Charged lepton decays from soft flavour violation in a two-Higgs doublet seesaw model

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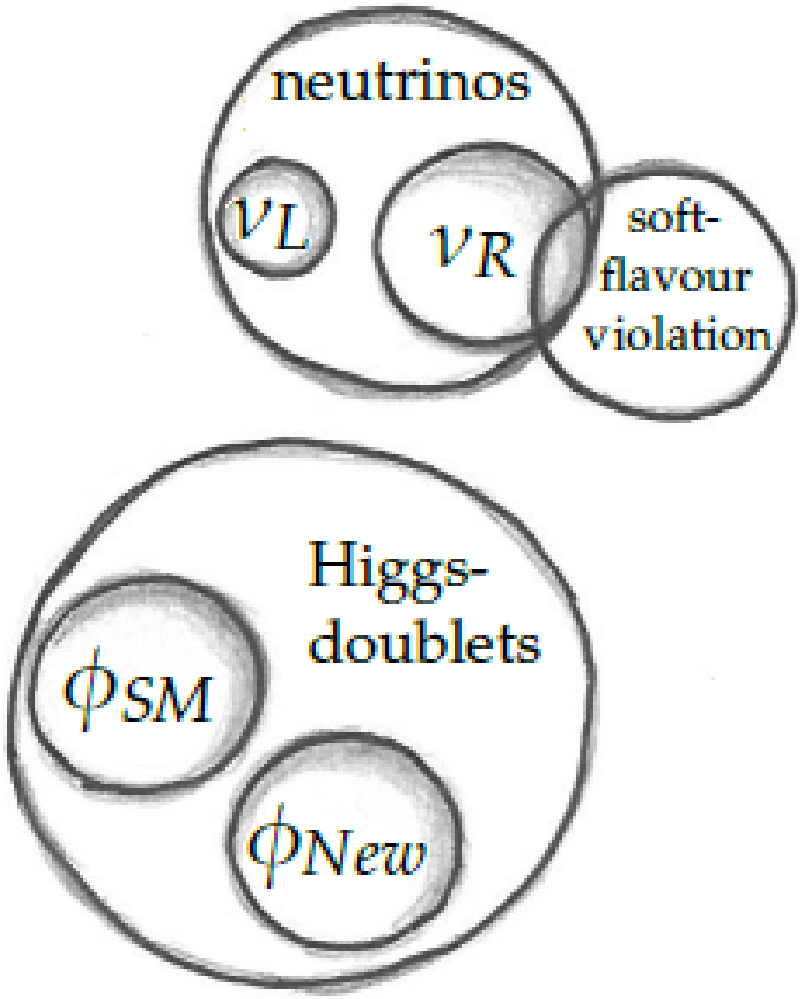
Doktoratskolleg Particles and Interactions

universität wien
Faculty of Physics

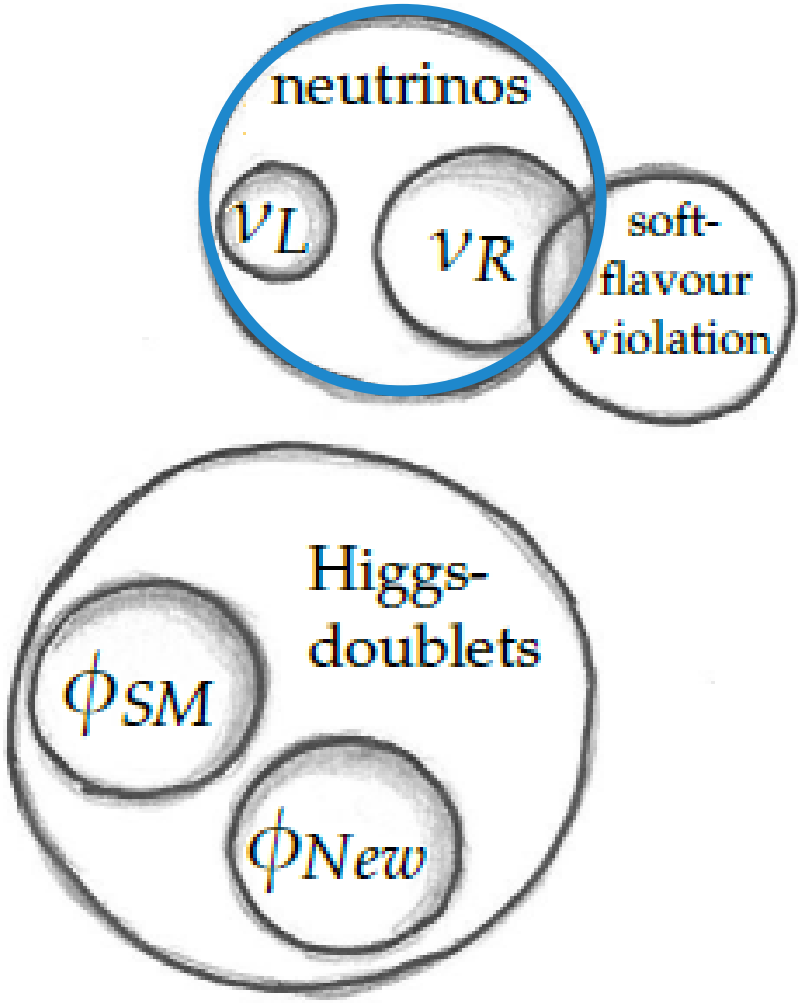
Overview

1. THE MODEL
   - Neutrinos - right handed neutrinos
   - Multi Higgs doublets
   - Soft flavour violation
   - Properties and advantages
2. CHARGED LEPTON DECAYS
   - Suppression of radiative corrections
   - Free Parameter
   - Magnetic dipole moments
   - Results
3. CONCLUSION & OUTLOOK

The model


neutrinos
ν_L
ν_R
soft-
flavour
violation
Higgs-
doublets
ϕ_{SM}
ϕ_{New}

The model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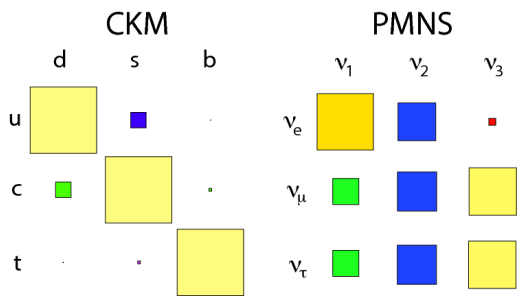
Why we care about neutrinos

experimentally unsolved: anomalies...

theoretical unsolved: (all about mass)

- different mixing matrices then quarks
- normal or inverted mass hierarchy
- hierarchy problem: very light mass
- origin of mass: Dirac, Majorana



properties:

- just weak interacting
- no observed right handed partner

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$$\mathcal{L}_M \stackrel{?}{=} \mathcal{L}_{Dirac} + \mathcal{L}_{Majorana}$$
$$\sim \bar{\nu}_R M_D \nu_L + \bar{\nu}_\alpha M_M \nu_\beta + h.c.$$

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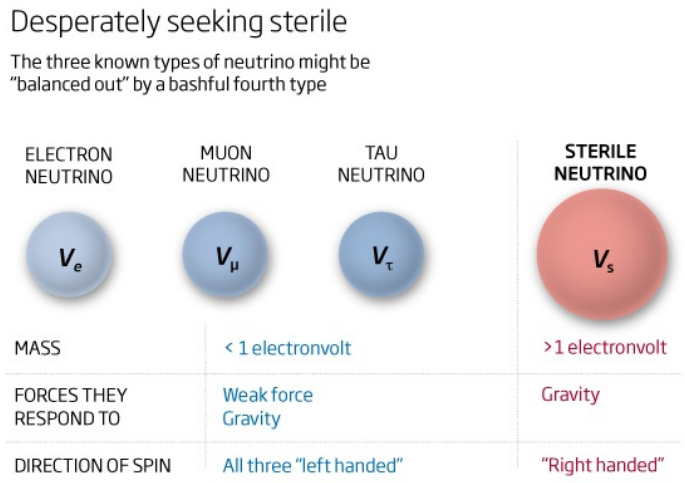


introduce:
right handed neutrinos ν_R

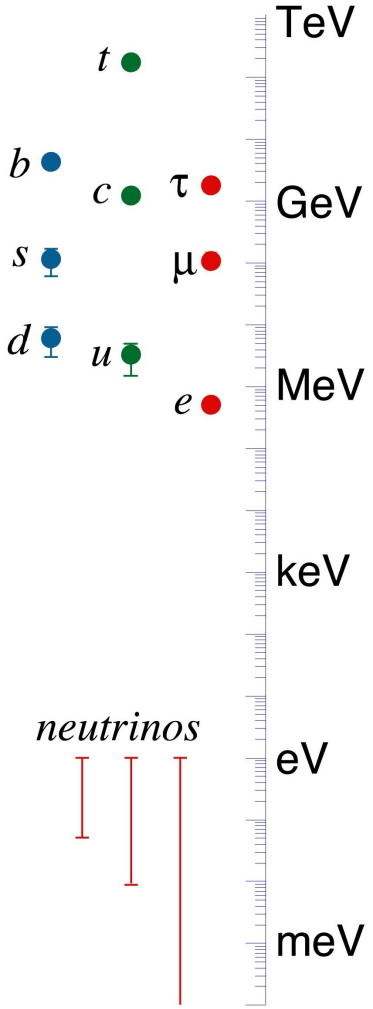
Heavy right handed neutrinos ν_R

Hierarchy problem:

Neutrino mass is small $m_\nu < 0.1$ eV (exp. limits)

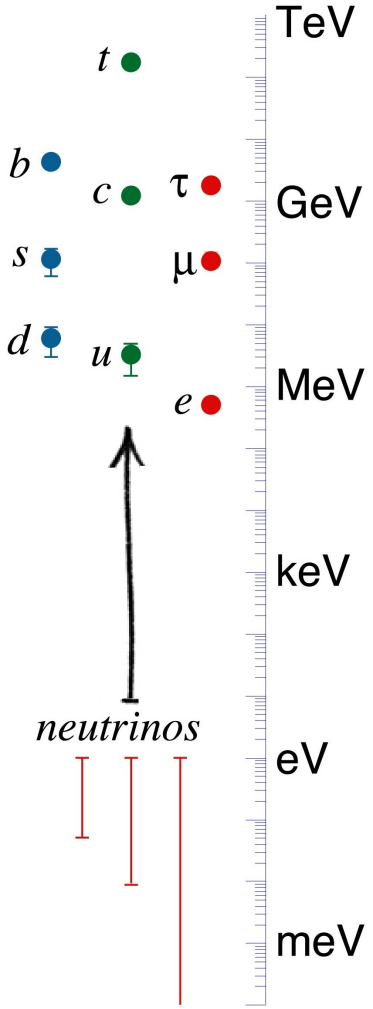
Masses are normally $m_e \simeq 0.5$ MeV to $m_t \simeq 173$ GeV

$\Rightarrow$ *small Yukawa masses seem to be unnatural*



Heavy right handed neutrinos ν_R

Soltion: **Majorana neutrinos with heavy ν_R in Seesaw mechanism**



flavour basis: scale $m_D \sim m_e$, $m_R \gtrsim$ TeV

$$\mathcal{L}_y \supset \mathcal{L}_{dirac} = \overline{\nu_R}\, M_D\, \nu_L + h.c.$$

$$\mathcal{L}_{maj} = -\frac{1}{2}\, \overline{(\nu_R)^c}\, M_R^*\, \nu_R + h.c.$$

mass basis: diagonalise $M_{maj} \rightarrow diag(\hat{m}_\nu, \hat{m}_R)$

scale $m_\nu = -m_D^2/m_R \quad \rightarrow \quad m_\nu$ small

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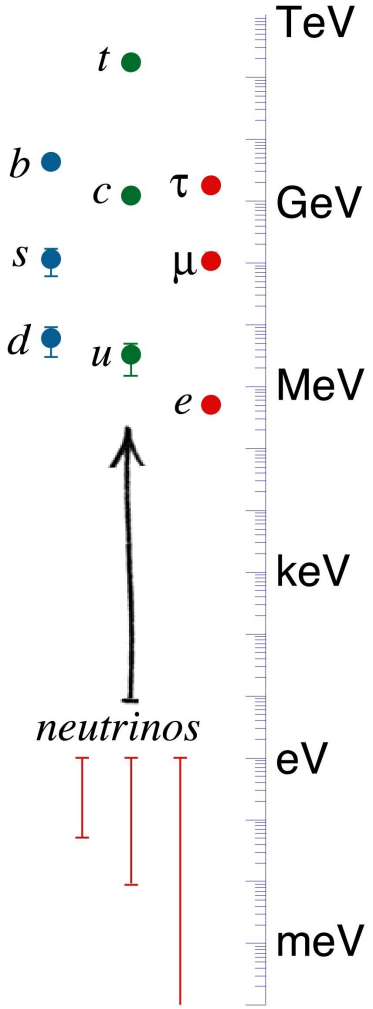

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$$\mathcal{L}_{\nu mass} = -\frac{1}{2}\left(\overline{(\nu_L)^c}, \overline{\nu_R}\right)\underbrace{\begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix}}_{M_{maj}}\begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} + h.c.$$

