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Lepton Flavour Violation

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Overview

- New Physics and Flavour
- Neutral Lepton Flavour Violation
  - Neutrino Oscillation
  - Dirac vs Majorana
- Charged Lepton Flavour Violation
- Effective Operator Approach
- The BSM Flavour Problem
- BSM Models
  - Effective Mass and Seesaw
  - Left-Right Symmetric Models
- Conclusions

New Physics and Flavour

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- Distinct pattern of fermion masses and mixing
  - Quarks

$$m_u : m_c : m_t \sim \lambda^8 : \lambda^4 : 1, \quad m_d : m_s : m_b \sim \lambda^4 : \lambda^2 : 1, \quad \lambda \sim 0.2,$$

$$\theta_{12}^Q \sim 13^\circ, \quad \theta_{23}^Q \sim 2.4^\circ, \quad \theta_{13}^Q \sim 0.2^\circ.$$

  - Leptons

$$m_e : m_\mu : m_\tau \sim \lambda^{4.5} : \lambda^2 : 1,$$
$$m_{\nu_2}^2 - m_{\nu_1}^2 \sim 7.6 \times 10^{-5}\,\mathrm{eV}^2,$$
$$|m_{\nu_3}^2 - m_{\nu_1}^2| \sim 2.4 \times 10^{-3}\,\mathrm{eV}^2,$$

$$m_{\nu_3} : m_{\nu_2} \sim \lambda.$$

for $m_{\nu_1} = 0$

$$\theta_{12}^L \sim 30^\circ, \quad \theta_{23}^L \sim 45^\circ, \quad \theta_{13}^L \sim 8^\circ.$$

New Physics and Flavour

- What is the origin behind these patterns?
- Most (except neutrino mixing?) seem to be non-random
- Quark and lepton mixing distinctly different
- Is this connected to the light neutrino masses / potential Majorana character?
- Standard Model tells us nothing about the flavour structure (+ neutrinos are massless)
- There is no theory of flavour
- Need to find signs of New Physics to make progress

Neutrino Oscillations

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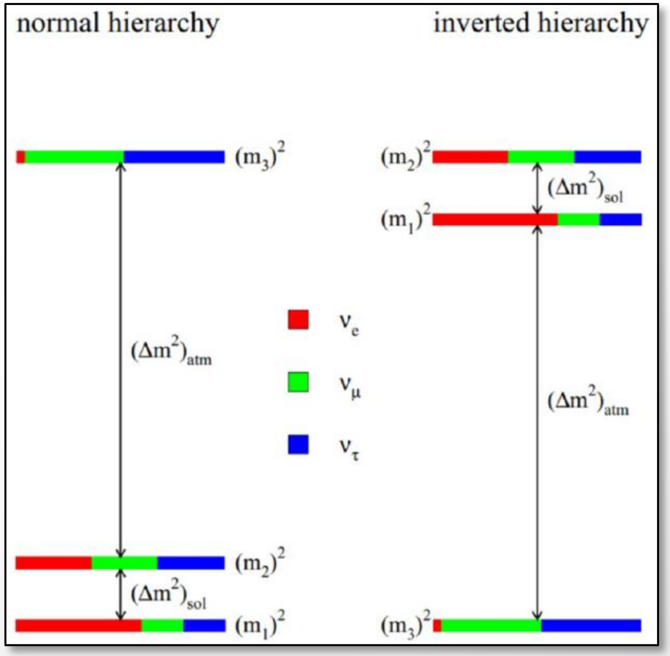
- Neutrino interaction eigenstates different from mass eigenstates
  - Neutrino flavour can change through propagation → LFV

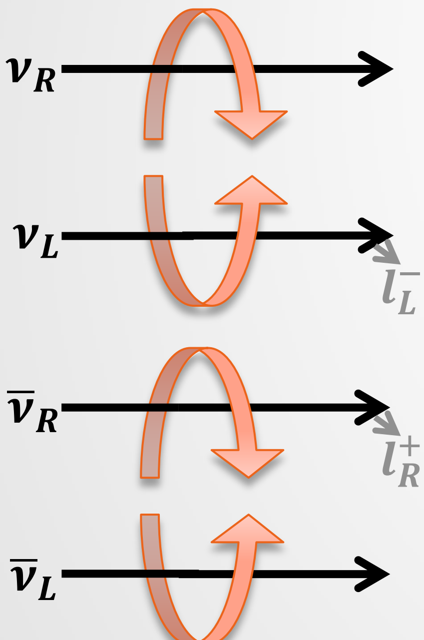
$$\nu_i = U_{\alpha i}\nu_\alpha, \qquad \nu_i(t) = e^{-i(E_i t - p_i x)}\nu_i(0)$$
$$\Longrightarrow P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(1.27\frac{\Delta m^2}{\mathrm{eV}^2}\frac{L/\mathrm{km}}{E/\mathrm{GeV}}\right)$$

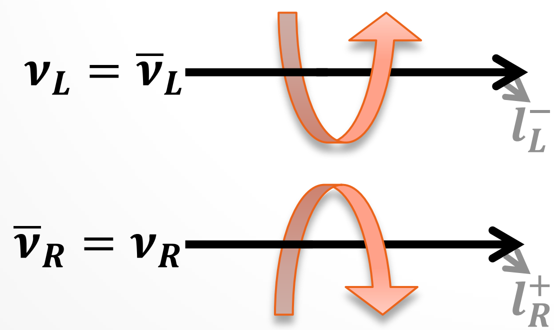


- Solar Neutrino Oscillations
  - Large Mixing
- Atmospheric Oscillations
  - $\approx$ Maximal Mixing
- Reactor and Accelerator Neutrinos
  - $\sin^2 2\theta_{13} = 0.092 \pm 0.021$
- Experimental Unknowns and Anomalies
  - CP Violation? Sign of Δm_{23}? Sterile Neutrinos?

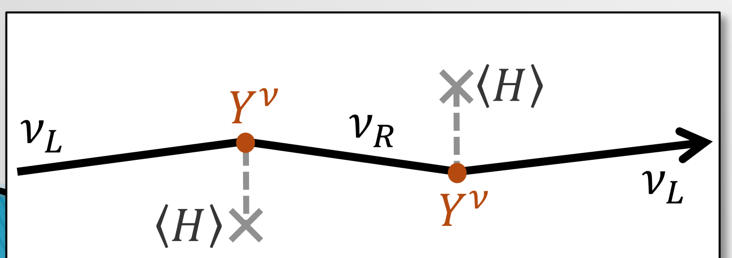
Dirac vs. Majorana

- Two possibilities to define Fermion mass

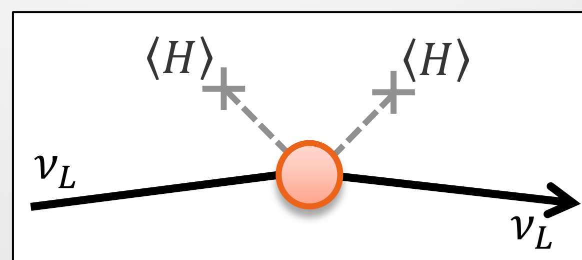




Dirac mass analogous to other fermions but with $^{m_\nu}/_{\Lambda_{EW}} \approx 10^{-12}$ couplings to Higgs



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



Dirac vs. Majorana

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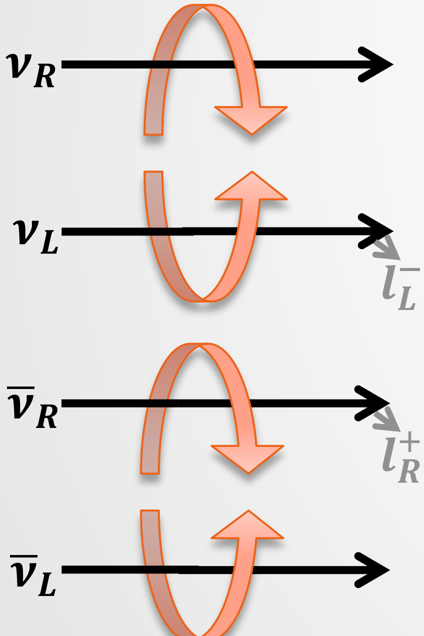

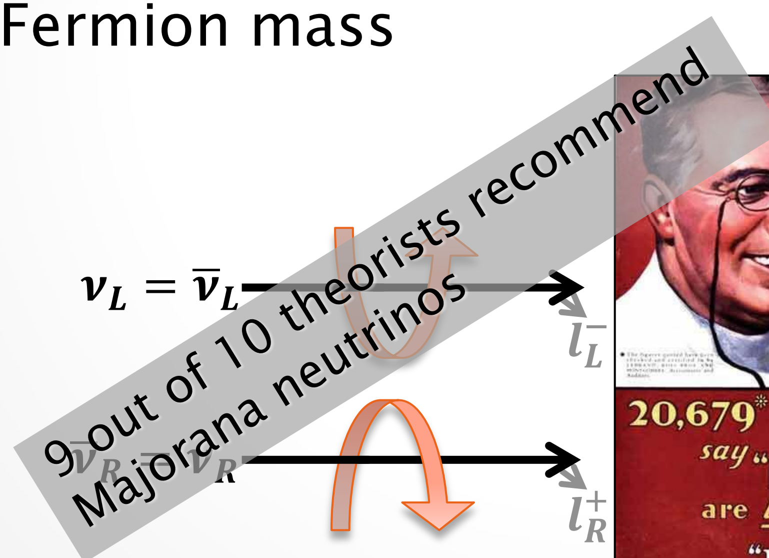

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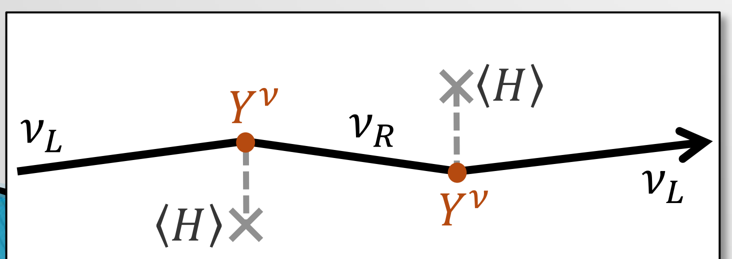

