Lepton flavor violation in charged leptons: a theory overview

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Open questions

1. **Which is the underlying mechanism regulating the EWSB?**
2. **Which is the connection between EWSB and flavor physics?**
3. **Are there new flavor symmetries beyind the puzzling fermion mass spectrum?**
4. **Are there new flavor violating interactions not governed by the SM Yukawas? That is, to which extent the MFV hypothesis is valid?**
5. **Do the new sources of CPV accounting for the BAU have an impact on flavor physics and/or EDMs?**
6. **Which is the role of flavor physics in the LHC era?**
7. **Do we expect to understand the (SM and NP) flavor puzzles through the interplay of flavor physics and the LHC?**
8. **......**

Flavour Physics in the LHC era

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

EDMs

Rare K decays

g-2

A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]

[Isidori @ LP07]

Where to look for New Physics at the low energy?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects in the electron/neutron EDMs, $d_{e,n}$...
  - FCNC & CPV in $B_{s,d}$ decay/mixing & D mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU in $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$

Experimental status

Brief status of Lepton Flavor Violation searches

- tau LFV
  - past: CLEO explored up to BRs $\sim 10^{-6}$
  - **present: B-factories are completing exploration up to BRs $\sim 10^{-8}$**
  - future: Super Flavor Factories can explore up to BRs $\sim 10^{-10}$
  - $\tau \to \mu\gamma$ **is the most sensitive channel for most mainstream NP models**
- muon LFV
  - past: LAMPF, MEGA, BF($\mu \to e\gamma$) $< 1.2 \cdot 10^{-11}$ at 90% CL
  - past: SINDRUM II, BF($\mu \to e$ in nucleon field) $< 7 \cdot 10^{-13}$ at 90% CL
  - **present: MEG, BF($\mu \to e\gamma$) $< 1.5 \cdot 10^{-11}$ at 90% CL, (sensitivity $6 \cdot 10^{-12}$)**
  - future: MEG will soon reach sensitivity $\sim 10^{-13}$
  - future: Mu2E and COMET/PRISM can much increase reach on BF($\mu \to e$ in nucleon field)

Process	Expected 90% CL upper limit	3σ evidence reach
BF($\tau \to \mu\gamma$)	$2.4 \cdot 10^{-9}$	$5.4 \cdot 10^{-9}$
BF($\tau \to e\gamma$)	$3.0 \cdot 10^{-9}$	$6.8 \cdot 10^{-9}$
BF($\tau \to \ell\ell\ell$)	$2.3 - 8.2 \cdot 10^{-10}$	$1.2 - 4.0 \cdot 10^{-9}$

[Lusiani @ HQL10]

The NP "scale"

- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}$ GeV
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}$ GeV
- **Hierarchy problem**: $m_h^{\rm SM}(\Lambda^2_{\rm NP}) \sim M_W \Longrightarrow \Lambda_{\text{NP}} \lesssim$ TeV
- **Dark Matter** $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim$ TeV
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim$ TeV
  - Leptogenesis $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}$ GeV

$$\Downarrow$$

SM = effective theory at the EW scale

- Going BSM model-independently:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_{ij}^{(d)}}{\Lambda_{NP}^{d-4}}\, O_{ij}^{(d)}$$

  - $\mathcal{L}^{d=5}_{\rm eff} = \frac{y_\nu^{ij}}{\Lambda_{\rm see-saw}} L_i L_j \phi\phi,$
  - $\mathcal{L}^{d=6}_{\rm eff}$ generates many FCNC operators **BR**$(\ell_{\bf i} \to \ell_{\bf j}\gamma) \sim \frac{1}{\Lambda^4_{NP}}$

- **Neutrino Oscillation** $\Rightarrow m_{\nu_i} \neq m_{\nu_j} \Rightarrow$ **LFV**
- **see-saw**: $m_\nu = \frac{(m_\nu^D)^2}{M_R} \sim eV$, $M_R \sim 10^{14-16} \Rightarrow m_\nu^D \sim m_{top}$
- LFV transitions like $\mu \to e\gamma$ @ 1 loop with exchange of
  - W and ν in the SM framework (GIM)

