Aligned Two Higgs Doublet Model and electric dipole moment of electron

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Based on: 2412.xxxxx

Jornadas científicas IFIC: Origin of mass. L1 Higgs Force

02/12/2024

EDM in non-relativistic QM

- **Imagine:** Electron in its rest frame with external $\vec{E}$ and $\vec{B}$.

- **NR-QM:** $\mathcal{H} = -\left(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}\right) = -\left[\mu\left(\frac{\vec{S}}{S}\right) \cdot \vec{B} + d\left(\frac{\vec{S}}{S}\right) \cdot \vec{E}\right]$

- **(C, P, T):**
  $$(\vec{E}, \vec{B}, \vec{S}) \xrightarrow{\text{C}} (-\vec{E}, -\vec{B}, \vec{S}) \xrightarrow{\text{P}} (\vec{E}, -\vec{B}, \vec{S}) \xrightarrow{\text{T}} (\vec{E}, \vec{B}, -\vec{S})$$

- **CPT invariance:** $d_f = -d_{\bar{f}}$ and $\mu_f = -\mu_{\bar{f}}$

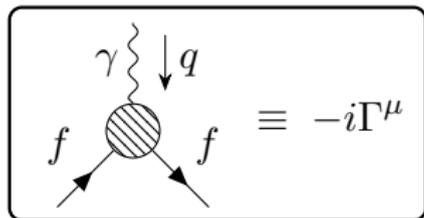- **CP invariance:** $d_f = d_{\bar{f}}$ and $\mu_f = -\mu_{\bar{f}}$

- **EDM:** CP symmetry (assuming CPT) $\implies d_f = 0$.
  Non-zero d_f is a measure for CP-violation.

Chupp, Fierlinger, Ramsey-Musolf, Singh Rev.Mod.Phys. 91 (2019) 1, 015001

EDM in Field Theory

$$\Gamma^\mu = \mathcal{F}_1(q^2)\,\gamma^\mu$$

$$+ \frac{i\sigma^{\mu\nu}}{2m_f}\,q_\nu\,\mathcal{F}_2(q^2)$$

$$+ i\epsilon^{\mu\nu\alpha\beta}\,\frac{\sigma_{\alpha\beta}}{4m_f}\,q_\nu\,\mathcal{F}_3(q^2)$$

$$+ \frac{1}{2m_f}\Big(q^\mu - \frac{q^2}{2m_f}\gamma^\mu\Big)\,\gamma^5\,\mathcal{F}_4(q^2)$$

$$\gamma \lessgtr \downarrow q$$
$$f \qquad f \qquad \equiv -i\Gamma^\mu$$

EDM in EFT:
$$\mathcal{L} \supset -\frac{i}{2}d_e(\mu)\,\bar\psi_e\,\sigma^{\mu\nu}\gamma^5\,\psi_e\,F_{\mu\nu}$$

$$e\,Q_f = \mathcal{F}_1(0)$$

$$\mu_f = \frac{1}{2m_f}[\mathcal{F}_1(0) + \mathcal{F}_2(0)]$$

$$d_f = -\frac{\mathcal{F}_3(0)}{2m_f}$$

Anapole moment: $\mathcal{F}_4(0)$

Motivation (eEDM)

☞ **SM Value:** eEDM starts at **4-loop**
$$d_e^{\mathsf{SM}} \approx 10^{-38} \text{ e cm}$$

☞ **Majorana neutrinos:** eEDM starts at 2-loop

☞ **Type-I seesaw:** $d_e^{\mathsf{seesaw-I}} \leq 10^{-33}$ e cm

☞ **Expt. bound:** $|d_e^{\mathsf{Exp}}| \leq 4.11 \times 10^{-30}$ e cm (90% C.L.)

