Charged Lepton Flavour Violation BSModels

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Flavour Physics Conference | Quy Nhon | 27/01-02/08/2014

Lepton Flavour versus Lepton Number Violation

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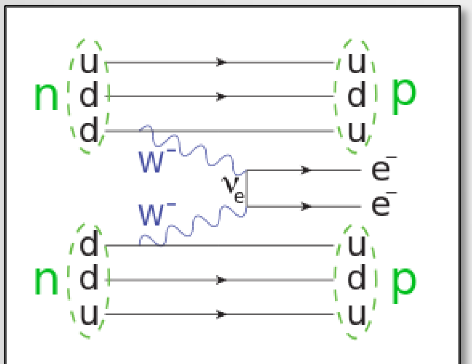
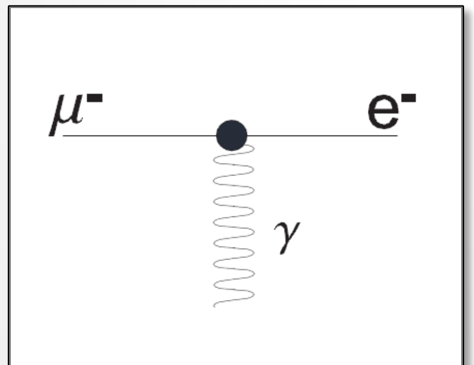
Neutrinoless double beta decay



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

Lepton Number Violation

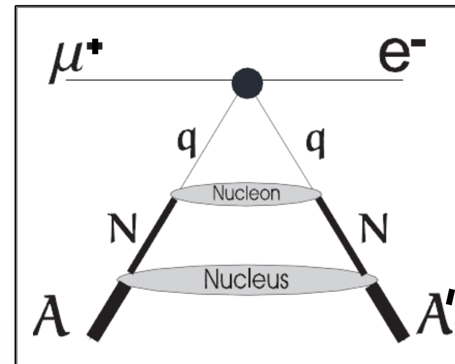
$\boldsymbol{\mu^- \to e^- \gamma}$



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

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

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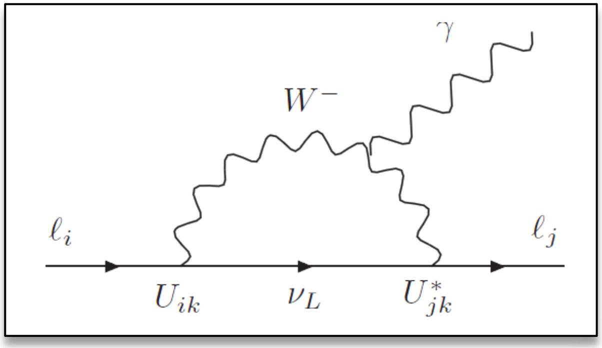
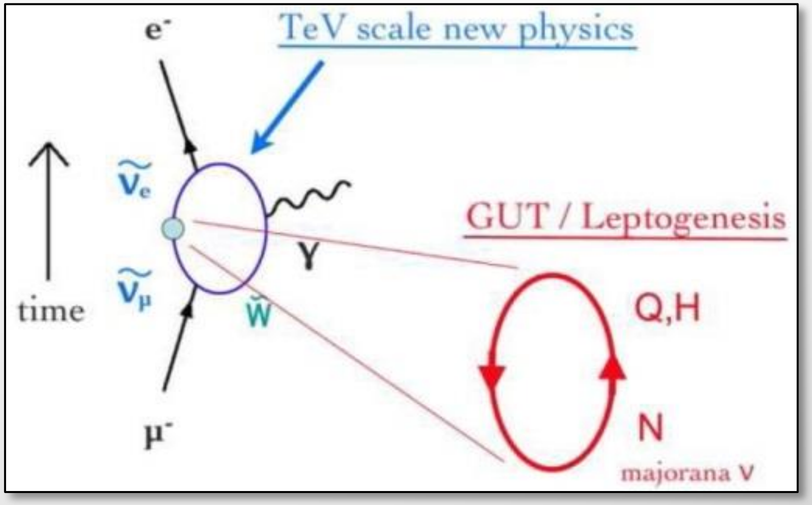
- Charged Lepton Flavour (practically) conserved in the SM (+ light ν)
  - LFV is clear sign for BSM physics

