Open questions in flavor physics

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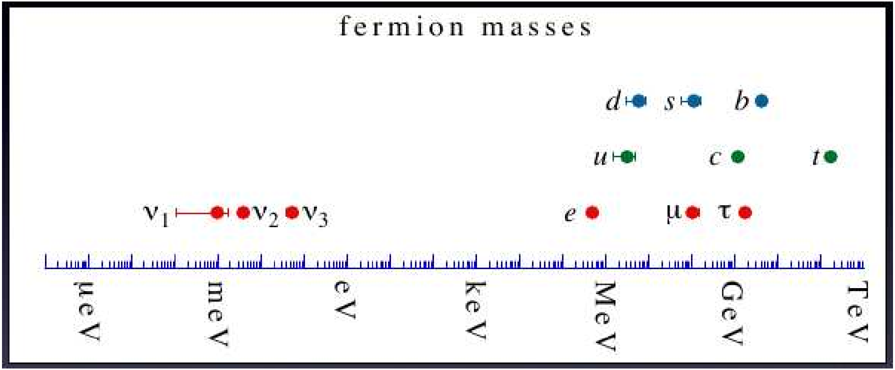
Plan of Talk

1. Open questions
2. The SM flavor puzzle
3. Messages from the B-factories and Tevatron
4. The NP flavor puzzle
5. "Flavor-test" of NP models: the case of SUSY
6. Flavor at the LHC

Open questions

1. **Which is the underlying mechanism regulating the EWSB?**
2. **Which is the connection between EWSB and flavor physics?**
3. **Are there new flavor symmetries beyind the puzzling fermion mass spectrum?**
4. **Are there new flavor violating interactions not governed by the SM Yukawas? That is, to which extent the MFV hypothesis is valid?**
5. **Do the new sources of CPV accounting for the BAU have an impact on flavor physics and/or EDMs?**
6. **Which is the role of flavor physics in the LHC era?**
7. **Do we expect to understand the (SM and NP) flavor puzzles through the interplay of flavor physics and the LHC?**
8. **......**

The fermion mass puzzle



$$|V_{CKM}| \sim \begin{pmatrix} 1 & \lambda_c & \lambda_c^3 \\ \lambda_c & 1 & \lambda_c^2 \\ \lambda_c^3 & \lambda_c^2 & 1 \end{pmatrix}, \quad |V_{PMNS}| \simeq \begin{pmatrix} 0.79-0.86 & 0.50-0.61 & 0.0-0.2 \\ 0.25-0.53 & 0.47-0.73 & 0.56-0.79 \\ 0.21-0.51 & 0.42-0.69 & 0.61-0.83 \end{pmatrix}_{3\sigma}$$

Hierarchical **Anarchic / Tribimaximal**

The fermion mass puzzle

- **Quark/charged-lepton mass hierarchy**

$$\begin{aligned} Y_t &\sim 1, \quad Y_c \sim 10^{-2}, \quad Y_u \sim 10^{-5} \\ Y_b &\sim 10^{-2}, \quad Y_s \sim 10^{-3}, \quad Y_d \sim 10^{-4} \\ Y_\tau &\sim 10^{-2}, \quad Y_\mu \sim 10^{-3}, \quad Y_e \sim 10^{-6} \end{aligned}$$

- **Quark mixing angles hierarchy**

$$|V_{us}| \sim 0.2, \quad |V_{cb}| \sim 0.04, \quad |V_{ub}| \sim 0.004 \quad (\delta_{KM} \sim 1)$$

- **Neutrinos**

$$\begin{aligned} \Delta m^2_{sol} &= (7.9 \pm 0.3) \times 10^{-5}\mathrm{eV}^2, \quad |\Delta m^2_{atm}| = (2.6 \pm 0.2) \times 10^{-3}\mathrm{eV}^2, \\ \sin^2\theta_{sol} &= 0.31 \pm 0.02, \quad \sin^2\theta_{atm} = 0.47 \pm 0.07, \quad \sin^2\theta_{e3} = 0^{+0.08}_{-0.0}, \end{aligned}$$

- **Quark-Lepton complementarity: GUT + Flavor Symmetry?** [Raidal '04]

$$\theta_{sol} + \theta_c \approx \frac{\pi}{4}, \qquad \theta_{atm} + \theta_{23} \approx \frac{\pi}{4}$$

- **SM gauge couplings**

$$g_s \sim 1, \quad g \sim 0.6, \quad g' \sim 0.3, \quad \lambda_{\mathrm{Higgs}} \sim 1$$

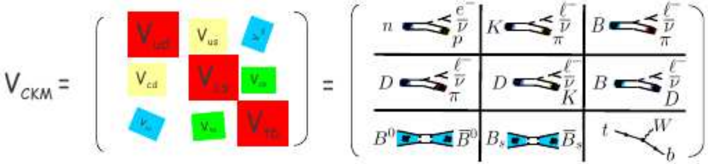
- $\mathcal{L}^{\rm SM}_{Kinetic+Gauge} + \mathcal{L}^{\rm SM}_{Higgs}$ has a large $U(3)^5$ global **flavour symmetry**

