Hadronic CP Violation in the 2HDM

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Based on arXiv 2511.08681
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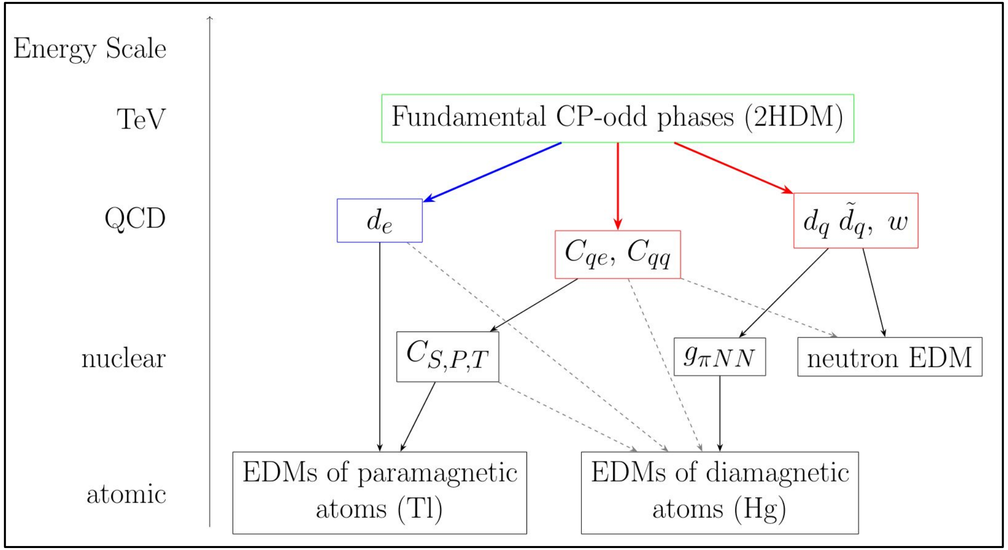
Outline

- Electric dipole moment
- Description of the general 2HDM
- Calculation outline
- Taming the coefficients
- Conclusions

Electric Dipole moment

- Low energy observable of high energy effects due to symmetry
    - Classical EDM flips under CP transformation, therefore it sources only CP violating operators
- Electron EDM is done by us in the previous work 2410.17313 (Blue line)
- Hadronic EDM + CP odd 4 Fermion operators is **new work** 2511.08681 (Red lines)
- All results (both new and old) are fully implemented in python code



2HDM Field Content

- Two complex SU(2) doublets instead of one
  - Additional 4 degrees of freedom
  - Scalar content: +2 charged, 3 neutral (2 new 1 old Higgs)
- Neutral scalars mix when switching to mass basis allowing for CP violation

$$H_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}\left(v + \varphi_1^0 + iG^0\right) \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}\left(\varphi_2^0 + ia^0\right) \end{pmatrix}$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} q_{11} & \mathrm{Re}(q_{12}) & \mathrm{Im}(q_{12}) \\ q_{21} & \mathrm{Re}(q_{22}) & \mathrm{Im}(q_{22}) \\ q_{31} & \mathrm{Re}(q_{32}) & \mathrm{Im}(q_{32}) \end{pmatrix} \begin{pmatrix} \varphi_1^0 \\ \varphi_2^0 \\ a^0 \end{pmatrix}$$

