Constraints on CP-violating Higgs couplings

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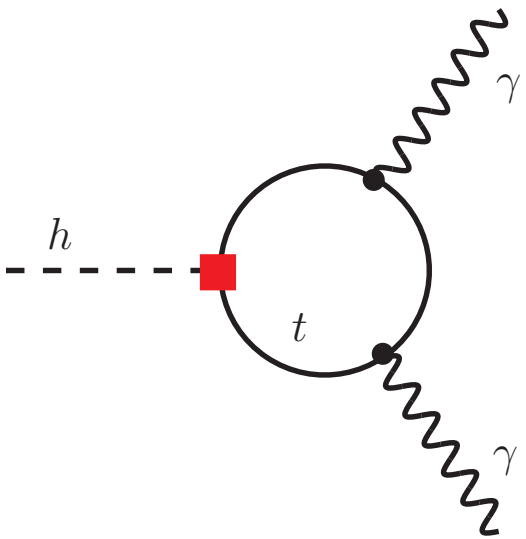
JHEP 1311 (2013) 180 [arXiv:1310.1385[hep-ph]]

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



- In the SM, Yukawa coupling to fermion f is

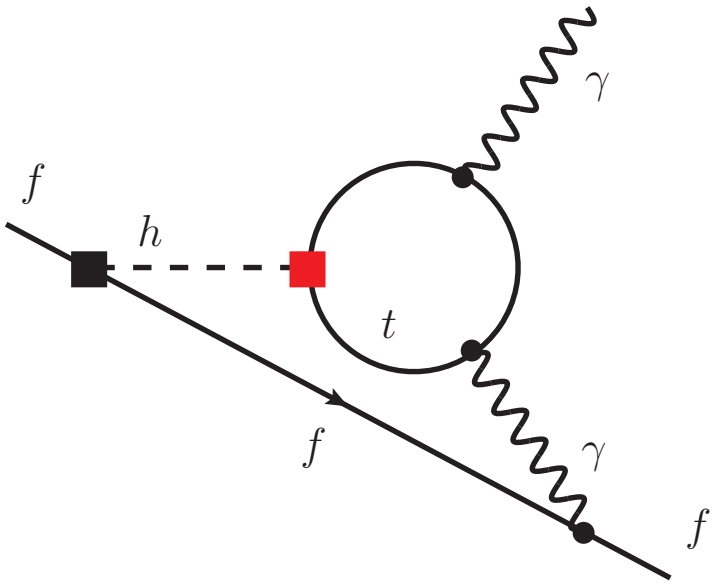
$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \bar{f} f \, h$$

- We will look at modification

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

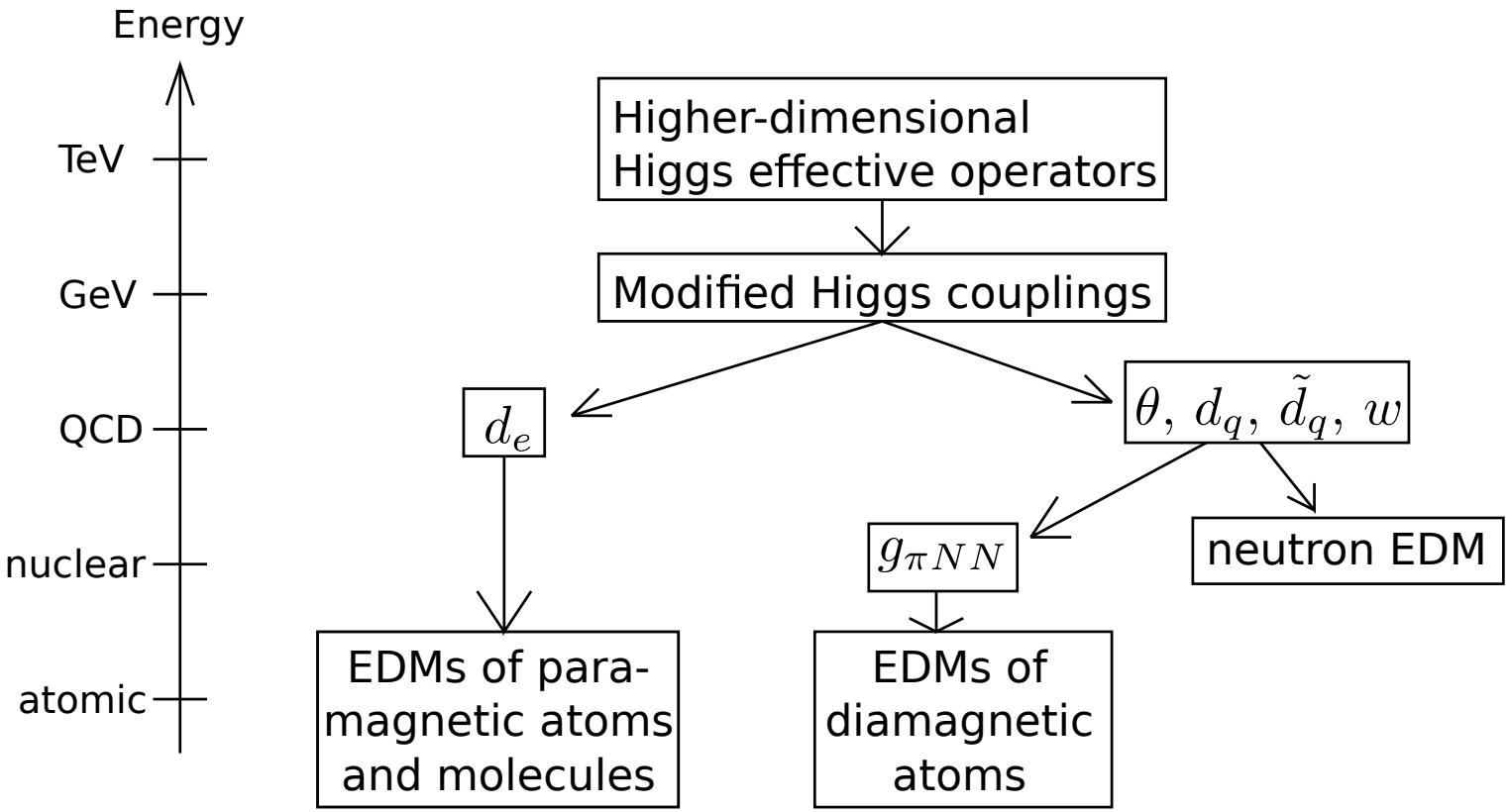
- New contributions will modify Higgs production cross section and decay rates

