Theory introduction

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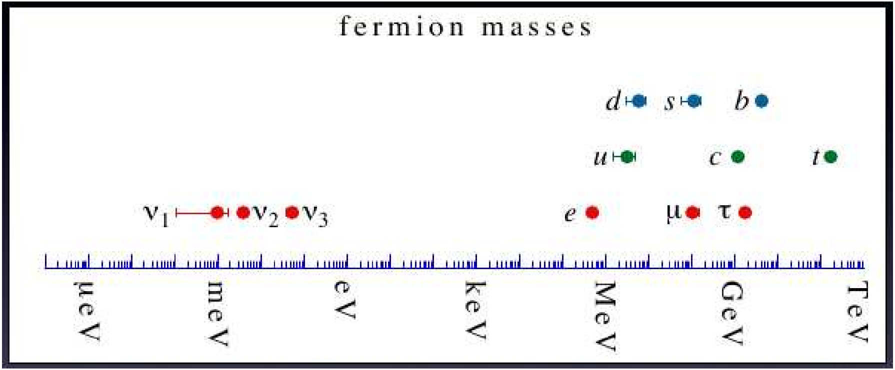
Plan of Talk

1. Open questions
2. The SM flavour puzzle
3. Messages from the B-factories and Tevatron
4. The New Physics flavour & CP problems
5. “Flavour-test” of NP models: the case of SUSY
   - SUSY MFV scenarios
   - SUSY GUT scenarios
   - SUSY flavour models
6. LHC vs. Flavour
7. Conclusions

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. **......**

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

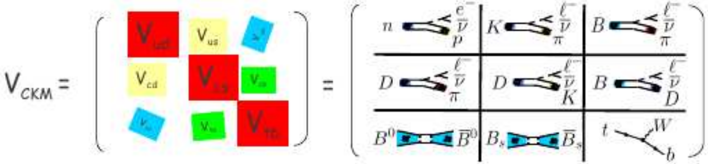
- $\mathcal{L}^{\rm SM}_{Kinetic+Gauge} + \mathcal{L}^{\rm SM}_{Higgs}$ has a large $U(3)^5$ global **flavour symmetry**

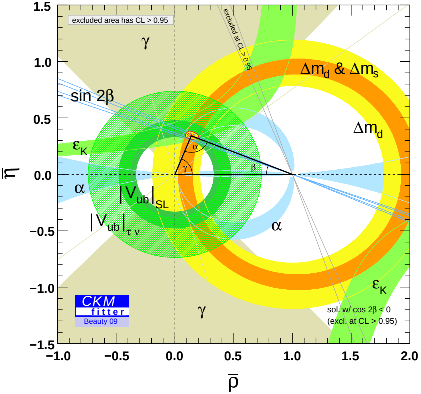
$$\mathbf{G} = \mathbf{U(3)^5} = \mathbf{U(3)_u} \otimes \mathbf{U(3)_d} \otimes \mathbf{U(3)_Q} \otimes \mathbf{U(3)_e} \otimes \mathbf{U(3)_L}$$

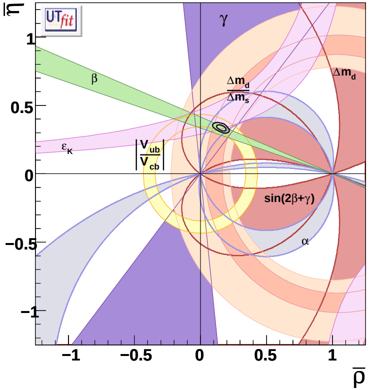
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R \phi + \bar{Q}_L \mathbf{Y_U} U_R \tilde{\phi} + \bar{L}_L \mathbf{Y_L} E_R \phi + h.c$ break G down to

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

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

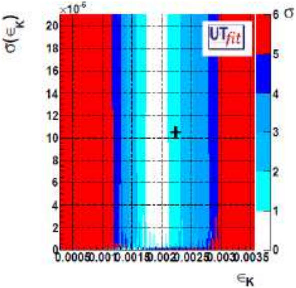




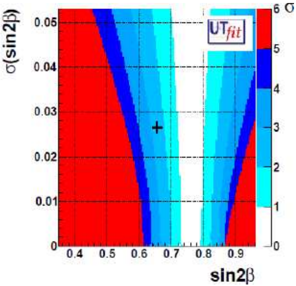


“Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism” (Nir)

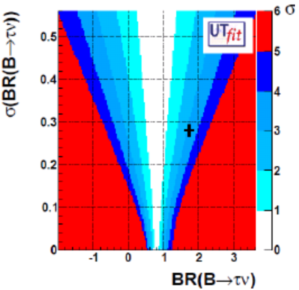
UT tensions



fit vs. exp. $\approx -1.7\sigma$



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



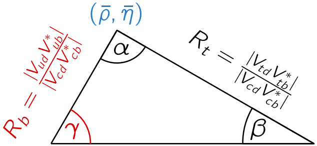
fit vs. exp. $\approx -3.2\sigma$

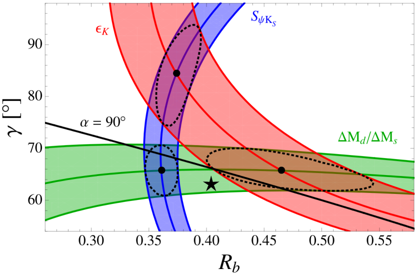
Similar conclusions from the CKMfitter collaboration ('10)

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 solutions of the "UT tension" in BSM scenarios.

UT tensions and NP

- "Tensions" in the the UT analysis
- Look at ϵ_K, $S_{\psi K_S}$, and $\Delta M_d/\Delta M_s$ in the R_b-γ plane from tree-level processes





[Altmannshofer, Buras, Gori, P.P, Straub, '09; Buras, Nagai, P.P, '10]

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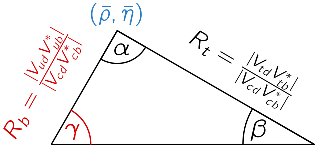

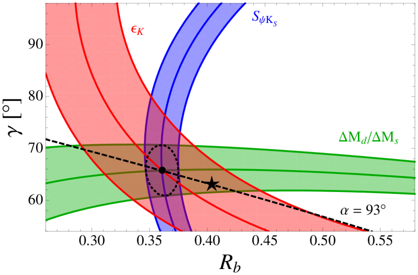

Possible solutions:

1. $+24\%$ NP effect in ϵ_K

[Altmannshofer, Buras, Gori, P.P, Straub, '09; Buras, Nagai, P.P, '10]

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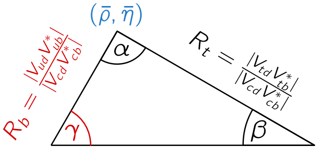

