The Electric Dipole Moment of the electron in the decoupling limit of the aligned Two-Higgs Doublet Model

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Introduction

Phenomena sensitive to Charge-Parity Violation (**CPV**) provide a powerful test of the SM structure → Electric Dipole Moments (**EDMs**) are an outstanding example [Pospelov, Ritz, '05]:

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Non-zero d_f is a CPV observable!

Introduction

The **electron EDM** (eEDM) can be defined as the coefficient of the effective operator [Pospelov, Ritz, '05]:

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{i}{2} d_e (\bar{e}\sigma^{\mu\nu}\gamma_5 e) F_{\mu\nu}$$

- High current experimental sensitivity for the eEDM [Roussy et al. '23]:

$$|d_e^{\mathrm{exp}}| < 4.1 \times 10^{-30} e\,\mathrm{cm}\,(90\%\,\mathrm{C.L.})$$

Introduction

The bounds on the eEDM are obtained from the measurement of an angular frequency in diatomic molecules, which is not only sensitive to d_e:

$$\boxed{\omega \ \propto \ W_d d_e + W_c C_S}$$

$$\boxed{d_e^{\text{equiv}} \ = \ d_e + k C_S}$$

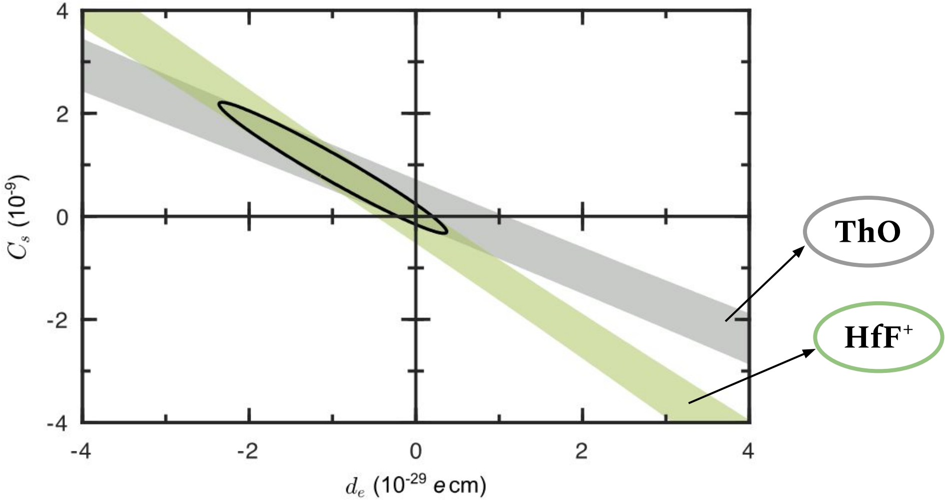
Electron-nucleon interaction, mimics:

$$\boxed{d_e^{\text{equiv}} \ \sim \ 10^{-35} e\,\text{cm}}$$

in the SM.

[Ema, Gao, Pospelov '22]

[Roussy et al. '23]



Introduction

Usually, contributions to the eEDM are highly suppressed:

- In the Standard Model (**SM**), taking into account hadronic effects [Yamaguchi, Yamanaka '20]:

$$d_e^{SM} = 5.8 \times 10^{-40} \text{ e cm}$$

- Assuming that neutrinos are **Majorana particles**, at two-loop order [Archambault, Czarnecki, Pospelov '04]:

$$d_e \sim 10^{-33} \text{ e cm}$$

Room for New Physics (**NP**) → new scalar sector with additional complex phases → **new** CPV sources

2HDMs

In 2 Higgs-Doublet Models (**2HDMs**), the SM is extended with a **second scalar doublet** with hypercharge **Y** = ½. Working in the **Higgs basis**, only the first doublet gets a vev:

$$\Phi_1 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\, G^+ \\ v + S_1 + i\, G^0 \end{pmatrix} \quad \Phi_2 = \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\, H^+ \\ S_2 + i\, S_3 \end{pmatrix}$$

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Charged scalar

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vev (246 GeV)

CP-even scalars

CP-odd scalar

2HDMs: Scalar Potential

Most general, CP-violating scalar potential:

$$V = \mu_1\Phi_1^\dagger\Phi_1 + \mu_2\Phi_2^\dagger\Phi_2 + \left[\mu_3\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] + \tfrac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \tfrac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right)$$

$$+\lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left[\left(\tfrac{\lambda_5}{2}\Phi_1^\dagger\Phi_2 + \lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + \text{h.c.}\right]$$

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- The neutral scalars will mix with each other and produce the **mass eigenstates**:

$$\varphi_i = \mathcal{R}_{ij}S_j \longrightarrow \varphi_i \in \{H_1, H_2, H_3\}$$

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- In general, some parameters from the potential can be **complex** → in usual 2HDMs, the parameters $\boldsymbol{\lambda_6}$ and $\boldsymbol{\lambda_7}$ **vanish** in the $\mathbb{Z}_2$-symmetric basis.

