New Two-loop Contributions to Hadronic EDMs in the MSSM

Minoru Nagai
(ICRR, Univ. of Tokyo)

Collaborated with:
J.Hisano (ICRR), P.Paradisi (Technion)

hep-ph/0606322

1. Introduction

- Supersymmetric standard models is the most well-motivated model beyond the Standard Model.

  Blessings

  - Hierarchy problem
  - Gauge coupling unification
  - Dark matter candidate
  - Light Higgs
  - ・・・

- Difficulty : SUSY CP & flavor problem ⇒ Hints for the SUSY SMs

CP phases and flavor structures must be highly constrained.

Off diagonal components of sfermion mass matrixes must be tiny.

$$\left(\delta^f_{cc}\right)_{ij} \equiv \left(m^2_{\tilde{f}c}\right)_{ij} / \overline{m}^2_{\tilde{f}c} \qquad c = L, R \qquad \text{for } i \neq j$$

Ex.) $$\mathrm{Re}\left[\left(\delta^q_{LL}\right)_{12}\left(\delta^d_{RR}\right)_{12}\right] \lesssim 7 \times 10^{-6}\left(\frac{m_{SUSY}}{500\mathrm{GeV}}\right)^2 \qquad \text{by } \Delta m_K$$

What can we probe by EDMs in supersymmetric SMs?

- F term SUSY breaking terms

$B,\ A_f,\ M_{\tilde{g}_i}$: complex in general

$$\phi_B \equiv arg(M_{\tilde{g}} B^*),\ \ \phi_A \equiv arg(M_{\tilde{g}} A^*)$$

strongly constrained by EDM experiments

These phases may be suppressed by some SUSY breaking & mediation mechanisms.

- D term SUSY breaking terms

$\left(m^2_{\tilde{f}}\right)_{ij}$: complex hermit matrix

off-diagonal components can have CP phases

Even if these is no phases at the tree level, it can be generated by radiative corrections.

Null results of EDMs severely constrained these off diagonal element.

EDM measurements are sensitive to not only CP phases but also flavor structures.

2. Flavor induced EDM

$$\mathcal{L}_{eff} = i\frac{d}{2}\bar{q}e\left(F_{\mu\nu}\sigma^{\mu\nu}\right)\gamma_5 q + i\frac{d^C}{2}\bar{q}e\left(G^a_{\mu\nu}T^a\sigma^{\mu\nu}\right)\gamma_5 q$$

Quark EDM　　　　Quark CEDM

CP violating
Dim-5 operators

CP violating effects can be estimated by basis-independent measure of CP violation, Jarlskog invariants.

The Standard Model

There is only one CP violating phase in the CKM matrix and the corresponding Jarlskog invariant is highly suppressed by the ninth orders of Yukawa couplings.

$$J^d_{\mathrm{SM}} = \mathrm{Im}\left(y_d y_d^\dagger\left[y_d y_d^\dagger,\, y_u y_u^\dagger\right] y_u y_u^\dagger\, y_d\right)_{11} \Rightarrow d_q \simeq 10^{-34}\, e\,\mathrm{cm}$$

at 3 loop level

Supersymmetric standard models

There are Jarlskog invariants originated from new CP phases of squark mass matrix. In this talk, we consider the down quark (C)EDM, which tend to dominate the up quark one.

Case 1) $\delta^q_{LL} \neq 0$ and $\delta^d_{RR} \neq 0$　Case 2) $\delta^q_{LL} \neq 0$　Case 3) $\delta^d_{RR} \neq 0$

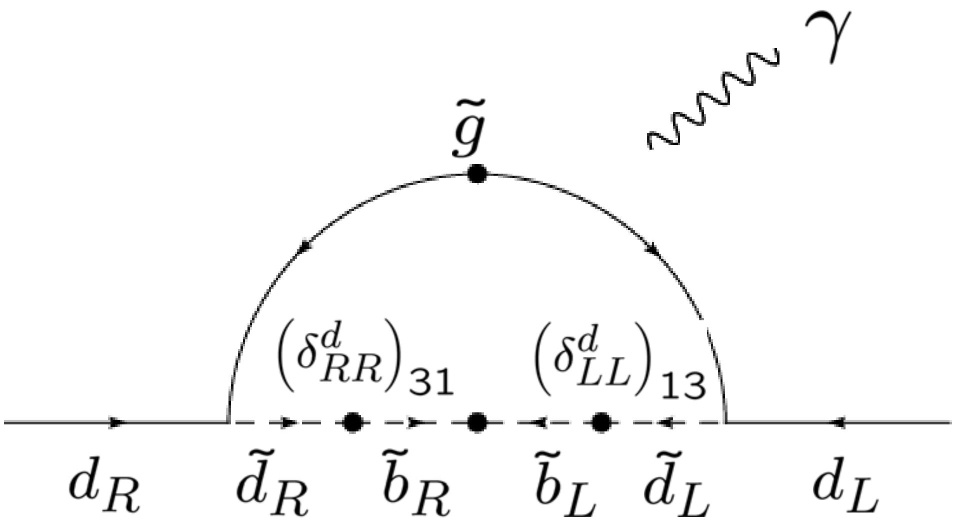
Case 1) $\delta^q_{LL} \neq 0$ and $\delta^d_{RR} \neq 0$

