Constraints on top (and bottom) couplings

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

With Admir Grelio, Emmanuel Stamou, Patipan Uttayarat – work in progress

SM EFT

[See, e.g., Buchmüller et al. 1986, Aguilar-Saavedra 2008, Grzadkowski et al. 2010]

$$\mathcal{L}^{\text{eff}} = \mathcal{L}^{\text{SM}} + \mathcal{L}^{\text{dim.6}} + \ldots$$

$$Q_{eH} \equiv (H^\dagger H)(\bar{L}_L e_R H)\,,$$

$$Q_{uH} \equiv (H^\dagger H)(\bar{Q}_L u_R H)\,,$$

$$Q_{dH} \equiv (H^\dagger H)(\bar{Q}_L d_R H)\,, \ldots$$

$$Q_{Hq}^{(3)} \equiv (H^\dagger i \overleftrightarrow{D}_\mu^a H)(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3})\,,$$

$$Q_{Hq}^{(1)} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{Q}_{L,3}\gamma^\mu Q_{L,3})\,,$$

$$Q_{Hu} \equiv (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{t}_R\gamma^\mu t_R)\,, \ldots$$

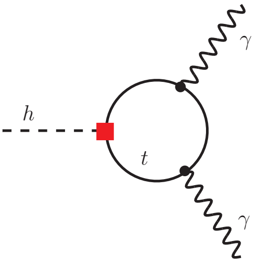
$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}} \sum_f \left(\kappa_f\, \bar{f} f + i\tilde{\kappa}_f\, \bar{f}\gamma_5 f\right) h$$

$$\mathcal{L}'_Z = g'_R\, \bar{t}_R \not{Z} t_R + g'_L\, \bar{t}_L \not{Z} t_L + g''_L\, \bar{b}_L \not{Z} b_L$$

Outline

- Anomalous Higgs couplings
  - ttH
  - bbH
- Anomalous ttZ couplings
- Conclusion

From $h \to \gamma\gamma$ ...



- In the SM, Yukawa coupling to fermion f is

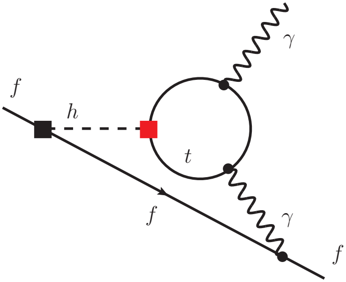
$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \bar{f} f \, h$$

- We will look at modification

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

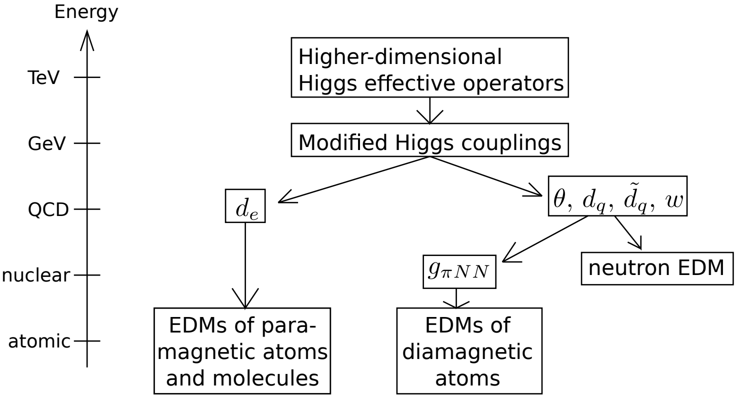
- New contributions will modify Higgs production cross section and decay rates

. . . to electric dipole moments



- Attaching a light fermion line leads to EDM
- Indirect constraint on *CP*-violating Higgs coupling
- SM "background" enters at three- and four-loop level
- Complementary to collider measurements
- Constraints depend on additional assumptions

Electric Dipole Moments (EDMs) – Generalities

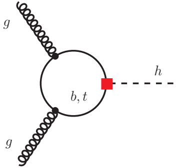


[Adapted from Pospelov et al., 2005]

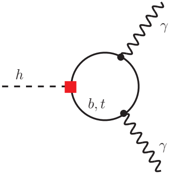
Anomalous ttH couplings

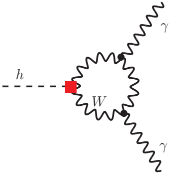
Constraints from Higgs production and decay

