The electron’s EDM in the decoupling limit of the aligned 2HDM

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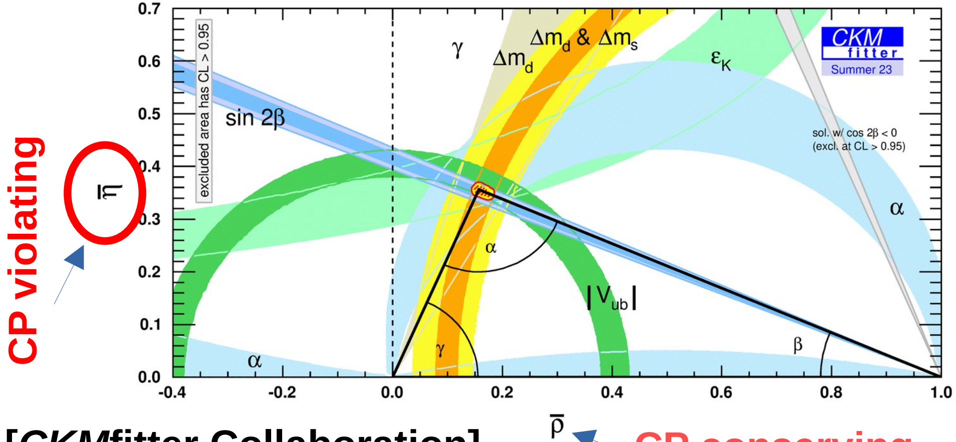
CP violation (CPV)

- <u>Small set of parameters in the SM</u>: the SU(3)$_{QCD}$ phase (probed by nEDM), and one CPV phase in the Cabibbo-Kobayashi-Maskawa matrix



[*CKM*fitter Collaboration]

CP conserving

- Sakharov conditions: CPV is a required ingredient in order to generate dynamically the matter/anti-matter asymmetry of the visible Universe

- Many extensions of the SM introduce new sources of CPV, <u>challenging this minimal picture</u>

LVS

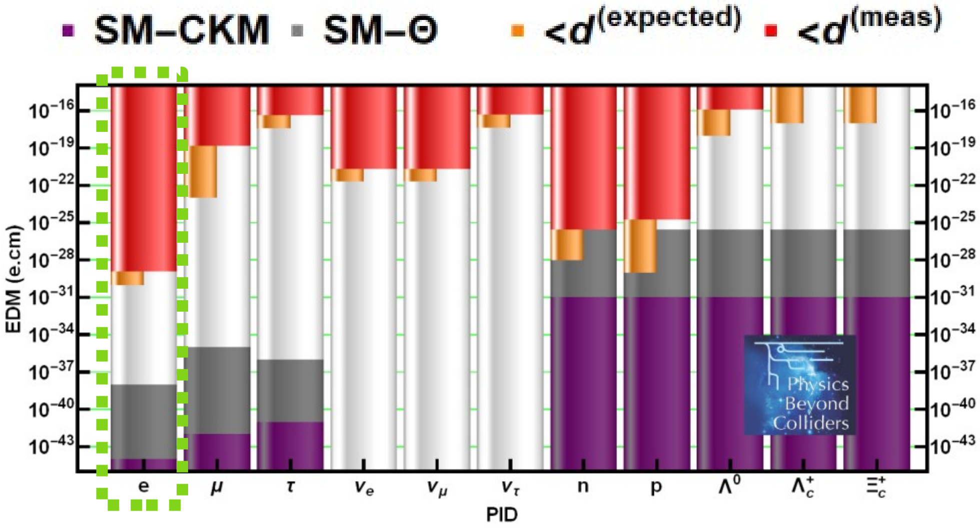
Electric Dipole Moments (EDMs)

- EDMs probe CPV in the SM and beyond, both <u>gauge and matter field content and properties</u>

- Experimental accuracies are very high & SM contributions are highly suppressed (EDMs require at least three loops):

  constrain New Physics (NP)

- Focus here on the **electron's** EDM: simpler description compared to the **neutron's** EDM, e.g., due to non-perturbative QCD dynamics



[from 1901.09966]

[Reviews: Pospelov, Ritz '05, Engel, Ramsey-M., van Kolck '13]

Two Higgs Doublet Models (2HDMs) 3

- Two weak-isospin doublets with the same hypercharge; among the simplest extensions of the SM

would-be Goldstone bosons

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

v : breaks spontaneously SU(2)xU(1)

in the “Higgs basis”

- Scalar degrees of freedom: two CP-even scalars and one CP-odd pseudoscalar in total, plus +/- charged scalars; can play an important role in micro to macroscopic problems
- Rich phenomenology to be tested: EW physics, flavor physics, etc.

In particular, **new sources of CPV**

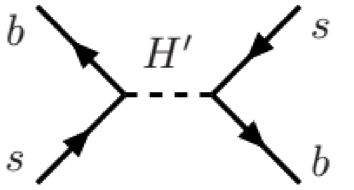
The fermionic sector of 2HDMs

4

- Dim.-4 Yukawa couplings (in agreement with the local SM symmetries):

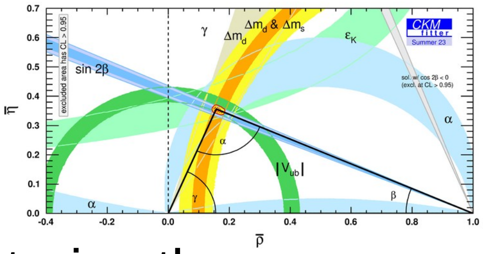
$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\left[\overline{Q}'_L(M'_d\Phi_1+Y'_d\Phi_2)d'_R+\overline{Q}'_L(M'_u\widetilde{\Phi}_1+Y'_u\widetilde{\Phi}_2)u'_R+\overline{L}'_L(M'_l\Phi_1+Y'_l\Phi_2)l'_R\right]+\text{h.c.}$$

$$\widetilde{\Phi} = i\tau_2\Phi^*$$



|ΔB|=2 meson mixing: used to extract SM-CPV

- To full generality: when diagonalizing fermion mass matrix *M'*, *M'**S_1 + *Y'**(S_2+iS_3) is not diagonal; scalar-mediated flavor-changing neutral currents (FCNCs)
- SM FCNCs: GIM and CKM suppressed; various precisely measured |ΔF|=1 and |ΔF|=2 observables



