

# Signals of Supersymmetry in Flavor Physics

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# Low Energy Probes of Flavor and CP Violation

processes strongly suppressed in the SM and not measured yet  
(or only poorly measured) → **Discovery Channels**

## Electric Dipole Moments

- ▶ of the electron  $d_e$
- ▶ of hadronic systems  $d_n, d_{\text{Hg}}$

## CP violation in $D^0 - \bar{D}^0$ mixing

(LHCb, superB)

- ▶ time dep. CP asymmetries  $S_f^D$
- ▶ semi leptonic asymmetry  $a_{\text{SL}}^D$

## (very) rare decays

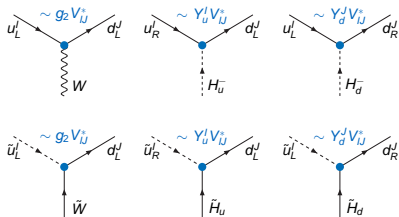
- ▶  $B_{s,d} \rightarrow \mu^+ \mu^-$  (LHCb)
- ▶  $B \rightarrow K^{(*)} \nu \bar{\nu}$  (superB)
- ▶  $K \rightarrow \pi \nu \bar{\nu}$  (NA62, KOTO)

## CP Violation in $b \rightarrow s$ transitions

- ▶  $B_s$  mixing phase,  $S_{\psi\phi}, a_{\text{SL}}^s$  (LHCb)
- ▶ CP asymmetries in  $B \rightarrow X_s \gamma$  and  $B \rightarrow K^* \gamma$  (superB)
- ▶ time dependent CP asymmetries in  $B \rightarrow \phi K_S$  and  $B \rightarrow \eta' K_S$  (superB)
- ▶ angular observables in  $B \rightarrow K^* \ell^+ \ell^-$  (LHCb, superB)

+ ...

# The MSSM Flavor Structure

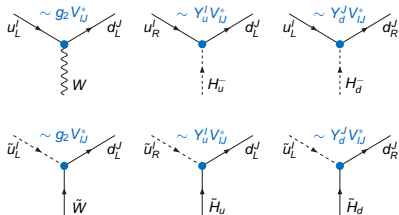


misalignment between up quarks and down quarks in flavor space

► CKM matrix

→ FCNCs naturally suppressed  
hierarchical CKM + GIM mechanism

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misalignment between quarks and squarks in flavor space

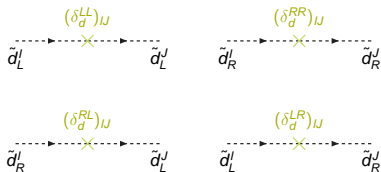
► Mass Insertions

$$M_q^2 = \tilde{m}^2 (\mathbb{1} + \delta_q)$$

→ Flavor and CP violating  
gluino-quark-squark interactions

► SUSY Flavor Problem

→ possible solutions:  
Alignment, degeneracy (superGIM),  
(partial) decoupling, ...



# The $B_{s,d} \rightarrow \mu^+ \mu^-$ Decays

# Standard Model Prediction and Experimental Status

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

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)^{\text{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$

$$\text{BR}(B_d \rightarrow \mu^+ \mu^-)^{\text{exp}} < 7.6 \times 10^{-9} \quad (\text{CDF})$$

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(LHCb status and prospects: see talk by Johannes Albrecht)

- ▶ the  $B_{s,d} \rightarrow \mu^+ \mu^-$  decays are **strongly helicity suppressed** in the SM

$$\text{BR}(B_q \rightarrow \mu^+ \mu^-) \propto m_\mu^2 (|P|^2 + |S|^2)$$

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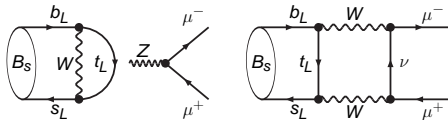
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$$P = (C_{10} - C'_{10}) + \frac{m_{B_q}^2}{2m_\mu} (C_P - C'_P) \quad S = \frac{m_{B_q}^2}{2m_\mu} (C_S - C'_S)$$

$C_{10}$ : only relevant SM Wilson coeff.  
 → induced by **Z penguins** and **boxes**



