CP Violation in B_s Mixing in Supersymmetric Models

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Fermilab

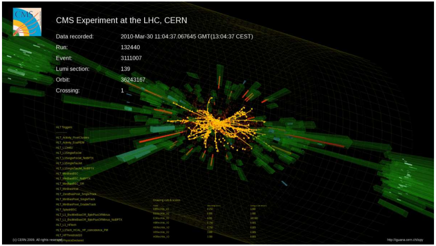
Particle Theory Seminar

Cornell University
December 8, 2010

Outline

- WA, A.J. Buras and P. Paradisi
  Phys. Lett. B **669** (2008) 239
- 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

High Energy vs. Low Energy



High Energy Frontier

- direct production
  of new particles
- Collider Physics
- determine the NP energy scale

LHC, Tevatron

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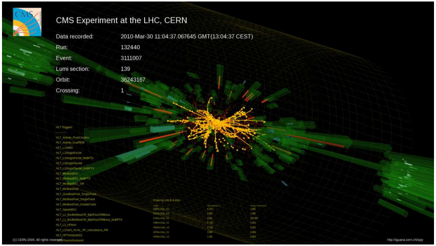

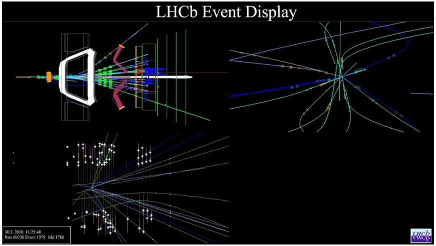

High Energy Frontier

- direct production of new particles
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High Intensity/Precision Frontier

- new particles probed through quantum corrections
- e.g. Flavor Physics
- determine the NP flavor structure

(Super-) B factories, LHCb, Tevatron, ...

Low Energy Probes of Flavor and CP Violation (I)

Observables that lead to strong constraints on NP models

- $\Delta F = 2$: Observables in Neutral Meson Mixing

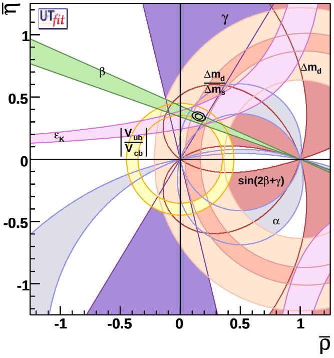
  mass differences: ΔM_K, ΔM_D, ΔM_d, ΔM_s
  CP violating observables: ϵ_K, ϕ_D, $|p/q|_D$, $S_{\psi K_S}$

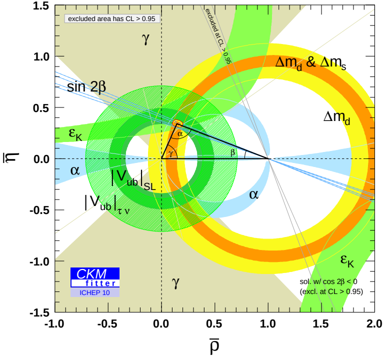
- $\Delta F = 1$: Rare Decays

  $\mathrm{BR}(B \to X_s \gamma)$
  $\mathrm{BR}(B \to X_s \ell^+ \ell^-)$
  $\mathrm{BR}(B \to \tau \nu)$
  $\mathrm{BR}(B_s \to \mu^+ \mu^-)$
  ...

- $\Delta F = 0$: Electric Dipole Moments

Success of the SM CKM Picture





- CKM matrix is the only source of flavor violation in the SM
- very good overall agreement of the exp. data entering the CKM fits (apart from a 2-3σ discrepancy between $\sin 2\beta$ and BR($B \to \tau\nu$))
- 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}	Δm_K; ϵ_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}	Δm_K; ϵ_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}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{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}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	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

Low Energy Probes of Flavor and CP Violation (II)

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

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- time dep. CP asymmetries S_f^D
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- of the electron d_e
- of hadronic systems d_n, $d_{\rm Hg}$

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(very) rare decays

- $B_{s,d} \rightarrow \mu^+\mu^-$ (LHCb)
- $B \rightarrow K^{(*)}\nu\bar{\nu}$ (superB)
- $K \rightarrow \pi\nu\bar{\nu}$ (NA62, K0TO)

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CP Violation in $b \rightarrow s$ transitions

