Charting A2HDM contributions to Electric Dipole Moment observables

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Introduction

Phenomena sensitive to **Charge-Parity Violation** (**CPV**)

↓

Powerful test of the SM structure

- **Electric Dipole Moments** (EDMs) of elementary particles, nucleons and molecules
- Effective **lepton-nucleon interactions**

Introduction

$$\mathcal{H}_{EDM} = -d_f \vec{E} \cdot \frac{\vec{S}}{S}$$

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$$\longrightarrow \quad d_f = -d_{\bar{f}}$$

$$CP(\vec{E} \cdot \vec{S}) = \vec{E} \cdot \vec{S}$$
$$CP(d_f) = d_{\bar{f}}$$
$$\longrightarrow \quad d_f = d_{\bar{f}}$$

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

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:

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

$$d_e^{\mathrm{equiv}} = d_e + kC_S$$

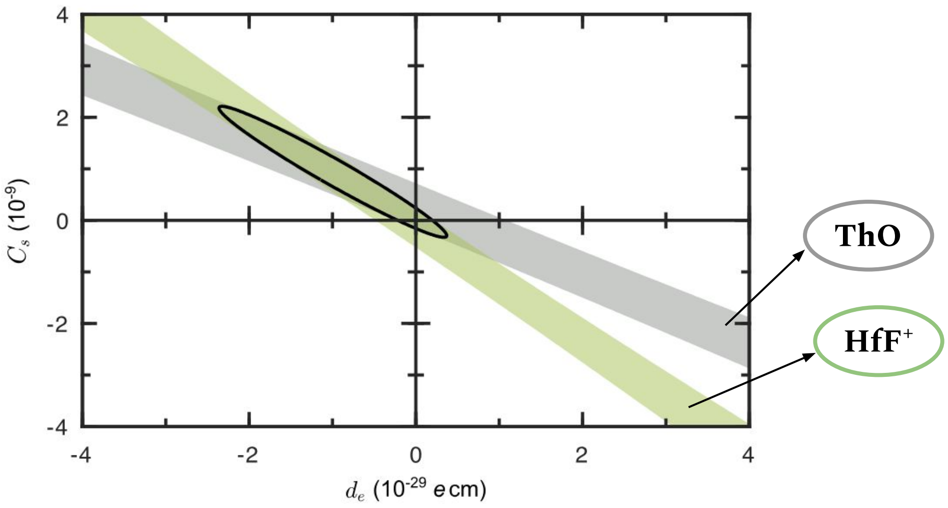
Electron-nucleon interaction, mimics:

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

in the SM.

[Ema, Gao, Pospelov '22]

[Roussy et al. '23]



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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Goldstone Bosons

Charged scalar

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

vev (246 GeV)

CP-even scalars

CP-odd scalar

2HDMs: Scalar Potential

Most general, CP-violating scalar potential:

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

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

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

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

2HDMs: Flavour Sector

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

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

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

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\end{aligned}
$$

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):

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

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

- **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):

$$-\mathcal{L}_Y = \frac{\sqrt{2}}{v} H^+ \left\{ \bar{u} \left[\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L \right] d + \varsigma_l \bar{\nu} M_l \mathcal{P}_R l \right\}$$
$$+ \frac{1}{v} \sum_{i,f} y_f^i \varphi_i \bar{f} M_f \mathcal{P}_R f + \text{h.c.}$$

