# Neutrino Masses and Lepton Flavour violating decays in the MSSM

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# A supersymmetric standard model

Find the most general Lagrangian which is

- invariant under Lorentz, $SU(3)_C \times SU(2)_L \times U(1)_Y$ and supersymmetry transformations; renormalizable

- minimal in particle content

Neither lepton number (L) nor baryon number (B) are conserved
Two options:

- constrain Lagrangian parameters

- impose a further discrete symmetry when constructing the lagrangian

# Superpotential

The most general superpotential is given by

$$\mathcal{W} = Y_E L H_1 E + Y_D H_1 Q D^c + Y_U Q H_2 U^c - \mu H_1 H_2$$

$$+\frac{1}{2}\lambda L L E^c + \lambda' L Q D^c - \kappa L H_2$$

$$+\frac{1}{2}\lambda'' U^c D^c D^c$$

Dreiner et al, building on work of Ibanez & Ross, show that there are three preferred discrete symmetries; R-parity, a $Z_3$ allowing $\not{L}$ and $P_6$, referred to as proton-hexality.


L. E. Ibanez and G. G. Ross, Nucl. Phys. B **368**, 3 (1992)
H. K. Dreiner, C. Luhn and M. Thormeier, Phys. Rev. D **73** (2006) 075007

# Neutrino Masses in $\not{L}$-MSSM

The mixing between neutrinos and neutral gauginos/higgsinos produces one tree-level, 'see-saw' suppressed, neutrino mass.

$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & m_\nu^{\mathsf{tree}} \end{pmatrix}$$

where

$$m_\nu^{\mathsf{tree}} = \left| \frac{v_d^2 \left( M_1 g_2^2 + M_2 g^2 \right)}{4\mathsf{Det}[M_{\chi^0}]} \right| \left( |\kappa_1|^2 + |\kappa_2|^2 + |\kappa_3|^2 \right)$$

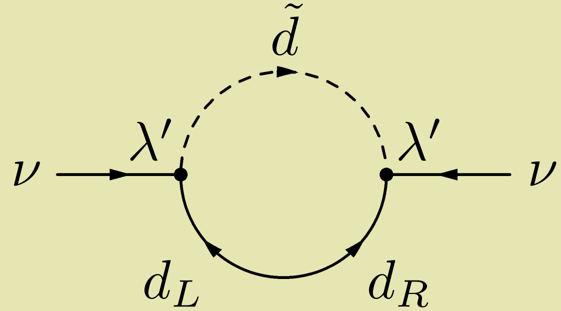
A. S. Joshipura and M. Nowakowski, Phys. Rev. D **51**, 2421 (1995)
M. Nowakowski and A. Pilaftsis, Nucl. Phys. B **461**, 19 (1996)

# Neutrino Masses in $\not{L}$-MSSM

- Loop corrections lift the degeneracy between the two massless neutrinos.

- The neutrino masses, and hence mass squared differences, are dependent on the values of lepton number violating couplings.

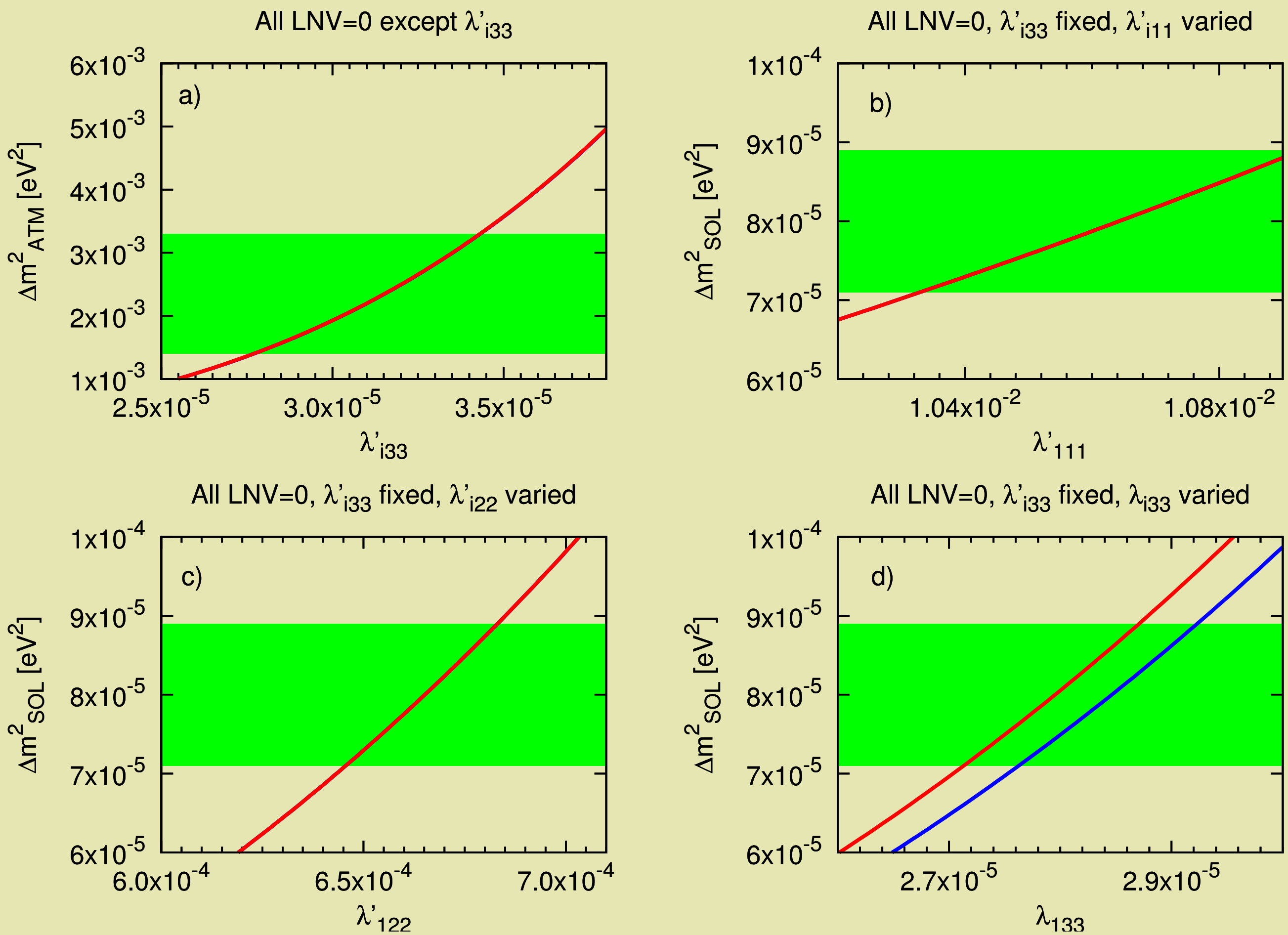
- Values for lepton violating couplings exist which reproduce experimental results for mass squared differences and mixing angles.




F. M. Borzumati et al, Phys. Lett. B **384**, 123 (1996) ; A. S. Joshipura et al, Phys. Rev. D **60**, 111303 (1999)
K. Choi et al, Phys. Rev. D **60**, 031301 (1999) ; D. E. Kaplan et al, JHEP **0001** (2000) 033
M. Hirsch et al, Phys. Rev. D **62**, 113008 (2000) ; A. Abada et al, Phys. Rev. D **65**, 075010 (2002)
Y. Grossman et al, Phys. Rev. D **69**, 093002 (2004)

A. Dedes, SR and J. Rosiek, JHEP **0608** (2006) 005

# Neutrino masses generated via $\lambda'$ couplings



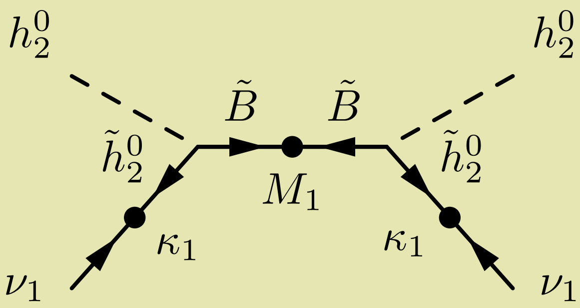

A. Dedes, SR and J. Rosiek, JHEP **0608** (2006) 005

# Interplay between $\mu$-decays and neutrino masses

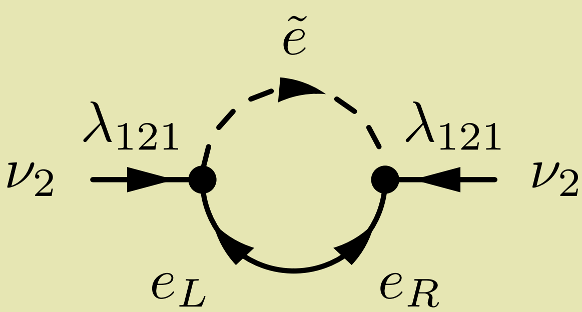
- In certain cases lepton number violating couplings which give rise to the mass squared differences observed in neutrino experiments will be correlated with the branching ratios for rare lepton decays.

