Low Energy Probes of CP Violation in Supersymmetric Models

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Theory Seminar

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1 Introduction

2 CP Violation in $B_s$ Mixing

3 Phenomenology of CP Violation in SUSY Models
   - Low Energy Probes of CPV in the MSSM with MFV
   - The $B_s$ Mixing Phase in SUSY Models Beyond MFV
   - CPV in $D^0$ Mixing and EDMs in SUSY Alignment Models

4 Summary
CKM matrix is the only source of flavor and CP violation in the SM

very good overall agreement of the exp. data entering the CKM fits (apart from a 2-3σ discrepancy between sin 2β and BR(B → τν))

how much room is left for additional sources of flavor violation?
$L_{\text{eff}} = L_{\text{SM}} + \sum_{i,j} \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$

<table>
<thead>
<tr>
<th>Operator</th>
<th>Bound on $\Lambda$ in TeV ($c_{ij} = 1$)</th>
<th>Bound on $c_{ij}$ (A = 1 TeV)</th>
<th>Observables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Re</td>
<td>Im</td>
<td>Re</td>
</tr>
<tr>
<td>$(\bar{s}_L \gamma^\mu d_L)^2$</td>
<td>$9.8 \times 10^2$</td>
<td>$1.6 \times 10^4$</td>
<td>$9.0 \times 10^{-7}$</td>
</tr>
<tr>
<td>$(\bar{s}_R d_L)(\bar{s}_L d_R)$</td>
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<td>$3.2 \times 10^5$</td>
<td>$6.9 \times 10^{-9}$</td>
</tr>
<tr>
<td>$(\bar{c}_L \gamma^\mu u_L)^2$</td>
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<td>$2.9 \times 10^3$</td>
<td>$5.6 \times 10^{-7}$</td>
</tr>
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<td>$(\bar{c}_R u_L)(\bar{c}_L u_R)$</td>
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<td>$1.5 \times 10^4$</td>
<td>$5.7 \times 10^{-8}$</td>
</tr>
<tr>
<td>$(\bar{b}_L \gamma^\mu d_L)^2$</td>
<td>$5.1 \times 10^2$</td>
<td>$9.3 \times 10^2$</td>
<td>$3.3 \times 10^{-6}$</td>
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</table>

Isidori, Nir, Perez ’10

- a generic flavor structure $c_{ij}$ requires a very high NP scale $\Lambda$
- NP at the natural TeV scale needs a highly non-generic flavor structure
processes strongly suppressed in the SM and not measured yet (or only poorly measured) → **Discovery Channels**
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**CP violation in $D^0 - \bar{D}^0$ mixing**

- time dep. CP asymmetries $S_f^D$
- semi leptonic asymmetry $a_{SL}^D$
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- of hadronic systems $d_n, d_{Hg}$
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**(very) rare decays**
- $B_{s,d} \rightarrow \mu^+ \mu^-$ (LHCb)
- $B \rightarrow K^{(*)} \nu \bar{\nu}$ (superB)
- $K \rightarrow \pi \nu \bar{\nu}$ (NA62, KOTO)
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**CP Violation in $b \rightarrow s$ transitions**
- $B_s$ mixing phase, $S_{\psi\phi}$, $a_{SL}^s$ (LHCb)
- direct CP asymmetry in $B \rightarrow X_s \gamma$
  $A_{CP}(b \rightarrow s \gamma)$ (superB)
- time dependent CP asymmetries in $B \rightarrow \phi K_S$ and $B \rightarrow \eta' K_S$
  $S_{\phi K_S}$ and $S_{\eta' K_S}$ (superB)
- angular observables in $B \rightarrow K^{*} \ell^+ \ell^-$ (LHCb, superB)
Evidence for New Physics?