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



- Flavour violation in the quark and neutrino sector
  - Strong case to look for CLFV
- Generic BSModels at TeV scale with couplings to leptons lead to large CLFV
- CLFV can shed light on
  - Grand Unification models
  - Flavour symmetries
  - Origin of flavour



(Charged) LFV Models

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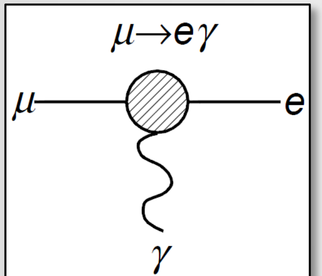
- Models of Neutrino Mass Generation around the TeV scale
  - **Seesaw Models**
    - I, II, III, Inverse etc.
  - Radiative Mass Models
    - Zee, **Babu-Zee**, etc.
- Supersymmetry
  - **R-Parity Conserving**
    - Arbitrary slepton masses or in combination with high-scale Seesaw
  - R-Parity Violating
    - L-violating couplings, Neutrino mass generation
- Extended Higgs/Gauge Sectors
  - Left-Right Symmetry, Little Higgs, Additional Doublets, etc.
- Extra Dimensions

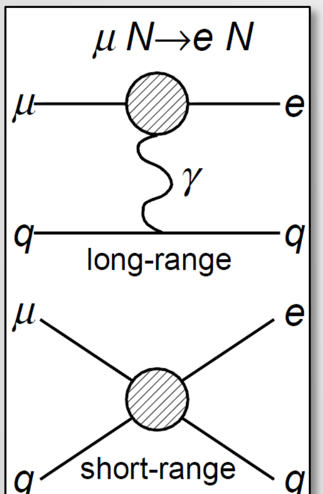
… etc.