- Both $gg \to h$, $h \to \gamma\gamma$ generated at one loop



$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\mathrm{SM}}} = \kappa_t^2 + 2.6\,\tilde{\kappa}_t^2 + 0.11\,\kappa_t\,(\kappa_t - 1)$$



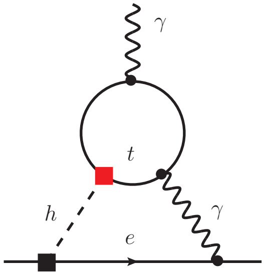


$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\mathrm{SM}}} = (1.28 - 0.28\,\kappa_t)^2 + (0.43\,\tilde{\kappa}_t)^2$$

- Naive weighted average of ATLAS, CMS

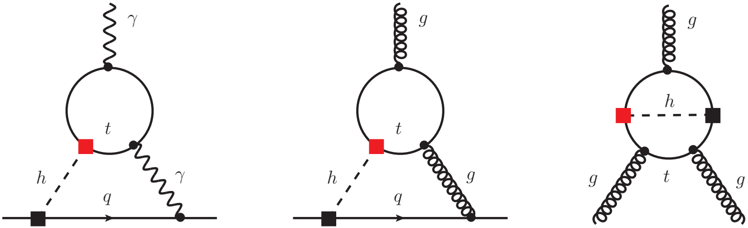
$$\kappa_{g,\mathrm{WA}} = 0.91 \pm 0.08\,, \quad \kappa_{\gamma,\mathrm{WA}} = 1.10 \pm 0.11$$

Electron EDM



- EDM induced via “Barr-Zee” diagrams [Weinberg 1989, Barr & Zee 1990]
- $|d_e/e| < 8.7 \times 10^{-29}\,\mathrm{cm}$ (90% CL) [ACME 2013] with ThO molecules
- Constraint on $\tilde{\kappa}_t$ vanishes if Higgs does not couple to electron

Neutron EDM



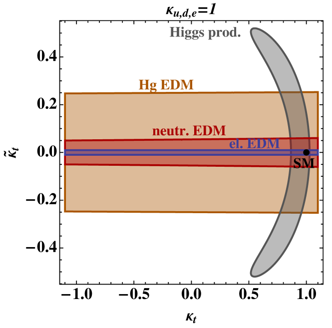
- Three operators; will mix, need to perform RGE analysis

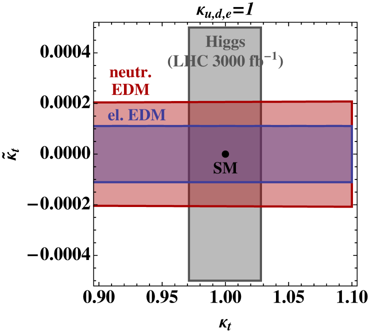
$$\frac{d_n}{e} = \Big\{(1.0 \pm 0.5)\left[-5.3\,\kappa_q\tilde{\kappa}_t + 5.1\cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\right]$$

$$+ (22 \pm 10)\,1.8\cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\Big\}\cdot 10^{-25}\,\mathrm{cm}\,.$$

- $w \propto \kappa_t\tilde{\kappa}_t$ subdominant
- $|d_n/e| < 2.9\times 10^{-26}\,\mathrm{cm}$ (90% CL) [Baker et al., 2006]

Combined constraints on top coupling

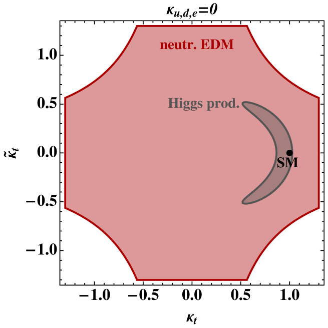


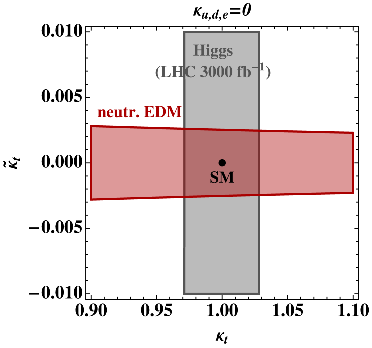


- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
  [J. Olsen, talk at Snowmass Energy Frontier workshop]
- Factor 90 (300) improvement on electron (neutron) EDM
  [Fundamental Physics at the Energy Frontier, arXiv:1205.2671]

