QCD Corrections to Neutron Electric Dipole Moment in the High-scale Supersymmetry

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- Introduction
- Effective Lagrangian
- Anomalous Dimensions of Effective Operators
- Results and Conclusion

Introduction

Neutron Electric Dipole Moment (EDM)

○ neutron EDM

$$\mathcal{L}_n = -\frac{i}{2} d_n \bar{N}(F\sigma)\gamma_5 N \qquad N : \text{neutron} \qquad F\sigma \equiv F_{\mu\nu}\sigma^{\mu\nu}$$

Upper bounds of neutron EDM,

$$|d_n| < 2.9 \times 10^{-26} e\text{cm}$$

C. A. Baker, D. D. Doyle, P. Geltenbort, K. Green, M. G. D. van der Grinten, P. G. Harris, P. Iaydjiev and S. N. Ivanov et al., Phys. Rev. Lett. 97, 131801 (2006).

Contribution from the CKM phase,

$$d_n \sim 10^{-(31-32)} \; e \cdot \text{cm}$$

I.B. Khriplovich, A.R. Zhitnitsky, Phys. Lett. B 109 (1982) 490.

◇ A clean, background-free probe of new physics.

◇ Good sensitivity to the TeV scale physics.

CP-violating effective operators at the parton level

The CP-violating effective operators at the hadron scale (∼1GeV) up to dimension 5,

$$\mathcal{L}_{\mathrm{CP-odd}} = -\sum_{q=u,d,s} m_q \bar{q} i\theta_q \gamma_5 q + \theta_G \frac{\alpha_s}{8\pi} G^A_{\mu\nu}\tilde{G}^{A\mu\nu}$$
$$-\frac{i}{2}\sum_{q=u,d,s} d_q \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q \bar{q} g_s \sigma^{\mu\nu}\gamma_5 T^A q G^A_{\mu\nu}.$$

$\theta_q,\ \theta_G,\ d_q,\ \tilde{d}_q$: CP-violating parameters

$$\tilde{G}^A_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} G^{A\rho\sigma}$$

The dimension 5 operators are quite sensitive to the high-scale physics.

Supersymmetry

SUSY Contribution

G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi, JHEP 9812, 027(1998)
J. D. Wells, hep-ph/0306127
N. Arkani-Hamed and S. Dimopoulos, JHEP 0506, 073(2005)

In particular, we consider the High-scale SUSY scenario.

Gauginos
O(1) TeV

Chiral symmetry

Large mass difference

Scalar particles
O(10^2 - 10^3) TeV

From a phenomenological point of view, this scenario is motivated by

- 126 GeV Higgs boson

  G. F. Giudice and A. Strumia, Nucl. Phys. B 858,63(2012)
  M. Ibe, S. Matsumoto and T. T. Yanagida, Phys. Rev. D85, 095011(2012)

- Gauge coupling unification

  N. Arkani-Hamed and S. Dimopoulos, JHEP 0506, 073(2005)
  J. Hisano, T. Kuwahara and N. Nagata, Phys. Lett. B723, 324(2013)

- SUSY CP/flavor problems

  F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini,
  Nucl. Phys. B 477,321

- Wino Dark Matter

  J. Hisano, S. Matsumoto, M. Nagai, O. Saito and M. Senami,
  Phys. Lett. B646,34

We discuss the QCD corrections to effective operators
in the presence of the large mass hierarchy.