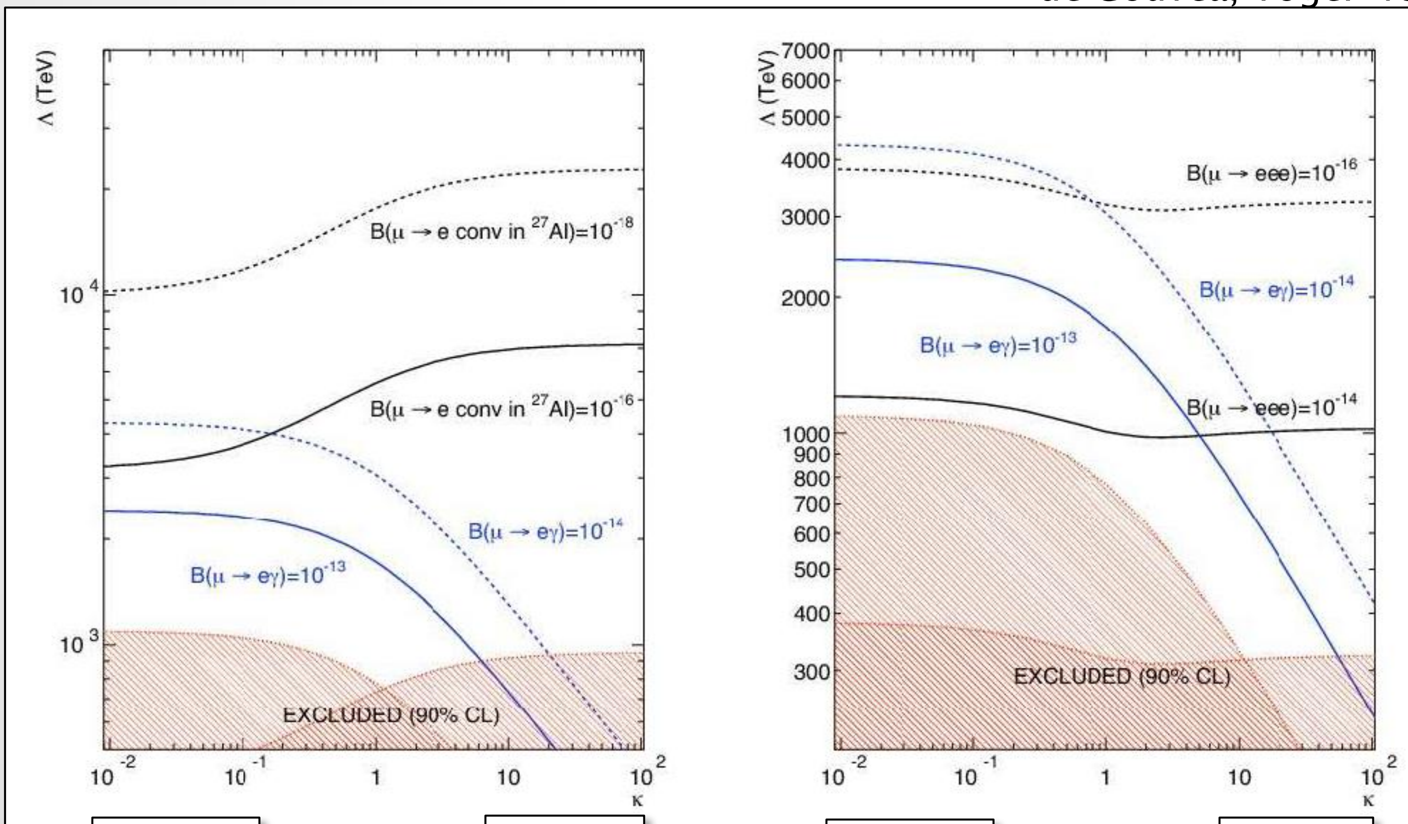
Effective Operators

- Models excite different (combinations of) operators

de Gouvea, Vogel '13







$\mu e\gamma H$ ↔ μeqq

$\mu e\gamma H$ ↔ μeee

BSM Flavour Problem

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- Stringent limits on NP operators, e.g.

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

  - $Br(\mu \to e\gamma) < 5.7 \times 10^{-13} \quad \Rightarrow \quad |C_{\mu e}| < 5 \times 10^{-9} \left(\frac{M_{NP}}{\mathrm{TeV}}\right)^2$
  - $Br(\tau \to l\gamma) < 4.0 \times 10^{-8} \quad \Rightarrow \quad |C_{\tau l}| < 6 \times 10^{-7} \left(\frac{M_{NP}}{\mathrm{TeV}}\right)^2, \ l = e, \mu$
- 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)

Neutrino Mass Models

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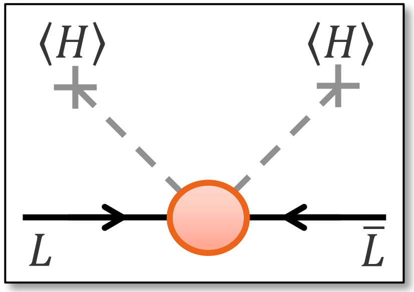
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM



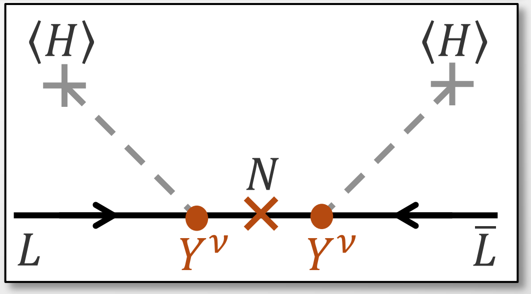
$$\mathcal{L} \supset \frac{1}{2}\frac{h_{ij}}{\Lambda_{LNV}}(\bar{L}_i^c \cdot H)\left(H^T \cdot L_j\right) \xrightarrow[\langle H\rangle]{} \frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i^c \nu_j$$

- Seesaw Mechanism
  - Add right-handed neutrinos N_i to SM

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

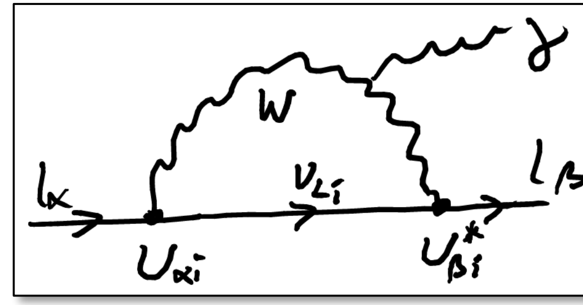
- Light neutrino mass

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



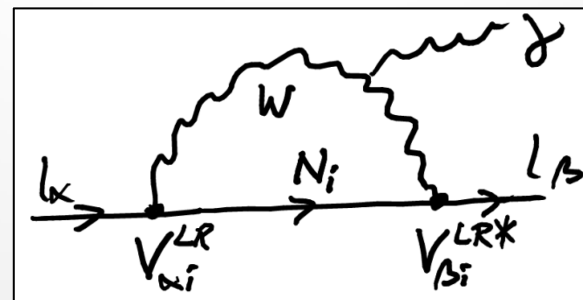
Neutrino Mass Models

- CLFV in the Seesaw Mechanism
  - Light neutrino exchange
    - Negligible due to small neutrino masses and ≈unitarity of PMNS mixing matrix



