EDM Constraints on Higgs CP Violation

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BSM circa 2020, PITT-PACC

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With Ulrich Haisch, Jure Zupan – JHEP 1311 (2013) 180 [arXiv:1310.1385]

With Wolfgang Altmannshofer, Martin Schmaltz – JHEP 1505 (2015) 125 [arXiv:1503.04830]

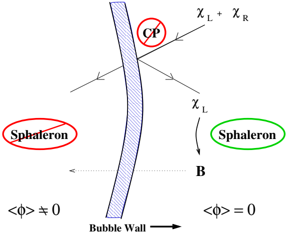
With Emmanuel Stamou – arXiv:1810.12303

With Dimitrios Skodras – JHEP 1901 (2019) 233 [arXiv:1811.05480]

With Jonathan Cornell, Dimitrios Skodras, Emmanuel Stamou – work in progress

Motivation – Electroweak Baryogenesis

- Baryogenesis fails within the SM
  - Need strong first-order phase transition
  - Need more CP violation
- A minimal setup for electroweak baryogenesis:
  [Huber, Pospelov, Ritz, hep-ph/0610003]



[Image credit: Morrissey et al., 1206.2942]

$$\mathcal{L} = \frac{1}{\Lambda^2}(H^\dagger H)^3 + \frac{Z_t}{\Lambda^2}(H^\dagger H)\bar{Q}_3 H^c t_R$$

- $\Lambda \sim 500 - 800\,\text{GeV}$ gives correct baryon-to-photon ratio η_b
- In principle, there are more operators
  [E.g., de Vries et al. 1710.04061]

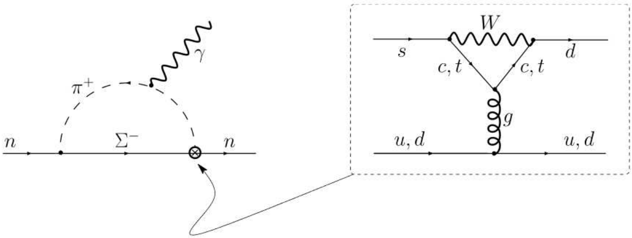
Outline

- EDM overview
- EDM constraints on CP-violating Higgs couplings
    - Top Yukawa
    - Bottom & charm Yukawa
    - Light-fermion Yukawas

EDM Overview

Sources of CP violation

- QCD is CP invariant...
  - ...apart from possible θ term $\propto \epsilon_{\mu\nu\alpha\beta} G^{\mu\nu} G^{\alpha\beta}$
  - Neglect for the purpose of this talk
- Microscopic origin of CP violation:
  - Weak interactions
  - New Physics
- E.g. neutron EDM: SM contribution is tiny, $d_n^{\mathrm{SM}} \sim 10^{-32}\, e\,\mathrm{cm}$
  [Khriplovich & Zhitnitsky, PLB 109 (1982) 490]



EDM experiments, bounds

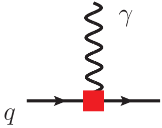
- Measure different EDMs
  - Elementary: neutron, proton, deuteron
  - Atomic: mercury, radium, xenon
  - Molecular: ThO (mainly electron)
- Current bounds and prospects:

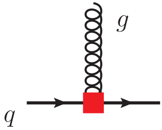
  [Hewett et al., 1205.2671; Baker et al., hep-ex/0602020; [ACME 2018]; Graner et al. 1601.04339]

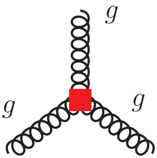
	d_e [e cm]	d_n [e cm]	$d_{p,D}$ [e cm]
current	1.1×10^{-29}	2.9×10^{-26}	–
expected	5.0×10^{-30}	1.0×10^{-28}	1.0×10^{-29}
	d_{Hg}	d_{Xe}	d_{Ra}
current	7.4×10^{-30}	5.5×10^{-27}	4.2×10^{-22}
expected	–	5.0×10^{-29}	1.0×10^{-27}

Low-energy operators

- At low scales, three types of operators contribute:
  - qEDM: $\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$
  - qCEDM: $\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu}$
  - Weinberg: $f^{abc}\epsilon_{\mu\nu\alpha\beta}G^a_{\alpha\beta}G^b_{\mu\rho}G^{c,\rho}_{\nu}$







- Hadronic matrix elements:
  - qEDM → lattice
    [Battacharya et al., 1506.04196, 1506.06411]
  - qCEDM: ChPT and NDA
    [E.g. Pospelov & Ritz, hep-ph/0504231]
  - Weinberg: No systematic calculation exists, even sign unknown
    [NDA: Weinberg PRL 63 (1989) 2333, Sum rules: Demir et al. hep-ph/0208257]

Connection to Higgs

Modified Yukawa couplings

- We will look at modification

$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}}\kappa_f \bar{f}(\cos\phi_f + i\gamma_5 \sin\phi_f) f\, h$$

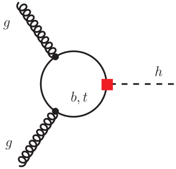
- Motivated by higher dimension operators

$$-\frac{\lambda}{\Lambda^2}|H|^2 \bar{Q}_L H d_R\,, \quad -\frac{\lambda'}{\Lambda^2}|H|^2 \bar{Q}_L \tilde{H} u_R$$

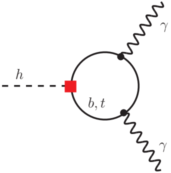
- In the SM, $\kappa_f = 1$ and $\phi_f = 0$

