

Low Energy Probes of CP Violation in Supersymmetric Models

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Theory Seminar

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WA, A.J. Buras and P. Paradisi

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WA, A.J. Buras, S. Gori, P. Paradisi and D. Straub

Nucl. Phys. B **830** (2010) 17



WA, A.J. Buras and P. Paradisi

Phys. Lett. B **688** (2010) 202

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Introduction

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CP Violation in B_s Mixing

3

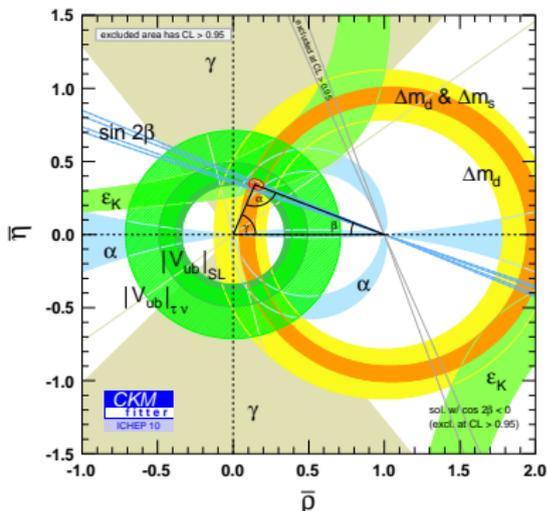
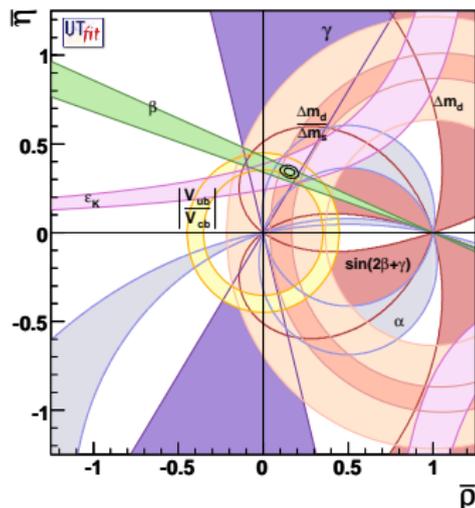
Phenomenology of CP Violation in SUSY Models

- 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

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Summary

Success of the SM CKM Picture



- ▶ 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 2-3 σ discrepancy between $\sin 2\beta$ and $\text{BR}(B \rightarrow \tau\nu)$)
- ▶ how much room is left for additional sources of flavor violation?

The New Physics Flavor Problem

Model independent analysis of
NP effects in flavor observables

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_{i,j} \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

Operator	Bounds on Λ in TeV ($c_{ij} = 1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K; \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K; \epsilon_K$
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D; q/p , \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D; q/p , \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d}; S_{\psi K_S}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d}; S_{\psi K_S}$
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$(\bar{b}_R s_L)(\bar{b}_L s_R)$		3.7×10^2		1.3×10^{-5}	Δm_{B_s}

Isidori, Nir, Perez '10

- ▶ a **generic flavor structure** c_{ij} requires a **very high NP scale** Λ
- ▶ 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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Electric Dipole Moments

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

Low Energy Probes of Flavor and CP Violation

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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, $S_{\psi\phi}, a_{\text{SL}}^s$ (LHCb)
- ▶ direct CP asymmetry in $B \rightarrow X_s \gamma$
 $A_{\text{CP}}(b \rightarrow s \gamma)$ (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:

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

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

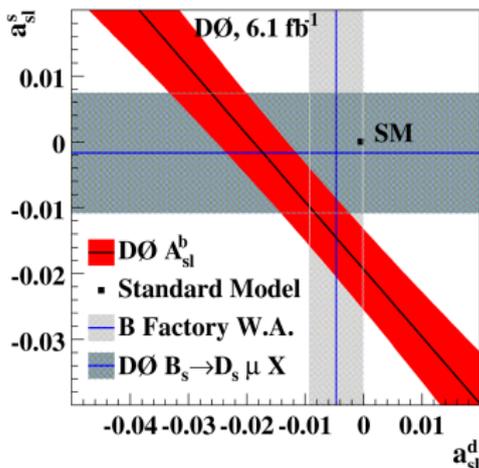
► **3.2 σ discrepancy** between SM prediction and recent D0 measurement

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

(Lenz, Nierste '06)

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

(D0, arXiv:1005.2757)



CP Violation in B_s Mixing

Schrödinger equation describing $B_s - \bar{B}_s$ mixing:

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

Three physical parameter:

$$|M_{12}^s|, |\Gamma_{12}^s|, \phi_s = -\arg\left(\frac{M_{12}^s}{\Gamma_{12}^s}\right) \quad ; \quad \phi_s^{\text{SM}} \simeq 0.004$$

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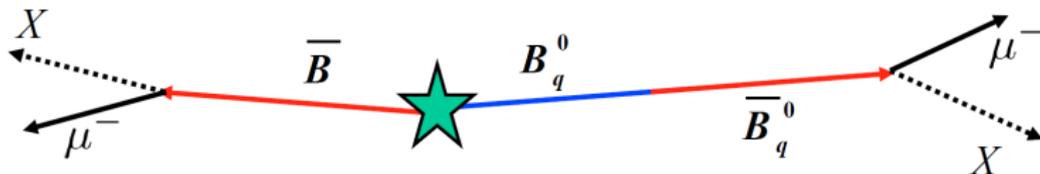
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Observables:

- ▶ mass and width difference $\Delta M_s = 2|M_{12}^s|$, $\Delta\Gamma_s = 2|\Gamma_{12}^s| \cos\phi_s$
- ▶ semileptonic asymmetry

$$a_{\text{SL}}^s = \frac{\Gamma(\bar{B}_s \rightarrow l^+ X) - \Gamma(B_s \rightarrow l^- X)}{\Gamma(\bar{B}_s \rightarrow l^+ X) + \Gamma(B_s \rightarrow l^- X)}, \quad a_{\text{SL}}^s = \left| \frac{\Gamma_{12}^s}{M_{12}^s} \right| \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

Like-Sign Dimuon Charge Asymmetry



► Definition:

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

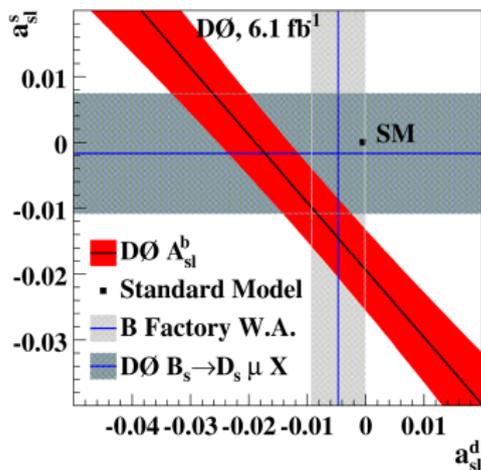
N_b^{++} : Number of same sign $\mu^+\mu^+$ events from $B \rightarrow \mu X$ decays

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

► Relation to the semileptonic asymmetry

$$A_{\text{SL}}^b = (0.506 \pm 0.043) a_{\text{SL}}^d + (0.494 \pm 0.043) a_{\text{SL}}^s$$

(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 β_s the phase of V_{ts}

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

- ▶ for a large B_s mixing phase $\phi_s \gg 2\beta_s$, ϕ_s^{SM} one has

$$S_{\psi\phi} \simeq -\sin \phi_s$$

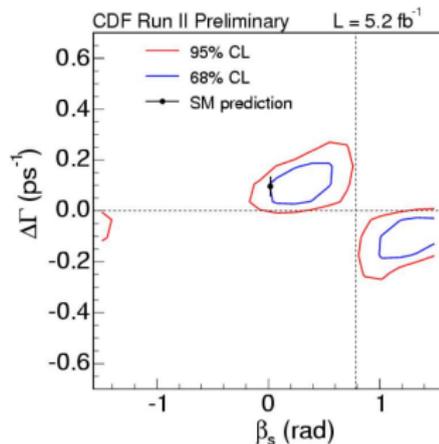
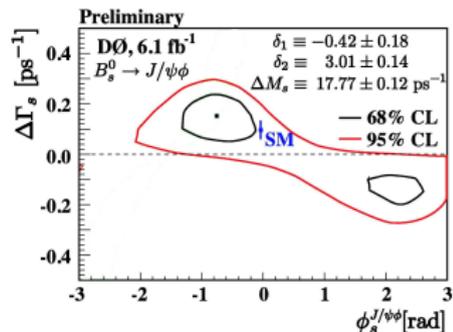
- ▶ model-independent relation between $S_{\psi\phi}$ and a_{SL}^s

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

$$a_{\text{SL}}^s = -\frac{\Delta\Gamma_s}{\Delta M_s} \frac{S_{\psi\phi}}{\sqrt{1 - S_{\psi\phi}^2}}$$

The Experimental Situation

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



The Experimental Situation

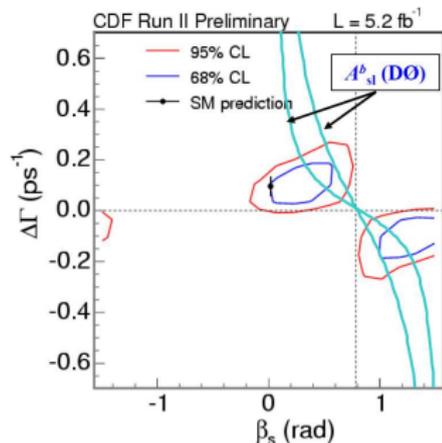
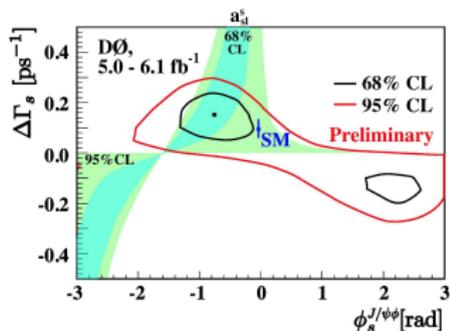
- ▶ data from CDF and D0 on $S_{\psi\phi}$ are in rather good agreement with the SM ($\simeq 1\sigma$)
- ▶ recent result from D0 on the like sign dimuon charge asymmetry A_{SL}^b shows a 3.2σ deviation from the SM

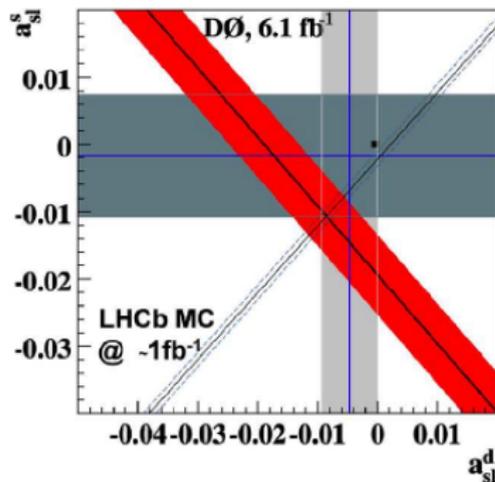
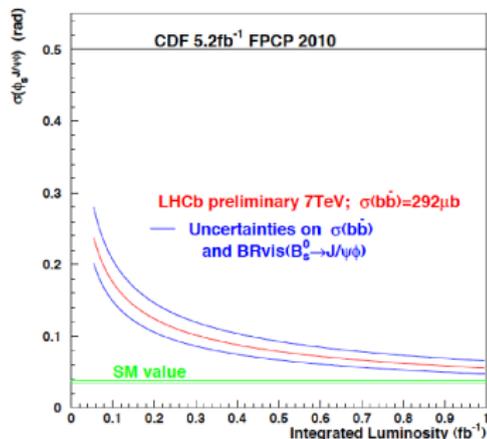
(arXiv:1005.2757 [hep-ex])

- ▶ global fits prefer large phase in B_s mixing

(e.g. Ligeti, Papucci, Perez, Zupan '10
Lenz, Nierste + CKMfitter '10)

$$S_{\psi\phi} \simeq 0.5$$





- ▶ **significant improvement** on the experimental side can be expected at LHCb both for $S_{\psi\phi}$ and a_{SL}^S

- ▶ absorptive part Γ_{12} dominated by SM tree level decays
- ⇒ CP violating short distance contributions to the dispersive part M_{12}

