

Flavour Physics in SUSY extensions of the SM in the LHC era

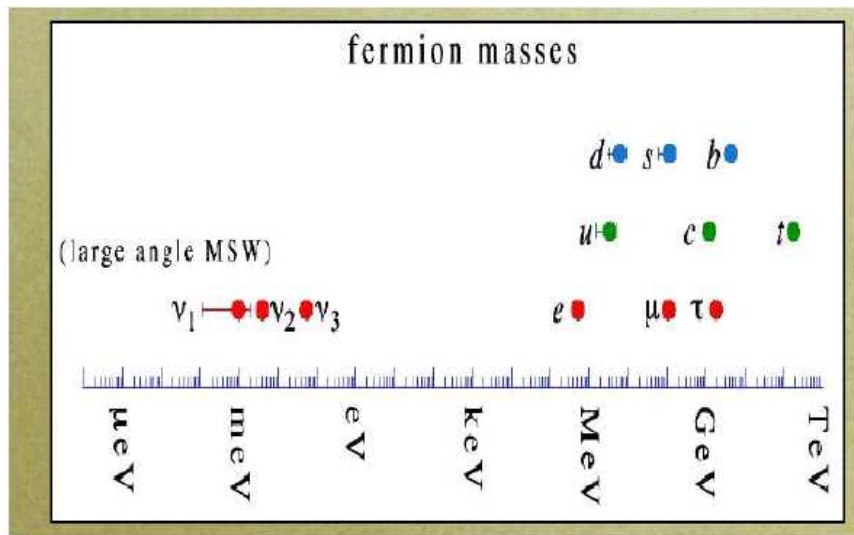
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Third Workshop on Theory, Phenomenology and Experiments in
Heavy Flavour Physics 2010
Capri, Italy
5-7 July, 2010

The fermion mass puzzle



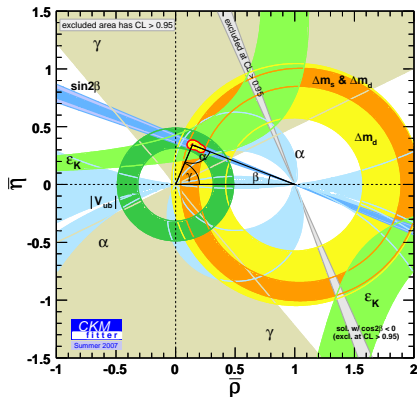
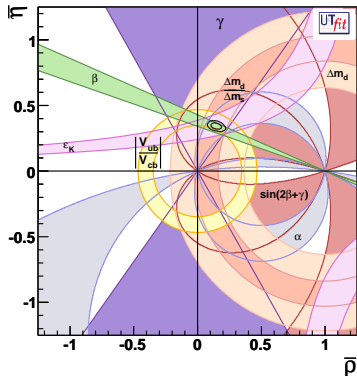
Smallness and Hierarchy

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

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

Nir

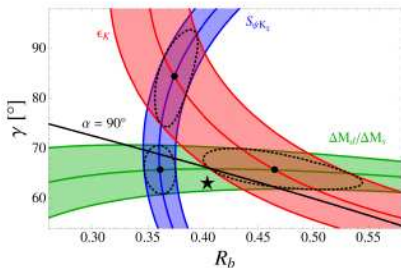
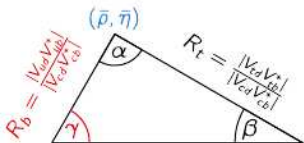
SM success



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

UT tensions

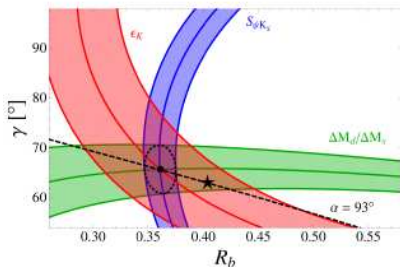
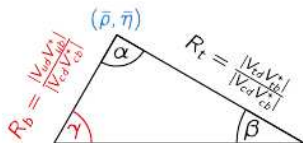
- Recent theoretical improvements in ϵ_K expose some tensions in the UT analysis [Lunghi & Soni, Buras & Guadagnoli]
- Look at ϵ_K , $S_{\psi K_S}$ ($\sin 2\beta$), $\Delta M_d / \Delta M_s$ in the R_b - γ plane
- R_b , γ can be obtained from tree-level processes



