Patterns of Flavor and CP Violation in Supersymmetric Theories

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Interplay of Collider and Flavour Physics
3^{rd} general meeting

CERN, December 14 - 16, 2009

Outline

based on:

- WA, A.J. Buras and P. Paradisi

  "Low Energy Probes of CP Violation in a Flavor Blind MSSM"

  Phys. Lett. B **669** (2008) 239

- WA, A.J. Buras, S. Gori, P. Paradisi and D. Straub

  "Anatomy and Phenomenology of FCNC and CPV effects in SUSY theories"

  arXiv:0909.1333 [hep-ph]

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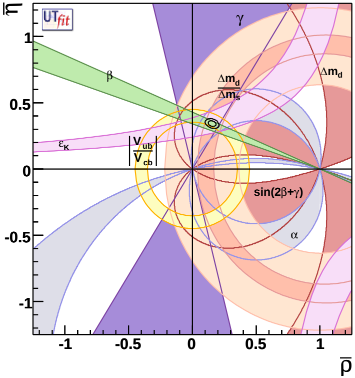
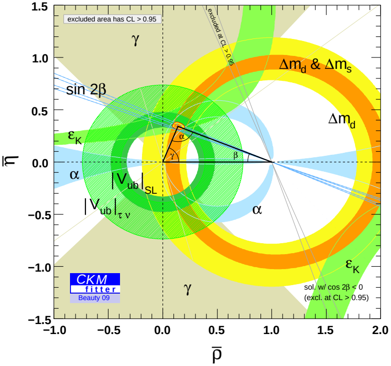
1. Introduction: Flavor Problems
2. Phenomenology of CP Violation in a MFV MSSM
3. Predictions for $S_{\psi\phi}$ in SUSY Flavor Models
4. Interplay between Flavor and Collider Physics
5. Summary

Flavor Violation in the SM





Impressive consistency of the SM CKM picture of flavor and CP violation

(apart from some small tensions...
Lunghi, Soni '08, '09; Buras, Guadagnoli 08', 09'; WA, Buras, Gori, Paradisi, Staub '09; Laiho, Lunghi, Van de Water 09')

The NP Flavor Problem

FCNC processes are strongly suppressed in the SM

- loop suppression
- GIM mechanism
- small CKM angles

$\Rightarrow$ highly sensitive probes of NP degrees of freedom

Consider a generic NP contribution to e.g. Kaon mixing

$$\frac{C}{\Lambda_{\text{NP}}^2} (\bar{s}\gamma_\mu P_L d)^2$$

Measurements of ΔM_K and ϵ_K lead to strong constraints on C/Λ_{NP}^2

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Measurements of ΔM_K and ϵ_K lead to strong constraints on $C/\Lambda_{\rm NP}^2$

ΔM_K	ϵ_K
$C \simeq 1 \Rightarrow \Lambda_{\rm NP} \gtrsim 10^3$TeV	$\text{Im}(C) \simeq 1 \Rightarrow \Lambda_{\rm NP} \gtrsim 10^4$TeV
$\Lambda_{\rm NP} \simeq 1$TeV $\Rightarrow C \lesssim 10^{-6}$	$\Lambda_{\rm NP} \simeq 1$TeV $\Rightarrow \text{Im}(C) \lesssim 10^{-8}$

- a generic flavor structure of NP requires a very high NP scale
- NP degrees of freedom at the TeV scale have to have a highly non-generic flavor structure

The SUSY Flavor Problem

Misalignment between quark and squark masses parametrized by Mass Insertions δ

$$M_{\tilde{q}}^2 = \tilde{m}^2 \left(1\!\!1 + \delta_q \right)$$

$$\delta_q = \begin{pmatrix} \delta_q^{LL} & \delta_q^{LR} \\ \delta_q^{RL} & \delta_q^{RR} \end{pmatrix}$$

Complex Mass Insertions lead to flavor and CP violating gluino-quark-squark interactions that will generate the dominant contributions to FCNCs

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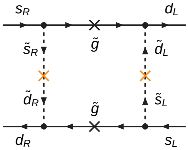
e.g. Kaon mixing in presence of δ_d^{LL} and δ_d^{RR}



$$\propto \frac{\alpha_s}{\tilde{m}^2} (\delta_d^{LL})_{21} (\delta_d^{RR})_{21} \quad (\bar{s} P_L d)\, (\bar{s} P_R d)$$

