EDM Constraints on Higgs CP Violation

Joachim Brod

UNIVERSITY OF Cincinnati

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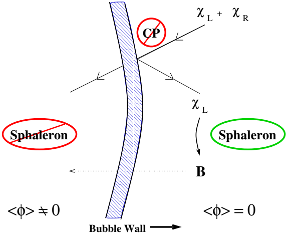
With Jonathan Cornell, Dimitrios Skodras, Emmanuel Stamou – work in progress

Motivation – Electroweak Baryogenesis

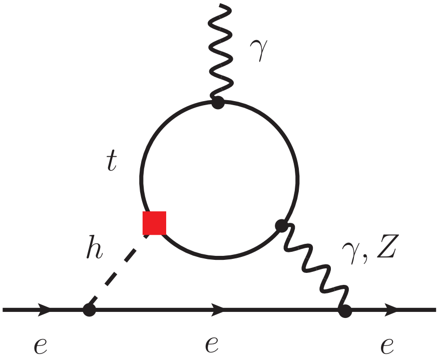
- Baryogenesis fails within the SM
  - Need strong first-order phase transition
  - Need more CP violation
- A minimal setup for electroweak baryogenesis:
  [Huber, Pospelov, Ritz, hep-ph/0610003]



[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



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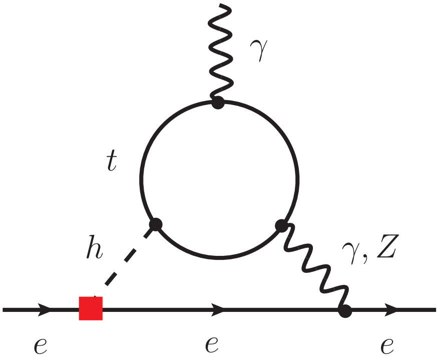

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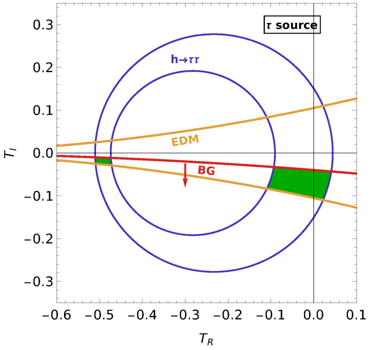
Beyond the top quark



- Third generation baryogenesis [Fuchs et al. 2003.00099]

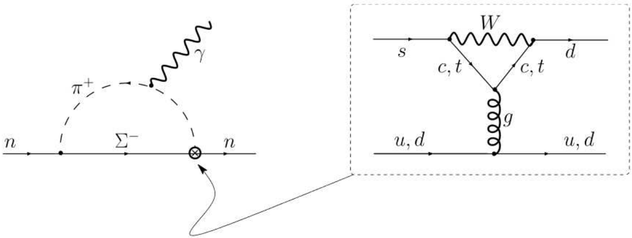
Outline

- EDM overview
- EDM constraints on CP-violating Higgs couplings
  - Top, tau
  - Bottom, charm
  - Light fermions
- Preliminary results

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, $d_n^{\text{SM}} \sim 10^{-32}\, e\,\text{cm}$
  [Khriplovich & Zhitnitsky, PLB 109 (1982) 490]



EDM experiments, bounds

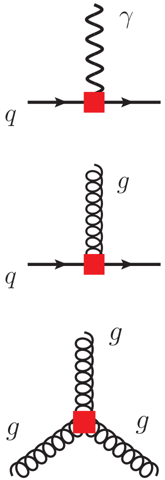
- Measure different EDMs
  - Elementary: neutron, proton, deuteron
  - Atomic: mercury, radium, xenon
  - Molecular: ThO (mainly electron)
- Polyatomic EDMs...
- Current bounds and prospects:

[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 $\to$ lattice [Gupta et al., 1808.07597]
  - qCEDM: ChPT and NDA [E.g. Pospelov & Ritz, hep-ph/0504231]
    Lattice calculations in progress
  - Weinberg: No systematic calculation exists, even sign unknown
    [NDA: Weinberg PRL 63 (1989) 2333, Sum rules: Demir et al. hep-ph/0208257]



Contributions to hadronic EDMs

- Neutron EDM:

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

- Mercury EDM:

$$\frac{d_{\mathrm{Hg}}}{e} = 7.2 \times (\tilde{d}_d - \tilde{d}_u) \times 10^{-4} + 10^{-2} \times \frac{d_e}{e}$$

Connection to Higgs

Modified Yukawa couplings in SMEFT

- We consider the SM + dim.-6 effective Lagrangian

$$\mathcal{L}_Y = \sum_f \left(Y_f + \frac{C_f}{\Lambda^2} |H|^2 \right) \bar{Q}_L H^{(c)} f_R + \text{h.c.}$$

  - Operators $Q^{u\varphi}$, $Q^{d\varphi}$, $Q^{\ell\varphi}$ in "standard SMEFT notation"

- Coefficients C_f are complex and can lead to CPV
  - Neglect flavor violation

Fermion masses

- C_f lead to complex fermion masses upon SSB

- Chiral rotation $f \to \exp(i\gamma_5\theta_f/2)f$ with

$$\tan\theta_f = \mathrm{Im}\,C_f \Big/ \Big[\frac{2y_f\Lambda^2}{v^2} - \mathrm{Re}\,C_f\Big]$$

- CPV is proportional to $\mathrm{Im}\,C_f \cos\theta_f + \mathrm{Re}\,C_f \sin\theta_f$

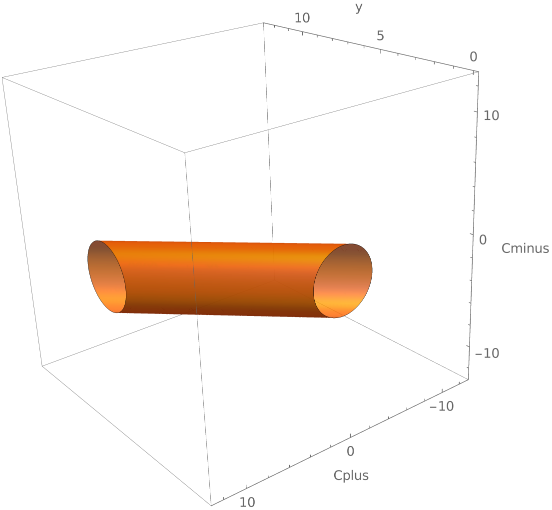
- The fermion masses are

$$m_f = \frac{y_f v}{\sqrt{2}} \sqrt{\left(1 - \frac{\mathrm{Re}\,C_f}{2y_f}\frac{v^2}{\Lambda^2}\right)^2 + \left(\frac{\mathrm{Im}\,C_f}{2y_f}\frac{v^2}{\Lambda^2}\right)^2}$$

- Nontrivial constraint; it follows

$$\big|\mathrm{Im}\,C_f\big| \leq 2\sqrt{2}\,\frac{\Lambda^2}{v^2}\,\frac{m_f}{v}$$

Fermion mass constraint



Relation to κ framework

- We can write

$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \bar{f} (\kappa_f + \tilde{\kappa}_f i\gamma_5) f\, h$$

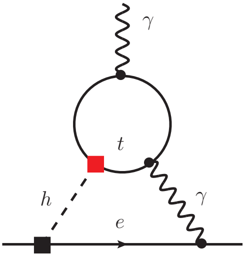
- Then

$$\kappa_f = 1 + \frac{\mathrm{Im}\, C_f \sin\theta_f - \mathrm{Re}\, C_f \cos\theta_f}{2\sqrt{2}} \frac{v}{m_f} \frac{v^2}{\Lambda^2}\,,$$
$$\tilde{\kappa}_f = -\frac{\mathrm{Im}\, C_f \cos\theta_f + \mathrm{Re}\, C_f \sin\theta_f}{2\sqrt{2}} \frac{v}{m_f} \frac{v^2}{\Lambda^2}\,.$$

- Not straightforward to use at higher orders
- SMEFT leads to additional couplings like $\bar{f}\, i\gamma_5 f\, h^2$