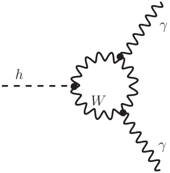
Top Yukawa

Constraints from Higgs production and decay



$$\mu_{gg} = \frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\text{SM}}}$$
$$\approx (\kappa_t \cos\phi_t)^2 + 2.6\,(\kappa_t \sin\phi_t)^2$$
$$+\,0.11\,\kappa_t \cos\phi_t\,(\kappa_t \cos\phi_t - 1)$$

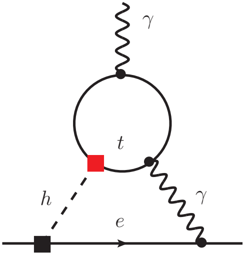




$$\mu_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\text{SM}}}$$
$$\approx (1.28 - 0.28\,\kappa_t \cos\phi_t)^2 + (0.43\,\kappa_t \sin\phi_t)^2$$

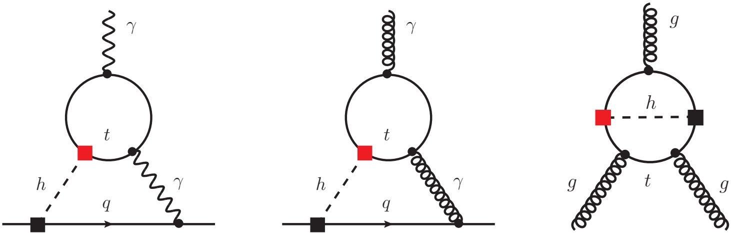
- Input from [1606.02266]
- More sophisticated analyses, e.g. angular analysis of final state jets
  [Del Duca et al., hep-ph/0608158; Klamke et al., hep-ph/0703202]

Electron EDM – Barr-Zee contributions



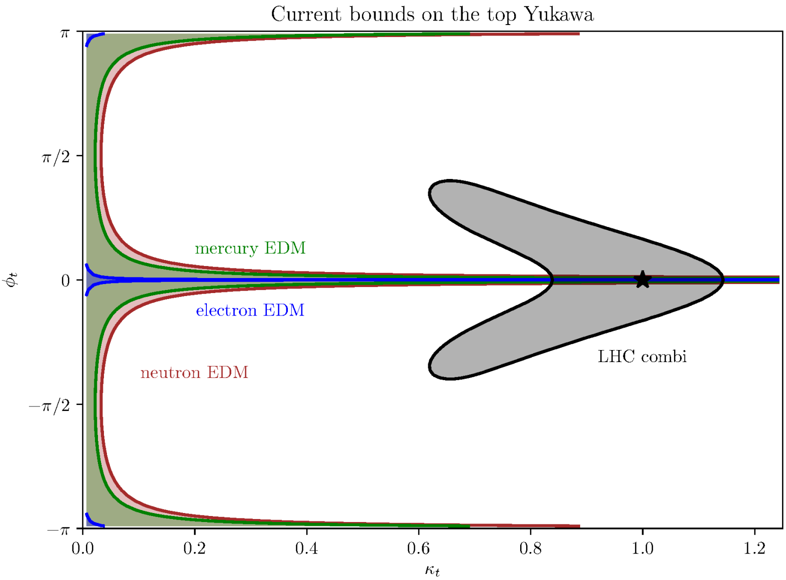
- "Barr-Zee" diagrams induce electron EDM
  [Weinberg PRL 63 (1989) 2333, Barr & Zee PRL 65 (1990) 21]
- $|d_e/e| < 1.1 \times 10^{-29}\,\text{cm}$ (90% CL) [ACME 2018]
- $\Rightarrow \kappa_t |\sin \phi_t| < 0.001$
- Constraint on ϕ_t vanishes if the Higgs does not couple to the electron

Hadronic EDMs – The Weinberg Operator



- Barr-Zee diagrams similar as in electron case
- Contribution of the Weinberg Operator: Higgs couples only to top quark
  - Get constraint even if couplings to light quarks vanish

Combined Constraints on Top Yukawa



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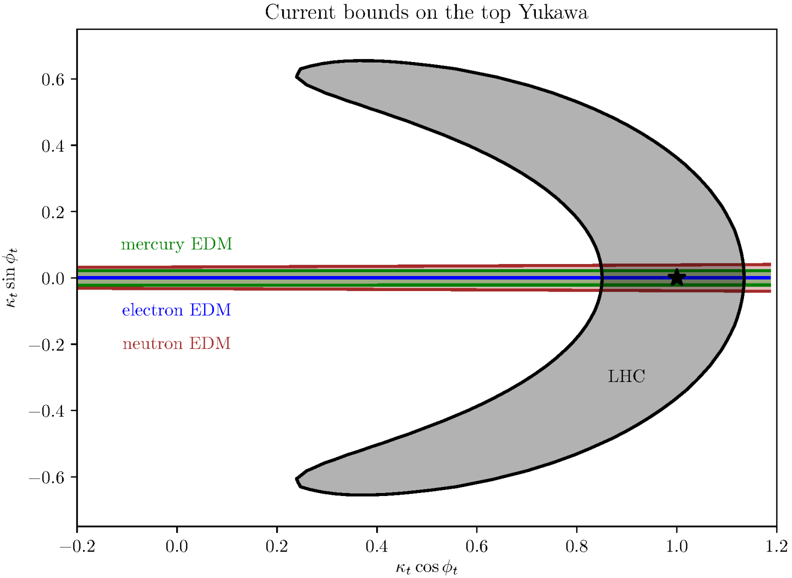