D0, arXiv:1005.2757:
Evidence for an anomalous like-sign dimuon charge asymmetry

Definition:

\[ A_{SL}^b = \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} \]

- \( N_{b}^{++} \): Number of same sign \( \mu^+ \mu^+ \) events from \( B \to \mu X \) decays
- \( N_{b}^{--} \): Number of same sign \( \mu^- \mu^- \) events from \( B \to \mu X \) decays

3.2\( \sigma \) discrepancy between SM prediction and recent D0 measurement

\[ A_{SL}^b (\text{SM}) = \left( -0.23^{+0.05}_{-0.06} \right) \times 10^{-3} \]

(Lenz, Nierste '06)

\[ A_{SL}^b (\text{exp}) = \left( -9.57 \pm 2.51 \pm 1.46 \right) \times 10^{-3} \]

(D0, arXiv:1005.2757)
CP Violation in $B_s$ Mixing
Schrödinger equation describing $B_s - \bar{B}_s$ mixing:

$$i\partial_t \left( \frac{B_s(t)}{\bar{B}_s(t)} \right) = \left( M^s + \frac{i}{2} \Gamma^s \right) \left( \frac{B_s(t)}{\bar{B}_s(t)} \right)$$

Three physical parameter:

$$|M^s_{12}|, \ |\Gamma^s_{12}|, \ \phi_s = -\text{arg}\left( \frac{M^s_{12}}{\Gamma^s_{12}} \right) \quad ; \quad \phi^{SM}_s \simeq 0.004$$
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Observables:

- mass and width difference
  \[ \Delta M_s = 2|M^s_{12}|, \quad \Delta \Gamma_s = 2|\Gamma^s_{12}| \cos \phi_s \]
- semileptonic asymmetry
  \[ a^s_{\text{SL}} = \frac{\Gamma(\bar{B}_s \rightarrow \ell^+ X) - \Gamma(B_s \rightarrow \ell^- X)}{\Gamma(\bar{B}_s \rightarrow \ell^+ X) + \Gamma(B_s \rightarrow \ell^- X)} \quad , \quad a^s_{\text{SL}} = \left| \frac{\Gamma^s_{12}}{M^s_{12}} \right| \sin \phi_s = \frac{\Delta \Gamma_s}{\Delta M_s} \tan \phi_s \]
Like-Sign Dimuon Charge Asymmetry

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\[ A_{SL}^b = \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} \]

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Relation to the semileptonic asymmetry:

\[ A_{SL}^b = (0.506 \pm 0.043) a_{sl}^d + (0.494 \pm 0.043) a_{sl}^s \]

(D0, arXiv:1005.2757)
CP violation in interference between decays with and without mixing

\[
\frac{\Gamma(\bar{B}_s(t) \rightarrow \psi\phi) - \Gamma(B_s(t) \rightarrow \psi\phi)}{\Gamma(\bar{B}_s(t) \rightarrow \psi\phi) + \Gamma(B_s(t) \rightarrow \psi\phi)} = S_{\psi\phi} \sin(\Delta M_s t)
\]

in the SM, \( S_{\psi\phi} \) measures \( \beta_s \) the phase of \( V_{ts} \)

\[
S_{\psi\phi}^{SM} = \sin 2|\beta_s| \simeq 0.038 \quad , \quad V_{ts} = -|V_{ts}| e^{-i\beta_s}
\]

for a large \( B_s \) mixing phase \( \phi_s \gg 2\beta_s \), \( \phi_s^{SM} \) one has

\[
S_{\psi\phi} \simeq -\sin \phi_s
\]

model-independent relation between \( S_{\psi\phi} \) and \( a_{SL}^s \)

(Ligeti, Papucci, Perez '06; Blanke, Buras, Guadagnoli, Tarantino '06; Grossman, Nir, Perez '09)

\[
a_{SL}^s = -\frac{\Delta \Gamma_s}{\Delta M_s} \frac{S_{\psi\phi}}{\sqrt{1 - S_{\psi\phi}^2}}
\]
data from CDF and D0 on $S_{\psi\phi}$ are in rather good agreement with the SM ($\sim 1\sigma$)
The Experimental Situation

- data from CDF and D0 on $S_{\psi\phi}$ are in rather good agreement with the SM ($\sim 1\sigma$)

- recent result from D0 on the like sign dimuon charge asymmetry $A_{\text{SL}}^b$ shows a $3.2\sigma$ deviation from the SM
  (arXiv:1005.2757 [hep-ex])

