Neutrinos and Physics Beyond the Standard Model

UCL

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Overview

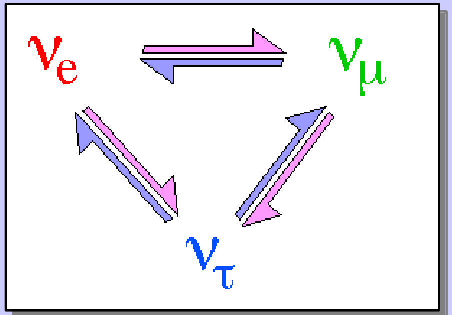
- **Neutrinos**
  - Oscillations
  - Absolute Mass
- **Neutrinoless Double Beta Decay**
- **Lepton Flavour Violation**
- **Neutrino Mass Generation**
  - Effective Operator and Seesaw Mechanism
  - SUSY Seesaw
  - Left-Right Symmetry
- **Conclusion**

Neutrino Oscillations

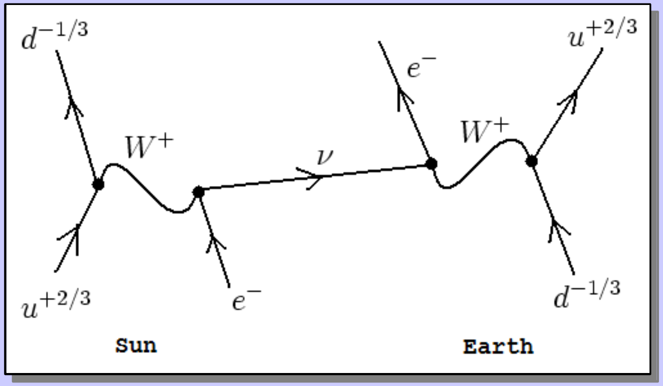
- **Neutrino interaction states different from mass eigenstates**
  Neutrino flavour can change through propagation

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

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



laguna-science.eu



- **Solar neutrino oscillations**
  Large mixing
- **Atmospheric oscillations**
  ≈ Maximal mixing
- **Reactor and accelerator neutrinos**
  Small, but significantly different from zero

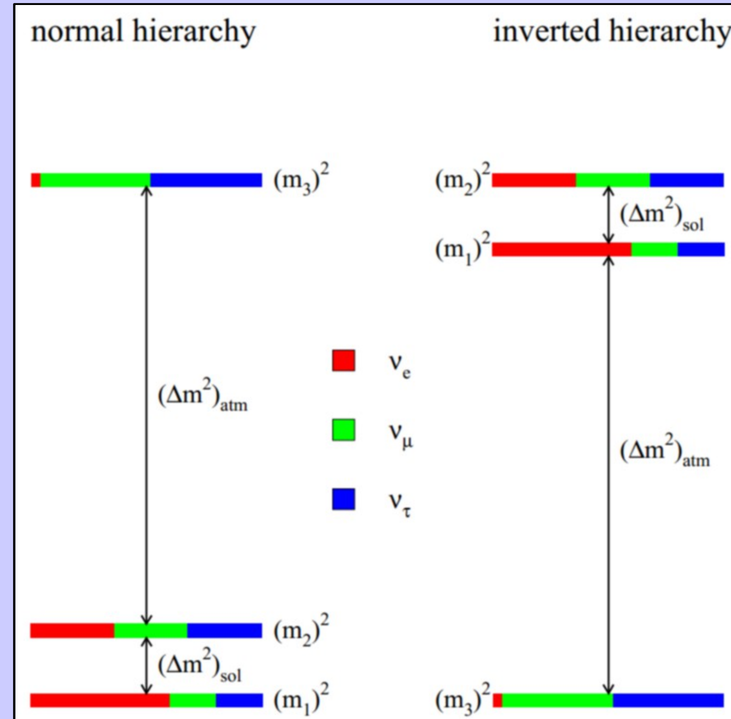
$$\sin^2(2\theta_{13}) = 0.092 \pm 0.021$$

- **Mixing Pattern very different from quarks**

Neutrino Oscillations

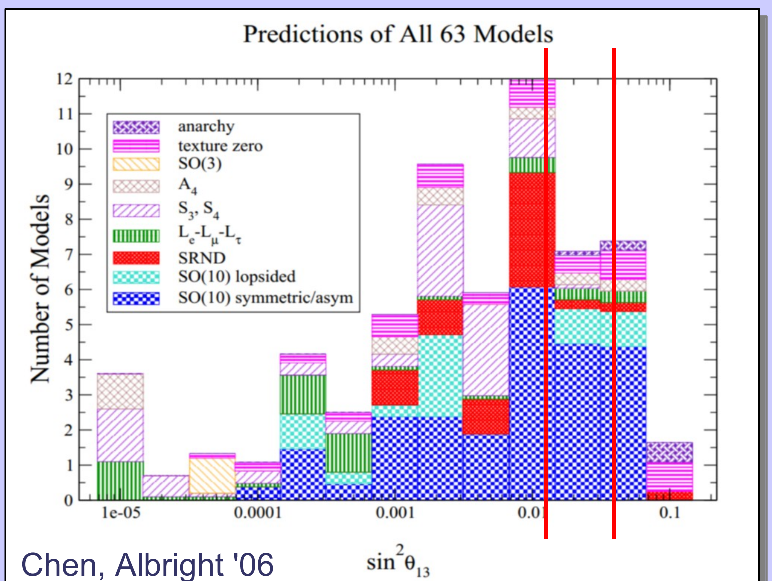
- **Neutrino mixing matrix and mass differences**

$$U \approx \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0.15\, e^{i\delta} \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix} \times \begin{pmatrix} e^{i\phi} & 0 & 0 \\ 0 & e^{i\theta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



De Gouvea '04

- **Constraining the model space**



Chen, Albright '06

- **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

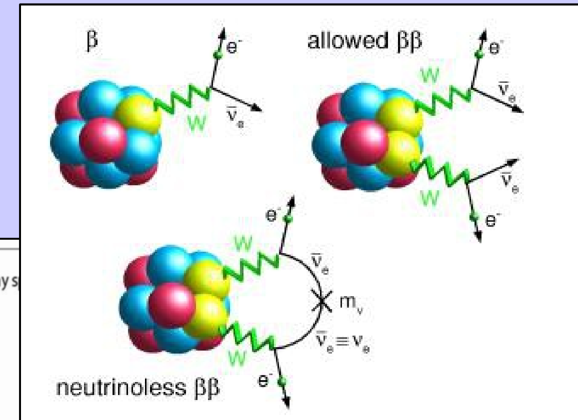
- **Impact on Large Scale Structure**

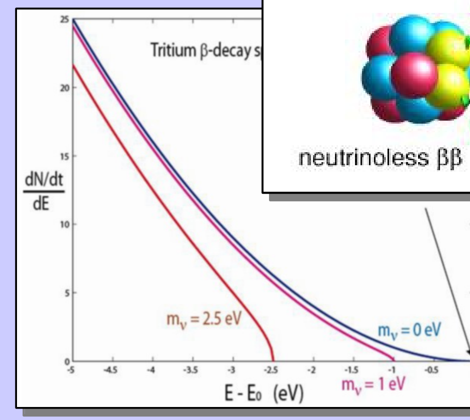
$$\Sigma = \sum_i m_i < 0.4 - 1\,\mathrm{eV}$$