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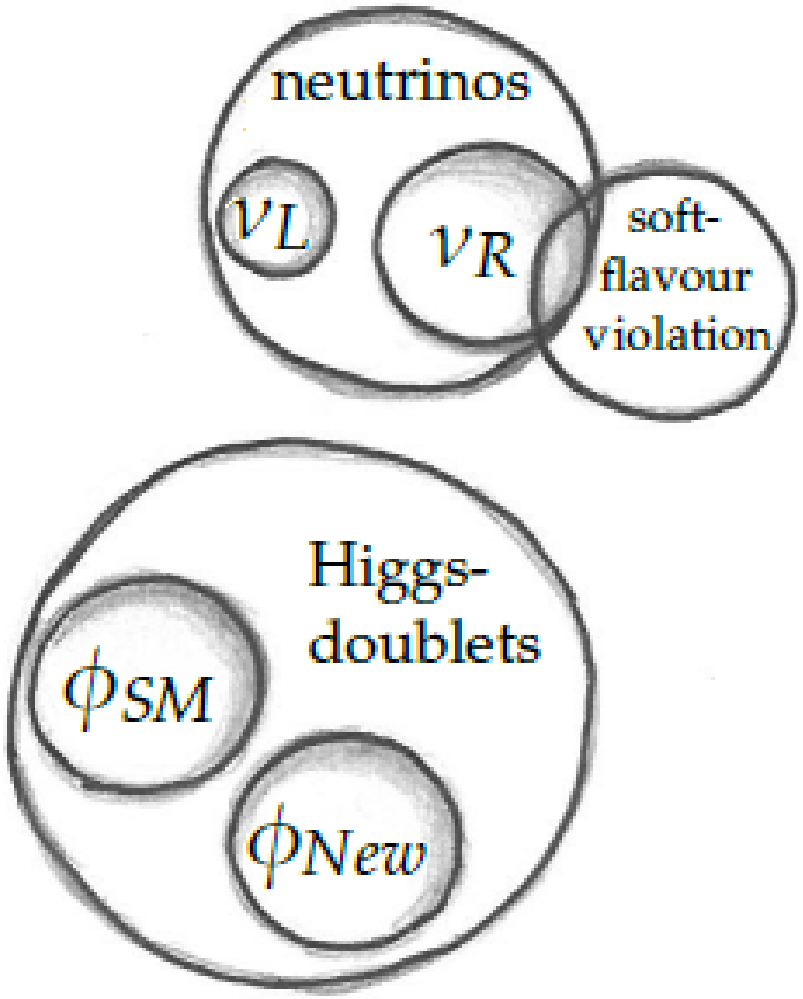
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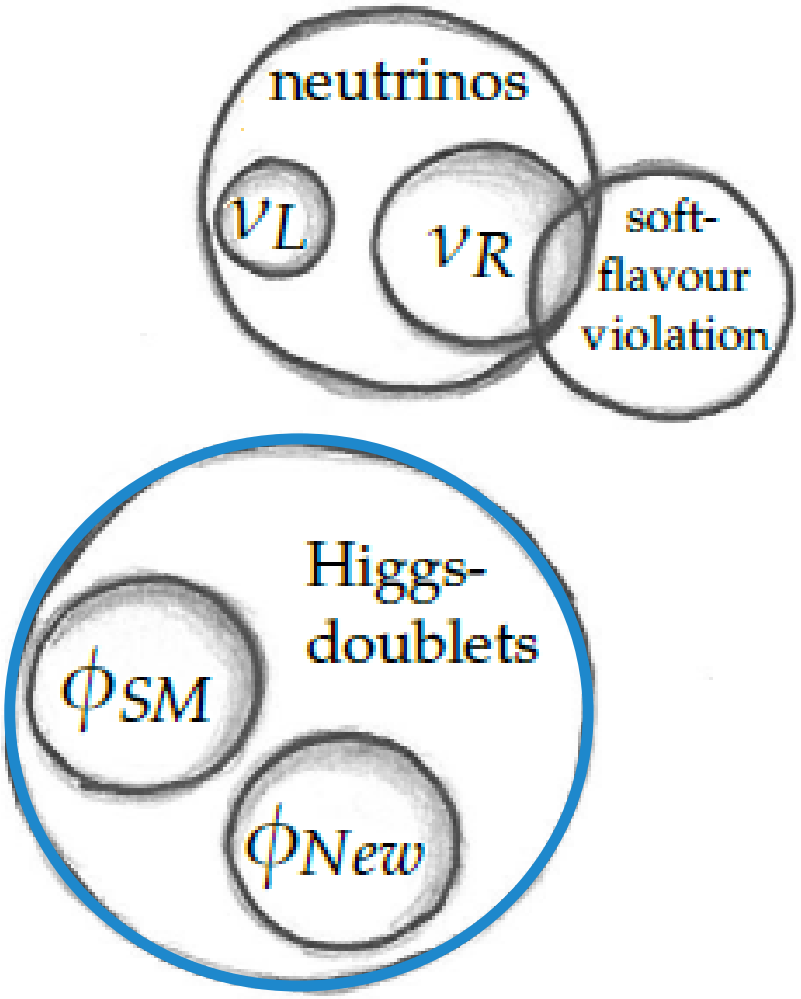
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Multi Higgs doublets Φ_k

SM: $n_H = 1$ **Higgs doublet**

$$\phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} \varphi^+ \\ \frac{v}{\sqrt{2}} + \varphi^{0\prime} \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} + H^0 \end{pmatrix}$$

Multi Higgs doublets Φ_k

Include: n_H **Higgs doublets**

$$\phi_k = \begin{pmatrix} \varphi_k^+ \\ \varphi_k^0 \end{pmatrix} = \begin{pmatrix} \varphi_k^+ \\ \frac{v_k}{\sqrt{2}} + \varphi_k^{0\prime} \end{pmatrix} = \begin{pmatrix} \sum_a^{n_H} U_{ka} S_a^+ \\ (v_k + \sum_b^{2n_H} V_{kb} S_b^0)/\sqrt{2} \end{pmatrix}$$

In our case $n_H = 2$: ϕ_1 SM Higgs doublet with VEV, and ϕ_2^{new}

$$\phi_1 = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} + H^0 \end{pmatrix}, \qquad \phi_2^{new} = \begin{pmatrix} S^+ \\ (S_3^0 + iS_4^0)/\sqrt{2} \end{pmatrix}$$

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Higgs-lepton interaction

$$\phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}, \quad \varphi^0 = \frac{v}{\sqrt{2}} + \varphi^{0\prime}$$

$$\mathcal{L}_Y = - \quad \left[\left(\varphi^-, \varphi^{0*} \right) \Gamma \ \bar{\ell}_R + \left(\varphi^0, -\varphi^+ \right) \Delta \ \bar{\nu}_R \right] \begin{pmatrix} \nu'_L \\ \ell'_L \end{pmatrix} + \text{h.c.}$$

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$$\supset \mathcal{L}_Y(\varphi^\pm) = -\sum_k \left\{ \bar{\ell}_R (\varphi_k^- \Gamma_k) \nu_L' - \bar{\nu}_R (\varphi_k^+ \Delta_k) \ell_L' + h.c. \right\}$$

$$\supset \mathcal{L}_Y(\varphi^0) = -\sum_k \left\{ \bar{\ell}_R \Big(\varphi_k^{0\prime *} \Gamma_k + \underbrace{M_\ell}_{\Gamma_k v_k/\sqrt{2}} \Big) \ell_L' + \bar{\nu}_R \Big(\varphi_k^{0\prime} \Delta_k + \underbrace{M_D}_{\Delta_k v_k/\sqrt{2}} \Big) \nu_L' + h.c. \right\}$$

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in our case:

$$-\mathcal{L}_Y(\varphi^\pm) = \bar{\ell}_R(\varphi^- \Gamma_2)\nu_L' - \bar{\nu}_R(\varphi^+ \Delta_2)\ell_L' + h.c.$$

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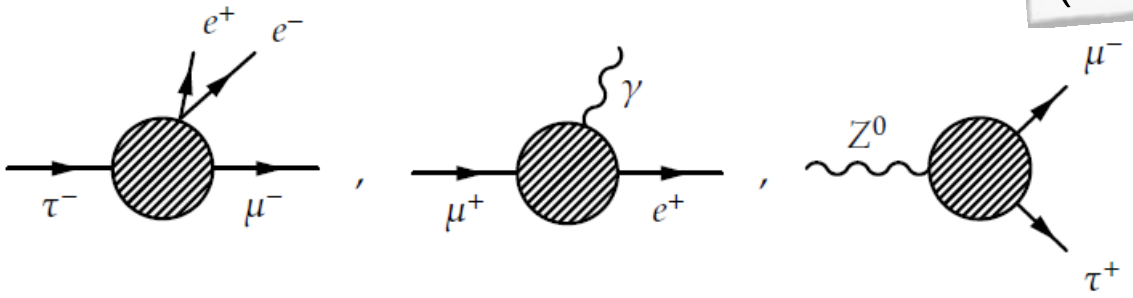
Multi Higgs doublets Φ_k

Include: n_H **Higgs doublets**

Higgs-lepton interaction

interesting effect:
observable processes!
(**F**lavour **C**hanging **N**eutral **I**nt.)

e.g.



in our case:

$$-\mathcal{L}_Y(\varphi^\pm) = \bar{\ell}_R(\varphi^- \Gamma_2)\nu'_L - \bar{\nu}_R(\varphi^+ \Delta_2)\ell'_L + h.c.$$

flav. non-diag.

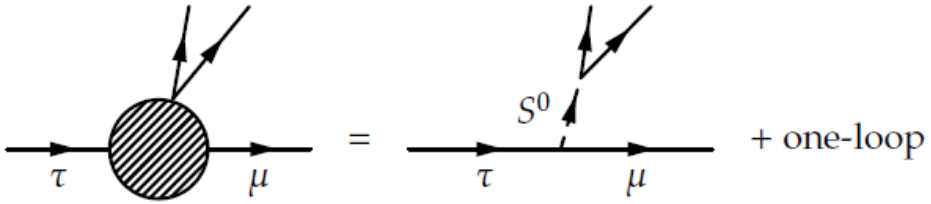
$$-\mathcal{L}_Y(\varphi^0) = \bar{\ell}_R \underbrace{M_\ell}_{\Gamma_1 v/\sqrt{2}} \ell'_L + \bar{\nu}_R \underbrace{M_D}_{\Delta_1 v/\sqrt{2}} \nu'_L + \bar{\ell}_R H^0 \Gamma_1 \ell'_L + \bar{\ell}_R\left(\varphi_3^0 + i\varphi_4^0\right)\Gamma_2 \ell'_L + \ldots$$

Multi Higgs doublets Φ_k

Problem:

strong experimental bounds on FCNIs at tree level!

e.g.



$\sim |\Gamma_2^{\tau\mu}\Gamma_2^{ee}/m_{S^0}^2|$
suppressed

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tree-level

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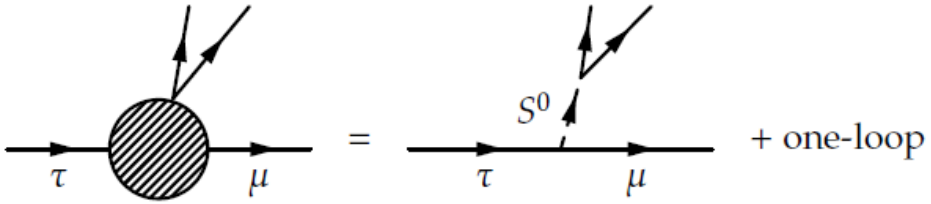

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suppressed

solution:

either very small Γ_2 & big m_{S^0}

or Lepton flavour symmetry
flavour diag. Γ, Δ

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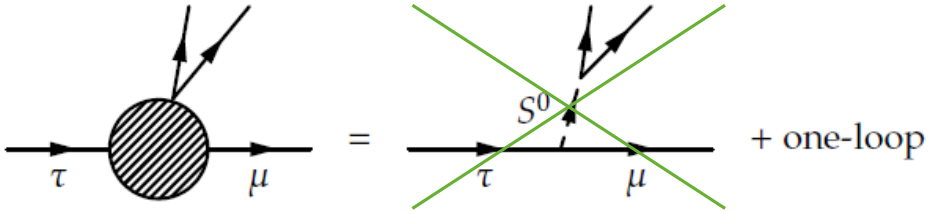

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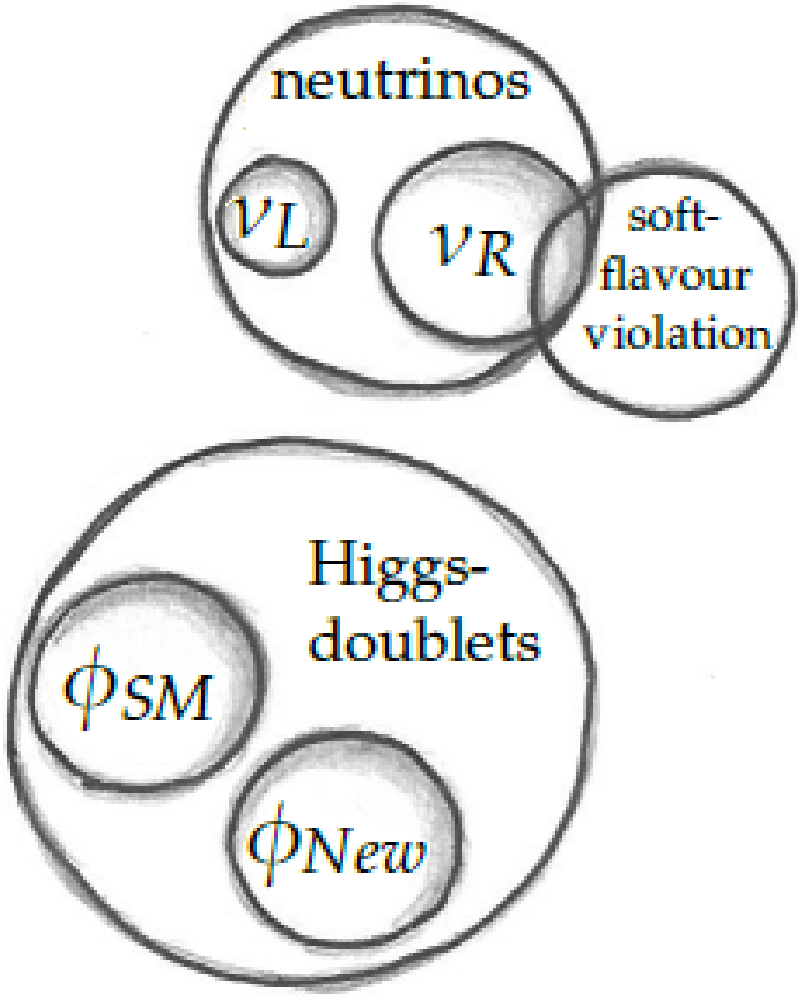
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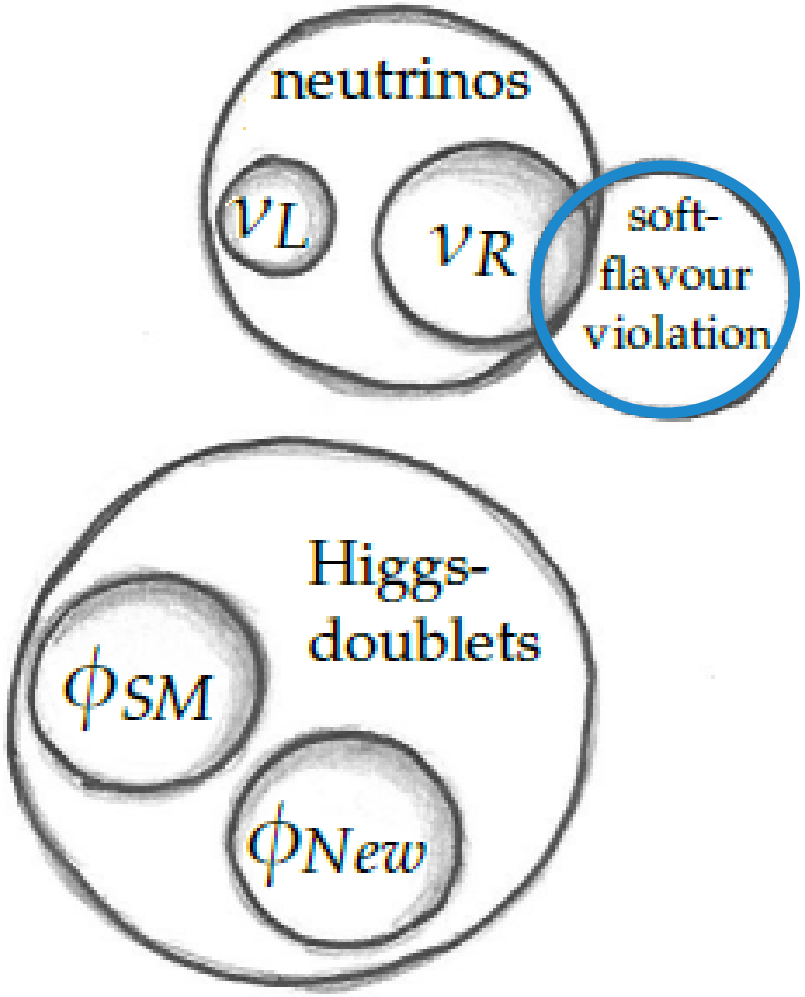
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Lepton flavour