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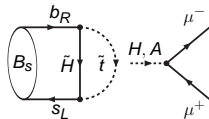
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$C_S^{(\prime)}$ ,  $C_P^{(\prime)}$ : scalar Wilson coefficients  
→ can **lift the helicity suppression**  
→ induced by MSSM **Higgs penguins**

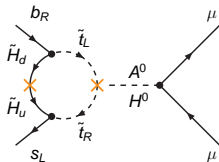




# SUSY contributions to $B_{s,d} \rightarrow \mu^+ \mu^-$

- ▶ Higgs penguins in the MSSM lift the helicity suppression
- ▶ for large  $\tan \beta$  huge enhancement possible (orders of magnitude) even in models with Minimal Flavor Violation

(Choudhury, Gaur '98; Babu, Kolda '99)



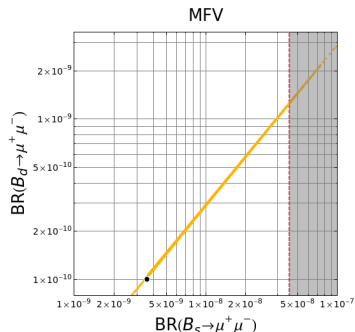
$$C_S, C_P \propto \frac{\alpha_2}{4\pi} \frac{1}{M_A^2} \frac{A_t \mu}{\tilde{m}^2} \tan^3 \beta \frac{m_b m_\mu}{M_W^2} V_{tb} V_{ts}^*$$

- ▶ does not decouple with the SUSY scale, but with the mass of the heavy MSSM Higgs bosons!
- ▶ strong constraints on many SUSY models, e.g. SUSY GUTs with Yukawa unification ( $\tan \beta \simeq 50$ )

# Correlations between $B_s \rightarrow \mu^+ \mu^-$ and $B_d \rightarrow \mu^+ \mu^-$

Golden MFV Relation: 
$$\frac{BR(B_s \rightarrow \mu^+ \mu^-)}{BR(B_d \rightarrow \mu^+ \mu^-)} \simeq \frac{|V_{ts}|^2}{|V_{td}|^2} \simeq 35$$

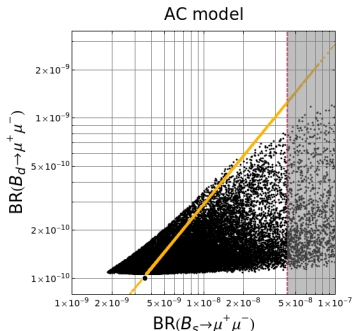
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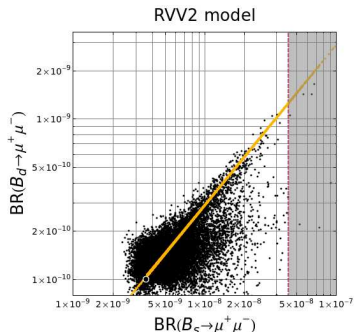
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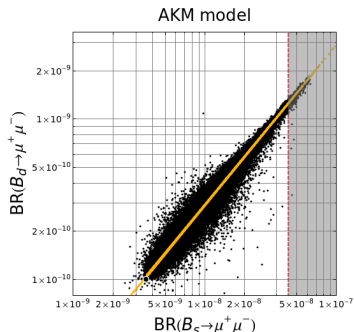
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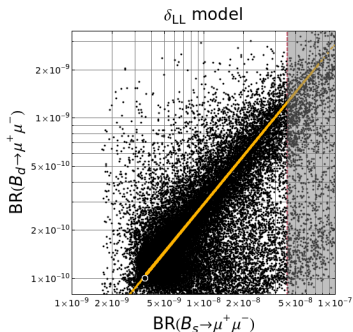
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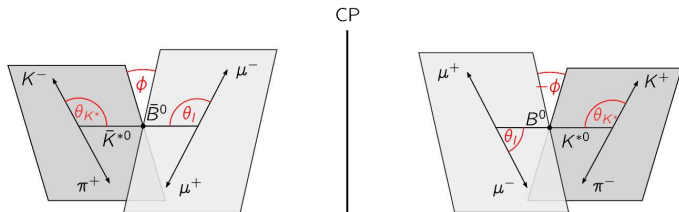
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- ▶ Hall, Murayama '95