2HDM Yukawa

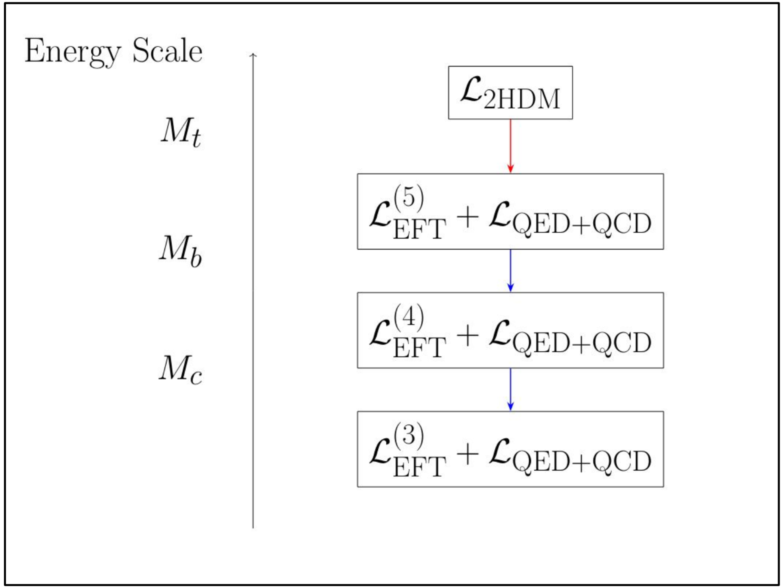
- **Main selling point:** extended Yukawa sector leading to complex entries
  - Complex parameters that cannot be reabsorbed via field redefinitions **manifest in CP violation**
- CP violation depends only on the imaginary combinations of ρ

$$\mathcal{L}_{\text{Yuk}} \supset -\sum_k \sum_{ij} h_k \Bigg[\bar{u}_{L,i} \left(\frac{m_{u_i}}{v} \delta_{ij} q_{k1} + \rho_{u,ij} q_{k2}^* \right) u_{R,j} + \sum_{f=d,e} \bar{f}_{L,i} \left(\frac{m_{f_i}}{v} \delta_{ij} q_{k1} + \rho^\dagger_{f,ij} q_{k2} \right) f_{R,j} \Bigg] + \text{c.c.}$$

$$- \sqrt{2} H^+ \left[\bar{u}_{L,i} \left(V \rho_d^\dagger \right)_{ij} d_{R,j} - \bar{u}_{R,i} \left(\rho_u^\dagger V \right)_{ij} d_{L,j} \right] - \sqrt{2} H^+ \bar{\nu}_{L,i} \rho^\dagger_{\ell,ij} e_{R,j} + \text{c.c.}$$

CP extraction via matching

- Basic idea: below electroweak symmetry breaking, heavy particles can be approximated by effective operators + QED + QCD
- Renormalization group equations describe evolution after 2HDM + top get integrated out (Red Line)
- Wilson coefficients are run to the end of the perturbative regime of ≈2 GeV (Blue Line)



Effective Lagrangian below electroweak symmetry breaking

- For consistent treatment of renormalization group we need all <6 mass dimensional operators
  - Subset of CP odd fermion/gauge field interactions
  - CP odd 4 fermion operators
- Closed under QED + QCD Running

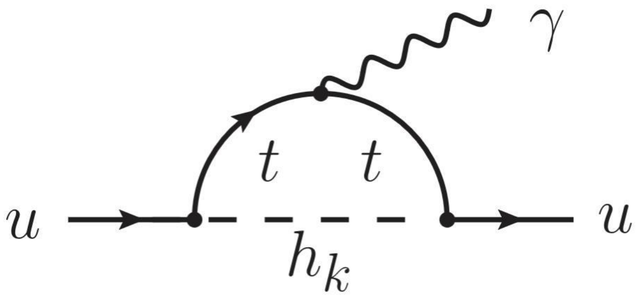
$$Q_3^q = \frac{eQ_q}{2}\frac{m_q}{g_s^2}\,\bar{q}\sigma^{\mu\nu}q\,\tilde{F}_{\mu\nu}, \qquad Q_4^q = -\frac{1}{2}\frac{m_q}{g_s}\,\bar{q}\sigma^{\mu\nu}T^a q\,\tilde{G}_{\mu\nu}, \qquad Q_w = -\frac{1}{3g_s}f^{abc}G^a_{\mu\sigma}G^{b,\sigma}_{\nu}\tilde{G}^{c,\mu\nu},$$

