The electron-EDM in the decoupling limit of the Aligned 2HDM

Juan Manuel Dávila Illán
IFIC (Universitat de València, CSIC)

Work in progress in collaboration with A. Karan, E. Passemar, A. Pich and L. Vale Silva

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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]:

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

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

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

Introduction

Usually, contributions to the eEDM are highly suppressed:

- In the Standard Model (**SM**), at 4-loop order [Pospelov, Ritz ‘14]:

$$d_e^{SM} \sim 10^{-38} \text{ e cm}$$

- 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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v → vev (246 GeV)

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Goldstone Bosons

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Goldstone Bosons (G^+, G^0)

Charged scalar (H^+)

vev (246 GeV) (v)

CP-even scalars (S_1, S_2)

CP-odd scalar (S_3)

2HDMs: Scalar Potential

Most general, CP-violating scalar potential:

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

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

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

$$\varphi_i = \mathcal{R}_{ij}S_j \longrightarrow \varphi_i \in \{h, H, A\}$$

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$$\varphi_i = \mathcal{R}_{ij} S_j \longrightarrow \varphi_i \in \{h, H, A\}$$

- In general, some parameters from the potential can be **complex** → the mass eigenstates do not have a **definite CP quantum number**.

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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$$+ \frac{\sqrt{2}}{v} H^+ \left\{\bar{u}_L\, V\, Y_d\, d_R - \bar{u}_R\, Y_u^\dagger\, V\, d_L + \bar{\nu}_L\, Y_l\, l_R\right\} + \text{h.c.}$$

Alignment condition:

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

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):

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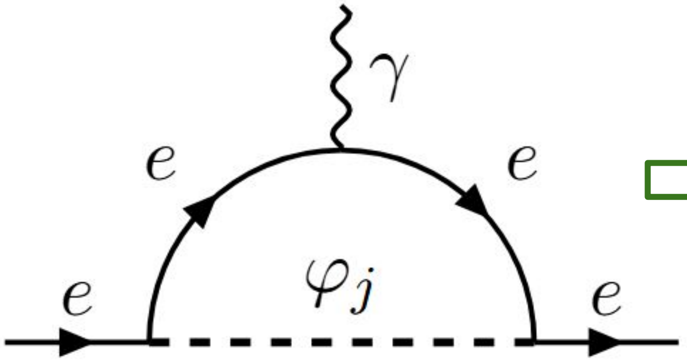
$$+ \frac{1}{v} \sum_{i,f} y_f^i \varphi_i \bar{f} M_f \mathcal{P}_R f + \text{h.c.}$$

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**:

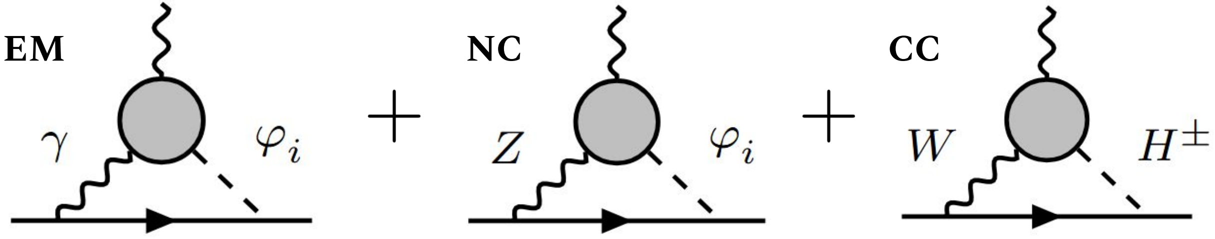


$$d_e^{\text{1-loop}} \propto G_F\, m_e\, (m_e^2/M_{\varphi_i}^2)$$

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
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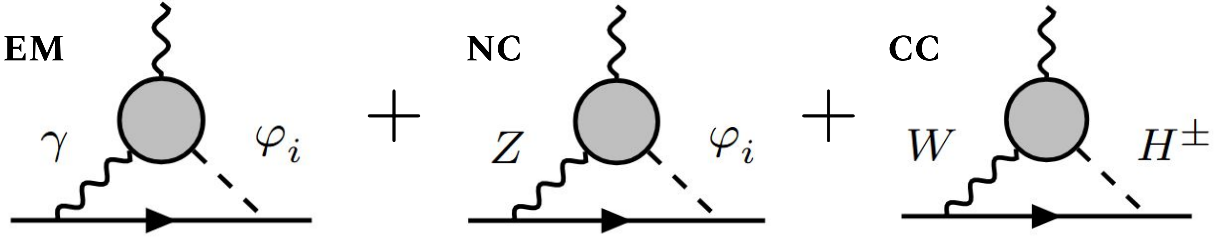

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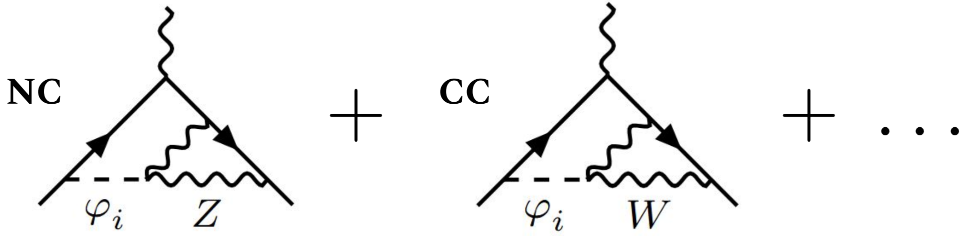
- Or "**kite**" diagrams:



The eEDM in the A2HDM

Notation:

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

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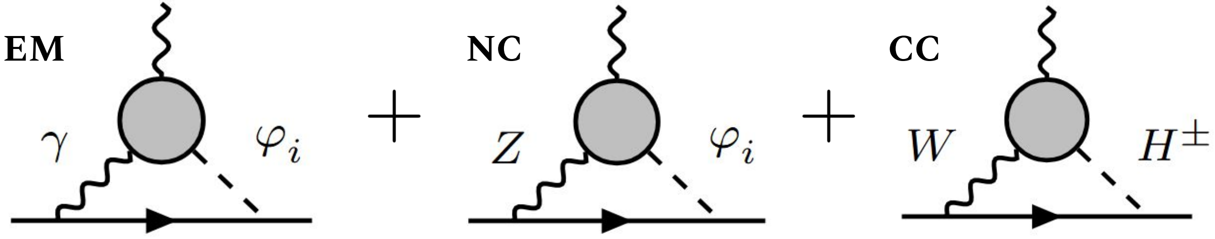
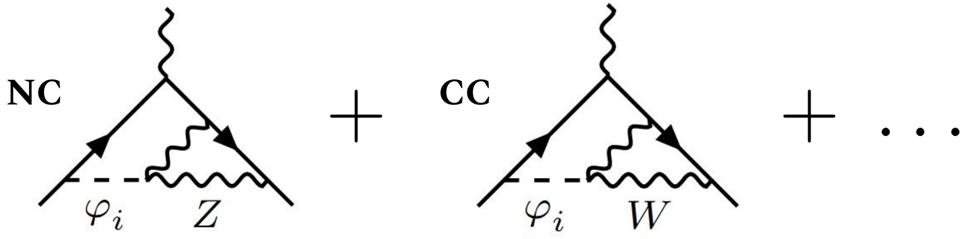


Internal Loop:
- Fermion (***i*** = ***f***)
- Gauge boson (***i*** = ***W***)
- Charged scalar (***i*** = ***H***$^{\pm}$)

