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Sensitivity of the Equivalent EDM to SMEFT

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The Electric Dipole Moment of the electron (eEDM) is typically investigated in experiments using paramagnetic molecules. However, the physical observable in these searches consists of a linear combination of CP-violating interactions, rather than the eEDM alone, which is commonly referred to as the *equivalent* EDM of the system. Assuming the presence of new CP-odd physics from heavy degrees of freedom, I parametrize its effects within the Standard Model Effective Field Theory (SMEFT) framework. In this talk, I will present the contributions to the full low-energy direction probed by EDM searches, focusing on leading-order effects at dimension six and one-loop level, while also discussing selected two-loop contributions. I will highlight that eEDM experiments are sensitive to a broader class of SMEFT operators than previously recognized.

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1. Introduction

Despite its extraordinary success in explaining fundamental interactions up to the TeV scale, the Standard Model (SM) of particle physics still fails to describe several experimental observations. In particular, according to cosmological observations, our universe is almost fully composed of matter, while the amount of antimatter is orders of magnitude smaller. So far, any attempt to explain this asymmetry within the SM has turned out to be unsuccessful, pointing to the presence of physics beyond the SM. One of the most popular mechanisms to explain the dominance of matter over anti-matter is the so-called baryogenesis, where the antimatter washout is dynamically obtained after imposing three conditions: the Sakharov conditions [4]. One of them requires the presence of CP violation in the theory describing fundamental interactions, in larger amounts than what the SM already provides. It is then crucial to search for signs of CP-violation beyond the SM in present-day experiments. In this regard, the EDMs turn out to be the ideal candidates, given the fact that the SM contribution lies many orders of magnitude below the current upper bounds. In particular, the electron EDM (eEDM) is able to probe scales higher than any other observable and it is less affected by QCD dynamics than the neutron EDM. As of today, the eEDM is not directly measured but it is instead indirectly inferred from atomic or molecular laboratory experiments. These are typically conducted on paramagnetic atoms or molecules, which are sensitive to the EDM of the unpaired electron, along with a CP-odd semileptonic interaction occurring between the electron and nucleons. It is then customary to define an *equivalent* EDM, which is a linear combination of the electron EDM and a term proportional to the semileptonic contribution: the *equivalent* EDM represents the experimental observable in all the present and future electron EDM searches. Crucially, a single experiment cannot distinguish between the two contributions, so if an *equivalent* EDM is detected, it is impossible to determine where the new sources of CP violation originate. In the following, I will present the sensitivity of the *equivalent* EDM to heavy new physics (NP). Given our ignorance about the possible UV completion of the SM, I will parametrize NP using the language of SMEFT, where the new heavy degrees of freedom are integrated out and their effects are encoded in the Wilson coefficients of higher-dimensional operators. By means of the Renormalization Group Evolution (RGE), I will show the sensitivity of the electron EDM experiments to dimension-six operators, beyond the leading log approximation and including selected two-loop effects.

2. The equivalent EDM

EDMs of elementary particles are defined as the proportionality constant in an interaction term between a particle with spin (S) and an external electric field (E) according to the Hamiltonian

$$H_{\mathrm{EDM}} = -d_f \vec{E} \cdot \frac{\vec{S}}{|\vec{S}|}. \tag{1}$$

The Hamiltonian in Eq. 1 is odd under T symmetry, as it can be derived from the transformation properties of E and S. Assuming the validity of the CPT theorem, it also violates CP. However, in order to link the description of the fundamental interactions at the electroweak scale (or above) with the low energy experiments, a QFT generalization of Eq. 1 is needed and the corresponding Lagrangian reads

Molecule	Current bound/Upcoming sensitivity
HfF^+	$< 4.1 \times 10^{-30}$ e cm
ThO	$\sim 1 \times 10^{-30}$ e cm
YbF	$\sim 1 \times 10^{-31}$ e cm
BaF	$\sim 1 \times 10^{-33}$ e cm

