Heavy Fermions and Flavor Physics beyond the SM

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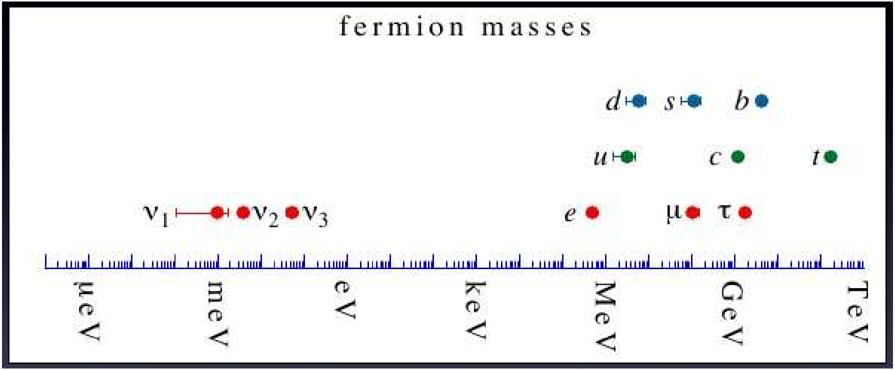
Open questions

- **The origin of flavour is still, to a large extent, a mystery. The most important open questions can be summarized as follow:**
  - **Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?**
  - **Are there extra sources of flavour symmetry breaking beside the SM Yukawa couplings which are relevant at the TeV scale?**
- **Related important questions are:**
  - **Which is the role of flavor physics in the LHC era?**
  - **Do we expect to understand the (SM and NP) flavor puzzles through the synergy and interplay of flavor physics and the LHC?**

The fermion mass puzzle



$$|\mathbf{V_{CKM}}| \sim \begin{pmatrix} 1 & \lambda_c & \lambda_c^3 \\ \lambda_c & 1 & \lambda_c^2 \\ \lambda_c^3 & \lambda_c^2 & 1 \end{pmatrix}, \quad |\mathbf{V_{PMNS}}| \simeq \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.0-0.2 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}_{3\sigma}$$

Hierarchical **Anarchic / Tribimaximal**

Flavor Physics within the SM

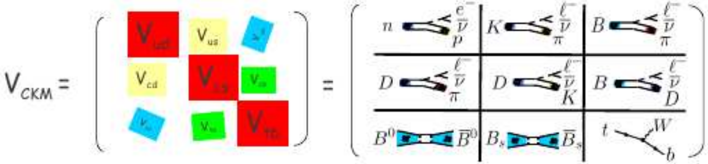
- $\mathcal{L}^{\rm SM}_{Kinetic+Gauge} + \mathcal{L}^{\rm SM}_{Higgs}$ has a large $U(3)^5$ global **flavour symmetry**

$$\mathbf{G} = \mathbf{U(3)^5} = \mathbf{U(3)_u} \otimes \mathbf{U(3)_d} \otimes \mathbf{U(3)_Q} \otimes \mathbf{U(3)_e} \otimes \mathbf{U(3)_L}$$

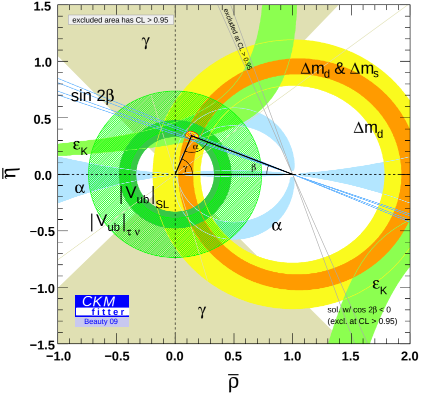
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R \phi + \bar{Q}_L \mathbf{Y_U} U_R \tilde{\phi} + \bar{L}_L \mathbf{Y_L} E_R \phi + h.c$ break G down to

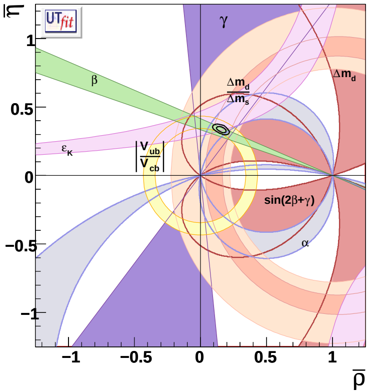
$$\mathbf{G} \rightarrow \mathbf{U(1)_B} \times \mathbf{U(1)_e} \times \mathbf{U(1)_\mu} \times \mathbf{U(1)_\tau}$$