- global fits prefer large phase in $B_s$ mixing
  (e.g. Ligeti, Papucci, Perez, Zupan '10
  Lenz, Nierste + CKMfitter '10)

\[ S_{\psi\phi} \sim 0.5 \]
LHCb Potential

- significant improvement on the experimental side can be expected at LHCb both for $S_{\psi\phi}$ and $a_{SL}^s$
Usual Interpretation of the Experimental Data

- absorptive part $\Gamma_{12}$ dominated by SM tree level decays
  $\Rightarrow$ CP violating short distance contributions to the dispersive part $M_{12}$

\[
M^s_{12} = \Delta_s \left( M^s_{12} \right)_{SM}
\]

\[
\Delta M_s = \Delta M^s_{SM} |\Delta_s|
\]

\[
\Delta \Gamma_s = \Delta \Gamma^s_{SM} \cos \left( \text{Arg}(\Delta_s) \right)
\]

\[
a^s_{SL} = \text{Im} \left( \Gamma^s_{12} / \left[ (M^s_{12})_{SM} \Delta_s \right] \right)
\]

\[
S_{\psi \phi} = \sin \left( 2|\beta_s| - \text{Arg}(\Delta_s) \right)
\]
Large New Physics in $B_s$ Mixing

\[ M_{12}^S = \Delta_s (M_{12}^S)^{SM} \]

\[ M_{12}^S = (1 + h_s e^{2i\sigma_s}) (M_{12}^S)^{SM} \]

Lenz, Nierste + CKMfitter '10

Ligeti, Papucci, Perez, Zupan '10
How to get Large NP Contributions in $B_s$ Mixing?

- **general MSSM**
  - Ciuchini et al.; Goto et al.;
  - WA, Buras, Gori, Paradisi, Straub ’09;
  - Crivellin, Nierste ’09;
  - Ko, Park ’10; Parry ’10; ...

- **SUSY GUTs**
  - Hisano, Shimizu ’08;
  - Dutta, Mimura, Santoso ’10;
  - Buras, Paradisi, Nagai ’10; ...

- **SUSY Flavor Models**
  - WA, Buras, Gori, Paradisi, Straub ’09;
  - King ’10; ...

- **Uplifted SUSY**
  - Dobrescu, Fox, Martin ’10

- **Minimal Flavor Violation**
  - Batell, Pospelov ’10;
  - Blum, Hochberg, Nir ’10

- **2 Higgs Doublet Models**
  - Jung, Pich, Tuzon ’10;
  - Buras, Carlucci, Gori, Isidori ’10;
  - Buras, Isidori, Paradisi ’10;

- **4th Generation**
  - Hou et al.; Soni et al.;
  - Buras et al. ’10

- **Warped Extra Dimensions**
  - Blanke et al.; Neubert et al. ’09

- **Little Higgs**
  - Blanke et al.

- **Z’**
  - Barger et al. ’09, ...

- **...**
Phenomenology of CP Violation in SUSY Models
The sources of flavor violation in the MSSM are the SM Yukawa couplings and the soft SUSY breaking terms of the sfermions:

1. Yukawa couplings: $Y_u$, $Y_d$
2. soft masses: $\tilde{m}_Q^2$, $\tilde{m}_D^2$, $\tilde{m}_U^2$
3. trilinear couplings: $\tilde{A}_u$, $\tilde{A}_d$

They break the global $SU(3)_Q \times SU(3)_U \times SU(3)_D$ flavor symmetry of the gauge sector

They are in general independent $3 \times 3$ matrices in flavor space

In a basis where quarks have diagonal masses (super CKM basis), squark masses are not necessarily flavor diagonal

\[
M^2_{\tilde{u}} = \begin{pmatrix}
V^* (\tilde{m}_Q^2)^T V^T & -(v_d \mu^* Y_u + v_u \tilde{A}_u^*) / \sqrt{2} \\
-(v_d \mu Y_u + v_u \tilde{A}_u^*) / \sqrt{2} & \frac{\tilde{m}_U^2}{\sqrt{2}}
\end{pmatrix} + O(\nu^2)
\]

\[
M^2_{\tilde{d}} = \begin{pmatrix}
(\tilde{m}_Q^2)^T & -(v_u \mu^* Y_d + v_d \tilde{A}_d) / \sqrt{2} \\
-(v_u \mu Y_d + v_d \tilde{A}_d) / \sqrt{2} & \frac{\tilde{m}_D^2}{\sqrt{2}}
\end{pmatrix} + O(\nu^2)
\]
misalignment between up quarks and down quarks in flavor space