Combined constraints on top couplings

- Set couplings to electron and light quarks to zero
- Contribution of Weinberg operator will lead to strong constraints in the future scenario





Anomalous bbH couplings

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 / total decay rate

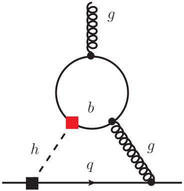
$$\mathrm{Br}(h \to b\bar{b}) = \frac{\left(\kappa_b^2 + \tilde{\kappa}_b^2\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

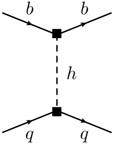
$$\mathrm{Br}(h \to X) = \frac{\mathrm{Br}(h \to X)_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

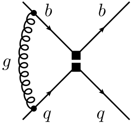
- Use naive averages of ATLAS / CMS signal strengths $\hat{\mu}_X$ for $X = b\bar{b}, \tau^+\tau^-, \gamma\gamma, WW, ZZ$
- $\hat{\mu}_X = \mathrm{Br}(h \to X)/\mathrm{Br}(h \to X)_{\mathrm{SM}}$ up to subleading corrections of production cross section

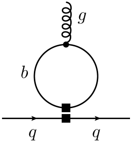
RGE analysis of the *b*-quark contribution to EDMs

- EDMs suppressed by small bottom Yukawa
- ≈ 3 scale uncertainty in CEDM Wilson coefficient
- Two-step matching at M_h and m_b:







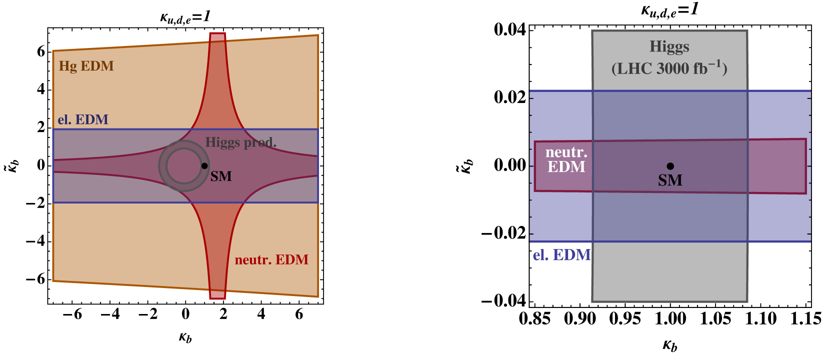


- Integrate out Higgs
- $\mathcal{O}_1^q = \bar{q}q\,\bar{b}i\gamma_5 b$

- Mixing into
- $\mathcal{O}_4^q = \bar{q}\sigma_{\mu\nu}T^a q\,\bar{b}i\sigma^{\mu\nu}\gamma_5 T^a b$

- Matching onto
- $\mathcal{O}_6^q = -\frac{i}{2}\frac{m_b}{g_s}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu}$

Combined constraints on bottom couplings



- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
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Combined constraints on bottom couplings

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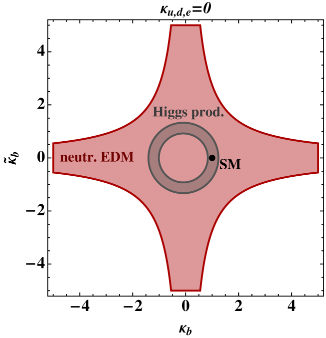
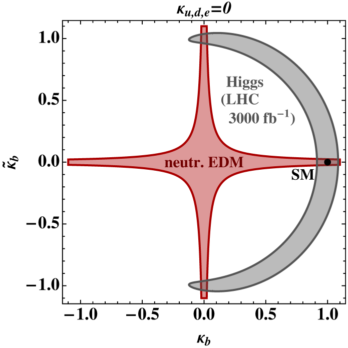
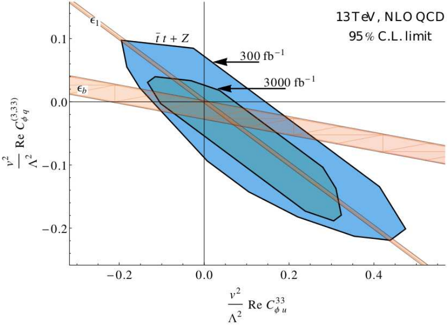
- Contribution of Weinberg operator will lead to competitive constraints in the future scenario

