Lower Bounds on Hadronic EDMs from CP Violation in D^0-$\bar{D}^0$ Mixing in SUSY Alingment Models

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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) $\rightarrow$ **Discovery Channels**

CP Violation in $b \rightarrow s$ transitions

- B_s mixing phase (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)

(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)

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

(LHCb, superB)

- time dependent CP asymmetries lifetime differences S_f
- semi leptonic asymmetry a_{SL}

Electric Dipole Moments

- of the neutron, deuteron
- of paramagnetic Atoms, Tl
- of diamagnetic Atoms, Hg

Electric Dipole Moments and the SUSY CP Problem

Electric Dipole Moments

$d_{\text{Tl}}^{\text{exp}} \lesssim 9.4 \times 10^{-25} e\text{cm}$

Regan et al. '02

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

Baker et al. '06

$d_{\text{Hg}}^{\text{exp}} \lesssim 3.1 \times 10^{-29} e\text{cm}$

Griffith et al. '09

- SM predictions are many orders of magnitude below the experimental bounds
- experimentally accessible EDMs are induced by EDMs and chromo-EDMs of the electron and the quarks

$$d_{\text{Tl}} \simeq -585\, d_e + \dots$$

$$d_n \simeq 0.7(d_d - 0.25\, d_u) + 0.55 e\, (\tilde{d}_d + 0.5\, \tilde{d}_u) + \dots$$

$$d_{\text{Hg}} \simeq 7 \cdot 10^{-3} e\, (\tilde{d}_u - \tilde{d}_d) + 10^{-2} d_e + \dots$$

- large uncertainties in the above equations for the neutron (50%) and especially for the mercury EDM ($>$ 100%)

The SUSY CP Problem

- the MSSM contains many new sources of CP violation:

$\rightarrow$ flavor diagonal phases of the Higgsino and Gaugino masses $\mu, M_1, M_2, M_{\tilde{g}}$ and of the trilinear couplings A_u, A_d, ...

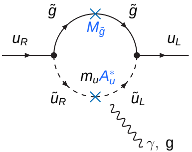
$\rightarrow$ "flavored phases" in the off-diagonal entries of the squark soft masses

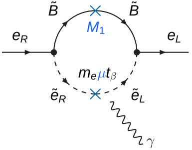
- EDMs can be induced already at the 1loop level

$\rightarrow$ tight constraints on the new phases

see e.g. Ellis, Lee, Pilaftsis '08;

Li, Profumo, Ramsey-Musolf '10





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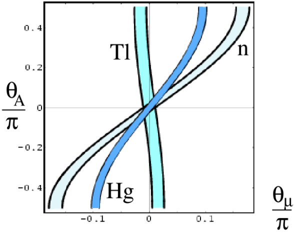
- flavor diagonal phases are constrained to be very close to 0



Pospelov, Ritz '05

$\tan\beta = 3$, $M_{\text{SUSY}} = 500\text{GeV}$

D^0-$\bar{D}^0$ Mixing and the SUSY Flavor Problem

D^0 - $\bar{D}^0$ Mixing Basics

Schrödinger equation describing D^0 - $\bar{D}^0$ mixing:

$$i\partial_t \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M + \frac{i}{2}\Gamma \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Three physical mixing parameter:

$$|M_{12}| \; , \quad |\Gamma_{12}| \; , \quad \phi_{12} = -\text{arg}\left(\frac{M_{12}}{\Gamma_{12}} \right)$$

Eigenstates D_1 and D_2 are linear combinations of D^0 and $\bar{D}^0$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \quad , \quad \frac{q}{p} = \sqrt{\frac{M_{12}{}^* - \frac{i}{2}\Gamma_{12}{}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}} \quad , \quad \phi = \text{Arg}(q/p)$$

CP conservation implies $\phi = 0$ and $|q/p| = 1$

- normalized mass and width differences

$$x = \frac{\Delta M_D}{\Gamma_D} = 2\tau_D \,\mathrm{Re}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

$$y = \frac{\Delta \Gamma_D}{2\Gamma_D} = -2\tau_D \,\mathrm{Im}\left[\frac{q}{p}\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\right]$$

