CP Violating Observables in a Flavor Blind MSSM

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Outline

based on:

- WA, Andrzej Buras and Paride Paradisi

- WA, Patricia Ball, Aoife Bharucha, Andrzej Buras, David Straub and Michael Wick
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1. Introduction: Hints for New Sources of CP Violation
2. A Flavor Blind MSSM
3. Phenomenology of CP Violation in the FBMSSM
4. Summary
Apart from the QCD $\theta$ term, the only source for CP violation in the SM is the phase in the CKM matrix.

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1 - \frac{1}{2} \lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \varrho - i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

CP violation from the CKM matrix can be visualized by Unitarity Triangles e.g.

$$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$$
Impressive confirmation of the CKM picture for CP violation
Hints for New Sources of CP violation?

1. CP Asymmetry in $B \rightarrow \psi K_S$ and $\sin 2\beta$

- **Tree level decay** → sensitivity to the phase of the $B_d$ mixing amplitude without NP in the decay amplitude

- in SM: $\text{Arg}(M_{12}^d) = \text{Arg}(V_{td}^2) = 2\beta$

$$\sin 2\beta \overset{\text{SM}}{=} S^{\text{exp.}}_{\psi K_S} = 0.671 \pm 0.024$$
Hints for New Sources of CP violation?

CP Asymmetry in $B \rightarrow \psi K_S$ and $\sin 2\beta$

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- in SM: $\text{Arg}(M_{12}^d) = \text{Arg}(V_{td}^2) = 2\beta$

$$\sin 2\beta^{SM} = S_{\psi K_S}^{\text{exp.}} = 0.671 \pm 0.024$$

- In the SM also *loop induced* modes like $B \rightarrow \phi K_S$ and $B \rightarrow \eta' K_S$ give the same value

$$S_{\phi K_S}^{SM} = S_{\eta' K_S}^{SM} = S_{\psi K_S}^{SM} = \sin 2\beta$$

- But experimentally one has

$$S_{\phi K_S}^{\text{exp.}} = 0.44 \pm 0.17, \quad S_{\eta' K_S}^{\text{exp.}} = 0.59 \pm 0.07$$

⇒ New Phases in decays?
Hints for New Sources of CP violation?

Tensions in the Unitarity Triangle
Lunghi, Soni '08; Buras, Guadagnoli '08, '09

- Construct the UT using only $S_{\psi K_S}$ and $\Delta M_d/\Delta M_s$
- $\sin 2\beta$ as determined from $B \to \psi K_S$ and $R_t$ as determined from $\Delta M_d/\Delta M_s$ lead to a prediction for CP violation in the $K$ system

$\epsilon_{SM}^K = (1.78 \pm 0.25) \times 10^{-3} \iff \epsilon_{exp}^K = (2.23 \pm 0.01) \times 10^{-3}$
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⇒ NP phase in $B_d$ mixing?
⇒ Additional CP violation in $K$ mixing?
Hints for New Sources of CP violation?

UTfit collaboration

3 CP Asymmetry in $B_s \rightarrow \psi\phi$ and $\sin 2\beta_s$

- Tree level decay $\rightarrow$ sensitivity to the phase of the $B_s$ mixing amplitude without NP in the decay amplitude
- in SM: $\text{Arg}(M_{12}^s) = \text{Arg}(V_{ts}^2) = 2\beta_s$ with $\beta_s \simeq 1^\circ$
- beyond the SM one has

$$S_{\psi\phi} = \sin 2(\beta_s + \Phi_{B_s}^{NP})$$

- recent analyses seem to hint towards large NP effects

$$\Phi_{B_s}^{NP} = (19^\circ \pm 8^\circ) \cup (69^\circ \pm 7^\circ)$$

⇒ Large $B_s$ mixing phase?
Natural way to address these tensions/problems:

- go beyond the SM and introduce new CP violating phases

A Minimal Flavor Violating MSSM with additional CP violating phases

Baek, Ko '99
Bartl, Gajdosik, Lunghi, Masiero, Porod, Stremnitzer, Vives '01 (Flavor Blind MSSM)
Ellis, Lee, Pilaftsis '07 (MCPMFVMSSM)
WA, Buras, Paradisi '08
In a flavor blind MSSM (FBMSSM) there are no additional flavor structures apart from the CKM matrix. In particular, we assume universal squark masses and diagonal trilinear couplings.

