamma^\mu e_R,$$

$$J_{W'}^{\mu-} = -\frac{g_L}{\sqrt{2}}\sin\zeta_W\left(\bar{\nu}U_{LL}+\bar{N}U_{LR}\right)\gamma^\mu e_L + \frac{g_R}{\sqrt{2}}\left(\bar{N}U_{RR}+\bar{\nu}^c U_{RL}\right)\gamma^\mu e_R,$$

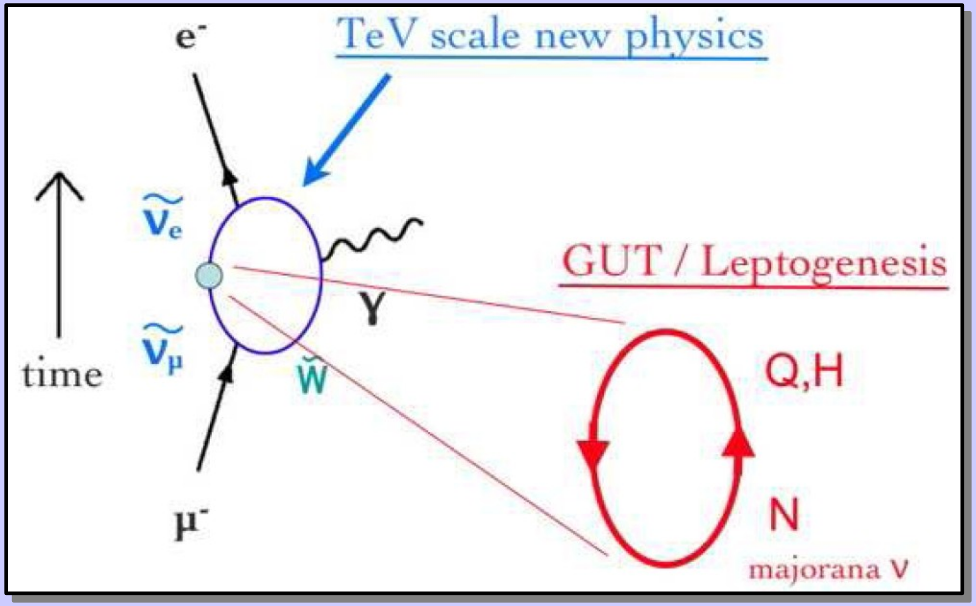
Charged Lepton Flavour Violation

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

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{m^2_W} \right|^2 \approx 10^{-56}$$

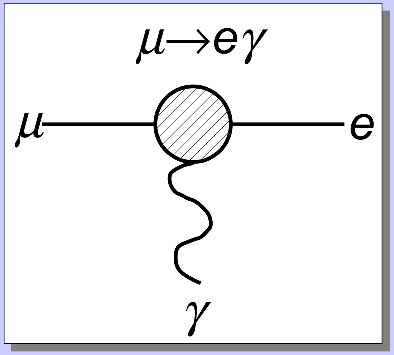
LFV is clear sign for BSM physics

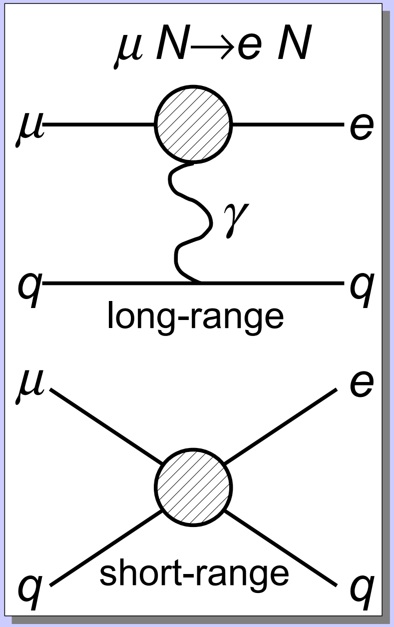
- **Flavour violation in quark and neutrino sector**
  Strong case to look for charged LFV
- **LFV can shed light on**
  - Grand Unification models
  - Flavour symmetries
  - Origin of flavour

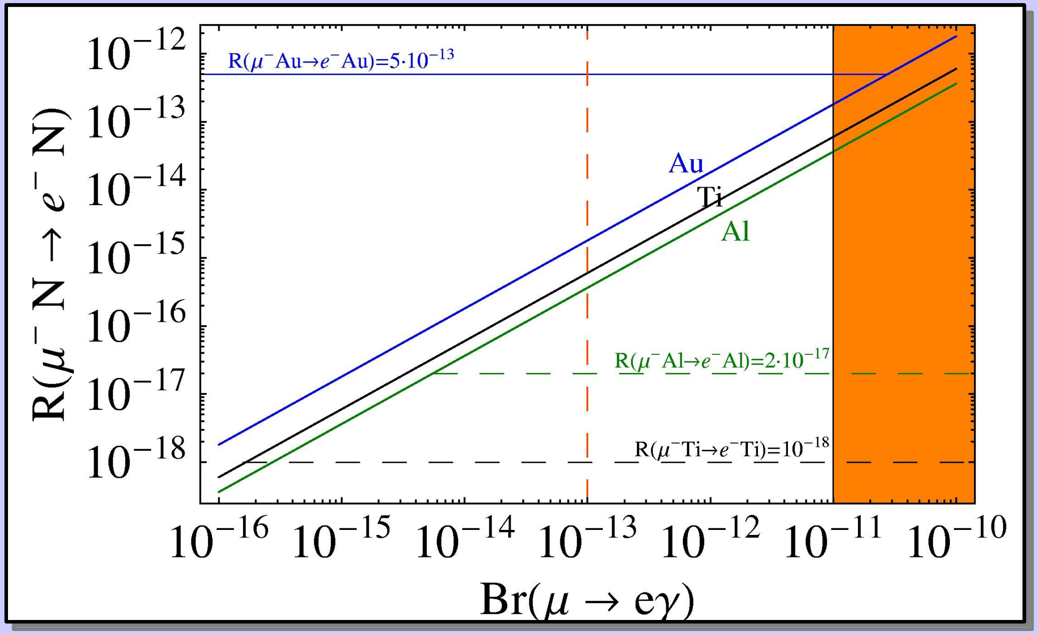


Rare LFV Processes

- **Current bounds** **and future sensitivities**
  - **Br($\mu \to e\gamma$) $< 2.4 \cdot 10^{-12}$ (MEG)** **10^{-13} (MEG, 2009)**
  - Br($\tau \to \mu\gamma$) $< 4.4 \cdot 10^{-8}$ (BaBar) 10^{-9} (Super-B Factory)
  - Br($\tau \to e\gamma$) $< 3.3 \cdot 10^{-8}$ (BaBar) 10^{-9} (Super-B Factory)
  - R($\mu N \to e N$) $< 7 \cdot 10^{-13}$ (Sindrum) 10^{-16} (COMET), μ–e conversion in nuclei
  - $\mu \to 3e$, $\tau \to 3\mu$ (LHC?), etc.
- **Correlation between processes of same flavour transition**