- Strong constraints on *H'* mediator masses and couplings

Various specific cases; assigning Z_2 quantum numbers constrains the Yukawa sector, thus avoiding FCNCs at the tree level

[Z_2: Glashow, Weinberg '77]

The Aligned 2HDM

- A different framework considers that the two sets of Yukawa couplings are proportional, or “aligned”, thus avoiding FCNCs

$$Y_d = \varsigma_d M_d\,, \qquad Y_u = \varsigma_u^* M_u\,, \qquad Y_l = \varsigma_l M_l$$

[Pich, Tuzón ‘09, + Jung ‘10]

- Radiative corrections, however, break this proportionality, but only by **small** amounts
- Freedom in Yukawa couplings w.r.t. SM parametrized by alignment parameters; couplings prop/ to masses
- Known Z_2-symmetric versions are special cases, including Complex-2HDMs (i.e., CPV in the scalar potential after soft breaking of Z_2)
- **New sources of CPV** w.r.t. Z_2-symmetric 2HDMs & Complex-2HDMs

Fermion-loop Barr-Zee in the A2HDM

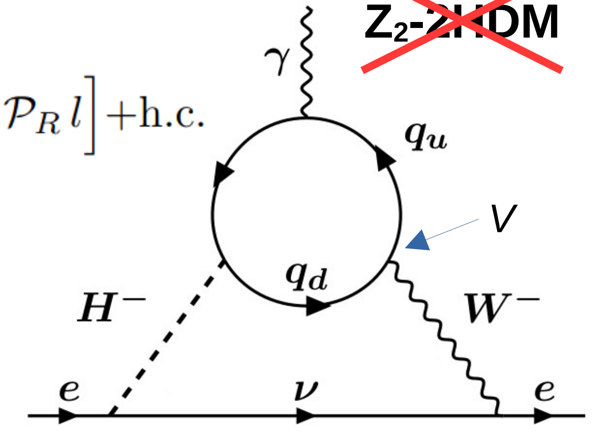
- Novel contributions in the A2HDM: **charged scalars** have CPV couplings to fermions

V: CKM matrix

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

alignment parameters, scalar potential

~~Z_2-2HDM~~



(plus reflections)

- Dominant: **top-bottom** V_{tb}; sub-dominant CKM contributions included since they involve large logarithms (thus use, e.g., $|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2=1$)

  => $H^\pm$: **CPV from alignment parameters only**

- Other charged-scalar contributions are suppressed by quark masses and/or CKM matrix elements

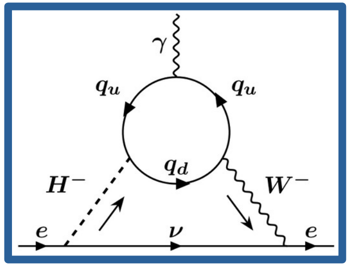
[Bowser-C., Chang, Keung '97, Jung, Pich '13, Altmannshofer, Assi, Brod, Hamer, Julio, Uttayarat, Volkov '24]

Phenomenological effects

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

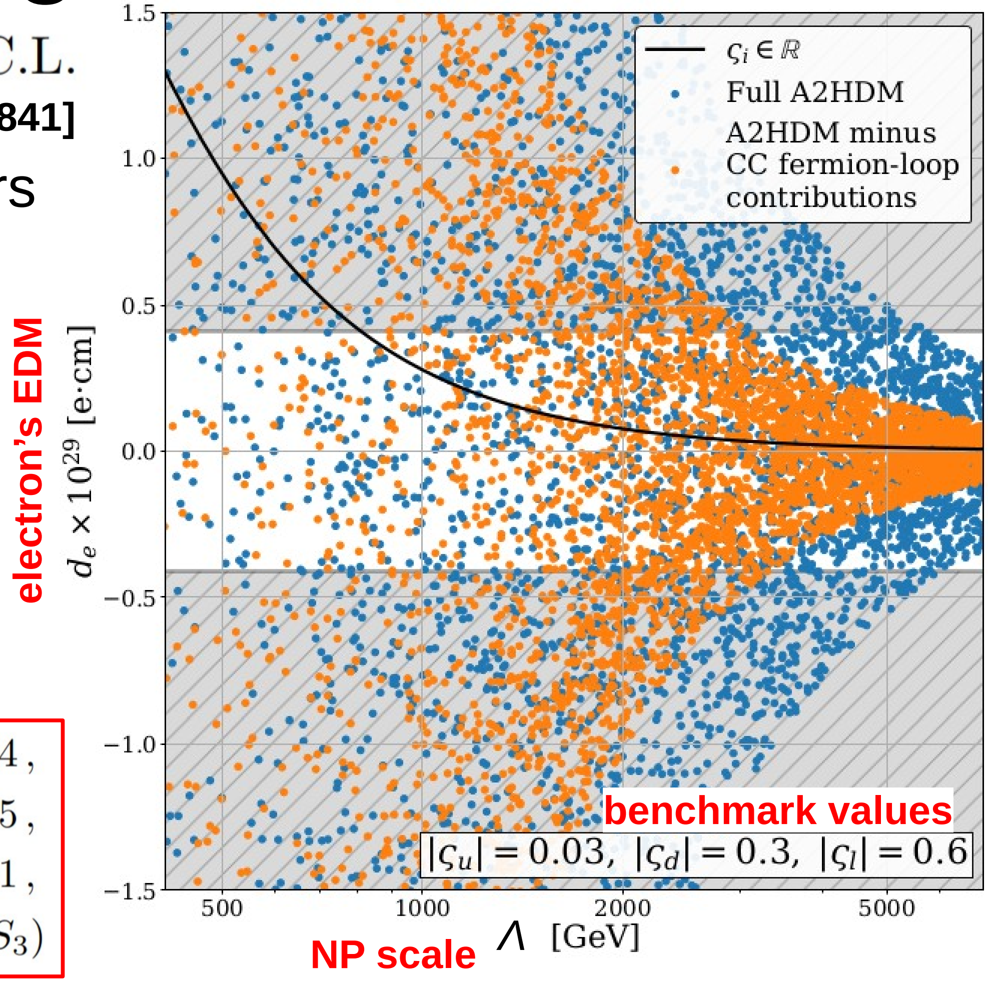
[from 2212.11841]

