Phenomenology of CP violation in Supersymmetry

P. Paradisi

Physik Department
Technische Universitat Munchen

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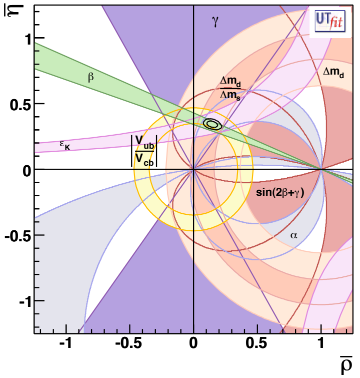
NP search strategies

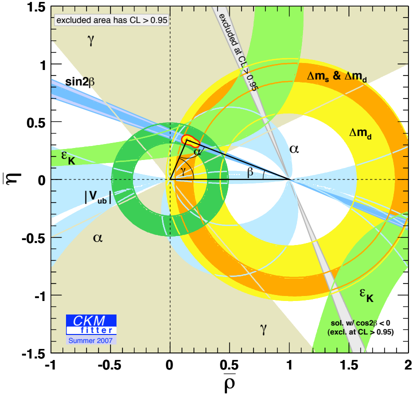
Where to look for New Physics at the low energy?

- **Processes very suppressed or even forbidden in the SM**
  - FCNC processes ($\mu \to e\gamma$, $\tau \to \mu\gamma$, $B^0_{s,d} \to \mu^+\mu^-$, $K \to \pi\nu\bar{\nu}$)
  - CPV effects in the electron/neutron EDMs, $d_{e,n}$...
  - FCNC & CPV in $B_{s,d}$ decay/mixing & D mixing amplitudes

- **Processes predicted with high precision in the SM**
  - EWPO as $\Delta\rho$, $(g-2)_\mu$....
  - LU in $R_M^{e/\mu} = \Gamma(K(\pi) \to e\nu)/\Gamma(K(\pi) \to \mu\nu)$

SM success in K and B_d systems

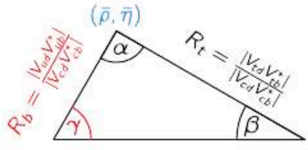


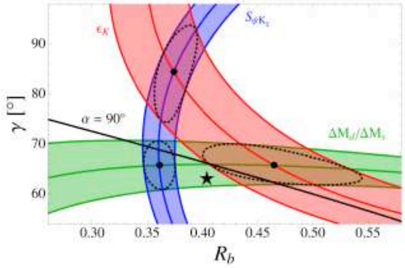


Very likely, flavour and CP violation in FC processes
are dominated by the CKM mechanism (Nir)

UT tensions

- Recent theoretical improvements in ϵ_K expose some tensions in the UT analysis [Lunghi & Soni, Buras & Guadagnoli]
- Look at ϵ_K, $S_{\psi K_S}$ (sin 2β), $\Delta M_d / \Delta M_s$ in the R_b-γ plane
- R_b, γ can be obtained from tree-level processes





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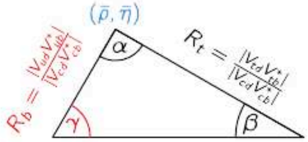

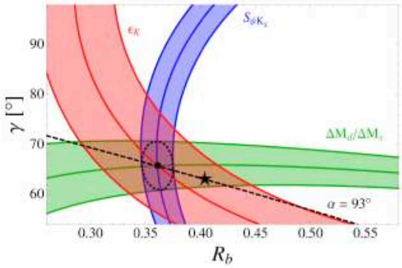

Possible solutions:

1. $+24\%$ NP effect in ϵ_K

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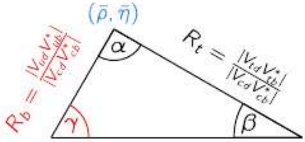