- semileptonic asymmetry

$$a_{\mathrm{SL}} = \frac{\Gamma(D^0 \to K^+\ell^-\nu) - \Gamma(\bar{D}^0 \to K^-\ell^+\nu)}{\Gamma(D^0 \to K^+\ell^-\nu) + \Gamma(\bar{D}^0 \to K^-\ell^+\nu)} = \frac{|q|^4 - |p^4|}{|q|^4 - |p^4|}$$

(asymmetry in the decay to "wrong sign" leptons)

Observables in D^0 - $\bar{D}^0$ Mixing (examples)

- Lifetime differences in decays to final CP eigenstates f

$$\Gamma(D^0 \to f) \propto \exp\left[-\hat{\Gamma}_{D^0\to f}t\right] \quad , \quad \Gamma(\bar{D}^0 \to f) \propto \exp\left[-\hat{\Gamma}_{\bar{D}^0\to f}t\right]$$

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

- S_f is independent of the final state f, if induced only by indirect CP violation in D^0 - $\bar{D}^0$ Mixing

$$\eta_f^{\rm CP} S_f = x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi - y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi$$

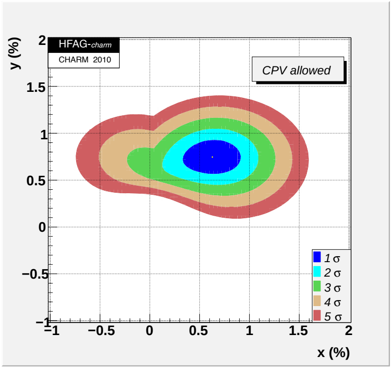
- direct CP violation in the decays can only lead to very small non-universalities $S_f \neq S_{f'}$

The Experimental Situation

- no mixing hypothesis $x = y = 0$ is excluded by more then 10σ
- HFAG result for the mixing parameter

$$x = 0.63^{+0.19}_{-0.20} \;\%$$

$$y = 0.75 \pm 0.12 \;\%$$



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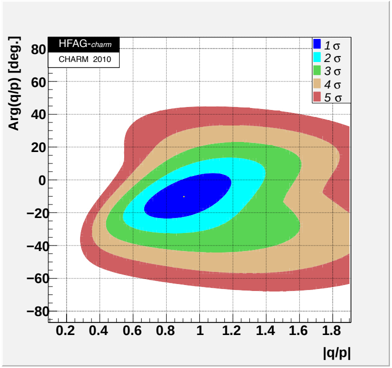
$$x = 0.63^{+0.19}_{-0.20}\ \%$$

$$y = 0.75 \pm 0.12\ \%$$

- no evidence for CP Violation
- $|q/p| = 1$ and $\phi = 0$ is consistent with the data

$$1 - |q/p| = 0.09^{+0.18}_{-0.16}$$

$$\phi = \text{Arg}(q/p) = -10.2^{+9.4}_{-8.9}\ {}^\circ$$



Contributions to D^0 - $\bar{D}^0$ Mixing in SUSY

The MSSM contains many sources of flavor violation in addition to the CKM matrix.
Most convenient parameterization in terms of Mass Insertions δ

$$M_{\tilde{q}}^2 = \tilde{m}^2(\mathbb{1} + \delta_q) \ , \quad \delta_q = \begin{pmatrix} \delta_d^{LL} & \delta_d^{LR} \\ \delta_d^{RL} & \delta_d^{RR} \end{pmatrix}$$

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

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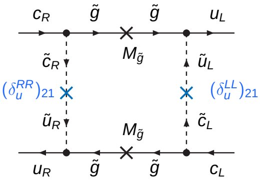


$$\propto \frac{\alpha_s^2}{\tilde{m}^2} (\delta_u^{LL})_{21} (\delta_u^{RR})_{21} \;\; (\bar{c} P_L u)(\bar{c} P_R u)$$