Rare LFV Processes in the LRSM

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

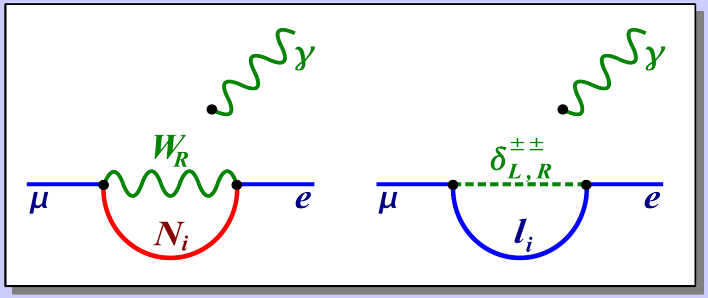
$$\mathrm{BR}(\mu \to e\gamma) \approx 2 \times 10^{-9} \sin^2(2\phi) \left(\frac{\Delta m^2_{12}}{m^2_{W_R}} \right)^2 \left(\frac{2\ \mathrm{TeV}}{m_{W_R}} \right)^4 ,$$

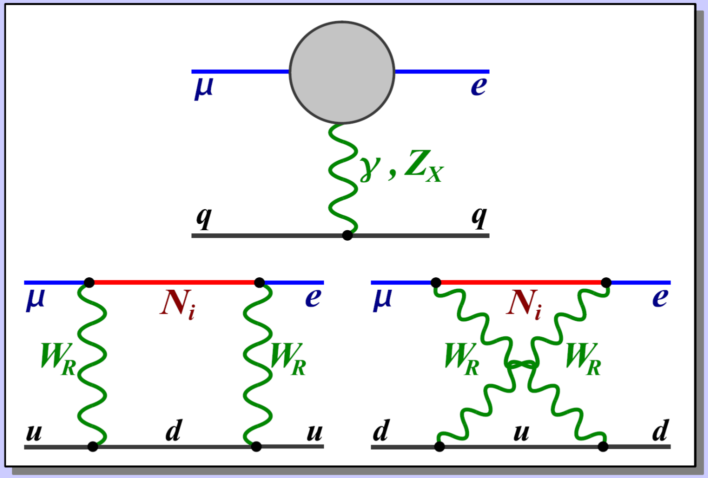
- ***μ*-e conversion in nuclei enhanced via box diagrams**

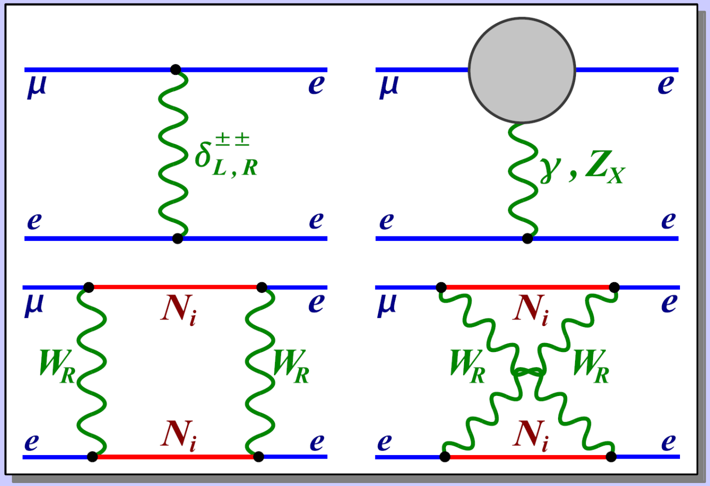
$$R(\mu \to e) \approx BR(\mu \to e\gamma)$$

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

$$BR(\mu \to eee) \approx 300 \times R(\mu \to e)$$

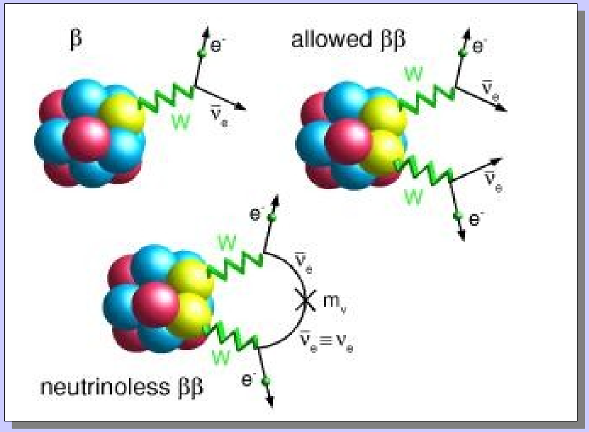






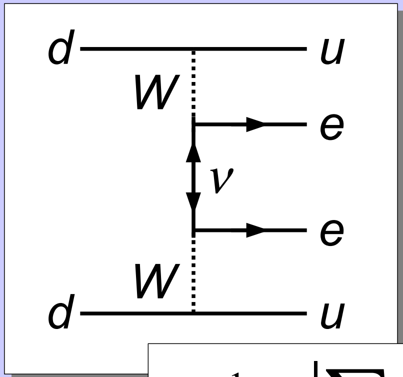
Neutrinoless Double Beta Decay

- **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)
- **Which mechanism triggers the decay?**



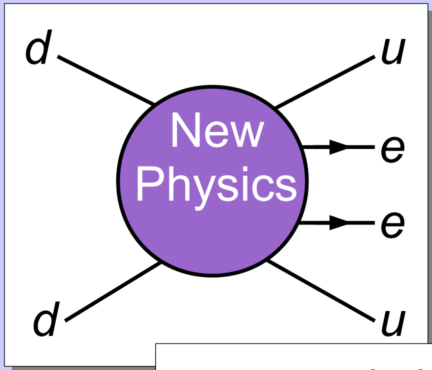
Heidelberg-Moscow
$T_{1/2}(^{76}\text{Ge}) \approx 1.9 \cdot 10^{25}$ y
$\langle m_\nu \rangle \approx (0.3 - 0.6)$ eV