SM:

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$\uparrow$

ℓ–mass basis

$\downarrow$

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \bar{\ell}_L \gamma^\mu W^+_\mu \nu_L + h.c.$$

Lepton flavour

SM + mixing neutrinos:

$$-\mathcal{L}_Y(\varphi^0) = \bar{\ell}_R \underbrace{M_\ell}_{\Gamma_1\, v/\sqrt{2}} \ell'_L + \bar{\nu}_R \underbrace{M_D}_{\Delta_1\, v/\sqrt{2}} \nu'_L + \bar{\ell}_R H^0 \Gamma_1 \ell'_L + \quad \ldots$$

$\uparrow$ ℓ–mass basis $\neq$ ν–mass basis $\uparrow$

$\downarrow$ $\downarrow$

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \bar{\ell}_L \gamma^\mu \underbrace{U_{PMNS}}_{U_\ell^\dagger U_\nu} W_\mu^+ \nu_L + h.c.$$

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flavour basis

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flavour basis

Lepton flavour symmetry: L_α

$U(1)_e \times U(1)_\mu \times U(1)_\tau$ continuous, global

Symmetry transf.

$$U_e(\theta) = \begin{pmatrix} e^{iL_e\theta} & & \\ & 1 & \\ & & 1 \end{pmatrix}, \; U_\mu(\theta) = \begin{pmatrix} 1 & & \\ & e^{iL_\mu\theta} & \\ & & 1 \end{pmatrix}, \; U_\tau(\theta) = \begin{pmatrix} 1 & & \\ & 1 & \\ & & e^{iL_\tau\theta} \end{pmatrix}$$

Fermion transf.

$$\begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix} \to U_\alpha(\theta) \begin{pmatrix} \nu_\ell \\ \ell \end{pmatrix}, \qquad \ell_R \to U_\alpha(\theta)\ell_R, \qquad \nu_R \to U_\alpha(\theta)\nu_R$$

$\Rightarrow$ $\mathcal{L} \supset \mathcal{L}_Y, \mathcal{L}_{CC}$ invariant under L_α-symmetry

Lepton flavour symmetry

SM + mixing neutrinos + Φ_2:

$$-\mathcal{L}_Y(\varphi^0) = \bar{\ell}_R \underbrace{M_\ell}_{\Gamma_1\, v/\sqrt{2}} \ell'_L + \bar{\nu}_R \underbrace{M_D}_{\Delta_1\, v/\sqrt{2}} \nu'_L + \bar{\ell}_R H^0 \Gamma_1 \ell'_L + \bar{\ell}_R \left(\varphi_3^0 + i\varphi_4^0\right) \underbrace{\Gamma_2}_{\text{non-diag.}} \ell'_L + \dots$$

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flavour basis

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$\downarrow$ $\downarrow$

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \bar{\ell}_L \gamma_\mu \underbrace{U_\ell^\dagger U_\nu}_{\mathbb{1}} W^{+\mu} \nu_L + h.c.$$

$\Rightarrow$ Yukawa couplings Γ, Δ diag.

$\Rightarrow$ no tree-level mixing ✓

$\Rightarrow$ no ν–mixing: $U_{PMNS} = \mathbb{1}$ ↯

$\Rightarrow$ $\underline{\mathcal{L} \supset \mathcal{L}_Y, \mathcal{L}_{CC} \text{ invariant under } L_\alpha\text{-symmetry}}$

Lepton flavour symmetry

SM + mixing neutrinos + Φ_2:

$$-\mathcal{L}_Y(\varphi^0) = \bar{\ell}_R \underbrace{M_\ell}_{\Gamma_1 v/\sqrt{2}} \ell'_L + \bar{\nu}_R \underbrace{M_D}_{\Delta_1 v/\sqrt{2}} \nu'_L + \bar{\ell}_R H^0 \Gamma_1 \ell'_L + \bar{\ell}_R \left(\varphi_3^0 + i\varphi_4^0\right) \underbrace{\Gamma_2}_{\text{diag.!}} \ell'_L + \dots$$

$\uparrow$ ℓ–mass basis $=$ ν–mass basis $\uparrow$

$\downarrow$ $\downarrow$

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \bar{\ell}_L \gamma_\mu \underbrace{U_\ell^\dagger U_\nu}_{\mathbb{1}} W^{+\mu} \nu_L + h.c.$$

$\Rightarrow$ Yukawa couplings Γ, Δ diag.

$\Rightarrow$ no tree-level mixing ✓

$\Rightarrow$ no ν–mixing: $U_{PMNS} = \mathbb{1}$ ↯

$\rightarrow$ break L_α soft

$\Rightarrow$ $\mathcal{L} \supset \mathcal{L}_Y, \mathcal{L}_{CC}$ invariant under L_α-symmetry

Soft flavour breaking $\not{L}_\alpha$

Impose: Lepton flavour symmetry

$$-\mathcal{L}_Y(\varphi^0) = \bar{\ell}_R M_\ell \, \ell'_L + \bar{\nu}_R M_D \, \nu'_L + \bar{\ell}_R H^0 \Gamma_1 \, \ell'_L + \bar{\ell}_R \left(\varphi_3^0 + i\varphi_4^0\right) \Gamma_2 \, \ell'_L + \dots$$

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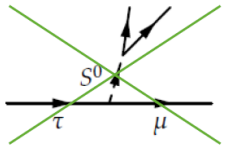
Break: Lepton flavour soft

explicit breaking in $\mathcal{O}(3)$ terms in energy dim. of fields (all terms $\leq \mathcal{O}(3)$ must be present)

- $\Rightarrow$ $\mathcal{O}(3)$: two fermions involved, propagator- or mass-term
- $\Rightarrow$ no flavour-violating vertex, no FCNIs at tree level! ✓



- $\Rightarrow$ no counterterms from a vertex $\rightarrow$ no UV divergences at one loop
- $\Rightarrow$ one loop contributions finite!

Soft flavour breaking $\not{L}_\alpha$

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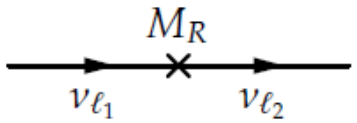
Break: Lepton flavour soft

$$\mathcal{L}_{maj} = -\tfrac{1}{2} \overline{(\nu_R)^c} \underbrace{M_R^*}_{non-diag.} \nu_R + h.c.$$



$$\mathcal{L}_{\nu mass} = -\frac{1}{2} \left(\overline{(\nu_L)^c}, \overline{\nu_R} \right) \begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L \\ (\nu_R)^c \end{pmatrix} + h.c. \quad \text{flavour basis}$$

$$= -\frac{1}{2} \overline{\chi} \, U^T(U_{PMNS}) \begin{pmatrix} \hat{m}_L & 0 \\ 0 & \hat{m}_R \end{pmatrix} U(U_{PMNS}) \, \chi + h.c. \quad \text{mass basis}$$

Soft flavour breaking $\not{L}_\alpha$

Impose: Lepton flavour symmetry

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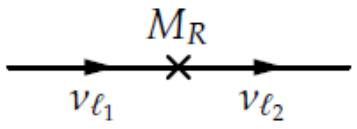
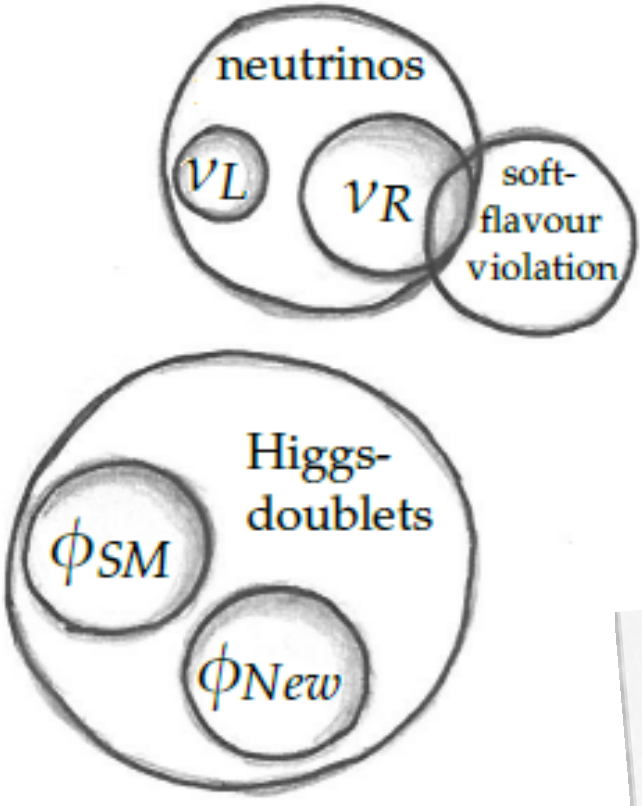


- ν_R responsible for flavour mixing (U_{PMNS})
- FCNIs at one loop in ℓ–decays

Properties and advantages



- explain tiny ν–masses
- additional particles: φ_3, φ_4, ν_R
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  - no FCNI at tree-level
  - one-loop contributions are finite
  - explains U_{PMNS} & V_{CKM} different

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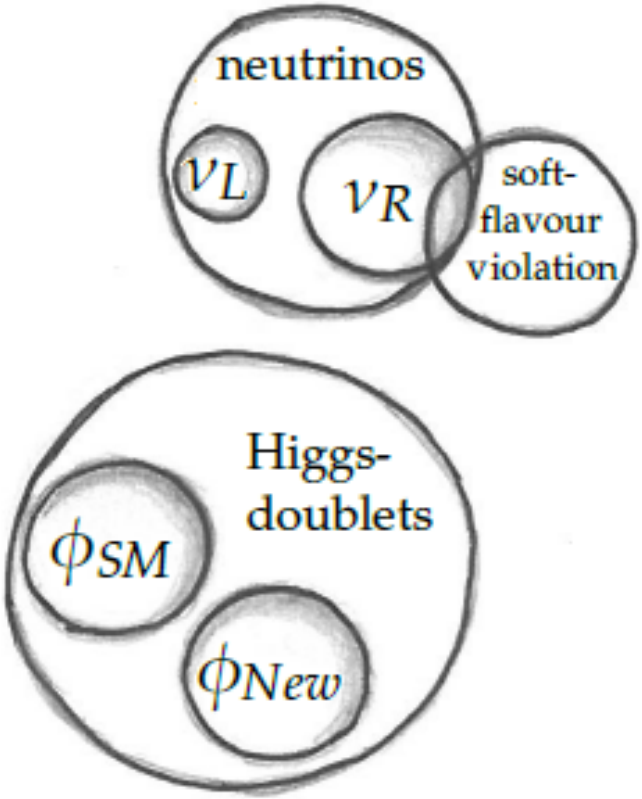

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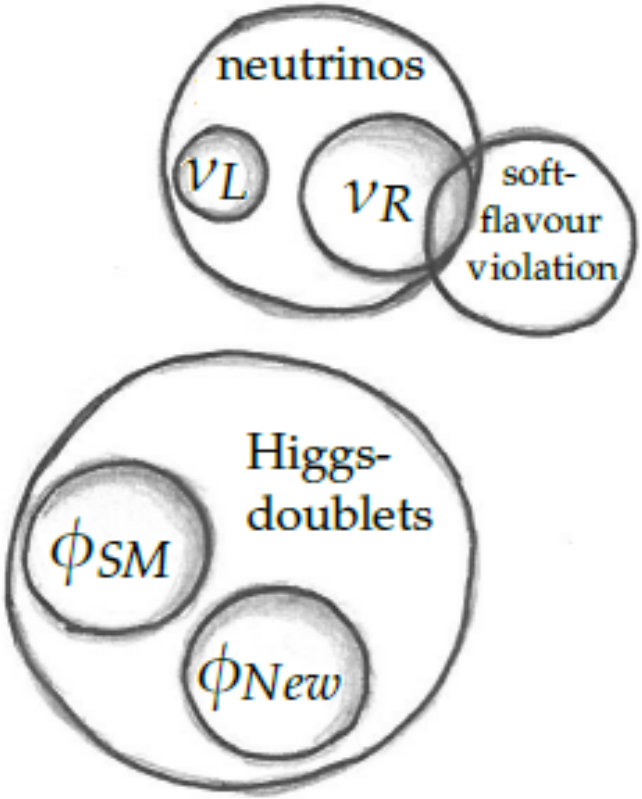