# The $B \rightarrow K^* \ell^+ \ell^-$ Decay

# Angular Observables in $B \rightarrow K^* \ell^+ \ell^-$

(Egede, Hurth, Matias, Ramon, Reece '08, '10; Bharucha, Reece '10; Bobeth, Hiller, Piranishvilli '08; Bobeth, Hiller, van Dyk '10, '11; WA, Ball, Bharucha, Buras, Straub, Wick '08; ... )

The angular decay distribution of  $B \rightarrow K^*(\rightarrow K\pi)\ell^+\ell^-$  gives access to a **plethora of observables sensitive to New Physics**



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_\ell d\cos\theta_{K^*} d\phi} = \frac{9}{32\pi} \sum_{i,a} I_i^{(a)}(q^2) f(\theta_\ell, \theta_{K^*}, \phi)$$

$$S_i^{(a)}(q^2) = \left( I_i^{(a)}(q^2) + \bar{I}_i^{(a)}(q^2) \right) / \frac{d(\Gamma + \bar{\Gamma})}{dq^2} \quad \text{CP averaged angular coefficients (e.g. } A_{FB} \sim S_0^s \text{)}$$

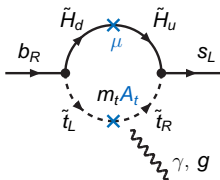
$$A_i^{(a)}(q^2) = \left( I_i^{(a)}(q^2) - \bar{I}_i^{(a)}(q^2) \right) / \frac{d(\Gamma + \bar{\Gamma})}{dq^2} \quad \text{CP Asymmetries}$$

(LHCb status and prospects: see talk by Johannes Albrecht)

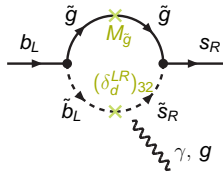


# Very Interesting Observables for SUSY

- ▶  $S_3 \sim A_T^{(2)}$ : sensitive to CP conserving right-handed magnetic penguins
- ▶  $A_9$ : sensitive to CP violation in right-handed magnetic penguins
- ▶  $A_7, A_8$ : sensitive to CP violation in left-handed magnetic penguins



$$\sim \frac{\alpha_2}{4\pi} \frac{1}{\tilde{m}^2} \tan \beta \frac{A_t \mu}{\tilde{m}^2} V_{tb} V_{ts}^*$$



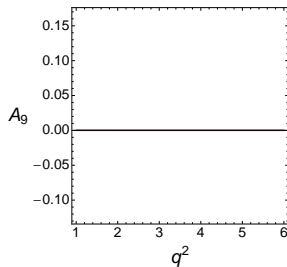
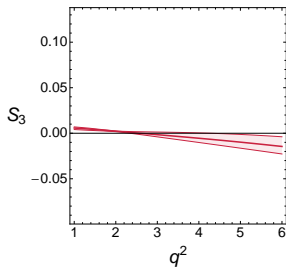
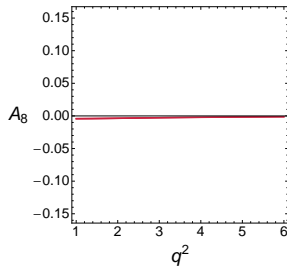
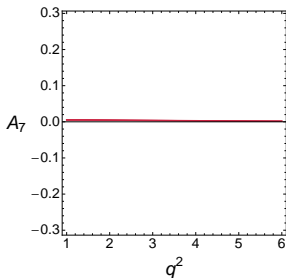
$$\sim \frac{\alpha_s}{4\pi} \frac{1}{\tilde{m}^2} \frac{M_{\tilde{g}}}{m_b} (\delta_d^{LR})_{32} + \dots$$

note:  $S_3, A_9$  can be extracted from the 1dim distribution in  $\phi$ ;  
should be easily doable at LHCb (also BaBar, Belle, CDF ?)

$$\frac{d(\Gamma + \bar{\Gamma})}{dq^2 d\phi} \sim 1 + S_3 \cos 2\phi + A_9 \sin 2\phi$$

