Fenomenologia della Fisica dei Sapori Pesanti

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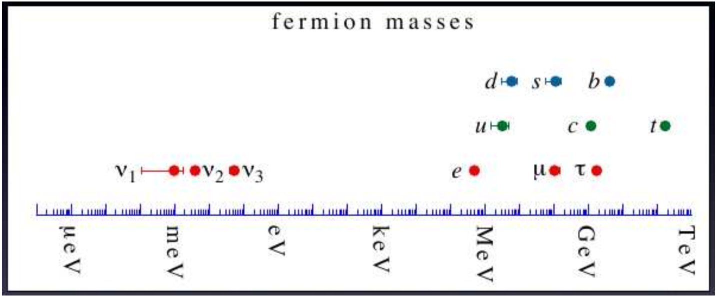
Plan of Talk

1. Open questions
2. The SM flavour puzzle
3. The New Physics flavour & CP puzzles
4. “Flavour-test” of NP models: the case of SUSY
    - SUSY MFV scenarios
    - SUSY GUT scenarios
    - SUSY flavour models
5. LHC vs. Flavour
6. Conclusions

Open questions

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

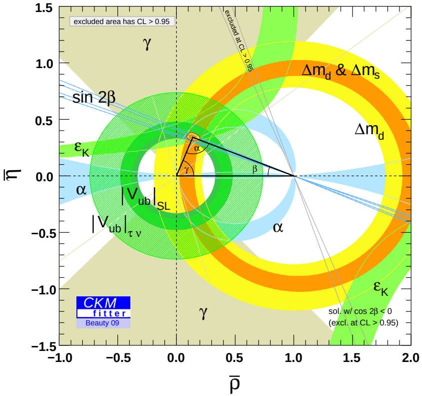
- **Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?**

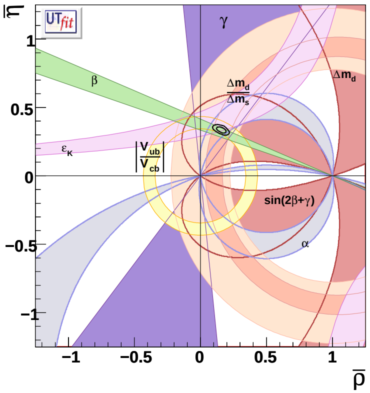


$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda_c & \lambda_c^3 \\ \lambda_c & 1 & \lambda_c^2 \\ \lambda_c^3 & \lambda_c^2 & 1 \end{pmatrix}, \quad |V_{PMNS}| \simeq \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.0-0.2 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}_{3\sigma}$$

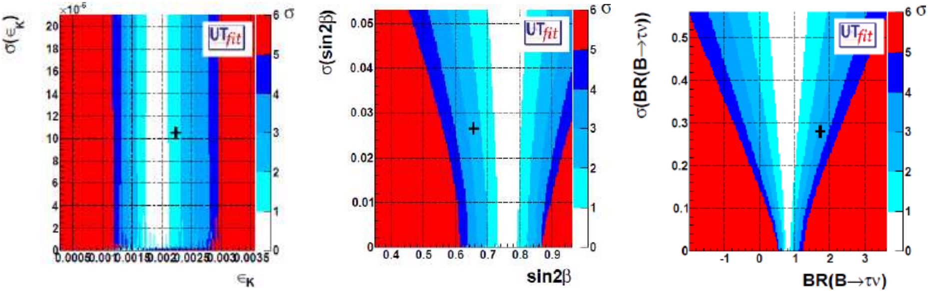
Hierarchical **Anarchic / Tribimaximal**

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





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

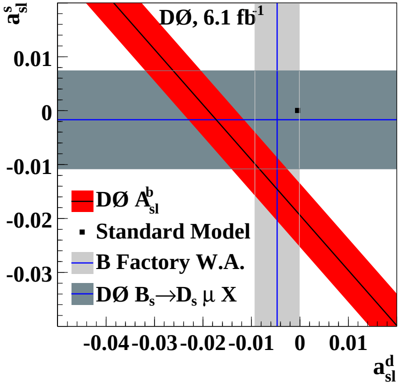


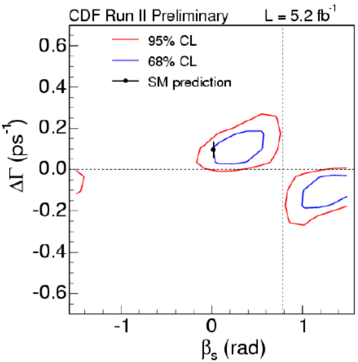
fit vs. exp. $\approx -1.7\sigma$ **fit vs. exp.** $\approx +2.6\sigma$ **fit vs. exp.** $\approx -3.2\sigma$

see Cecilia's talk

1. These "UT tension" are interesting but not significant yet.
2. To monitor the impact of BSM scenarios on the UT analyses.
3. To monitor the implications of possible "UT tension" solutions in BSM scenarios.