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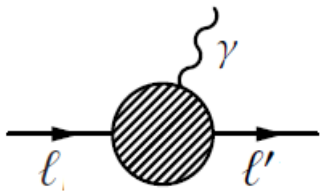
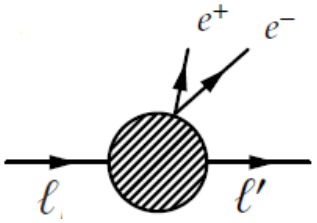
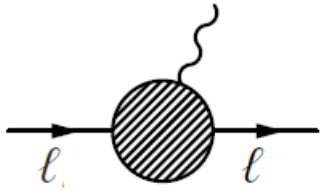
Test with Charged lepton decays

Charged lepton decays

high exp. bounds	model contributions
$\mathrm{BR}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ $\mathrm{BR}(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8}$	 radiative decay
$\mathrm{BR}(\mu^- \to e^-e^+e^-) < 1.0 \times 10^{-12}$ $\mathrm{BR}(\tau^- \to e^-e^+e^-) < 2.7 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to e^-\mu^+\mu^-) < 2.7 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to \mu^-e^+e^-) < 1.8 \times 10^{-8}$	 three part. decay
$a_e^{exp-err} = \pm 2.6 \times 10^{-13}$ (exp/SM = 1) $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = \begin{cases} (287 \pm 80) \times 10^{-11} \\ (261 \pm 78) \times 10^{-11} \end{cases}$ (3.6σ)	 magn.DM

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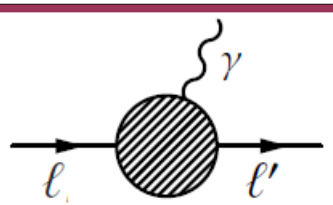
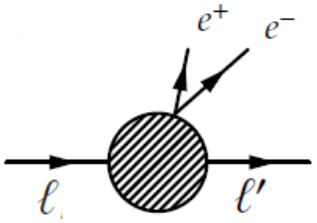
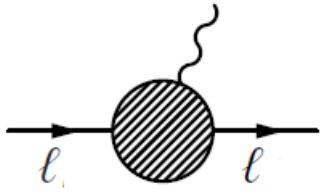
$\mathrm{BR}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ $\mathrm{BR}(\tau^- \to e^-\gamma) < 3.3 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to \mu^-\gamma) < 4.4 \times 10^{-8}$	 radiative decay
$\mathrm{BR}(\mu^- \to e^-e^+e^-) < 1.0 \times 10^{-12}$ $\mathrm{BR}(\tau^- \to e^-e^+e^-) < 2.7 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to e^-\mu^+\mu^-) < 2.7 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to \mu^-\mu^+\mu^-) < 2.1 \times 10^{-8}$ $\mathrm{BR}(\tau^- \to \mu^-e^+e^-) < 1.8 \times 10^{-8}$	 three part. decay
$a_e^{exp-err} = \pm 2.6 \times 10^{-13}$ (exp/SM = 1) $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = \begin{cases} (287 \pm 80) \times 10^{-11} \\ (261 \pm 78) \times 10^{-11} \end{cases}$ (3.6σ)	 magn.DM

Short analysis of ℓ-decays

One-loop model contributions:

characteristics of this model

$$\mathcal{A}(Z \to \tau^+\mu^-) \propto 1/m_R^2,$$
$$\mathcal{A}(\tau^- \to \mu^-\gamma) \propto 1/m_R^2,$$
$$\mathcal{A}(\tau^- \to \mu^- e^+ e^-) \propto \begin{cases} 1/m_R^2 & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases}$$

Processes including the sub-process $\ell^- \to \ell'^- S^{0*}$, ($S^{0*} \to e^+e^-$) have ($n_H \geq 2$) non-$m_R$-suppressed contributions from graphs with charged-scalar exchange $S^\pm$ (plot) in their Amplitudes $\mathcal{A}$, [Grimus, Lavoura, 02].

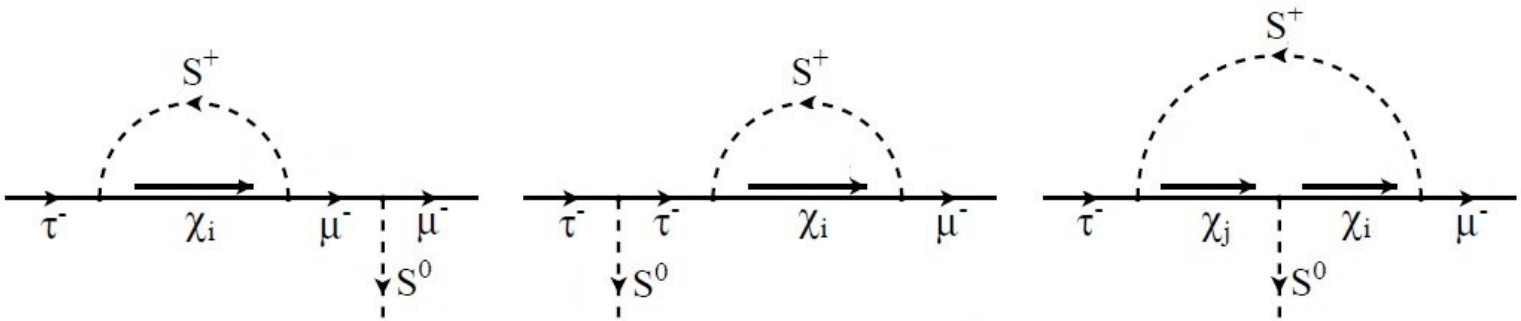


Figure: non-supressed diagrams for $\tau^- \to \mu^- S^{0*}$

Short analysis of ℓ-decays

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$$\mathcal{A}(\tau^- \to \mu^-\gamma) \propto 1/m_R^2,$$ via m_R

$$\mathcal{A}(\tau^- \to \mu^- e^+ e^-) \propto \begin{cases} 1/m_R^2 & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases}$$ only contr.

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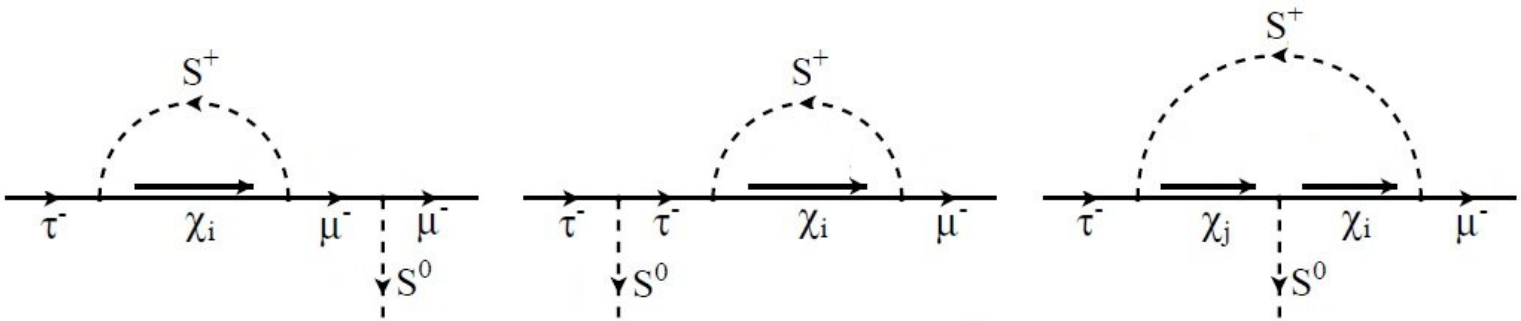

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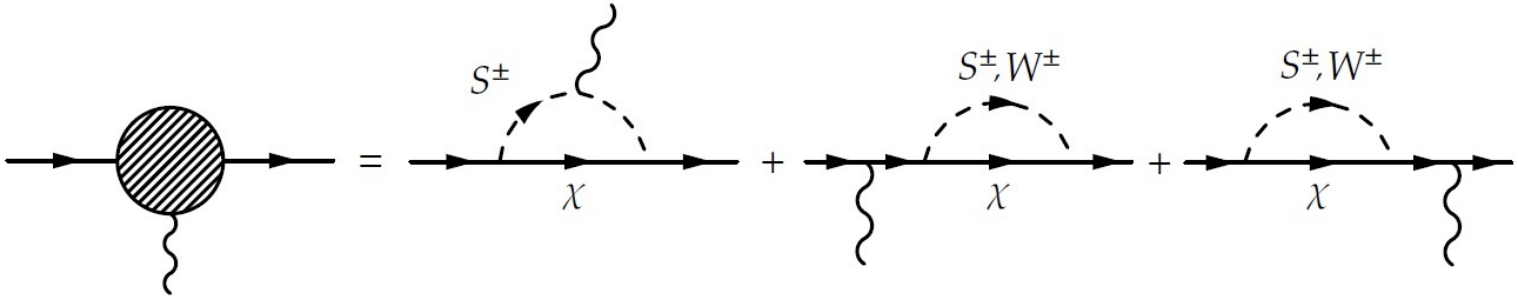
Suppression of radiative corrections



$$\Gamma\left(\ell_1^\pm \to \ell_2^\pm \gamma\right) = \frac{\alpha m_{\ell_1}^3}{4}\left(|A_L|^2 + |A_R|^2\right), \qquad \text{with } A_{L,R} \sim \frac{1}{16\pi^2}\frac{m_{\ell_1}}{m_R^2}$$

A **lower bound on** m_R **the seesaw scale**:

$$\mathrm{BR}\left(\mu^+ \to e^+\gamma\right) < 4.2 \times 10^{-13} \quad \Rightarrow \quad m_R \gtrsim 50\,\mathrm{TeV}$$

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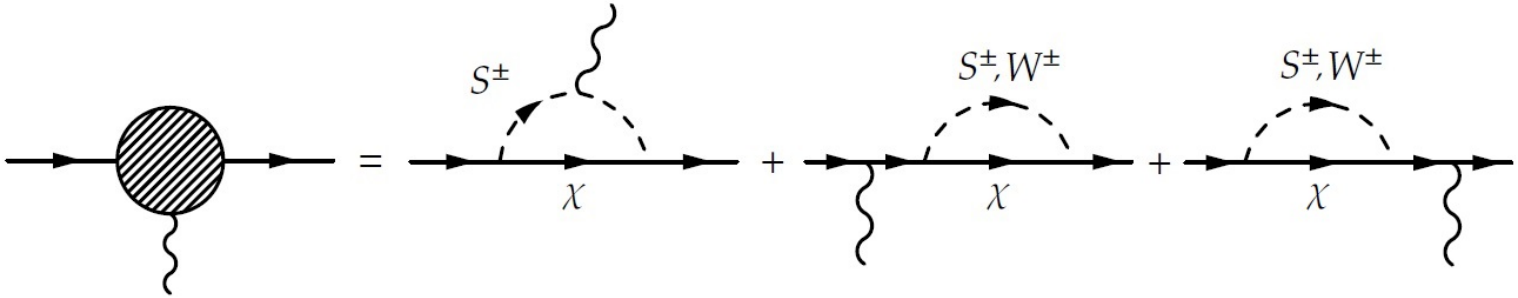

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$m_R \gtrsim 500\,\mathrm{TeV}$

Model tested: for $m_R \gtrsim 500$ TeV

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$\mathrm{BR}(\mu^+ \to e^+\gamma)$	$<$	4.2×10^{-13}	$\sim \frac{1}{m_R^4}$ **suppressed!**
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Free Parameter

seesaw scale:

$$\hat{m}_R = \begin{pmatrix} m_4 & & \\ & m_5 & \\ & & m_6 \end{pmatrix} \gtrsim \mathcal{O}(500\,\text{TeV})$$

Yukawa couplings:

$$\left(\Gamma_1 = \frac{\sqrt{2}}{v}\,\text{diag}(m_e, m_\mu, m_\tau) = \frac{\sqrt{2}}{v}\,M_\ell\right)$$

$$\Gamma_2 = \text{diag}\left(\gamma_e, \gamma_\mu, \gamma_\tau\right)$$

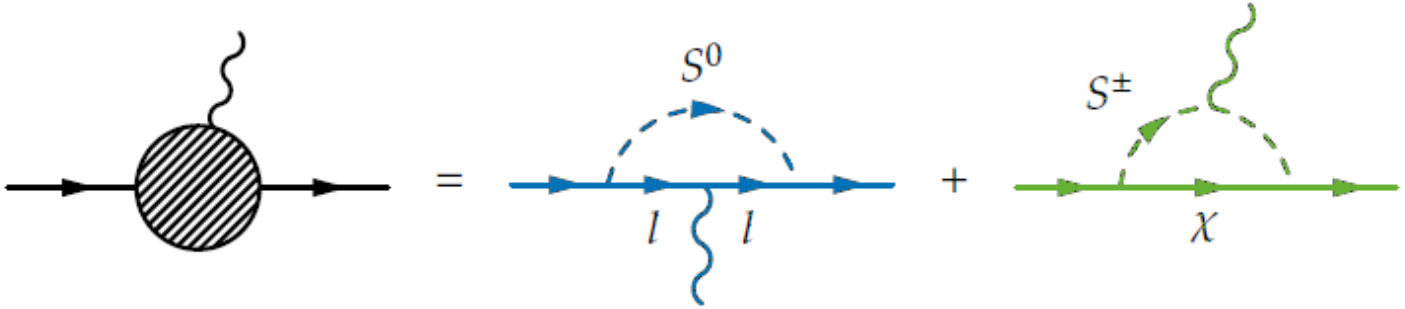
$$\Delta_1 = \text{diag}\left(d_e, d_\mu, d_\tau\right) = \frac{\sqrt{2}}{v} M_D$$

$$\Delta_2 = \text{diag}\left(\delta_e, \delta_\mu, \delta_\tau\right)$$

scalar masses: SM Higgs boson, 2 other scalars:

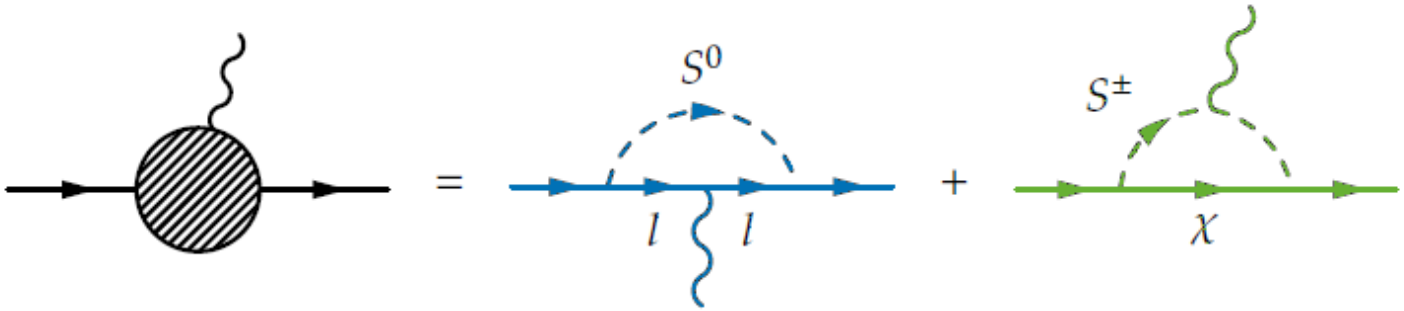
$$M_3,\ M_4\ ,\ (M_{higgs} = 125\,\text{TeV})$$

Magnetic dipole moments



$$a_\ell^{(S)} \simeq \frac{m_\ell^2}{96\pi^2}\left\{2\left|\gamma_\ell\right|^2\left(\frac{1}{M_3^2}+\frac{1}{M_4^2}\right)\right.$$
$$-3\,\mathrm{Re}\left(e^{2i\alpha}\gamma_\ell^2\right)\left[\frac{1}{M_3^2}\left(3+2\ln\frac{m_\ell^2}{M_3^2}\right)-\frac{1}{M_4^2}\left(3+2\ln\frac{m_\ell^2}{M_4^2}\right)\right]$$
$$\left.-\frac{\left|\gamma_\ell\right|^2}{\mu_2^2}\right\}$$

Magnetic dipole moments



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$$\left.-\frac{\left|\gamma_\ell\right|^2}{\mu_2^2}\right\}$$

free parameters: M_3, M_4, γ_μ, γ_e

Magnetic dipole moments

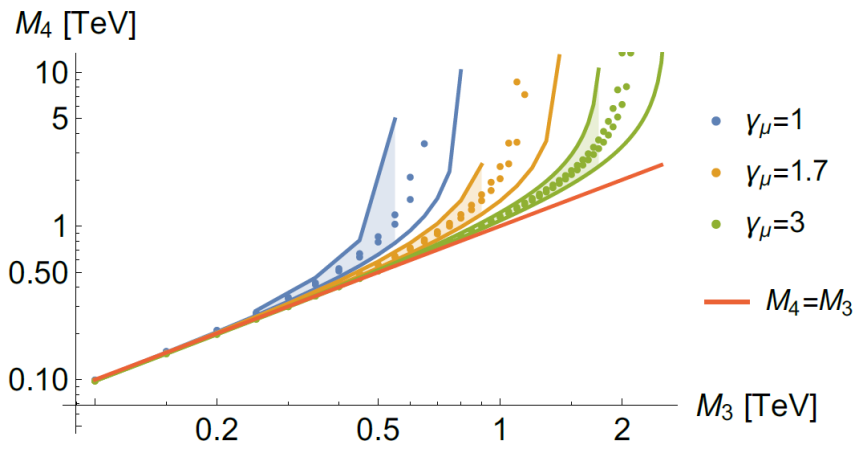
Constrains on M_3, M_4, γ_μ, γ_e:

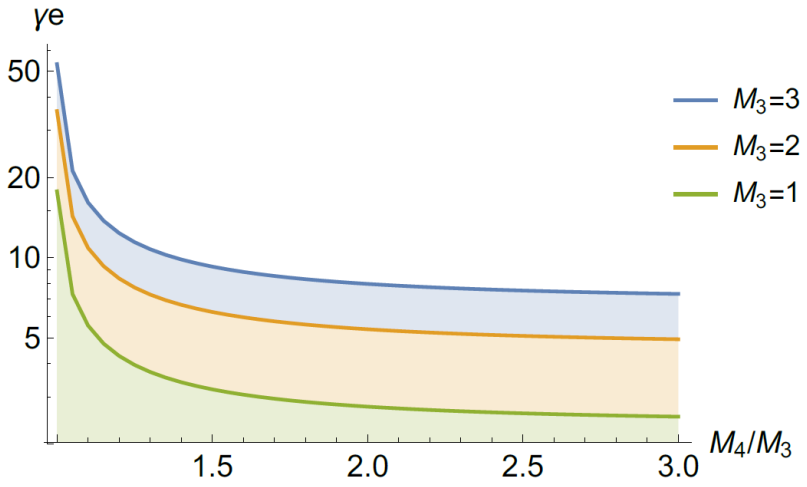
μ–MDM

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = \begin{cases} (287 \pm 80) \times 10^{-11} \,(\text{at } 3.6\,\sigma)^{\rm a} \\ (261 \pm 78) \times 10^{-11} \,(\text{at } 3.6\,\sigma)^{\rm b} \end{cases}$$

e–MDM

$$a_e^{err} = \pm 2.6 \times 10^{-13}$$





M_3, $M_4 \gtrsim 1$ TeV
$\Rightarrow \quad \gamma_\mu \geq 1.7$

$M_3 = 1$ TeV, $M_4 = 2$ TeV
$\Rightarrow \quad \gamma_e < 2.76$

[a][1010.4180/hep-ph], [b][1105.3149/hep-ph]

Further assumptions for simplicity:

- all parameters are real, also U_{PMNS}
- additional phases: $e^{i\hat{\alpha}} = e^{i\hat{\beta}} = \mathbb{1}$

BR($\ell \to 3\ell$) close to exp. bounds...

Parameter set

seesaw scale: $\hat{m}_R = \begin{pmatrix} m_4 & & \\ & m_5 & \\ & & m_6 \end{pmatrix} \gtrsim \mathcal{O}(500\,\text{TeV})$

Yukawa couplings:

$$\left(\Gamma_1 = \frac{\sqrt{2}}{v}\,\text{diag}(m_e, m_\mu, m_\tau) = \frac{\sqrt{2}}{v}\,M_\ell\right)$$

$$\Gamma_2 = \text{diag}\left(\gamma_e, \gamma_\mu, \gamma_\tau\right) = \text{diag}\,(1.7, 1.7, 1.7)$$

$$\Delta_1 = \text{diag}\left(d_e, d_\mu, d_\tau\right) = \text{diag}\,(0.6, 0.1, 0.1)$$

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scalar masses: SM Higgs boson, Goldstone boson, 2 other scalars:

$$M_3 = 1\,\text{TeV},\ M_4 = 2\,\text{TeV},\ (M_{higgs} = 125\,\text{GeV})$$

[EA, Grimus, Lavoura, 17]

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Γ, Δ not small

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scalar masses: SM Higgs boson, Goldstone boson, 2 other scalars:

not too large $M_3 = 1\,\text{TeV}$, $M_4 = 2\,\text{TeV}$, ($M_{higgs} = 125\,\text{GeV}$)

[EA, Grimus, Lavoura, 17]

Results

exp. bounds			model contributions
$\mathrm{BR}\,(\mu^+ \to e^+\gamma)$	$<$	4.2×10^{-13}	
$\mathrm{BR}\,(\tau^- \to e^-\gamma)$	$<$	3.3×10^{-8}	$\sim \frac{1}{m_R^4}$
$\mathrm{BR}\,(\tau^- \to \mu^-\gamma)$	$<$	4.4×10^{-8}	
$\mathrm{BR}\,(\mu^- \to e^-e^+e^-)$	$<$	1.0×10^{-12}	3.872×10^{-13}
$\mathrm{BR}\,(\tau^- \to e^-e^+e^-)$	$<$	2.7×10^{-8}	1.111×10^{-8}
$\mathrm{BR}\,(\tau^- \to e^-\mu^+\mu^-)$	$<$	2.7×10^{-8}	1.280×10^{-8}
$\mathrm{BR}\,(\tau^- \to \mu^-\mu^+\mu^-)$	$<$	2.1×10^{-8}	1.307×10^{-8}
$\mathrm{BR}\,(\tau^- \to \mu^-e^+e^-)$	$<$	1.8×10^{-8}	1.506×10^{-8}
$a_e^{exp-err} = \pm 2.6 \times 10^{-13}$ (exp/SM $= 1$)			$a_e^{mod} = 1.0 \times 10^{-13}$
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = \begin{cases} (287 \pm 80) \times 10^{-11} \\ (261 \pm 78) \times 10^{-11} \end{cases}$ (3.6σ)			$a_\mu^{mod} = 258 \times 10^{-11}$

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and other experiments...

Conclusion

Model:

- explains light m_ν
- introduce new particles: φ_3, φ_4, ν_R^{maj}
  without heavy restr. on Γ, Δ, m_S from FCNI (broken L-symmetry)
- explains difference: U_{PMNS}, V_{CKM}
  $\Rightarrow$ lepton flavour violation comes solely from ν_R

ℓ-decays:

- Explains exp. and theo. discrepancy of μ–MDM
- Pointing out experimental signatures

Outlook

- examine $m_R < 500\,\text{TeV}$, look at suppressed diag.
  [Talk: D. Jurciukonis yesterday]
- examine corrections to ν-mass
- get more boundaries on our parameters
  for more information about Γ, Δ
- searching for compatibility with other models/problems

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Thank you!

Backup slides

Charged lepton decays

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$\mathrm{BR}\,(\tau^- \to e^-e^+e^-)$	$<$	2.7×10^{-8}	$\mathcal{A}(\ell_1^- \to \ell_2^-\ell_3^+\ell_3^-) \propto$
$\mathrm{BR}\,(\tau^- \to e^-\mu^+\mu^-)$	$<$	2.7×10^{-8}	$\begin{cases} \frac{1}{m_R^2} & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases}$
$\mathrm{BR}\,(\tau^- \to \mu^-\mu^+\mu^-)$	$<$	2.1×10^{-8}	
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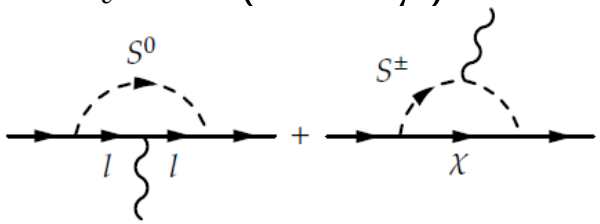
$(\text{exp/SM} = 1)\quad a_e^{err}$	$=$	$\pm 2.6 \times 10^{-13}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$
$a_\mu^{\exp} - a_\mu^{\mathrm{SM}}$	$=$	$\begin{cases} (287 \pm 80) \times 10^{-11} \\ (261 \pm 78) \times 10^{-11} \end{cases}$	

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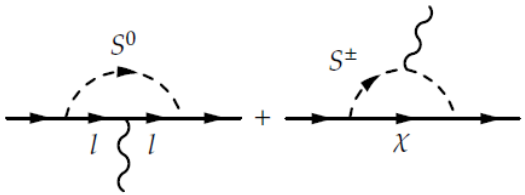
a_e^{err} $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	

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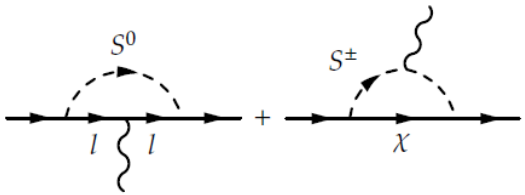
a_e^{err} $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	

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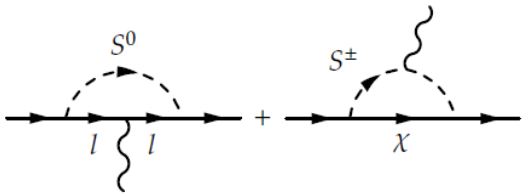
a_e^{err} $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	**explain μ–MDM**

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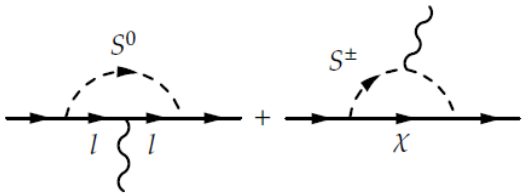
a_e^{err} $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$  	**explain μ–MDM** $\to$ constrain free param.

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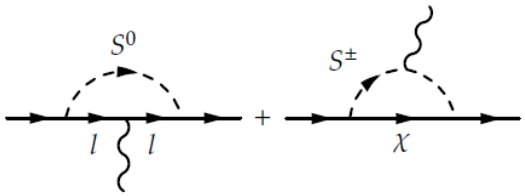
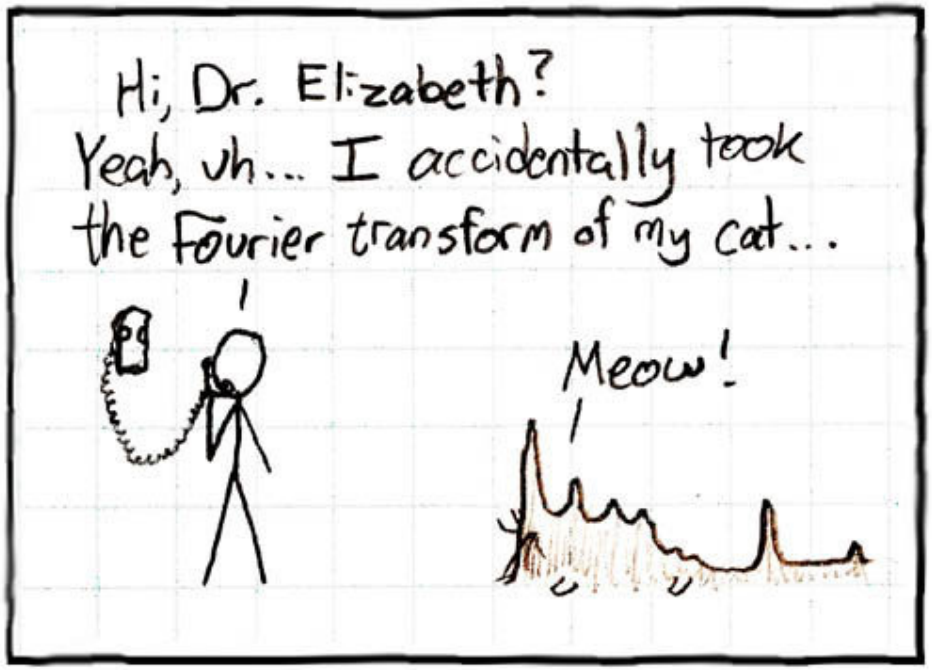
a_e^{err} $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$  	**explain μ–MDM** $\to$ constrain free param.

