Phenomenology of CP Violation in the MSSM

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Outline

based on work done in collaborations with

Patricia Ball, Aoife Bharucha, Andrzej Buras, Stefania Gori, Paride Paradisi, David Straub and Michael Wick

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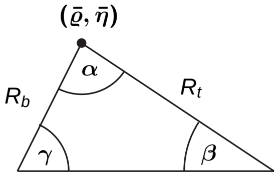
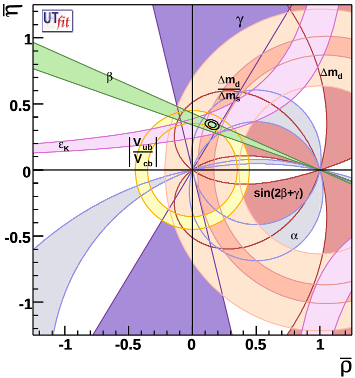
Apart from the QCD θ term,
the only source for CP violation in the SM
is the phase in the CKM matrix.

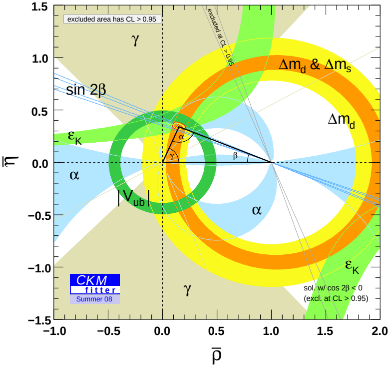
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

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

$$V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0$$



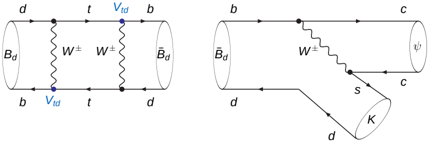


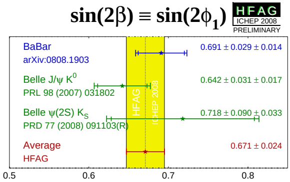


Impressive confirmation of the CKM picture for CP violation

Hints for New Sources of CP Violation?

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





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

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

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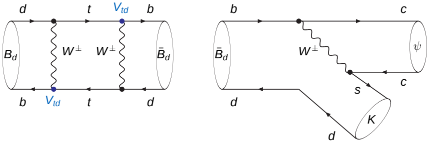

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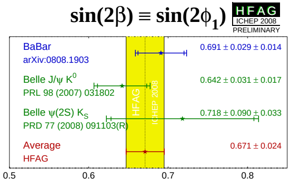
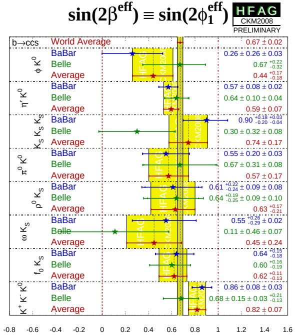
- In the SM also loop induced modes like $B \to \phi K_S$ and $B \to \eta' K_S$ give the same value

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

- But experimentally one has

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





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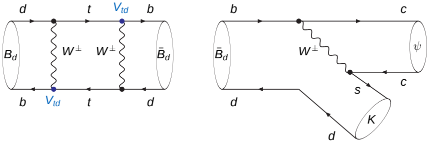

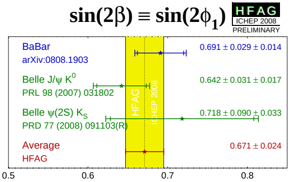

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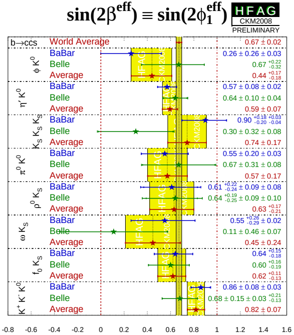
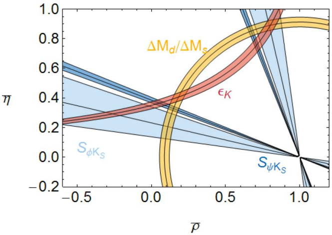
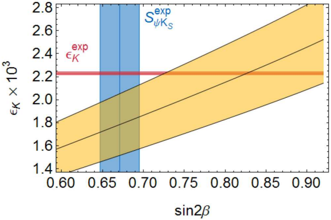


> $\Rightarrow$ New Phases in $b \to s$ decay amplitudes?