CPV in B_s mixing





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

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

New Physics in the B_s mixing phase?

The NP flavor problem

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

[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

- 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)

MFV & the NP flavor problem

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

$\Delta F = 1, 2$ 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}
$H_D^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	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	$< 2.9 \times 10^{-10}$	$2.9(5) \times 10^{-11}$

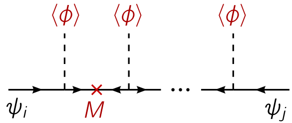
[D'Ambrosio et al. '02; Hurth et al. '08, Isidori, Nir & Perez '10]

SM vs. NP flavor problems

1. MFV is not a theory of flavour and it has not been probed yet.
2. Can the SM and NP flavour problems have a common explanation?

- **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 protection from flavor models:** [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	$y_s \times \lambda^5$

- Is the this flavor protection enough?
- Is it possible to disentangle among different flavour models by means of their predicted pattern of deviation w.r.t. the SM predictions in flavour physics?

- **Why CP violation? Motivation:**
  - Baryogenesis requires extra sources of CPV
  - The QCD $\overline{\theta}$-term $\mathcal{L}_{CP} = \overline{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$ is a CPV source beyond the CKM
  - Most UV completion of the SM, e.g. the MSSM, have many CPV sources
  - However, TeV scale NP with $\mathcal{O}(1)$ CPV phases generally leads to EDMs many orders of magnitude above the current limits $\Rightarrow$ the New Physics CP problem.

- **How to solve the New Physics CP problem?**
  - Decoupling some NP particles in the loop generating the EDMs (e.g. hierarchical sfermions, split SUSY, 2HDM limit...)
  - Generating CPV phases radiatively $\phi^f_{CP} \sim \alpha_w/4\pi \sim 10^{-3}$
  - Generating CPV phases via small flavour mixing angles $\phi^f_{CP} \sim \delta_{fj}\delta_{fj}$ with $f = e, u, d$: maybe the absence of NP signals in FCNC processes and EDMs have a common origin?

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 $(g-2)_\mu$: $a_\mu^{exp} - a_\mu^{SM} \approx (3 \pm 1) \times 10^{-9}$, a discrepancy at 3σ!
  - LU in $R_M^{e/\mu} = \Gamma(M \to e\nu)/\Gamma(M \to \mu\nu)$ with $M = \pi, K$

Experimental status

Process	Present	Future	Experiment
BR($\mu \to e\gamma$)	1.2×10^{-11}	$\mathcal{O}(10^{-13})$	**MEG, PSI**
BR($\mu \to e\,e\,e$)	1.1×10^{-12}	$\mathcal{O}(10^{-14})$	?
BR($\mu + \mathrm{Ti} \to e + \mathrm{Ti}$)	1.1×10^{-12}	$\mathcal{O}(10^{-18})$	J-PARC
BR($\tau \to e\gamma$)	1.1×10^{-7}	$\mathcal{O}(10^{-8})$	SuperB
BR($\tau \to e\,e\,e$)	2.7×10^{-7}	$\mathcal{O}(10^{-9})$	SuperB
BR($\tau \to e\,\mu\,\mu$)	$2. \times 10^{-7}$	$\mathcal{O}(10^{-9})$	SuperB
BR($\tau \to \mu\gamma$)	6.8×10^{-8}	$\mathcal{O}(10^{-8})$	SuperB
BR($\tau \to \mu\,\mu\,\mu$)	2×10^{-7}	$\mathcal{O}(10^{-9})$	LHCb
BR($\tau \to \mu\,e\,e$)	2.4×10^{-7}	$\mathcal{O}(10^{-9})$	SuperB
$\lvert d_{Tl}\rvert$ [e cm]	$< 9.0 \times 10^{-25}$	$\approx 10^{-29}$	Pospelov & Ritz, 2005
$\lvert d_{Hg}\rvert$ [e cm]	$< 3.1 \times 10^{-29}$	?	?
$\lvert d_n\rvert$ [e cm]	$< 2.9 \times 10^{-26}$	$\approx 10^{-28}$	PSI, Institute Laue-Langevin