[S.Dimopoulos & L.J.Hall (1995)]

Jarlskog invariant

$$J^d_{LR} = \mathrm{Im}\left(\delta^d_{LL}\, y_d\, \delta^d_{RR}\right)_{11}$$

An odd number of Yukawa coupling appear to have a chirality-flip



gluino contribution to EDMs

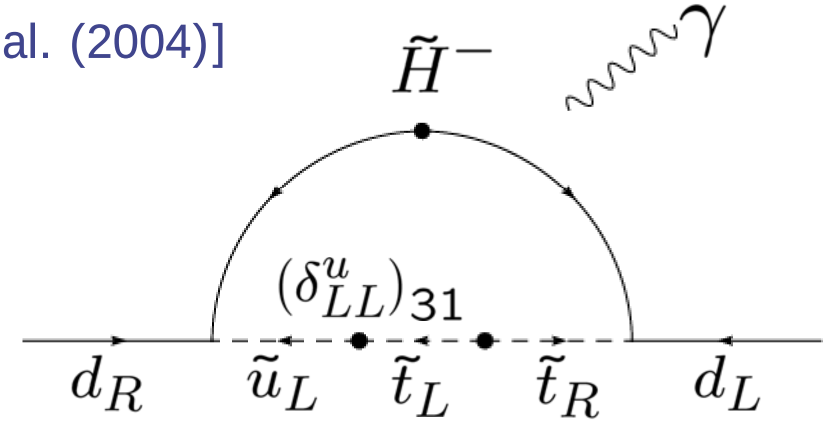
$$d_d/e \sim \frac{\alpha_s}{4\pi}\frac{m_b \tan\beta}{m^2_{SUSY}}\,\mathrm{Im}\left[\left(\delta^d_{LL}\right)_{13}\left(\delta^d_{RR}\right)_{31}\right]$$

$$\sim 1 \times 10^{-25}\ \mathrm{cm}\ \left(\frac{m_{SUSY}}{500\mathrm{GeV}}\right)^2 \left(\frac{\tan\beta}{10}\right) \frac{\left(\delta^d_{LL}\right)_{13}\left(\delta^d_{RR}\right)_{31}}{(0.2)^6}$$

Heavy quark mass enhancement

Case 2) $\delta^q_{LL} \neq 0$

[M.Endo et al. (2004)]



$$J^d_{LL} = \text{Im}\left(\left[y_u y_u^\dagger,\, \delta^q_{LL}\right] y_d\right)_{11}$$

Higgsino contribution to EDMs

$$d_d/e \sim \frac{\alpha_2}{4\pi}\frac{m_t^2}{m_W^2}\frac{m_d \tan\beta}{m_{SUSY}^2}\,\text{Im}\left[(\delta^u_{LL})_{13} V_{31}\right]$$

$$\sim 2\times 10^{-29}\ \text{cm}\ \left(\frac{m_{SUSY}}{500\text{GeV}}\right)^2\left(\frac{\tan\beta}{10}\right)\frac{(\delta^d_{LL})_{13}}{(0.2)^3}$$

Case 3) $\delta^d_{RR} \neq 0$

$$J^d_{RR} = \text{Im}\left(y_u y_u^\dagger\, y_d\, \delta^d_{RR}\right)_{11}$$

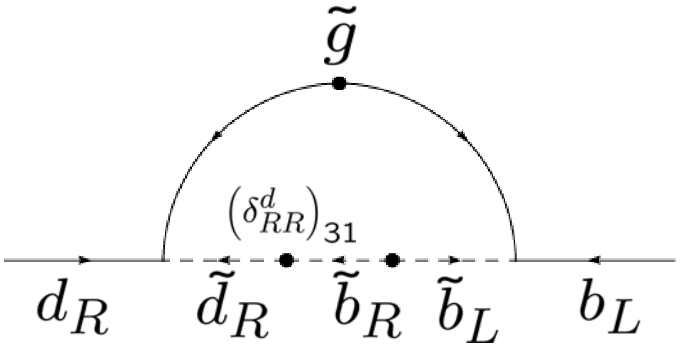
$$\bar{d}_L\left[(y_u)_{1i}\cdots(\delta^d_{RR})_{j1}\right] d_R$$