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



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

Neutrinoless Double Beta Decay in the LRSM

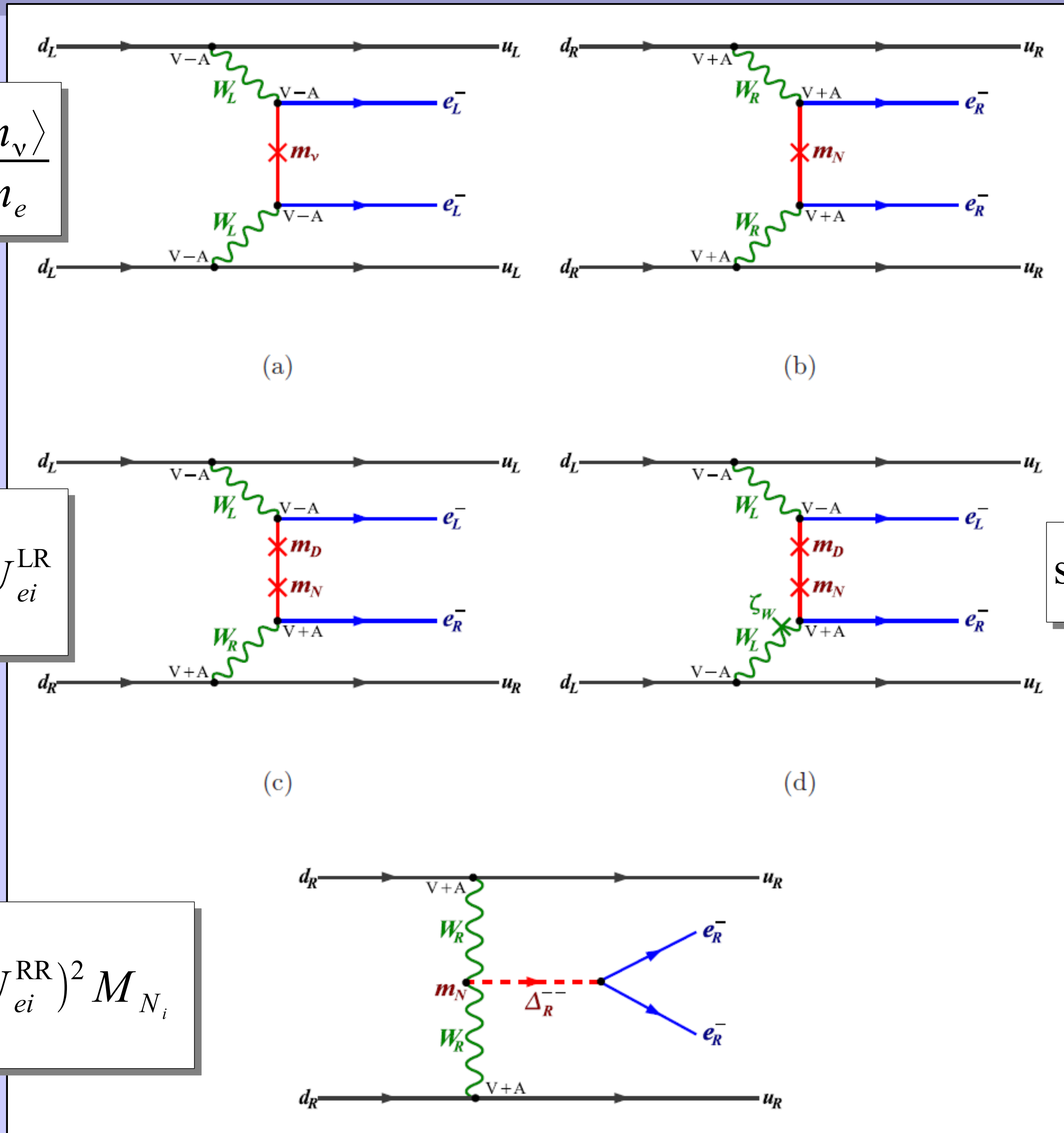
$$\sum_i (U_{ei}^{LL})^2 \frac{m_{\nu_i}}{m_e} = \frac{\langle m_\nu \rangle}{m_e}$$

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

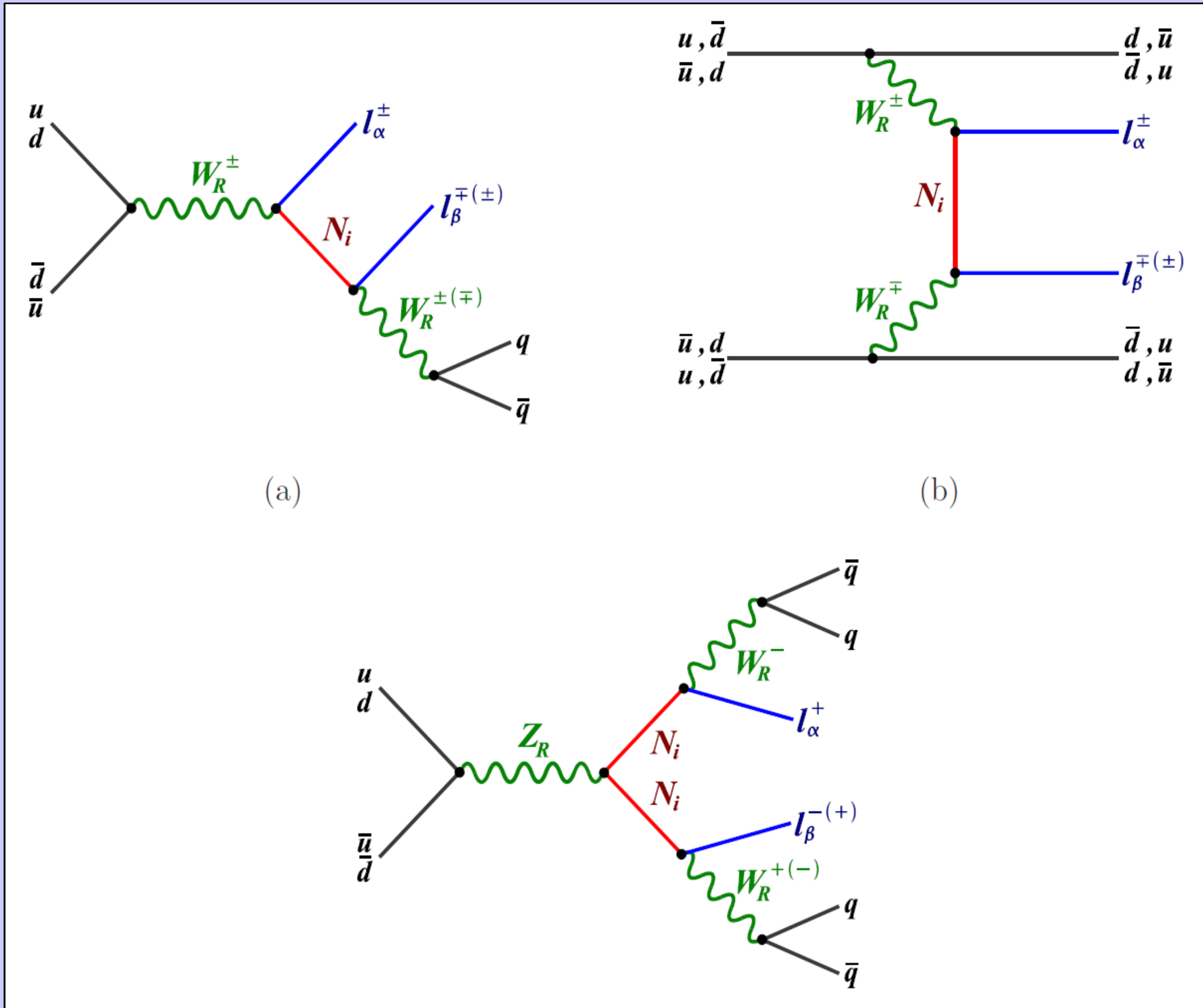
$$\left(\frac{M_{W_L}}{M_{W_R}}\right)^2 \sum_i U_{ei}^{LL} U_{ei}^{LR}$$