- **CKM matrix**: $Y_U = V_{CKM} \times {\rm diag}(y_u, y_c, y_t)$ for $\mathbf{Y_D} = {\rm diag}(y_d, y_s, y_b)$



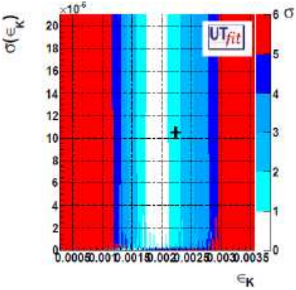
Messages from the B-factories





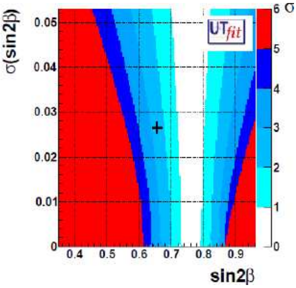
“Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism” (Nir)

UT tensions

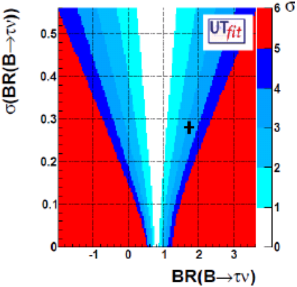


1. $\sim$ 6% reduction of $\epsilon_K^{\rm SM}$
   [Buras & Guadagnoli; BG & Isidori]
2. smaller $\hat{B}_K$ from unquenced analyses
   [Antonio et al. '08; Aubin et al. '10]
3. fit vs. exp. $\approx -1.7\sigma$

NEW: $\epsilon_K^{\rm SM}$ @ NNLO QCD: $\sim +3\%$ [Brod & Gorbahn, '10]



1. fit vs. exp. $\approx +2.6\sigma$



1. $B(B\to\ell\nu) \sim f_B^2|V_{ub}|^2$
2. $B(B\to\ell\nu)/\Delta M_d \sim (\sin\beta/\sin\gamma)^2/\hat{B}_{B_d}$
3. fit vs. exp. $\approx -3.2\sigma$

Similar conclusions also by Lenz & Nierste + CKMfitter collaboration ('10)

The NP flavor puzzle

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d=6} \frac{c_{ij}^{(6)}}{\Lambda_{NP}^2}\, O_{ij}^{(6)}$$

[Isidori, Nir, Perez '10]

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar s_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar s_R d_L)(\bar s_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar c_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar c_R u_L)(\bar c_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar b_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar b_R d_L)(\bar b_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar b_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar b_R s_L)(\bar b_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

$\Downarrow$

"Generic" flavor violating sources at the TeV scale are excluded

MFV & the NP flavor puzzle

- SM without Yukawa interactions: $U(3)^5$ global **flavour symmetry**

$$\mathbf{U(3)_u \otimes U(3)_d \otimes U(3)_Q \otimes U(3)_e \otimes U(3)_L}$$

- Yukawa interactions break this symmetry
- Proposal for any New Physics model:

Yukawa structures as the only sources of flavour violation

$$\Downarrow$$

Minimal Flavour Violation [D'Ambrosio et al. '02]

Notice that MFV allows new "flavour blind"CPV phases!

[Kagan et al. '09] (model-independent)
[Ellis et al. '07] (SUSY)
[Colangelo et al., '08], [Smith et al. '09] (SUSY)
[Altmannshofer et al., '08,'09], [P.P & Straub, '09] (SUSY)
[Buras et al., '10,'10] (2HDM)

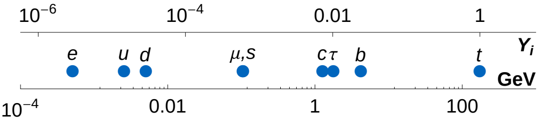
$$(c^{\Delta F=1}_{\rm MFV})_{ij} \sim V^{\star}_{ti} V_{tj}\,, \qquad (c^{\Delta F=2}_{\rm MFV})_{ij} \sim (V^{\star}_{ti} V_{tj})^2$$

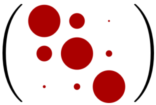
$\Delta F = 1, 2$ MFV operators	Λ(TeV)	Observables
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H^\dagger_D \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (\overline{E}_R \gamma_\mu E_R)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

Observable	Experiment	MFV prediction	SM prediction
$\mathcal{A}_{\rm CP}(B_s \to \psi\phi)$	[0.10, 1.44] @ 95% CL	0.04(5)	0.04(2)
$\mathcal{A}_{\rm CP}(B \to X_s\gamma)$	$< 6\%$ @ 95% CL	< 0.02	< 0.01
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$< 1.8 \times 10^{-8}$	$< 1.2 \times 10^{-9}$	$1.3(3) \times 10^{-10}$
$\mathcal{B}(B \to X_s\tau^+\tau^-)$	–	$< 5 \times 10^{-7}$	$1.6(5) \times 10^{-7}$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ @ 90% CL	$< 2.9 \times 10^{-10}$	$2.9(5) \times 10^{-11}$