Roussy et al. Science 381 (2023) 6653

☞ **Motivation:** Room for BSM Physics,
Observed BAU suggests CPV beyond CKM matrix

Pospelov, Ritz Annals Phys. 318 (2005) 119-169

Motivation (A2HDM)

➠ **2HDM:** SM + another scalar doublet.

➠ **Prospects:** New sources of CP violation, Axion-like phenomenology, Dark matter aspects, Electroweak Baryogenesis, Stability of scalar potential till Planck scale, EFT for SUSY, etc.

➠ **Problems:** **FCNC**

➠ **Solutions:** 1) Additional $\mathcal{Z}_2$ symmetry, 2) **A2HDM**

➠ **A2HDM:** The Yukawa matrices corresponding to two scalars are proportional to each other. Pich, Tuzon PRD 80 (2009) 091702

➠ **Misalignment:** The misalignment generated through quantum corrections are well-below the experimental reach. Braeuninger, Ibarra, Simonetto PLB 692 (2010) 189; Jung, Pich, Tuzon JHEP 11 (2010) 003

➠ **Advantages:** 1) More generic framework to study 2HDM.
2) There could be additional sources of CP violation.
3) Rich phenomenology.

Ferreira, Lavoura, Silva PLB 688 (2010) 341; Bijnens, Lu, Rathsman JHEP 05 (2012) 118; Li, Lu, Pich JHEP 06 (2014) 022; Abbas, et al. JHEP 06 (2015) 005; Botella, et al. EPJC 75 (2015) 286; Gori, Haber, Santos JHEP 06 (2017) 110; Kanemura, Mondal, Yagyu JHEP 02 (2023) 237; Eberhardt, Peñuelas, Pich JHEP 05 (2021) 005; Karan, Miralles, Pich PRD 109 (2024) 3; etc...

Scalar Potential

$$\phi_a : \langle 0| \, \phi_a^T \, |0\rangle = (0, v_a e^{i\theta_a}) \quad a \in \{1, 2\}$$

Global $SU(2) \implies$ "Higgs basis"

Charged

Goldstone

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

Physical states
(not CP eigenstates)

CP-even

CP-odd

$$\implies \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \mathcal{R} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad \text{with } \mathcal{R}^T \mathcal{R} = I \quad \text{and } R \to \{\alpha_{12}, \alpha_{13}, \alpha_{23}\}$$

✎ **Scalar Potential:**

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

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

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✎ **Minimization condition:** $v^2 = -\dfrac{2\mu_1}{\lambda_1} = -\dfrac{2\mu_3}{\lambda_6}$

✎ **Independent CPV parameters:** λ_5 and λ_6

Decoupling Limit

* **Masses:**

$$\begin{pmatrix} S_1 \\ S_2 \\ S_3 \end{pmatrix} \quad \mathcal{R} \quad \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

$$\mathcal{M}_S = \begin{pmatrix} v^2\,\lambda_1 & v^2\,\mathrm{Re}(\lambda_6) & -v^2\,\mathrm{Im}(\lambda_6) \\ v^2\,\mathrm{Re}(\lambda_6) & M_{H^\pm}^2 + \frac{1}{2}v^2\,\{\lambda_4 + \mathrm{Re}(\lambda_5)\} & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) \\ -v^2\,\mathrm{Im}(\lambda_6) & -\frac{1}{2}v^2\,\mathrm{Im}(\lambda_5) & M_{H^\pm}^2 + \frac{1}{2}v^2\,\{\lambda_4 - \mathrm{Re}(\lambda_5)\} \end{pmatrix}$$

with, $\quad M_{H^\pm}^2 = \mu_2 + \dfrac{\lambda_3}{2}\,v^2$

$$\mathcal{M}_S \quad \textbf{Diagonalize} \quad \{M_{h_j}\}$$

* **Decoupling Limit:** $\boxed{\sqrt{\mu_2} \gg v} \implies$ 1) $M_{\{H,A,H^\pm\}} \approx M \gg M_h$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ 2) $\{\alpha_{12},\,\alpha_{13}\} \to 0$

