Neutron EDM
and
physics beyond the standard model

Junji Hisano (Nagoya Univ.)

CP VIOLATION IN ELEMENTARY PARTICLES AND COMPOSITE SYSTEMS (PCPV2013)

DATES: Thursday 19 Feb, 2013 - Saturday 23 Feb, 2013

VENUE: Fountain Hotel, Mahabaleshwar, Maharashtra, India

Contents

- Introduction
- CP-violating parton-level interactions and their contributions to neutron EDM
- Neutron EDM in supersymmetric standard model
- Summary

1 Introduction

Magnetic and electric dipole moments (MDM and EDM) with spin **S**

$$H = -\mu\, \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\, \mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

Under time (T) and space (P) reflections,

$$P : \mathbf{E} \to -\mathbf{E},\ \ \mathbf{B} \to +\mathbf{B},\ \ \mathbf{S} \to +\mathbf{S}$$
$$T : \mathbf{E} \to +\mathbf{E},\ \ \mathbf{B} \to -\mathbf{B},\ \ \mathbf{S} \to -\mathbf{S}$$

Thus, the EDM is sensitive to CP violation under CPT invariance since it is P- and T-odd.

EDM is known to a good probe to CP violation in particle physics models.

EDM sensitive to TeV-scale physics

Upper bounds on electron and neutron EDMs:

$$|d_e| < 1.0 \times 10^{-27} e\mathrm{cm} \qquad |d_n| < 2.9 \times 10^{-26} e\mathrm{cm}$$

Dimensional analysis for fermionic EDM:

$$H = -d\ \mathbf{E} \cdot \frac{\mathbf{S}}{S} \ \rightarrow\ \mathcal{L}_{\mathrm{eff}} = -d\frac{i}{2}\overline{\psi}(\sigma_{\mu\nu}F^{\mu\nu})\gamma_5\psi$$

$$d_d \sim e\frac{m_d}{M^2} = 10^{-22} e\mathrm{cm}\left(\frac{1\mathrm{TeV}}{M}\right)^2$$

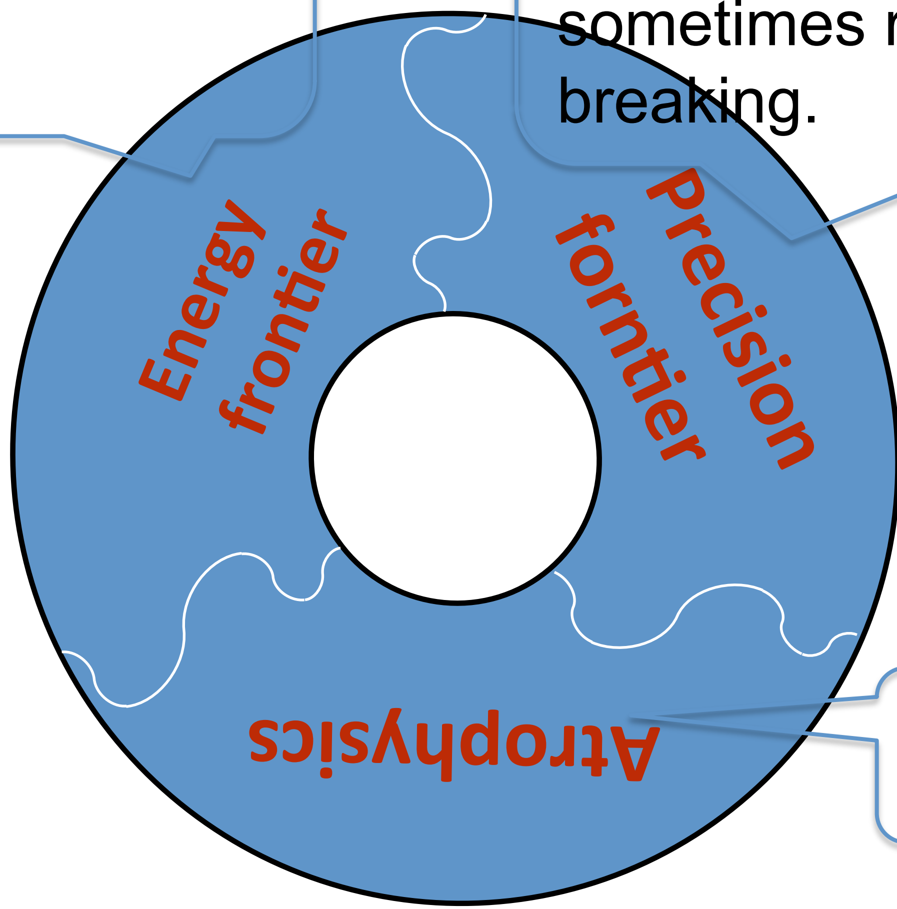
(In renormalization theories, EDMs are suppressed by loop factors (~O($10^{-(2\text{-}3)}$)).)

New physics is expected at TeV scale from viewpoints of the naturalness, the dark matter, baryogenesis and so on.

Tools to probe new physics

Direct search for TeV-scale physics
- LHC
- ILC

- High statistical experiment
- High precise theoretical prediction, sometimes related to symmetry breaking.



- Underground exp.
- Cosmology

Searches for symmetry breaking

Global symmetries in nature are not exact in nature.

- **CP violation (CKM in the SM)**

  EDMs

- **Lepton-flavor violation（neutrino oscillation）**

  Charged lepton flavor-violating decay

  Charged lepton universality

- **Lepton and/or baryon number violation (Baryon asymmetry in the universe)**

  $0\nu\beta\beta$decay

  Proton decay

Neutron EDM in the SM (CKM phase)

Origin of CPV in SM: CKM phase in flavor changing.

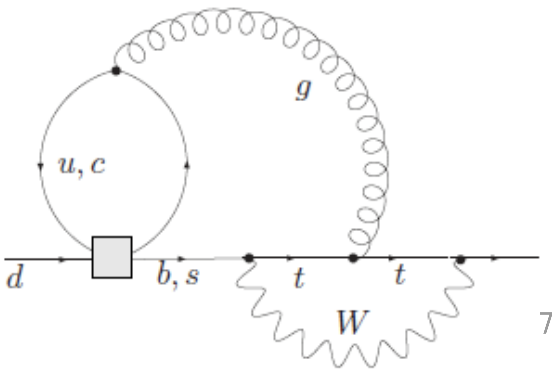
CPV obs are prpto to Jarlskog (rephasing) invariant:

$$J_{\mathrm{CP}} = \mathrm{Im} V_{cs}^{\star} V_{us} V_{cd} V_{ud}^{\star} \sim 10^{-5}$$

- Quark EDMs are suppressed by GIM mechanism and also a 3-loop factor (2loop EW+1loop QCD).

$$d_d = e \frac{m_d m_c^2 \alpha_s G_F^2 J_{CP}}{108\pi^5} \ln^2(m_b^2/m_c^2) \ln(M_W^2/m_b^2)$$

$$\sim 10^{-34} e\mathrm{cm}$$



Neutron EDM in the SM (CKM phase)

Origin of CPV in SM: CKM phase in flavor changing.