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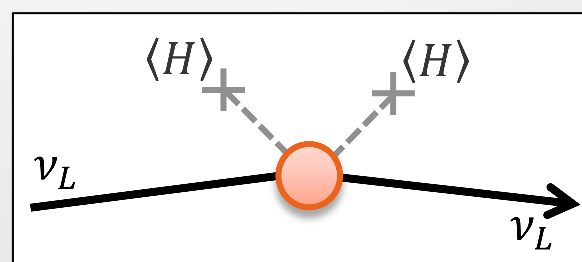


Absolute Neutrino Mass

- Energy Endpoint in Beta Decay

$$m_\beta^2 = \Sigma_i |U_{ei}|^2 m_{\nu_i}^2 < (2.2\ \text{eV})^2$$

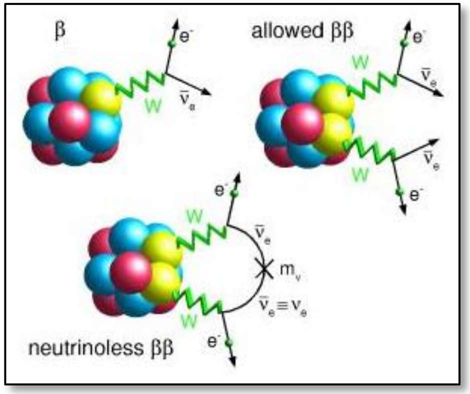
$\approx (0.2\ \text{eV})^2$ (KATRIN, 2018)

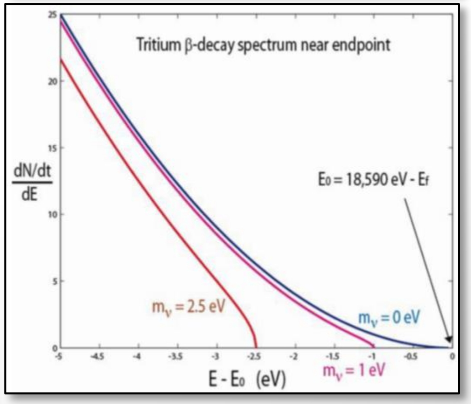
- Neutrinoless Double Beta Decay

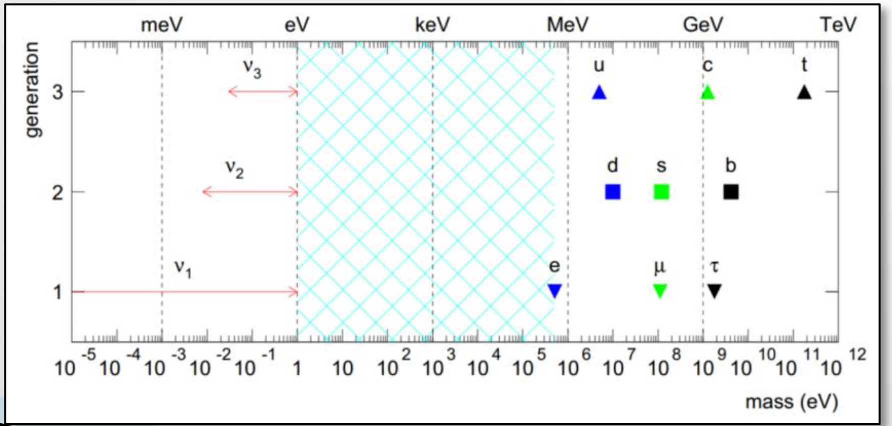
$$m_{\beta\beta} = |\Sigma_i U_{ei}^2 m_{\nu_i}| < 0.2 \cdots 1.0\ \text{eV}$$

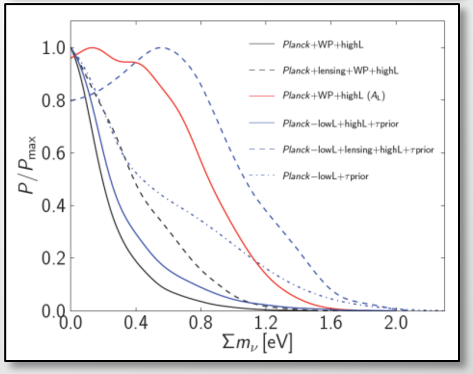
- Impact on Large Scale Structure

$$\Sigma = \Sigma_i m_{\nu_i} < 0.3 \cdots 1.0\ \text{eV}$$



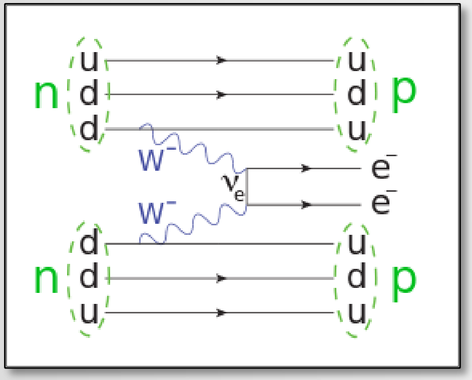






Lepton Flavour versus Lepton Number Violation

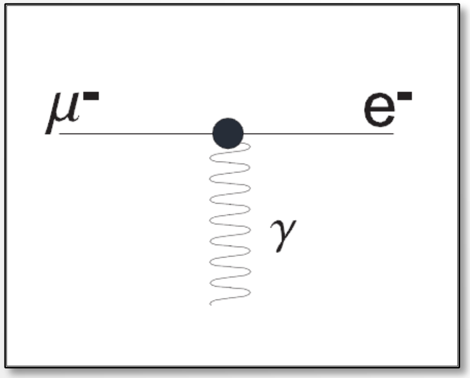
Neutrinoless double beta decay



$$\Delta L_e = 2, \Delta L_\mu = 0, \Delta L = 2$$

Lepton Number Violation

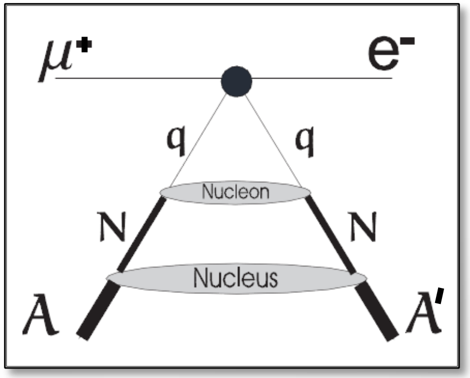
$\mu^- \to e^- \gamma$



$$\Delta L_e = 1, \Delta L_\mu = -1, \Delta L = 0$$

Lepton Flavour Violation

$\mu^+ \to e^-$ conversion in nuclei



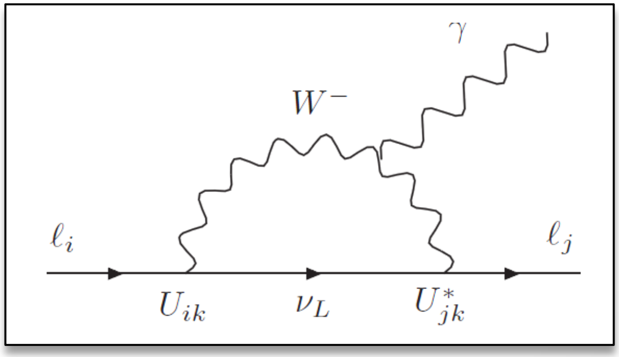
$$\Delta L_e = 1, \Delta L_\mu = 1, \Delta L = 2$$

Lepton Flavour Violation + Lepton Number Violation

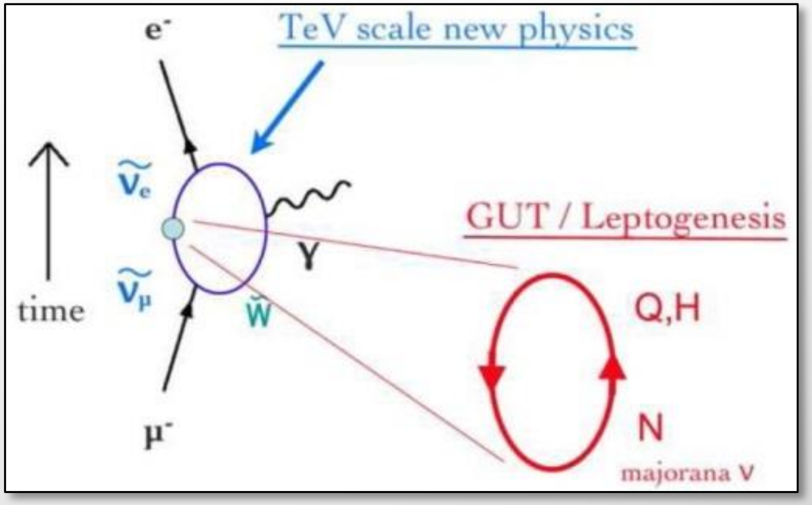
Charged Lepton Flavour Violation

- Lepton Flavour practically conserved in the νSM
  - LFV is clear sign for BSM physics