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

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

- Definition:

$$A^b_{\rm SL} = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

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

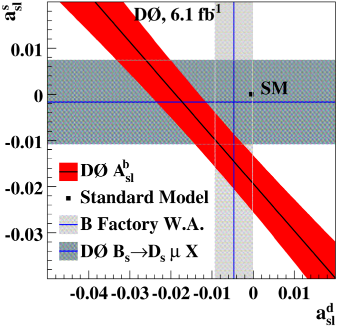
- 3.2σ discrepancy between SM prediction and recent D0 measurement

$$A^b_{\rm SL}({\rm SM}) = \left(-0.23^{+0.05}_{-0.06}\right) \times 10^{-3}$$

(Lenz, Nierste '06)

$$A^b_{\rm SL}({\rm exp}) = (-9.57 \pm 2.51 \pm 1.46) \times 10^{-3}$$

(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:

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

B_s Mixing Basics

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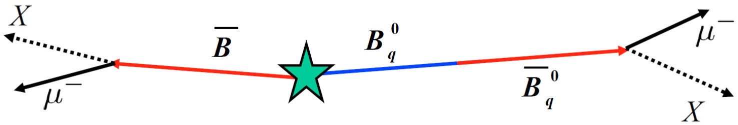
Observables:

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

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

Like-Sign Dimuon Charge Asymmetry



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N_b^{++}: Number of same sign $\mu^+\mu^+$ events from $B \to \mu X$ decays
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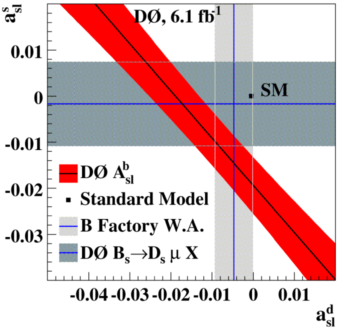
- Relation to the semileptonic asymmetry

$$A^b_{SL} = (0.506{\pm}0.043)\, a^d_{SL} + (0.494{\pm}0.043)\, a^s_{SL}$$

(D0, arXiv:1005.2757)



Time Dependent CP Asymmetry

- CP violation in interference between decays with and without mixing

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

- 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

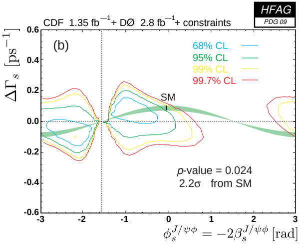
(Ligeti, Papucci, Perez '06; Blanke, Buras, Guadagnoli, Tarantino '06; Grossman, Nir, Perez '09)

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

The Experimental Situation

Status 2009

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



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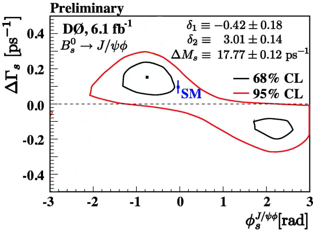
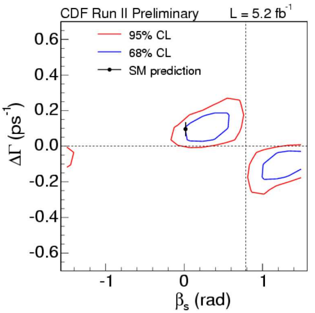


Recent Progress

- updates from CDF and D0 are in better agreement with the SM ($\simeq 1\sigma$)



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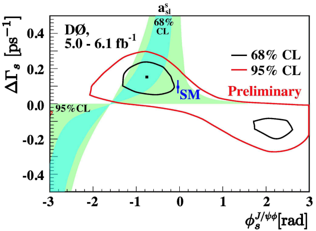
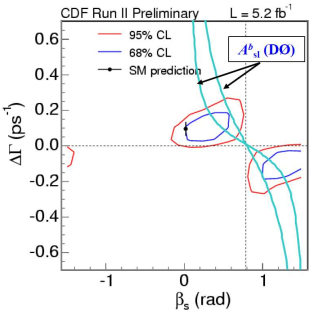
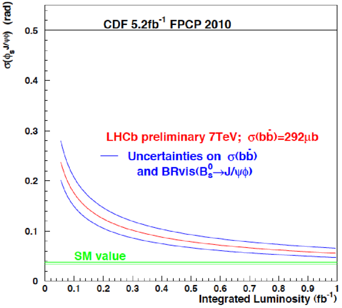


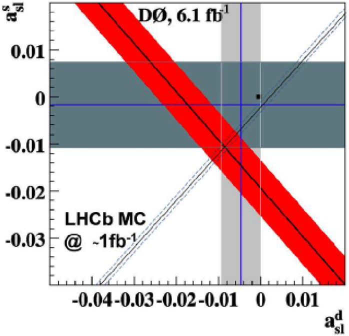
Recent Progress

- updates from CDF and D0 are in better agreement with the SM ($\simeq 1\sigma$)
- new result from D0 on the like sign dimuon charge asymmetry A^b_{SL} 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^s_{SL}