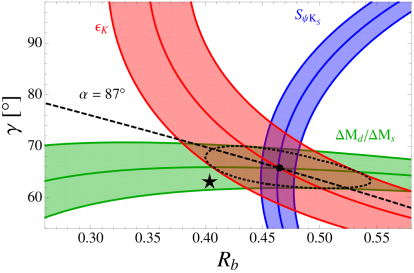

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2. $-6.5°$ NP phase in B_d mixing

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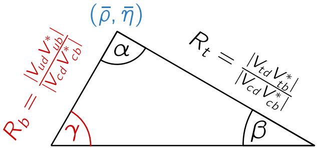
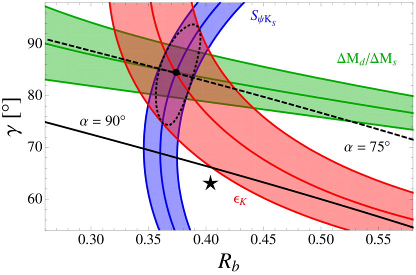
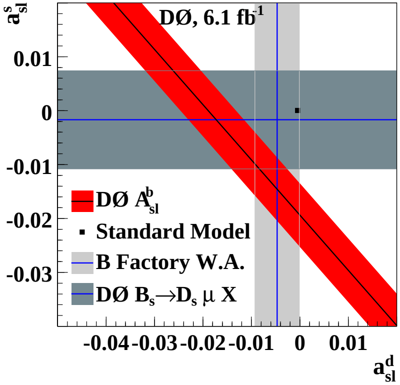


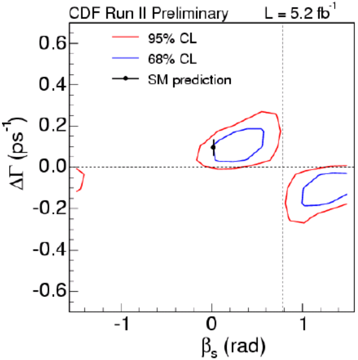


Possible solutions:

1. $+24\%$ NP effect in ϵ_K
2. $-6.5°$ NP phase in B_d mixing
3. -22% NP effect in $\Delta M_d/\Delta M_s$

[Altmannshofer, Buras, Gori, P.P, Straub, '09; Buras, Nagai, P.P, '10]





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

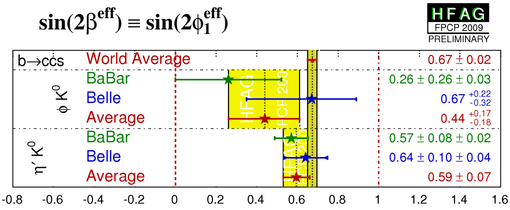
$$S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s})$$

New Physics in the B_s mixing phase?

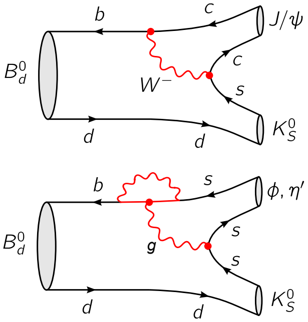
$\sin 2\beta_{\text{eff}}$ tensions

- In the SM, $(\sin 2\beta)_{\psi K_S} \approx (\sin 2\beta)_{\phi K_S} \approx (\sin 2\beta)_{\eta' K_S}$
- $B_d \to \psi K_S$ dominated by tree level, ϕK_S and $\eta' K_S$ are loop-induced

Data indicate $S_{\phi K_S} < S_{\eta' K_S} < S_{\psi K_S}$



[adapted from HFAG]



New physics in the decay amplitudes?

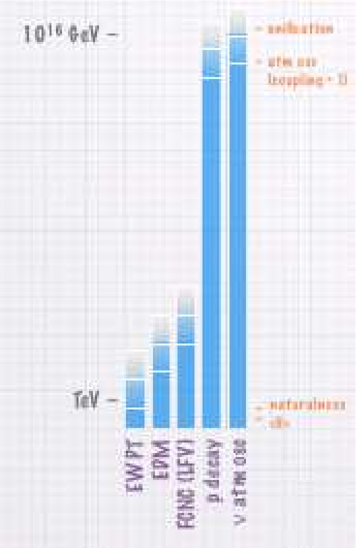
The SuperB will tell us...

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

SM = effective theory at the EW scale

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

- $\mathcal{L}_{\rm eff}^{d=5} = \frac{y_\nu^{ij}}{\Lambda_{\rm see-saw}} L_i L_j \phi\phi$,
- $\mathcal{L}_{\rm eff}^{d=6}$ generates FCNC operators



$$\mathbf{BR}(\ell_i \to \ell_j \gamma) \sim \frac{1}{\Lambda_{NP}^4}$$

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)

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

$\Delta F = 1,2$ 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	$B \to X_s\ell^+\ell^-$

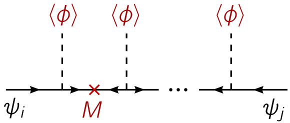
Observable	Experiment	MFV prediction	SM prediction
$\mathcal{A}_{\rm CP}(B_s \to \psi\phi)$	[0.10, 1.44] @ 95% CL	0.04(5)	0.04(2)
$\mathcal{A}_{\rm CP}(B \to X_s\gamma)$	$< 6\%$ @ 95% CL	< 0.02	< 0.01
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$< 1.8 \times 10^{-8}$	$< 1.2 \times 10^{-9}$	$1.3(3) \times 10^{-10}$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

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?

The New Physics CP problem

- **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

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$S_{B_s\to\psi\phi}$	**0.036**	≤ 0.01	$\lesssim \|0.2\|$	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}	$-(5.8\pm3.4)10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$<10^{-5}$	$(1.6\pm8.5)10^{-3}$	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}	$20\%\to5\%$	$(1.73\pm0.35)10^{-4}$	5%	Super-B
$\mathcal{B}(B\to\mu\nu)$	4×10^{-7}	$20\%\to5\%$	$<1.3\times10^{-6}$	6%	Super-B
$\mathcal{B}(B_s\to\mu^+\mu^-)$	3×10^{-9}	$20\%\to5\%$	$<1.1\times10^{-8}$	10%	**LHCb**
$\mathcal{B}(B_d\to\mu^+\mu^-)$	1×10^{-10}	$20\%\to5\%$	$<1.5\times10^{-8}$	**[?]**	**LHCb**
$B\to K\nu\bar\nu$	4×10^{-6}	$20\%\to10\%$	$<1.4\times10^{-5}$	20%	Super-B
$\|q/p\|_{D-\rm mixing}$	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%	$<2.6\times10^{-8}$	[?]	K factory

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

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

$B \to K^* \ell^+ \ell^-$ observables [Altmannshofer, P.P., Straub, '11]