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



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



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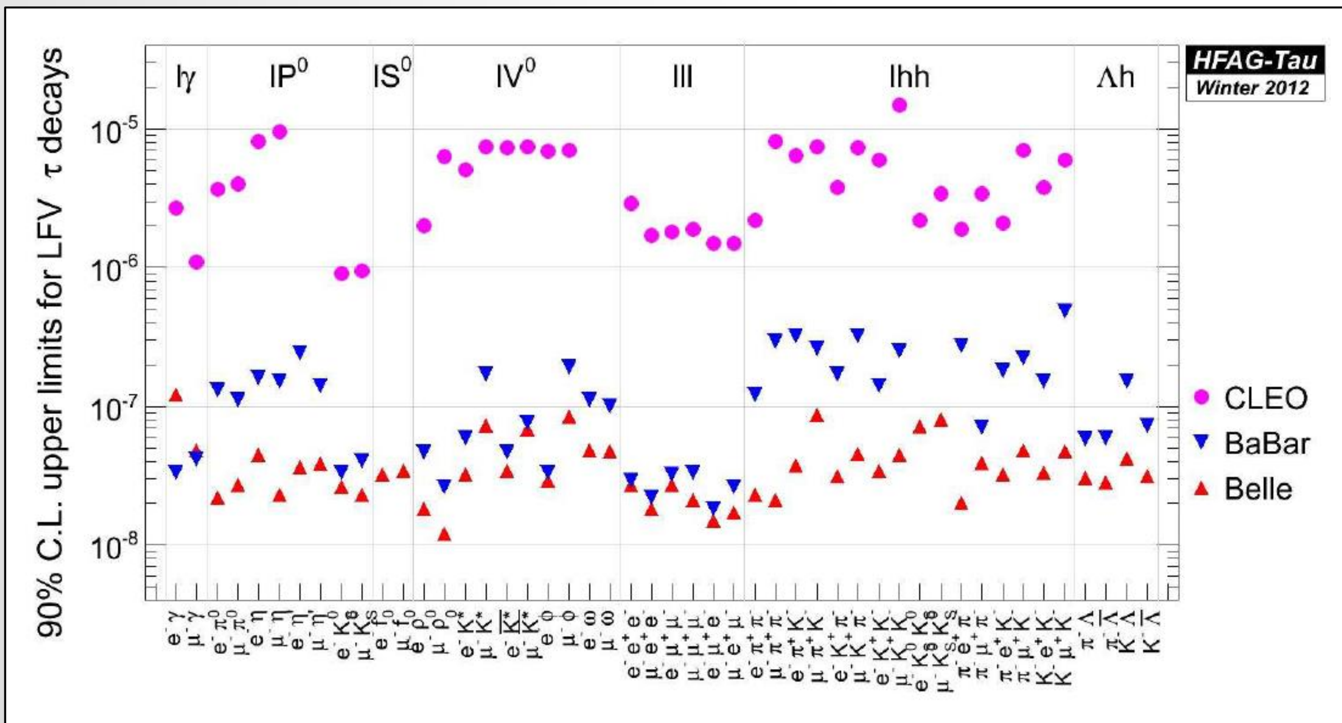
Charged Lepton Flavour Violation

- Large number of observables
  - $\mu \to e\gamma$, $\mu^- \to e^- e^- e^+$
  - $\mu - e$ conversion in nuclei: $\mu^- + A \to e^- + A$, $\mu^- + A \to e^+ + A'$
  - τ decays



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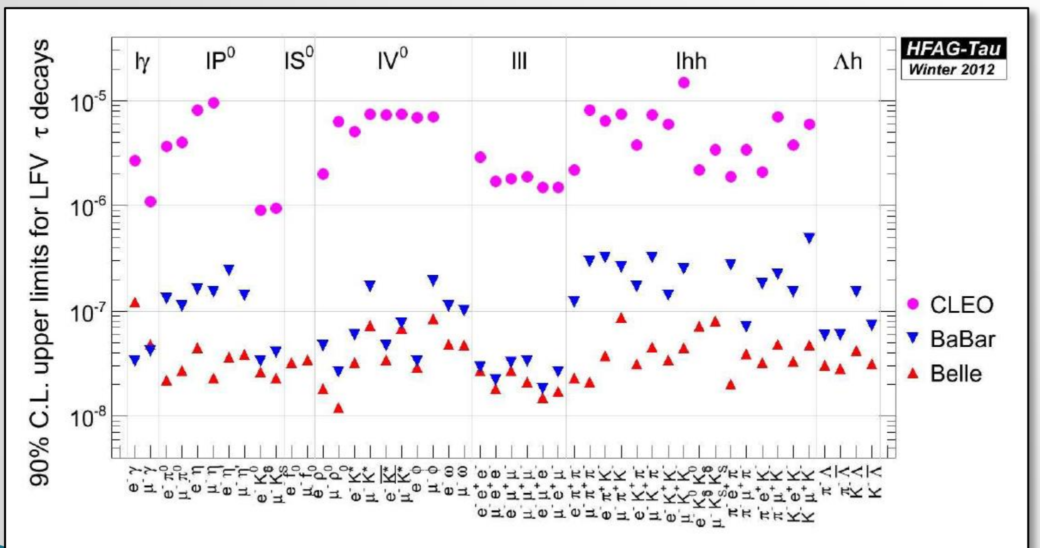
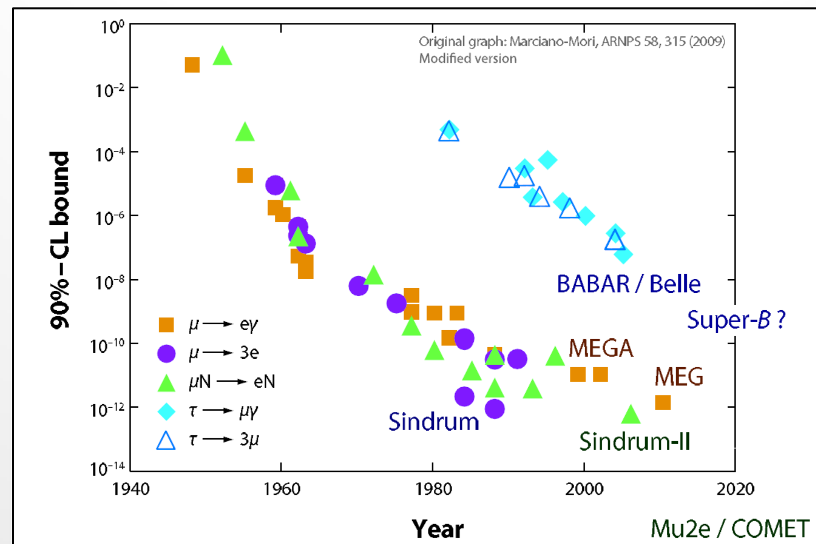
Charged Lepton Flavour Violation

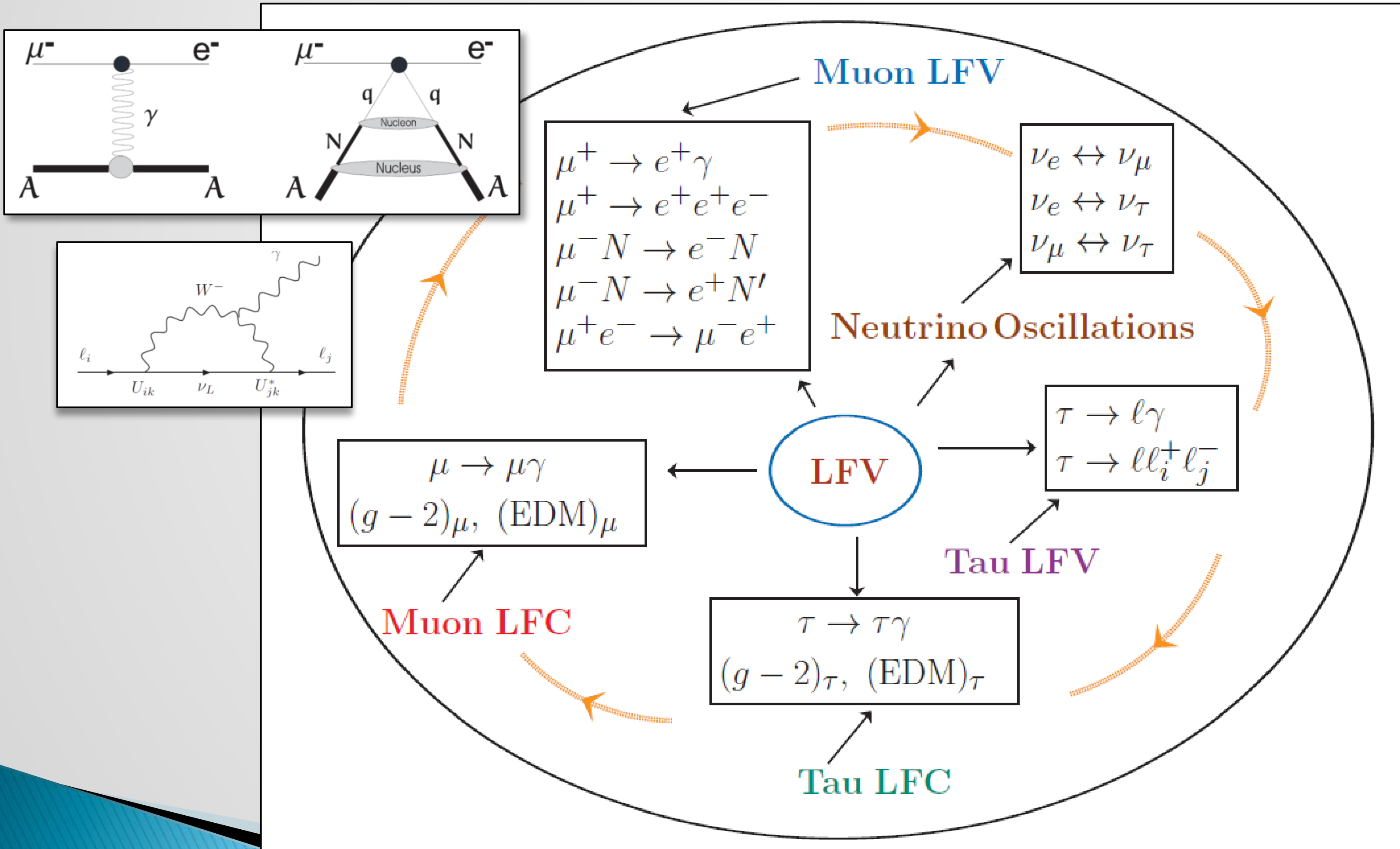
- Current experimental situation (future sensitivity)
  - $Br(\mu \to e\gamma) < 5.7 \times 10^{-13}$ @ MEG ($\approx 10^{-13}$ @ MEG)
  - $Br(\mu \to eee) < 1.0 \times 10^{-12}$ @ SINDRUM-I ($\approx 10^{-15}$ @ MuSIC, μ3e)
  - $R(\mu \to e, Au) < 7.0 \times 10^{-13}$ @ SINDRUM-II ($\approx 10^{-16}$ @ COMET, Mu2e)
  - $Br(\tau \to l\gamma) < 4.0 \times 10^{-8}$ @ Belle, Babar ($\approx 10^{-9}$ @ SuperB factory)