Experimental status

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$S_{B_s\to\psi\phi}$	**0.036**	≤ 0.01	$0.81^{+0.12}_{-0.32}$	0.01	**LHCb**
$S_{B_d\to\phi K}$	$\sin(2\beta)$	≤ 0.05	0.44 ± 0.18	0.1	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8\pm 3.4)10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6\pm 8.5)10^{-3}$	10^{-3}	LHCb
$A_{CP}(b\to s\gamma)$	< 0.01	< 0.01	-0.012 ± 0.028	0.005	Super-B
$\mathcal{B}(B\to\tau\nu)$	1×10^{-4}	$20\%\to 5\%$	$(1.73\pm 0.35)10^{-4}$	5%	Super-B
$\mathcal{B}(B\to\mu\nu)$	4×10^{-7}	$20\%\to 5\%$	$< 1.3\times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s\to\mu^+\mu^-)$	3×10^{-9}	$20\%\to 5\%$	$< 5\times 10^{-8}$	10%	**LHCb**
$\mathcal{B}(B_d\to\mu^+\mu^-)$	1×10^{-10}	$20\%\to 5\%$	$< 1.5\times 10^{-8}$	**[?]**	**LHCb**
$B\to K\nu\bar\nu$	4×10^{-6}	$20\%\to 10\%$	$< 1.4\times 10^{-5}$	20%	Super-B
$\lvert q/p\rvert_{D-\rm mixing}$	1	$< 10^{-3}$	$(0.86^{+0.18}_{-0.15})$	0.03	Super-B
ϕ_D	0	$< 10^{-3}$	$-(9.6^{+8.3}_{-9.5})^\circ$	2°	Super-B
$\mathcal{B}(K^+\to\pi^+\nu\bar\nu)$	8.5×10^{-11}	8%	$(1.73^{+1.15}_{-1.05})10^{-10}$	10%	K factory
$\mathcal{B}(K_L\to\pi^0\nu\bar\nu)$	2.6×10^{-11}	10%	$< 2.6\times 10^{-8}$	[?]	K factory

[Altmannshofer, Buras, Gori, Paradisi, and Straub, '09; Isidori, Nir, and Perez, '10]

Superstars of 2011-2013 in flavour physics: $\mu\to e\gamma$, $B_s\to\psi\phi$, $B_{s,d}\to\mu^+\mu^-$

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

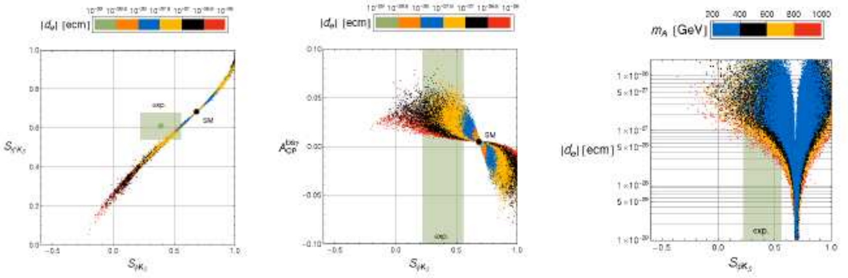
Flavor problem: solutions

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



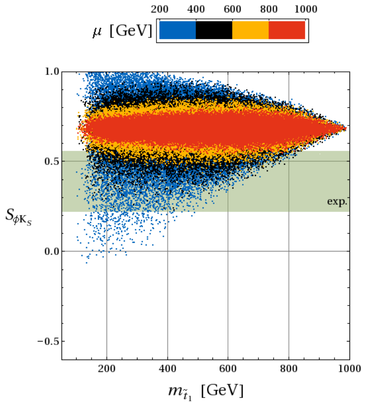
- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- lower bounds on the electron and neutron 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)

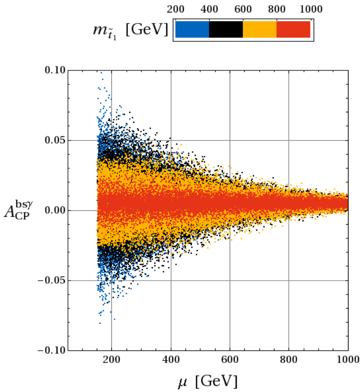
- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

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

[Altmannshofer,Buras & P.P., ’08]