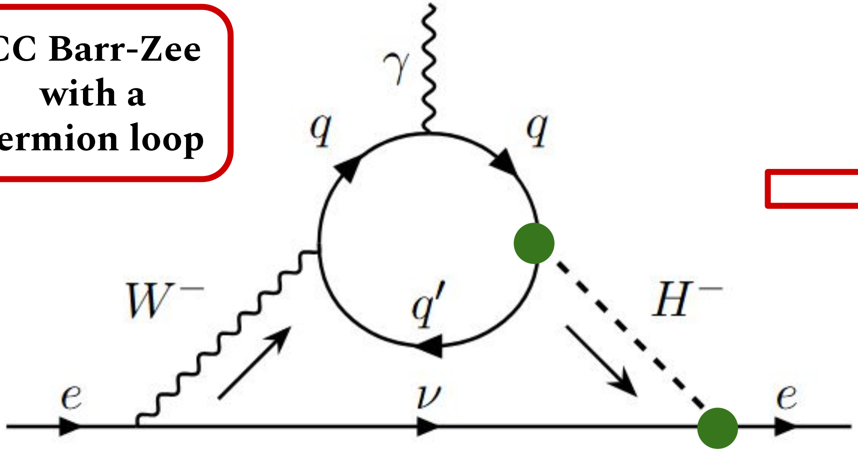
- Or "**kite**" diagrams:



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]:

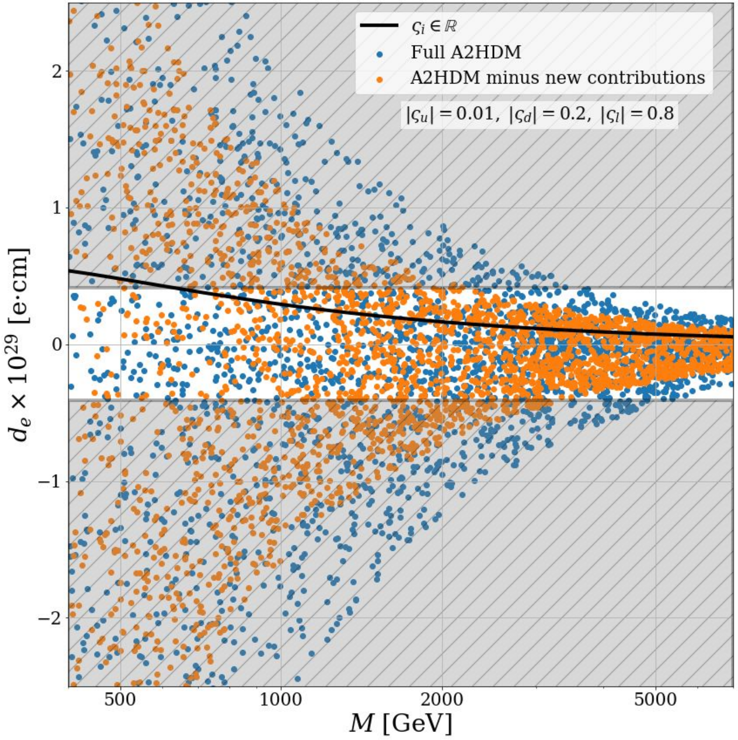
CC Barr-Zee with a fermion loop



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

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

The eEDM in the A2HDM



- The **scattered points** are generated selecting a random value for the phases of the 3 alignment parameters $\boldsymbol{\varsigma}$.
- The '**new**' CC Barr-Zee fermion-loop **contributions** are particularly relevant close to the decoupling limit.
- With **complex** $\boldsymbol{\varsigma}$, it is possible to satisfy the constraints with lower values for $\boldsymbol{M}$.

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:

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

The eEDM in the Decoupling Limit

Working in the decoupling limit of the A2HDM, it is possible to isolate the dominant logarithmic contributions to the eEDM:

Fermion-loop Barr-Zees →

$$d_{e,f} \sim \frac{G_F m_e}{(4\pi)^4} \frac{m_t^2}{M^2} \log^2\left(\frac{M^2}{m_t^2}\right), \quad \frac{G_F m_e}{(4\pi)^4} \frac{m_b^2}{M^2} \log\left(\frac{M^2}{m_t^2}\right)$$