Usual Interpretation of the Experimental Data

- absorptive part Γ_{12} dominated by SM tree level decays

$\Rightarrow$ CP violating short distance contributions to the dispersive part M_{12}

$$M_{12}^s = \Delta_s \, (M_{12}^s)^{\rm SM}$$

- $\Delta M_s = \Delta M_s^{\rm SM} |\Delta_s|$
- $\Delta\Gamma_s = \Delta\Gamma_s^{\rm SM} \cos\left(\text{Arg}(\Delta_s)\right)$
- $a_{\rm SL}^s = \text{Im}\left(\Gamma_{12}^s / [(M_{12}^s)_{\rm SM} \Delta_s]\right)$
- $S_{\psi\phi} = \sin\left(2|\beta_s| - \text{Arg}(\Delta_s)\right)$

$$M_{12}^s = \left(1 + h_s e^{2i\sigma_s}\right) (M_{12}^s)^{\rm SM}$$

- $\Delta M_s = \Delta M_s^{\rm SM} |1 + h_s e^{2i\sigma_s}|$
- $\Delta\Gamma_s = \Delta\Gamma_s^{\rm SM} \cos\left(\text{Arg}(1 + h_s e^{2i\sigma_s})\right)$
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Large New Physics in B_s Mixing

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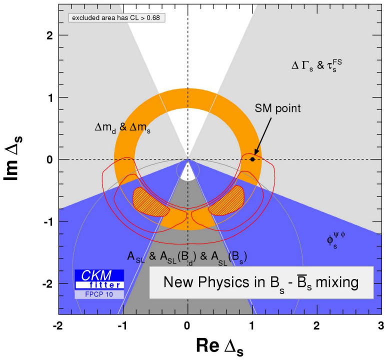
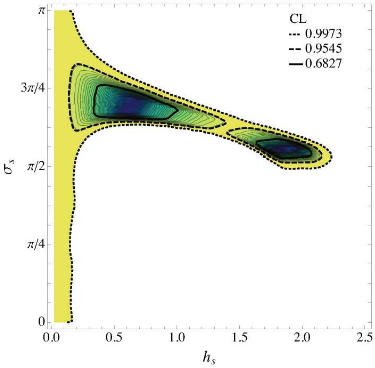


Lenz, Nierste + CKMfitter ’10



Ligeti, Papucci, Perez, Zupan ’10

How to get Large NP Contributions in B_s Mixing?

- general MSSM
  Ciuchini et al.; Goto et al.;
  WA, Buras, Gori, Paradisi, Straub '09;
  Crivellin, Nierste '09;
  Ko, Park '10; Parry '10; ...
- SUSY GUTs
  Hisano, Shimizu '08;
  Dutta, Mimura, Santoso '10;
  Buras, Paradisi, Nagai '10; ...
- SUSY Flavor Models
  WA, Buras, Gori, Paradisi, Straub '09;
  King '10; ...
- Uplifted SUSY
  Dobrescu, Fox, Martin '10
- Minimal Flavor Violation
  Batell, Pospelov '10;
  Blum, Hochberg, Nir '10
- 2 Higgs Doublet Models
  Jung, Pich, Tuzon '10;
  Buras, Carlucci, Gori, Isidori '10;
  Buras, Isidori, Paradisi '10;
- 4th Generation
  Hou et al.; Soni et al.;
  Buras et al. '10
- Warped Extra Dimensions
  Blanke et al.; Neubert et al. '09
- Little Higgs
  Blanke et al.
- Z'
  Barger et al. '09, ...
- ...

Phenomenology of CP Violation in SUSY Models

The 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:

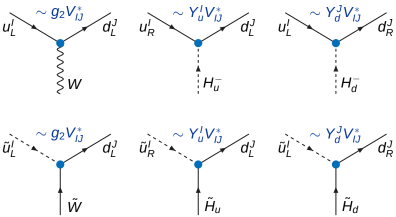
  1. Yukawa couplings: Y_u, Y_d
  2. soft masses: $\tilde{m}_Q^2$, $\tilde{m}_D^2$, $\tilde{m}_U^2$
  3. trilinear couplings: $\tilde{A}_u$, $\tilde{A}_d$