Fermionic interaction

⚙ **Yukawa interaction:**

$$-\mathcal{L}_Y = \left(1 + \frac{S_1}{v}\right)\left\{\bar{u}_L\,M_u\,u_R + \bar{d}_L\,M_d\,d_R + \bar{\ell}_L\,M_\ell\,\ell_R\right\}$$

$$+ \frac{1}{v}\,(S_2 + iS_3)\left\{\bar{u}_L\,Y_u\,u_R + \bar{d}_L\,Y_d\,d_R + \bar{\ell}_L\,Y_\ell\,\ell_R\right\}$$

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

Diagonal

non-Diagonal

⚙ **Alignment:** $\quad Y_u = \varsigma_u^*\,M_u \quad$ and $\quad Y_{d,\ell} = \varsigma_{d,\ell}\,M_{d,\ell}\,,$

$$-\mathcal{L}_Y \supset \sum_{i,f}\left(\frac{y_f^{h_i}}{v}\right)h_i\left[\bar{f}M_f\mathcal{P}_R f\right] + \left(\frac{\sqrt{2}}{v}\right)H^+\left[\bar{u}\left\{\varsigma_d VM_d\mathcal{P}_R - \varsigma_u M_u^\dagger V\mathcal{P}_L\right\}d + \varsigma_\ell\,\bar{\nu}M_\ell\mathcal{P}_R\ell\right] + \text{h.c.}$$

$$y_u^{h_j} = \mathcal{R}_{i1} + (\mathcal{R}_{j2} - i\,\mathcal{R}_{j3})\,\varsigma_u^* \quad \text{and} \quad y_{d,\,\ell}^{h_j} = \mathcal{R}_{i1} + (\mathcal{R}_{j2} + i\,\mathcal{R}_{j3})\,\varsigma_{d,\,\ell}^*$$

⚙ **Independent CPV parameters:** ς_u, ς_d, ς_ℓ

Complex 2HDM (C2HDM)

✏ **Fields:**

$$\phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, h_1^+ \\ v_1 + h_1^0 + i\, a_1^0 \end{pmatrix} \quad \text{and} \quad \phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, h_2^+ \\ v_2 + h_2^0 + i\, a_2^0 \end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2} \quad \text{and} \quad \tan\beta = \frac{v_2}{v_1}$$

✏ **Scalar potential:**

$$\widetilde{V} = \tilde{\mu}_1\, \phi_1^\dagger \phi_1 + \tilde{\mu}_2\, \phi_2^\dagger \phi_2 + \left[\tilde{\mu}_3\, \phi_1^\dagger \phi_2 + h.c. \right] + \frac{\tilde{\lambda}_1}{2}\, (\phi_1^\dagger \phi_1)^2 + \frac{\tilde{\lambda}_2}{2}\, (\phi_2^\dagger \phi_2)^2 + \tilde{\lambda}_3\, (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2)$$

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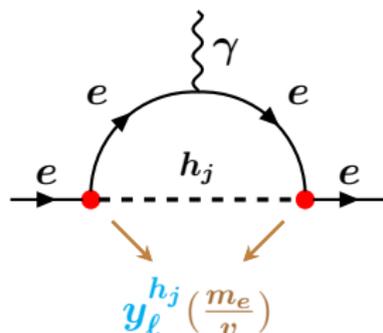
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✏ **Yukawa interactions:**

Type I: $\varsigma_u = \varsigma_d = \varsigma_\ell = \cot\beta$,   **Type II:** $\varsigma_u = -\dfrac{1}{\varsigma_d} = -\dfrac{1}{\varsigma_\ell} = \cot\beta$,   **Inert:** $\varsigma_u = \varsigma_d = \varsigma_\ell = 0$,

Type X: $\varsigma_u = \varsigma_d = -\dfrac{1}{\varsigma_\ell} = \cot\beta$ and   **Type Y:** $\varsigma_u = -\dfrac{1}{\varsigma_d} = \varsigma_\ell = \cot\beta$.