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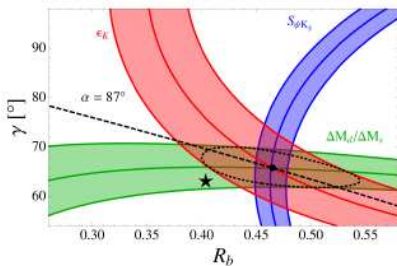
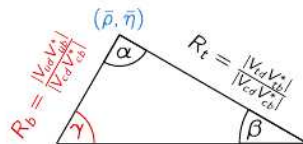
Possible solutions:

- 1 +24% NP effect in ϵ_K

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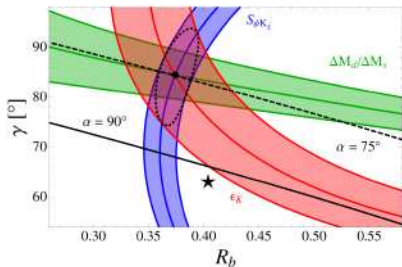
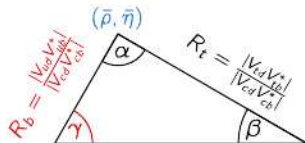
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- +24% NP effect in ϵ_K
- -6.5° NP phase in B_d mixing

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Possible solutions:

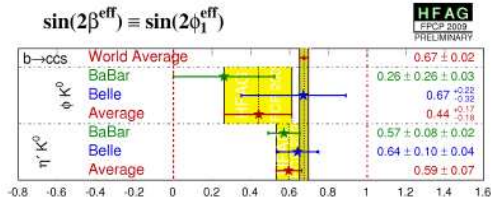
- 1 +24% NP effect in ϵ_K
- 2 -6.5° NP phase in B_d mixing
- 3 -22% NP effect in $\Delta M_d / \Delta M_s$ (requiring $\alpha \sim 74^\circ$)

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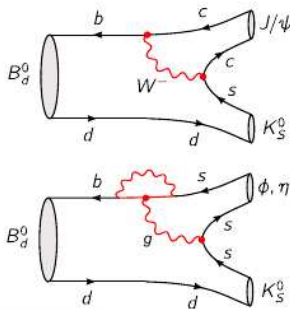
$\sin 2\beta_{\text{eff}}$ tensions

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

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



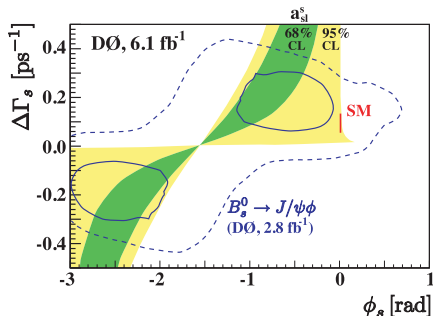
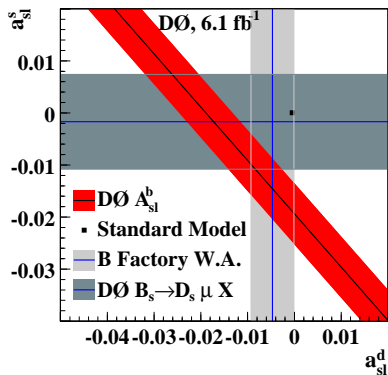
[adapted from HFAG]



New physics in the decay amplitudes?

Can only be resolved at SuperB

CPV in B_s mixing



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

$$A_{SL}^q \equiv \frac{\Gamma(\bar{B}_q \rightarrow l^+ X) - \Gamma(B_q \rightarrow l^- X)}{\Gamma(\bar{B}_q \rightarrow l^+ X) + \Gamma(B_q \rightarrow l^- X)}$$

New Physics in the B_s mixing phase?

Why CP violation?

- **Motivation:**

- **Baryogenesis** requires extra sources of CPV
- The QCD $\bar{\theta}$ -term $\mathcal{L}_{CP} = \bar{\theta} \frac{\alpha_s}{8\pi} G\tilde{G}$ is a CPV source beyond the CKM
- Most UV completion of the SM have many CPV sources

Where to look for **New Physics** at the low energy?