CPV obs are prpto to Jarlskog (rephasing) invariant:

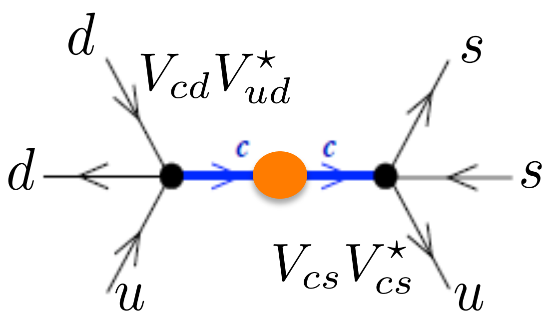
$$J_{\rm CP} = {\rm Im} V_{cs}^\star V_{us} V_{cd} V_{ud}^\star \sim 10^{-5}$$

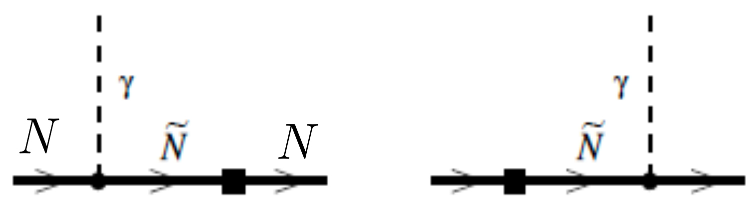
- Neutron EDM induced by long-distance effect (from six-quark operator) estimated conservatively as

$$d_n \sim J_{\rm CP} G_F^2 \frac{\mu_{\rm had}^5}{m_c^2} \sim 10^{-(31-32)} e{\rm cm}$$

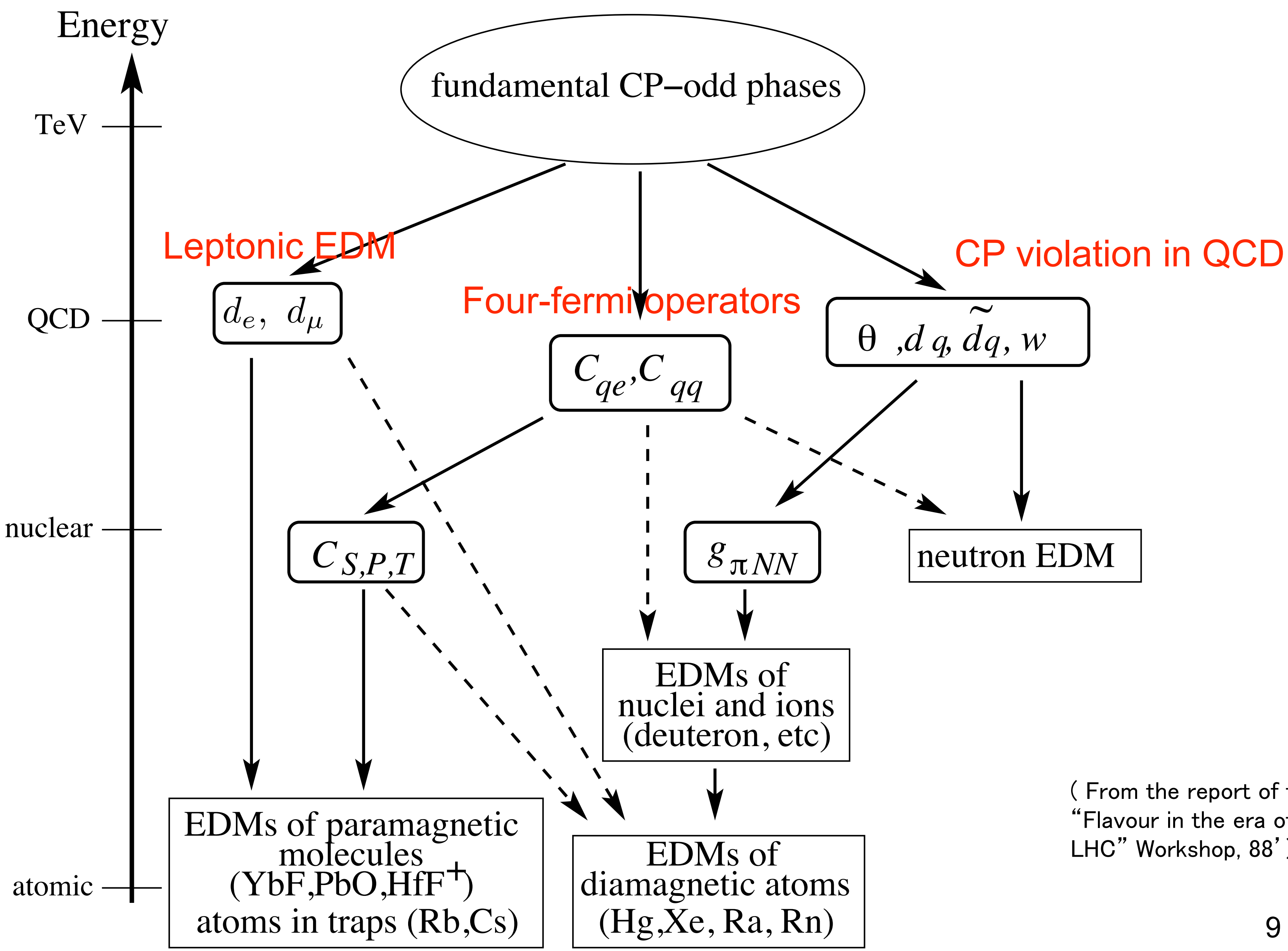
(Mannel and Uraltsev)

while it might reach to 10^{-30} e cm.





Evaluation of EDMs



(From the report of the "Flavour in the era of the LHC" Workshop, 88')

(Flavor-conserving) CPV interaction in QCD

$$-\mathcal{L} = \frac{g_s^2\bar{\theta}}{32\pi^2}G\tilde{G} + \sum_{f=u,d,s,e} d_f \frac{i}{2}\bar{f}(\sigma\cdot F)\gamma_5 f + \sum_{q=u,d,s} d_f^c \frac{i}{2}\bar{q}(\sigma\cdot G)\gamma_5 q$$

QCD theta EDM CEDM

$$+\frac{1}{3}wGG\tilde{G} + \sum_{f,f'=u,d,s,e}(\bar{f}f)(\bar{f}\gamma_5 f)$$

Weinberg op 4-Fermi

$$\sigma\cdot F = \sigma_{\mu\nu}F^{\mu\nu}$$

$$\sigma\cdot G = \sigma_{\mu\nu}G^{\mu\nu}$$

(Flavor-conserving) CPV interaction in QCD

$$-\mathcal{L} = \frac{g_s^2\bar{\theta}}{32\pi^2}G\tilde{G} + \sum_{f=u,d,s,e} d_f \frac{i}{2}\bar{f}(\sigma\cdot F)\gamma_5 f + \sum_{q=u,d,s} d_f^c \frac{i}{2}\bar{q}(\sigma\cdot G)\gamma_5 q$$

QCD EDM CEDM

Strong-CP problem: $d_n \sim e\bar{\theta}\times 10^{-(16-17)}e\mathrm{cm}$

The most promising solution is Peccei-Quinn mechanism.

$$\bar{\theta} = \langle S\rangle \simeq 0 \quad (S:\mathrm{axion})$$

Though, the effective theta is generated if there is CP violation in QCD, since the tad pole term for S is generated. (Bigi&Uraltsev)

For example, $\bar{\theta}^{\mathrm{eff}} = m_0^2/2\sum_q d_q^c/m_q$. $(m_0^2 = 0.8\mathrm{GeV}^2)$

Other proposal: spontaneous CPV, vanishing quark mass.

(Flavor-conserving) CPV interaction in QCD

$$-\mathcal{L} = \frac{g_s^2\bar{\theta}}{32\pi^2}G\tilde{G} + \sum_{f=u,d,s,e} d_f \frac{i}{2}\bar{f}(\sigma\cdot F)\gamma_5 f + \sum_{q=u,d,s} d_f^c \frac{i}{2}\bar{q}(\sigma\cdot G)\gamma_5 q$$

QCD theta EDM CEDM

$$+\frac{1}{3}wGG\tilde{G} + \sum_{f,f'=u,d,s,e} (\bar{f}f)(\bar{f}\gamma_5 f)$$

Weinberg op 4-Fermi

Quark EDMs and CEDMs are sensitive to TeV-scale physics.
Evaluation of the QCD sum rules:

$$d_n = 0.95 d_d - 0.24 d_u + e(0.37 d_d^c - 0.37 d_u^c) \\ +8\times 10^{-17}\bar{\theta}[\mathrm{ecm}]$$

(No PQ mechanism)

$$d_n = 0.95 d_d - 0.24 d_u + e(0.71 d_d^c + 0.36 d_u^c)$$

(PQ mechanism)

Due to input parameter uncertainties, this prediction still has O(1) uncertainties.