✏ **Independent CPV parameter:** $\tilde{\lambda}_5$

Boto, Fernandes, Haber, Romão, Silva PRD 101 (2020) 5, 055023

One-loop eEDM
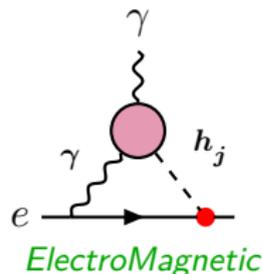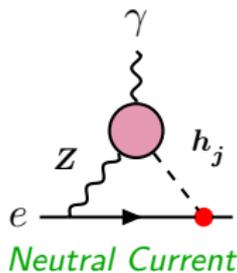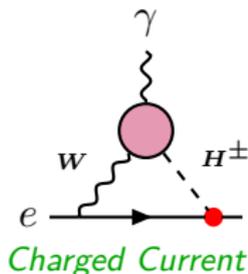

$$d_e^{1-loop} \propto (m_e^3/(v^2 M^2)) \to G_F m_e (m_e^2/M^2)$$

Two-loop diagrams with one $\bar{e}eh_j$ (or $\bar{\nu}eH^+$) vertex create larger contributions.
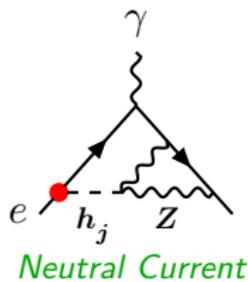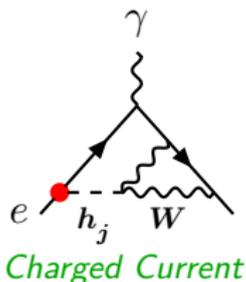
Altmannshofer et al. arXiv:2410.17313 [hep-ph]
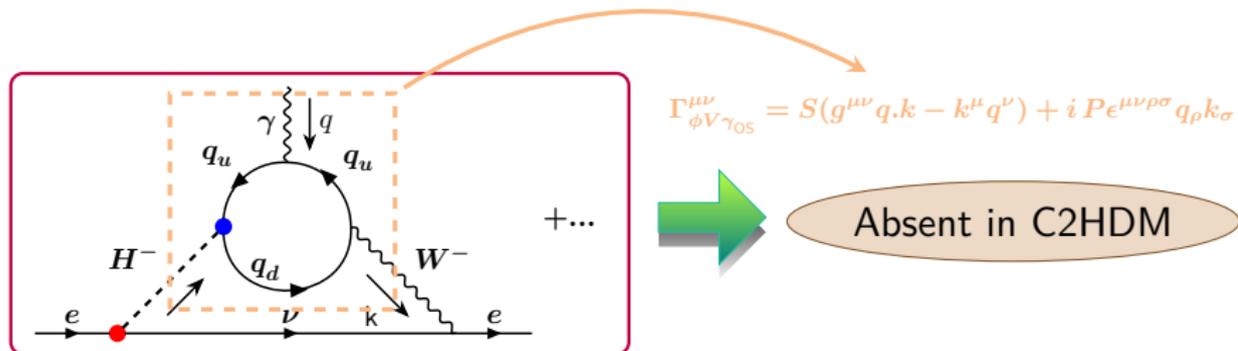
Two-loop eEDM

Barr-Zee diagrams

γ

W $H^{\pm}$

e *Charged Current*

γ

Z h_j

e *Neutral Current*

γ

γ h_j

e *ElectroMagnetic*

Each category has three types of loops: **fermion-loop, W-loop, $H^{\pm}$-loop**

Kite or non–Barr-Zee diagrams

γ

e h_j W

Charged Current

γ

e h_j Z

Neutral Current

Gauge invariance is assured only after adding all the diagrams.