QCD Corrections

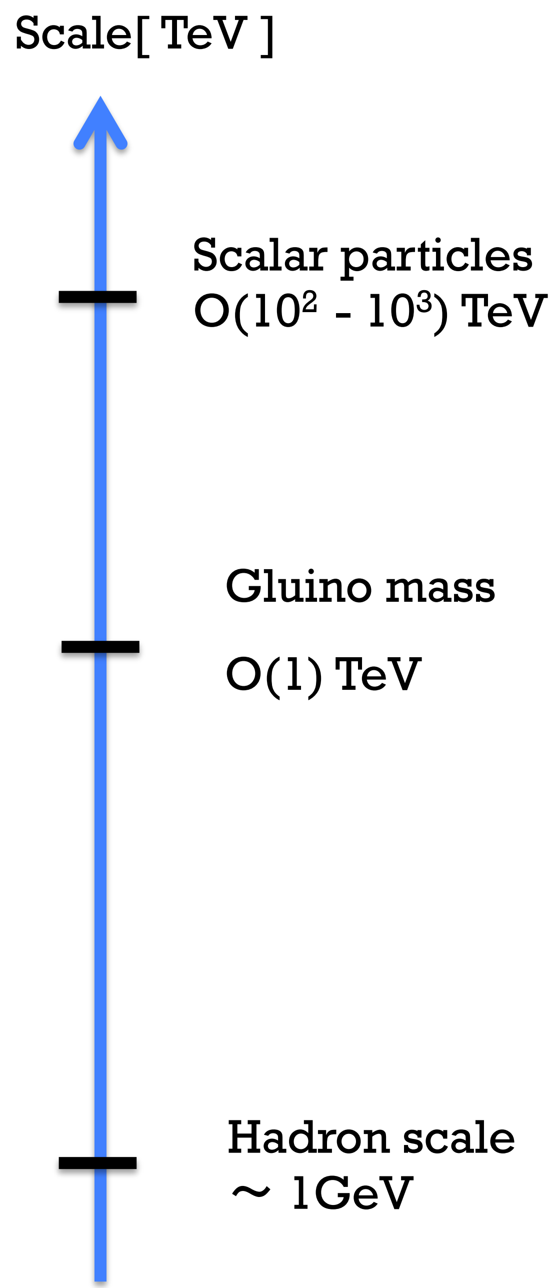
In our study, we proceed to the following steps,

1. To construct the **Effective Lagrangian**.

   (only gluinos + SM particles)

2. To evolve the effective operators down to the gluino threshold according to the **RGEs**.

Setup : Minimal Supersymmetric Standard Model (MSSM)



Effective Lagrangian

Effective Lagrangian

The effective lagrangian below the scalar mass scale are,

$$\mathcal{L}_{\rm eff} = \sum_{q=u,d,s} C_1^q(\mu)\mathcal{O}_1^q(\mu) + \sum_{q=u,d,s} C_2^q(\mu)\mathcal{O}_2^q(\mu) + \sum_{q=u,d,s}\sum_{i=1}^{5} \widetilde{C}_i^q(\mu)\widetilde{\mathcal{G}}_i^q(\mu).$$

$C_i^q,\ \widetilde{C}_i^q$: Wilson coefficients

(Dipole operators)

$$\mathcal{O}_1^q \equiv -\frac{i}{2} e Q_q m_q \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$$

$$\mathcal{O}_2^q \equiv -\frac{i}{2} g_s m_q \bar{q}\sigma^{\mu\nu}\gamma_5 T^A q G_{\mu\nu}^A$$

(4-fermi operators)

$$\widetilde{\mathcal{G}}_1^q \equiv \frac{1}{2}\bar{q}q\bar{\tilde{g}}^A i\gamma_5\tilde{g}^A$$

$$\widetilde{\mathcal{G}}_2^q \equiv \frac{1}{2}\bar{q}i\gamma_5 q\bar{\tilde{g}}^A\tilde{g}^A$$

$$\widetilde{\mathcal{G}}_3^q \equiv \frac{1}{2}d_{ABC}\bar{q}T^A q\bar{\tilde{g}}^B i\gamma_5\tilde{g}^C$$

$$\widetilde{\mathcal{G}}_4^q \equiv \frac{1}{2}d_{ABC}\bar{q}i\gamma_5 T^A q\bar{\tilde{g}}^B\tilde{g}^C$$

$$\widetilde{\mathcal{G}}_5^q \equiv \frac{i}{2}f_{ABC}\bar{q}\sigma^{\mu\nu}i\gamma_5 T^A q\bar{\tilde{g}}^B\sigma_{\mu\nu}\tilde{g}^C$$

Anomalous dimensions

The RGE for the Wilson coefficients is written as,

$$\mu\frac{\partial}{\partial\mu}\vec{C}(\mu) = \vec{C}(\mu)\Gamma, \qquad \vec{C} \equiv (\underbrace{C_1^q, C_2^q}_{\text{EDM, CEDM}}, \underbrace{\widetilde{C}_1^q, \widetilde{C}_2^q, \widetilde{C}_3^q, \widetilde{C}_4^q, \widetilde{C}_5^q}_{\text{4-fermi}})$$