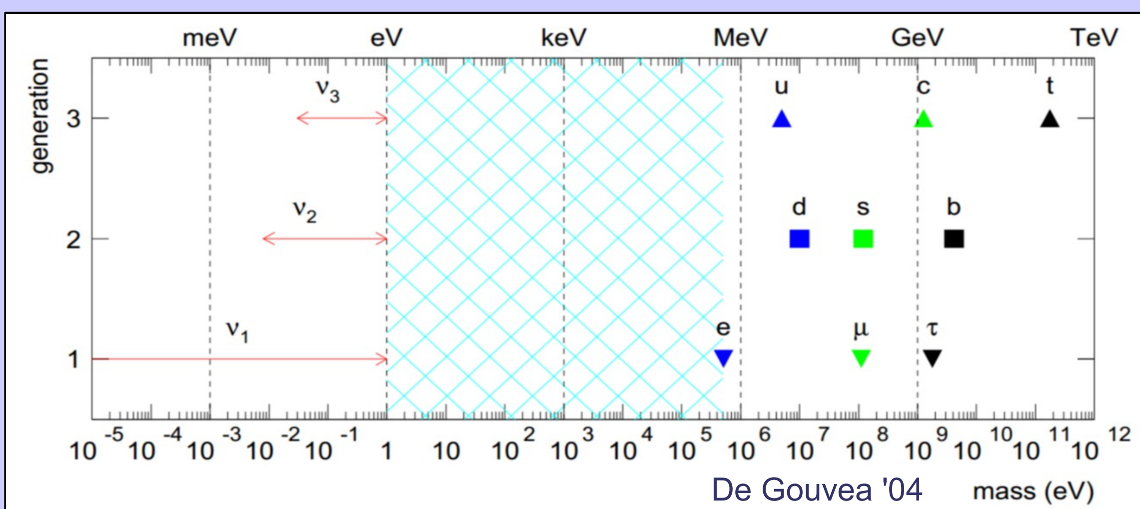
- **Neutrinoless Double Beta Decay**

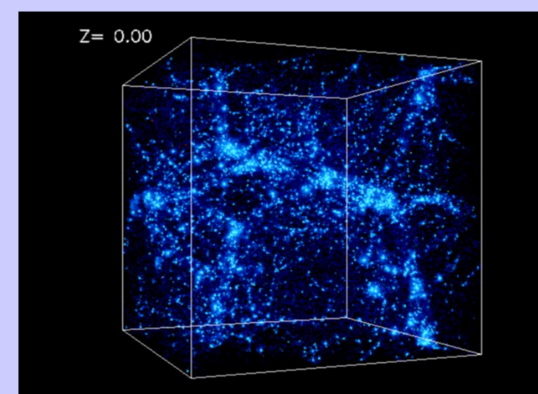
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_{\nu_i}\right| < 0.2 - 2.0\,\mathrm{eV}$$

