Electric dipole moment of light nuclei

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Introduction

Introduction

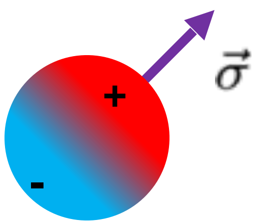
CP violation of Standard model is not sufficient to explain matter/antimatter asymmetry …

	ratio photon : matter
Prediction of Standard model:	10^{28} : 1
Real observed data:	10^{10} : 1

We need new source(s) of
large CP violation beyond the standard model !

How to search ?

Electric dipole moment: $\langle \vec{d} \rangle = \langle \psi | \, e\vec{r} \, | \psi \rangle$



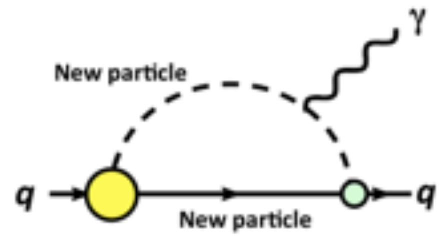
EDM is CP-odd !

$$\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$$

EDM as a sensitive probe of BSM physics

Naïve estimation of neutron EDM:

- Coupling of new physics ~ O(1) (naturalness assumption)
- Contribute from one-loop graph
- 1 Yukawa coupling (required for chirality flip)
- d_n/d_q ~ O(1) (hadron level analysis)



$$d_n = \frac{Y_q e}{4\pi^2 M_{\rm NP}} \sim \frac{10^{-21}}{M_{\rm NP}/{\rm GeV}} e\, cm$$

Exp data: $d_n < 2.9 \times 10^{-26}$ e cm

C. A. Baker *et al.*, Phys. Rev. Lett. **97**, 131801 (2006).

⇒ Current exp data of Neutron EDM can probe M_{NP} ~ 10TeV!

(for $d_n < 10^{-28}$ e cm , M_{NP} ~ 1000TeV can be probed: well beyond reach of LHC!)

EDM is an attractive observable!

Nuclear EDM

Why the nuclear EDM?

- Nuclear EDM is sensitive to hadron level CP violation

  (hadron level CP violation is generated by CP violating operator with gluons and quarks)

- Standard model contribution is very small : $O(10^{-31})$e cm

  NY and E. Hiyama, to be submitted soon

- Nuclear EDM may enhance the CP violation through many-body effect

  (Cluster, deformation make the parity violation easier)

  V. V. Flambaum, I. B. Khriplovich and O. P. Sushkov, Phys. Lett. B**162**, 213 (1985);
  NY and E. Hiyama, Phys. Rev. C **91**, 054005 (2015).

- Nuclear EDM does not suffer from Schiff's screening encountered in atomic EDM

  (No electron to screen the nucleus)

- Very accurate measurement of EDM is possible using storage rings

  $\Rightarrow O(10^{-29})$e cm !