- Processes very **suppressed** or even **forbidden** in the SM

- **FCNC** processes ($\mu \rightarrow e\gamma$, $\tau \rightarrow \mu\gamma$, $B_{s,d}^0 \rightarrow \mu^+\mu^-$, $K \rightarrow \pi\nu\bar{\nu}$)
- **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

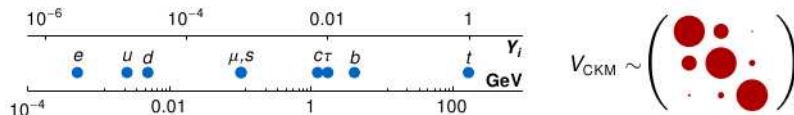
- **EWPO** as $\Delta\rho$, $(g-2)_\mu...$
- **LU** in $R_M^{e/\mu} = \Gamma(K(\pi) \rightarrow e\nu)/\Gamma(K(\pi) \rightarrow \mu\nu)$

Flavour Matrix

		FLAVOUR COUPLING		
		$b \rightarrow s$ [$\sim \lambda^2$ in SM]	$b \rightarrow d$ [$\sim \lambda^3$ in SM]	$s \rightarrow d$ [$\sim \lambda^5$ in SM]
ELECTROWEAK STRUCTURE	$\Delta F=2$ box	ΔM_{B_s} $A_{CP}(B_s \rightarrow \psi\phi), \epsilon_{B_s}$	ΔM_{B_d} $A_{CP}(B_d \rightarrow \psi K), \epsilon_{B_d}$	ϵ_K
	$\Delta F=1$ 4-quark ops.	$A_{CP}(B_d \rightarrow \phi K)$	$A_{CP}(B_s \rightarrow \phi K)$	
	gluon penguin	$A_{CP}(B_d \rightarrow \phi K)$ $[\Gamma, \Delta\Gamma_{CP}](B \rightarrow X_s \gamma)$	$[\Gamma, \Delta\Gamma_{CP}](B \rightarrow \rho/\pi \gamma)$	$\Gamma(K_L \rightarrow \pi^0 l l)$
	γ penguin	$[\Gamma, \Delta\Gamma_{CP}](B \rightarrow X_s \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \rightarrow X_s l l)$ $A_{FB}(B \rightarrow X_s l l)$	$[\Gamma, \Delta\Gamma_{CP}](B \rightarrow \rho/\pi \gamma)$ $[\Gamma, \Delta\Gamma_{CP}](B \rightarrow \rho/\pi l l)$ $A_{FB}(B \rightarrow \rho/\pi l l)$	$\Gamma(K_L \rightarrow \pi^0 l l)$
	Z^0 penguin	$[\Gamma, \Delta\Gamma_{CP}](B \rightarrow X_s l l)$ $A_{FB}(B \rightarrow X_s l l)$ $\Gamma(B_s \rightarrow \mu\mu)$	$[\Gamma, \Delta\Gamma_{CP}](B \rightarrow \rho/\pi l l)$ $A_{FB}(B \rightarrow \rho/\pi l l)$ $\Gamma(B_d \rightarrow \mu\mu)$	$\Gamma(K^* \rightarrow \pi^+ \nu \nu)$ $\Gamma(K_L \rightarrow \pi^0 \nu \nu)$ $\Gamma(K_L \rightarrow \pi^0 l l)$
	H^0 penguin	$\Gamma(B_s \rightarrow \mu\mu)$	$\Gamma(B_d \rightarrow \mu\mu)$	

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**

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

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

Yukawa structures as the **only sources of flavour violation**

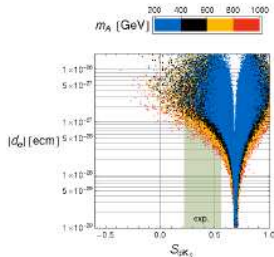
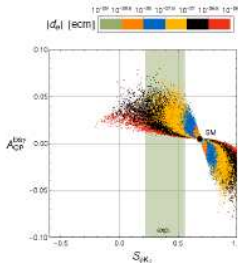
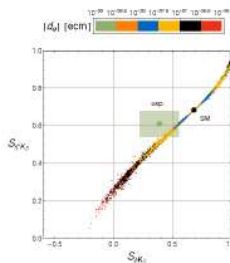


Minimal Flavour Violation

MFV allows for new “flavour blind” CPV phases!