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

  - Heavy neutrino exchange
    - Sizable for TeV scale heavy neutrinos and large LR mixing $V^{LR} \approx 10^{-2}$



$$Br(\mu \to e\gamma) \approx 4 \times 10^{-3}\left|\sum_i V^{LR*}_{\mu i} V^{LR}_{ei}\, G\left(\frac{m^2_{N_i}}{m^2_W}\right)\right|^2 \approx 10^{-11}\left(\frac{V^{LR}}{10^{-2}}\right)^4$$

$$\mathcal{U}^\nu = \begin{pmatrix} U & V^{LR} \\ (V^{LR})^\intercal & U^R \end{pmatrix}$$

Neutrino Mass Models

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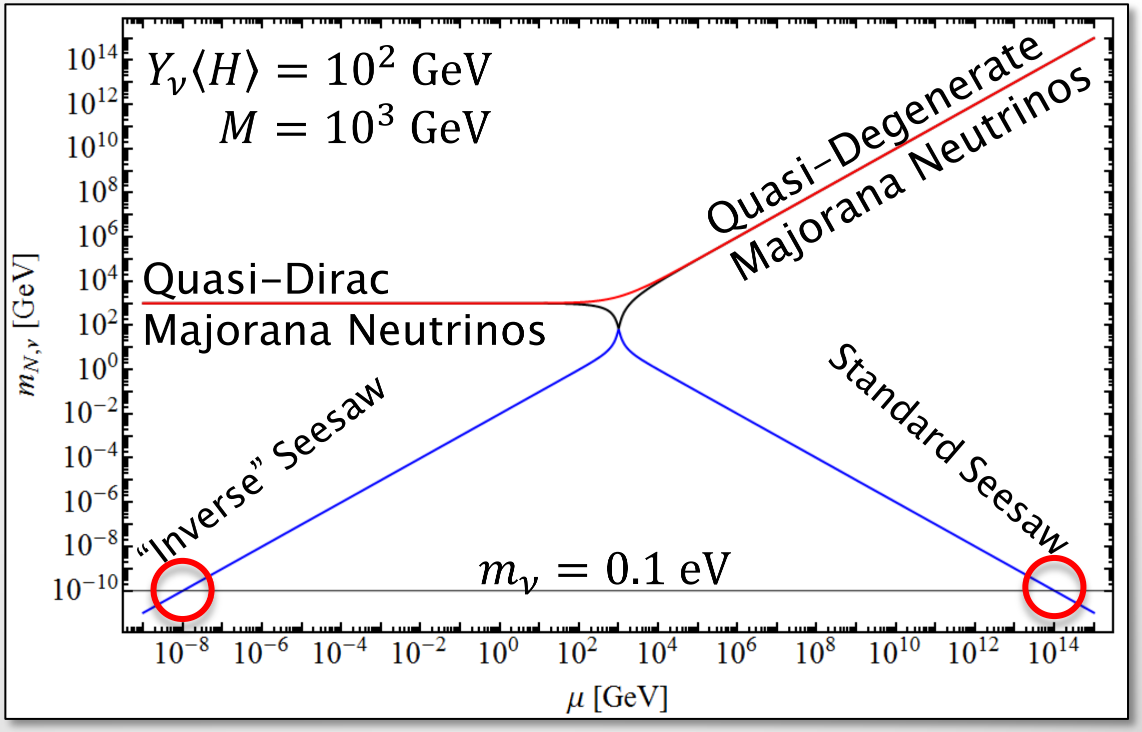
- Correct light neutrino masses for TeV scale heavy neutrinos
  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings
    - CLFV remains small

$$V^{LR} \approx Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$$

  - "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 CLFV
- In the limit $\mu \to 0$, no LNV but CLFV