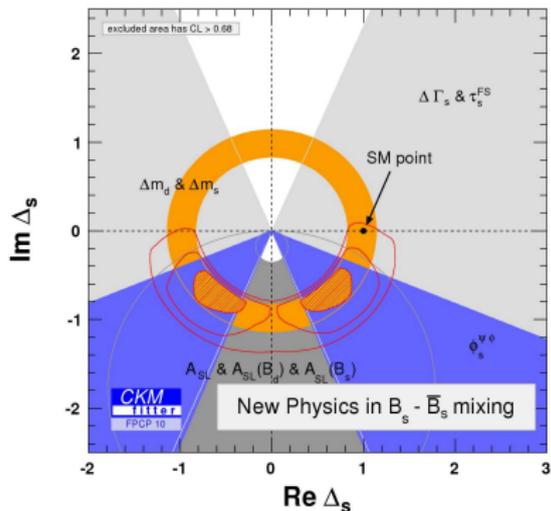
$$M_{12}^S = \Delta_s (M_{12}^S)^{\text{SM}}$$

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

- | | |
|--|--|
| ▶ $\Delta M_s = \Delta M_s^{\text{SM}} \Delta_s $ | ▶ $\Delta M_s = \Delta M_s^{\text{SM}} 1 + h_s e^{2i\sigma_s} $ |
| ▶ $\Delta \Gamma_s = \Delta \Gamma_s^{\text{SM}} \cos(\text{Arg}(\Delta_s))$ | ▶ $\Delta \Gamma_s = \Delta \Gamma_s^{\text{SM}} \cos(\text{Arg}(1 + h_s e^{2i\sigma_s}))$ |
| ▶ $a_{\text{SL}}^s = \text{Im}(\Gamma_{12}^s / [(M_{12}^S)_{\text{SM}} \Delta_s])$ | ▶ $a_{\text{SL}}^s = \text{Im}(\Gamma_{12}^s / [(M_{12}^S)_{\text{SM}} (1 + h_s e^{2i\sigma_s})])$ |
| ▶ $S_{\psi\phi} = \sin(2 \beta_s - \text{Arg}(\Delta_s))$ | ▶ $S_{\psi\phi} = \sin(2 \beta_s - \text{Arg}(1 + h_s e^{2i\sigma_s}))$ |

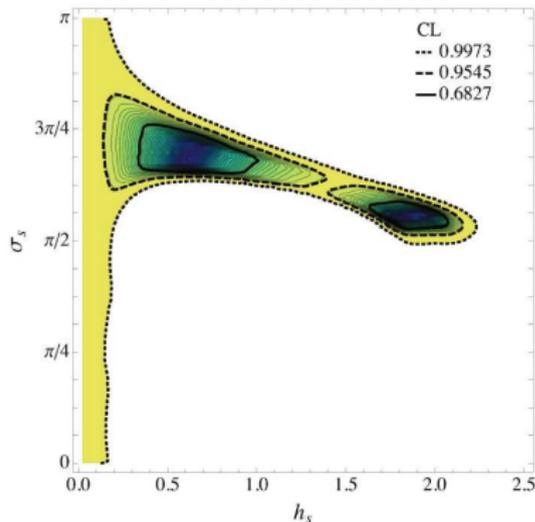
Large New Physics in B_s Mixing

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Lenz, Nierste + CKMfitter '10

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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

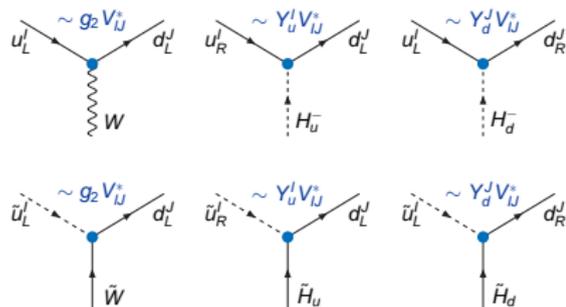
The MSSM Flavor Structure (I)

- ▶ 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 3×3 matrices in flavor space
- ▶ in a basis where quarks have diagonal masses (super CKM basis), squark masses are not necessarily flavor diagonal

$$M_{\tilde{u}}^2 = \begin{pmatrix} V^*(\tilde{m}_Q^2)^T V^T & -(v_d \mu^* Y_u + v_u \tilde{A}_u)/\sqrt{2} \\ -(v_d \mu Y_u + v_u \tilde{A}_u^*)/\sqrt{2} & \tilde{m}_U^2 \end{pmatrix} + O(v^2)$$

$$M_{\tilde{d}}^2 = \begin{pmatrix} (\tilde{m}_Q^2)^T & -(v_u \mu^* Y_d + v_d \tilde{A}_d)/\sqrt{2} \\ -(v_u \mu Y_d + v_d \tilde{A}_d^*)/\sqrt{2} & \tilde{m}_D^2 \end{pmatrix} + O(v^2)$$

The MSSM Flavor Structure (II)

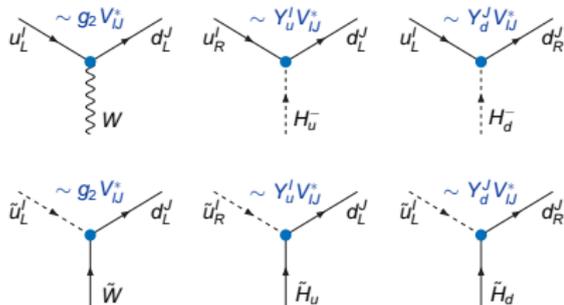


misalignment between up quarks and down quarks in flavor space

► CKM matrix

→ appears in W and Higgs charged currents and their supersymmetrized versions

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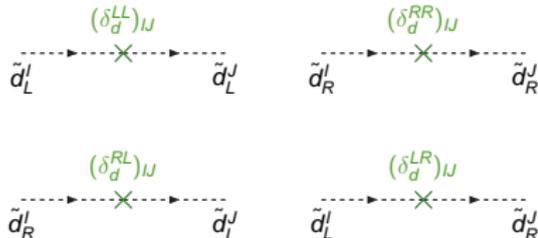
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misalignment between quarks and squarks in flavor space