The obtained anomalous dimensions at 1-loop level,

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_q & 0 \\ \frac{1}{(4\pi)^2}\gamma_{q\tilde{g}} & \frac{\alpha_s}{4\pi}\gamma_{\tilde{g}} \end{pmatrix}$$

For the dimension 5 operators,

$$\gamma_q = \begin{pmatrix} 8C_F & 0 \\ 8C_F & 16C_F - 4N \end{pmatrix}$$

N : Number of color

$$C_F = (N^2-1)/2N$$

M. A. Shifman, A. I. Vainshtein and V. I. Zakharov, Phys. Rev. D18, 2583(1987)[Erratum-ibid. D19, 2815(1979)]
M. Ciuchini, E. Franco, L. Reina and L. Silvestrini, Nucl. Phys. B421, 41(1994)

Anomalous dimensions

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For the 4-fermi operators,

$$\gamma_{\tilde{g}}=\begin{pmatrix}-6C_F-6N & 0 & 0 & 0 & 2\\ 0 & -6C_F-6N & 0 & 0 & 2\\ 0 & 0 & -6C_F & 0 & (N^2-4)/2N\\ 0 & 0 & 0 & -6C_F & (N^2-4)/2N\\ 24 & 24 & 12N & 12N & 2C_F-4N\end{pmatrix}$$

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Anomalous dimensions

The RGE for the Wilson coefficients is written as,

$$\mu \frac{\partial}{\partial \mu} \vec{C}(\mu) = \vec{C}(\mu)\Gamma, \qquad \vec{C} \equiv (\underbrace{C_1^q, C_2^q}_{\text{EDM, CEDM}}, \underbrace{\widetilde{C}_1^q, \widetilde{C}_2^q, \widetilde{C}_3^q, \widetilde{C}_4^q, \widetilde{C}_5^q}_{\text{4-fermi}})$$

The obtained anomalous dimensions at 1-loop level,

$$\Gamma = \begin{pmatrix} \frac{\alpha_s}{4\pi}\gamma_q & 0 \\ \frac{1}{(4\pi)^2}\gamma_{q\tilde{g}} & \frac{\alpha_s}{4\pi}\gamma_{\tilde{g}} \end{pmatrix}$$

For between the dimension 5 operators and the 4-fermi operators,

$$\gamma_{q\tilde{g}} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 8N\frac{M_{\tilde{g}}}{m_q} \end{pmatrix}$$

$M_{\tilde{g}}$: Mass of gluino

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Results

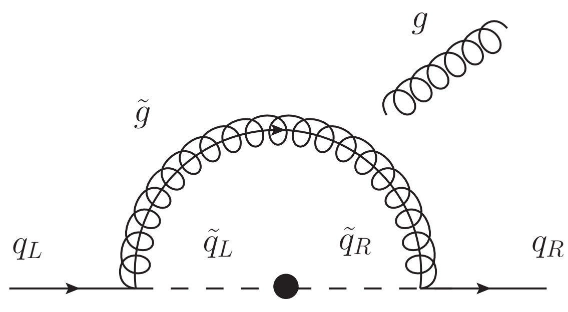
Minimal flavor violation

Initial Conditions for RGEs

EDM and CEDM operators

$$C_1^q(M_S) = +\frac{1}{(4\pi)^2}\frac{16}{3}\frac{M_{\tilde{g}}}{m_q}\widetilde{C}_5^q(M_S)$$

$$C_2^q(M_S) = +\frac{1}{(4\pi)^2}\frac{88}{3}\frac{M_{\tilde{g}}}{m_q}\widetilde{C}_5^q(M_S)$$



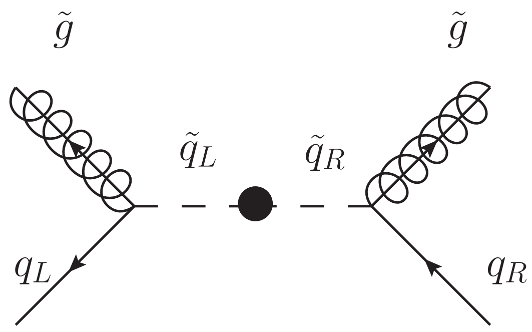
$$m^2_{\tilde{q}_L} = m^2_{\tilde{q}_R} = M_S^2$$