(JH, Lee, Nagata, Shimizu)

Evaluation of neutron EDM with QCD sum rules

- Neutron current $\eta_n(x)$ and one particle state under CP-violating BG:

$$\langle \Omega_{\not{C}\not{P}} | \eta_n(x) | N_{\not{C}\not{P}}(\boldsymbol{p}, s) \rangle = \lambda_n e^{\frac{i}{2}\alpha_n \gamma_5} \; u_n(\boldsymbol{p}, s) \; e^{-ip\cdot x}$$

- Correlator of neutron current under constant electromagnetic BG, F:

$$\Pi(q) \equiv i \int d^4x \; e^{iq\cdot x} \; \langle \Omega_{\not{C}\not{P}} | T\{\eta_n(x)\bar{\eta}_n(0)\} | \Omega_{\not{C}\not{P}} \rangle_F$$

Procedure in QCD sum rules

1. Π is evaluated with the Operator Product Expansion (OPE), where the long-distance quark-gluon interactions are parametrized in terms of universal vacuum condensates.
2. By taking the Borel transformation, which suppresses excited and continuum states, and constants contributions in the relation, information of the grand state is extracted.
3. Systematic errors are evaluated by modeling the excited and continuum states.

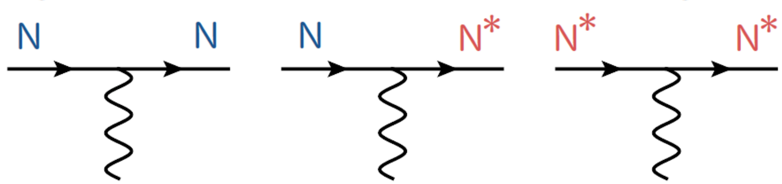
Phenomenological side of correlator

On the CP-violating BG, γ_5 -mass term for neutron is generated though neutron EDM is defined on a basis it vanishes. It is tedious to extract neutron EDM from terms non-invariant under neutron-chiral rotation.

Term invariant for neutron chiral rotation and proportional to neutron EDM d_n is

$$\Pi^{(\mathrm{phen})}(q) = \frac{1}{2} f(q^2)\{\tilde{F}\cdot\sigma, \not{q}\} + \ldots$$

where $f(q^2) = \left(\frac{\lambda_n^2 d_n m_n}{(q^2 - m_n^2)^2} + \frac{A(q^2)}{q^2 - m_n^2} + B(q^2) \right)$. $(q^2 \simeq m_n^2)$



Double pole　　Single pole　　No pole

(Pospelov&Ritz)

Operator-product expansion (OPE)

Neutron Current under CP-violating BG:

$$\eta_n(x) = j_1(x) + \beta j_2(x) + i\epsilon[i_1(x) + \beta i_2(x)]$$

where $j_1(x) = 2\epsilon_{abc}\left(d_a^T(x)C\gamma_5 u_b(x)\right)d_c(x)$ and $j_2(x) = 2\epsilon_{abc}\left(d_a^T(x)Cu_b(x)\right)\gamma_5 d_c(x)$

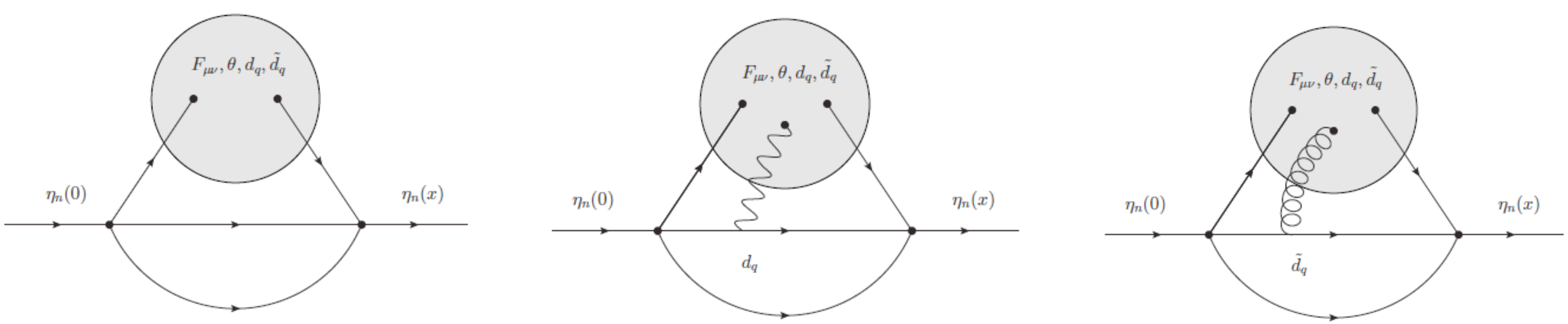
and P-odd currents, $i_1(x) = \gamma_5 j_2(x)$ and $i_2(x) = \gamma_5 j_1(x)$.

We take β =1 since

1) Mixing to P-odd currents can be neglected.

$$\begin{aligned}\langle\Omega_{\not{C}\not{P}}|T\{\eta_n(x)\bar{\eta}_n(0)\}|\Omega_{\not{C}\not{P}}\rangle_F|_{\gamma\ \mathrm{odd}} &= \langle j_1, \bar{j}_1\rangle + \beta[\langle j_1, \bar{j}_2\rangle + \langle j_2, \bar{j}_1\rangle] + \beta^2\langle j_2, \bar{j}_2\rangle \\ &\quad + i\epsilon(1-\beta^2)[\langle j_1, \bar{j}_2\rangle - \langle j_2, \bar{j}_1\rangle]\gamma_5\ .\end{aligned}$$

2) Higher-order terms in OPE are suppressed.



Evaluation of neutron EDM

Sum rules after Borel transformation (M: Borel mass parameter)

$$\lambda_n^2 d_n m_n - AM^2 = -\Theta\langle\bar{q}q\rangle\frac{M^4}{8\pi^2}e^{\frac{m_n^2}{M^2}}$$

(double pole) (single pole)

where θ comes from OPE at NLO,

$$\Theta \equiv (4e_d m_d \rho_d - e_u m_u \rho_u)\chi\bar{\theta} + (4d_d - d_u) + (\kappa - \frac{1}{2}\xi)(4e_d d_d^C - e_u d_u^C)$$

We used condensations under electromagnetic BG.

$$\langle\bar{q}\sigma_{\mu\nu}q\rangle_F = e_q\chi F_{\mu\nu}\langle\bar{q}q\rangle,$$

$$g_s\langle\bar{q}G_{\mu\nu}^A T^A q\rangle_F = e_q\kappa F_{\mu\nu}\langle\bar{q}q\rangle\ ,$$

