CP violation in the MSSM with MFV

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Interplay of Collider and Flavour Physics,
CERN, December 2009

in collaboration with Ulrich Nierste, Dominik Scherer
arXiv:0907.5408 [hep-ph]

Flavour Problem for TeV-scale New Phyics

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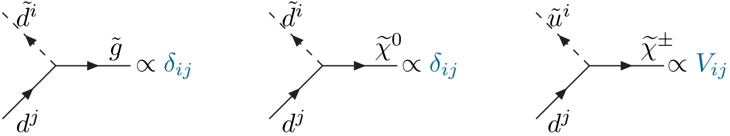
- CKM mechanism for flavour violation experimentally well confirmed $\Rightarrow$ Flavour Problem for TeV-scale New Phyics
- Minimal Flavour Violation (MFV): New Physics does not introduce new sources of flavour violation

Naive MFV in the MSSM

- Soft SUSY-breaking terms (Squark mass terms and A-terms) are flavour-diagonal in Super-CKM basis



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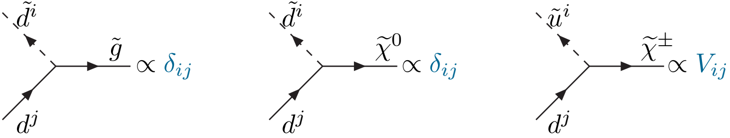

- This naive definition is not RG-invariant
  - Usually this condition is imposed at the GUT-scale $\leftrightarrow$ flavour-blind SUSY breaking
  - RG evolution induces flavour-violating $\tilde{g}$- and $\widetilde{\chi}^0$-couplings at the electro-weak scale.
  - Impact of RG-effects on FCNC transitions is small .

[Baer, Brhlik, Castano, Tata; Dudley, Kolda]

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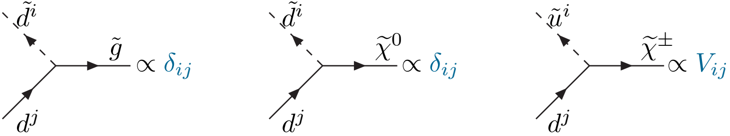

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    [Baer, Brhlik, Castano, Tata; Dudley, Kolda]

- Better: Symmetry-based definition of MFV
  Yukawa's $=$ only source of flavour violation

  [D'Ambrosio, Giudice, Isidori, Strumia]

Large FCNC effects in MFV

- Typical contributions to FCNC processes in the MSSM with MFV are of the order

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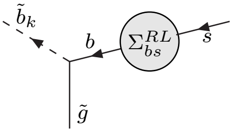
- MFV does not forbid flavour-diagonal CP-violating phases (e.g. complex A_t)
  $\longrightarrow$ large effects in CPV observables possible

Summary of large-tanβ effects

effect	decoupling limit	beyond
modified relation $y_{d_i} \leftrightarrow m_{d_i}$	[Hall, Rattazzi, Sarid; Carena, Olechowski, Pokorski, Wagner]	[Carena, Garcia, Nierste, Wagner; LH, Nierste, Scherer]
corrections to CKM matrix	[Blazek, Raby, Pokorski]	[Buras, Chankowski, Rosiek, Slawianowska; LH, Nierste, Scherer]
enhanced FCNCs $d_i\, d_j\, H^0/A^0$	[Hamzaoui, Pospelov, Toharia; Babu, Kolda; Buras, Chankowski, Rosiek, Slawianowska]	[Buras, Chankowski, Rosiek, Slawianowska; LH, Nierste, Scherer]
enhanced FCNCs $d_i\, \tilde{d}_j\, \tilde{g}/\tilde{\chi}^0$	not accessible	[LH, Nierste, Scherer]
vertex corrections $\bar{u}_{i,R}\, d_{j,L}\, H^+$	[Degrassi, Gambino, Giudice; Carena, Garcia, Nierste, Wagner]	process-dependent (non-universal)

FCNC couplings at large $\tan\beta$

- $\tan\beta$-enhanced self-energies Σ_{ij}^{RL} induce FCNC couplings for on-shell down-type quarks:



$$\Sigma_{bs}^{RL} \propto \epsilon_{FC} m_b \tan\beta$$

$$\mathcal{M} \propto \frac{\Sigma_{bs}^{RL}}{m_b} \propto \epsilon_{FC} \tan\beta$$