- **Black line**: real alignment parameters
- Orange points: A2HDM, minus charged-current fermion-loop Barr-Zee contributions
- Blue points: A2HDM
- Accidental cancellation among contributions is possible



benchmark values

$$\lambda_3 = 0.02\,, \qquad \lambda_4 = 0.04\,,$$
$$\lambda_7 = 0.03\,, \qquad \mathrm{Re}(\lambda_5) = 0.05\,,$$
$$\mathrm{Re}(\lambda_6) = -0.05\,, \quad \mathrm{Im}(\lambda_6) = 0.01\,,$$
$$\alpha_3 = \pi/6 \text{ (mixing } S_2 \text{ and } S_3)$$



The decoupling limit

- When the NP scale Λ >> EW scale μ_{EW}: ignore the dynamics of the heavy new scalars at low energies
- The effects of the heavy dof's are encoded in couplings among the light dof's of the low-energy theory
- Wilson coefficients of dim.-6 SMEFT operators

$$X^3\,,\quad X^2H^2\,,\quad \psi^2H^3\,,\quad \psi^2XH\,,\quad \psi^2H^2D\,,\quad \psi^4$$

X: field strength tensor, *D*: covariant derivative

[SMEFT: Hisano, Tsumura, Yang '12, Engel, Ramsey-M., van Kolck '13, Cirigliano, Dekens, de Vries, Mereghetti '16, + Chien '15, Cirigliano, Crivellin, Dekens, de Vries, Hoferichter, Mereghetti '19, ...; decoupling limit: Egana-U., Thomas '15, Crivellin, Ghezzi, Procura '16, Dermisek, Hermanek '24, ...]

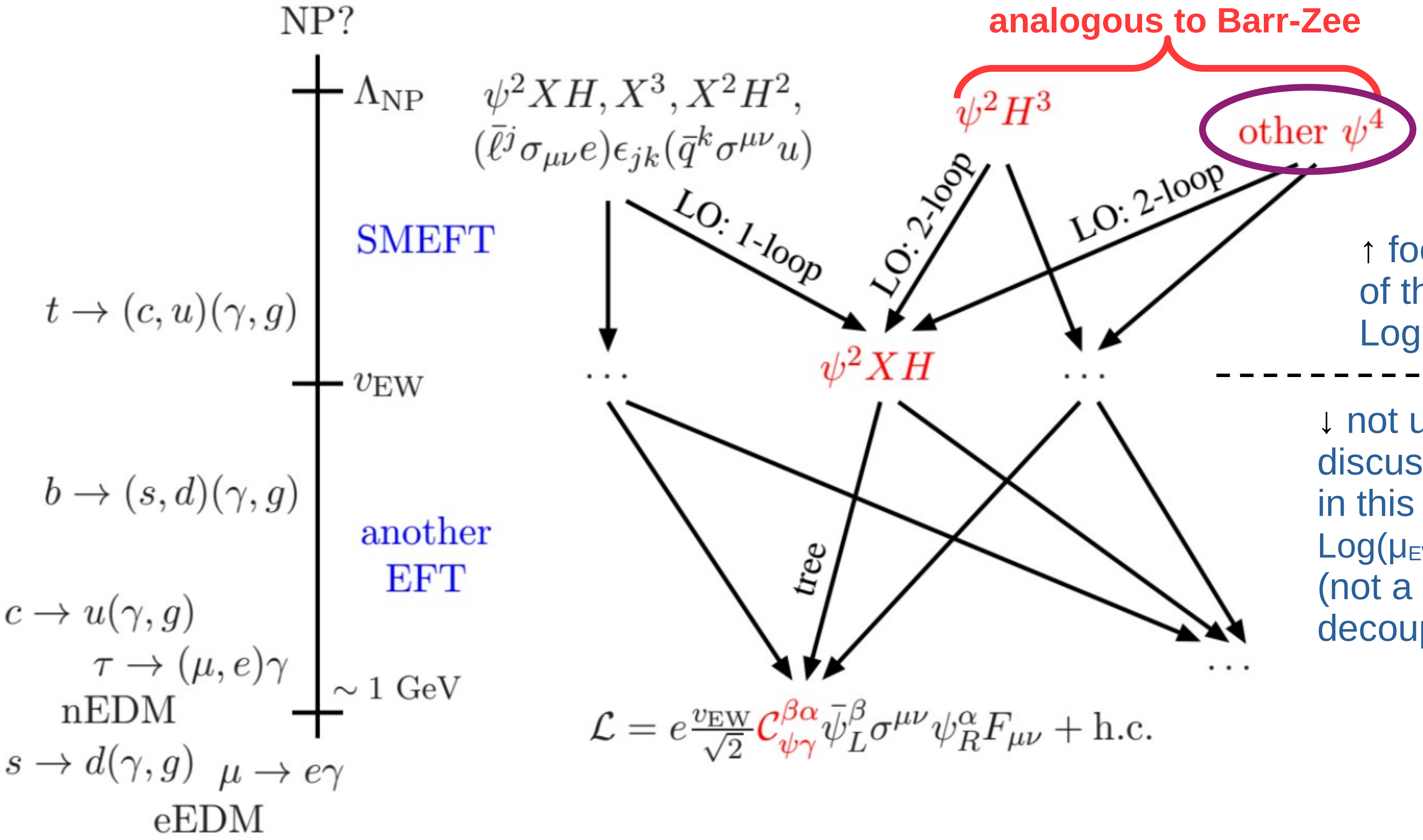
The A2HDM in the decoupling limit

9

- Logarithmic structure of contributions to the eEDM:
  - $\mathrm{Log}(\Lambda/\mu_{EW})$: prop/ to the **scalar potential** parameter λ_6 [no $\mathrm{Log}(\Lambda/\mu_{EW})^2$]
  - $\mathrm{Log}(\Lambda/\mu_{EW})^2$, $\mathrm{Log}(\Lambda/\mu_{EW})$: accompanied by the **top**-quark mass^2
  - $\mathrm{Log}(\Lambda/\mu_{EW})$: accompanied by the **bottom**-quark mass^2 [no $\mathrm{Log}(\Lambda/\mu_{EW})^2$]
  - 2HDMs more general than A2HDM: $\mathrm{Log}(\Lambda/\mu_{EW})$ times **tau**-lepton mass^2
- Use SMEFT to **understand the large logarithms in the A2HDM in the decoupling limit**
- $\mathrm{Log}(\mu_{EW}/\mu_{low})^{\#}$ also present and numerically important, but beyond the scope of the current discussion (non-SMEFT operators)