Table 1: Current (HfF^+) bound on the electron EDM and expected future sensitivities of the upcoming searches. Table taken from [1].

$$\mathcal{L}_{\text{EDM}} = -\frac{i}{2} d_f \, \bar{f} \, \sigma_{\mu\nu} \, f \, F^{\mu\nu}, \tag{2}$$

where $\sigma_{\mu\nu} = \frac{i}{2}[\gamma_\mu, \gamma_\nu]$ and $F^{\mu\nu}$ is the electromagnetic field strength tensor. Crucially, an EDM Lagrangian term cannot be associated to a tree-level process in any renormalizable theory. As a consequence, EDMs must appear at loop level, making them sensitive to heavy virtual particles, such as those predicted by many SM extensions, even if those particles are too massive to be directly produced in colliders. In particular, the EDM of the electron is sensitive to scale as large as $\sim 10^6$ TeV, if we do not assume Minimal Flavor Violation. This estimate can be obtained by imposing the present-day upper bound $d_e < 4.1 \times 10^{-30}\, \text{e} \cdot \text{cm}$, which is expected to improve by up to three orders of magnitude in the following years. A summary of the current bound and future projections is shown in Tab. 1. In comparison, the SM prediction is extremely suppressed, showing the first contribution to the electron EDM at four loops in perturbation theory. Nowadays, the state-of-the-art estimate of the dominant contribution to the eEDM stems from long-distance effects and points to $d_e \sim 10^{-40}\, \text{e} \cdot \text{cm}$, a value ten orders of magnitude smaller than the present-day sensitivity and unlikely to be reached even in the most daring future experiments. As a result, any detection of an eEDM would be a clear sign of NP.

However, experiments searching for an eEDM are typically conducted on paramagnetic systems which are sensitive to the eEDM and a semileptonic interaction between electrons and nucleons. Moreover, a single experiment cannot distinguish between the two different contributions, so that the actual observable results in a linear combination of the eEDM and the Wilson coefficient of the semileptonic interaction, commonly referred to as the *equivalent* EDM. Starting from the low-energy theory at the experimental scale ($\sim m_e$), the relevant Lagrangian reads

$$\mathcal{L} = -i\frac{d_e}{2}\bar{e}\sigma_{\mu\nu}\gamma_5 e F^{\mu\nu} + \frac{G_F}{\sqrt{2}} C_S \bar{e} i\gamma_5 e \bar{N} N, \tag{3}$$

that allows one to express the *equivalent* EDM as

$$d_{sys}^{equiv.} = d_e \, + \, f_{sys.} C_S \ , \tag{4}$$

where f_{sys} is a proportionality constant that depends on the specific paramagnetic system. In the case of the HfF^+ molecule, this value amounts to $0.9 \times 10^{-20} e \cdot cm$. Within the SM, d_{sys}^{equiv} is predicted to be five orders of magnitude larger than d_e, due to the fact that δ_{CKM} predominantly feeds into the semileptonic Lagrangian term. In addition, since the experimental bounds in Tab. 1 are typically inferred from the upper bounds of $d_{sys}^{equiv.}$ (by assuming a negligible contribution from C_S), it turns out that there is still large room for NP in electron EDM experiments. Since no new particles have been detected at colliders, it is useful to parametrize such heavy NP effects by means of effective field theory.

