Rare Leptonic Decays

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Outline

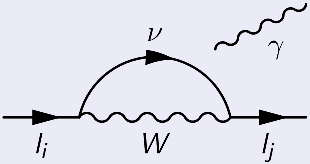
Expectations from the SM

The old SM

Each Lepton Flavor is symmetry of Lagrangian.
$\longrightarrow$ No LFV. Rare lepton decays forbidden.

The SM with ν-masses (νSM)

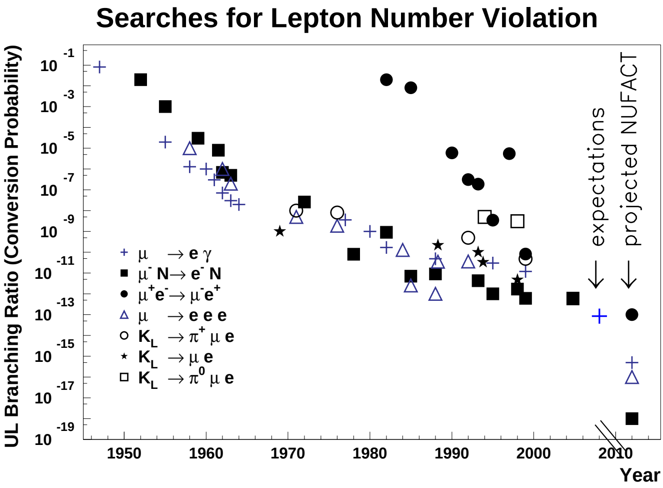
- Neutrino oscillations $\rightarrow$ LF broken!
- Via one loop LFV is induced in charged sector (cLFV)



$$\mathrm{BR}(\tau \rightarrow \mu\gamma) > 10^{-54}$$

- Lagrangian of νSM unknown $\Rightarrow$ Rate of cLFV unknown!

Experimental bounds [King, Long et al.]



Experimental bounds

Process	BR	Process	BR
$\tau \to \mu\,\gamma$	$< 4.5\,10^{-8}$	$\mu \to e\,\gamma$	$< 1.2\,10^{-11}$
$\tau \to \mu\,\mu\,\mu$	$< 3.2\,10^{-8}$	$\mu \to e\,e\,e$	$< 1.0\,10^{-12}$
$\tau \to \mu\,\mathrm{meson}$	$\lesssim 5\,10^{-8}$	$\mu\,\mathrm{Ti} \to e\,\mathrm{Ti}$	$\frac{\sigma^{\mathrm{LFV}}}{\sigma^{\mathrm{capture}}} < 4.3\,10^{-12}$

Similar for $\tau \to e\ldots$

[PDG 2008, Belle]

$\longrightarrow$ Bounds comparable within each flavor

$\longrightarrow$ No chance to go down to νSM lower bound

Parametrization of the Unknown

$$\mathcal{L} \supset \frac{e m_{l_j}}{\Lambda_D^2} \bar{l}_i \sigma^{\mu\nu} l_j F_{\mu\nu} + \quad \text{Dipole, leads to } \tau \to \mu\gamma$$

$$\frac{1}{\Lambda_L^2} \bar{l}_i l_j \; \bar{l}_i l_i + \quad \text{4 Fermi, leads to } \tau \to \mu\,\mu\,\mu$$

$$\frac{1}{\Lambda_Q^2} \bar{l}_i l_j \; \bar{q}_i q_i \quad \text{4 Fermi, } \tau \to \mu\,\mathrm{meson} \text{ / Conversion}$$

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From experiment $\Lambda_D^{\mu e} \gtrsim 300 \text{ TeV}$ $\Lambda_D^{\tau\mu} \gtrsim 20 \text{ TeV}$
$\Rightarrow$ Constraints on New Physics (NP) at very high scales
(More detailed treatment on next slide)

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If there is any source of cLFV, the others will be induced:

Constraining the scale of NP

Bounds on effective couplings translate into a bound on the scale of NP depending on the suppression at work. Typically:

- Non-maximal flavor mixing: $\Lambda^{NP} > \Lambda^{ij}\theta_{ij}$
- loop-suppression: $\Lambda^{NP} > \sqrt{\alpha}\Lambda$
- maybe additional GIM suppression: $\Lambda^{NP} > \sqrt{\alpha}\frac{\sqrt{\Delta m^2}}{\Lambda^{NP}}\Lambda$

In some models:

- Triplet Higgs: flavor mixing: $(\Lambda^{\mathrm{TH}})^2 > (100\ \mathrm{TeV})^2 \times Y_{11}Y_{12}$
- Anarchic Randall Sundrum: flavor mixing "known": $\Lambda^{\mathrm{RS}} > 3\ \mathrm{TeV}$
- SUSY: loop suppression, flavor mixing: $(\Lambda^{\mathrm{SUSY}})^2 > (30\ \mathrm{TeV})^2 \times \frac{m^2_{\mu e}}{(\Lambda^{\mathrm{SUSY}})^2},\ \ (2\ \mathrm{TeV})^2 \times \frac{m^2_{\tau\mu}}{(\Lambda^{\mathrm{SUSY}})^2}$

Model discrimination with cLFV

What do we learn about underlying models, if

- cLFV is found?
  →Need additionally scale of NP to draw any conclusion.
- cLFV is found in several processes within the same flavor violation?
  →This determines ratios of effective couplings. Lots of models can typically be ruled out.
- cLFV is found in different flavor violations?
  →Can rule out models, where cLFV in different flavors are connected.

