Low Energy Probes of CP Violation in a Flavor Blind MSSM

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Outline

based on:

- WA, Andrzej Buras and Paride Paradisi
- WA, Andrzej Buras and Paride Paradisi
  in preparation

1 Introduction
2 The 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.

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

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

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

- Tree level decay $\to$ sensitivity to the phase of the mixing amplitude without NP in the decay amplitude
- in SM: $\text{Arg}(M_{12}^d) = \text{Arg}(V_{td}^2) = 2\beta$

\[
\sin(2\beta) \equiv \sin(2\phi_1) = 0.680 \pm 0.025
\]

![Graph of sin(2β) values from various experiments](image)
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    \sin 2\beta^{\text{SM}} = S_{\psi K_S}^{\text{exp.}} = 0.680 \pm 0.025
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- In the SM also **loop induced** modes like $B \rightarrow \phi K_S$ and $B \rightarrow \eta' K_S$ give the same value

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    S_{\phi K_S}^{\text{SM}} = S_{\eta' K_S}^{\text{SM}} = S_{\psi K_S}^{\text{SM}} = \sin 2\beta
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- In the SM also **loop induced** modes like $B \to \phi K_S$ and $B \to \eta' K_S$ give the same value

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

$$S_{\phi K_S}^{\text{exp.}} = 0.39 \pm 0.17 \quad S_{\eta' K_S}^{\text{exp.}} = 0.61 \pm 0.07$$

$\Rightarrow$ New Phases in decays?
Hints for new sources of CP violation?

Lunghi, Soni '08

2 Tensions in the Unitarity Triangle

perform UT fit including only $\epsilon_K$ and $\Delta M_d / \Delta M_s$ using

- non perturbative parameter
  $B_K = 0.72 \pm 0.013 \pm 0.037$ (Antonio et al. '07)

- additional effective suppression factor in $\epsilon_K$:
  $\kappa_\epsilon = 0.92$ (Buras, Guadagnoli '08)
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$B_s \rightarrow \psi \phi$ and $\sin 2\beta_s$

$S_{\psi \phi} = \sin 2(\beta_s + \Phi_{B_s}^{NP})$, $\beta_s \simeq 1^\circ$
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$\Phi_{B_s}^{NP} = (19.9^\circ \pm 5.6^\circ) \cup (68.2^\circ \pm 4.9^\circ)$

$\Rightarrow$ Large $B_s$ mixing phase?

$\psi \phi$-mixing: $\Phi_{B_s}^{NP}$

Bona et al. '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 a flavor blind MSSM

- 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.
Main role is played by one complex parameter combination

$$\mu A_t$$

→ Interesting correlated effects in CP violating observables

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

$\mathcal{B}\mathcal{R}[B \rightarrow X_s\gamma]^{\text{exp.}} = (3.52 \pm 0.25) \times 10^{-4}$  
HFAG ’08

$\mathcal{B}\mathcal{R}[B \rightarrow X_s\gamma]^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$  
Misiak et al. ’06

- $b \rightarrow s\gamma$ 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_{\tilde{t}}^4} A_{t\mu} \tan \beta \times f_{7,8} \left( \frac{|\mu|^2}{m_t^2} \right)
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$$C_{7,8}^{\text{SUSY}} \approx \frac{m_t^2}{m_t^4} A_t \mu \tan \beta \times f_{7,8} \left( \frac{|\mu|^2}{m_t^2} \right)$$

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

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

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

- In the MSSM, EDMs can be induced already at the 1loop level
- → typically tight constraints on CP violating phases
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- In the MSSM, EDMs can be induced already at the 1-loop level → typically tight constraints on CP violating phases
- Example: Gluino contribution to the up-quark EDM

\[
\begin{align*}
d_u & \approx \frac{e g_s^2}{16\pi^2} \frac{m_u}{\bar{m}_u^4} \frac{\text{Im}(M_{\bar{g}} A_u^*)}{\bar{m}_u^2} F\left(\frac{|M_{\bar{g}}|^2}{\bar{m}_u^2}\right)
\end{align*}
\]
Most important constraints: EDMs and $b \rightarrow s\gamma$

- $d^\text{exp.}_e \lesssim 1.6 \times 10^{-27}$ ecm
- $d^\text{exp.}_n \lesssim 2.9 \times 10^{-26}$ ecm
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Constraints can be avoided by e.g.
- hierarchical trilinear couplings $A_{u,c} \ll A_t$, $A_{d,s} \ll A_b$
- heavy 1st and 2nd generation of squarks