# Interplay between $\mu$-decays and neutrino masses

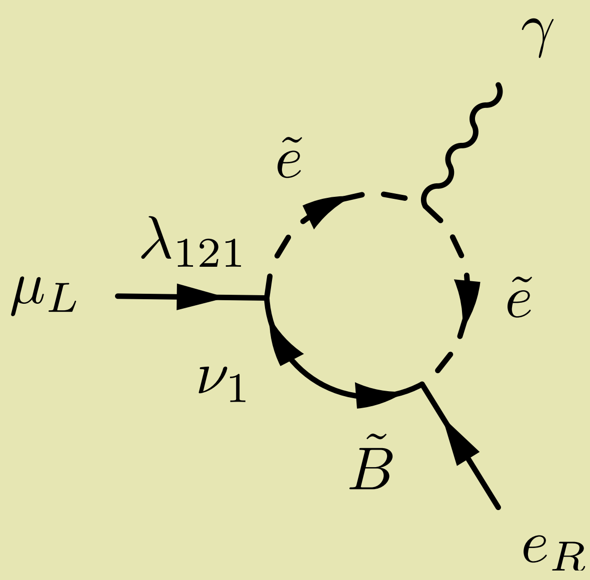
- Generate atmospheric mass difference




- Generate solar mass difference

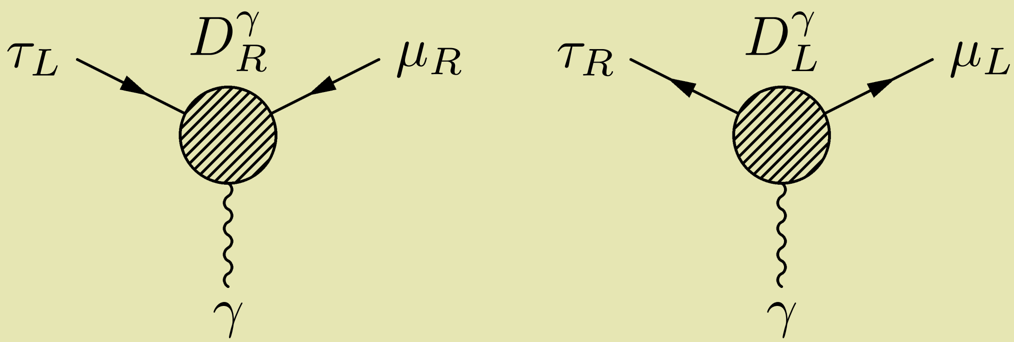



- Generate $\mu \to e\gamma$



# Effective Operators

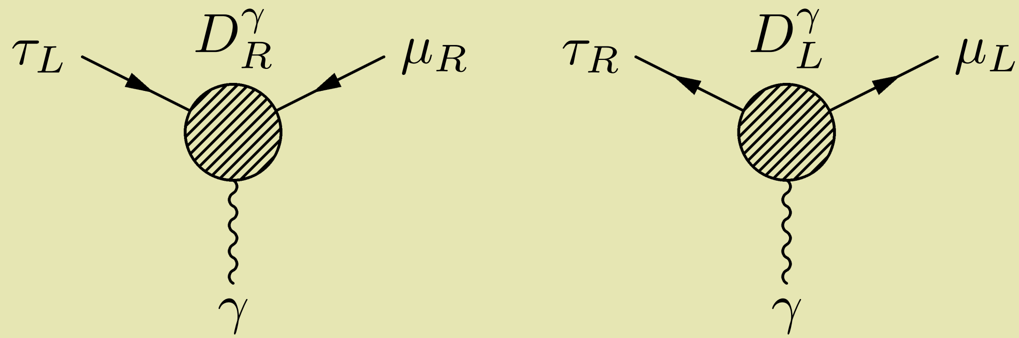
- LFV events can be derived in terms of effective operators, in a model independent manner.
- Leading contributions to the effective operators arise from $d = 6$, $SU(2)_L \times U(1)_Y$ invariant operators.
- For example, the $\tau - \mu - \gamma$ vertex, with an on-shell photon, arises from the following terms in the effective Lagrangian.




$$\mathcal{L}_{\rm eff} = e m_\tau \left[ i D^\gamma_L \bar{\mu_L} \bar{\sigma}^{\mu\nu} \bar{\tau_R} + i D^\gamma_R \mu_R \sigma^{\mu\nu} \tau_L + \text{H.c.} \right] F_{\mu\nu}$$

A. Brignole and A. Rossi, Nucl. Phys. B **701** (2004) 3

# Effective Operators




$$\mathcal{L}_{\rm eff} = e m_\tau \left[ i D_L^\gamma \bar{\mu_L} \bar{\sigma}^{\mu\nu} \bar{\tau_R} + i D_R^\gamma \mu_R \sigma^{\mu\nu} \tau_L + \text{H.c.} \right] F_{\mu\nu}$$

$$\mathcal{B}(\tau \to \mu\gamma) = \frac{48\pi^3\alpha}{G_F^2} \left[ \left|D_L^\gamma\right|^2 + \left|D_R^\gamma\right|^2 \right] \mathcal{B}(\tau \to \mu \bar{\nu}_\mu \nu_\tau)$$

A. Brignole and A. Rossi, Nucl. Phys. B **701** (2004) 3

# Bounds

$$\Delta m^2_{\text{solar}} = (7.1 - 8.9) \times 10^{-5}\ \text{eV}^2$$

$$|\Delta m^2_{\text{atm}}| = (1.9 - 3.2) \times 10^{-3}\ \text{eV}^2$$ (hep-ph/0606060)

$$\mathcal{B}(\mu \to e\gamma) < 1.2 \times 10^{-11}$$ MEGA (hep-ex/0111030)

$$\mathcal{B}(\tau \to \mu\gamma) < 6.8 \times 10^{-8}$$ BaBar (hep-ex/0502032)

$$\mathcal{B}(\tau \to e\gamma) < 1.1 \times 10^{-7}$$ BaBar (hep-ex/0508012)

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T. Schwetz, Acta Phys. Polon. B **36** (2005) 3203

M. Ahmed *et al.* [MEGA Collaboration], Phys. Rev. D **65**, 112002 (2002)

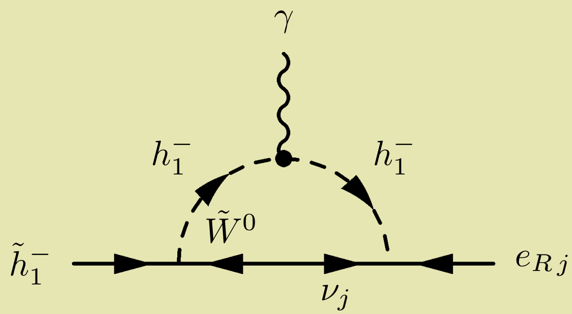
B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **95**, 041802 (2005)

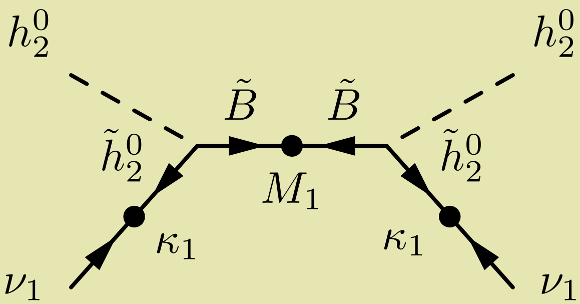
B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **96**, 041801 (2006)

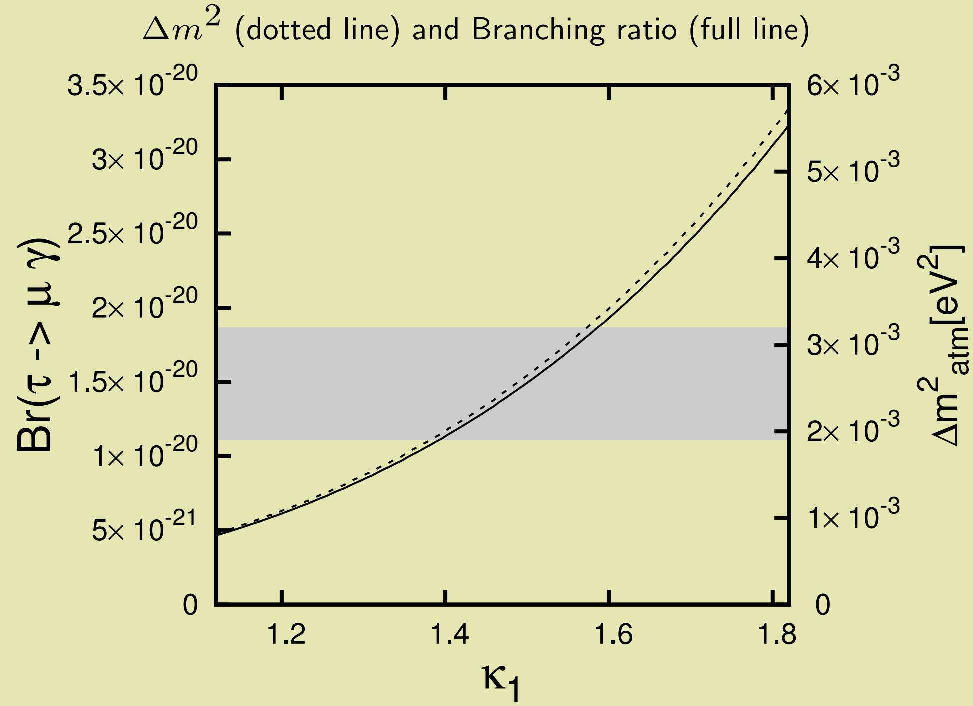
# Results

- Set all R-parity conserving parameters to SPS1a benchmark point
- Vary lepton number violating couplings
- Calculate resulting mass squared difference and branching ratio