2HDMs: Flavour Sector

In the Higgs basis, the most general Yukawa Lagrangian is:

$$
\begin{aligned}
-\mathcal{L}_Y = &\left(1+\frac{S_1}{v}\right)\left\{\bar{u}_L\, M_u\, u_R + \bar{d}_L\, M_d\, d_R + \bar{l}_L\, M_l\, l_R\right\} \\
&+ \frac{1}{v}\,(S_2 + iS_3)\left\{\bar{u}_L\, Y_u\, u_R + \bar{d}_L\, Y_d\, d_R + \bar{l}_L\, Y_l\, l_R\right\} \\
&+ \frac{\sqrt{2}}{v}\, H^+ \left\{\bar{u}_L\, V\, Y_d\, d_R - \bar{u}_R\, Y_u^\dagger\, V\, d_L + \bar{\nu}_L\, Y_l\, l_R\right\} + \text{h.c.}
\end{aligned}
$$

In general, 2HDMs suffer from tree-level **Flavour Changing Neutral Currents** (FCNCs), which are tightly constrained.

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$$

Alignment condition: $\boxed{Y_u = \varsigma_u^* M_u \qquad Y_{d,l} = \varsigma_{d,l} M_{d,l}}$

2HDMs: Flavour Sector

Interaction part of the Yukawa Lagrangian (with mass eigenstates):

$$-\mathcal{L}_Y = \frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \varsigma_l \bar{\nu} M_l \mathcal{P}_R l \right\}$$

$$+ \frac{1}{v} \sum_{i,f} y_f^i \varphi_i \bar{f} M_f \mathcal{P}_R f + \text{h.c.}$$

- **C2HDM**: imposition of a discrete $\mathbb{Z}_2$ **symmetry** → it is possible to find a basis where only one of the doublets couples to a given kind of fermion: the **flavour alignment parameters** are real and dependent on each other.

The Aligned 2HDM

Interaction part of the Yukawa Lagrangian (with mass eigenstates):

$$-\mathcal{L}_Y = \frac{\sqrt{2}}{v} H^+ \Big\{ \bar{u} \left[\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \varsigma_l \bar{\nu} M_l \mathcal{P}_R l \Big\}$$

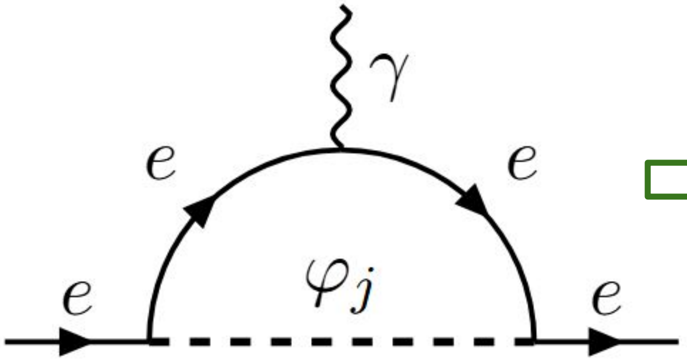
$$+ \frac{1}{v} \sum_{i,f} y_f^i \varphi_i \bar{f} M_f \mathcal{P}_R f + \text{h.c.}$$

Alternatively, the **Aligned 2HDM** (A2HDM) solves the issue of FCNCs by considering that the ς are **independent, complex parameters**, without assuming any additional symmetry [Pich, Tuzón '09].

- Thus, we have **new complex phases** in our model that can act as **CP-violating** sources.