MSSM with MFV and “flavour blind” phases

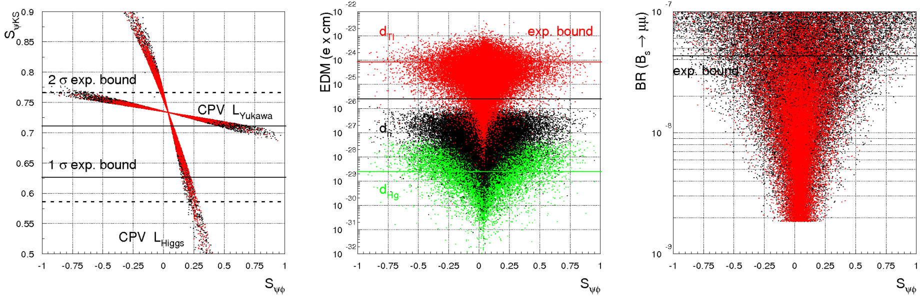




- $S_{\phi K_S} \simeq 0.4$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 700$GeV
- $A_{CP}^{bs\gamma} \gtrsim 2\%$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 800$GeV

[Altmannshofer,Buras& P.P., ’08]

2HDM with MFV and “flavour blind” phases



- Main messages:
  - The **“UT tension”** is “solved” by a **NP phase in B_d-mixing** ($S_{\psi K_S}$) implying a **large NP phase in B_s-mixing** ($S_{\psi\phi}$), in agreement with present data (ϵ_K remains SM-like).
  - **Non-standard** CPV effects in B_s mixing $S_{\psi\phi}$ imply **lower bounds for the EDMs** in the experimental reach as well as **non-standard** values for $\mathrm{BR}(B_{s,d} \to \mu^+\mu^-)$.
  - **An extended Higgs sector below the TeV** scale is required for such a pattern of deviation from the SM $\Rightarrow$ the **interplay** of **LHC** (M_H), **LHCb** ($S_{\psi\phi}$, $B_{s,d} \to \mu^+\mu^-$), and **EDMs experiments** (d_n, d_{Tl}, d_{Hg}) will probe or falsify the scenario.

[Buras, Isidori & P.P., ’10]

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)

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

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

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

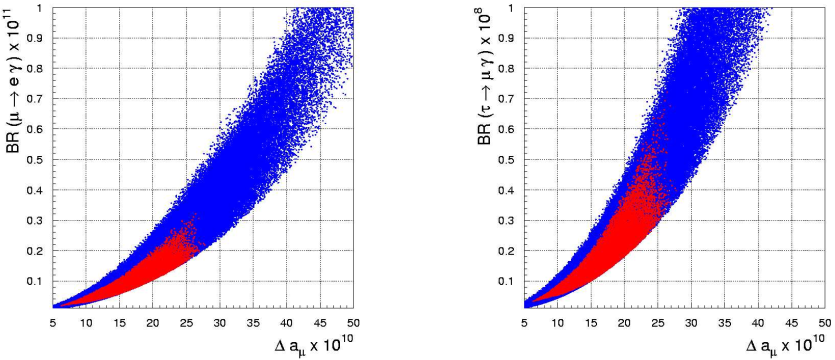
- If $h^e = h^e_{ij}\delta_{ij}$ and $M_R = (M_R)_{ij}\delta_{ij} \Rightarrow h^\nu \neq h^\nu_{ij}\delta_{ij}$ in general. Flavour universal SUSY breaking and yet large LFV from SUSY see-saw

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

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

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

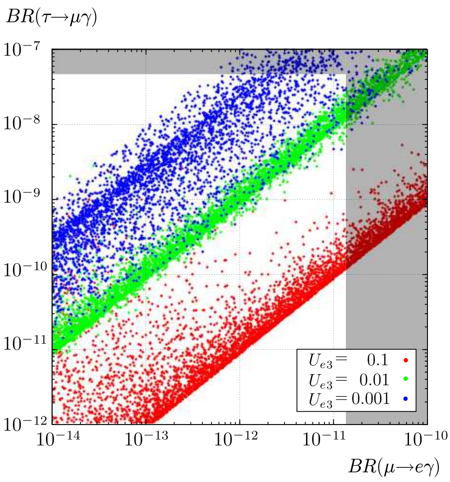
$R^\dagger R = 1 \Rightarrow$ **three angles** and **three phases**