- chiral, color and RGE enhancement if $(\delta_u^{LL})_{21}$ and $(\delta_u^{RR})_{21}$ are present simultaneously

The SUSY Flavor Problem

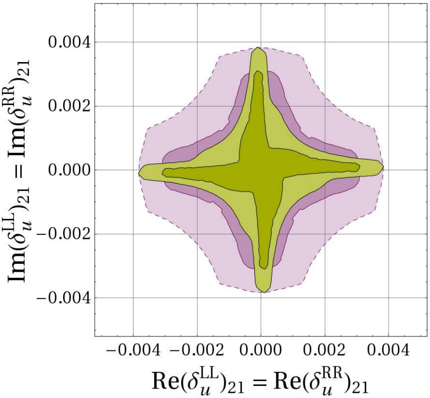
- severe constraints on the Mass Insertions from $D^0 - \bar{D}^0$ mixing
  (and similarly also in the down sector from K, B_d and B_s mixing as well as rare decays like $B \to X_s\gamma$ and $B \to X_s\ell^+\ell^-$)
- for all δs of $\mathcal{O}(1)$, the SUSY scale has to be extremely high $\tilde{m} \gtrsim 10^4$ TeV
- SUSY at the TeV scale has to exhibit a highly non-generic flavor structure

Gabbiani, Gabrielli, Masiero, Silvestrini '96

Ciuchini et al. ; Foster et al.

WA, Buras, Gori, Paradisi, Straub '09

...



$\tilde{m} = M_{\tilde{g}} = 500\text{GeV}$

Correlation between EDMs and D^0-$\bar{D}^0$ Mixing in SUSY Alignment Models

Mass Insertions in Alignment Models

Alignment models use flavor symmetries to align quark and squark masses, such that both can be (approximately) diagonalized simultaneously (Nir, Seiberg '93)

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$$
\begin{aligned}
(\delta_d^{LL})_{21} &= \lambda^5 \div \lambda^3 & \qquad (\delta_d^{RR})_{21} &= \lambda^7 \div \lambda^3 \\
(\delta_u^{LL})_{21} &= \lambda & \qquad (\delta_u^{RR})_{21} &= \lambda^4 \div \lambda^2 \\
(\delta_d^{LL})_{31} &= \lambda^3 & \qquad (\delta_d^{RR})_{31} &= \lambda^7 \div \lambda^3 \\
(\delta_d^{LL})_{32} &= \lambda^2 & \qquad (\delta_d^{RR})_{32} &= \lambda^4 \div \lambda^2
\end{aligned}
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$$\begin{aligned} (\delta_d^{LL})_{21} &= \lambda^5 \div \lambda^3 & (\delta_d^{RR})_{21} &= \lambda^7 \div \lambda^3 \\ (\delta_u^{LL})_{21} &= \lambda & (\delta_u^{RR})_{21} &= \lambda^4 \div \lambda^2 \\ (\delta_d^{LL})_{31} &= \lambda^3 & (\delta_d^{RR})_{31} &= \lambda^7 \div \lambda^3 \\ (\delta_d^{LL})_{32} &= \lambda^2 & (\delta_d^{RR})_{32} &= \lambda^4 \div \lambda^2 \end{aligned}$$

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

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

- irreducible flavor violating term $(\delta_u^{LL})_{21} \sim \lambda$ in the up sector for natural $\mathcal{O}(1)$ splitting of squark masses and $(\delta_d^{LL})_{21} \ll 1$
- note: $(\delta_u^{LL})_{21}$ is real to a very good approximation

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

- consequence of $(\delta_u^{LL})_{21} \sim \lambda$:
  large NP effects
  in $D^0 - \bar{D}^0$ mixing
  (Nir, Seiberg '93)

- SUSY alignment models are strongly constrained
  (Golowich, Hewett, Pakvasa, Petrov '07
  Gedalia, Grossman, Nir, Perez '09)

$\rightarrow$ either heavy spectrum $\tilde{m} \gtrsim 2\text{TeV}$

$\rightarrow$ or only small mass splitting between the first two generations $\lesssim 10\%$

