CP Violation in Meson Mixing: Implications for Supersymmetric Models

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Outline

based on:

- WA, A.J. Buras, S. Gori, P. Paradisi and D. Straub
  "Anatomy and Phenomenology of FCNC and CPV Effects in SUSY Theories"
  Nucl. Phys. B **830** (2010) 17
- WA, A.J. Buras and P. Paradisi
  "A Lower Bound on Hadronic EDMs from CPV in $D^0 - \bar{D}^0$ mixing in SUSY Alignment Models"
  Phys. Lett. B **688** (2010) 202

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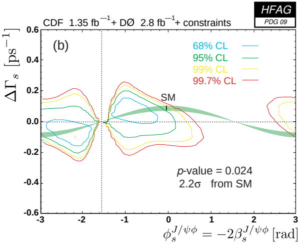
1. The B_s Mixing Phase in the Minimal Flavor Violating MSSM
2. The B_s Mixing Phase in SUSY Frameworks beyond MFV
3. CP Violation in $D^0 - \bar{D}^0$ mixing and EDMs in Abelian Flavor Models

Hints for New Physics in B_s Mixing?

Status 2009

- data from Tevatron seems to hint towards a large B_s mixing phase (2-3σ deviation from SM prediction)



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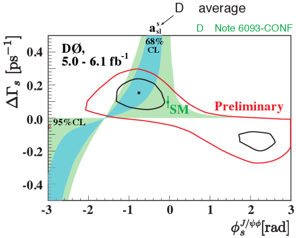
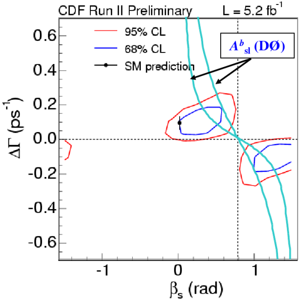
Recent Progress

- updates from CDF and D0 are in better agreement with the SM
- new result from D0 on the like sign dimuon charge asymmetry A^b_{SL} shows a 3.2 deviation from the SM
- global fits prefer large phase in B_s mixing $S_{\psi\phi} \simeq 0.5$ (e.g. Ligeti, Papucci, Perez, Zupan '10 Lenz et al. '10)

Possible Interpretation

- large CP violating short distance contributions to the B_s mixing amplitude M^s_{12}





The B_s Mixing Phase in the Minimal Flavor Violating MSSM

The MFV MSSM with CP Violating Phases

Minimal Flavor Violation (Buras et al. '00; D'Ambrosio, Giudice, Isidori, Strumia '02)

- the global $U(3)^5$ flavor symmetry of the (MS)SM gauge sector is only broken by the SM Yukawa couplings
- the MSSM soft terms can be expanded in powers of Yukawas

$$m_Q^2 = \tilde{m}_Q^2 \left(1 + b_1 V^\dagger \hat{Y}_u^2 V + b_2 \hat{Y}_d^2 + b_3 \hat{Y}_d^2 V^\dagger \hat{Y}_u^2 V + b_3^* V^\dagger \hat{Y}_u^2 V \hat{Y}_d^2\right)$$

$$m_U^2 = \tilde{m}_U^2 \left(1 + b_4 \hat{Y}_u^2\right) \ , \quad A_u = \tilde{A}_u \left(1 + b_6 V^* \hat{Y}_d^2 V^T\right) \hat{Y}_u$$

$$m_D^2 = \tilde{m}_D^2 \left(1 + b_5 \hat{Y}_d^2\right) \ , \quad A_d = \tilde{A}_d \left(1 + b_7 V^T \hat{Y}_u^2 V^*\right) \hat{Y}_d$$

- CKM matrix is the only source of flavor violation
- Flavor Changing Neutral Currents naturally suppressed

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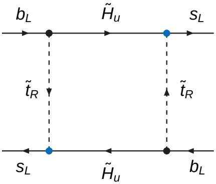
- CKM matrix is the only source of flavor violation
- Flavor Changing Neutral Currents naturally suppressed

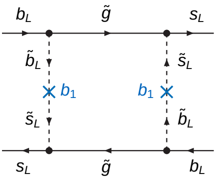
- additional sources of CP violation are in principle allowed! (M_1 , M_2 , $M_{\tilde{g}}$, μ)
- what is their impact on CP violation in meson mixing?

