EDMs in Two Higgs Doublet Models

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Introduction

Phenomena sensitive to
Charge-Parity Violation (CPV)

↓

Powerful test of the Standard Model (**SM**) structure, where CPV stems from the **CKM** matrix and the **QCD θ term**

Introduction

[Pospelov, Ritz '25]

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Charge-Parity Violation (**CPV**)

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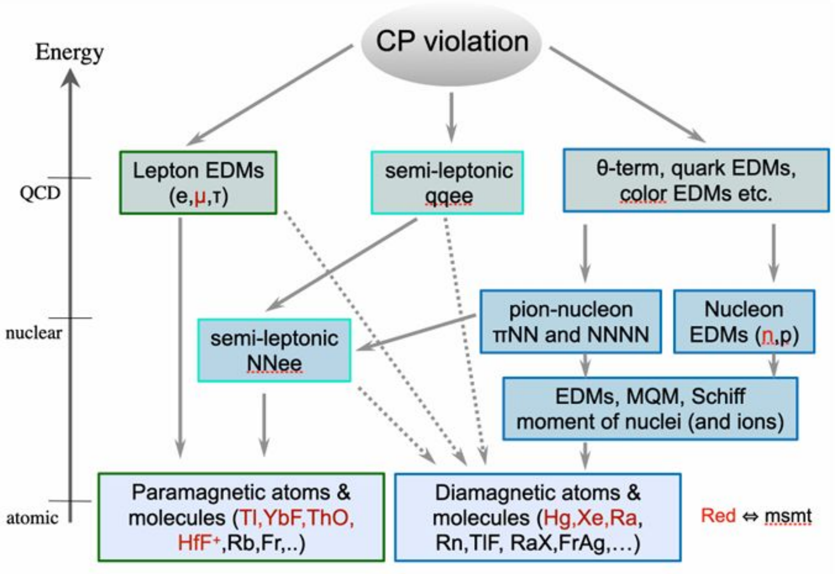
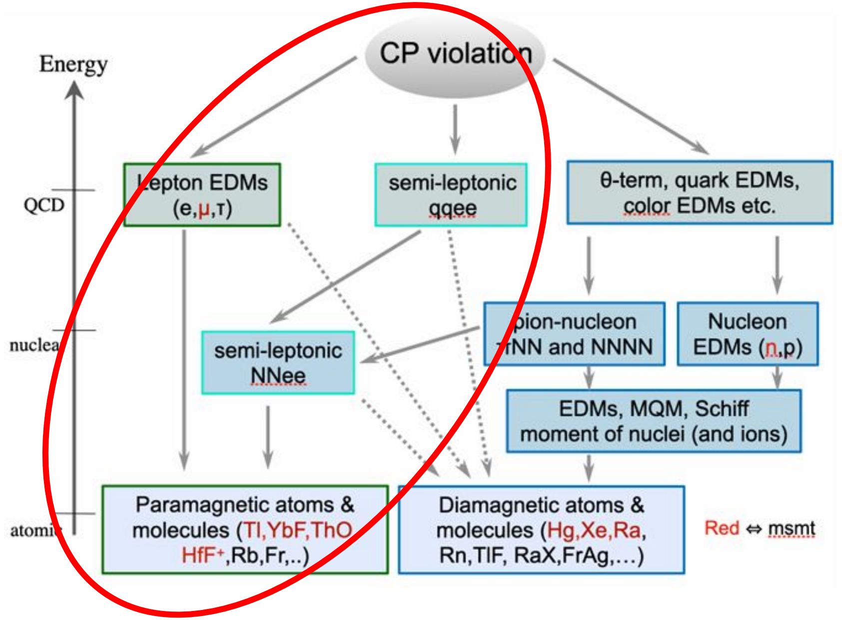


Introduction

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

Powerful test of the Standard Model (**SM**) structure, where **CPV** stems from the **CKM** matrix and the **QCD** θ **term**

[Pospelov, Ritz '25]



Electron EDM

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 [JILA '23]:

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

Using HfF^{+} molecular ions

Electron EDM

Usually, contributions to the eEDM are highly suppressed:

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

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

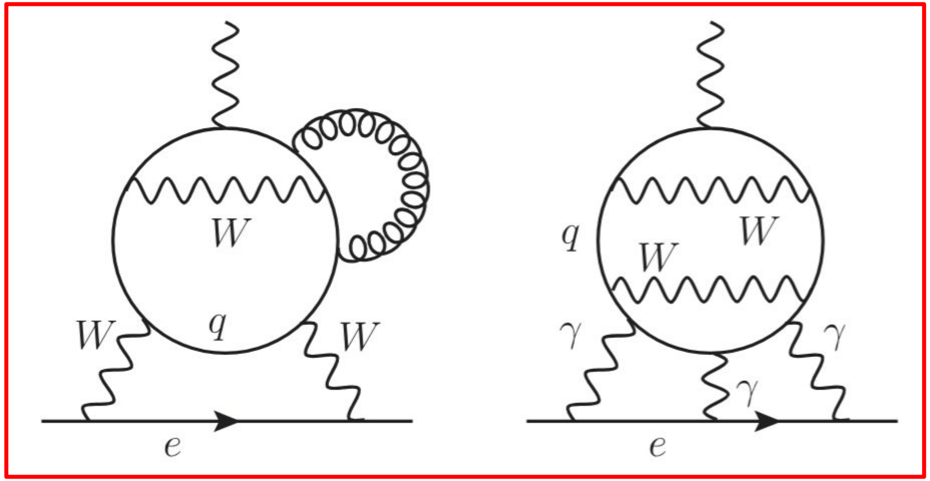
~70% theoretical uncertainty

- Assuming that neutrinos are **Majorana particles**, at two-loop order (highly fine-tuned) [Archambault, Czarnecki, Pospelov ‘04]:

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

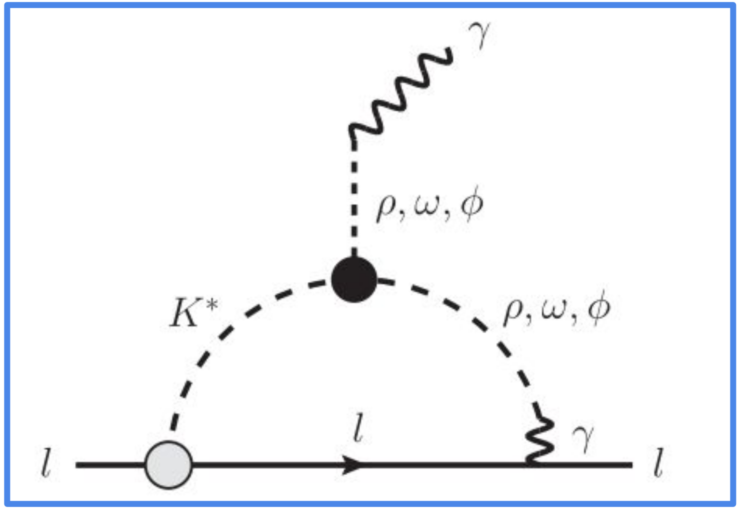
Electron EDM

4- and 5-loop SM contributions
(CPV comes from CKM)