- **CKM matrix**

  → appears in W and Higgs charged currents and their supersymmetrized versions
misalignment between up quarks and down quarks in flavor space

- **CKM matrix**
  
  \[ \begin{pmatrix} V & \bar{V} \end{pmatrix} \] appears in W and Higgs charged currents and their supersymmetrized versions

misalignment between quarks and squarks in flavor space

- **Mass Insertions**
  
  \[ \begin{pmatrix} \delta_{d}^{LL} & \delta_{d}^{LR} \\ \delta_{d}^{RL} & \delta_{d}^{RR} \end{pmatrix} \]

  \[ M_q^2 = \bar{m}^2 (1 + \delta_q) \]

  → most transparent treatment in the Mass Insertion Approximation

  → flavor change through mass insertions along squark propagators
Complex Mass Insertions lead to flavor and CP violating gluino-quark-squark interactions that typically generate the dominant contributions to FCNCs.
The SUSY Flavor Problem

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

- **severe constraints** on the SUSY scale $\tilde{m}$ and the Mass Insertions $\delta$s from meson mixing and rare decays like $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$
- for all $\delta$s of $\mathcal{O}(1)$, the SUSY scale has to be extremely high $\tilde{m} \gtrsim 10^4$ TeV
- SUSY at the TeV scale has to exhibit a highly non-generic flavor structure

\[ \tan \beta = 5, \quad \tilde{m} = M_{\tilde{g}} = 500\text{GeV} \]
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**Minimal Flavor Violation**

Buras et al. ’00
D’Ambrosio, Giudice, Isidori, Strumia ’02

- the global $SU(3)^3$ 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
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**Partial Decoupling**

- **Split SUSY**  
  Arkani-Hamed, Dimopoulos ’04; Giudice, Romanino ’04
- squarks are decoupled
- Effective SUSY  
  Cohen, Kaplan, Nelson ’96
- hierachical sfermion spectrum, with heavy 1st and 2nd generation
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Alignment
Nir, Seiberg ’93
- quark and squark masses are approximately aligned
  $\delta_{ij} \ll 1$, $i \neq j$
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How to Address the SUSY Flavor Problem

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**Degeneracy**
Dimopoulos, Georgi ’81
- squark masses are approximately universal
  $\delta_{ij} \ll 1$
  (FCNCs suppressed by super-GIM mechanism)
- can e.g. be realized in frameworks with gauge mediated SUSY breaking or in non-abelian flavor models

**(partial) Decoupling**
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Minimal Flavor Violation
The MFV MSSM with CP Violating Phases

- The global $SU(3)^3$ 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
The MFV MSSM with CP Violating Phases

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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!
  ($M_1$, $M_2$, $M_{\tilde{g}}$, $\mu$, $\tilde{A}_u$, $\tilde{A}_d$, $b_3$, $b_6$, $b_7$)

- what is their impact on CP violation in meson mixing?
MFV Box Contributions to $B_s$ Mixing (I)

- Leading box contributions to meson mixing are not sensitive to flavor diagonal phases! (WA, Buras, Paradisi ’08)

\[
\propto \frac{\alpha_s^2}{\tilde{m}^2} b_1^2 (V_{tb} V^*_{ts})^2
\]

\[
\propto \frac{\alpha_s^2}{\tilde{m}^2} \left( V_{tb} V^*_{ts} \right)^2
\]
MFV Box Contributions to $B_s$ Mixing (II)

\[ \propto \frac{\alpha_2^2}{\langle m^2 \rangle (V_{tb} V_{ts}^*)^2} \left[ \frac{m_b^2}{\langle m^2 \rangle} \tan^2 \beta \left( \frac{\mu A_t^2}{\langle m^4 \rangle} \right) \right] \]

\[ \propto \frac{\alpha_s^2}{\langle m^2 \rangle (V_{tb} V_{ts}^*)^2} \left[ \frac{m_b^2}{M_W^2} \tan^2 \beta b_1 b_3 \right], \ldots \]