[D'Ambrosio et al. '02; Hurth et al. '08, Isidori, Nir & Perez '10]

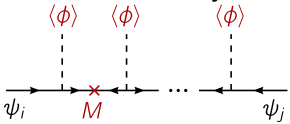
SM vs. NP flavor puzzle



$V_{\rm CKM} \sim$ 

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

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



- **Flavor Models flavor protection**

[Lalak, Pokorski & Ross '10]

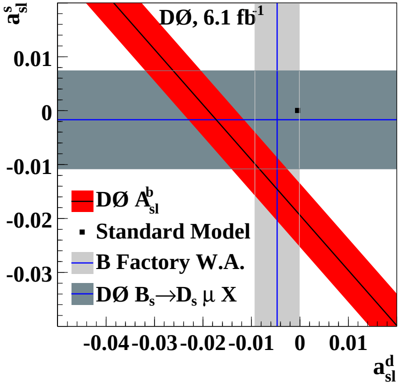
Operator	$U(1)$	$U(1)^2$	$SU(3)$	MFV
$(\overline{Q}_L X^Q_{LL} Q_L)_{12}$	λ	λ^5	λ^3	λ^5
$(\overline{D}_R X^D_{RR} D_R)_{12}$	λ	λ^{11}	λ^3	$(y_d y_s) \times \lambda^5$
$(\overline{Q}_L X^D_{LR} D_R)_{12}$	λ^4	λ^9	λ^3	$y_s \times \lambda^5$

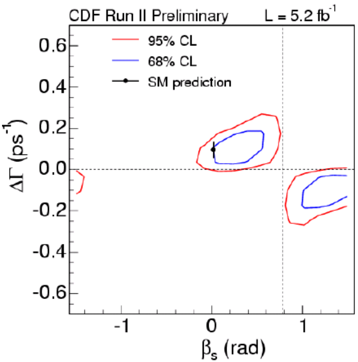
NP search strategies

- **High-energy frontier: A unique effort to determine the NP scale**
- **High-intensity frontier (flavor physics): A collective effort to determine the flavor structure of NP**

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 $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$





$$A^q_{\rm SL} \equiv \frac{\Gamma(\bar{B}_q \to l^+ X) - \Gamma(B_q \to l^- X)}{\Gamma(\bar{B}_q \to l^+ X) + \Gamma(B_q \to l^- X)}\,,$$

$$S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s})$$

New Physics in the B_s mixing phase?

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($\tau \to \ell\ell\ell$)	$2.3\text{–}8.2 \cdot 10^{-10}$	$1.2\text{–}4.0 \cdot 10^{-9}$

[Lusiani @ HQL10]

The SUSY flavour and CP problems

The soft-sector contains a huge number of FV and/or CPV parameters: natural $O(1)$ values for these parameters are excluded by the exp. data

Flavor problem: solutions

1. **Decoupling**: $m_{SUSY} \gg$ TeV, the hierarchy problem is (partly) reintroduced
2. **Degeneracy**: sfermion masses nearly degenerate, e.g. gauge mediation, flavour models, MFV...
3. **Alignment**: quark and squark mass matrices aligned [Nir & Seiberg '93]

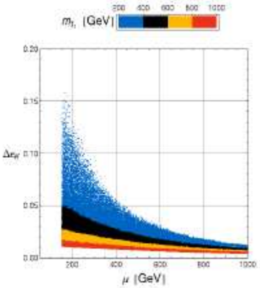
CP problem: solutions

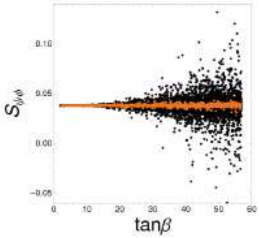
1. Degeneracy & Alignment do not solve the CP problem as flavor blind phases are allowed
2. **CPV** from **flavor effects** $\Rightarrow$ EDMs suppressed by small mixing angles
3. Hp in flavor models: CP spontaneously broken in the flavor sector by flavon VEVs [Nir & Rattazzi '96]
4. Applying the same idea to MFV: CPV only from MFV-compatible terms breaking the flavour blindness [P.P & Straub, '09]