[Pospelov, Ritz ‘13]

Long-distance
contribution



[Yamaguchi, Yamanaka ‘20]

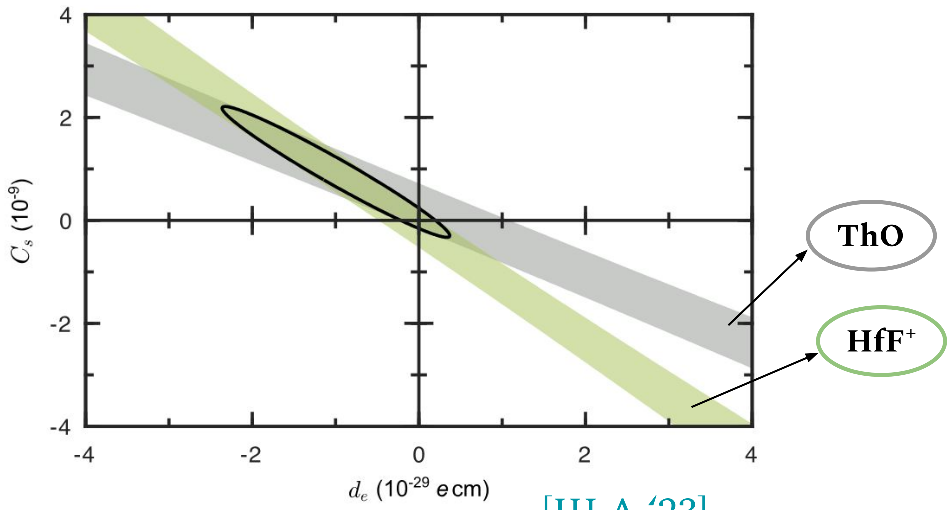
Electron EDM

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:

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

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

Electron-nucleon interaction



[JILA ‘23]

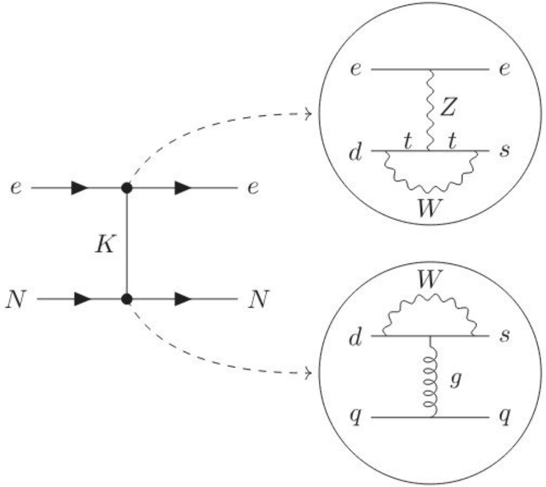
Electron-nucleon interactions

Contributions to electron-nucleon interactions in the SM:

- In the chiral limit, the **dominant** contribution involves the exchange of a Kaon.

$$C_S(\mathrm{LO}) \simeq 5 \times 10^{-16}$$

[Ema, Gao, Pospelov '22]



Electron-nucleon interactions

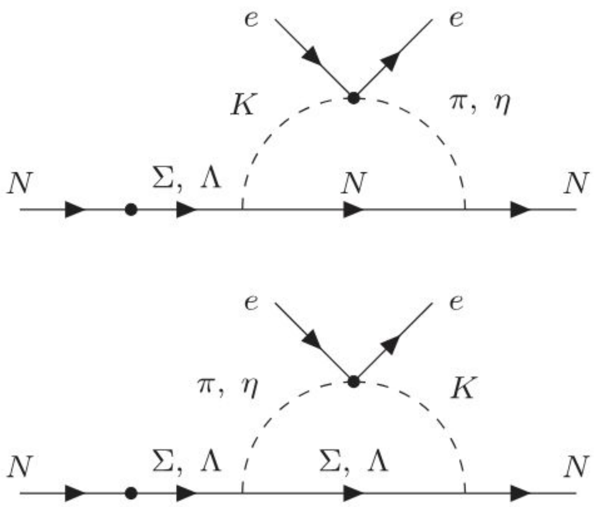
Contributions to electron-nucleon interactions in the SM:

- At Next-to-Leading Order (**NLO**), baryon pole diagrams contribute to C_S.

$$C_S(\mathrm{LO}+\mathrm{NLO}) \simeq 6.9\times 10^{-16}$$
$$\Rightarrow d_e^{\mathrm{equiv}} \simeq 1.0\times 10^{-35}\ e\,\mathrm{cm}.$$

ThO

[Ema, Gao, Pospelov '22]



Equivalent eEDM measurements

The equivalent eEDM can be measured in different systems:

- EDM of paramagnetic atoms:

Atom	Current bound on equivalent eEDM
Tl	1.1×10^{-24} e cm
Cs	1.4×10^{-23} e cm

$$d_i = \alpha_{i,d_e} d_e + \alpha_{i,C_S} C_S + \ldots$$

[Degenkolb et al. '24]

Equivalent eEDM measurements

The equivalent eEDM can be measured in different systems:

- EDM of paramagnetic molecules (recent theoretical advance in sensitivity to nucleon EDMs [Dekens at al. '25]):

Experiment/ Collaboration	Molecule	Current bound on equivalent eEDM
JILA	HfF^+	4.1×10^{-30} e cm
ACME	ThO	1.1×10^{-29} e cm
Imperial College London	YbF	1.1×10^{-27} e cm

P and T-violating frequency shift

[Degenkolb et al. '24]

$$\omega_i = \eta^{(m)}_{i,d_e} d_e + k^{(m)}_{i,C_S} C_S + \dots$$

Equivalent eEDM measurements

The equivalent eEDM can be measured in different systems:

- Upcoming sensitivities:

Experiment/ Collaboration	Molecule	Upcoming sensitivity on equivalent eEDM
JILA Gen III	ThF^+	1×10^{-31} e cm
NL-eEDM	BaOH	1×10^{-30} e cm
EDM^3	BaF	1×10^{-33} e cm
Imperial College London	YbF	1×10^{-30} e cm

Equivalent eEDM measurements

- Diamagnetic (closed-shell) systems → also sensitive to pion-nucleon interactions and nucleon EDMs:

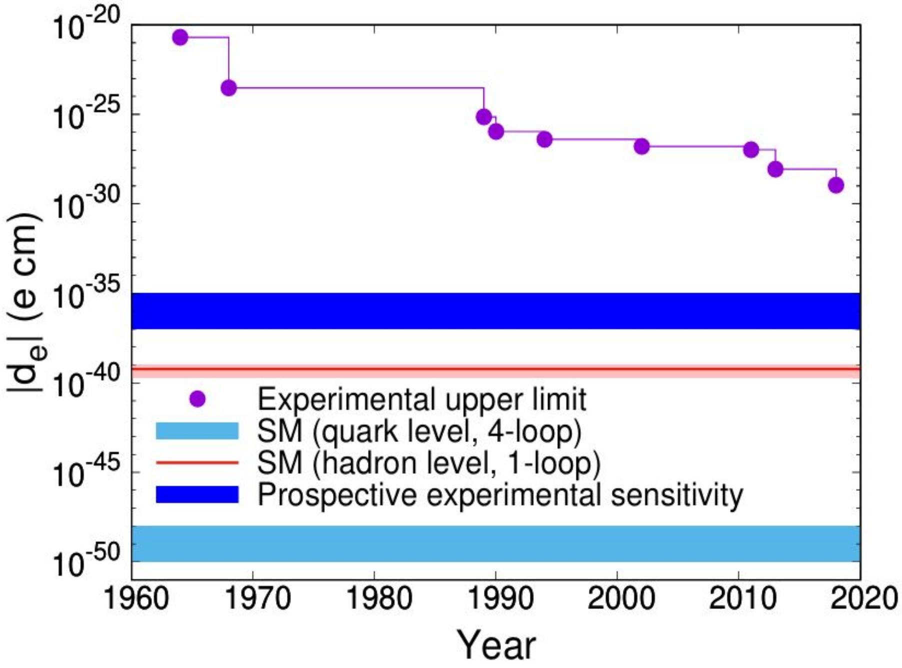
Atom/Molecule	Current bound on equiv. eEDM
Hg	7.4×10^{-30} e cm
Xe	4.8×10^{-28} e cm
Yb	1.5×10^{-26} e cm
Ra	1.4×10^{-23} e cm
TlF	6.5×10^{-23} e cm

[Degenkolb et al. '24]

$$k_{i,S} S_i = \sum_{c_j \in \{d_{n,p}, g_\pi^{(0,1,2)}\}} \alpha_{i,c_j} c_j$$

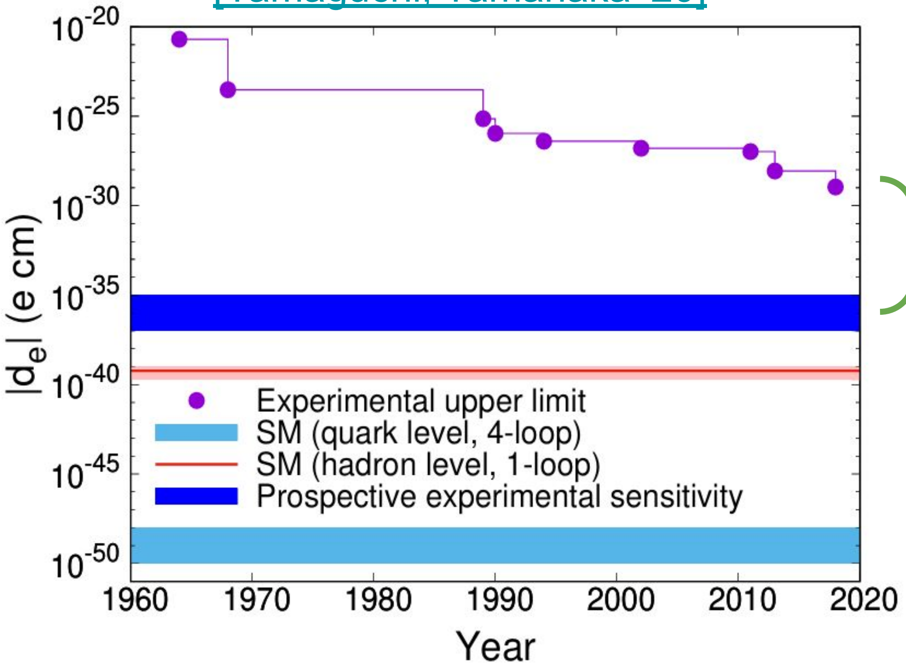
NP contributions to eEDM

[Yamaguchi, Yamanaka ‘20]



NP contributions to eEDM

[Yamaguchi, Yamanaka '20]

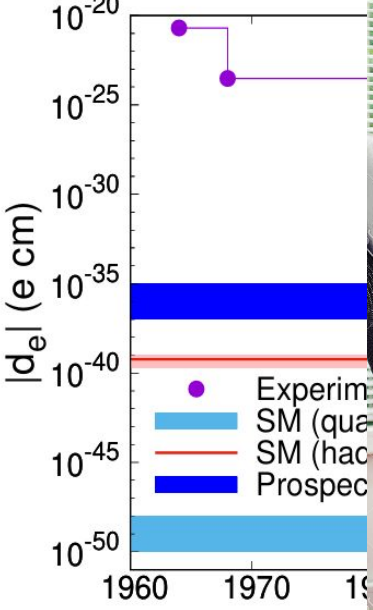


Room for **New Physics** (NP)!!!

Additional sources of CPV through **complex phases** of the parameters of the NP model

Table-top "experiment"

[Yamagu



Stock image: Dreamtime.com

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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 vacuum expectation value (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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- G^+, G^0: Goldstone Bosons
- H^+: Charged scalar
- v: vev (246 GeV)
- S_1, S_2: CP-even scalars
- S_3: CP-odd scalar

2HDMs: Scalar Potential

Most general, CP-violating scalar potential:

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

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

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

$$S_1, S_2, S_3 \overset{\mathcal{R}}{\Longrightarrow} H_j \in \{H_1, H_2, H_3\}$$

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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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):

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

- **Complex 2HDM**: 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.
  - Only sources of CPV: λ_5 ,λ_6 from the scalar potential (in the Higgs basis).

2HDMs: Flavour Sector

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

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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.

2HDMs: Flavour Sector

Different models have different flavour alignment parameters:

- General 2HDM: $\varsigma_i \in \mathbb{C}^3$

Full eEDM computation in
Altmannshofer et. al. '24

2HDMs: Flavour Sector

Different models have different flavour alignment parameters:

- General 2HDM: $\varsigma_i \in \mathbb{C}^3$
- General Aligned 2HDM: $\varsigma_i \in \mathbb{C}^3$, diagonal

} Matrices

Generation-dependent flavour alignment parameters

2HDMs: Flavour Sector

Different models have different flavour alignment parameters:

- General 2HDM: $\varsigma_i \in \mathbb{C}^3$
- General Aligned 2HDM: $\varsigma_i \in \mathbb{C}^3$, diagonal

(Matrices)

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

2HDMs: Flavour Sector

Different models have different flavour alignment parameters:

- General 2HDM: $\varsigma_i \in \mathbb{C}^3$
- General Aligned 2HDM: $\varsigma_i \in \mathbb{C}^3$, diagonal
- (Minimal) Aligned 2HDM: $\varsigma_i \in \mathbb{C}$
- $\mathbb{Z}_2$-conserving 2HDMs:

Matrices

Model used in this work

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

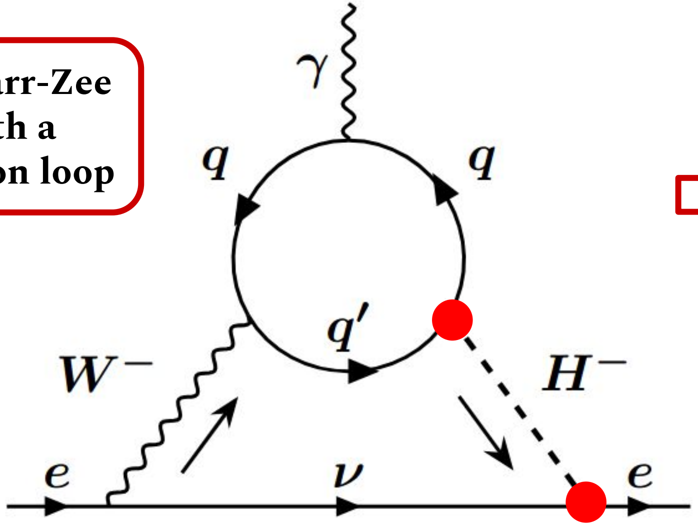
$$\text{Type X:}\ \varsigma_u = \varsigma_d = -\frac{1}{\varsigma_l} = \cot\beta \quad \text{and} \quad \text{Type Y:}\ \varsigma_u = -\frac{1}{\varsigma_d} = \varsigma_l = \cot\beta\,.$$

[Karan, Miralles, Pich '23]

The eEDM in the A2HDM

Although already contributing at 1 loop, 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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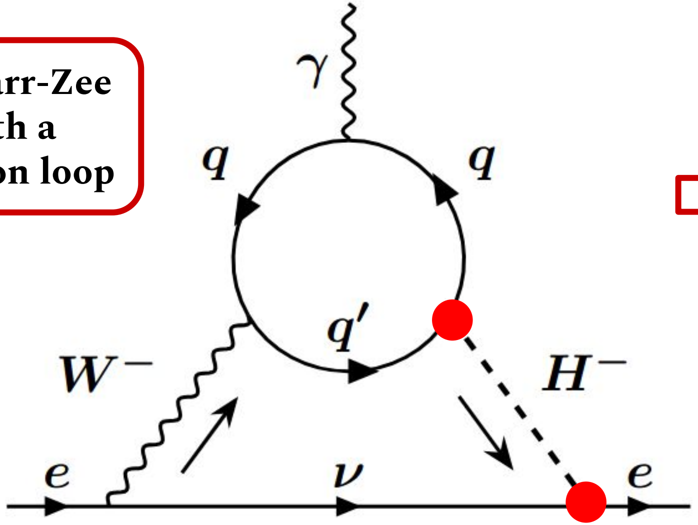
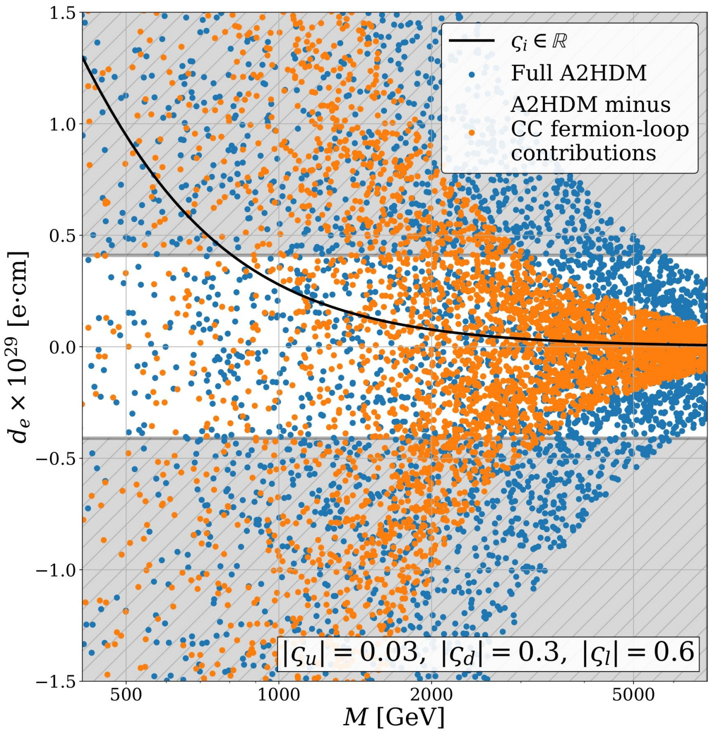


$$d_{e,f}^{CC} \propto \mathrm{Im}(\varsigma_{u,d}^{*}\varsigma_l)$$

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

The eEDM in the A2HDM



- **Black line**: real alignment parameters $\boldsymbol{\varsigma}$.
- **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 $\boldsymbol{M}$ → motivated by **EW Baryogenesis** [van de Vis, de Vries, Postma ‘25, Enomoto, Kanemura, Mura ‘22].

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:

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

- This condition means that the **scalars from the second doublet** will be **much heavier** than the SM Higgs boson:

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

The Decoupling Limit

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].

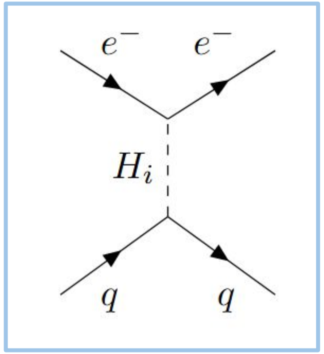
The SMEFT

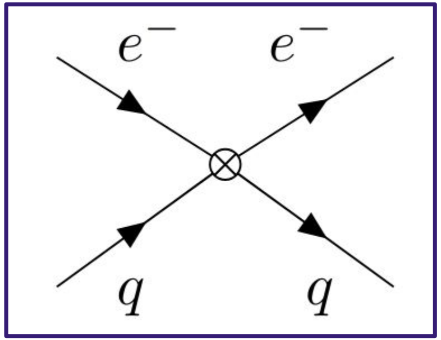
The decoupling limit allows us to make an **Effective Field Theory** (EFT) description of the contributions to the eEDM and electron-nucleon interactions in the A2HDM → this contributions can be characterized by a set of **effective operators** of dimension higher that 4:

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

The SMEFT

These CP-violating **effective operators** are generated when the heavy scalars from A2HDM get integrated out → matching at **tree-level:**





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

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

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

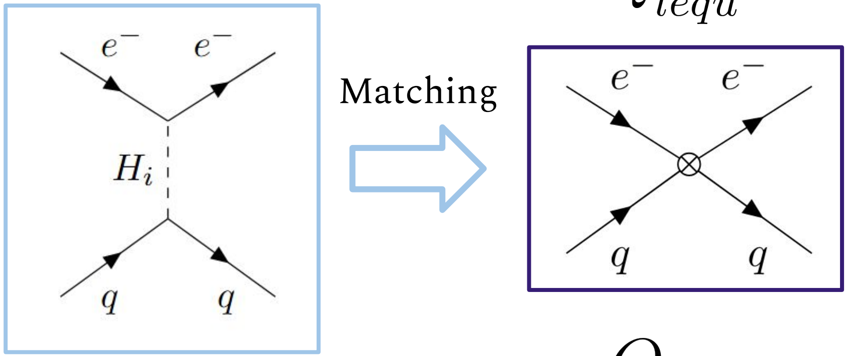
- **Integrating** these equations between the scale of new physics (***M***) and the EW scale we can compute **logarithmic contributions** to the eEDM, which help us understand the leading contributions that we computed in the **Decoupling Limit**. [Panico, Pomarol, Riembau '18], [Vale Silva, Jäger,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

