CP-violating Bottom Yukawa at NLO

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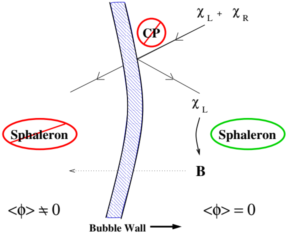
With Emmanuel Stamou – work in progress

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]



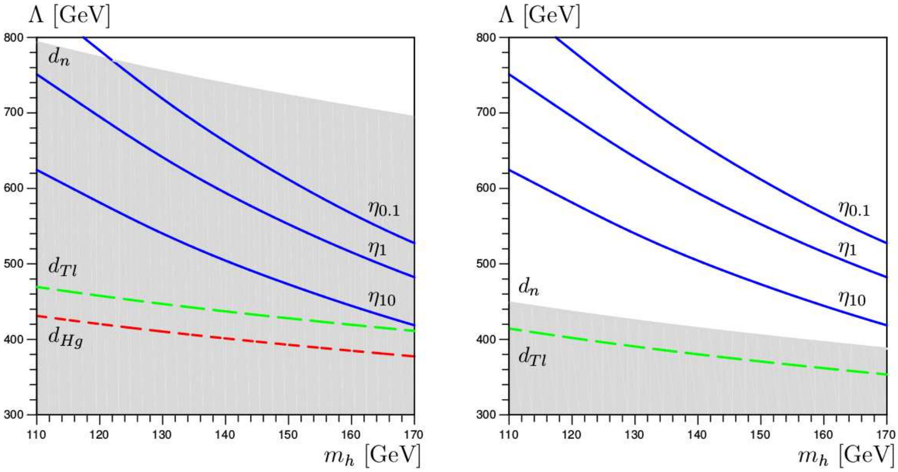
[Image credit: Morrissey et al., 1206.2942]

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

- $\Lambda \sim 500 - 800\,\text{GeV}$ gives correct baryon-to-photon ratio η_b
- In principle, there are more operators

Motivation – EDM constraints on baryogenesis

[Huber, Pospelov, Ritz, hep-ph/0610003]



Modified Bottom Yukawa

- In the SM, Yukawa coupling to fermion b is

$$\mathcal{L}_Y = -\frac{y_b}{\sqrt{2}}(\bar{b}b)\,h$$

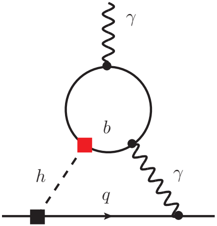
- We will look at modification

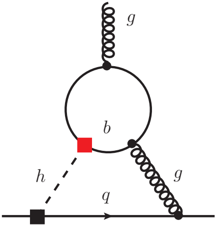
$$\mathcal{L}'_Y = -\frac{y_b}{\sqrt{2}}\left(\kappa_b\,\bar{b}b + i\tilde{\kappa}_b\,\bar{b}\gamma_5 b\right)h$$

- In the SM, $\kappa_b = 1$ and $\tilde{\kappa}_b = 0$

- New contributions will
  - modify Higgs production cross section and decay rates
  - generate EDMs via higher loop effects

“Naive” Barr-Zee





- Generate two operators:
  - EDM (d_q): $\bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu}$
  - CEDM ($\tilde{d}_q$): $\bar{q}\sigma^{\mu\nu} T^a \gamma_5 q G^a_{\mu\nu}$

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

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

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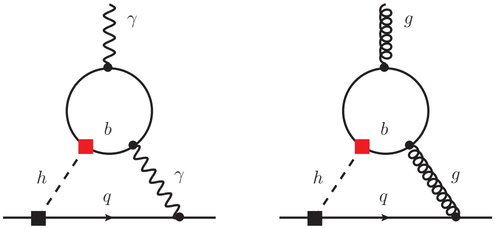