MSSM with MFV and “flavour blind” phases

① Kaon mixing

- The mixing amplitude M_{12}^K has no sensitivity to the new flavor blind phases
- Still, $\epsilon_K \propto \text{Im}(M_{12}^K)$ can get a positive NP contribution up to 15%
- But only for a very light SUSY spectrum: $\mu, m_{\tilde{t}_1} \simeq 200\text{GeV}$



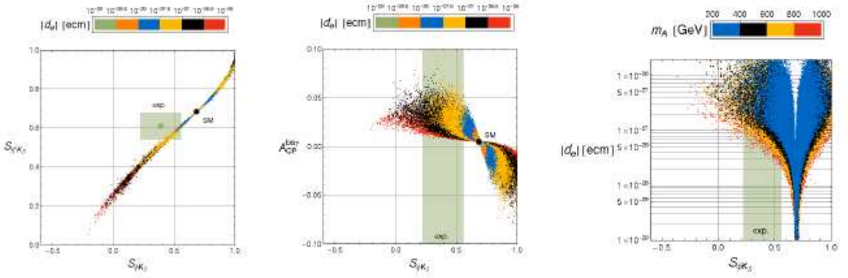


② B_d and B_s mixing

- Leading NP contributions to $M_{12}^{d,s}$ are insensitive to the new phases of a FBMSSM. (at least for moderate $\tan\beta$ ...)
- For large $\tan\beta$, the constraint from $b \to s\gamma$ does not allow for sizeable effects
- $S_{\psi K_S}$ and $S_{\psi\phi}$ are SM like ($S_{\psi\phi} \simeq 0.03 - 0.05$)

[Altmannshofer,Buras & P.P., ’08]

MSSM with MFV and “flavour blind” phases



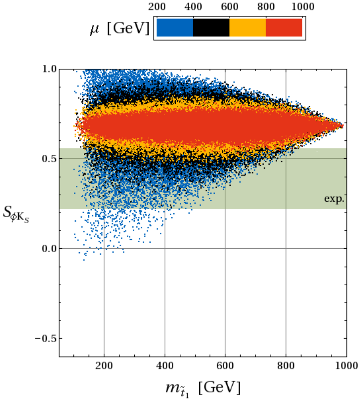
- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- lower bounds on the electron and neutron EDMs at the level of $d_{e,n} \gtrsim 10^{-28}\,ecm$
- large and correlated effects in the CP asymmetries in $B \to K^* \mu^+ \mu^-$ (WA, Ball, Bharucha, Buras, Straub, Wick)

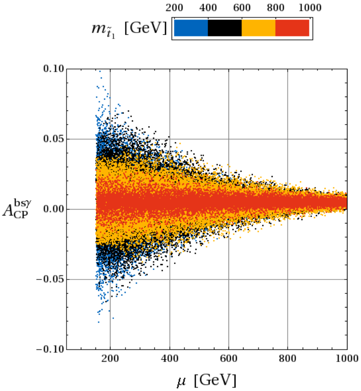
- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

[Altmannshofer,Buras & P.P., ’08]

Implications for direct searches of SUSY particles





- $S_{\phi K_S} \simeq 0.4$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 700$GeV
- $A_{CP}^{bs\gamma} \gtrsim 2\%$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 800$GeV

[Altmannshofer,Buras & P.P., '08]

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) with $\Lambda_{NP} \equiv M_R$

$$Br(\mu \to e\gamma) \sim \frac{m_\nu^{D\,4}}{M_R^4} \leq 10^{-50}$$

  - $\tilde{W}$ and $\tilde{\nu}$ in the MSSM framework (SUPER-GIM) with $\Lambda_{NP} \equiv \tilde{m}$

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

$$\Downarrow$$

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

LFV in SUSY see-saw

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

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

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

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

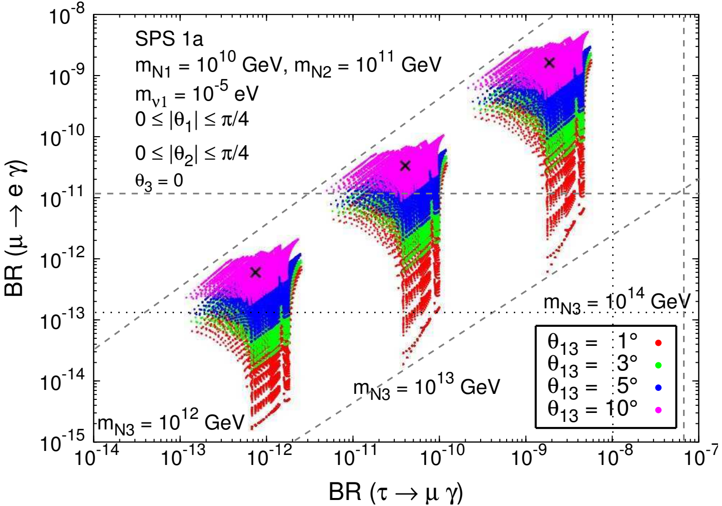
$$\delta_{LL}^{ij} \approx -\frac{3}{8\pi^2}(h^\nu h^{\nu\dagger})_{ij} \ln\frac{M_X}{M_R}$$ [Borzumati & Masiero, '86]