Neutrino Mass Models

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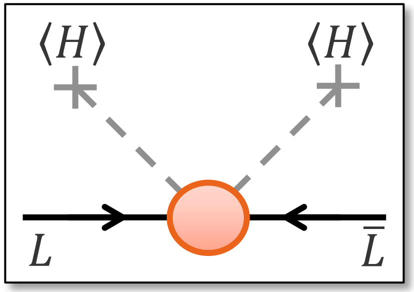
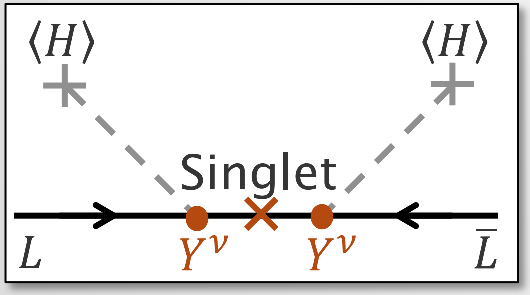
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

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

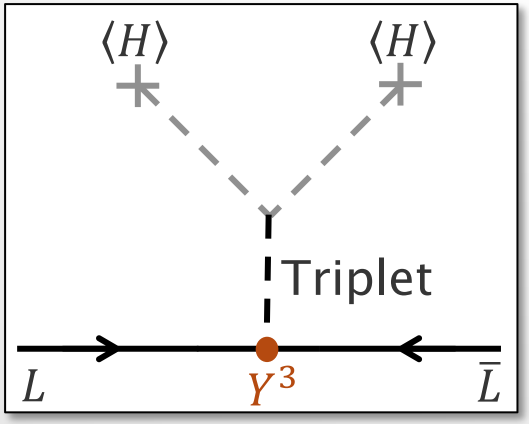


- Seesaw Mechanism

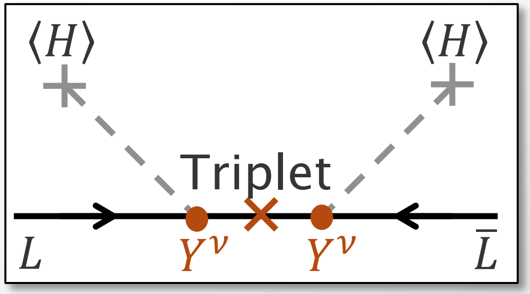
Seesaw I



Seesaw II



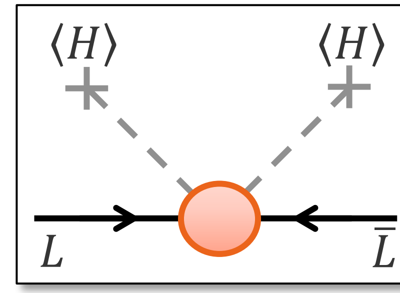
Seesaw III



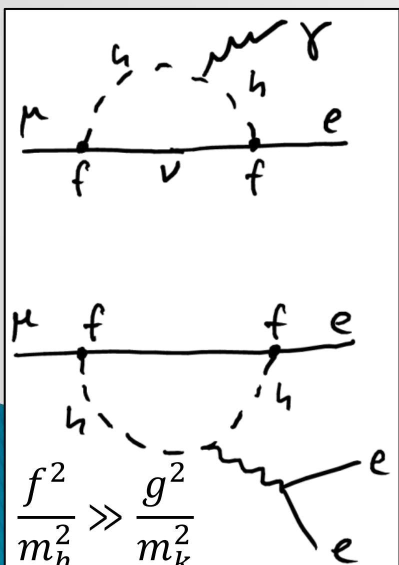
Neutrino Mass Models

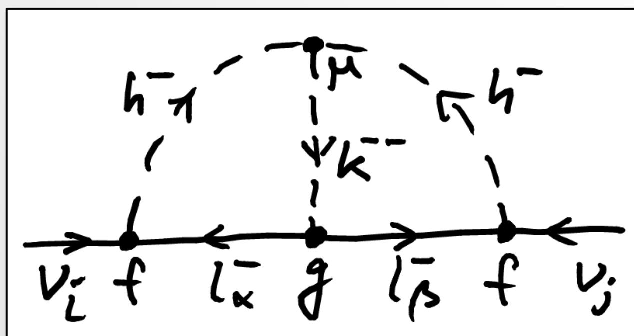
- Effective operator for Majorana neutrino mass
  - Only dimension-5 operator beyond SM