. . . 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
- Need to make assumptions

Electric Dipole Moments (EDMs) – Generalities



[Adapted from Pospelov et al., 2005]

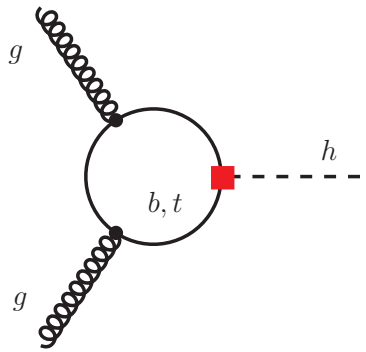
Outline

- Constraints on the top coupling
- Constraints on the bottom coupling
- Constraints on the τ coupling

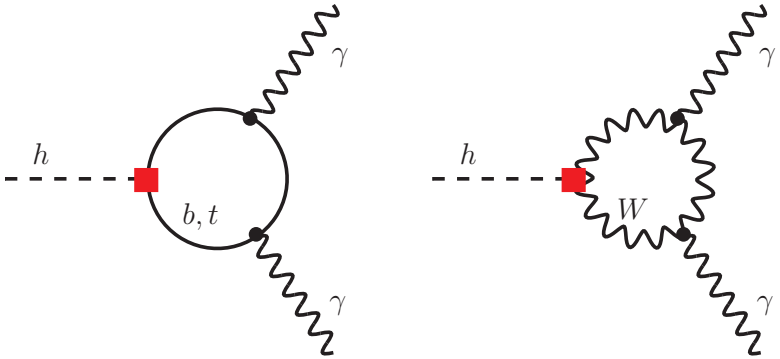
Constraints on the top coupling

Constraints from Higgs production and decay

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



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

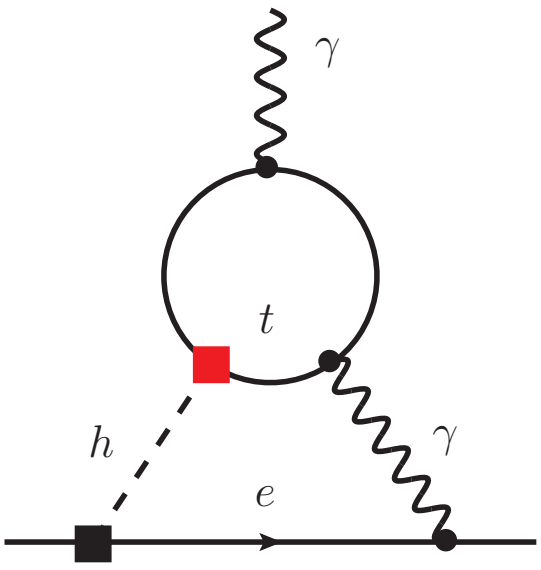


$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\text{SM}}} = (1.28 - 0.28\,\kappa_t)^2 + (0.43\,\tilde{\kappa}_t)^2$$

- Naive weighted average of ATLAS, CMS

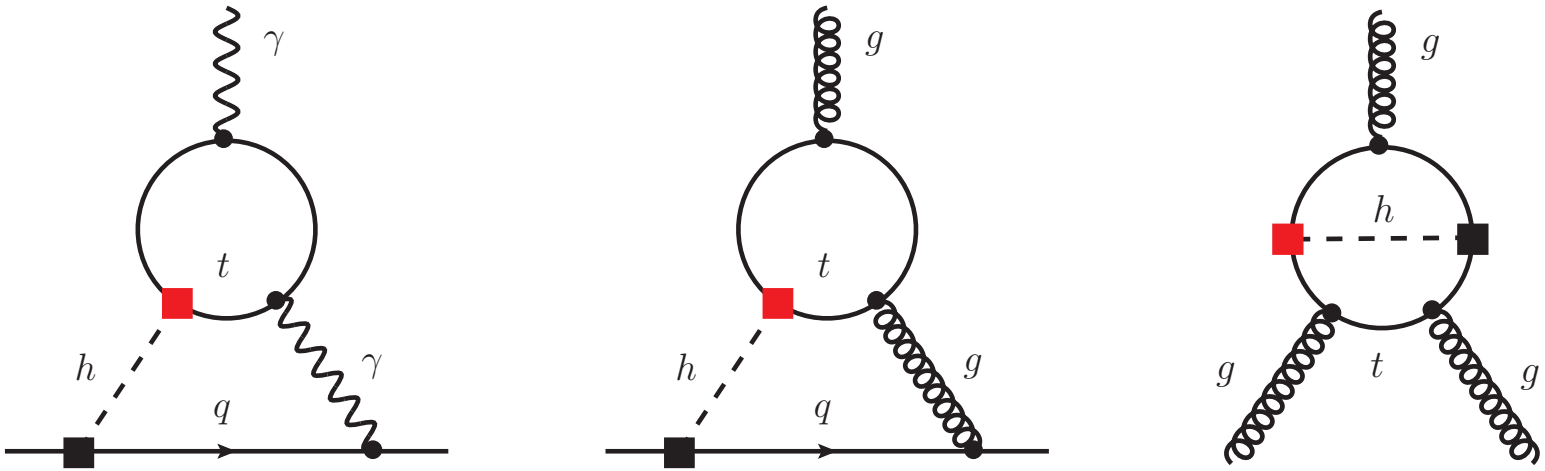
$$\kappa_{g,\text{WA}} = 0.91 \pm 0.08\,, \quad \kappa_{\gamma,\text{WA}} = 1.10 \pm 0.11$$