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

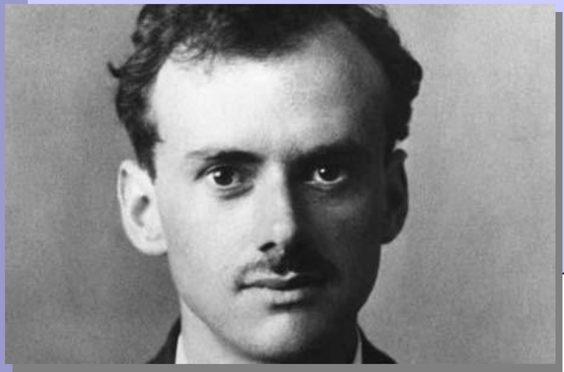




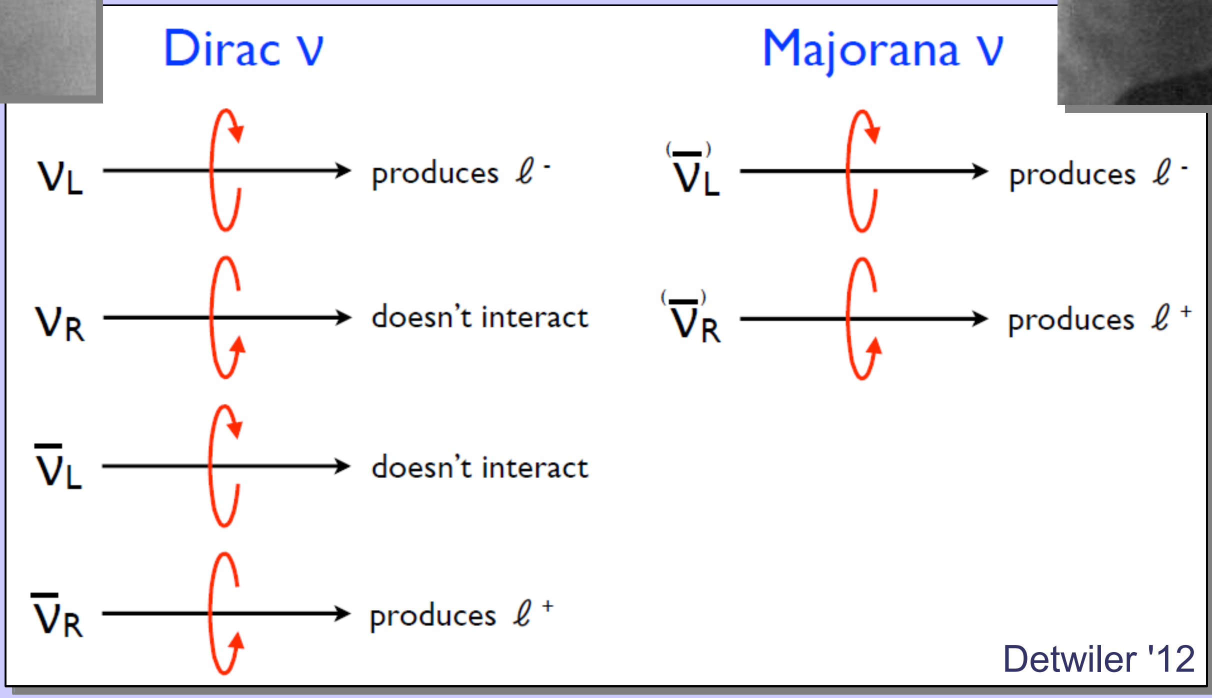


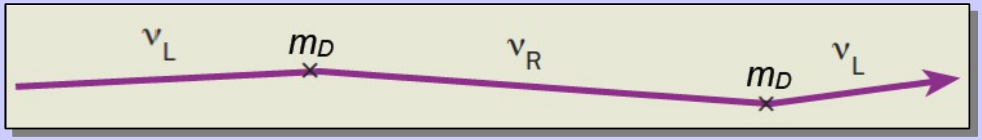


Dirac vs Majorana



Two possibilities to define mass





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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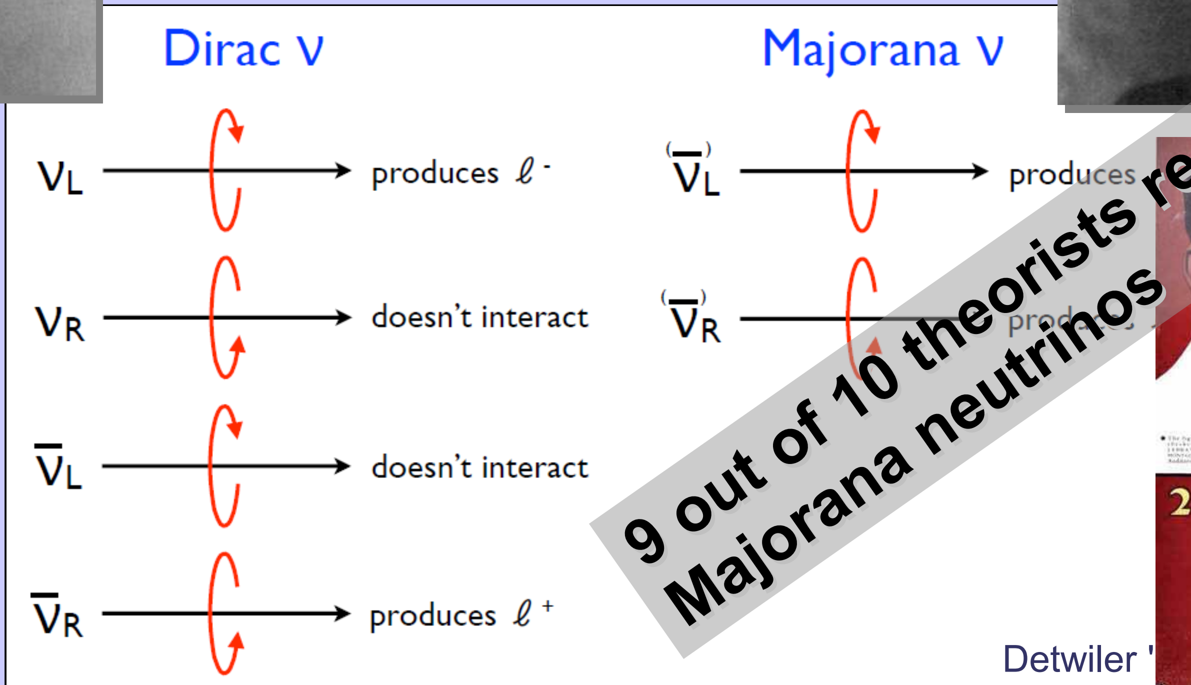
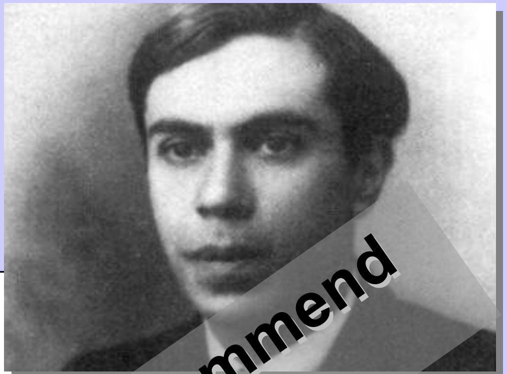
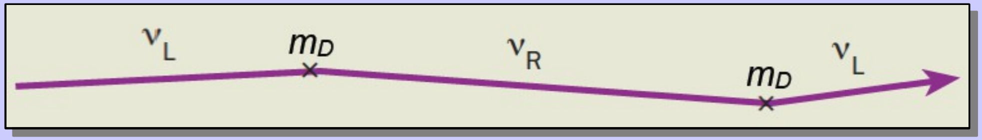




9 out of 10 theorists recommend Majorana neutrinos



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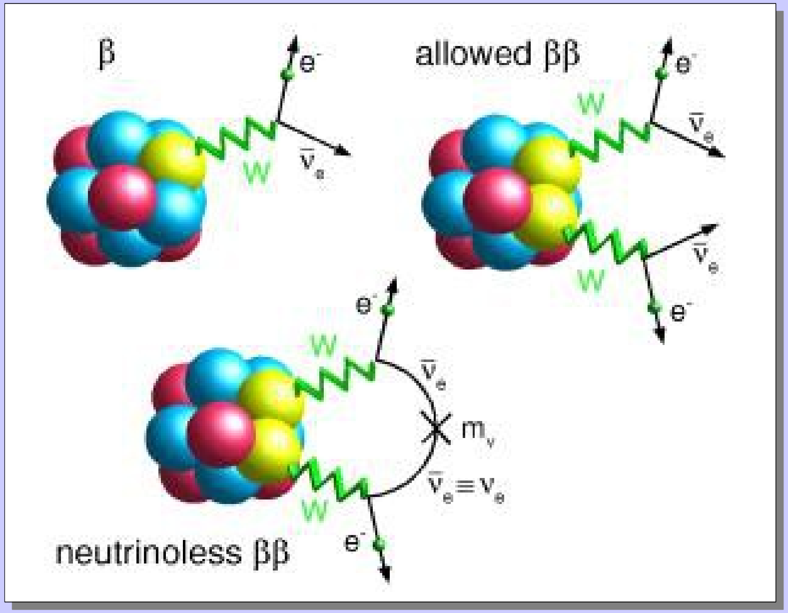
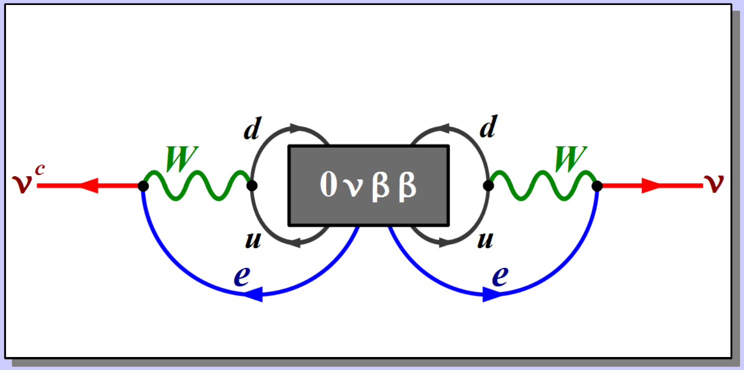
Neutrinoless Double Beta Decay

- **Two neutrino double beta decay**
  Allowed in the SM, Observed
- **Neutrinoless double beta decay**
  $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- **Uncontroversial detection of 0νββ of utmost importance**
  - Signal of New Physics
  - Prove lepton number to be broken
  - Prove neutrinos to be Majorana particles (Schechter, Valle '82)

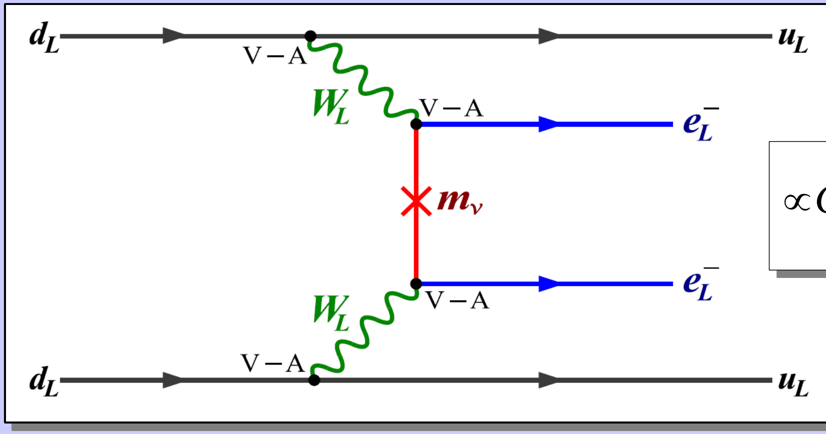




$$\delta m_\nu \approx \frac{1}{(16\pi^2)^4} \frac{\text{MeV}^5}{M_W^4} \approx 10^{-23}\ \text{eV}$$