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

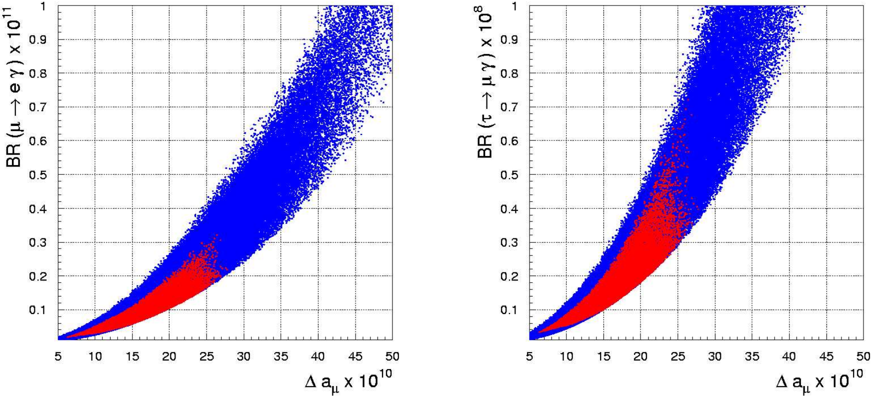
$$h^\nu = U^\star_{\mathrm{MNS}}\, \mathcal{D}_{\sqrt{\mathcal{M}_\nu}}\, R^T\, \mathcal{D}_{\sqrt{M_R}}\, \frac{1}{v_2}$$ [Casas & Ibarra, '01]

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

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



[Herrero et al., '06]



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

[Isidori, Mescia, Paradisi & Temes, 07]

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

RG induced LFV interactions in SUSY GUTs

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

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

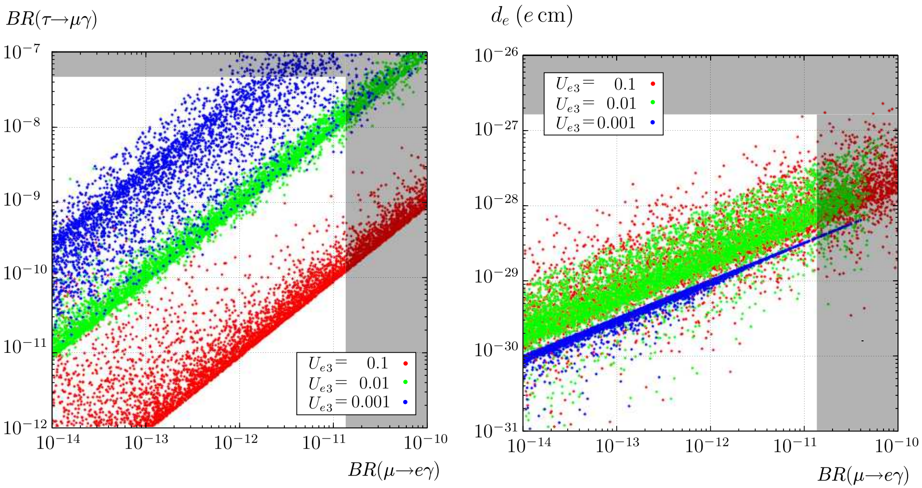
- **SUSY SU(5)+RN** [Yanagida et al., '95]

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

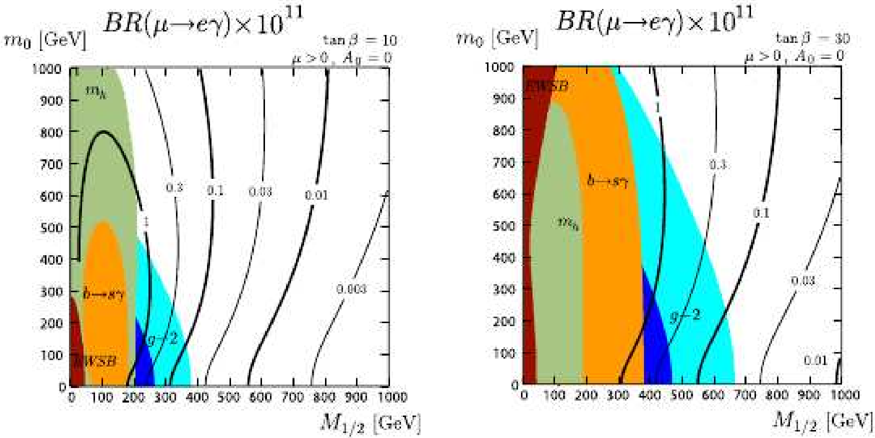
- **SUSY SU(5)+RN** [Moroi, '00] **&** **SO(10)** [Chang, Masiero & Murayama, '02]