Altmannshofer, Buras and P.P., '08

Flavor blind MSSM \approx 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 $A_{CP}^{B\to\eta} \simeq 1\% - 6\%$
- ▶ **lower bounds** on the electron and neutron EDMs at the level of $d_{e,n} \gtrsim 10^{-26} \text{ ecm}$
- ▶ large and correlated effects in the CP asymmetries in $B \rightarrow K^* \mu^+ \mu^-$ (WA, Ball, Bharucha, Buras, Straub, Wick)

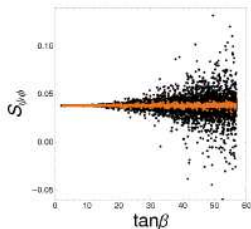
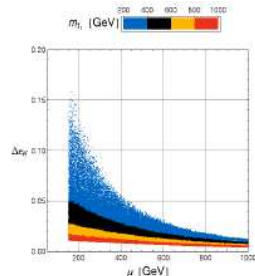
- ▶ the leading NP contributions to $\Delta F = 2$ amplitudes are **not sensitive** to the new phases of the FBMSSM
- ▶ CP violation in meson mixing is **SM like**
- ▶ i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- ▶ in particular: $0.03 < S_{\psi\phi} < 0.05$

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, $\epsilon_K \propto \text{Im}(M_{12}^K)$ can get a **positive NP contribution** up to 15%
- ▶ But only for a **very light SUSY spectrum**:
 $\mu, m_{\tilde{t}_1} \simeq 200\text{GeV}$



2 B_d and B_s mixing

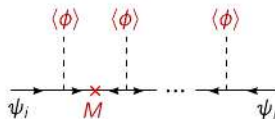
- ▶ Leading NP contributions to $M_{12}^{d,s}$ are **insensitive to the new phases** of a FBMSSM. (at least for moderate $\tan\beta \dots$)
- ▶ For large $\tan\beta$, the constraint from $b \rightarrow s\gamma$ does not allow for sizeable effects
- ▶ $S_{\psi K_S}$ and $S_{\psi\phi}$ are **SM like**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

SUSY flavour models

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

- Generalization of the Froggatt-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 generation 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: $M_d^2 = \text{diag}(\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta_d^{LL} & \delta_d^{LR} \\ \delta_d^{RL} & \delta_d^{RR} \end{pmatrix}$
- 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:

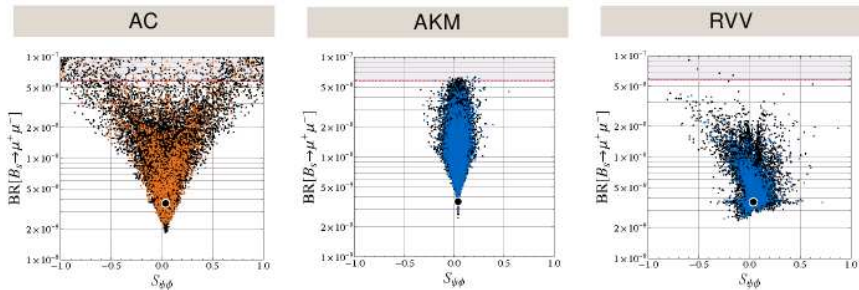
AC model [Agashe, Carone]	AKM model [Antusch, King, Malinsky]	RVV model [Ross, Velasco-Sevilla, Vives]	δ LL model [e.g. Hall, Murayama]
$U(1)$ Large, $O(1)$ RR mass insertions	$SU(3)$ Only CKM-like RR mass insertions	$SU(3)$ CKM-like LL & RR mass insertions	$(S_3)^3$ Only CKM-like LL mass insertions

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

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

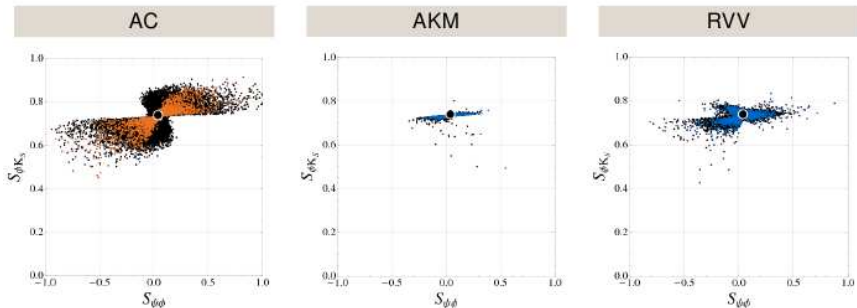
- Both observables can deviate significantly from the SM in all 3 models
- large $S_{\psi\phi} \Rightarrow$ large $Br(B_s \rightarrow \mu^+ \mu^-)$ in the AC and AKM models
- Correlation arises from dominance of Higgs penguin contributions