[Davidson ‘16, Panico, Pomarol, Riembau ‘18, Altmannshofer, Gori, Hamer, Patel ‘20]

Mixing of SMEFT operators



↑ focus
of this talk,
Log(Λ/μ_{EW})#

↓ not under
discussion
in this talk,
Log(μ_{EW}/μ_{low})#
(not a feature of
decoupling limit)

Renormalization Group Equations 11

- Log in one-loop and two-loop computations:

μ: renormalization scale; C: Wilson coefficients

$$\frac{d}{d\log\mu}C_i = \frac{1}{(4\pi)^2}\,\gamma_{ji}^{(1)}\,C_j \;\Rightarrow\; C_i(\mu) \simeq \frac{1}{(4\pi)^2}\,\gamma_{ji}^{(1)}\log\left(\frac{\mu}{\Lambda}\right)C_j(\Lambda) \qquad (C_i(\Lambda)=0)$$

$$\frac{d}{d\log\mu}C_i = \frac{1}{(4\pi)^4}\,\gamma_{ji}^{(2)}\,C_j \;\Rightarrow\; C_i(\mu) \simeq \frac{1}{(4\pi)^4}\,\gamma_{ji}^{(2)}\log\left(\frac{\mu}{\Lambda}\right)C_j(\Lambda) \quad \left(\gamma_{ji}^{(1)}=0\,,\; C_i(\Lambda)=0\right)$$

- Log^2 when there is a <u>chain</u> of operator mixing:

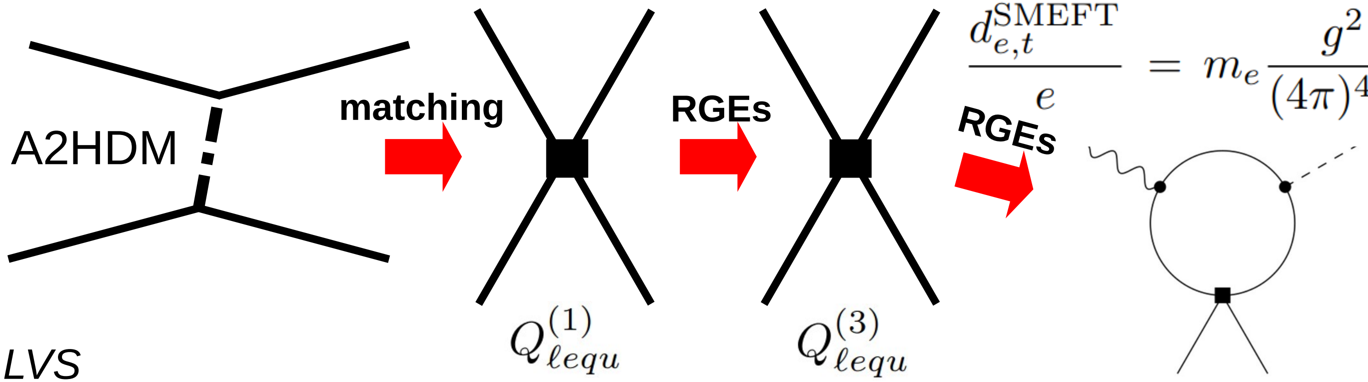
$$\frac{d}{d\log\mu}C_C = \frac{1}{(4\pi)^2}\,\gamma_{BC}^{(1)}\,C_B\,, \qquad \frac{d}{d\log\mu}C_B = \frac{1}{(4\pi)^2}\,\gamma_{AB}^{(1)}\,C_A$$

$$\Rightarrow C_C(\mu) \simeq \frac{1}{2\,(4\pi)^4}\,\gamma_{AB}^{(1)}\,\gamma_{BC}^{(1)}\log^2\left(\frac{\mu}{\Lambda}\right)C_A(\Lambda) \qquad (C_B(\Lambda)=C_C(\Lambda)=0)$$

- γ: Anomalous Dimension Matrices (ADMs)

Four-fermion operator lequ(1): m_t^2 12

- Chain of one-loop mixing [Jenkins, Manohar, Trott ‘13 ‘13, + Alonso ‘13]
- Single logarithm Log(Λ/μ_{EW}): requires calculating one-loop finite contributions combined with one-loop ADM elements, and the ADM element at two loops
- 2HDMs more general than A2HDM: generation-dependent alignment parameters; include charm quark contributions $\left(\varsigma_u \neq \varsigma_c \neq \varsigma_t\right)$



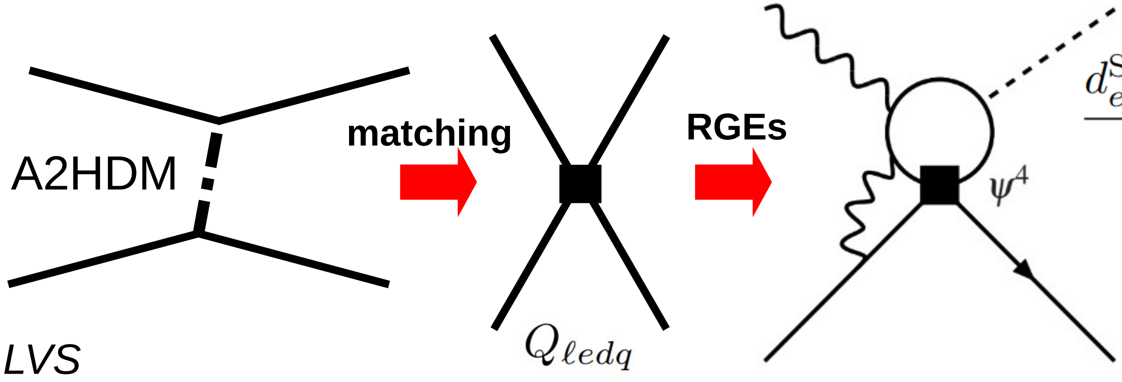
$$\frac{d_{e,t}^{\mathrm{SMEFT}}}{e} = m_e \frac{g^2}{(4\pi)^4 v^2}(5t_w^2+3)\mathrm{Im}(\varsigma_u^* \varsigma_l)\frac{m_t^2}{\Lambda^2}\log^2\left(\frac{\Lambda^2}{v_{EW}^2}\right)$$