Bottom Yukawa

Collider constraints

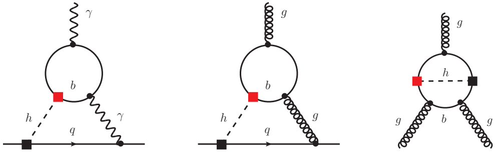
- Modifications of $gg \to h$, $h \to \gamma\gamma$ due to $\kappa_b \neq 1$, $\tilde{\kappa}_b \neq 0$ are subleading
- $\Rightarrow$ Main effect: modifications of branching ratios

$$\text{Br}(h \to b\bar{b}) = \frac{{\kappa_b}^2 \text{Br}(h \to b\bar{b})_{\text{SM}}}{1 + \left({\kappa_b}^2 - 1\right)\text{Br}(h \to b\bar{b})_{\text{SM}}}$$

$$\text{Br}(h \to X) = \frac{\text{Br}(h \to X)_{\text{SM}}}{1 + \left({\kappa_b}^2 - 1\right)\text{Br}(h \to b\bar{b})_{\text{SM}}}$$

- Input from [1606.02266]

"Naive" Barr-Zee



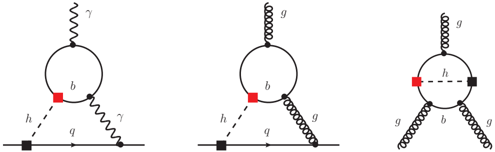
- Generate three operators:
  - EDM (d_q): $\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$
  - CEDM ($\tilde{d}_q$): $\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu}$
  - Weinberg (w): $-\frac{1}{3}f^{abc}\,G^a_{\mu\sigma}G^{b,\sigma}_{\nu}\widetilde{G}^{c,\mu\nu}$

$$d_q(\mu_W) \simeq -4\,e\,Q_q\,N_c\,Q_b^2\,\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\kappa_b\sin\phi_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

$$\tilde{d}_q(\mu_W) \simeq -2\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\kappa_b\sin\phi_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

$$w(\mu_W) \simeq -g_s\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,\kappa_b^2\sin\phi_b\cos\phi_b\,\frac{m_b^2}{M_h^2}\left(\log\frac{m_b^2}{M_h^2}+\frac{3}{2}\right).$$

“Naive” Barr-Zee



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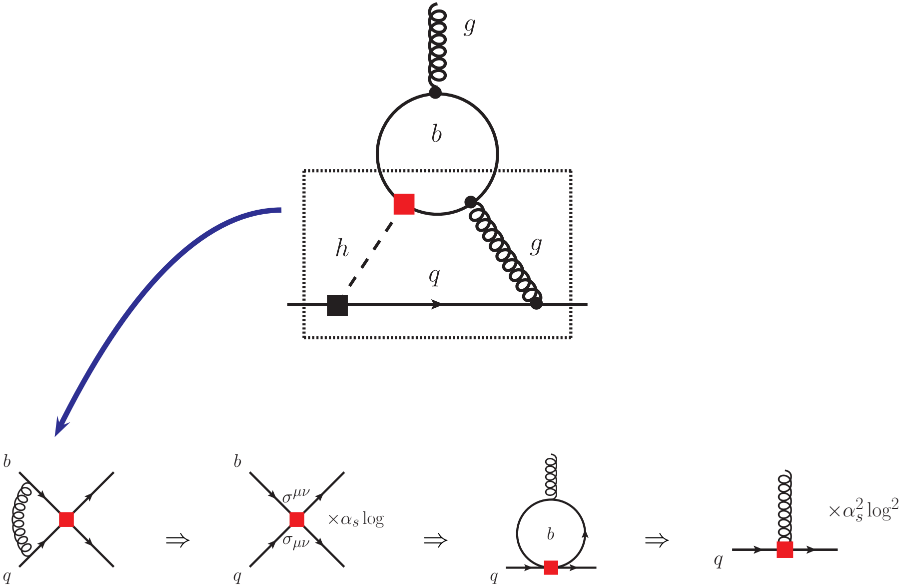
$$w(\mu_W) \simeq -g_s \frac{\alpha_s}{(4\pi)^3} \sqrt{2} G_F\, \kappa_b^2 \sin\phi_b \cos\phi_b \frac{m_b^2}{M_h^2} \left(\log \frac{m_b^2}{M_h^2} + \frac{3}{2} \right).$$

- $\alpha_s(M_h)^2 \sim 0.01?$ $\quad$ $\alpha_s(m_b)^2 \sim 0.045?$ $\quad$ $[\alpha_s(2\,\text{GeV})^2 \sim 0.07?]$

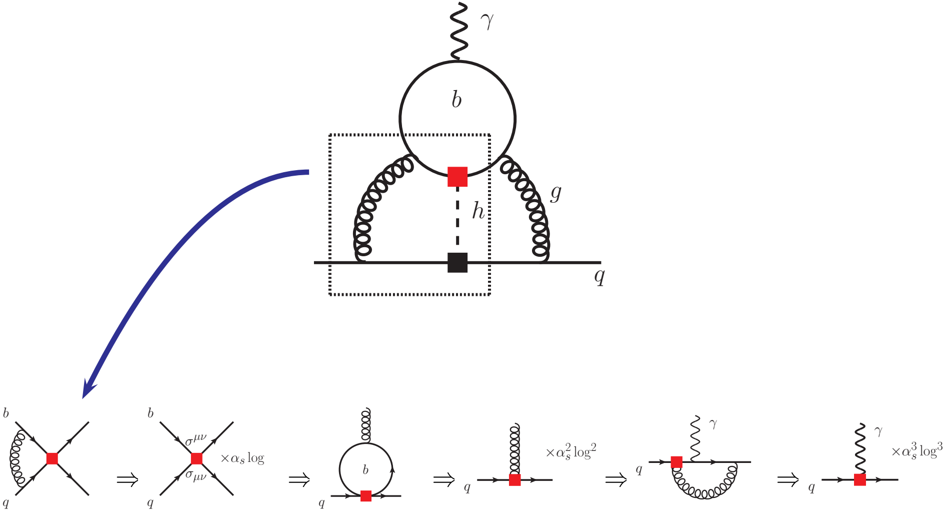
RG analysis of the b-quark contribution to EDMs

- Factor ≈ 5 scale uncertainty in CEDM Wilson coefficient
- Related to different scales in problem: $\alpha_s \log(M_h/m_b) \sim 1$ is large!
- Use techniques of effective theory and the renormalization group:
  - Sum $\alpha_s^n \log^n(M_h/m_b)$ to all orders ("LL")
    [Brod, Haisch, Zupan, 1310.1385]

RG in a nutshell



More RG in a nutshell



- This contribution dominates over two-loop Barr-Zee by a factor of ≈ 10!