# Example MSSM scenarios

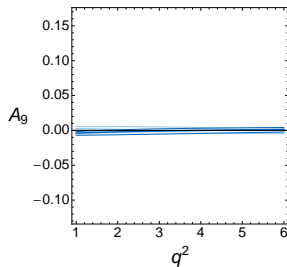
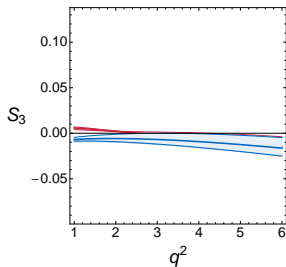
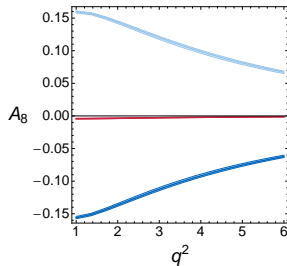
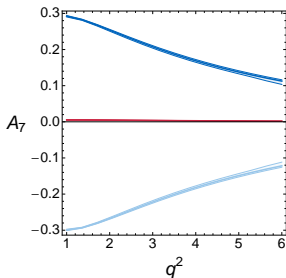
- SM predictions for  $A_{7,8,9}$  and  $S_3$  are strongly suppressed



(for studies of these obs.  
in concrete SUSY models  
see e.g.  
WA, Buras, Gori, Paradisi,  
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# Example MSSM scenarios

- ▶ **SM predictions** for  $A_{7,8,9}$  and  $S_3$  are strongly suppressed
- ▶ MFV with **complex trilinear coupling**  $A_t$  of the stop

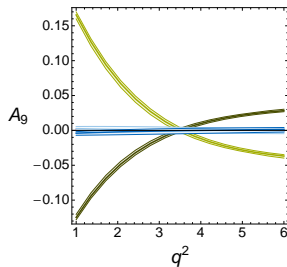
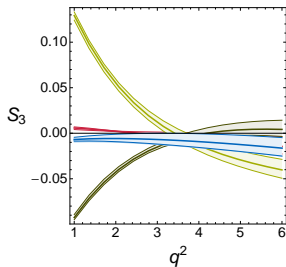
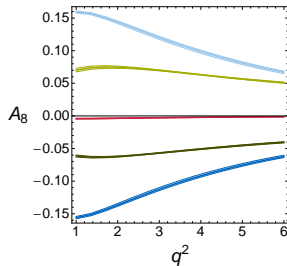
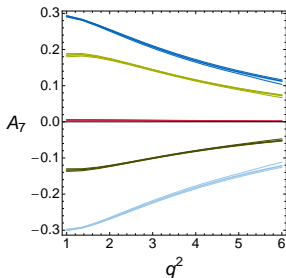


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# Example MSSM scenarios

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- ▶ MFV with **complex trilinear coupling**  $A_t$  of the stop
- ▶ beyond MFV: right-handed currents induced by **complex**  $(\delta_d^{LR})_{32}$

(for studies of these obs. in concrete SUSY models see e.g. WA, Buras, Gori, Paradisi, Straub '09; Barbieri, Lodone, Straub '11)



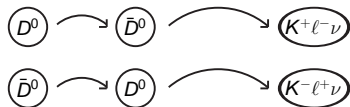
# CP Violation in $D^0$ - $\bar{D}^0$ Mixing

# CPV Observables in $D^0 - \bar{D}^0$ Mixing

CP violation in  $D^0 - \bar{D}^0$  mixing is strongly suppressed in the SM

$$\sim O\left(\frac{V_{ub}V_{cb}}{V_{us}V_{cs}}\right) \sim 10^{-3} \rightarrow \text{excellent probe of NP}$$

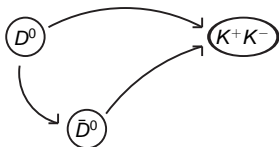
- ▶ **semileptonic asymmetry** (asymmetry in the decay to “wrong sign” leptons)



$$a_{\text{SL}} = \frac{\Gamma(D^0 \rightarrow K^+ l^- \nu) - \Gamma(\bar{D}^0 \rightarrow K^- l^+ \nu)}{\Gamma(D^0 \rightarrow K^+ l^- \nu) + \Gamma(\bar{D}^0 \rightarrow K^- l^+ \nu)}$$

- ▶ **time dependent CP asymmetries**, aka **lifetime CP asymmetries** in decays to final CP eigenstates  $f$  (e.g.  $K^+ K^-$ ,  $\pi^+ \pi^-$ ,  $K_S \phi$ , ...)