- 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

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

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

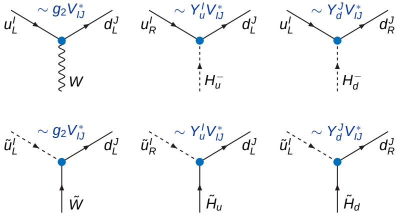
The MSSM Flavor Structure (II)



misalignment between up quarks and down quarks in flavor space

- ► CKM matrix

$\rightarrow$ appears in W and Higgs charged currents and their supersymmetrized versions



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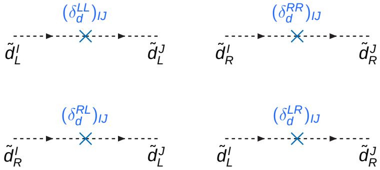

misalignment between quarks and squarks in flavor space

- ▶ Mass Insertions

$\rightarrow$ parameterize the off-diagonal parts of the squark masses

$$M^2_{\tilde{q}} = \tilde{m}^2(\mathbb{1} + \delta_q)$$

$\rightarrow$ most transparent treatment in the Mass Insertion Approximation

$\rightarrow$ flavor change through mass insertions along squark propagators

The SUSY Flavor Problem

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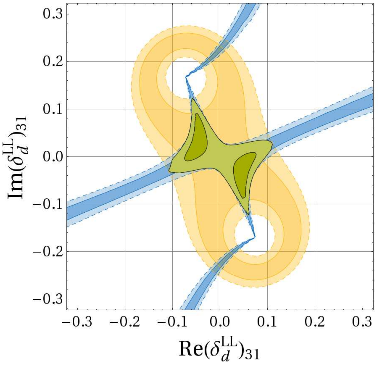
- severe constraints on the SUSY scale $\tilde{m}$ and the Mass Insertions δs from meson mixing and rare decays like $B \to X_s \gamma$ and $B \to X_s \ell^+ \ell^-$
- for all δs of $\mathcal{O}(1)$, the SUSY scale has to be extremely high $\tilde{m} \gtrsim 10^4$ TeV
- SUSY at the TeV scale has to exhibit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



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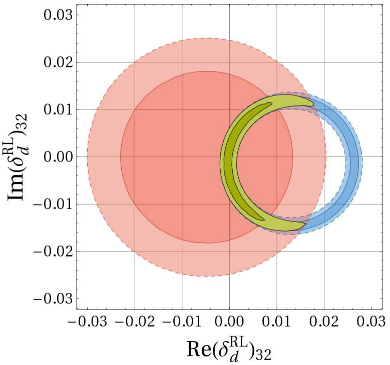

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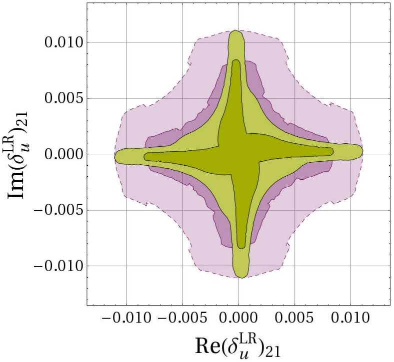

$\tan\beta = 5\,, \quad \tilde{m} = M_{\tilde{g}} = 500\text{GeV}$

The SUSY Flavor Problem

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

- severe constraints on the SUSY scale $\tilde{m}$ and the Mass Insertions δs from meson mixing and rare decays like $B \to X_s \gamma$ and $B \to X_s \ell^+ \ell^-$
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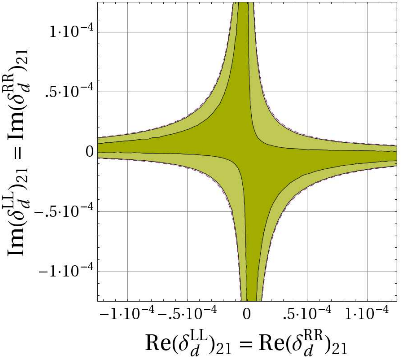

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How to Address the SUSY Flavor Problem

Minimal Flavor Violation

Buras et al. '00

D'Ambrosio, Giudice, Isidori, Strumia '02

- the global $SU(3)^3$ flavor symmetry of the gauge sector is only broken by the SM Yukawa couplings
- CKM matrix is the only source of flavor violation
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- Split SUSY
  Arkani-Hamed, Dimopoulos '04;
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- squarks are decoupled
- Effective SUSY
  Cohen, Kaplan, Nelson '96
- hierachical sfermion spectrum, with heavy 1st and 2nd generation

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- quark and squark masses are approximately aligned
  $\rightarrow \delta_{ij} \ll 1 \ , \ i \neq j$
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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

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

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

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

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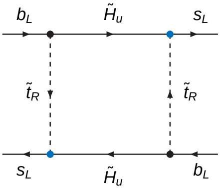
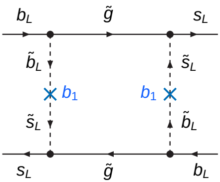
- additional sources of CP violation are in principle allowed!
  $(M_1 \,,\, M_2 \,,\, M_{\tilde{g}} \,,\, \mu \,,\, \tilde{A}_u \,,\, \tilde{A}_d \,,\, b_3 \,,\, b_6 \,,\, b_7)$
- what is their impact on CP violation in meson mixing?