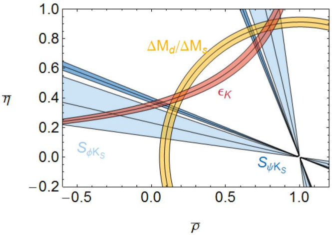


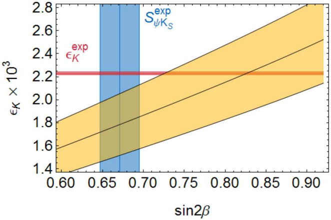
2 Tensions in the Unitarity Triangle

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

$$\epsilon_K^{SM} = (1.78 \pm 0.25) \times 10^{-3} \quad \Leftrightarrow \quad \epsilon_K^{exp.} = (2.23 \pm 0.01) \times 10^{-3}$$





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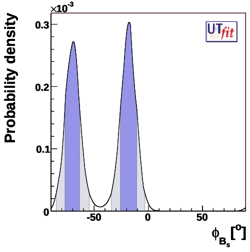
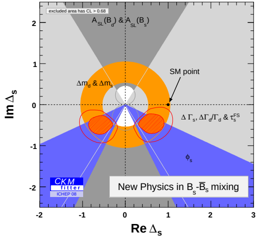
$\Rightarrow$ NP phase in B_d mixing?

$\Rightarrow$ Additional CP violation in K mixing?

Hints for New Sources of CP Violation?

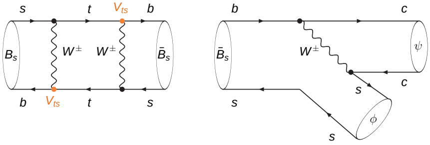


UTfit collaboration



CKM fitter collaboration

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



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- 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

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

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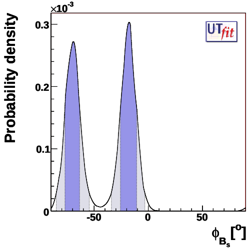

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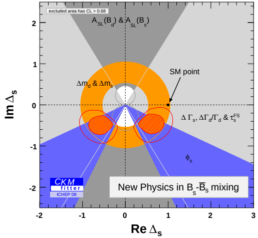

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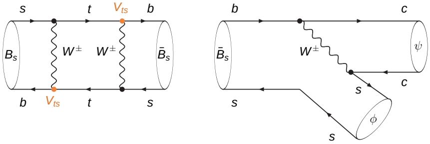

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$$\Phi_{B_s}^{NP} = (19^\circ \pm 8^\circ) \cup (69^\circ \pm 7^\circ)$$

$\Rightarrow$ Large B_s mixing phase?

Going Beyond the Standard Model

Natural way to address these tensions/problems:

- go beyond the SM and introduce
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The MSSM has many free parameters that can provide such phases

- Higgsino mass: μ
- Gaugino masses: M_1, M_2, M_3
- squark masses: m_Q^2, m_U^2, m_D^2
- trilinear couplings: A_u, A_d

$$\Delta F = 0$$

e.g.

- Electric Dipole Moments (EDMs) of the electron and neutron, d_e and d_n

CP Violating Low Energy Observables

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$\Delta F = 1$

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- Direct CP asymmetry in $b \to s\gamma$, $A_{CP}^{bs\gamma}$
- CP asymmetries in $B \to K^* \ell^+ \ell^-$

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$\Delta F = 2$

e.g.

- CP violation in Kaon mixing, ϵ_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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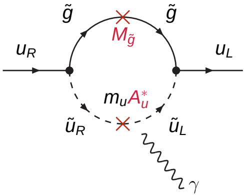
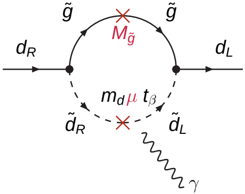
- Time dependent CP asymmetries in $B_d \to \phi K_S$ and $B_d \to \eta' K_S$, $S_{\phi K_S}$ and $S_{\eta' K_S}$