Light Neutrino Exchange

- **Standard Mass Mechanism**

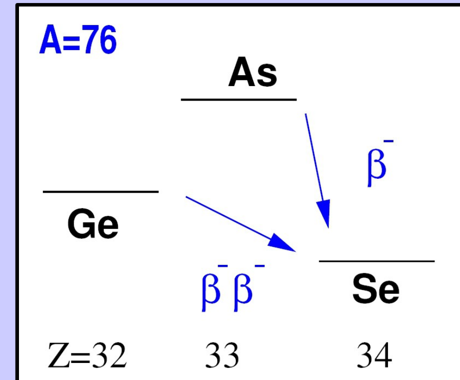


$$\propto G_F^2 \sum_i U_{ei}^2 \gamma_\mu P_L \frac{\not{q} + m_{\nu_i}}{q^2 - m_{\nu_i}^2} \gamma_\nu P_L$$

Heidelberg-Moscow

$T_{1/2}(^{76}Ge) \approx 1.9 \cdot 10^{25}$ y

$\langle m_\nu \rangle \approx (0.3 - 0.6)$ eV



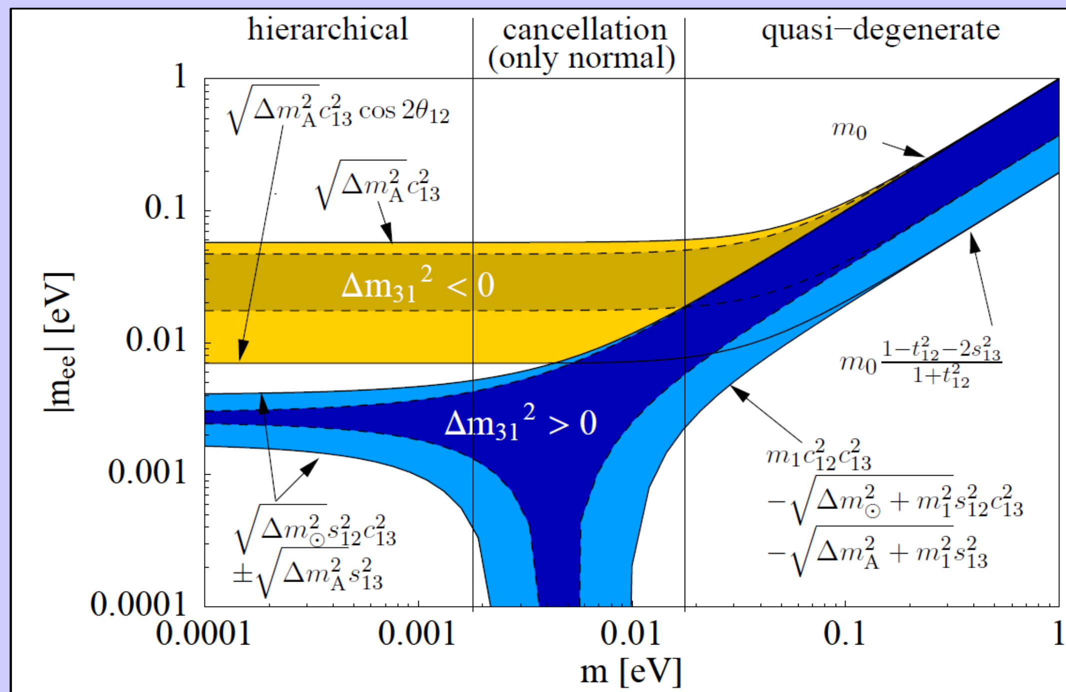
- **Decay Rate**

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

- **Effective Mass**

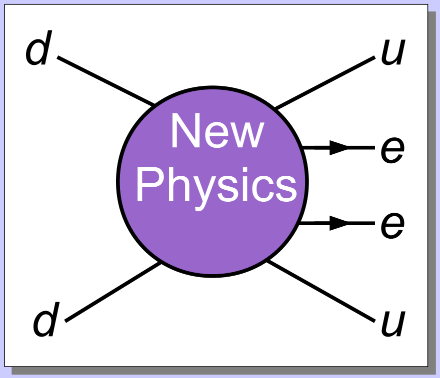
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_{\nu_i} \right| \equiv (m_\nu)_{ee}$$

Lindner, Merle, Rodejohann (2005)



New Physics Contributions to 0νββ

- **Plethora of New Physics Scenarios**



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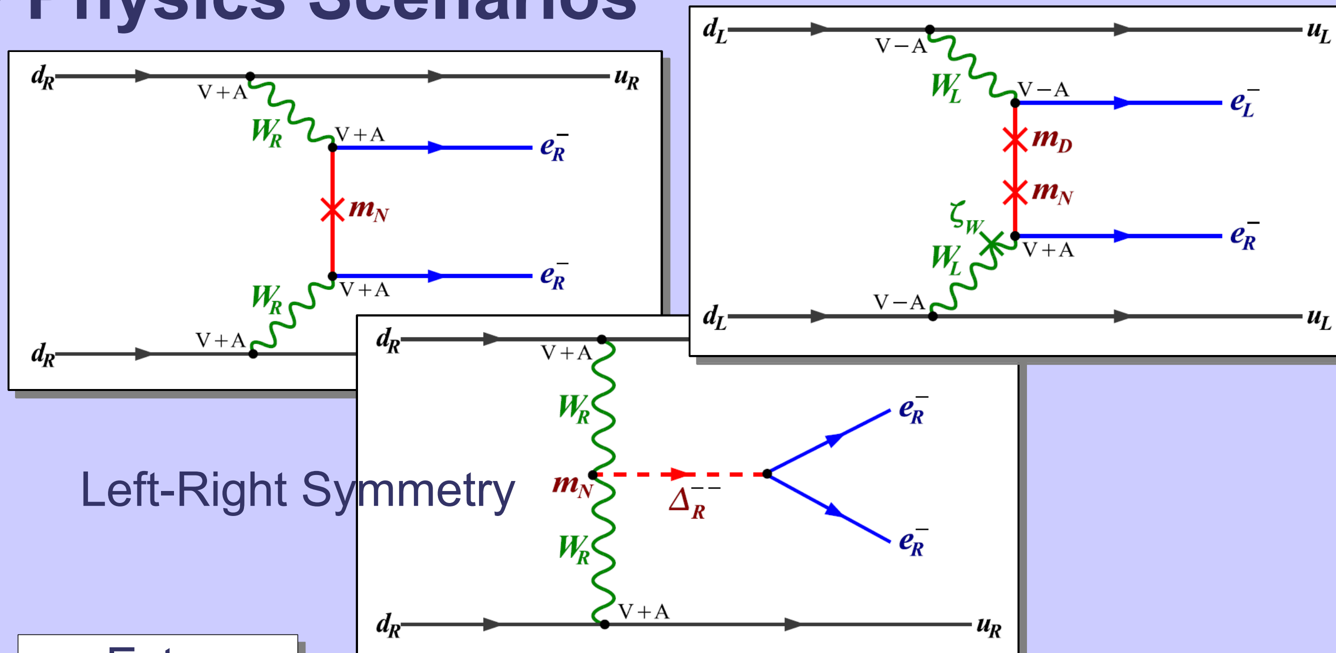
$$T_{1/2}^{-1} \approx 10^{25}\ \mathrm{y} \rightarrow M \approx 1\ \mathrm{TeV}$$