Electron EDM



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

Neutron EDM



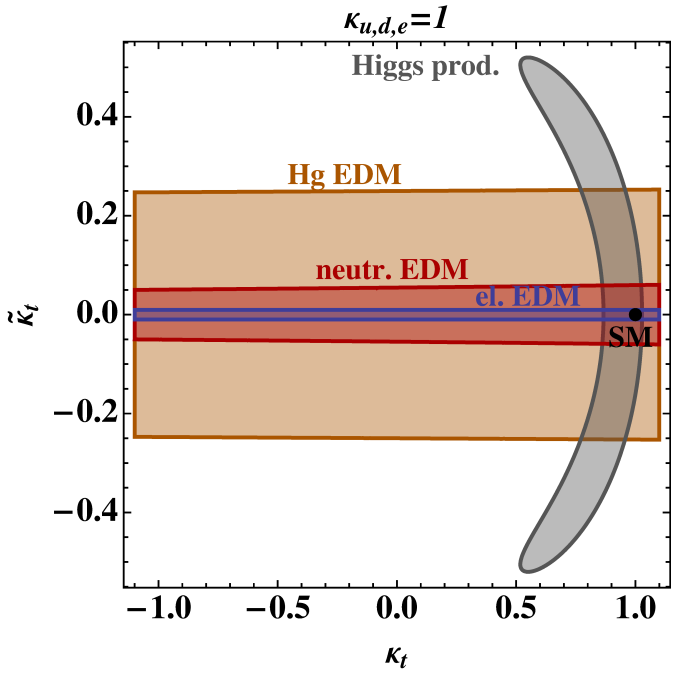
- Three operators; will mix, need to perform RGE analysis

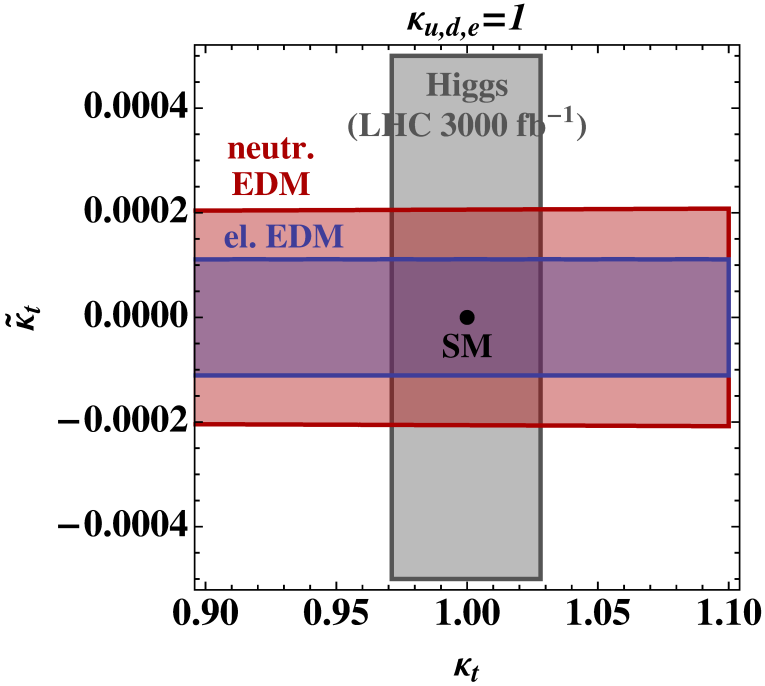
$$\frac{d_n}{e} = \Big\{(1.0 \pm 0.5)\left[-5.3\,\kappa_q\tilde{\kappa}_t + 5.1\cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\right]$$

