Charged lepton decays from soft flavour violation

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$\int dk \Pi$ Doktoratskolleg Particles and Interactions

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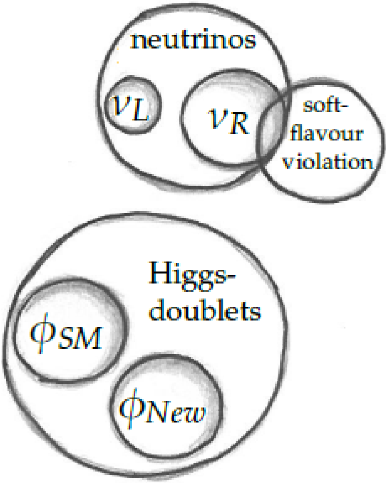
Faculty of Physics

Overview

1. THE MODEL
   - Neutrinos - right handed neutrinos
   - Multi Higgs doublets
   - Soft flavour violation
   - Properties and advantages
2. CHARGED LEPTON DECAYS
   - Free parameters
   - Radiative corrections
   - Magnetic dipole moments
   - Constrains from 4ℓ-decay
   - Results
3. SUMMARY

The model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ϕ_{SM}
ϕ_{New}

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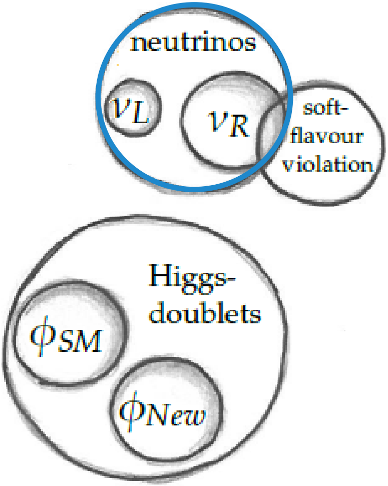
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Why we care about neutrinos

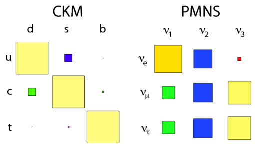
experimentally unsolved: anomalies...

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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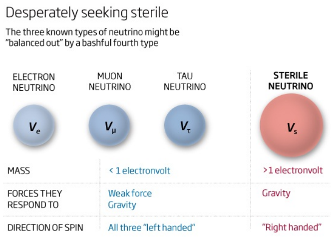


introduce:
right handed neutrinos ν_R

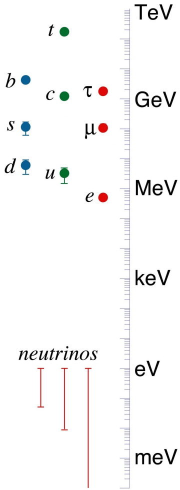
Heavy right handed neutrinos ν_R

Hierarchy problem:

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

Masses are normally $m_e \simeq 0.5\,\mathrm{MeV}$ to $m_t \simeq 173\,\mathrm{GeV}$

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



Heavy right handed neutrinos ν_R

Soltion: Majorana neutrinos
with heavy righthanded partners
in Seesaw mechanism

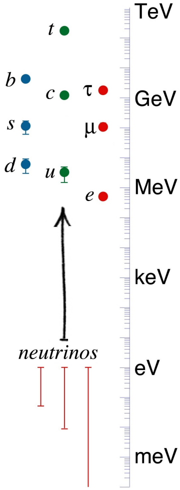
$$\mathcal{L}_{maj} = -\frac{1}{2}\overline{(\nu_R)^c}\, M_R^* \,\nu_R + \text{H.c.}\,, \quad \text{scale } m_R \gtrsim \text{TeV}$$

flavour basis: scale $m_D \sim m_e$

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

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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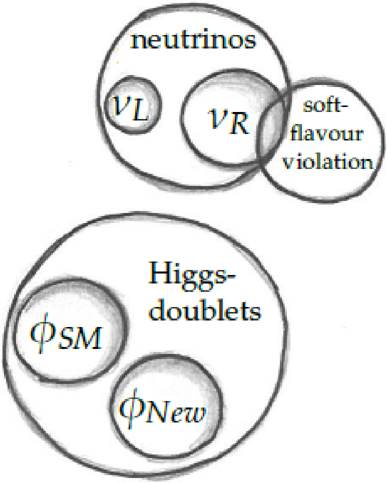
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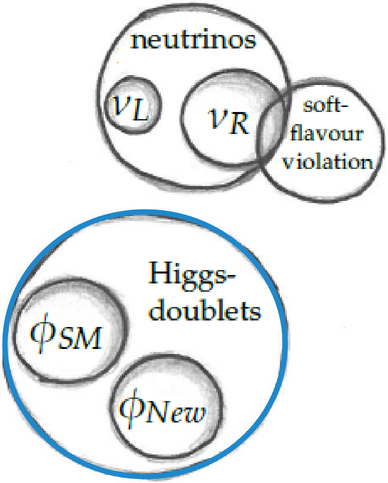
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Multi Higgs doublets Φ_k