# Atmospheric Scale set by $\kappa_{1,2,3}$



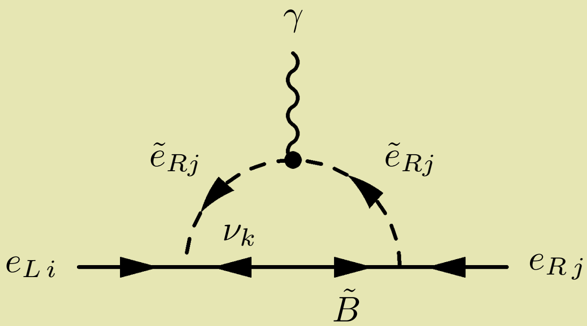



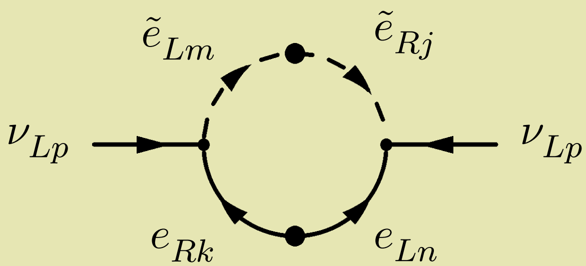



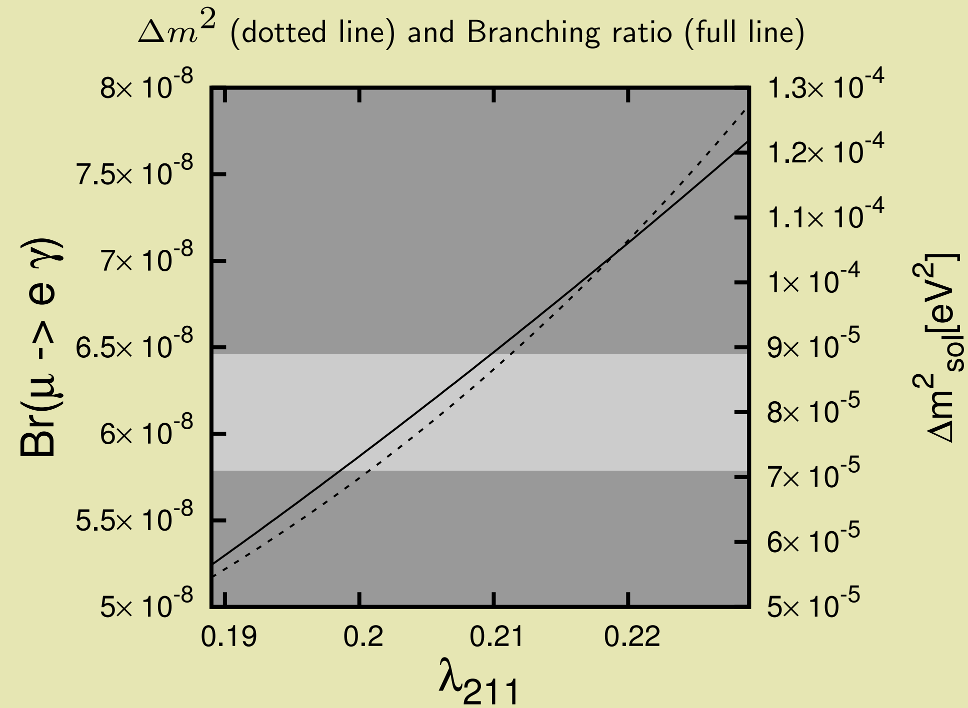

$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda_{0jj}|^2}{G_F^2 m_i^2} \frac{e^2}{s_w^2} M_{\chi^0}^2 \left[ \left( \frac{1}{M_{H^-}^2} \right) \left( \frac{\mu_0 \mu_i}{M_{\chi^\pm}^2} \right) \left( \frac{\mu_j g_2 v_u}{M_{\chi^0}^2} \right) \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)$$

SR hep-ph/0610406

# Atmosphric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

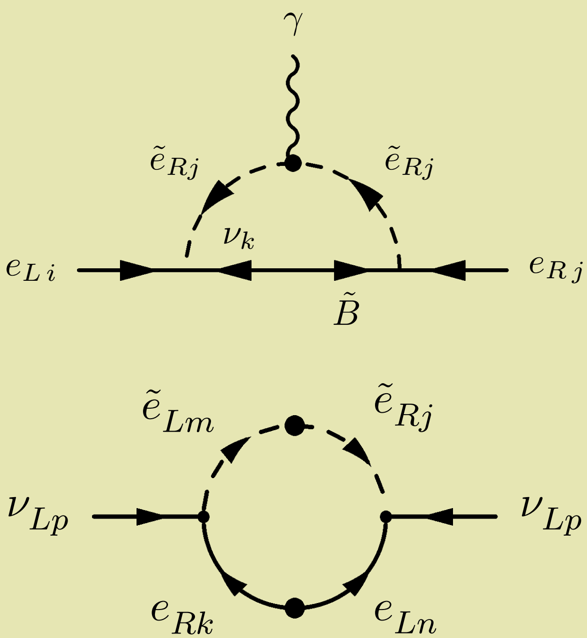


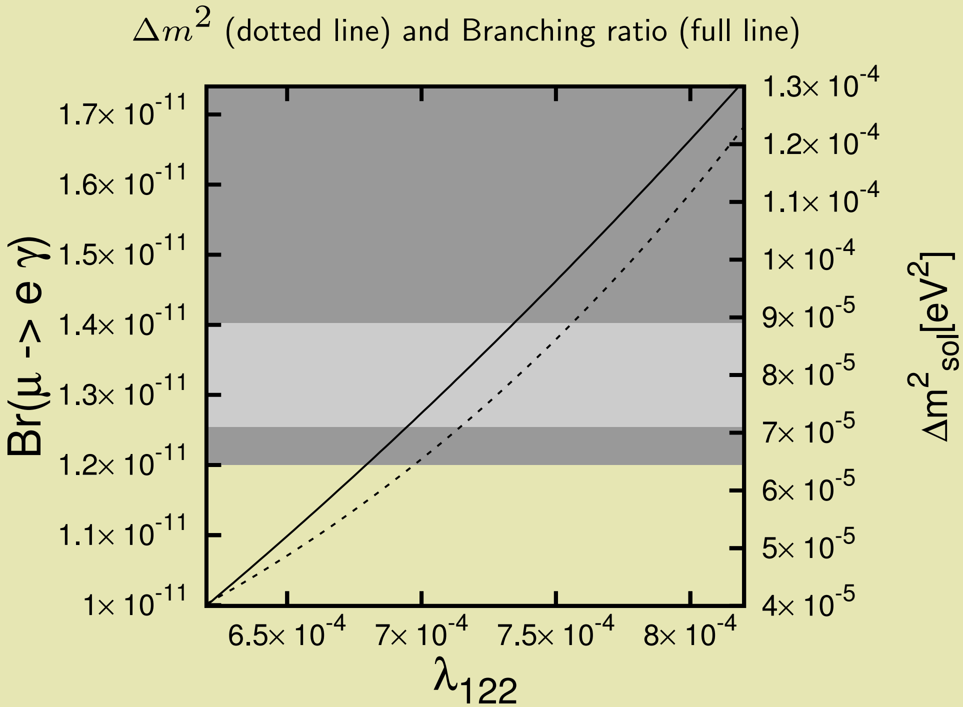




$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2}\,\frac{e^2}{c_w^2}\,M_{\chi^0}^2\left[\left(\frac{1}{m_{\tilde{e}}^2}\right)\,\left(\frac{\mu_k g v_u}{M_{\chi^0}^2}\right)\right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)\ .$$

# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

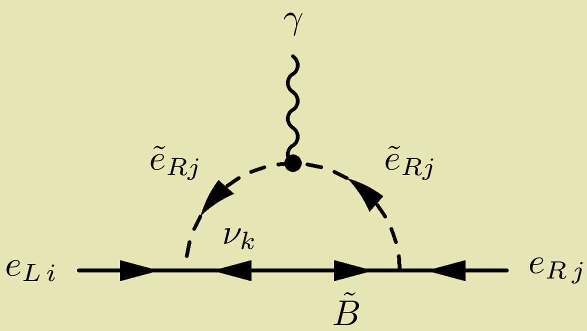


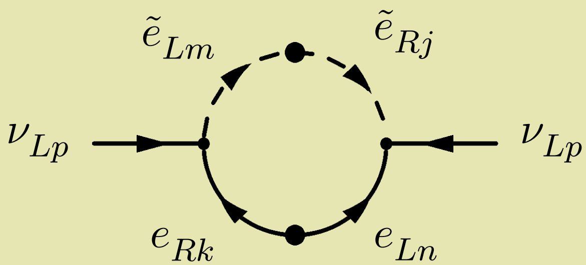



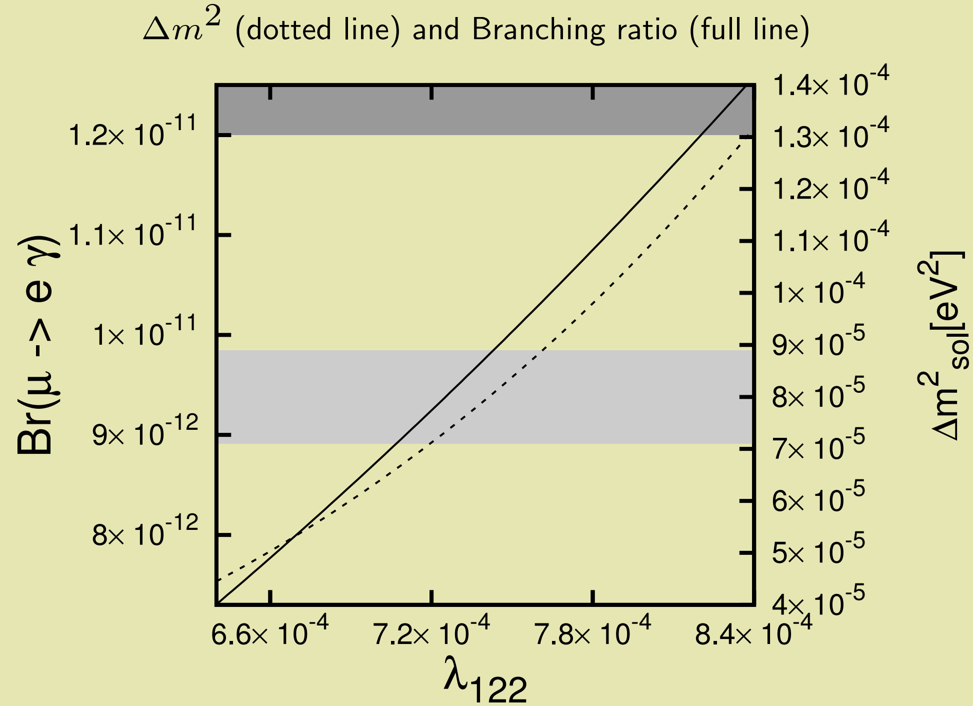

SPS1a benchmark point: $m_{\tilde{\mu}} = 143$GeV

$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2} \frac{e^2}{c_w^2} M^2_{\chi^0} \left[ \left( \frac{1}{m^2_{\tilde{e}}} \right) \left( \frac{\mu_k g v_u}{M^2_{\chi^0}} \right) \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j) \; .$$

# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$



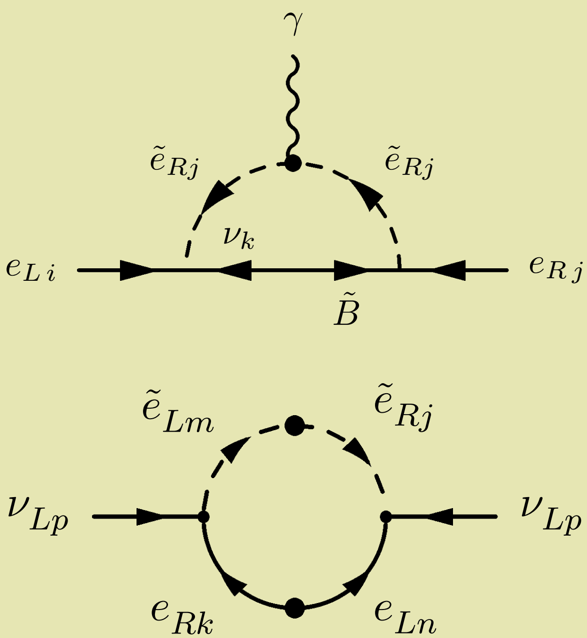



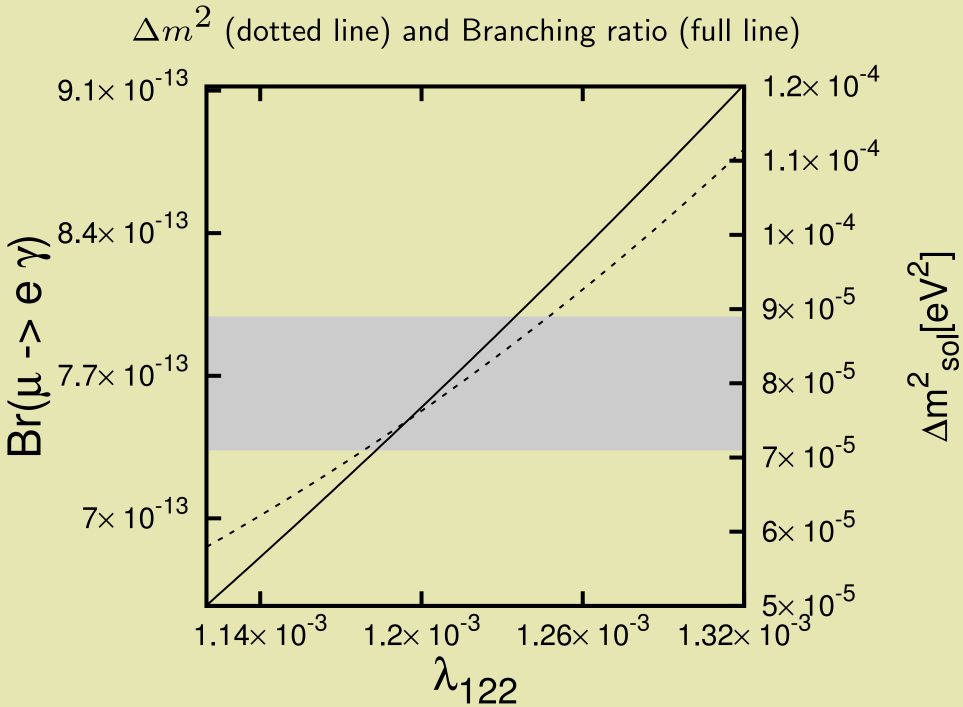




$m_{\tilde{\mu}} = 145\text{GeV}$

$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2}\,\frac{e^2}{c_w^2}\,M^2_{\chi^0}\left[\left(\frac{1}{m^2_{\tilde{e}}}\right)\,\left(\frac{\mu_k g v_u}{M^2_{\chi^0}}\right)\right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)\ .$$

# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

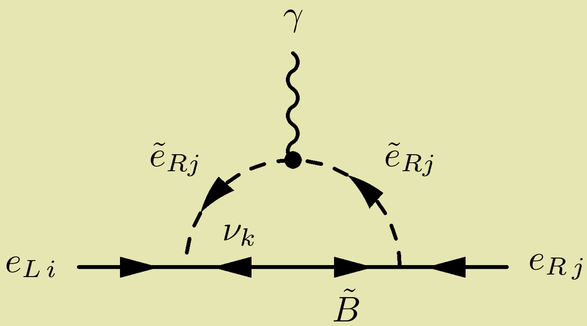


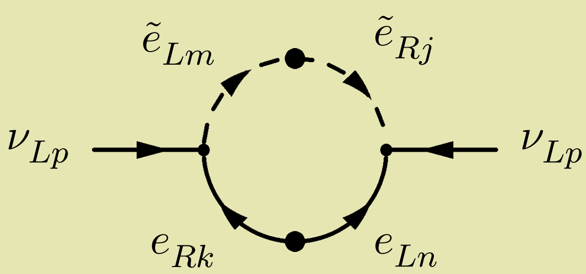



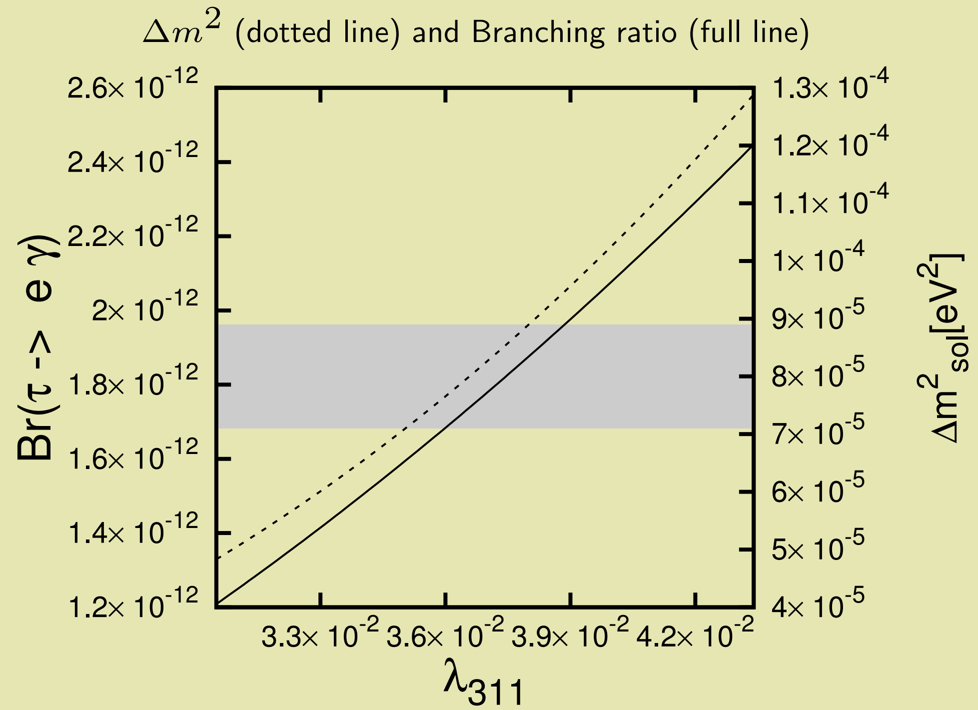

$m_{\tilde{\mu}} = 265\text{GeV}$

$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2}\,\frac{e^2}{c_w^2}\,M_{\chi^0}^2\left[\left(\frac{1}{m_{\tilde{e}}^2}\right)\,\left(\frac{\mu_k g v_u}{M_{\chi^0}^2}\right)\right]^2\Gamma(l_i \to l_j\nu_i\bar{\nu}_j)\;.$$

# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

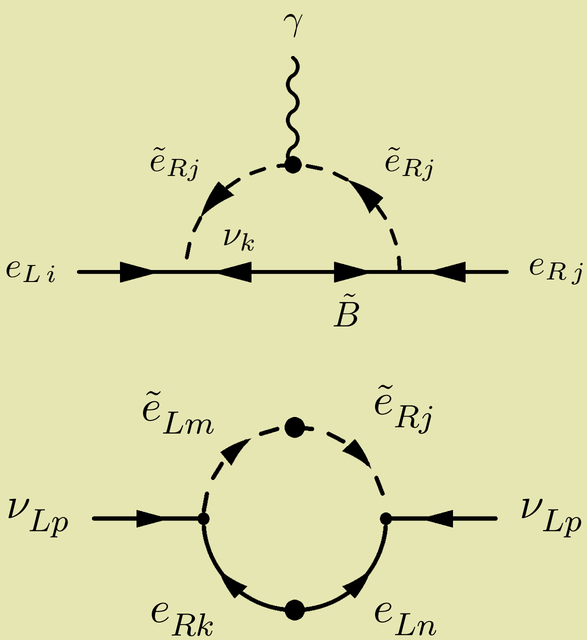


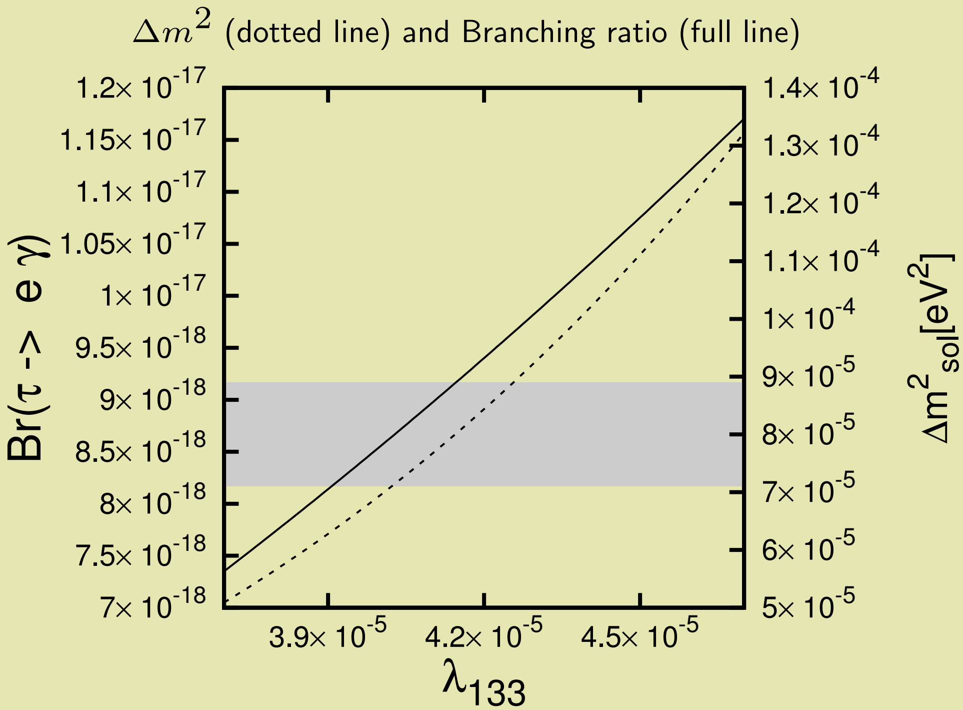




$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2} \frac{e^2}{c_w^2} M_{\chi^0}^2 \left[ \left( \frac{1}{m_{\tilde{e}}^2} \right) \left( \frac{\mu_k g v_u}{M_{\chi^0}^2} \right) \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j) \ .$$

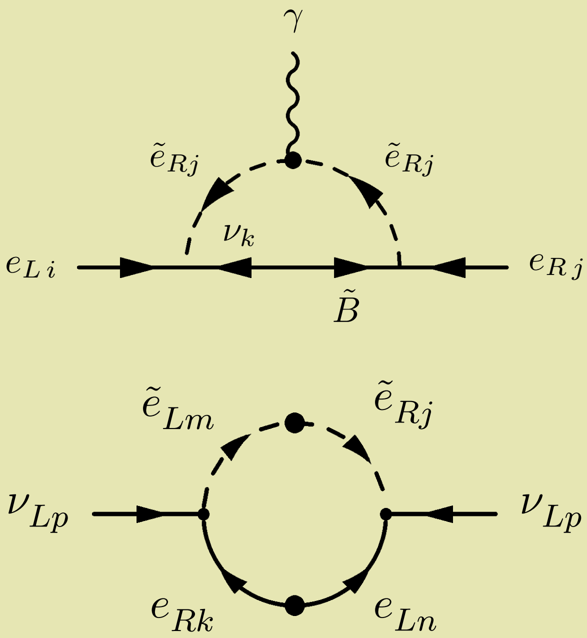
# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

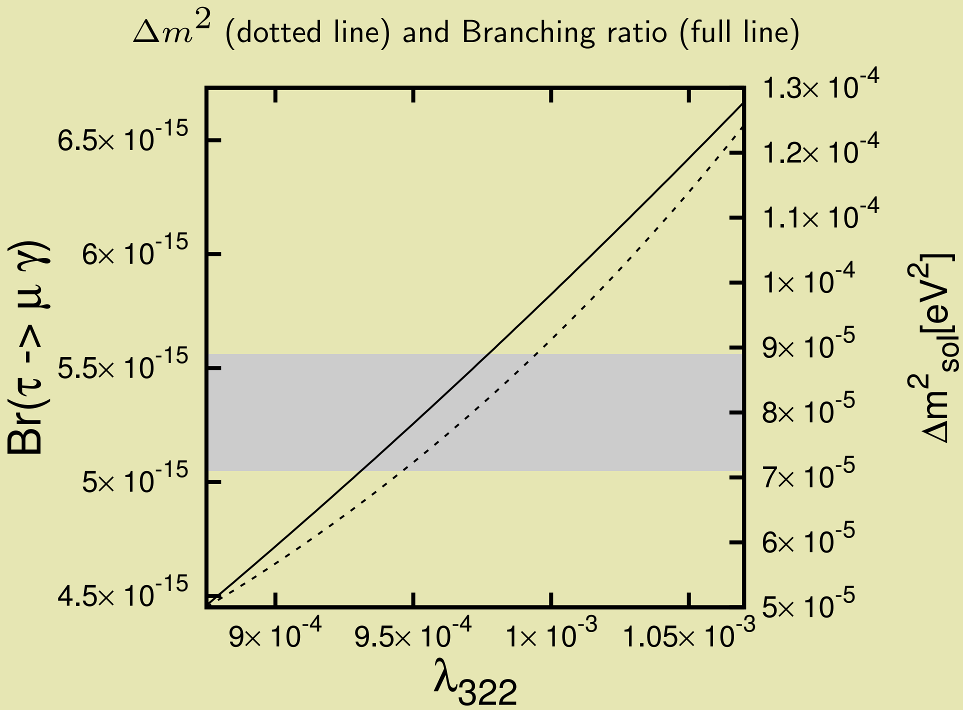



$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2}\,\frac{e^2}{c_w^2}\,M^2_{\chi^0}\left[\left(\frac{1}{m^2_{\tilde{e}}}\right)\,\left(\frac{\mu_k g v_u}{M^2_{\chi^0}}\right)\right]^2\Gamma(l_i \to l_j\nu_i\bar{\nu}_j)\ .$$

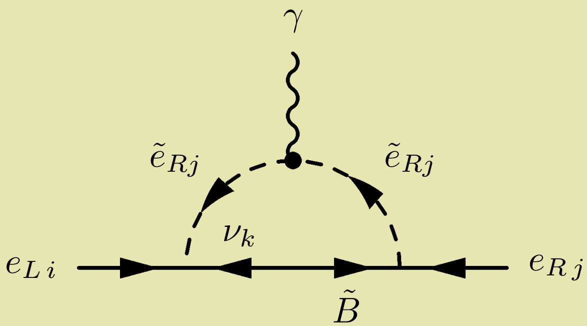
# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