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

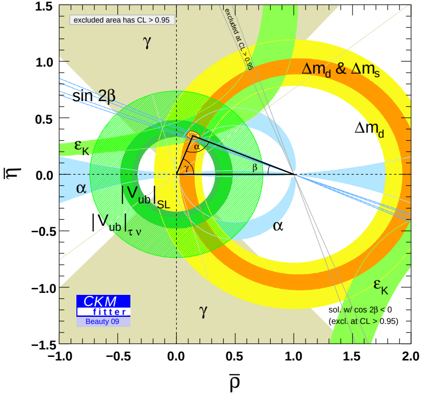
- $\mathcal{L}_{\rm Yukawa} = \bar{Q}_L \mathbf{Y_D} D_R \phi + \bar{Q}_L \mathbf{Y_U} U_R \tilde{\phi} + \bar{L}_L \mathbf{Y_L} E_R \phi + h.c$ break

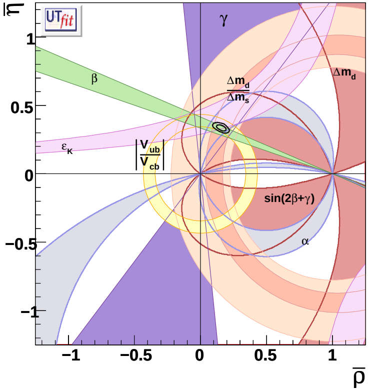
$$\mathbf{G} \to \mathbf{U(1)_B} \times \mathbf{U(1)_e} \times \mathbf{U(1)_\mu} \times \mathbf{U(1)_\tau}$$

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



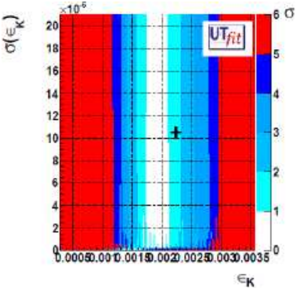
Messages from the B-factories





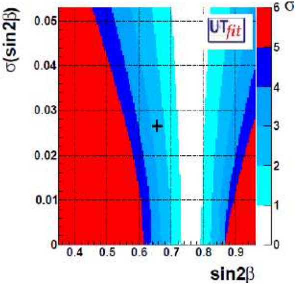
"Very likely, flavour and CP violation in FC processes are dominated by the CKM mechanism" (Nir)

UT tensions

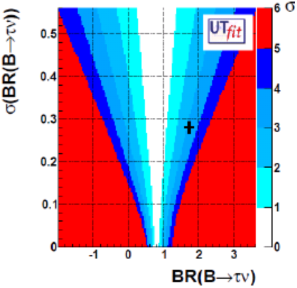


1. $\sim$ 6% reduction of $\epsilon_K^{\rm SM}$
   [Buras & Guadagnoli; BG & Isidori]
2. smaller $\hat{B}_K$ from unquenced analyses
   [Antonio et al. '08; Aubin et al. '10]
3. fit vs. exp. $\approx -1.7\sigma$

NEW: $\epsilon_K^{\rm SM}$ @ NNLO QCD: $\sim +3\%$ [Brod & Gorbahn, '10]



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

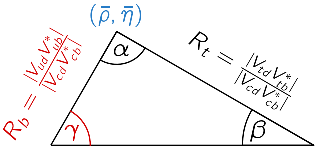


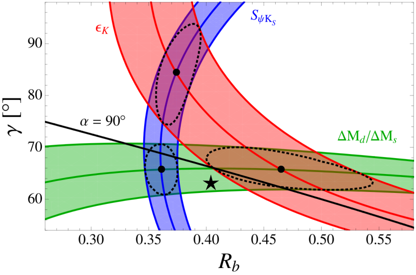
1. $B(B \to \ell\nu) \sim f_B^2 |V_{ub}|^2$
2. $B(B \to \ell\nu)/\Delta M_d \sim (\sin\beta/\sin\gamma)^2/\hat{B}_{B_d}$
3. fit vs. exp. $\approx -3.2\sigma$

Similar conclusions also by Lenz & Nierste + CKMfitter collaboration ('10)

UT tensions and NP

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





Altmannshofer et al. '09

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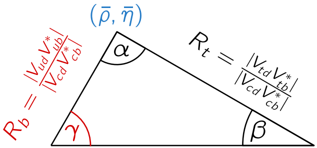

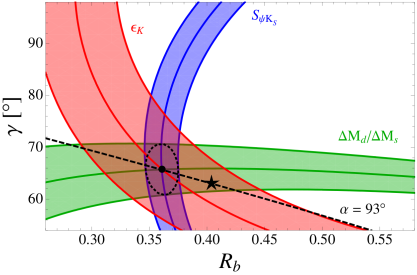

Possible solutions:

1. $+24\%$ NP effect in ϵ_K

Altmannshofer et al. '09

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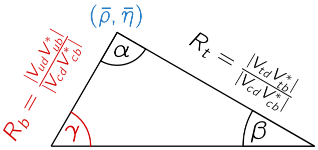