► Mass Insertions

→ parameterize the off-diagonal parts of the squark masses

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



→ most transparent treatment in the **Mass Insertion Approximation**

→ flavor change through mass insertions along squark propagators

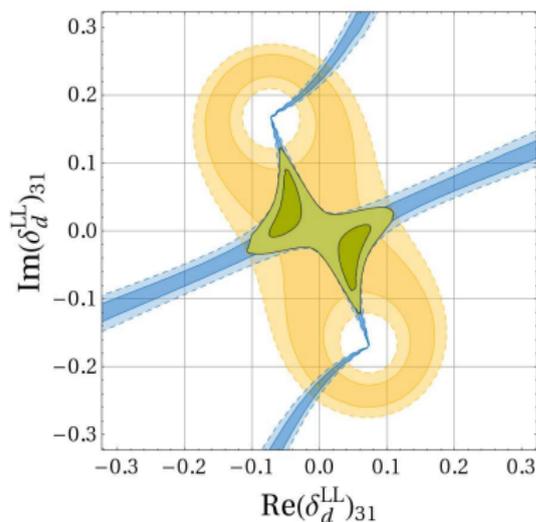
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- ▶ **severe constraints** on the SUSY scale \tilde{m} and the Mass Insertions δ s from meson mixing and rare decays like $B \rightarrow X_s \gamma$ and $B \rightarrow X_s l^+ l^-$
- ▶ for all δ s of $\mathcal{O}(1)$, the SUSY scale has to be extremely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

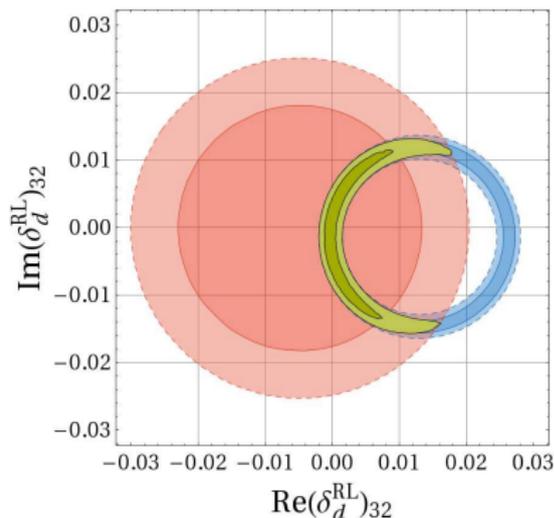


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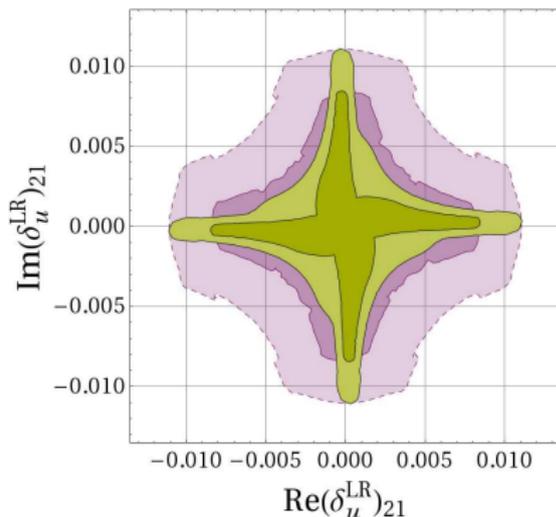


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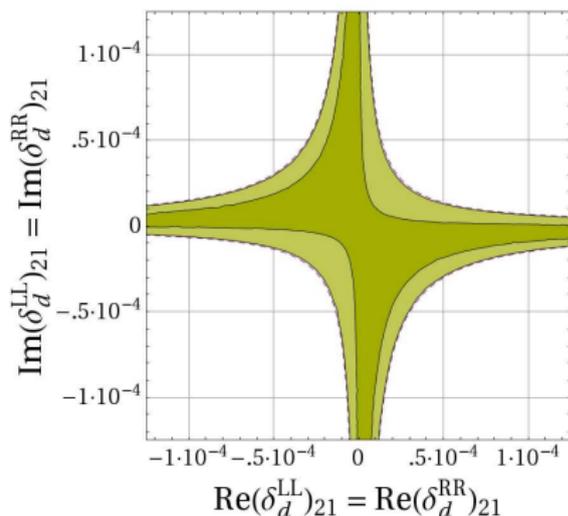


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Buras et al. '00

D'Ambrosio, Giudice, Isidori, Strumia '02

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(partial) Decoupling

▶ Split SUSY

Arkani-Hamed, Dimopoulos '04;
Giudice, Romanino '04

▶ squarks are decoupled

▶ Effective SUSY

Cohen, Kaplan, Nelson '96

▶ hierarchical sfermion spectrum, with heavy 1st and 2nd generation

How to Address the SUSY Flavor Problem

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- ▶ quark and squark masses are approximately aligned
 $\rightarrow \delta_{ij} \ll 1, i \neq j$
- ▶ naturally realized in abelian flavor models

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Degeneracy Dimopoulos, Georgi '81

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

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

$$m_Q^2 = \tilde{m}_Q^2 \left(1 + b_1 V^\dagger \hat{Y}_u^2 V + b_2 \hat{Y}_d^2 + b_3 \hat{Y}_d^2 V^\dagger \hat{Y}_u^2 V + b_3^* V^\dagger \hat{Y}_u^2 V \hat{Y}_d^2 \right)$$

$$m_U^2 = \tilde{m}_U^2 \left(1 + b_4 \hat{Y}_u^2 \right), \quad A_u = \tilde{A}_u \left(1 + b_6 V^* \hat{Y}_d^2 V^\dagger \right) \hat{Y}_u$$

$$m_D^2 = \tilde{m}_D^2 \left(1 + b_5 \hat{Y}_d^2 \right), \quad A_d = \tilde{A}_d \left(1 + b_7 V^\dagger \hat{Y}_u^2 V^* \right) \hat{Y}_d$$

- ▶ **CKM matrix** is the only **source of flavor violation**
- ▶ Flavor Changing Neutral Currents naturally suppressed

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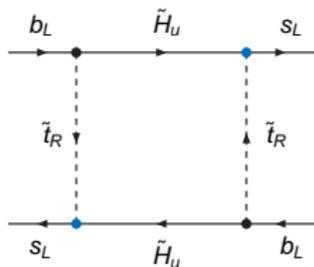
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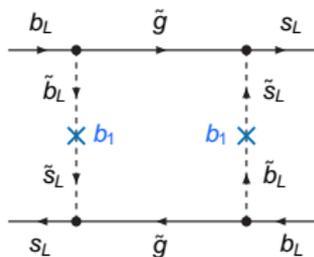
- ▶ **CKM matrix** is the only **source of flavor violation**
- ▶ Flavor Changing Neutral Currents naturally suppressed
- ▶ additional **sources of CP violation** are in principle allowed!
(M_1 , M_2 , $M_{\tilde{g}}$, μ , \tilde{A}_u , \tilde{A}_d , b_3 , b_6 , b_7)
- ▶ what is their impact on CP violation 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)