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

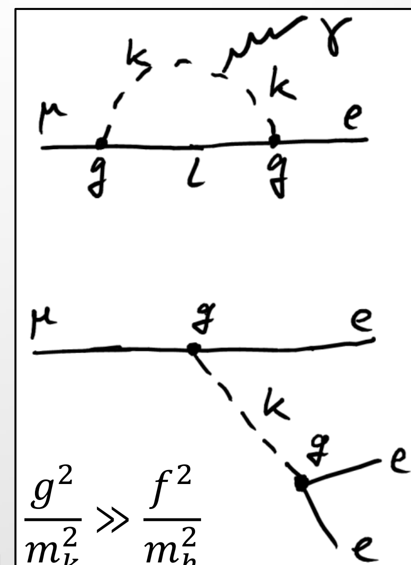


- Radiative Generation via Loops
  - Alternative to Seesaw, e.g. Babu-Zee model (Zee ’85, Babu ‘88)





Neutrino masses suppressed at 2-loop



SUSY Seesaw

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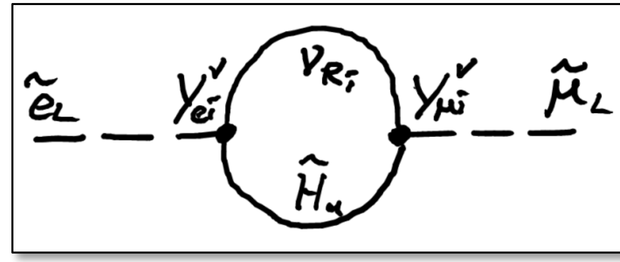
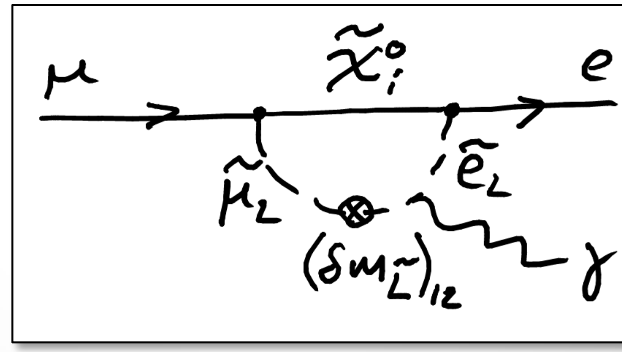
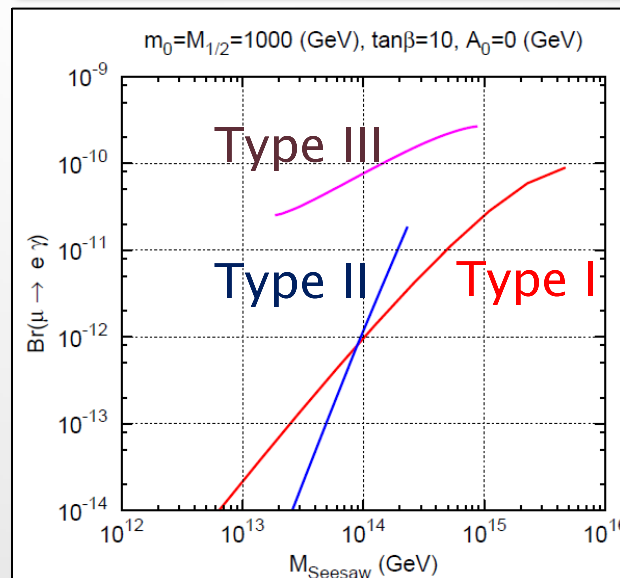
- Neutrino flavour mixing radiatively induces slepton flavour mixing
(Borzumati, Masiero '86)
- Correlation between slepton and neutrino flavour mixing (Type I)

$$\left(\delta m^2_{\tilde{L}}\right) = \begin{pmatrix} \delta_{11} & \delta_{12} & \delta_{13} \\ \delta^*_{12} & \delta_{22} & \delta_{23} \\ \delta^*_{13} & \delta^*_{23} & \delta_{33} \end{pmatrix} \propto \left(Y^{\nu\dagger} \cdot Y^{\nu}\right) \log(M_X/M_{\nu_R})$$

- Induces observable charged LFV rates despite high scale Seesaw $M_{\nu_R} \approx 10^{14}\mathrm{GeV}$



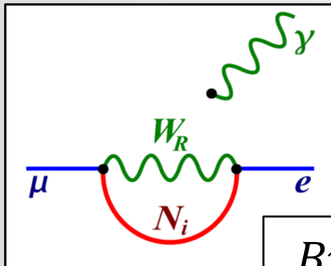




Esteves et al. '11

Observable High Energy CLFV at LHC?