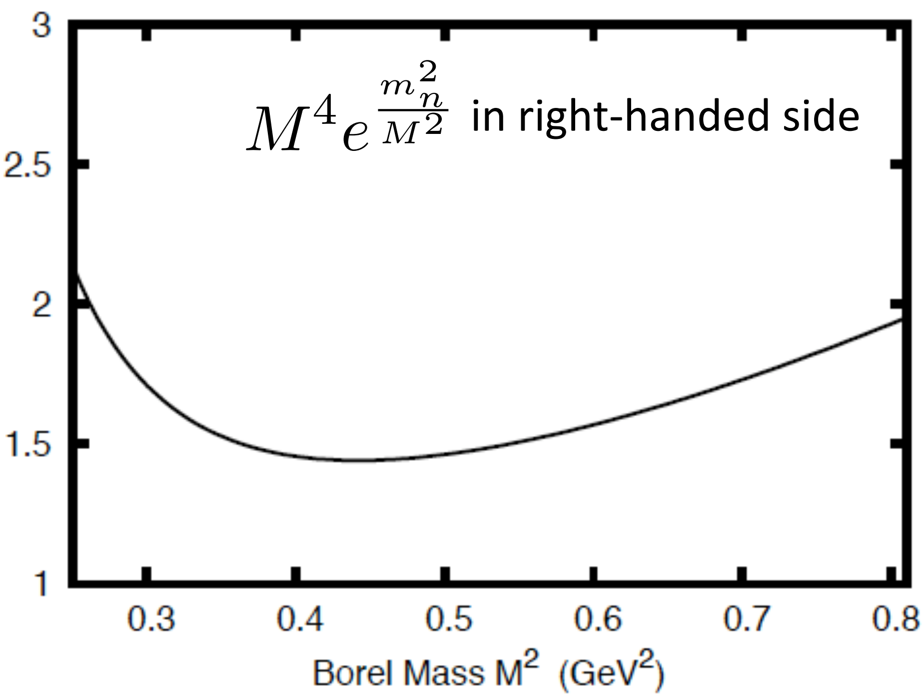
$$2g_s\langle\bar{q}\gamma_5\tilde{G}_{\mu\nu}^A T^A q\rangle_F = ie_q\xi F_{\mu\nu}\langle\bar{q}q\rangle$$

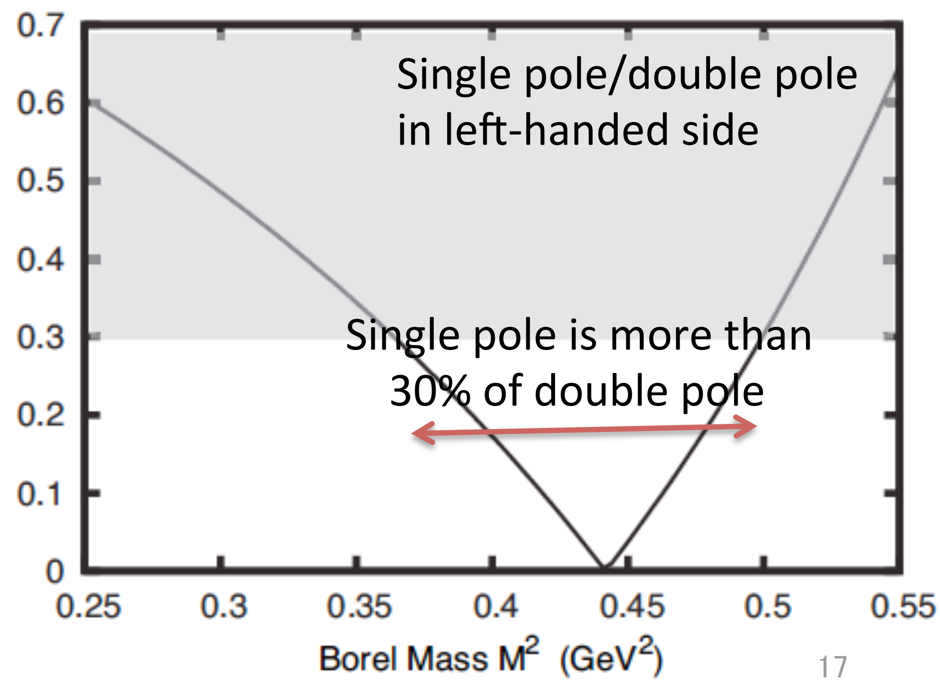
Evaluation of neutron EDM

Sum rules after Borel transformation (M: Borel mass parameter)

$$\lambda_n^2 d_n m_n - AM^2 = -\Theta\langle\bar{q}q\rangle\frac{M^4}{8\pi^2}e^{\frac{m_n^2}{M^2}}$$

(double pole)   (single pole)





Evaluation of neutron EDM

Low-energy constant λ_n($\langle \Omega_{\not{C}\not{P}} | \eta_n(x) | N_{\not{C}\not{P}}(\boldsymbol{p}, s) \rangle = \lambda_n e^{\frac{i}{2}\alpha_n \gamma_5} u_n(\boldsymbol{p}, s)\, e^{-ip\cdot x}$)

1) Lattice evaluation (Y.Aoki et al, 08)

$$\lambda_n = -0.0436 \pm 0.0047_{(\mathrm{stat})} \pm 0.0084_{(\mathrm{syst})}\ \mathrm{GeV}^3$$

2) QCD sum rules (Leinweber, 97)

$$\lambda_n \simeq 0.022\ \mathrm{GeV}^3$$

The lattice-predicted value gives more conservative prediction for neutron EDM.

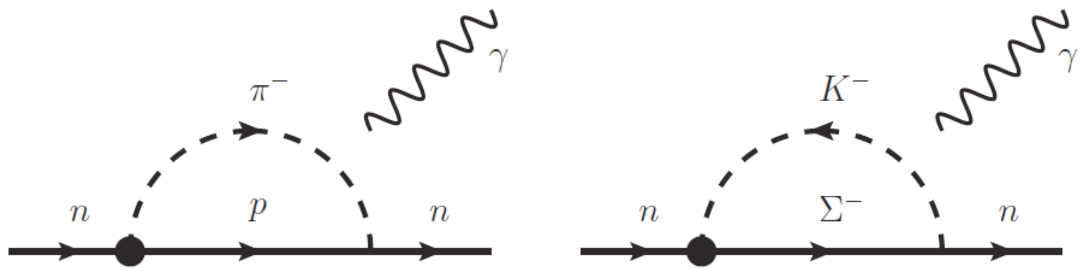
$$d_n = 2.3\ ^{+0.6}_{-0.3} \pm 0.1\ ^{+0.7}_{-0.4} \times 10^{-1}\ \Theta$$ (pheno)(OPE)(lattice)

For the center value

$$d_n = e(8.2 \times 10^{-17}\bar{\theta}\ [\mathrm{cm}] - 0.37 d_u^C + 0.37 d_d^C - 0.02 d_s^C)$$
$$+ 0.95 d_d - 0.24 d_u$$

May strange quark CEDM dominate?

Strange quark CEDM may still contribute to CPV n-Σ^--K^+ coupling (though lattice simulation predict tiny <n|$\bar{s}$s|n>). Meson loop diagrams induce neutron EDM.



(JH, Nagata, Fuyuto)

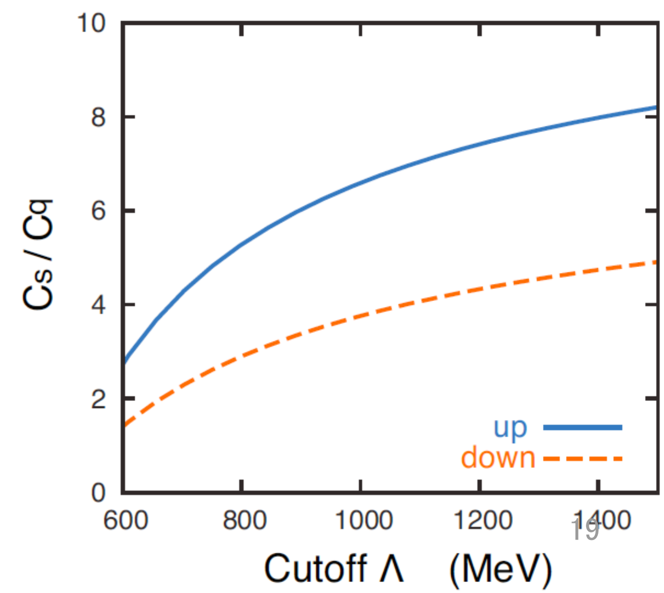
When the neutron EDM is written as (PQ mechanism is operative),

$$d_n = \sum_q C_q \times e d_q^c / m_q$$

When CP violaton is flavor-indep,

$$d_u^c / m_u = d_d^c / m_d = d_s^c / m_s$$

Cs seems to be larger than the others.