MFV Box Contributions to B_s Mixing (I)

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

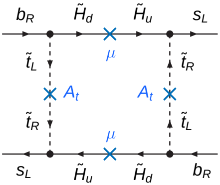


$$\propto \frac{\alpha_2^2}{\tilde{m}^2} (V_{tb} V_{ts}^*)^2$$

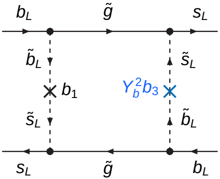


$$\propto \frac{\alpha_s^2}{\tilde{m}^2} b_1^2 (V_{tb} V_{ts}^*)^2$$

MFV Box Contributions to B_s Mixing (II)



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



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

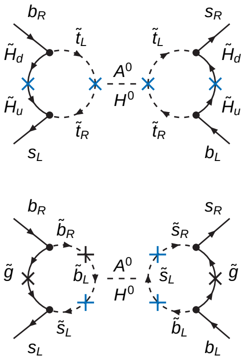
- CP violating contributions are suppressed by at least two powers of the bottom Yukawa Y_b^2

  (WA, Buras, Gori, Paradisi, Straub ’09; Blum, Hochberg, Nir ’10)

- might be relevant in the large $\tan\beta$ regime ?

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)



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

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

- 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 β resummation factors which come from a modified relation between the fermion masses and Yukawa couplings in the large tan β regime (Hall, Rattazzi, Sarid '93)

$$m_b = y_b v_d$$

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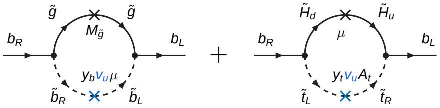

$$\sim \; m_b(\epsilon_b^{\tilde{g}} + \epsilon_b^{\tilde{H}} + \ldots)\tan\beta$$

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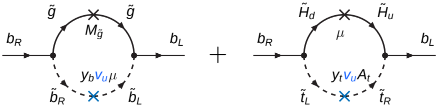

$$\sim \quad m_b(\epsilon_b^{\tilde{g}} + \epsilon_b^{\tilde{H}} + \ldots) \tan\beta$$

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

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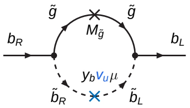

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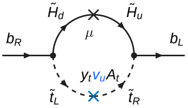


$$\sim \; m_b(\epsilon_b^{\tilde{g}} + \epsilon_b^{\tilde{H}} + \ldots) \tan\beta$$

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

- 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

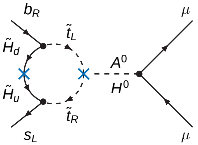
  (Hofer, Nierste, Scherer '09; Dobrescu, Fox, Martin '10)

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

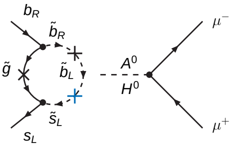
$$\text{BR}(B_s \to \mu^+\mu^-)^{\text{exp}} < 4.3 \times 10^{-8} \qquad \text{CDF}$$

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

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



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



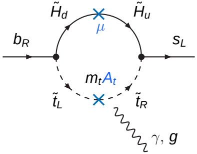
$$\sim \frac{\alpha_s}{4\pi}\frac{1}{M_A^2}\frac{\mu M_{\tilde{g}}}{\tilde{m}^2}\tan^3\beta\,(b_1 + Y_b^2 b_3)\,\frac{m_b m_\mu}{M_W^2}\,V_{tb}V_{ts}^*$$

Strong Constraints from $b \to s\gamma$

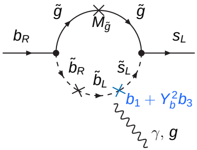
$$\text{BR}(B \to X_s\gamma)^{\text{exp}} = (3.52 \pm 0.25) \times 10^{-4}$$ HFAG

$$\text{BR}(B \to X_s\gamma)^{\text{SM}} = (3.15 \pm 0.23) \times 10^{-4}$$ Misiak et al. '06