Top

Electron EDM – Barr-Zee contributions

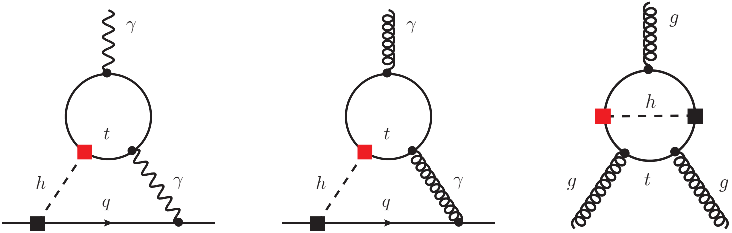


- “Barr-Zee” diagrams induce electron EDM
  [Weinberg PRL 63 (1989) 2333, Barr & Zee PRL 65 (1990) 21]

- $|d_e/e| < 1.1 \times 10^{-29}$ cm (90% CL) [ACME 2018]

- $|\mathrm{Im}\, C_f| = 2\tilde{\kappa}_t \leq 6.7 \times 10^{-4}$

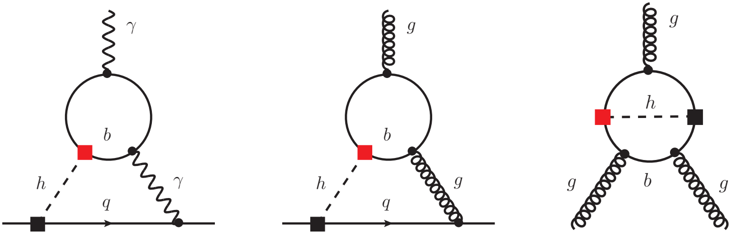
Hadronic EDMs – The Weinberg Operator



- Barr-Zee diagrams similar as in electron case
- RG evolution to hadronic scale
- Similar electric dipole diagrams for τ CP violation

Bottom & Charm

“Naive” Barr-Zee

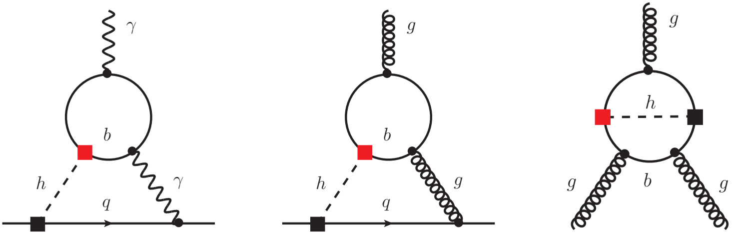


$$d_q(\mu_W) \propto {\color{blue}\alpha_s} \frac{m_b^2}{M_h^2} \left(\log^2 \frac{m_b^2}{M_h^2} + \frac{\pi^2}{3} \right) ,$$

$$\tilde{d}_q(\mu_W) \propto {\color{blue}\alpha_s^2} \frac{m_b^2}{M_h^2} \left(\log^2 \frac{m_b^2}{M_h^2} + \frac{\pi^2}{3} \right) ,$$

$$w(\mu_W) \propto {\color{blue}\alpha_s^2} \frac{m_b^2}{M_h^2} \left(\log \frac{m_b^2}{M_h^2} + \frac{3}{2} \right) .$$

“Naive” Barr-Zee



$$d_q(\mu_W) \propto \alpha_s \frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

$$\tilde{d}_q(\mu_W) \propto \alpha_s^2 \frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

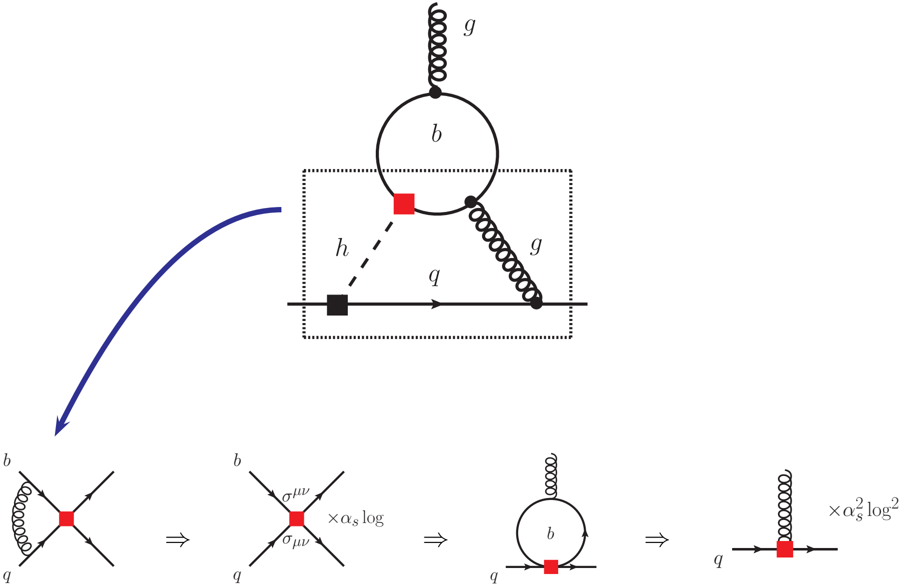
$$w(\mu_W) \propto \alpha_s^2 \frac{m_b^2}{M_h^2}\left(\log\frac{m_b^2}{M_h^2}+\frac{3}{2}\right).$$

