Unitary Triangle and New Physics

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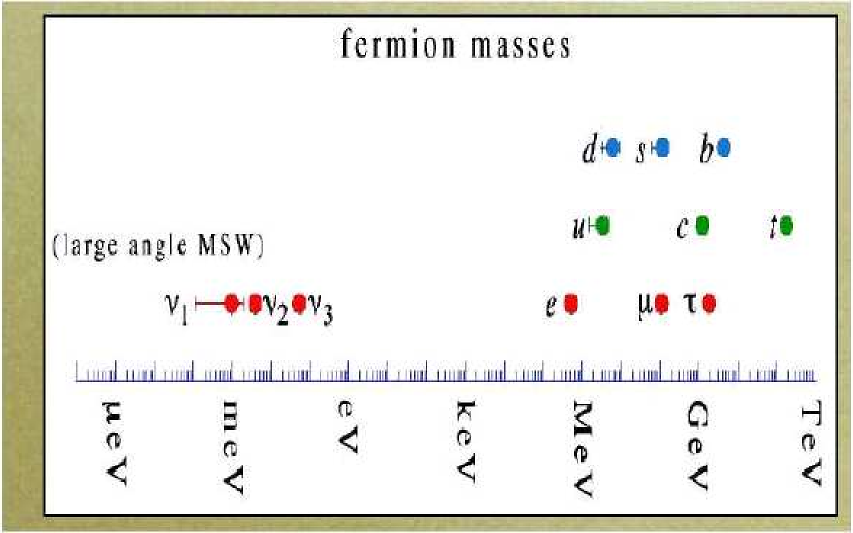
The fermion mass puzzle



SM flavour puzzle

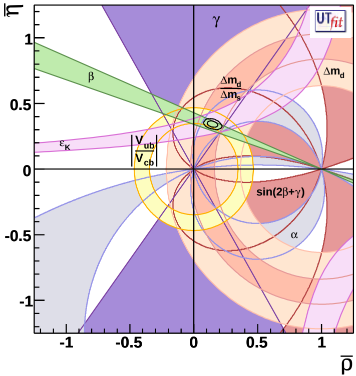
Smallness and Hierarchy

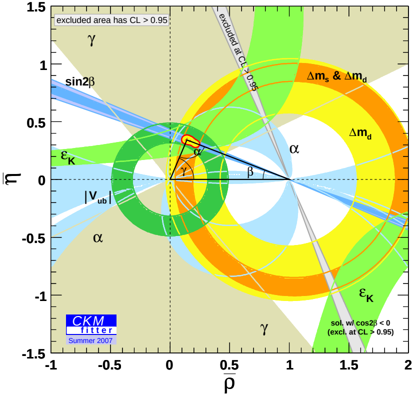
$$Y_t \sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5}$$
$$Y_b \sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4}$$
$$Y_\tau \sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6}$$
$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004, \quad \delta_{\rm KM} \sim 1$$

- For comparison: $g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda \sim 1$
- The SM flavor parameters have structure: smallness and hierarchy
- $\boxed{\text{Why?} = \text{The SM flavor puzzle}}$

Nir

SM success

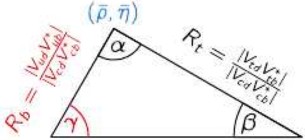


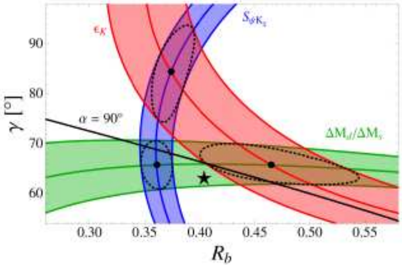


Very likely, flavour and CP violation in FC processes
are dominated by the CKM mechanism (Nir)

UT tensions

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





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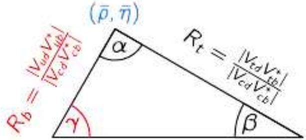