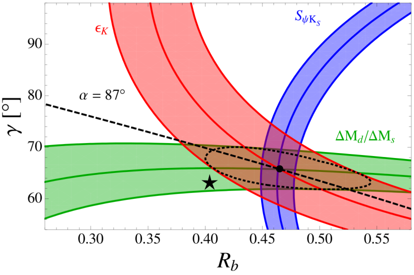

Possible solutions:

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

Altmannshofer et al. '09

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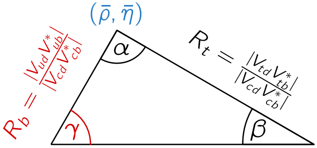
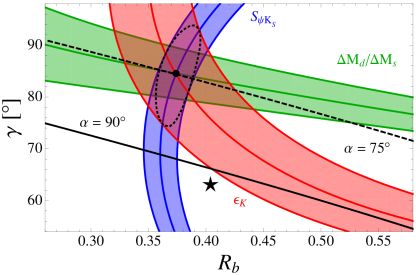
- Look at ϵ_K, $S_{\psi K_S}$, and $\Delta M_d/\Delta M_s$ in the R_b-γ plane from tree-level processes



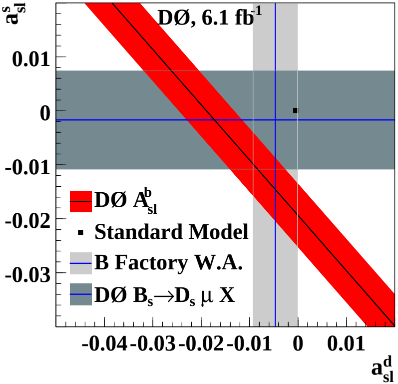


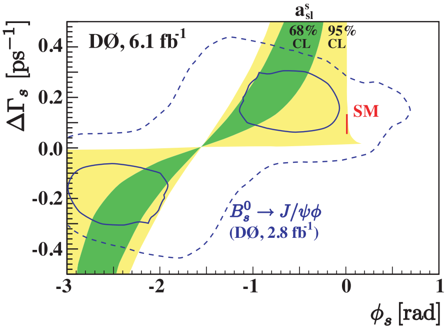
Possible solutions:

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

Altmannshofer et al. '09

CPV in B_s mixing (before ICHEP 2010)

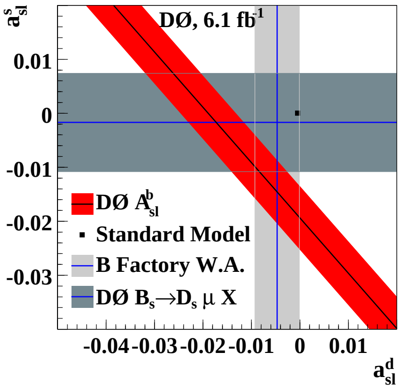


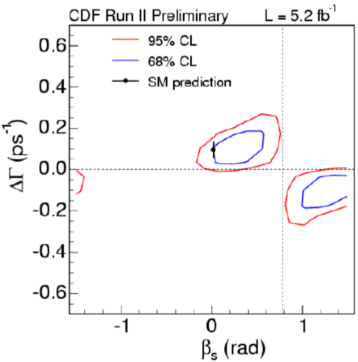


$$A_{SL}^{q} \equiv \frac{\Gamma(\bar{B}_q \to l^+ X) - \Gamma(B_q \to l^- X)}{\Gamma(\bar{B}_q \to l^+ X) + \Gamma(B_q \to l^- X)}\,, \qquad S_{\psi\phi} = \sin(2|\beta_s| - 2\phi_{B_s})$$

New Physics in the B_s mixing phase?

CPV in B_s mixing (after ICHEP 2010)





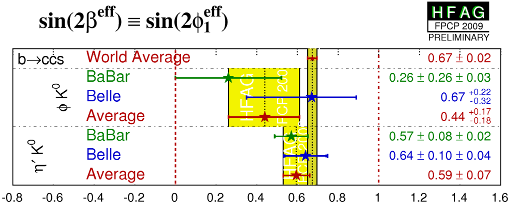
$$A^q_{SL} \equiv \frac{\Gamma(\bar{B}_q \to l^+ X) - \Gamma(B_q \to l^- X)}{\Gamma(\bar{B}_q \to l^+ X) + \Gamma(B_q \to l^- X)} \,,$$

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

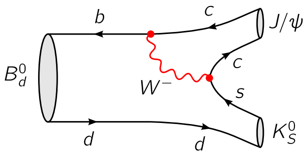
New Physics in the B_s mixing phase?

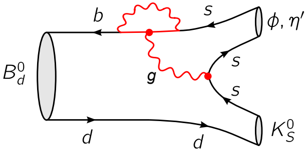
- In the SM, $(\sin 2\beta)_{\psi K_S} \approx (\sin 2\beta)_{\phi K_S} \approx (\sin 2\beta)_{\eta' K_S}$
- $B_d \to \psi K_S$ dominated by tree level, ϕK_S and $\eta' K_S$ are loop-induced

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



[adapted from HFAG]





New physics in the decay amplitudes?