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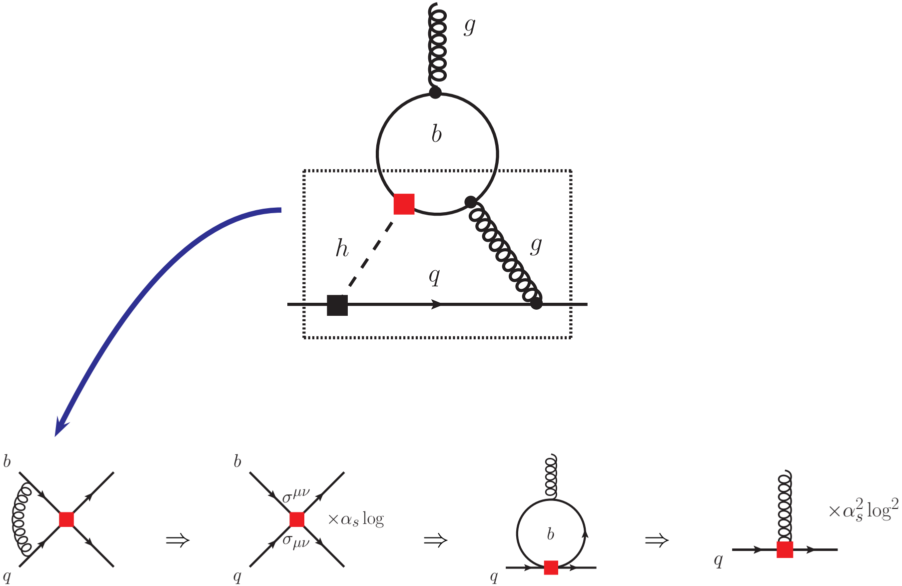
- $\alpha_s(M_h)^2 \sim 0.01?$ $\qquad \alpha_s(m_b)^2 \sim 0.045?$ $\qquad [\alpha_s(2\,(GeV))^2 \sim 0.07?]$

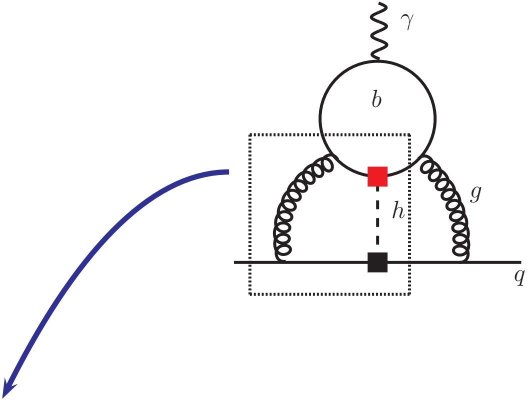
RG analysis of the b-quark contribution to EDMs

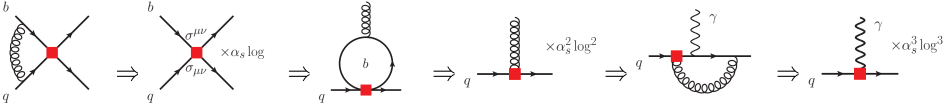
- Factor ≈ 5 scale uncertainty in CEDM Wilson coefficient
- Related to different scales in problem: $\alpha_s \log(M_h/m_b) \sim 1$ is large!
- Use techniques of effective theory and the renormalization group:
  - Sum $\alpha_s^n \log^n(M_h/m_b)$ to all orders ("LL")
    [Brod, Haisch, Zupan, 1310.1385]

RG in a nutshell



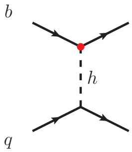
More RG in a nutshell



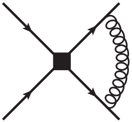


- This contribution dominates over two-loop Barr-Zee by a factor of ≈ 10!

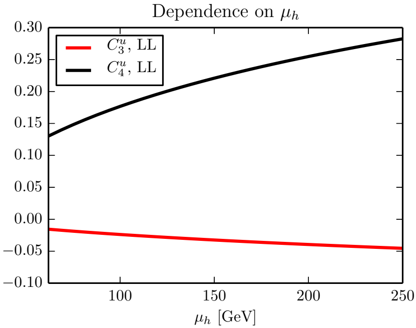
Leading-logarithmic results



- Tree-level matching

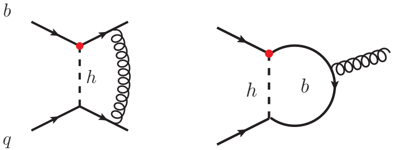


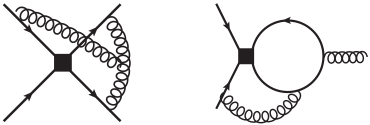
- One-loop running
  [Hisano et al., 1205.2212, Misiak et al., hep-ph/9409454]