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

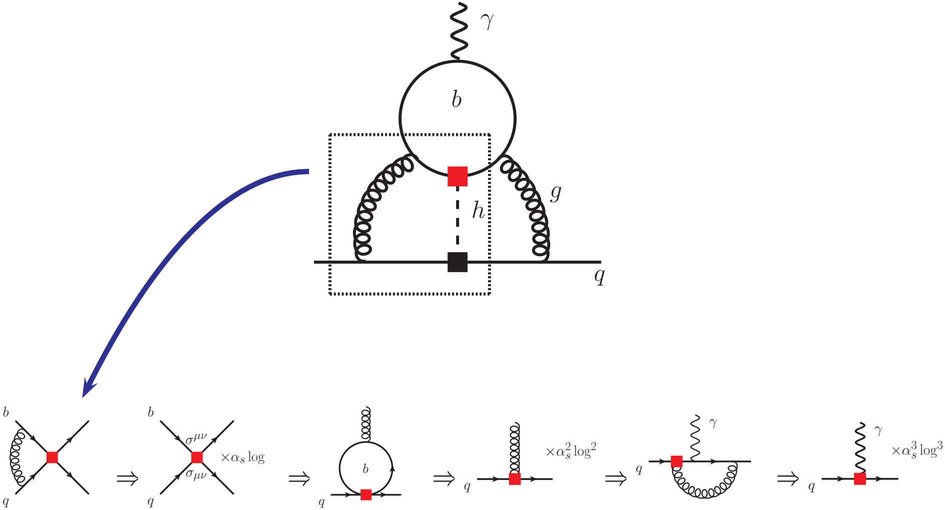
RG analysis of the b-quark contribution to EDMs

- 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]
- Large scale uncertainty – two-loop RG [Brod & Stamou, 1810.12303]

RG in a nutshell

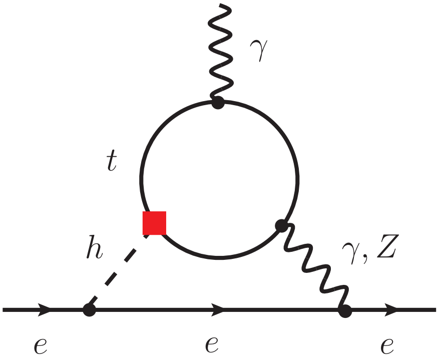


More RG in a nutshell



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

Light Fermions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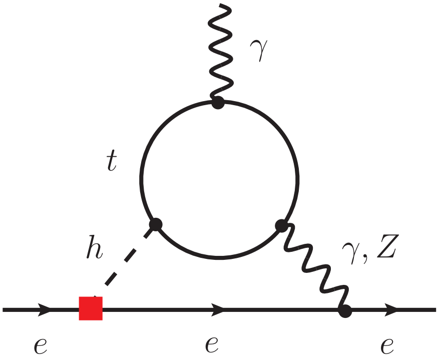