The SuperB will tell us...

The NP "scale"

- **Gravity** $\Longrightarrow$ $\Lambda_{\text{Planck}} \sim 10^{18-19}\ \mathrm{GeV}$
- **Neutrino masses** $\Longrightarrow$ $\Lambda_{\text{see-saw}} \lesssim 10^{15}\ \mathrm{GeV}$
- **Hierarchy problem**: $m_h^{\mathrm{SM}}(\Lambda^2_{\mathrm{NP}}) \sim M_W \Longrightarrow \Lambda_{\text{NP}} \lesssim \mathrm{TeV}$
- **Dark Matter** $\Longrightarrow$ $\Lambda_{\text{NP}} \lesssim \mathrm{TeV}$
- **BAU**: evidence of CPV beyond SM
  - Electroweak Baryogenesis $\Longrightarrow \Lambda_{\text{NP}} \lesssim \mathrm{TeV}$
  - Leptogenesis $\Longrightarrow \Lambda_{\text{see-saw}} \lesssim 10^{15}\ \mathrm{GeV}$
  - ....

$$\Downarrow$$

SM = effective theory at the EW scale

- Going BSM model-independently:

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

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

The NP flavor puzzle

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d=6} \frac{c_{ij}^{(6)}}{\Lambda_{NP}^2} O_{ij}^{(6)}$$

[Isidori, Nir, Perez '10]

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} (Λ = 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" FV sources at the TeV scale are excluded

MFV & the NP flavor puzzle

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

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

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

Yukawa structures as the only sources of flavour violation

$$\Downarrow$$

Minimal Flavour Violation [D'Ambrosio et al. '02]

Notice that MFV allows new "flavour blind"CPV phases!

[Kagan et al. '09] (model-independent)
[Ellis et al. '07] (SUSY)
[Colangelo et al., '08], [Smith et al. '09] (SUSY)
[Altmannshofer et al., '08,'09], [P.P & Straub, '09] (SUSY)
[Buras et al., '10,'10] (2HDM)

MFV & the NP flavor puzzle

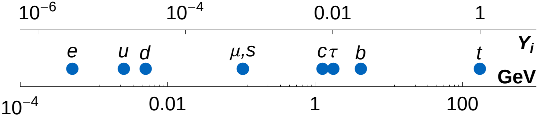
$$(c^{\Delta F=1}_{\mathrm{MFV}})_{ij} \sim V^\star_{ti} V_{tj}\,, \qquad (c^{\Delta F=2}_{\mathrm{MFV}})_{ij} \sim (V^\star_{ti} V_{tj})^2$$

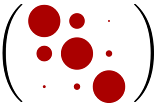
$\Delta F = 1,2$ MFV operators	Λ(TeV)	Observables
$H^\dagger \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} Q_L\right) (eF_{\mu\nu})$	6.1 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\frac{1}{2}(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L)^2$	5.9 TeV	ϵ_K, Δm_{B_d}, Δm_{B_s}
$H^\dagger_D \left(\overline{D}_R Y^{d\dagger} Y^u Y^{u\dagger} \sigma_{\mu\nu} T^a Q_L\right) (g_s G^a_{\mu\nu})$	3.4 TeV	$B \to X_s\gamma$, $B \to X_s\ell^+\ell^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (\overline{E}_R \gamma_\mu E_R)$	2.7 TeV	$B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$
$\left(\overline{Q}_L Y^u Y^{u\dagger} \gamma_\mu Q_L\right) (eD_\mu F_{\mu\nu})$	1.5 TeV	$B \to X_s\ell^+\ell^-$

Observable	Experiment	MFV prediction	SM prediction
$\mathcal{A}_{\mathrm{CP}}(B_s \to \psi\phi)$	[0.10, 1.44] @ 95% CL	0.04(5)	0.04(2)
$\mathcal{A}_{\mathrm{CP}}(B \to X_s\gamma)$	$< 6\%$ @ 95% CL	< 0.02	< 0.01
$\mathcal{B}(B_d \to \mu^+\mu^-)$	$< 1.8 \times 10^{-8}$	$< 1.2 \times 10^{-9}$	$1.3(3) \times 10^{-10}$
$\mathcal{B}(B \to X_s\tau^+\tau^-)$	–	$< 5 \times 10^{-7}$	$1.6(5) \times 10^{-7}$
$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$	$< 2.6 \times 10^{-8}$ @ 90% CL	$< 2.9 \times 10^{-10}$	$2.9(5) \times 10^{-11}$

[D'Ambrosio et al. '02; Hurth et al. '08, Isidori, Nir & Perez '10]

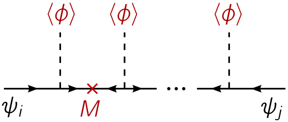
SM vs. NP flavor puzzle



$V_{\rm CKM} \sim$ 

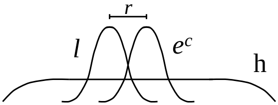
Froggat-Nielsen '79: Hierarchies from SSB of a Flavour Symmetry

$$\epsilon = \frac{\langle\phi\rangle}{M} \ll 1 \Rightarrow Y_{ij} \propto \epsilon^{(a_i+b_j)}$$