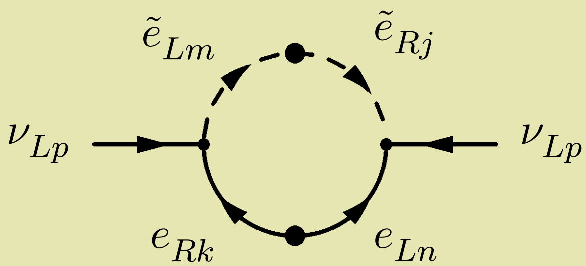


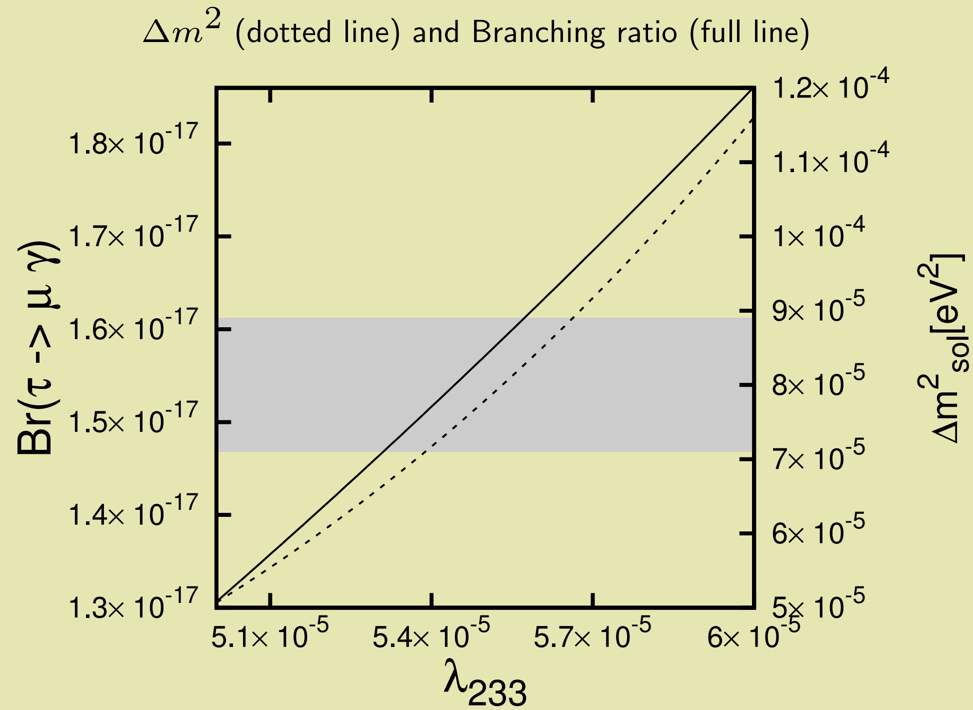




$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2}\,\frac{e^2}{c_w^2}\,M^2_{\chi^0}\left[\left(\frac{1}{m^2_{\tilde{e}}}\right)\;\left(\frac{\mu_k g v_u}{M^2_{\chi^0}}\right)\right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)\;.$$

# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda_{ikk}$

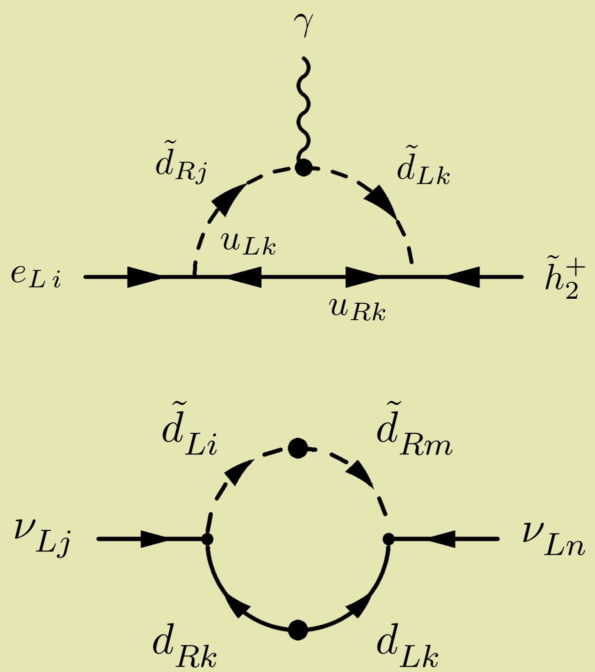


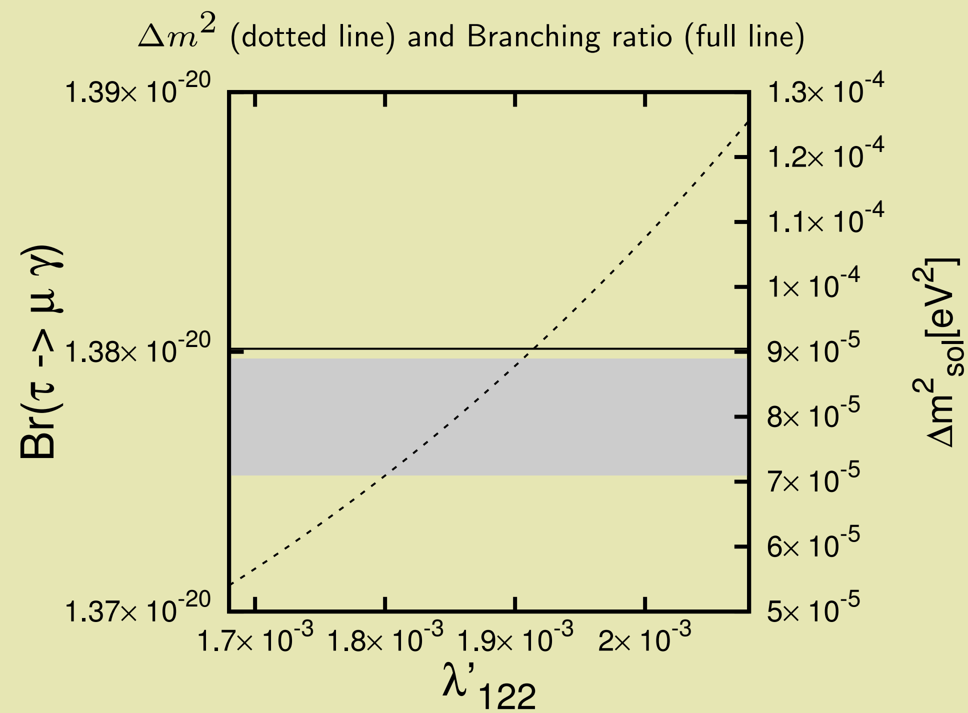




$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda_{ikk}|^2}{G_F^2 m_i^2} \frac{e^2}{c_w^2} M^2_{\chi^0} \left[ \left( \frac{1}{m^2_{\tilde{e}}} \right) \left( \frac{\mu_k g v_u}{M^2_{\chi^0}} \right) \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j) \; .$$

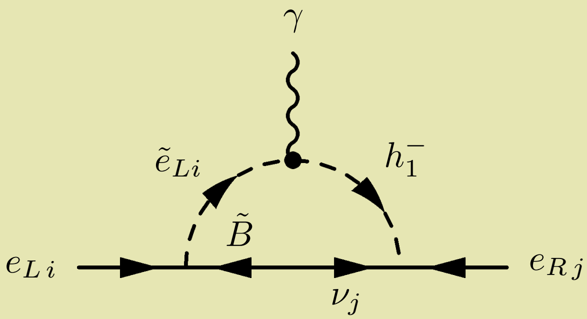
# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $\lambda'_{ikk}$