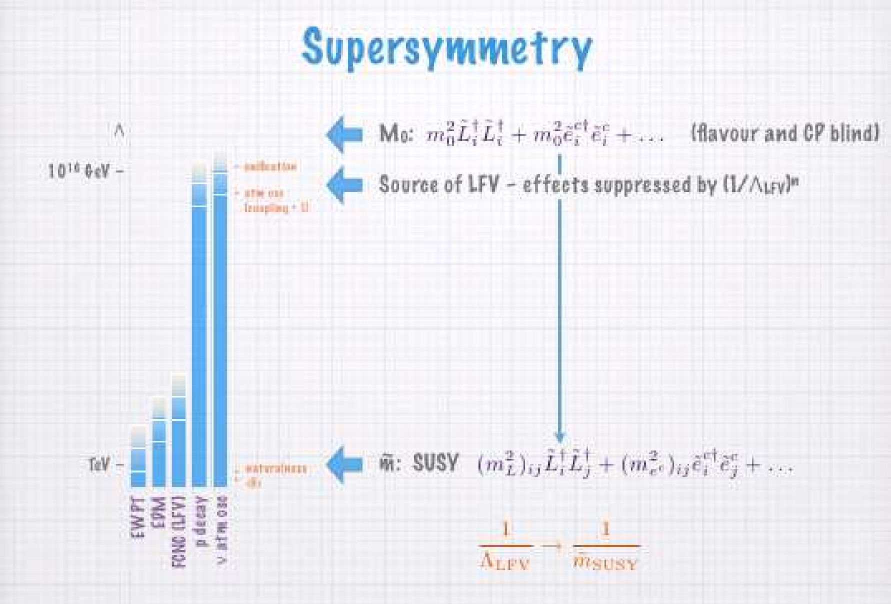
$$Br(\mu \to e\gamma) \sim \frac{m_\nu^4}{M_W^4} \leq 10^{-50} \qquad m_\nu \sim \mathrm{eV}$$

  - $\tilde{W}$ and $\tilde{\nu}$ in the MSSM framework (SUPER-GIM)

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^{D\,4}}{\tilde{m}^4} \leq 10^{-11} \qquad m_\nu^D \sim m_{top}$$

$$\Downarrow$$

- LFV signals are undetectable (detectable) in the SM (MSSM)



[Romanino @ CERN ’06]

Flavour universal SUSY breaking and yet large LFV from SUSY see-saw

- SUSY see-saw superpotential (MSSM + RN)

$$W = h^e L e^c H_1 + h^\nu L \nu^c H_2 + M_R \nu^c \nu^c + \mu H_1 H_2,$$

$$\mathcal{M}_\nu = -h^\nu M_R^{-1} h^{\nu\ T} v_2^2,$$

$$M^2_{\tilde{\ell}} = \begin{pmatrix} m_L^2(1+\delta_{LL}^{ij}) & (A-\mu t_\beta)m_\ell + m_L m_R \delta_{LR}^{ij} \\ (A-\mu t_\beta)m_\ell + m_L m_R {\delta_{LR}^{ij}}^\dagger & m_R^2(1+\delta_{RR}^{ij}) \end{pmatrix}$$

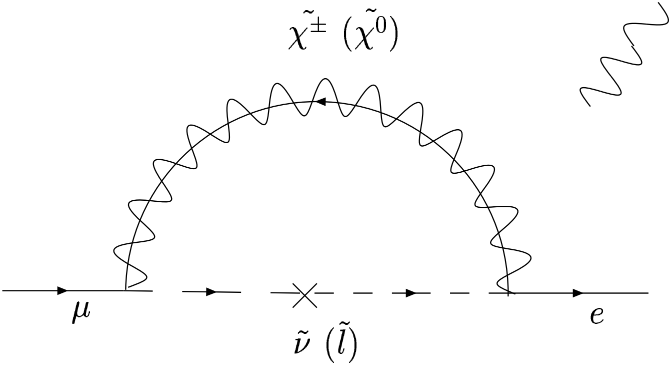
- If $h^e = h^e_{ij}\delta_{ij}$ and $M_R = (M_R)_{ij}\delta_{ij} \Rightarrow h^\nu \neq h^\nu_{ij}\delta_{ij}$ in general.