The eEDM in the A2HDM

In the A2HDM, the eEDM gets a contribution at **1-loop order**:



$$\boxed{d_e^{\text{1-loop}} \propto G_F\, m_e \left(m_e^2/M_{\varphi_i}^2\right)}$$

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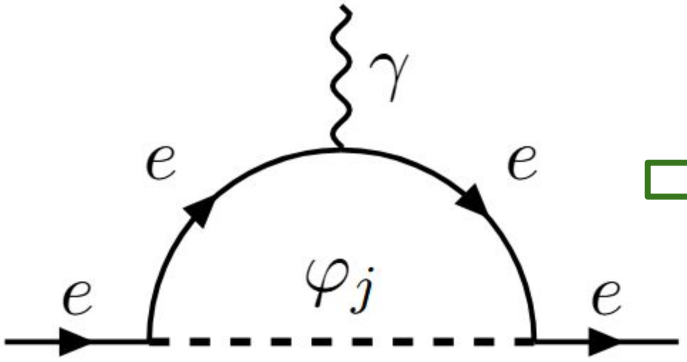

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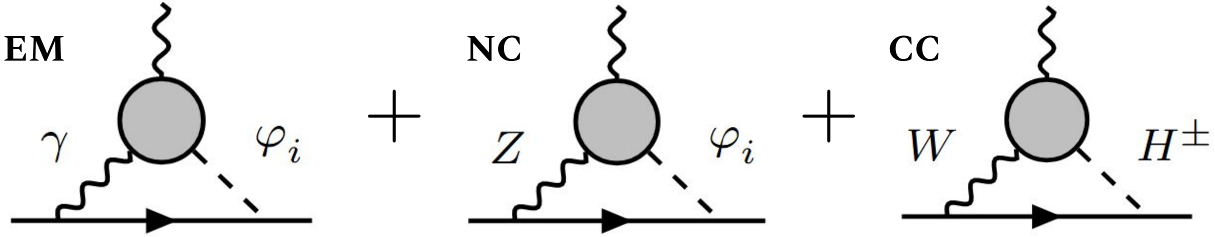
Logarithmic contribution in **decoupling limit** coming from **dim-8 operator**

The eEDM in the A2HDM

But actually, the **dominant** contributions come at **2-loop order**:

- These contributions can be classified as **Barr-Zee**:



Internal Loop:
- Fermion
- Gauge boson
- Charged scalar

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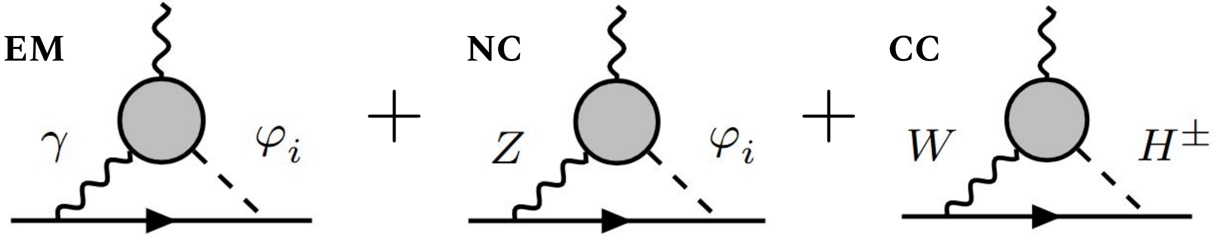

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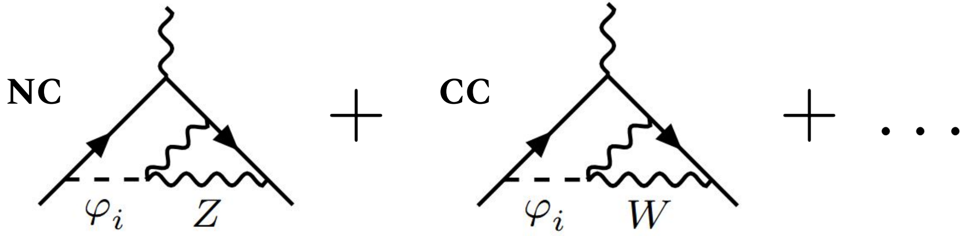
- Or "**kite**" diagrams:



The eEDM in the A2HDM

Notation:

$d_{e,i}^{\mathrm{EM,NC,CC}}$

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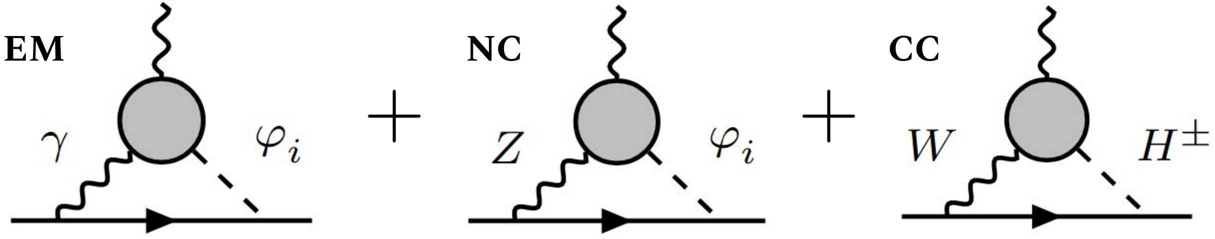
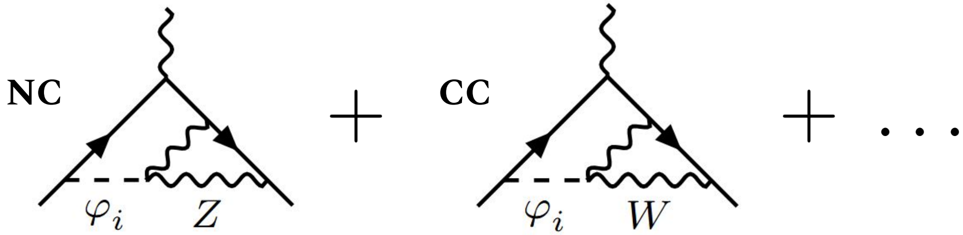


Internal Loop:
- Fermion (***i*** = ***f***)
- Gauge boson (***i*** = ***W***)
- Charged scalar (***i*** = $\boldsymbol{H^{\pm}}$)

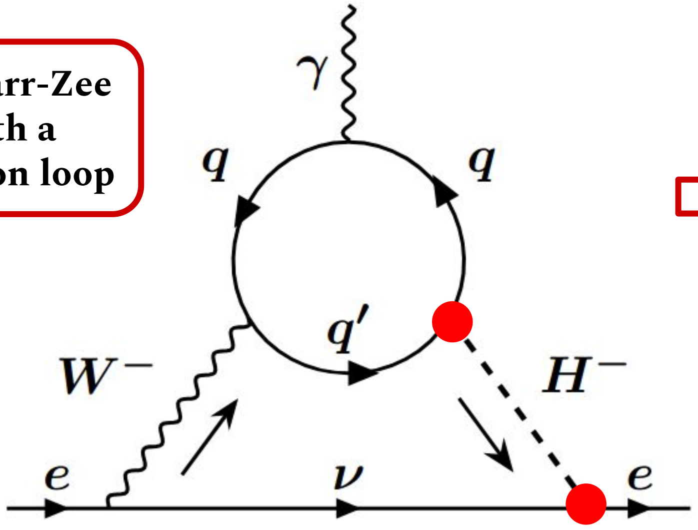
- Or "**kite**" diagrams:



The eEDM in the A2HDM

Some of these contributions only arise when considering a **complex value** for the ς parameters [Bowser-Chao, Chang, Keung '97; Jung, Pich '14; Altmannshofer et. al. '24]:

CC Barr-Zee with a fermion loop



$$\boxed{d_{e,f}^{CC} \propto \mathrm{Im}(\varsigma_{u,d}^{*}\varsigma_l)}$$

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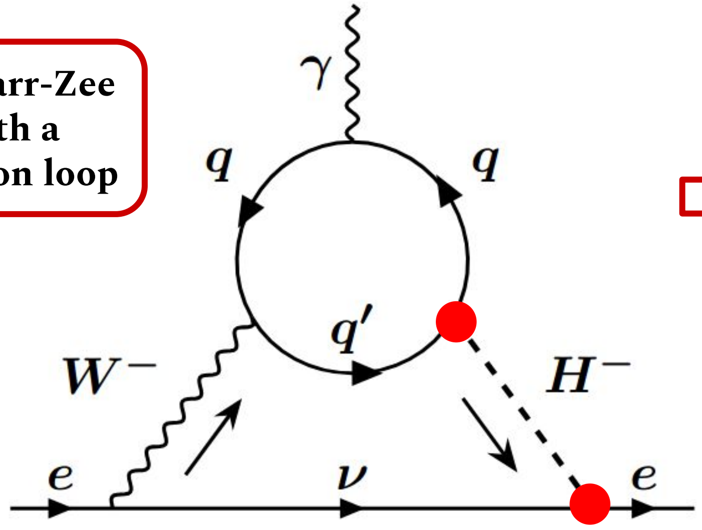