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Gauge boson-loop BZs + kites →

$$d_{e,W+\text{kite}} \sim \frac{G_F m_e}{(4\pi)^4} \frac{v^2}{M^2} \log\left(\frac{M^2}{m_W^2}\right)$$

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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**:

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

- These operators will **run** from the NP scale down to the EW scale and **mix** with the **electromagnetic dipole operator**. The imaginary part of its coefficient is proportional to the EDM:

$$d_e = -\sqrt{2}\, v\, \mathrm{Im}(C_{e\gamma})$$

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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1-loop mixing **2-loop mixing**

- **Integrating** these equations between the scale of new physics (***M***) and the EW scale we can compute **logarithmic contributions** to the EDM, which can be **compared** to the leading contributions that we computed in the **decoupling limit**. In this work, we use the **Anomalous Dimension Matrix** elements from [Panico, Pomarol, Riembau '18].

The eEDM in the SMEFT

Outline of RGE mixing:

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

2-loops

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

The eEDM in the SMEFT

$$d_{e,W+\text{kite}} \sim \frac{G_F m_e}{(4\pi)^4}\frac{v^2}{M^2}\log\left(\frac{M^2}{m_W^2}\right)$$

$$\Downarrow$$

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

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The eEDM in the SMEFT

$$d_{e,f} \sim \frac{G_F m_e}{(4\pi)^4} \frac{m_b^2}{M^2} \log\left(\frac{M^2}{m_t^2}\right)$$

⇓

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1-loop

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1-loop

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

$$\mathcal{C}_{e\gamma} \rightarrow d_e$$

2-loops

The eEDM in the SMEFT

$$d_{e,f} \sim \frac{G_F m_e}{(4\pi)^4} \frac{m_t^2}{M^2} \log^2\left(\frac{M^2}{m_t^2}\right)$$

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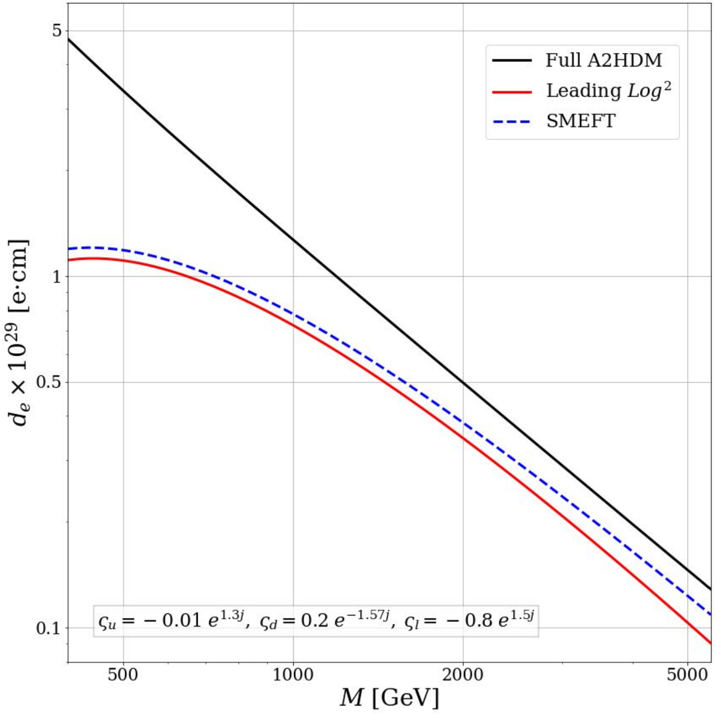
2-loops

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

Agreement with full-model computation!

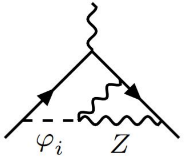
Full calculation vs. SMEFT

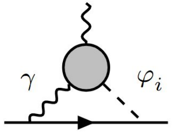


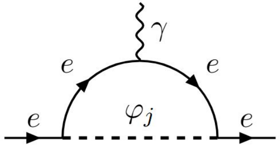
- The leading **squared logarithm** contribution coming from fermion-loop Barr-Zee diagrams provides the correct order of magnitude for the eEDM.
- The **SMEFT** result, which also takes into account single logarithms, is closer to the full-model result in the decoupling limit.