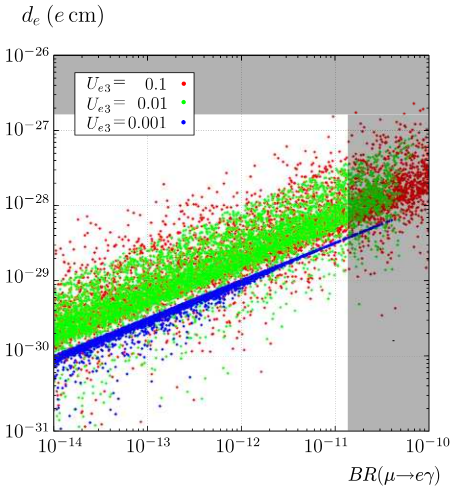


- Main messages: [Isidori, Mescia, P.P. & Temes, 07]
  - Observable LFV effects even for CKM-like mixing angles $\delta_{LL}^{12(23)} = 10^{-4}(10^{-2})$.
  - $BR(\ell_i \to \ell_j\gamma)$ and the SUSY effects to $(g-2)_\mu$ are strongly correlated

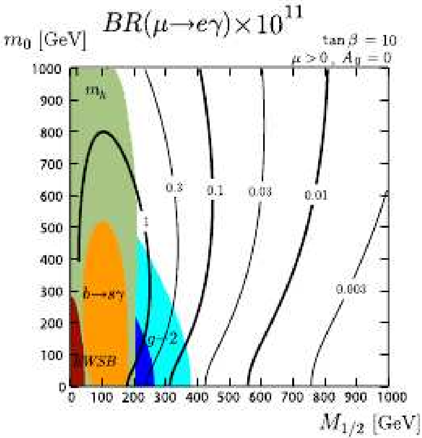
$$BR(\ell_i \to \ell_j\gamma) \approx \left[\frac{\Delta a_\mu}{3\times 10^{-9}}\right]^2 \times \left\{ \begin{array}{ll} 10^{-12} \left|\frac{\delta_{LL}^{12}}{10^{-4}}\right|^2 & [\mu \to e] \\ 10^{-9} \left|\frac{\delta_{LL}^{23}}{10^{-2}}\right|^2 & [\tau \to \mu] \end{array} \right\}$$

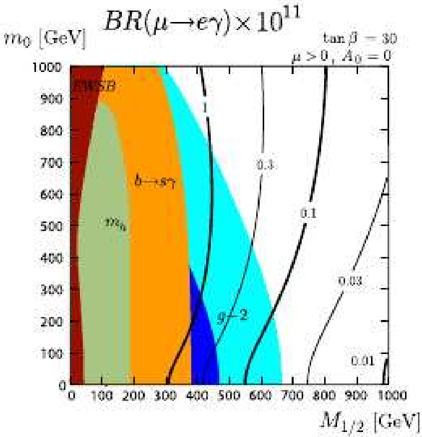
$\mu \to e\gamma$ and $\tau \to \mu\gamma$ in SUSY SU(5)+RN





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





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

[Hisano, Nagai, P.P. & Shimizu, '09]

Pattern of LFV in NP models

- **Ratios like** $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma)$ **probe the NP flavor structure**
- **Ratios like** $Br(\mu \to e\gamma)/Br(\mu \to eee)$ **probe the NP operator at work**

ratio	LHT	MSSM	SM4
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{Br(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$10^{-12}\ldots 26$
$\frac{Br(\mu\to eee)}{Br(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$0.07\ldots 2.2$
$\frac{Br(\tau\to\mu\mu\mu)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{Br(\tau\to e\mu\mu)}{Br(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.03\ldots 1.3$
$\frac{Br(\tau\to\mu ee)}{Br(\tau\to\mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$0.04\ldots 1.4$
$\frac{Br(\tau\to eee)}{Br(\tau\to e\mu\mu)}$	$0.8\ldots 2$	~ 5	$1.5\ldots 2.3$
$\frac{Br(\tau\to\mu\mu\mu)}{Br(\tau\to\mu ee)}$	$0.7\ldots 1.6$	~ 0.2	$1.4\ldots 1.7$

[Buras et al., ’07, ’10]

RG induced Quark & Lepton FV interactions in SUSY GUTs

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

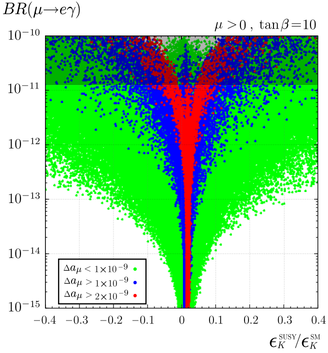
$$(\delta^{\tilde{q}}_{LL})_{ij} \sim {h^u h^{u\dagger}}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \longrightarrow (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