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

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



Dilepton signals at the LHC in the LRSM

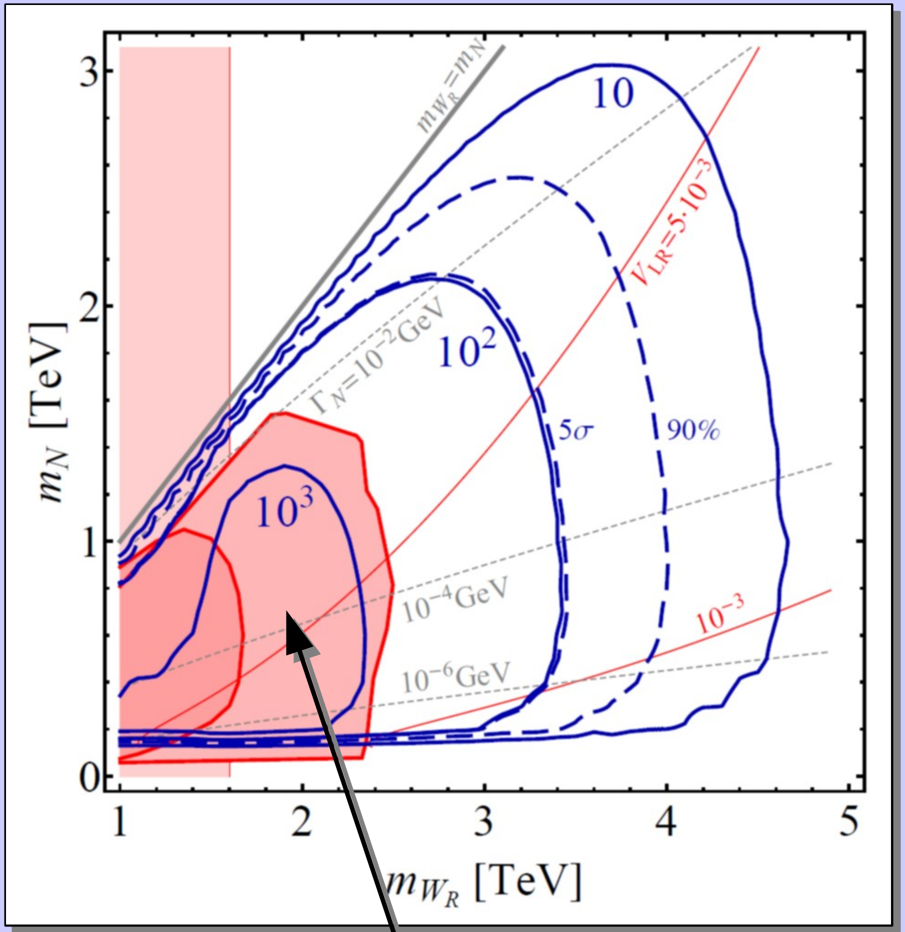


Single Right-handed Neutrino Production

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

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

	OS, SF		OS, OF		SS, OF		SS, SF			
	e^+e^-	$\mu^+\mu^-$	$e^+\mu^-$	$e^-\mu^+$	$e^+\mu^+$	$e^-\mu^-$	e^+e^+	e^-e^-	$\mu^+\mu^+$	$\mu^-\mu^-$
$t+\bar{t}$	190	170	149	164	$\lesssim 10$	$\lesssim 10$	$\lesssim 10$	$\lesssim 10$	$\lesssim 10$	$\lesssim 10$
$Z+j$	181	187	0	2	0	0	$\lesssim 10$	$\lesssim 10$	$\lesssim 10$	$\lesssim 10$
Signal	289	192	228	230	330	108	204	74	146	45
Eff. [%]	51	33	42	43	41	41	49	50	35	32