top-Yukawa coupling, **double-logarithm**

LVS

Four-fermion operator ledq: m_b^2

- No one-loop mixing; nor chain of one-loop mixing [so no $\mathrm{Log}(\Lambda/\mu_{EW})^2$]
- ADM element only available in [Panico, Pomarol, Riembau '18]
- Independent calculation ongoing [Ferrando Solera, Jaeger, LVS] [talk later today at "Multicultural Greek"]
  - Treatment of γ_5: in BMHV, need for finite renormalization to restore Ward identities
  - Extension to other dimension-6 four-fermion operators (e.g., to discuss nEDM; applications beyond 2HDMs)
- 2HDMs more general than A2HDM: m_τ^2 from lee'l' SMEFT operator $\left(\mathrm{Im}(\varsigma_e^* \varsigma_\tau) \neq 0\right)$



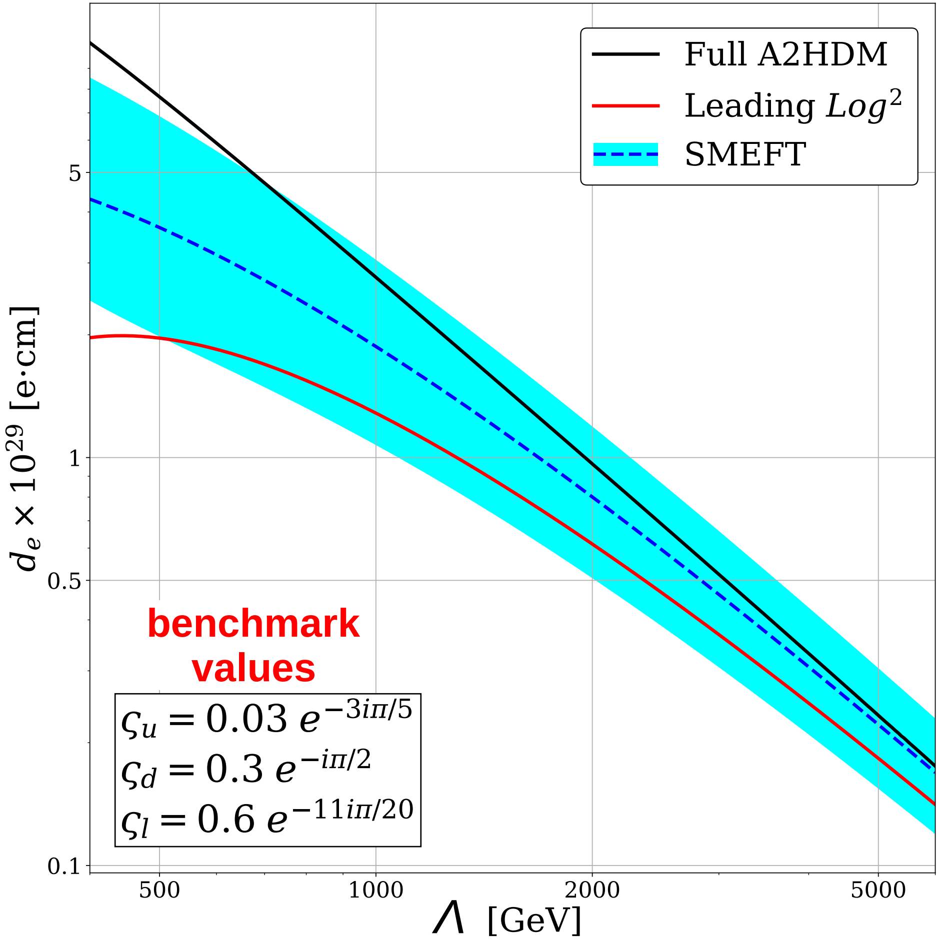
$$\frac{d_{e,b}^{\mathrm{SMEFT}}}{e} = -m_e \frac{g^2}{(4\pi)^4 v^2} \frac{t_w^2}{2} \mathrm{Im}(\varsigma_d^* \varsigma_l) \frac{m_b^2}{\Lambda^2} \log\left(\frac{\Lambda^2}{v_{EW}^2}\right)$$

bottom-Yukawa coupling, **single-logarithm**

Illustrating the decoupling limit

- **Black line**: A2HDM
- Red line: only m_t^2*Log$(\Lambda/\mu_{EW})^2$
- Blue line: previously discussed SMEFT (λ_6, m_b^2)*Log(Λ/μ_{EW}) contributions

  Blue band: vary the scale Λ
- Decoupling limit: the larger the energy the closer the curves, i.e., logarithmic terms tend to dominate



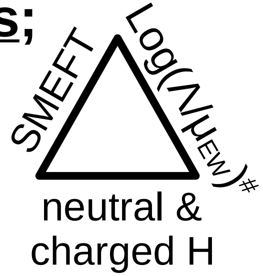
benchmark values

$$\begin{aligned} \lambda_3 &= 0.02\,, & \lambda_4 &= 0.04\,, \\ \lambda_7 &= 0.03\,, & \mathrm{Re}(\lambda_5) &= 0.05\,, \\ \mathrm{Re}(\lambda_6) &= -0.05\,, & \mathrm{Im}(\lambda_6) &= 0.01\,, \\ \alpha_3 &= \pi/6 \text{ (mixing } S_2 \text{ and } S_3) \end{aligned}$$

A2HDM vs. Z_2-2HDMs

- Large logarithms prop/ to m_t^2 and m_b^2 <u>**absent in Z_2-symmetric 2HDMs**</u>**;** large logarithms emerge from the mixing among SMEFT operators
- SMEFT contributions encode both heavy neutral and charged scalars <u>in a SU(2)xU(1) symmetric way</u>;