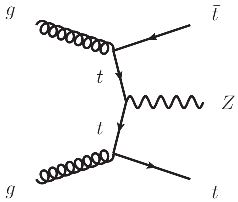




Anomalous ttZ couplings

Constraints from colliders





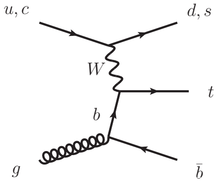
- ttZ production at NLO
  [Röntsch, Schulze, arXiv:1404.1005]
- $\approx 20\% - 30\%$ deviation from SM still allowed even with 3000 fb^{-1}
- Other constraints?

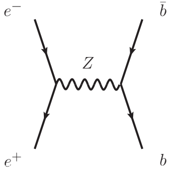
Further constraints from colliders

$$\mathcal{L}' = g'_R\, \bar{t}_R \not{Z}\, t_R + g'_L\, \bar{t}_L \not{Z}\, t_L + g''_L\, V^*_{3i} V_{3j} \bar{d}_{L,i} \not{Z}\, d_{L,j} + (k_L\, \bar{t}_L \not{W}^+ b_L + \text{h.c.})$$

$$g'_R \propto C_{Hu}, \qquad g'_L \propto C^{(3)}_{Hq} - C^{(1)}_{Hq}, \qquad g''_L \propto C^{(3)}_{Hq} + C^{(1)}_{Hq}, \qquad k_L \propto C^{(3)}_{Hq}$$

- t-channel single top production constrains $C^{(3)}_{Hq}$

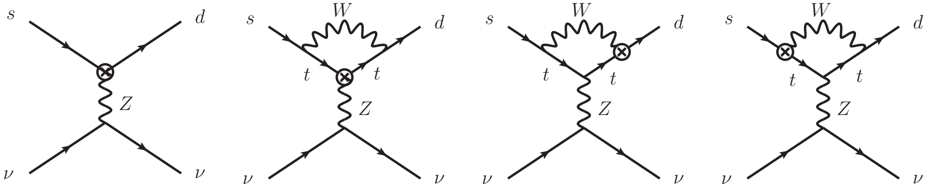




- Bottom pair production (LEP) constrains $C^{(3)}_{Hq} \approx -C^{(1)}_{Hq}$ at permil level
- This relation forbids also tree-level FCNCs

Indirect contraints

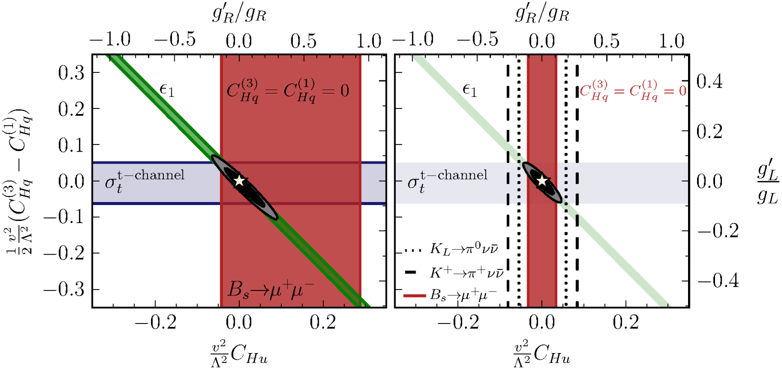
- Complementary constraints from rare decays $K \to \pi\nu\bar{\nu}$, $B_s \to \mu^+\mu^-$



$\propto C_{Hq}^{(3)} + C_{Hq}^{(1)} \approx 0$ $\quad \propto C_{Hu}\,,\ C_{Hq}^{(3)} - C_{Hq}^{(1)}$ $\quad \propto C_{Hq}^{(3)}$ $\quad \propto C_{Hq}^{(3)}$

- Strong constraints from T parameter

Preliminary results



$\Lambda = 1$ TeV

$\mathrm{Br}(B_s \to \mu^+\mu^-) = 2.9(7) \times 10^{-9}$ [LHCb, CMS naive avg.]
$\epsilon_1 = 5.6(1.0) \times 10^{-3}$ [Ciuchini et al., 2013]
$f_{V_L} V_{tb} = 0.99(4)$ [ATLAS, CMS naive avg.]