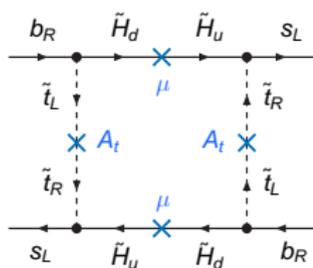


$$\propto \frac{\alpha_2^2}{\tilde{m}^2} (V_{tb} V_{ts}^*)^2$$

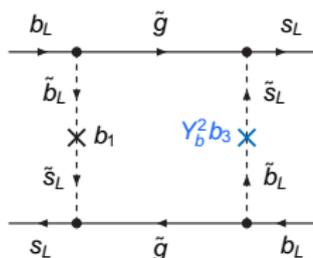


$$\propto \frac{\alpha_s^2}{\tilde{m}^2} b_1^2 (V_{tb} V_{ts}^*)^2$$

MFV Box Contributions to B_s Mixing (II)



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

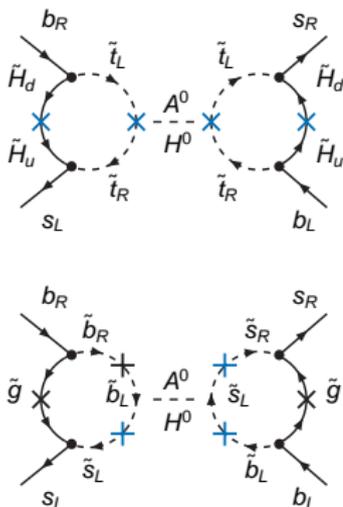


$$\propto \frac{\alpha_s^2}{\tilde{m}^2} (V_{tb} V_{ts}^*)^2 \left[\frac{m_b^2}{M_W^2} \tan^2 \beta b_1 b_3 \right], \dots$$

- ▶ 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** ?

Double Penguins in the MFV MSSM (I)

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



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

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

- also **no sensitivity** to flavor diagonal CP phases at the leading order
- **possibility to have CPV** through a **complex b_3**

Double Penguins in the MFV MSSM (II)

- ▶ 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)

$$m_b = y_b v_d$$

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

$$\sim m_b (\epsilon_b^{\tilde{g}} + \epsilon_b^{\tilde{H}} + \dots) \tan \beta$$

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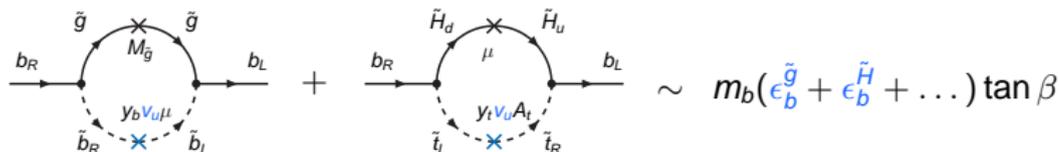
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$$\tan^4\beta \rightarrow \frac{\tan^4\beta}{|1 + \epsilon_b t_\beta|^2 |1 + \epsilon_b^0 t_\beta|^2}$$

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

- ▶ But: possible difference in ϵ_b and ϵ_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)

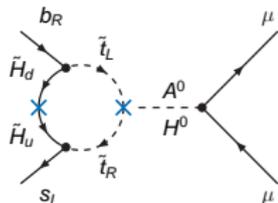
Strong Constraints from $B_s \rightarrow \mu^+ \mu^-$

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

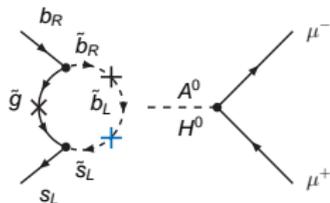
CDF

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

- ▶ $B_s \rightarrow \mu^+ \mu^-$ amplitude is strongly helicity suppressed in the SM
- ▶ for large $\tan \beta$ huge enhancement possible (orders of magnitude)



$$\sim \frac{\alpha_2}{4\pi} \frac{m_t^2}{M_W^2} \frac{1}{M_A^2} \frac{A_{t\mu}}{\tilde{m}^2} \tan^3 \beta \frac{m_b m_\mu}{M_W^2} V_{tb} V_{ts}^*$$



$$\sim \frac{\alpha_s}{4\pi} \frac{1}{M_A^2} \frac{\mu M_{\tilde{g}}}{\tilde{m}^2} \tan^3 \beta (b_1 + Y_b^2 b_3) \frac{m_b m_\mu}{M_W^2} V_{tb} V_{ts}^*$$

Strong Constraints from $b \rightarrow s\gamma$

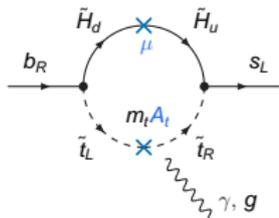
$$\text{BR}(B \rightarrow X_s \gamma)^{\text{exp}} = (3.52 \pm 0.25) \times 10^{-4}$$

HFAG

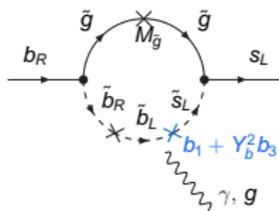
$$\text{BR}(B \rightarrow X_s \gamma)^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$

Misiak et al. '06

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



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



$$C_{7,8}^{\tilde{g}} \sim \frac{\alpha_s}{4\pi} \frac{1}{\tilde{m}^2} \frac{\mu M_{\tilde{g}}}{\tilde{m}^2} \tan \beta (b_1 + Y_b^2 b_3) V_{tb} V_{ts}^*$$

