Flavour Physics in SUSY at large tan β

P. Paradisi

Valencia University, SPAIN

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Plan

Where to look for New Physics?

- Processes **forbidden** or much **suppressed** in the SM
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$ ....) or
  - CPV effects (electron/neutron EDMs, $d_{e,n}$....)
- Processes predicted with **high precision** in the SM
  - EWPO as $\Delta\rho$, $(g-2)_\mu$,....
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ $(M = \pi, K)$

Marriage of LFV and 1) LU in $R_M^{e/\mu}$ 2) CPV in d_e

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Marriage of LFV and 1) LU in $R_M^{e/\mu}$ 2) CPV in d_e

LFV frameworks

- **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)

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LFV in SUSY

RG induced LFV interactions in SUSY see-saw

- SUSY see-saw superpotential (MSSM + RN)

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

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

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

- 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 in SUSY

RG induced LFV interactions in SUSY GUTs

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

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

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

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

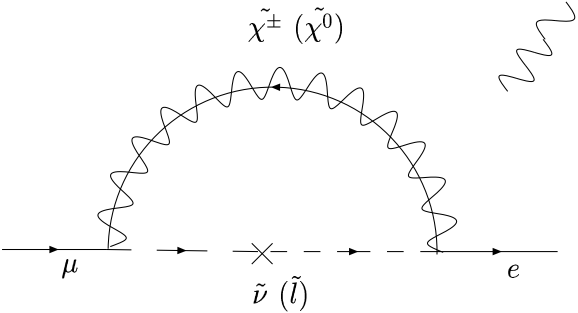
- **SUSY SU(5)+RN** [Moroi, '00] **& SO(10)** [Chang et al., 02]

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

LFV in SUSY

LFV interactions – leptons/sleptons/gauginos

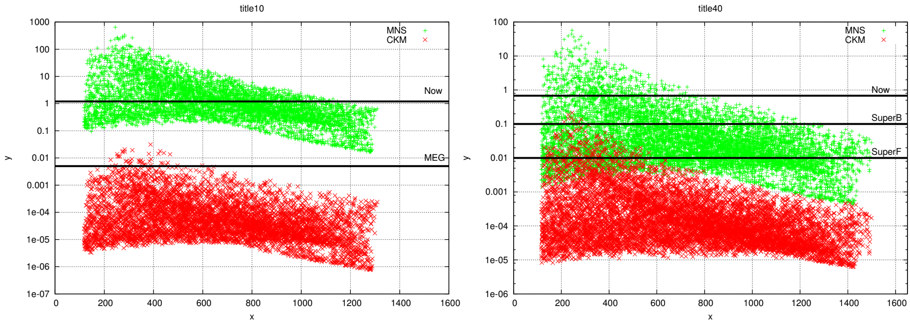
$$\mathcal{L} = \overline{\ell}_i \left(C^R_{ijA} P_R + C^L_{ijA} P_L \right) \tilde{\chi}^-_A \tilde{\nu}_j + \overline{\ell}_i \left(N^R_{ijA} P_R + N^L_{ijA} P_L \right) \tilde{\chi}^0_A \tilde{\ell}_j . \quad (1)$$



$$\left. \frac{BR(\ell_i \to \ell_j \gamma)}{BR(\ell_i \to \ell_j \nu_i \bar{\nu}_j)} \right|_{\text{Gauge}} \simeq \frac{\alpha_{el}}{20\pi} \left(\frac{m_W^4}{m_{SUSY}^4} \right) \left(\delta^{21}_{LL} \right)^2 t_\beta^2 \qquad \delta_{LL} \sim h^\nu h^{\nu\dagger}$$

$\mu \to e\gamma$ and $\tau \to \mu\gamma$

Br($\mu \to e\gamma$) Br($\tau \to \mu\gamma$)