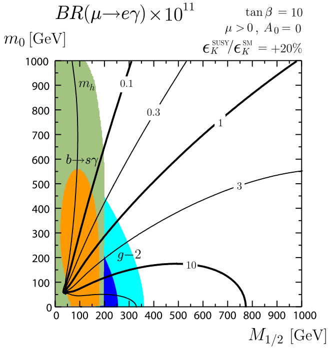
- **SUSY SU(5)+RN** [Yanagida et al., '95]

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

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

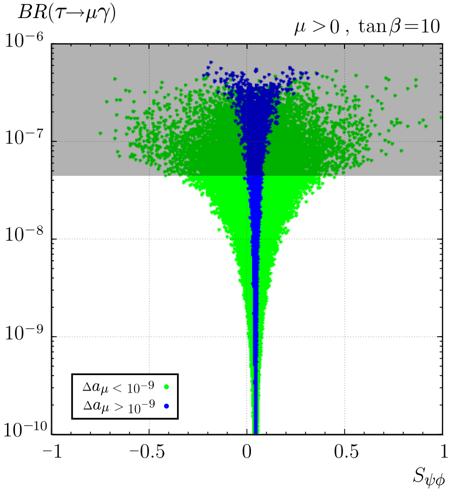
$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde{\ell}}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde{q}}_{RR})_{23} \sim 1$$

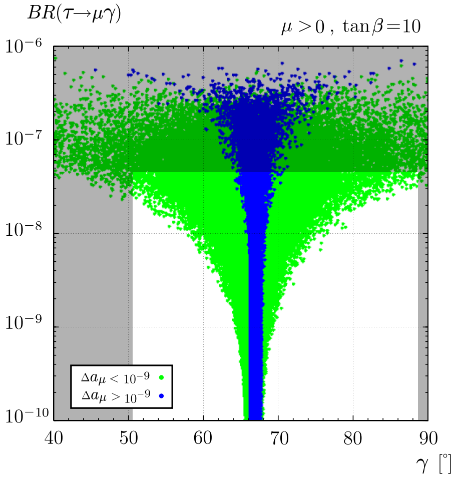




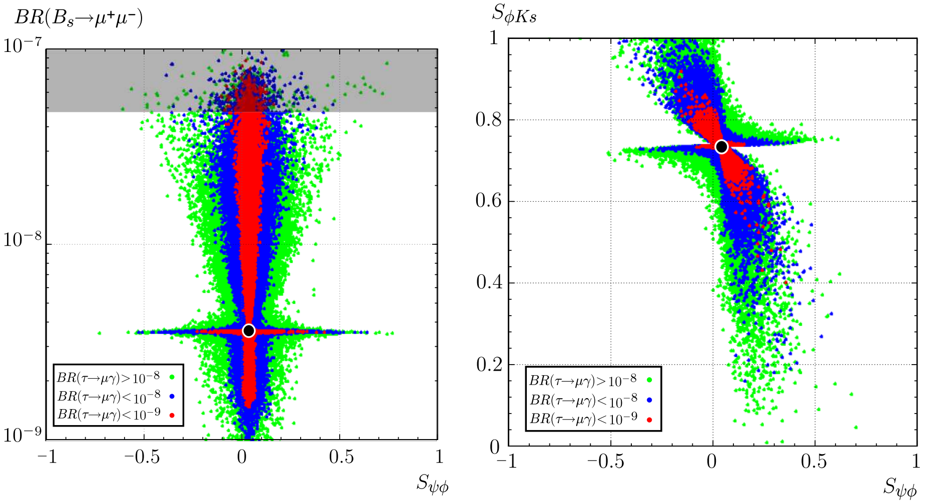
- Main messages:
  - Parameter scan: $(m_0, M_{1/2}) < 1\,\mathrm{TeV}$, $|A_0| < 3m_0$, $\tan\beta = 10$ and $\mu > 0$. Hierarchical ν_L & N_R, $10^{11} \le M_{\nu_3}(\mathrm{GeV}) \le 10^{15}$ and $10^{-5} \le U_{e3} \le 0.1$.
  - The **"UT tension"** is "solved" through SUSY effects in ϵ_K implying a **lower bound** for $\mathrm{BR}(\mu \to e\gamma)$ in the reach of MEG.
  - A simultaneous explanation for both the $(g-2)_\mu$ and the **UT anomalies** implies $\mathrm{BR}(\mu \to e\gamma) \ge 10^{-12}$ and SUSY particles in the LHC reach.