Observable	Experiment		SM prediction	
$10^4 \times \mathrm{BR}(B \to X_s \gamma)$	3.55 ± 0.26	[26]	3.15 ± 0.23	[27]
$S_{K^*\gamma}$	-0.16 ± 0.22	[26]	(-2.3±1.6)%	[31]
$10^6 \times \mathrm{BR}(B \to X_s \ell^+ \ell^-)_{[1,6]}$	1.63 ± 0.50	[37, 38]	1.59 ± 0.11	[42]
$10^7 \times \mathrm{BR}(B \to X_s \ell^+ \ell^-)_{>14.4}$	4.3 ± 1.2	[37, 38]	2.3 ± 0.7	[10]
$10^7 \times \mathrm{BR}(B \to K^* \ell^+ \ell^-)_{[1,6]}$	1.71 ± 0.22	[7, 49, 68]	2.28 ± 0.63	
$10^7 \times \mathrm{BR}(B \to K^* \ell^+ \ell^-)_{[14.18,16]}$	1.11 ± 0.13	[7, 49, 68]	1.13 ± 0.33	
$10^7 \times \mathrm{BR}(B \to K^* \ell^+ \ell^-)_{[16,19]}$	1.35 ± 0.15	[7, 49, 68]	1.34 ± 0.51	
$\langle F_L \rangle (B \to K^* \ell^+ \ell^-)_{[1,6]}$	0.61 ± 0.09	[7, 49, 51]	0.77 ± 0.04	
$\langle F_L \rangle (B \to K^* \ell^+ \ell^-)_{[14.18,16]}$	0.28 ± 0.09	[7, 49, 51]	0.37 ± 0.17	
$\langle F_L \rangle (B \to K^* \ell^+ \ell^-)_{[16,19]}$	0.23 ± 0.08	[7, 49, 51]	0.34 ± 0.22	
$\langle A_{FB} \rangle (B \to K^* \ell^+ \ell^-)_{[1,6]}$	-0.04 ± 0.12	[7, 49, 51]	0.03 ± 0.02	
$\langle A_{FB} \rangle (B \to K^* \ell^+ \ell^-)_{[14.18,16]}$	-0.50 ± 0.07	[7, 49, 51]	-0.41 ± 0.11	
$\langle A_{FB} \rangle (B \to K^* \ell^+ \ell^-)_{[16,19]}$	-0.38 ± 0.10	[7, 49, 51]	-0.35 ± 0.11	
$\langle S_3 \rangle (B \to K^* \ell^+ \ell^-)_{[1,6]}$	0.27 ± 0.56	[51]	$(-0.3 \pm 1.1)\,10^{-2}$	
$\langle A_9 \rangle (B \to K^* \ell^+ \ell^-)_{[1,6]}$	0.09 ± 0.39	[51]	$(1.5 \pm 2.4)\,10^{-4}$	

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}	$\mathcal{O}(10^{-9})$	SuperB, 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

Formalism for $B_{d,s}$ mixing amplitudes

- **Theory:**

$$M_{12}^q = \left(M_{12}^q\right)_{\rm SM} C_{B_q} e^{2i\varphi_{B_q}} , \qquad (q = d, s) .$$

$$\begin{aligned} \Delta M_q &= 2\left|M_{12}^q\right| = (\Delta M_q)_{\rm SM} C_{B_q} , \\ S_{\psi K_S} &= \sin(2\beta + 2\varphi_{B_d}) , \\ S_{\psi\phi} &= \sin(2|\beta_s| - 2\varphi_{B_s}) , \end{aligned}$$

where $V_{td} = |V_{td}|e^{-i\beta}$ and $V_{ts} = -|V_{ts}|e^{-i\beta_s}$. From global CKM fits based only on tree-level observables

$$\begin{aligned} \sin(2\beta)_{\tt tree} &= 0.775 \pm 0.035 , \\ \sin(2\beta_s)_{\tt tree} &= 0.038 \pm 0.003 . \end{aligned}$$

- **Experiments:**

$$\begin{aligned} S_{\psi K_S}^{\rm exp} &= 0.676 \pm 0.020 , \\ S_{\psi\phi(f_0)}^{\rm exp} &= -0.03 \pm 0.18 . \end{aligned}$$

- **Theory**

$$\mathcal{A}_f(t) = S_f \sin(\Delta M t) - C_f \cos(\Delta M t) \; . \tag{1}$$

In the SM, $|S_f|$ and C_f are universal for $\bar{b} \to \bar{q}' q' \bar{s}$ ($q' = c, s, d, u$): $-\eta_f S_f \simeq \sin 2\beta$ and $C_f \simeq 0$ where $\eta_f = \pm 1$. NP effects can contribute to

i) the B_d mixing amplitude;
ii) the decay amplitudes $\bar{b} \to \bar{q} q \bar{s}$ ($q = s, d, u$).

$$\lambda_f = e^{-2i(\beta + \phi_{B_d})} (\overline{A}_f / A_f) \; , \tag{2}$$

$\phi_{B_d} \equiv$ NP phase of B_d mixing, A_f ($\overline{A}_f$) is the decay amplitude for $B_d(\overline{B_d}) \to f$.

$$A_f = \langle f | \mathcal{H}_{\rm eff} | B_d \rangle \; , \;\; \overline{A}_f = \langle f | \mathcal{H}_{\rm eff} | \overline{B_d} \rangle \; , \tag{3}$$

$$S_f = \frac{2 {\rm Im}(\lambda_f)}{1 + |\lambda_f|^2} \; , \;\; C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \; . \tag{4}$$

$$A_f = A_f^c \left[1 + a_f^u e^{i\gamma} + \sum_i \left(b_{fi}^c + b_{fi}^u e^{i\gamma} \right) \left(C_i^{\rm NP*}(M_W) + \eta_f \tilde{C}_i^{\rm NP*}(M_W) \right) \right] \; , \tag{5}$$

- **Theory**

$$\mathcal{H}_{\rm eff} = -C_S Q_S - C_P Q_P - \tilde{C}_S \tilde{Q}_S - \tilde{C}_P \tilde{Q}_P$$

$$\begin{aligned} Q_S &= m_b\,(\bar{s}P_R b)\,(\bar{\ell}\ell)\,, \quad Q_P = m_b\,(\bar{s}P_R b)\,(\bar{\ell}\gamma_5\ell) \\ \tilde{Q}_S &= m_b\,(\bar{s}P_L b)\,(\bar{\ell}\ell)\,, \quad \tilde{Q}_P = m_b\,(\bar{s}P_L b)\,(\bar{\ell}\gamma_5\ell) \end{aligned}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{\tau_{B_s} F_{B_s}^2 m_{B_s}^3}{32\pi}\sqrt{1-4\frac{m_\mu^2}{m_{B_s}^2}}\left(|B|^2\left(1-4\frac{m_\mu^2}{m_{B_s}^2}\right)+|A|^2\right)$$

$$A = 2\frac{m_\mu}{m_{B_s}} C_{10}^{\rm SM} + m_{B_s}\left(C_P - \tilde{C}_P\right)\,, \quad B = m_{B_s}\left(C_S - \tilde{C}_S\right)$$

$$C_{10}^{\rm SM} \approx \frac{g_2^2}{16\pi^2}\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^*$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.60 \pm 0.37) \times 10^{-9}$$