$M_{1/2}$ $M_{1/2}$

$m_0 \leq 1\mathrm{TeV}$, $\tan\beta = 40$

Calibbi, Faccia, Masiero and Vempati, '06

Higgs Mediated LFV

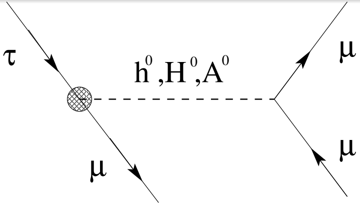
- LFV Yukawa Int. (if $\delta_{ij} = \tilde{m}^2_{ij}/\tilde{m}^2 \neq 0$) [Babu & Kolda, '02]:

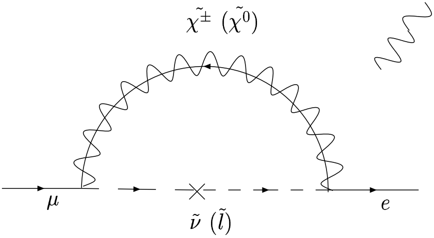
$$
\begin{aligned}
-\mathcal{L} \;\simeq\;& (2G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \bar{\tau}_R l_L^j + \Delta_R^{3j} \bar{\tau}_L l_R^j \right) \left(c_{\beta-\alpha} h^0 - s_{\beta-\alpha} H^0 - i A^0 \right) \\
+\;& (8G_F^2)^{\frac{1}{4}} \frac{m_\tau}{c_\beta^2} \left(\Delta_L^{3j} \bar{\tau}_R \nu_L^j + \Delta_R^{3j} \nu_L^\tau \bar{l}_R^j \right) H^\pm + h.c.
\end{aligned}
$$

$$
\Delta_{3j} \sim \frac{\alpha_2}{4\pi} \delta_{3j}
$$

- **Higgs** (gaugino) mediated LFV effects decouple as $m_H \to \infty$ ($m_{SUSY} \to \infty$),
- Key ingredients in the Higgs mediated LFV:
  - large $\tan\beta \sim 50$
  - large slepton mixings, $\delta_{3j} \sim \mathcal{O}(1)$, ($m_{SUSY} > 1\mathrm{TeV}$)

Phenomenology: $\tau \to l_j X \ (X = \gamma, \eta, l_j l_j (l_k l_k))$





$$\frac{BR(\tau\to 3\mu)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \left(\frac{\alpha_2}{48\pi}\right)^2 \left(\frac{m_\tau m_\mu}{M_H^2}\right)^2 \delta_{32}^2 t_\beta^6 \qquad \frac{BR(\tau\to\mu\gamma)}{BR(\tau\to\mu\nu\bar{\nu})} \simeq \frac{\alpha_{el}}{20\pi}\frac{m_w^4}{\tilde{m}^4}\delta_{32}^2 t_\beta^2$$

If $t_\beta \sim 50$ and $M_H \ll \tilde{m}$, i.e. $M_H \sim m_w$ and $\tilde{m} \sim TeV$

$$\Downarrow$$

$$\frac{BR(\tau\to 3\mu)}{BR(\tau\to\mu\gamma)} \not\propto \alpha_{el}$$

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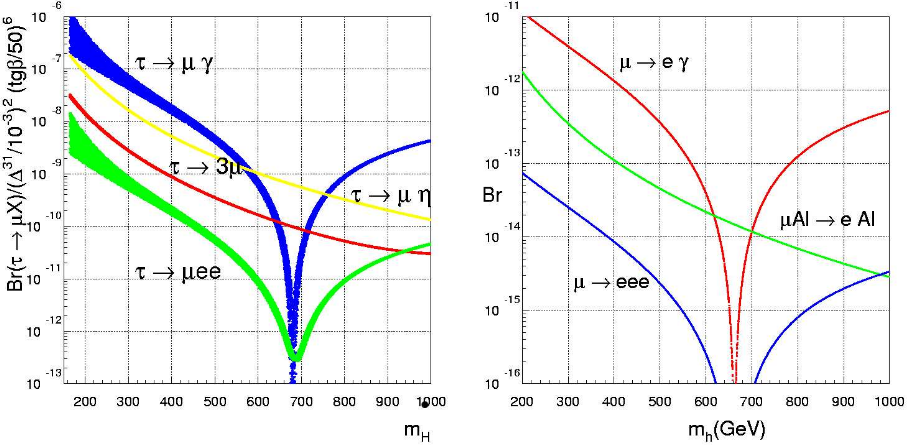