Lepton Flavour Physics

- Connection between observables



Effective Operator Approach

- Describe LFV processes using effective, non-renormalizable interactions,

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{M_{\text{NP}}^2}\mathcal{L}_5 + \frac{1}{M_{\text{NP}}^2}\mathcal{L}_6 + \cdots$$

$$\mathcal{L}_n = \sum_i C_n^i \mathcal{O}_n^i(\text{SM fields}) + h.c.$$

  - Dimension-5

    $$\mathcal{O}_5 = 1/2\,(\bar{L}_i \cdot H)(H^+ \cdot L_j)^c$$ → Neutrino Majorana masses

  - Dimension-6
    - Two Lepton-Higgs-Photon

      $$\mathcal{O}_6(ll\gamma H) = \bar{L}_i \sigma^{\mu\nu} e_j^c H^+ F_{\mu\nu}$$ → $\mu \to e\gamma$ etc., $g-2$, EDMs

    - Four Lepton

      $$\mathcal{O}_6(llll) = (\bar{L}_i \gamma^\mu L_j)(\bar{L}_k \gamma^\mu L_l), \text{ etc.}$$ → $\mu \to eee$ etc., NSIs in neutrino oscillations

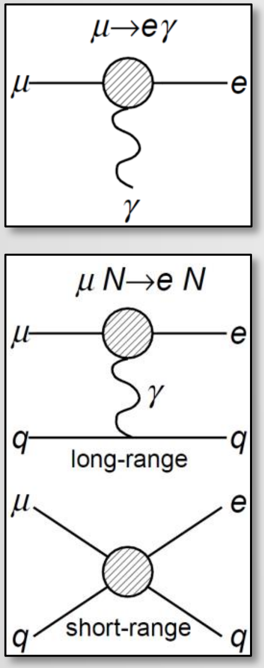
    - Two Lepton-Two Quark

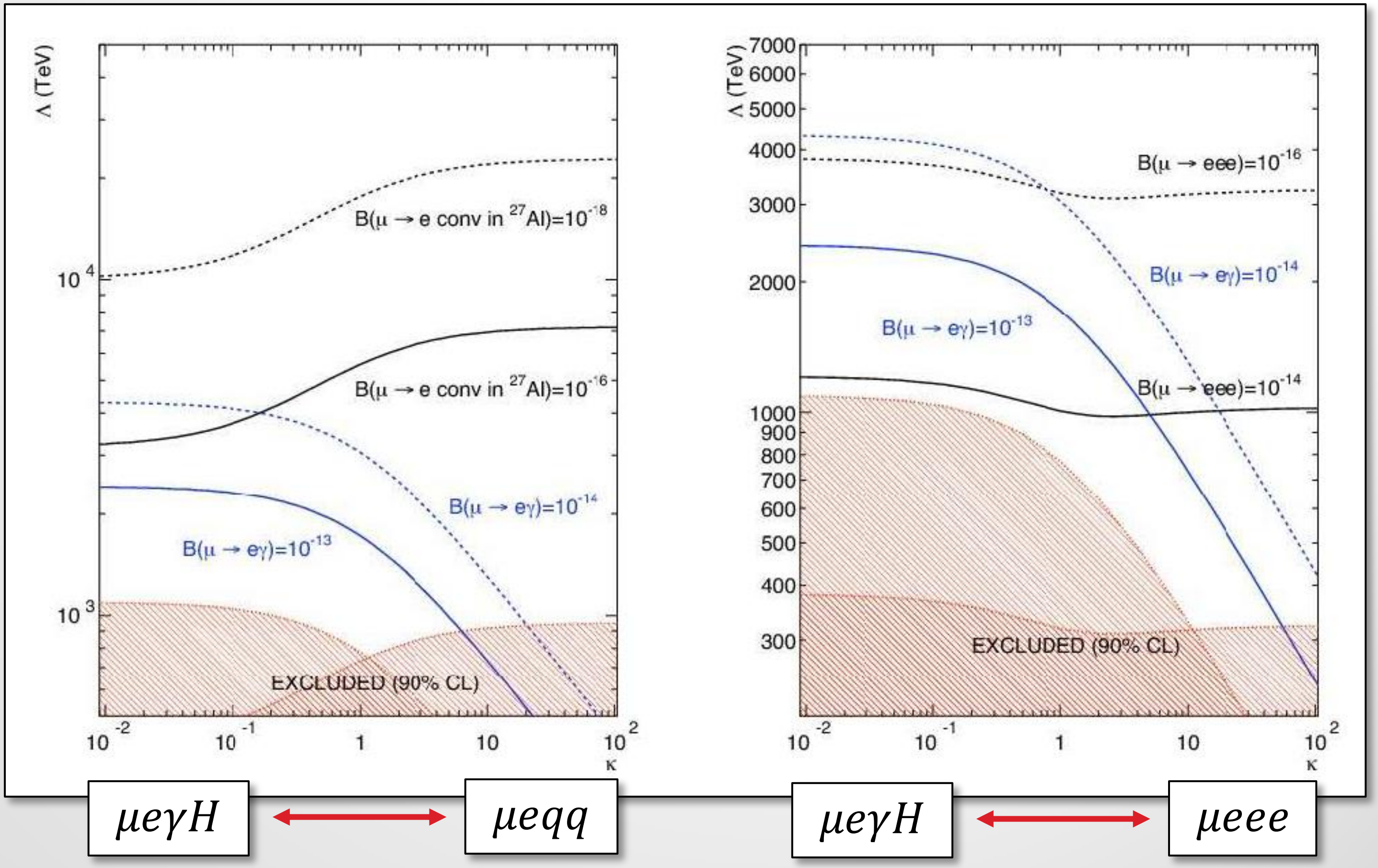
      $$\mathcal{O}_6(llqq) = (\bar{L}_i \gamma^\mu L_j)(\bar{Q}_k \gamma^\mu Q_l), \text{ etc.}$$ → $\mu \to e$ conversion in nuclei, Meson decays

Effective Operator Approach

- Different processes probe different (combinations of) operators

de Gouvea, Vogel '13





Effective Operator Approach

- Different flavour transitions probe flavour structure
- Compare two example discrete flavour symmetries

$$\boxed{A_4 \times Z_3 \times U(1)_{FN}}$$

$$\boxed{S_4 \times Z_3 \times U(1)_{FN}}$$

- Dipole operator coefficients

$$C \approx \begin{pmatrix} \lambda^2\epsilon & \lambda^2\epsilon^2 & \lambda^2\epsilon^2 \\ \lambda\epsilon^2 & \lambda\epsilon & \lambda\epsilon^2 \\ \epsilon^2 & \epsilon^2 & \epsilon \end{pmatrix},$$

$$C \approx \begin{pmatrix} \lambda^2\epsilon^2 & \lambda^2\epsilon^2\epsilon' & \lambda^2\epsilon^2\epsilon \\ \lambda\epsilon\epsilon' & \lambda\epsilon & \lambda\epsilon\epsilon'^2 \\ \epsilon\epsilon' & \epsilon\epsilon'^2 & \epsilon \end{pmatrix},$$

- LFV process rates

$$Br(\mu \to e\gamma) \approx Br(\tau \to e\gamma) \approx Br(\tau \to \mu\gamma).$$

$$Br(\mu \to e\gamma) \approx Br(\tau \to e\gamma) \gg Br(\tau \to \mu\gamma).$$

The Flavour Problem

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The BSM Flavour Problem

- Stringent limits on NP operators, e.g.

$$\boxed{Br(l_i \to l_j\gamma) \approx \frac{24\sqrt{2}\pi^3\alpha}{G_F^3 m_{l_i}^2 M_{NP}^4}|C_{ij}|^2}$$

  - $Br(\mu \to e\gamma) < 5.7 \times 10^{-13} \quad \Rightarrow \quad |C_{\mu e}| < 5 \times 10^{-9}\left(\frac{M_{NP}}{\mathrm{TeV}}\right)^2$
  - $Br(\tau \to l\gamma) < 4.0 \times 10^{-8} \quad \Rightarrow \quad |C_{\tau l}| < 6 \times 10^{-7}\left(\frac{M_{NP}}{\mathrm{TeV}}\right)^2, \ l = e, \mu$
- LFV couplings must be suppressed and/or New Physics scale is larger $\approx 10^3$ TeV
- Solutions
  - No New Physics at the TeV scale
  - Specific flavour structure of New Physics
    - Degeneracy
    - Symmetry (e.g. Minimal Flavour Violation)

Effective Mass and Seesaw

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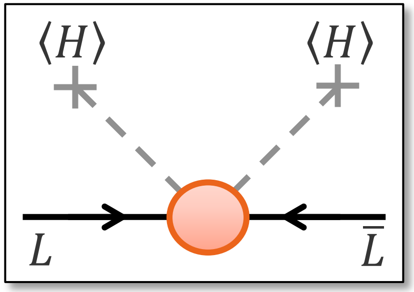
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

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

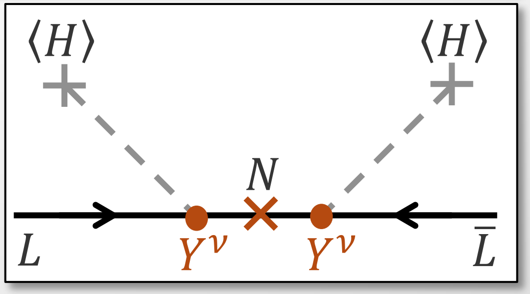


- Seesaw Mechanism
  - Add right-handed neutrinos N_i to SM, $M_N \approx 10^{14}$ GeV

$$\mathcal{L} \supset Y_{ij}^\nu \bar{N}_i L_j \cdot H - \frac{1}{2} M_{ij} \bar{N}_i N_j^c \xrightarrow[\mu \ll M_N]{} \frac{1}{2}(Y_{ki}^\nu M_{kl}^{-1} Y_{lj}^\nu)(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right)$$