Include: (e.g. $n_H = 2$) Higgs doublets
and lepton flavour breaking

$$\phi_k = \begin{pmatrix} \varphi_k^+ \\ \varphi_k^0 \end{pmatrix}, \quad \varphi_k^0 = \frac{v_k}{\sqrt{2}} + \varphi_k^{0\prime}$$

$$\mathcal{L}_Y = -\sum_{k=1}^{n_H} \sum_{\ell,\ell'=e,\mu,\tau} \left[\left(\varphi_k^-, \varphi_k^{0*}\right) \Gamma_{k\ell\ell'}\, \bar{\ell}_R + \left(\varphi_k^0, -\varphi_k^+\right) \Delta_{k\ell\ell'}\, \bar{\nu}_{\ell R}\right] \begin{pmatrix} \nu_{\ell' L} \\ \ell'_L \end{pmatrix} + \text{H.c.}$$

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- NC & mass:
  $$\mathcal{L}_Y(\varphi^0) = -\sum_{k\ell\ell'} \left\{ \ell'_L (\varphi_k^{0\prime *} \Gamma_{k\ell\ell'} + (M_\ell)_{\ell\ell'}) \bar{\ell}_R + \nu_{\ell' L} (\varphi_k^{0\prime} \Delta_{k\ell\ell'} + (M_D)_{\ell\ell'}) \bar{\nu}_{\ell R} \right\}$$
- CC :
  $$\mathcal{L}_Y(\varphi^\pm) = -\sum_{k\ell\ell'} \left\{ \nu_{\ell' L} (\varphi_k^- \Gamma_{k\ell\ell'}) \bar{\ell}_R - \ell'_L (\varphi_k^+ \Delta_{kll'}) \bar{\nu}_{\ell R} + H.c. \right\}$$

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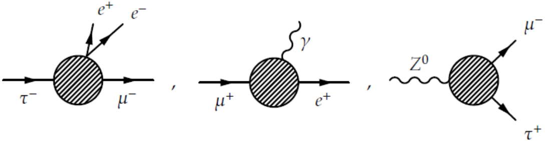

interesting effect:
observable processes!

- NC & mass:

$$\mathcal{L}_Y(\varphi^0) = -\sum_{k\ell\ell'} \left\{ \ell_L'(\varphi_k^{0\prime *}\Gamma_{k\ell\ell'} + (M_\ell)_{\ell\ell'})\bar{\ell}_R + \nu_{\ell' L}(\varphi_k^{0\prime}\Delta_{k\ell\ell'} + (M_D)_{\ell\ell'})\bar{\nu}_{\ell R} \right\}$$

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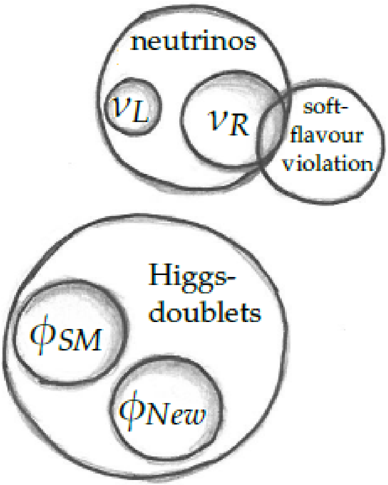
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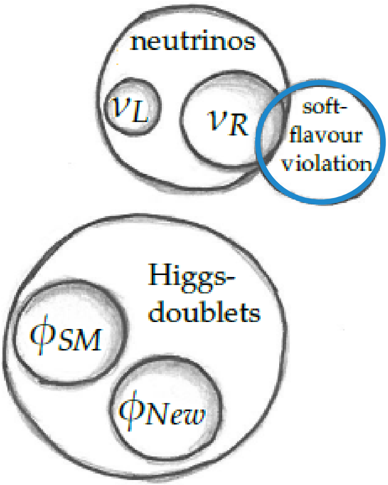
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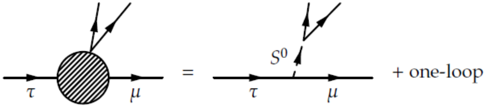
Soft flavour violation $\not{L}_\alpha$