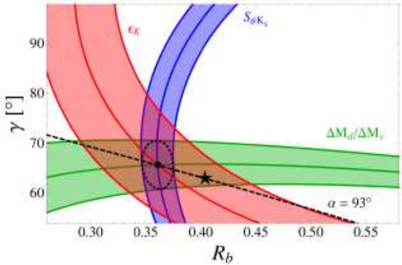

Possible solutions:

1. $+24\%$ NP effect in ϵ_K

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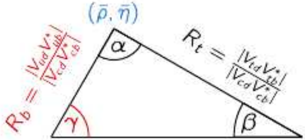

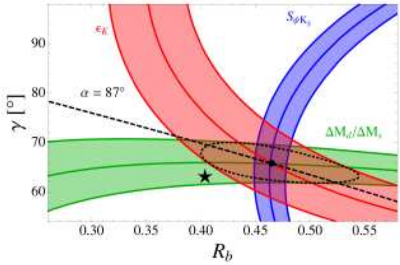

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1. $+24\%$ NP effect in ϵ_K
2. -6.5° NP phase in B_d mixing

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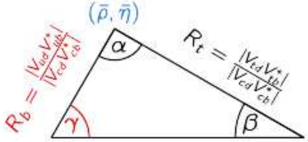

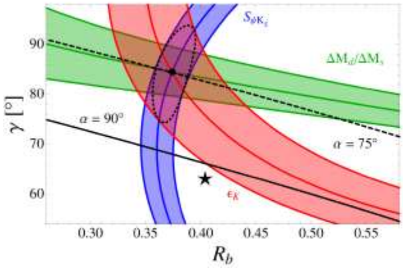

Possible solutions:

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

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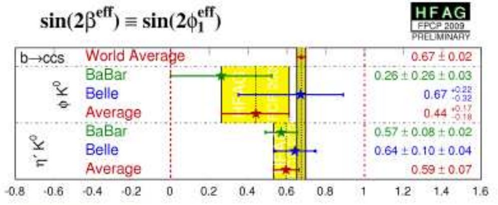
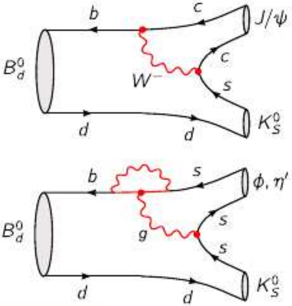
$\sin 2\beta_{eff}$ tensions

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

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



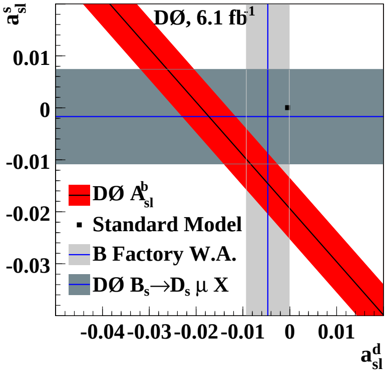
[adapted from HFAG]

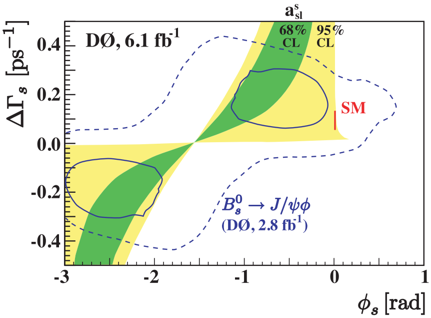


New physics in the decay amplitudes?