- Light neutrino mass

$$m_\nu \approx 0.1 \text{ eV} \left(\frac{Y_\nu \langle H \rangle}{100 \text{ GeV}}\right)^2 \left(\frac{10^{14} \text{ GeV}}{M}\right)$$



Effective Mass and Seesaw

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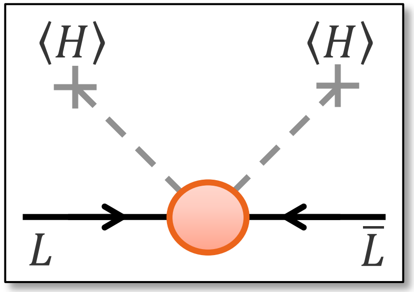

- Seesaw Mechanism
  - Sterile Neutrino Mass Scale Unknown
    - $\approx 10^{14}$ GeV — Naïve Seesaw, GUTs
    - $\gtrsim 10^{9}$ GeV — Thermal Leptogenesis
    - **$\approx 10^{3}$ GeV — Resonant Leptogenesis, LFV Contribution Production at LHC**
    - ≈ 1 keV — Dark Matter Candidate
    - ≈ 1 eV — Oscillation, Cosmology, $0\nu\beta\beta$

Effective Mass and Seesaw

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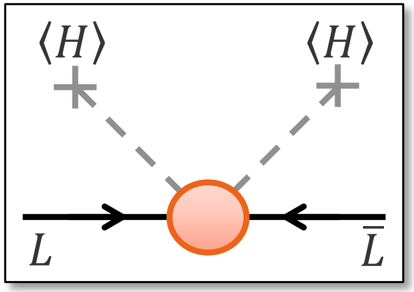
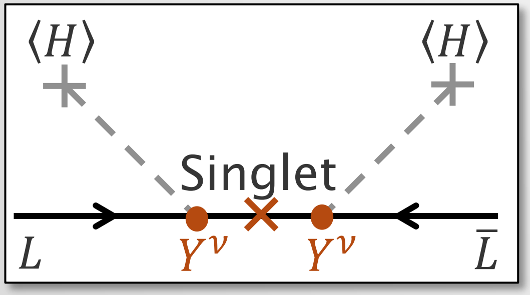
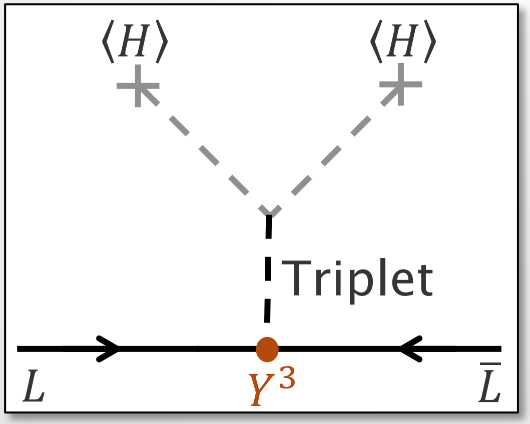


- Seesaw Mechanism
  - Three possible mediators at tree level

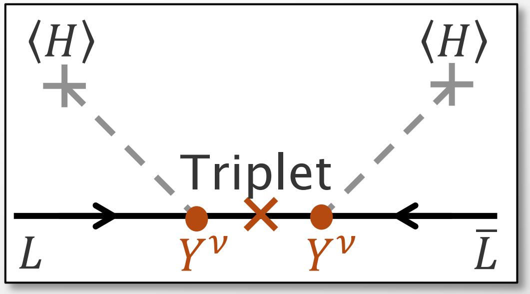
Seesaw I



Seesaw II



Seesaw III



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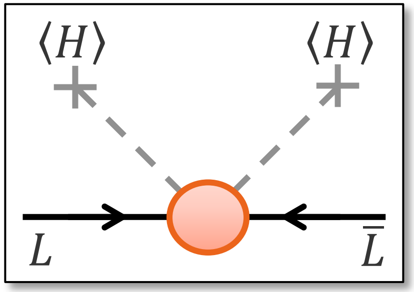
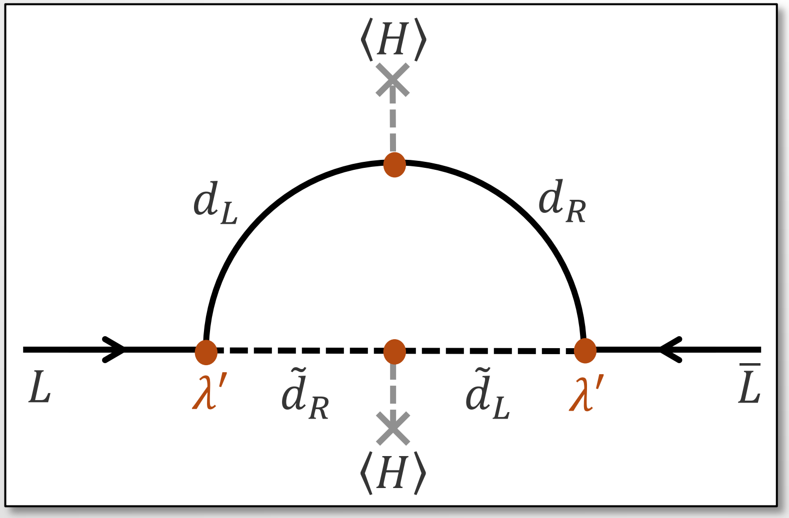


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. R-Parity Violating SUSY



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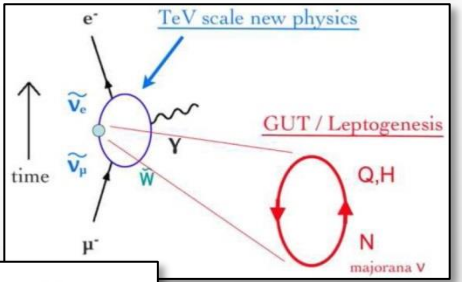
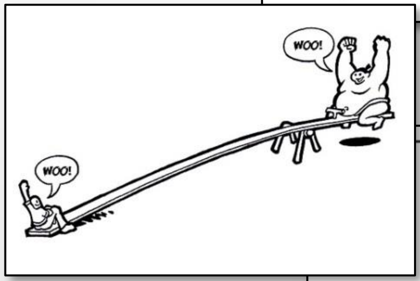
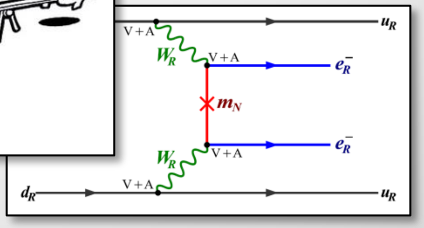
Problems of Naïve Seesaw

- Introduces high energy scale
- Right-handed neutrinos are singlets
  - Couple only via small mixture with active neutrinos
- Mechanism not testable with low energy observables
  - Negligible charged LFV
- Possible Solutions
  - SUSY Seesaw
    - Testable LFV effects from sleptons
  - "Bent" Seesaw mechanisms
    - Decouple Λ_{LNV} from heavy neutrino mass
  - Left-Right symmetric models
    - Right-handed neutrinos couple with gauge strength to charged leptons







Small Yukawas vs "Bent" Seesaw

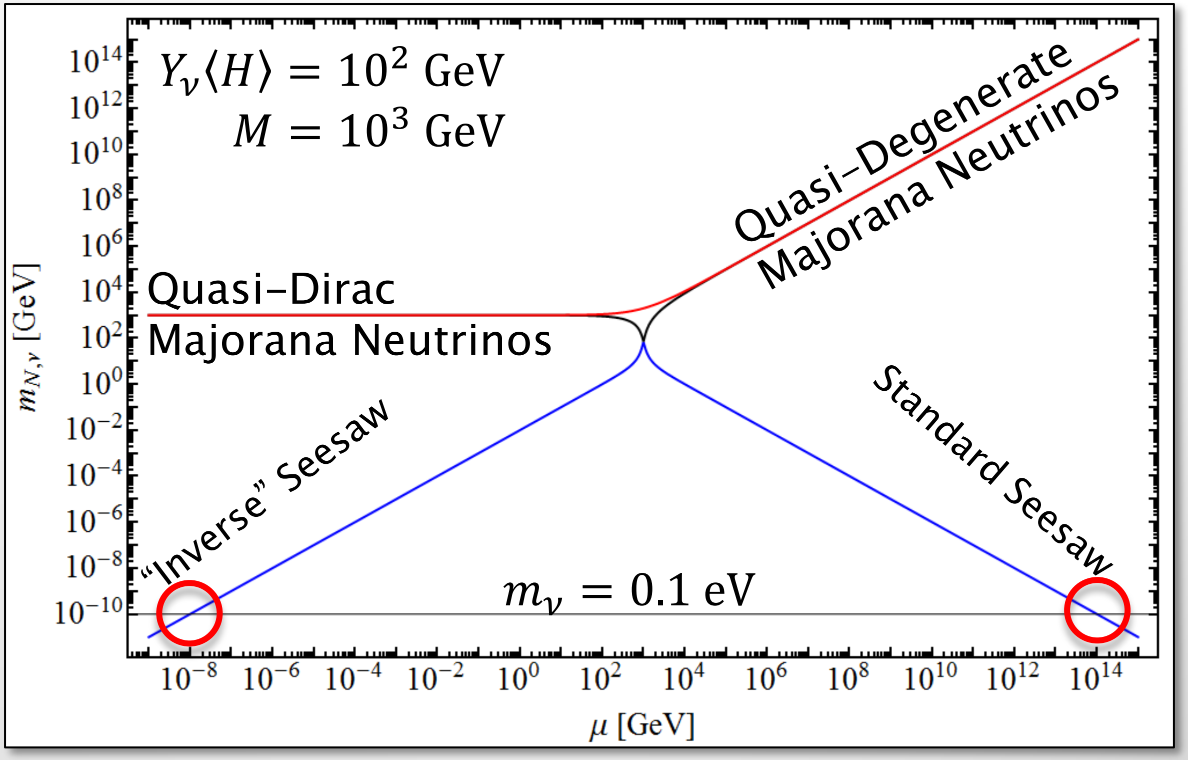
- Seesaw Mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings
    - Charged LFV remains small