- 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?
For large values of $\tan \beta$ also so-called double Higgs penguins become important (Hamzaoui, Pospelov, Toharia '98; Buras, Chankowski, Rosiek, Slawianowska '02)

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

$$\times \left[ \frac{|\mu A_t|^2}{\tilde{m}^4}, \frac{|\mu M_{\tilde{g}}|^2}{\tilde{m}^4} (b_1 + b_3 Y_b^2)^2, \ldots \right]$$

Also no sensitivity to flavor diagonal CP phases at the leading order

Possibility to have CPV through a complex $b_3$
consider also higher order \( \tan \beta \) resummation factors which come from a modified relation between the fermion masses and Yukawa couplings in the large \( \tan \beta \) regime (Hall, Rattazzi, Sarid '93)

\[ m_b = y_b v_d \]
consider also higher order $\tan \beta$ resummation factors which come from a modified relation between the fermion masses and Yukawa couplings in the large $\tan \beta$ regime (Hall, Rattazzi, Sarid ’93)

$$m_b = y_b v_d + y_b \epsilon_b v_u = y_b v_d (1 + \epsilon_b \tan \beta) \rightarrow y_b \simeq \frac{m_b}{v} \frac{\tan \beta}{1 + \epsilon_b \tan \beta}$$

$$\sim m_b (\epsilon_b \tilde{g} + \epsilon_b \tilde{H} + \ldots) \tan \beta$$
consider also higher order $\tan \beta$ resummation factors which come from a modified relation between the fermion masses and Yukawa couplings in the large $\tan \beta$ regime (Hall, Rattazzi, Sarid '93)

$$m_b = y_b v_d + y_b \epsilon_b v_u = y_b v_d (1 + \epsilon_b \tan \beta) \rightarrow y_b \simeq \frac{m_b}{v} \frac{\tan \beta}{1 + \epsilon_b \tan \beta}$$

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\[
\tan^4 \beta \rightarrow \frac{\tan^4 \beta}{|1 + \epsilon_b t_\beta|^2 |1 + \epsilon_b^0 t_\beta|^2} \times \left( \frac{1 + \epsilon_b^0 t_\beta}{1 + \epsilon_s^0 t_\beta} + \frac{\epsilon_{FC}^* (1 + \epsilon_b^0 t_\beta)}{\epsilon_{FC} (1 + \epsilon_b^0 t_\beta)^* (1 + \epsilon_s^0 t_\beta)} \right) \]

But: possible difference in $\epsilon_b$ and $\epsilon_s$ resummation factors can in principle lead to CP violation and is sensitive to flavor diagonal phases (Hofer, Nierste, Scherer '09; Dobrescu, Fox, Martin '10)
Strong Constraints from $B_s \rightarrow \mu^+ \mu^-$

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)^{\text{exp}} < 4.3 \times 10^{-8} \quad \text{CDF}$$

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)^{\text{SM}} = (3.5 \pm 0.4) \times 10^{-9}$$

$\triangleright$ $B_s \rightarrow \mu^+ \mu^-$ amplitude is strongly helicity suppressed in the SM

$\triangleright$ for large $\tan \beta$ huge enhancement possible (orders of magnitude)

\begin{align*}
&\sim \frac{\alpha_2}{4\pi} \frac{m_t^2}{M_W^2} \frac{1}{M_A^2} \frac{A_{t\mu}}{\tilde{m}^2} \tan^3 \beta \frac{m_b m_{\mu}}{M_W^2} V_{tb} V_{ts}^* \\
&\sim \frac{\alpha_s}{4\pi} \frac{1}{M_A^2} \frac{\mu M_{\tilde{g}}}{\tilde{m}^2} \tan^3 \beta (b_1 + Y_b^2 b_3) \frac{m_b m_{\mu}}{M_W^2} V_{tb} V_{ts}^*
\end{align*}
Strong Constraints from $b \rightarrow s\gamma$