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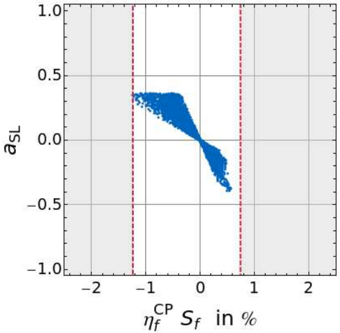
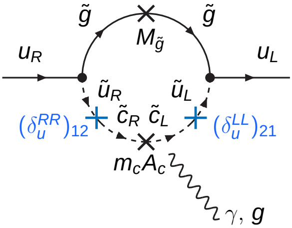


- for complex $(\delta_u^{RR})_{21} \sim \lambda^3$, large CP violation in $D^0 - \bar{D}^0$ mixing is generically predicted

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

Correlation with Electric Dipole Moments

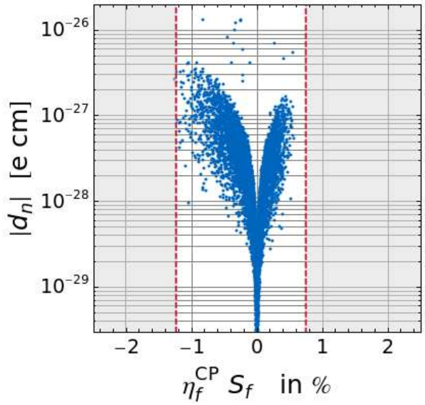
- a complex $(\delta_u^{RR})_{21}$ leads also to a up quark EDM by means of flavor effects



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

- suppression by small mass insertions, but chiral enhancement by m_c/m_u

Correlation with Electric Dipole Moments



mSUGRA spectrum at $M_{\rm GUT}$:
$m_0 < 2$TeV, $M_{1/2} < 1$TeV, $|A_0| < 3m_0$,
$5 < \tan\beta < 55$, $|(\delta_u^{RR})_{21}| \simeq \lambda^3$
order 1 mass splitting $m_{\tilde{u}_L} = 2m_{\tilde{c}_L} = 2m_0$

- large CP violation in $D^0 - \bar{D}^0$ mixing in abelian flavor models (that are assumed to be realized at some high scale $\sim M_{\rm GUT}$) implies
  lower bounds on hadronic EDMs
  (WA, Buras, Paradisi '10)

$$d_n \gtrsim 10^{-(28-29)} e\,\text{cm}$$
$$d_{\rm Hg} \gtrsim 10^{-(30-31)} e\,\text{cm}$$

(for $|S_f| \gtrsim 0.1\%$)

- only 1-2 orders of magnitude below the present experimental constraints

Summary

- Electric Dipole Moments and CP Violation in $D^0 - \bar{D}^0$ mixing are strongly suppressed in the SM
  $\rightarrow$ potential discovery channels for New Physics
- SUSY alignment models predict an flavor violating $(\delta_u^{LL})_{21} \sim \lambda$ for natural $O(1)$ splitting of the left handed squark masses
  $\rightarrow$ generically large effects in D^0 - $\bar{D}^0$ mixing
- within SUSY alignment models, CP Violation in D^0 - $\bar{D}^0$ mixing generically implies lower bounds on hadronic EDMs that are induced by flavor effects and that are only 1-2 orders of magnitude below the current constraints

Back Up

A Model Independent Relation

- three theory parameter M_{12}, Γ_{12}, ϕ_{12} and four "observables" x, y, $|q/p|$, ϕ
  $\Rightarrow$ a model independent relation

  (Grossman, Nir, Perez '09)

$$1 - \left|\frac{q}{p}\right| = \frac{x}{y} \tan\phi$$

- correspondingly, in absence of direct CP violation:
  correlation between S_f and a_{SL}

  (Bigi, Blanke, Buras, Recksiegel '09,
  Kagan, Sokoloff '09)

$$S_f = -\eta_f^{CP} \frac{x^2 + y^2}{|y|} a_{SL}$$