Model discrimination with upcoming data

- BaBar and Belle continue to search for τ-cLFV. In case of a positive signal
  - Lots of different processes measured with similar accuracy
  - We would know that τ-cLFV $\gg$ μ-e-cLFV

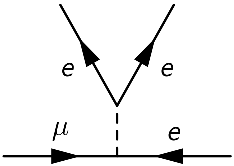
$\Rightarrow$ Great model discrimination!

- MEG at PSI is running and will soon provide information about $\mu \to e\gamma$. In case of a positive signal
  - $\mu \to e\gamma$ the only found, but $\mu \to e\,e\,e$ already well measured.
  - Measurement of the dependence on the muon chirality possible.

$\Rightarrow$ Good model discrimination!

Triplet Higgs model [Schechter, Valle]

- Introduce $\mathrm{SU}(2)$ triplet $(\Delta^{++}, \Delta^{+}, \Delta^{0})$, lepton number -2.
  $\mathcal{L} \supset \frac{1}{2} Y_{ij} \bar{L}_i^c \Delta L_j$
- $\langle \Delta^0 \rangle \neq 0 \Rightarrow$ neutrino masses $m_\nu = Y \langle \Delta^0 \rangle$
- Tree level cLFV diagram



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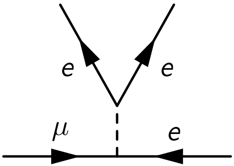
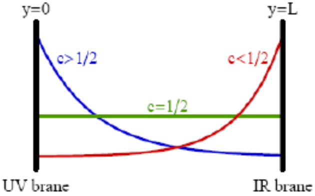


Predictions [Kakizaki, Ogura, Shima]

- Negligible τ-cLFV
- cLFV only in left-handed sector
- $\mu \to e\,e\,e$ more frequently than muon conversion

Anarchic Randall Sundrum model



[Agashe et al.]

- Add small extra dimension with warped geometry
  $ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$
- Higgs at IR-brane, gauge fields and fermions in the bulk.
  4D Yukawas from fermion shape functions on IR-brane
- anarchic 5D-Yukawas, different localizations in small dim.
  $\Rightarrow$ Hierarchical pattern of Yukawas
- Non-universal couplings of KK gauge bosons to fermions
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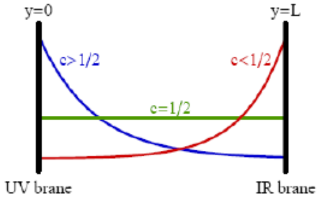

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Predictions

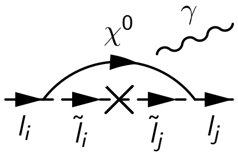
Scale (=naturalness) of this scenario already probed!

SUSY

- unbroken SUSY: no new couplings ⇒ no cLFV
- broken SUSY (R-Parity conserved):
  Generation of scalar masses and trilinears

$$\mathcal{L} \supset \tilde{l}^*_{Li} m^2_{Lij} \tilde{l}^*_{Lj} + \tilde{l}^*_{Ri} m^2_{Rij} \tilde{l}^*_{Rj} + \tilde{l}^*_{Ri} A_{ij} \tilde{l}^*_{Lj} H^0_d$$

  cLFV might be introduced via SUSY breaking or afterwards
- Leading cLFV diagram



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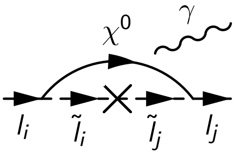

Predictions

Dipole operator dominant.

Correlations between different flavor violations

Definition

$\Delta^{LL} = m_L^2$, $\Delta^{RR} = m_R^2$, $\Delta^{LR} = (\Delta^{RL})^\dagger = A\langle H_d^0 \rangle$,

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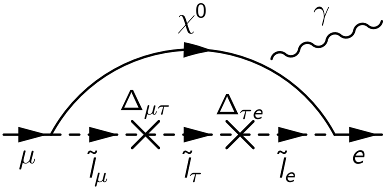
Plan for the remainder of the talk

Study the implications of

- minimal assumptions [Ibarra, Shindou, CS]
- leptogenesis [Ibarra, CS]

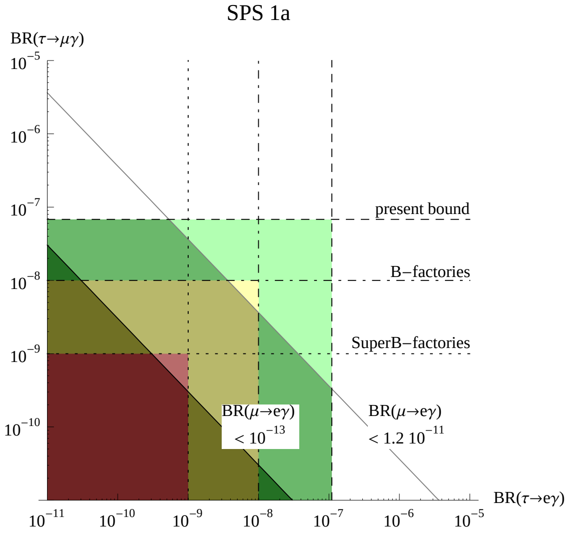
Correlations under the minimal assumption