Can only be resolved at Super*B*

CPV in B_s mixing





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

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 have many CPV sources

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

Flavour Matrix

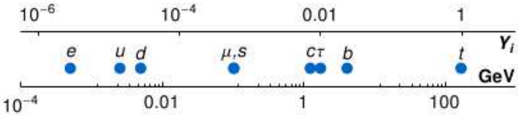
FLAVOUR COUPLING

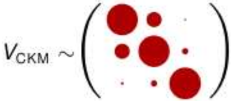
ELECTROWEAK STRUCTURE

	$b \to s$ [$\sim \lambda^2$ in SM]	$b \to d$ [$\sim \lambda^3$ in SM]	$s \to d$ [$\sim \lambda^5$ in SM]
ΔF=2 box	ΔM_{Bs} $A_{CP}(B_s \to \psi\phi)$, ϵ_{Bs}	ΔM_{Bd} $A_{CP}(B_d \to \psi K)$, ϵ_{Bd}	ϵ_K
ΔF=1 4-quark ops.	$A_{CP}(B_d \to \phi K)$	$A_{CP}(B_s \to \phi K)$	
gluon penguin	$A_{CP}(B_d \to \phi K)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ \gamma)$	$\Gamma(K_L \to \pi^0 \ell\ell)$
γ penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to X_s \ell\ell)$ $A_{FB}(B \to X_s \ell\ell)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ \ell\ell)$ $A_{FB}(B \to \rho/\pi\ \ell\ell)$	$\Gamma(K_L \to \pi^0 \ell\ell)$
Z^0 penguin	$[\Gamma, \Delta\Gamma_{CP}](B \to X_s \ell\ell)$ $A_{FB}(B \to X_s \ell\ell)$ $\Gamma(B_s \to \mu\mu)$	$[\Gamma, \Delta\Gamma_{CP}](B \to \rho/\pi\ \ell\ell)$ $A_{FB}(B \to \rho/\pi\ \ell\ell)$ $\Gamma(B_d \to \mu\mu)$	$\Gamma(K^+ \to \pi^+ \nu\nu)$ $\Gamma(K_L \to \pi^0 \nu\nu)$ $\Gamma(K_L \to \pi^0 \ell\ell)$
H^0 penguin	$\Gamma(B_s \to \mu\mu)$	$\Gamma(B_d \to \mu\mu)$	

SM vs. SUSY flavour problems

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

Minimal Flavour Violation

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

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

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

Yukawa structures as the only sources of flavour violation

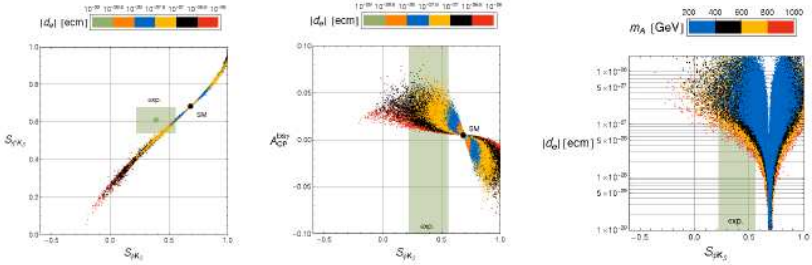
$$\Downarrow$$

Minimal Flavour Violation

MFV allows for new “flavour blind” CPV phases!

Altmannshofer, Buras and P.P., ’08

Flavor blind MSSM ≈ MFV + CPV



- 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)

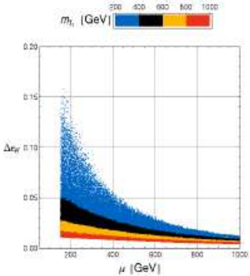
- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

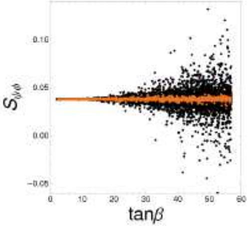
A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

Phenomenology of the flavor blind 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

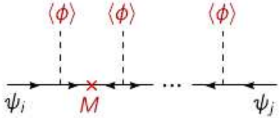
- Leading NP contributions to $M_{12}^{d,s}$ are insensitive to the new phases of a FBMSSM. (at least for moderate tan β ...)
- For large tan β, the constraint from $b \to s\gamma$ does not allow for sizeable effects
- $S_{\psi K_S}$ and $S_{\psi\phi}$ are SM like ($S_{\psi\phi} \simeq 0.03 - 0.05$)