MFV Box Contributions

leading box contributions to meson mixing are not sensitive to flavor diagonal phases!
(WA, Buras, Paradisi '08)

$$\propto \frac{\alpha^2}{\tilde{m}^2}(V_{tb}V_{ts}^*)^2$$





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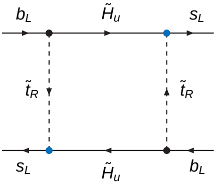
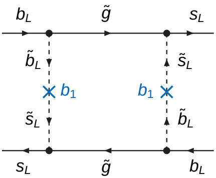
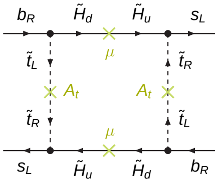
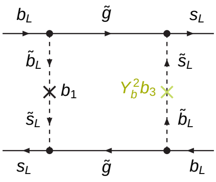








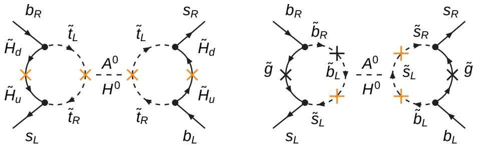
$$\propto \frac{\alpha^2}{\tilde{m}^2}(V_{tb}V_{ts}^*)^2 \left[\frac{m_b^2}{\tilde{m}^2}\tan^2\beta \frac{(\mu A_t)^2}{\tilde{m}^4}\right] ,$$

$$\propto \frac{\alpha^2}{\tilde{m}^2}(V_{tb}V_{ts}^*)^2 \left[\frac{m_b^2}{M_W^2}\tan^2\beta \, b_1 b_3\right] , \quad \ldots$$

- CP violating contributions are suppressed by at least two powers of the bottom Yukawa Y_b^2
  (WA, Buras, Gori, Paradisi, Straub '09
  Blum, Hochberg, Nir '10)
- might be relevant in the large $\tan\beta$ regime ?

Double Penguins in the MFV MSSM

For large values of $\tan\beta$ also so-called
double Higgs penguins become important



$$\propto \frac{\alpha^3}{4\pi}\frac{1}{M_A^2}(V_{tb}V_{ts}^*)^2\frac{m_b m_s}{M_W^2}\tan^4\beta$$

$$\times\left[\frac{|\mu A_t|^2}{\tilde{m}^4}\,,\quad \frac{|\mu M_{\tilde{g}}|^2}{\tilde{m}^4}(b_1+b_3Y_b^2)^2\,,\quad \ldots\right]$$

- also no sensitivity to flavor diagonal CP phases at the leading order
- possibility to have CPV through a complex b_3
  (see also talk by Stefania Gori
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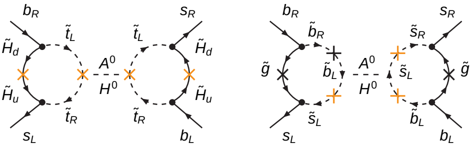

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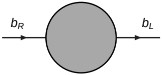
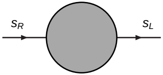
- consider also higher order $\tan\beta$ resummation factors; naively:

$$\tan^4\beta \to \frac{\tan^4\beta}{|1+\epsilon\tan\beta|^4}$$

- But: possible difference in ϵ_b and ϵ_s resummation factors can in principle lead to CP violation and is sensitive to flavor diagonal phases
  (Hofer, Nierste, Scherer '09
  Dobrescu, Fox, Martin '10)



$\supset m_b\epsilon_b\tan\beta$



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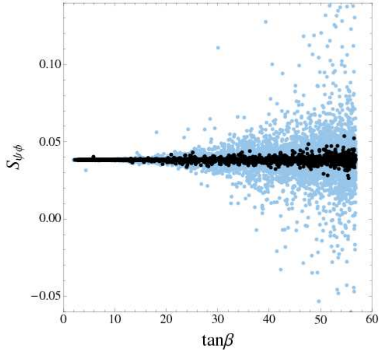
A Large B_s Mixing Phase in the MFV MSSM?



Result of a Numerical Scan

- CP violation in meson mixing is generically SM like in the MFV MSSM
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_K
- reason: strong constraints from BR($B \to X_s\gamma$) and BR($B_s \to \mu^+\mu^-$)

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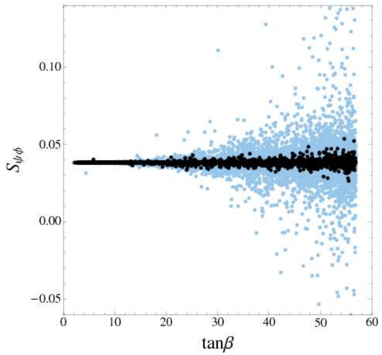

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- some effects in $S_{\psi\phi}$ might still be possible in the uplifted SUSY region with $\tan\beta \simeq O(100-200)$
  (Dobrescu, Fox '10; Dobrescu, Fox, Martin '10)
- But: such a scenario is strongly constrained by $B \to \tau\nu$, $(g-2)_\mu$ and EDMs
  (WA, Straub '10; see also talk by David Straub)

The B_s Mixing Phase Beyond MFV

Additional Sources of Flavor and CP Violation

Soft squark masses and trilinear couplings can contain additional flavor structures beyond the CKM matrix