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

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



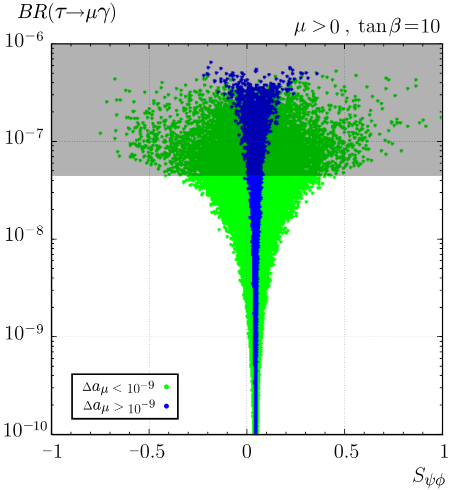
hierarchical ν_L and N_R [Hisano, Nagai, Paradisi & Shimizu, '09]

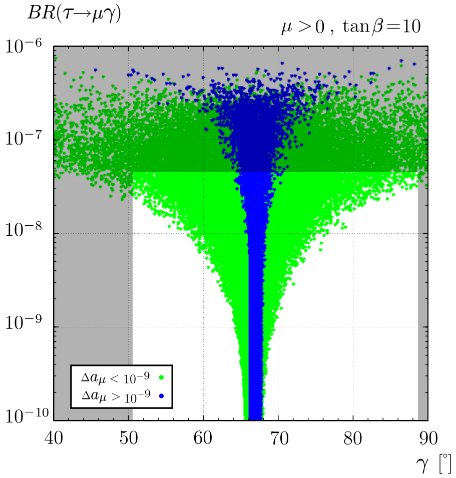


hierarchical ν_L **and** N_R**,** $U_{e3} = 0.1$**,** $M_{N_3} = 10^{-13}\,\mathrm{GeV}$

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

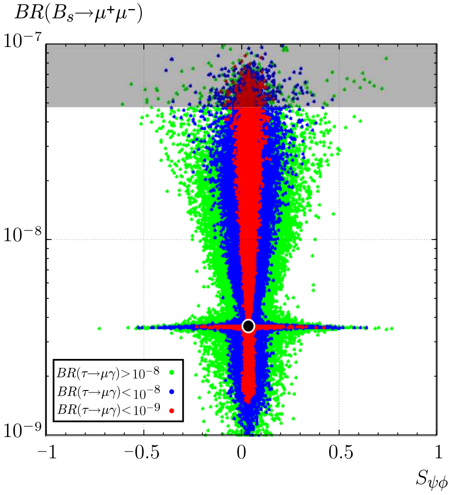
Quark-Lepton correlations in SUSY SU(5)+RN

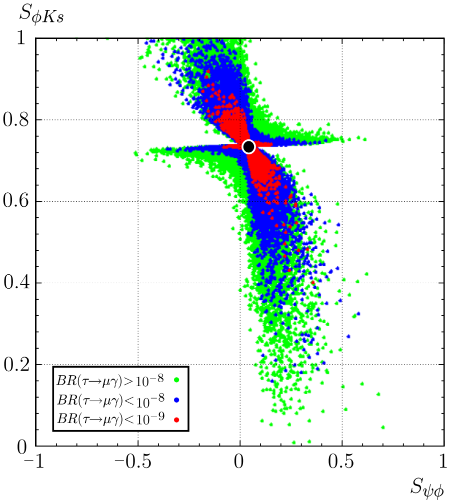




hierarchical ν_L and N_R [Buras, Nagai & Paradisi, '10]

Quark-Lepton correlations in SUSY SU(5)+RN





hierarchical ν_L and N_R [Buras, Nagai & Paradisi, '10]