- operator matrix element is chirally enhanced by M_K^2 / m_s^2
- Wilson coefficient is color and RGE enhanced

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$$\delta_q = \begin{pmatrix} \delta_q^{LL} & \delta_q^{LR} \\ \delta_q^{RL} & \delta_q^{RR} \end{pmatrix}$$

- severe constraints on the SUSY scale and the Mass Insertions

$$(\delta_d^{LL})_{21} \simeq (\delta_d^{RR})_{21} \simeq 1$$

$$\Rightarrow \quad \tilde{m} \gtrsim 10^3 (10^4) \text{TeV}$$

$$\tilde{m} \simeq 1 \text{TeV}$$

$$\Rightarrow \quad (\delta_d^{LL})_{21}, (\delta_d^{RR})_{21} \lesssim 10^{-3} (10^{-4})$$

- SUSY at the TeV scale has to exhibit a highly non-generic flavor structure

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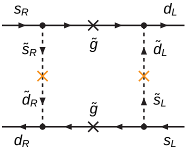

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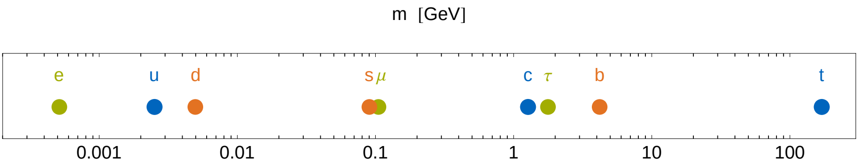
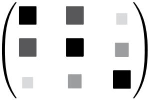


$V_{\rm CKM} =$



$$\approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Also the SM flavor parameters are highly non generic.
Both the fermion masses and mixing angles show a hierarchical structure.

Possible ways to address these problems

Minimal Flavor Violation

D'Ambrosio, Giudice, Isidori, Strumia '02

- the global $U(3)^5$ flavor symmetry of the gauge sector is only broken by the SM Yukawa couplings
- CKM matrix is the only source of flavor violation
- FCNCs naturally suppressed
- visible effects possible in helicity suppressed processes as $b \to s\gamma$, $B_s \to \mu^+\mu^-$, $B \to \tau\nu$
- additional sources of CP violation are in principle allowed!

But: only a solution to the NP/SUSY flavor problem, no explanation of the Yukawa hierarchies...

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Alignment
Nir, Seiberg '93

- quark and squark masses are approximately aligned $\to \delta_{ij} \ll 1$, $i \neq j$
- naturally realized in abelian flavor models

Degeneracy

- squark masses are approximately universal $\to \delta_{ij} \ll 1$
- can e.g. be realized in frameworks with low scale gauge mediation or in non-abelian flavor models

Ambitious approach of SUSY flavor models: simultaneous explanation of the Yukawa hierarchies and a non-generic squark flavor structure

How to test such scenarios?

Look for characteristic NP effects in flavor observables that are not/only poorly measured.

the rare decay $B_s \to \mu^+\mu^-$	$\text{BR}(B_s \to \mu^+\mu^-)_{\text{SM}} = (3.6 \pm 0.4) \times 10^{-9}$ $\text{BR}(B_s \to \mu^+\mu^-)_{\text{exp}} < 5.8 \times 10^{-8}$
the B_s mixing phase	$S_{\psi\phi}^{\text{SM}} \simeq 0.036$ $S_{\psi\phi}^{\text{exp}} = 0.81^{+0.12}_{-0.32}$
the direct CP asymmetry in $b \to s\gamma$	$A_{CP}(b \to s\gamma)_{\text{SM}} = (-0.44^{+0.}_{-0.})\%$ $A_{CP}(b \to s\gamma)_{\text{exp}} = (-0.4 \pm 3.6)\%$
the time dependent CP asymmetry in $B \to \phi K_S$	$S_{\phi K_S}^{\text{SM}} = 0.71 \pm 0.03$ $S_{\phi K_S}^{\text{exp}} = 0.44 \pm 0.17$

+ $D_0 - \bar{D}_0$ mixing, $B \to K^*\ell^+\ell^-$, $B \to K^*\gamma$, $B \to K^{(*)}\nu\bar{\nu}$, ...