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



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



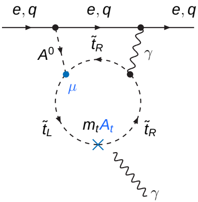
$$\mathcal{C}_{7,8}^{\tilde{g}} \sim \frac{\alpha_s}{4\pi}\frac{1}{\tilde{m}^2}\frac{\mu M_{\tilde{g}}}{\tilde{m}^2}\tan\beta\,(b_1 + Y_b^2 b_3)\, V_{tb}V_{ts}^*$$

Strong Constraints from Electric Dipole Moments

$$d_e^{\rm exp} \lesssim 1.6 \times 10^{-27} e{\rm cm}$$
$$d_e^{\rm SM} \simeq 10^{-38} e{\rm cm}$$

$$d_n^{\rm exp} \lesssim 2.9 \times 10^{-26} e{\rm cm}$$
$$d_n^{\rm SM} \simeq 10^{-32} e{\rm cm}$$

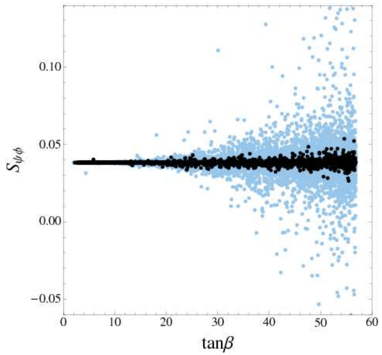
- In the MSSM, EDMs can be induced already at the 1loop level
  $\rightarrow$ tight constraints on CP violating phases of gaugino and Higgsino masses
- phases of 3rd generation trilinear couplings $A_{t,b,\tau}$ remain basically unconstrained at 1loop
- important 2loop Barr-Zee type diagrams that involve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



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

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

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 BR($B \to X_s\gamma$) and BR($B_s \to \mu^+\mu^-$) and the EDMs

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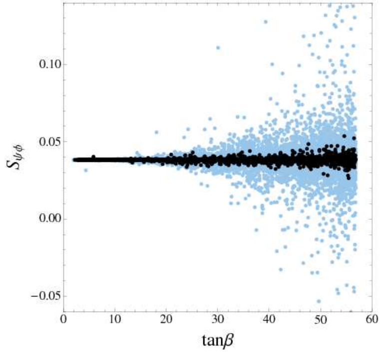

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- some effects in $S_{\psi\phi}$ might still be possible in the uplifted SUSY region with $\tan\beta \simeq O(100-200)$
  (Dobrescu, Fox '10; Dobrescu, Fox, Martin '10)
- But: such a scenario is strongly constrained by B physics observables, $(g-2)_\mu$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

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

- The MFV principle is intended to naturally suppress FCNC effects
- Naturally, large NP effects only show up in helicity suppressed processes

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

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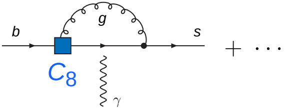

- Best low energy probes of CP Violation in the MFV MSSM are EDMs and observables sensitive to CPV in the $b \to s\gamma$ transition (WA, Buras, Paradisi '08)

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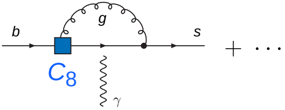

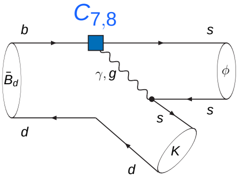

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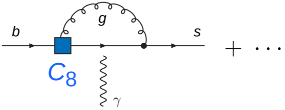
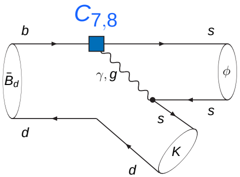
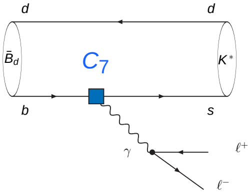
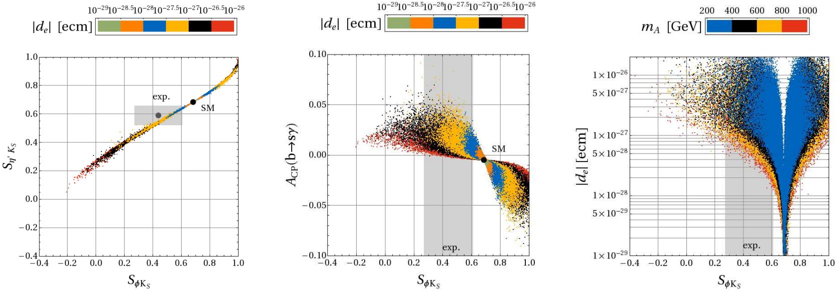
$\to$ angular observables in $B \to K^*\ell^+\ell^-$