$$\delta_{LL}^{ij} \approx -\frac{3}{8\pi^2}(h^\nu h^{\nu\dagger})_{ij} \ln\frac{M_X}{M_R},$$

[Borzumati & Masiero, '86]

LFV interactions – leptons/sleptons/gauginos

$$\mathcal{L} = \bar{\ell}_i \left(C^R_{ijA} P_R + C^L_{ijA} P_L \right) \tilde{\chi}^-_A \tilde{\nu}_j + \bar{\ell}_i \left(N^R_{ijA} P_R + N^L_{ijA} P_L \right) \tilde{\chi}^0_A \tilde{\ell}_j$$



$$\frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} \sim \left(\frac{m_W^4}{m_{SUSY}^4} \right) \left(\delta^{21}_{LL} \right)^2 t_\beta^2 \qquad \delta_{LL} \sim h^\nu h^{\nu\dagger}$$

h^ν **is unknown** $\Rightarrow$ **No model independent predictions for LFV**

$$h^\nu = U^\star_{\rm MNS}\, \mathcal{D}_{\sqrt{\mathcal{M}_\nu}}\, R^T\, \mathcal{D}_{\sqrt{M_R}}\, \frac{1}{v_2},$$

$R^\dagger R = 1 \Rightarrow$ **three angles** and **three phases**

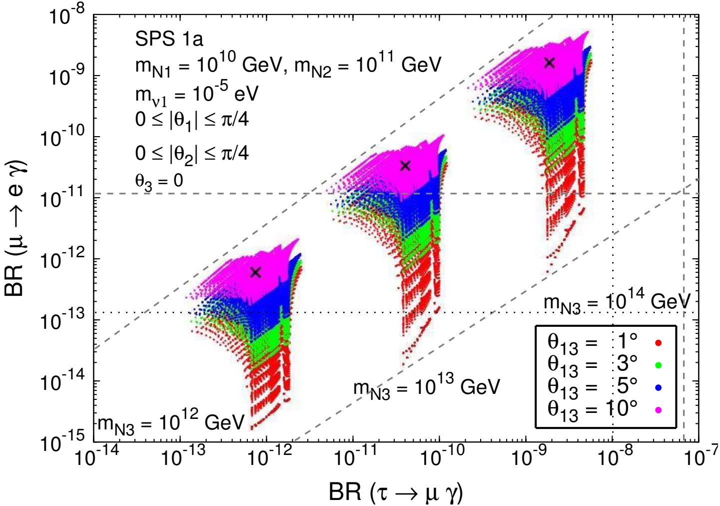
- ν_L **&** ν_R **hierarchical (and R real)**

$$\frac{B(\mu \to e\gamma)}{B(\tau \to \mu\gamma)} \sim \frac{|U_{e3}|^2}{B(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}$$

- ν_L **hierarchical and** ν_R **degenerate (and R real)**

$$\frac{B(\mu \to e\gamma)}{B(\tau \to \mu\gamma)} \sim \frac{|s_{12}c_{12}\,(m_{sol}/m_{atm}) + U_{e3}|^2}{B(\tau \to \mu\nu_\tau\bar{\nu}_\mu)}$$

$\mu \to e\gamma$ and $\tau \to \mu\gamma$ in SUSY see-saw



[Herrero et al., '06]

RG induced LFV interactions in SUSY GUTs

- **SUSY SU(5)** [Barbieri & Hall, '95]

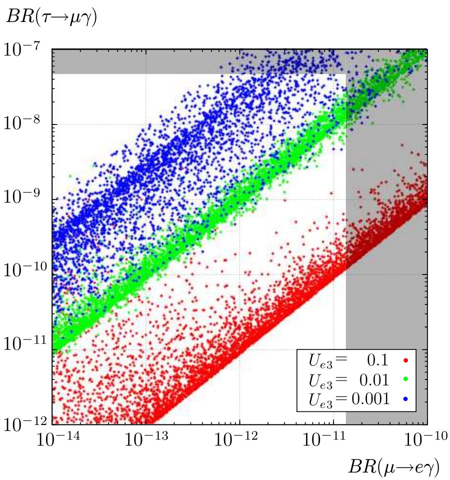
$$(\delta^{\tilde{q}}_{LL})_{ij} \sim h^u h^{u\dagger}{}_{ij} \sim h_t^2 V_{CKM}^{ik} V_{CKM}^{kj*} \longrightarrow (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