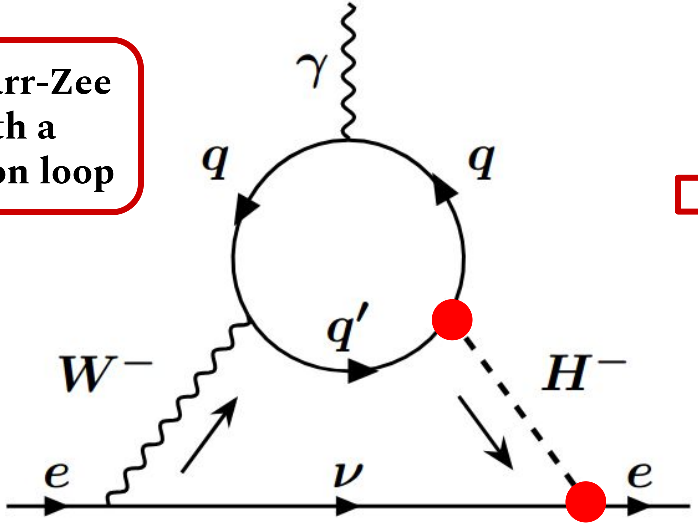
Alternatively, the **Aligned 2HDM** (A2HDM) solves the issue of FCNCs by considering that the ς are **independent, complex parameters**, without assuming any additional symmetry [Pich, Tuzón '09].

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

The eEDM in the A2HDM

Dominant contributions at 2 loops: some of them 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



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

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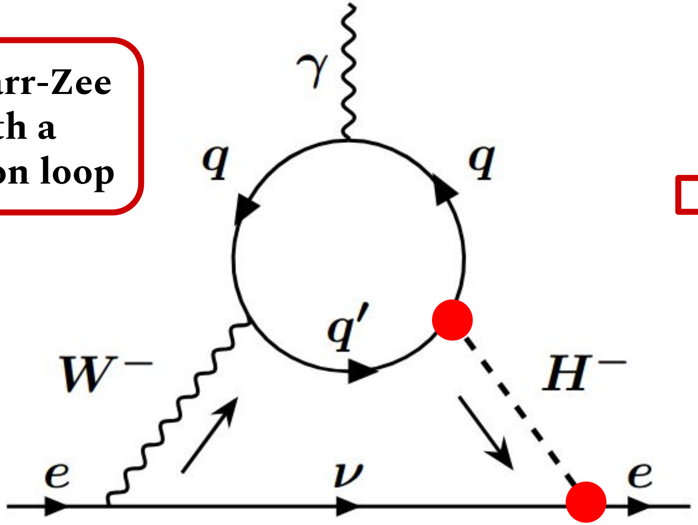
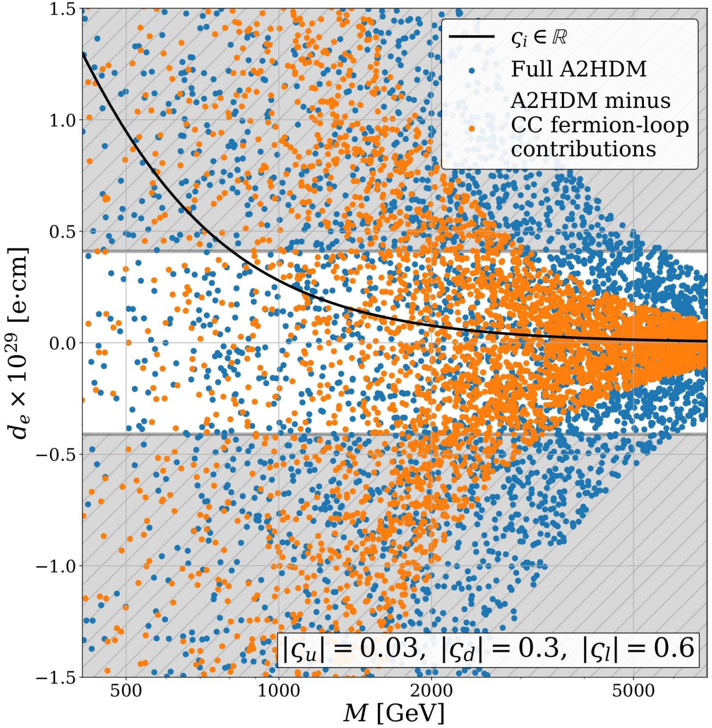


$$d_{e,f}^{CC} \propto \mathrm{Im}(\varsigma_{u,d}^{*}\varsigma_{l})$$

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

The eEDM in the A2HDM



- **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 $\boldsymbol{M}$.