Left-Right Symmetry

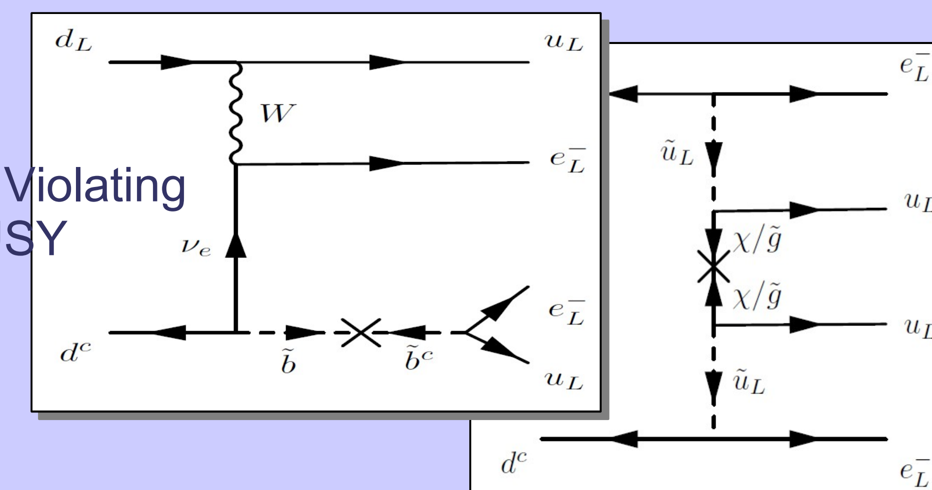
Extra Dimensions

Majorons

Leptoquarks

...

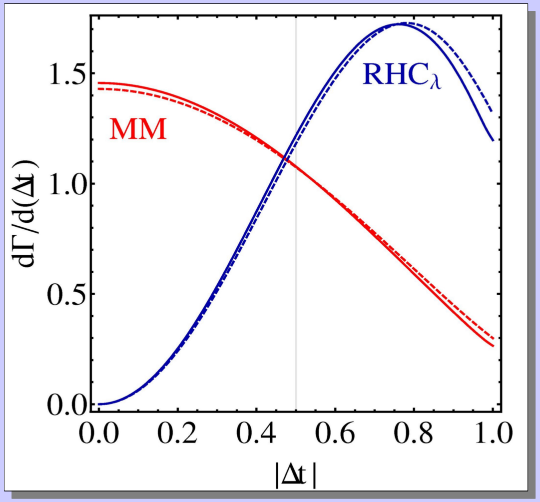
R-Parity Violating SUSY



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 0νββ mechanism

- **Comparison of 0νββ 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 0νββ mechanism
  - Independent of details of new physics (if one mechanism dominates)

Effective Mass and Seesaw Mechanism

- **Effective operator for Majorana neutrino mass**

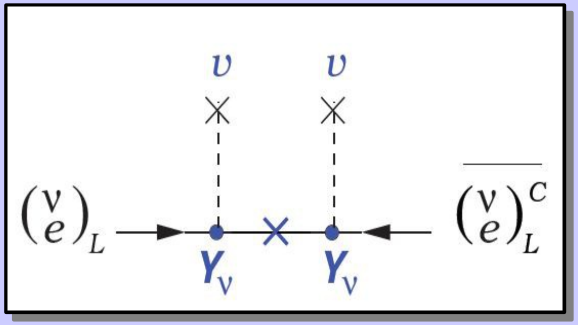
$$L = \frac{1}{2}\frac{h_{ij}}{\Lambda_{\mathrm{LNV}}}\left(\overline{L_i^c}\cdot\tilde{H}\right)\left(\tilde{H}^T\cdot L_j\right) \rightarrow \frac{1}{2}(m_\nu)_{ij}\overline{\nu_i^c}\nu_j$$

Unique dim-5 Operator

- **Seesaw Mechanism**

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

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



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

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

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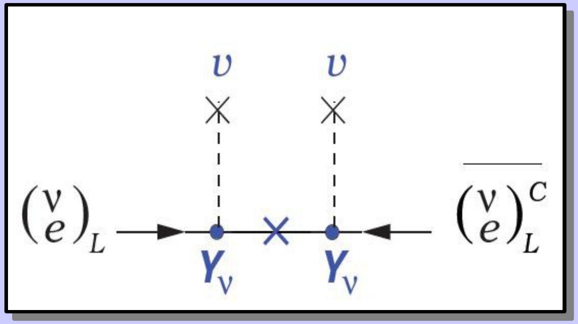
Unique dim-5 Operator

- **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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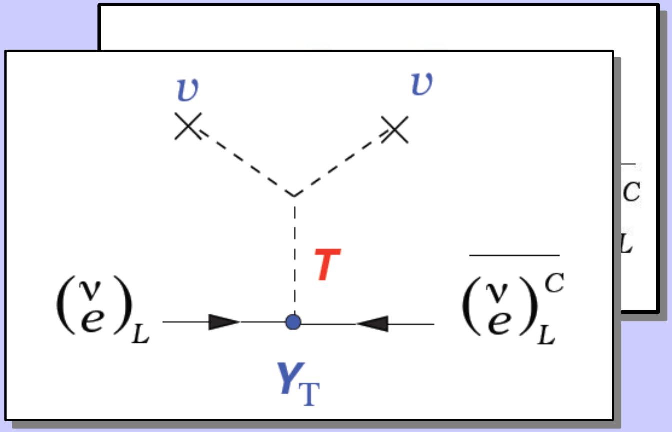
Unique dim-5 Operator

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



Seesaw II

Effective Mass and Seesaw Mechanism

- **Effective operator for Majorana neutrino mass**

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

Unique dim-5 Operator

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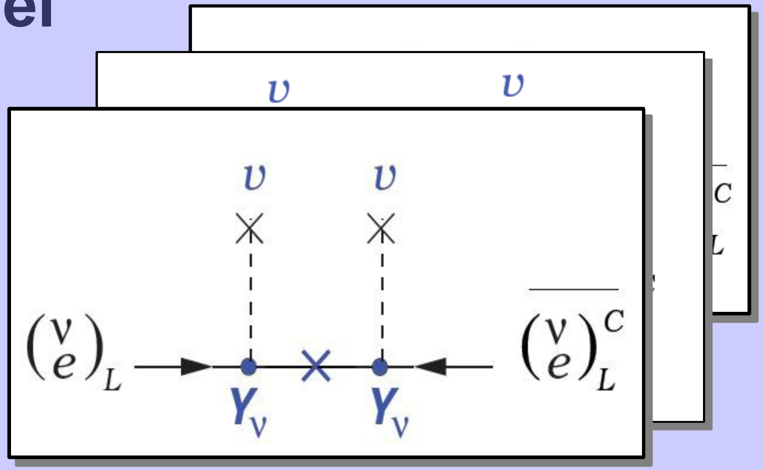