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

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

Combined constraints on top coupling

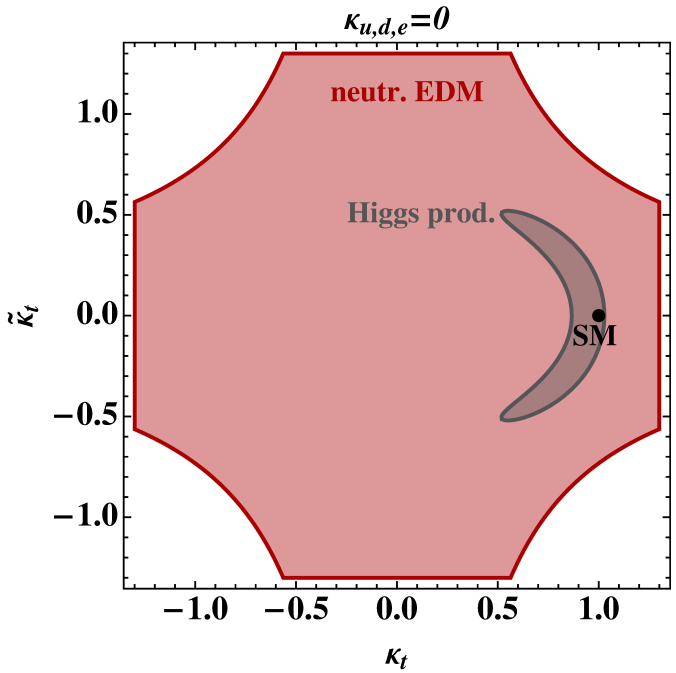


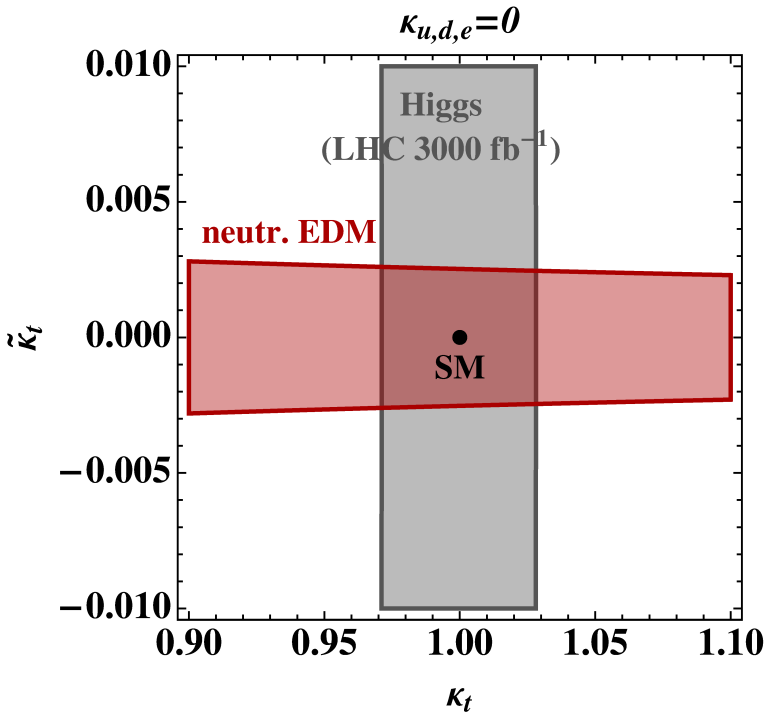


- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
  [J. Olsen, talk at Snowmass Energy Frontier workshop]
- Factor 90 (300) improvement on electron (neutron) EDM
  [Fundamental Physics at the Energy Frontier, arXiv:1205.2671]

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





Constraints on the bottom coupling

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

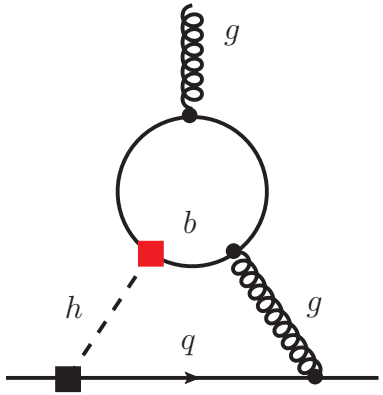
$$\mathrm{Br}(h \to b\bar{b}) = \frac{\left(\kappa_b^2 + \tilde{\kappa}_b^2\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

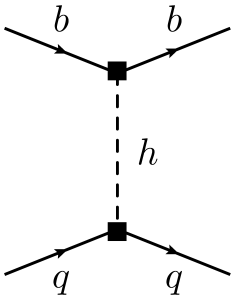
$$\mathrm{Br}(h \to X) = \frac{\mathrm{Br}(h \to X)_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

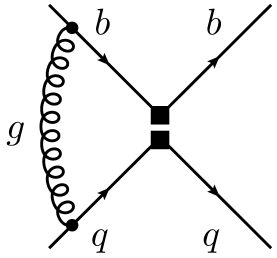
- Use naive averages of ATLAS / CMS signal strengths $\hat{\mu}_X$ for $X = b\bar{b}$, $\tau^+\tau^-$, $\gamma\gamma$, WW, ZZ
- $\hat{\mu}_X = \mathrm{Br}(h \to X)/\mathrm{Br}(h \to X)_{\mathrm{SM}}$ up to subleading corrections of production cross section

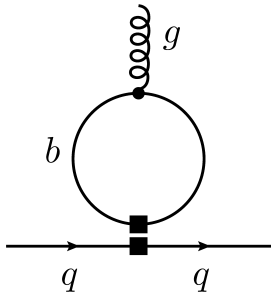
RGE analysis of the b-quark contribution to EDMs

- EDMs suppressed by small bottom Yukawa
- $\mathcal{O}(3)$ scale uncertainty in CEDM Wilson coefficient
- Two-step matching at M_h and m_b:







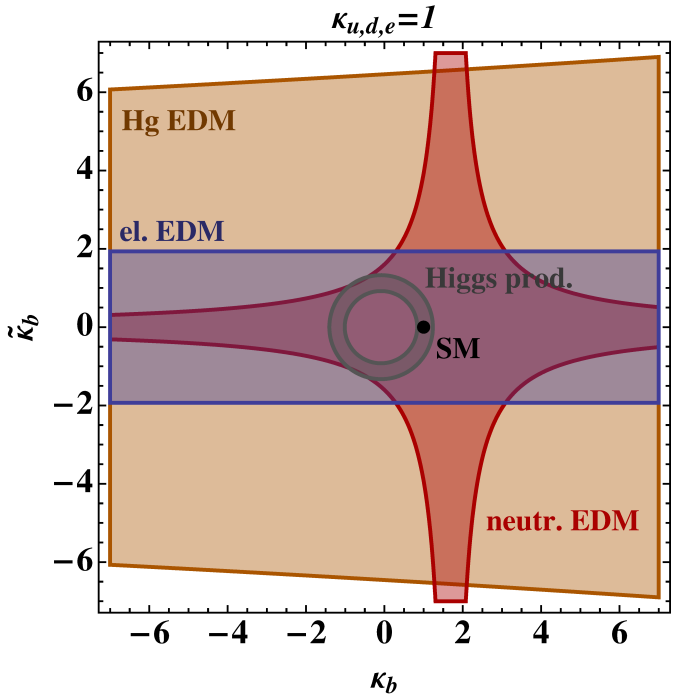


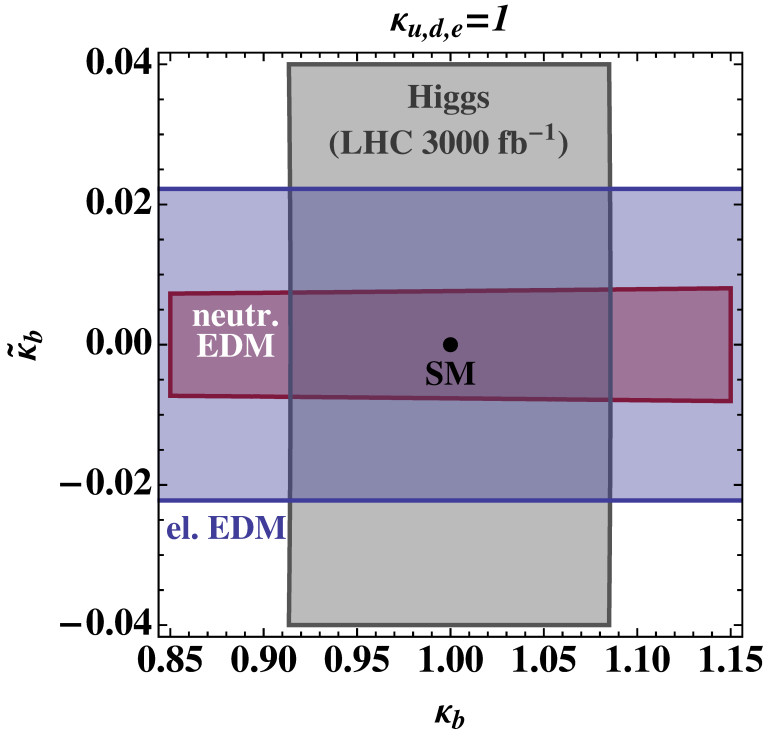
- Integrate out Higgs
- $\mathcal{O}_1^q = \bar{q}q\,\bar{b}i\gamma_5 b$

- 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 bottoms couplings





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Combined constraints on bottom couplings