$\text{BR}(B \rightarrow X_s\gamma)^{\text{exp}} = (3.52 \pm 0.25) \times 10^{-4}$ \hspace{1cm} HFAG

$\text{BR}(B \rightarrow X_s\gamma)^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$ \hspace{1cm} Misiak et al. ’06

- $b \rightarrow s\gamma$ amplitude is helicity suppressed in the SM
- Typically large NP effects, even in MFV, in particular for large $\tan \beta$

\[ C_{7,8}^{\tilde{H}} \sim \frac{\alpha_2}{4\pi} \frac{m_t^2}{M_W^2} \frac{1}{\tilde{m}^2} \frac{A_{t\mu}}{\tilde{m}^2} \tan \beta \ V_{tb} V_{ts}^* \]

\[ C_{7,8}^{\tilde{g}} \sim \frac{\alpha_s}{4\pi} \frac{1}{\tilde{m}^2} \frac{\mu M_{\tilde{g}}}{\tilde{m}^2} \tan \beta \ (b_1 + \gamma Y_b^2 b_3) \ V_{tb} V_{ts}^* \]
Strong Constraints from Electric Dipole Moments

\[
\begin{align*}
 d_e^{\text{exp}} &\lesssim 1.6 \times 10^{-27} \text{ ecm} \\
 d_e^{\text{SM}} &\simeq 10^{-38} \text{ ecm}
\end{align*}
\]

\[
\begin{align*}
 d_n^{\text{exp}} &\lesssim 2.9 \times 10^{-26} \text{ ecm} \\
 d_n^{\text{SM}} &\simeq 10^{-32} \text{ ecm}
\end{align*}
\]

- In the MSSM, EDMs can be induced already at the 1loop level → tight constraints on CP violating phases of gaugino and Higgsino masses
- phases of 3rd generation trilinear couplings \( A_{t,b,\tau} \) remain basically unconstrained at 1loop
- important 2loop Barr-Zee type diagrams that involve the 3rd generation (Chang, Keung, Pilaftsis '98)

\[d_e \propto \frac{\alpha_{\text{em}}}{4\pi} \frac{m_e}{16\pi^2} \tan \beta \sum_{f=t,b,\tau} q_f^2 Y_f^2 \text{Im}(\mu A_f) \hat{m}^4\]

\[d_d^{(c)} \propto \frac{\alpha_s}{4\pi} \frac{m_d}{16\pi^2} \tan \beta \sum_{f=t,b} Y_f^2 \text{Im}(\mu A_f) \hat{m}^4\]
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 (WA, Buras, Gori, Paradisi, Straub '09)
- i.e. small effects in $S_{\psi\phi}$, $S_{\psi KS}$ and $\epsilon_K$
- reason: strong constraints from $\text{BR}(B \rightarrow X_s\gamma)$ and $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ and the EDMs
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- 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 physics observables, $(g - 2)_\mu$ and EDMs (WA, Straub '10)
The MFV principle is intended to naturally suppress FCNC effects.

Naturally, large NP effects only show up in helicity suppressed processes:

\[ B_{s,d} \rightarrow \mu^+ \mu^- , \quad B^+ \rightarrow \tau^+ \nu \]

\[ b \rightarrow s \gamma \]
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Best low energy probes of CP Violation in the MFV MSSM are EDMs and observables sensitive to CPV in the \( b \rightarrow s\gamma \) transition (WA, Buras, Paradisi ’08):

\[ \rightarrow \text{direct CP asymmetry in } B \rightarrow X_s\gamma, \ A_{CP}^{bs\gamma} \]
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\[ \to \text{angular observables in } B \to K^* \ell^+ \ell^- \]
\( S_{\phi K_S} \) and \( S_{\eta/\eta' K_S} \) can simultaneously be brought in agreement with the data

- sizeable and correlated effects in 
  \[ A_{CP}(b \rightarrow s\gamma) \simeq 0\%-5\% \]