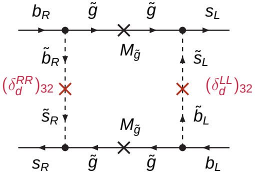
Convenient parametrization through mass insertions

$$M_q^2 = \tilde{m}^2(\mathbb{1} + \delta_q)$$

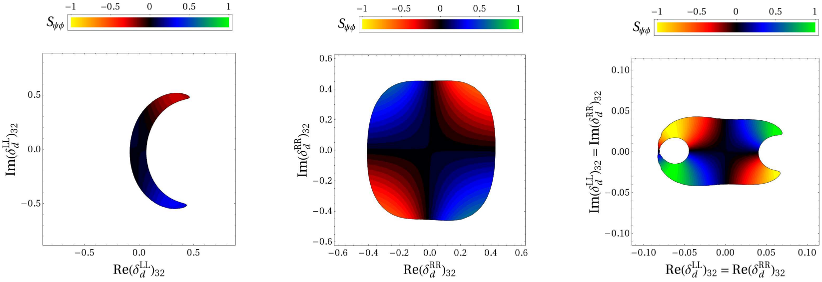
$$\delta_q = \begin{pmatrix} \delta_q^{LL} & \delta_q^{LR} \\ \delta_q^{RL} & \delta_q^{RR} \end{pmatrix} \; , \quad q = u, d$$

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

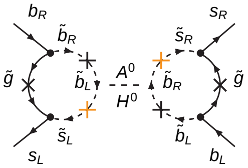
- color and RGE enhancement if $(\delta_d^{LL})_{32}$ and $(\delta_d^{RR})_{32}$ present simultaneously
- (δ_d^{LL}) mass insertions are always generated radiatively
- most natural way to generate visible NP effects in $S_{\psi\phi}$ is through large complex $(\delta_d^{RR})_{32}$ mass insertions



$$\propto \frac{\alpha_s^2}{\tilde{m}^2}(\delta_d^{LL})_{32}(\delta_d^{RR})_{32}$$



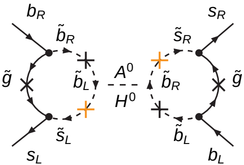
* common SUSY scale $\tilde{m} = 500$ GeV , $\tan\beta = 10$



$$\propto \frac{\alpha^3}{4\pi}\frac{1}{M_A^2}(\delta_d^{LL})_{32}(\delta_d^{RR})_{32}\frac{m_b^2}{M_W^2}\tan^4\beta\frac{|\mu M_{\tilde{g}}|^2}{\tilde{m}^4}$$

- proportionality to m_b^2 because of the presence of flavor changing RH currents
- sizable contributions to meson mixing are expected in the large $\tan\beta$ regime
- such contributions do not decouple with the SUSY scale! (but with $1/M_A^2$)

Double Higgs Penguins and $B_s \to \mu^+\mu^-$



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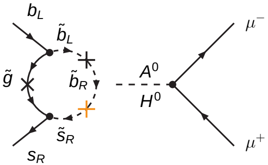
- ▶ for large double penguin contributions to B_s mixing, a correlation with $B_s \to \mu^+\mu^-$ is expected



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Concrete Example: An Abelian Flavor Model

Example: Agashe, Carone '03 (AC)

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

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

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Expected phenomenology:

- small effects in $b \longrightarrow d$ and $s \longrightarrow d$ transitions
- large effects in D_0-$\bar{D}_0$ mixing (generic for abelian models)
- large effects in B_s-$\bar{B}_s$ mixing

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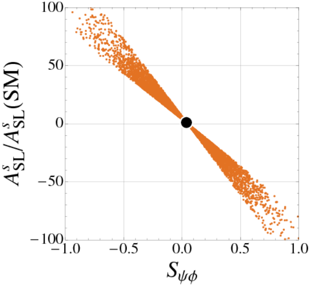

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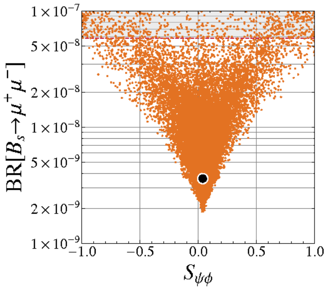

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- double penguins dominate $\Rightarrow$ lower bound on BR($B_s \to \mu^+\mu^-$) at the level of 10^{-8} (WA, Buras, Gori, Paradisi, Straub '09)

A Generic Prediction of Abelian Flavor Models

$D^0 - \bar{D}^0$ Mixing in Abelian Flavor Models

$SU(2)_L$ invariance implies a relation between LL mass insertions in the up and down sector

$$(\delta_u^{LL}) = V^*(\delta_d^{LL})V^{\mathsf{T}}$$

$$(\delta_u^{LL})_{21} = (\delta_d^{LL})_{21} + \lambda \left(\frac{m^2_{\tilde{c}_L}}{\tilde{m}^2} - \frac{m^2_{\tilde{u}_L}}{\tilde{m}^2} \right)$$