Summary

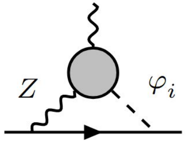
- **EDMs** serve as a **powerful probe** of the amount of **violation of CP** symmetry in nature.
- There is still **room for NP** that contribute to CPV, such as an extended scalar sector → **2HDMs**
- The **Aligned 2HDM** contains additional **complex phases** that allow for **new contributions** to the electron-EDM.
- Thanks to these new complex phases, it is possible to **satisfy experimental constraints** with lower values for the scalar masses.
- Particular case → **Decoupling Limit**, which allows for an **EFT description** of the eEDM → The **leading logarithmic** contributions found in SMEFT are **consistent** with the full-model computation.

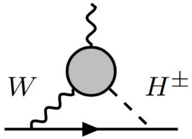

φ_i
Z

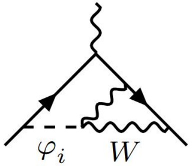

γ
φ_i

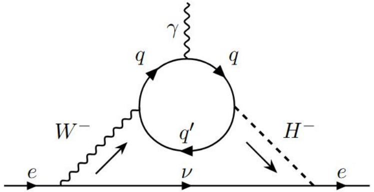

γ
e
e
e
φ_j
e

THANKS!!


Z
φ_i


W
$H^\pm$


φ_i
W


γ
q
q
W^-
q'
H^-
e
ν
e

BACKUP

Flavour Alignment Parameters

Different models have different flavour alignment parameters:

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

} Matrices

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

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

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

(From [Karan, Miralles, Pich ‘23])

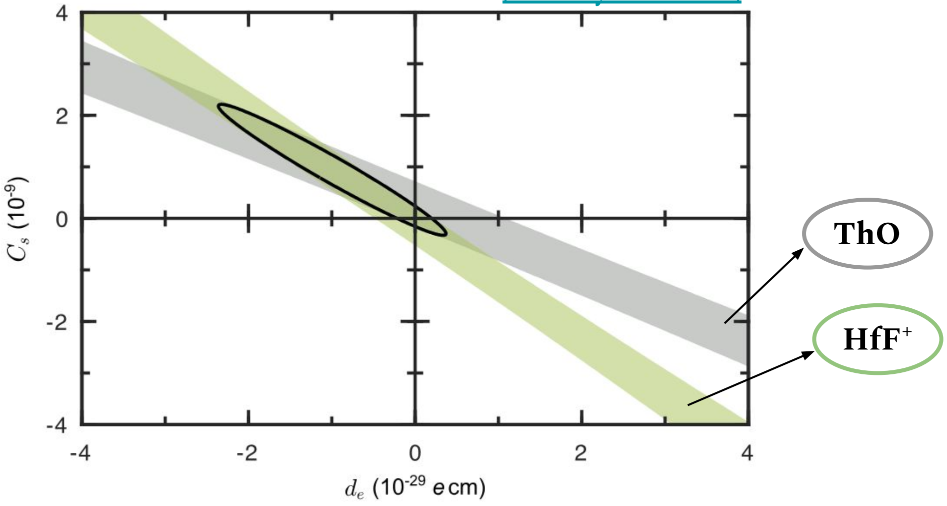
Experimental Constraints on the eEDM

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:

$$\omega \propto W_d d_e + W_c C_S$$

Electron-nucleon interaction

[Roussy et al. '23]



Benchmark

Parameter	SMEFT Comparison Plot	Scatter Plot
λ_2	3	3.2
λ_3	5	5
λ_4	2×10^{-6}	7×10^{-6}
$\mathrm{Re}(\lambda_5)$	8×10^{-8}	1.5×10^{-7}
λ_7	-0.4	-0.4
α_3	0.002	0.002

For both plots, the mass of the new scalars is set as equal.