Arkani-Hamed & Schmaltz '99: Hierarchies from Extra Dimensions

$x = \mu r$	1	2	3	4	5
$e^{-\frac{x^2}{2}}$	1	10^{-1}	10^{-2}	10^{-4}	10^{-6}
	λ_t		$\cdots$		λ_e



The Gaussian wave functions of l and e^c overlap in an exponentially small region

$\Downarrow$

Small Yukawa couplings without Symmetries

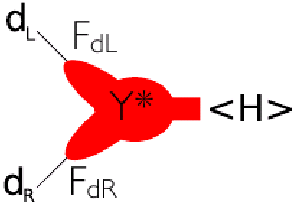
SM vs. NP flavor puzzle

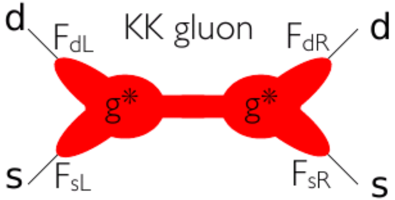
- **Flavor Models flavor protection**

[Lalak, Pokorski & Ross '10]

Operator	$U(1)$	$U(1)^2$	$SU(3)$	MFV
$(\overline{Q}_L X^Q_{LL} Q_L)_{12}$	λ	λ^5	λ^3	λ^5
$(\overline{D}_R X^D_{RR} D_R)_{12}$	λ	λ^{11}	λ^3	$(y_d y_s) \times \lambda^5$
$(\overline{Q}_L X^D_{LR} D_R)_{12}$	λ^4	λ^9	λ^3	$y_s \times \lambda^5$

- **RS flavor protection** [Gerghetta & Pomarol, '99; Huber, '03; Agashe, Perez & Soni, '04]





$$m_d \sim v\, F_{d_L} Y^\star F_{d_R}$$

$$(V_{CKM})_{ij} \sim F_{d_{L_i}} / F_{d_{L_j}}$$

$$(\epsilon_K)_{\mathbf{RS-GIM}} \sim \frac{(g^\star)^2}{M^2_{\rm KK}} \frac{\mathbf{m_d\, m_s}}{(v\ Y^\star)^2}$$

[Csaki, Falkowski & Weiler, '08]

[Blanke, Buras, Duling, Gori, Weiler, '08]

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

Flavor in the LHC era

[Isidori, Nir & Perez '10]

Observable	SM prediction	Theory error	Present result	Future error	Future Facility
$\|V_{us}\|$ $[K \to \pi\ell\nu]$	input	$0.5\% \to 0.1\%_{\rm Latt}$	0.2246 ± 0.0012	0.1%	K factory
$\|V_{cb}\|$ $[B \to X_c\ell\nu]$	input	1%	$(41.54 \pm 0.73) \times 10^{-3}$	1%	Super-B
$\|V_{ub}\|$ $[B \to \pi\ell\nu]$	input	$10\% \to 5\%_{\rm Latt}$	$(3.38 \pm 0.36) \times 10^{-3}$	4%	Super-B
γ $[B \to DK]$	input	$< 1^\circ$	$(70^{+27}_{-30})^\circ$	3°	LHCb
$S_{B_d \to \psi K}$	$\sin(2\beta)$	$\lesssim 0.01$	0.671 ± 0.023	0.01	LHCb
$S_{B_s \to \psi\phi}$	0.036	$\lesssim 0.01$	$0.81^{+0.12}_{-0.32}$	0.01	LHCb
$S_{B_d \to \phi K}$	$\sin(2\beta)$	$\lesssim 0.05$	0.44 ± 0.18	0.1	LHCb
$S_{B_s \to \phi\phi}$	0.036	$\lesssim 0.05$	—	0.05	LHCb
$S_{B_d \to K^*\gamma}$	few $\times$ 0.01	0.01	-0.16 ± 0.22	0.03	Super-B
$S_{B_s \to \phi\gamma}$	few $\times$ 0.01	0.01	—	0.05	LHCb
$A^d_{\rm SL}$	-5×10^{-4}	10^{-4}	$-(5.8 \pm 3.4) \times 10^{-3}$	10^{-3}	LHCb
$A^s_{\rm SL}$	2×10^{-5}	$< 10^{-5}$	$(1.6 \pm 8.5) \times 10^{-3}$	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}	$20\% \to 5\%_{\rm Latt}$	$(1.73 \pm 0.35) \times 10^{-4}$	5%	Super-B
$\mathcal{B}(B \to \mu\nu)$	4×10^{-7}	$20\% \to 5\%_{\rm Latt}$	$< 1.3 \times 10^{-6}$	6%	Super-B
$\mathcal{B}(B_s \to \mu^+\mu^-)$	3×10^{-9}	$20\% \to 5\%_{\rm Latt}$	$< 5 \times 10^{-8}$	10%	LHCb
$\mathcal{B}(B_d \to \mu^+\mu^-)$	1×10^{-10}	$20\% \to 5\%_{\rm Latt}$	$< 1.5 \times 10^{-8}$	[?]	LHCb
$A_{\rm FB}(B \to K^*\mu^+\mu^-)_{q_0^2}$	0	0.05	(0.2 ± 0.2)	0.05	LHCb
$B \to K\nu\bar\nu$	4×10^{-6}	$20\% \to 10\%_{\rm Latt}$	$< 1.4 \times 10^{-5}$	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%	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	10%	K factory
$\mathcal{B}(K_L \to \pi^0\nu\bar\nu)$	2.6×10^{-11}	10%	$< 2.6 \times 10^{-8}$	[?]	K factory
$R^{(e/\mu)}(K \to \pi\ell\nu)$	2.477×10^{-5}	0.04%	$(2.498 \pm 0.014) \times 10^{-5}$	0.1%	K factory
$\mathcal{B}(t \to c\,Z,\gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-13})$	$< 0.6 \times 10^{-2}$	$\mathcal{O}(10^{-5})$	LHC ($100\,{\rm fb}^{-1}$)