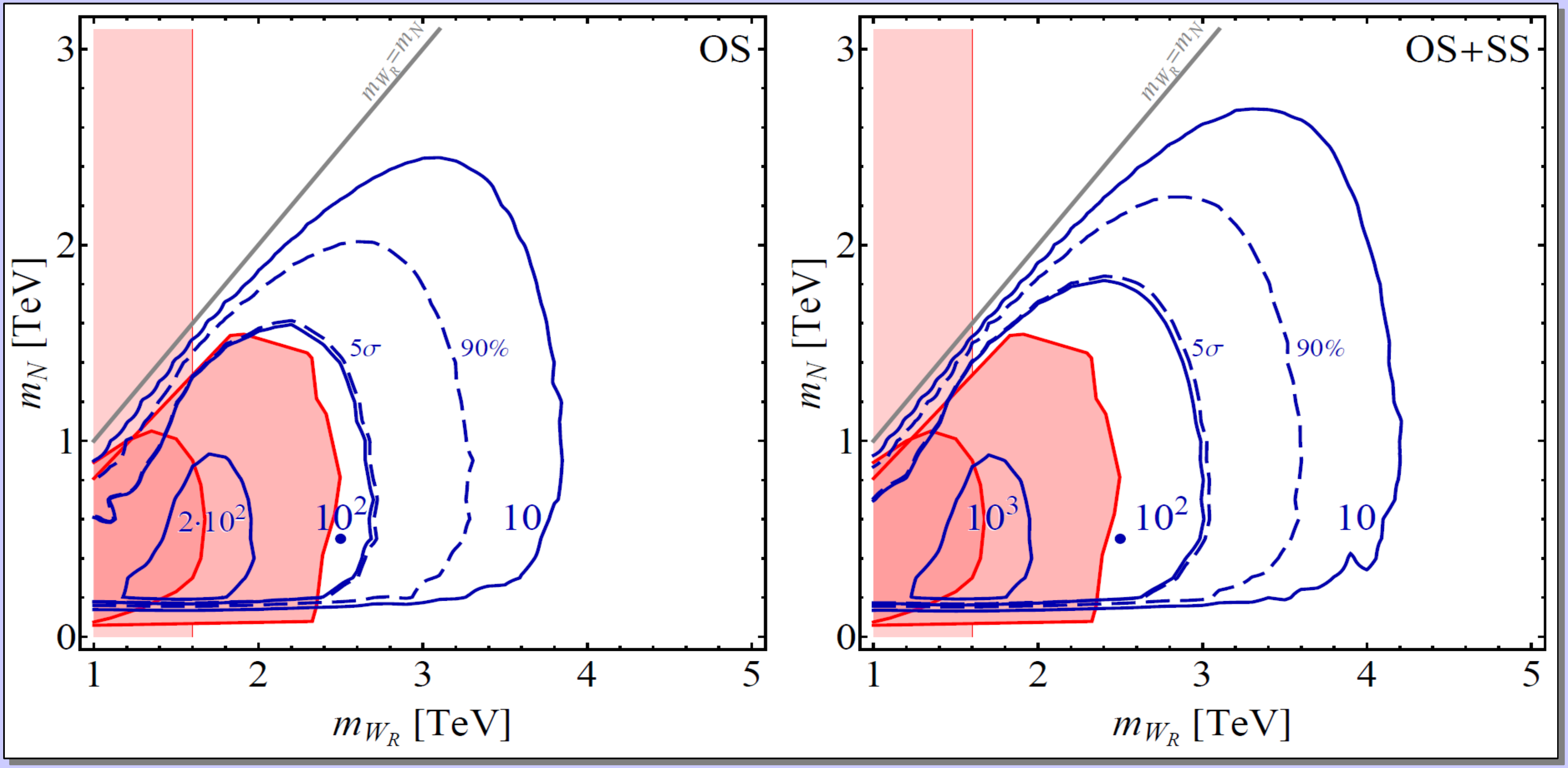


ATLAS exclusion @ 2.1 fb^{-1}

Lepton Flavour Violation

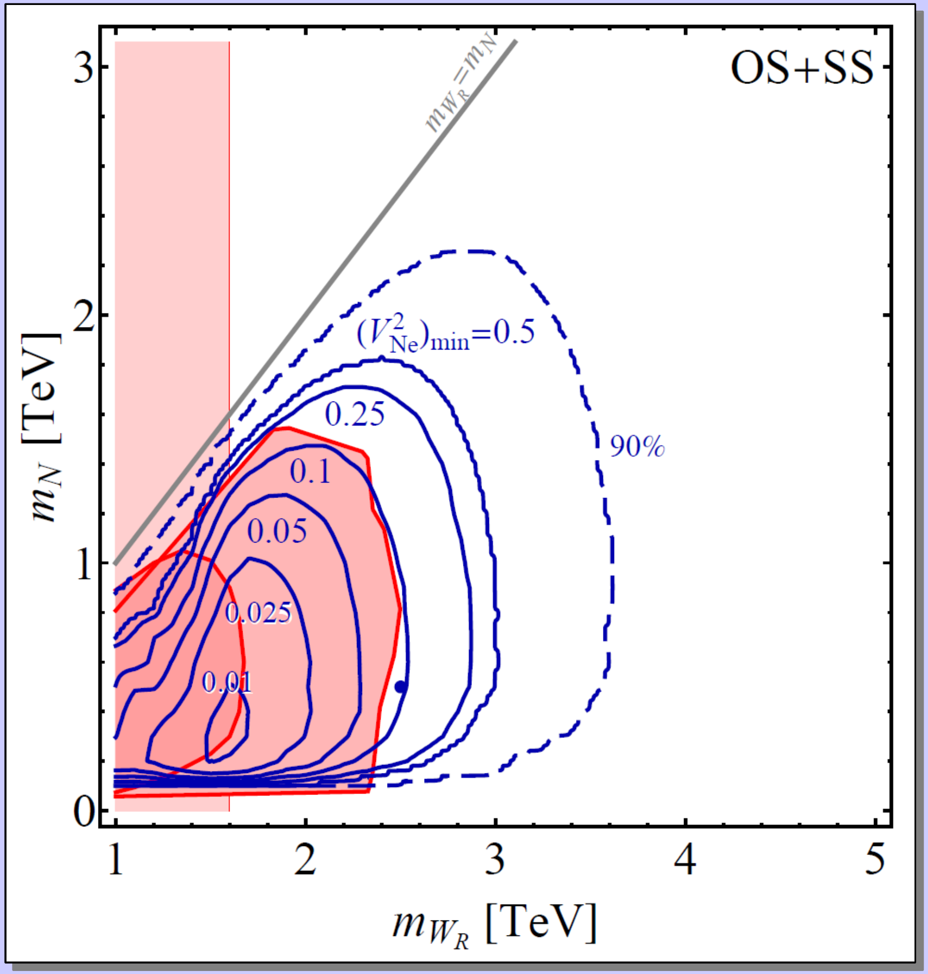
- **Single r.h. Neutrino Exchange**
- **Maximal mixing of r.h. neutrino to e and μ only**