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

NLO calculation



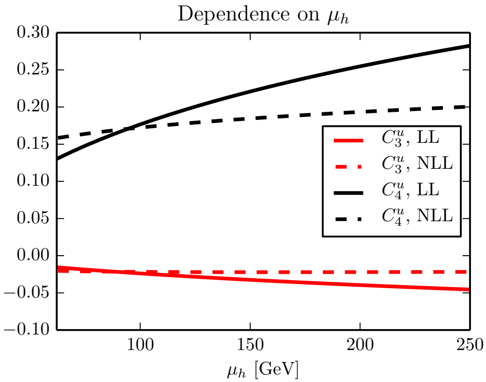


- One-loop matching:
  - Cancels linear $\log \mu$ dependence in LL running
  - Finite part is scheme dependent

- Two-loop running:
  - Sums $\alpha_s^{n+1} \log^n$ to all orders
  - Cancels scheme dependence of one-loop initial conditions
  - Partial results available
    [Misiak et al., hep-ph/9409454, Buras et al. hep-ph/0005183, Degrassi et al. hep-ph/0510137]

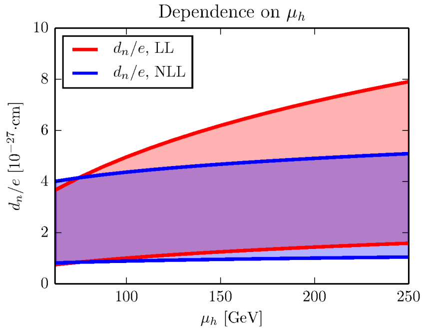
Next-to-leading-logarithmic results

- PARTIAL RESULT excluding full NLO running (scheme dependent!)



Contribution to the neutron EDM

- Hadronic matrix elements:
  - qEDM $\to$ lattice: $g_T^u = -0.233(28)$, $g_T^d = 0.774(66)$ ($\overline{\text{MS}}$ @ 2 GeV)
    [Battacharya et al., 1506.04196, 1506.06411]
  - qCEDM: 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]



$$\frac{d_n}{e} = (1.1 \pm 0.55)(\tilde{d}_d + 0.5\tilde{d}_u) - \left(\frac{g_T^u}{e} d_u + \frac{g_T^d}{e} d_d\right)$$

Summary

- EDMs yield strong constraints on new sources of CP violation
- Large scale dependence hints at large NLO corrections
- Need to complete NLO calculation
- Study theory uncertainty in more detail
- Future: Systematic analysis of all Yukawas

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

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

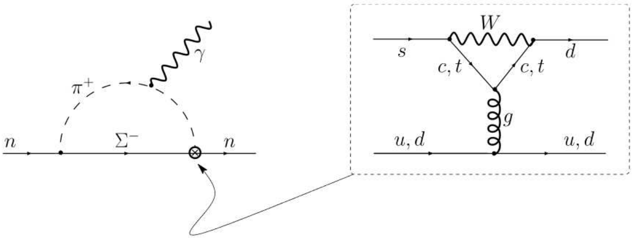
- Remains true if interactions are T-invariant (e.g. static electric fields)
- Since Hamiltonian H commutes with T, both Ψ and $\mathrm{T}\Psi$ are eigenstates
- They cannot be the same state, since $\Psi = \zeta\Psi$ implies

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

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

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 [e cm]:

	d_e	d_n	$d_{p,D}$
current	8.7×10^{-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	2.6×10^{-29}	5.5×10^{-27}	4.2×10^{-22}
expected	1.0×10^{-29}	5.0×10^{-29}	1.0×10^{-27}

Hadronic matrix elements

- 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
    [Battacharya et al., 1506.04196, 1506.06411]
  - qCEDM: ChPT and NDA, strangeness
    [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]