The SUSY flavour and CP problems

The soft-sector contains a huge number of FV and/or CPV parameters: natural $O(1)$ values for these parameters are excluded by the exp. data

Flavor problem: solutions

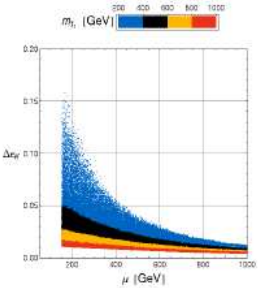
1. **Decoupling**: $m_{SUSY} \gg$ TeV, the hierarchy problem is (partly) reintroduced
2. **Degeneracy**: sfermion masses nearly degenerate, e.g. gauge mediation, flavour models, MFV...
3. **Alignment**: quark and squark mass matrices aligned [Nir & Seiberg '93]

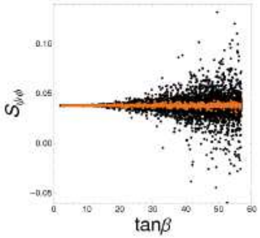
CP problem: solutions

1. Degeneracy & Alignment do not solve the CP problem as flavor blind phases are allowed
2. **CPV** from **flavor effects** $\Rightarrow$ EDMs suppressed by small mixing angles
3. Hp in flavor models: CP spontaneously broken in the flavor sector by flavon VEVs [Nir & Rattazzi '96]
4. Applying the same idea to MFV: CPV only from MFV-compatible terms breaking the flavour blindness [P.P & Straub, '09]

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: $\mu, m_{\tilde{t}_1} \simeq 200\mathrm{GeV}$



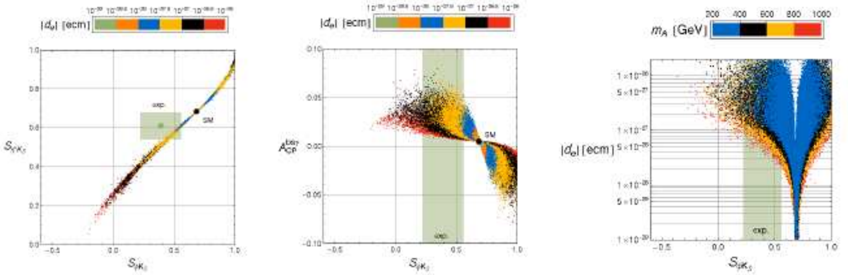


2 B_d and B_s mixing

- 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 ($S_{\psi\phi} \simeq 0.03 - 0.05$)

[Altmannshofer,Buras & P.P., ’08]

MSSM with MFV and “flavour blind” phases



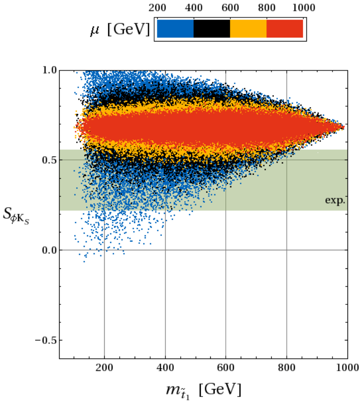
- CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- lower bounds on the electron and neutron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

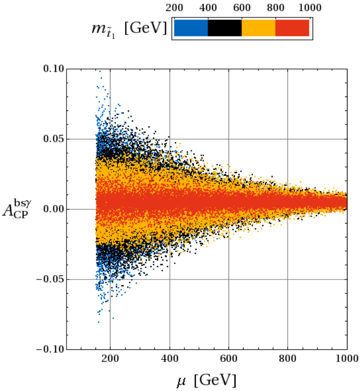
- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- in particular: $0.03 < S_{\psi\phi} < 0.05$

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

[Altmannshofer,Buras & P.P., ’08]