- **Experiment**

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm exp} \lesssim 1.1 \times 10^{-8}$$ [LHCb '11]

Obs.	[46]	[47]	[16]	[48, 50]	[51]	most sensitive to
F_L	$-S_2^c$	F_L		F_L	F_L	$C^{(\prime)}_{7,9,10}$
$A_{\rm FB}$	$\frac{3}{4} S_6^s$	$A_{\rm FB}$	$A_{\rm FB}$	$-A_{\rm FB}$	$-A_{\rm FB}$	C_7, C_9
S_5	S_5					C_7, C_7', C_9, C_{10}'
S_3	S_3	$\frac{1}{2}(1-F_L)A_T^{(2)}$			$\frac{1}{2}(1-F_L)A_T^{(2)}$	$C'_{7,9,10}$
A_9	A_9		$\frac{2}{3} A_9$		A_{im}	$C'_{7,9,10}$
A_7	A_7		$-\frac{2}{3} A_7^D$			$C^{(\prime)}_{7,10}$

Table 1: Dictionary between different notations for the $B \to K^* \mu^+ \mu^-$ observables and Wilson coefficients they are most sensitive to (the sensitivity to $C_7^{(\prime)}$ is only present at low q^2).

$$S_i = (I_i + \bar{I}_i) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}\,, \qquad A_i = (I_i - \bar{I}_i) \Big/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2}\,.$$

see references in Altmannshofer, P.P., Straub, '11

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

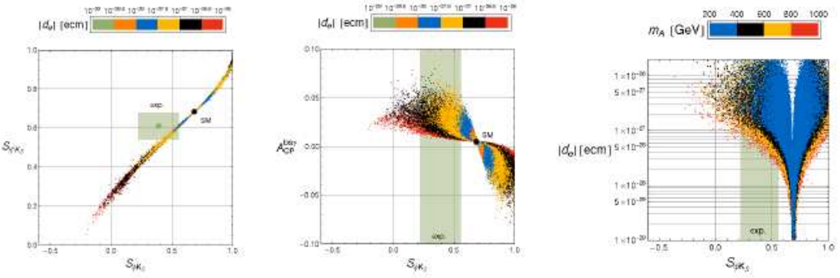
Flavor problem: solutions

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

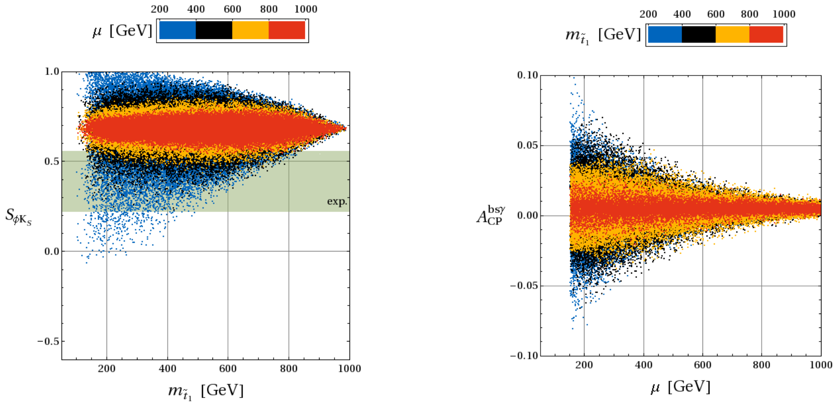


- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- lower bounds on the electron and neutron 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: $0.03 < S_{\psi\phi} < 0.05$

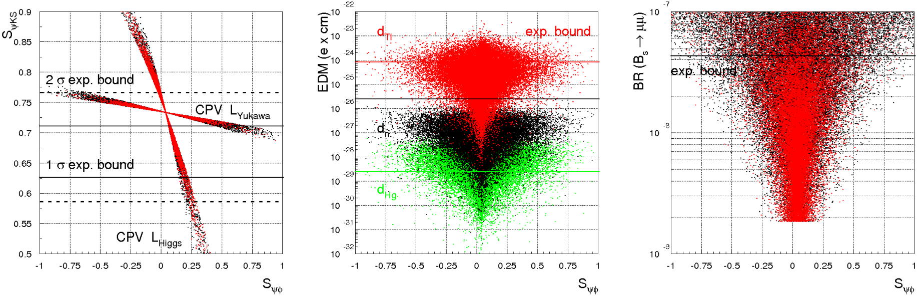
A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

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



- $S_{\phi K_S} \simeq 0.4$ 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]



- 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]

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...!)

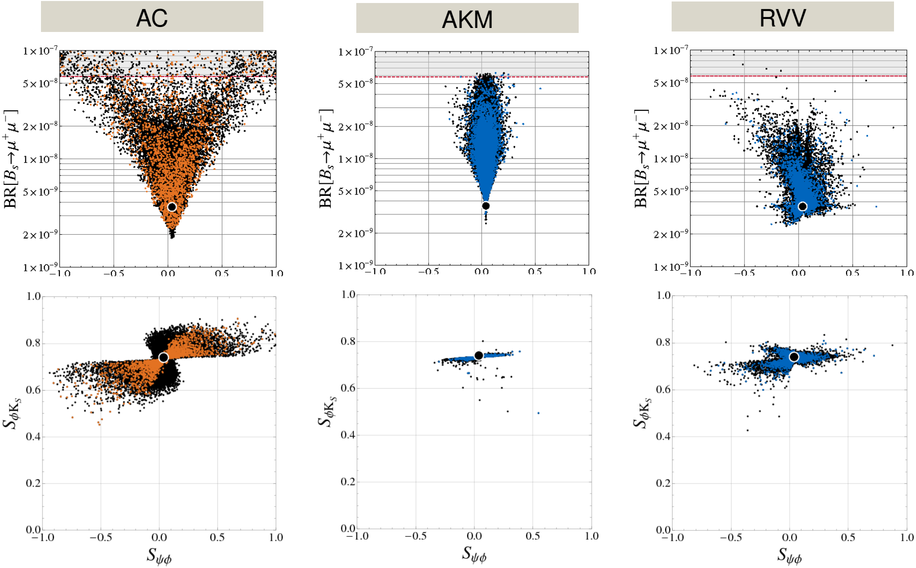
AC model $U(1)$ [Agashe, Carone]	AKM model $SU(3)$ [Antusch, King, Malinsky]	RVV model $SU(3)$ [Ross, Velasco-S., Vives]	δLL model $(S_3)^3$ [e.g. Hall, Murayama]
Large, $O(1)$ RR mass insertions	Only CKM-like RR mass insertions	CKM-like LL & RR mass insertions	Only CKM-like LL mass insertions