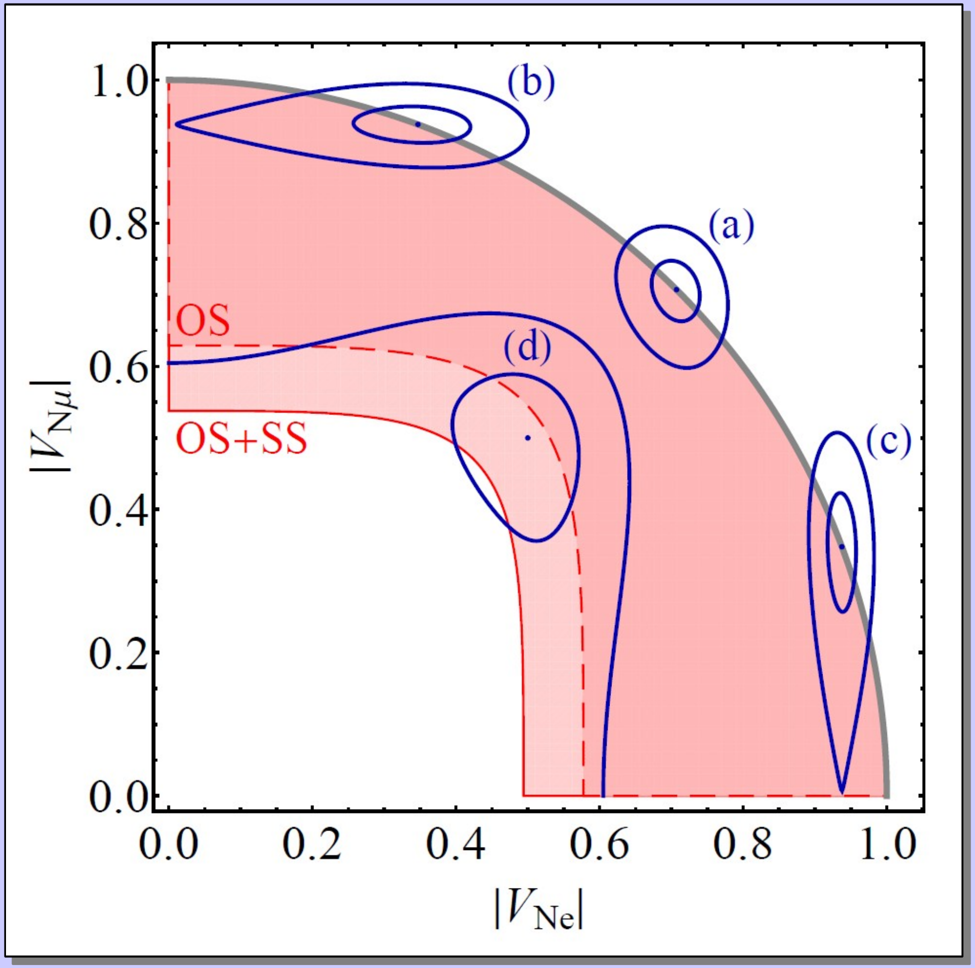
LHC reach @ 14 TeV, 30 fb^{-1}



Single Right-handed Neutrino Production

- **Sensitivity to lepton mixing couplings**





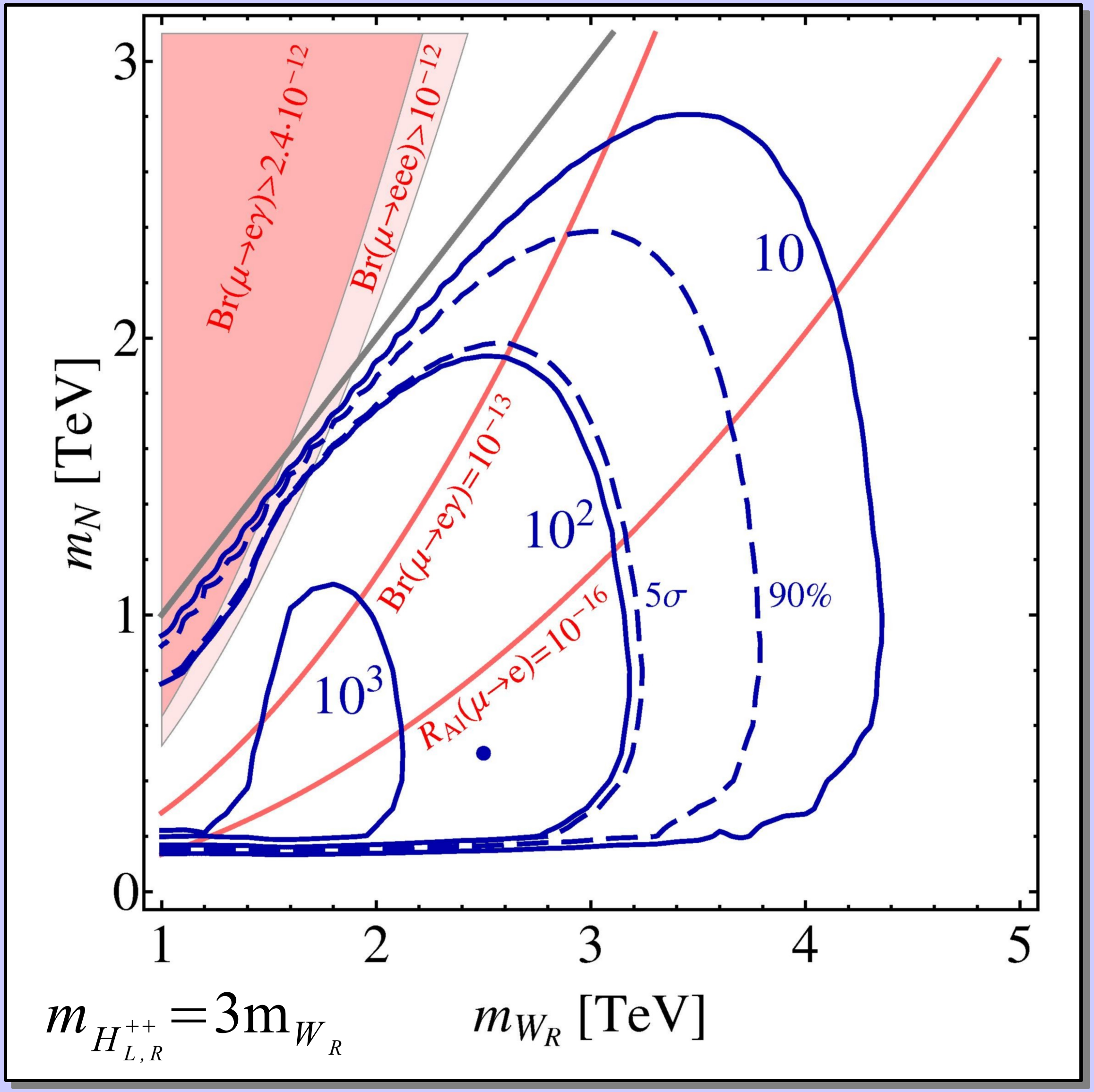
$M_{W_R} = 2.5$ TeV, $M_N = 0.5$ TeV

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

Two Neutrino Exchange

- **Two neutrinos exchanged with maximal mixing and 1% mass splitting**
- **Correlation with low energy LFV processes**

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



$m_{H^{++}_{L,R}} = 3m_{W_R}$

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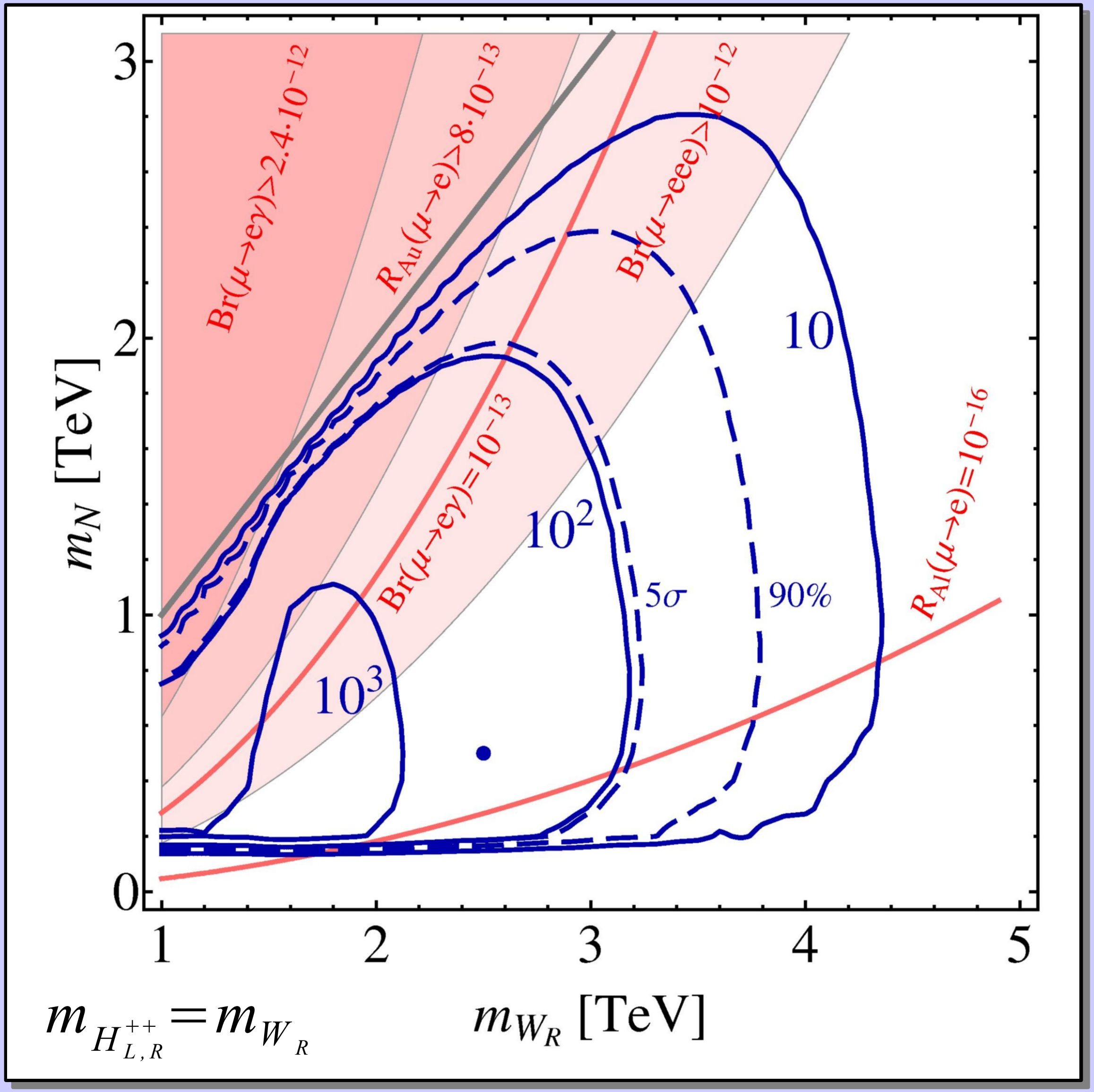

