Rassegna teorica: decadimenti rari e charm

Paride Paradisi

CERN

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Plan of Talk

1. Status of flavour physics in the SM
2. New Physics in $b \to s$ transitions: a model-independent analysis
3. "Flavour-test" of NP models:
   - Models with non-standard Z couplings
   - SUSY MFV scenarios & 2HDM with MFV
   - SUSY GUT scenarios
   - SUSY flavour models
4. Direct vs. indirect charm-CPV
5. Conclusions

Flavor Physics within the SM

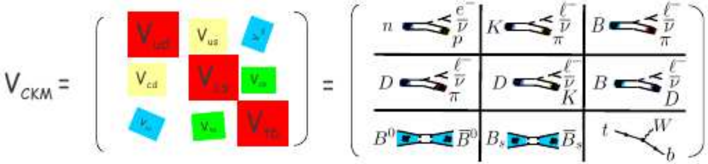
- $\mathcal{L}^{\rm SM}_{Kinetic+Gauge} + \mathcal{L}^{\rm SM}_{Higgs}$ has a large $U(3)^5$ global **flavour symmetry**

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

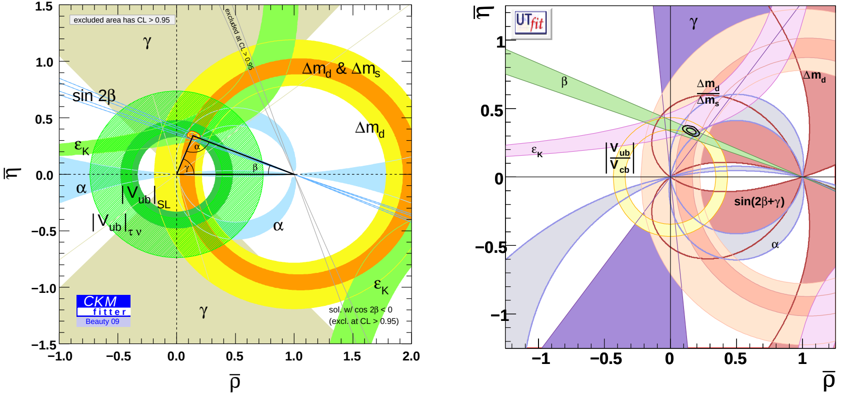
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R \phi + \bar{Q}_L \mathbf{Y_U} U_R \tilde{\phi} + \bar{L}_L \mathbf{Y_L} E_R \phi + h.c$ break G down to

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

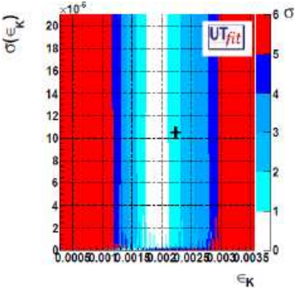
- **CKM matrix**: $Y_U = V_{CKM} \times {\rm diag}({\rm y_u}, {\rm y_c}, {\rm y_t})$ for $\mathbf{Y_D} = {\rm diag}({\rm y_d}, {\rm y_s}, {\rm y_b})$



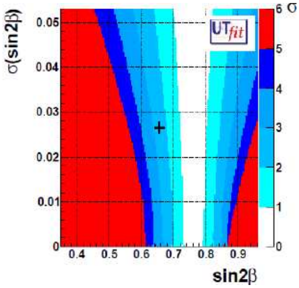
Messages from the B-factories



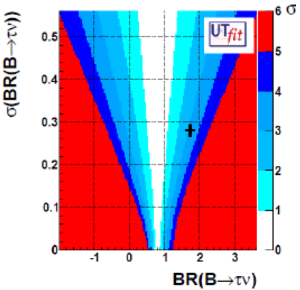
"Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism" (Nir)



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



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



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

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.

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 $B_{s,d}$, D decay/mixing

- **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**	$\lesssim 0.01$	$\lesssim \|0.2\|$	0.01	**LHCb**
$S_{B_d\to\phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	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}	$20\%\to5\%$	$< 4.5\times10^{-9}$	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]

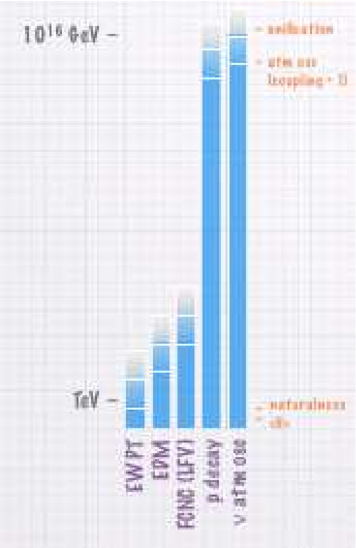
Superstars of 2011-2013 in flavour physics: $\mu\to e\gamma$, $B_s\to\psi\phi$, $B_{s,d}\to\mu^+\mu^-$

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

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]	$(-2.3 \pm 1.6)\%$ [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]	$(1.5 \pm 2.4)\,10^{-4}$

The NP “scale”

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



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

SM = effective theory at the EW scale

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

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

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

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

- **Theory:**

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

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

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

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

- **Experiments:**

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

- **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**

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\rm exp} \lesssim 4.5 \times 10^{-9}$$ [LHCb '12]

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

Obs.	[46]	[47]	[16]	[48-50]	[51]	most sensitive to
F_L	$-S_2^c$	F_L		F_L	F_L	$C_{7,9,10}^{(\prime)}$
$A_{\rm FB}$	$\frac{3}{4}S_6^s$	$A_{\rm FB}$	$A_{\rm FB}$	$-A_{\rm FB}$	$-A_{\rm FB}$	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		$-\frac{2}{3}A_7^D$			$C_{7,10}^{(\prime)}$

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).