(LHCb status and prospects: see talk by Vladimir Gligorov)



$$S_f = 2\Delta Y_f = \frac{1}{\Gamma_D} \left( \hat{\Gamma}_{D^0 \rightarrow f} - \hat{\Gamma}_{\bar{D}^0 \rightarrow f} \right)$$

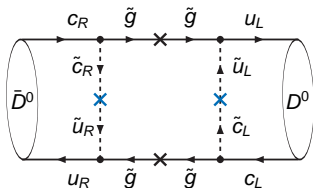
(model independent correlation between the two observables:  
Grossman, Nir, Perez '09; Bigi, Blanke, Buras, Recksiegel '09)

# Large $D^0 - \bar{D}^0$ Mixing in SUSY Alignment Models

- ▶  $D^0 - \bar{D}^0$  mixing remains **SM like** in the MSSM with **Minimal Flavor Violation**
- ▶ **SUSY Alignment models** based on abelian flavor symmetries predict a **large mass insertion in the up-sector**
- ▶ strong constraints on alignment models (Golowich, Hewett, Pakvasa, Petrov '07; Gedalia, Grossman, Nir, Perez '09) (heavy spectrum  $\tilde{m} \gtrsim 2\text{TeV}$ , or only small mass splitting between the first two gen.  $\lesssim 10\%$ )

$$(\delta_U^{LL})_{21} \sim \lambda \quad (\text{Nir, Seiberg '93})$$

- ▶ consequence: **gluino boxes** induce large NP effects in  $D^0 - \bar{D}^0$  mixing



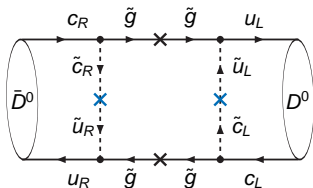
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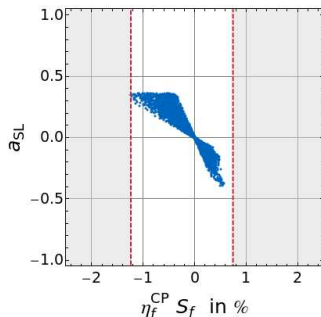
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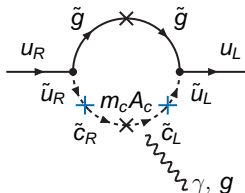


large CP violation in  $D^0 - \bar{D}^0$  mixing  
is generically predicted



# Correlation with Electric Dipole Moments

- ▶ the flavor structures of Alignment models also lead to an **up quark EDM** by means of **flavor effects**

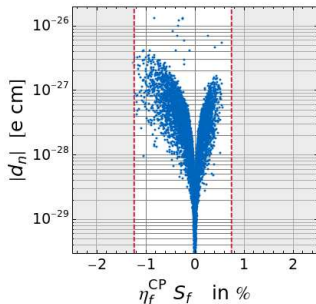
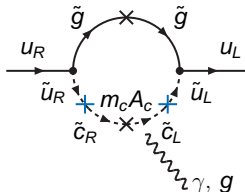


$$d_u^{(c)} \propto \text{Im} \left[ (\delta_u^{LL})_{21}^* (\delta_u^{RR})_{21} \right] m_c \frac{A_c M_{\tilde{g}}}{\tilde{m}^2}$$

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SUSY Alignment models generically predict also **lower bounds on hadronic EDMs** only 1-2 orders of magnitude below present exp. constraints (WA, Buras, Paradisi '10)

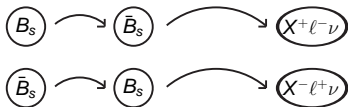
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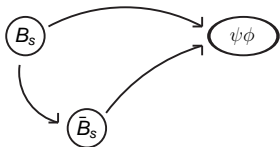
$$\sim \text{Arg}(V_{ts}) \simeq 1^\circ \rightarrow \text{excellent probe of NP}$$

► **semileptonic asymmetry**



$$a_{\text{SL}}^s = \frac{\Gamma(\bar{B}_s \rightarrow X^{\ell^+ \nu}) - \Gamma(B_s \rightarrow X^{\ell^- \bar{\nu}})}{\Gamma(\bar{B}_s \rightarrow X^{\ell^+ \nu}) + \Gamma(B_s \rightarrow X^{\ell^- \bar{\nu}})}$$