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Minimal Flavor Violation

A Flavor Blind MSSM with CP Violating Phases

In a flavor blind MSSM (FBMSSM) there are no additional flavor structures apart from the CKM matrix. In particular, we assume

- universal squark masses
- hierarchical and flavor diagonal trilinear couplings
- flavor conserving but CP violating phases (in particular in the A-terms)

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Within this setup large NP effects arise dominantly through the magnetic and chromo-magnetic dipole operators

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} F_{\mu\nu} b_R \ ,$$

$$\mathcal{O}_8 = \frac{g_s}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} G_{\mu\nu} b_R$$

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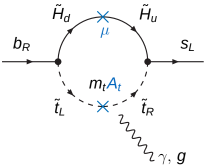
The corresponding Wilson coefficients recieve the dominant contributions from Higgsino-stop loops* and are therefore mainly sensitive to one complex parameter combination

$$C_{7,8} \propto \mu A_t$$

* see Hofer, Nierste, Scherer '09 for additional 2loop gluino contributions



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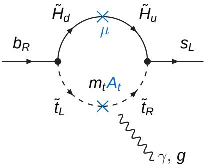


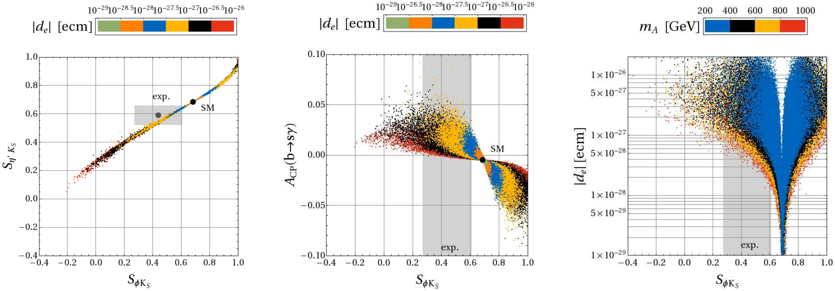
→ Interesting correlated effects in CP violating observables

WA, Buras, Paradisi '08

For analyses of similar frameworks see:

Baek, Ko '99; Bartl, Gajdosik, Lunghi, Masiero, Porod, Stremnitzer, Vives '01; Ellis, Lee, Pilaftsis '07; Mercolli, Smith '09; Paradisi, Straub '09

Phenomenology of CP Violation in a FBMSSM



- 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 $A_{CP}^{bs\gamma} \simeq 0\% - 5\%$
- 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)

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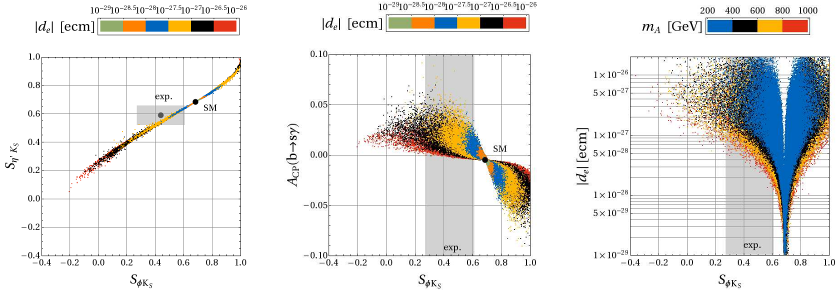

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- the leading NP contributions to $\Delta F = 2$ amplitudes are not sensitive to the new phases of the FBMSSM
- CP violation in meson mixing is SM like
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
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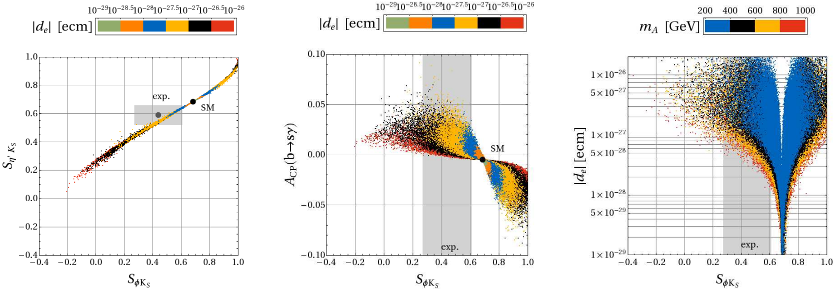