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

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

- **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 $B_d(\overline{B_d}) \to f$.

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

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

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

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

Scenario	$BR(B_s \to \mu^+\mu^-)$	$BR(B_s \to \tau^+\tau^-)$	$\lvert\langle A_7\rangle_{[1,6]}\rvert$	$\lvert\langle A_8\rangle_{[1,6]}\rvert$	$\lvert\langle A_9\rangle_{[1,6]}\rvert$	$\langle S_3\rangle_{[1,6]}$
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.

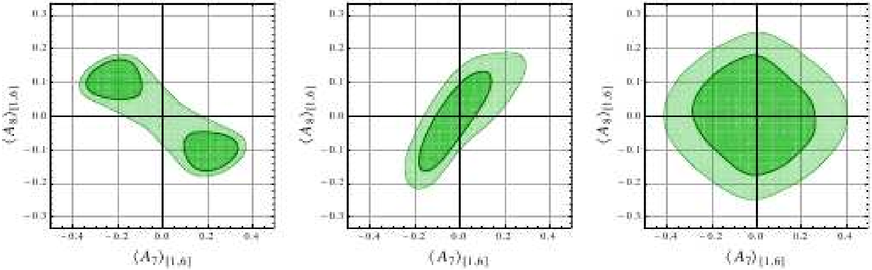


Figure 7: Fit predictions for the low-q^2 CP asymmetries $\langle A_{7,8} \rangle$ in $B \to K^* \mu^+ \mu^-$ in the case of complex left-handed currents (left), complex right-handed currents (centre) and generic NP (right). Shown are 68% and 95% C.L. regions.

Altmannshofer, P.P., Straub, '11

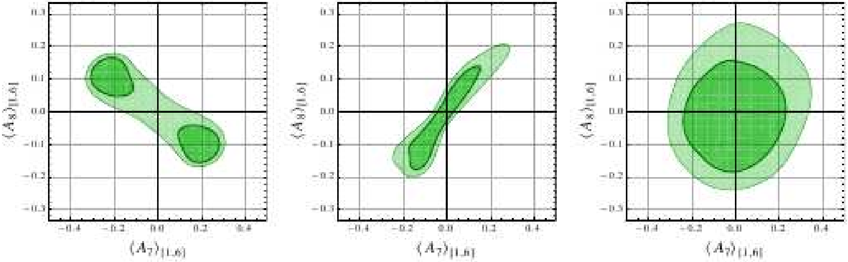
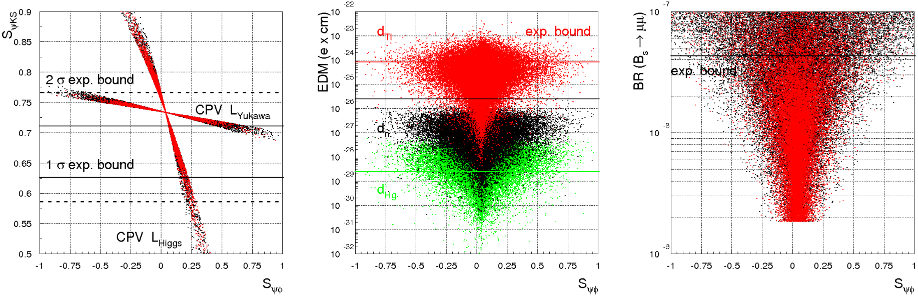


Figure 11: Fit predictions for the low-q^2 CP asymmetries $\langle A_{7,8} \rangle$ in $B \to K^* \mu^+ \mu^-$ for the scenario with left-handed (left), right-handed (centre) or generic (right) modified Z couplings. Shown are 68% and 95% C.L. regions.

Altmannshofer, P.P., Straub, '11

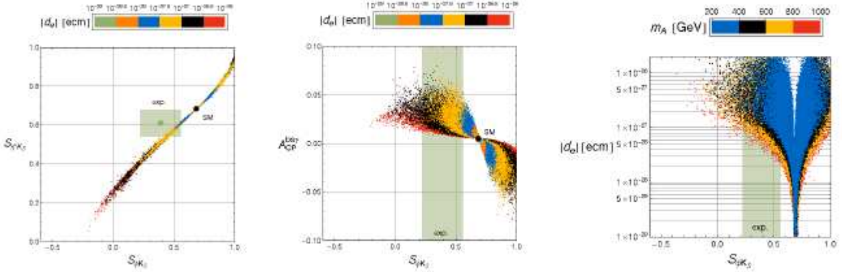
2HDM with MFV and “flavour blind” phases



- 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]

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]

RG induced Quark & Lepton FV interactions in SUSY GUTs

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

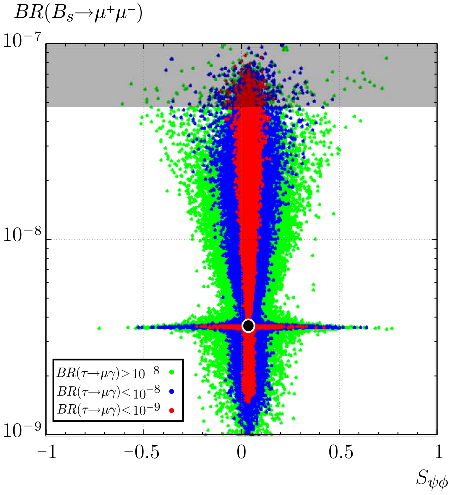
$$(\delta^{\tilde{q}}_{LL})_{ij} \sim h^u h^{u\dagger}{}_{ij} \sim h_t^2 V^{ik}_{CKM} V^{kj*}_{CKM} \rightarrow (\delta^{\tilde{\ell}}_{RR})_{ij} \simeq (\delta^{\tilde{q}}_{LL})_{ij}$$