⇨ Nuclear EDM is a very good probe of BSM

EDM of charged particles using storage rings

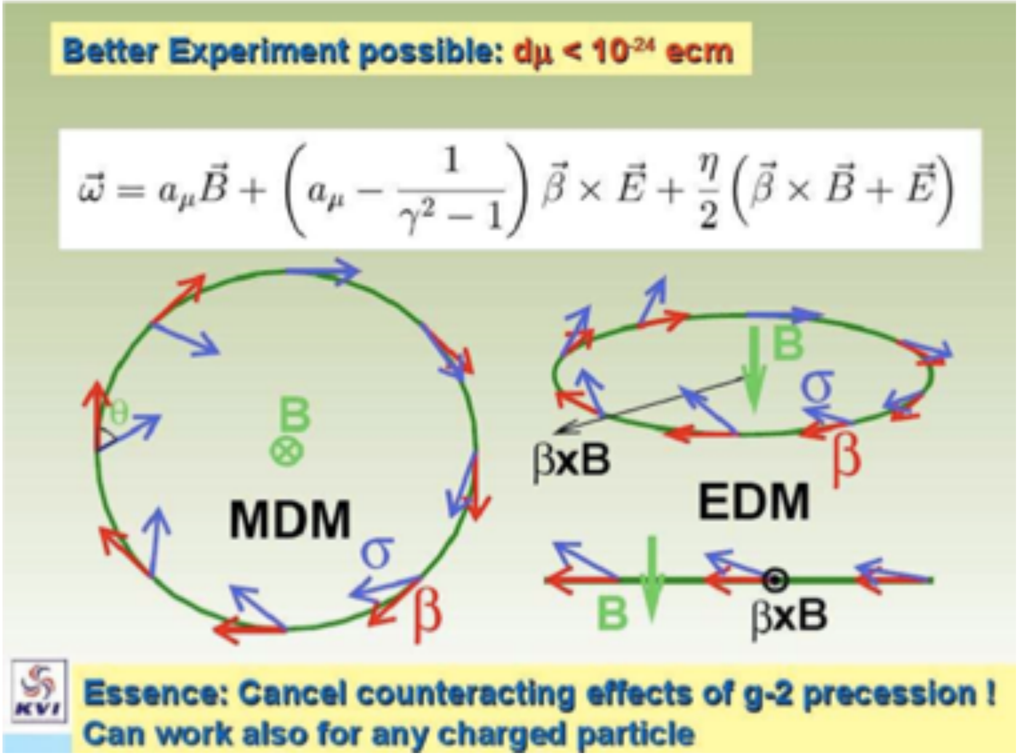
Rotating particles in a storage ring feel very strong central effective electric field

The spin precession of the charged particle can be measured
if magnetic moment is kept collinear to the particle momentum.
(strong electric field normal to the precession plane)

Measurements of the EDMs of muon, proton, deuteron, ^{3}He are planned.

Prospective sensitivity:

➡ $O(10^{-29})$ e cm!!



(prepared at BNL)

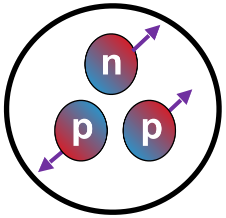
➡ EDM of <u>light nuclei</u> is accurately measurable!

Nuclear EDM from nucleon level CP violation

Two leading contributions to be evaluated:

1) Nucleon's intrinsic EDM:

Contribution from the nucleon EDM

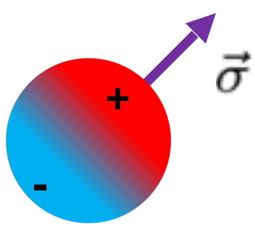


$$D^{(1)} = \langle \psi | \sum_{i=1}^{A} \frac{1}{2} [(d_p + d_n) + (d_p - d_n)\tau_i^z] \sigma_i^z | \psi \rangle$$

⇒ Spin expectation value (CP-even)

2) Polarization of the nucleus:

Contribution from the P, CP-odd nuclear force



$$D^{(\mathrm{pol})} = \langle 0 | \hat{D}_z | \tilde{0} \rangle + \mathrm{c.c.}, \qquad \hat{D}_z = \frac{e}{2} \sum_{i=1}^{A} (1 + \tau_i^z) z_i$$

⇒ EDM generated by the CP-even ⇄ CP-odd mixing

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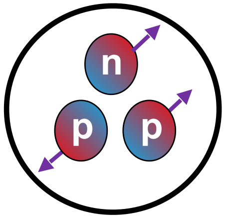

⇒ Spin expectation value (CP-even)

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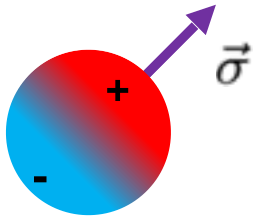


⇒ EDM generated by the CP-even ⇄ CP-odd mixing

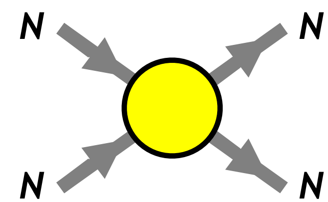
May be enhanced by many-body effect!