Effective Lagrangian

$$\mathcal{L}_{\rm eff} = -\sqrt{2} G_F \left\{ \sum_{q \neq q'} \left[\sum_{i=1,2} C_i^{qq'} O_i^{qq'} + \frac{1}{2} \sum_{i=3,4} C_i^{qq'} O_i^{qq'} \right] + \sum_q \sum_{i=1,\ldots,4} C_i^q O_i^q + O_w \right\}$$

$$O_1^{qq'} = (\bar{q} q)\,(\bar{q}'\, i\gamma_5 q')\,,$$

$$O_2^{qq'} = (\bar{q}\, T^a q)\,(\bar{q}'\, i\gamma_5 T^a q')\,,$$

$$O_3^{qq'} = (\bar{q}\sigma_{\mu\nu} q)\,(\bar{q}'\, i\sigma^{\mu\nu}\gamma_5 q')\,,$$

$$O_4^{qq'} = (\bar{q}\sigma_{\mu\nu} T^a q)\,(\bar{q}'\, i\sigma^{\mu\nu}\gamma_5 T^a q')\,,$$

$$O_1^q = (\bar{q} q)\,(\bar{q}\, i\gamma_5 q)\,,$$

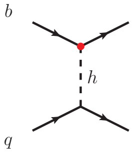
$$O_2^q = (\bar{q}\sigma_{\mu\nu} q)\,(\bar{q}\, i\sigma^{\mu\nu}\gamma_5 q)\,,$$

$$O_3^q = \frac{ieQ_q}{2}\frac{m_q}{g_s^2}\,\bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu}\,,$$

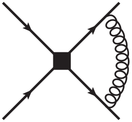
$$O_4^q = -\frac{i}{2}\frac{m_q}{g_s}\,\bar{q}\sigma^{\mu\nu} T^a \gamma_5 q\, G^a_{\mu\nu}\,,$$

$$O_w = -\frac{1}{3\, g_s} f^{abc}\, G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}\,.$$

Leading-logarithmic results



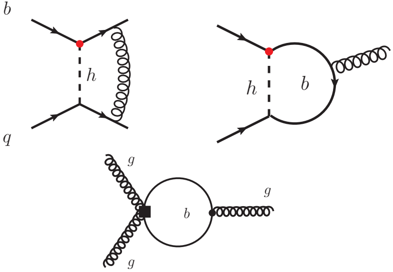
- Tree-level matching

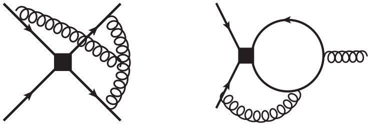


- One-loop running
  [Hisano et al., 1205.2212, Misiak et al., hep-ph/9409454]

- LL RG sums $\alpha_s^n \log^n$ to all orders
- Still factor 2 uncertainty after LL resummation
- $\Rightarrow$ need NLO analysis