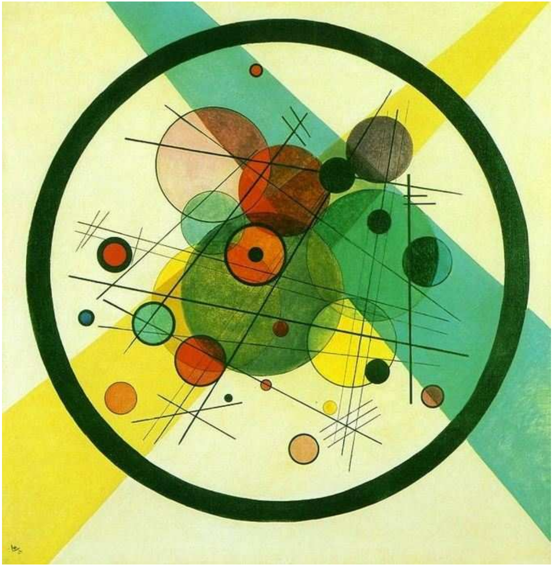
Future projection:
$\mathrm{Br}(B_s \to \mu^+\mu^-) =$
$2.9(15) \times 10^{-9}$

PRELIMINARY – Note that rare decay constraints include only $C_{Hu} \neq 0$

Summary

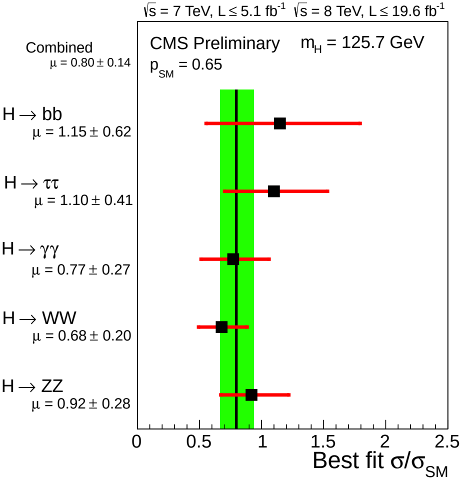
- LHC experiments and precision observables put complementary constraints on anomalous Higgs and Z couplings to the third generation
- Most bounds will improve in the future

Outlook



Appendix

Is it the SM Higgs?



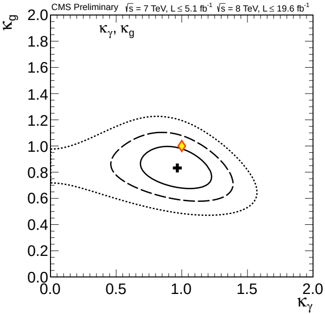
[CMS-PAS-HIG-13-005]

LHC input

- Naive weighted average of ATLAS, CMS

$$\kappa_{g,\mathrm{WA}} = 0.91 \pm 0.08\,, \quad \kappa_{\gamma,\mathrm{WA}} = 1.10 \pm 0.11$$

- We set $\kappa^2_{g/\gamma,\mathrm{WA}} = |\kappa_{g/\gamma}|^2 + |\tilde{\kappa}_{g/\gamma}|^2$



[CMS-PAS-HIG-13-005]

ACME result on electron EDM

Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron

The ACME Collaboration*: J. Baron[1], W. C. Campbell[2], D. DeMille[3], J. M. Doyle[1], G. Gabrielse[1], Y. V. Gurevich[1,**], P. W. Hess[1], N. R. Hutzler[1], E. Kirilov[3,#], I. Kozyryev[3,†], B. R. O'Leary[3], C. D. Panda[1], M. F. Parsons[1], E. S. Petrik[1], B. Spaun[1], A. C. Vutha[4], and A. D. West[3]

The Standard Model (SM) of particle physics fails to explain dark matter and why matter survived annihilation with antimatter following the Big Bang. Extensions to the SM, such as weak-scale Supersymmetry, may explain one or both of these phenomena by positing the existence of new particles and interactions that are asymmetric under time-reversal (T). These theories nearly always predict a small, yet potentially measurable (10^{-27}-10^{-30} e cm) electron electric dipole moment (EDM, d_e), which is an asymmetric charge distribution along the spin ($\vec{S}$). The EDM is also asymmetric under T. Using the polar molecule thorium monoxide (ThO), we measure $d_e = (-2.1 \pm 3.7_{\rm stat} \pm 2.5_{\rm syst}) \times 10^{-29}$ e cm. This corresponds to an upper limit of $|d_e| < 8.7 \times 10^{-29}$ e cm with 90 percent confidence, an order of magnitude improvement in sensitivity compared to the previous best limits. Our result constrains T-violating physics at the TeV energy scale.