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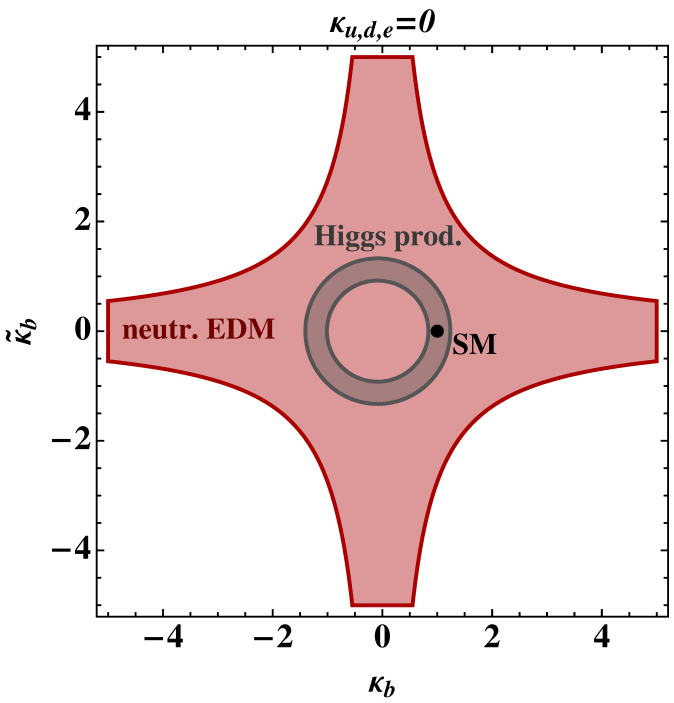
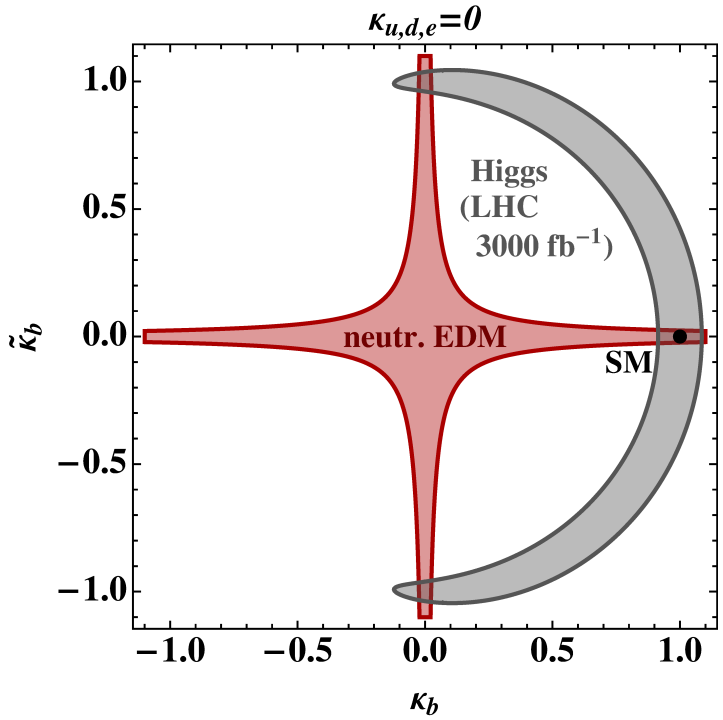
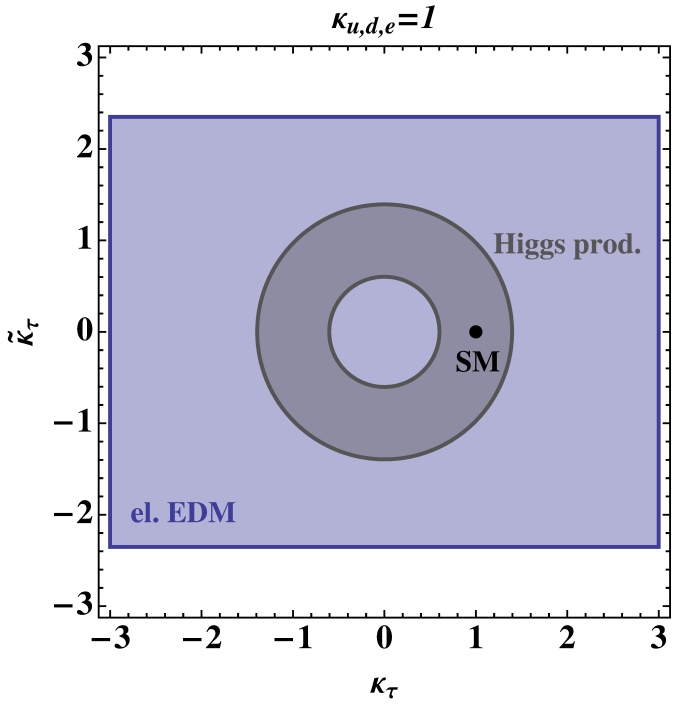
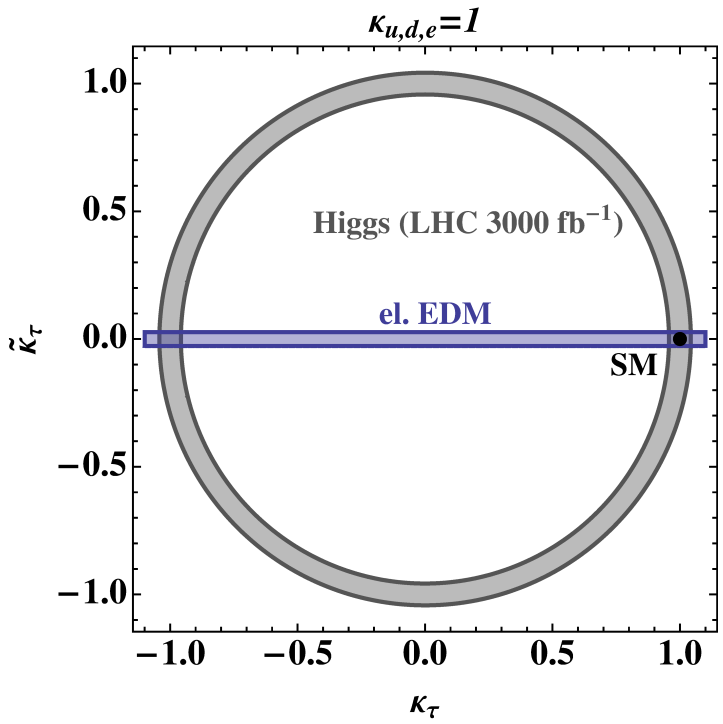