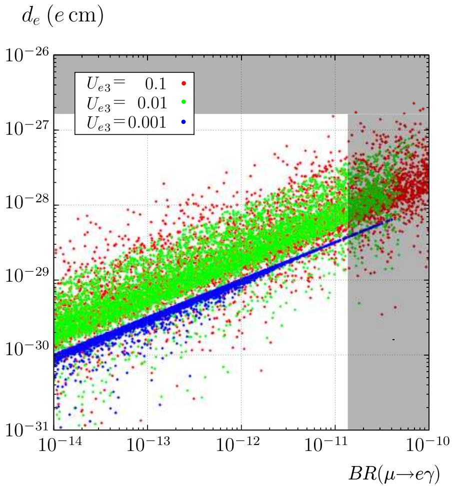
- **SUSY SU(5)+RN** [Yanagida et al., '95]

$$(\delta^{\tilde{\ell}}_{LL})_{ij} \sim (h^\nu h^{\nu\dagger})_{ij} \qquad \& \qquad (\delta^{\tilde{\ell}}_{RR})_{ij} \sim (h^u h^{u\dagger})_{ij}$$

- **SUSY SU(5)+RN** [Moroi, '00] **&** **SO(10)** [Chang, Masiero & Murayama, '02]

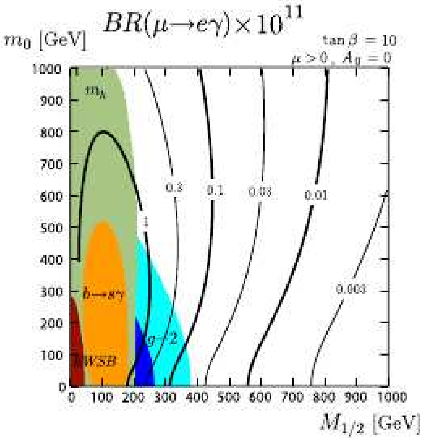
$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde{\ell}}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde{q}}_{RR})_{23} \sim 1$$

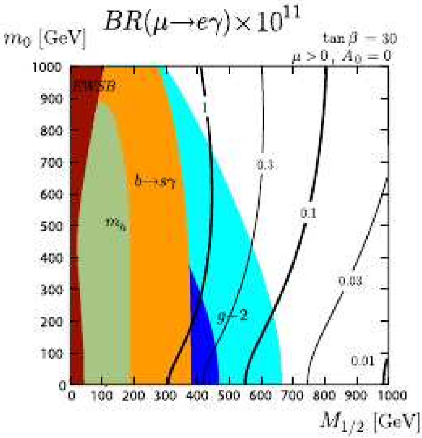




[Hisano, Nagai, Paradisi & Shimizu, '09]

$\mathrm{BR}(\mu \to e\gamma)$ in $SU(5)_{RN}$ and the LHC reach





hierarchical ν_L and N_R, $U_{e3} = 0.1$, $M_{N_3} = 10^{-13}\,\mathrm{GeV}$

[Hisano, Nagai, Paradisi & Shimizu, ’09]

The P-odd asymmetry in $\mu^+ \to e^+\gamma$ [Okada et al., '96]