[Buras, Nagai & P.P., '10]





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



hierarchical ν_L and N_R [Buras, Nagai & P.P., '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 and neutron EDM

Chirality structure of flavour violating terms

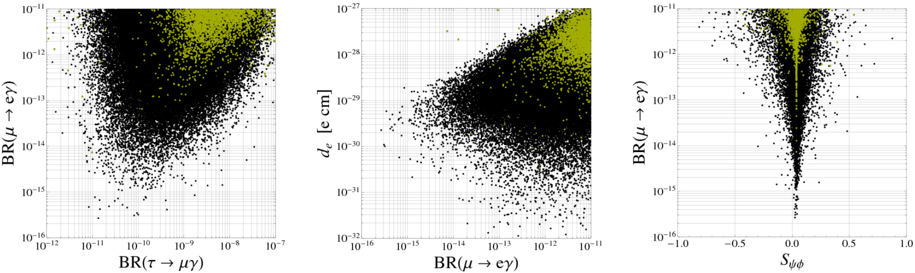
- Different flavour symmetries lead to different patterns of flavour violation
- Mass insertions: $M^2_{\tilde{d}} = \mathrm{diag}(\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta^{LL}_d & \delta^{LR}_d \\ \delta^{RL}_d & \delta^{RR}_d \end{pmatrix}$
- δ^{LL}, δ^{RR}, δ^{LR} fixed by the flavour symmetry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

Representative (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
$\delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & \lambda^2 \\ 0 & \lambda^2 & \cdot \end{pmatrix}$	$\delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix}$	$\delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix}$	$\delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^5 & \lambda^3 \\ \lambda^5 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix}$
$\delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 1 \\ 0 & 1 & \cdot \end{pmatrix}$	$\delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^3 \\ \lambda^3 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix}$	$\delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix}$	$\delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix}$

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

Phenomenology of a non-Abelian flavor models (RVV)



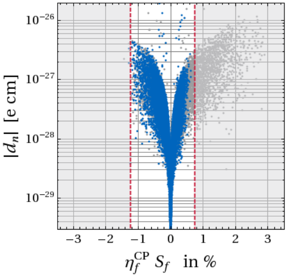
- Main messages: [Altmannshofer, Buras, Gori, P.P. and Straub, '09]
  - Scan: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $5 < \tan\beta < 55$. Yellow points: $\Delta a_\mu > 10^{-9}$.
  - $\mathrm{BR}(\mu \to e\gamma) \geq 10^{-13}$, $\mathrm{BR}(\tau \to \mu\gamma) \geq 10^{-9}$, $d_e > 10^{-29}$ $e$cm and $d_n > 10^{-28}e$ cm, required by the solution of the $(g-2)_\mu$ anomaly.
  - Large CPV effects in B_s systems typically imply predictions for the neutron EDM within the expected future experimental resolutions $d_n \approx 10^{-28}e$ cm.
  - $-0.5 < S_{\psi\phi} < 0.5 \Rightarrow \mathrm{BR}(\mu \to e\gamma) > 10^{-13}$. The simultaneous explanation of the $(g-2)_\mu$ anomaly and non-standard effects for $S_{\psi\phi}$ imply $\mathrm{BR}(\mu \to e\gamma) \gtrsim 10^{-12}$.

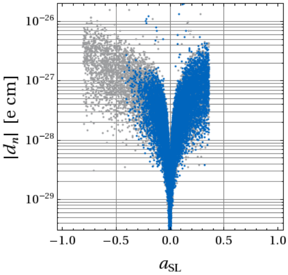
Phenomenology of Abelian flavour models

- Abelian flavour models naturally suppress FCNC in the down-quark sector (ϵ_K, $B - \bar{B}$ mixing) but large FCNC effects in the up-quark sector are unavoidable.
- SUSY Abelian flavour models predict large **CPV** effects in $\mathbf{D^0 - \overline{D}^0}$ mixing and a correlated neutron EDM $d_n \gtrsim 10^{-28} e\,\mathbf{cm}$. [Altmannshofer, Buras, & P.P, '10]
- CPV observables sensitive to $\mathbf{D^0 - \overline{D}^0}$ mixing