Strong Constraints from Electric Dipole Moments

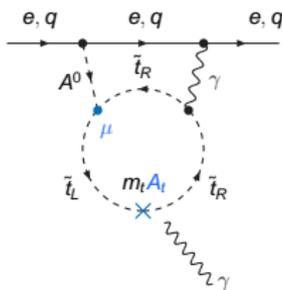
$$d_e^{\text{exp}} \lesssim 1.6 \times 10^{-27} \text{ ecm}$$

$$d_e^{\text{SM}} \simeq 10^{-38} \text{ ecm}$$

$$d_n^{\text{exp}} \lesssim 2.9 \times 10^{-26} \text{ ecm}$$

$$d_n^{\text{SM}} \simeq 10^{-32} \text{ ecm}$$

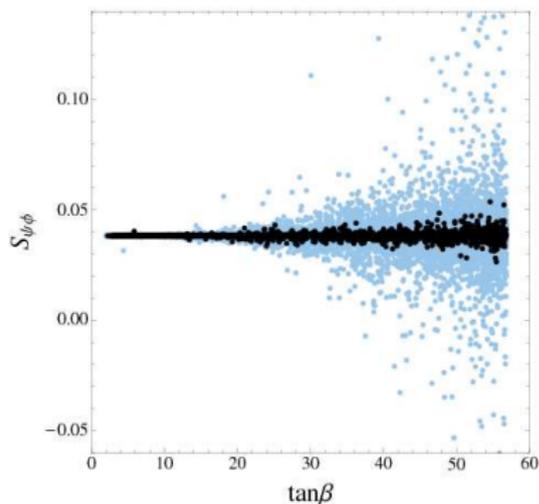
- ▶ In the MSSM, EDMs can be induced already at the **1loop level**
→ tight constraints on CP violating phases of **gaugino and Higgsino masses**
- ▶ phases of 3rd generation **trilinear couplings** $A_{t,b,\tau}$ remain basically **unconstrained at 1loop**
- ▶ important **2loop Barr-Zee type diagrams**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



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

$$d_d^{(c)} \propto \frac{\alpha_s}{4\pi} \frac{m_d}{16\pi^2} \tan \beta \sum_{f=t,b} Y_f^2 \frac{\text{Im}(\mu A_f)}{\tilde{m}^4}$$

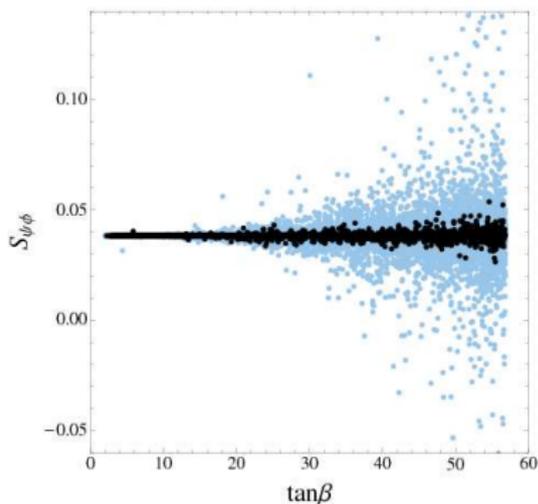
A Large B_s Mixing Phase in the MFV MSSM?



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 $S_{\psi\phi}$, $S_{\psi K_S}$ and ϵ_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**

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

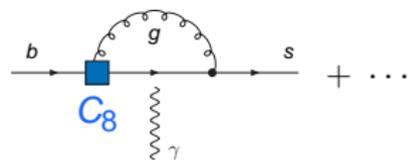
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- direct CP asymmetry in $B \rightarrow X_s \gamma$, $A_{CP}^{bs\gamma}$

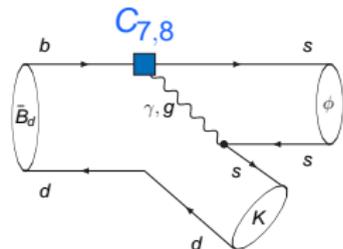
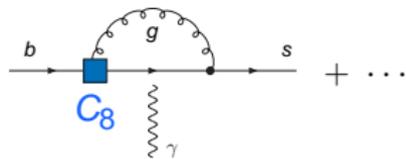
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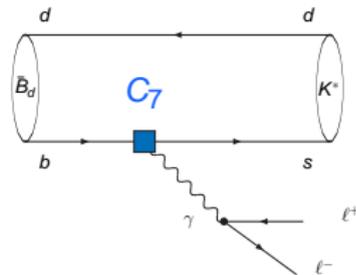
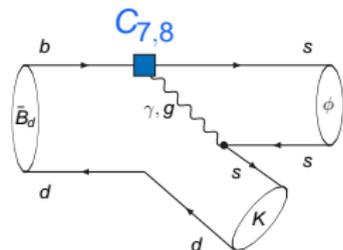
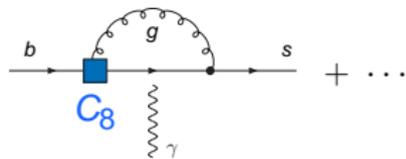
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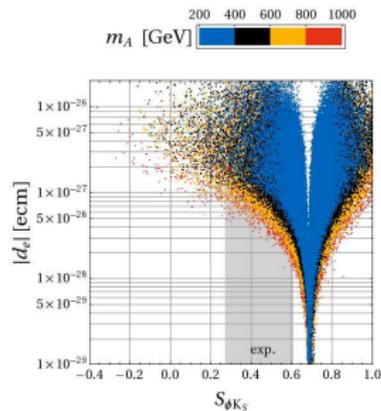
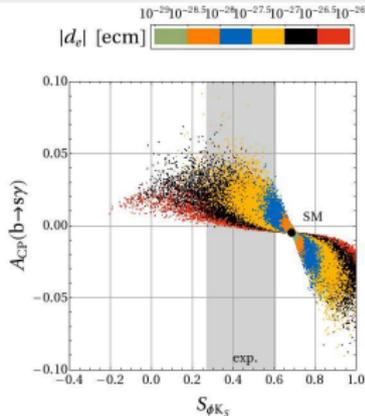
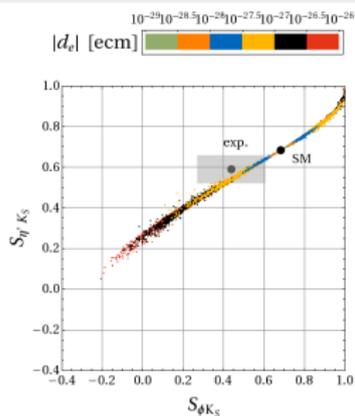
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 - angular observables in $B \rightarrow K^* \ell^+ \ell^-$