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

  - "Bent" Seesaw mechanisms
    - Decouple Λ_{LNV} from heavy neutrino mass
    - Example

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

    - Potentially large charged LFV
    - In the limit $\mu \to 0$, no LNV but LFV



Left–Right Symmetric Models

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- 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 + $\mathrm{SU}(2)_R$)
- Generating N_i, W_R, Z_R masses $M_{N_i} \approx M_{W_R} \approx M_{Z_R} \approx \langle H_R \rangle \approx 0.5 - 5\,\mathrm{TeV}$
- General Seesaw I+II mechanism $M_\nu = \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix},$
- Charged current weak interactions

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

Neglect any Left-Right mixing

$$J_{W_L}^{\mu-} \approx \frac{g_L}{\sqrt{2}} U_{\ell i} \bar{\nu}_i \gamma^\mu \ell_L,$$
$$J_{W_R}^{\mu-} \approx \frac{g_R}{\sqrt{2}} V_{\ell i} \bar{N}_i \gamma^\mu \ell_R,$$

Rare LFV Processes

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

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

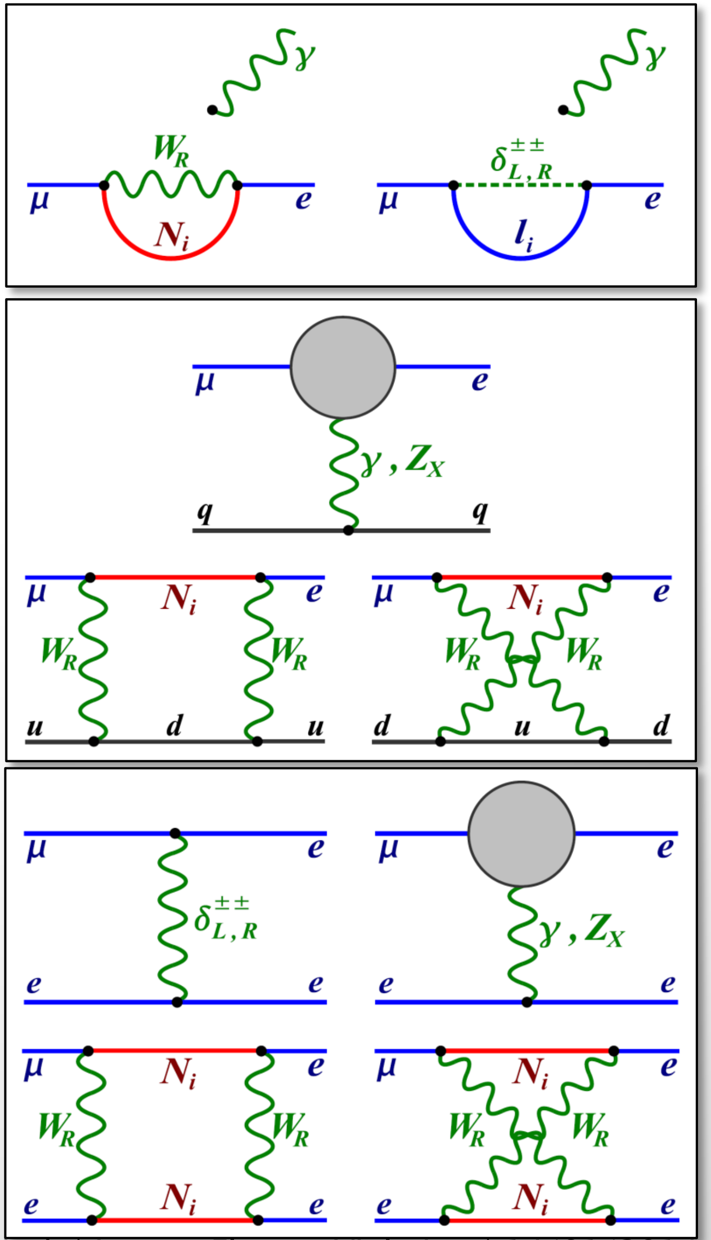
- μ–e conversion in nuclei enhanced via box diagrams

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

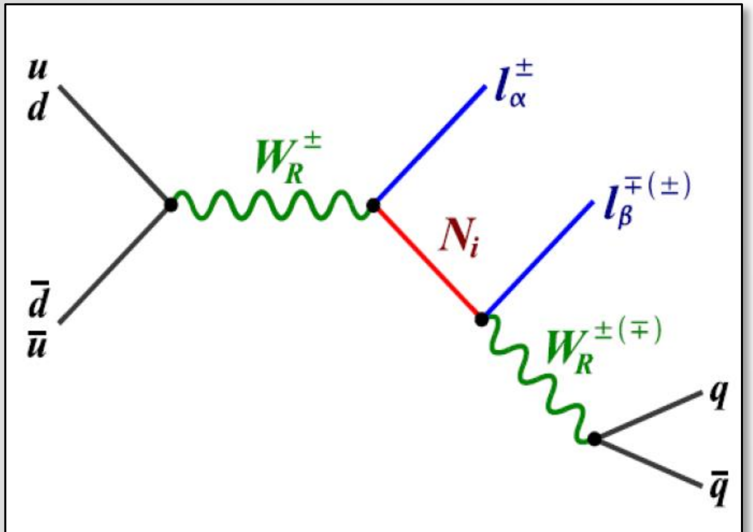
- $\mu \to eee$ strongly enhanced due to tree level contribution

$$Br(\mu \to eee) \approx 300 \times Br(\mu \to e\gamma)$$

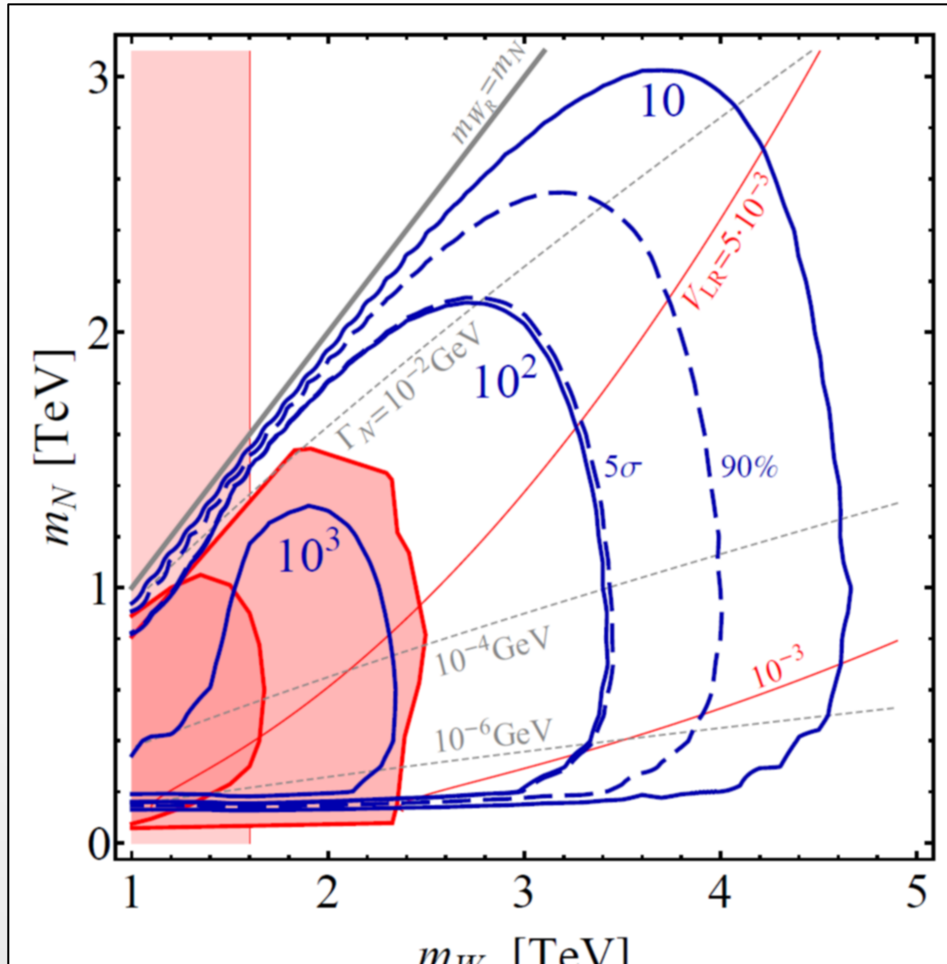
- BSM Flavour Problem
  - Small mixing and/or mass differences required



LHC Searches



- Monte Carlo Simulation (PROTOS)
- Main background $t\bar{t}$, Z + jets (Pythia, Alpgen)
- Fast Detector Simulation (AcerDET)
- Selection Criteria
  - Number of jets $N_j > 2$
  - Number of isolated leptons $N_l = 2$
  - Invariant di-lepton mass $m_{ll} > 300$ GeV
  - Total invariant mass $m_{lljj} > 1.5$ TeV