Problem:

strong experimental bounds on FCNIs at tree level



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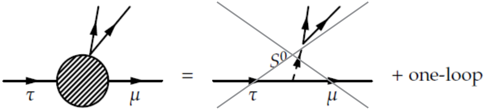

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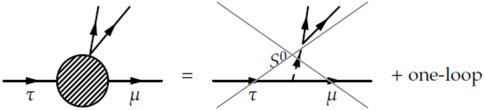
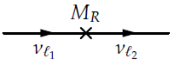


Solution: **SOFT flavour violation** L_α $\{\alpha = e, \mu, \tau\}$

L_α conservation:
in Yukawa interactions
$\Rightarrow$ diag. $\Gamma(\ell)$, $\Delta(\nu)$

L_α explicit soft breaking:
in Majorana term $\Rightarrow$ **non-diag. $\mathbf{M}_R$**

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

→ Flavour violation comes solely from neutrinos. 

→ FCNIs appear at one loop in charged Lepton decays.

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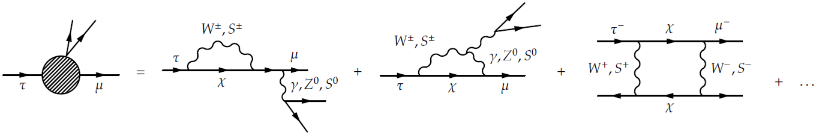

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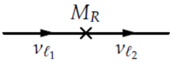
→ Flavour violation comes solely from neutrinos. 

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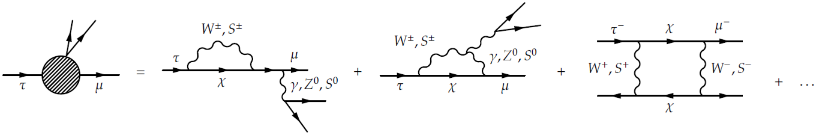

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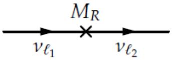
→ Flavour violation comes solely from neutrinos. 

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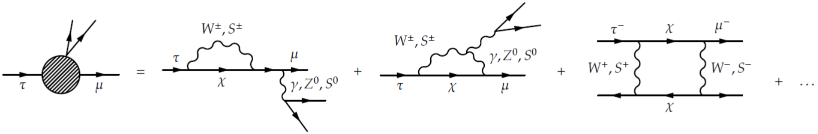

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$\Rightarrow$ diag. $\Gamma(\ell)$, $\Delta(\nu)$ $\quad\Rightarrow\quad$ **diag.** $\mathbf{M}_\ell, \mathbf{M}_D = diag(m_e, m_\mu, m_\tau)$

L_α explicit soft breaking:
in Majorana term $\quad\Rightarrow\quad$ **non-diag.** $\mathbf{M}_R$

Short analysis of FCNIs

Evtl. experimentally testable processes:

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

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].

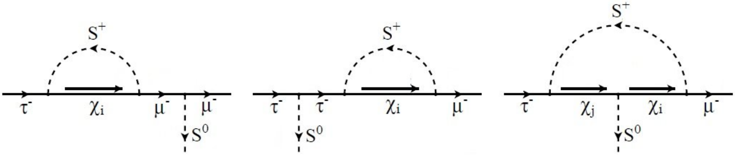

Figure: non-supressed diagrams for $\tau^- \to \mu^- S^{0*}$

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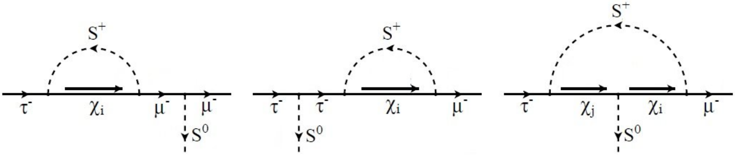
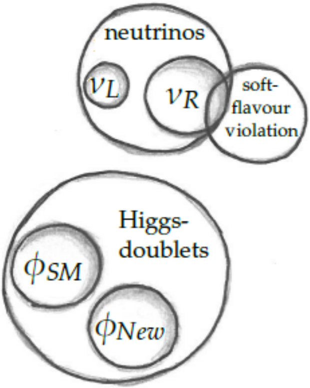


Figure: non-supressed diagrams for $\tau^- \to \mu^- S^{0*}$

Properties and advantages



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- observable processes: charged ℓ-decays

Additional advantages:

- ampl. of FC processes are finite at one-loop
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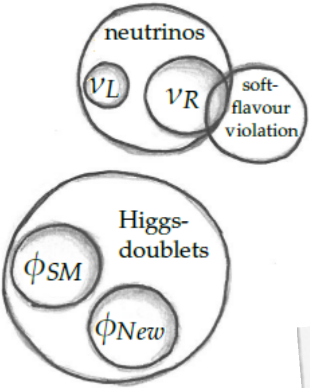