► **time dependent CP asymmetry** in the  $B_s \rightarrow \psi\phi$  decay



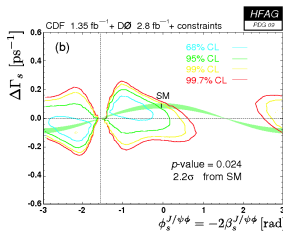
$$S_{\psi\phi} \sin(\Delta M_s t) = \frac{\Gamma(\bar{B}_s(t) \rightarrow \psi\phi) - \Gamma(B_s(t) \rightarrow \psi\phi)}{\Gamma(\bar{B}_s(t) \rightarrow \psi\phi) + \Gamma(B_s(t) \rightarrow \psi\phi)}$$

(model independent correlation between the two observables:  
Ligeti, Papucci, Perez '06; Grossman, Nir, Perez '09)

# The Experimental Situation

## Status 2009

- ▶ data from Tevatron seems to hint towards a large time dep. CP asymmetry  $S_{\psi\phi}$  (2-3 $\sigma$  deviation from SM prediction)



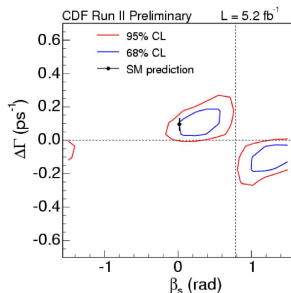
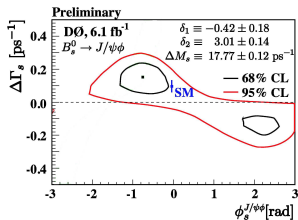
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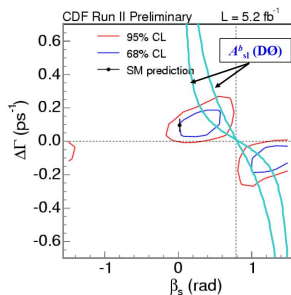
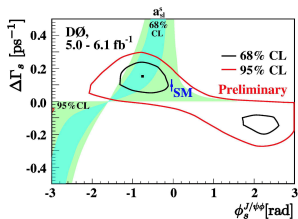
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(e.g. Ligeti, Papucci, Perez, Zupan '10)

Lenz, Nierste + CKMfitter '10)

$$S_{\psi\phi} \simeq 0.78^{+0.12}_{-0.19} \quad \leftrightarrow \quad S_{\psi\phi}^{SM} \simeq 0.04$$

(from Lenz, Nierste '11)



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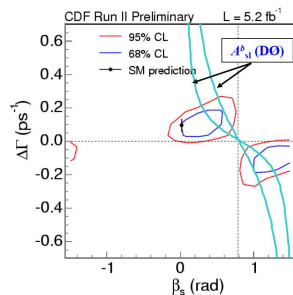
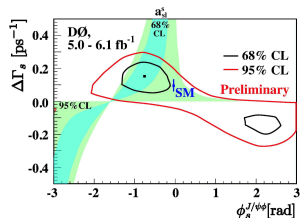
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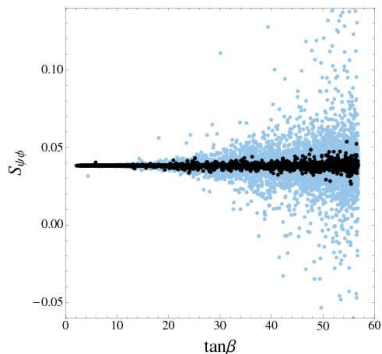
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(LHCb status and prospects: see talk by Greig Cowan)

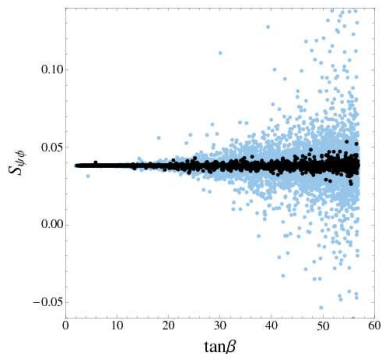


# A Large $B_s$ Mixing Phase in the MFV MSSM?



- ▶ CP violation in meson mixing is **generically SM like** in the MFV MSSM (WA, Buras, Paradisi '08, WA, Buras, Gori, Paradisi, Straub '09)
- ▶ i.e. **small effects** in  $S_{\psi\phi}$ ,  $S_{\psi K_S}$  and  $\epsilon_K$
- ▶ reason: strong constraints from  $\text{BR}(B \rightarrow X_s \gamma)$ , EDMs and in particular  $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$