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A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM

Beyond MFV

Representative Flavor Structures

only CKM like δ_d^{LL} mass insertions	comparable δ_d^{LL} and δ_d^{RR} mass insertions that are CKM like	large δ_d^{RR} mass insertions ($\mathcal{O}(1)$ in the 32 sector)

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large δ_d^{RR} mass insertions ($\mathcal{O}(1)$ in the 32 sector)

- many phenomenological features are similar to MFV frameworks (in particular typically small effects in $\Delta F = 2$ amplitudes)
- distinction from MFV through the violation of "golden MFV relations" like

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu-)}{\mathrm{BR}(B_d \to \mu^+\mu-)} = \frac{\hat{B}_d \tau_{B_s}}{\hat{B}_s \tau_{B_d}} \frac{\Delta M_s}{\Delta M_d}$$

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- $(\delta_d^{RR})_{32}$ is only poorly constrained by data
- What are the phenomenological implications of a large $(\delta_d^{RR})_{32}$?

Implications of a large $(\delta_d^{RR})_{32}$ on B_s mixing

1 Gluino boxes

$$\propto \frac{\alpha_s^2}{\tilde{m}^2}(\delta_d^{LL})_{32}(\delta_d^{RR})_{32} \quad (\bar{b}P_L s)(\bar{b}P_R s)$$

$$\propto \frac{\alpha_s^2}{\tilde{m}^2}(\delta_d^{RR})_{32}^2 \quad (\bar{b}\gamma_\mu P_R s)^2$$

- color and RGE enhancement if $(\delta_d^{LL})_{32}$ and $(\delta_d^{RR})_{32}$ present simultaneously
- decoupling with $1/\tilde{m}^2$

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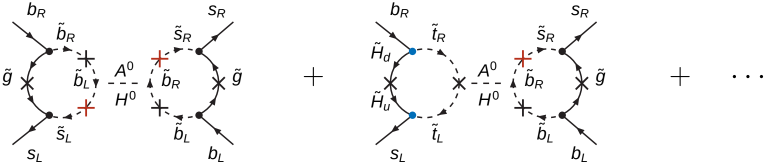
2 Double Higgs Penguins



$$\propto \frac{\alpha_2}{4\pi} \frac{\alpha_s^2}{M_A^2} \frac{m_b^2}{M_W^2} \tan^4\beta \, \frac{\mu^2 M_{\tilde{g}}^2}{\tilde{m}^4} \, (\delta_d^{LL})_{32} (\delta_d^{RR})_{32}$$

$$\propto \frac{\alpha_s}{4\pi} \frac{\alpha_2^2}{M_A^2} \frac{m_b^2}{M_W^2} \tan^4\beta \, \frac{\mu^2 A_t M_{\tilde{g}}}{\tilde{m}^4} \, V_{tb} V_{ts}^* (\delta_d^{RR})_{32}$$

- proportionality to m_b^2
- no decoupling with the SUSY scale! (but with $1/M_A^2$)

There are many flavor models that predict sizable δ_d^{RR}

- Abelian:
  Nir, Seiberg '93; Nir, Raz '02;
  Agashe, Carone '03; ...
- Non Abelian:
  Barbieri, Hall, Romanino '97;
  Carone, Hall, Moroi '97; ...
  Ross, Velasco-Sevilla, Vives '04;
  Antusch, King, Malinsky '07 ...

Concrete Examples

Example: Agashe, Carone '03 (AC)

- Abelian flavor model based on a $U(1)$ horizontal symmetry
- "remarkable level of alignment"

$$(\delta_d^{LL}) \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix}$$

$$(\delta_d^{RR}) \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$$

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Expected phenomenology:

- Small effects in $b \to d$ and $s \to d$ transitions
- Large effects in D_0-$\bar{D}_0$ mixing (general feature of abelian models)
- Large effects in B_s-$\bar{B}_s$ mixing (in particular in $S_{\psi\phi}$ for complex δs)

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- Non abelian flavor model based on a $SU(3)$ flavor symmetry
- 1st and 2nd generation of squarks approximately degenerate

$$(\delta_d^{LL}) \sim \begin{pmatrix} \lambda^4 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$(\delta_d^{RR}) \sim \begin{pmatrix} \lambda^3 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^3 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