4-fermi operators

$$\widetilde{C}_1^q(M_S) = \widetilde{C}_2^q(M_S) = -\frac{1}{2N}\frac{g_s^2 m_q}{M_S^4}\mathrm{Im}(X_q)$$

$$\widetilde{C}_3^q(M_S) = \widetilde{C}_4^q(M_S) = -\frac{1}{2}\frac{g_s^2 m_q}{M_S^4}\mathrm{Im}(X_q)$$

$$\widetilde{C}_5^q(M_S) = +\frac{1}{4}\frac{g_s^2 m_q}{M_S^4}\mathrm{Im}(X_q)$$



$$X_u \equiv A_u^* - \mu\cot\beta$$

$$X_d \equiv A_d^* - \mu\tan\beta$$

Result of CEDM

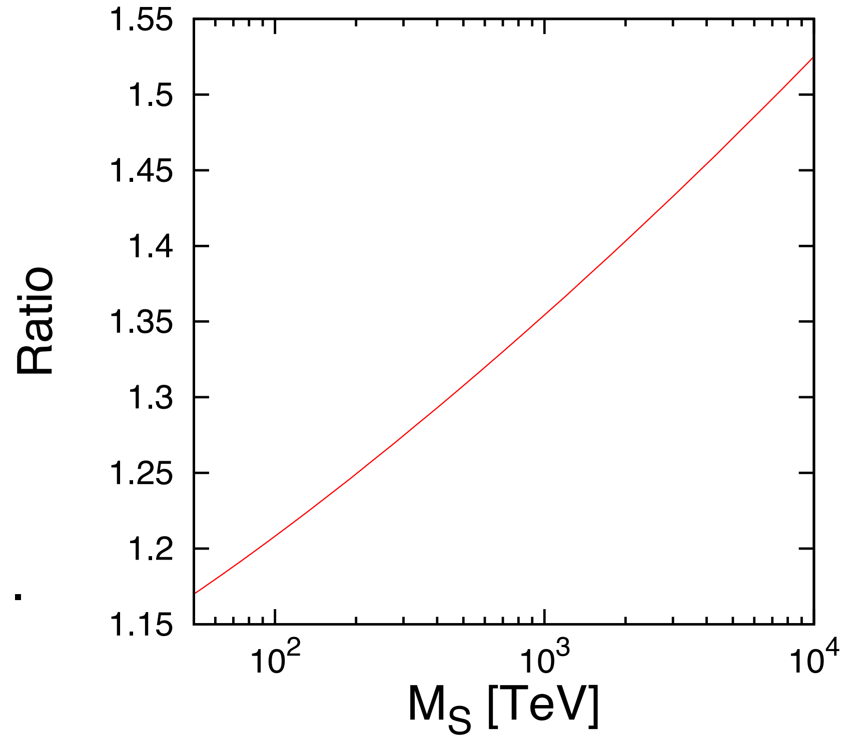
(1-loop result)

G. Degrassi, E. Franco, S. Marchetti and L. Silvestrini, JHEP 0511, 044 (2005).

$$C_2^q|_{1\mathrm{loop}} = -\frac{1}{(4\pi)^2}\left[8N\ln\left(\frac{M_S}{M_{\tilde g}}\right)-\frac{88}{3}\right]\frac{M_{\tilde g}}{m_q}\widetilde{C}_5^q(M_S)$$

The ratio of $C_2^q(M_{\tilde g})\ /\ C_2^q|_{1\mathrm{loop}}$

- Gluino mass : 3 TeV



As the squark mass scale becomes large, the running-effects yield the O(10)% difference between $C_2^q(M_{\tilde g})$ and $C_2^q|_{1\mathrm{loop}}^{(L)}$.