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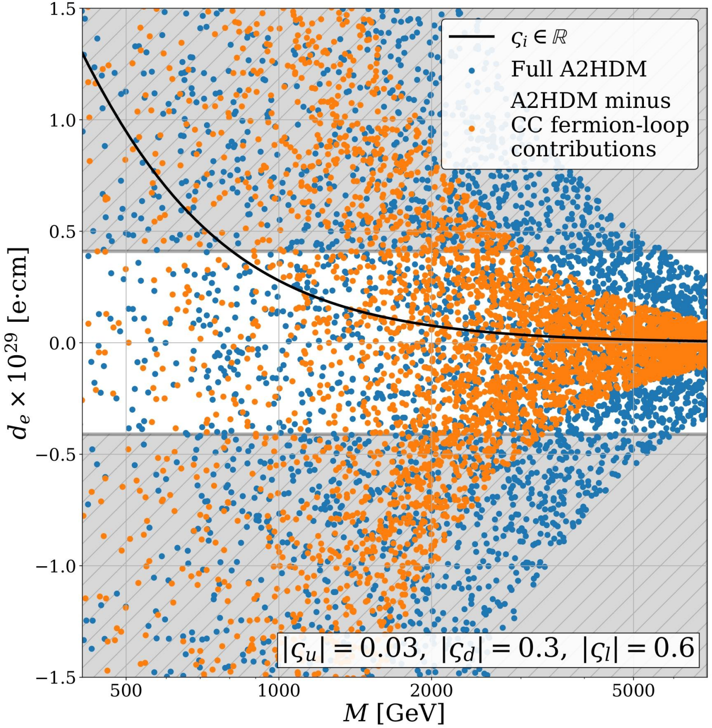
Vanishing contribution from diagrams with a **lepton loop**!

The eEDM in the A2HDM



- **Black line**: real alignment parameters ς.
- **Orange points**: A2HDM minus CC Barr-Zee fermion-loop contributions.
- **Blue points**: full A2HDM.
- **Destructive interference** with complex ς, → satisfy the experimental constraints (**grey** bands) with lower values for ***M***.

The eEDM in the Decoupling Limit

If the mass parameter of the second doublet $\mathbf{\Phi}_2$ becomes very large compared to the vev of $\mathbf{\Phi}_1$, we get the ***decoupling limit*** of the 2HDM:

$$\sqrt{\mu_2} \gg v$$

- If the **masses of the scalars** from the second doublet are assumed to be **independent**, this condition means that they will be **much heavier** than the SM Higgs boson:

$$M_{H^\pm},\ M_H,\ M_A \approx M \gg m_h$$

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Fermion-loop Barr-Zees $\rightarrow$ $$d_{e,f} \sim \boxed{m_e \mathrm{Im}(\varsigma_u^* \varsigma_l) \frac{m_t^2}{M^2} \log^2\left(\frac{M^2}{m_t^2}\right)}, \boxed{m_e \mathrm{Im}(\varsigma_d^* \varsigma_l) \frac{m_b^2}{M^2} \log\left(\frac{M^2}{m_t^2}\right)}$$

Gauge boson-loop BZs + kites $\rightarrow$ $$d_{e,W+\mathrm{kite}} \sim \boxed{m_e \mathrm{Im}(\lambda_6^* \varsigma_l) \frac{v^2}{M^2} \log\left(\frac{M^2}{m_W^2}\right)}$$

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- The logarithmic contributions from fermion-loop BZs are **exclusive** of the A2HDM: in $\mathbb{Z}_2$-conserving 2HDMs they naturally vanish [Altmannshofer, Gori, Hamer, Patel '20].

The eEDM in the SMEFT

The decoupling limit also allows us to make an **Effective Field Theory** (EFT) description of the eEDM → the heavy scalars can be integrated out and we can characterize new contributions by a set of **effective operators**.

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i C_i(\mu) Q_i .$$

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$$\boxed{C_i} \xrightarrow{\textbf{RGE}} \boxed{C_{e\gamma}} \xrightarrow{\textbf{Tree}} \boxed{d_e}$$

- These operators will **run** from the NP scale down to the EW scale and **mix** with the **electromagnetic dipole operator**.