Altmannshofer, Gori, Hamer, Patel PRD 102 (2020) 11, 115042

Barr-Zee: Charged-Current-Fermion-Loop

$$\Gamma_{\phi V\gamma_{OS}}^{\mu\nu} = S(g^{\mu\nu}q.k - k^\mu q^\nu) + i\,P\epsilon^{\mu\nu\rho\sigma}q_\rho k_\sigma$$

Absent in C2HDM

$$\frac{d_{e,f}^{CC}}{e}\bigg|_{tb} = m_e\,\frac{\sqrt{2}\,\alpha\,G_F}{(4\pi)^3\,s_w^2}\,N_C|V_{tb}|^2\bigg\{\text{Im}(\varsigma_u^*\varsigma_l)\big(Q_t\widetilde{F}_t + Q_b\widetilde{F}_b\big)$$

$$\bar{b}b\gamma$$

$$\bar{t}t\gamma \qquad + \bigg(\frac{m_b^2}{m_t^2}\bigg)\text{Im}(\varsigma_d^*\varsigma_l)\big(Q_t\widetilde{G}_t + Q_b\widetilde{G}_b\big)\bigg\}$$

No contribution from lepton loop; it only appears if ς_ℓ is generation-dependent.

Bowser-Chao, Chang, Keung PRL 79 (1997) 1988-1991; Jung, Pich JHEP 04 (2014) 076; Altmannshofer et al. arXiv:2410.17313 [hep-ph]

A2HDM vs C2HDM
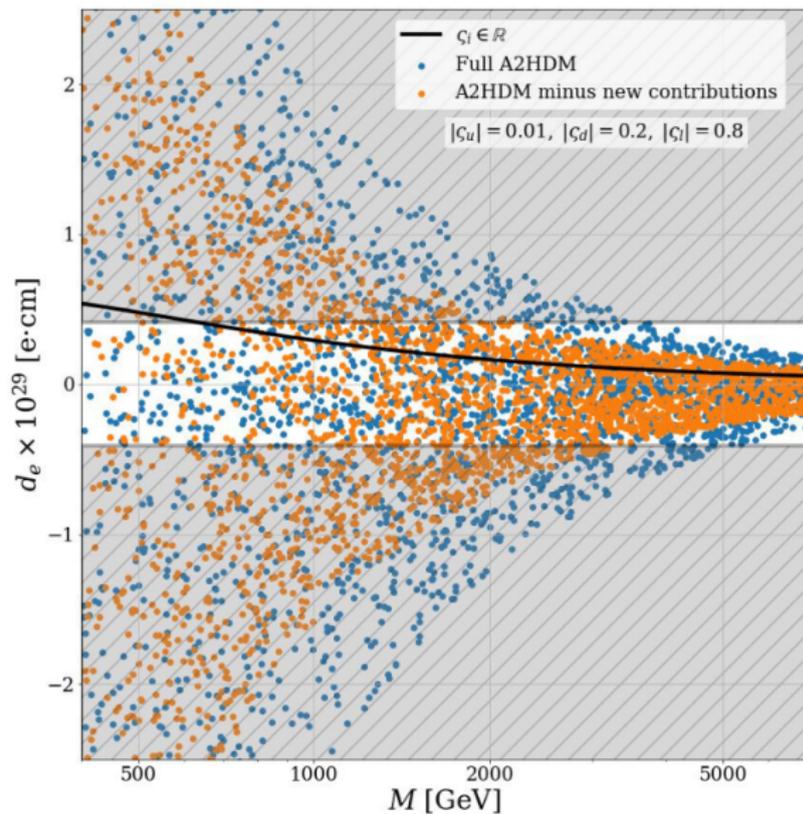
Overview: eEDM in SMEFT

- Lagrangian at EW scale:
$\mathcal{L} = \mathcal{L}_{SM} + \sum C_i(\mu)\mathcal{O}_i$