There is no contribution at 1-loop

Need couplings with both charged and neutral particles

3. New Higgs-mediated two loop contribution

Effective Higgs coupling induced by radiative corrections to down-quark mass matrix



Non-decoupling at the large SUSY particle mass limit

$$\mathcal{L}_{\text{eff}} \simeq \frac{g\ m_d}{\sqrt{2}m_W}\tan\beta \left(V_{31} + \frac{\alpha_3 \tan\beta}{9\pi}\frac{m_b}{m_d}\left(\delta^d_{RR}\right)_{31}\right)\bar{t}_L d_R H^+ + h.c.$$

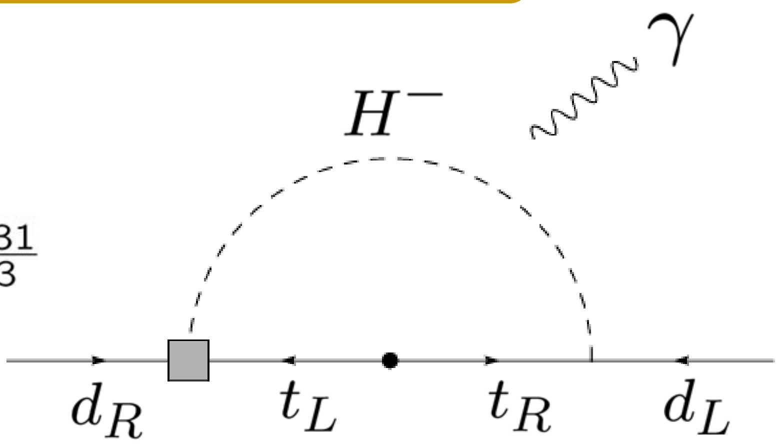
Tree level   1-loop level

Charged Higgs contribution to EDMs

$$J^d_{RR} = \text{Im}\left(y_u y_u^\dagger\, y_d\, \delta^d_{RR}\right)_{11}$$

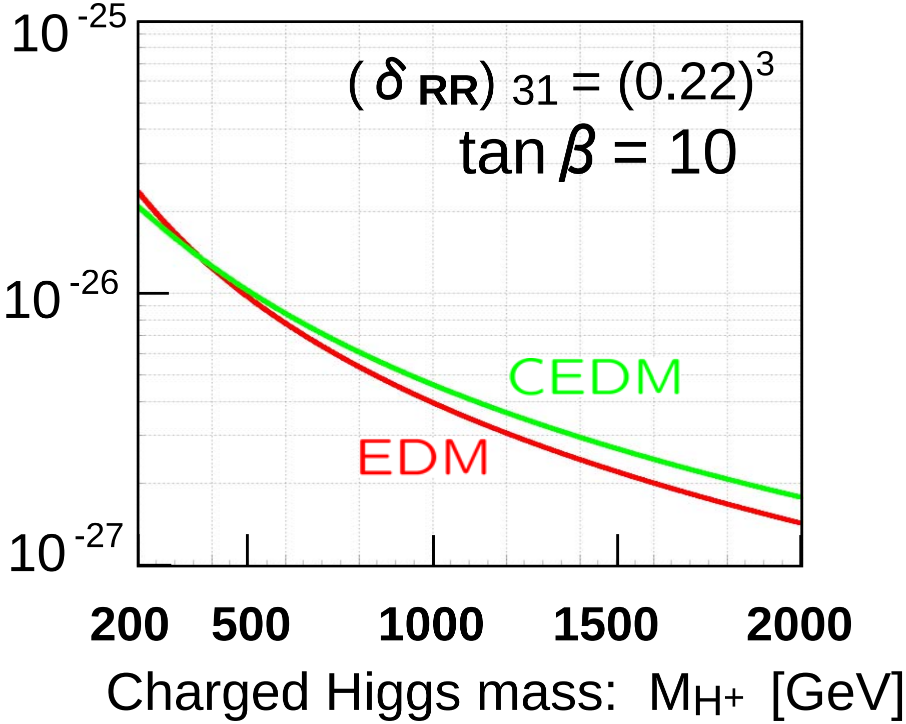
$$d_d/e \sim \frac{\alpha_2}{4\pi}\frac{\alpha_3}{4\pi}\left(\frac{m_t^2}{m_W^2}\right)\frac{m_b \tan\beta}{M^2_{H^+}}\ \text{Im}\left[V^*_{31}\left(\delta^d_{RR}\right)_{31}\right]$$