- The minimal assumption:
  No cancellation between terms of different origin.
- If both rare τ decays are there, then necessarily also $\mu \to e\,\gamma$



- Therefore $\mathrm{BR}(\mu \to e\gamma) \gtrsim C\ \mathrm{BR}(\tau \to \mu\gamma)\ \mathrm{BR}(\tau \to e\gamma)$
  C depending on SUSY paramaters and which of Δ^{LL}, Δ^{RR}, Δ^{LR} is leading.

Taking further – low energy MSSM (SPS1a [Allanach et al.])
– that Δ^{LL} or Δ^{RR} is leading (e.g. in see-saw, GUT)



Constraints in SUSY leptogenesis

Connect different things:

- low energy MSSM
- see-saw
  - add heavy right-handed neutrino $\nu_R Y_\nu \nu_L H_u^0 - \frac{1}{2}\nu_R M \nu_R$
  - effective light neutrino mass: $m_\nu = Y_\nu^T M^{-1} Y_\nu \langle H_u^0 \rangle^2$
  - flavor off-diagonals induced the soft mass: $m_L^2 \propto Y_\nu^\dagger \log \frac{M_X}{M} Y_\nu$

Still not enough information to draw any conclusion about cLFV.

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- baryon asymmetry via leptogenesis [Fukugita, Yanagida]
  - See-saw includes possibility of CP violation in decay of ν_R $\rightarrow$ leptogenesis
  - Converted via sphaleron processes into baryon asymmetry $\rightarrow$ baryogenesis
  - Usually final lepton asymmetry from decay of lightest ν_R Then lower bound on its mass M_1 depending on $\tilde{m}_1 = \frac{\langle H_u^o \rangle^2}{M_1} (Y_\nu Y_\nu^\dagger)_{11}$

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Even more (but well motivated) assumptions)

- hierarchical Y_ν
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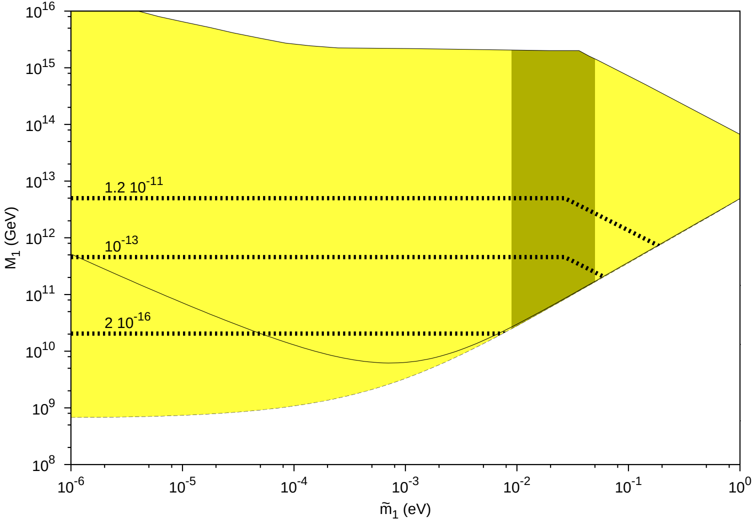
Implications for the see-saw

- Small BRs of rare decays $\leftrightarrow$ small off-diagonals in $m_L^2 \leftrightarrow$ small mixings in the left-handed sector
- No mixing in left-handed sector $\Rightarrow$ minimal $\mathrm{BR}(\mu \to e\gamma)$
- Under the assumptions, from see-saw formulae:
  - $\mathrm{BR}(\mu \to e\gamma) \propto (Y_\nu)^4_{11} \to$ Upper bound on $(Y_\nu)_{11}$
  - $M_1 \gtrsim (Y_\nu)^2_{11} \frac{\langle H_u^0 \rangle^2}{\sqrt{\Delta m^2_{sol}}} \to$ Upper bound on M_1
  - $\tilde{m}_1 \gtrsim \sqrt{\Delta m^2_{sol}}$

$\Rightarrow$ Possibility to exclude leptogenesis.


10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
M_1 (GeV)
1.2 10^{-11}
10^{-13}
2 10^{-16}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
$\tilde{m}_1$ (eV)

Summary

- Lepton Flavor is violated! But minimal expected rate in the νSM cannot be observed.
- If there is some NP close to the EW scale, it needs a mechanism to suppress cLFV.
- Excellent prospects for experimental improvement in $\mu \to e\,\gamma$. But still hope to find cLFV in B-factories.
- Although indirect, measurements of cLFV would be a very clean signal of NP and would exclude/constrain models a lot.