The SMEFT

Outline of RGE mixing:

A2HDM

$$Q_{lequ}^{(1)}$$



$$Q_{ledq}$$

The SMEFT

Outline of RGE mixing:

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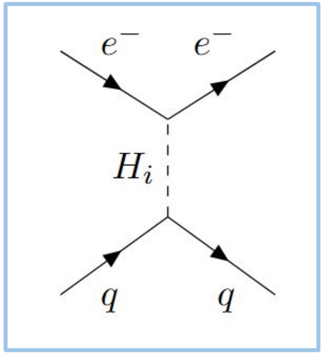
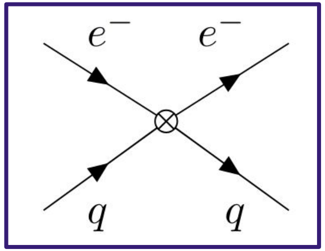


Matching

$Q^{(1)}_{lequ}$ RGE $\Rightarrow$ $Q^{(3)}_{lequ}$

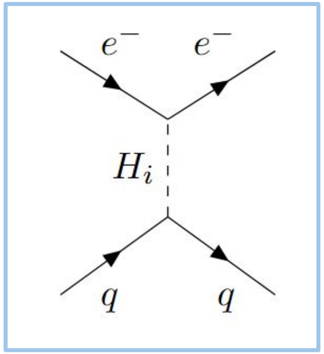


Q_{ledq}

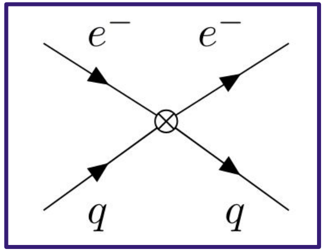
The SMEFT

Outline of RGE mixing:

A2HDM



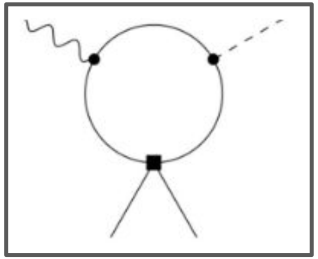
Matching $\Rightarrow$



Q_{ledq}

$Q^{(1)}_{lequ}$ $\xrightarrow{\text{RGE}}$ $Q^{(3)}_{lequ}$ RGE

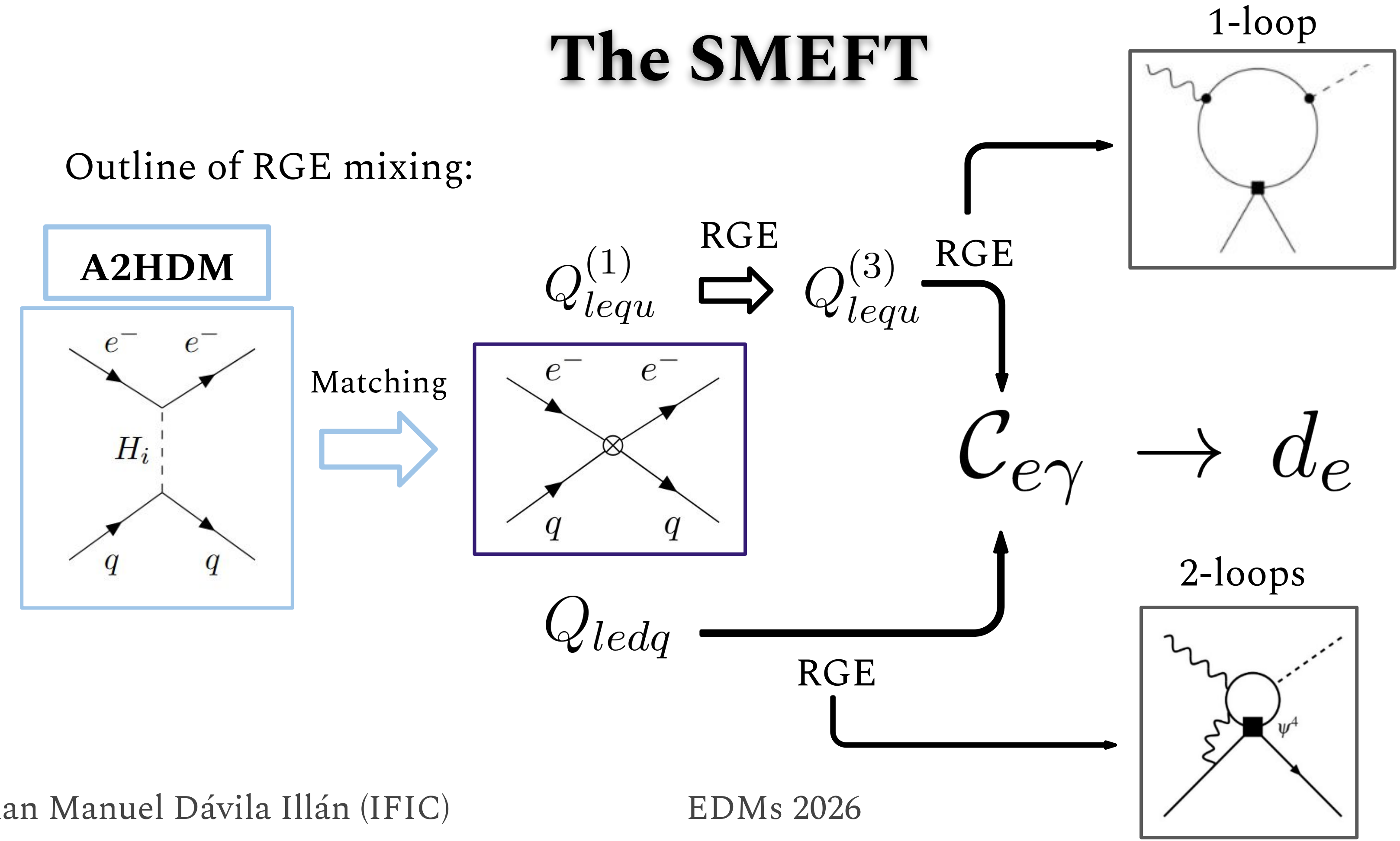
1-loop



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

The SMEFT

Outline of RGE mixing:



The SMEFT

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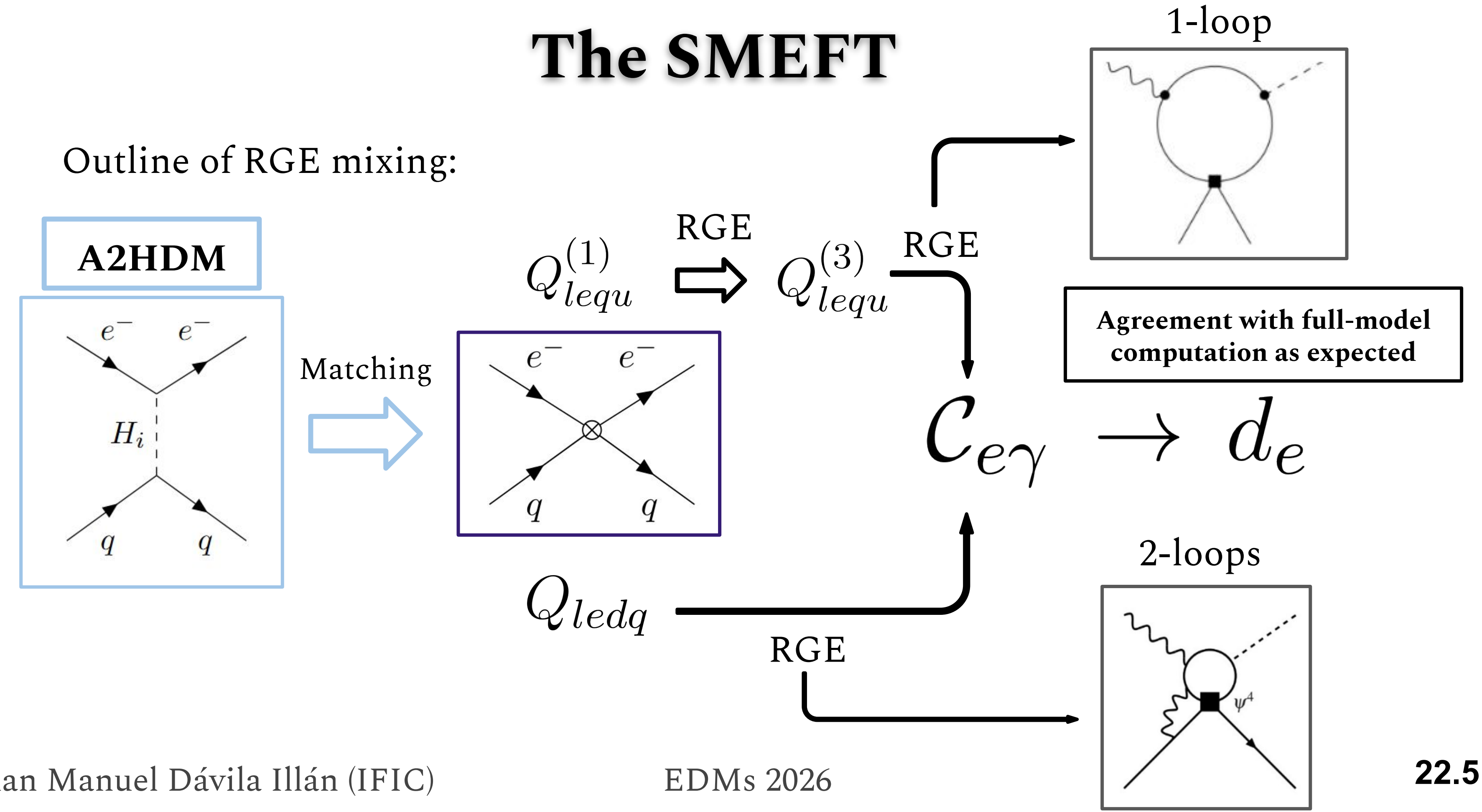
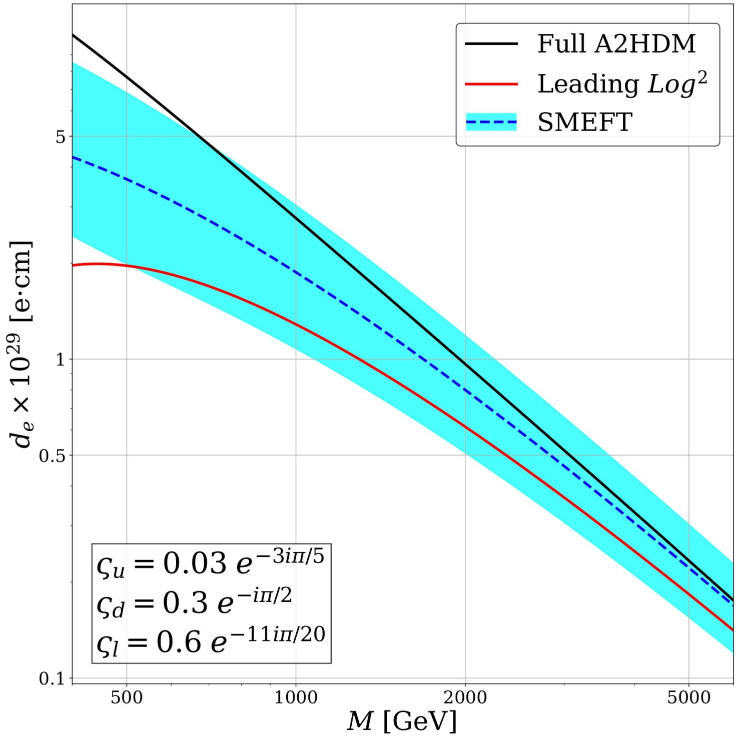


The SMEFT

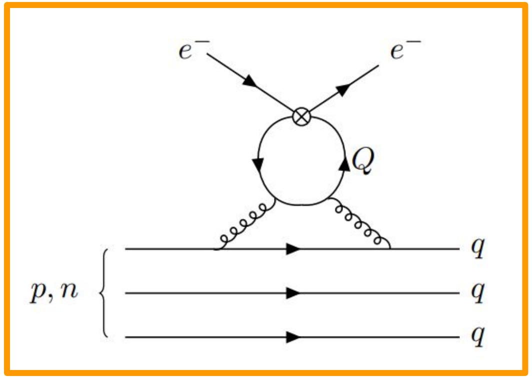


- **Black line**: full A2HDM
- **Red line**: only leading squared logarithm term → dominates close to the decoupling limit.
- **Blue line**: all the previously discussed SMEFT logarithms.
- **Blue band**: variation of the NP scale.