Seesaw III

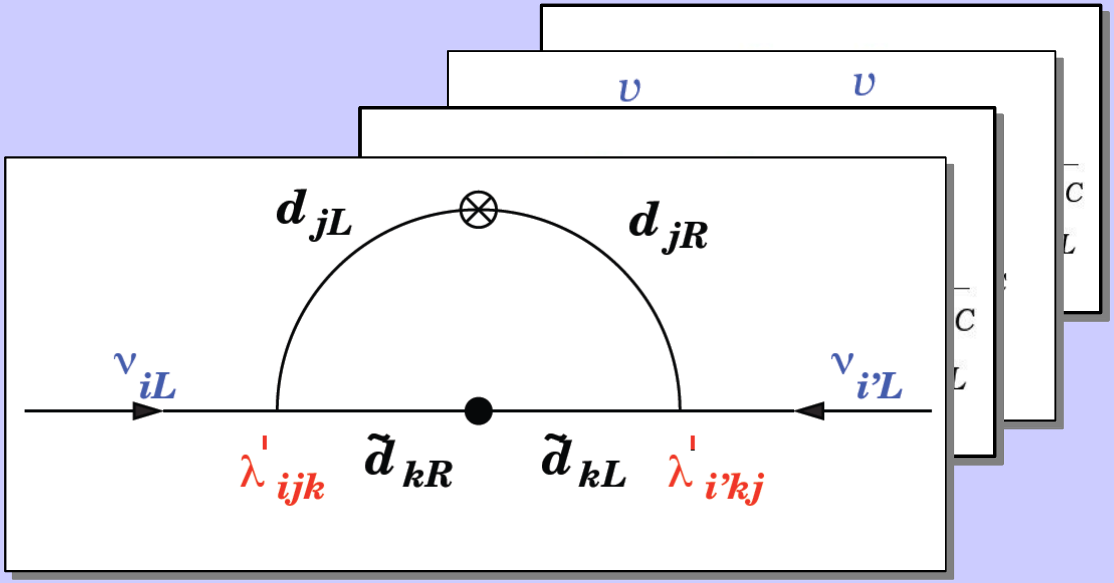
Effective Mass and Loops

- **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

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



R-Parity Violating SUSY

Charged Lepton Flavour Violation

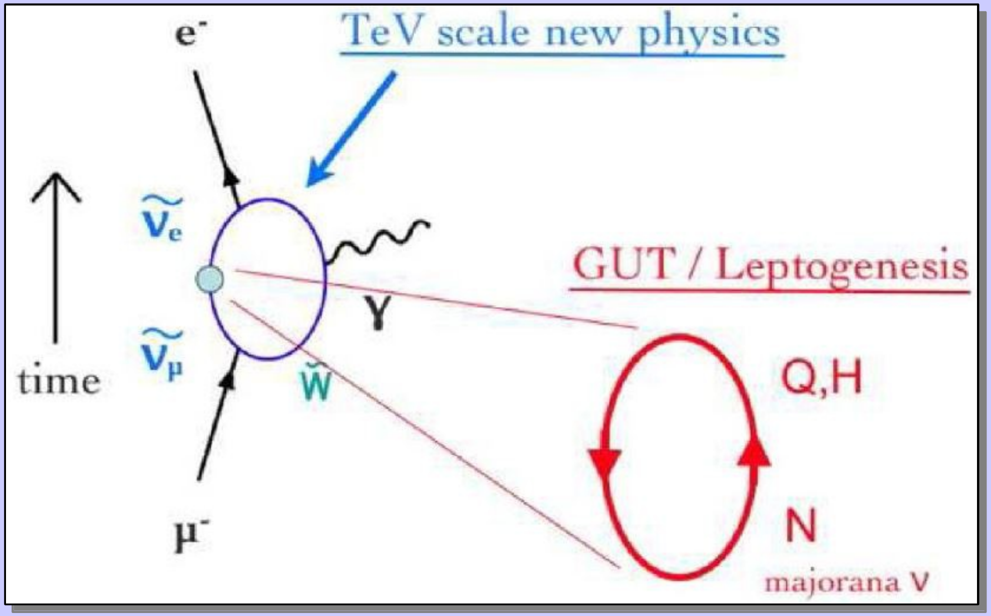
- **Lepton flavour practically conserved in the Standard Model**

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

  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
  - Connection to neutrino mixing



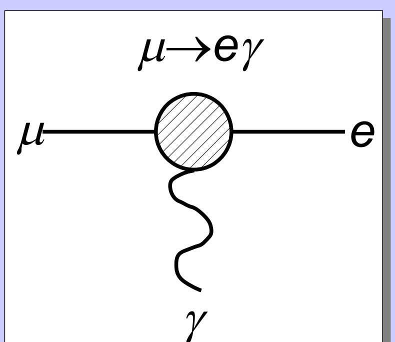
Rare LFV Processes

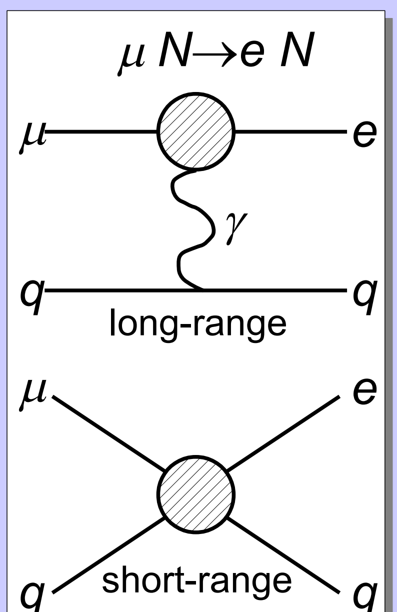
- **Current bounds** | **and future sensitivities**

Process	Current bound	Future sensitivity
Br($\mu \to e\gamma$)	**$< 6.0 \cdot 10^{-13}$ (MEG)**	**10^{-13} (MEG, 2018)**
Br($\tau \to \mu\gamma$)	$< 6.8 \cdot 10^{-8}$ (Belle)	10^{-8} (Super-B Factory, LHC?)
Br($\tau \to e\gamma$)	$< 3.7 \cdot 10^{-7}$ (BaBar)	10^{-8} (Super-B Factory)
R($\mu N \to e N$)	$< 7 \cdot 10^{-13}$ (Sindrum)	10^{-16} (COMET), μ–e conversion in nuclei

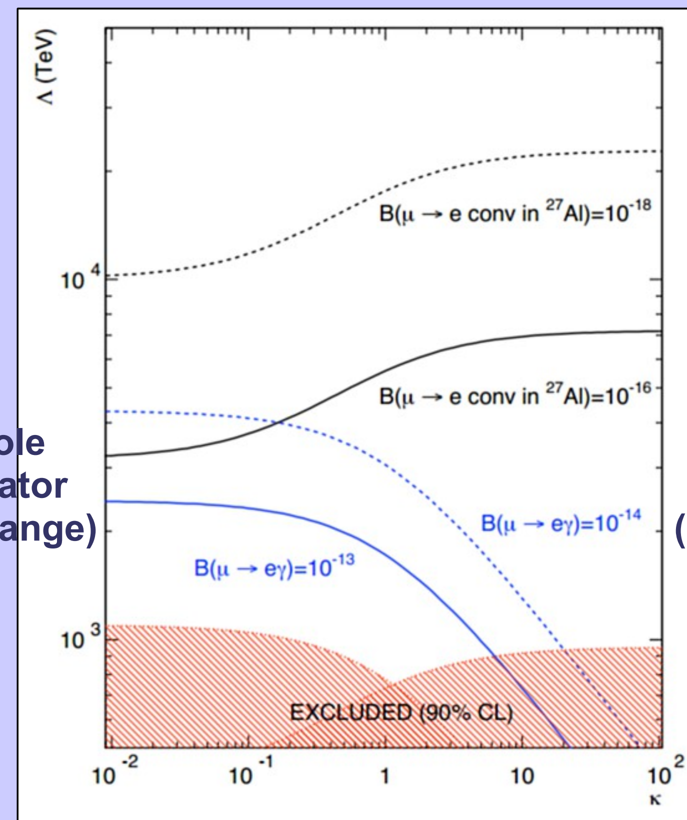
  - $\mu \to 3e$, $\tau \to 3\mu$ (LHC), etc.