- **After $\mu^+ \to e^+\gamma$ will be (hopefully!) observed...**

$$\frac{\mathrm{BR}(\ell_i \to \ell_j\gamma)}{\mathrm{BR}(\ell_i \to \ell_j\nu_i\bar{\nu}_j)} = \frac{48\pi^3\alpha_{em}}{G_F^2}\left(|A_L^{\ell_i\ell_j}|^2 + |A_R^{\ell_i\ell_j}|^2\right)$$

$$A(\mu^+ \to e^+\gamma) = \frac{|A_L|^2 - |A_R|^2}{|A_L|^2 + |A_R|^2}$$

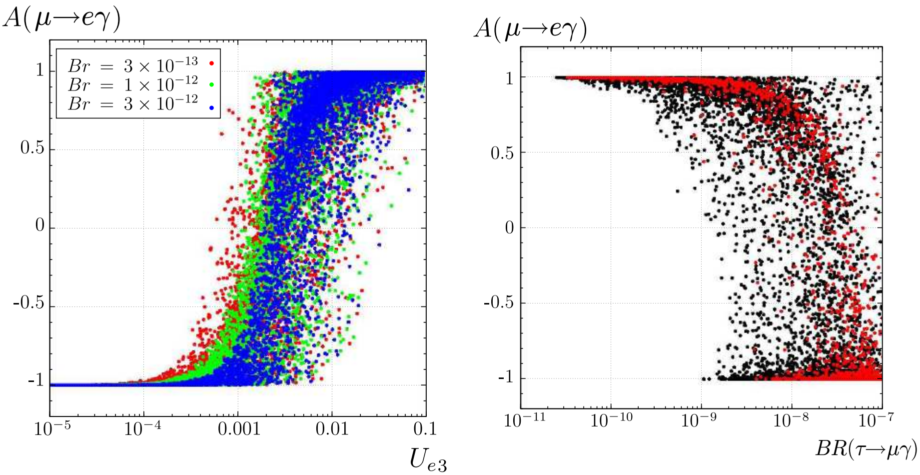
- **SUSY see-saw**

$$A_L^{\mu e} = \frac{\alpha_2}{4\pi}\frac{t_\beta}{\tilde{m}^2}\frac{\delta^L_{\mu e}}{15} \qquad A_R^{\mu e} \simeq \frac{m_e}{m_\mu}A_L^{\mu e}$$

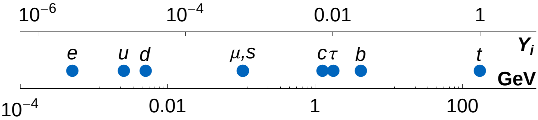
- **SUSY SU(5)+RN**

$$A_L^{\mu e} = \frac{\alpha_2}{4\pi}\frac{t_\beta}{\tilde{m}^2}\frac{\delta^L_{\mu e}}{15} \qquad A_R^{\mu e} = -\frac{\alpha_Y}{4\pi}\frac{t_\beta}{\tilde{m}^2}\frac{m_\tau}{m_\mu}\frac{\delta^L_{\mu\tau}\delta^R_{\tau e}}{30}$$

$A(\mu \to e\gamma)$ in SUSY SU(5)+RN



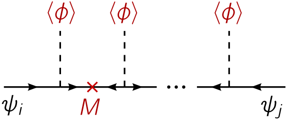
[Hisano, Nagai, Paradisi & Shimizu, '09]



$V_{\rm CKM} \sim$ 

Froggat-Nielsen '79: Hierarchies from SSB of a Flavour Symmetry

$$\epsilon = \frac{\langle\phi\rangle}{M} \ll 1 \Rightarrow Y_{ij} \propto \epsilon^{(a_i+b_j)}$$

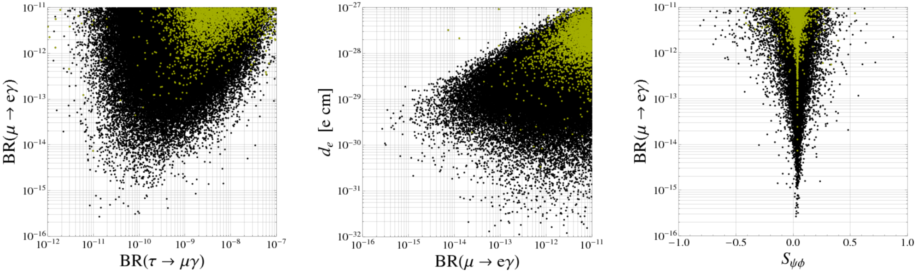


Non-abelian $SU(3)$ SUSY flavour model [Ross, Velasco-S., Vives]