Constraints from the EDMs

- In the MSSM, EDMs can be induced already at the 1loop level
  $\rightarrow$ typically tight constraints on CP violating phases from the upper bounds on EDMs
- Example: Gluino contributions to up and down quark EDMs



$$d_u \simeq \frac{e g_s^2}{16\pi^2} m_u \frac{\text{Im}(M_{\tilde{g}} A_{\tilde{u}}^*)}{\bar{m}_{\tilde{u}}^4} F\left(\frac{|M_{\tilde{g}}|^2}{\bar{m}_{\tilde{u}}^2}\right)$$



$$d_d \simeq \frac{e g_s^2}{16\pi^2} m_d \tan\beta \frac{\text{Im}(M_{\tilde{g}} \mu)}{\bar{m}_{\tilde{d}}^4} F\left(\frac{|M_{\tilde{g}}|^2}{\bar{m}_{\tilde{d}}^2}\right)$$

Constraints from the EDMs

Constraints can be controlled by

- decoupling 1st and 2nd generation of squarks
  $\rightarrow$ hierachical squark masses $m^2_{\tilde{u},\tilde{c}} \gg m^2_{\tilde{t}}, m^2_{\tilde{d},\tilde{s}} \gg m^2_{\tilde{b}}$
- hierarchical trilinear couplings $A_{u,c} \ll A_t, A_{d,s} \ll A_b$

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- sizeable effects in flavor observables still possible, as 3rd generation squarks enter

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

and allow for

flavor conserving but CP violating phases.

For analyses of similar frameworks see:

Baek, Ko ’99
Bartl, Gajdosik, Lunghi, Masiero, Porod, Stremnitzer, Vives ’01 (Flavor Blind MSSM)
Ellis, Lee, Pilaftsis ’07 (MCPMFVMSSM)
Mercolli, Smith ’09

A Flavor Blind MSSM with CP Violating Phases

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

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} F_{\mu\nu} b_R \quad , \quad \mathcal{O}_8 = \frac{g_s}{16\pi^2} m_b \bar{s}_L \sigma^{\mu\nu} G_{\mu\nu} b_R$$

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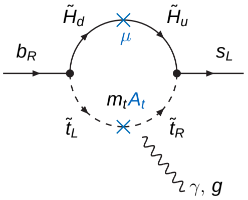
The corresponding Wilson coefficients recieve the dominant contributions from Higgsino-stop loops and are therefore mainly sensitive to one complex parameter combination

$$C_{7,8} \propto \mu A_t$$



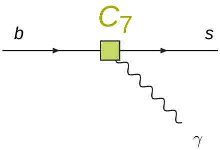
→ Interesting correlated effects in CP violating observables

WA, Buras, Paradisi '08

Most important constraints: EDMs and $b \to s\gamma$

1. The $b \to s\gamma$ branching ratio

- $b \to s\gamma$ amplitude is helicity suppressed
- typically large NP effects, even in a FBMSSM with low $\tan\beta$
- branching ratio constrains mostly $\text{Re}(\mu A_t)$



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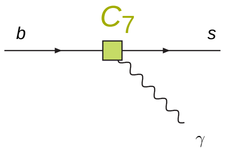

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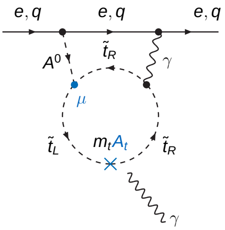
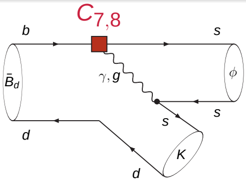


2. Electric Dipole Moments of the electron and the neutron

- 2 loop Barr-Zee type contributions sensitive to the 3rd generation of squarks
- decouple for heavy Higgses with $1/M_{A^0}^2$
- put constraints on $\mathrm{Im}(\mu A_t)$

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

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

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

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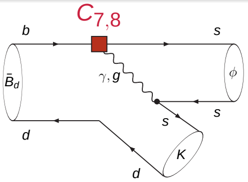

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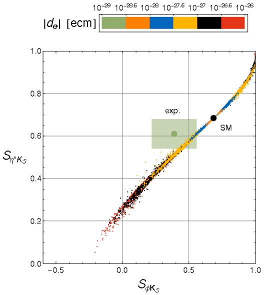

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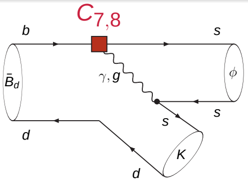