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

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

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

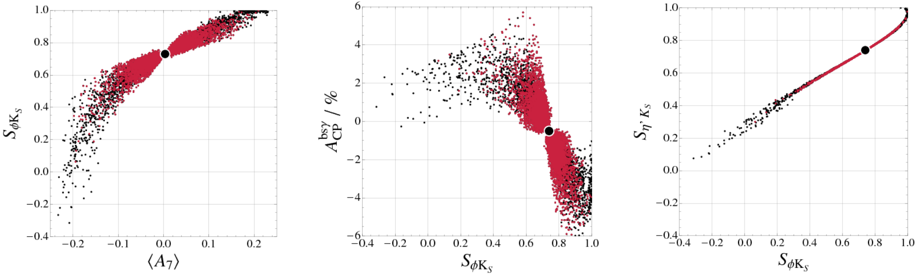
$b \to s$ transitions & SUSY flavor models [Altmannshofer et al., '09]



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

Pattern of NP effects in the δLL model:

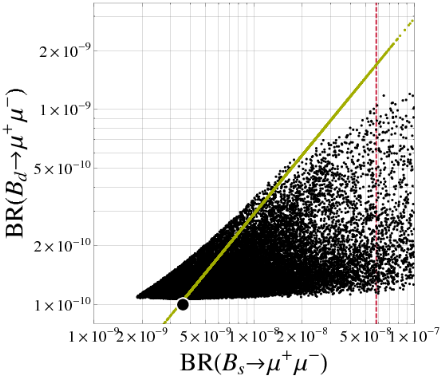
- No large effects in $S_{\psi\phi}$
- Large, correlated effects in $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{CP}(b \to s\gamma)$, $\langle A_{7,8} \rangle$ and EDMs
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \to K^* \ell^+ \ell^-$



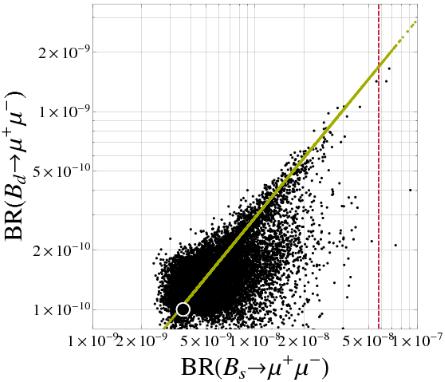
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$,

[Altmannshofer et al., '09]

Abelian (AC)



Non abelian (RVV)

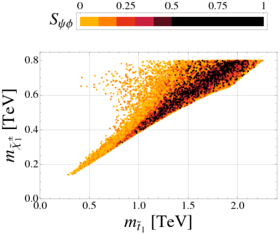


[Altmannshofer et al., '09]

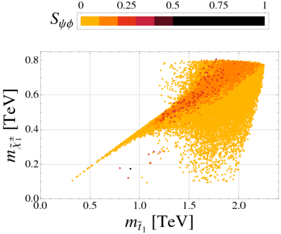
$Br(B_s \to \mu^+\mu^-)/Br(B_d \to \mu^+\mu^-) = |V_{ts}/V_{td}|^2$ **in MFV models**

[Hurth, Isidori, Kamenik & Mescia, '08]

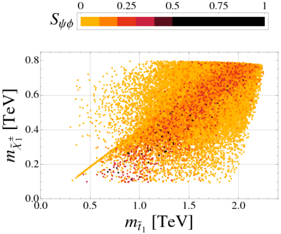
AC



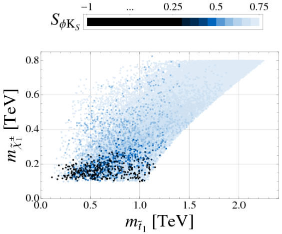
AKM



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, P.P. and Straub, '09]

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)

RG induced Quark & Lepton FV interactions in SUSY GUTs

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

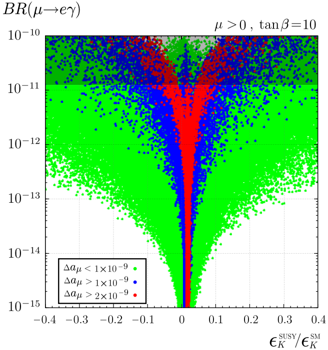
$$(\delta^{\tilde{q}}_{LL})_{ij} \sim h^u h^{u\dagger}{}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \rightarrow (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

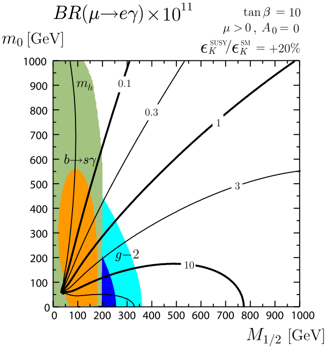
- **SUSY SU(5)+RN** [Yanagida et al., '95]

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

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

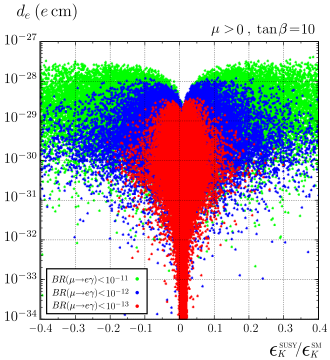
$$\sin\theta_{\mu\tau} \sim \frac{\sqrt{2}}{2} \Rightarrow (\delta^{\tilde{\ell}}_{LL})_{23} \sim 1 \Rightarrow (\delta^{\tilde{q}}_{RR})_{23} \sim 1$$

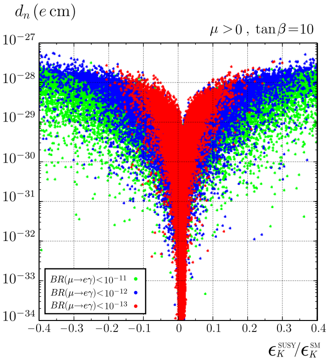




- Main messages:
  - Parameter scan: $(m_0, M_{1/2}) < 1\,\mathrm{TeV}$, $|A_0| < 3m_0$, $\tan\beta = 10$ and $\mu > 0$. Hierarchical ν_L & N_R, $10^{11} \leq M_{\nu_3}(\mathrm{GeV}) \leq 10^{15}$ and $10^{-5} \leq U_{e3} \leq 0.1$.
  - The **"UT tension"** is "solved" through SUSY effects in ϵ_K implying 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 $\mathrm{BR}(\mu \to e\gamma) \geq 10^{-12}$ and SUSY particles in the LHC reach.