The eEDM in the SMEFT

The effective **SMEFT** operators will mix with each other via the **Renormalization Group Equations** (RGEs):

$$\frac{d}{d\log\mu}C_i = \left(\frac{1}{(4\pi)^2}\gamma_{ij}^{(1)} + \frac{1}{(4\pi)^4}\gamma_{ij}^{(2)}\right)C_j$$

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1-loop mixing

2-loop mixing

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- **Integrating** these equations between the scale of new physics (***M***) and the EW scale we can compute **logarithmic contributions** to the eEDM, which can be **compared** to the leading contributions that we computed in the **decoupling limit**. [Panico, Pomarol, Riembau ‘18], [Vale Silva, Jäger, Leslie ‘20], [Altmannshofer et al. ‘20].

The eEDM in the SMEFT

Outline of RGE mixing:

$$\boxed{Q_{eH} = (H^\dagger H)(\bar{l} e H)}$$

2-loops

$$C_{e\gamma} \to d_e$$

The eEDM in the SMEFT

$$\boxed{d_{e,W+\text{kite}} \;\propto\; \frac{G_F m_e}{(4\pi)^4}\,\mathrm{Im}(\lambda_6^*\varsigma_l)\,\frac{v^2}{M^2}\,\log\left(\frac{M^2}{m_W^2}\right)}$$

$$\Downarrow$$

$$\boxed{d_{e,eH}^{\mathrm{SMEFT}} \;\propto\; \frac{1}{(4\pi)^4}\,\mathrm{Im}(C_{eH})\,\log\left(\frac{M^2}{m_{EW}^2}\right)}$$

The eEDM in the SMEFT

Outline of RGE mixing:

2-loops

$$Q_{eH} = (H^\dagger H)(\bar{l} e H)$$

$$Q_{ledq} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$

$$C_{e\gamma} \to d_e$$

2-loops

The eEDM in the SMEFT

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1-loop

$$Q_{ledq} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$

1-loop

$$Q_{lequ}^{(3)} = (\bar{l}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$$

$$C_{e\gamma} \rightarrow d_e$$

2-loops

The eEDM in the SMEFT

$$\boxed{d_{e,f} \;\propto\; \frac{G_F m_e}{(4\pi)^4}\,\mathrm{Im}(\varsigma_u^*\varsigma_l)\,\frac{m_t^2}{M^2}\,\log^2\left(\frac{M^2}{m_t^2}\right)}$$

$$\Downarrow$$

$$\boxed{d_{e,lequ}^{\mathrm{SMEFT}} \;\propto\; \frac{1}{((4\pi)^2)^2}\,\mathrm{Im}(C_{lequ})\,\log^2\left(\frac{M^2}{m_{EW}^2}\right)}$$

The eEDM in the SMEFT

Outline of RGE mixing:

$$Q_{eH} = (H^\dagger H)(\bar{l}eH)$$

2-loops

$$Q^{(1)}_{lequ} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$

1-loop

$$Q_{ledq} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$

1-loop

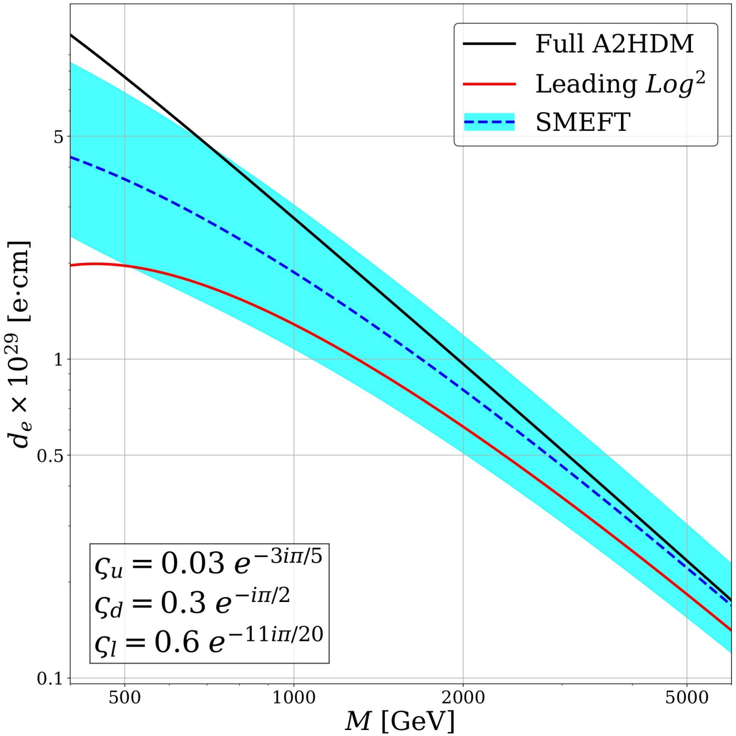
$$Q^{(3)}_{lequ} = (\bar{l}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$$

2-loops

$$C_{e\gamma} \to d_e \Longrightarrow$$

Agreement with full-model computation!