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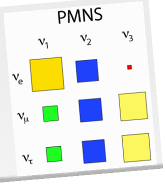

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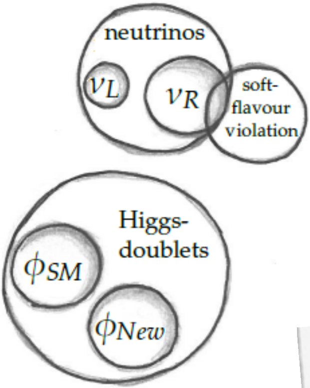

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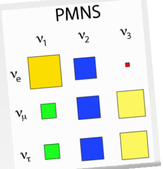
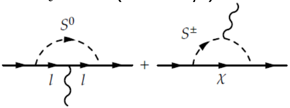


Charged lepton decays

exp. bounds			model contributions
$\mathrm{BR}\,(\mu^+ \to e^+\gamma)$	$<$	4.2×10^{-13}	
$\mathrm{BR}\,(\tau^- \to e^-\gamma)$	$<$	3.3×10^{-8}	$\mathcal{A}(\tau^- \to \mu^-\gamma) \propto \frac{1}{m_R^2}$
$\mathrm{BR}\,(\tau^- \to \mu^-\gamma)$	$<$	4.4×10^{-8}	
$\mathrm{BR}\,(\mu^- \to e^-e^+e^-)$	$<$	1.0×10^{-12}	$\mathcal{A}(\ell_1^- \to \ell_2^-\ell_3^+\ell_3^-) \propto$
$\mathrm{BR}\,(\tau^- \to e^-e^+e^-)$	$<$	2.7×10^{-8}	$\begin{cases} \frac{1}{m_R^2} & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases}$
$\mathrm{BR}\,(\tau^- \to e^-\mu^+\mu^-)$	$<$	2.7×10^{-8}	
$\mathrm{BR}\,(\tau^- \to \mu^-\mu^+\mu^-)$	$<$	2.1×10^{-8}	
$\mathrm{BR}\,(\tau^- \to \mu^-e^+e^-)$	$<$	1.8×10^{-8}	
(exp/SM = 1) a_e^{err}	$=$	$\pm 2.6 \times 10^{-13}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$=$	$\begin{cases} (287 \pm 80) \times 10^{-11} \\ (261 \pm 78) \times 10^{-11} \end{cases}$	

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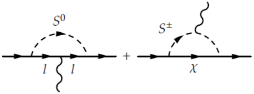
a_e^{err} $a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	

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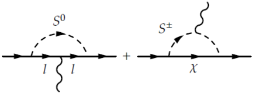
a_e^{err} $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$  	

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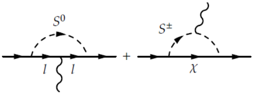
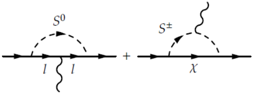
a_e^{err} $a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	**explain μ−MDM**

Charged lepton decays

exp. bounds	model contributions	come out
$\text{BR}(\mu^+ \to e^+\gamma)$ $\text{BR}(\tau^- \to e^-\gamma)$ $\text{BR}(\tau^- \to \mu^-\gamma)$	$\mathcal{A}(\tau^- \to \mu^-\gamma) \propto \frac{1}{m_R^2}$	constrains on seesaw scale m_R
$\text{BR}(\mu^- \to e^-e^+e^-)$ $\text{BR}(\tau^- \to e^-e^+e^-)$ $\text{BR}(\tau^- \to e^-\mu^+\mu^-)$ $\text{BR}(\tau^- \to \mu^-\mu^+\mu^-)$ $\text{BR}(\tau^- \to \mu^-e^+e^-)$	$\mathcal{A}(\ell_1^- \to \ell_2^-\ell_3^+\ell_3^-) \propto$ $\begin{cases} \frac{1}{m_R^2} & n_H = 1 \\ \text{const.} & n_H > 1 \end{cases}$	**BR close to exp. bounds** $\rightarrow$ constrain free param.
a_e^{err} $a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	**explain μ–MDM** $\rightarrow$ constrain free param.