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 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

Gauge boson-loop BZs + kites

$$d_e \sim m_e \mathrm{Im}(C_1^* C_2) \frac{v^2}{M^2} \log^{(2)} \left(\frac{M^2}{m_{EW}^2} \right)$$

- 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].

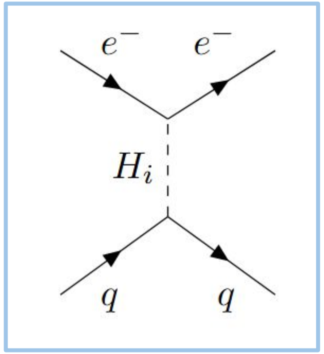
The SMEFT

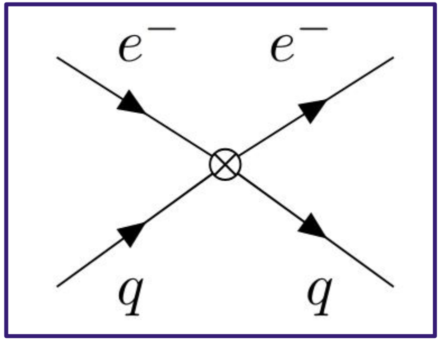
The decoupling limit allows us to make an **Effective Field Theory** (EFT) description of the eEDM and electron-nucleon interactions → new contributions can be characterized by a set of **effective operators** of dimension higher that 4:

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

The SMEFT

These CP-violating **effective operators** are generated when the heavy scalars from A2HDM get integrated out:





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

$$Q_{lequ}^{(1)} = (\bar{l}^j e)\epsilon_{jk}(\bar{q}^k u)$$
$$Q_{ledq} = (\bar{l}^j e)(\bar{d} q^j)$$