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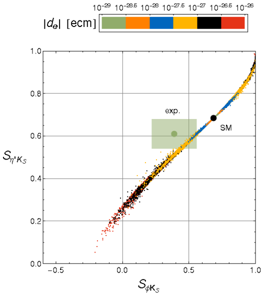
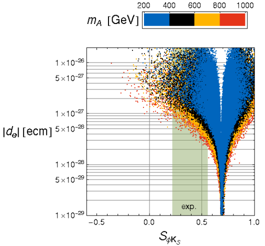
- sizable, correlated effects in $S_{\phi K_S}$ and $S_{\eta' K_S}$
- both asymmetries can simultaneously be brought in agreement with the data
- for $S_{\phi K_S} \simeq 0.4$, lower bounds on the electron and neutron EDMs:

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

  (roughly one order of magnitude below the current experimental constraints)

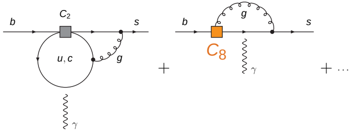




Direct CP Asymmetry in $b \to s\gamma$

Soares '91; Kagan, Neubert '98

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



- arises first at order α_s
- doubly Cabibbo and GIM suppressed in the SM
- sizable value would be clear signal for New Physics

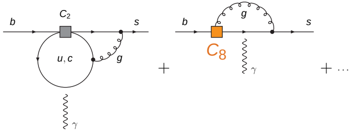
$A_{CP}^{bs\gamma}$(SM)	$\simeq (0.44^{+0.24}_{-0.14})\%$	Hurth, Lunghi, Porod '03
$A_{CP}^{bs\gamma}$(exp.)	$\simeq (0.4 \pm 3.6)\%$	HFAG

$$A_{CP}^{bs\gamma} \simeq \frac{\alpha_s}{|C_7|^2} \left(b_{27} \mathrm{Im}(C_2 C_7^*) + b_{87} \mathrm{Im}(C_8 C_7^*) + b_{28} \mathrm{Im}(C_2 C_8^*) \right)$$

Direct CP Asymmetry in $b \to s\gamma$

Soares '91; Kagan, Neubert '98

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



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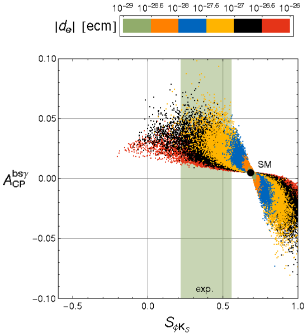
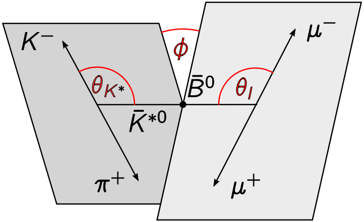
- Sign of $A_{CP}^{bs\gamma}$ is correlated with sign of $S_{\phi K_S}$
- For $S_{\phi K_S} < S_{\phi K_S}^{\text{SM}}$, $A_{CP}^{bs\gamma}$ is unambiguously positive
- values typically in the range $1\% - 6\%$



Bobeth, Hiller, Piranishvili '08
Egede, Hurth, Matias, Ramon, Reece '08
WA, Ball, Bahrucha, Buras, Straub, Wick '09



Perfoming a full angular reconstruction of both
$B^0 \to K^{0*}(\to K^+\pi^-)\ell^+\ell^-$
and the CP conjugate mode
$\bar{B}^0 \to \bar{K}^{0*}(\to K^-\pi^+)\ell^+\ell^-$
one has access to up to
24 observables! $(I_i, \bar{I}_i)$