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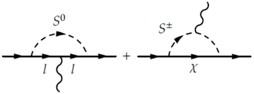
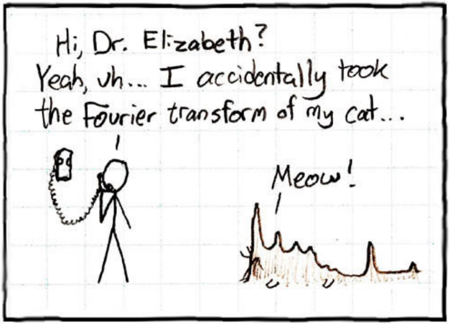
a_e^{err} $a_\mu^{\rm exp} - a_\mu^{\rm SM}$	$a_\ell \subset \mathcal{A}(\ell \to \ell\gamma) \sim$ 	**explain μ–MDM** $\to$ constrain free param.

Things might become a bit technical here...

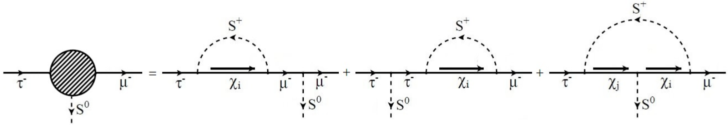
calculating problems:



Finding free parameters

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

→ 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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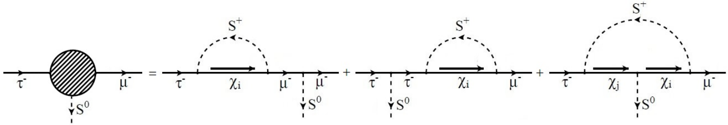

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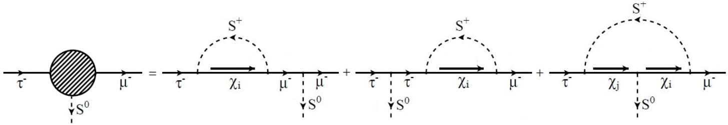

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$\mathrm{BR}(\ell) = \Gamma(\ell)/\Gamma_{\mathrm{tot}}$

Free parameters

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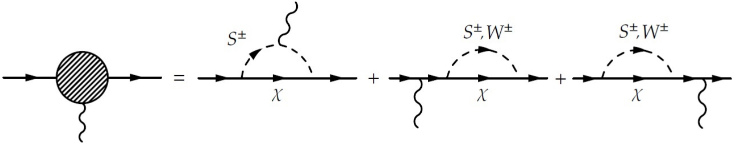

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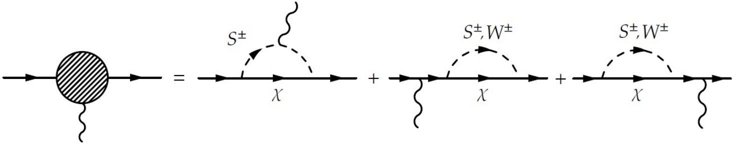

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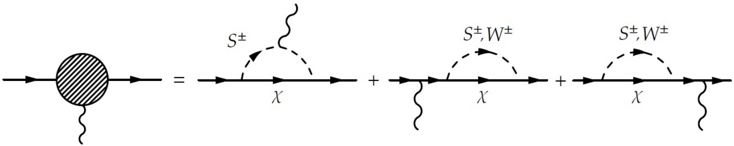

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$$X_{\ell_1\ell_2} \sim \sum_{i=4}^{6} (U_R)_{\ell_1 i} \left(U_R^*\right)_{\ell_2 i} \ln \frac{m_i^2}{\mu^2},$$

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

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

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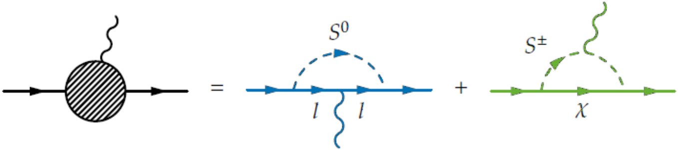
scalar masses: SM Higgs boson, Goldstone boson, 2 other scalars:

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

Magnetic dipole moments

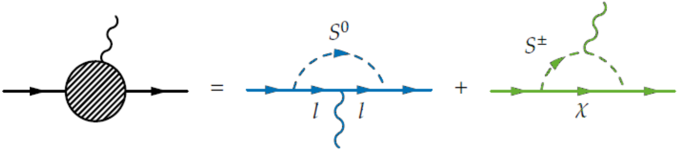


$$a_\ell^{(S)} \simeq \frac{m_\ell^2}{96\pi^2}\left\{2\left|\gamma_\ell\right|^2\left(\frac{1}{M_3^2}+\frac{1}{M_4^2}\right)\right.$$

$$-3\,\mathrm{Re}\left(e^{2i\alpha}\gamma_\ell^2\right)\left[\frac{1}{M_3^2}\left(3+2\ln\frac{m_\ell^2}{M_3^2}\right)-\frac{1}{M_4^2}\left(3+2\ln\frac{m_\ell^2}{M_4^2}\right)\right]$$