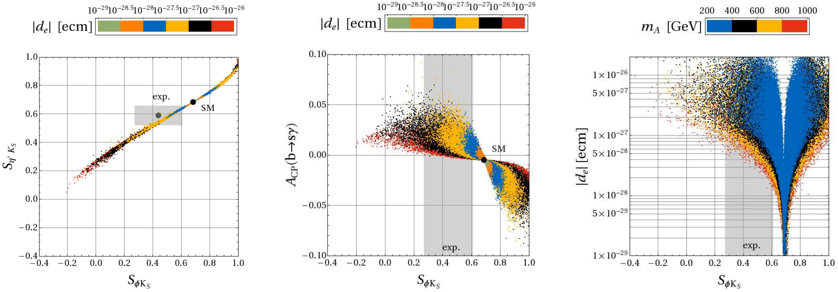


Low Energy Probes of CPV in the MFV MSSM (II)



- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}(b \to s\gamma) \simeq 0\% - 5\%$
- 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 $B \to K^* \mu^+ \mu^-$

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

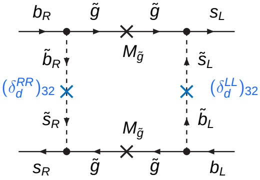


- $S_{\phi K_S}$ and $S_{\eta' K_S}$ can simultaneously be brought in agreement with the data
- sizeable and correlated effects in $A_{CP}(b \to s\gamma) \simeq 0\% - 5\%$
- for $S_{\phi K_S} \simeq 0.4$ lower bounds on the electron and neutron EDMs at the level of $d_{e,n} \gtrsim 10^{-28}$ecm
- large and characteristic effects in the CP asymmetries in $B \to K^* \mu^+ \mu^-$

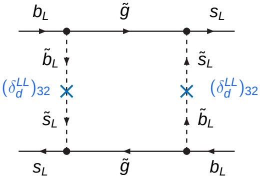
(WA, Ball, Bharucha, Buras, Straub, Wick '08)

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

Beyond MFV



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

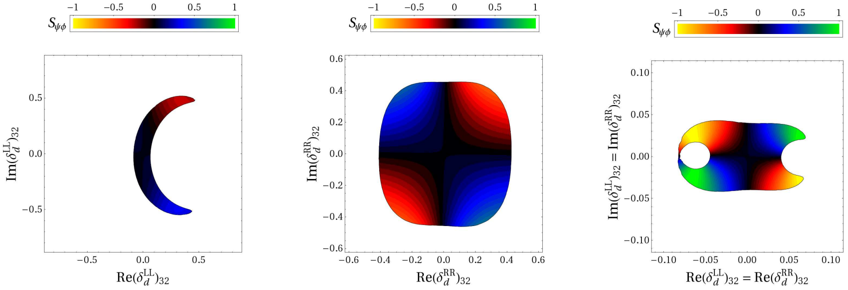


$$\propto \frac{\alpha_s^2}{\tilde{m}^2}(\delta_d^{LL})_{32}^2 \qquad (\bar{b}\gamma_\mu P_L s)^2$$

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

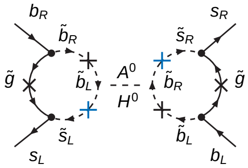
- color and RGE enhancement if $(\delta_d^{LL})_{32}$ and $(\delta_d^{RR})_{32}$ present simultaneously

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

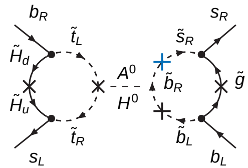


- large effects in $S_{\psi\phi}$ possible for O(1) RR or LL mass insertions
- If LL and RR insertions are present simultaneously, large effects in $S_{\psi\phi}$ can be generated even for moderate mass insertions

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 $\propto m_b m_s$)

$\rightarrow$ 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

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

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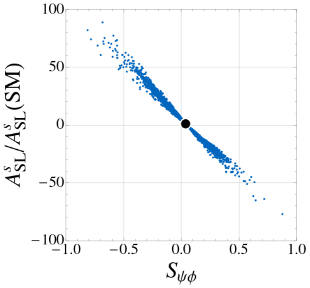

- a large $S_{\psi\phi}$ can be accomodated for in this model
- strong (model independent) correlation with the semileptonic asymmetry a^s_{SL}
  (Ligeti, Papucci, Perez '06
  Grossman, Nir, Perez '09)