$$\sim 1 \times 10^{-26}\ \text{cm}\ \left(\frac{M_{H^+}}{300\text{GeV}}\right)^2 \frac{\tan\beta}{10}\frac{\left(\delta^d_{RR}\right)_{31}}{(0.2)^3}$$

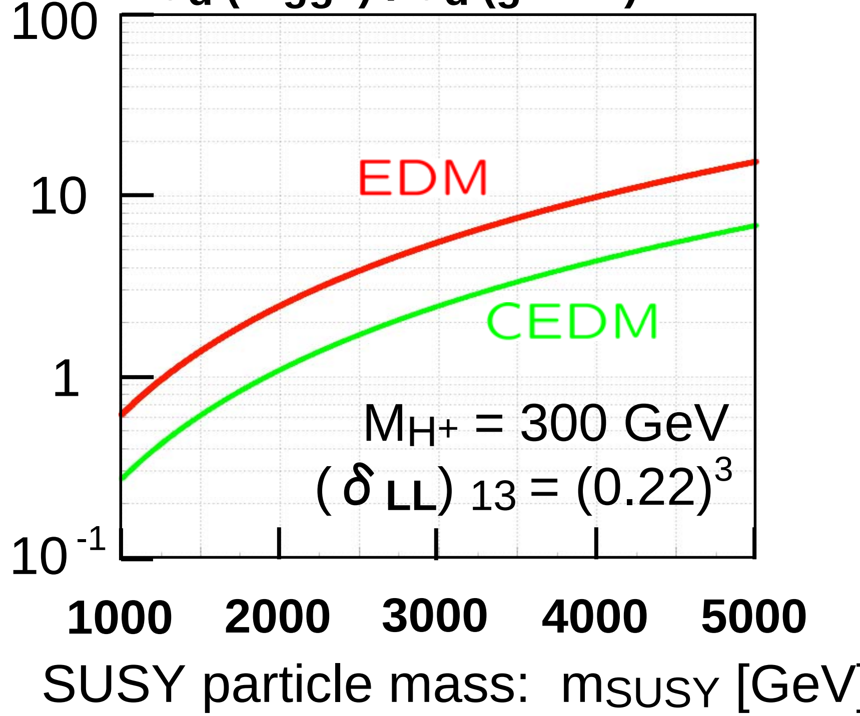


Features of the higgs-mediated two loop contribution

down quark (C)EDM: d_d/e (d^c_d) [cm]



Ratio of 1 and 2-loop contribution: d_d (Higgs) / d_d (gluino)



- It is slowly decoupled for heavy charged Higgs mass.

$$d_d \propto \log(M_{H+}/m_t)/M_{H+}^2 \quad \text{for } M_{H+} \gg m_t$$

- It may dominate over 1-loop gluino contribution for m_{SUSY}> 1-2 TeV.

4. Summary

We discussed the flavor induced EDMs.

- We found a charged-Higgs mediated 2-loop contribution to down quark (C)EDMs can become large and it already constrains some parameter spaces in SUSY SMs.
- As long as the charged Higgs mass is light, this contribution is not decoupled even if SUSY particles is heavy and can become dominant for m_{SUSY}> 1-2 TeV.
- Even if charged Higgs is heavy, (C)EDMs originated from this contribution may be detected in future experiments due to the slow decoupling feature.