Things might become a bit technical here...

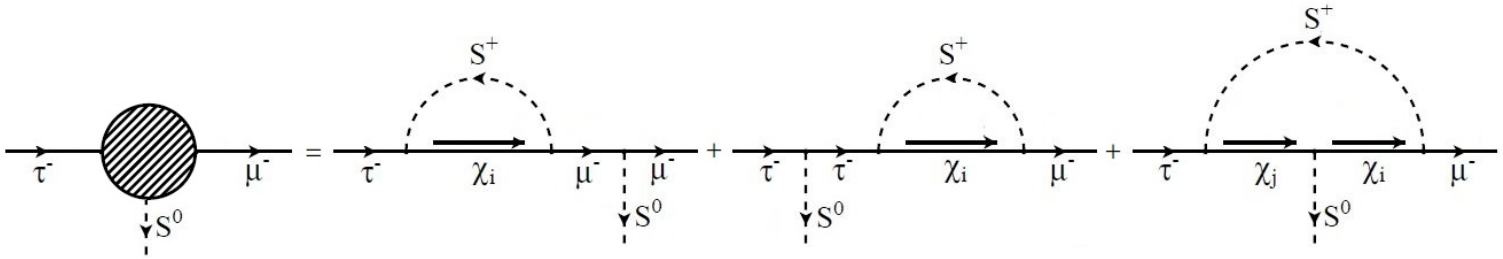
calculating problems:



Finding free parameters

Goal: BR($\ell_1^- \to \ell_2^- \ell_3^+ \ell_3^-$) close to exp. bounds

$\to$ constrain free parameters in non-suppressed contributions to BR:



BR calculation (one loop): (S^0: Higgs φ^0 in mass space)

$$\mathcal{L}_Y(S^0) = -\frac{1}{\sqrt{2}} \sum_{b\ell} S_b^0 \, \bar{\ell} \left[(\hat{\Gamma}_b)_{\ell\ell} \gamma_L + (\hat{\Gamma}_b^\dagger)_{\ell\ell} \gamma_R \right] \ell$$

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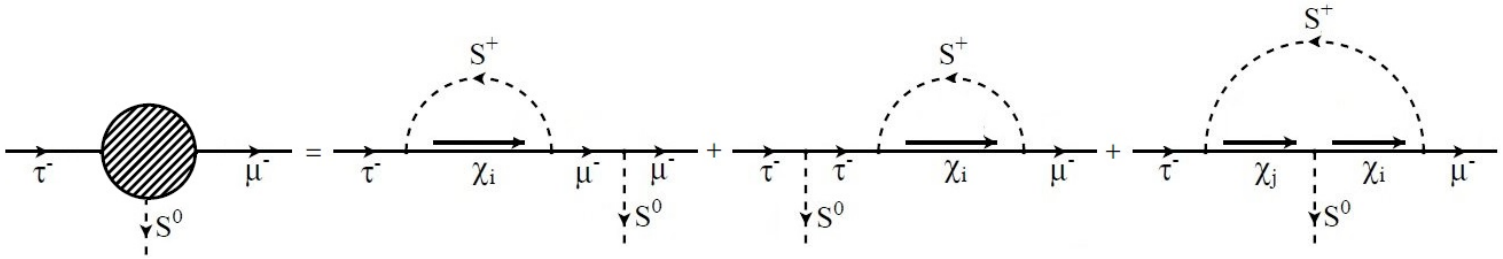

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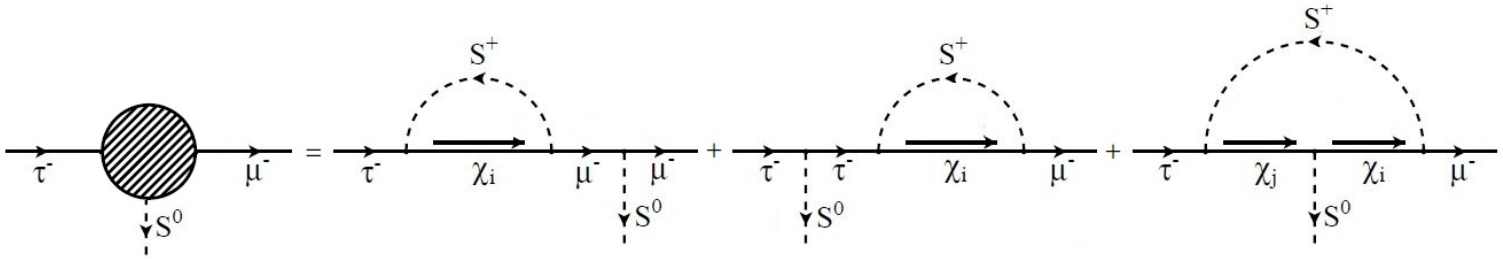

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$$\to \Gamma\left(\ell_1^- \to \ell_2^- \ell_3^+ \ell_3^-\right) = \frac{m_{\ell_1}^5}{6144\pi^3} \left|X_{\ell_2\ell_1}\right|^2 \left|\gamma_{\ell_3}\right|^2 \frac{\left|A_{\ell_2\ell_1}\right|^2 + \left|A_{\ell_1\ell_2}\right|^2}{\left(m_{\ell_2}^2 - m_{\ell_1}^2\right)^2} \left(\frac{1}{M_3{}^4} + \frac{1}{M_4{}^4}\right)$$

$\mathrm{BR}(\ell) = \Gamma(\ell)/\Gamma_{\mathrm{tot}}$

Free parameters

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$$X_{\ell_1\ell_2} \sim \sum_{i=4}^{6} (U_R)_{\ell_1 i} \left(U_R^*\right)_{\ell_2 i} \ln \frac{m_i^2}{\mu^2},$$

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Free parameters

$$\mathrm{BR}(\ell_1^- \to \ell_2^- \ell_3^+ \ell_3^-) = \frac{m_{\ell_1}^5}{6144\pi^3} \left|X_{\ell_2\ell_1}\right|^2 \left|\gamma_{\ell_3}\right|^2 \frac{\left|A_{\ell_2\ell_1}\right|^2 + \left|A_{\ell_1\ell_2}\right|^2}{\left(m_{\ell_2}^2 - m_{\ell_1}^2\right)^2} \left(\frac{1}{M_3^4} + \frac{1}{M_4^4}\right) / \Gamma_{\mathrm{tot}}$$

$$X_{\ell_1\ell_2} \sim \sum_{i=4}^{6} (U_R)_{\ell_1 i} \left(U_R^*\right)_{\ell_2 i} \ln \frac{m_i^2}{\mu^2},$$

$$A_{\ell_1\ell_2}\left(\gamma_{\ell_i}, d_{\ell_i}, \delta_{\ell_i}, m_\ell\right)$$

seesaw scale: m_R

Yukawa couplings:

$$\left(\Gamma_1 = \frac{\sqrt{2}}{v} \mathrm{diag}(m_e, m_\mu, m_\tau) = \frac{\sqrt{2}}{v} M_\ell\right),$$

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scalar masses: SM Higgs boson, Goldstone boson, 2 other scalars:

$$M_3,\ M_4,\ (M_{higgs} = 125\,\mathrm{GeV})$$

Seesaw scale - Dirac masses

With the choice for neutrino mass $m_1 = 0.05\,\mathrm{eV}$,
given best-fit values $\Delta m_{21}^2 = 7.50\times10^{-5}\,\mathrm{eV}^2$, $\Delta m_{31}^2 = 2.457\times10^{-3}\,\mathrm{eV}^2$
$\left(m_2 = \sqrt{m_1^2 + \Delta m_{21}^2},\, m_2 = \sqrt{m_1^2 + \Delta m_{31}^2}\right)$
and fixing $\Delta_1 \sim d_\ell$ we can calculate $M_R = \mathrm{diag}(m_4,\, m_5,\, m_6) \sim \mathcal{O}(m_R)$:

$$M_\nu = -M_D^T M_R^{-1} M_D, \quad M_D = -\frac{v}{\sqrt{2}}\,\Delta_1$$

$$M_R = -\frac{v^2}{2}\,\Delta_1 M_\nu^{-1} \Delta_1$$

$$= -\frac{v^2}{2}\, e^{i\hat{\alpha}} \Delta_1\, U_{\mathrm{PMNS}} \left(e^{2i\hat{\beta}} \hat{m}^{-1}\right) U_{\mathrm{PMNS}}^T\, \Delta_1 e^{i\hat{\alpha}}$$

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$$\begin{pmatrix} 0 & M_D^T \\ M_D & M_R \end{pmatrix} \xrightarrow{2\times2\,\mathrm{diag.}} \begin{pmatrix} M_\nu & \\ & M_R \end{pmatrix} \xrightarrow{\mathrm{diag.}\,(U_{PMNS})} \begin{pmatrix} \hat{m}_\nu & \\ & \hat{m}_R \end{pmatrix}$$

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- **Dirac masses** ($m_{D\ell} = \frac{v}{\sqrt{2}} d_\ell$): $d_e = 0.6, \quad d_\mu = d_\tau = 0.1$
- **Seesaw scale** $m_R > 10^{12}\,\mathrm{GeV}$:
  $m_4 = 4.3\times10^{12}\,\mathrm{GeV},\ m_5 = 6.0\times10^{12}\,\mathrm{GeV},\ m_6 = 2.2\times10^{14}\,\mathrm{GeV}$

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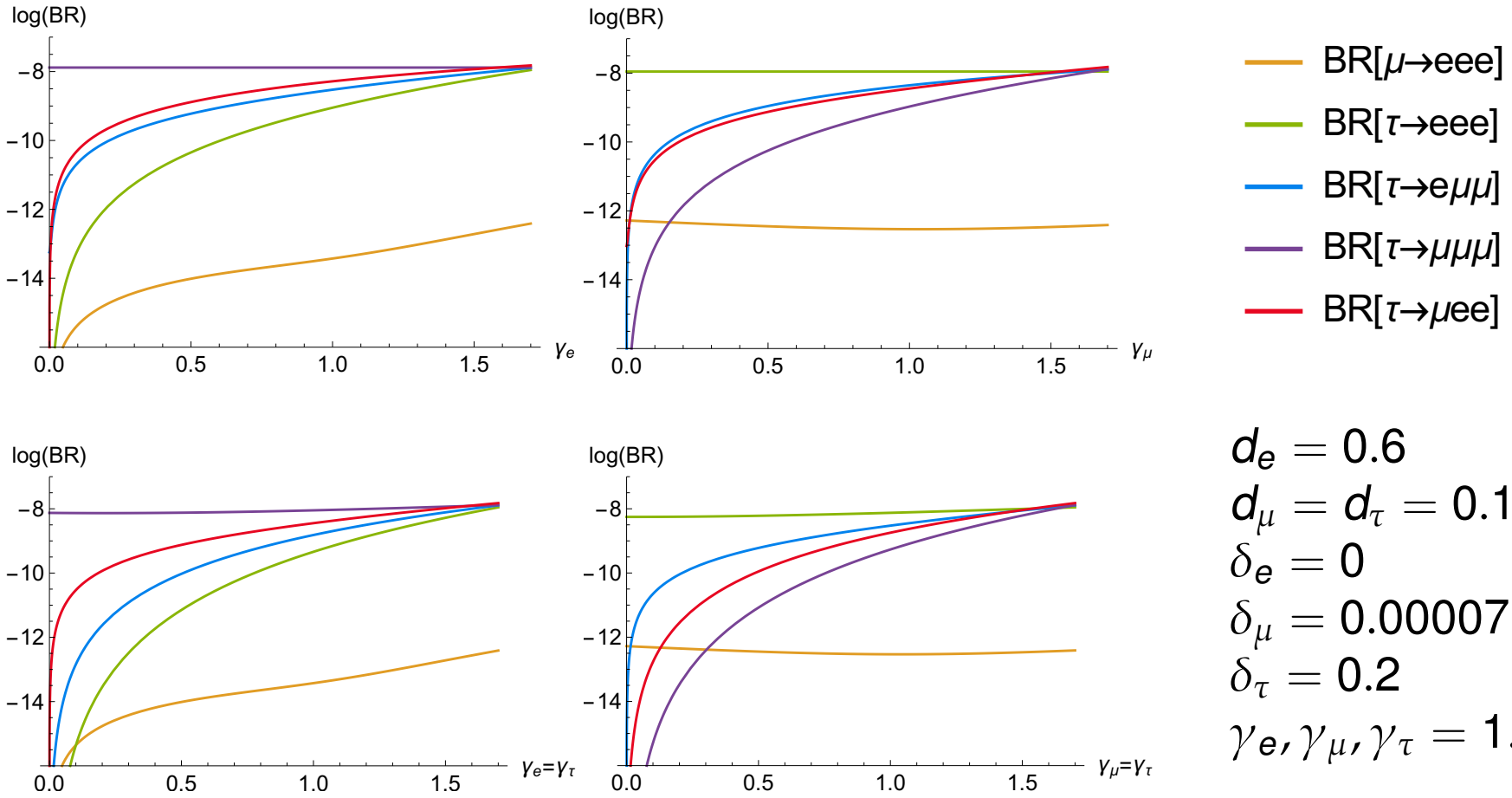
Constrain from 4ℓ-decays

We want BR $[\tau^- \to \ell^- e^+ e^-]\left(\gamma_e, \gamma_\mu, \gamma_\tau\right)$ and BR $[\tau^- \to \ell^- \mu^+ \mu^-]\left(\gamma_e, \gamma_\mu, \gamma_\tau\right)$ close to their experimental upper bounds ($< 2.7 \times 10^{-8}$):