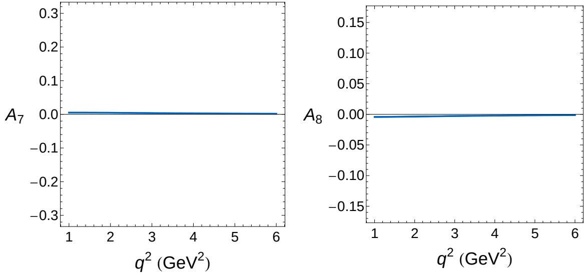
CP averaged angular coefficients

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

CP asymmetries

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

CP Asymmetries in $B^0 \to K^{0*}(\to K^+\pi^-)\ell^+\ell^-$



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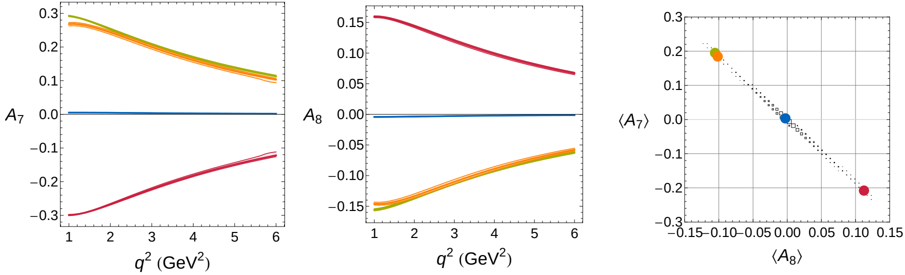
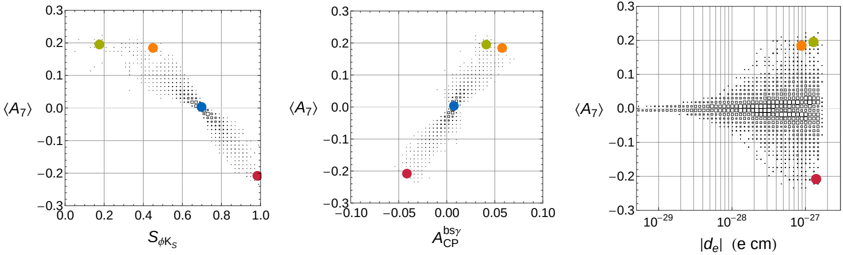


- The CP asymmetries A_7 and A_8 are negligible small in the SM
- In the FBMSSM huge effects are possible and they are highly correlated
- Deviations from the correlation point clearly towards sizeable complex NP contributions to other Wilson coefficients than $\mathcal{C}_7$

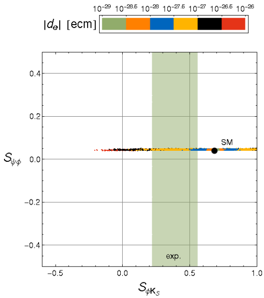


- $\langle A_7 \rangle$ and $\langle A_8 \rangle$ are correlated with $S_{\phi K_S}$ and $S_{\eta' K_S}$
- $S_{\phi K_S} \simeq 0.4$ implies positve $\langle A_7 \rangle \simeq 0.05 \div 0.2$ and negative $\langle A_8 \rangle \simeq -0.11 \div -0.03$
- Finally, $\langle A_7 \rangle$ and $\langle A_8 \rangle$ are also correlated with the CP asymmetry in $b \to s\gamma$ and the EDMs

CP Violation in $\Delta F = 2$ Transitions

1. B_d and B_s mixing phases

- Leading NP contributions to the mixing amplitudes $M_{12}^{d,s}$ are insensitive to the new phases of a FBMSSM.
  (at least for moderate $\tan\beta$ ...)
- $S_{\psi K_S}$ and $S_{\psi\phi}$ are SM like



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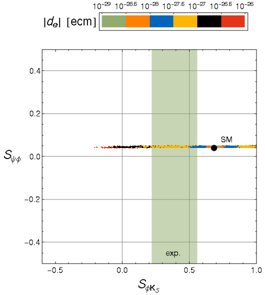

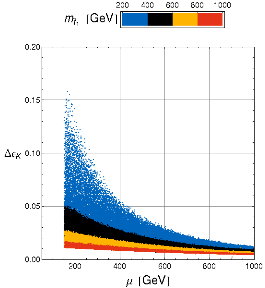

2. CP violation in K mixing

- 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: $\mu, m_{\tilde{t}_1} \simeq 200\text{GeV}$

Summary for the FBMSSM

In the flavor blind MSSM sizable, 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 $d_{e,n} \gtrsim 10^{-28}e\text{cm}$
- a positive, sizable direct CP asymmetry $A_{CP}^{bs\gamma} \simeq 1\% - 6\%$
- large, correlated effects in the CP asymmetries of $B \to K^* \ell^+ \ell^-$

In addition, within the framework of the FBMSSM, there are

- small CP violating effects in $\Delta F = 2$ amplitudes
  $\rightarrow$ $S_{\psi\phi}$ and $S_{\psi K_S}$ are SM like
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- small CP violating effects in $\Delta F = 2$ amplitudes
  $\to S_{\psi\phi}$ and $S_{\psi K_S}$ are SM like
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A combined study of all these observables and their correlations constitutes a very powerfull test of the FBMSSM