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

Abelian vs. non-Abelian flavour models

Abelian vs. Non-abelian

- In most non-abelian models, 1st & 2nd generatio sfermions are approximately degenerate
  - Suppressed contributions to $1 \leftrightarrow 2$ transitions, in particular D^0-$\bar{D}^0$ mixing
- In abelian models, sfermions of different generations need not be degenerate
  - $O(1)$ 1-2 mass splitting leads to $O(\lambda)$ $(\delta_u^{LL})_{12}$ in the SCKM basis
  - Large effects in D^0-$\bar{D}^0$ mixing

Chirality structure of flavour violating terms

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

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

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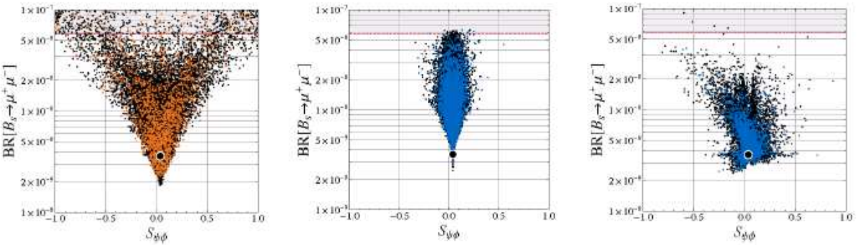
$Br(B_s \to \mu^+\mu^-)$ vs. $S_{\psi\phi}$

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

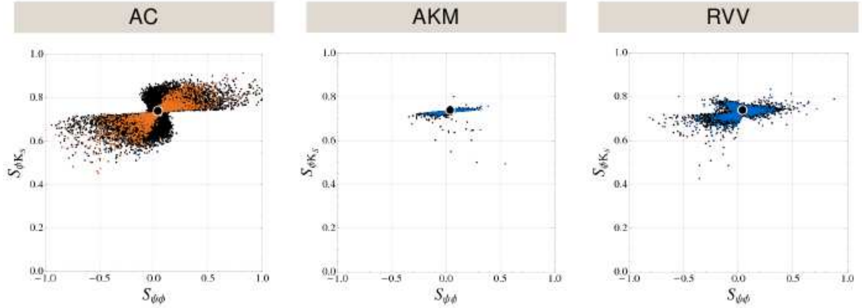
AC	AKM	RVV



- 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



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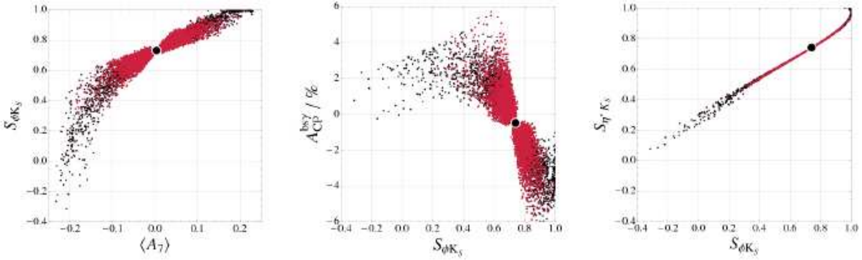
Model with purely left-handed currents

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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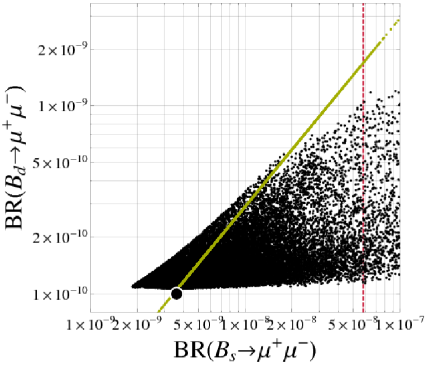
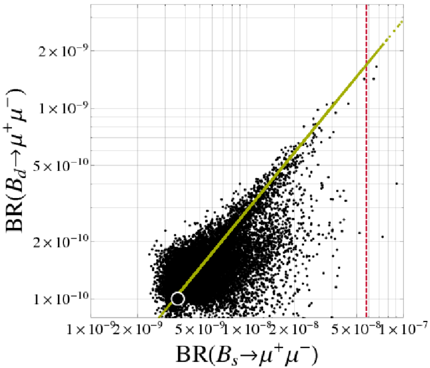
$Br(B_s \to \mu^+\mu^-)$ vs. $Br(B_d \to \mu^+\mu^-)$