$d_e = 0.6$
$d_\mu = d_\tau = 0.1$
$\delta_e = 0$
$\delta_\mu = 0.00007$
$\delta_\tau = 0.2$
$\gamma_e, \gamma_\mu, \gamma_\tau = 1.7$

$\to \quad \gamma_e = \gamma_\mu = 1.7$

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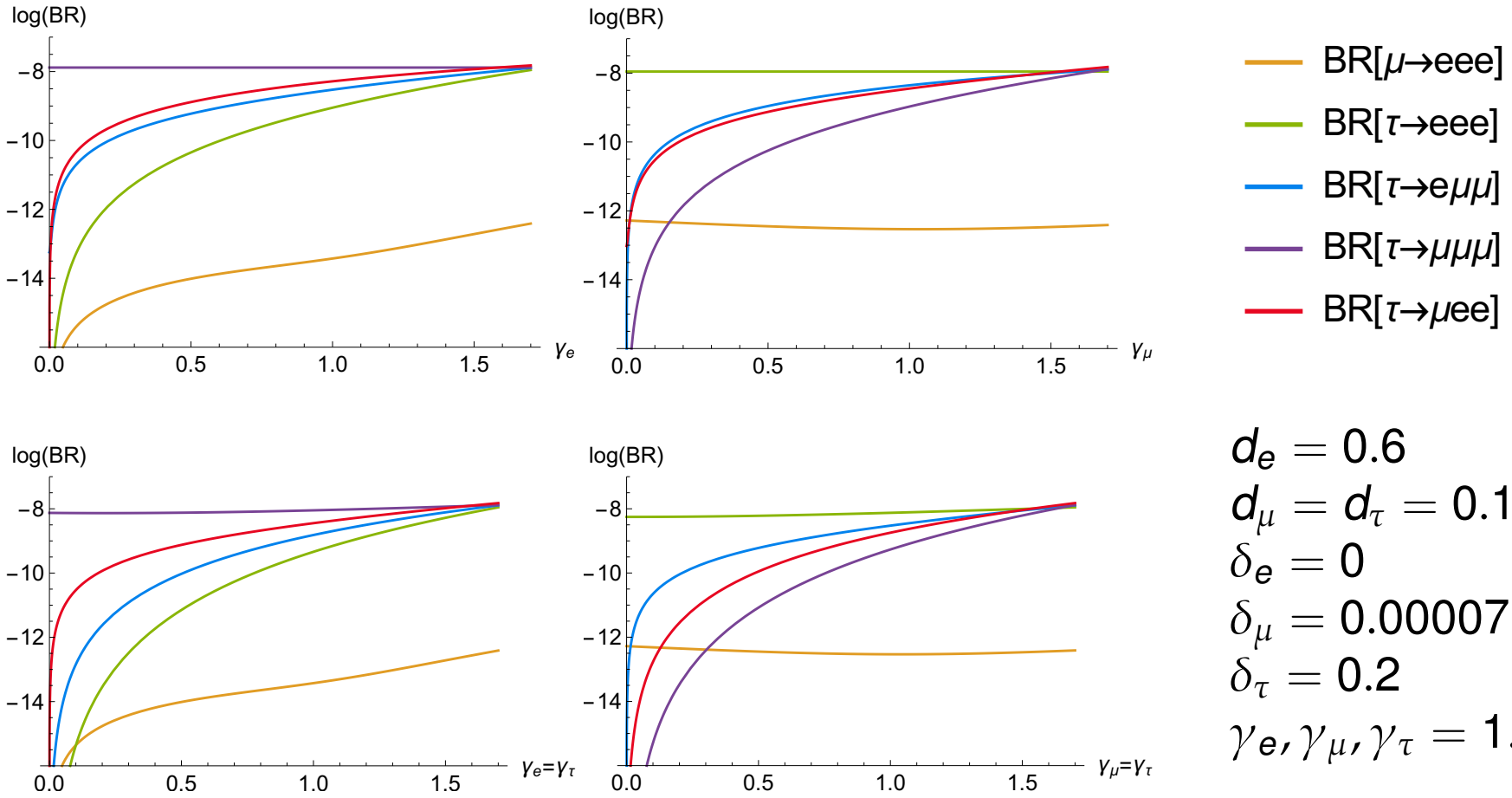

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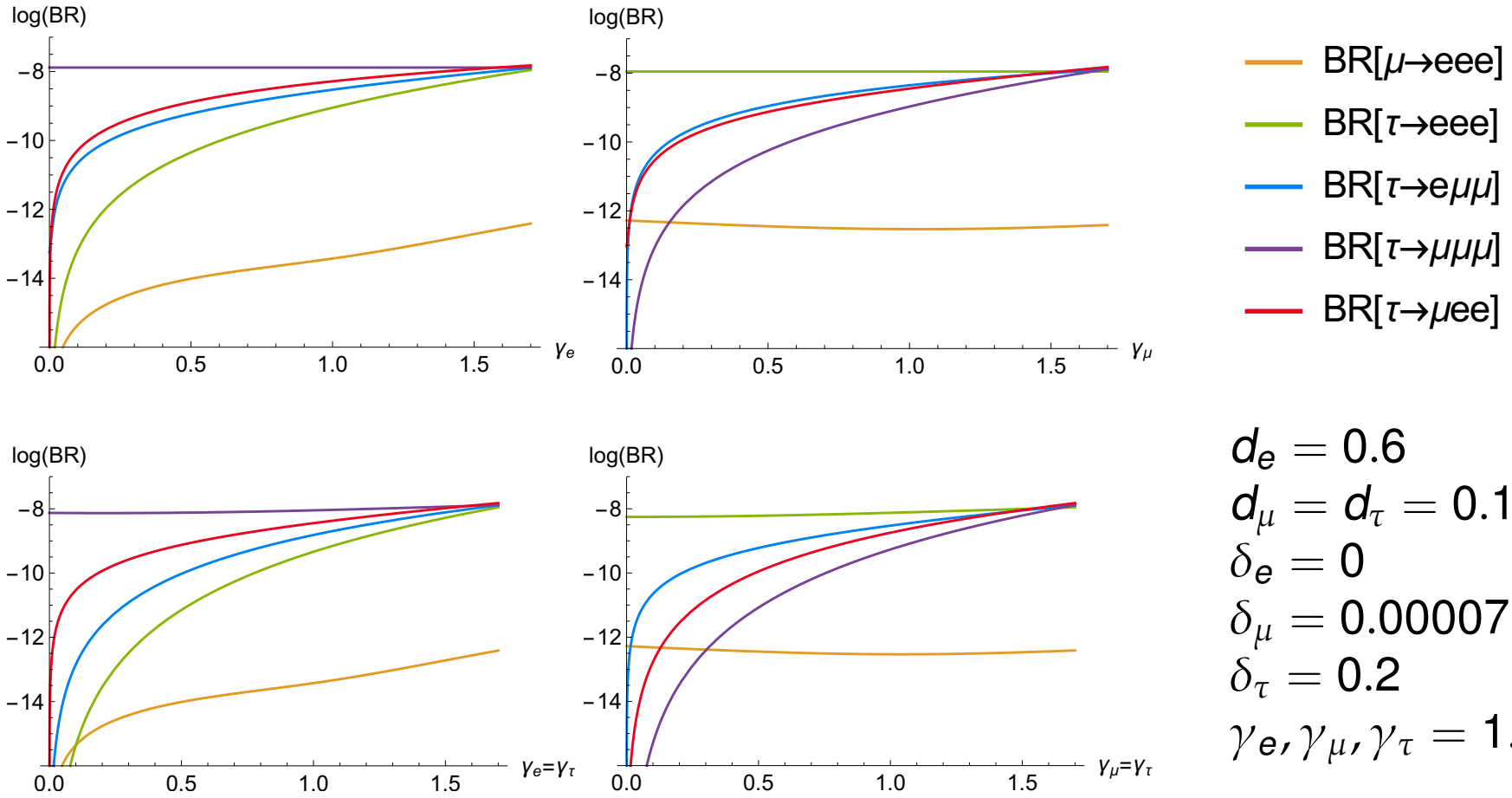

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$\to$ $\gamma_e = \gamma_\mu = 1.7$ ✓ *MDM* ($\gamma_\mu \geq 1.7, \gamma_e < 2.76$ *TeV*)

Free parameters

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seesaw scale: m_R

Yukawa couplings:

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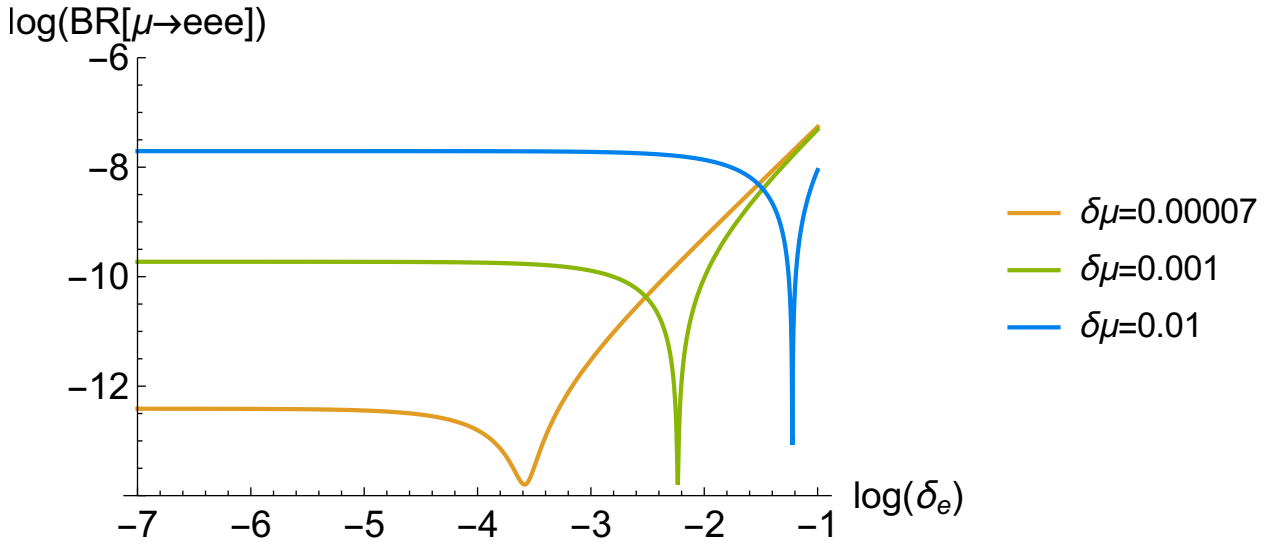
Further constrains from 4ℓ-decays

$$\mathrm{BR}\left(\mu^- \to e^- e^+ e^-\right) < 1.0 \times 10^{-12}$$



Large $\gamma_e = \gamma_\mu = 1.7$, $d_e = 0.6$, $d_\mu = 0.1$ give a too large contrib. to BR, unless there is a cancellation between terms prop. to δ_e and δ_μ.

$$\mathrm{BR}\left[\mu^- \to e^- e^+ e^-\right]\left(\delta_e, \delta_\mu\right) \sim \left|\gamma_e\right|^2 \left(\left|A_{e\mu}\right|^2 + \left|A_{\mu e}\right|^2\right)$$

$$A_{\mu e} \approx \frac{v m_e}{\sqrt{2}} \gamma_\mu \gamma_e \left(d_\mu \delta_e - \delta_\mu d_e\right) + \frac{v m_\mu}{\sqrt{2}} \left(\delta_\mu \left|\gamma_e\right|^2 d_e - \gamma_\mu^2 d_\mu \delta_e\right)$$

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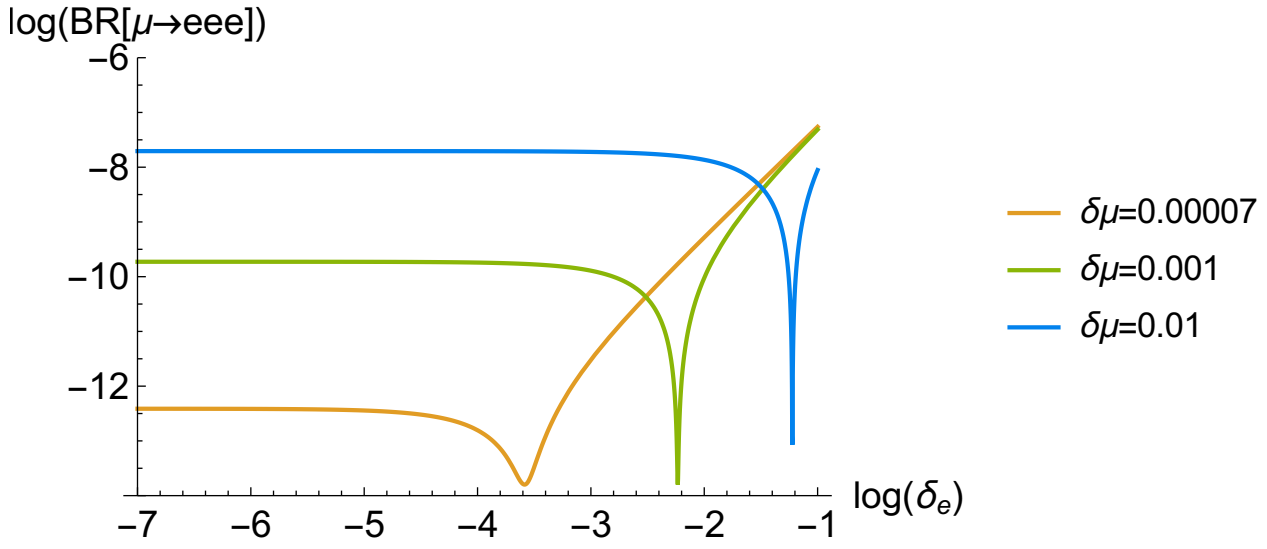