Combined constraints on τ couplings

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

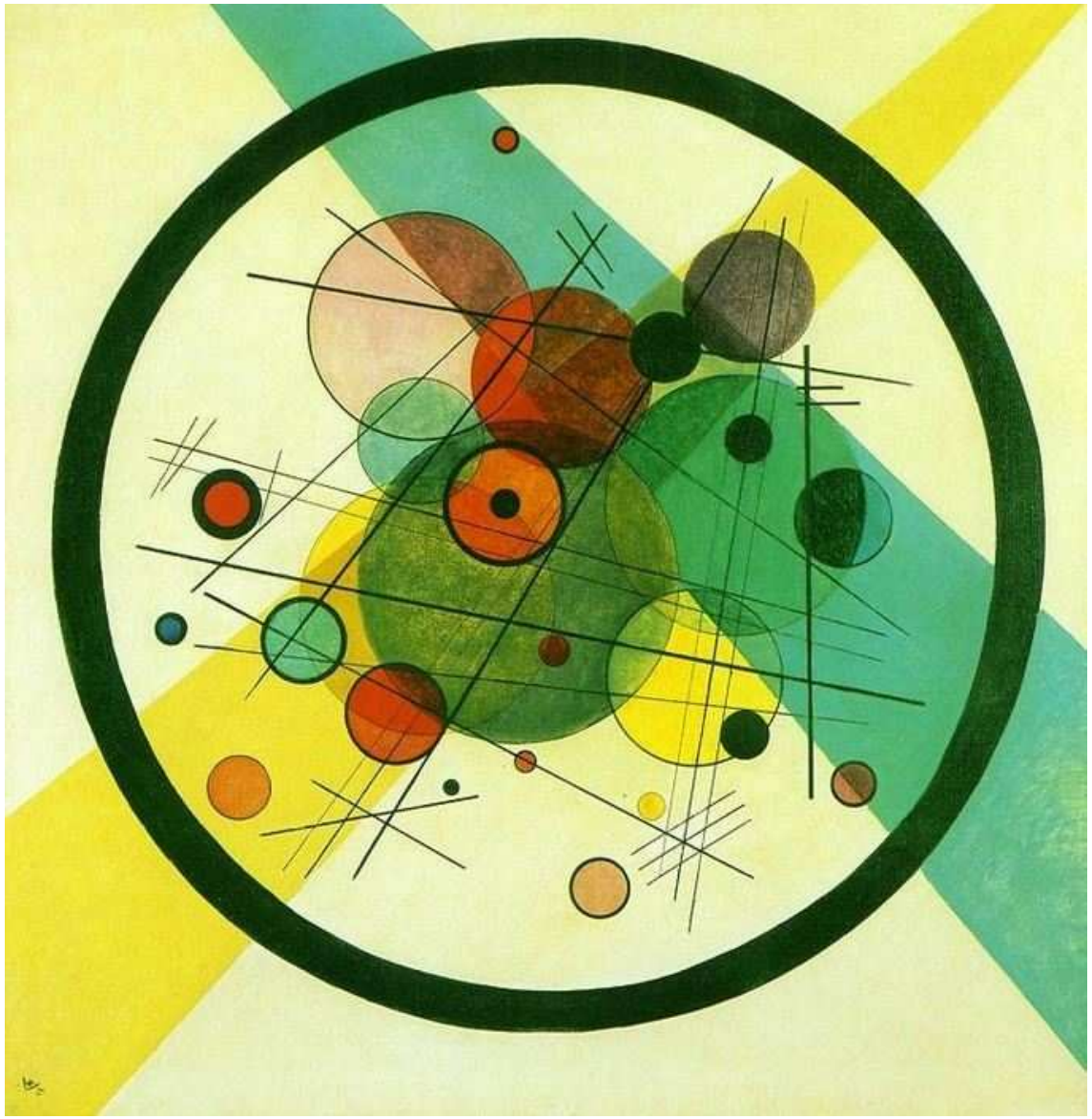




Summary

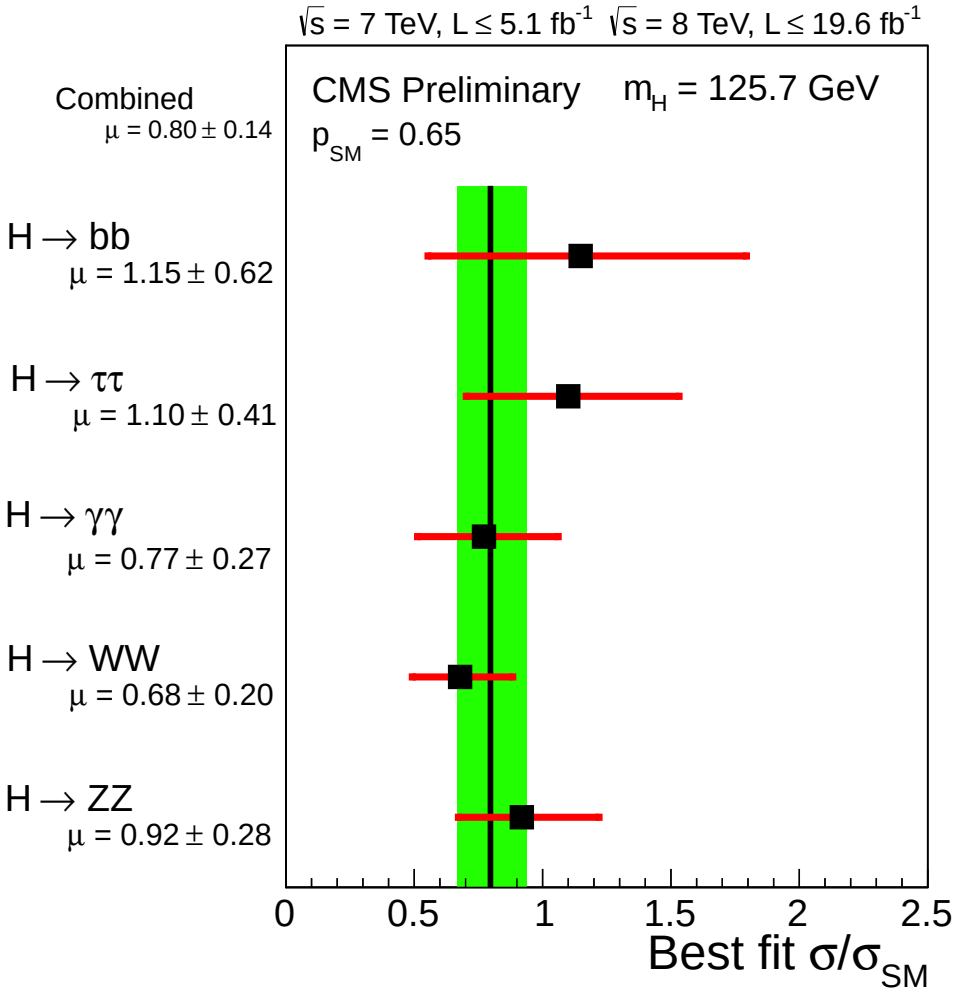
- Need to understand the properties of the newly discovered Higgs boson
- LHC experiments and EDMs put complementary constraints on CP-violating Higgs couplings to the third generation
- Get meaningful constraints even if couplings to light fermions are absent
- EDM constraints will become strong in particular in the future

Outlook



Appendix

Is it the SM Higgs?