Concrete Example: An Abelian Flavor Model

Example: Agashe, Carone '03 (AC)

- abelian flavor model based on a $U(1)$ horizontal symmetry
- "remarkable level of alignment"

$$(\delta_d^{LL}) \sim \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \lambda^2 \\ 0 & \lambda^2 & 1 \end{pmatrix}$$

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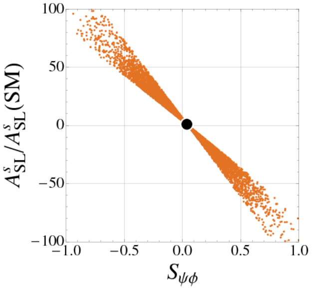

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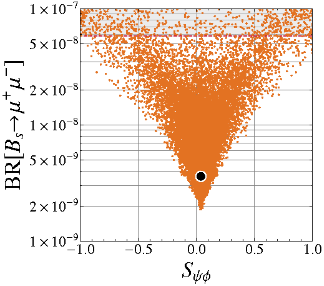

- a large $S_{\psi\phi}$ can easily be accomodated for in this model
- strong (model independent) correlation with the semileptonic asymmetry a_{SL}^s
- double penguins dominate
  $\Rightarrow$ lower bound on $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at the level of 10^{-8}
  (WA, Buras, Gori, Paradisi, Straub '09)

A Generic Prediction of Abelian Flavor Models

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

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

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

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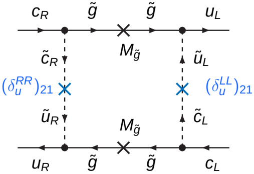
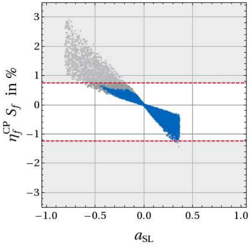




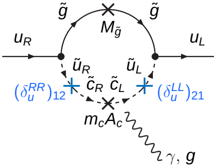
- immediate consequence: Large NP effects in $D^0 - \bar{D}^0$ mixing (Nir, Seiberg '93)
- already for tiny complex $\delta_u^{RR} \sim \lambda^3$ large CP violation in $D^0 - \bar{D}^0$ mixing

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

- 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

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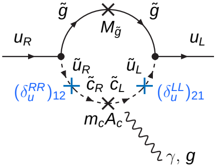

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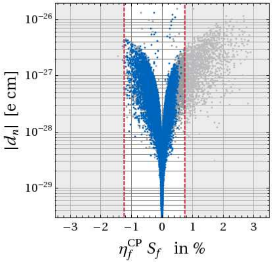

- large CP violation in $D^0 - \bar{D}^0$ mixing in abelian flavor models implies lower bounds on hadronic EDMs (WA, Buras, Paradisi '10)

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

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

- interesting level for expected future experimental resolutions

Summary

- CP violation in $\Delta F = 2$ transitions remains generically SM like in the MFV MSSM (in particular: small effects in the B_s mixing phase)
- best low energy probes of CP violation in the MFV MSSM are EDMs and observables sensitive to CPV in the $b \to s\gamma$ transition
- sizable NP effects in meson mixing can be naturally generated in non-MFV scenarios with large flavor changing right handed currents induced by $(\delta_d^{RR})_{32}$ mass insertions
- if in addition $\tan\beta$ is large, double Higgs penguin contributions to B_s mixing are correlated with the rare decay $B_s \to \mu^+\mu^-$, implying a lower bound on BR($B_s \to \mu^+\mu^-$) at the level of 10^{-8} for $S_{\psi\phi} \simeq 0.5$

“Flavor DNA”

	MFVMSSM	GMSSM	AC	RVV	SSU(5)$_{RN}$ $^{(*)}$	RSc $^{(**)}$
CPV in $D^0 - \bar{D}^0$	★	★★★	★★★	★	★	?
CPV in $B_s - \bar{B}_s$	★	★★★	★★★	★★★	★★★	★★★
$S_{\phi K_S}, S_{\eta' K_S}$	★★★	★★★	★★	★	★★★	?
$A_{CP}(b \to s\gamma)$	★★★	★★★	★	★	★	?
$A_{7,8}(B \to K^* \ell\ell)$	★★★	★★★	★	★	★	?
$A_9(B \to K^* \ell\ell)$	★	★★★	★	★	★	?
$B_{s,d} \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★
$B \to K^{(*)}\nu\bar{\nu}$	★	★★	★	★	★	★
$K \to \pi\nu\bar{\nu}$	★	★★★	★	★	★	★★★
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