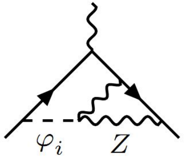
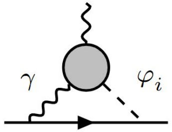
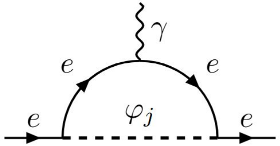
Full calculation vs. SMEFT



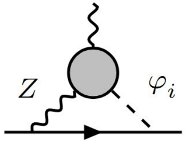
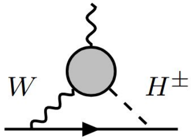
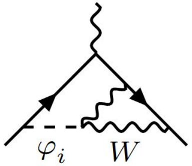
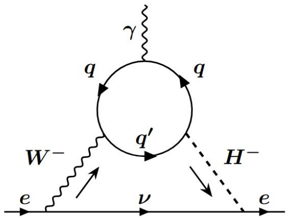
- **Black line**: full A2HDM
- **Red line**: only leading squared logarithm term → dominates close to the decoupling limit.
- **Blue line**: all the previously discussed SMEFT logarithms.
- **Blue band**: variation of the NP scale.

Summary

- **EDMs → powerful probe** of the amount of **violation of CP** symmetry in nature.
- There is still **room for NP** that contribute to CPV, such as an extended scalar sector → **2HDMs**
- The **Aligned 2HDM** contains additional **complex phases** that allow for **new contributions** to the electron-EDM which are **absent** in **$\mathbb{Z}_2$-symmetric** 2HDMs, while still avoiding FCNCs.
- **Destructive interference** among contributions → satisfy experimental constraints with lower values for the scalar masses.
- **Outlook** → discussion of CP-violating electron-nucleon interaction.


φ_i
Z

γ
φ_i

γ
e
e
e
φ_j
e

THANKS!!


Z
φ_i

W
$H^{\pm}$

φ_i
W

γ
q
q
q'
W^-
H^-
e
ν
e

BACKUP

Flavour Alignment Parameters

Different models have different flavour alignment parameters:

- (Minimal) Aligned 2HDM: $\varsigma_i \in \mathbb{C} \longrightarrow$ Model used in this work
- General Aligned 2HDM: $\varsigma_i \in \mathbb{C}^3$, diagonal
- General 2HDM: $\varsigma_i \in \mathbb{C}^3$

$\left.\begin{matrix} \\ \\ \end{matrix}\right\}$ Matrices

- $\mathbb{Z}_2$-conserving 2HDMs:

$$\text{Type I:}\ \ \varsigma_u = \varsigma_d = \varsigma_l = \cot\beta, \quad \text{Type II:}\ \ \varsigma_u = -\frac{1}{\varsigma_d} = -\frac{1}{\varsigma_l} = \cot\beta\,, \quad \text{Inert:}\ \ \varsigma_u = \varsigma_d = \varsigma_l = 0\,,$$

$$\text{Type X:}\ \ \varsigma_u = \varsigma_d = -\frac{1}{\varsigma_l} = \cot\beta \qquad \text{and} \qquad \text{Type Y:}\ \ \varsigma_u = -\frac{1}{\varsigma_d} = \varsigma_l = \cot\beta\,.$$

(From [Karan, Miralles, Pich ‘23])