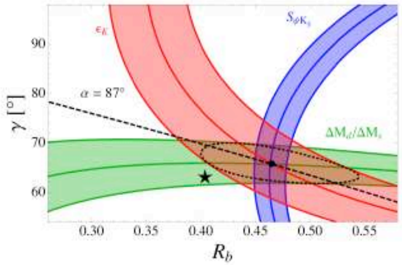

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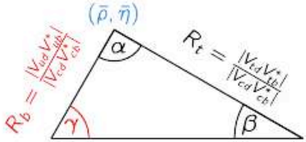
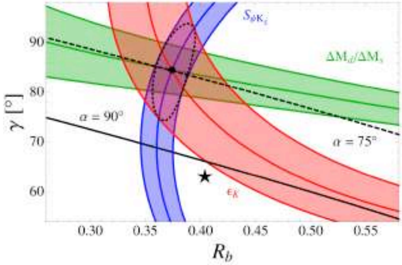




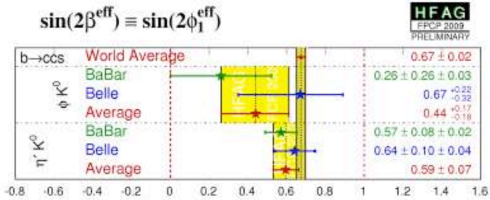
Possible solutions:

1. $+24\%$ NP effect in ϵ_K
2. $-6.5°$ NP phase in B_d mixing
3. -22% NP effect in $\Delta M_d / \Delta M_s$ (requiring $\alpha \sim 74°$)

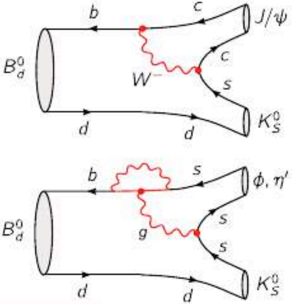
$\sin 2\beta_{eff}$ tensions

- In the SM, mixing-induced CP asymmetries in $B_d \to \psi K_S$, ϕK_S, $\eta' K_S$ all $\approx \sin 2\beta$
- $B_d \to \psi K_S$ dominated by tree level, ϕK_S and $\eta' K_S$ are loop-induced

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



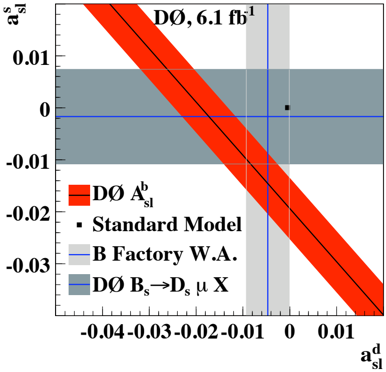
[adapted from HFAG]

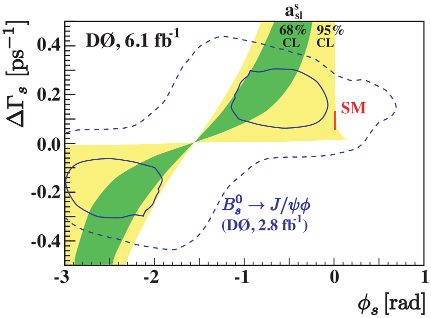


New physics in the decay amplitudes?

Can only be resolved at Super*B*

CPV in B_s mixing





$$S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s}) \, , \qquad A^q_{SL} \equiv \frac{\Gamma(\bar{B}_q \to l^+ X) - \Gamma(B_q \to l^- X)}{\Gamma(\bar{B}_q \to l^+ X) + \Gamma(B_q \to l^- X)}$$

New Physics in the B_s mixing phase?