$m_0 = M_{1/2}$, $\tan\beta = 50$, $\Delta^{32} = 10^{-3}$ and $\Delta^{21} = 5 \times 10^{-6}$

P. P, '05,06

Correlations

- **Higgs mediated $\tau - \mu(e)$ transitions**

$$\frac{Br(\tau \to l_j\gamma)}{Br(\tau \to l_j\eta)} \geq 1\,, \frac{Br(\tau \to l_j\mu\mu)}{Br(\tau \to l_j\gamma)} \geq \frac{3+5\delta_{j\mu}}{36}$$

$$\frac{Br(\mu N \to eN)}{Br(\mu \to e\gamma)} \sim 10^{-1}$$

- **Gaugino mediated transitions**

$$\frac{BR(\tau \to l_j l_k l_k)}{BR(\tau \to l_j\gamma)} \simeq \alpha_{el}\,, \frac{Br(\mu N \to eN)}{Br(\mu \to e\gamma)} \simeq \alpha_{el}.$$

$$\frac{Br(\tau \to \mu\mu\mu)}{Br(\tau \to \mu\eta)} \simeq \tan^2\beta \gg 1$$

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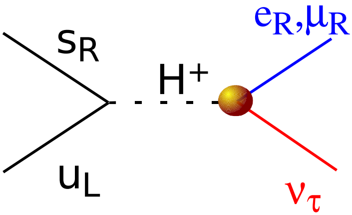
$\mu - e$ universality in $M \to l\nu$

$$R_K = (1+\Delta r_K^{e-\mu}) = \frac{\sum_i K \to e\nu_i}{\sum_i K \to \mu\nu_i} \simeq \frac{\Gamma_{SM}(K \to e\nu_e) + \Gamma(K \to e\nu_\tau)}{\Gamma_{SM}(K \to \mu\nu_\mu)}$$



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

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

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

$$\Downarrow$$

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

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

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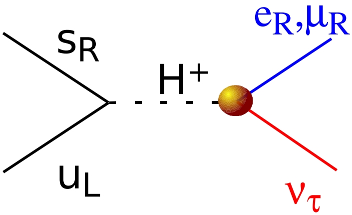

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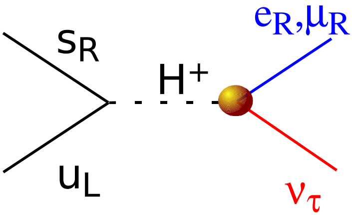

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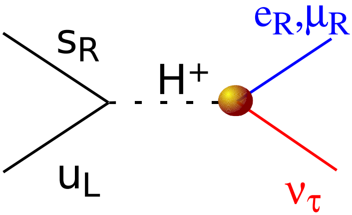

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LFV channels in $B \to \ell\nu$

- Including LFV channels in $B \to \ell\nu$, with $\ell = e, \mu$

$$R_{LFV}^{\ell/\tau} \simeq R_{SM}^{\ell/\tau}\left[1 + r_H^{-1}\left(\frac{m_B^4}{M_{H^\pm}^4}\right)\left(\frac{m_\tau^2}{m_\ell^2}\right)|\Delta_R^{3\ell}|^2 \tan^6\beta\right]$$

- Imposing the $\tau \to \ell_j X$ $(X = \gamma, \eta, \ell_j\ell_j(\ell_k\ell_k))$ constraints

$$R_{LFV}^{\mu/\tau} \leq 1.5 R_{SM}^{\mu/\tau} \;, \qquad R_{LFV}^{e/\tau} \leq 2 \cdot 10^4 \cdot R_{SM}^{e/\tau}$$

- Imposing the $\mu - e$ universality constraints in R_K

$$\frac{R_{LFV}^{e/\tau}}{R_{SM}^{e/\tau}} \simeq \left[1 + r_H^{-1}\frac{m_B^4}{m_K^4}\Delta r_{K\,Susy}^{e-\mu}\right] \leq 4 \cdot 10^2$$

[A.Masiero, P.P, R.Petronzio '05]
[G.Isidori, P.P., '06]

The large $\tan\beta$ scenario

How natural is the large $\tan\beta$ scenario?