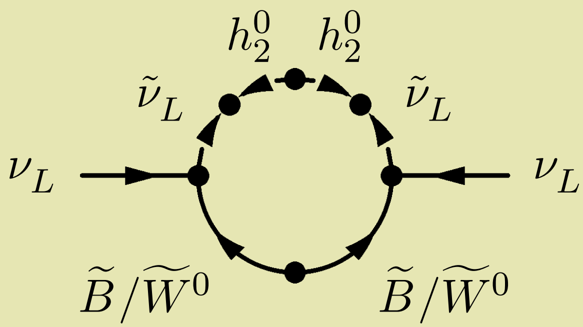


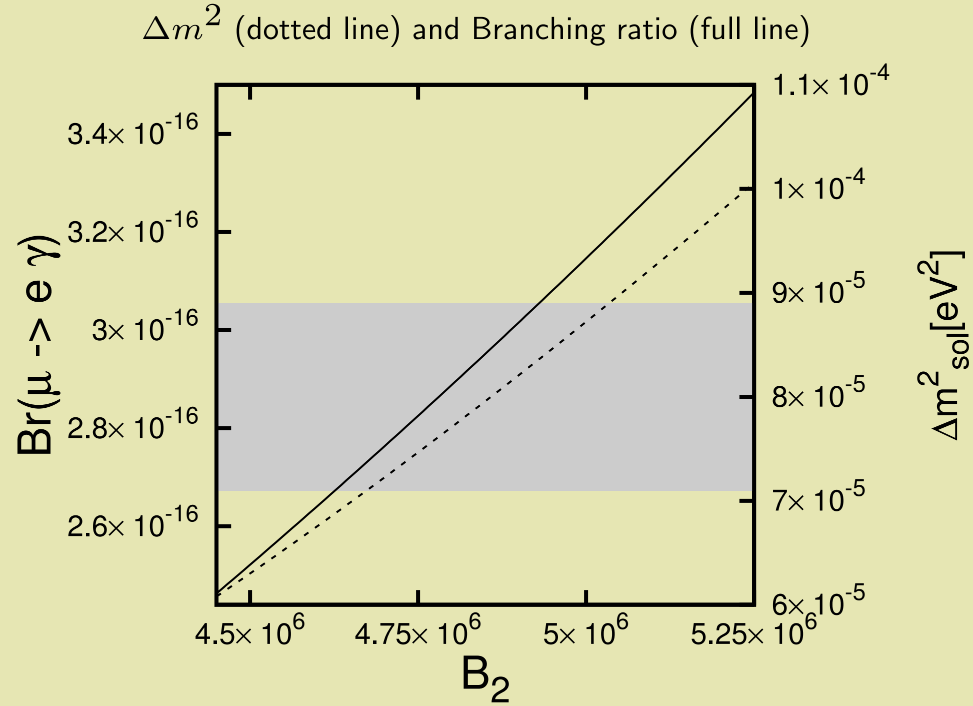




$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda'_{ikk}|^2}{G_F^2 m_i^2} |(Y_U)_{kk}|^2 \, m_{u_k}^2 \left[ 3 \left( \frac{1}{m_{\tilde{d}}^2} \right) \left( \frac{\mu_k m_{e_k}}{m_{\chi^\pm}^2} \right) \left( \frac{\mathcal{M}^2_{\tilde{d}\,LR}}{\mathcal{M}^2_{\tilde{d}\,R} - \mathcal{M}^2_{\tilde{d}\,L}} \right) \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j) \, ,$$

# Atmospheric scale $\kappa_{1,2,3}$ – Solar scale $B_i$

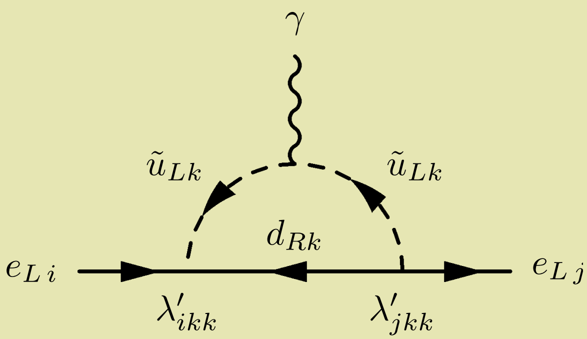


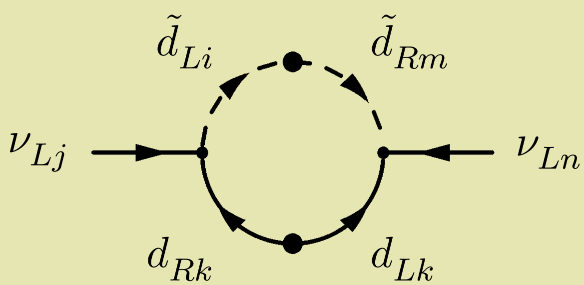



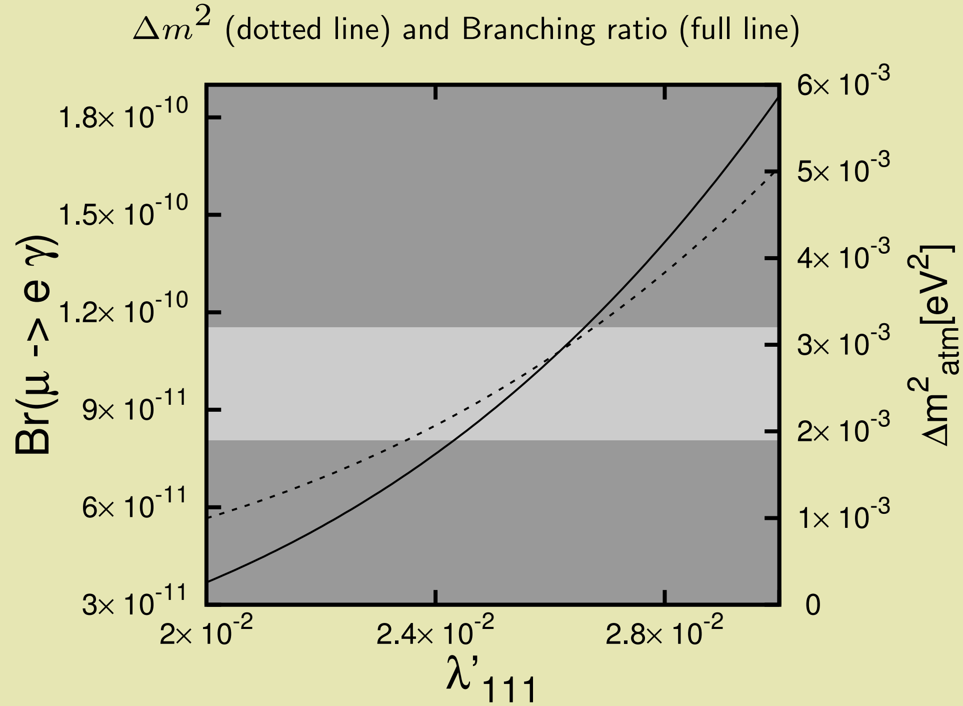




$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda_{0jj}|^2}{G_F^2 m_i^2}\frac{e^2}{c_w^2}\left[\left(\frac{1}{m^2_{H^+}}\right)\left(\frac{B_i}{m^2_{H^+}}\right)\left(\frac{\mu_j g v_u}{m_{\chi^0}}\right)\right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)$$

# Atmospheric scale $\lambda'_{1kk,2kk,3kk}$

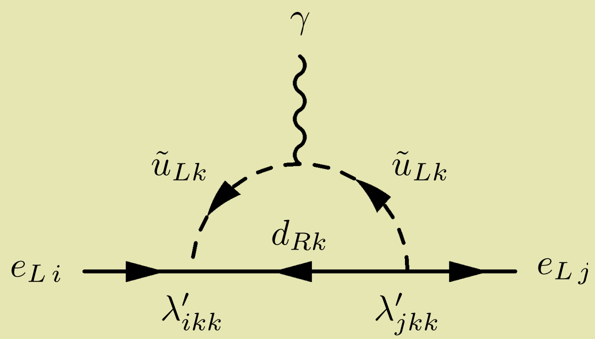


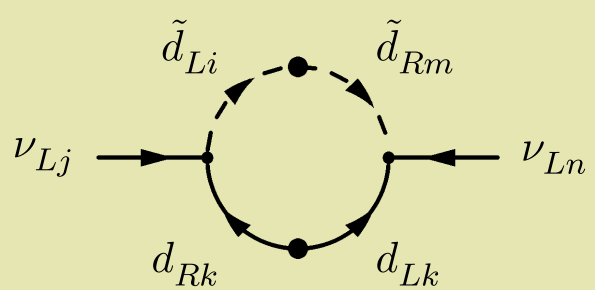



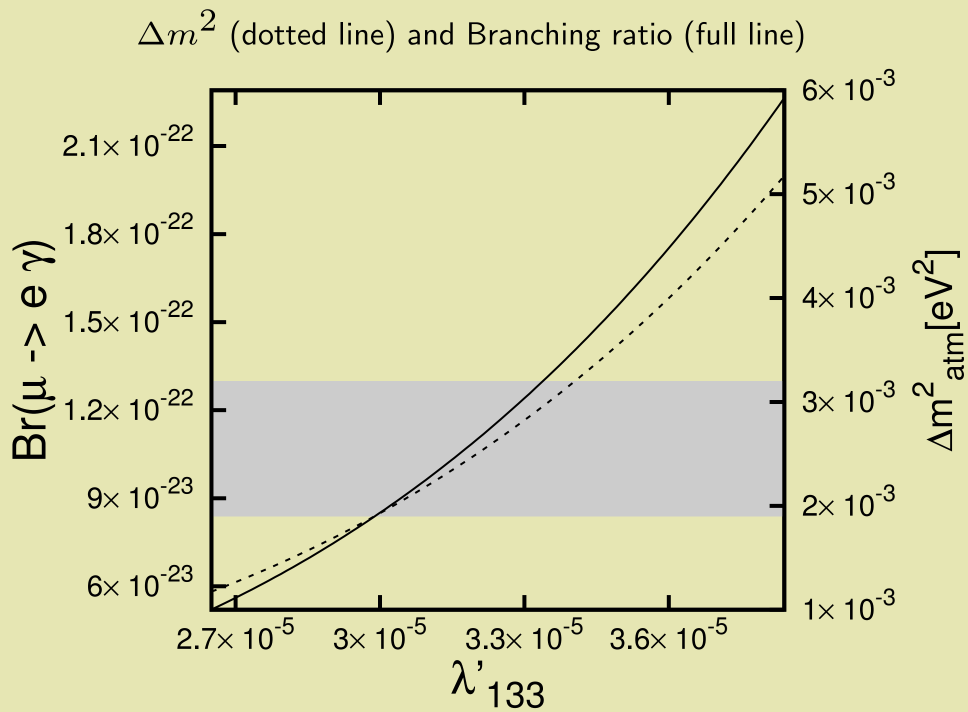




$$\Gamma(l_i \to l_j\gamma) \approx \frac{3}{(4\pi)^2}\frac{|\lambda'_{ikk}|^2\,|\lambda'_{jkk}|^2}{G_F^2}\left[\frac{1}{3}\frac{1}{m_{\tilde{u}}^2}\right]^2 \Gamma(l_i \to l_j\nu_i\bar{\nu}_j)\ .$$