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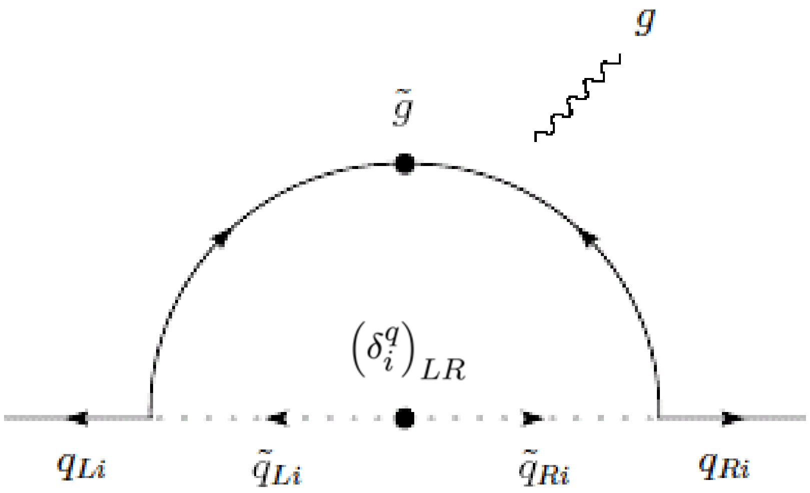
CP phase constraints

$$d_{q_i}^C \sim \frac{\alpha_s}{4\pi}\frac{1}{m_{\mathrm{SUSY}}}\mathrm{Im}\left[\left(\delta_i^q\right)_{LR}\right]$$



$$\left(\delta_i^d\right)_{LR} \equiv \frac{m_{d_i}(A_i^{(d)} - \mu\tan\beta)}{\bar{m}_{\tilde{d}}^2}$$

$$(\delta_i^u)_{LR} \equiv \frac{m_{u_i}(A_i^{(u)} - \mu\cot\beta)}{\bar{m}_{\tilde{u}}^2}$$

$$\tan\beta = \langle H_2\rangle/\langle H_1\rangle$$

From the neutron EDM experiment, CP phases in the MSSM are constrained by

$$|\sin\phi_A| \lesssim \left(\frac{m_{\mathrm{SUSY}}}{3.6\mathrm{TeV}}\right)^2$$

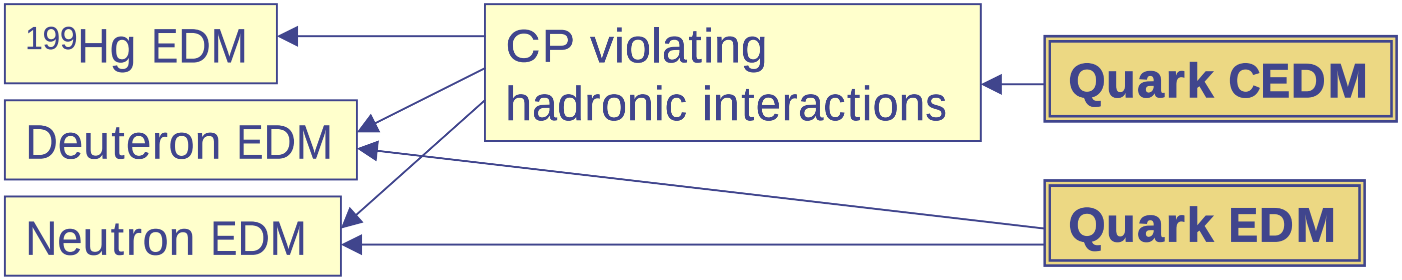
$$|\sin\phi_\mu| \lesssim \left(\frac{m_{\mathrm{SUSY}}}{12\mathrm{TeV}}\right)^2\left(\frac{\tan\beta}{10}\right)^{-1}$$

Here, we use the following formula.

$$\frac{d_n}{e} = 1.1\left(d_d^C + 0.5\times d_u^C\right) + 1.4\left(\frac{d_d}{e} - 0.25\frac{d_u}{e}\right) \ < 2.9\times 10^{-26} e\,\mathrm{cm}$$

[M.Pospelov and A.Ritz (1999)]

Hadronic EDMs



$$\mathcal{L}_{eff} = i\frac{d}{2}\bar{q}e\left(F_{\mu\nu}\sigma^{\mu\nu}\right)\gamma_5 q + i\frac{d^C}{2}\bar{q}e\left(G^a_{\mu\nu}T^a\sigma^{\mu\nu}\right)\gamma_5 q$$

quark EDM — quark CEDM

CP violating Dim-5 operator

Although there can be large hadronic uncertainty, [Hisano & Shimizu (2004)]
it can be estimated as

$$d_{\mathrm{Hg}} = -8.7\times 10^{-3}\times e(d_u^C - d_d^C + 0.005\times d_s^C) \quad < 1.9\times 10^{-28} e\,\mathrm{cm}$$

$$d_n = -1.6\times e(d_u^C + 0.81\times d_d^C + 0.16\times d_s^C) \quad < 2.9\times 10^{-26} e\,\mathrm{cm}$$

Present experimental bounds