- Top-Bottom Yukawa unification in GUT (minimal $SO(10)$) $\Rightarrow$ $\tan\beta = (m_t/m_b)$
- WMAP constraints are naturally satified for $\tan\beta = (m_t/m_b)$
- Correlations between $(B \to \tau\nu)$ and $(B \to X_s\gamma)$, ΔM_{B_s}, $(B_{s,d} \to \ell^+\ell^-)$, $(g-2)_\mu$ and m_{h^0}

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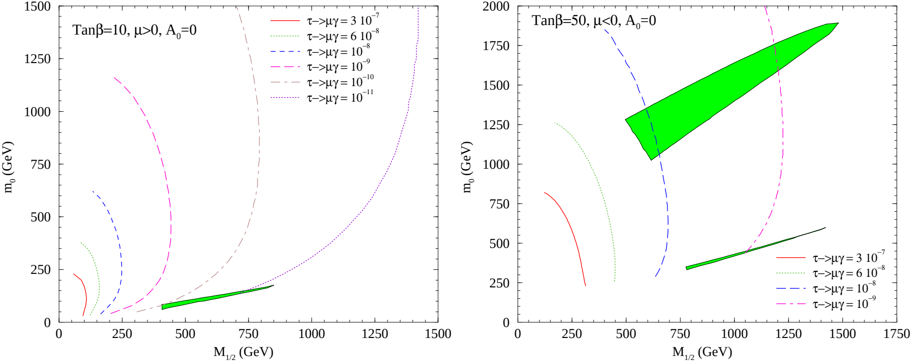
[G.Isidori, P.P., 06]

$\tau \longrightarrow \mu\gamma$

Br($\tau \to \mu\gamma$) under Dark Matter constraints



Masiero, Profumo, Vempati and Yaguna, '04

The large $\tan\beta$ scenario

- $B \to \tau\bar{\nu}$

$$BR(B \to \tau\bar{\nu}) = \left(1.79^{+0.56+0.39}_{-0.49-0.46}\right) \times 10^{-4} \; BELLE\ '06$$
$$= \left(0.88^{+0.68}_{-0.67} \pm 0.11\right) \times 10^{-4} \; BABAR\ '06$$
$$= (1.36 \pm 0.48) \times 10^{-4}$$

- $B_s^0 - \bar{B}_s^0$

$$(\Delta M_{B_s})^{\rm exp} = (17.77 \pm 0.12)\ ps^{-1} \qquad CDF\ '06$$

- $B \to X_s\gamma$

$$0.76 < \frac{(B \to X_s\gamma)^{\rm SUSY}}{(B \to X_s\gamma)^{\rm SM}} < 1.15 \qquad [90\%\ \text{C.L.}]\ (\ldots beforeNNLO).$$

- $(g-2)_\mu$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} \approx (2 \pm 1) \times 10^{-9}\,.$$

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$$0.76 < \frac{(B \to X_s\gamma)^{\rm SUSY}}{(B \to X_s\gamma)^{\rm SM}} < 1.15 \qquad [90\% \text{ C.L.}] \; (\ldots \textit{beforeNNLO}).$$

- $(g-2)_\mu$

$$\Delta a_\mu = a_\mu^{\exp} - a_\mu^{\rm SM} \approx (2 \pm 1) \times 10^{-9} \; .$$