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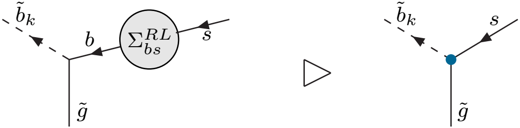

$$\Sigma^{RL}_{bs} \propto \epsilon_{FC} m_b \tan\beta \qquad\qquad \kappa_{bs} \propto \epsilon_{FC} \tan\beta$$

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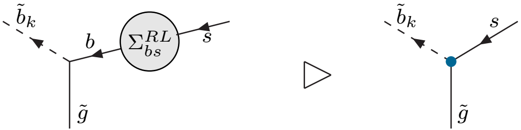

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- FCNC-couplings of order $\epsilon_{FC} \tan\beta$ of down-type quarks to
  - H^0, A^0 (known in the decoupling limit)
  - $\tilde{g}, \widetilde{\chi}^0$ (New! Not accessible in the decoupling limit)

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  Estimate for equal SUSY-Masses:
  $|\kappa| \sim 0.08$, for $\mu > 0$ $|\kappa| \sim 0.24$, for $\mu < 0$

- $\epsilon_{FC} \propto A_t$ $\Rightarrow$ larger values for $|\kappa|$ for large $|A_t|$

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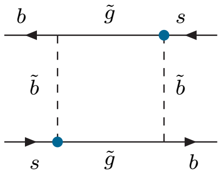
- $\epsilon_{FC} \propto A_t$ $\Rightarrow$ complex values of A_t induce additional CP violation

Contributions to $\mathcal{H}_{\mathit{eff}}^{\Delta B=1}$ and $\mathcal{H}_{\mathit{eff}}^{\Delta B=2}$

- Flavour-changing gluino-coupling enters $\mathcal{H}_{\text{eff}}^{\Delta B=1}$ and $\mathcal{H}_{\text{eff}}^{\Delta B=2}$.

- Example: Gluino-contribution to $B_s - \overline{B}_s$–mixing



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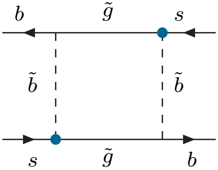
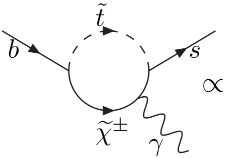


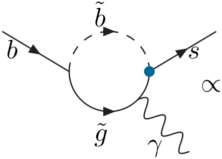
- Most of these contributions are small because
  - FCNC gluino coupling is numerically small, $|\kappa| \sim 0.1$
  - gluino contributions suffer from GIM-suppression

Enhanced contributions to C_7 and C_8

- Exception: Chirally enhanced contributions to C_7 and C_8 avoid the GIM-suppression



$\propto \epsilon \tan\beta$



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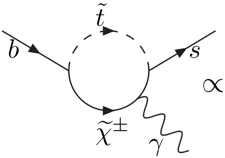

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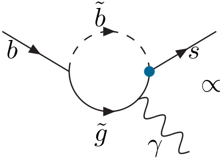

$\propto (\epsilon \tan\beta)^2$

- Gluino contribution sizable in C_8:
  Estimate for equal SUSY-masses

$\mu > 0$: $|C_7^{\tilde{g}}/C_7^{\widetilde{\chi}^{\pm}}| \sim 0.07$, $|C_8^{\tilde{g}}/C_8^{\widetilde{\chi}^{\pm}}| \sim 0.42$

$\mu < 0$: $|C_7^{\tilde{g}}/C_7^{\widetilde{\chi}^{\pm}}| \sim 0.2$, $|C_8^{\tilde{g}}/C_8^{\widetilde{\chi}^{\pm}}| \sim 1.3$

- e.g. impact on mixing-induced CP asymmetries in $B_d \to \phi K_s$, $B_s \to \phi\phi$.

Scan over MSSM parameter space

- Scan ranges: $\tan\beta = 40 - 60,$ arbitrary φ_{A_t} ,

	min (GeV)	max (GeV)
$\tilde{m}_{Q_L}, \tilde{m}_{u_R}, \tilde{m}_{d_R}$	200	1000
$\lvert A_t\rvert$	100	1000
μ, M_1, M_2	200	1000
M_3	300	1000
m_{H^+}	200	1000

- Constraints:
  - squark masses larger than 200 GeV
  - LSP charge- and colour-neutral
  - experimental 2σ bound on the lightest Higgs boson mass
  - $\mathcal{B}(\overline{B} \to X_s\gamma)$ within experimental 2σ range
  - $\left|C_7^{\text{SUSY}}\right| < \left|C_7^{\text{SM}}\right|$ is imposed to avoid unatural fine-tuning