  EDMs in the decoupling limit in presence of Z_2 symmetry => no contributions from four-fermion SMEFT operators, since **no charged-scalar counterpart**



- Discussion holds only for CPV, which is the novelty in $H^{\pm}$ sector in the A2HDM
- Bottomline: the presence of the Z_2 symmetry controls the basis of effective operators needed in the description of EDMs => <u>**suppression mechanism in Z_2-symmetric 2HDMs**</u>

Conclusions

- A2HDM: avoids FCNCs while introducing **new sources of CPV**
- **Novel contribution** from the charged Higgs w.r.t. Z_2-2HDMs
- Discussing SMEFT/decoupling limit:
  - **Anatomy of logarithmic contributions** ($\psi^2 H^3$ in back-up)
  - **Cancellation mechanism**: Z_2 symmetry suppresses large logarithms
- Outlook (see back-up): role of lepton-nucleon operators in the interpretation of experimental bounds on EDMs; nEDM

Thanks!

BACK UP

Cover: Jim Musil

The Higgs particle

- Crucial piece to understand EW dynamics
- Up to the present accuracy, behaves as predicted by the SM

(Gauge couplings to fermions)

$$\mathcal{L}_{SM(NP)} \sim -\frac{1}{4}(F_{\mu\nu})^2 + i\bar{\psi}\not{D}\psi$$

(Higgs self-interaction)

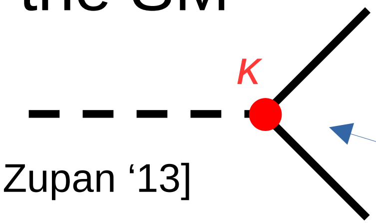
$$+ |D_\mu H|^2 - V(H)$$

(short-range weak interactions)

$$+ \mathbf{Y} H \bar{\psi}\psi + \mathrm{h.c.}$$

(spectrum of quark masses, CKM matrix)

$$\left(+\sum_{d>4} \frac{1}{\Lambda^{d-4}} C_k O_k^d\right)$$



[e.g., Brod, Haisch, Zupan ‘13]

- **Deviations** w.r.t. the SM can be probed in various ways, e.g., flavor conserving observables such as electron’s EDM

In particular, due to the presence of a heavy NP sector compatible with the local SM symmetries

New Physics energy scale

- Scalar potential in the Higgs-basis; CPV phases

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

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

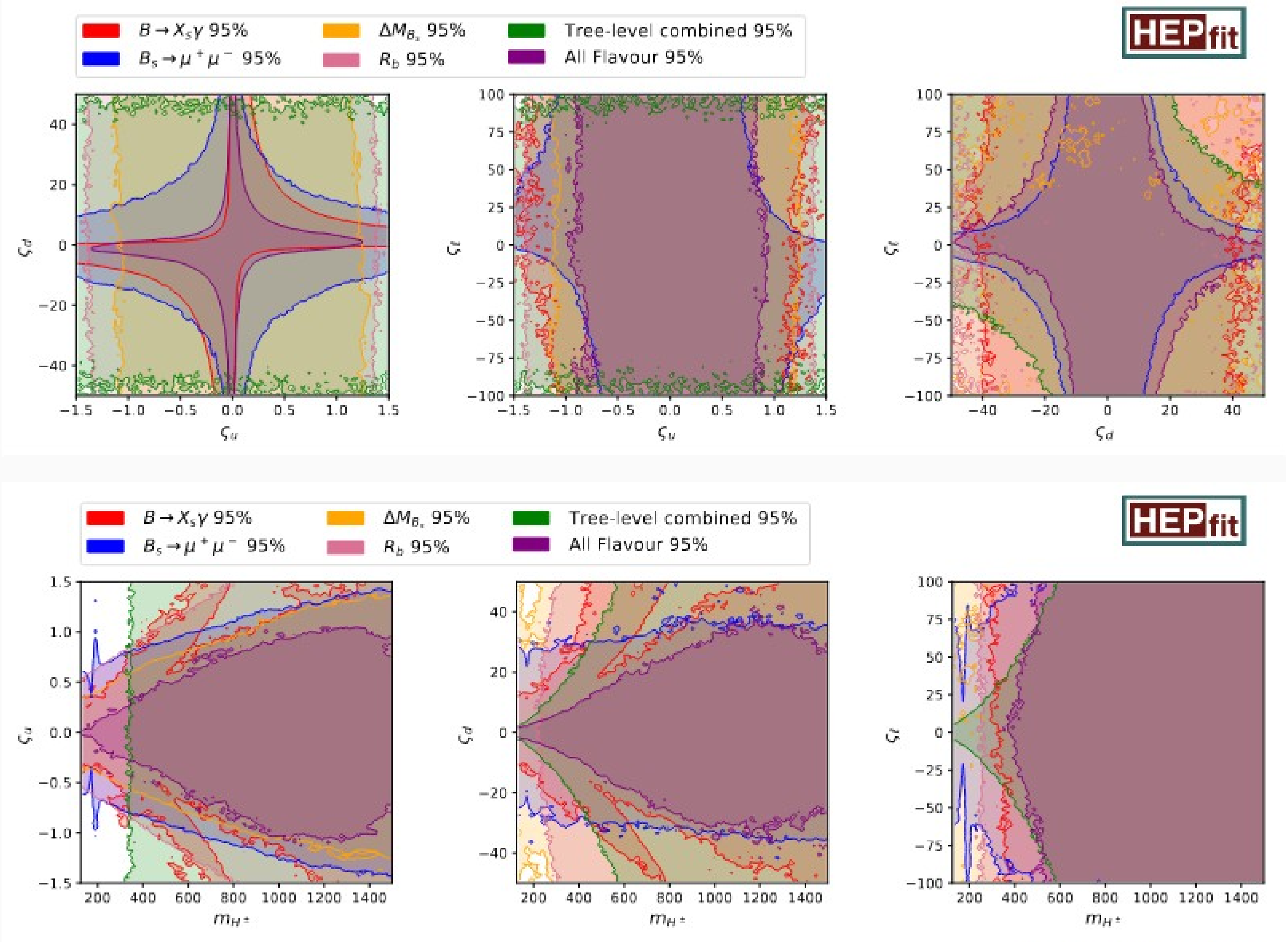
- The mass scale of the second doublet is not controlled by the EW scale, but by the dimensionful parameter $\mu_2 \sim \Lambda$
- Current bounds on the A2HDM from a global fit analysis: Higgs strength, theoretical constraints, flavor observables, etc.