⇒ no gluino contributions to FCNCs

Parameters of our setup

- Higgs sector: \( \tan \beta, M_{H^\pm} \)
- Higgsino mass: \( \mu \)
- Gaugino masses: \( M_1, M_2, M_3 \)
- Squark masses: \( m_{Q}^2, m_{U}^2, m_{D}^2 \)
- Trilinear couplings: \( A_d, A_s, A_b, A_u, A_c, A_t \)

The Higgsino and Gaugino masses as well as the trilinear couplings can in general be complex.

Observables only depend on particular combinations of complex parameters.
Within this setup large NP effects arise dominantly through the magnetic and chromomagnetic dipole operators

\[ O_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} F_{\mu\nu} b_R , \quad O_8 = \frac{g_s}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} G_{\mu\nu} b_R \]

The corresponding Wilson coefficients are mainly sensitive to one complex parameter combination

\[ C_{7,8} \propto \mu A_t \]

→ Interesting correlated effects in CP violating observables

WA, Buras, Paradisi ’08
Most important constraints: EDMs and $b \to s\gamma$

\[ \mathcal{BR}[B \to X_s\gamma]^{\text{exp.}} = (3.52 \pm 0.25) \times 10^{-4} \quad \text{HFAG '08} \]

\[ \mathcal{BR}[B \to X_s\gamma]^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4} \quad \text{Misiak et al. '06} \]

- $b \to s\gamma$ amplitude is helicity suppressed
- typically large NP effects, even in a FBMSSM with low $\tan\beta$
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$$C_{7,8}^{\pm} (\mu_{\text{SUSY}}) \simeq \frac{m_t^2}{m_t^4} A_t \mu \tan \beta \times f_{7,8} \left( \frac{|\mu|^2}{\bar{m}_t^2} \right)$$
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$\mathcal{BR}[B \to X_s \gamma]^{\text{exp.}} = (3.52 \pm 0.25) \times 10^{-4}$ \hspace{1cm} HFAG '08

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$$C_{7,8}^{\pm (\mu_{\text{SUSY}})} \approx \frac{m_t^2}{m_{\tilde{t}}^4} A_t \mu \tan \beta \times f_{7,8} \left( \frac{|\mu|^2}{m_t^2} \right)$$

$\mathcal{BR}[B \to X_s \gamma] \propto |C_7^{\text{SM}}(m_b) + C_7^{\text{NP}}(m_b)|^2 \approx |C_7^{\text{SM}}(m_b)|^2 + 2 \text{Re}(C_7^{\text{SM}}(m_b)C_7^{\text{NP}}(m_b))$

$\to$ Constraint on $\text{Re}(\mu A_t)$
Most important constraints: EDMs and $b \rightarrow s\gamma$

- $d_e^{\text{exp.}} \lesssim 1.6 \times 10^{-27} \text{ ecm}$
- $d_n^{\text{exp.}} \lesssim 2.9 \times 10^{-26} \text{ ecm}$
- $d_e^{\text{SM}} \approx 10^{-38} \text{ ecm}$
- $d_n^{\text{SM}} \approx 10^{-32} \text{ ecm}$

- In the MSSM, EDMs can be induced already at the 1loop level
  → typically tight constraints on CP violating phases
Most important constraints: EDMs and $b \to s\gamma$

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    d_e^{\text{exp.}} & \lesssim 1.6 \times 10^{-27} \text{ ecm} \\
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- Example: Gluino contribution to the up-quark EDM

\[
d_u \simeq \frac{e g_s^2}{16\pi^2} m_u \frac{\text{Im}(M_{\tilde{g}} A_u^*)}{m_{\tilde{u}}^4} F \left( \frac{|M_{\tilde{g}}|^2}{m_{\tilde{u}}^2} \right)
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\end{align*}
\]

Constraints can be avoided by e.g.