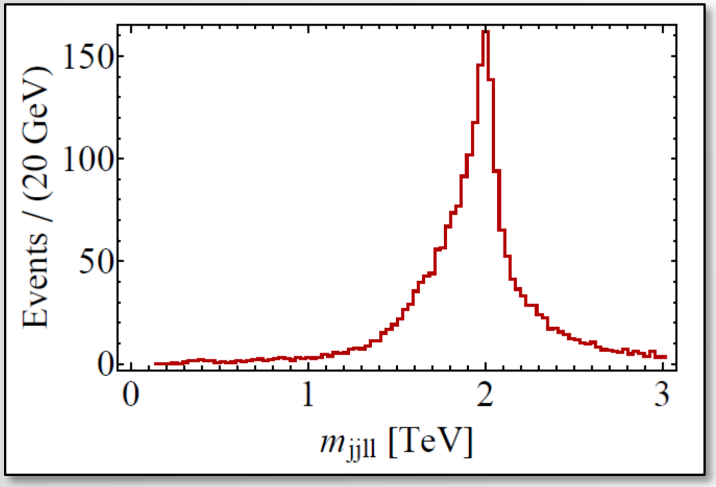


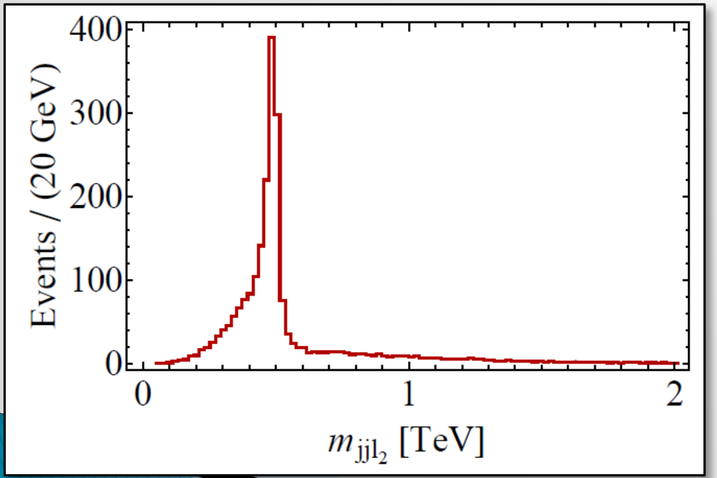
Das, FFD, Kittel, Valle '12

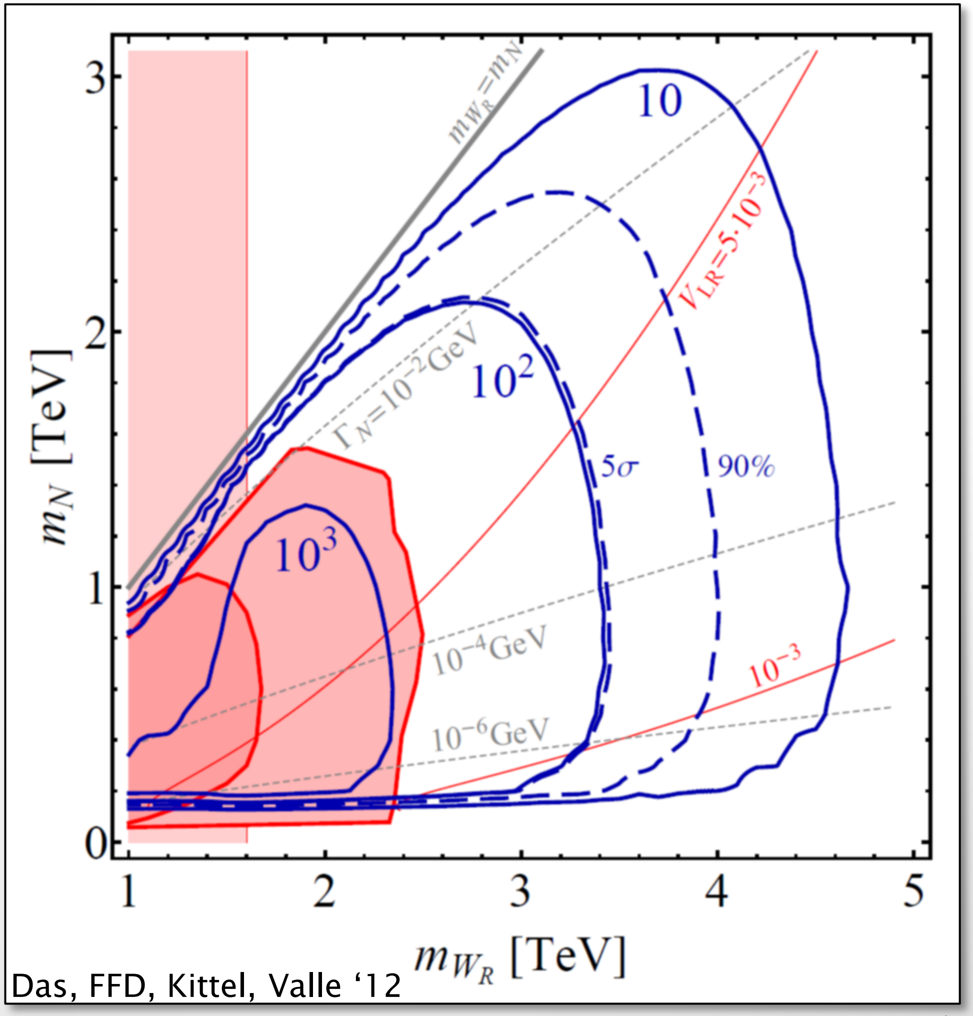
LHC reach @ 14 TeV, 30 fb^{-1}

LHC Searches

- Reconstruct W_R and N







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

LFV at the LHC

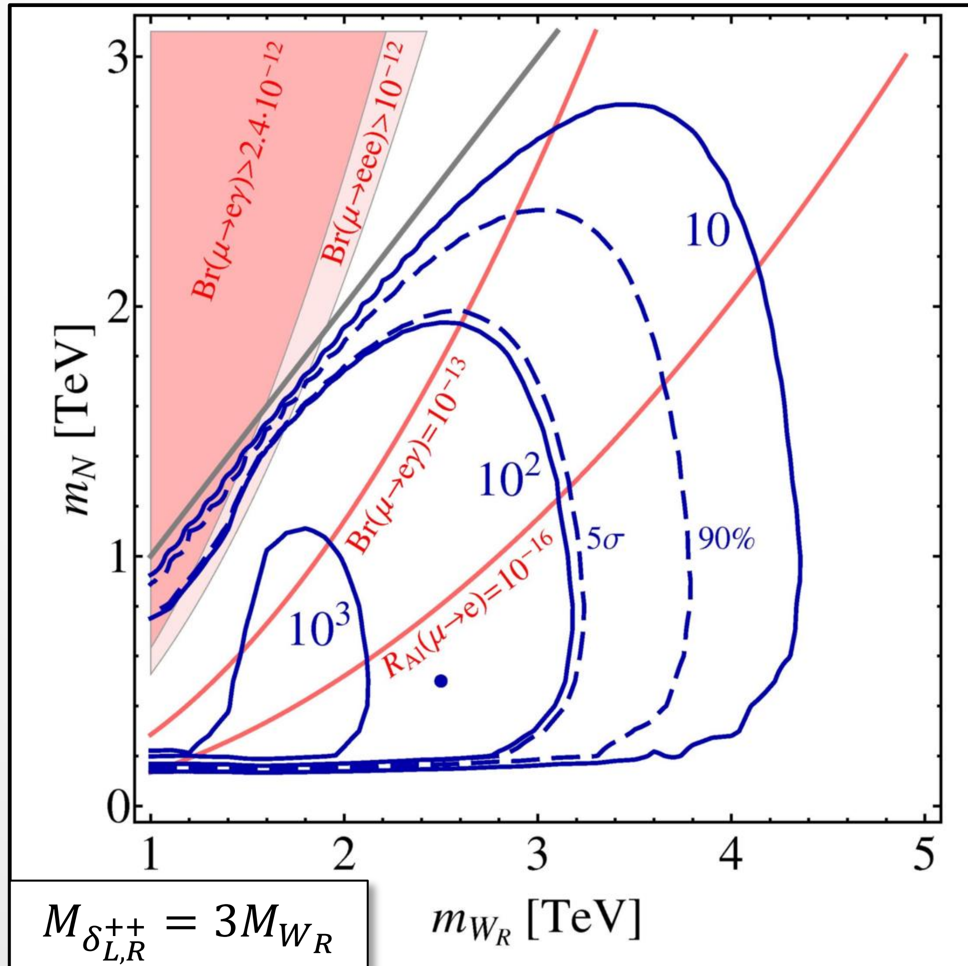
University College London

- Two heavy neutrinos with maximal mixing and 1% mass splitting

$$
\begin{array}{cc}
 & \begin{array}{ccc} \nu_L & N_e & N_\mu \end{array} \\
 & \begin{pmatrix} U_{PMNS} & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{array}{c} \nu_L \\ N_e \\ N_\mu \end{array}
\end{array}
$$