$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^5 & \lambda^3 \\ \lambda^5 & \cdot & \lambda^2 \\ \lambda^3 & \lambda & \cdot \end{pmatrix} \qquad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix}$$

$$\delta_\ell^{LL} \sim \begin{pmatrix} \cdot & \frac{\lambda^5}{3} & \frac{\lambda^3}{3} \\ \frac{\lambda^5}{3} & \cdot & \lambda^2 \\ \frac{\lambda^3}{3} & \lambda & \cdot \end{pmatrix} \qquad \delta_\ell^{RR} \sim \begin{pmatrix} \cdot & \frac{\lambda^3}{3} & \frac{\lambda^2}{3} \\ \frac{\lambda^3}{3} & \cdot & \lambda \\ \frac{\lambda^2}{3} & \lambda & \cdot \end{pmatrix}$$

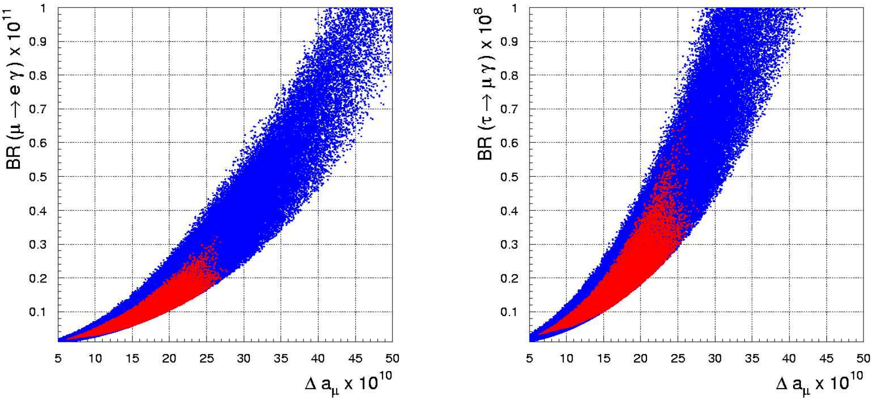
Phenomenology of a SUSY SU(3) flavor models



- Yellow points satisfy $\Delta a_\mu > 10^{-9}$
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$

[Altmannshofer, Buras, Gori, Paradisi and Straub, '09]

$(g-2)_\mu$ vs $\ell_i \to \ell_j \gamma$



$|\delta_{LL}^{12}| = 10^{-4}$ and $|\delta_{LL}^{23}| = 10^{-2}$,

[Isidori, Mescia, Paradisi & Temes, 07]

$$BR(\ell_i \to \ell_j \gamma) \approx \left[\frac{\Delta a_\mu}{20 \times 10^{-10}} \right]^2 \times \left\{ \begin{array}{lll} 1 \times 10^{-4} & \left|\delta_{LL}^{12}\right|^2 & [\mu \to e] \\ 2 \times 10^{-5} & \left|\delta_{LL}^{23}\right|^2 & [\tau \to \mu] \end{array} \right\}$$

- **Ratios of BR for different flavor transitions**
- **Ratios of BR for different processes**

ratio	LHT	MSSM	SM4
$\frac{Br(\mu\to eee)}{Br(\mu\to e\gamma)}$	$0.02\ldots1$	$\sim 2\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.4$	$\sim 1\cdot10^{-2}$	$0.07\ldots2.2$
$\frac{Br(\tau\to \mu\mu\mu)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.4$	$\sim 2\cdot10^{-3}$	$0.06\ldots2.2$
$\frac{Br(\tau\to e\mu\mu)}{Br(\tau\to e\gamma)}$	$0.04\ldots0.3$	$\sim 2\cdot10^{-3}$	$0.03\ldots1.3$
$\frac{Br(\tau\to \mu ee)}{Br(\tau\to \mu\gamma)}$	$0.04\ldots0.3$	$\sim 1\cdot10^{-2}$	$0.04\ldots1.4$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\mu\mu)}$	$0.8\ldots2$	~ 5	$1.5\ldots2.3$
$\frac{Br(\tau\to \mu\mu\mu)}{Br(\tau\to \mu ee)}$	$0.7\ldots1.6$	~ 0.2	$1.4\ldots1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots10^{2}$	$\sim 5\cdot10^{-3}$	$10^{-12}\ldots26$