- Effective Lagrangian for EDM:
$\mathcal{L} \supset -\frac{i}{2}d_e(\mu)\,\bar{\psi}_e\,\sigma^{\mu\nu}\gamma^5\,\psi_e\,F_{\mu\nu}$

- Dim-6 operators contributing to eEDM at tree level:
$\mathcal{O}_{eW} = (\bar{L}_L\sigma^a\sigma^{\mu\nu}e_R)HW^a_{\mu\nu}$
$\mathcal{O}_{eB} = (\bar{L}_L\sigma^{\mu\nu}e_R)HB_{\mu\nu}$

- eEDM:
$d_e(\mu) = \sqrt{2}v\mathsf{Im}[s_w C_{eW}(\mu) - c_w C_{eB}(\mu)]$

- RGE:
$\mu\frac{dC_i}{d\mu} = \left[\frac{1}{(4\pi)^2}\gamma^{(1)}_{ij} + \frac{1}{(4\pi)^4}\gamma^{(2)}_{ij}\right]C_j$

$$\boxed{\mathcal{O}_j\,(\mu = M)}$$

RGE

$$\boxed{C_{eW}(\mu),\ C_{eB}(\mu)}$$

eEDM in SMEFT (2-loop, dim-6)

tree level

$\mathcal{O}_{eW} = (\bar{L}_L \sigma^a \sigma^{\mu\nu} e_R) H W^a_{\mu\nu}$

$\mathcal{O}_{eB} = (\bar{L}_L \sigma^{\mu\nu} e_R) H B_{\mu\nu}$

1-loop

$\mathcal{O}_{luqe} = (\bar{L}_L u_R)(\bar{Q}_L e_R)$

$\mathcal{O}_{W\widetilde{W}} = |H|^2 W^{a\,\mu\nu} \widetilde{W}^a_{\mu\nu}$

$\mathcal{O}_{B\widetilde{B}} = |H|^2 B^{\mu\nu} \widetilde{B}_{\mu\nu}$

$\mathcal{O}_{W\widetilde{B}} = (H^\dagger \sigma^a H) W^{a\,\mu\nu} \widetilde{B}_{\mu\nu}$

$\mathcal{O}_{\widetilde{W}} = \varepsilon_{abc} \widetilde{W}^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$

Feirzing $\rightarrow$ Warsaw basis

2-loop

$\mathcal{O}^{(1)}_{lequ} = (\bar{L}_L e_R)(\bar{Q}_L u_R)$

$\mathcal{O}_{e'W} = (\bar{L}'_L \sigma^a \sigma^{\mu\nu} e'_R) H W^a_{\mu\nu}$

$\mathcal{O}_{e'B} = (\bar{L}'_L \sigma^{\mu\nu} e'_R) H B_{\mu\nu}$

$\mathcal{O}_{uW} = (\bar{Q}_L \sigma^a \sigma^{\mu\nu} u_R) \widetilde{H} W^a_{\mu\nu}$