Result of EDM

(1-loop result)

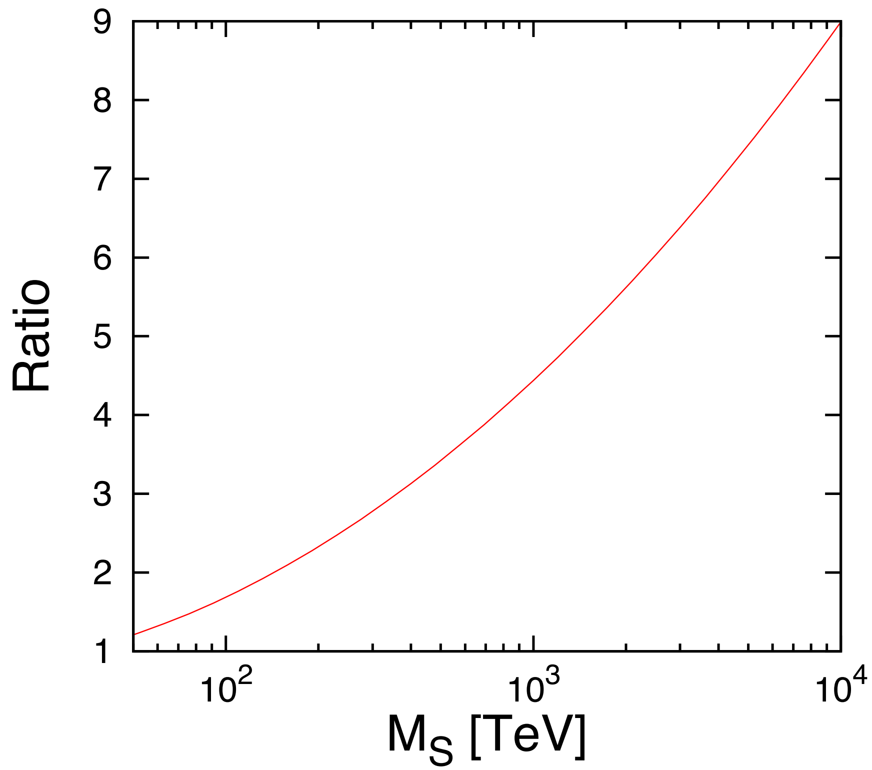
G. Degrassi, E. Franco, S. Marchetti and L. Silvestrini, JHEP 0511, 044 (2005).

$$C_1^q|_{1\text{loop}} = +\frac{1}{(4\pi)^2}\frac{16}{3}\frac{M_{\tilde{g}}}{m_q}\widetilde{C}_5^q(M_S)$$

The ratio of $C_1^q(M_{\tilde{g}})\ /\ C_1^q|_{1\text{loop}}$

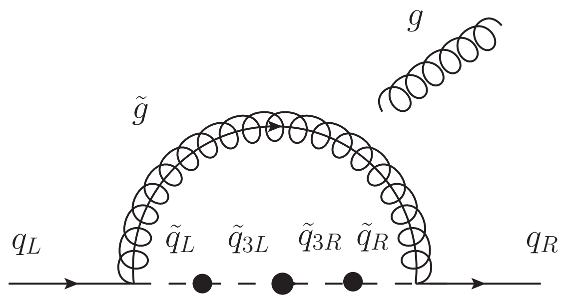
In the case of EDM, the RGE result is several times larger than the explicit one-loop result.

This enhancement is caused by the mixing of the CEDM operators, whose contribution becomes dominant as the squark mass scale taken to be higher.



Generic flavor violation

Initial Conditions for RGEs



EDM and CEDM operators

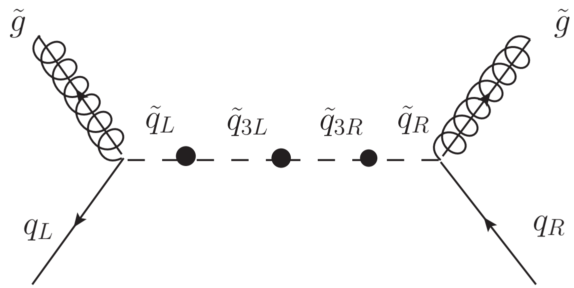
$$C_1^q(M_S) = +\frac{1}{(4\pi)^2}\frac{16}{3}\frac{M_{\tilde{g}}}{m_q}\widetilde{C}_5^q(M_S) \qquad C_2^q(M_S) = +\frac{1}{(4\pi)^2}\frac{118}{3}\frac{M_{\tilde{g}}}{m_q}\widetilde{C}_5^q(M_S)$$