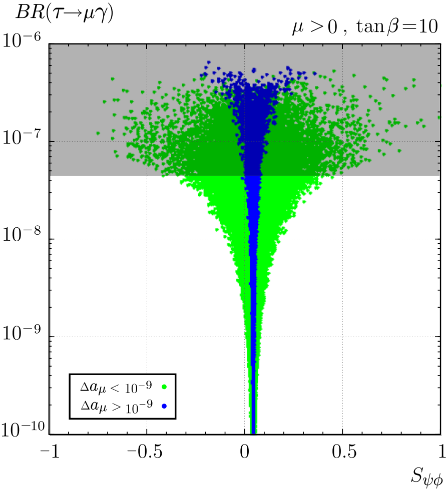
[Buras, Nagai & P.P., '10]

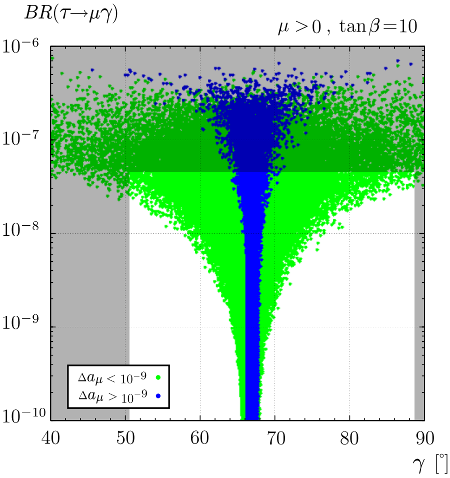




- Main messages:
  - Parameter scan: $(m_0, M_{1/2}) < 1\,\mathrm{TeV}$, $|A_0| < 3m_0$, $\tan\beta = 10$ and $\mu > 0$. Hierarchical ν_L & N_R, $10^{11} \leq M_{\nu_3}(\mathrm{GeV}) \leq 10^{15}$ and $10^{-5} \leq U_{e3} \leq 0.1$.
  - Sizable **non-standard** effects in ϵ_K always implies large values for the **electron and neutron EDMs**, in the reach of the planned experimental resolutions.

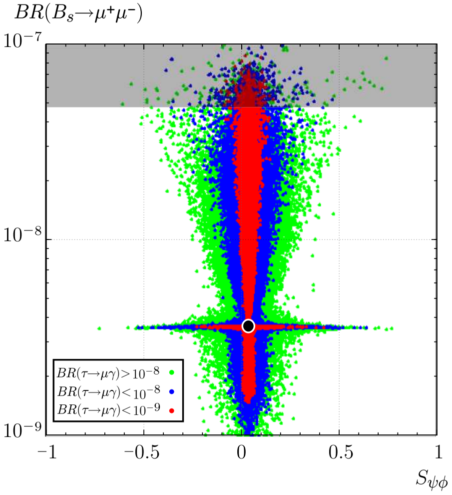
[Buras, Nagai & P.P., '10]

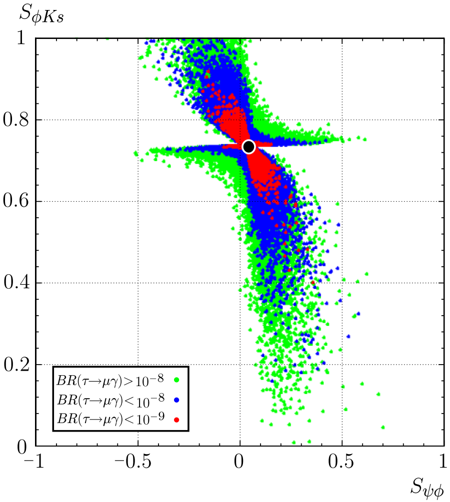




hierarchical ν_L and N_R [Buras, Nagai & P.P., '10]

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





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

New Physics scenarios

1. **Real left-handed currents**, $C_i \in \mathbf{R}$, $C_i' = 0$. This is realised e.g. in models with MFV in the definition of D'Ambrosio et al., i.e. no CP violation beyond the CKM phase.

2. **Complex left-handed currents**, $C_i \in \mathbf{C}$, $C_i' = 0$. This is realised e.g. in models with MFV and flavour-blind phases.

3. **Complex right-handed currents**, $C_i' \in \mathbf{C}$, $C_i = 0$.

4. **Generic NP**, $C_i \in \mathbf{C}$, $C_i' \in \mathbf{C}$.

5. Models with non-standard Z couplings: only $C_{9,10}^{(\prime)}$ with $C_9^{(\prime)} = -(1 - 4s_w^2) C_{10}^{(\prime)}$)

$$\chi^2(\vec{C}) = \sum_i \frac{\left(O_i^{\rm exp} - O_i^{\rm th}(\vec{C})\right)^2}{(\sigma_i^{\rm exp})^2 + (\sigma_i^{\rm th}(\vec{C}))^2} \, .$$

Altmannshofer, P.P., Straub, '11

$B \to K^* \ell^+ \ell^-$ observables

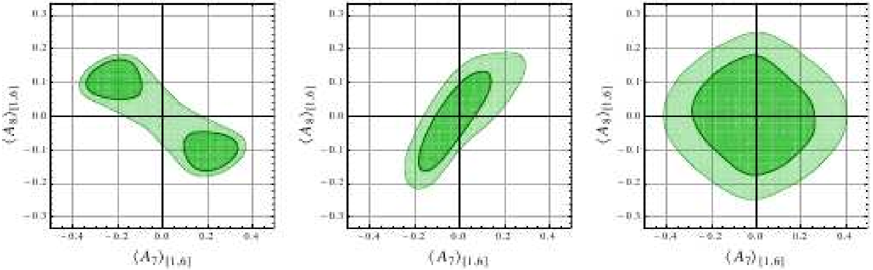


Figure 7: Fit predictions for the low-q^2 CP asymmetries $\langle A_{7,8} \rangle$ in $B \to K^* \mu^+ \mu^-$ in the case of complex left-handed currents (left), complex right-handed currents (centre) and generic NP (right). Shown are 68% and 95% C.L. regions.

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$B \to K^* \ell^+ \ell^-$ observables

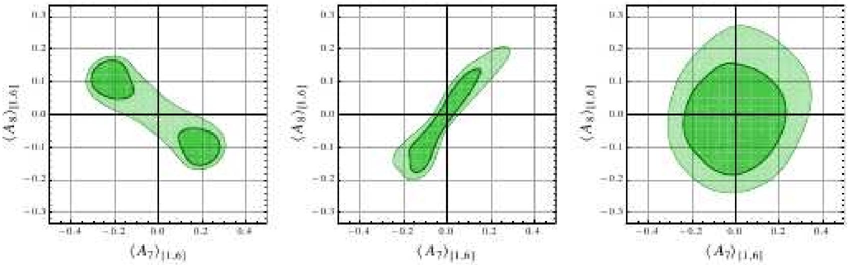

Figure 11: Fit predictions for the low-q^2 CP asymmetries $\langle A_{7,8} \rangle$ in $B \to K^* \mu^+ \mu^-$ for the scenario with left-handed (left), right-handed (centre) or generic (right) modified Z couplings. Shown are 68% and 95% C.L. regions.