3. SMEFT and the Equivalent EDM

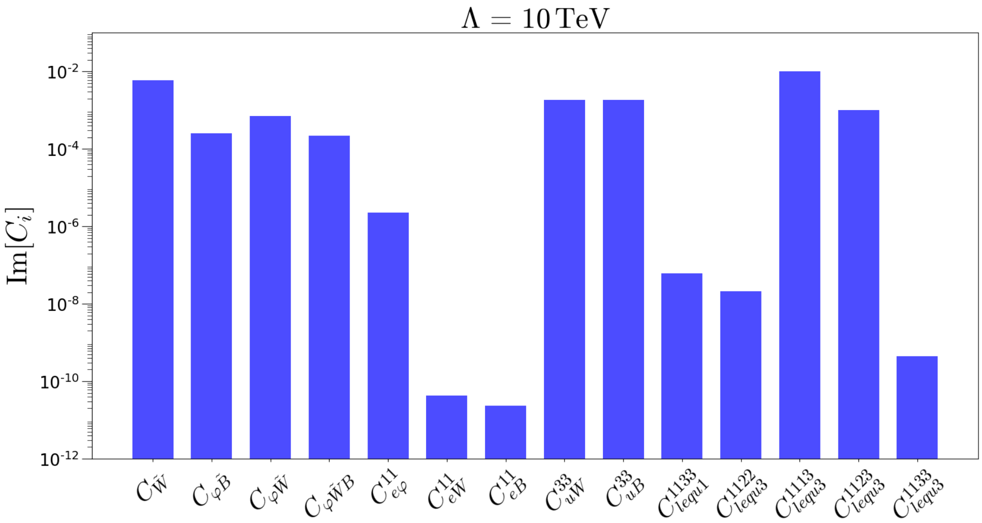

Figure 1: Sensitivities on the imaginary part of the SMEFT Wilson coefficients for the operators that primarily contribute to d_e, from the EDM limit in Tab. (1), assuming Λ = 10 TeV as the initial scale for the running. The first four columns refer to the real part of the corresponding Wilson coefficients, due to the fact that the violation of CP stems from the operators themselves and not from an imaginary coupling [2].

Under the assumption that the NP scale is far above the electroweak scale, Effective Field Theories are a powerful framework to conduct model independent studies. In this context, Heavy NP can be encoded in coefficients of higher dimensional operators built upon SM particles and respecting the SM gauge group, according to the following Lagrangian:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n,i} \frac{C_i^{(n)}}{\Lambda^{n-4}} O_i^{(n)}, \tag{5}$$

where n stands for the energy dimension of the operator. Crucially, higher dimensional operators mix under Renormalization Group Evolution (RGE), allowing us to constrain operators that otherwise are difficult to probe directly. Given the stringent present-day upper bound, the *equivalent* EDM is extremely sensitive to a large class of operators.

In this analysis, I will focus on dimension-six operators expressed in the Warsaw basis [3]. I select one operator at a time at the benchmark energy scale of 10 TeV, which coincides with the starting scale of the running. Then, the one-loop running in SMEFT and tree-level matching at the

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electroweak scale to the Low Energy Effective Theory (LEFT) are performed. Subsequently, the corresponding one-loop running in LEFT until the confinement energy scale Λ_χ is obtained. All the steps above are carried out by using the Python package *wilson*, so that the results are numerical and beyond the leading log approximation. Finally, I match the quarks bilinear in semileptonic operators to the nucleons bilinear by using both EFT and lattice QCD results. The whole procedure enables one to express the *equivalent* EDM at the experimental energy scale $\sim m_e$ in terms of the Wilson coefficient at the UV scale. After imposing the current experimental bound in Tab. 1, a sensitivity on the SMEFT coefficient at the UV scale is obtained.

In Fig. 1, I show a large set of operators where the semileptonic direction is largely suppressed compared to the eEDM, so that $d_{equiv} \sim d_e$. Apart from the dipole operators themselves, large contributions to the eEDM are given by semileptonic operators featuring heavy up quarks, typically providing an enhancement $\sim Y_u$ in the one-loop RGE. Another relevant effect arises from the modification of the electron Yukawa coupling in the SM via $O_{e\varphi}$, providing a large contribution to the eEDM in two-loop Barr-Zee diagrams.

However, some semileptonic operators mainly contribute to the C_S coefficient, showing that this term cannot be neglected when studying NP effects in EDM experiments. The corresponding Wilson coefficients are shown in Fig. 2, where the orange (blue) bars represent the sensitivities of $d_{equiv.}$ (d_e) to the SMEFT operators on the horizontal axis in the case of the HfF$^+$ molecule.