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- Non abelian flavor model based on a $SU(3)$ flavor symmetry
- 1st and 2nd generation of squarks approximately degenerate

$$(\delta_d^{LL}) \sim \begin{pmatrix} \lambda^4 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

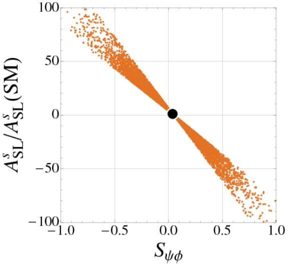
$$(\delta_d^{RR}) \sim \begin{pmatrix} \lambda^3 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^3 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

Expected phenomenology:

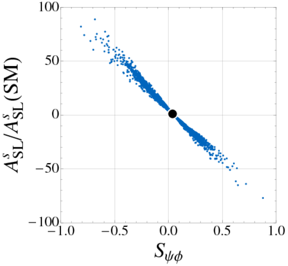
- Moderate effects in $b \to d$ and $s \to d$ transitions (large effects in ϵ_K)
- Small effects in D_0-$\bar{D}_0$ mixing
- Sizeable effects in B_s-$\bar{B}_s$ mixing (in particular in $S_{\psi\phi}$ for complex δs)

- Both models can have large effects in $S_{\psi\phi}$
- Strong (model independent) correlation with the semileptonic asymmetry A^s_{SL}

  (Ligeti, Papucci, Prerez '06)



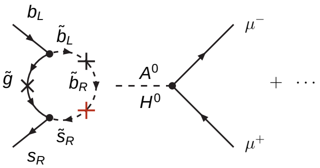
AC



RVV

$^{(*)}$ plots for the flavor models based on MSUGRA like spectrum
$5 < \tan\beta < 55$, $m_0 < 2$TeV, $m_{12} < 1$TeV,
$-3m_0 < A_0 = 3m_0$, $\mu > 0$
with flavor structures implemented at the GUT scale

- for large double penguin contributions to B_s mixing, a correlation with $B_s \to \mu^+\mu^-$ is expected



$$\propto \frac{\alpha_s \alpha_2}{M_A^2} \; \frac{m_b m_\mu}{M_W^2} \tan^3\beta \; \frac{\mu M_{\tilde{g}}}{\tilde{m}^2} \; (\delta_d^{RR})_{32} \quad + \quad \cdots$$

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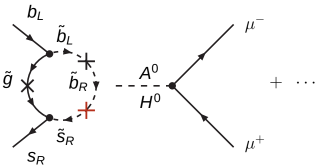

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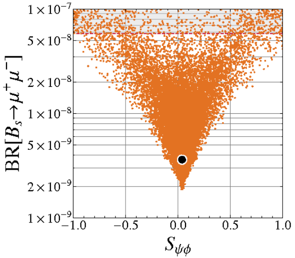
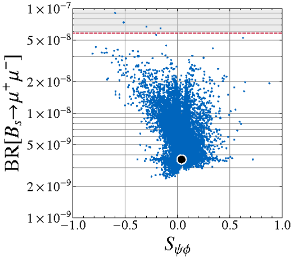
- double penguins are dominant in the AC model $\Rightarrow$ lower bound on BR($B_s \to \mu^+\mu^-$) at the level of 10^{-8}
- in RVV model also boxes play a role $\Rightarrow$ no correlation



AC

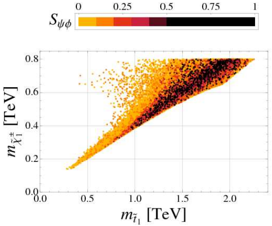


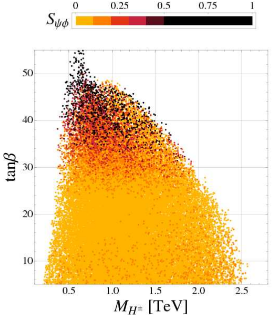
RVV

Flavor vs. Collider

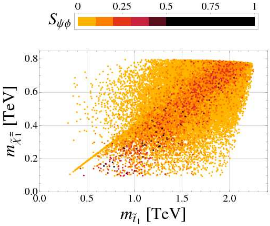
Flavor Model Implications for Direct Searches

