Large electron electric dipole moment in the standard model

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(based on arXiv:2003.08195 [hep-ph])

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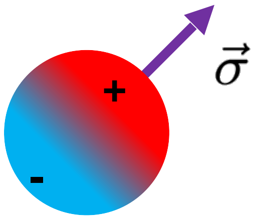
The electric dipole moment (EDM) is a powerful tool to search CP violation beyond standard model

EDM: $$\langle \vec{d} \rangle = \langle \psi | \, e\vec{r} \, | \psi \rangle$$



EDM is CP-odd ! $$\begin{cases} \vec{E} \xrightarrow{\mathrm{T}} \vec{E} \\ \vec{\sigma} \xrightarrow{\mathrm{T}} -\vec{\sigma} \end{cases}$$

Recent development of electron EDM experiments is impressive

Molecular beam experiment
(Electron EDM record : $d_e < 1.1\times10^{-29}$e cm!).

V. Andreev et al. [ACME Collaboration], Nature **562**, no. 7727, 355 (2018).

We are expecting to unveil BSM CP violation

But we do not have to forget that standard model (phase of CKM matrix) also contributes to the EDM

We actually found a 10^{10} times larger contribution than previous works!

What about the standard model contribution?

The SM contributes to the EDM through the CP phase of CKM matrix

It is often said that the SM contribution is small for the electron EDM.

We found a much larger contribution to the electron EDM at the hadron level

The calculation of the SM contribution is important because

- The SM contribution is an important background in EDM exp.
- If the SM contribution is large, good probe of CKM unitarity.

Object of Study:

➡ **Quantify the SM (CKM) contribution to the electron EDM.**

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CP violation in the Standard model:

Complex phase of Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

δ : CP violating phase

Relevant CP violation:

Jarlskog invariant (invariant in parametrization of CKM)

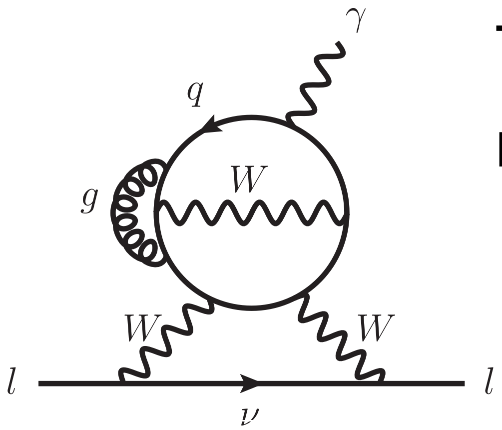
$$J = \mathrm{Im}[V_{ts}^* V_{td} V_{us} V_{ud}^*] = -\mathrm{Im}[V_{cs}^* V_{cd} V_{us} V_{ud}^*]$$

C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985).

$$= (3.06 \pm 0.21)\times 10^{-5} \text{ (PDG value)}$$

Leading CP violation of CKM appears
through the Jarlskog combinations

Quark level calculation of the electron EDM: 4-loop



To form the Jarlskog constant, 4 CKM elements are needed

Lepton connected to quark via W bosons

⇒ At least 3 W bosons needed : 3-loop?

⇒ 3-loop diagram cancels due to GIM mechanism!

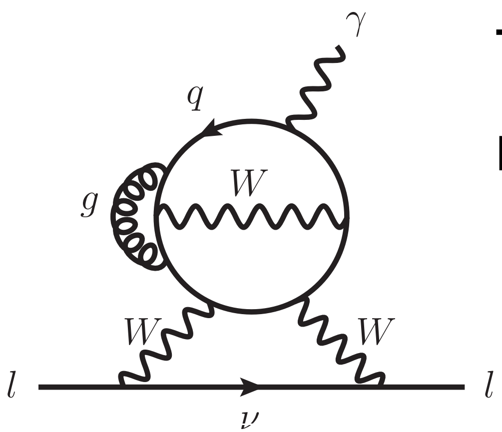
M. E. Pospelov and I. B. Khriplovich, Sov. J. Nucl. Phys. **53**, 638 (1991);
M. Pospelov and A. Ritz, Phys. Rev. D **89**, 056006 (2014).

Estimation at 4-loop level:

$$d_e \sim \frac{eJ\alpha_W^3 \alpha_s m_e m_s^2 m_c^2 m_b^2}{(4\pi)^4 m_W^8} \sim O(10^{-50}) e\,\mathrm{cm}$$

(Appearance of this suppression factor can be proven at all order: see our paper, to be submitted soon)

But we found a much bigger contribution at the hadron level !



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This suppression factor always appears!