- 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

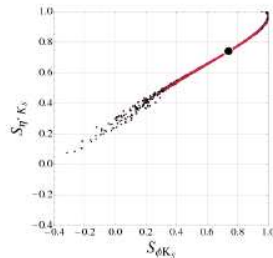
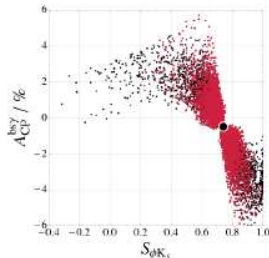
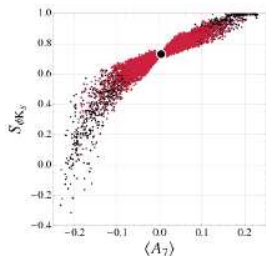


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Model with purely left-handed currents

Pattern of NP effects in the δLL model:

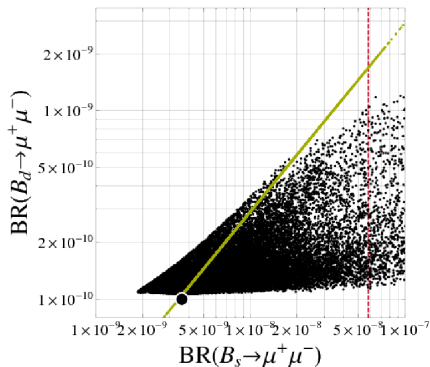
- No large effects in $S_{\psi\phi}$
- Large, correlated effects in $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{\text{CP}}(b \rightarrow s\gamma)$, $\langle A_{7,8} \rangle$
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \rightarrow K^* \ell^+ \ell^-$



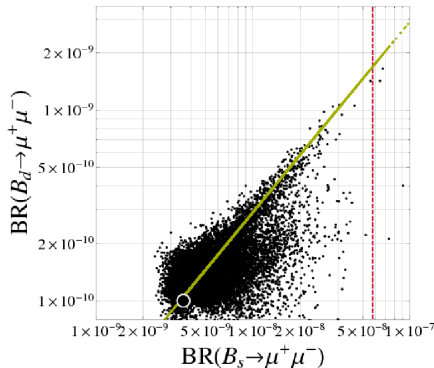
- Scan ranges: $m_0 < 2 \text{ TeV}$, $M_{1/2} < 1 \text{ TeV}$, $|A_0| < 3m_0$, $5 < \tan \beta < 55$, $O(1)$ parameters varied within $[\frac{1}{2}, 2]$

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

Abelian (AC)



Non abelian (RVV)



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

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

- $\langle D^0 | \mathcal{H}_{\text{eff}} | \bar{D}^0 \rangle = M_{12} - \frac{i}{2} \Gamma_{12}, \quad |D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

- $\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}}}, \quad \phi = \text{Arg}(q/p)$

- $x = \frac{\Delta M_D}{\Gamma} = 2\tau \text{Re} \left[\frac{q}{p} (M_{12} - \frac{i}{2} \Gamma_{12}) \right]$

- $y = \frac{\Delta \Gamma}{2\Gamma} = -2\tau \text{Im} \left[\frac{q}{p} (M_{12} - \frac{i}{2} \Gamma_{12}) \right]$

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

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

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

CPV in D-physics vs. neutron EDM in SUSY

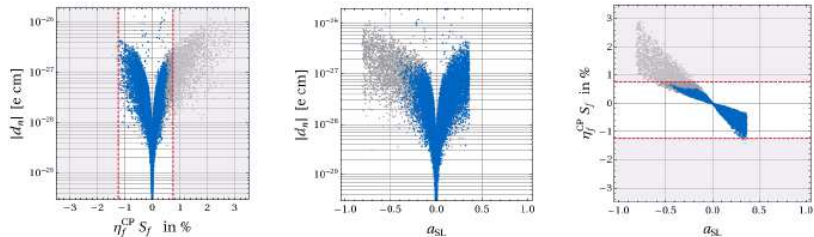


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ . Dashed lines stand for the allowed range (18) for S_f .