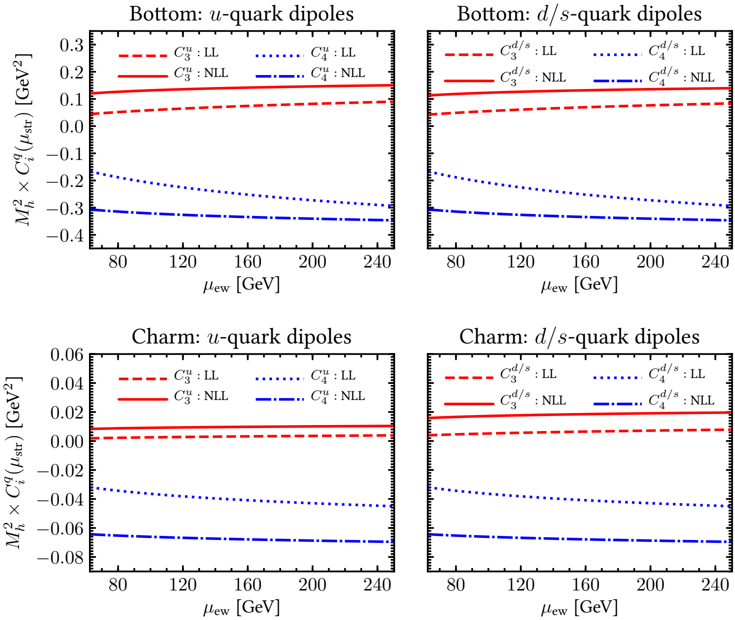
NLO calculation



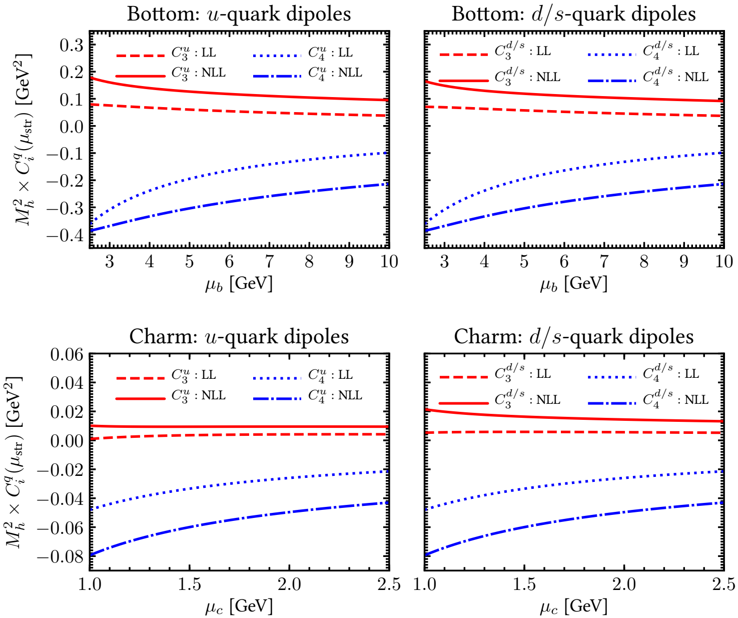


- One-loop matching:
  - Cancels linear $\log\mu$ dependence in LL running
  - Finite part is scheme dependent
- Two-loop running:
  - $\mathcal{O}(1000)$ two-loop diagrams
  - Sums $\alpha_s^{n+1}\log^n$ to all orders
  - Cancels scheme dependence of one-loop initial conditions

Next-to-leading-logarithmic results



Next-to-leading-logarithmic results



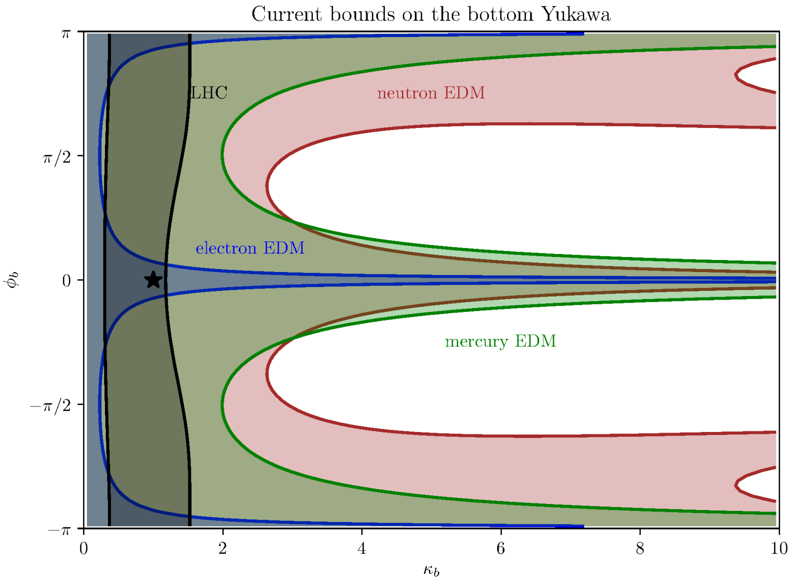
Contribution to hadronic EDMs

- Hadronic matrix elements:
  - qEDM → lattice: $g_T^u = -0.204(11)(10)$, $g_T^d = 0.784(28)(10)$, $g_T^s = 0.0027(16)$
    ($\overline{\text{MS}}$ @ 2 GeV) [Battacharya et al., 1808.07597]
  - qCEDM, Weinberg op.: ChPT and NDA
    [E.g. Pospelov & Ritz, hep-ph/0504231]
- Exp. bound: $|d_n/e| < 2.9 \times 10^{-26}\,\text{cm}$ (90% CL) [Baker et al., hep-ex/0602020]

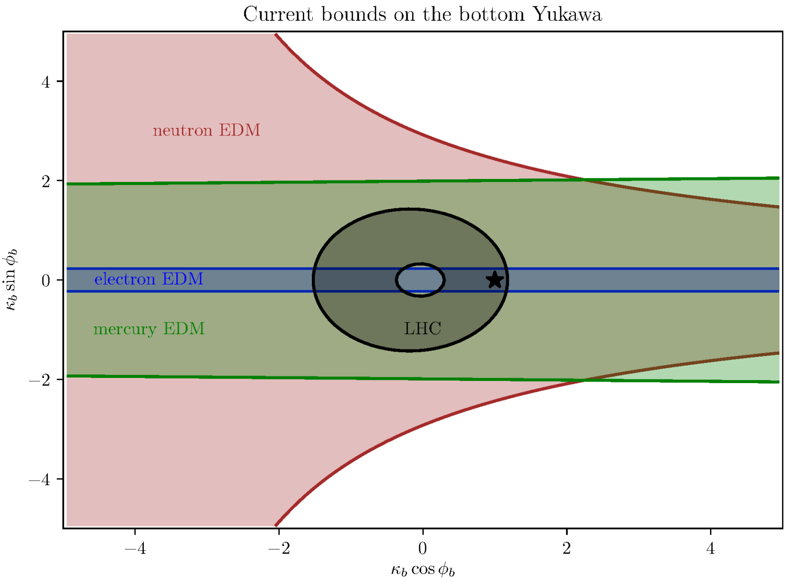
$$\frac{d_n}{e} = 1.1(\tilde{d}_d + 0.5\tilde{d}_u) - \left(\frac{g_T^u}{e} d_u + \frac{g_T^d}{e} d_d + \frac{g_T^s}{e} d_s\right) \pm 2.2 \cdot 10^{-2} w$$

- $d_{\text{Hg}}/e = 7.2(\tilde{d}_d - \tilde{d}_u) \times 10^{-4} < 7.4 \times 10^{-30}$ (95% CL)