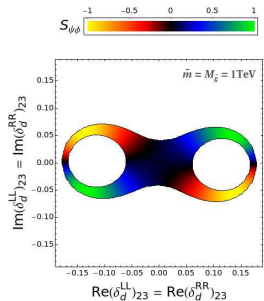
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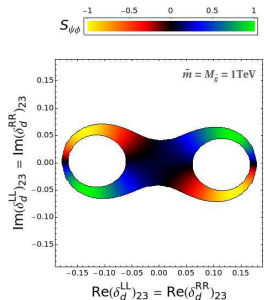
- ▶ effects in  $S_{\psi\phi}$  might still be possible in the **uplifted SUSY region** with  $\tan\beta \simeq O(100 - 200)$  (Dobrescu, Fox '10; Dobrescu, Fox, Martin '10)
- ▶ But: such a scenario is highly constrained by B physics observables and  $(g - 2)_\mu$  (WA, Straub '10)
- ▶ what about EDMs?

# The $B_s$ Mixing Phase Beyond MFV



- ▶ large  $S_{\psi\phi}$  can be accommodated for presence of non-MFV bottom - strange Squark mixing
- ▶ If LL and RR mass insertions are present simultaneously, large effects in  $S_{\psi\phi}$  can be generated even for moderate mass insertions

# The $B_s$ Mixing Phase Beyond MFV



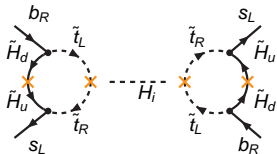
- ▶ large  $S_{\psi\phi}$  can be accommodated for presence of **non-MFV** bottom - strange **Squark mixing**
- ▶ If LL and RR mass insertions are present **simultaneously**, large effects in  $S_{\psi\phi}$  can be generated even for **moderate mass insertions**

There are many concrete non-MFV SUSY models in the literature that can accommodate a large  $S_{\psi\phi}$

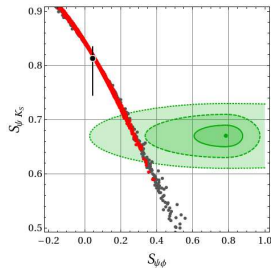
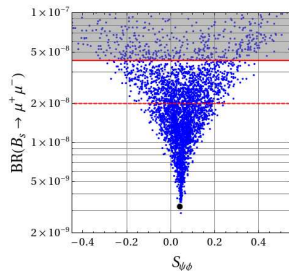
- ▶ **abelian and non-abelian SUSY flavor models**  
(e.g. WA, Buras, Gori, Paradisi, Straub '09; Barbieri, Isidori, Jones-Perez, Lodone, Straub '11; ...)
- ▶ **SUSY GUTs with right-handed neutrinos**  
(Hisano, Shimizu '08; Dutta, Mimura '09; Buras, Nagai, Paradisi '10; Girschbach et. al. '11; ...)
- ▶ **models with flavor violating trilinear couplings**  
(Crivellin, Hofer, Nierste, Scherer '11)

# The $B_s$ Mixing Phase Beyond the MSSM

- ▶ new degrees of freedom **Beyond the MSSM** might be present at the TeV scale
- ▶ leading corrections from the BMSSM physics to the MSSM Higgs sector can be described by two **dim. 5 operators** (Dine, Seiberg, Thomas '07)
- ▶ the modified Higgs sector leads to **double penguin contributions** that in contrast to the MFV MSSM are not suppressed by the strange quark mass



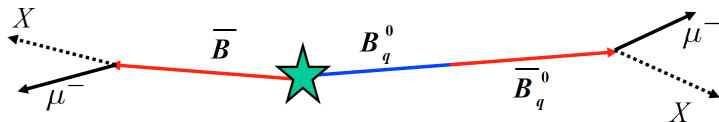
- ▶ even for MFV,  $S_{\psi\phi}$  can be as large as 0.4 in this framework
- ▶  $S_{\psi\phi} \simeq 0.4$  unambiguously implies sizable **suppression of  $S_{\psi K_S}$**  and  **$BR(B_s \rightarrow \mu^+ \mu^-)$  close to the current bound** (WA, Carena, Gori, de la Puente, in preparation)