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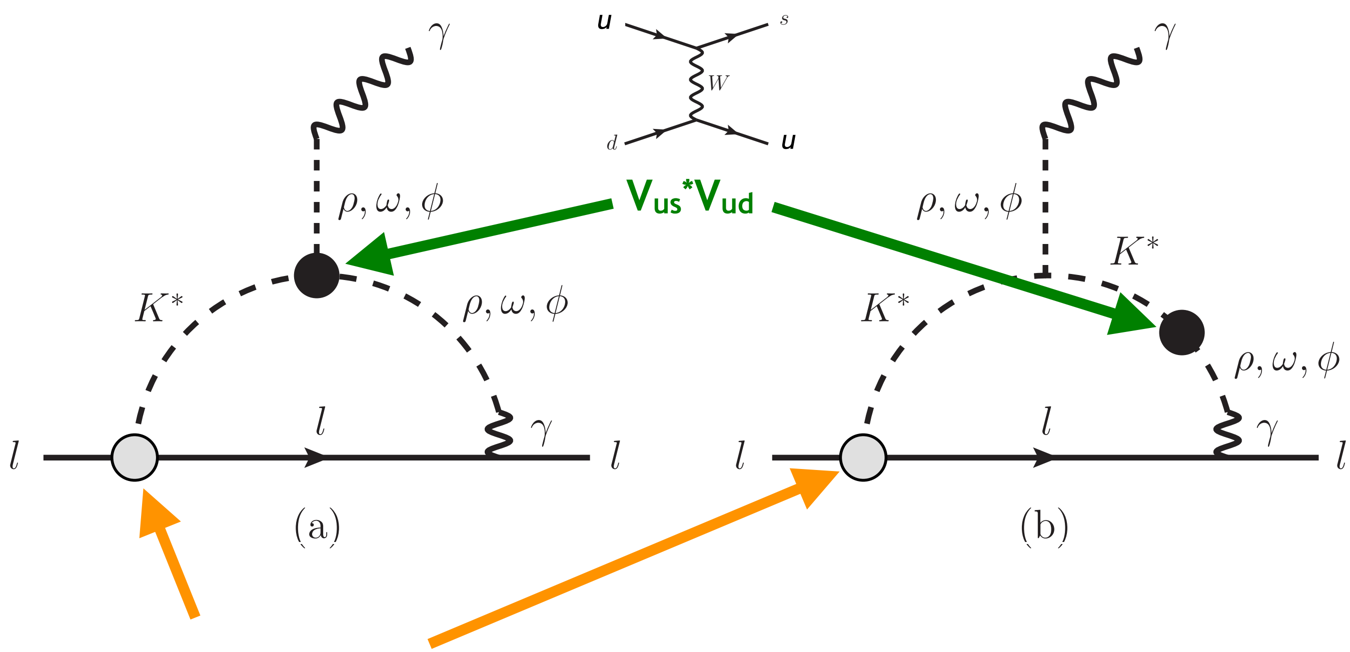
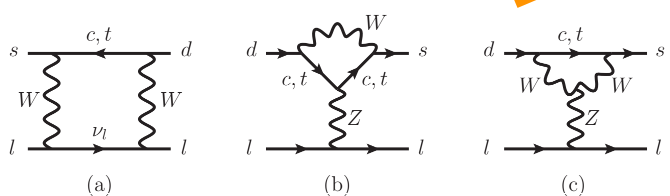
Electron EDM generated at hadron level





Semi-leptonic one-loop diagram generates effective K*-electron interaction!

(with $V_{cs}^* V_{cd}$, $V_{ts}^* V_{td}$)

Naive estimation of this loop diagram:

$$d_e \propto \frac{m_e\, J\, G_F^2\, \alpha_{QED}^2}{(4\pi)^4} \Rightarrow d_e \sim O(10^{-39}) e\ \text{cm !!}$$

Y. Yamaguchi and NY, arXiv:2003.08195 [hep-ph].

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Hadron level effective interaction

- **Strong interaction: Hidden local symmetry (HLS)**

$$\mathcal{L}_{\rm HLS} = -\frac{1}{2}{\rm Tr}[\rho_{\mu\nu}\rho^{\mu\nu}] + m_\rho^2 {\rm Tr}[\rho_\mu \rho^\mu] - f_\rho {\rm Tr}[\rho_{\mu\nu}F^{\mu\nu}] - 4ig_V {\rm Tr}[\rho_{\mu\nu}\alpha_\perp^\mu \alpha_\perp^\nu]$$

⇒ **Vector mesons are gauge bosons of the HLS**

⇒ **Determined from the ρ meson as a P-wave resonance of ππ scattering**

M. Bando, T. Kugo, S. Uehara, K. Yamawaki, and T. Yanagida, PRL **54**, 1215 (1985).
U.-G. Meissner, Phys. Rep. **161**, 213 (1988);
M. Harada and K. Yamawaki, Phys. Rep. **381**, 1 (2003).