Nuclear EDM (polarization) from CP-odd nuclear force

Electric dipole operator requires CP mixing to have finite expectation value

Total hamiltonian:

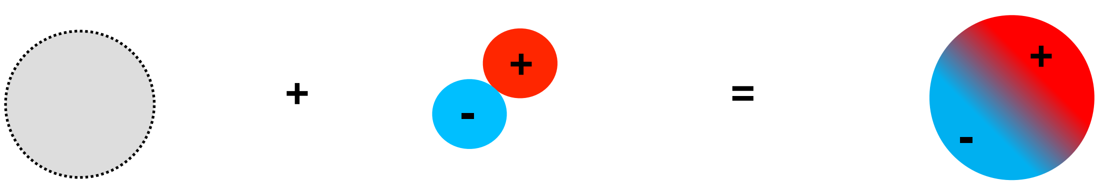
$$H = \begin{pmatrix} H_{\text{realistic}} & H_{\not{P}\not{T}} \\ H_{\not{P}\not{T}} & H_{\text{realistic}} \end{pmatrix}$$



P, CP-odd nuclear force

P, CP-even realistic nuclear force (e.g. Av18,xEFT,...)

CP-odd N-N interactions mixes opposite parity states

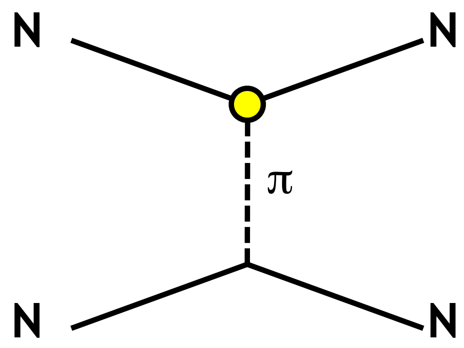


s-wave p-wave polarized system

Parity mixing ⇒ Polarized ground state!

P, CP-odd nuclear force from one pion exchange

P, CP-odd nuclear force : we assume one-pion exchange process



$$\sim \frac{1}{q^2 - m_\pi^2} \bar{N}N \; \bar{N} i \gamma_5 N$$

- **P, CP-odd Hamiltonian (3-types):**

$$H_{\not P \not T} = -\frac{g_{\pi NN}}{8\pi m_p} \left[\left(\underbrace{\bar{g}^{(0)}_{\pi NN}}_{\text{Isoscalar}} \tau_a \cdot \tau_b + \underbrace{\bar{g}^{(2)}_{\pi NN}}_{\text{Isotensor}} (\tau_a \cdot \tau_b - 3\tau_a^z \tau_b^z) \right) (\vec{\sigma}_a - \vec{\sigma}_b) + \underbrace{\bar{g}^{(1)}_{\pi NN}}_{\text{Isovector}} (\tau_a^z \vec{\sigma}_a - \tau_b^z \vec{\sigma}_b) \right] \cdot \vec{\nabla}_a \frac{e^{-m_\pi r_{ab}}}{r_{ab}} ,$$

- **4 important properties:**
  - Coherence in nuclear scalar density : enhanced in nucleon number
  - One-pion exchange : suppress long distance contribution
  - Spin dependent interaction : closed shell has no EDM
  - Derivative : contribution from the surface

- **What is expected:**
  - Polarization effect grows in *A* for small nuclei
  - May have additional enhancements with cluster, deformation, …

What we want to do

⇒ Nucleon level CPV is unknown and small : linear dependence

⇒ Linear coefficients depends on the nuclear structure

⇒ We want to find nuclei with large enhancement factors

⇒ We must calculate the nuclear structure with nucleon level CPV

Dependence of nuclear EDM on nucleon level CP violation must be written as:

Unknown parameter of CP violation beyond standard model

$$d_A = \left(c_0 \bar{g}^{(0)}_{\pi NN} + c_1 \bar{g}^{(1)}_{\pi NN} + c_2 \bar{g}^{(2)}_{\pi NN} \right) \times 10^{-13} e\,\mathrm{cm}$$

Depends on the nuclear structure!

⇒ We want to evaluate red factors and find interesting nuclei!

Infinitesimally shifted Gaussian expansion method

A sophisticated method to calculate few-body system

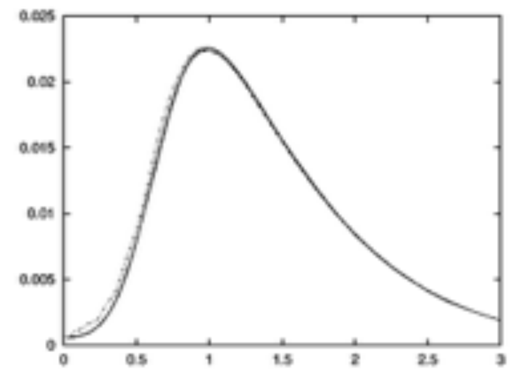
E. Hiyama *et al.*, Prog. Part. Nucl. Phys. **51**, 223 (2003).