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

Magnetic dipole moments



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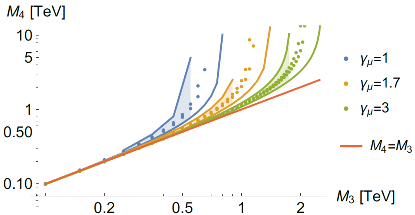
$$\left.-\frac{\left|\gamma_\ell\right|^2}{\mu_2^2}\right\}$$

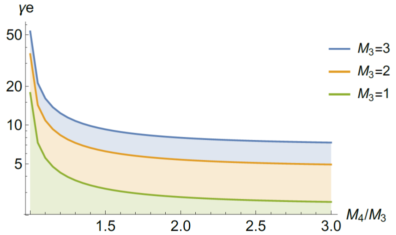
free parameters: M_3, M_4, γ_μ, γ_e

Magnetic dipole moments

Constrains on M_3, M_4, γ_μ, γ_e:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = \begin{cases} (287 \pm 80) \times 10^{-11} (\text{at } 3.6\,\sigma)^{a} \\ (261 \pm 78) \times 10^{-11} (\text{at } 3.6\,\sigma)^{b} \end{cases}, \quad a_e^{err} = \pm 2.6 \times 10^{-13}$$





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

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

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

Magnetic dipole moments

Constrains on M_3, M_4, γ_μ, γ_e:

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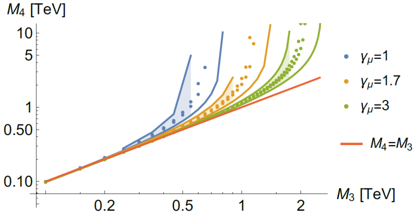

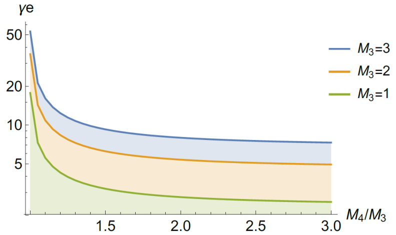

For M_3, $M_4 \gtrsim 1$ TeV $\Rightarrow \gamma_\mu \geq 1.7$

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

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

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:

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

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

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

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

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

Free parameters

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

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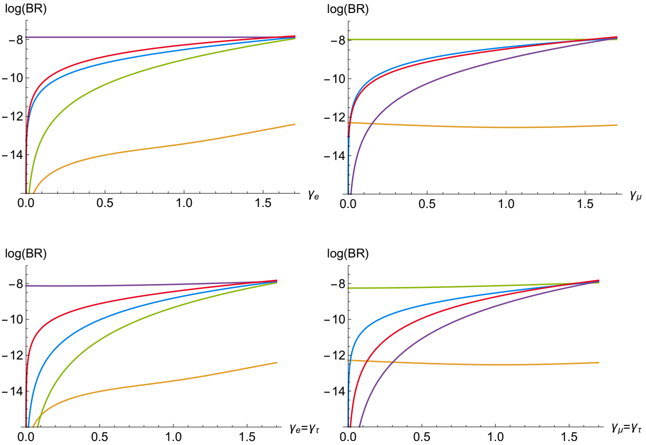
Constrain from 4ℓ-decays

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



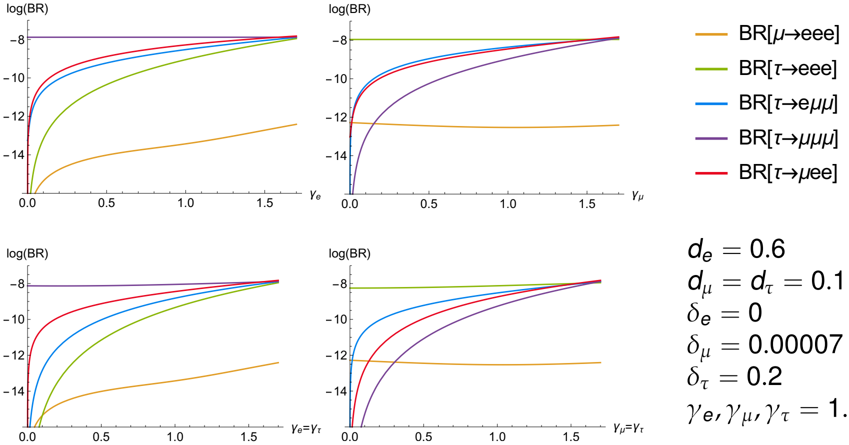
BR[μ→eee]
BR[τ→eee]
BR[τ→eμμ]
BR[τ→μμμ]
BR[τ→μee]