- **Effective Operators**





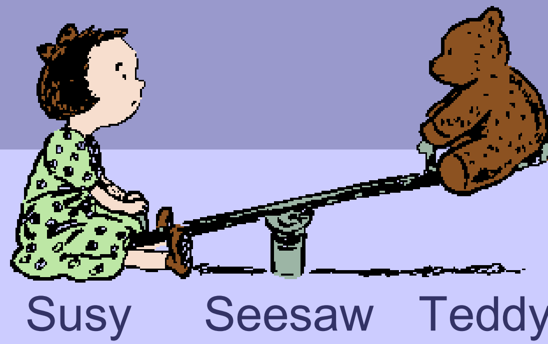
Dipole Operator (long-range)



Contact Operator (short-range)

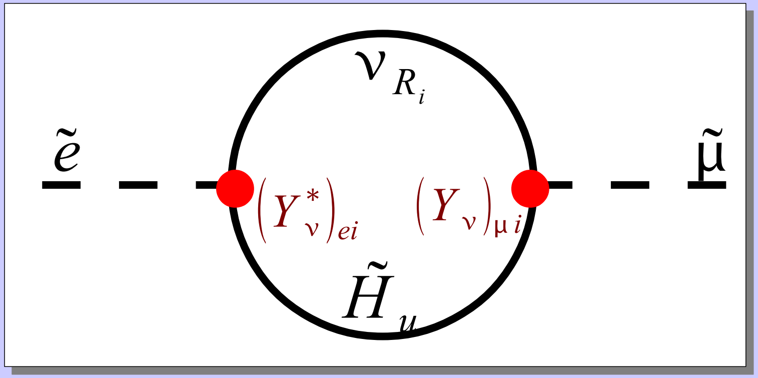
de Gouvea, Vogel, 2013

SUSY Seesaw



Achieve testability via impact on sleptons

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



$|\delta_{12}| \Rightarrow Br(\mu \to e\gamma)$, etc.

$$(\delta m_{\tilde{L}}^2)_{ij} = \begin{pmatrix} \delta_{11} & \delta_{12} & \delta_{13} \\ \delta_{12}^* & \delta_{22} & \delta_{23} \\ \delta_{13}^* & \delta_{23}^* & \delta_{33} \end{pmatrix} \propto Y_\nu^+ \cdot Y_\nu \log(M_{GUT}/M_R)$$

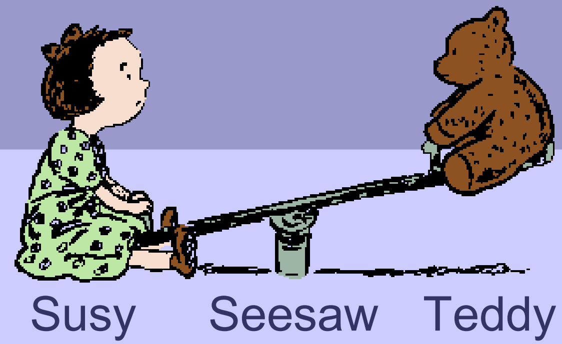
$\Im(\delta_{ij}) \Rightarrow$ EDMs d_e, d_μ

Slepton mass differences (Colliders)

⇒ 9 potential observables

⇒ SUSY Seesaw testable (in principle)