Chiral lagrangian vs. QCD sum rules

Chiral lagrangian technique seems to predict larger neutron EDM than QCD sum rules though Chiral lagrangian technique suffers from uncertainties from counter terms (or cutoff scale in log).

i) Chiral lagrangian

$$d_n = e(5.8 \times 10^{-16}\bar{\theta}\ [\mathrm{cm}] - 1.5\tilde{d}_u + 0.6\tilde{d}_d + 0.4\tilde{d}_s),$$

ii) QCD sum rules

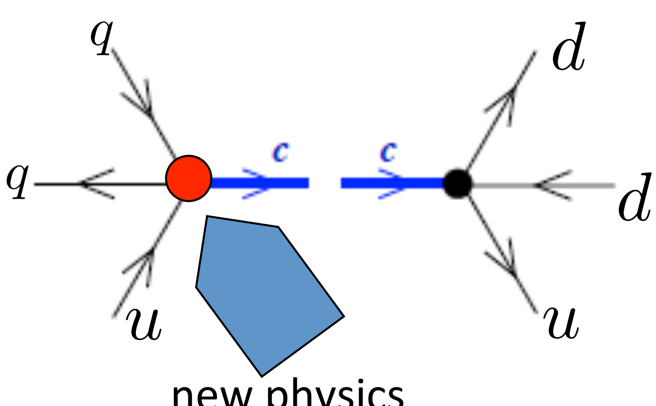
$$d_n = e(8.2 \times 10^{-17}\bar{\theta}\ [\mathrm{cm}] - 0.37\tilde{d}_u + 0.37\tilde{d}_d - 0.02\tilde{d}_s),$$

(Flavor-changing) CP violation

Direct CP violation in D meson decay @LHCb and CDF

$$\Delta a_{\rm CP} = a_{\rm CP}(D^0 \to K^+K^-) - a_{\rm CP}(D^0 \to \pi^+\pi^-) = -(0.82 \pm 0.21 \pm 0.11)\%,$$
$$-(0.62 \pm 0.21 \pm 0.10)\%$$

Five time larger than naïve evaluation of SM prediction may come from new physics? New interaction with ΔC ≠0 may generate neutron EDM, similar to the SM. (Mannel and Uraltsev)



(Flavor-changing) CP violation

New interaction with $\Delta C \neq 0$ may generate neutron EDM.

$$O_1 = e m_c \bar{c}\, i\sigma_{\alpha\beta} F^{\alpha\beta} \gamma_5 u\,, \qquad O_2 = g_s m_c \bar{c}\, i\sigma_{\alpha\beta} G^{\alpha\beta} \gamma_5 u\,,$$

$$O_3 = [\bar{c}\Gamma_\mu u]([\bar{s}\Gamma^\mu s] + [\bar{d}\Gamma^\mu d]), \qquad O_4 = (\bar{c}\gamma_\mu(1+\gamma_5)u)\,(\bar{d}\gamma^\mu(1-\gamma_5)d)$$

Depending on the operators, the neutron EDM is enhanced compared with the SM prediction.

	$i\langle\pi^+\pi^-\vert O_k\vert D^0\rangle$	$\vert\sin\delta_{\rm FSI}\,{\rm Im}\,c_k\vert$	$\vert d_n\vert$, $e\cdot$cm
O_1	$8\sqrt{2}\pi\alpha\, q_d\, f_\pi f_+^{D\to\pi}(0) M_D^2$	$5.2\cdot 10^{-2}$	$4\cdot 10^{-27}$
O_2	$4\pi g_s\sqrt{3}\, f_\pi f_+^{D\to\pi}(0) M_D^2$	$1.0\cdot 10^{-4}$	$8\cdot 10^{-30}$ | $3\cdot 10^{-30}$
O_3	$f_\pi f_+^{D\to\pi}(0) M_D^2$	$2\ \cdot 10^{-3}$	10^{-30}
O_4	$f_\pi f_+^{D\to\pi}(0) M_D^2\ \frac{1}{N_c}\ \frac{2m_\pi^2}{(m_u+m_d)m_c}$	$4.6\cdot 10^{-3}$	10^{-29}

Heavy quark contributions

CP-violating (flavor-conserving) operators up to D=6:

$$\mathcal{L}_{\rm CPV} = \sum_{i=1,2,4,5} \sum_q C_i^q(\mu) \mathcal{O}_i^q(\mu) + C_3(\mu)\mathcal{O}_3(\mu)$$

$$+ \sum_{i=1,2} \sum_{q' \neq q} \widetilde{C}_i^{q'q}(\mu) \widetilde{\mathcal{O}}_i^{q'q}(\mu) + \frac{1}{2} \sum_{i=3,4} \sum_{q' \neq q} \widetilde{C}_i^{q'q}(\mu) \widetilde{\mathcal{O}}_i^{q'q}(\mu)$$

$$\mathcal{O}_1^q = -\frac{i}{2} m_q \bar{q}\, e Q_q (F \cdot \sigma) \gamma_5 q\,,$$

$$\mathcal{O}_2^q = -\frac{i}{2} m_q \overline{q}\, g_s (G \cdot \sigma) \gamma_5 q\,,$$

$$\mathcal{O}_3 = -\frac{1}{6} g_s f^{ABC} \epsilon^{\mu\nu\rho\sigma} G^A_{\mu\lambda} G^{B\ \lambda}_{\ \nu} G^C_{\rho\sigma}$$

$$\mathcal{O}_4^q = \overline{q_\alpha} q_\alpha \overline{q_\beta}\, i\gamma_5 q_\beta\,,$$

$$\mathcal{O}_5^q = \overline{q_\alpha} \sigma^{\mu\nu} q_\alpha \overline{q_\beta}\, i\sigma_{\mu\nu} \gamma_5 q_\beta\,,$$

$$\widetilde{\mathcal{O}}_1^{q'q} = \overline{q'_\alpha} q'_\alpha \overline{q_\beta}\, i\gamma_5 q_\beta\,,$$

$$\widetilde{\mathcal{O}}_2^{q'q} = \overline{q'_\alpha} q'_\beta \overline{q_\beta}\, i\gamma_5 q_\alpha\,,$$

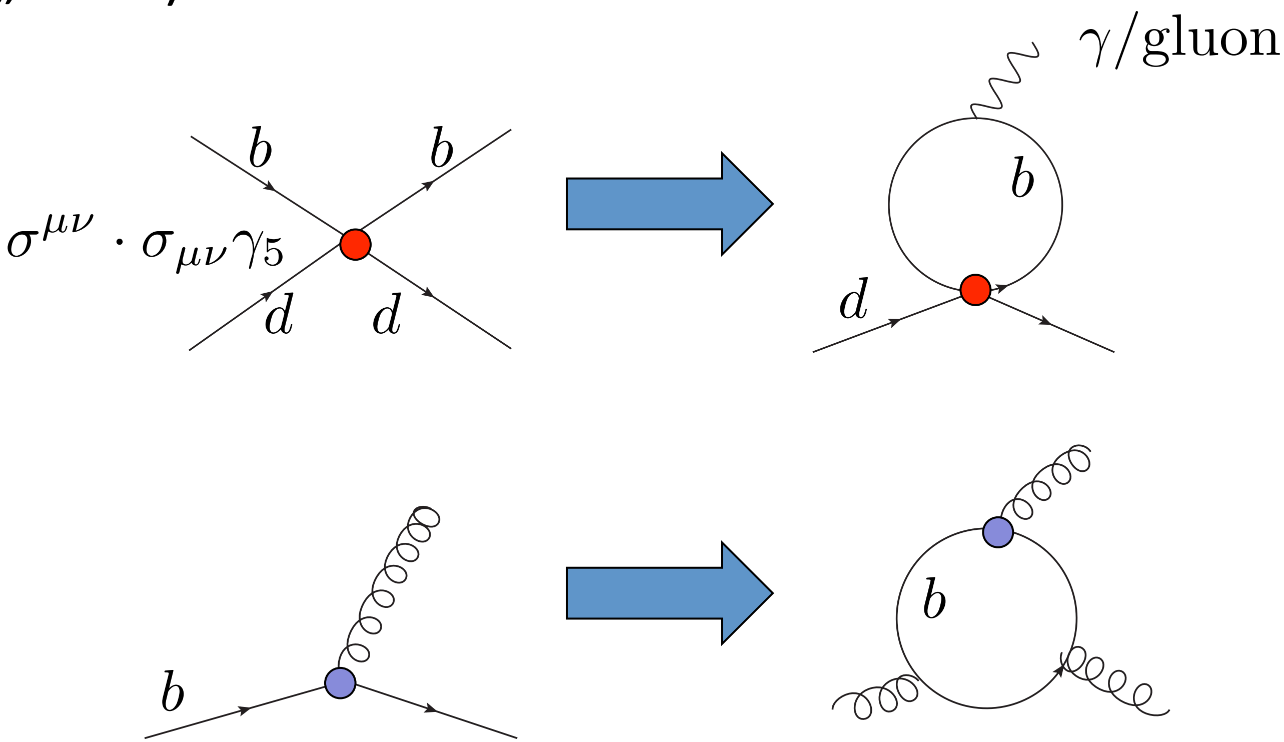
$$\widetilde{\mathcal{O}}_3^{q'q} = \overline{q'_\alpha} \sigma^{\mu\nu} q'_\alpha \overline{q_\beta}\, i\sigma_{\mu\nu} \gamma_5 q_\beta\,,$$