The SMEFT

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

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

1-loop mixing

2-loop mixing

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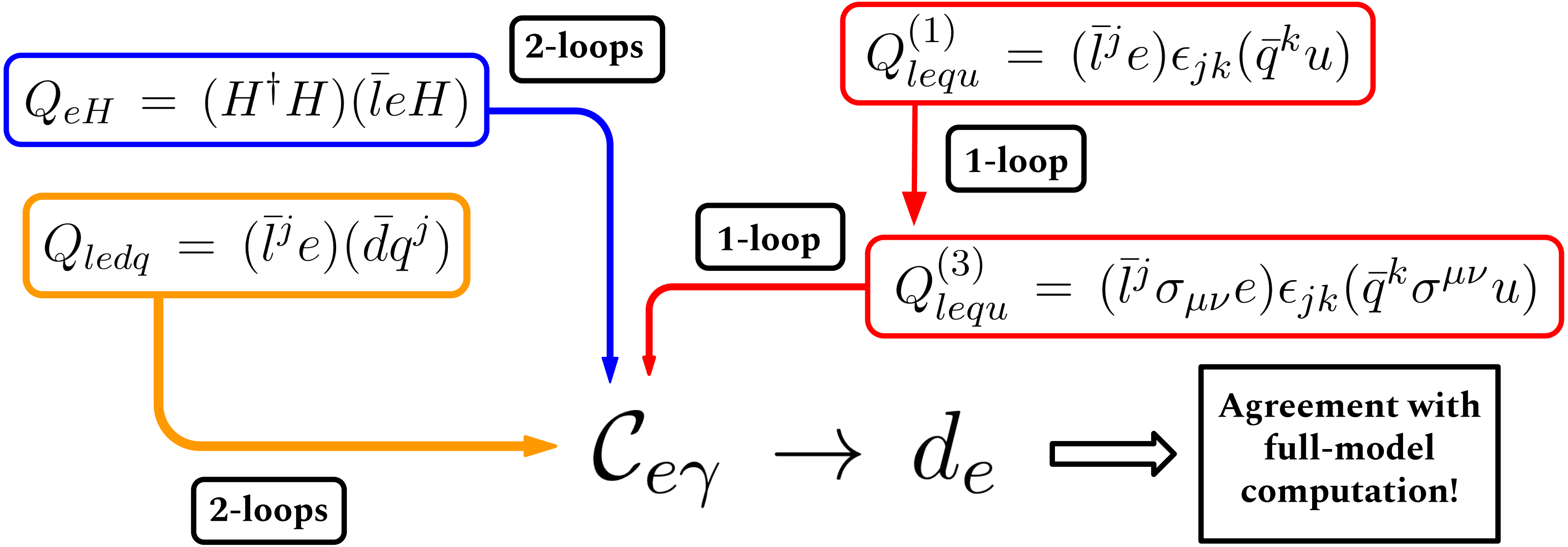
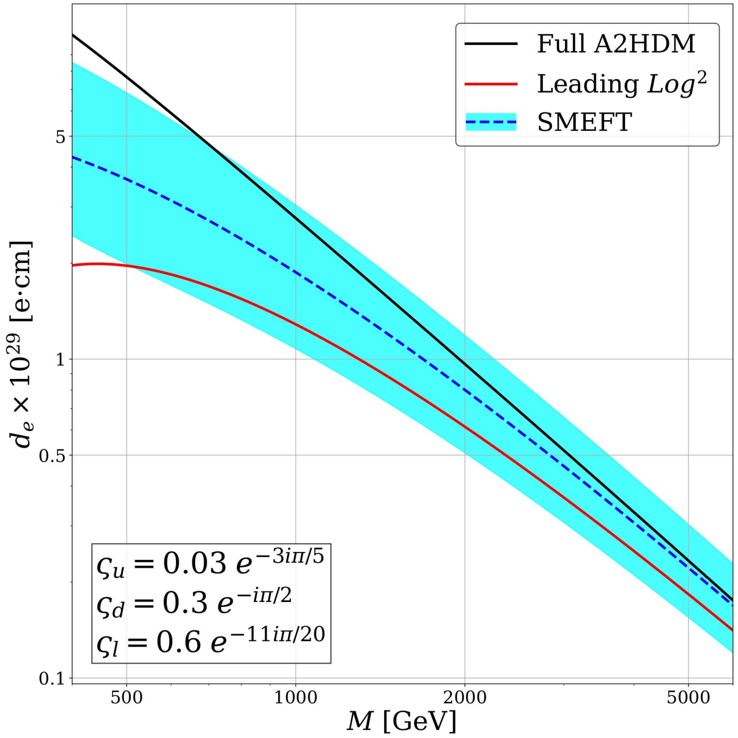
- **Integrating** these equations between the scale of new physics (***M***) and the EW scale we can compute **logarithmic contributions** to the eEDM, which can be **compared** to the leading contributions that we computed in the **Decoupling Limit**. [Panico, Pomarol, Riembau '18], [Vale Silva, Jäger,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

The SMEFT

Outline of RGE mixing:



The SMEFT

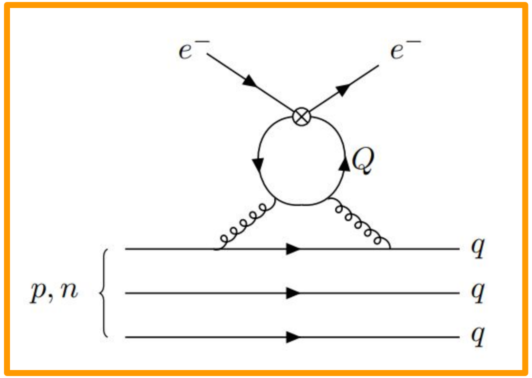


- **Black line**: full A2HDM
- **Red line**: only leading squared logarithm term → dominates close to the decoupling limit.
- **Blue line**: all the previously discussed SMEFT logarithms.
- **Blue band**: variation of the NP scale.

