Identifying the Flavor Structure of SUSY Theories through Low Energy CP Violating Observables

Wolfgang Altmannshofer

Physik Department
Technische Universität München

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Based on:

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

- WA, P. Ball, A. Bharucha, A.J. Buras, D. Straub and M. Wick
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- WA, A.J. Buras, S. Gori, P. Paradisi and D. Straub
  in preparation

1. Introduction: Hints for New Sources of CP Violation
2. CP Violation in the MSSM
   - Phenomenology of CP Violation in a Flavor Blind MSSM
   - Introducing New Sources of Flavor Violation
3. Summary and Outlook
The SM CKM picture for CP violation seems confirmed in an impressive way.
Hints for New Sources of CP Violation?

1 Tensions in the Unitarity Triangle
Lunghi, Soni ’08,’09; Buras, Guadagnoli ’08,’09
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   - Additional CP violation in $K$ mixing?
   - NP contributions to $\Delta M_d / \Delta M_s$?

   Wolfgang Altmannshofer (TUM)
   CP Violation in SUSY
   SUSY09, June 6, 2009
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[Diagram showing $\epsilon_K$ and $\Delta M_d/\Delta M_s$]
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   - Recent data from CDF and D0 seem to indicate large NP effects in $S_{\psi\phi}$
     $S_{\psi\phi} = \sin 2(\beta_s + \Phi_{B_s}^{NP}) = 0.54^{+0.24}_{-0.28}$, $\beta_s \approx 1^\circ$
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The MSSM has many free parameters that can provide such phases

- Higgsino mass: $\mu$
- Gaugino masses: $M_1, M_2, M_3$
- squark masses: $m^2_Q, m^2_U, m^2_D$
- trilinear couplings: $A_u, A_d$
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Which low energy observables can be affected by these phases?
\[ \Delta F = 0 \]
\[ \Delta F = 1 \]
\[ \Delta F = 2 \]
Electric Dipole Moments (EDMs) of the electron and neutron, $d_e$ and $d_n$
CP Violating Low Energy Observables

\[ \Delta F = 0 \]

- E.g.
  - Electric Dipole Moments (EDMs) of the electron and neutron, \( d_e \) and \( d_n \)

\[ \Delta F = 1 \]

- E.g.
  - Direct CP asymmetry in \( b \to s \gamma, A_{CP}^{bs\gamma} \)
  - CP asymmetries in \( B \to K^* \ell^+ \ell^- \)

\[ \Delta F = 2 \]


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\[ \Delta F = 2 \]

- CP violation in Kaon mixing, \( \epsilon_K \)
- Time dependent CP asymmetries in \( B_d \to \psi K_S \) and \( B_s \to \psi \phi, S_{\psi K_S} \) and \( S_{\psi \phi} \)
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- universal squark masses
- hierarchical and flavor diagonal trilinear couplings
- and allow for flavor conserving but CP violating phases
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Within this setup large NP effects arise dominantly through the magnetic and chromo-magnetic dipole operators

\[ O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} F_{\mu\nu} b_R , \]

\[ O_8 = \frac{g_s}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} G_{\mu\nu} b_R \]
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The corresponding Wilson coefficients receive the dominant contributions from Higgsino-stop loops and are therefore mainly sensitive to one complex parameter combination:

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C_{7,8} \propto \mu A_t
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→ Interesting correlated effects in CP violating observables

For analyses of similar frameworks see:
Baek, Ko '99; Bartl, Gajdosik, Lunghi, Masiero, Porod, Stremnitzer, Vives '01; Ellis, Lee, Pilaftsis '07; Mercolli, Smith '09

WA, Buras, Paradisi '08
Sizable, correlated effects in the time dependent CP asymmetries in $B \to \phi K_S$ and $B \to \eta' K_S$, i.e. $S_{\phi K_S}$ and $S_{\eta' K_S}$

Both asymmetries can simultaneously be brought in agreement with the data
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2 loop Barr-Zee type contributions to the EDMs are proportional to $\text{Im}(\mu A_t)$

For $S_{\phi K_S} \approx 0.4$, lower bounds on the electron and neutron EDMs:

$$d_e \gtrsim 5 \times 10^{-28} \text{ ecm}, \quad d_n \gtrsim 8 \times 10^{-28} \text{ ecm}$$

(only one order of magnitude below the current experimental constraints)
The direct CP Asymmetry in $b \rightarrow s\gamma$ is highly suppressed in the SM: $A_{CP}^{bs\gamma} \simeq 0.4\%$

$\rightarrow$ very suitable place to look for New Physics

In the FBMSSM $A_{CP}^{bs\gamma}$ is correlated with $S_{\phi K_S}$

For $S_{\phi K_S} < S_{\phi K_S}^{SM}$, $A_{CP}^{bs\gamma}$ is unambiguously positive

values for $A_{CP}^{bs\gamma}$ typically in the range 1% – 6%
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The $B \rightarrow K^*\ell^+\ell^-$ offers up to 24 observables that can be accessed by measuring the full differential decay distribution (Bobeth et al ’08; Egede et al ’08; WA, Ball, Bharucha, Buras, Straub, Wick ’09)

Many asymmetries that can be constructed are strongly enhanced in the FBMSSM and also highly correlated
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The asymmetries are also correlated with $S_{\phi K_S}$, $A_{\text{CP}}^{bs\gamma}$ and the EDMs
Kaon mixing

- The mixing amplitude $M^K_{12}$ has no sensitivity to the new flavor blind phases
- Still, $\epsilon_K \propto \text{Im}(M^K_{12})$ can get a positive NP contribution up to 15%
- But only for a very light SUSY spectrum: $\mu, m_{\tilde{t}_1} \simeq 200\text{GeV}$
CP Violation in $\Delta F = 2$ Transitions

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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 ($S_{\psi \phi} \simeq 0.03 - 0.05$).
In a flavor blind 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 $B \rightarrow K^*\ell^+\ell^-$, $S_{\phi K_S}$ and $S_{\eta' K_S}$.