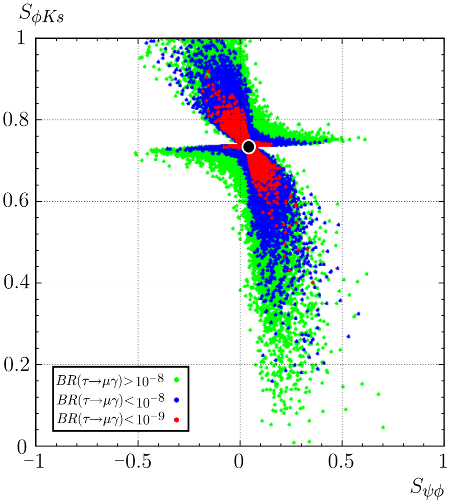
- **SUSY SU(5)+RN** [Yanagida et al., '95]

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

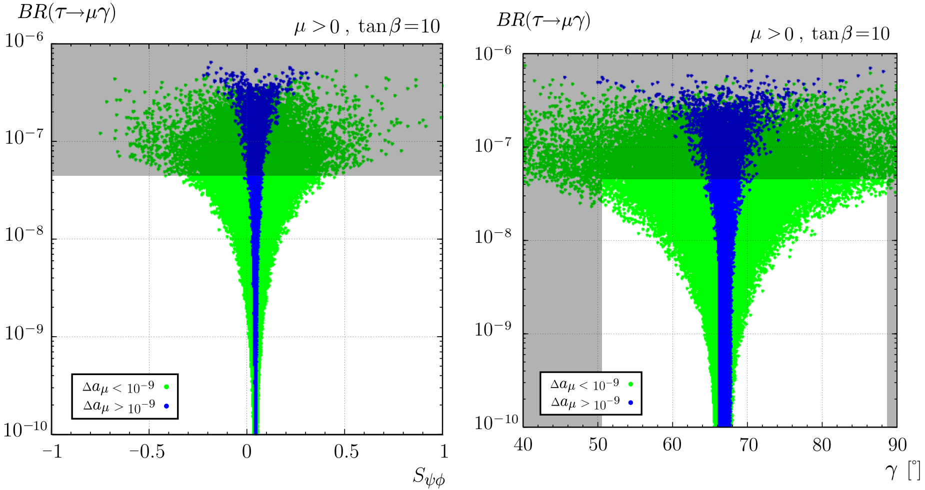
- **SUSY SU(5)+RN** [Moroi, '00] **&** **SO(10)** [Chang, Masiero & Murayama, '02]

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





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 SUSY 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: $M^2_{\tilde{d}} = \text{diag}(\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta^{LL}_d & \delta^{LR}_d \\ \delta^{RL}_d & \delta^{RR}_d \end{pmatrix}$
- δ^{LL}, δ^{RR}, δ^{LR} fixed by the flavour symmetry up to $O(1)$ factors

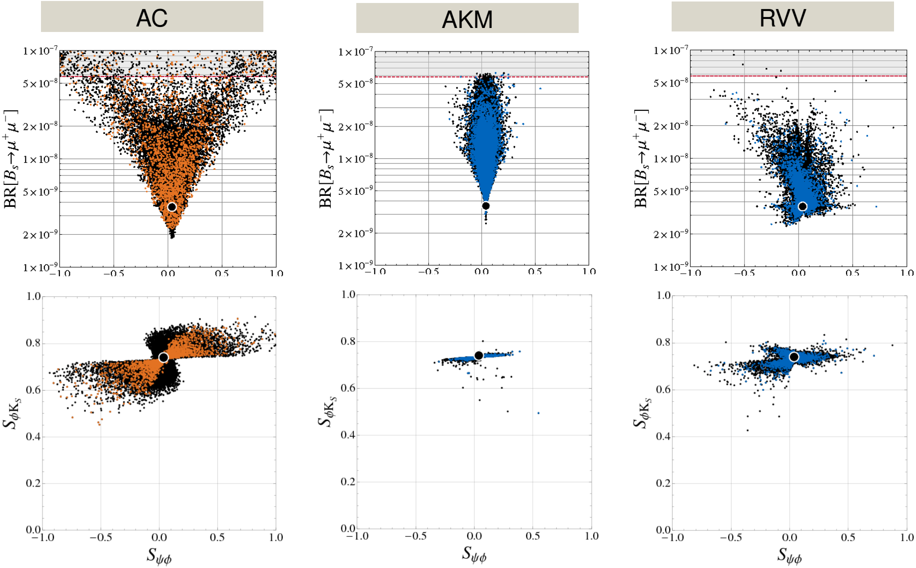
Representative flavour models

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

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

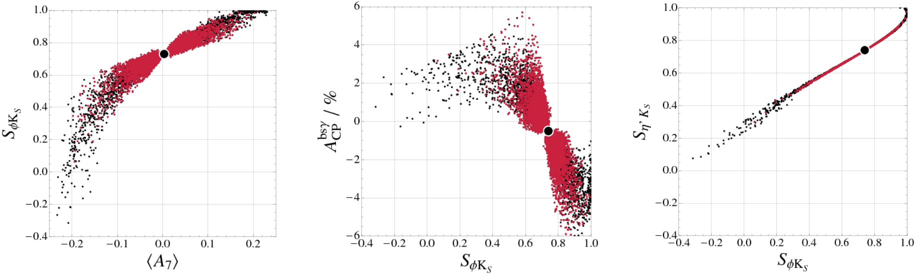
$b \to s$ transitions & SUSY flavor models [Altmannshofer et al., '09]