- **Basis function:** $$\phi_{lm}(\mathbf{r}) = \sum_n N_{nl} \sum_k C_{lm,k} e^{-\nu_n (\mathbf{r}-\mathbf{D}_{lm,k})^2}$$

- **Variational method**

- **Successful in the benchmark calculation of ^{4}He binding energy**

  H. Kamada et al., Phys. Rev. C **64**, 044001 (2001).



^{4}He Density distribution

- **It is applied in many subjects: Nuclei, Hypernuclei, atoms, hadrons, astrophysics, …**

We expect accurate calculation of nuclear EDM!

Results
(^{2}H, ^{3}He, ^{3}H, ^{6}Li, ^{9}Be, ^{13}C, ^{13}N EDM)

Ab initio evaluations (^2H, ^3He)

Ab initio:

Solve the full many-body Schroedinger equation with given hamiltonian.

- **Deuteron EDM:**

Group	Nuclear force	c_0	c_1	c_2
Liu & Timmermans Liu et al., PRC **70**, 055501 (2004)	Av18	0	$1.43 \times 10^{-2} e$ fm	0
GEM (our work)	Av18	0	$1.45 \times 10^{-2} e$ fm	0

- **^{3}He EDM:**

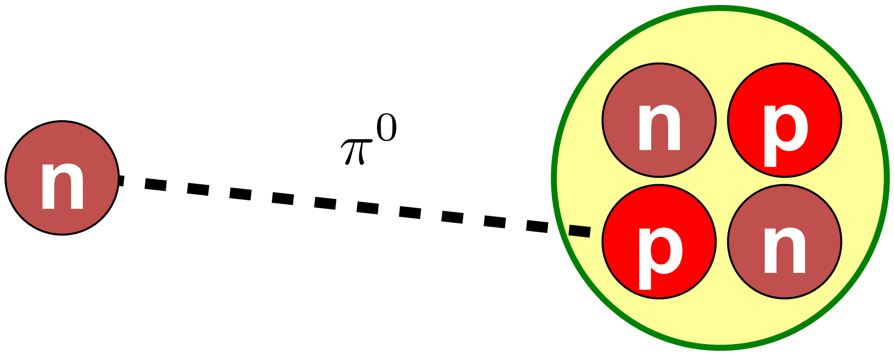
Group	Nuclear force	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Faddeev Bsaisou et al., JHEP **1503** (2015) 104	N^2LO chiral EFT	0.0079 *e* fm	0.0101 *e* fm	0.0169 *e* fm
GEM (our work) NY, E. Hiyama, PRC **91**, 054005 (2015)	Av18	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm

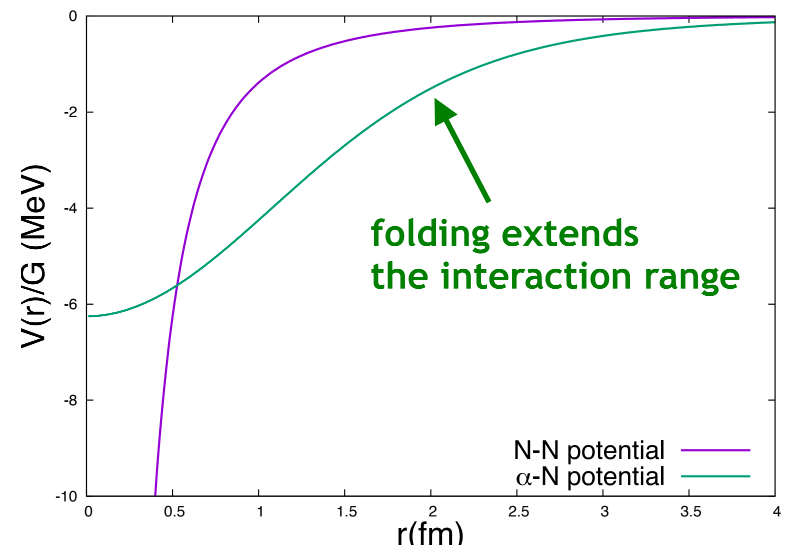
⇒ Consistent with previous works!