Electron-nucleon interactions

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

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

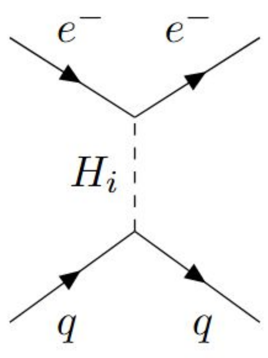


[Ardu, Valori '25]

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



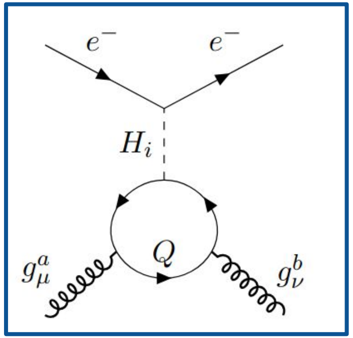
$$\langle N|\bar{q}q|N\rangle = g_S^{q,(0)}\bar{\psi}_N\psi_N + g_S^{q,(1)}\bar{\psi}_N\tau_3\psi_N$$

$$\langle N|\bar{q}i\gamma_5 q|N\rangle = g_P^{q,(0)}\bar{\psi}_N i\gamma_5\psi_N + g_P^{q,(1)}\bar{\psi}_N i\gamma_5\tau_3\psi_N$$

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]:

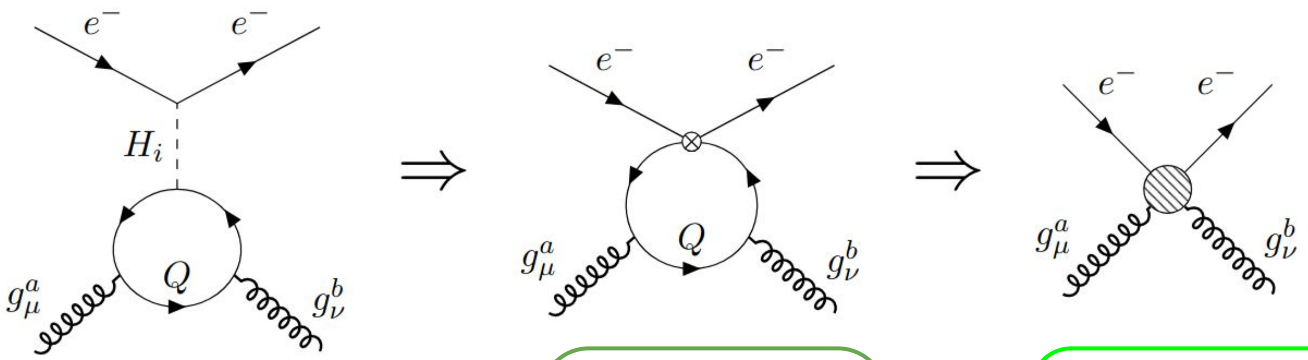
Heavy Quarks



$$\langle N|\bar{Q}Q|N\rangle \propto \langle N|G_{\mu\nu}G^{\mu\nu}|N\rangle \propto \bar{\psi}_N\psi_N$$

$$\langle N|\bar{Q}i\gamma_5 Q|N\rangle \propto \langle N|G_{\mu\nu}\tilde{G}^{\mu\nu}|N\rangle \propto \bar{\psi}_N i\gamma_5\psi_N$$

Electron-nucleon interactions



A2HDM

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

⇒

SMEFT/LEFT dim-6

$$C_q^S(\bar{e}i\gamma_5 e)(\bar{q}q)$$

$$C_q^P(\bar{e}e)(\bar{q}i\gamma_5 q)$$

LEFT dim-7

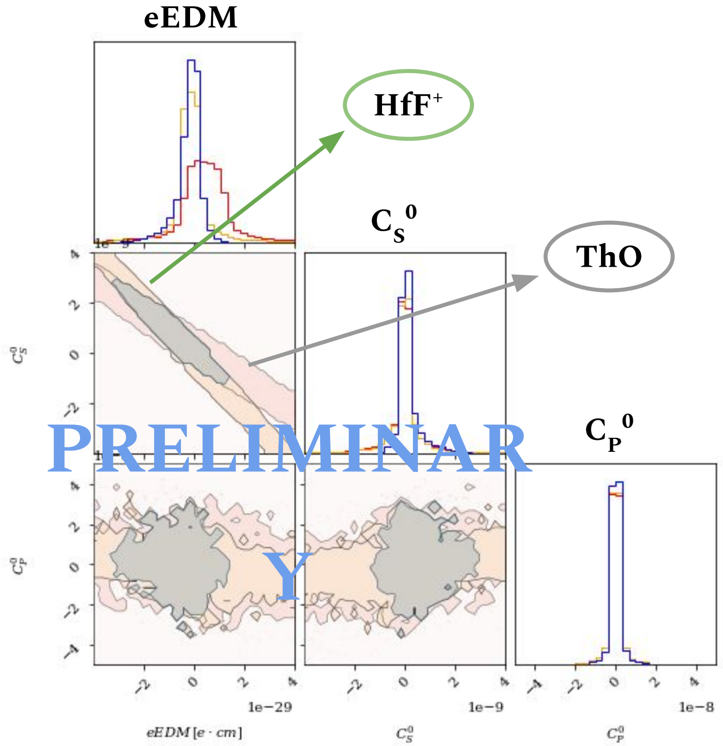
$$O_{eG} = C_{eG}(\bar{e}i\gamma_5 e)(G^a_{\mu\nu}G^{\mu\nu,a})$$

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

⇓

eN interaction

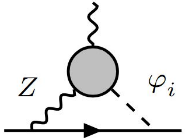
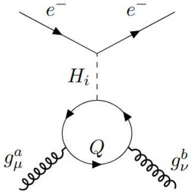
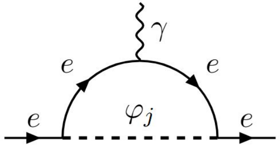
Constraints from EDMs



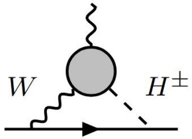
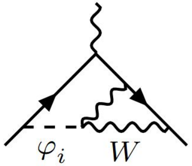
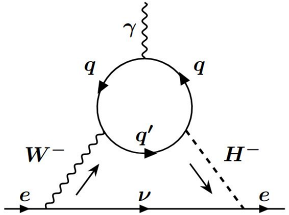
- Estimates on **correlation plots** in A2HDM between different parameters.
- Points satisfy CP-conserving bounds.
- **Tight constraints** on the eEDM and C_S from combined paramagnetic systems EDM data.
- Need to include constraints from **additional systems** (e.g. diamagnetic atoms).
- Ongoing: better constraints on the **down-type** alignment parameter

Summary

- **eEDM** and **electron-nucleon** interactions → **powerful probes** of the amount of **violation of CP** symmetry in nature in the SM and beyond.
- 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.
- **Constrained** parameter space from EDM bounds.
- **Outlook** → Account of hadronic uncertainties, incorporate constraints from diamagnetic systems, neutron EDM. **Stay tuned!!**


Z
φ_i

e^-
e^-
H_i
Q
g^a_μ
g^b_ν

γ
e
e
e
φ_j
e

THANKS!!


W
$H^\pm$

φ_i
W

γ
q
q
q'
W^-
H^-
e
ν
e

BACKUP

Benchmark (eEDM plots)

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	$\pi/6$

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 $\boldsymbol{\mu_2}$.

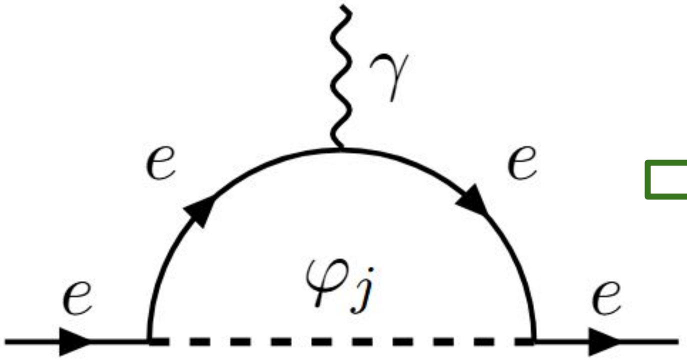
CP-conserving constraints (eEDM-C_S plots)

Global fit performed in [Karan, Miralles, Pich '23].