$$\widetilde{\mathcal{O}}_4^{q'q} = \overline{q'_\alpha} \sigma^{\mu\nu} q'_\beta \overline{q_\beta}\, i\sigma_{\mu\nu} \gamma_5 q_\alpha\,.$$

Heavy quarks are coupled with light quarks via D=6 operators.

Integrating out heavy quarks

- EDMs and CEDMs for light quarks are generated via Renormalization-group (RG) equations for Wilson coefficients for D=6 operators with heavy quarks.（JH, Tsumura, Yang)
- Weinberg's gluon operators are also generated from CEDMs of heavy quarks when heavy quarks are decoupled. (Chang, Kephart, Keung, Yuan)

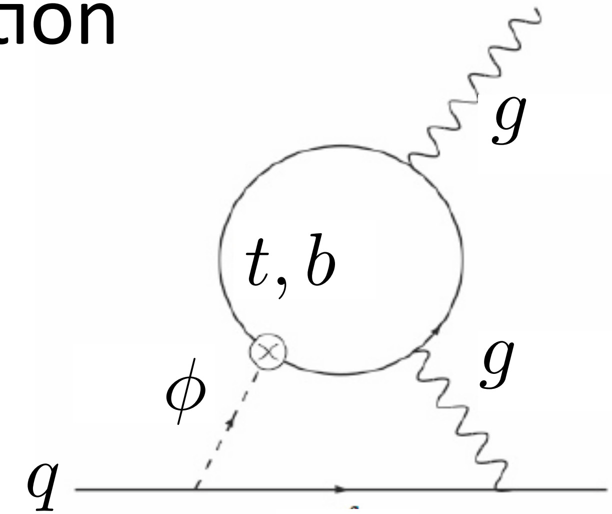


Higgs boson contribution

CP-violating Higgs (Φ) interaction:

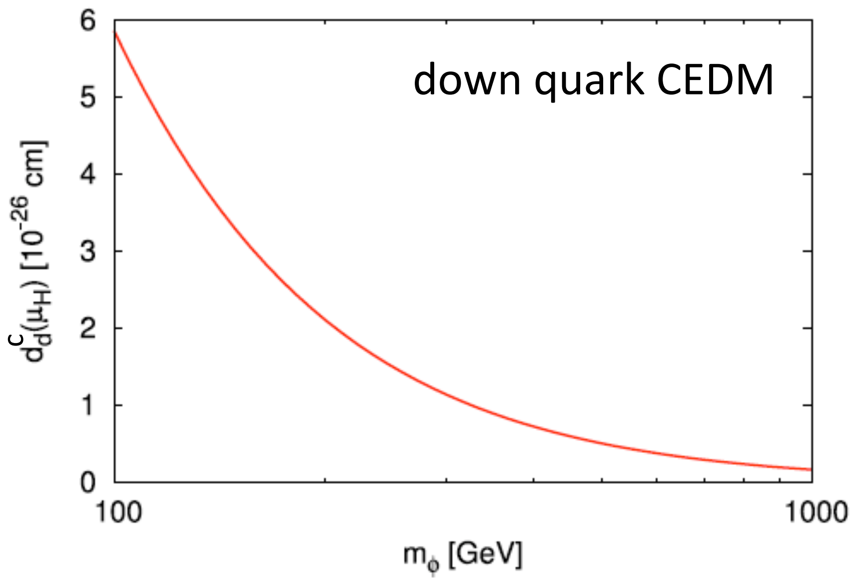
$$\mathcal{L}_\phi = 2^{1/4} G_F^{1/2} m_q \overline{q_\alpha} (f_S^q + i\, f_P^q \gamma_5) q_\alpha \phi,$$

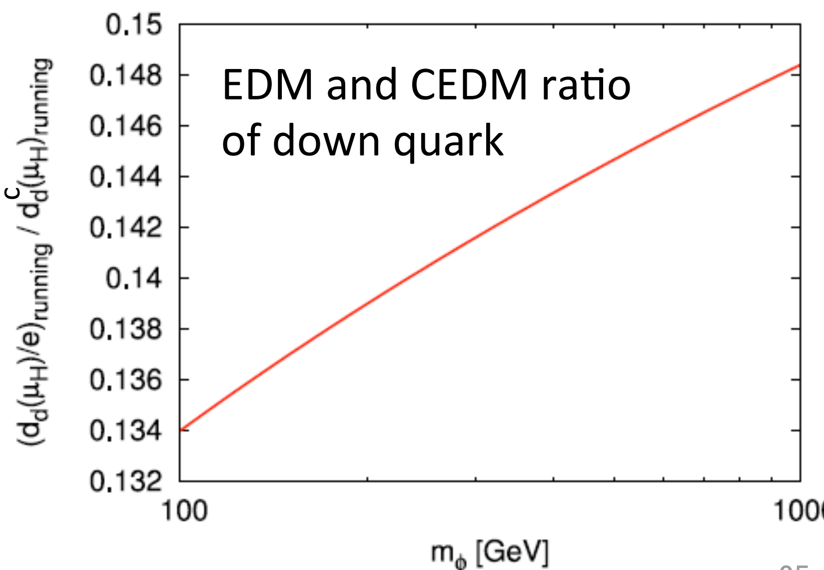
Four-quark scalar operators generate CEDM and EDM at $O(\alpha_s)$ and $O(\alpha_s^2)$, respectively.