Phenomenology of MFV at large tan β

- MFV at large tan β predicts a suppression of $B \to \tau\nu$ and ΔM_s with respect to the SM

$$\frac{(\Delta M_{B_s})}{(\Delta M_{B_s})^{SM}} \simeq 1 - \frac{3\times 10^{-2}}{\left(\frac{2}{3}+\frac{1}{3}\frac{t_\beta}{50}\right)^4}\left(\frac{\mu A_U}{m_{\tilde q}^2}\right)^2\left(\frac{t_\beta}{50}\right)^4\left(\frac{400\mathrm{GeV}}{M_H}\right)^2 .$$

$$Br(B_s \to \mu^+\mu^-) \simeq \frac{6\times 10^{-8}}{\left(\frac{2}{3}+\frac{1}{3}\frac{t_\beta}{50}\right)^4}\left(\frac{400\mathrm{GeV}}{M_H}\right)^4\left(\frac{\mu A_U}{m_{\tilde q}^2}\right)^2\left(\frac{t_\beta}{50}\right)^6$$

$$Br(B\to\ell\nu) = \frac{G_F^2}{8\pi}|V_{ub}|^2 f_B^2 m_B m_\ell^2\left(1-\frac{m_\ell^2}{m_B^2}\right)^2 \times r_B$$

$$r_B \simeq \left(1 - 0.3\frac{(t_\beta/50)^2}{\left(\frac{2}{3}+\frac{1}{3}\frac{t_\beta}{50}\right)}\left(\frac{400\mathrm{GeV}}{m_{H^\pm}}\right)^2\right)^2$$

$\frac{Br(B\to\tau\nu)}{(\Delta M_{B_d})} \sim (V_{ub}/V_{td})^2/\hat{B}_d$ much better then $|V_{ub}|^2 f_B^2$!

Phenomenology of MFV at large $\tan\beta$

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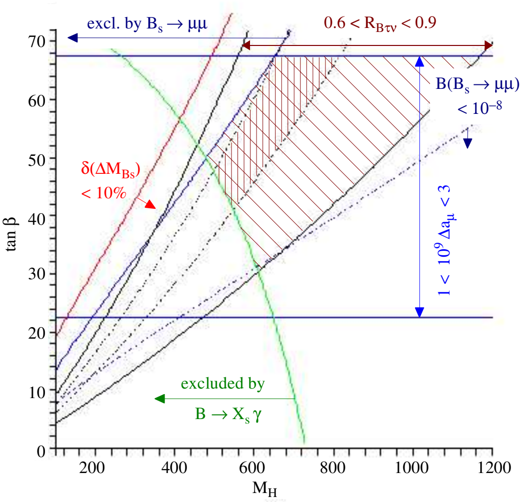
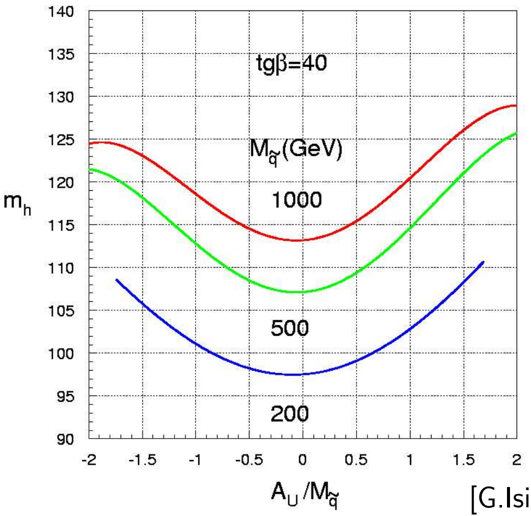
Phenomenology of MFV at large $\tan\beta$



- $A_U/M_{\tilde{q}} = 2$, $M_{\tilde{q}} = \mu = 1\text{TeV}$, $M_{\tilde{\ell}} = M_{\tilde{\chi}} = 0.5\text{TeV}$,

Phenomenology of MFV at large $\tan\beta$



[G.Isidori, P.P., '06]

Conclusions

Where to look for **N**ew **P**hysics?

- LFV can probe $\Lambda_{NP} > \mathrm{TeV}$, even beyond the LHC reach
- LU breaking @ % in $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$ is generated by the LFV
- A combined analysis of B physics observables ($B^0_{s,d} \to \mu^+\mu^-$, $B \to \ell\nu \ldots$) offers a unique chance to probe SUSY even in the elegant (but quite pessimistic) MFV framework
- All the above effects are strongly reduced (or completely disappear!) at moderate to low t_β
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Flavor Physics strongly loves SUSY @ LARGE $\tan\beta$!

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