Electron-nucleon interactions

CP-violating **electron-nucleon** interactions can be described by effective dimension-6 operators [Engel, Ramsey-Musolf, van Kolck ‘13]:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left(C_S^{(0)}\bar{e}i\gamma_5 e\bar{N}N + C_S^{(1)}\bar{e}i\gamma_5 e\bar{N}\tau_3 N\right)$$



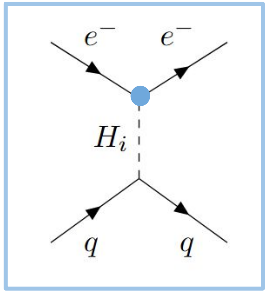
[Ardu, Valori ‘25]

Electron-nucleon interactions

Light (u, d, s) and **heavy** (c, b, t) quarks contribute to electron-nucleon interactions in different ways at low energies [Ardu, Valori '25]:

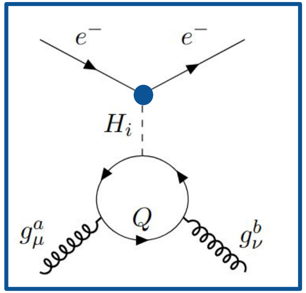
Light Quarks →

$$\langle N|\bar{q}q|N\rangle = g_S^{N,q}\bar{N}N$$

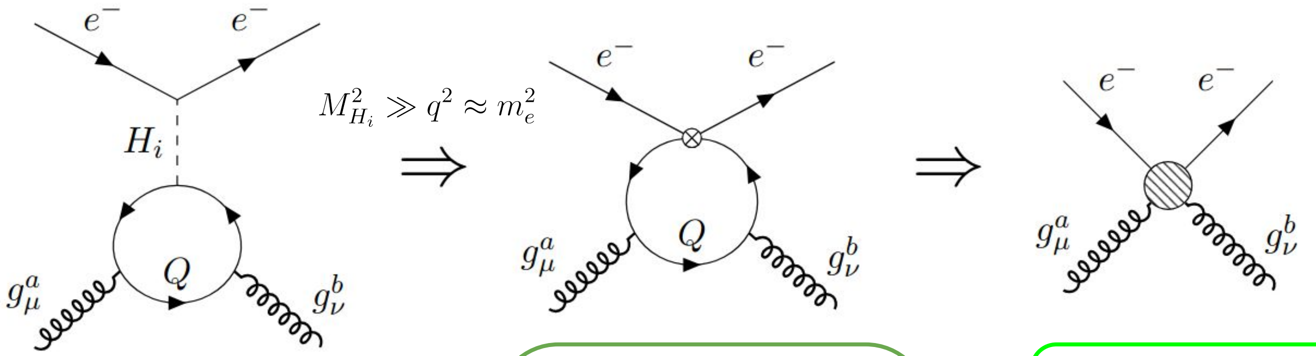


Heavy Quarks →

$$\begin{cases} \langle N|\bar{Q}Q|N\rangle \propto \langle N|G_{\mu\nu}G^{\mu\nu}|N\rangle \\ \langle N|G_{\mu\nu}G^{\mu\nu}|N\rangle \propto \bar{N}N \end{cases}$$



EFT description of electron-nucleon interactions



A2HDM

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

SMEFT/LEFT dim-6

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

$$C^S_q(\bar{e} i\gamma_5 e)(\bar{q}q)$$

$Q = c, b, t$

$q = u, d, s$

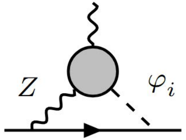
LEFT dim-7

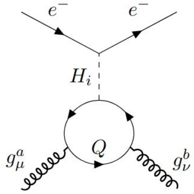
$$O_{eG} = C_{eG}(\bar{e} i\gamma_5 e)(G^a_{\mu\nu} G^{\mu\nu,a})$$

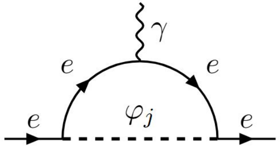
eN interaction

Summary

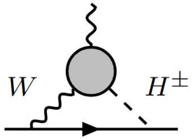
- **EDMs** and **electron-nucleon** interactions → **powerful probes** of the amount of **violation of CP** symmetry in nature.
- There is still **room for NP** that contribute to CPV, such as an extended scalar sector → **2HDMs**
- The **Aligned 2HDM** contains additional **complex phases** that allow 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** → more robust and complete set of constraints on parameters from the A2HDM based on **EDMs of hadronic systems**.