- abelian flavor models that realize the alignment mechanism ensure $(\delta_d^{LL}) \simeq 0$
- irreducible flavor violating term $(\delta_u^{LL})_{21} \sim \lambda$ in the up sector for natural $\mathcal{O}(1)$ splitting of squark masses

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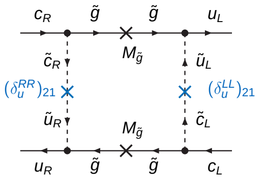
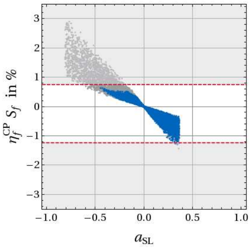




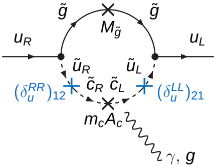
- immediate consequence: Large NP effects in $D^0 - \bar{D}^0$ mixing (Nir, Seiberg '93)
- already for tiny complex $\delta_u^{RR} \sim \lambda^3$ large CP violation in $D^0 - \bar{D}^0$ mixing

$$\mathrm{Im}\, M_{12}^D \propto \mathrm{Im} \left[(\delta_u^{LL})_{21} (\delta_u^{RR})_{21} \right]$$

- current experimental bounds are easily reached

Correlation with Electric Dipole Moments

- a complex $(\delta_u^{RR})_{21}$ leads also to a up quark EDM by means of flavor effects



$$d_u^{(c)} \propto \mathrm{Im}\left[(\delta_u^{LL})_{21}(\delta_u^{RR})_{21}\right]$$

- suppression by small mass insertions, but chiral enhancement by m_c / m_u
- the up quark EDM leads in turn to EDMs e.g. of the neutron and of mercury

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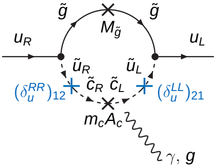

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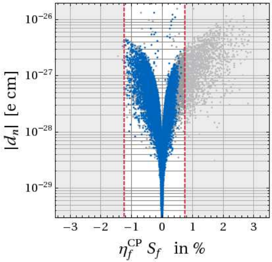


- large CP violation in $D^0 - \bar{D}^0$ mixing in abelian flavor models implies lower bounds on hadronic EDMs (WA, Buras, Paradisi '10)

$$d_n \gtrsim 10^{-(28-29)} e\,\mathrm{cm}$$

$$d_{\rm Hg} \gtrsim 10^{-(30-31)} e\,\mathrm{cm}$$

- interesting level for expected future experimental resolutions

Summary

- CP violation in $\Delta F = 2$ transitions remains generically SM like in the MFV MSSM (in particular: small effects in $S_{\psi\phi}$)
- sizable NP effects in meson mixing can be naturally generated in non-MFV scenarios with large flavor changing right handed currents
- if in addition $\tan\beta$ is large, double Higgs penguin contributions to B_s mixing are correlated with the rare decay $B_s \to \mu^+\mu^-$, implying a lower bound on $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at the level of 10^{-8} for $S_{\psi\phi} \simeq 0.5$

Summary

- in abelian flavor models, the squark and quark masses can be aligned and flavor violating effects in the down sector can be suppressed
- however, large effects in $D^0 - \bar{D}^0$ mixing are *generically* predicted
- large CP violation in $D^0 - \bar{D}^0$ mixing implies lower bounds on hadronic EDMs at an experimentally interesting level

Back Up

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)

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

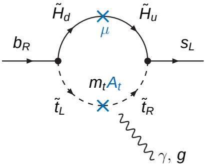
$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} F_{\mu\nu} b_R \ ,$$

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

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



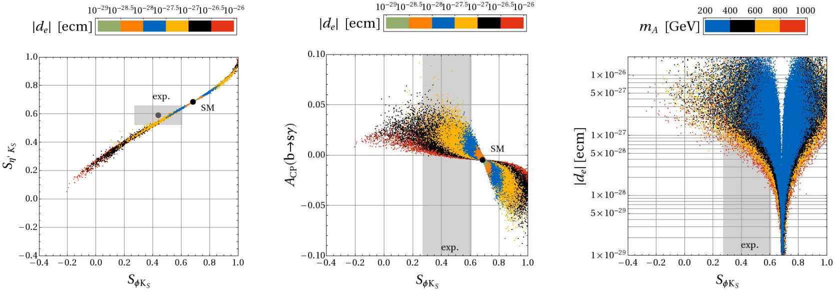
→ Interesting correlated effects in CP violating observables

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

Flavor and CP Phenomenology 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 $A_{CP}(b \to s\gamma) \simeq 0\% - 5\%$
- 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 '08)

- 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