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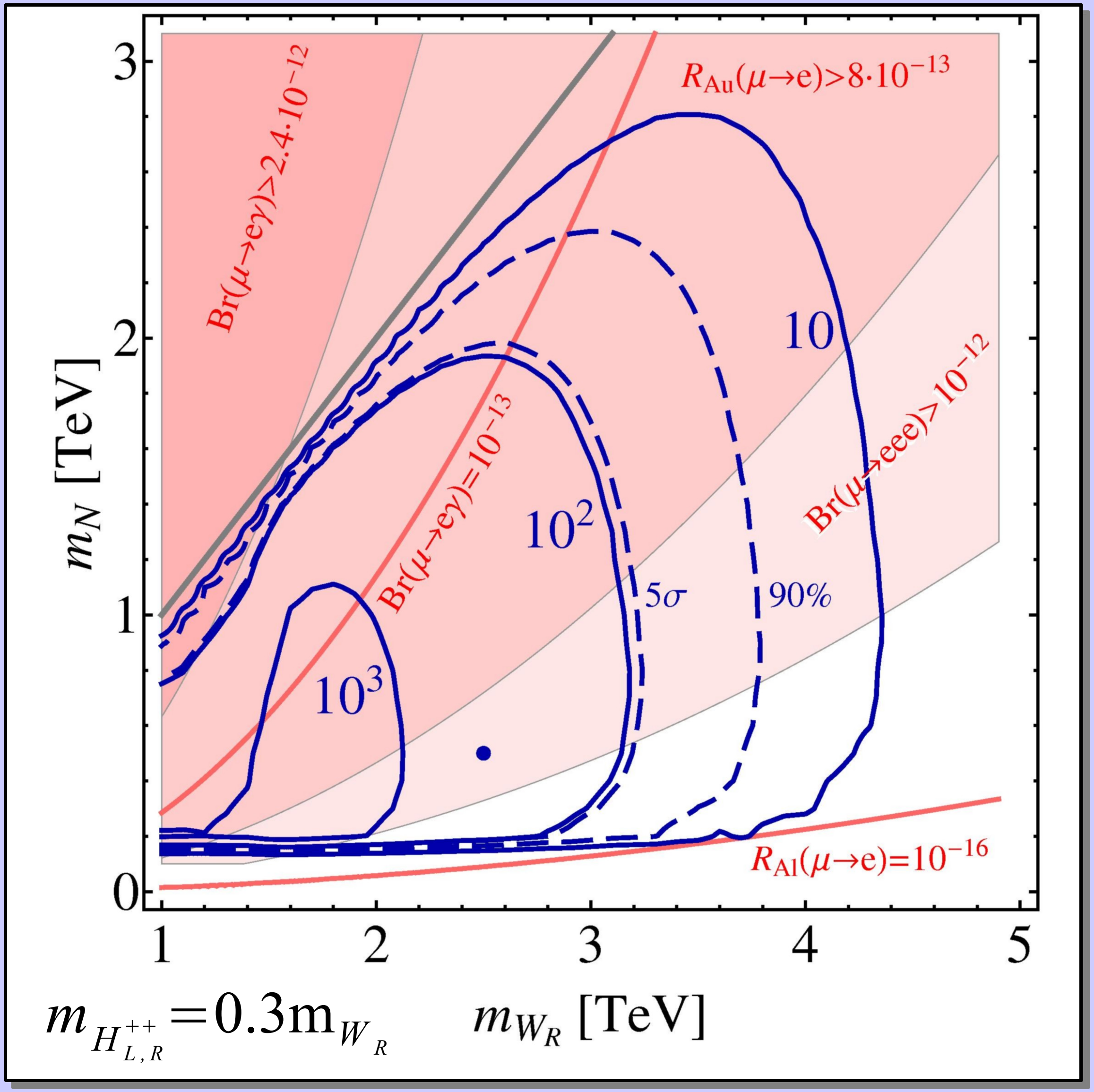


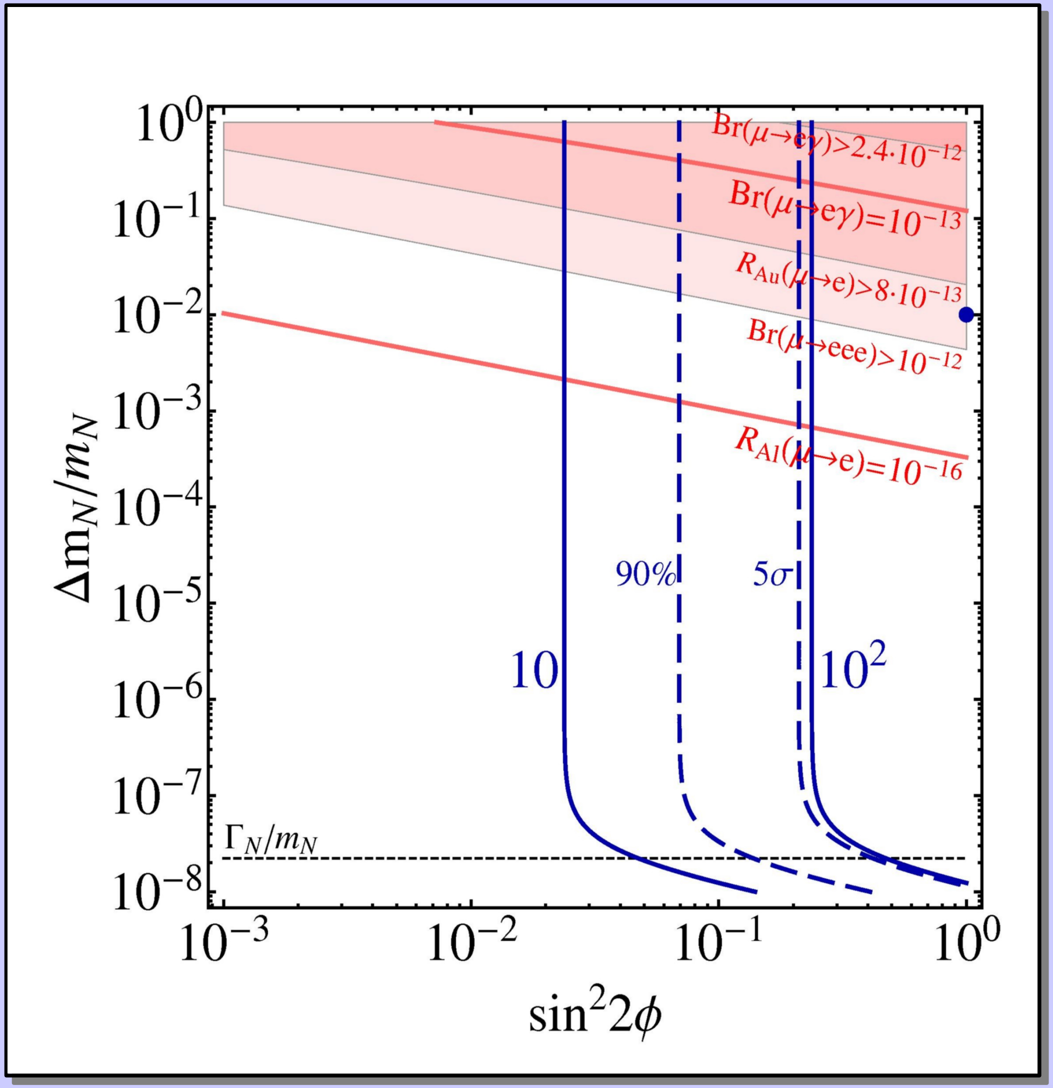
Two Neutrino Exchange

- **Two neutrinos exchanged with maximal mixing and 1% mass splitting**
- **Correlation with low energy LFV processes**
- **Low energy LFV processes GIM suppressed as**