- hierarchical trilinear couplings $A_{u,c} \ll A_t, A_{d,s} \ll A_b$
- heavy 1$^\text{st}$ and 2$^\text{nd}$ generation of squarks

But: sizeable effects in flavor observables still possible, as 3$^\text{rd}$ generation squarks enter
Most important constraints: EDMs and $b \rightarrow s \gamma$

Chang, Keung, Pilaftsis '98

2-loop Barr-Zee type diagrams generating both lepton and quark EDMs

- sensitive to 3$^{\text{rd}}$ generation of squarks
- decouple with $1/\max(M_{A_0}^2, m_{\tilde{t}}^2)$

\[
d_f \propto \text{Im}(\mu A_t)
\]
Most important constraints: EDMs and $b \rightarrow s\gamma$

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2-loop Barr-Zee type diagrams generating both lepton and quark EDMs

- sensitive to 3$^{\text{rd}}$ generation of squarks
- decouple with $1/\max(M^2_{A_0}, m^2_t)$

$$d_f \propto \text{Im}(\mu A_t)$$

$\rightarrow$ Constraint on $\text{Im}(\mu A_t)$
CP Asymmetries in $B \to \phi K_S$ and $B \to \eta' K_S$

Time dependent CP Asymmetries in decays of neutral B mesons to final CP Eigenstates

\[
A_{CP}(t, \phi K_S) = \frac{\Gamma(B(t) \to \phi K_S) - \Gamma(\bar{B}(t) \to \phi K_S)}{\Gamma(B(t) \to \phi K_S) + \Gamma(\bar{B}(t) \to \phi K_S)}
= C_{\phi K_S} \cos(\Delta M_d t) - S_{\phi K_S} \sin(\Delta M_d t)
\]

\[
S_{\phi K_S} = -\frac{2\text{Im}(\xi_{\phi K_S})}{1 + |\xi_{\phi K_S}|^2}, \quad \xi_{\phi K_S} = e^{-i\text{Arg}(M^d_{12})} \frac{A(\bar{B} \to \phi K_S)}{A(B \to \phi K_S)}
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- sizeable, correlated effects in $S_{\phi K_S}$ and $S_{\eta' K_S}$
- larger effects in $S_{\phi K_S}$ as indicated by the data
CP Asymmetries in $B \to \phi K_S$ and $B \to \eta' K_S$

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- sizeable, correlated effects in $S_{\phi K_S}$ and $S_{\eta' K_S}$
- larger effects in $S_{\phi K_S}$ as indicated by the data
- for $S_{\phi K_S} \simeq 0.4$, lower bounds on the electron and neutron EDMs:

$$d_e \gtrsim 5 \times 10^{-28} \text{ ecm}, \quad d_n \gtrsim 8 \times 10^{-28} \text{ ecm}$$
Direct CP Asymmetry in $b \rightarrow s \gamma$

Soares '91; Kagan, Neubert '98

$$A_{CP}^{bs\gamma} = \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_\bar{s} \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_\bar{s} \gamma)}$$

- arises first at order $\alpha_s$
- doubly Cabibbo and GIM suppressed in the SM
- sizeable value would be clear signal for New Physics

$$A_{CP}^{bs\gamma}(SM) \simeq (0.44^{+0.24}_{-0.14})\% \quad \text{Hurth, Lunghi, Porod '03}$$

$$A_{CP}^{bs\gamma}(exp.) \simeq (0.4 \pm 3.6)\% \quad \text{HFAG}$$

$$A_{CP}^{bs\gamma} \simeq \frac{\alpha_s}{|C_7|^2} \left( b_{27} \text{Im}(C_2 C_7^*) + b_{87} \text{Im}(C_8 C_7^*) + b_{28} \text{Im}(C_2 C_8^*) \right)$$
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- Sign of $A_{CP}^{bs\gamma}$ is correlated with sign of $S_{\phi K_S}$
- For $S_{\phi K_S} < S^{SM}_{\phi K_S}$, $A_{CP}^{bs\gamma}$ is unambiguously positive
- values typically in the range 1% – 6%
The Decay $B^0 \rightarrow K^0 \star (\rightarrow K^+ \pi^-) \ell^+ \ell^-$...