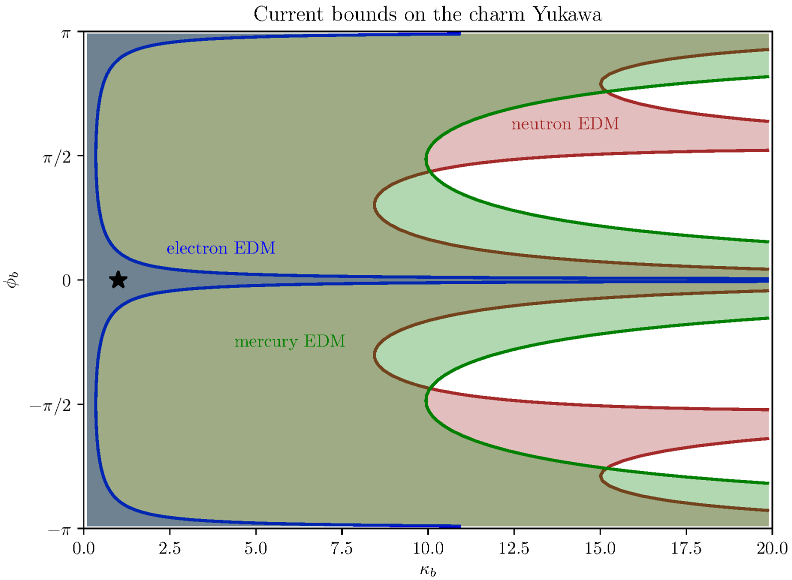
Combined Constraints on Bottom Yukawa



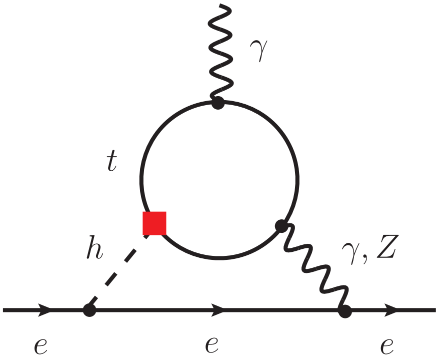
Combined Constraints on Bottom Yukawa



Combined Constraints on Charm Yukawa



Light-Fermion Yukawas



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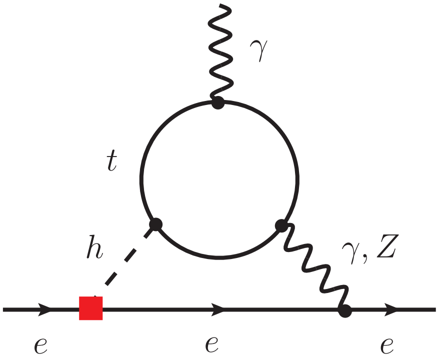
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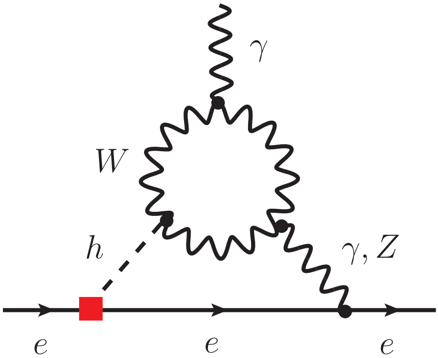
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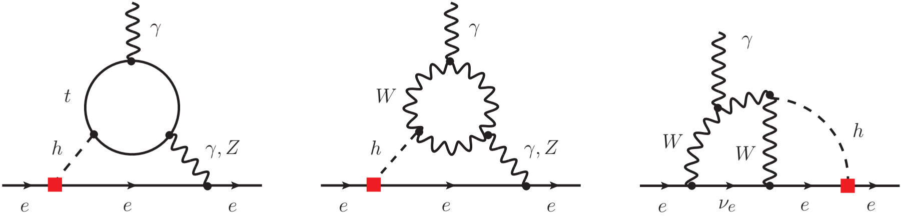
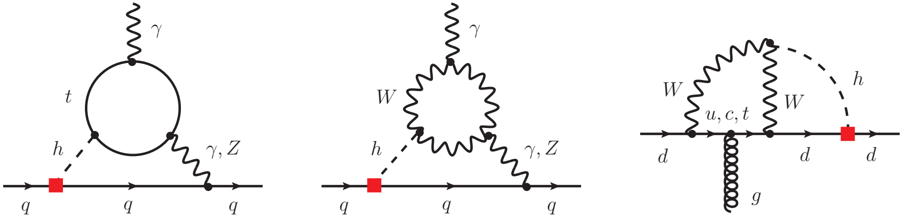
Light fermions: electron



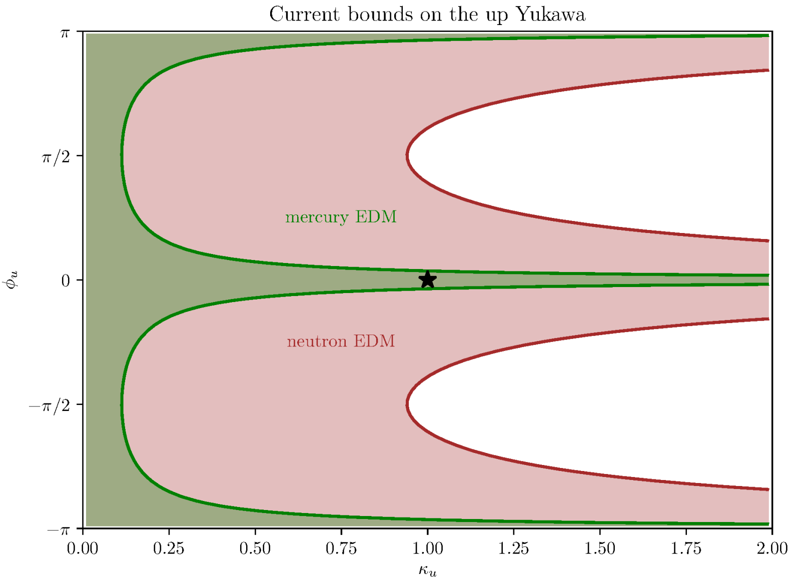
- . . . + 117 more two-loop diagrams (use background-field gauge)
- Complete analytic result [Altmannshofer, Brod, Schmaltz, 1503.04830]
  - See also [Czarnecki & Gribouk hep-ph/0509205]
- Electron EDM: $|d_e/e| < 1.1 \times 10^{-29}$ cm (90% CL) [ACME 2018]
- . . . leads to $\kappa_e|\sin\phi_e| < 0.002$