Implications for direct searches of SUSY particles





- $S_{\phi K_S} \simeq 0.4$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 700$GeV
- $A_{CP}^{bs\gamma} \gtrsim 2\%$ implies $\mu \lesssim 600$GeV and $m_{\tilde{t}_1} \lesssim 800$GeV

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

Abelian vs. Non-abelian flavor models

- Non-abelian models predict $\approx$ degenerate 1st & 2nd sfermion masses
  - Suppressed contributions to $1 \leftrightarrow 2$ transitions
  - Potentially large contributions to $2 \leftrightarrow 3$ transitions

- In abelian models, sfermions of different generations need not be degenerate
  - A single $U(1)$ & $O(1)$ 1-2 mass splitting lead to $(\delta^{LL}_{d,u})_{12} \sim \mathcal{O}(\lambda)$
  - $U(1) \times U(1)$ allows *alignement* in the down sector $(\delta^{LL}_{d})_{12} \approx 0 \Rightarrow (\delta^{LL}_{u})_{12} \sim \mathcal{O}(\lambda)$
  - Large effects in D^0-$\bar{D}^0$ mixing

Chirality structure of flavour violating terms

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

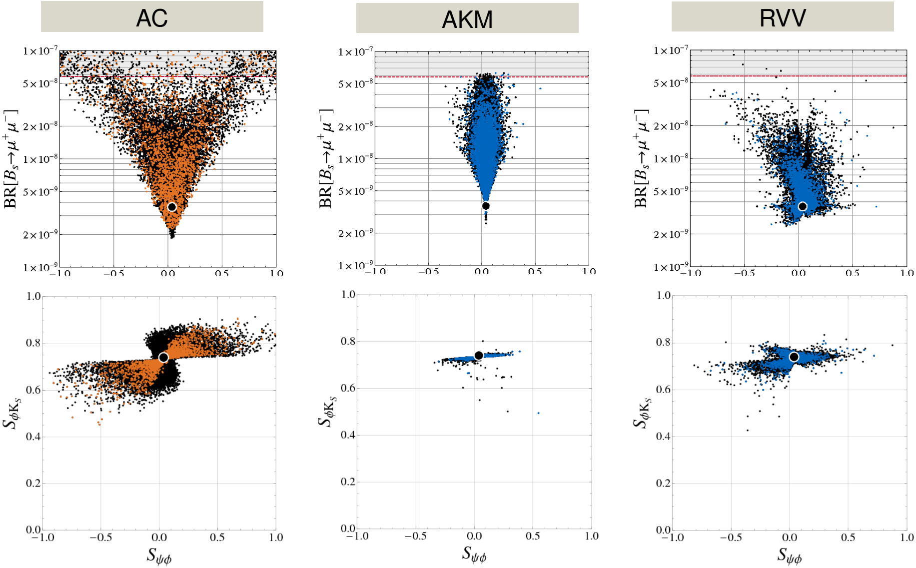
Representative flavour models

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]

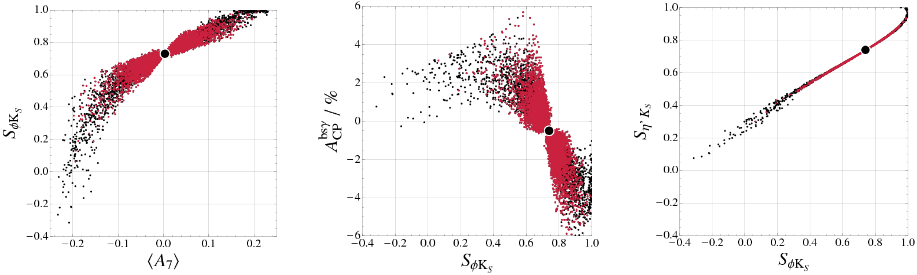
$b \to s$ transitions & SUSY flavor models [Altmannshofer et al., '09]



- 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 $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{\rm CP}(b \to s\gamma)$, $\langle A_{7,8} \rangle$ and EDMs
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \to K^* \ell^+ \ell^-$

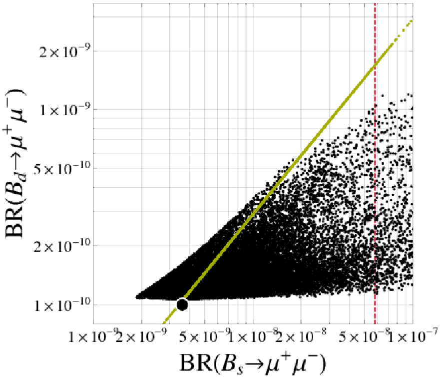


- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$,

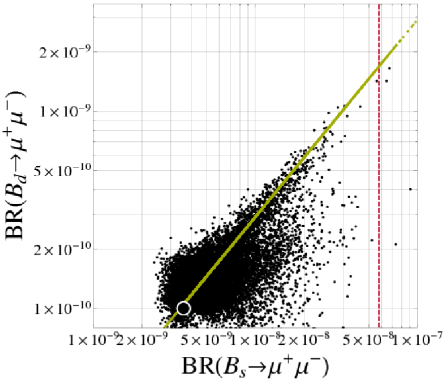
[Altmannshofer et al., '09]

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

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]

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

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

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

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

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

[Nir et al.,Kagan et al., Petrov et al., Bigi et al., Buras et al., ...]