# Atmospheric scale $\lambda'_{1kk,2kk,3kk}$

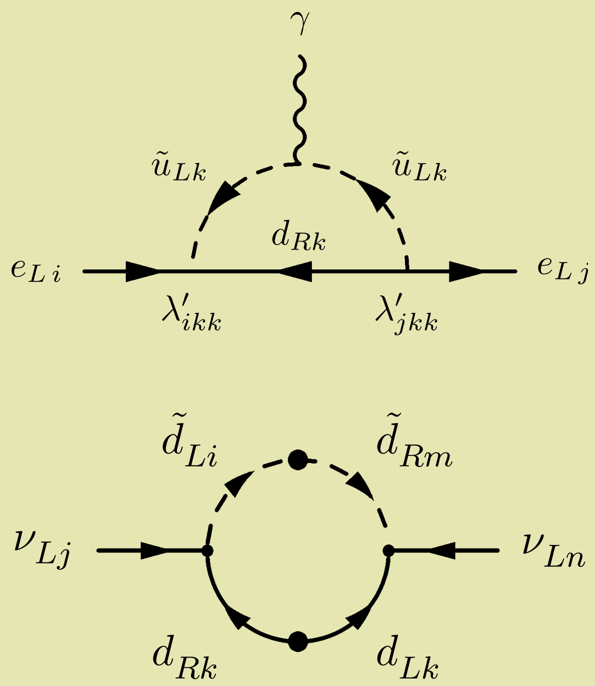


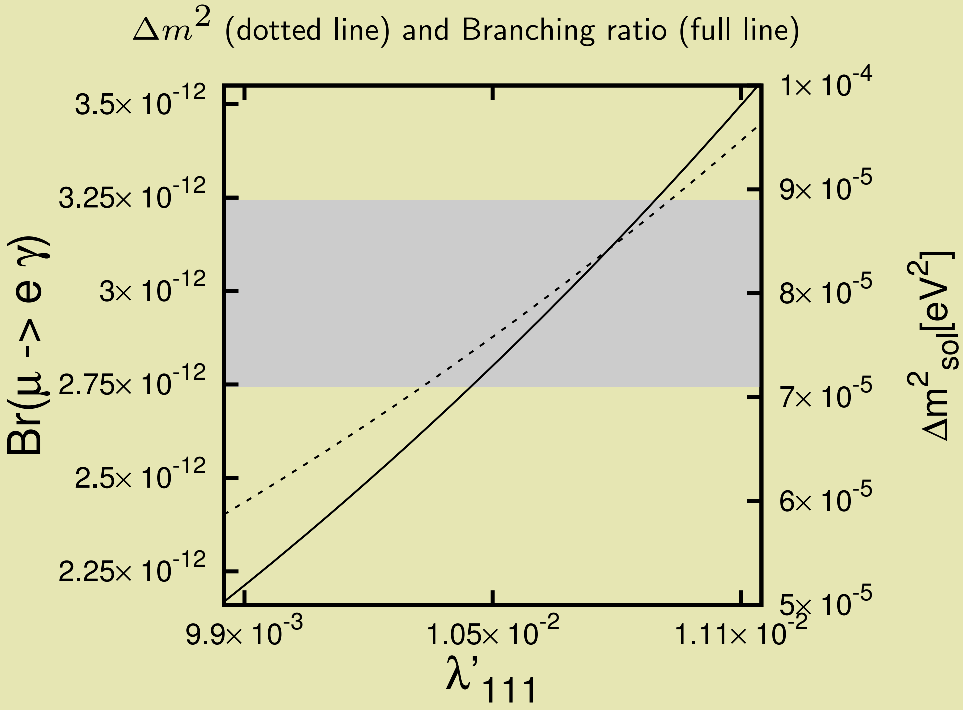




$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda'_{ikk}|^2 \, |\lambda'_{jkk}|^2}{G_F^2} \left[ \frac{1}{3} \frac{1}{m_{\tilde{u}}^2} \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j) \; .$$

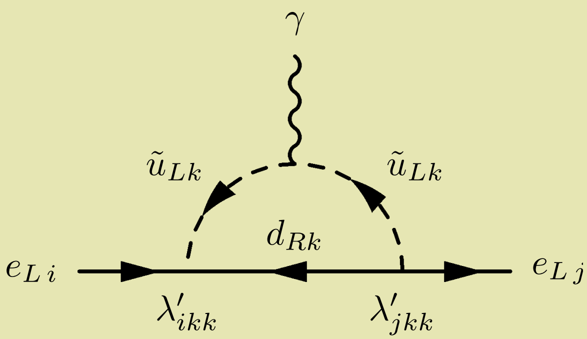
# Atmospheric scale $\lambda'_{1kk,2kk,3kk}$ – Solar scale $\lambda'_{1jj,2jj,3jj}$

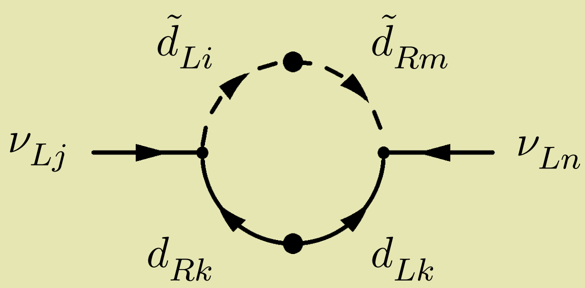


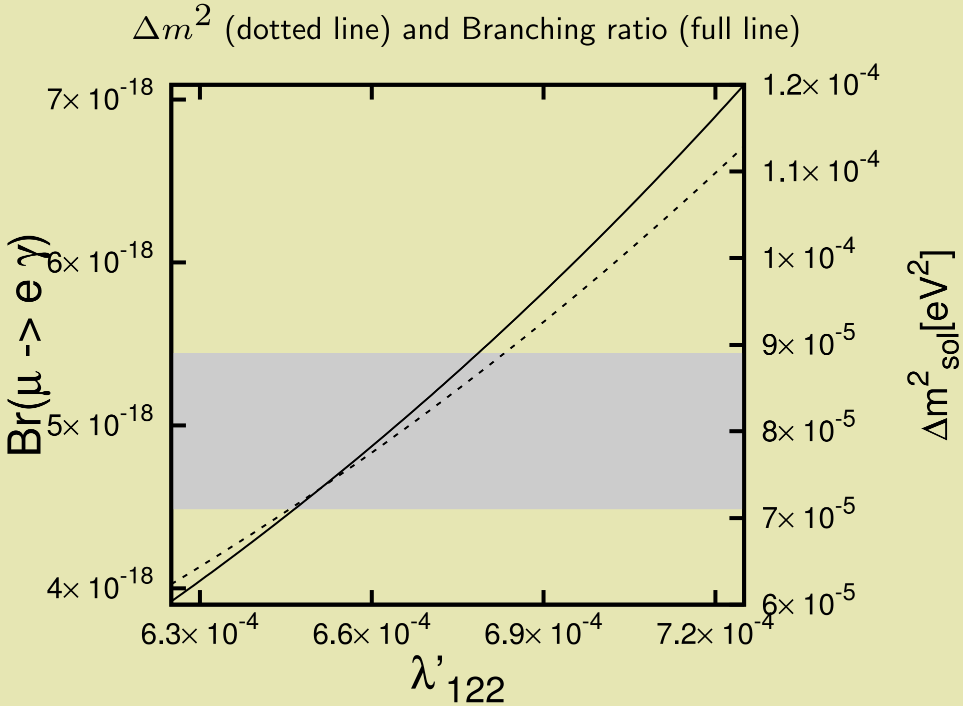




$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda'_{ikk}|^2\,|\lambda'_{jkk}|^2}{G_F^2} \left[\frac{1}{3}\frac{1}{m_{\tilde{u}}^2}\right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)\ .$$

# Atmospheric scale $\lambda'_{1kk,2kk,3kk}$ – Solar scale $\lambda'_{1jj,2jj,3jj}$




$$\Gamma(l_i \to l_j \gamma) \approx \frac{3}{(4\pi)^2} \frac{|\lambda'_{ikk}|^2 \, |\lambda'_{jkk}|^2}{G_F^2} \left[ \frac{1}{3} \frac{1}{m^2_{\tilde{u}}} \right]^2 \Gamma(l_i \to l_j \nu_i \bar{\nu}_j)$$

# Summary and Conclusions

- The one-loop corrections to the neutrino masses in the $\not{L}$-MSSM have been calculated, and it has been shown that the current values for mass squared differences and leptonic mixing angles can be reproduced.

- In some cases, the operators which determine neutrino masses, either at tree or loop level, will also give rise to observable flavour violating leptonic decays.

- When one neutrino mass is generated at tree level and a single $\lambda$ coupling sets the solar scale, $\lambda_{211,122}$ are excluded for SPS1a. Neutrino masses set stronger bounds on the values for the $\lambda'$ and bilinear soft breaking terms, however.

- If trilinear couplings set both neutrino scales, rare lepton decays set bounds on the set $\{\lambda'_{111,211,311}\}$.