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

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

Constrain from 4ℓ-decays

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



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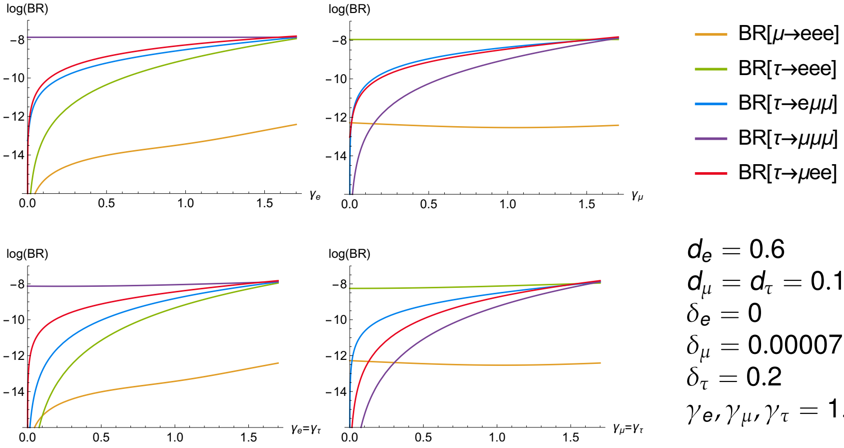

$d_e = 0.6$
$d_\mu = d_\tau = 0.1$
$\delta_e = 0$
$\delta_\mu = 0.00007$
$\delta_\tau = 0.2$
$\gamma_e, \gamma_\mu, \gamma_\tau = 1.7$

$\to \gamma_e = \gamma_\mu = 1.7$ ✓ *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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Free parameters

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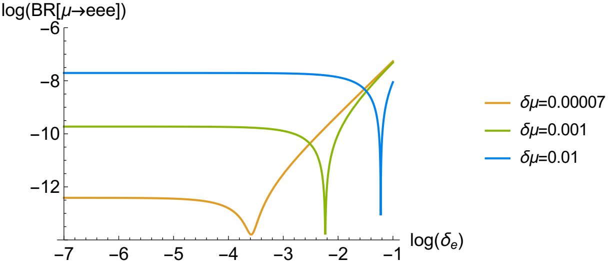
Further constrains from 4ℓ-decays

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



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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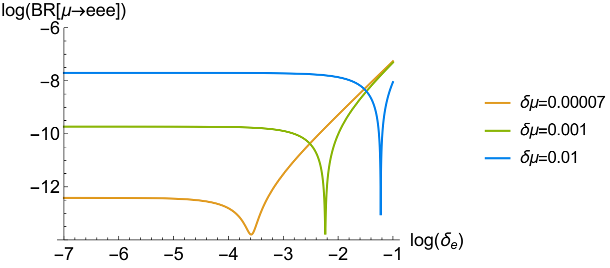

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no finetuning with:

$$\delta_e = 0$$
$$\delta_\mu = 0.00007$$

Free parameters

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seesaw scale: m_R

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Free parameters

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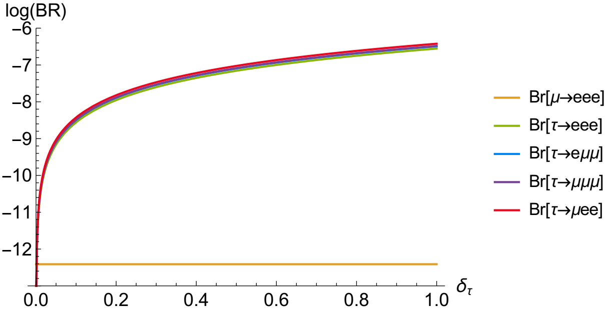
Further constrain from 4ℓ-decays



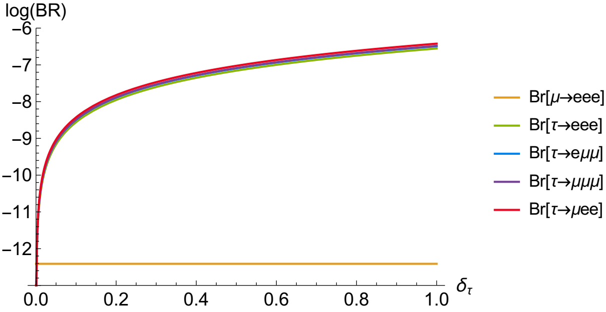
We need, since we have tiny δ_e, δ_μ, large δ_τ, d_e, d_μ, γ_ℓ $(\ell = e, \mu, \tau)$.