- **Weak interaction:**

Use factorization and lattice QCD results

Example : $\langle K^* | \bar s \gamma_\mu u \, \bar u \gamma^\mu d | \rho \rangle \approx \langle K^* | \bar s \gamma_\mu u | 0 \rangle \langle 0 | \bar u \gamma^\mu d | \rho \rangle$

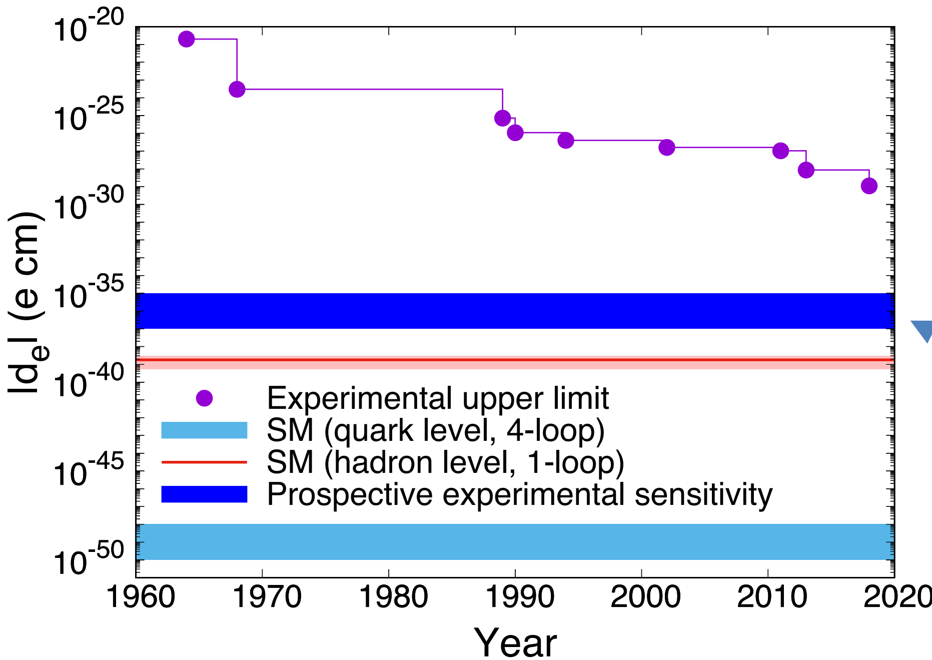
$$\approx f_{K^*} f_\rho \epsilon_\mu^* \epsilon^\mu$$

Known from lattice QCD, phenomelogy
(f ∼ 200 MeV)

(Factorization works with error bar of O(1/N_c) for mesons)

Result of hadronic loop calculation

$d_e = 2 \times 10^{-39}$ e cm



⇒ More than 8 orders of enhancement compared to quark loop!

Prospective experimental sensitivity

Vutha et al., Atoms **6**, 3 (2018)
Special Issue on High Precision Measurements of Fundamental Constants.
(arXiv:1710.08785 [physics.atom-ph])

Still below the experimental sensitivity, but some hope in the future??

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Y. Yamaguchi and NY, arXiv:2003.08195 [hep-ph].

Summary

- The electron EDM at the quark level starts from the four-loop level, very small $d_e = O(10^{-50})$e cm, due to quark mass suppression factor $m_s^2 m_c^2 m_b^2 m_t^2$.
- Electron EDM receives large contribution from vector meson loops : $d_e = O(10^{-39})$e cm ⇒ Enhancement by many orders of magnitude compared to the quark loop estimation.

Future works:

- Analysis of systematics : contribution from heavier axial/vector mesons ($K_1(1270)$, a_1, D^* mesons, etc) ?
- We are waiting for experiments.

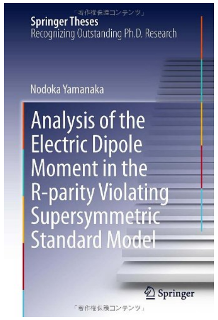
End

Advertisement : some reviews

- N. Yamanaka,
  Review of the electric dipole moment of light nuclei,
  International Journal of Modern Physics E 26, 1730002 (2017)
  arXiv:1609.04759 [nucl-th].

- N. Yamanaka, B. K. Sahoo, N. Yoshinaga, T. Sato, K. Asahi and B. P. Das,
  Probing exotic phenomena at the interface of nuclear and particle physics
  with the electric dipole moments of diamagnetic atoms ,
  European Physical Journal A 53, 54 (2017)
  arXiv:1703.01570 [nucl-th].

- N. Yamanaka,
  Analysis of the Electric Dipole Moment
  in the R-parity Violating Supersymmetric Standard Model,
  Springer, 2014.



→ **EDM Physics is reviewed !!**

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