Light fermions: 1st generation quarks

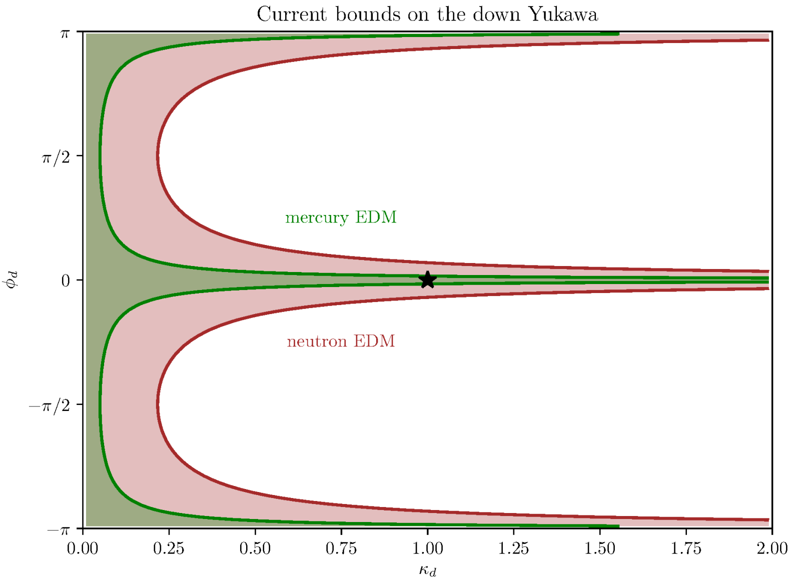


- Complete analytic result [Brod, Skodras, 1811.05480], e.g.
  - $\tilde{d}_u(\mu_{\text{had}}) = (14.0 \pm 3.0) \times 10^{-26}\,\text{cm}$
  - $\tilde{d}_d(\mu_{\text{had}}) = (31.8 \pm 6.4) \times 10^{-26}\,\text{cm}$
- $d_n/e = 1.1(\tilde{d}_d + 0.5\tilde{d}_u) + \ldots$
- $d_{\text{Hg}}/e = 7.2(\tilde{d}_d - \tilde{d}_u) \times 10^{-4}$

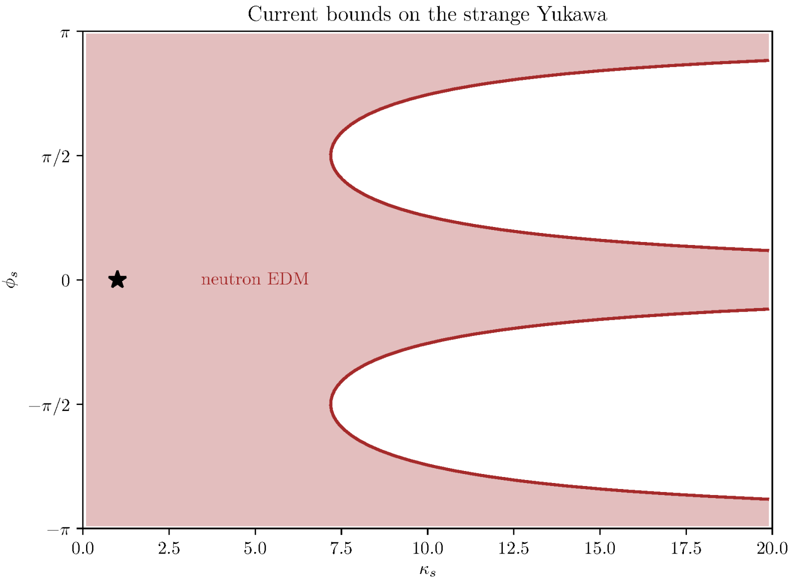
Combined Constraints on Up Yukawa



Combined Constraints on Down Yukawa



Combined Constraints on Strange Yukawa



Summary

- EDMs yield strong constraints on new sources of CP violation
- Many competing contributions to EDMs
  - Only top quark important for electroweak baryogenesis
  - What is the contribution of all other Yukawas?
- Combine more EDMs: xenon, radium, proton,. . .
  - Cancellations, hadronic uncertainties,. . .
    [See, e.g., Chien et al., 1510.00725]
- Perform a "global analysis" [Brod, Cornell, Skodras, Stamou; work in progress]
- Study implications for models of baryogenesis

Appendix

EDMs as probes of CP violation

- T^2 acts on any one-particle state as

$$\mathrm{T}^2\Psi_{p,\sigma} = (-1)^{2j}\Psi_{p,\sigma}$$

- For odd number of non-interacting spin-1/2 particles, have

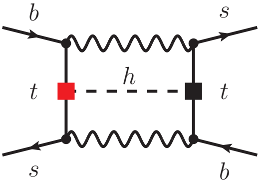
$$\mathrm{T}^2\Psi = -\Psi$$

- Remains true if interactions are T-invariant (e.g. static electric fields)
- Since Hamiltonian H commutes with T, both Ψ and $\mathrm{T}\Psi$ are eigenstates
- They cannot be the same state, since $\Psi = \zeta\Psi$ implies