Abelian vs. Non-abelian flavor models

- Non-abelian models predict $\approx$ degenerate 1st & 2nd sfermion masses
  - Suppressed contributions to $1 \leftrightarrow 2$ transitions
  - Potentially large contributions to $2 \leftrightarrow 3$ transitions
- In abelian models, sfermions of different generations need not be degenerate
  - A single $U(1)$ & $O(1)$ 1-2 mass splitting lead to $(\delta^{LL}_{d,u})_{12} \sim \mathcal{O}(\lambda)$
  - $U(1) \times U(1)$ allows *alignement* in the down sector $(\delta^{LL}_{d})_{12} \approx 0 \Rightarrow (\delta^{LL}_{u})_{12} \sim \mathcal{O}(\lambda)$
  - Large effects in D^0-$\bar{D}^0$ mixing

Chirality structure of flavour violating terms

- Different flavour symmetries lead to different patterns of flavour violation
- Mass insertions: $M^2_{\tilde{d}} = \mathrm{diag}(\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta^{LL}_d & \delta^{LR}_d \\ \delta^{RL}_d & \delta^{RR}_d \end{pmatrix}$
- δ^{LL}, δ^{RR}, δ^{LR} fixed by the flavour symmetry up to $O(1)$ factors

Representative flavour models

Representative (non-) abelian flavour models (not just 4 examples...!)

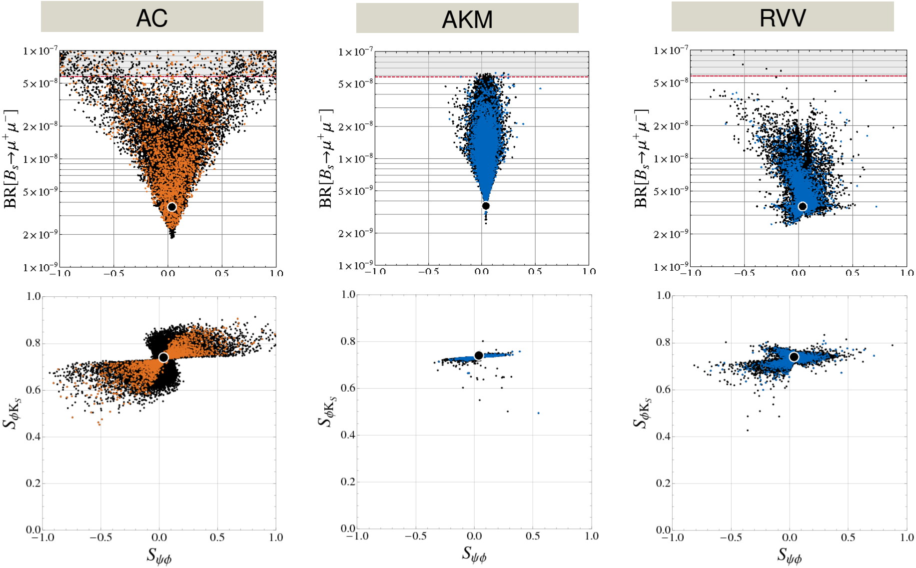
AC model $U(1)$ [Agashe, Carone]	AKM model $SU(3)$ [Antusch, King, Malinsky]	RVV model $SU(3)$ [Ross, Velasco-S., Vives]	δLL model $(S_3)^3$ [e.g. Hall, Murayama]
Large, $O(1)$ RR mass insertions	Only CKM-like RR mass insertions	CKM-like LL & RR mass insertions	Only CKM-like LL mass insertions

$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & \lambda^2 \\ 0 & \lambda^2 & \cdot \end{pmatrix} \quad \delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix} \quad \delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix} \quad \delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^5 & \lambda^3 \\ \lambda^5 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix}$$

$$\delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 1 \\ 0 & 1 & \cdot \end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^3 \\ \lambda^3 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix}$$

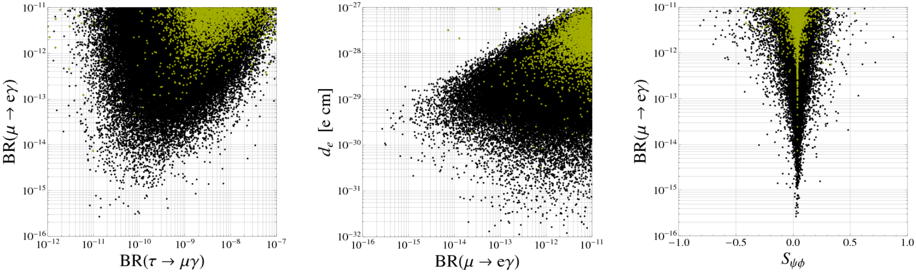
Hp: CP is spontaneously broken in the flavor sector [Nir & Rattazzi '96]

$b \to s$ transitions & SUSY flavor models [Altmannshofer et al., '09]



- Orange (Blue) points: UT tension solved through contribution to $\Delta M_d/\Delta M_s$ (ϵ_K)
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$