Comparison between $C_{7,8}^{\tilde{g}}$ and $C_{7,8}^{\widetilde{\chi}^{\pm}}$

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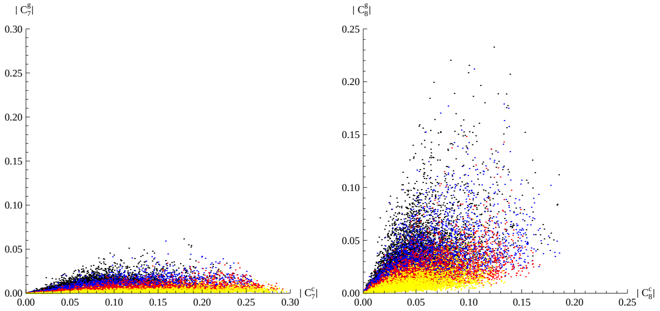
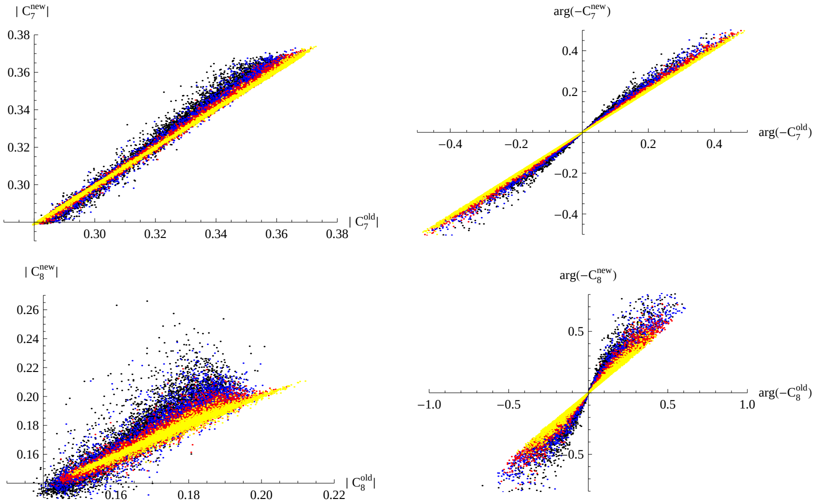


The Wilson coefficients C_7 and C_8

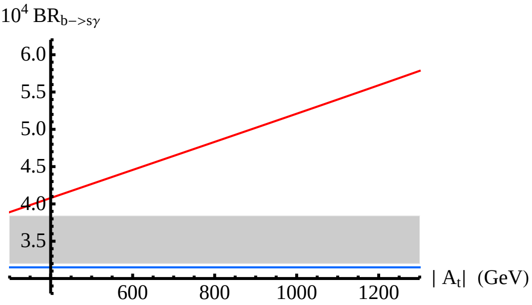
$$C_{7,8}^{\text{old}} = C_{7,8}^{\tilde{\chi}^{\pm}} + C_{7,8}^{H^{+}}, \qquad C_{7,8}^{\text{new}} = C_{7,8}^{\tilde{\chi}^{\pm}} + C_{7,8}^{H^{+}} + C_{7,8}^{\tilde{g}} + C_{7,8}^{\tilde{\chi}^{0}}$$



$\overline{B} \to X_s\gamma$ constraint on A_t

Parameter point:

$\tilde{m}_{Q_L}, \tilde{m}_{u_R}, \tilde{m}_{d_R}$	600 GeV	$\tan\beta$	50
μ	800 GeV	m_{A^0}	400 GeV
M_1	300 GeV	M_2	400 GeV
M_3	500 GeV	φ_{A_t}	0



$\mathcal{B}(\overline{B} \to X_s\gamma)$ constrains the size of $|A_t|$.

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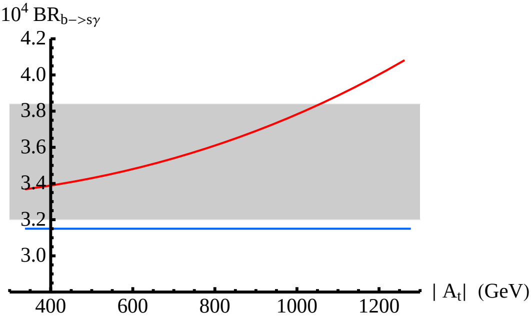
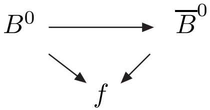


For complex A_t, the bound on $|A_t|$ is much weaker.
[Pokorski, Rosiek, Savoy]