Marginalized individual results			
Masses up to 1 TeV			
$M_{H^\pm} \geq 390$ GeV	$M_H \geq 410$ GeV		$M_A \geq 370$ GeV
λ_2: 3.2 ± 1.9	λ_3: 5.9 ± 3.5		λ_7: 0.0 ± 1.1
$\tilde{\alpha}$: $(0.05 \pm 21.0) \times 10^{-3}$	ς_u: 0.006 ± 0.257	ς_d: 0.12 ± 4.12	ς_l: -0.39 ± 11.69
Masses up to 1.5 TeV			
$M_{H^\pm} \geq 480$ GeV	$M_H \geq 490$ GeV		$M_A \geq 480$ GeV
λ_2: 3.2 ± 1.9	λ_3: 5.9 ± 3.8		λ_7: 0.0 ± 1.2
$\tilde{\alpha}$: $(0.8 \pm 16.8) \times 10^{-3}$	ς_u: -0.011 ± 0.407	ς_d: -0.096 ± 6.22	ς_l: -1.18 ± 17.54

The eEDM in the A2HDM

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



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

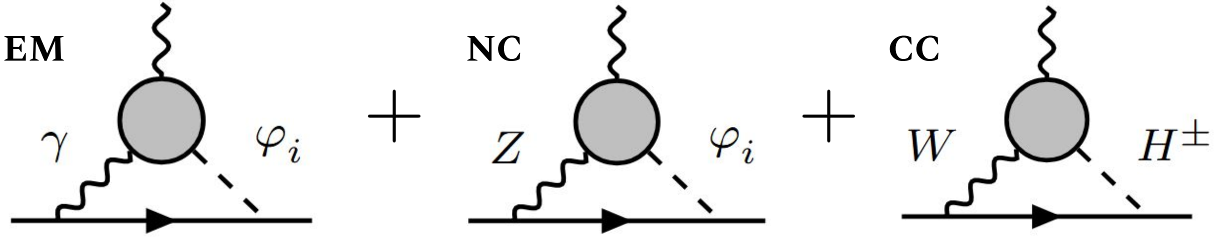
The eEDM in the A2HDM

Notation:

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

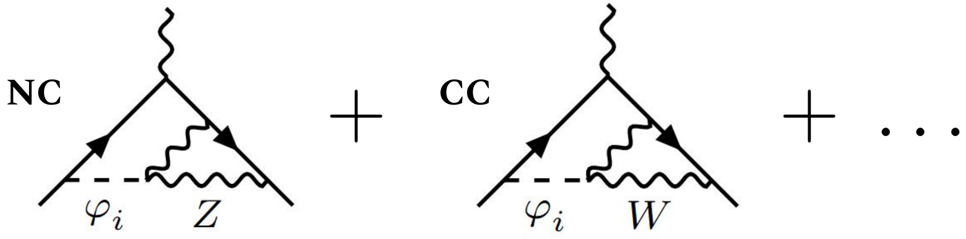
The **dominant** contributions come at **2-loop order**:

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



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

- Or "**kite**" diagrams:



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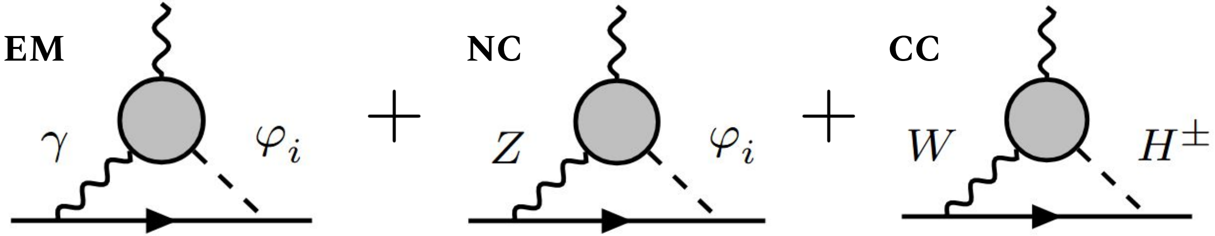

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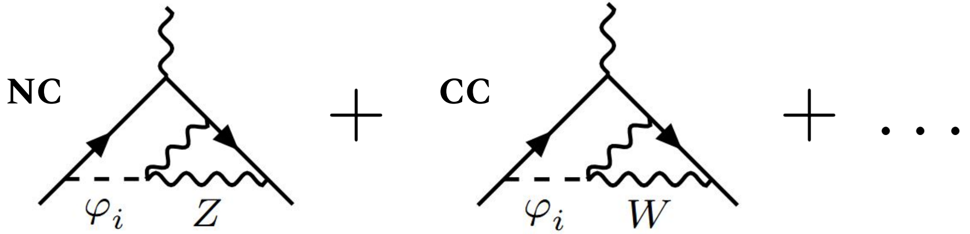

Nucleon form factors

Scalar form factors connecting quark currents to nucleon currents:

$$g_S^{(0)} = \frac{1}{2}\frac{\sigma_{\pi N}}{m_{ud}}, \qquad g_S^{(1)} = \frac{1}{2} g_S^{u-d}, \qquad g_S^{s} = \frac{\sigma_s}{m_s}$$

	$\sigma_{\pi N}$ (MeV)	g_S^{u-d}	σ_s (MeV)
$N_f = 2+1$	42.2(2.4)	1.085(114)	44.9(6.4)
$N_f = 2+1+1$	60.9(6.5)	1.083(69)	41.0(8.8)

[FLAG '25]

Nucleon form factors

Axial form factors, axial currents related to pseudoscalar currents:

$$\langle N | J_{\mu 5} | N \rangle = g_A^{(0)} \langle N | \bar{N} \gamma_\mu \gamma_5 N | N \rangle \qquad \langle N | \partial^\mu J_{\mu 5} | N \rangle = 2 m_N g_A^{(0)} \langle N | \bar{N} i \gamma_5 N | N \rangle$$

$$g_A^{u,(0)} = \frac{1}{2}(g_A^u + g_A^d) = g_A^{d,(0)}, \qquad g_A^{u,(1)} = \frac{1}{2} g_A^{u-d} = -g_A^{d,(1)},$$

$$g_A^{s,(0)} = g_A^s, \qquad g_A^{s,(1)} = 0.$$

	g_A^u	g_A^d	g_A^s	g_A^{u-d}
$N_f = 2+1$	0.847(18)(32)	-0.407(16)(18)	-0.035(6)(7)	1.265(20)
$N_f = 2+1+1$	0.777(25)(30)	-0.438(18)(30)	-0.053(8)	1.263(10)

[FLAG ‘25]