$$\theta = \pi/4$$

- Correlation with low energy LFV processes



$M_{\delta^{++}_{L,R}} = 3M_{W_R}$

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

LFV at the LHC

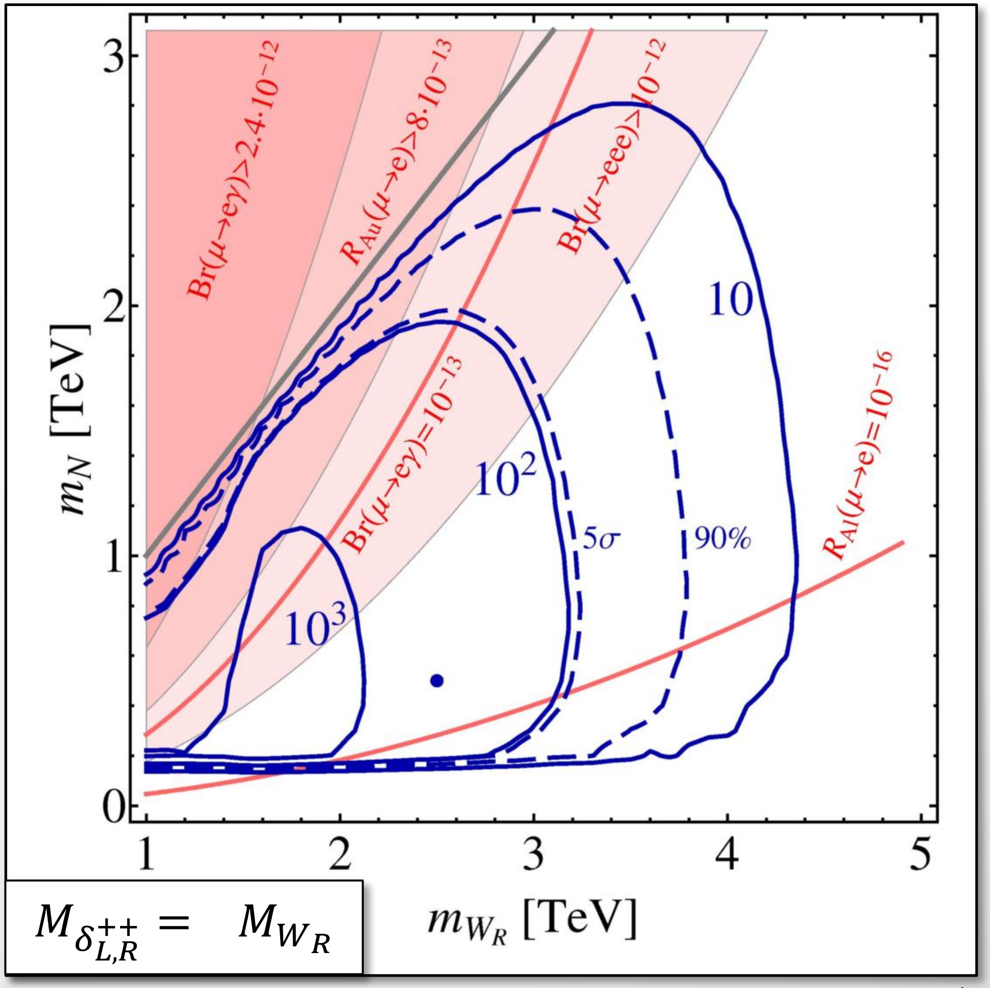
University College London

- Two heavy neutrinos with maximal mixing and 1% mass splitting

$$
\begin{array}{cccc}
\nu_L & N_e & N_\mu & \\
\left(\begin{array}{ccc} U_{PMNS} & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{array}\right) & & & \begin{array}{c}\nu_L \\ N_e \\ N_\mu\end{array}
\end{array}
$$

$$\theta = \pi/4$$

- Correlation with low energy LFV processes



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

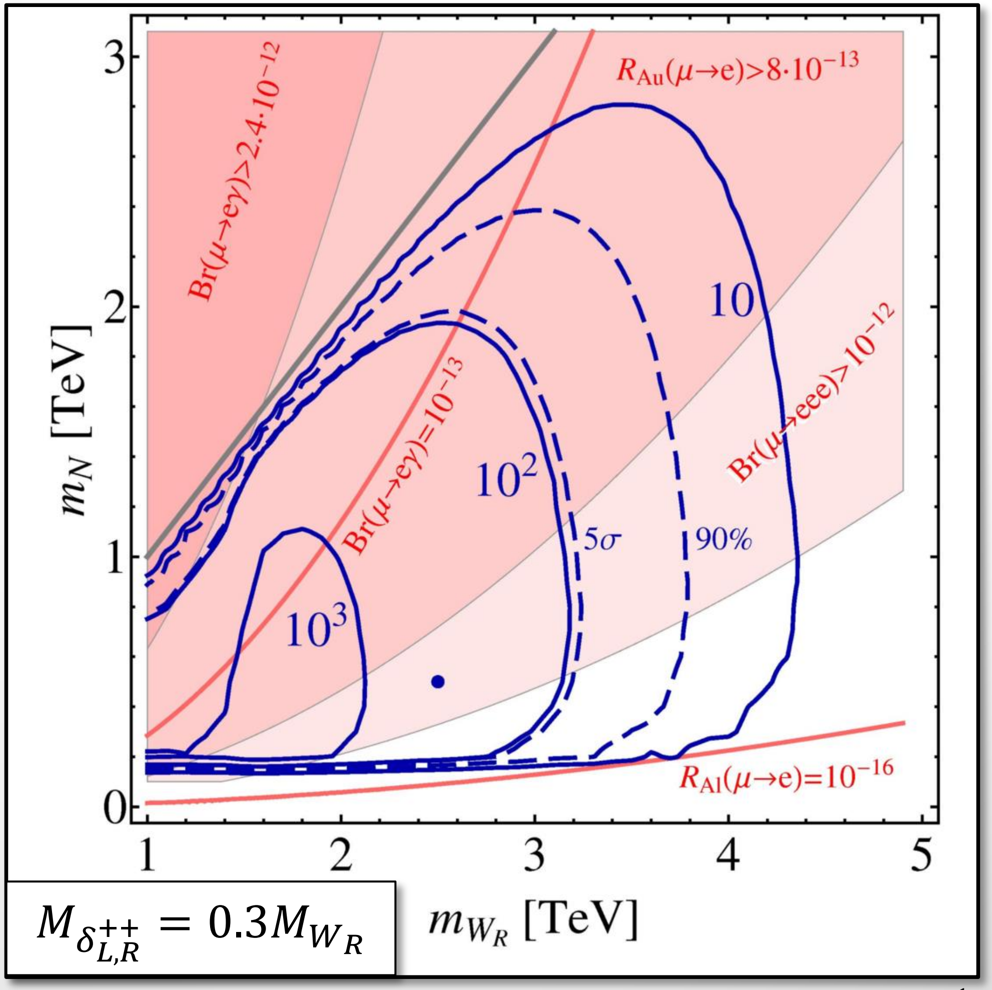
LFV at the LHC

- Two heavy neutrinos with maximal mixing and 1% mass splitting

$$\begin{array}{cc} & \begin{array}{ccc} \nu_L & N_e & N_\mu \end{array} \\ & \begin{pmatrix} U_{PMNS} & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix} \begin{array}{c} \nu_L \\ N_e \\ N_\mu \end{array} \end{array}$$

$$\boxed{\theta = \pi/4}$$

- Correlation with low energy LFV processes



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

LFV at the LHC

University College London

- Two heavy neutrinos with mixing angle θ and mass splitting ΔM_N

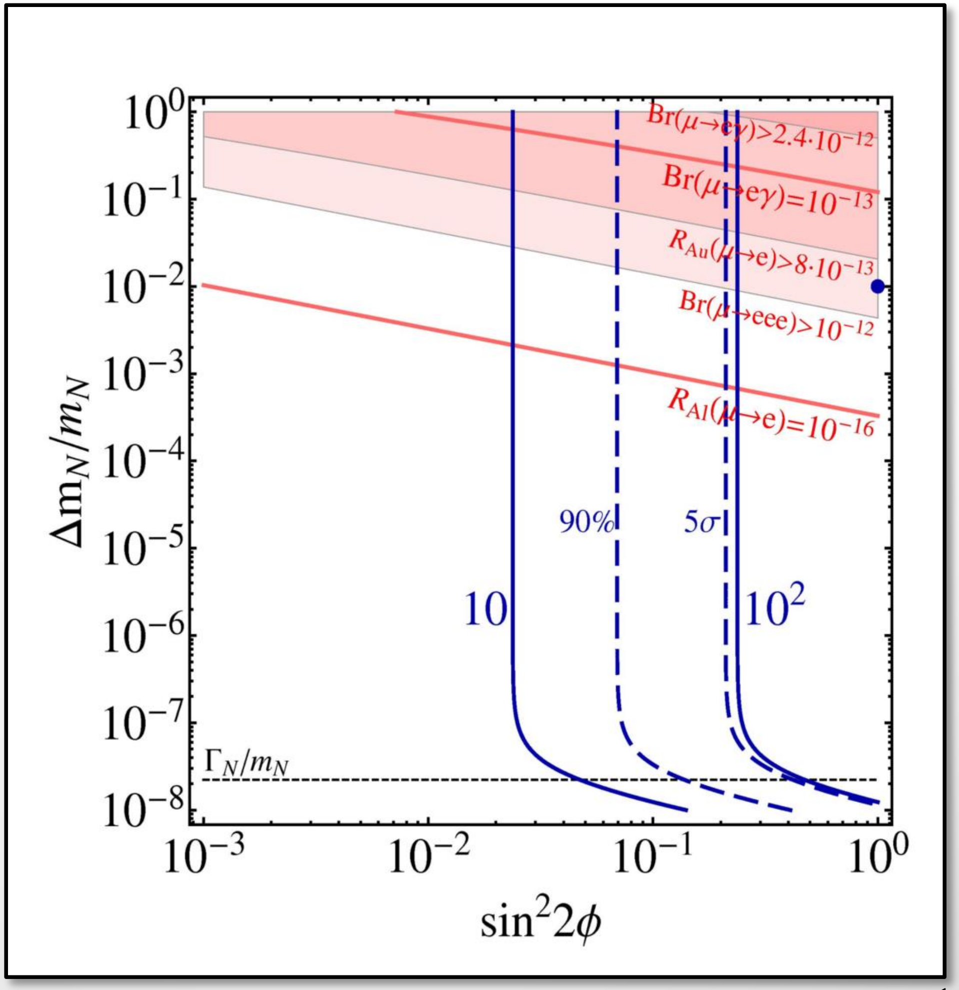
$$\begin{array}{cccc} \nu_L & N_e & N_\mu & \\ \left(\begin{array}{ccc} U_{PMNS} & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{array}\right) & & & \begin{array}{c} \nu_L \\ N_e \\ N_\mu \end{array} \end{array}$$

suppressed as

$$\boxed{\sigma_{LHC} \propto \Delta M_N^2/(M_N \Gamma_N)}$$

- Correlation with low energy LFV processes suppressed as

$$\boxed{\propto \Delta M_N^2/M_N^2}$$



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

Conclusion

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- **LFV is crucial probe for BSM physics**
  - Discovery is smoking gun for BSM physics
  - Strong experimental program with high sensitivity $\Lambda \approx 10^{3-4}$ TeV
  - Observation is critical to solve flavour puzzle
  - Experimental problem: Comparatively weak sensitivity to τ
- **Strong connection to neutrino physics**
  - Oscillations demonstrate that lepton flavour is violated
  - Models of neutrino mass generation predict wildly different LFV rates → LFV can be used to discriminate
- **Synergy with LHC searches**
  - Potential to observe charged Lepton Flavour Violation
  - Complementarity of Observables