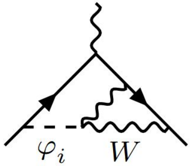

Z
φ_i

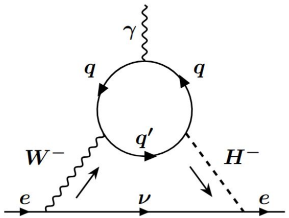

e^-
e^-
H_i
Q
g^a_μ
g^b_ν


γ
e
e
e
e
φ_j

THANKS!!


W
$H^\pm$


φ_i
W


γ
q
q
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W^-
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])

Benchmark

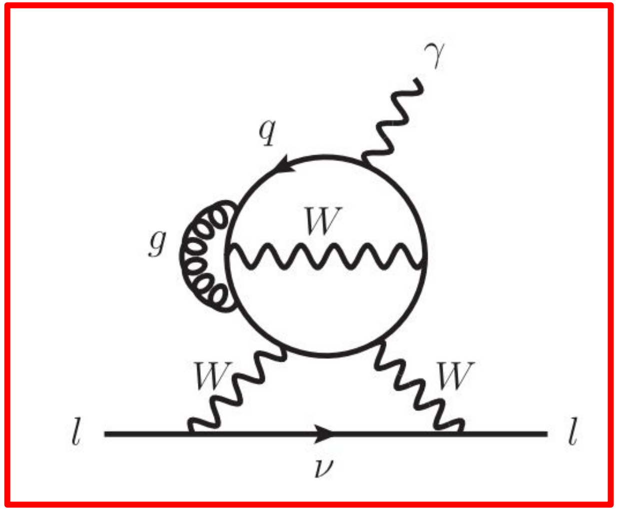
Parameter	Benchmark Value
λ_3	0.02
λ_4	0.04
λ_7	0.03
$\mathrm{Re}(\lambda_5)$	0.05
$\mathrm{Re}(\lambda_6)$	-0.05
$\mathrm{Im}(\lambda_6)$	0.01
α_3	$\pi/6$

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

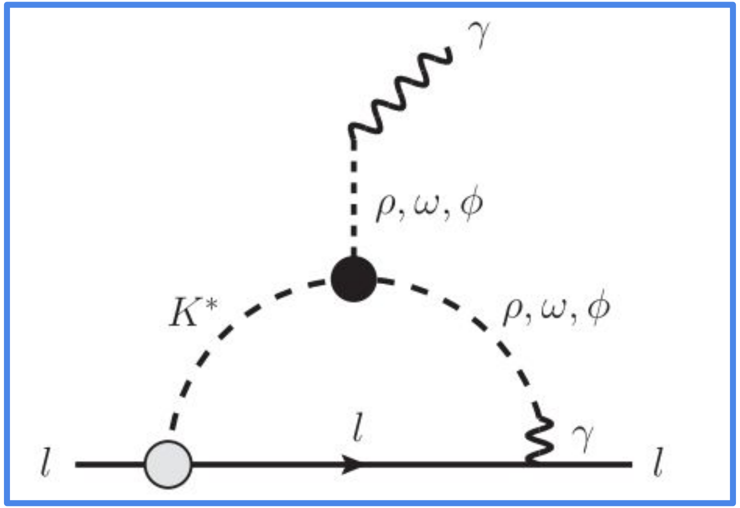
The value of the mass ***M*** corresponds to the mass of the charged scalar, which is related to the mass parameter $\boldsymbol{\mu_2}$.

eEDM in the SM

4-loop SM contribution
(CPV comes from CKM)



Long-distance
contribution



[Yamaguchi, Yamanaka ‘20]

eEDM in the SM

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]:

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