$\mathcal{O}_{uB} = (\bar{Q}_L \sigma^{\mu\nu} u_R) \widetilde{H} B_{\mu\nu}$

$\mathcal{O}_{dW} = (\bar{Q}_L \sigma^a \sigma^{\mu\nu} d_R) H W^a_{\mu\nu}$

$\mathcal{O}_{dB} = (\bar{Q}_L \sigma^{\mu\nu} d_R) H B_{\mu\nu}$

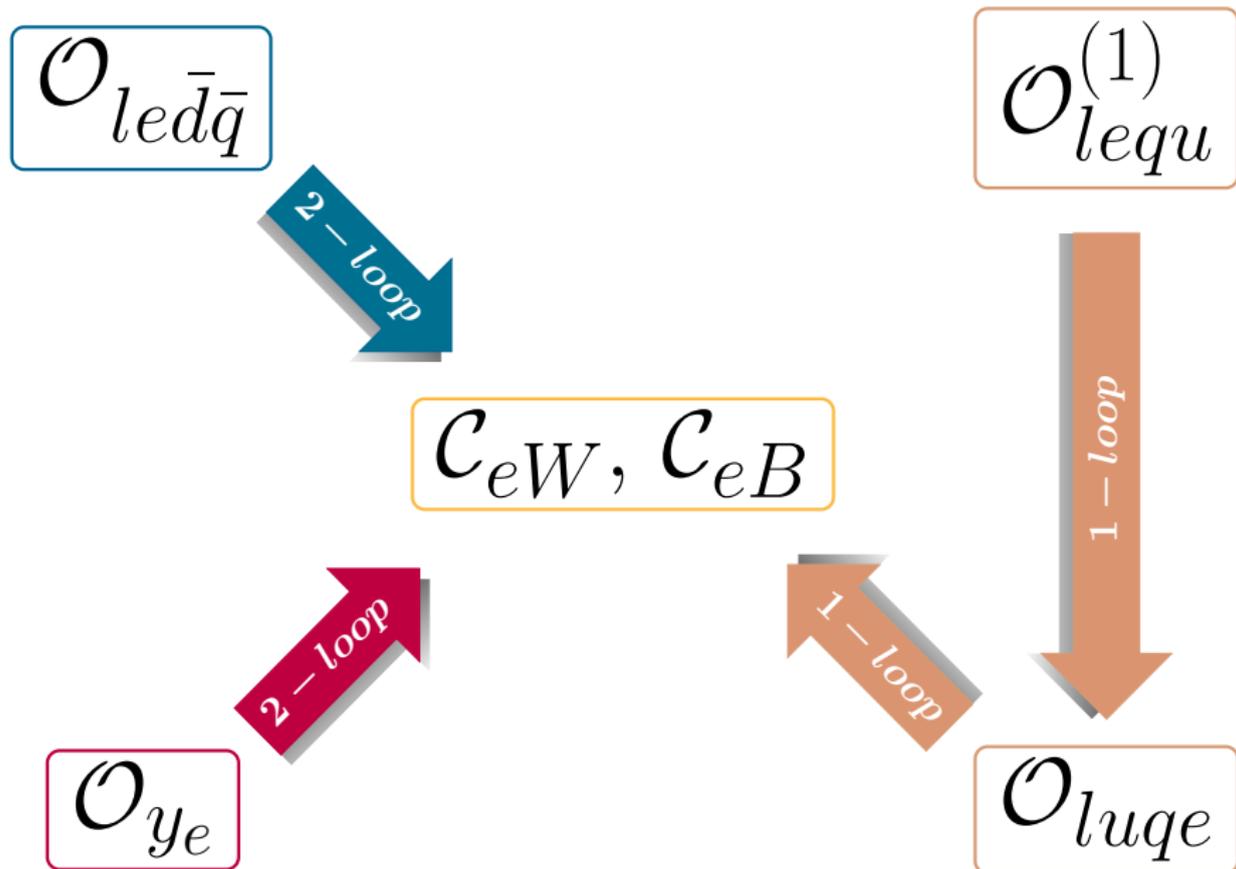$\mathcal{O}_{led\bar{q}} = (\bar{L}_L e_R)(\bar{d}_R Q_L)$