SUSY Seesaw



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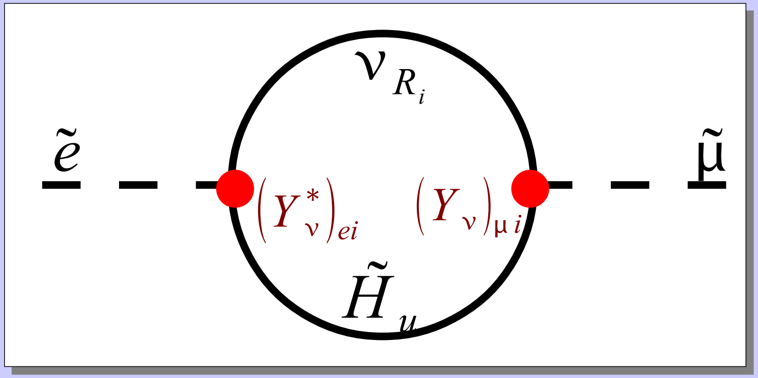
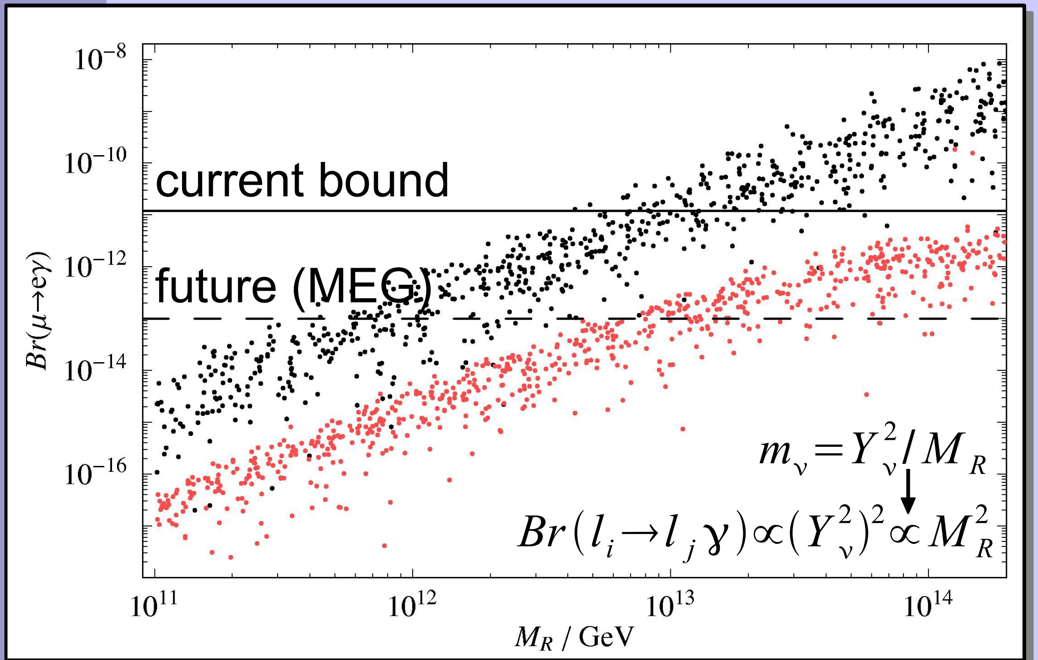
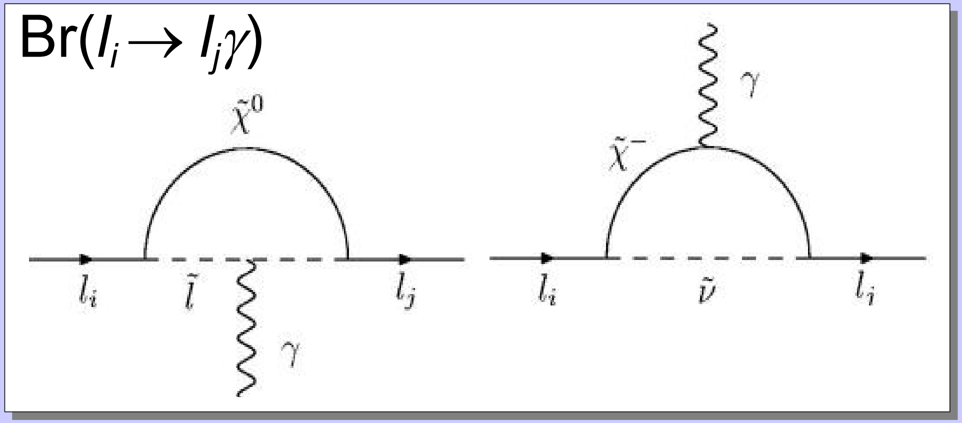
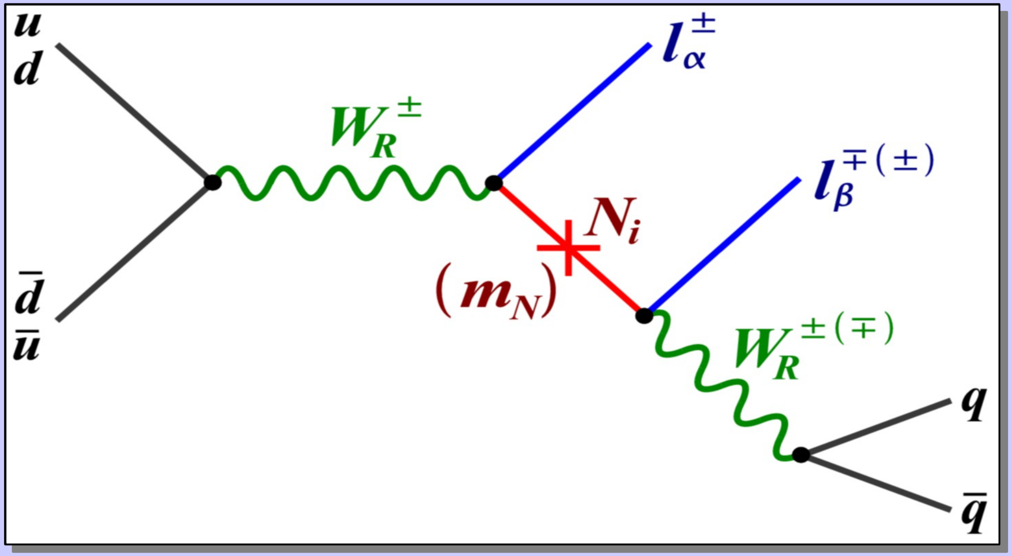




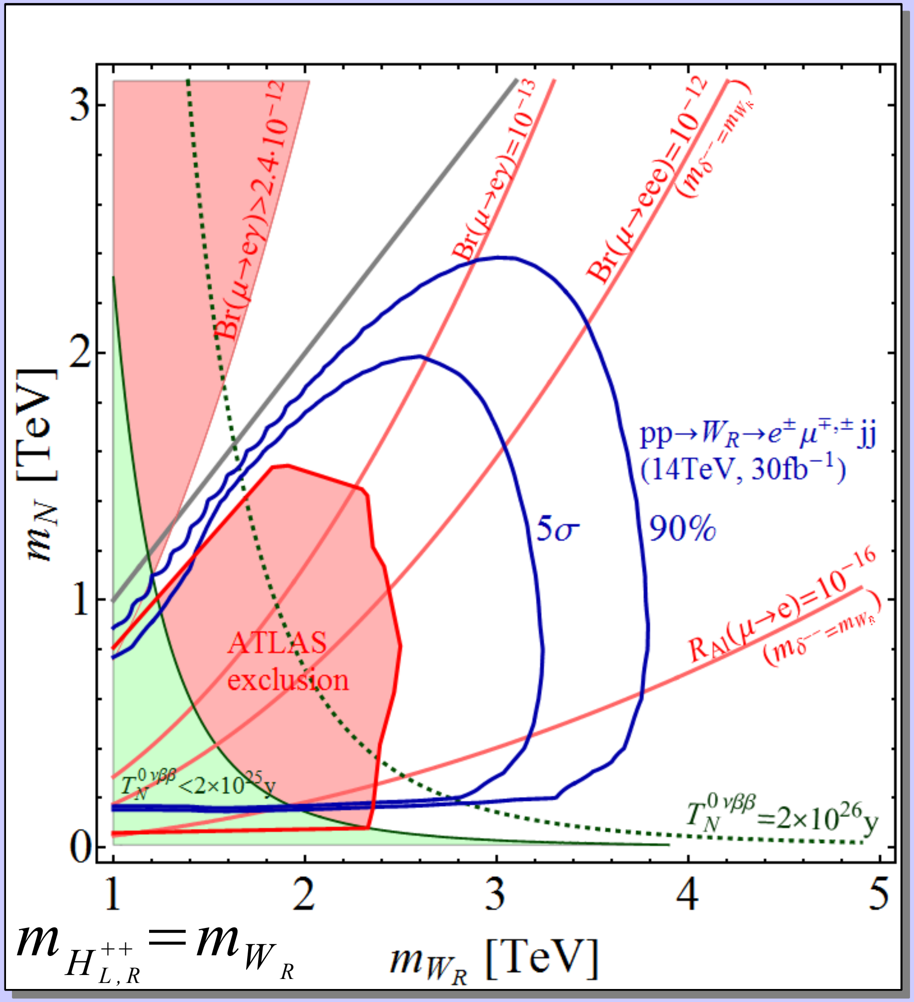


Light Right-Handed Neutrinos

- **Inverse Seesaw mechanism**
- **“Anti”-Seesaw mechanism**
- **Left-Right symmetric models**
  Right-handed neutrinos couple with gauge strength to charged leptons



Probing right-handed neutrino mixing,
Large LFV and LNV rates at LHC



Aguila, Aguilar-Saavedra, Das, FFD, Kittel, Valle '12

Conclusion

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  Strong experimental program to probe absolute mass

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  Flavour symmetry? CP Violation?

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  Mechanism of Neutrino Mass Generation?
- **Strong theoretical preference for Majorana**
  Lepton Number Violation with $0\nu\beta\beta$ as crucial probe

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  Dirac or Majorana? Lepton Number Violation?
- **Crucial question:**
  Mechanism of Neutrino Mass Generation?
- **Strong theoretical preference for Majorana**
  Lepton Number Violation with $0\nu\beta\beta$ as crucial probe
- **Rich phenomenology in models of neutrino mass generation**
  - Charged lepton flavour violation
  - LFV and LNV processes at the LHC
  - Baryogenesis via Leptogenesis