Mixing-induced CP asymmetry in $B^0 \to \phi K_S$

- CP violation in the inteference of mixing and decay



- Time-dependent CP asymmetry:

$$a_f(t) = \frac{\Gamma(\overline{B}^0(t)\to f) - \Gamma(B^0(t)\to f)}{\Gamma(\overline{B}^0(t)\to f) + \Gamma(B^0(t)\to f)} = S\sin(\Delta m_B t) + C\cos(\Delta m_B t)$$

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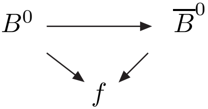

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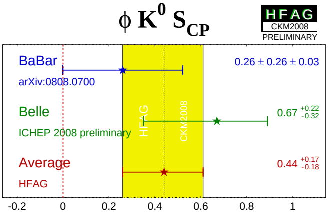

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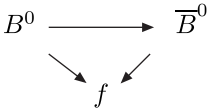

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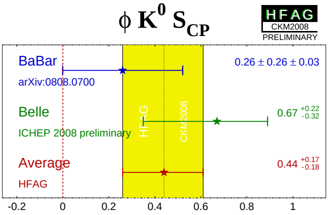

- Large effects possible in the MSSM with MFV and complex A_t

[Altmannshofer, Buras, Paradisi]

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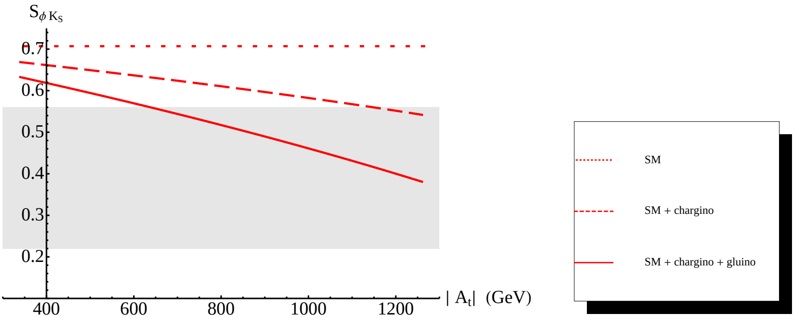

Gluino contribution is sizeable!

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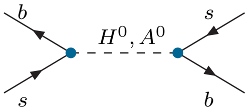

- Neutral Higgs exchange:
  - Superficially leading C_1^{SLL} vanishes because H^0- and A^0 cancel each other. [Hamzaoui,Pospelov,Toharia]
  - C_2^{LR} important despite m_s/m_b suppression. [Buras,Chankowski,Rosiek,Slawianowska]

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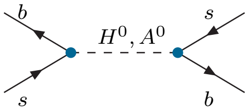

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  - C_2^{LR} important despite m_s/m_b suppression. [Buras,Chankowski,Rosiek,Slawianowska]
- Higgs contribution in [Gorbahn,Jäger,Nierste,Trine]: $\widetilde{C}_2^{LR}$ = real

CP-violating phase in C_2^{LR}

- We find for the Higgs contribution to C_2^{LR} in our scenario:

$$C_2^{LR} = \widetilde{C}_2^{LR}(1 + r), \qquad \text{with} \qquad r = (1 - e^{2i\phi})\frac{(\epsilon_b^* - \epsilon_{FC}^* - \epsilon_s^*)\tan\beta}{1 + \epsilon_s^* \tan\beta},$$

$$\phi = \arg\left\{\epsilon_{FC}\tan\beta\,\left(1 + (\epsilon_b^* - \epsilon_{FC}^*)\tan\beta\right)\right\}$$

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- Beyond the decoupling limit squark masses are split due to electro-weak symmetry breaking $\rightarrow$ small effect:

  $|r| \lesssim 0.01$, for $\mu > 0$, $\qquad |r| \lesssim 0.1$, for $\mu < 0$.

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- $|\widetilde{C}_2^{LR}|$ highly constrained from $B_s \to \mu^+\mu^-$

  [Buras,Chankowski,Rosiek,Slawianowska]

Conclusions

- Not only H^0, A^0 but also $\tilde{g}$, $\widetilde{\chi}^0$ develop flavour-changing couplings at large $\tan\beta$.
- For complex A_t these couplings are CP-violating.
- The Wilson coefficients C_7 and C_8 receive $\tan\beta$-enhanced corrections, the value of C_8 is significantly modified by the gluino contribution.
- For complex A_t the gluino contribution to C_8 has a large impact on the mixing induced CP asymmetries in $B^0 \to \phi K_S$, $B_s \to \phi\phi$.