[CP conserving limit: Eberhardt, Martínez, Pich ‘20, Karan, Miralles, Pich ‘23, + Coutinho ‘24]

S_1, S_2 mixing (68% C.L.)

<table>
<tr><td colspan="2">$M_{H^\pm} \geq 390$ GeV (95%)</td><td colspan="2">$M_H \geq 410$ GeV (95%)</td><td colspan="2">$M_A \geq 370$ GeV (95%)</td></tr>
<tr><td colspan="2">λ_2: 3.2 ± 1.9</td><td colspan="2">λ_3: 5.9 ± 3.5</td><td colspan="2">λ_7 : 0.0 ± 1.1</td></tr>
<tr><td>$\tilde{\alpha}$: $(0.05 \pm 21.0) \cdot 10^{-3}$</td><td colspan="2">$\varsigma_u$: 0.006 ± 0.257</td><td colspan="2">ς_d : 0.12 ± 4.12</td><td>ς_ℓ : -0.39 ± 11.69</td></tr>
</table>

Global fits



ArXiv: 2307.15419

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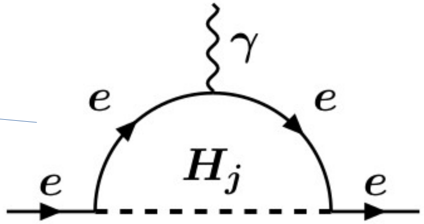
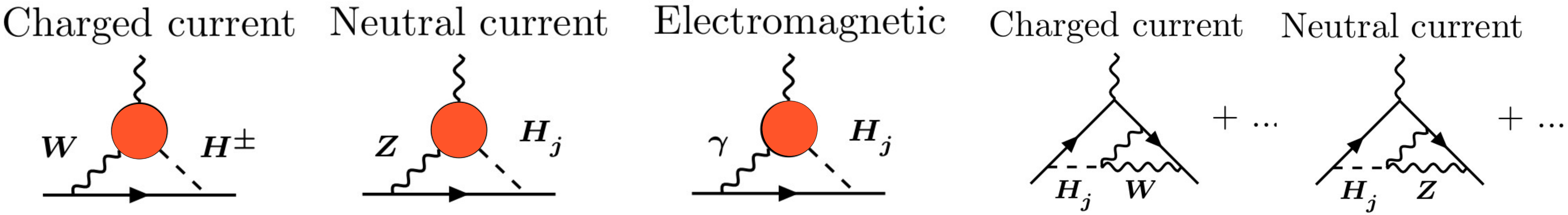
Electron's EDM in 2HDMs



- Contribution at one loop: prop/ to $m_e^3/(4\pi)^2/\Lambda^2$
- Barr-Zee diagrams: two-loop effect scaling as $m_e/(4\pi)^4/\Lambda^2$; avoids mass/chiral suppression at one loop



Red blobs: EW gauge bosons and scalar sector

- EW sector in the loop: not gauge invariant by itself; combine with kite diagrams [e.g., Abe, Hisano, Kitahara, Tobioka '13, Altmannshofer, Gori, Hamer, Patel '20]
- Large logarithms $\mathrm{Log}(\Lambda/\mu_{\mathrm{low}})^\#$ can be present

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EDMs in SMEFT

- At tree level, only dipole operators $\psi^2 XH$ contribute to EDMs
- At one loop, a few dimension-6 operators contribute via mixing

  (finite contributions also possible, but not logarithmic enhanced)

$$\psi^2 XH\,,\ X^3\,,\ X^2H^2\,,\ Q^{(3)}_{\ell equ} = (\bar{\ell}^j \sigma_{\mu\nu} e)\epsilon_{jk}(\bar{q}^k \sigma^{\mu\nu} u)$$

- At two loops, novel dimension-6 operators can contribute via mixing; their anomalous dimension matrix elements at one loop vanish

$$\psi^2 H^3\,,\ Q^{(1)}_{\ell equ} = (\bar{\ell}^j e)\epsilon_{jk}(\bar{q}^k u)\,,\ Q_{\ell edq} = (\bar{\ell} e)(\bar{d} q)\,,\ Q'_{\ell e} = (\bar{\ell} e)(\bar{e}\ell)\,,\ \ldots$$

- Use SMEFT to understand the large logarithms in the A2HDM in the decoupling limit

Dim.-6 Yukawa operators $\psi^2 H^3$

- Mixing into dipoles absent at one loop
- Moreover, there is no chain of one-loop mixing [so no $\text{Log}(\Lambda/\mu_{EW})^2$]
- ADM: calculated in [Altmannshofer, Gori, Hamer, Patel ‘20, Jaeger, Leslie, LVS ‘20]

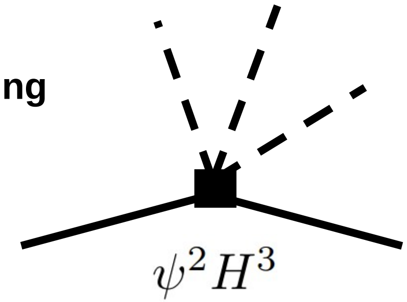
[global sign difference w.r.t. Panico, Pomarol, Riembau ‘18, Elias M., Ingoldby, Riembau ‘20]

- A2HDM: in the decoupling limit, a single parameter from the scalar potential

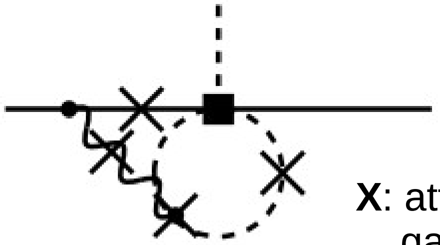
$$\frac{d_{e,\,eH}^{\text{SMEFT}}}{e} = m_e \frac{g^2}{(4\pi)^4}\frac{3}{4}t_w^2 \frac{\text{Im}(\lambda_6^* \varsigma_l)}{\Lambda^2} \log\left(\frac{\Lambda^2}{v_{EW}^2}\right)$$