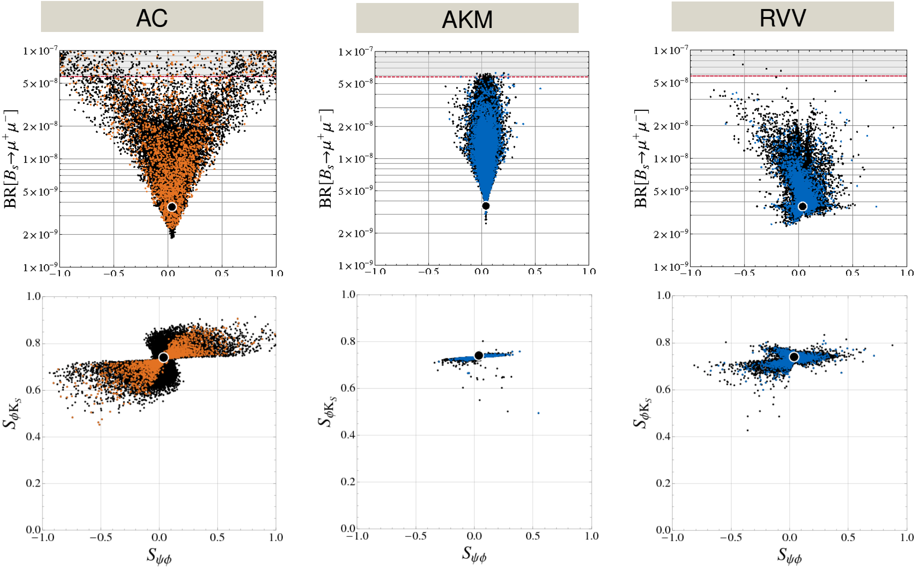
$$\mathbf{S_f} = \frac{1}{\Gamma_D}\left(\hat{\Gamma}_{\bar{D}^0 \to f} - \hat{\Gamma}_{D^0 \to f}\right), \quad \mathbf{a}_{\rm SL} = \frac{\Gamma(D^0 \to K^+\ell^-\nu) - \Gamma(\bar{D}^0 \to K^-\ell^+\nu)}{\Gamma(D^0 \to K^+\ell^-\nu) + \Gamma(\bar{D}^0 \to K^-\ell^+\nu)}$$

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



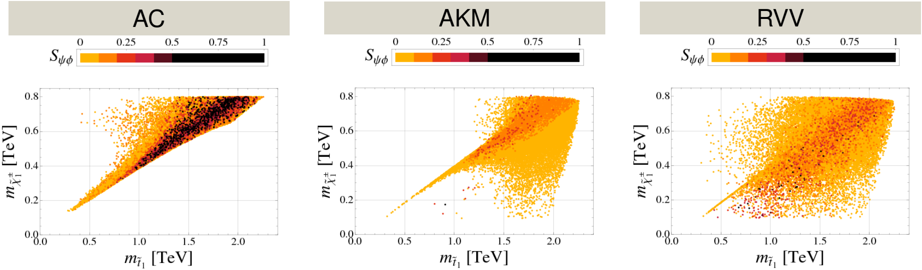


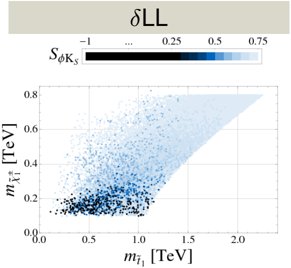
$b \to s$ transitions & SUSY flavor models [Altmannshofer et al., '09]



- 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, $|A_0| < 3m_0$, $5 < \tan\beta < 55$

LHC vs. flavour





- 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, P.P. and Straub, '09]

“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	★★★	★★★	★★★	●●	■	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	

★★★, ●●, ■ = **Large**, **Moderate**, **Invisible** NP effects [Altmannshofer, Buras, Gori, P.P., and Straub, ’09]

Conclusions and future prospects

- **The important questions in view of future experiments are**:
  - What are the expected deviations from the SM predictions induced by TeV NP?
  - Which observables are not limited by theoretical uncertainties?
  - In which case we can expect a substantial improvement on the experimental side?
  - What will the measurements teach us if deviations from the SM are [not] seen?

- **Answers**:
  - Generic FV sources at the TeV scale are excluded by orders of magnitudes.
  - We can expect any size of deviation below the current bounds.
  - Channels with leptons in the final state and selected time-dependent asymmetries have a th. errors well below the current exp. sensitivity.
  - Excellent experimental prospects in several clean $B_{s,d}$, D, and K observables, LFV processes ($\mu \to e\gamma$, $\mu Ti \to eTi$) and EDM experiments (d_n, d_{Tl}).

Conclusions and future prospects

- **Low-energy flavor data will be complementary with the high-p_T part of the LHC program.**

- **The synergy of both data sets can teach us a lot about the new physics at the TeV scale.**