- 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:

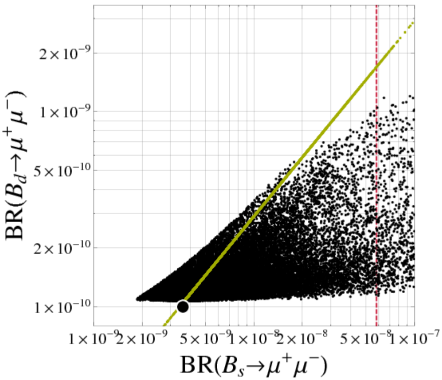
- No large effects in $S_{\psi\phi}$
- Large, correlated effects in $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{CP}(b \to s\gamma)$, $\langle A_{7,8} \rangle$ and EDMs
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \to K^* \ell^+ \ell^-$



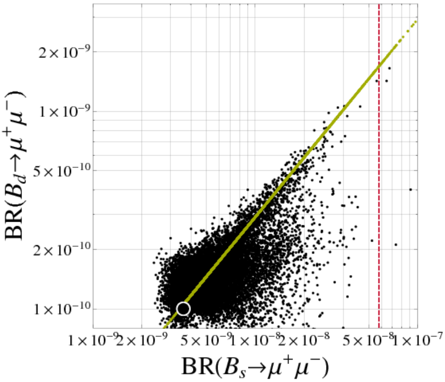
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$,

[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]

	SSU(5)	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	■	★★★	★★★	SuperB
$A_{\rm CP}\,(B \to X_s\gamma)$	■	■	■	■	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	■	■	■	■	■	■	
$\tau \to \mu\gamma$	★★★	★★★	★★★	■	★★★	★★★	
$D^0 - \bar{D}^0$	■	★★★	■	■	■	■	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]

- **Experiment:** $\Delta a_{CP} = a_{K^+K^-} - a_{\pi^+\pi^-}$

$$\Delta a_{CP} = -(0.82 \pm 0.21 \pm 0.11) \quad \text{[LHCb '11]}$$
$$\Delta a_{CP} = -(0.65 \pm 0.18) \quad \text{[LHCb '11, CDF '11, Belle '08 and BaBar '07]}$$

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

- **Theory**

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

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

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

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

- **Effective Hamiltonian**

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

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

- **Δa_{CP}: SM + NP**

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

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

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

- **Direct** "12″ **transition**

$$C_8^{(\tilde{g})} = -\frac{\sqrt{2}\pi\alpha_s\tilde{m}_g}{G_F m_c}\frac{(\delta_{12}^u)_{LR}}{\tilde{m}_q^2}\, g_8(x_{gq})\,, \qquad g_8(1) = -\frac{5}{36}$$

- **Effective** "12″ = "13″ × "32″ **transition: quasi-degenerate squarks**

$$C_8^{(\tilde{g})} = -\frac{\sqrt{2}\pi\alpha_s\tilde{m}_g}{G_F m_c}\frac{(\delta_{13}^u)_{LL}\,(\delta_{33}^u)_{LR}\,(\delta_{32}^u)_{RR}}{\tilde{m}_q^2}\, F(x_{gq})\,, \qquad F(1) = -\frac{11}{360}$$

- **Effective** "12″ = "13″ × "32″ **transition: split squark-families**

$$C_8^{(\tilde{g})} = -\frac{\sqrt{2}\pi\alpha_s\tilde{m}_g}{G_F m_c}\frac{(\delta_{13}^u)_{LL}\,(\delta_{33}^u)_{LR}\,(\delta_{32}^u)_{RR}}{\tilde{m}_{q_3}^2}\, g_8(x_{gq})$$

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

- **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**

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

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

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

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

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

D^0–$\bar{D}^0$ mixing

- **The D^0–$\bar{D}^0$ transition amplitude can be decomposed into a dispersive (M_{12}) and an absorptive (Γ_{12}) component:**

$$\langle D^0|\mathcal{H}_{\rm eff}|\bar{D}^0\rangle = M_{12}^D - \frac{i}{2}\Gamma_{12}^D\,.$$

- **Physical parameters**

$$x_{12} \equiv 2\frac{|M_{12}^D|}{\Gamma^D}\,, \quad y_{12} \equiv \frac{|\Gamma_{12}^D|}{\Gamma^D}\,, \quad \phi_{12} \equiv \arg\left(\frac{M_{12}^D}{\Gamma_{12}^D}\right)\,,$$

- **The 95% C.L. allowed ranges by HFAG are**

$$x_{12} \in [0.25,\, 0.99]\,\%\,, \qquad y_{12} \in [0.59,\, 0.99]\,\%\,, \qquad \phi_{12} \in [-7.1^\circ,\, 15.8^\circ]\,,$$

- **Effective Hamiltonian**

$$\mathcal{H}_{\rm eff}^{\Delta C=2} = \frac{1}{(1\ {\rm TeV})^2}\sum_i z_i Q_i^{cu} + {\rm H.c.}\,,$$

$$Q_2^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta\,, \qquad Q_3^{cu} = \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha\,,$$
$$Q_4^{cu} = \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta\,, \qquad Q_5^{cu} = \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha\,,$$

$$|z_2| < 1.6\times 10^{-7}\,, \qquad |z_3| < 5.8\times 10^{-7}\,,$$
$$|z_4| < 5.6\times 10^{-8}\,, \qquad |z_5| < 1.6\times 10^{-7}\,,$$