CP-odd nuclear force with cluster (CP-odd α-N interaction)

Integrate the CP-odd N-N interaction with the ^{4}He nucleon density

(α cluster is indestructible)





Gaussian approximation of density:

$$\rho_\alpha(r) = Ae^{-\frac{r^2}{b}}$$

Spread : b = (1.358 fm)^2

Only isovector CP-odd nuclear force is relevant in N-α interaction

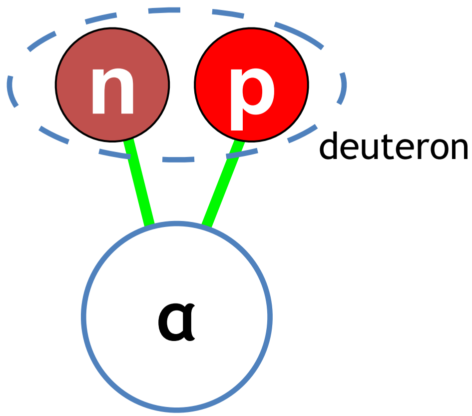
(Isoscalar and isotensor CP-odd nuclear forces cancel by folding)

⇒ Can reduce the calculation of p-shell nuclei

to few-body problem

NY, E. Hiyama, Phys. Rev. C **91**, 054005 (2015).

Result : ^{6}Li EDM



Binding energy : 3.7 MeV

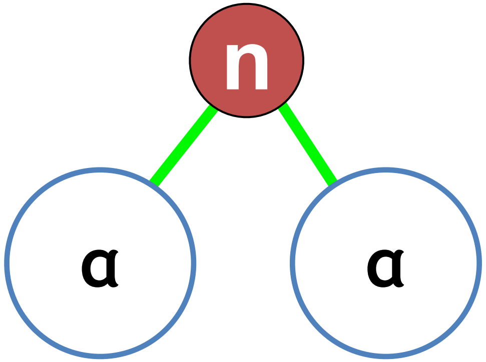
^{6}Li is well described with α+d

Nuclear force	<σ>	<στ>	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Av8'+cluster model	0.88	–	–	0.028 e fm	–

- ^{6}Li EDM is made of 2 comparable components:
  - Deuteron cluster polarization : slightly smaller than deuteron EDM
  - CP-odd α-N interaction effect
- Compare with deuteron EDM (c_1 = 0.0145 e fm) :

⇒ ^{6}Li enhances the CP-odd effect ! (twice deuteron EDM)

Result : ^{9}Be EDM



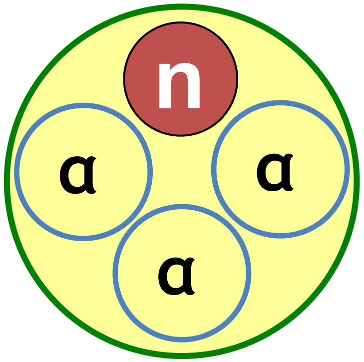
Binding energy : 1.57 MeV

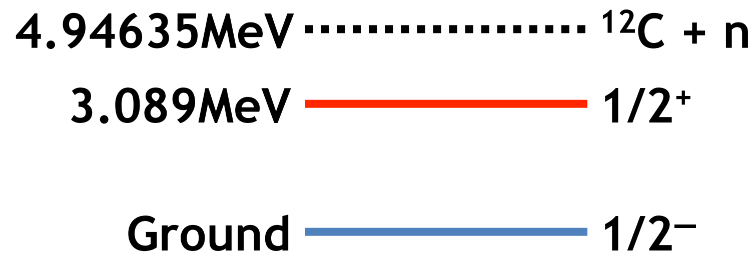
Nuclear force	$\langle\sigma\rangle$	$\langle\sigma\tau\rangle$	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Cluster model	0.38	-0.38	–	0.017 *e* fm	–

- Sensitivity to isovector CP-odd nuclear force comparable to deuteron
- Polarization due to the CP-odd α-N interaction

(No polarization from α-α system)

Result : ^{13}C EDM





Energy levels of ^{13}C

Nuclear force	$\langle\sigma\rangle$	$\langle\sigma\tau\rangle$	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
Cluster model	-0.17	0.17	–	-0.0061 *e* fm	–

- Smaller sensitivity than lighter nuclei

  Bad overlap with 1/2+ excited state?