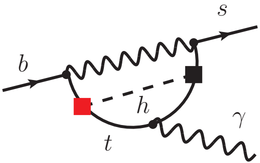
$$\mathrm{T}^2\Psi = \mathrm{T}(\zeta\Psi) = \zeta^*\mathrm{T}\Psi = |\zeta|^2\Psi = \Psi$$

- An EDM would entirely remove this degeneracy in a static electric field
- Thus, EDMs are forbidden by T (CP) invariance

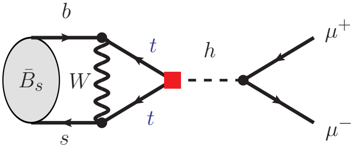
Other low-energy constraints



- No effects in dim. six operators



- $\mathcal{O}(100)$ effects allowed by data



- $\mathcal{O}(100)$ effects allowed by data

Electron Yukawa – Collider bounds

- Light quarks: $|y_u/y_b^{\rm SM}| \sim |y_d/y_b^{\rm SM}| \sim |y_s/y_b^{\rm SM}| \lesssim 1.0$ [Kagan et al. 1406.1722]
- Electron:

$$\text{Br}(h \to e^+e^-) = \frac{\big(\kappa_e^2 + \tilde\kappa_e^2\big)\text{Br}(h \to e^+e^-)_{\rm SM}}{1 + \big(\kappa_e^2 + \tilde\kappa_e^2 - 1\big)\text{Br}(h \to e^+e^-)_{\rm SM}}$$

- CMS limit $\text{Br}(h \to e^+e^-) < 0.0019$ [CMS, 1410.6679] leads to $\sqrt{\kappa_e^2 + \tilde\kappa_e^2} < 611$
- Estimated future sensitivities at hadron colliders:
  - 14 TeV LHC with 3000/fb: $\sqrt{\kappa_e^2 + \tilde\kappa_e^2} \sim 150$
  - 100 TeV collider with 3000/fb: $\sqrt{\kappa_e^2 + \tilde\kappa_e^2} \sim 75$
- Future e^+e^- colliders could be sensitive down to SM value

Pecularities of two-loop Calculation I

- Extract UV poles using dimensional regularization ($4 \to 4 - 2\epsilon$)
- This introduces infinitely many "evanescent" operators that affect the two-loop anomalous dimension
- For instance,

$$E_1^q = (\bar{q} T^a q)(\bar{q} i\gamma_5 T^a q) + \frac{5}{12} O_1^q + \frac{1}{16} O_2^q$$

$$E_2^q = (\bar{q}\sigma^{\mu\nu} T^a q)(\bar{q}\sigma_{\mu\nu} i\gamma_5 T^a q) + 3O_1^q - \frac{1}{12} O_2^q$$

$$E_3^q = (\bar{q}\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho}\gamma^{\sigma]} q)\,(\bar{q}\gamma_{[\mu}\gamma_{\nu}\gamma_{\rho}\gamma_{\sigma]}\, i\gamma_5 q) - 24 O_1^q$$

$$E_4^q = (\bar{q}\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho}\gamma^{\sigma]}\, T^a q)\,(\bar{q}\gamma_{[\mu}\gamma_{\nu}\gamma_{\rho}\gamma_{\sigma]}\, i\gamma_5\, T^a q) + 10 O_1^q + \frac{3}{2} O_2^q$$

$$E_5^q = (\bar{q}\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho}\gamma^{\sigma}\gamma^{\tau}\gamma^{\upsilon]} q)\,(\bar{q}\gamma_{[\mu}\gamma_{\nu}\gamma_{\rho}\gamma_{\sigma}\gamma_{\tau}\gamma_{\upsilon]}\, i\gamma_5 q)\,,$$

$$E_6^q = (\bar{q}\gamma^{[\mu}\gamma^{\nu}\gamma^{\rho}\gamma^{\sigma}\gamma^{\tau}\gamma^{\upsilon]}\, T^a q)\,(\bar{q}\gamma_{[\mu}\gamma_{\nu}\gamma_{\rho}\gamma_{\sigma}\gamma_{\tau}\gamma_{\upsilon]}\, T^a\, i\gamma_5 q)\,,$$

Pecularities of two-loop Calculation II

- Have traces with γ_5 for which $[\gamma^\mu, \gamma_5] = 0$ is inconsistent
- Use 't Hooft - Veltman scheme with mixed (anti-)commutation relations

$$[\tilde{\gamma}^\mu, \gamma_5] = 0\,, \qquad \{\hat{\gamma}^\mu, \gamma_5\} = 0$$

- More evanescents, e.g.
  $\hat{E}_1^q = \frac{ieQ_q}{2} \frac{m_q}{g_s^2}\, \bar{q} \left(\frac{i}{2}[\hat{\gamma}^\mu, \gamma^\nu] + \frac{i}{2}[\gamma^\mu, \hat{\gamma}^\nu] - \frac{i}{2}[\hat{\gamma}^\mu, \hat{\gamma}^\nu] \right) \gamma_5 q\, F_{\mu\nu}$
- IR regulator mass breaks gauge invariance in intermediate steps
- $\Rightarrow$ Need gauge-variant counterterms, e.g. $N_2^q = \frac{im_q}{g_s} \bar{q} \left[\overleftarrow{\not{D}}\, \not{G} - \not{G}\, \not{D} \right] i\gamma_5 q$
- Ensure that physical result is gauge invariant and independent of arbitrary choices