Δa_{CP} vs. D^0–$\bar{D}^0$ & ϵ'/ϵ in SUSY

- Δa_{CP}

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

- **D^0–$\bar{D}^0$ mixing**

$$z_2^{(\tilde{g})} \approx -5\times 10^{-10}\left(\frac{\rm TeV}{m_{\tilde{q}}}\right)^2\left[\frac{(\delta^u_{12})_{RL}}{1\times 10^{-3}}\right]^2,$$

$$z_4^{(\tilde{g})} \approx -2\times 10^{-10}\left(\frac{\rm TeV}{m_{\tilde{q}}}\right)^2\frac{(\delta^u_{12})_{LR}\,(\delta^u_{12})_{RL}}{(1\times 10^{-3})^2},$$

- ϵ'/ϵ

$$\frac{\epsilon'/\epsilon}{(\epsilon'/\epsilon)_{SM}} \sim \frac{(\delta^u_{12})_{LR}\,(\delta^u_{22})_{RL}}{\lambda^5}\frac{M_W^2}{\tilde{m}^2} \sim \frac{m_c^2 M_W^2}{\tilde{m}^4}\frac{A^2\theta^u_{12}}{\lambda^5},$$

- Values of $(\delta^u_{12})_{LR,RL} \sim 10^{-3}$ leading to $\Delta a_{CP} \approx 0.6\%$ are well below the current bounds from $D^0 - \bar{D}^0$ mixing
- NP contribution to ϵ'/ϵ are generated through loops of charginos and up-squarks, but they are suppressed by $(\delta^u_{12})_{LR}\,(\delta^u_{22})_{RL}\,/\tilde{m}^2 \sim m_c^2/\tilde{m}^4$ and therefore they remains insignificant, even for $(\delta^u_{12})_{LR} \sim 10^{-3}$.

- **Disoriented A terms**

$$(\delta^q_{ij})_{LR} \sim \frac{A\theta^q_{ij} m_{q_j}}{\tilde{m}} \qquad q = u, d \,,$$

	θ^q_{11}	θ^q_{12}	θ^q_{13}	θ^q_{23}
q=d	< 0.2	< 0.5	< 1	–
q=u	< 0.2	–	< 0.3	< 1

[G.F.Giudice, G.Isidori, & P.P, ’12]

- Down-quark FCNC (in particular ϵ'/ϵ and $b \to s\gamma$) are under control thanks to the smallness of m_{down}
- EDMs are suppressed by $m_{u,d}$ (yet they are quite enhanced)
- Up-quark FCNC (induced by gluino & up-squarks) and Down-quark FCNC like $K \to \pi\nu\nu$ and $B_{s,d} \to \mu\mu$ (induced by charginos & up-squarks) receive the largest effects from disoriented A terms.

Δa_{CP} in SUSY alignment models

- In SUSY alignment models it turns out that

$$\left(\delta^u_{21}\right)^{\rm eff}_{RL} = \left(\delta^u_{22}\right)_{RL}\left(\delta^u_{21}\right)_{LL} \sim \frac{Am_c}{\tilde{m}}\lambda.$$

- $(\delta^u_{21})_{LL} \sim \lambda$ arises from the $SU(2)$ relation $\tilde{M}^{(u)2}_{LL} = V\tilde{M}^{(d)2}_{LL}V^\dagger$ and the assumption of non-degeneracy for different squark families

$$(\tilde{M}^{(u)2}_{LL})_{21} \approx (\tilde{M}^{(d)2}_{LL})_{21} + \lambda\left[(\tilde{M}^{(d)2}_{LL})_{22} - (\tilde{M}^{(d)2}_{LL})_{11}\right] \,.$$

$$\left(\delta^u_{21}\right)_{LL} \approx \lambda\,\frac{\Delta\tilde{m}^2_{21}}{\tilde{m}^2}\,,$$

- The bounds from D–$\bar{D}$ mixing imply $|\,(\delta^u_{21})_{LL}\,| < 3\times 10^{-2}$ for TeV squarks, and $(\delta^u_{22})_{RL} \approx Am_c/\tilde{m} < 10^{-3}$ from vacuum stability.

- Therefore, in SUSY alignment models $\Delta a^{\rm SUSY}_{CP}$ is predicted to be well below the central LHCb value.

Δa_{CP} in SUSY with split squark families

- **Δa_{CP} in the split family scenario**

$$\Delta a_{CP} \approx 2 \times \mathrm{Im}\, C_8^{(\tilde{g})} = -\frac{2\sqrt{2}\pi\alpha_s \tilde{m}_g}{G_F m_c} \frac{\mathrm{Im}\left[(\delta^u_{13})_{LL}\,(\delta^u_{33})_{LR}\,(\delta^u_{32})_{RR}\right]}{\tilde{m}^2_{q_3}}\; g_8(x_{gq})$$

- **EDMs in the split family scenario**

$$\left\{\frac{d_u}{e},\; d^c_u\right\} = -\frac{\alpha_s m_{\tilde{g}}}{2\pi \tilde{m}^2_{q_3}}\; f_3^{d_u, d^c_u}(x_{gq})\; \mathrm{Im}\left[(\delta^u_{13})_{LL}(\delta^u_{33})_{LR}(\delta^u_{31})_{RR}\right]\,,$$