  - Ground state is shell like, but 1/2+ is neutron halo like.
  - Bad core overlap between Ground and 1/2+ states.

- Opposite sign : orbital angular momentum and spin are antiparallel

Result

EDM	isoscalar (c_0)	isovector (c_1)	isotensor (c_2)
^{129}Xe atom N. Yoshinaga et al., talk of this conference Dzuba et al., PRA 80, 032120 (2009)	1.0×10^{-7} e fm	3.0×10^{-8} e fm	7.6×10^{-8} e fm
^{199}Hg atom Ban et al., PRC 82, , 015501 (2010) Dzuba et al., PRA 80, 032120 (2009)	4.7×10^{-6} e fm	-1.8×10^{-6} e fm	7.5×10^{-6} e fm
^{225}Ra atom Dobaczewski et al., PRL 94, 232502 (2005) Dzuba et al., PRA 80, 032120 (2009)	0.00088 e fm	-0.0052 e fm	0.0035 e fm
Neutron (Chiral analysis)	0.01 e fm	–	– 0.01 e fm
Deuteron Liu et al., PRC **70**, 055501 (2004) NY and EH, PRC **91**, 054005 (2015)	–	0.0145 e fm	–
^{3}He nucleus Bsaisou et al., JHEP **1503** (2015) 104 NY and EH, PRC **91**, 054005 (2015)	0.0060 *e* fm	0.0108 *e* fm	0.0168 *e* fm
^{6}Li nucleus NY and EH, PRC **91**, 054005 (2015)	–	0.028 *e* fm	–
^{9}Be nucleus NY and EH, PRC **91**, 054005 (2015)	–	0.017 *e* fm	–
^{13}C nucleus	–	–0.0061 *e* fm	–
^{13}N nucleus	–	–0.0071 *e* fm	–

Preliminary

Our result

Summary:

- We have studied the EDM of light nuclei using the Gaussian Expansion Method.
- Large EDM for ^{6}Li : suggest enhancement of EDM due to cluster structure.
- Small EDM for ^{13}C EDM : may be understood by the small overlap between 1/2- and 1/2+ states.
- Our results are a very good guide to search for nuclei with large enhancement factors.

Future subjects:

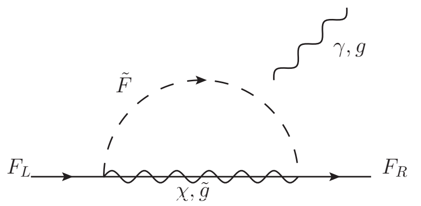
- Further study of EDM of light nuclei: find sensitive nuclei respecting the analysis of this work.
- We are waiting for experiments!

Sensitivity to new physics beyond standard model

If the EDM of light nuclei can be measured at $O(10^{-29})$e cm:

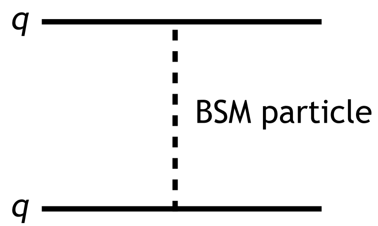
- **Supersymmetric model:**

  ⇒ Can probe 10 TeV scale SUSY breaking



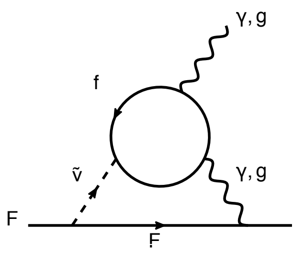
- **Models with 4-quark interactions:**

  ⇒ Can probe PeV scale physics
  (Left-right symmetric model, …)



- **Models with Barr-Zee type diagrams:**

  ⇒ Can probe PeV scale physics
  (Higgs doublet models, RPV SUSY, …)



EDM is an attractive observable in the search for BSM physics!

End