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 $(\ell = e, \mu, \tau)$.

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

e.g.

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

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

Results

seesaw scale: $m_R > 10^{12}$ GeV

Yukawa couplings:

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

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

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

$$\Delta_2 = \mathrm{diag}\left(\delta_e, \delta_\mu, \delta_\tau\right) = \mathrm{diag}\,(0, 0.00007, 0.2)$$

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

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

Results

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

Results

exp. bounds				model contributions
$\mathrm{BR}\,(\mu^+ \to e^+\gamma)$	$<$	4.2×10^{-13}	*MEG II, impr.* 10^{-14}	$\sim \frac{1}{m_R^4}$
$\mathrm{BR}\,(\tau^- \to e^-\gamma)$	$<$	3.3×10^{-8}		
$\mathrm{BR}\,(\tau^- \to \mu^-\gamma)$	$<$	4.4×10^{-8}		
$\mathrm{BR}\,(\mu^- \to e^-e^+e^-)$	$<$	1.0×10^{-12}	*Mu3e, impr.* 10^{-16}	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}
(exp/SM $=1$) a_e^{err}	$=$	$\pm 2.6 \times 10^{-13}$		$a_e^{mod} = 1.0 \times 10^{-13}$
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$=$	$\begin{cases} (287 \pm 80) \times 10^{-11} \\ (261 \pm 78) \times 10^{-11} \end{cases}$		$a_\mu^{mod} = 258 \times 10^{-11}$

Summary

Model:

- Right handed neutrinos, in seesaw formulation: expl. light m_μ
- 2 Higgs doublets: FCNI
- Soft flavour violation: violation only through neutrinos

ℓ-decays:

- Found upper bounds on flavour diagonal Yukawa couplings (Γ_ℓ, Δ_ν) at one loop.
- Found lower benchmarks on seesaw scale $m_R > 50\,\text{TeV}$
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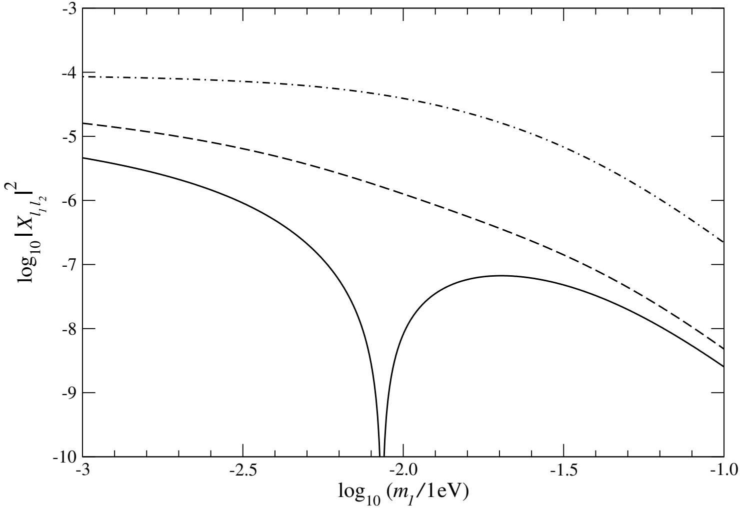
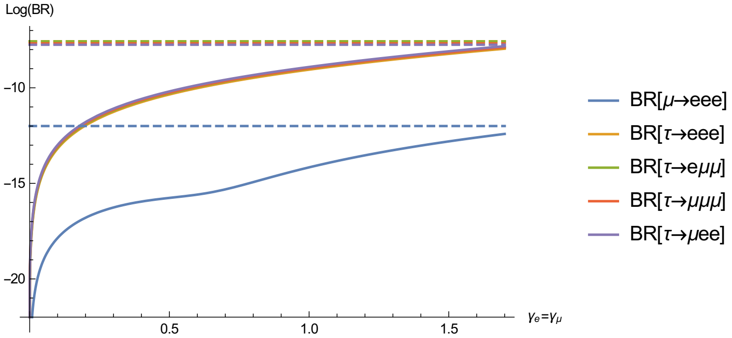
We found a different approach to make things work!

Thank you!

Backup slides



-3
-4
-5
-6
-7
-8
-9
-10
-3
-2.5
-2.0
-1.5
-1.0
$\log_{10}|X_{l_1 l_2}|^2$
$\log_{10}(m_1/1\text{eV})$


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]

Advantage of right handed neutrinos

- **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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- **Boundaries from BBN**
- **CMB measurement** from PLANCK sets limits on N_ν and also the **Large Scale Structure**.

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