- **Δa_{CP} vs. the neutron EDM in the split family scenario**

$$\left|\Delta a_{CP}^{\mathrm{SUSY}}\right| \approx 2 \times 10^{-3} \times \left|\frac{d_n}{3 \times 10^{-26}}\right| \left|\frac{\mathrm{Im}\,(\delta^u_{32})_{RR}}{0.2}\right| \left|\frac{10^{-3}}{\mathrm{Im}\,(\delta^u_{31})_{RR}}\right|\,.$$

where $(\delta^u_{33})_{RL} \approx A\, m_t/\tilde{m}$. A strong hierarchical structure in the off-diagonal terms of the RR up-squark mass matrix is required. This happens for instance models of alignment

$$(\delta^u_{ij})_{RR} \sim \frac{m_{u_i}/m_{u_j}}{|V_{ij}|} \;\Rightarrow\; \frac{(\delta^u_{31})_{RR}}{(\delta^u_{32})_{RR}} \sim \frac{m_u}{\lambda m_c} \sim 10^{-2}$$

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

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

- **Theory:**

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

$$S_{\psi K_S} = \sin(2\beta + 2\varphi_{B_d})\,, \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\varphi_{B_s})\,,$$

$$\sin(2\beta)_{\rm tree} = 0.775 \pm 0.035\,, \qquad \sin(2\beta_s)_{\rm tree} = 0.038 \pm 0.003 \qquad (\text{CKM fit}).$$

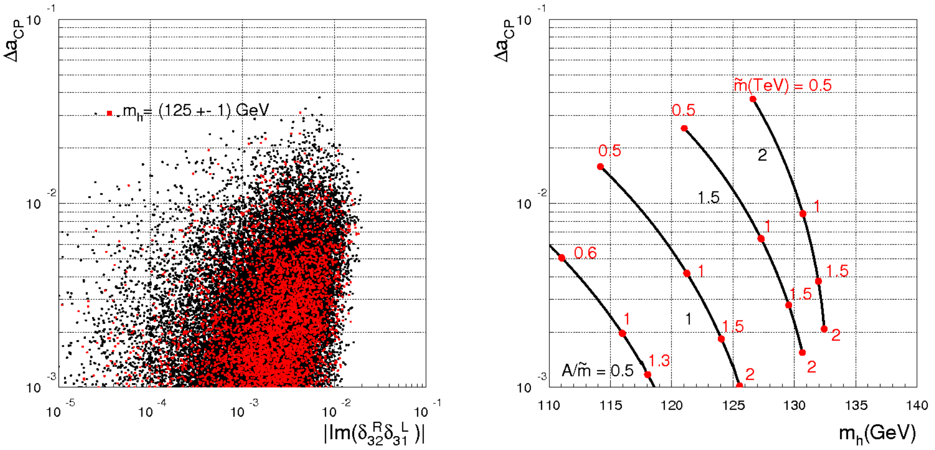
- **Experiments:**

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

- **Δa_{CP} vs. $S_{\psi K_S}$ in SUSY with split squark families**

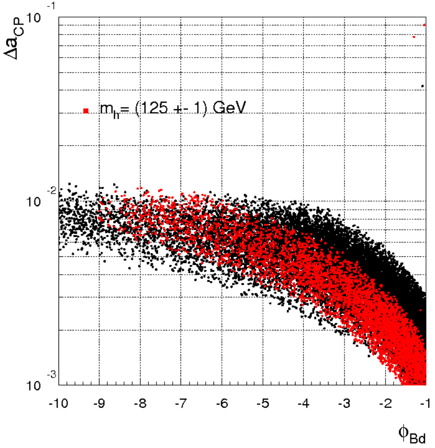
$$M_{12}^q \approx \left(M_{12}^q\right)^{\rm SM} \left[1 + \frac{\left(\delta_{3q}^d\right)_{LL}^2}{V_{tq}^2} F_0\right]\,, \qquad F_0 \approx \frac{1}{3}\left(\frac{g_s}{g}\right)^4 \frac{m_W^2}{\tilde{m}_{q_3}^2}$$

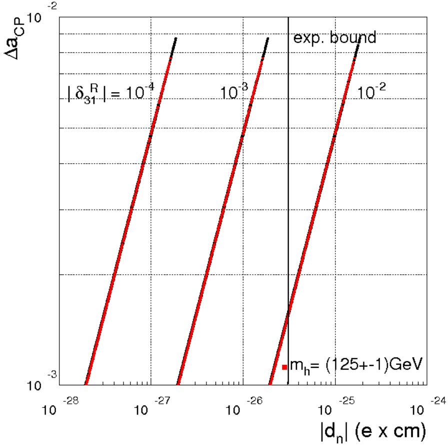
$$\Delta a_{CP} \sim {\rm Im}\left[\left(\delta_{13}^u\right)_{LL}\left(\delta_{33}^u\right)_{LR}\left(\delta_{32}^u\right)_{RR}\right]\,, \qquad (\Delta S_{\psi K_S})_{\rm NP} \sim {\rm Im}\left[\frac{\left(\delta_{31}^d\right)_{LL}^2}{V_{td}^2}\right]$$



Left: 0.5 $\text{TeV} \leq \tilde{m}, \tilde{m}_g \leq 2$ TeV, $\tan\beta = 10$, $|A| \leq 3$.
Right: $|\text{Im}[(\delta^u_{32})_{RR}(\delta^u_{31})_{LL}]| = 10^{-2}$, $\tilde{m} \leq 2$ 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: $(\delta^u_{13})_{LL} = 10^{-2}$, $(\delta^u_{32})_{RR} = 0.2i$.