The exceptionally high internal effective electric field ($\mathcal{E}_{\rm eff}$) of heavy neutral atoms and molecules can be used to precisely probe for d_e via the energy shift $U = -\vec{d}_e \cdot \vec{\mathcal{E}}_{\rm eff}$, where $\vec{d}_e = d_e\vec{S}/(\hbar/2)$. Valence electrons travel relativistically near the heavy nucleus,

is prepared using optical pumping and state preparation lasers. Parallel electric ($\vec{\mathcal{E}}$) and magnetic ($\vec{\mathcal{B}}$) fields exert torques on the electric and magnetic dipole moments, causing the spin vector to precess in the xy plane. The precession angle is measured with a readout laser and fluorescence detection. A change in this angle as $\vec{\mathcal{E}}_{\rm eff}$ is reversed is proportional to d_e.

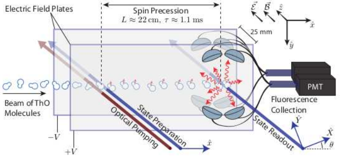
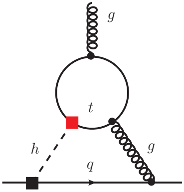


FIG. 1. Schematic of the apparatus (not to scale). A collimated pulse of ThO molecules enters a magnetically shielded region. An aligned spin

- Expect order-of-magnitude improvements!

Mercury EDM



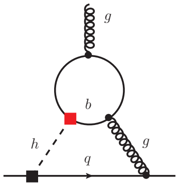
- Diamagnetic atoms also provide constraints
- $|d_{\rm Hg}/e| < 3.1 \times 10^{-29}\,$cm (95% CL) [Griffith et al., 2009]
- Dominant contribution from CP-odd isovector pion-nucleon interaction

$$\frac{d_{\rm Hg}}{e} = -\left(4^{+8}_{-2}\right)\,\left[3.1\,\tilde\kappa_t - 3.2\cdot 10^{-2}\,\kappa_t\tilde\kappa_t\right]\cdot 10^{-29}\,\mathrm{cm}$$

- Again, $w \propto \kappa_t\tilde\kappa_t$ subdominant, but does not vanish if Higgs does not couple to light quarks

Constraints from EDMs

- Contributions to EDMs suppressed by small Yukawas; still get meaningful constraints in future scenario
- For electron EDM, simply replace charges and couplings
- Have extra scale $m_b \ll M_h \Rightarrow \log m_b^2/M_h^2$

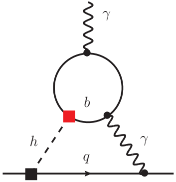


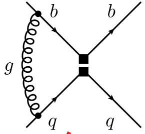
$$d_q(\mu_W) \simeq -4\,e\,Q_q\,N_c\,Q_b^2\,\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

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

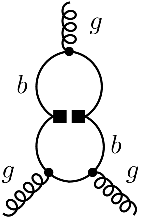
$$w(\mu_W) \simeq -g_s\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,\kappa_b\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log\frac{m_b^2}{M_h^2}+\frac{3}{2}\right).$$

RGE analysis of the b-quark contribution to EDMs





- $\mathcal{C}_5^q(\mu_b) = -4\,\frac{\alpha\,\alpha_s}{(4\pi)^2}\,Q_q \log^2 \frac{m_b^2}{M_h^2} + \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}\gamma_{87}^{(0)}}{48} \log^3 \frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^4)\,,$
- $\mathcal{C}_6^q(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}}{8} \log^2 \frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)\,,$
- $\mathcal{C}_7(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{5,11}^{(1)}}{2} \log \frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)\,.$



Combined constraints on τ couplings

- Effect on κ_γ, $\tilde{\kappa}_\gamma$ again subleading
- Modification of branching ratios