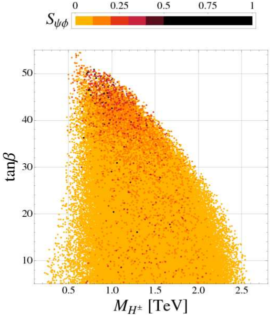
AC





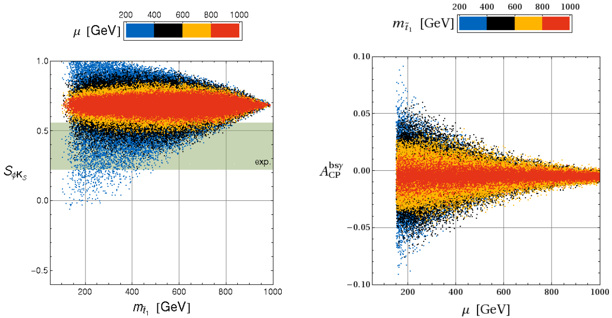
RVV





- Sizeable effects in $S_{\psi\phi}$ are possible in a large region of parameter space
- Even **sparticles beyond the LHC reach** can lead to **visible departures of $S_{\psi\phi}$ from its SM prediction** (non decoupling of double Higgs penguins)

FBMSSM Implications for Direct Searches



- $S_{\phi K_S} \simeq 0.4$ implies $\boldsymbol{\mu} \lesssim$ **600GeV** and $\boldsymbol{m_{\tilde{t}_1}} \lesssim$ **700GeV**
- similarly, large non standard effects in $A_{CP}^{bs\gamma} \gtrsim 2\%$ imply $\boldsymbol{\mu} \lesssim$ **600GeV** and $\boldsymbol{m_{\tilde{t}_1}} \lesssim$ **800GeV**
- squarks lie well **within the reach of LHC**

Summary

- in a MFV MSSM, CP violating $\Delta F = 0$ and $\Delta F = 1$ dipole amplitudes can be strongly modified
- one finds highly correlated effects in the EDMs, $A_{CP}^{bs\gamma}$, CP asymmetries in $B \to K^* \ell^+ \ell^-$, $S_{\phi K_S}$ and $S_{\eta' K_S}$
- such effects imply SUSY particles in the reach of LHC
- $\Delta F = 2$ amplitudes remain however SM like (in particular: small effects in $S_{\psi\phi}$)

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- one finds highly correlated effects in the EDMs, $A_{CP}^{bs\gamma}$, CP asymmetries in $B \to K^* \ell^+ \ell^-$, $S_{\phi K_S}$ and $S_{\eta' K_S}$
- such effects imply SUSY particles in the reach of LHC
- $\Delta F = 2$ amplitudes remain however SM like (in particular: small effects in $S_{\psi\phi}$)

- sizeable δ_d^{RR} mass insertions lead to flavor changing right handed currents that imply a qualitatively very different phenomenology
- $\Delta F = 2$ amplitudes can recieve large NP effects
- in the large $\tan\beta$ regime, double Higgs penguin contributions to B_s mixing lead to a correlation between $S_{\psi\phi}$ and $B_s \to \mu^+\mu^-$, implying a lower bound on BR($B_s \to \mu^+\mu^-$) at the level of 10^{-8} for $S_{\psi\phi} \simeq 0.8$
- these effects do not decouple with the SUSY scale
- testable SUSY signatures in flavor observables even for sparticles that are beyond the LHC reach

"Flavor DNA"

	GMSSM	AC	RVV	δ_{LL} only	FBMSSM
$D^0 - \bar{D}^0$ mixing	★★★	★★★	★	★	★
ϵ_K	★★★	★	★★★	★	★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★
$S_{\phi K_S}, S_{\eta' K_S}$	★★★	★★★	★★	★★★	★★★
$A_{CP}^{bs\gamma}$	★★★	★	★	★★★	★★★
$\langle A_{7,8}\rangle(B \to K^*\mu^+\mu^-)$	★★★	★	★	★★★	★★★
$\langle A_9\rangle(B \to K^*\mu^+\mu^-)$	★★★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★
$B \to K^{(*)}\nu\bar{\nu}$	★★	★	★	★	★
$K \to \pi\nu\bar{\nu}$	★★★	★	★	★	★
d_e	★★★	★★★	★★★	★	★★★

★★★: large effects, ★★: moderate effects, ★: small effects