4-fermi operators

$$\widetilde{C}_1^q(M_S) = \widetilde{C}_2^q(M_S) = -\frac{1}{2N}\frac{g_s^2 m_{q_3}}{M_S^4}\mathrm{Im}\left[(\delta_{LL})_{qq_3}X_{q_3}(\delta_{RR})_{q_3 q}\right]$$

$$\widetilde{C}_3^q(M_S) = \widetilde{C}_4^q(M_S) = -\frac{1}{2}\frac{g_s^2 m_{q_3}}{M_S^4}\mathrm{Im}\left[(\delta_{LL})_{qq_3}X_{q_3}(\delta_{RR})_{q_3 q}\right]$$

$$\widetilde{C}_5^q(M_S) = +\frac{1}{4}\frac{g_s^2 m_{q_3}}{M_S^4}\mathrm{Im}\left[(\delta_{LL})_{qq_3}X_{q_3}(\delta_{RR})_{q_3 q}\right]$$



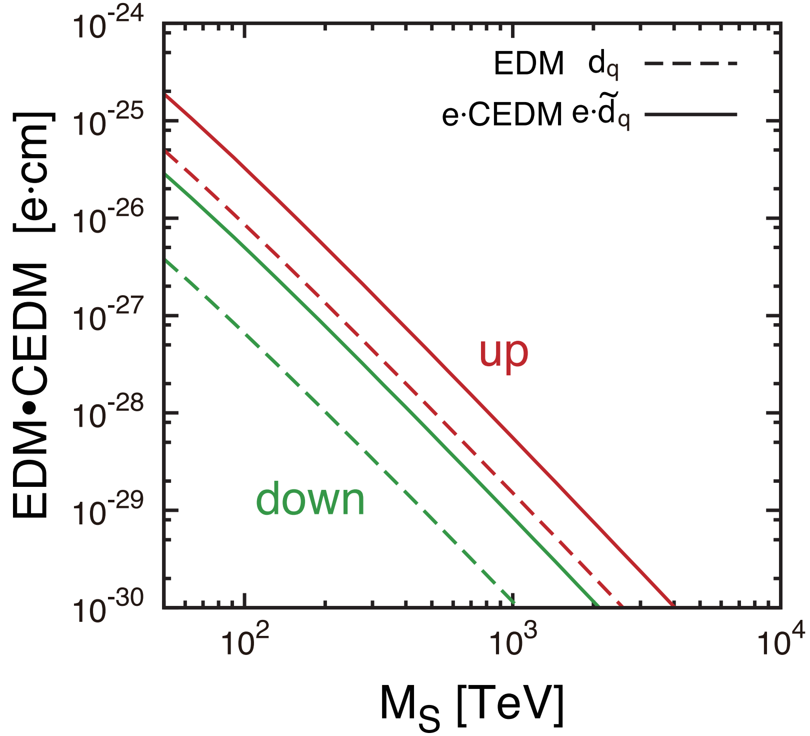
$$(\delta_{RR})_{ij} \equiv \frac{(m^2_{\tilde{q}_R})_{ij}}{M_S^2} \qquad (\delta_{LL})_{ij} \equiv \frac{(m^2_{\tilde{q}_L})_{ij}}{M_S^2}$$

F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini, Nucl. Phys. B477, 321
L. J. Hall, V. A. Kostelecky and S. Raby, Nucl. Phys. B267, 415 (1986)

Result of EDM and CEDM

Figure shows the values of quark EDMs $|d_q|$ and CEDMs $e|\tilde{d}_q|$ at the hadron scale as functions of the squark mass M_S.

Solid lines : CEDMs
Dashed lines : EDMs



The CEDMs dominate the EDMs.
Further, the contribution of up quark is larger than that of down quark in low $\tan\beta$.