Introducing New Sources of Flavor Violation

- 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

$$M_q^2 = \tilde{m}^2 \mathbb{1} + \tilde{m}^2 \delta_q \quad , \quad \delta_q = \begin{pmatrix} \delta_q^{LL} & \delta_q^{LR} \\ \delta_q^{RL} & \delta_q^{RR} \end{pmatrix} \quad , \quad q = u, d$$

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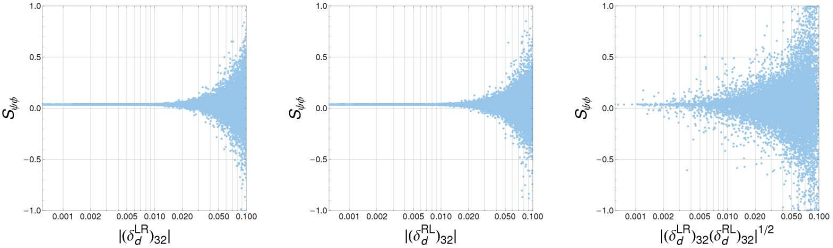
Complex mass insertions lead to
flavor and CP violating gluino interactions
that will generate the dominant contributions to FCNCs

The Impact of LR and RL Mass Insertions on $S_{\psi\phi}$



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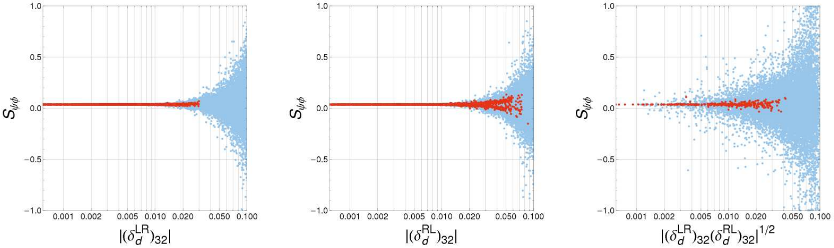


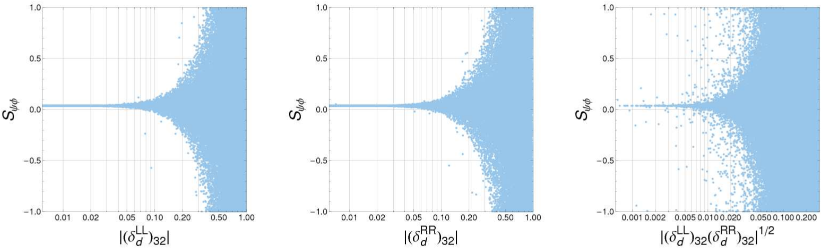
- $b \to s\gamma$ strongly constrains the LR and RL mass insertions, because the corresponding contributions to the amplitude are helicity enhanced

$$C_7 \propto \frac{M_{\tilde{g}}}{m_b}(\delta_d^{LR})_{32} + \frac{M_{\tilde{g}}\mu \tan\beta}{\tilde{m}^2}(\delta_d^{LL})_{32}$$

$$C_7' \propto \frac{M_{\tilde{g}}}{m_b}(\delta_d^{RL})_{32} + \frac{M_{\tilde{g}}\mu \tan\beta}{\tilde{m}^2}(\delta_d^{RR})_{32}$$

- No large effects in $S_{\psi\phi}$ can be generated

The Impact of LL and RR Mass Insertions on $S_{\psi\phi}$



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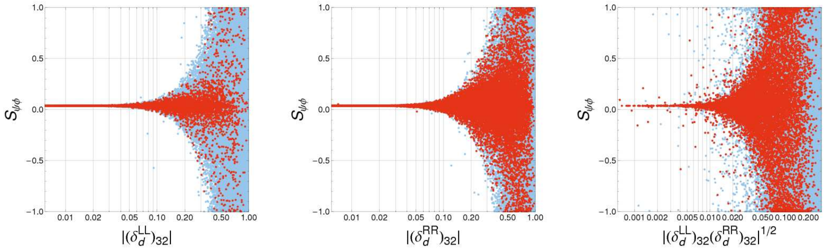