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 (MSSM) have many CPV sources

- **CPV in the MSSM**
  - **"Flavour blind"** CPV phases $\mathrm{Im}(\mathrm{A_i M^*_{1/2}})$ & $\mathrm{Im}(\mathrm{B M^*_{1/2}})$

$$|\sin\phi_A| \leq 10^{-2}\left(\frac{m_{SUSY}}{100\mathrm{GeV}}\right)^2, \qquad |\sin\phi_B| \leq 10^{-3}\left(\frac{m_{SUSY}}{100\mathrm{GeV}}\right)^2 \frac{10}{\tan\beta}.$$

  - **"Flavoured"** CPV phases (**Hisano, Nagai, P.P., '06,'07,'08**)

$$J_{LL}^{(d_i)} = \mathrm{Im}\left\{[Y_u, \delta^q_{LL}]f_d\right\}_{ii}$$
$$J_{LR}^{(d_i)} = \mathrm{Im}\left\{\delta^q_{LL} f_d \delta^d_{RR}\right\}_{ii}$$
$$J_{RR}^{(d_i)} = \mathrm{Im}\left\{Y_u f_d \delta^d_{RR}\right\}_{ii}$$

where $Y_d \equiv f_d f_d^\dagger$ ($f_d =$ Yukawa coupling) and $(\delta^q_{AB})_{ij} \equiv (m^2_{\tilde{q}_{AB}})_{ij}/m_{\tilde{q}_A} m_{\tilde{q}_B}$

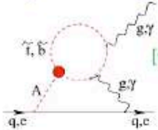
Solutions for the SUSY CP problem

- **How to solve (naturally) the SUSY CP problem?**
  - Decoupling some sparticles in the loop generating the EDMs (hierarchical sfermions, split SUSY, 2HDM limit...)
  - Generating the CPV phases radiatively
  - Suppressing the ”flavoured“ CPV phases by means of small flavour mixing angles

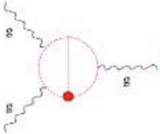
EDMs and “flavour blind” phases

MSSM parameter space: $phases < O(10^{-3} - 1)$

Decoupling 1st/2nd generation



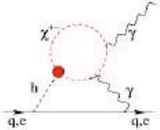
[Chang, Keung & Pilaftsis '98]



[Weinberg '89; Dai et al. 90]

Decoupling scalars (split SUSY, EW baryogenesis)

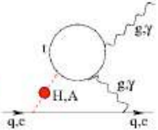
[Arkani-Hamed et al. '04]



Decoupling fermions

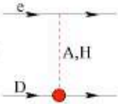
2 HDM

[Barr, Zee '92]

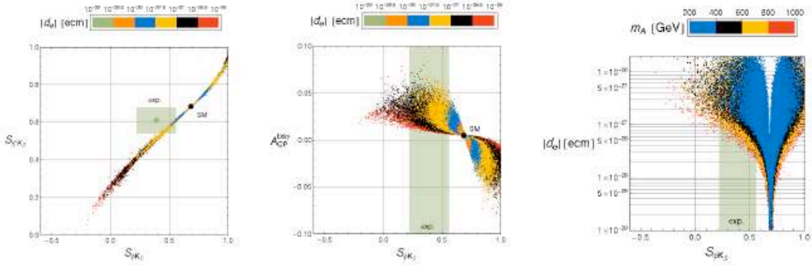


large tanβ

[Barr '92; Lebedev & Pospelov '02]



"Flavour blind" phases in the MFV MSSM



- 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)

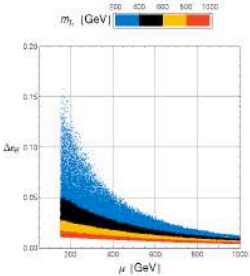
- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

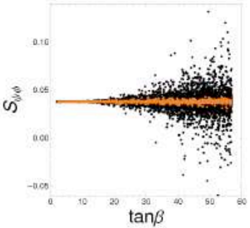
A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