Set up : $M_{\tilde{g}} = 3\mathrm{TeV}, \quad \tan\beta = 3 \quad |\mu| = M_S, \quad A_q = 0$

$$|(\delta_{LL})_{qq_3}| = |(\delta_{RR})_{qq_3}| = 1/3$$

$$\theta_q = 1/\sqrt{2}, \quad \theta_q \equiv \mathrm{Arg}[\mu(\delta_{LL})_{qq_3}(\delta_{RR})_{q_3 q}]$$

Result of neutron EDM

We plot the neutron EDM as a function of M_S using the following result,

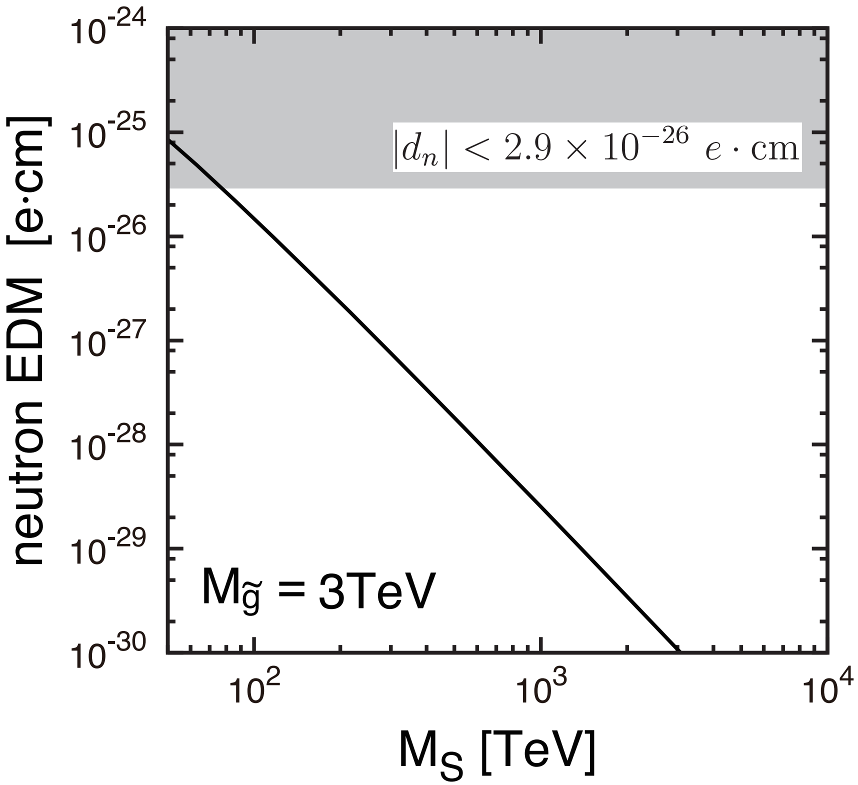
$$d_n = 0.79 d_d - 0.20 d_u + e(0.30 \tilde{d}_u + 0.59 \tilde{d}_d) \qquad \text{(QCD sum rules)}$$

J. Hisano, J. Y. Lee, N. Nagata, Phys. Rev. D85, 114044(2012)

Shaded region :
The current experimental limit

The present experimental limit has already excluded the squark mass scale nearly up to 10^2 TeV.

Future experiments of the neutron EDM are expected to reach $\sim 10^3$ TeV.



Conclusion

- We discuss the QCD corrections to the effective operators in the case of high-scale supersymmetry.

- To evaluate the radiative corrections in the presence of a large hierarchy, we use the RGEs in an effective theory.

- As a result, the values of the low-energy quark EDMs and CEDMs may differ from those evaluated in the explicit 1-loop results by O(100)% , O(10) %, respectively.

Back Up

High-scale SUSY

Scalar particles : the order of the SUSY breaking scale

Fermionic superpartners : much lighter than the other sparticles

Mechanism :

SUSY is broken by a non-singlet field and the breaking effects are transmitted to the visible sector via a generic Kahler potential.

$\longrightarrow$ The gaugino masses are induced by the anomaly mediation and suppressed by one-loop factors compared with the scalar mass.

L. Randall and R. Sundrum, Nucl. Phys. B557, 79
G. F. Giudice, M. A. Luty, H. Murayama and R. Rattazzi, JHEP9812, 027(1998)

Another operators

○ Mass term which contains γ_5 and QCD Θ term

→ They do not contribute to the RGEs for the dimension-five operators.

When the Peccei- Quinn symmetry is imposed, these dimension-four operators are suppressed and the EDMs and CEDMs give dominant contributions.

○ Dimension 5 gluino CEDM operators

→ It does not affects the runnning of the operators at the leading order in α_S.

○ Dimension 6 Weinberg operators, 4-quark operators, 4-gluino operators

→ These dimension-six operators are generated at O($\alpha_S{}^2$) in the case of the MSSM.