Full angular reconstruction possible at LHCb

7200 events with $2fb^{-1}$ (≈ 1 year of running)

$\frac{d^2 \Gamma}{dq^2 \, d \cos \theta_K \, d \phi} = \frac{9}{32\pi} \frac{(q^2, \theta_l, \theta_K^*, \phi)}{D(q^2, \theta_l, \theta_K^*, \phi)}$
Consider both $B^0 \rightarrow K^0 \ast (\rightarrow K^+ \pi^-) \ell^+ \ell^-$ and the CP conjugate mode $\bar{B}^0 \rightarrow \bar{K}^0 \ast (\rightarrow K^- \pi^+) \ell^+ \ell^-$ allows to construct up to 24 observables that can be measured through the angular analysis.

**CP averaged angular coefficients**

$$S_i = (I_i + \bar{I}_i) \left/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} \right.$$  

**CP asymmetries**

$$A_i = (I_i - \bar{I}_i) \left/ \frac{d(\Gamma + \bar{\Gamma})}{dq^2} \right.$$  

most interesting ones in the context of the FBMSSM are $S_4$, $S_5$, $S_6^s$, $A_7$ and $A_8$
$S_6^s$ is basically the well known forward-backward asymmetry in $B \rightarrow K^* \ell^+ \ell^-$.

The CP averaged angular observables $S_4$, $S_5$ and $S_6^s$ have zeros in their $q^2$ distributions.
NP Effects in the Angular Observables

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- The CP averaged angular observables $S_4$, $S_5$ and $S_6^s$ have zeros in their $q^2$ distributions

- The large complex NP contributions to $C_7$ in the FBMSSM lead to significant shifts in the zeros of $S_4$, $S_5$ and $S_6^s$ towards lower values
The CP asymmetries $A_7$ and $A_8$ are negligible small in the SM.
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In the FBMSSM huge effects are possible and they are highly correlated.

Deviations from the correlation point clearly towards sizeable complex NP contributions to other operators, e.g. $C'_7$. 
There are also strong correlations between the integrated CP asymmetries $\langle A_7 \rangle$ and $\langle A_8 \rangle$ and the zeros of $S_4$, $S_5$ and $S_6$

- Large shifts in the zeros unambiguously lead to large effects in the CP asymmetries
Correlations with Other CP Violating Observables

$\langle A_7 \rangle$ and $\langle A_8 \rangle$ are also correlated with $S_{\phi K_S}$ and $S_{\eta' K_S}$

- $S_{\phi K_S} \approx 0.4$ implies positive $\langle A_7 \rangle \approx 0.05 \div 0.2$
  and negative $\langle A_8 \rangle \approx -0.11 \div -0.03$

- Finally, $\langle A_7 \rangle$ and $\langle A_8 \rangle$ are also correlated with the CP asymmetry in $b \to s\gamma$ and the EDMs
Phases in the $B_d$ and $B_s$ mixing amplitudes

- Leading NP contributions to the mixing amplitudes $M^d_{12}$ and $M^s_{12}$ turn out to be insensitive to the new phases of a flavor blind MSSM.

$$\text{Arg}(M^d_{12}, s_{12}) \approx \text{Arg}(M^d_{12}, s_{12}(\text{SM}))$$

→ $S_{\psi K_S}$ and $S_{\psi \phi}$ are SM like
CP violation in $\Delta F = 2$ Transitions

- Also $M_{12}^K$ has no sensitivity to the new flavor blind phases
- Still, $\epsilon_K \propto \text{Im}(M_{12}^K)$ can get a positive NP contribution up to 15%
- But only for a very light SUSY spectrum: $\mu, m_{\tilde{t}_1} \approx 200\text{GeV}$
Implications for the Unitarity Triangle