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

- **On-shell production suppressed as**

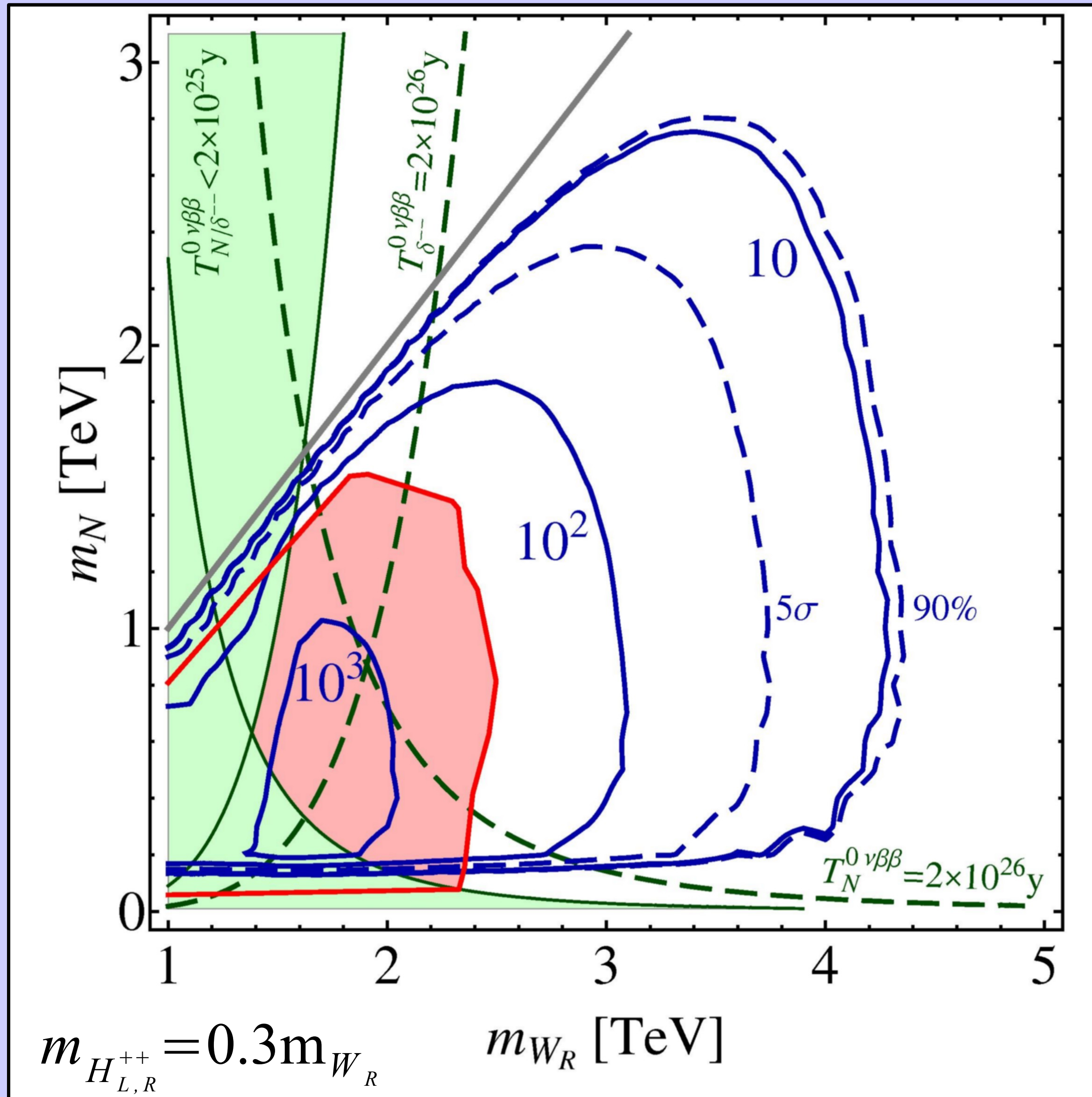
$$\Delta m_N^2 / (m_N \Gamma_N)$$



Lepton Number Violation

- **Correlation with neutrinoless double beta decay**
- **Contributions from triplet Higgs and heavy neutrinos**

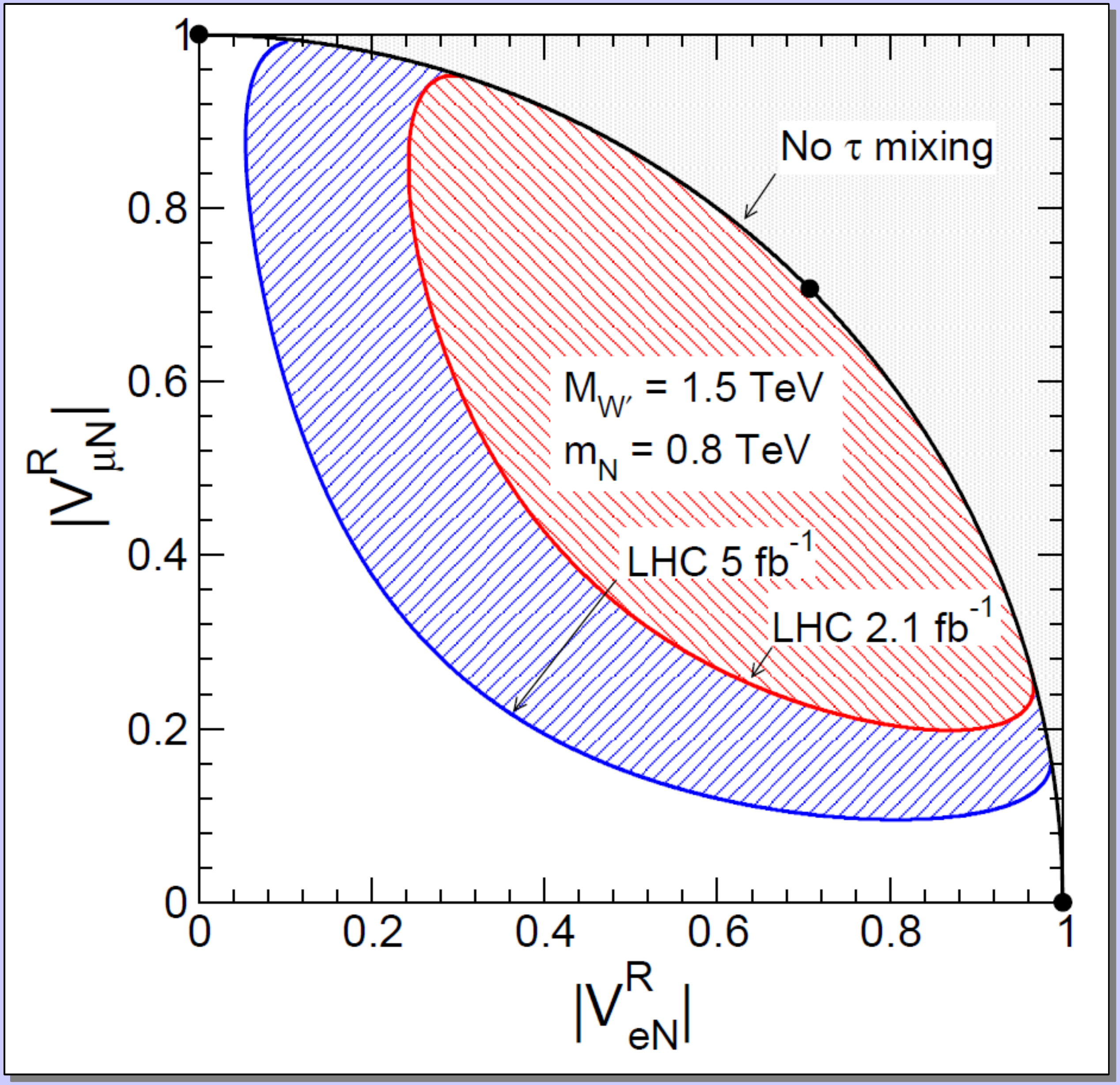
LHC reach @ 14 TeV, 30 fb^{-1}



Conclusion

- **Neutrinos much lighter than other fermions**
  Strong experimental program to probe absolute mass
  Mechanism of mass generation?
  What about charged lepton flavour violation?
- **High Energy Seesaw Mechanism not testable**
  Consider alternatives with lower masses and stronger couplings?
- **Seesaw Mechanism in Left-Right Symmetry Models**
  Strong interplay with low energy LFV and LNV processes
- **LHC still has chance to probe individual flavour couplings**

Including couplings to taus



	(1.5, 0.8) TeV		
$\ell \setminus \ell'$	e	μ	τ
e	0.555	0.501	0.175
μ	0.524	0.480	0.172
τ	0.203	0.192	0.058