Abelian (AC)



Non abelian (RVV)



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

CPV in D-physics

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

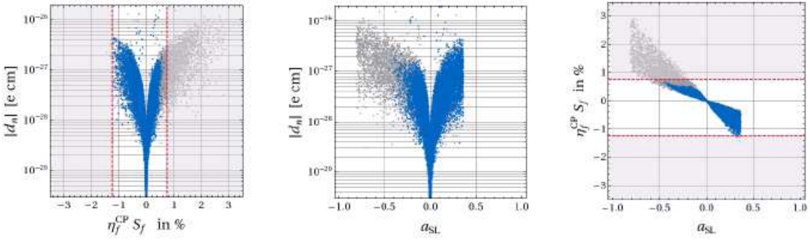


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

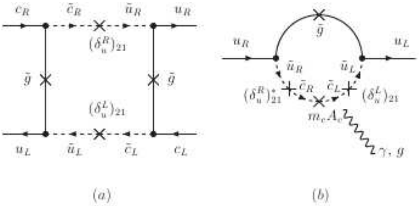


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

"DNA-Flavour Test"

	GMSSM	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	■	★★★	★★★	
$A_{CP}(B \to X_s\gamma)$	★★★	■	■	■	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	●●	■	■	■	■	■	
$\tau \to \mu\gamma$	★★★	★★★	★★★	■	★★★	★★★	
$D^0 - \bar{D}^0$	★★★	★★★	■	■	■	■	
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	★★★	★★★	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	★★★	★★★	★★★	●●	■	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	

Altmannshofer et al. '09

Isidori's view

▸ *Flavour physics in the LHC era*

LHC [high p_T]

A *unique* effort toward the high-energy frontier

[to determine the energy scale of NP]

Flavour physics

Improved CKM fits

Rare B decays

CPV in the Bs system

LFV in μ & τ decays

Universality tests in B & K

EDMs

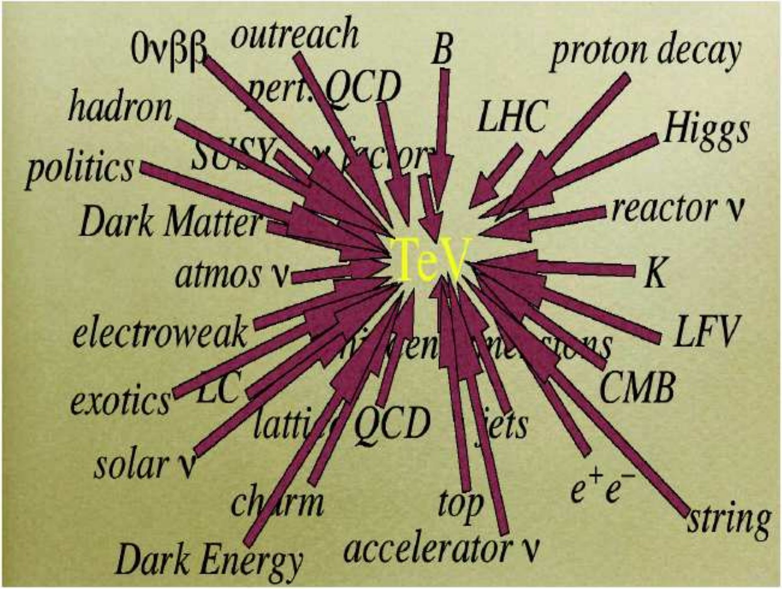
Rare K decays

g-2

A *collective* effort toward the high-intensity frontier

[to determine the flavour structure of NP]

Murayama’s view



Masiero’s view