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no finetuning with:

$$\delta_e = 0$$
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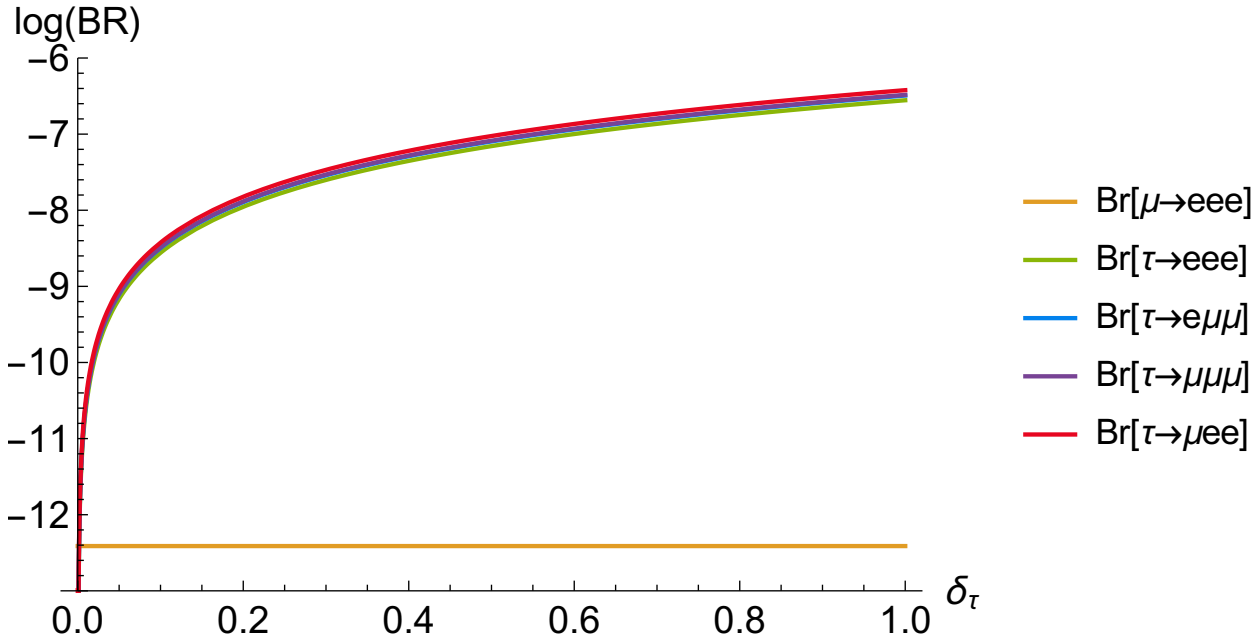
Further constrain from 4ℓ-decays



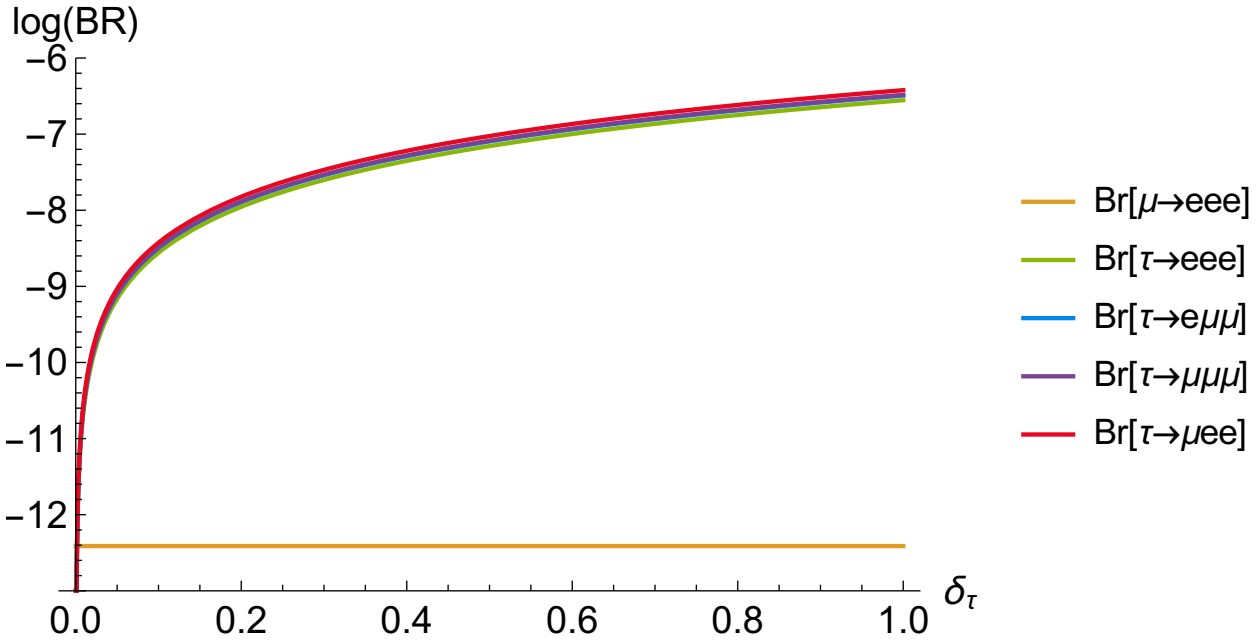
We need, since we have tiny δ_e, δ_μ, large δ_τ, d_e, d_μ, γ_ℓ ($\ell = e, \mu, \tau$).

e.g.

$$\Gamma(\tau^- \to e^- e^+ e^-) \sim \left|\gamma_e\right|^2 \left(|A_{e\tau}|^2 + |A_{\tau e}|^2\right)$$

$$A_{\tau e} \approx \frac{v m_e}{\sqrt{2}} \gamma_\tau \gamma_e \left(d_\tau \delta_e - \delta_\tau d_e\right) + \frac{v m_\tau}{\sqrt{2}} \left(\delta_\tau \left|\gamma_e\right|^2 d_e - \gamma_\tau^2 d_\tau \delta_e\right)$$

Further constrain from 4ℓ-decays



We need, since we have tiny δ_e, δ_μ, large δ_τ, d_e, d_μ, γ_ℓ ($\ell = e, \mu, \tau$).

$$\delta_\tau = 0.2$$
$$d_e = 0.6, d_\mu = 0.1$$
$$\gamma_\ell = 1.7$$

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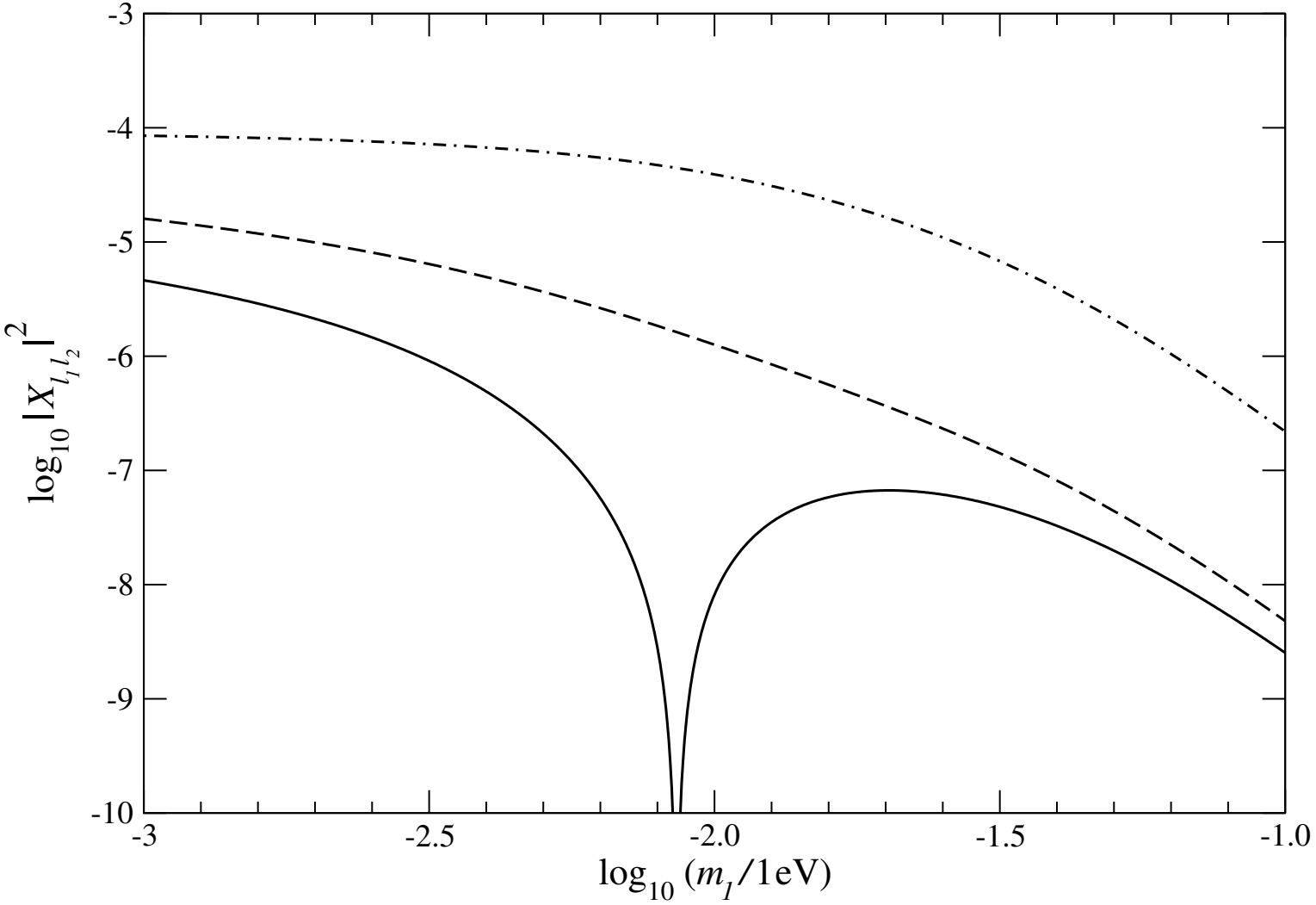
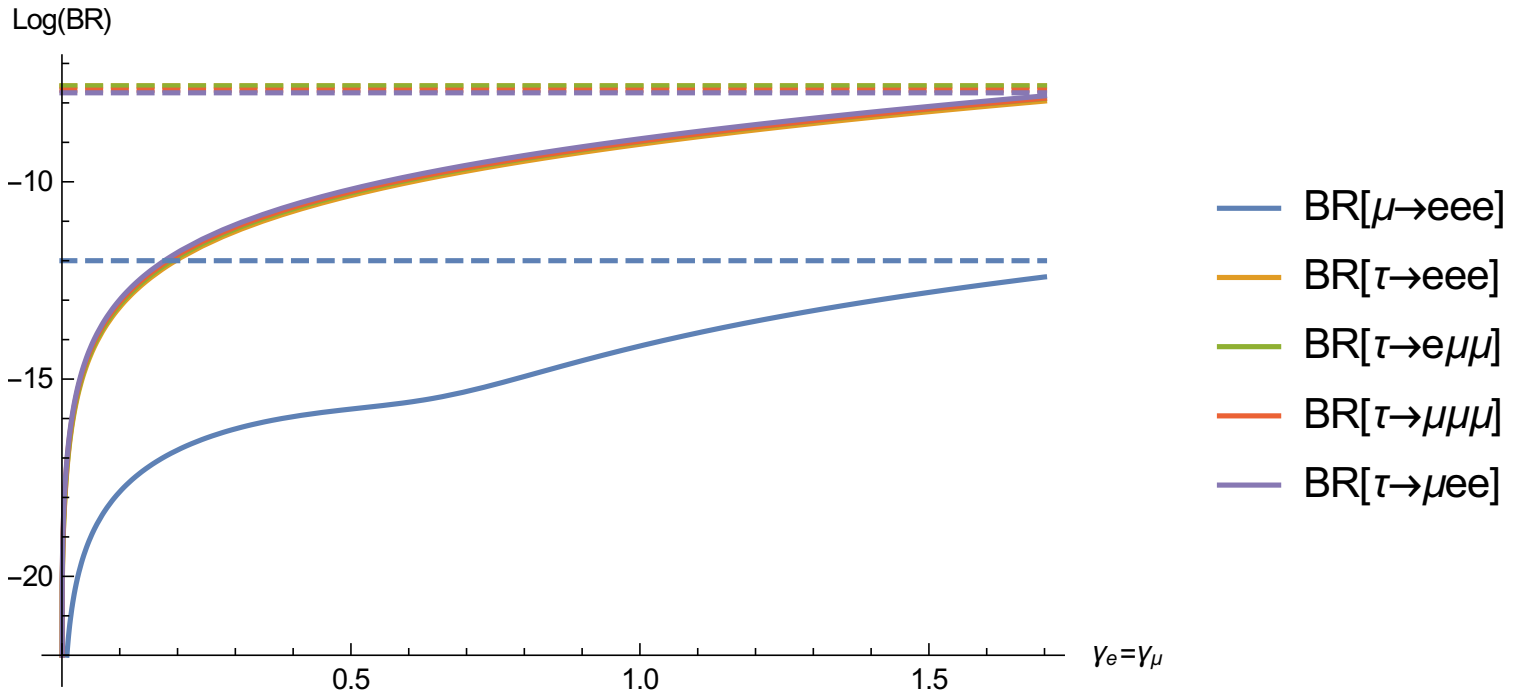

-3
-4
-5
-6
-7
-8
-9
-10
-3
-2.5
-2.0
-1.5
-1.0
$\log_{10}|X_{l_1 l_2}|^2$
$\log_{10}(m_l/1\text{eV})$


Log(BR)
−10
−15
−20
0.5
1.0
1.5
$\gamma_e=\gamma_\mu$
BR[$\mu\to$eee]
BR[$\tau\to$eee]
BR[$\tau\to$e$\mu\mu$]
BR[$\tau\to\mu\mu\mu$]
BR[$\tau\to\mu$ee]

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- **Explain mass hierarchy** in right handed neutrino mass models via the seesaw mechanism. $[\mathrm{m}_{\nu_R} \gtrsim \mathrm{TeV}]$
  (with additional Higgs doublets...)
- **Dark matter candidates** $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_R} \lesssim \mathrm{TeV}]$
- **Baryon asymmetry** via Leptogenesis in νMSM models $[\mathrm{keV} \lesssim \mathrm{m}_{\nu_R} \lesssim \mathrm{GeV}]$
- **Detected anomalies** at: LSND, MiniBooNE, gallium detectors: GALLEX, SAGE, reactor experiments... $[\mathrm{m}_{\nu_R} \sim \mathrm{eV}]$
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