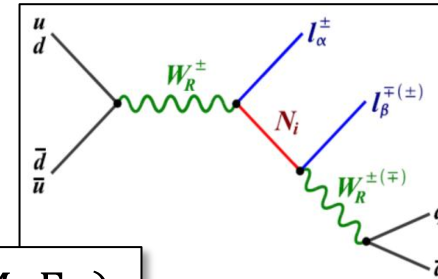
- $\tau\mu/\tau e$ flavour transitions less constrained ($h \to \mu\tau$ observed?)
- Small CLFV messenger mass splitting



Off-shell
GIM mechanism

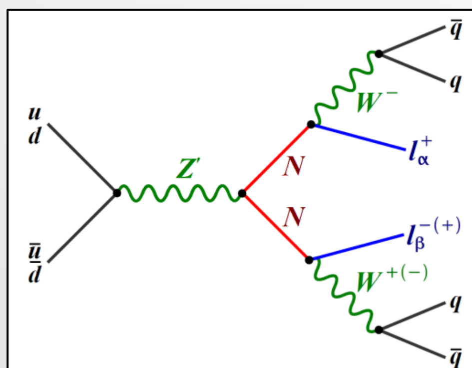
$Br(\mu \to e\gamma) \propto \Delta M_N^2 / M_{W_R}^2$

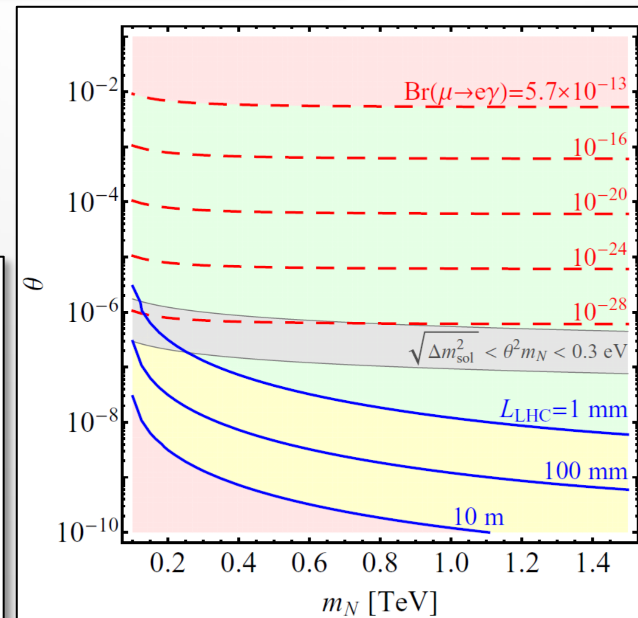
On-shell (resonant)
GIM mechanism



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

- CLFV through heavy portal
  (FFD, Desai, Valle, Phys. Rev. D89 051302)
  - N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$





Conclusion

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- **LFV is crucial probe for BSM physics**
  - Smoking gun for BSM physics
  - Strong experimental sensitivity $\Lambda \approx 10^{3-4}$ TeV
- **Connection to neutrino physics**
  - But possibly indirect (LNV vs LFV)
  - Models of neutrino mass predict wildly different CLFV rates
  - CLFV as discriminator
    - $\tau \to l\gamma$ vs $\mu \to e\gamma$ vs $\mu - e$ conversion vs $\mu \to eee$
    - $\mu - e$ conversion in different nuclei
- **Flavour Symmetries and Structures**
  - Discrete, Continuous, Textures, Minimal Flavour Violation
  - CLFV critical to solve flavour puzzle
- **Synergy with LHC searches**
  - Potential to observe CLFV (Already seen in $h \to \mu\tau$?)
  - Complementarity of Observables