Phenomenology of a SUSY SU(3) flavor models

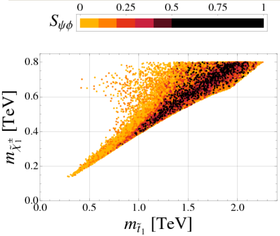


- Yellow points satisfy $\Delta a_\mu > 10^{-9}$
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$

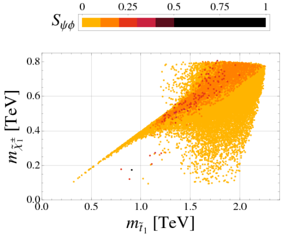
[Altmannshofer, Buras, Gori, Paradisi and Straub, '09]

LHC vs. flavour

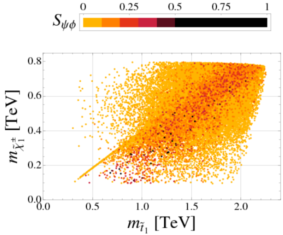
AC



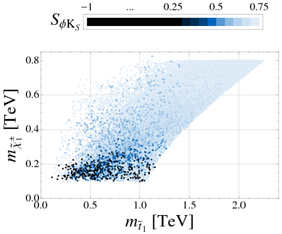
AKM



RVV



δLL



- Large effects in $S_{\psi\phi}$ even possible for spectra beyond the LHC reach in the models with RH currents
- Large effects in $S_{\phi K_S}$ not possible for spectra beyond the LHC reach in the δLL model

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

CPV in $\mathbf{D^0} - \overline{\mathbf{D}}^{\mathbf{0}} \sim \mathrm{Im}((V_{cb}V_{ub})/(V_{cs}V_{us})) \sim \mathbf{10^{-3}}$ in the **SM**

- $\langle D^0|\mathcal{H}_{\rm eff}|\bar{D}^0\rangle = M_{12} - \frac{i}{2}\Gamma_{12}, \qquad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
- $\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}, \qquad \phi = \mathrm{Arg}(q/p)$
- $x = \frac{\Delta M_D}{\Gamma} = 2\tau \mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$
- $y = \frac{\Delta\Gamma}{2\Gamma} = -2\tau \mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$

$$\mathbf{S_f} = 2\Delta Y_f = \frac{1}{\Gamma_D}\left(\hat{\Gamma}_{\bar{D}^0\to f} - \hat{\Gamma}_{D^0\to f}\right)$$

$$\eta_f^{\rm CP} S_f = x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi - y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi$$

$$\mathbf{a}_{\rm SL} = \frac{\Gamma(D^0 \to K^+\ell^-\nu) - \Gamma(\bar{D}^0 \to K^-\ell^+\nu)}{\Gamma(D^0 \to K^+\ell^-\nu) + \Gamma(\bar{D}^0 \to K^-\ell^+\nu)} = \frac{|q|^4 - |p|^4}{|q|^4 + |p|^4}$$

[Nir et al.,Kagan et al., Petrov et al., Bigi et al., Buras et al., ...]

CPV in D-physics vs. neutron EDM in SUSY [Altmannshofer, Buras, & P.P, '10]

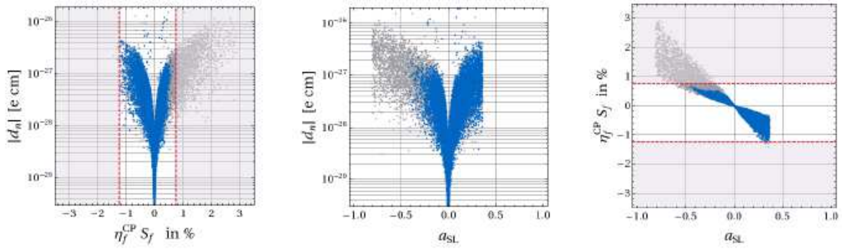


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

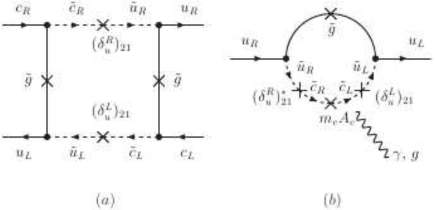


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

“DNA-Flavour Test”

	SSU(5)	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]

Conclusions

The origin of flavour is still, to a large extent, a mystery. The most important open questions can be summarized as follow:

- **Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?**

- **Are there extra sources of flavour symmetry breaking beside the SM Yukawa couplings which are relevant at the TeV scale?**

The synergy and interplay of flavor physics and the LHC will tell us a lot...