CPV in D-physics vs. neutron EDM in SUSY [Altmannshofer, Buras, & P.P, '10]

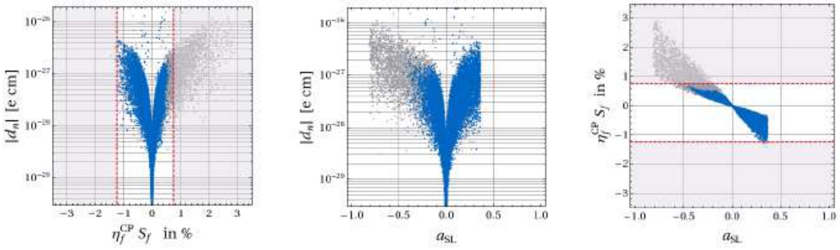


FIG. 3: Correlations between d_n and S_f (left), d_n and a_{SL} (middle) and a_{SL} and S_f (right) in SUSY alignment models. Gray points satisfy the constraints (8)-(10) while blue points further satisfy the constraint (11) from ϕ. Dashed lines stand for the allowed range (18) for S_f.

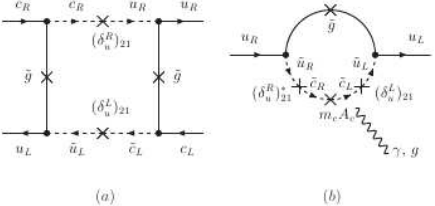
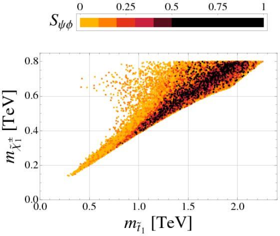
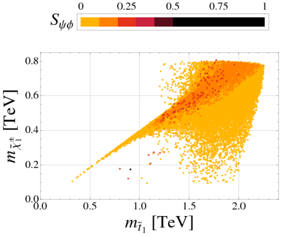


FIG. 2: Examples of relevant Feynman diagrams contributing (a) to $D^0 - \bar{D}^0$ mixing and (b) to the up quark (C)EDM in SUSY alignment models.

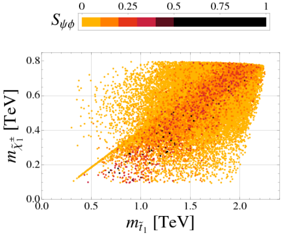
AC



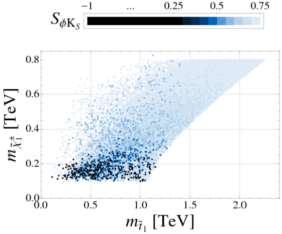
AKM



RVV



δLL



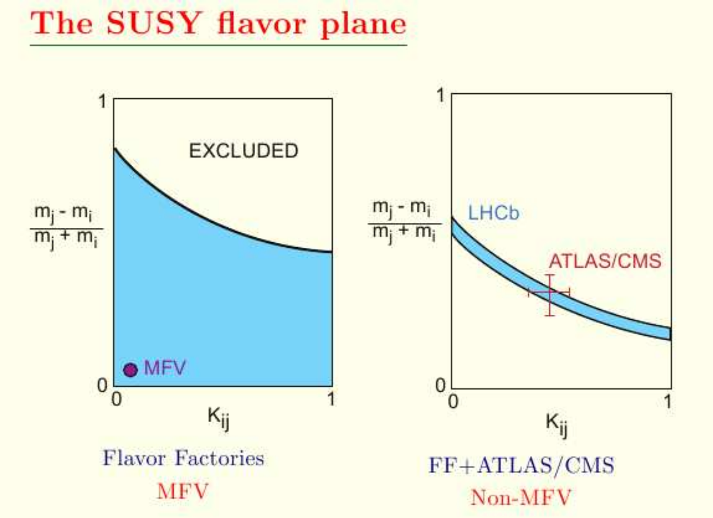
- Large effects in $S_{\psi\phi}$ even possible for spectra beyond the LHC reach in the models with RH currents
- Large effects in $S_{\phi K_S}$ not possible for spectra beyond the LHC reach in the δLL model

"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]

Flavor in the LHC era



[Nir @ Planck '09]

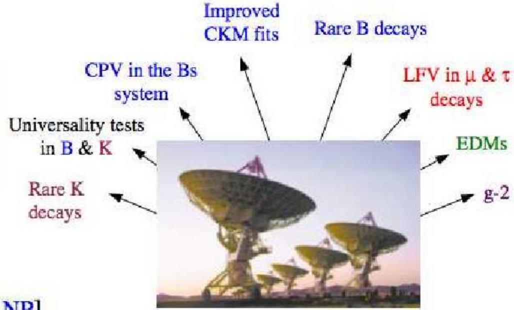
Flavour physics in the LHC era

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]