But: sizeable effects in flavor observables still possible, as 3rd 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 $1/\max(M_{A_0}^2, m_{\tilde{t}}^2)$

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

$$A_{\text{CP}}(t, \phi K_S) = \frac{\Gamma(B(t) \to \phi K_S) - \Gamma(\bar{B}(t) \to \phi K_S)}{\Gamma(B(t) \to \phi K_S) + \Gamma(\bar{B}(t) \to \phi K_S)}$$

$$= C_{\phi K_S} \cos(\Delta M_d t) - S_{\phi K_S} \sin(\Delta M_d t)$$

$$S_{\phi K_S} = -\frac{2 \text{Im}(\xi_{\phi K_S})}{1 + |\xi_{\phi K_S}|^2}, \quad \xi_{\phi K_S} = e^{-i \text{Arg}(M_{12}^d)} \frac{A(\bar{B} \to \phi K_S)}{A(B \to \phi K_S)}$$
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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
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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

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

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

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

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

$$A_{CP}^{bs\gamma} \simeq \frac{\alpha_s}{|C_7|^2} \left( b_{27} \text{Im}(C_2^*C_7^*) + b_{87} \text{Im}(C_8C_7^*) + b_{28} \text{Im}(C_2^*C_8^*) \right)$$
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- Sign of $A_{\text{CP}}^{bs\gamma}$ is correlated with sign of $S_{\phi K_S}$
- For $S_{\phi K_S} < S_{\phi K_S}^{\text{SM}}$, $A_{\text{CP}}^{bs\gamma}$ is unambiguously positive
- values typically in the range $1\% - 6\%$

ABP’08
Phases in the $B_d$ and $B_s$ mixing amplitudes

- Leading NP contributions to $M_{12}^d$ and $M_{12}^s$ turn out to be insensitive to the new phases of a flavor blind MSSM.

$$\text{Arg}(M_{12}^{d,s}) \simeq \text{Arg}(M_{12}^{d,s}(\text{SM}))$$

$\rightarrow S_{\psi K_S}$ and $S_{\psi \phi}$ are SM like
CP Violation in $\Delta F = 2$ transitions

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2 CP violation in $K$ mixing

- Also $M_{12}^K$ has no sensitivity to the new 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 $R_t$

\[
\sin 2\beta = S_{\psi K_S} = 0.680 \pm 0.025
\]

\[
R_t = \frac{\xi}{\lambda} \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 $\gamma$

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

$$\gamma = 63.5^\circ \pm 4.7^\circ$$
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$\epsilon_K$ constraint ($B_K = 0.75 \pm 0.07$) and with +10% NP corrections
Implications for direct searches of SUSY particles

\[ S_{\phi K_S} \approx 0.4 \implies \mu \lesssim 600 \text{GeV} \text{ and } m_{\tilde{t}_1} \lesssim 700 \text{GeV} \]

\[ \text{similarly, large non standard effects in } A_{CP}^{b s \gamma} \gtrsim 2\% \implies \mu \lesssim 600 \text{GeV} \text{ and } m_{\tilde{t}_1} \lesssim 800 \text{GeV} \]
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 $d_{e,n} \gtrsim 10^{-28} \text{ecm}$
- a positive, sizeable direct CP asymmetry $A_{CP}^{bs\gamma} \sim 1\% - 6\%$
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- a positive, sizeable direct CP asymmetry $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$

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%
Back Up
The Anomalous Magnetic Moment of the Muon

$\alpha^{\text{exp.}}_{\mu} = 1165920.80(63) \times 10^{-9}$ \quad \text{Muon (g-2) collaboration}

$\alpha^{\text{SM}}_{\mu} = 1165917.85(61) \times 10^{-9}$ \quad \text{Miller et al. ’07}

$\Delta \alpha_{\mu} = \alpha^{\text{exp.}}_{\mu} - \alpha^{\text{SM}}_{\mu} \simeq (3 \pm 1) \times 10^{-9}$

$\simeq 3\sigma$ discrepancy

A very rough formula for SUSY contributions to $\alpha_{\mu}$

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

with common SUSY mass $m_{\tilde{\ell}}$

$S_{\phi K_S} \simeq 0.4$ naturally leads to $\alpha^{\text{SUSY}}_{\mu} \simeq \text{few} \times 10^{-9}$