- for \( S_{\phi K_S} \simeq 0.4 \) lower bounds on the electron and neutron EDMs at the level of 
  \( d_{e,n} \gtrsim 10^{-28} \text{ ecm} \)

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(WA, Ball, Bharucha, Buras, Straub, Wick '08)

A combined study of all these observables and their correlations constitutes a very powerful test of the MFV MSSM with CPV phases.
The $B_s$ Mixing Phase
Beyond MFV
Gluino Box Contributions to $B_s$ Mixing (I)

\[ \propto \frac{\alpha_s^2}{\tilde{m}^2} \left( \delta_d^{LL} \right)_{32} \left( \delta_d^{RR} \right)_{32} \left( \bar{b} P_L s \right) \left( \bar{b} P_R s \right) \]

\[ \propto \frac{\alpha_s^2}{\tilde{m}^2} \left( \delta_d^{LL} \right)_{32} \left( \bar{b} \gamma_\mu P_L s \right)^2 \]

\[ \propto \frac{\alpha_s^2}{\tilde{m}^2} \left( \delta_d^{RR} \right)_{32} \left( \bar{b} \gamma_\mu P_R s \right)^2 \]

- color and RGE enhancement if $\left( \delta_d^{LL} \right)_{32}$ and $\left( \delta_d^{RR} \right)_{32}$ present simultaneously
Gluino Box Contributions to $B_S$ Mixing (II)

$\tan \beta = 5$, $\tilde{m} = M_{\tilde{g}} = 500\text{GeV}$

- Large effects in $S_{\psi \phi}$ possible for $O(1)$ RR or LL mass insertions
- If LL and RR insertions are present simultaneously, large effects in $S_{\psi \phi}$ can be generated even for moderate mass insertions
Double Penguins in Presence of \( (\delta_{d}^{RR})_{32} \)

\[
\sim \frac{\alpha_2}{4\pi} \frac{\alpha_s^2}{M_A^2} \frac{m_b^2}{M_W^2} \tan^4 \beta \frac{\mu^2 M_{\tilde{g}}^2}{\tilde{m}^4} (\delta_{d}^{LL})_{32} (\delta_{d}^{RR})_{32}
\]

\[
\sim \frac{\alpha_s}{4\pi} \frac{\alpha_2^2}{M_A^2} \frac{m_b^2}{M_W^2} \tan^4 \beta \frac{\mu^2 A_t M_{\tilde{g}}}{\tilde{m}^4} V_{tb} V_{ts}^* (\delta_{d}^{RR})_{32}
\]

- **proportionality to** \( m_b^2 \) **due to the presence of flavor changing right-handed currents** (remember: in MFV \( \propto m_b m_s \))

- **very important contributions from double penguins** for large \( \tan \beta \) in presence of a \( (\delta_{d}^{RR})_{32} \) mass insertion
A Large $B_s$ Mixing Phase Beyond MFV

- A $(\delta^L_d)_{32}$ mass insertion of $O(\lambda^2)$ is always induced radiatively.

→ Models that predict a sizable $(\delta^R_d)_{32}$ mass insertion are frameworks where a large $B_s$ mixing phase can naturally be generated.
A Large $B_s$ Mixing Phase Beyond MFV

- A $(\delta^{LL}_{d})_{32}$ mass insertion of $O(\lambda^2)$ is always induced radiatively

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There are many SUSY models where sizable $(\delta^{RR}_{d})_{32}$ mass insertions can be expected

- **abelian flavor models**
  Nir, Seiberg '93; Nir, Raz '02; Agashe, Carone '03; . . .

- **non-abelian flavor models**
  Barbieri, Hall, Romanino '97; Carone, Hall, Moroi '97; . . .
  Ross, Velasco-Sevilla, Vives '04; Antusch, King, Malinsky '07; . . .