Barr-Zee diagrams

$$f_S^d = f_P^d = 1 \qquad f_S^b = f_P^b = 1.$$





(JH, Tsumura, Yang)

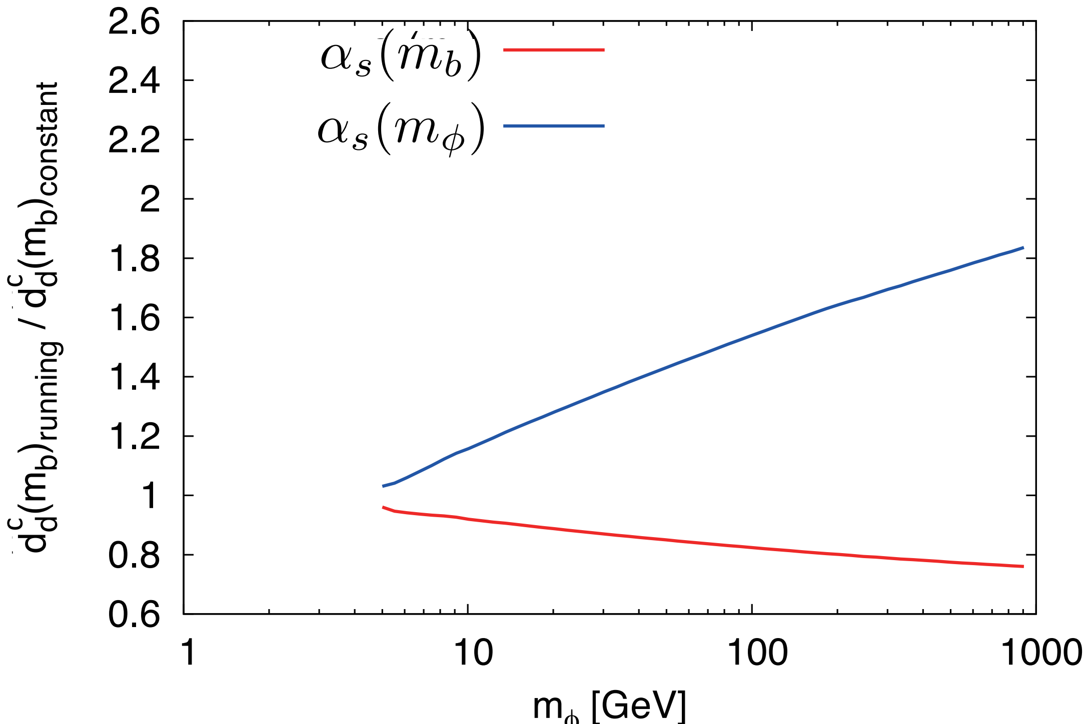
Renormalization-group effects

CP-violating Higgs contribution to CEDM at $O(\alpha_s)$:

$$\frac{d_q^c}{m_q} = C_2^q = \frac{\alpha_s}{8\pi^3}\frac{m_{q'}}{m_q}\left(\ln\frac{m_\phi}{m_{q'}}\right)^2\left[\widetilde{C}_1^{q'q} + \widetilde{C}_1^{qq'}\right].$$

Renormalization-group effects can change the EDM up to O(10) %:

$$f_S^d = f_P^d = 1 \qquad f_S^b = f_P^b = 1.$$

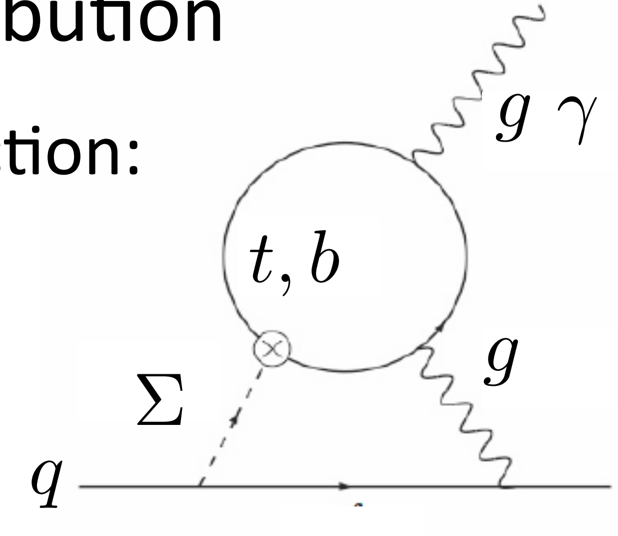


(JH, Tsumura, Yang)

Color-octet boson contribution

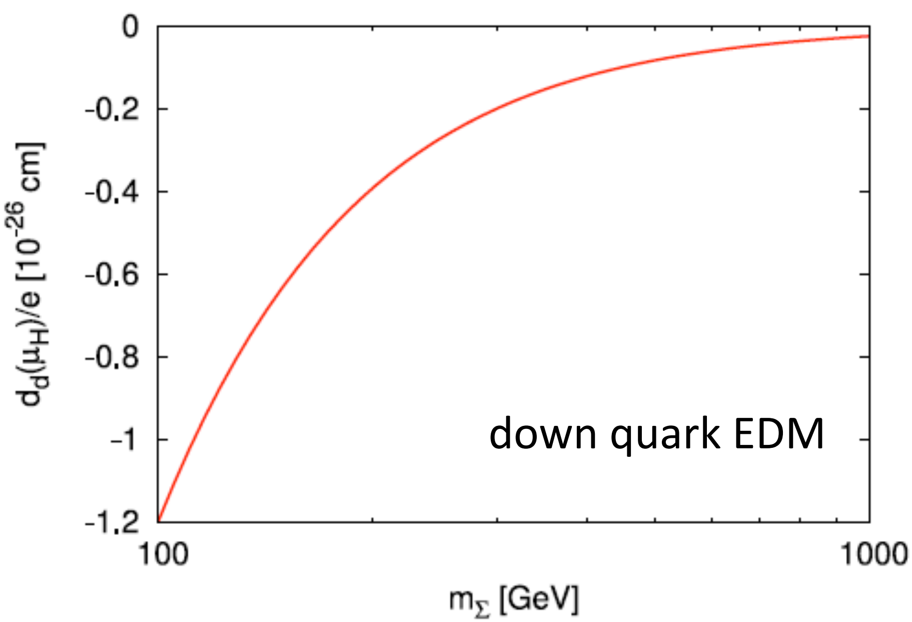
CP-violating color-octet Higgs (Σ) interaction:

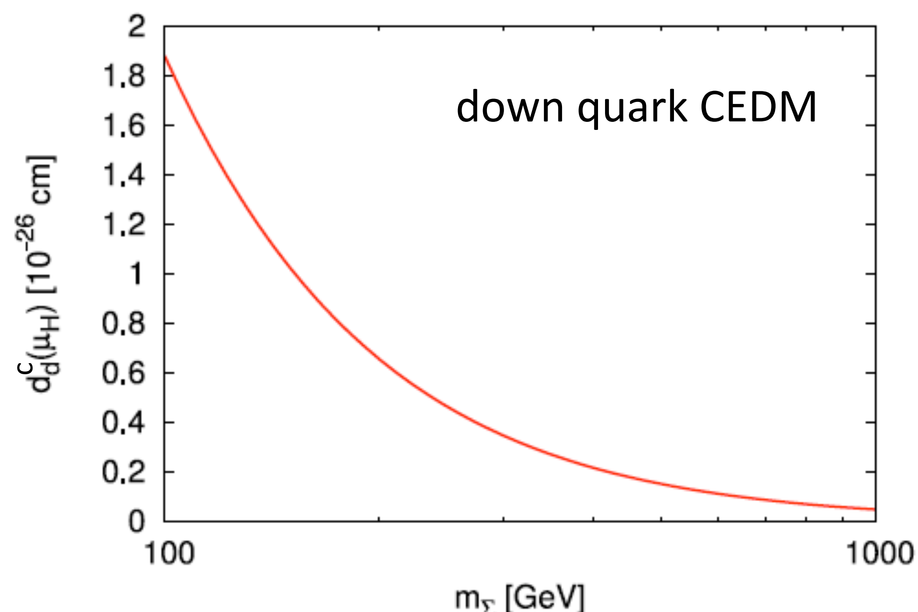
$$\mathcal{L}_\Sigma = 2^{1/4} G_F^{1/2} m_q \overline{q_\alpha} (f_S^q + i\, f_P^q \gamma_5) q_\beta \Sigma_{\alpha\beta}$$



Four-quark scalar operators generate both CEDM and EDM at $O(\alpha_s)$.