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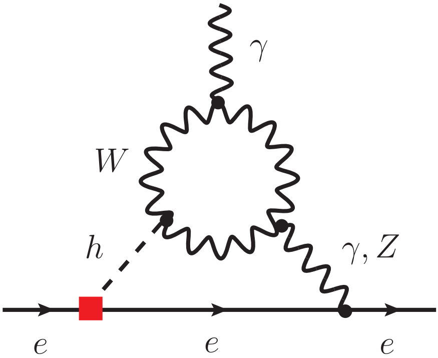
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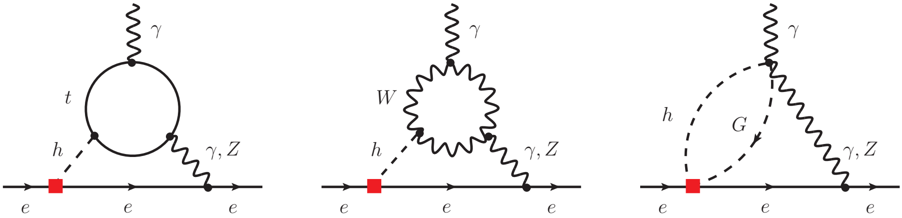
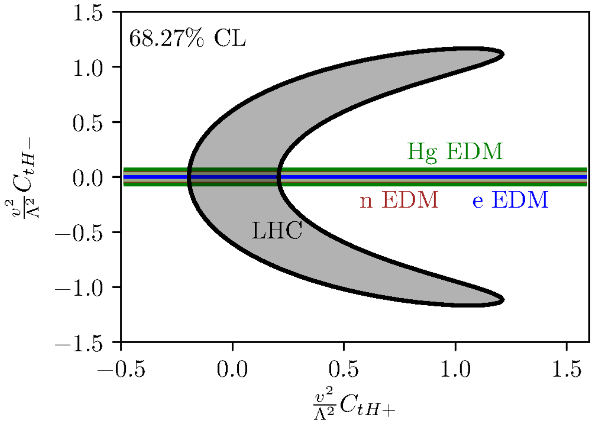
Light fermions: electron and u,d,s



- Top-loop diagrams are finite
- Bosonic diagrams are divergent
  [Panico, Pomarol 1810.09413; Altmannshofer et al. 2009.01258]
- Keep log-enhanced part only

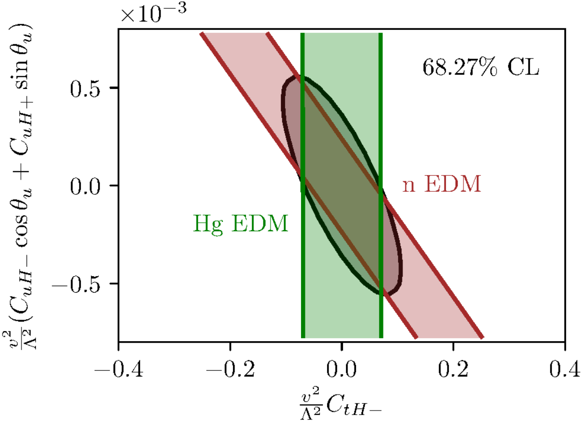
Preliminary Results

Combined Constraints on Top Yukawa



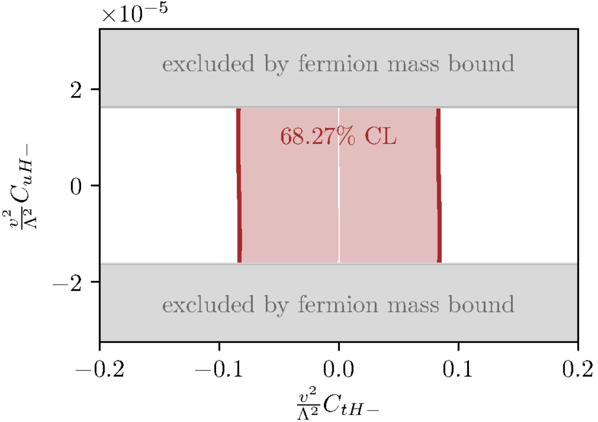
- All other Higgs couplings SM like

Combined Constraints on Up and Top Yukawa



- Non-trivial constraints due to including neutron and mercury EDM

Combined Constraints on Up and Top Yukawa



- Purely CPV in the UV is strongly constrained by fermion mass

Outlook

- EDMs yield strong constraints on Higgs CP violation
- Many competing contributions to EDMs
  - Only third generation 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" using GAMBIT
  [Brod, Cornell, Skodras, Stamou; work in progress]