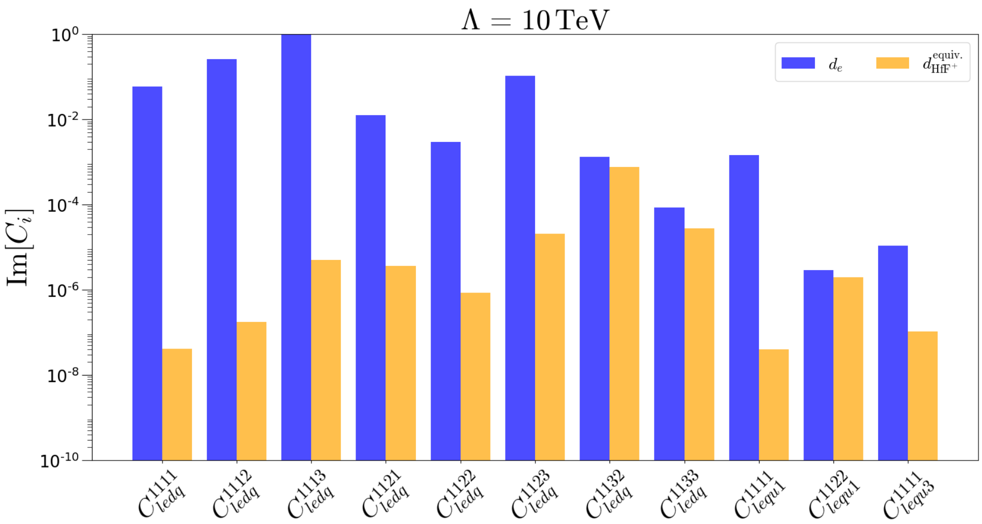

Figure 2: Comparison between the sensitivities on the imaginary part of SMEFT Wilson coefficients from $d^{\text{equiv.}}_{\text{HfF}^+}$ and d_e, considering the experimental limit in Tab. (1) and Λ = 10 TeV as the initial scale for the running. The figure shows only the operators where the upper bound from $d^{\text{equiv.}}_{\text{HfF}^+}$ is stronger than from d_e [2].

In particular, the impact of scalar operators involving down quarks is significantly larger when considering the full direction than when considering the eEDM alone.

Regarding the up quarks sector, only the scalar operator with the up quark results in a large contribution to C_S. Indeed, this operator directly matches onto the semileptonic operator, while it is suppressed by the small up Yukawa in the chain of mixing that leads to the eEDM.

Finally, I report that the only relevant mixing effect in the one-loop RGE stems from the tensor operator with the up quark, which mixes into the corresponding scalar operator at one-loop level through gauge-boson exchange.

4. Conclusion

In this work, I studied how heavy NP affects low energy electron EDM experiments. By using the framework of SMEFT, I systematically analyzed the impact of dimension-six operators in the Warsaw basis to the *equivalent* EDM, which consists of a linear combination of a semileptonic interaction and the electron EDM itself. Crucially, by means of the RGE, higher dimensional operators mix into each other so that the *equivalent* EDM turns out to be highly sensitive to a large class of operators. Previous works in literature focused only on the electron EDM direction, leaving the CP-odd effects due to electron-nucleon interactions in paramagnetic systems so far unprobed. What we find, by exploring the actual observable probed by the eEDM searches, is that this class of experiments is sensitive to a broader class of SMEFT operators than previously recognized.

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References

[1] Marco Ardu, Moinul Hossain Rahat, Nicola Valori, and Oscar Vives. Electric Dipole Moments as indirect probes of dark sectors. *JHEP*, 11:049, 2024.

[2] Marco Ardu and Nicola Valori. The equivalent Electric Dipole Moment in SMEFT. 3 2025.

[3] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek. Dimension-Six Terms in the Standard Model Lagrangian. *JHEP*, 10:085, 2010.

[4] A. D. Sakharov. Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe. *Pisma Zh. Eksp. Teor. Fiz.*, 5:32–35, 1967.