Top and stop phenomenology

- The effective $\Delta C = 1$ transition through stops opens up the possibility of observing flavor violations in the up-quark sector at the LHC.
  - **Production processes:** $pp \to \tilde{t}^* \tilde{u}_i$, where $\tilde{u}_i = \tilde{u}, \tilde{c}$. The rate for single $\tilde{u}_i$ production in association with a single stop is proportional to $(\delta^u_{i3})^2_{RR}$, since the mixings in the right-handed sector are larger then in the left sector.
  - **Flavor-violating stop decays**

$$\frac{\Gamma(\tilde{t} \to c\chi^0)}{\Gamma(\tilde{t} \to t\chi^0)} = \left|(\delta^u_{i3})_{RR}\right|^2 \left(1 - \frac{m_t^2}{\tilde{m}_t^2}\right)^{-2},$$

    where $u_i = u, c$ and χ^0 is the lightest neutralino.
  - **Flavor-violating gluino decays**

$$\frac{\Gamma(\tilde{g} \to \tilde{t} u_i)}{\Gamma(\tilde{g} \to \tilde{t} t)} = \left|(\delta^u_{i3})_{RR}\right|^2 \left[1 + O\left(\frac{m_t}{\tilde{m}_g}\right)\right].$$

    In models with split families, the gluino can decay only into $\tilde{g} \to \bar{t}\tilde{t},\ \bar{b}\tilde{b}$. Once we include flavor violation, the decay $\tilde{g} \to \bar{u}_i \tilde{t}$ is also allowed
  - **Flavor-violating top decays** [De Divitiis, Petronzio, Silvestrini, '97]

$$\mathrm{BR}(t \to qX) \sim \left(\frac{\alpha}{4\pi}\right)^2 \left(\frac{m_W}{m_{\mathrm{SUSY}}}\right)^4 |\delta^u_{3q}|^2$$

    where $m_{\mathrm{SUSY}} = \max(m_{\tilde{g}}, m_{\tilde{t}})$ for $X = \gamma, g, Z$ and $m_{\mathrm{SUSY}} = m_A$ for $X = h$. Even for $\delta^u_{3q} \sim 1$ and $m_{\mathrm{SUSY}} \gtrsim 3m_W$, $\mathrm{BR}(t \to qX) \lesssim 10^{-6}$.

New-physics scenarios with Z-mediated FCNC

- **Effective Lagrangian for FCNC couplings of the Z-boson to fermions**

$$\mathcal{L}_{\rm eff}^{Z-\rm FCNC} = -\frac{g}{2\cos\theta_W}\bar{F}_i\gamma^\mu\left[(g_L^Z)_{ij}\,P_L + (g_R^Z)_{ij}\,P_R\right] q_j\,Z_\mu + \text{ h.c.}$$

F can be either a SM quark ($F = q$) or some heavier non-standard fermion. If F is a SM fermion

$$(g_L^Z)_{ij} = \frac{v^2}{M_{\rm NP}^2}(\lambda_L^Z)_{ij} \qquad (g_R^Z)_{ij} = \frac{v^2}{M_{\rm NP}^2}(\lambda_R^Z)_{ij}$$

- **Direct CPV in charm**

$$\left|\Delta a_{CP}^{Z-\rm FCNC}\right| \approx 0.6\% \left|\frac{{\rm Im}\left[(g_L^Z)_{ut}^*(g_R^Z)_{ct}\right]}{2\times 10^{-4}}\right| \approx 0.6\% \left|\frac{{\rm Im}\left[(\lambda_L^Z)_{ut}^*(\lambda_R^Z)_{ct}\right]}{5\times 10^{-2}}\right| \left(\frac{1~\rm TeV}{M_{\rm NP}}\right)^4$$

- **Neutron EDM**

$$|d_n| \approx 3\times 10^{-26}\left|\frac{{\rm Im}\left[(g_L^Z)_{ut}^*(g_R^Z)_{ut}\right]}{2\times 10^{-7}}\right| e\,{\rm cm}$$

- **Top FCNC**

$${\rm Br}(t\to cZ) \approx 0.7\times 10^{-2}\left|\frac{(g_R^Z)_{tc}}{10^{-1}}\right|^2$$

Top FCNC

- **Effective Lagrangian**

$$
\begin{aligned}
-\mathcal{L}^{\rm eff} &= \frac{g}{2c_W}\,\bar{q}\gamma_\mu\left(g^{qt}_{ZL}P_L + g^{qt}_{ZR}P_R\right)tZ^\mu + \frac{e}{2m_t}\bar{q}\left(g^{qt}_{\gamma L}P_L + g^{qt}_{\gamma R}P_R\right)\sigma_{\mu\nu}tF^{\mu\nu} \\
&+ \frac{g_s}{2m_t}\bar{q}\left(g^{qt}_{gL}P_L + g^{qt}_{gR}P_R\right)\sigma_{\mu\nu}T^a tG^{a\mu\nu} + \bar{q}\left(g^{qt}_{hL}P_L + g^{qt}_{hR}P_R\right)tH + \mathrm{h.c.}
\end{aligned}
$$

- **Top FCNC decay widths**

$$
\begin{aligned}
\Gamma(t\to qZ) &= \frac{\alpha_2}{32c_W^2}|g^{qt}_Z|^2\frac{m_t^3}{m_Z^2}\left(1-\frac{m_Z^2}{m_t^2}\right)^2\left(1+2\frac{m_Z^2}{m_t^2}\right), \\
\Gamma(t\to q\gamma) &= \frac{\alpha}{4}|g^{qt}_\gamma|^2 m_t\,, \\
\Gamma(t\to qg) &= \frac{\alpha_s}{3}|g^{qt}_\gamma|^2 m_t\,, \\
\Gamma(t\to qH) &= \frac{m_t}{32\pi}|g^{qt}_h|^2\left(1-\frac{M_H^2}{m_t^2}\right)^2,
\end{aligned}
$$

where $|g^{qt}_X|^2 = (|g^{qt}_{XL}|^2 + |g^{qt}_{XR}|^2)$ with $X = Z,\gamma,g,h$.