[Buras et al., '07, '10]

$$R_K = \frac{\Gamma(K \to e\nu_e) + \Gamma(K \to e\nu_\mu) + \Gamma(K \to e\nu_\tau)}{\Gamma(K \to \mu\nu_\mu) + \Gamma(K \to \mu\nu_e) + \Gamma(K \to \mu\nu_\tau)}$$

- Violations of **LU** in **CCI** can be classified as $(R_K/R_K^{SM} = 1 + \Delta r^{e-\mu}_{K\,NP})$
  - i) **Corrections** to $(V-A)\times(V-A)$ interaction through $W\ell\nu_\ell$ vertex correction induced by a loop of NP particles

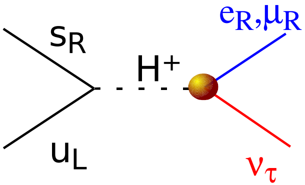
$$\Delta r^{e-\mu}_{SUSY} \sim \frac{\alpha_2}{4\pi}\left(\frac{\tilde{m}^2_\mu - \tilde{m}^2_e}{\tilde{m}^2_\mu + \tilde{m}^2_e}\right)\frac{m^2_W}{M^2_{SUSY}} \leq 10^{-4}$$

  - ii) **New Lorentz Structures**, i.e. **scalar CCI** with $H\ell\nu \sim m_\ell \tan\beta$.

	$(R_K^{e/\mu})_{exp.}$ $[10^{-5}]$
PDG 2006	2.45 ± 0.11
KLOE '09.	2.477 ± 0.01
NA62 '11.	2.487 ± 0.013
SM prediction (Cirigliano & Rossel '07)	2.477 ± 0.001

R_K^{LFV} in SUSY

$$R_K^{LFV} = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)} \;, \quad i = e, \mu, \tau$$



$$eH^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta_R^{31} \tan^2\beta$$

$$\Delta_R^{31} \sim \frac{\alpha_2}{4\pi}\, \delta_{RR}^{31}$$

$$\Delta_R^{31} \sim 5 \cdot 10^{-4} \;\; t_\beta = 40 \;\; M_{H^\pm} = 500\mathrm{GeV}$$

$$\Downarrow$$

$$\Delta r_{K\,SUSY}^{e-\mu} \simeq \left(\frac{m_K^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right) |\Delta_R^{31}|^2 \tan^6\beta \approx 10^{-2}$$

$$\Delta r_{K\,SUSY}^{e-\mu} \approx 10^{-2} \quad \Longrightarrow \quad Br^{th.(exp.)}(\tau \to eX) \leq 10^{-10(-7)}$$

[Masiero, Paradisi and Petronzio, ’05]

"DNA-Flavour Test"

SUSY model	GMSSM	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	■	★★★	★★★	SuperB
$A_{CP}(B \to X_s\gamma)$	★★★	■	■	■	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	●●	■	■	■	■	■	
$\tau \to \mu\gamma$	★★★	★★★	★★★	■	★★★	★★★	
$D^0 - \bar{D}^0$	★★★	★★★	■	■	■	■	SuperB
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	★★★	★★★	vs.
$A_9(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	■	■	LHCb
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	■	■	LHCb
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★★★	
ϵ_K	★★★	■	★★★	★★★	■	■	
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	■	■	■	■	■	
$K_L \to \pi^0\nu\bar{\nu}$	★★★	■	■	■	■	■	
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	
d_n	★★★	★★★	★★★	★★★	●●	★★★	
d_e	★★★	★★★	★★★	●●	■	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	

[Altmannshofer et al., '09]

Open questions

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4. **Are there new flavor violating interactions not governed by the SM Yukawas? That is, to which extent the MFV hypothesis is valid?**
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7. **Do we expect to understand the (SM and NP) flavor puzzles through the interplay of flavor physics and the LHC?**
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Evidence of LFV in charged leptons would tell us a lot!