- LL and RR mass insertions are less constrained
- If only LL or RR insertions are switched on, large δs are required to generate effects in $S_{\psi\phi}$
- If both LL and RR insertions are present simultaneously, contributions are generated that are strongly renormalization group enhanced
- Even for moderate values for δ_d^{LL} and δ_d^{RR}, sizeable effects in $S_{\psi\phi}$ are possible

Summary and Outlook

- In a flavor blind MSSM, CP violating $\Delta F = 0$ and $\Delta F = 1$ amplitudes (in particular dipole transitions) can be strongly modified
- One finds highly correlated effects in the EDMs, $A_{CP}^{bs\gamma}$, CP asymmetries in $B \to K^* \ell^+ \ell^-$, $S_{\phi K_S}$ and $S_{\eta' K_S}$

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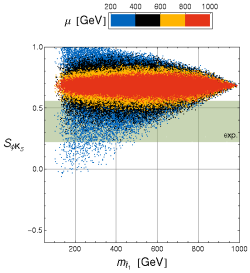
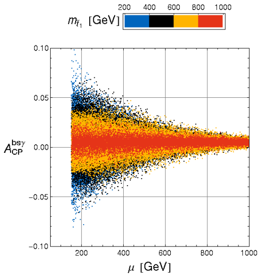
- To get large CP violating NP effects in $\Delta F = 2$ amplitudes, as indicated by the measurement of $S_{\psi\phi}$, additional flavor violating structures have to be present in the soft sector
- The most promising way to generate large effects in $S_{\psi\phi}$ is through simultaneous δ_d^{LL} and δ_d^{RR} insertions
- Which concrete flavor models predict such patterns? ...

Back Up

FBMSSM Implications for Direct Searches





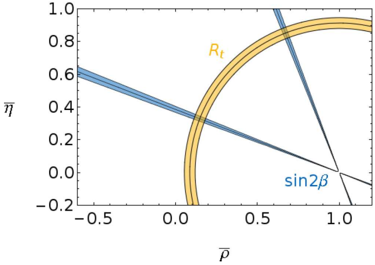
- $S_{\phi K_S} \simeq 0.4$ implies $\mu \lesssim 600\text{GeV}$ and $m_{\tilde{t}_1} \lesssim 700\text{GeV}$
- similarly, large non standard effects in $A_{CP}^{bs\gamma} \gtrsim 2\%$ imply $\mu \lesssim 600\text{GeV}$ and $m_{\tilde{t}_1} \lesssim 800\text{GeV}$
- stops and Higgsinos lie well within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

FBMSSM 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 β and the side R_t

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

$$R_t = \xi \frac{1}{\lambda} \sqrt{\frac{m_{B_s}}{m_{B_d}}} \sqrt{\frac{\Delta M_d}{\Delta M_s}} = 0.913 \pm 0.033$$



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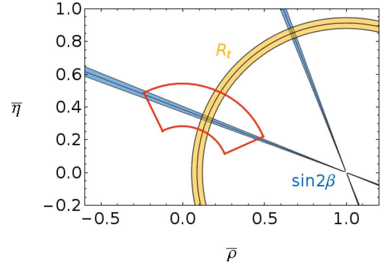
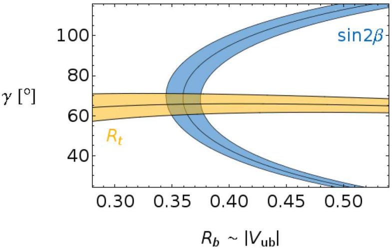
$$|V_{ub}| = (3.5 \pm 0.2) \times 10^{-3}$$

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

$\rightarrow$ can be tested at a SuperB Factory





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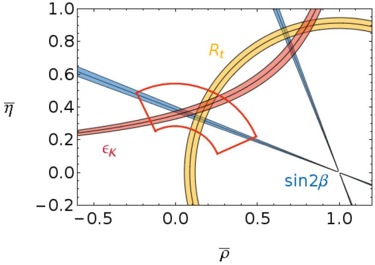

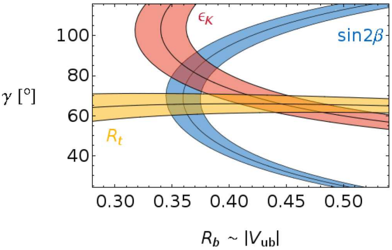

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