New-physics scenarios with scalar-mediated FCNC

- **Effective Lagrangian for FCNC scalar couplings to fermions**

$$\mathcal{L}_{\rm eff}^{h-{\rm FCNC}} = -\bar{q}_i \left[(g_L^h)_{ij} \, P_L + (g_R^h)_{ij} \, P_R \right] q_j \; h + \text{ h.c.} \,,$$

$$(g_L^h)_{ij} = \frac{v^2}{M_{\rm NP}^2} (\lambda_L^h)_{ij} \,, \qquad (g_R^h)_{ij} = \frac{v^2}{M_{\rm NP}^2} (\lambda_R^h)_{ij} \,,$$

- **Direct CPV in charm**

$$\left| \Delta a_{CP}^{h-{\rm FCNC}} \right| \approx 0.6\% \left| \frac{{\rm Im}\left[(g_L^h)_{ut}^* (g_R^h)_{tc} \right]}{2 \times 10^{-4}} \right| \approx 0.6\% \left| \frac{{\rm Im}\left[(\lambda_L^h)_{ut}^* (\lambda_R^h)_{ct} \right]}{5 \times 10^{-2}} \right| \left(\frac{1 \ {\rm TeV}}{M_{\rm NP}} \right)^4 \,.$$

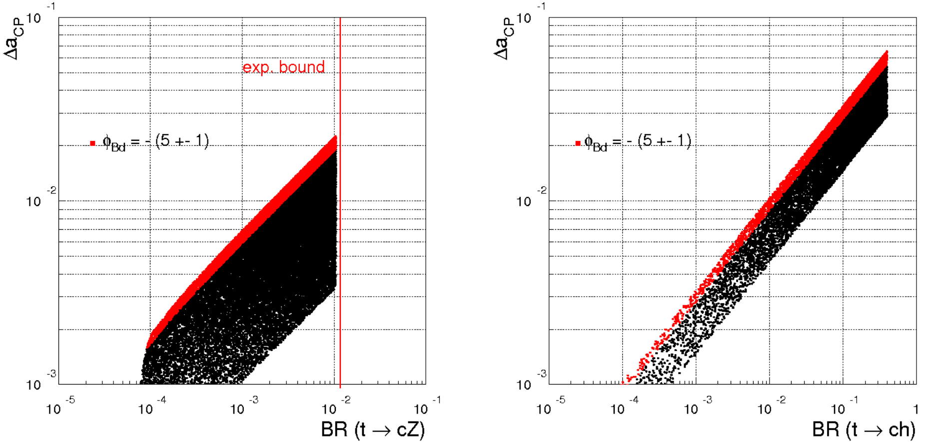
- **Neutron EDM**

$$|d_n| \approx 3 \times 10^{-26} \left| \frac{{\rm Im}\left[(g_L^h)_{ut}^* (g_R^h)_{tu} \right]}{2 \times 10^{-7}} \right| \; e\,{\rm cm} \,,$$

- **Top FCNC**

$${\rm Br}(t \to qh) \approx 0.4 \times 10^{-2} \left| \frac{(g_R^h)^{tq}}{10^{-1}} \right|^2 \,,$$

Δa_{CP} in scenarios with Z- and scalar-mediated FCNC [G.F.Giudice, G.Isidori, & P.P,



Left: $\mathrm{BR}(t \to cZ)$ vs. $\Delta a_{CP}^{Z-\mathrm{FCNC}}$. Right: $\mathrm{BR}(t \to ch)$ vs. $\Delta a_{CP}^{h-\mathrm{FCNC}}$. The plots have been obtained by means of the scan: $|(g_L^X)_{ut}| > 10^{-3}$, $|(g_R^X)_{ct}| > 10^{-2}$, where $X = Z, h$, with $\arg[(g_L^X)_{ut}] = \pm\pi/4$ and $\arg[(g_R^X)_{ct}] = 0$. The points in the red regions solve the tension in the CKM fits through a non-standard phase in B_d–$\bar{B}_d$ mixing, assuming for the corresponding down-type coupling $(g_L^X)_{db} = 5 \times 10^{-2} (g_L^X)_{ut}$.

CPV in D-physics

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

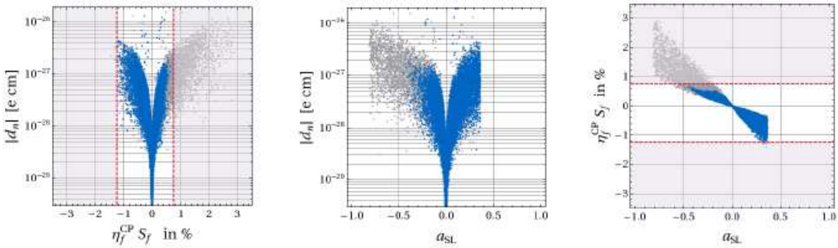


FIG. 3: Correlations between d_n and S_f (left), d_n and $a_{\rm SL}$ (middle) and $a_{\rm SL}$ and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

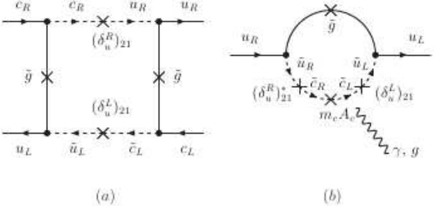


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

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.**
- **CPV in charm and rare B-decays will play a special role**