$\mathcal{O}_{le\bar{e}'\bar{l}'} = (\bar{L}_L e_R)(\bar{e}'_R L'_L)$

$\mathcal{O}_{y_e} = |H|^2 \bar{L}_L e_R H$

Not generated at one-loop in A2HDM

Panico, Pomarol, Riembau JHEP 04 (2019) 090

eEDM in A2HDM and SMEFT

Decoupling Limit & SMEFT

$$d_{e,f}^{\varsigma_u} \propto \text{Im}(\varsigma_u^* \varsigma_l) \left(\frac{m_t^2}{M^2} \right) \log^2 \left(\frac{M^2}{m_t^2} \right)$$

$$d_{e,f}^{\varsigma_d} \propto \text{Im}(\varsigma_d^* \varsigma_l) \left(\frac{m_b^2}{M^2} \right) \log \left(\frac{M^2}{m_t^2} \right)$$
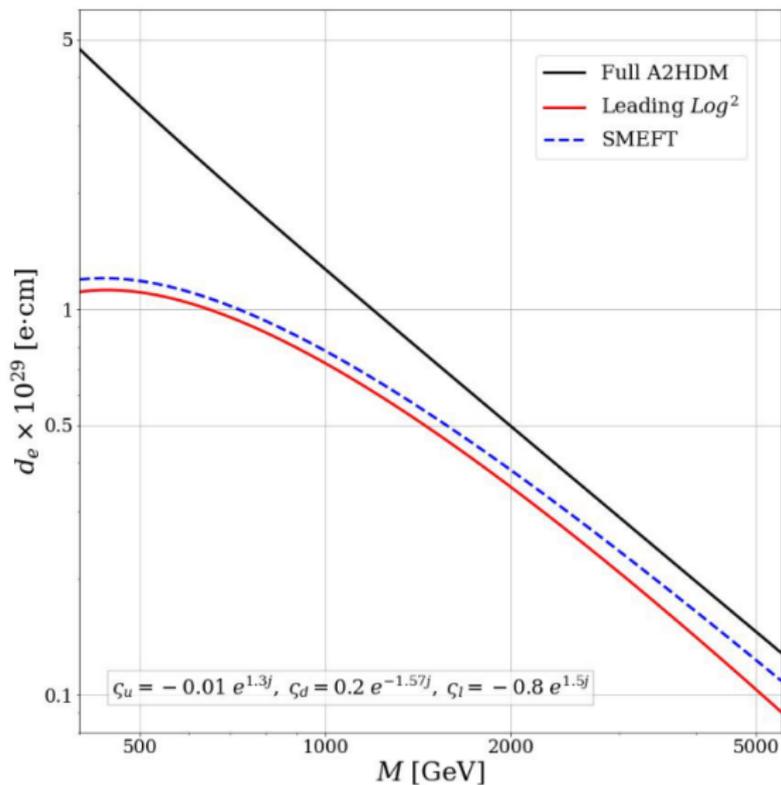
$$d_e^{other} \propto \frac{v^2}{M^2} \log \left(\frac{M^2}{m_W^2} \right)$$

$$d_{e,y_e}^{\mathsf{SMEFT}} \propto \text{Im}(C_{ye}) \log \left(\frac{M^2}{m_{EW}^2} \right)$$

$$d_{e,le\bar{d}\bar{q}}^{\mathsf{SMEFT}} \propto \text{Im}(C_{le\bar{d}\bar{q}}) \log \left(\frac{M^2}{m_{EW}^2} \right)$$

$$d_{e,lequ}^{\mathsf{SMEFT}} \propto \text{Im}(C_{lequ}) \log^2 \left(\frac{M^2}{m_{EW}^2} \right)$$

Full Calculation vs SMEFT

Conclusion

✍ EDM is an interesting observable, it is sensitive to CPV.

✍ The values of d_e^{SM} and d_e^{Exp} leave enough room for New Physics.

✍ A2HDM is a simple extension of the SM in the scalar sector.

✍ A2HDM can incorporate new sources of CPV in scalar potential as well as in Yukawa interaction, and thus it can generate larger eEDM than SM.

✍ In comparison with C2HDM, new Barr-Zee diagram with charged-current-fermion-loop contributes to eEDM in A2HDM. It also has a dominant effect over other diagrams.

✍ In the decoupling limit, one can study eEDM through SMEFT; the leading log behaviour of SMEFT calculation matches with the full theory asymptotically.

THANK YOU