$$f_S^d = f_P^d = 1 \qquad f_S^b = f_P^b = 1.$$



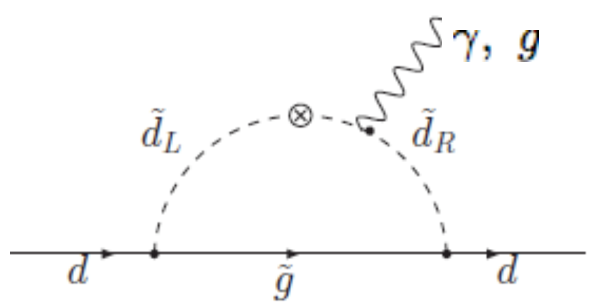


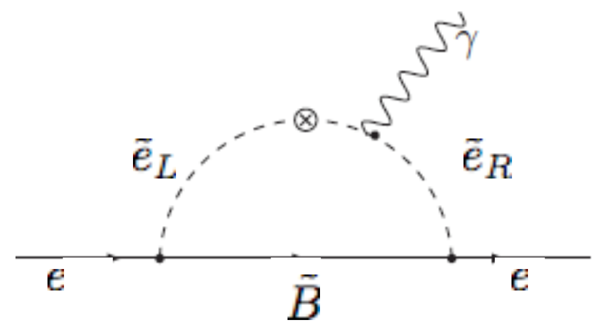
(JH, Tsumura, Yang)

Supersymmetric standard model

SUSY SM is a leading candidate for BSM. Many SUSY breaking parameters introduced there are complex so that EDMs are predicted. One-loop diagrams of SUSY particles generate (C)EDMs. Assuming maximal CP violation,

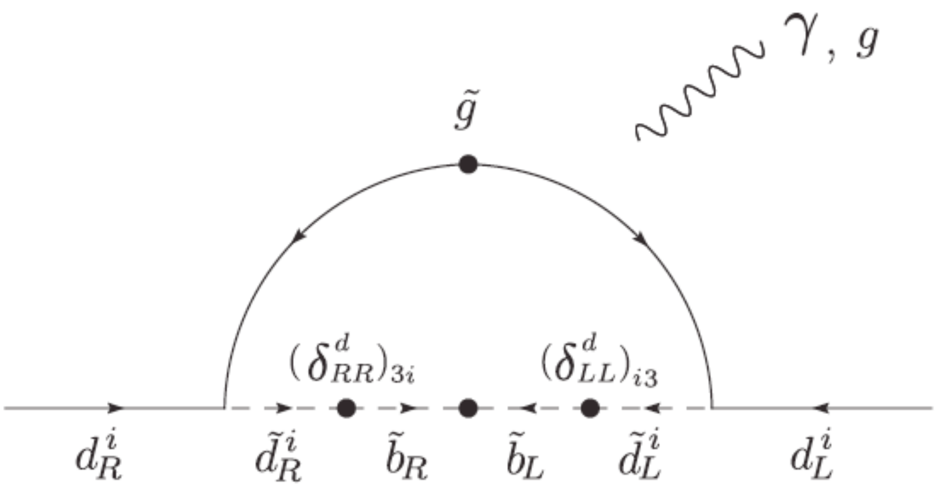
$$d_d/e \sim d_d^c \sim 10^{-25}\mathrm{cm} \times Q_d \left(\frac{M_{\mathrm{SUSY}}}{1\mathrm{TeV}}\right)^{-2} \tan\beta$$





Flavor-violation and EDM in SUSY SM (1)

In SUSY SM, new flavor violation is introduced in squark and slepton mass matrices. Relative phases between two mixing matrices for diagonalizing the mass matrices contribute to EDMs.

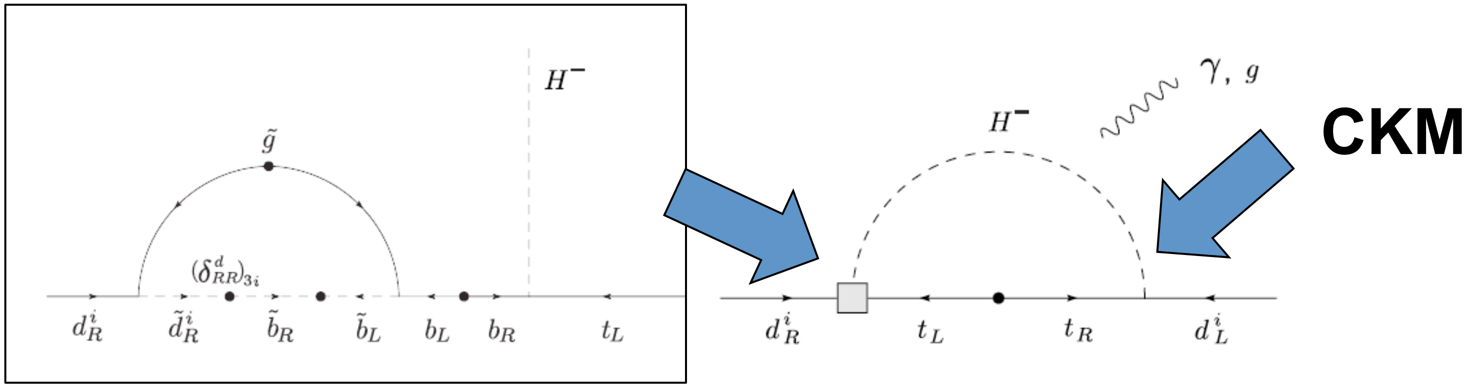


When both left- and right-handed squark mass matrices have off-diagonal (flavor-violating) terms, the relative phase contributes to EDM

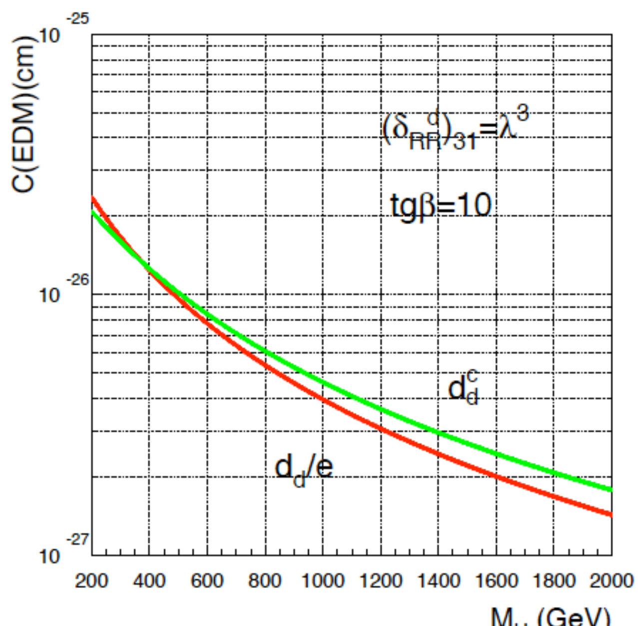
$$d^c_d \simeq 10^{-25}\mathrm{cm} \times \left(\frac{m_{\mathrm{SUSY}}}{500\mathrm{GeV}}\right)^{-2} \left(\frac{(\delta^d_{LL})_{13}}{8\times 10^{-3}}\right)\left(\frac{(\delta^d_{RR})_{31}}{0.1}\right)\tan\beta$$

Flavor-violation and EDM in SUSY SM (2)

Anomalous flavor-changing charged Higgs interaction generates EDM.



Even if SUSY particles are much heavier than the weak scale, the charged Higgs may generate sizable EDM.



(JH, Nagai, Paradisi)

Summary of my talk

While EDMs in the SM are suppressed, they are sensitive to CP violation in new physics at TeV scale. It is expected for the measurements to be improved furthermore. The measurements will be important whether the LHC discovers new physics or not.

Neutron EDM has various sensitivities to beyond the standard model since neutron is a composite particle. On the other hand, it is still difficult to evaluate neutron EDM from parton-level interactions. While it should be evaluated with lattice (it's dream), we also have to develop other methods for a while. I hope you join in and consider with us.