- $S_{\psi K_S}$ and $\Delta M_d/\Delta M_s$ basically NP free
- UT can be constructed from the angle $\beta$ and the side $R_t$

$$\sin 2\beta = S_{\psi K_S} = 0.671 \pm 0.024$$

$$R_t = \xi \sqrt{\frac{m_{B_s}}{m_{B_d}}} \sqrt{\frac{\Delta M_d}{\Delta M_s}} = 0.913 \pm 0.033$$


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Predictions for $|V_{ub}|$ and the angle $\gamma$

$$|V_{ub}| = (3.5 \pm 0.2) \times 10^{-3}$$

$$\gamma = 63.5^\circ \pm 4.7^\circ$$

→ can be tested at a SuperB Factory
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$\epsilon_K$ constraint ($B_K = 0.72 \pm 0.05$)
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$\epsilon_K$ constraint ($B_K = 0.72 \pm 0.05$) and with +15% NP corrections
Implications for direct searches of SUSY particles

- $S_{\phi K_S} \simeq 0.4$ 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 $m_{\tilde{t}_1} \lesssim 800\text{GeV}$
In the flavor blind MSSM sizeable, correlated effects in \( S_{\phi K_S} \) and \( S_{\eta' K_S} \) are possible. Such effects imply:

- lower bounds on the electron and neutron EDMs at the level of \( d_{e,n} \gtrsim 10^{-28} \) ecm
- a positive, sizeable direct CP asymmetry \( A_{CP}^{bs\gamma} \simeq 1\% - 6\% \)
The decay $B \rightarrow K^* \ell^+ \ell^-$ offers a multitude of observables sensitive to new CP violating phases. In the FBMSSM we find:

- The zeros of the CP averaged coefficients $S_4$, $S_5$ and $S_6^s$ are shifted towards lower values
- Sizeable effects in the CP asymmetries $A_7$ and $A_8$
- These effects are highly correlated among themselves and also with $S_{\phi K_S}$, $A_{CP}^{bs\gamma}$ and $d_{e,n}$
- The definite pattern of effects allows a clear distinction from scenarios where Wilson coefficients other than $C_7$ play an important role
In addition, within the framework of the FBMSSM, there are

- small effects in $S_{\psi \phi} \simeq 0.03 - 0.05$
- small effects in $S_{\psi K_S}$ and in $\Delta M_d/\Delta M_s$
  $\Rightarrow$ The Unitarity Triangle can be constructed from the side $R_t$ and the angle $\beta$. Predictions: $|V_{ub}| = (3.5 \pm 0.2) \times 10^{-3}$ and $\gamma = 63.5^\circ \pm 4.7^\circ$.
- positive NP effects in $\epsilon_K$ up to 15%
The Anomalous Magnetic Moment of the Muon

\[ a_{\mu}^{\text{exp.}} = 1165920.80(63) \times 10^{-9} \text{ Muon (g-2) collaboration} \]

\[ a_{\mu}^{\text{SM}} = 1165917.85(61) \times 10^{-9} \text{ Miller et al. '07} \]

\[ \Delta a_{\mu} = a_{\mu}^{\text{exp.}} - a_{\mu}^{\text{SM}} \simeq (3 \pm 1) \times 10^{-9} \]

\[ \simeq 3\sigma \text{ discrepancy} \]

A very rough formula for SUSY contributions to \( a_{\mu} \)

\[ a_{\mu}^{\text{SUSY}} \simeq 1.5 \left( \frac{\tan \beta}{10} \right) \left( \frac{300 \text{GeV}}{m_\tilde{\ell}} \right)^2 \text{sign}(\text{Re}(\mu)) \times 10^{-9} \]

with common SUSY mass \( m_\tilde{\ell} \)

\[ S_{\phi K_S} \simeq 0.4 \text{ naturally leads to } a_{\mu}^{\text{SUSY}} \simeq \text{few} \times 10^{-9} \]