"Flavour blind" phases in the MFV MSSM

① Kaon mixing

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

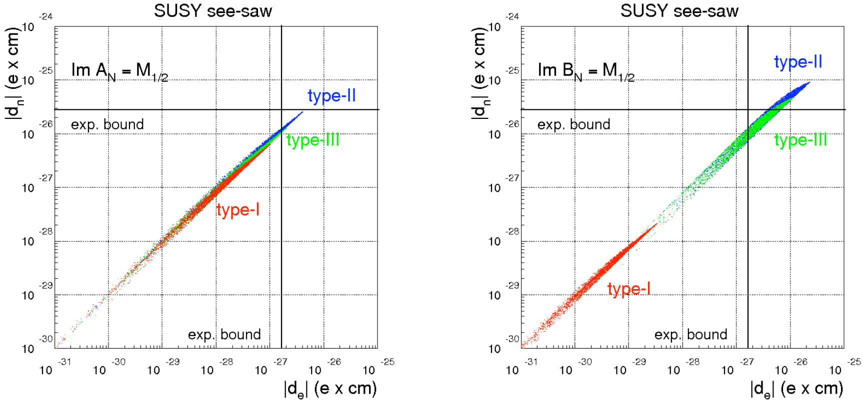




② B_d and B_s mixing

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

CPV in SUSY see-saw

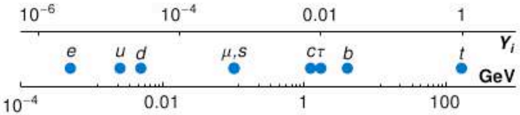


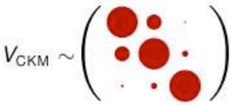
Radiative “flavour blind” CPV phases from the neutrino soft sector

Giudice, P.P. and Strumia, ’10

SUSY flavour models

Flavour violation is highly non-generic already in the SM!





The two problems should be related!

Minimal Flavour Violation (MFV)

- Yukawa couplings are the only sources of flavour violation
- Effective theory
- Pragmatic approach
- Pessimistic phenomenology

Flavour Models

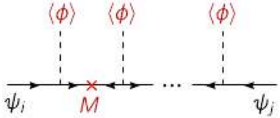
- Flavour structure of Yukawa couplings and soft terms generated by spontaneous breaking of a flavour symmetry
- Ambitious approach
- Diverse phenomenology

SUSY flavour models

Main idea: hierarchies in Yukawa couplings generated by spontaneous breakdown of flavour symmetry (horizontal symmetry, family symmetry)

- Generalization of the Froggat-Nielsen mechanism
- Yukawa hierarchies explained by different powers of small ϵ:

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



- Possible to relate Yukawa matrices and sfermion mass matrices/trilinear couplings

SUSY flavour models can explain the origin of the hierarchies in the Yukawa couplings *and* solve the SUSY flavour problem

- Many different viable models exist, with abelian or non-abelian flavour symmetries

Hp: CP is spontaneously broken in the flavour sector

Examples of flavour models

4 representative flavour models with different chirality structures in the $\tilde{d}$ sector:

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

AC model:

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

AKM model:

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

RVV model:

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

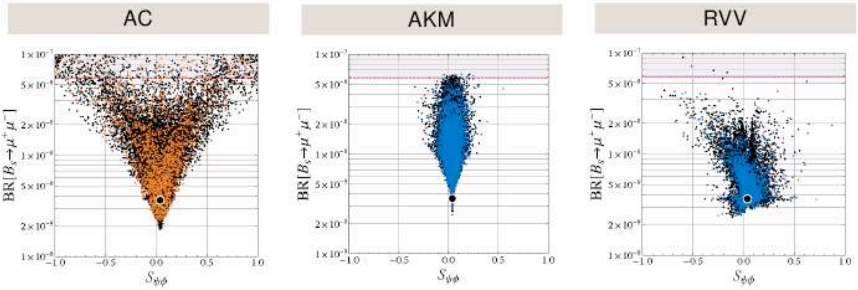
δLL model:

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

Altmannshofer et al. ’09,’10

$Br(B_s \rightarrow \mu^+\mu^-)$ vs. $S_{\psi\phi}$

- Both observables can deviate significantly from the SM in all 3 models
- large $S_{\psi\phi}$ $\Rightarrow$ large BR$(B_s \rightarrow \mu^+\mu^-)$ in the AC and AKM models
- Correlation arises from dominance of Higgs penguin contributions

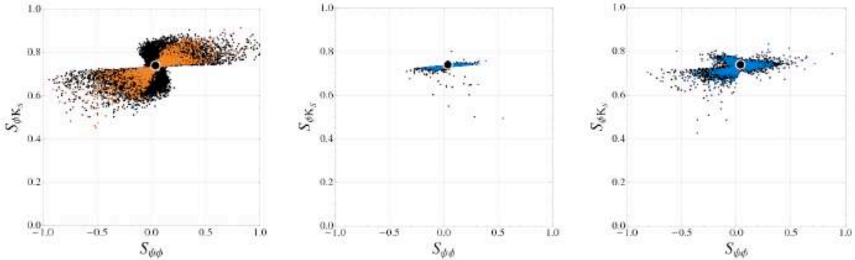


- Orange points: UT tension solved through contribution to $\Delta M_d / \Delta M_s$
- Blue points: UT tension solved through contribution to ϵ_K
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$, $O(1)$ parameters varied within $[\frac{1}{2}, 2]$

$S_{\phi K_S}$ vs. $S_{\psi\phi}$

- In the AC model, both $S_{\phi K_S}$ and $S_{\psi\phi}$ can have large effects, but a simultaneous *enhancement* of $S_{\psi\phi}$ and *suppression* of $S_{\phi K_S}$ (as indicated by the data) is impossible
- $S_{\phi K_S}$ nearly SM-like in AKM and RVV models

AC	AKM	RVV



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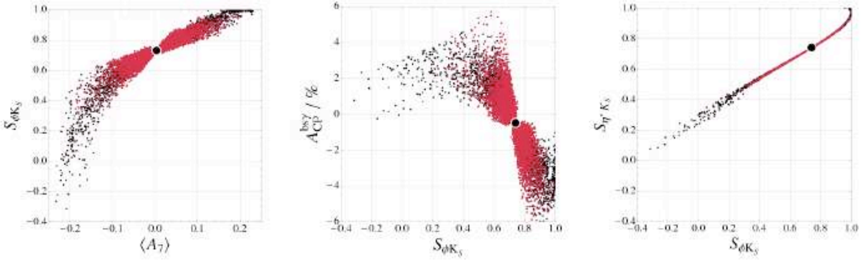
Model with purely left-handed currents

Pattern of NP effects in the δLL model:

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



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CPV in D-physics

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

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

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

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

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

CPV in D-physics vs. neutron EDM in SUSY

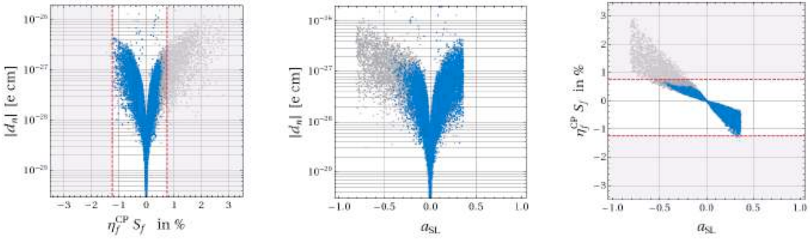

FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

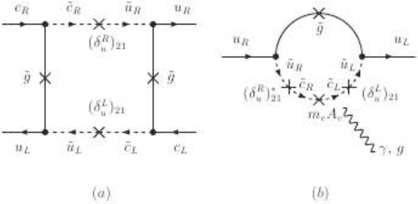

FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

"DNA-Flavour Test"

	GMSSM	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 vs. LHCb
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	★★★	★★★	
$A_9(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	■	■	
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	■	■	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	★★★	★★★	★★★	●●	■	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	

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