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$B \to K^* \ell^+ \ell^-$ observables

Scenario	$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$\mathrm{BR}(B_s \to \tau^+\tau^-)$	$\lvert\langle A_7\rangle_{[1,6]}\rvert$	$\lvert\langle A_8\rangle_{[1,6]}\rvert$	$\lvert\langle A_9\rangle_{[1,6]}\rvert$	$\langle S_3\rangle_{[1,6]}$
Real LH	$[1.0, 5.6] \times 10^{-9}$	$[2, 12] \times 10^{-7}$	0	0	0	0
Complex LH	$[1.0, 5.4] \times 10^{-9}$	$[2, 12] \times 10^{-7}$	< 0.31	< 0.15	0	0
Complex RH	$< 5.6 \times 10^{-9}$	$< 12 \times 10^{-7}$	< 0.22	< 0.17	< 0.12	$[-0.06, 0.15]$
Generic NP	$< 5.5 \times 10^{-9}$	$< 12 \times 10^{-7}$	< 0.34	< 0.20	< 0.15	$[-0.11, 0.18]$
LH Z peng.	$[1.4, 5.5] \times 10^{-9}$	$[3, 12] \times 10^{-7}$	< 0.27	< 0.14	0	0
RH Z peng.	$< 3.8 \times 10^{-9}$	$< 8 \times 10^{-7}$	< 0.22	< 0.18	< 0.12	$[-0.03, 0.18]$
Generic Z p.	$< 4.1 \times 10^{-9}$	$< 9 \times 10^{-7}$	< 0.28	< 0.21	< 0.13	$[-0.07, 0.19]$
scalar current	$< 1.1 \times 10^{-8}$	$< 1.3(2.3) \times 10^{-6}$	0	0	0	0

Table 3: Predictions at 95% C.L. for the branching ratios of $B_s \to \mu^+\mu^-$ and $B_s \to \tau^+\tau^-$ and predictions for low-q^2 angular observables in $B \to K^*\mu^+\mu^-$ (neglecting tiny SM effects below the percent level) in all the scenarios. The scenarios "Real LH", "Complex LH", "Complex RH", "Generic NP", "LH Z peng.", "RH Z peng.", and "Generic Z p." correspond to the scenarios discussed in sec. 3.2.1, sec. 3.2.2, sec. 3.2.3, sec. 3.2.4, sec. 4.1.1, sec. 4.1.2 and sec. 4.1.3 respectively, assuming negligible (pseudo)scalar currents. In the scenario "scalar current" *only* scalar currents are considered. The number quoted for $B_s \to \tau^+\tau^-$ in the "scalar current" scenario refers to the maximum value for its branching ratio in the case of dominant scalar (pseudoscalar) currents.

Time-integrated CP asymmetries in $D^0 \to K^+K^-(\pi^+\pi^-)$

- **Theory**

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,, \quad f = K^+K^-, \pi^+\pi^-$$

SCS decay amplitude $A_f(\bar{A}_f)$ of D^0 ($\bar{D}^0$) to a CP eigenstate f

$$\begin{aligned} A_f &= A_f^T\, e^{i\phi_f^T} \left[1 + r_f\, e^{i(\delta_f + \phi_f)}\right], \\ \bar{A}_f &= \eta_{CP}\, A_f^T\, e^{-i\phi_f^T} \left[1 + r_f e^{i(\delta_f - \phi_f)}\right] \end{aligned}$$

Direct CPV $\Longleftrightarrow$ $r_f \neq 0$, $\delta \neq 0$ and $\phi_f \neq 0$

$$a_f^{\rm dir} \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = -2 r_f \sin\delta_f \sin\phi_f$$

- **Experiment**

$$a_{K^+K^-} - a_{\pi^+\pi^-} = -(0.82 \pm 0.21 \pm 0.11)$$ [LHCb '11]

$$\Delta a_{CP} = a_K^{\rm dir} - a_\pi^{\rm dir} = -(0.65 \pm 0.18)$$ [LHCb '11, CDF '11, Belle '08 and BaBar '07]

Time-integrated CP asymmetries in $D^0 \to K^+K^-(\pi^+\pi^-)$

- **Effective Hamiltonian**

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i Q_i + \mathrm{h.c.}\,,$$

$$\begin{aligned} Q_8 &= \frac{m_c}{4\pi^2}\,\bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R\,, \\ \tilde{Q}_8 &= \frac{m_c}{4\pi^2}\,\bar{u}_R \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_L\,. \end{aligned}$$

- **Master formula for Δa_{CP}: SM + NP**

$$\begin{aligned} \Delta a_{CP} &\approx \frac{-2}{\sin\theta_c}\left[\mathrm{Im}(V_{cb}^* V_{ub})\mathrm{Im}(\Delta R^{\mathrm{SM}}) + \sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\mathrm{Im}(\Delta R^{\mathrm{NP}_i})\right] \\ &= -(0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) - 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R^{\mathrm{NP}_i}) \end{aligned}$$

$\Delta R^{\mathrm{SM}} \approx \alpha_s(m_c)/\pi \approx 0.1$ in perturbation theory and $a_K^{\mathrm{dir}} = -a_\pi^{\mathrm{dir}}$ in the $SU(3)$ limit. In naive factorization

$$\left|\mathrm{Im}(\Delta R^{\mathrm{NP}_{8,\tilde{8}}})\right| \approx 0.2$$

- **Δa_{CP} in SUSY**

$$\left|\Delta a_{CP}^{\rm SUSY}\right| \approx 0.6\% \left(\frac{\left|{\rm Im}\,(\delta^u_{12})^{eff}_{LR}\right|}{10^{-3}}\right)\left(\frac{\rm TeV}{\tilde m}\right)\,,$$

- **Disoriented A terms**

$${\rm Im}\,(\delta^u_{12})_{LR} \approx \frac{{\rm Im}(A)\,\theta_{12}\,m_c}{\tilde m} \approx \left(\frac{{\rm Im}(A)}{3}\right)\left(\frac{\theta_{12}}{0.5}\right)\left(\frac{\rm TeV}{\tilde m}\right)\times 10^{-3}\,,$$

- **Split families:** $m_{\tilde q_{1,2}} \gg m_{\tilde q_3}$, $(\delta^u_{33})_{RL} = A\, m_t/m_{\tilde q_3}$