- ▶ **The  $B_s \rightarrow \mu^+ \mu^-$  and  $B_d \rightarrow \mu^+ \mu^-$  decays**
  - BRs can be strongly enhanced by SUSY Higgs penguins
  - Correlation between  $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$  and  $\text{BR}(B_d \rightarrow \mu^+ \mu^-)$  offers a clean test of MFV
- ▶ **Angular observables in  $B \rightarrow K^* \mu^+ \mu^-$** 
  - are highly sensitive to SUSY effects in magnetic penguins
  - allow to disentangle effects from CP conserving or CP violating left-handed or right-handed currents
- ▶ **CP violation in  $D^0 - \bar{D}^0$  mixing**
  - large effects are generically predicted in SUSY alignment models
  - also lower bounds on hadronic EDMs in that models
- ▶ **The  $B_s$  mixing phase**
  - remains SM like in the MSSM with MFV
  - large  $S_{\psi\phi}$  can be accommodated for in presence of squark mixing, or  
Beyond the MSSM with a modified Higgs sector

Back Up

# Like-Sign Dimuon Charge Asymmetry



Definition: 
$$A_{\text{SL}}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

$N_b^{++}$ : Number of same sign  $\mu^+\mu^+$  events from  $B \rightarrow \mu X$  decays

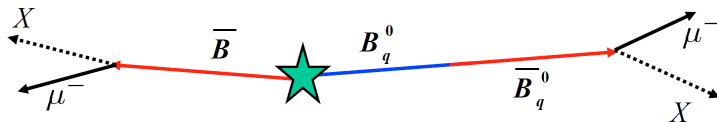
$N_b^{--}$ : Number of same sign  $\mu^-\mu^-$  events from  $B \rightarrow \mu X$  decays

- Relation to the semileptonic asymmetry

$$A_{\text{SL}}^b \simeq 0.5 a_{\text{SL}}^d + 0.5 a_{\text{SL}}^s$$



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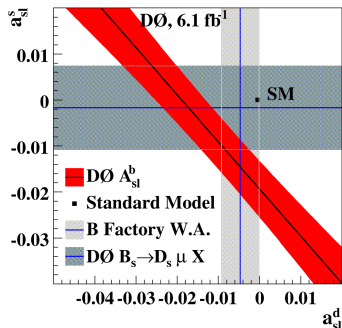
► Relation to the semileptonic asymmetry

$$A_{\text{SL}}^b \simeq 0.5 a_{\text{SL}}^d + 0.5 a_{\text{SL}}^s$$

► **3.2 $\sigma$  discrepancy** between SM prediction and recent D0 measurement

$$A_{\text{SL}}^b(\text{SM}) = (-0.2 \pm 0.03) \times 10^{-3}, \quad A_{\text{SL}}^b(\text{exp}) = (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$

(Lenz, Nierste '11),      (D0, arXiv:1005.2757)



# “Flavor DNA”

	MFV MSSM	GMSSM	AC	RVV2	SSU(5) <sub>RN</sub>	MFV BMSSM
CPV in $D^0 - \bar{D}^0$	★	★★★★	★★★★	★	★	★
CPV in $B_s - \bar{B}_s$	★	★★★★	★★★★	★★★★	★★★★	★★
$S_{\phi K_S}, S_{\eta' K_S}$	★★★★	★★★★	★★	★	★★★★	★★★★
$A_{CP}(b \rightarrow s\gamma)$	★★★★	★★★★	★	★	★	★★★★
$A_{7,8}(B \rightarrow K^* \ell\ell)$	★★★★	★★★★	★	★	★	★★★★
$A_9(B \rightarrow K^* \ell\ell)$	★	★★★★	★	★	★	★
$B_{s,d} \rightarrow \mu^+ \mu^-$	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★
$B \rightarrow K^{(*)} \nu \bar{\nu}$	★	★★	★	★	★	★
$K \rightarrow \pi \nu \bar{\nu}$	★	★★★★	★	★	★	★
$d_n$	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★
$d_e$	★★★★	★★★★	★★★★	★★★★	★★★★	★★★★

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