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A combined study of all these observables and their correlations constitutes a very powerful test of the FBMSSM.
How to generate large effects in $S_{\psi\phi}$?
The soft squark masses $m_{Q}^2$, $m_{U}^2$, $m_{D}^2$ and the trilinear couplings $A_{u}$, $A_{d}$ can contain additional flavor structures beyond the CKM matrix.

Such structures lead to flavor off-diagonal entries in the squark masses.
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Convenient parametrization through mass insertions

$$M_q^2 = \tilde{m}^2 \mathbf{1} + \tilde{m}^2 \delta_q$$

$$\delta_q = \begin{pmatrix} \delta_{qL}^{LL} & \delta_{qL}^{LR} \\ \delta_{qR}^{RL} & \delta_{qR}^{RR} \end{pmatrix}, \quad q = u, d$$
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$$\delta_q = \begin{pmatrix} \delta_{qLL} & \delta_{qLR} \\ \delta_{qRL} & \delta_{qRR} \end{pmatrix}, \quad q = u, d$$

Complex mass insertions lead to flavor and CP violating gluino-quark-squark interactions that will generate the dominant contributions to FCNCs.
- LR and RL mass insertions are highly constrained by the $b \rightarrow s\gamma$ decay
- No large effects in the $B_s$ mixing amplitude can be generated
The Impact of Mass Insertions on $S_{\psi\phi}$

- LR and RL mass insertions are highly constrained by the $b \rightarrow s\gamma$ decay
- No large effects in the $B_s$ mixing amplitude can be generated

- LL and RR mass insertions are much less constrained
- If only LL or RR insertions are on, large $\delta$s are required to generate effects in $S_{\psi\phi}$
- If both LL and RR insertions are present simultaneously, contributions are generated that are strongly renormalization group enhanced
- Even for moderate values for $\delta_d^{LL}$ and $\delta_d^{RR}$, sizeable effects in $S_{\psi\phi}$ are possible
Which Flavor Models predict that patterns

- Even starting with universal squark masses at the GUT scale, LL insertions are always generated through the running
- Look for flavor models with large RR insertions
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There are many flavor models that predict large RR insertions

- **Abelian:** Nir, Seiberg ’93; Nir, Raz ’02; Agashe, Carone ’03; ...
- **Non Abelian:** Barbieri, Hall, Romanino ’97; Carone, Hall, Moroi ’97; ...
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Concrete example: Agashe, Carone ’03

- Abelian flavor model based on a $U(1) \times U(1)$ horizontal symmetry
- “remarkable level of alignment”

\[
\begin{align*}
(\delta_{LL}^d) & = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \chi^2 \\ 0 & \chi^2 & 1 \end{pmatrix} \\
(\delta_{RR}^d) & = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} \\
(\delta_{LL}^u)_{21} & = \lambda \left( \frac{\tilde{m}_1^2}{\tilde{m}_2^2} - 1 \right) \\
\end{align*}
\]

\[(*) \quad \mathcal{O}(1) \text{ coefficients are omitted}\]
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- "remarkable level of alignment"

Expected phenomenology in that model

- 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 $\delta$s)

\[
\begin{pmatrix}
\delta^{LL}_{d} \\
\delta^{RR}_{d}
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & \lambda^2 \\
0 & \lambda^2 & 1
\end{pmatrix}\]

\[
\delta^{LL}_{u}
= \lambda\begin{pmatrix}
\tilde{m}_1^2 \\
\tilde{m}_2^2
\end{pmatrix} - 1
\]

\((*) \ O(1) \ coefficients \ are \ omitted\)
First Numerical Results (*)

- It is possible to get $S_{\psi\phi}$ in the entire range $-1 < S_{\psi\phi} < 1$
- Strong (model independent) correlation with the semileptonic asymmetry $A_{SL}^s$

Ligeti, Papucci, Prerez ’06

\[ 5 < \tan \beta < 15, \quad m_0 < 3 \text{TeV}, \quad m_{1/2} < 2 \text{TeV}, \quad A_0 = 0, \quad \mu > 0 \]
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Ligeti, Papucci, Prerez ’06

- Large $S_{\psi\phi} > 0.5$ can be obtained even for very large SUSY masses
  $m_{\tilde{t}} < 3$ TeV, $m_{\tilde{\chi}_1^\pm} < 2$ TeV

- For a light spectrum, strong constraints are put by $b \rightarrow s\gamma$ and in particular $D_0$-$\bar{D}_0$ mixing

(*)  $5 < \tan \beta < 15$, $m_0 < 3$ TeV, $m_{1/2} < 2$ TeV, $A_0 = 0$, $\mu > 0$
In a flavor blind 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 $B \rightarrow K^* \ell^+ \ell^-$, $S_{\phi K_S}$ and $S_{\eta' K_S}$.

CP violation in $\Delta F = 2$ amplitudes is however SM like.

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To get large CP violating NP effects in $\Delta F = 2$ amplitudes, as indicated by the data on $S_\psi \phi$, additional flavor violating structures have to be present in the soft sector.

Flavor models that predict sizeable $\delta_d^{RR}$ insertions are very promising frameworks to generate large effects in $S_\psi \phi$.

Which testable correlations exist between CP violating $\Delta F = 1$ and $\Delta F = 2$ observables that allow to discriminate between different models? ...
FBMSSM Implications for Direct Searches

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