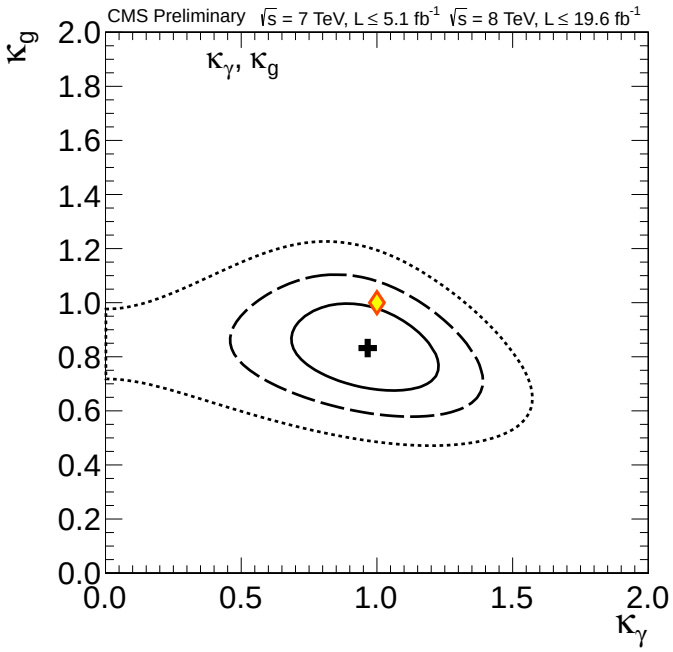
[CMS-PAS-HIG-13-005]

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.

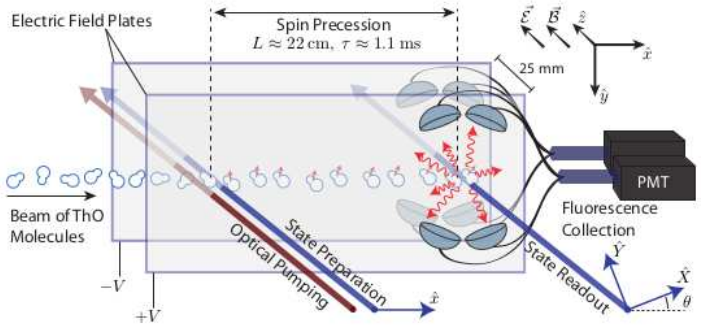
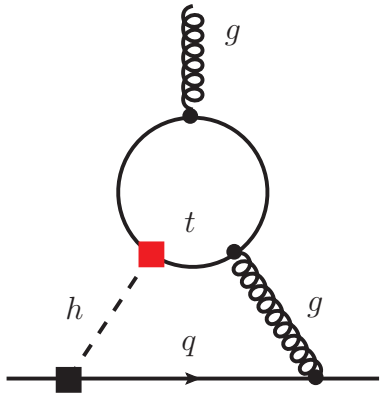


FIG. 1. Schematic of the apparatus (not to scale). A collimated pulse of ThO molecules enters a magnetically shielded region. An aligned spin

- Expect order-of-magnitude improvements!

Mercury EDM



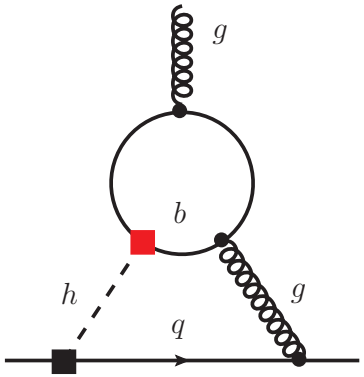
- Diamagnetic atoms also provide constraints
- $|d_{\mathrm{Hg}}/e| < 3.1 \times 10^{-29}$ cm (95% CL) [Griffith et al., 2009]
- Dominant contribution from CP-odd isovector pion-nucleon interaction

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

- 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 $m_b \ll M_h \Rightarrow \log m_b^2/M_h^2$



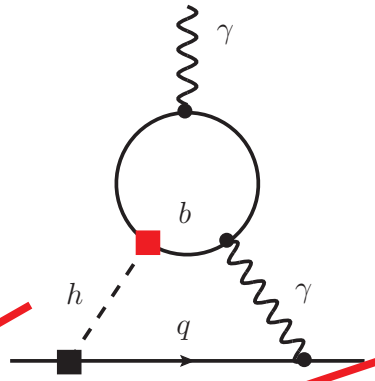
$$d_q(\mu_W) \simeq -4\, e\, Q_q\, N_c\, Q_b^2\, \frac{\alpha}{(4\pi)^3} \sqrt{2} G_F\, m_q\, \kappa_q \tilde{\kappa}_b\, \frac{m_b^2}{M_h^2} \left(\log^2 \frac{m_b^2}{M_h^2} + \frac{\pi^2}{3} \right) ,$$

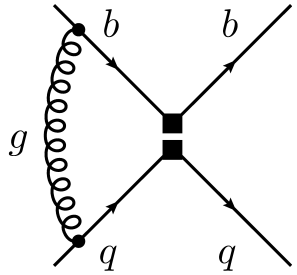
$$\tilde{d}_q(\mu_W) \simeq -2\, \frac{\alpha_s}{(4\pi)^3} \sqrt{2} G_F\, m_q\, \kappa_q \tilde{\kappa}_b\, \frac{m_b^2}{M_h^2} \left(\log^2 \frac{m_b^2}{M_h^2} + \frac{\pi^2}{3} \right) ,$$

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

RGE analysis of the b-quark contribution to EDMs

- $\mathcal{O}_5^q = -\frac{i}{2} e Q_b \frac{m_b}{g_s^2} \bar{q} \sigma^{\mu\nu} \gamma_5 q F_{\mu\nu}$
- $\mathcal{O}_6^q = -\frac{i}{2} \frac{m_b}{g_s} \bar{q} \sigma^{\mu\nu} T^a \gamma_5 q G^a_{\mu\nu}$
- $\mathcal{O}_7 = -\frac{1}{3 g_s} f^{abc} G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}$





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