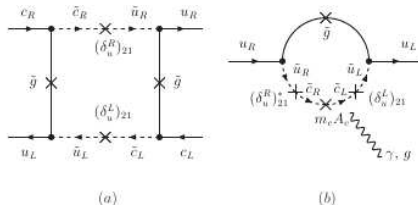




FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

“DNA-Flavour Test”

	GMSSM	AC	RVV2	AKM	δ LL	FBMSSM	
$S_{\phi K_S}$ $A_{CP}(B \rightarrow X_s \gamma)$ $B \rightarrow K^{(*)} \nu \bar{\nu}$ $\tau \rightarrow \mu \gamma$	★★★	★★★	●●	■	★★★	★★★	
$D^0 - \bar{D}^0$ $A_{7,8}(B \rightarrow K^* \mu^+ \mu^-)$ $A_9(B \rightarrow K^* \mu^+ \mu^-)$	★★★	★★★	■	■	■	■	
	★★★	■	■	■	★★★	★★★	
	★★★	■	■	■	■	■	
$S_{\psi \phi}$ $B_s \rightarrow \mu^+ \mu^-$	★★★	★★★	★★★	★★★	■	■	
	★★★	★★★	★★★	★★★	★★★	★★★	
ϵ_K $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ $K_L \rightarrow \pi^0 \nu \bar{\nu}$ $\mu \rightarrow e \gamma$ $\mu + N \rightarrow e + N$ d_n d_e $(g-2)_\mu$	★★★	■	★★★	★★★	■	■	
	★★★	■	■	■	■	■	
	★★★	■	■	■	■	■	
	★★★	★★★	★★★	★★★	★★★	★★★	
	★★★	★★★	★★★	★★★	★★★	★★★	
	★★★	★★★	★★★	★★★	●●	★★★	
	★★★	★★★	★★★	●●	■	★★★	
	★★★	★★★	★★★	●●	★★★	★★★	

Altmannshofer et al. '09

► Flavour physics in the LHC era

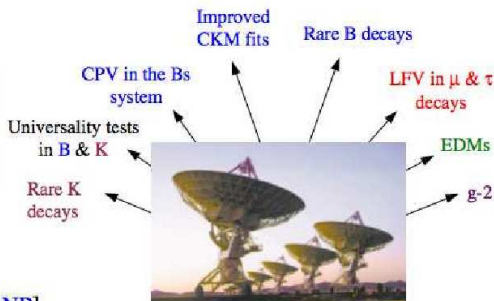
LHC [high p_T]

A *unique* effort toward the
high-energy frontier



[to determine the energy scale of NP]

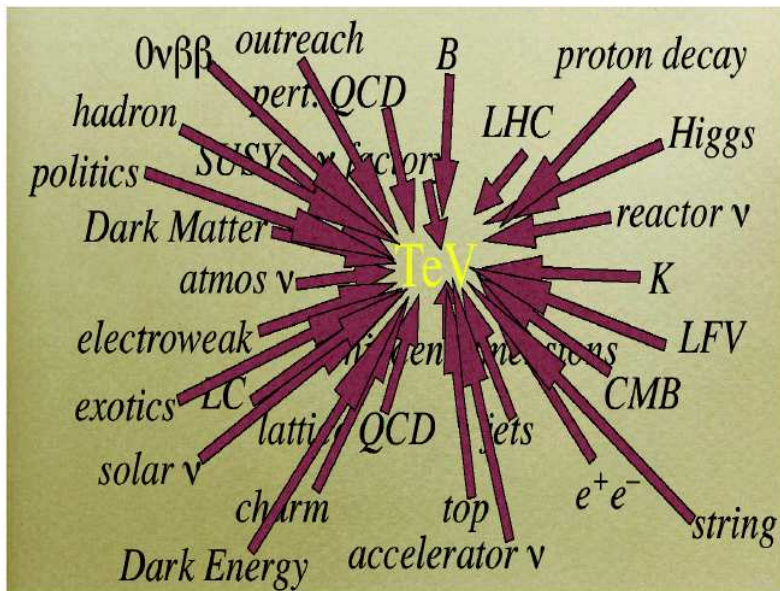
Flavour physics



A *collective* effort toward the
high-intensity frontier

[to determine the flavour structure of NP]

Murayama's view



Masiero's view