Benchmark

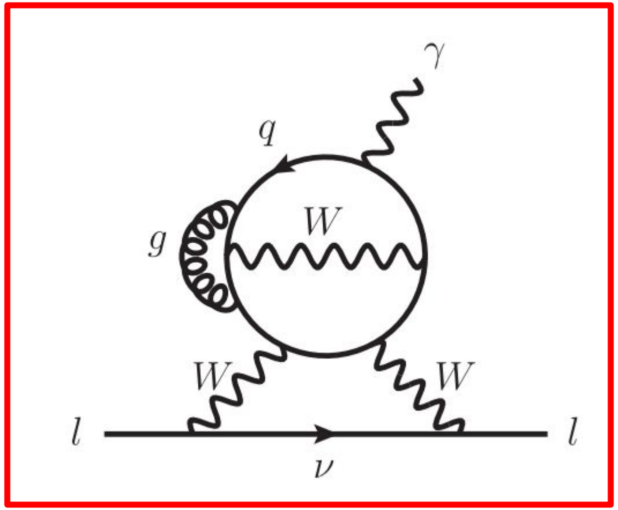
Parameter	Benchmark Value
λ_3	0.02
λ_4	0.04
λ_7	0.03
$\mathrm{Re}(\lambda_5)$	0.05
$\mathrm{Re}(\lambda_6)$	-0.05
$\mathrm{Im}(\lambda_6)$	0.01
α_3	$\pi/6$

All benchmark values are consistent with the global fit performed in [Karan, Miralles, Pich '23].

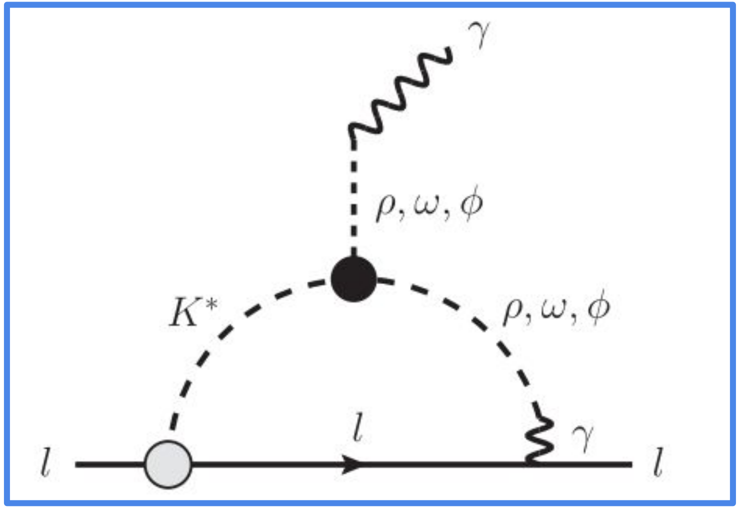
The value of the mass $\boldsymbol{M}$ corresponds to the mass of the charged scalar, which is related to the mass parameter $\boldsymbol{\mu_2}$.

eEDM in the SM

4-loop SM contribution
(CPV comes from CKM)



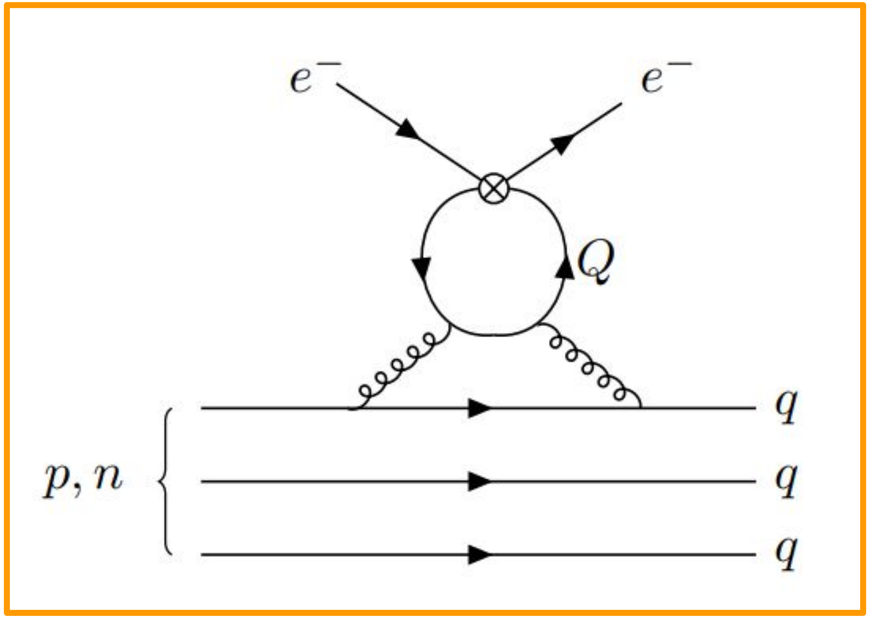
Long-distance
contribution



[Yamaguchi, Yamanaka '20]

Electron-nucleon interaction

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} C_S \bar{e} i \gamma_5 e \bar{N} N$$



[Ardu, Valori ‘25]