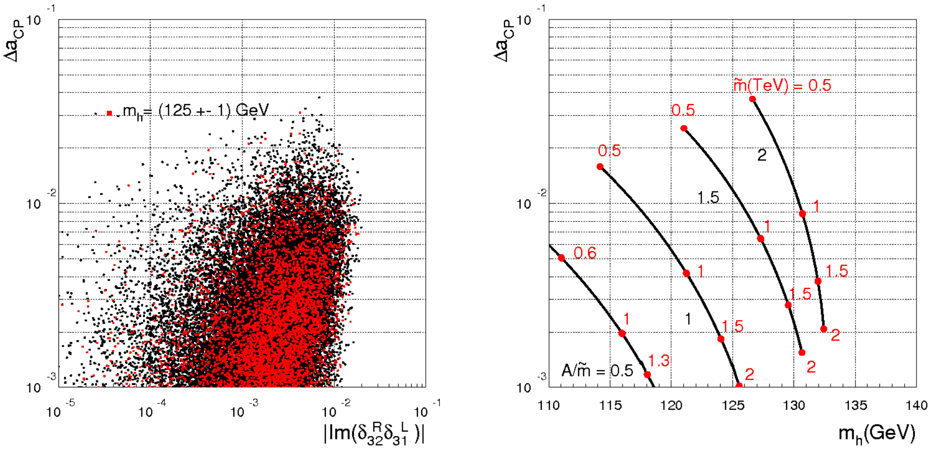
$$(\delta^u_{12})^{\rm eff}_{RL} = (\delta^u_{13})_{RR}\,(\delta^u_{33})_{RL}\,(\delta^u_{32})_{LL}\,, \qquad (\delta^u_{12})^{\rm eff}_{LR} = (\delta^u_{13})_{LL}\,(\delta^u_{33})_{RL}\,(\delta^u_{32})_{RR}\,.$$

$$(\delta^u_{32})_{LL} = O(\lambda^2),\quad (\delta^u_{13})_{RR} = O(\lambda^2) \quad \rightarrow \quad (\delta^u_{12})^{\rm eff}_{RL} = O(\lambda^4) = O(10^{-3})\,,$$

$$(\delta^u_{13})_{LL} = O(\lambda^3),\quad (\delta^u_{32})_{RR} = O(\lambda) \quad \rightarrow \quad (\delta^u_{12})^{\rm eff}_{LR} = O(\lambda^4) = O(10^{-3})\,.$$

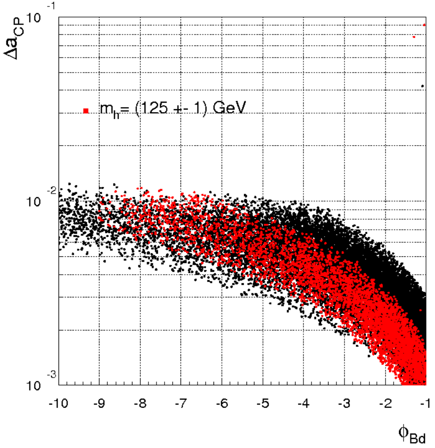
[G.F.Giudice, G.Isidori, & P.P, '12]

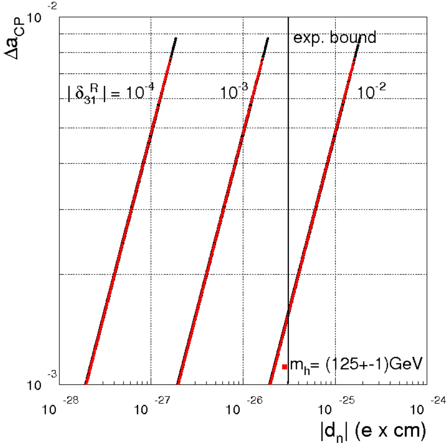
Δa_{CP} and SUSY [G.F.Giudice, G.Isidori, & P.P, '12]



Left: 0.5 TeV $\leq \tilde{m}, \tilde{m}_g \leq 2$ TeV, $\tan\beta = 10$, $|A| \leq 3$.
Right: $|\mathrm{Im}[(\delta^u_{32})_{RR}(\delta^u_{31})_{LL}]| = 10^{-2}$, $\tilde{m} \leq 2$ TeV, and $A = 0.5, 1, 1.5, 2$.

Δa_{CP} and SUSY [G.F.Giudice, G.Isidori, & P.P, '12]





Left: $(\delta^u_{32})_{RR} = 0.2$ and $\phi_{\delta^L_{31}} \in \pm(30^\circ, 60^\circ)$, $|(\delta^d_{31})_{LL}| < 0.1$.

Right: $(\delta^u_{13})_{LL} = 10^{-2}$, $(\delta^u_{32})_{RR} = 0.2i$.

CPV in D-physics

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

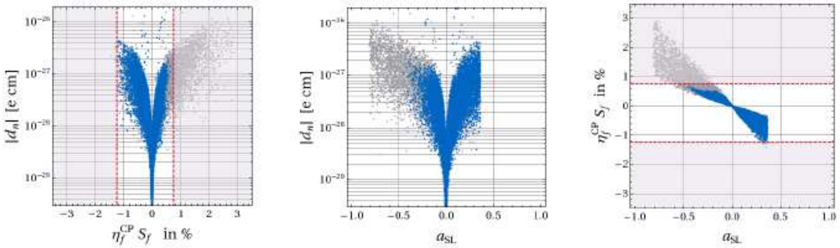


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

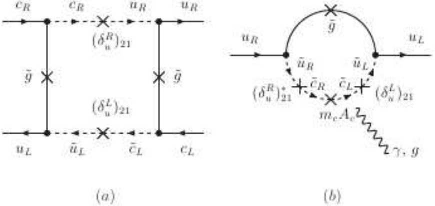


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

“DNA-Flavour Test”

	SSU(5)	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	■	★★★	★★★	
$A_{\rm CP}(B \to X_s\gamma)$	■	■	■	■	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	■	■	■	■	■	■	
$\tau \to \mu\gamma$	★★★	★★★	★★★	■	★★★	★★★	
$D^0 - \bar{D}^0$	■	★★★	■	■	■	■	
$A_{7,8}(B \to K^*\mu^+\mu^-)$	■	■	■	■	★★★	★★★	vs.
$A_9(B \to K^*\mu^+\mu^-)$	■	■	■	■	■	■	
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	■	■	
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★★★	
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?

- **Our (personal) answers are**:
  - The expected deviations from the SM predictions induced by NP at the TeV scale with generic flavor structure are already ruled out by many orders of magnitudes.
  - On general grounds, we can expect any size of deviation below the current bounds.
  - The theoretical limitations are highly process dependent. Several channels involving leptons in the final state, and selected time-dependent asymmetries, have a theoretical errors well below the current experimental sensitivity.
  - On the experimental side there are excellent prospects of improvements. One order of magnitude improvements in several clean $B_{s,d}$, D, K, and π (LFU tests in $\pi_{\ell 2}$) observables are possible within a few years. Improvements of several orders of magnitudes are expected in LFV processes ($\mu \to e\gamma$, $\mu Ti \to e Ti$) and EDM experiments (d_n, d_{Tl}).

Conclusions and future prospects

- **There is no doubt that new 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.**