A2HDM

matching



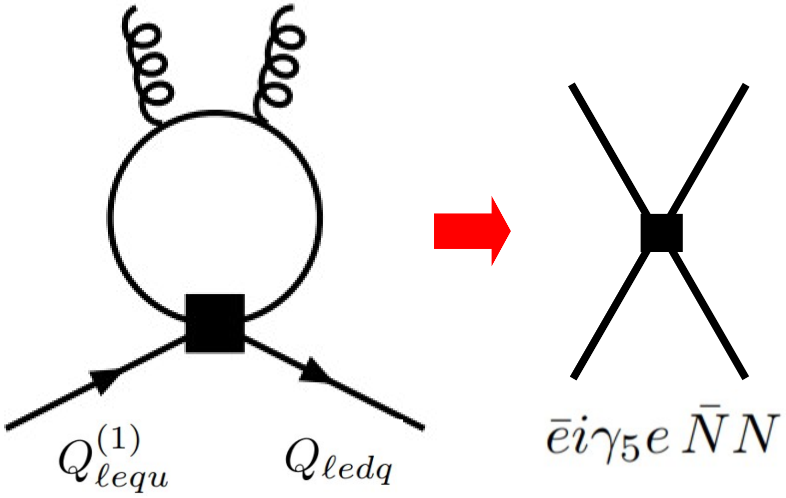
RGEs



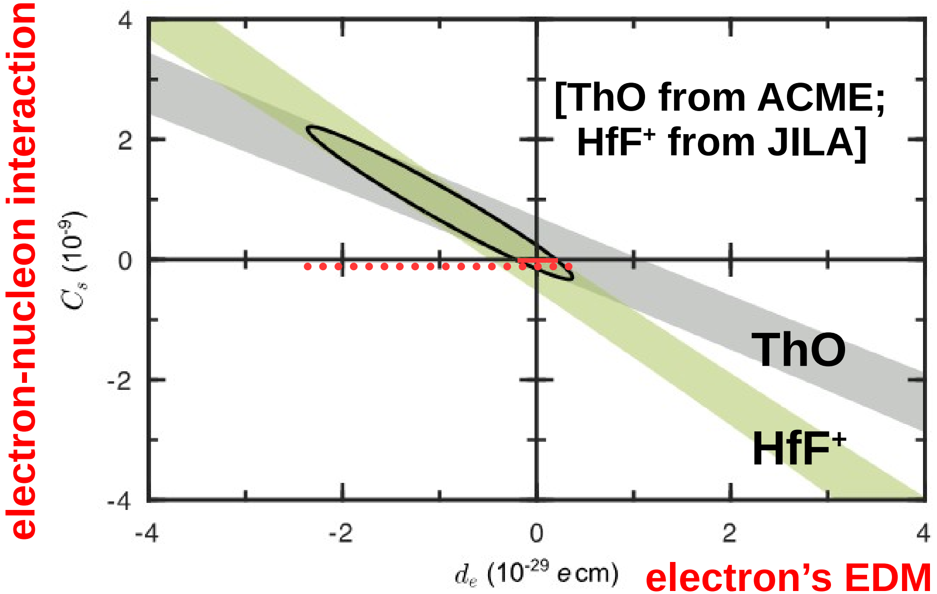
X: attach external gauge boson

Outlook: lepton-gluonic operators

- Experimental bound: EDM & electron-nucleon interaction of coupling C_s;
  it was assumed in this talk that C_s=0: **factor ~5 impact on the bound on |d$_e$|!**
- Semi-leptonic operators with heavy quarks lead to lepton-gluonic effective operators (dim.>6) at low-energies; need to include non-perturbative dynamics

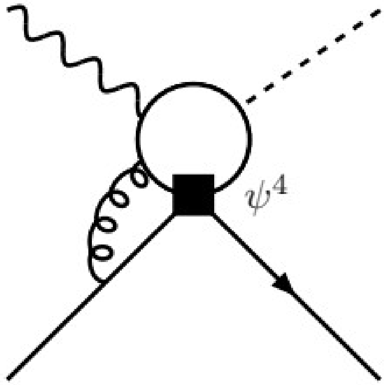


[Shifman, Vainshtein, Zakharov '78,
Cheung, Keung, Mao, Zhang '19]



Outlook: neutron's EDM

- Further dimension-6 SMEFT operators, including chromo-magnetic dipole and Weinberg (chromo-EDM of gluons) operators
- Color group factors and strong coupling constant can enhance their contributions
- ADM elements not yet available [Jaeger, LVS]



$$Q^{(1)}_{quqd} = (\bar{q}^j u)\epsilon_{jk}(\bar{q}^k d)\,,\; Q^{(1)'}_{qu} = (\bar{q}u)(\bar{u}q)\,,\; Q^{(1)'}_{qd} = (\bar{q}d)(\bar{d}q)\,,\; \ldots$$

Sym breaking at the quantum level

- **Single insertions of the BRST variation of the action**

$$\int \mathrm{d}^D x \frac{\delta_R \Gamma[X,K]}{\delta K_n(x)} \frac{\delta_L \Gamma[X,K]}{\delta X^n(x)} = \underbrace{\lim_{Q\to 0} \int \mathrm{d}^D x \frac{\delta_R \Gamma[X,K,Q]}{\delta Q(x)}}_{\text{true or trivial obstruction}}$$

[cf. Quantum Action Principle; Martin, Sanchez-R. ‘00;
Barnich, Brandt, Henneaux ‘00;
Bélusca-M., Ilakovac, Madzor-B., Stoeckinger ‘20]

Q: source for the **BRST transformation** of the sym.-breaking term $i\bar{\xi}\hat{\partial}\xi$

- This equation provides a unified framework for ‘true anomalies’ (e.g., chiral anomalies) and ‘trivial anomalies’
- ‘Trivial anomalies’ can be removed with the addition of <u>appropriate finite=non-evanescent, local counter terms</u>