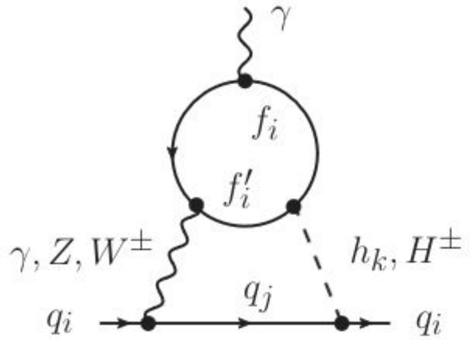
$$Q_1^q = (\bar{q}q)(\bar{q}i\gamma_5 q), \qquad Q_1^{qq'} = (\bar{q}q)(\bar{q}'i\gamma_5 q'), \qquad Q_2^{qq'} = (\bar{q}T^a q)(\bar{q}'i\gamma_5 T^a q'),$$

$$Q_2^{qq} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}(\bar{q}\sigma_{\mu\nu}q)(\bar{q}\sigma_{\rho\sigma}q), \qquad Q_3^{qq'} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}(\bar{q}\sigma_{\mu\nu}q)(\bar{q}'\sigma_{\rho\sigma}q'), \qquad Q_4^{qq} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}(\bar{q}\sigma_{\mu\nu}T^a q)(\bar{q}\sigma_{\rho\sigma}T^a q).$$

Precision requirements

- We do not make any a priori assumptions about the size of the Yukawas
- First contribution comes with quadratic Yukawas at 1-loop
- Therefore in order to be consistent, we calculated **all** contributions to EDM's that are quadratic in Yukawas





Taming of the Gauge

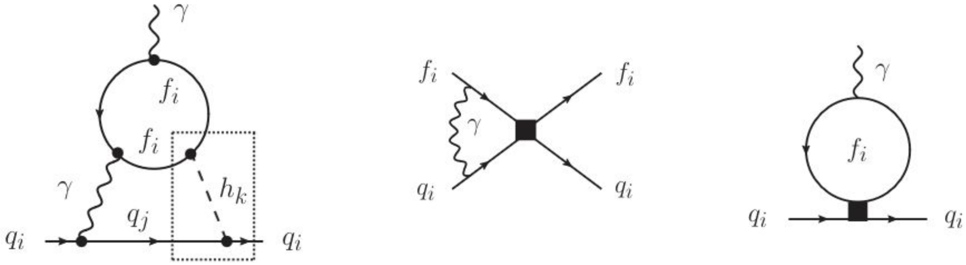
- Background field gauge was utilized
  - Allowed to keep Rxi propagators
  - Simplified several gauge vertices
- Two loop contributions split into several gauge-independent contributions
- Overall gauge independence served as a check of the calculations

$$C_3^{d_i,\text{two-loop}} = C_3^{d_i,th} + C_3^{d_i,tH^\pm} + \sum_j C_3^{d_i,\ell_j H^\pm} + C_3^{d_i,hZ} + C_3^{d_i,\text{kin.}} + C_3^{d_i,H^\pm\gamma} + C_3^{d_i,H^\pm Z} + C_3^{d_i,H^\pm W} \,.$$

Taming of the Large Logs

- QCD corrections to matching are known to be large, so we used RGE to resum αLog
- However, it also allows understanding of large logs that come from "naive" matching
  - In case of leptons QED corrections to QCD running had to be utilized in order to resum leptonic large logs of the form:

$$\alpha\alpha_s \log^2(x_{\ell_j h_k})(1 + \alpha_s \log(x_{\ell_j h_k}) + \alpha_s^2 \log^2(x_{\ell_j h_k}) + \ldots).$$



Conclusions

- We present the complete calculation of hadronic EDM, CEDM and Weinberg operator in the most general 2HDM
- Matching coefficients were verified to not have any gauge dependency and all large logs were treated via RGE
- We have achieved full python implementation of CP odd RGE below weak symmetry breaking
- Final punch line? Results are fully implemented in python code and **do not require extra work to be utilized**