- **SUSY GUTs**
  Chang, Masiero, Murayama '02; . . .
Concrete Example: A non-abelian Flavor Model

Example: Ross, Velasco-Sevilla, Vives ’04 (RVV)
- non-abelian flavor model based on $SU(3)$
- $1^{\text{st}}$ and $2^{\text{nd}}$ generation of squarks approximately degenerate

\[
(\delta^L_d) \sim \begin{pmatrix}
\lambda^4 & \lambda^5 & \lambda^3 \\
\lambda^5 & \lambda^4 & \lambda^2 \\
\lambda^3 & \lambda^2 & 1
\end{pmatrix}
\]

\[
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Expected phenomenology:
- Moderate effects in $b \to d$ and $s \to d$ transitions (strongest constraint from $\epsilon_K$)
- Small effects in $D_0 - \bar{D}_0$ mixing
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- a large $S_{\psi\phi}$ can be accommodated for in this model
- strong (model independent) correlation with the semileptonic asymmetry $a^s_{SL}$
  (Ligeti, Papucci, Perez ’06 Grossman, Nir, Perez ’09)
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”

\[
\begin{align*}
(\delta_d^{LL}) & \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix} \\
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- double penguins dominate ⇒ lower bound on $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ at the level of $10^{-8}$ (WA, Buras, Gori, Paradisi, Straub ’09)
CPV in $D^0$ Mixing and EDMs in SUSY Alignment Models
$SU(2)_L$ invariance implies a relation between LL mass insertions in the up and down sector

$$ (\delta^{LL}_u) = V^* (\delta^{LL}_d) V^T $$

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

- abelian flavor models that realize the alignment mechanism ensure $(\delta^{LL}_d) \simeq 0$

- irreducible flavor violating term $(\delta^{LL}_u)_{21} \sim \lambda$ in the up sector for natural $\mathcal{O}(1)$ splitting of squark masses
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\begin{align*}
\text{immediate consequence: } & \text{Large NP effects in } D^0 - \bar{D}^0 \text{ mixing} \\
& \text{(Nir, Seiberg '93)}
\end{align*}

- already for tiny complex \(\delta^{RR}_u \sim \lambda^3\) large CP violation in \(D^0 - \bar{D}^0\) mixing

\[ \text{Im } M^D_{12} \propto \text{Im} \left[ (\delta^{LL}_u)_{21} (\delta^{RR}_u)_{21} \right] \]

- current experimental bounds are easily reached
a complex \((\delta^R_u)_{21}\) leads also to a up quark EDM by means of flavor effects

\[
d_u^{(c)} \propto \text{Im} \left[ (\delta^L_u)_{21} (\delta^R_u)_{21} \right]
\]

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
Correlation with Electric Dipole Moments

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- The up quark EDM leads in turn to EDMs e.g. of the neutron and of mercury

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

\[
d_n \gtrsim 10^{-(28-29)} e\text{ cm}
\]
\[
d_{\text{Hg}} \gtrsim 10^{-(30-31)} e\text{ cm}
\]

- Interesting level for expected future experimental resolutions
MSSM with Minimal Flavor Violation

non-MFV MSSM frameworks with sizable $(\delta_d^{RR})_{32}$ mass insertions

SUSY alignment models
MSSM with Minimal Flavor Violation

→ CP violation in $\Delta F = 2$ transitions remains generically SM like
  (in particular: small effects in the $B_s$ mixing phase)
→ best low energy probes of CP violation are
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- in the large $\tan \beta$ regime, strong correlation between $B_s$ mixing and the rare decay $B_s \rightarrow \mu^+\mu^-$

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NP models predict characteristic patterns of effects in flavor observables
measurement of these observables provide important information on
the flavor structure of NP models and allows to rule them out
### Flavour DNA

<table>
<thead>
<tr>
<th></th>
<th>MFVMSSM</th>
<th>GMSSM</th>
<th>AC</th>
<th>RVV</th>
<th>SSU(5)$_{RN}$ (*)</th>
<th>RSc (**)</th>
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<tr>
<td>CPV in $D^0 - \bar{D}^0$</td>
<td>★</td>
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<td>★★★★</td>
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</tr>
<tr>
<td>$d_e$</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
<td>★★★★</td>
</tr>
</tbody>
</table>

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

(★) SU(5) SUSY GUT as analysed by Buras, Nagai, Paradisi ’10
(★★) Randall-Sundrum model with custodial protection as analysed by Blanke, Buras, Duling, Gemmler, Gori, Weiler ’08