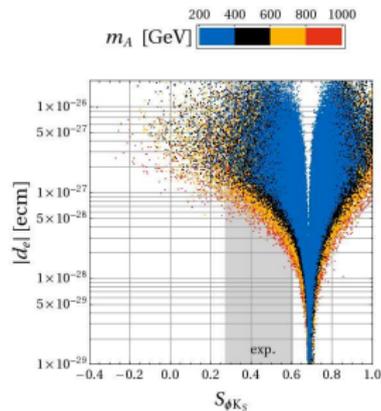
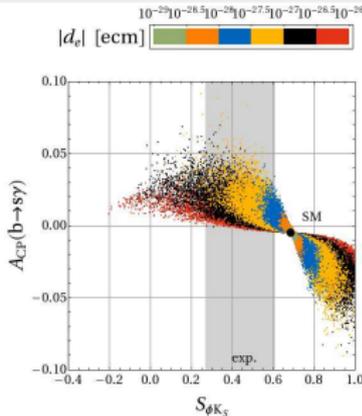
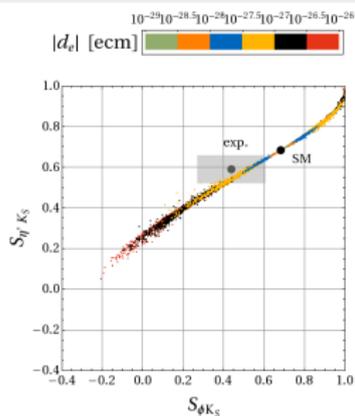


Low Energy Probes of CPV in the MFV MSSM (II)



- ▶ $S_{\phi K_S}$ and $S_{\eta' K_S}$ 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 $d_{e,n} \gtrsim 10^{-28}$ ecm
- ▶ large and characteristic effects in the CP asymmetries in $B \rightarrow K^* \mu^+ \mu^-$ (WA, Ball, Bharucha, Buras, Straub, Wick '08)

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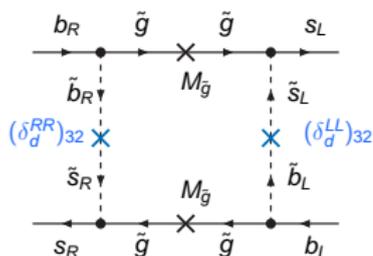


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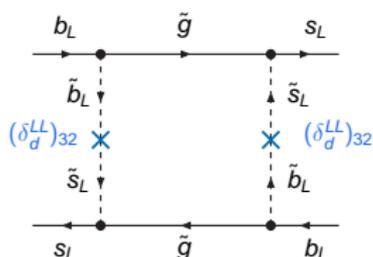
A combined study of all these observables and their correlations constitutes a **very powerful test** of the MFV MSSM with CPV phases

The B_s Mixing Phase Beyond MFV

Glino Box Contributions to B_s Mixing (I)



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



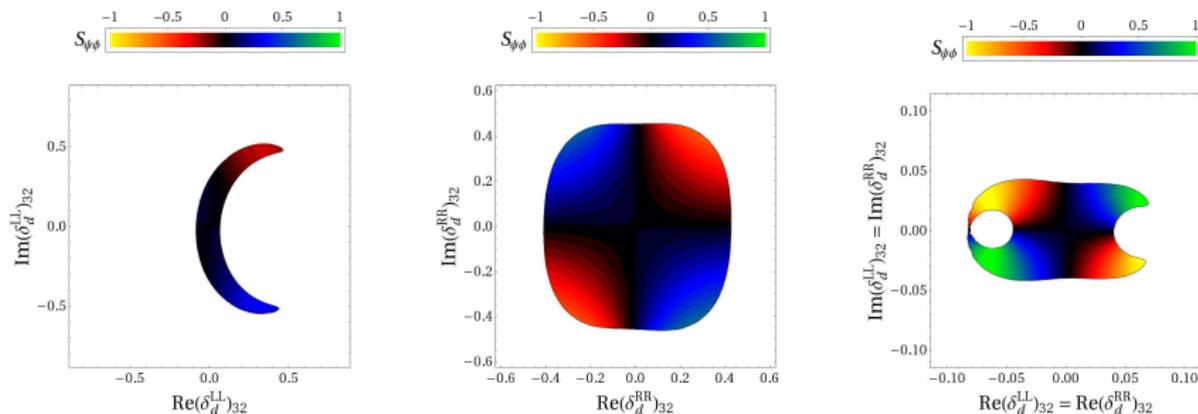
$$\propto \frac{\alpha_s^2}{\tilde{m}^2} (\delta_d^{LL})_{32}^2 (\bar{b} \gamma_\mu P_L s)^2$$

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

- color and RGE enhancement if $(\delta_d^{LL})_{32}$ and $(\delta_d^{RR})_{32}$ present simultaneously

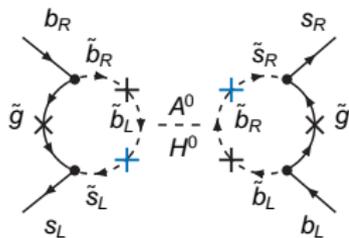
Glino Box Contributions to B_s Mixing (II)

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

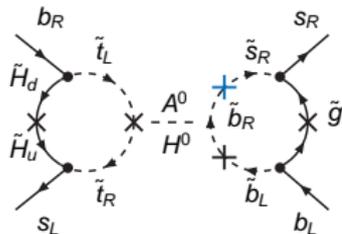


- ▶ large effects in $S_{\psi\phi}$ possible for O(1) RR or LL mass insertions
- ▶ If LL and RR insertions are present simultaneously, large effects in $S_{\psi\phi}$ can be generated even for moderate mass insertions

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 $(\delta_d^{LL})_{32}$ mass insertion of $O(\lambda^2)$ is always induced radiatively
- models that predict a sizable $(\delta_d^{RR})_{32}$ mass insertion are frameworks where a large B_s mixing phase can naturally be generated

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There are many SUSY models where sizable $(\delta_d^{RR})_{32}$ 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 $SU(3)$
- ▶ 1st and 2nd generation of squarks approximately degenerate

$$(\delta_d^{LL}) \sim \begin{pmatrix} \lambda^4 & \lambda^5 & \lambda^3 \\ \lambda^5 & \lambda^4 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$(\delta_d^{RR}) \sim \begin{pmatrix} \lambda^3 & \lambda^4 & \lambda^3 \\ \lambda^4 & \lambda^3 & \lambda \\ \lambda^3 & \lambda & 1 \end{pmatrix}$$

Expected phenomenology:

- ▶ Moderate effects in $b \rightarrow d$ and $s \rightarrow d$ transitions (strongest constraint from ϵ_K)
- ▶ Small effects in D_0 - \bar{D}_0 mixing
- ▶ Sizeable effects in B_s - \bar{B}_s mixing

Concrete Example: A non-abelian Flavor Model

Example: Ross, Velasco-Sevilla, Vives '04 (RVV)

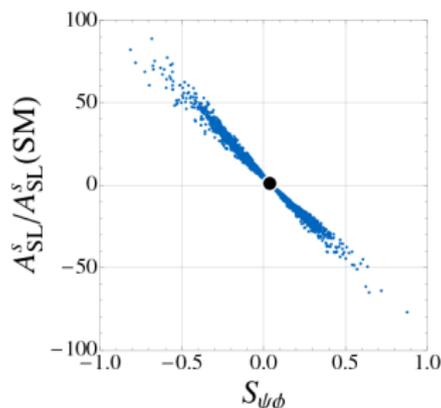
- ▶ non-abelian flavor model based on $SU(3)$
- ▶ 1st and 2nd generation of squarks approximately degenerate

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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_{SL}^s (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”

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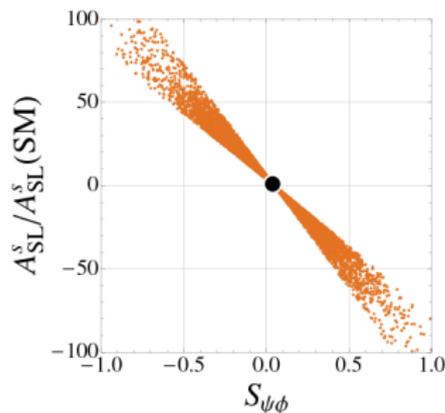
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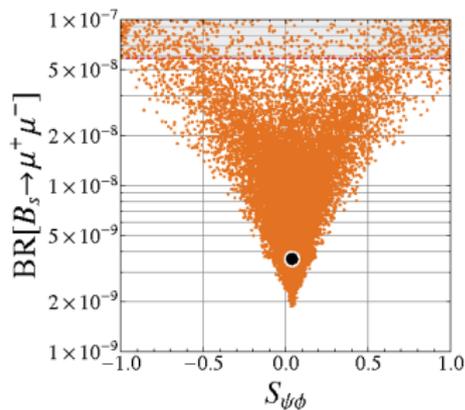
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- ▶ strong (model independent) correlation with the semileptonic asymmetry a_{SL}^s
- ▶ double penguins dominate \Rightarrow lower bound on $BR(B_s \rightarrow \mu^+ \mu^-)$ at the level of 10^{-8} (WA, Buras, Gori, Paradisi, Straub '09)

CPV in D^0 Mixing and EDMs in SUSY Alignment Models

A Generic Prediction of Abelian Flavor Models

$SU(2)_L$ invariance implies a **relation between LL mass insertions** in the up and down sector

$$(\delta_u^{LL}) = V^* (\delta_d^{LL}) V^T$$

$$(\delta_u^{LL})_{21} = (\delta_d^{LL})_{21} + \lambda \left(\frac{m_{\tilde{c}_L}^2}{\tilde{m}^2} - \frac{m_{\tilde{u}_L}^2}{\tilde{m}^2} \right)$$

- ▶ abelian flavor models that realize the alignment mechanism ensure $(\delta_d^{LL}) \simeq 0$
- ▶ **irreducible flavor violating term** $(\delta_u^{LL})_{21} \sim \lambda$ in the up sector for natural $\mathcal{O}(1)$ splitting of squark masses

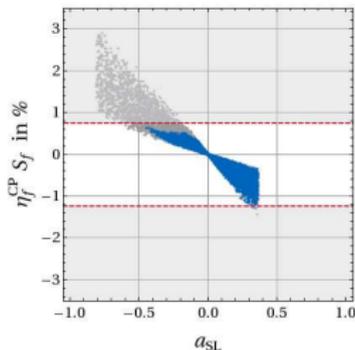
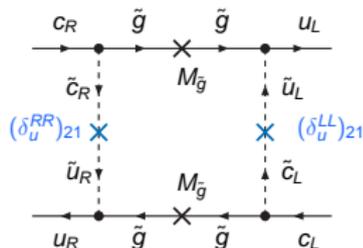
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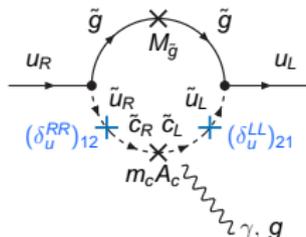
- ▶ **immediate consequence:** Large NP effects in $D^0 - \bar{D}^0$ mixing (Nir, Seiberg '93)
- ▶ already for tiny complex $\delta_u^{RR} \sim \lambda^3$ large CP violation in $D^0 - \bar{D}^0$ mixing

$$\text{Im } M_{12}^D \propto \text{Im} \left[(\delta_u^{LL})_{21} (\delta_u^{RR})_{21} \right]$$

- ▶ current experimental bounds are easily reached

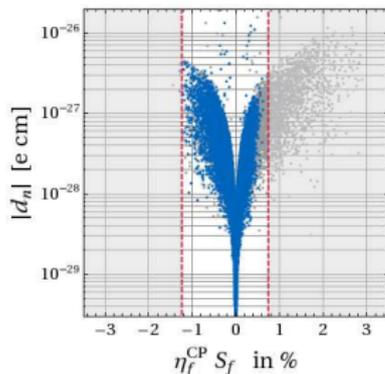
Correlation with Electric Dipole Moments

- ▶ a complex $(\delta_u^{RR})_{21}$ leads also to a **up quark EDM** by means of **flavor effects**



$$d_u^{(c)} \propto \text{Im} \left[(\delta_u^{LL})_{21} (\delta_u^{RR})_{21} \right]$$

- ▶ 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



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

$$d_n \gtrsim 10^{-(28-29)} \text{ e cm}$$

$$d_{\text{Hg}} \gtrsim 10^{-(30-31)} \text{ e cm}$$

- ▶ interesting level for expected future experimental resolutions

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

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 - CP Violation in $D^0 - \bar{D}^0$ mixing implies lower bounds on hadronic EDMs
- ▶ 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

Back Up

“Flavor DNA”

	MFVMSSM	GMSSM	AC	RVV	SSU(5) _{RN} ^(*)	RSc ^(**)
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

(*) 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