Constraints on CP-violating Higgs couplings

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From Dark Matter to the LHC and Beyond
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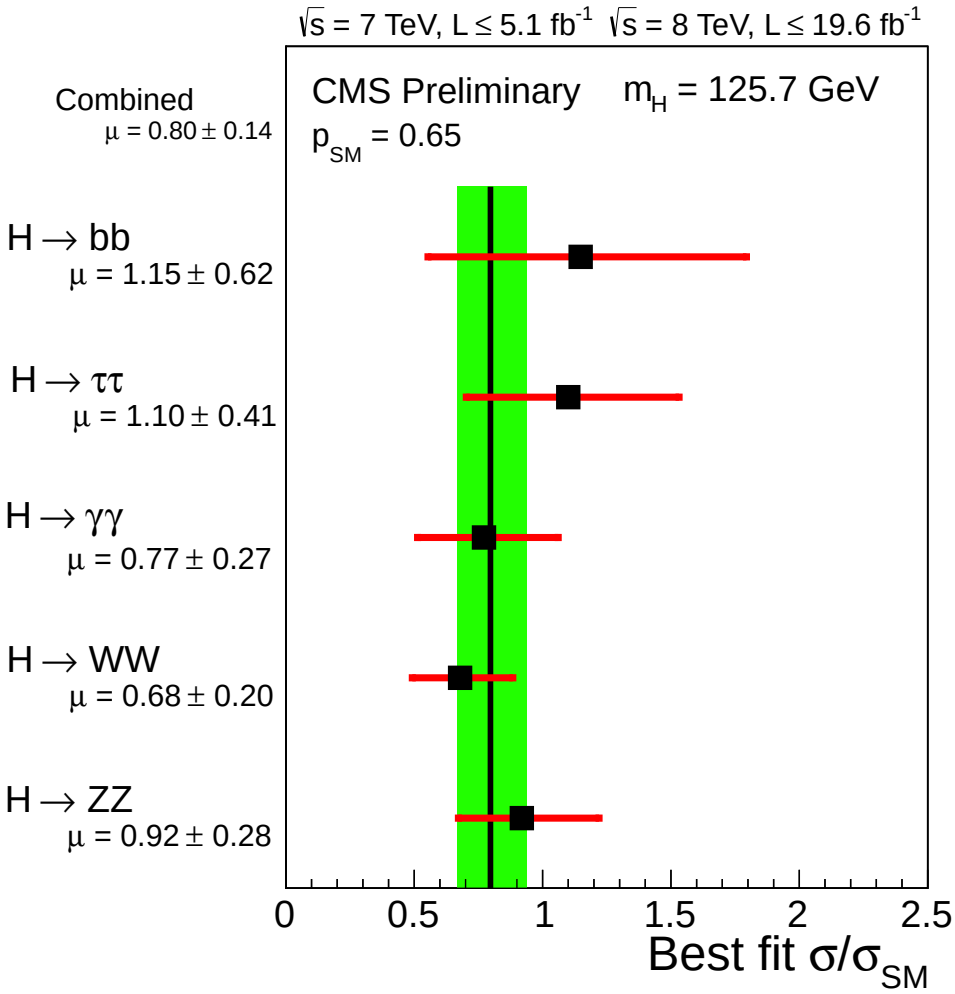
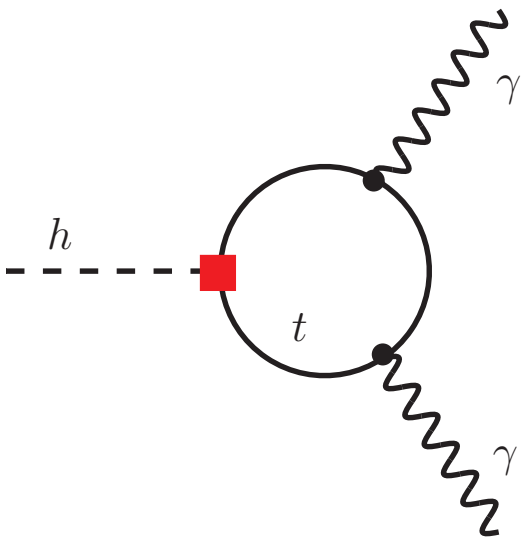
JHEP 1311 (2013) 180 [arXiv:1310.1385[hep-ph]]

Status of SM Higgs couplings



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



- In the SM, Yukawa coupling is

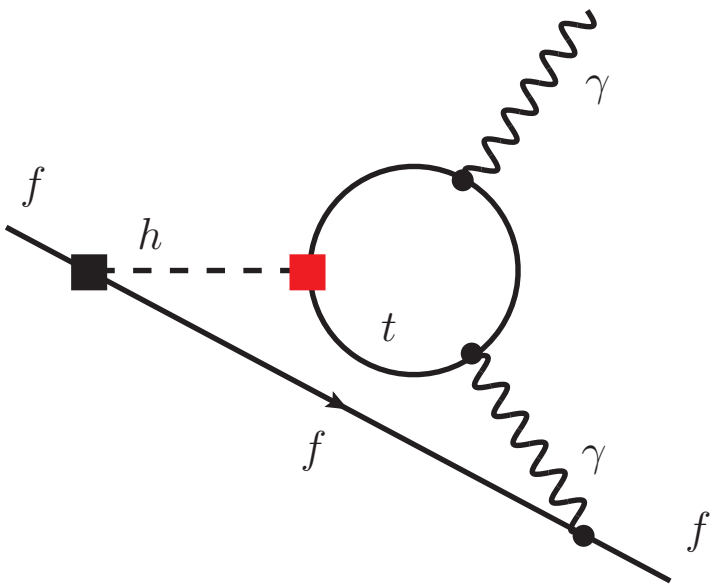
$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \bar{f} f \, h$$

- We will look at modification

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

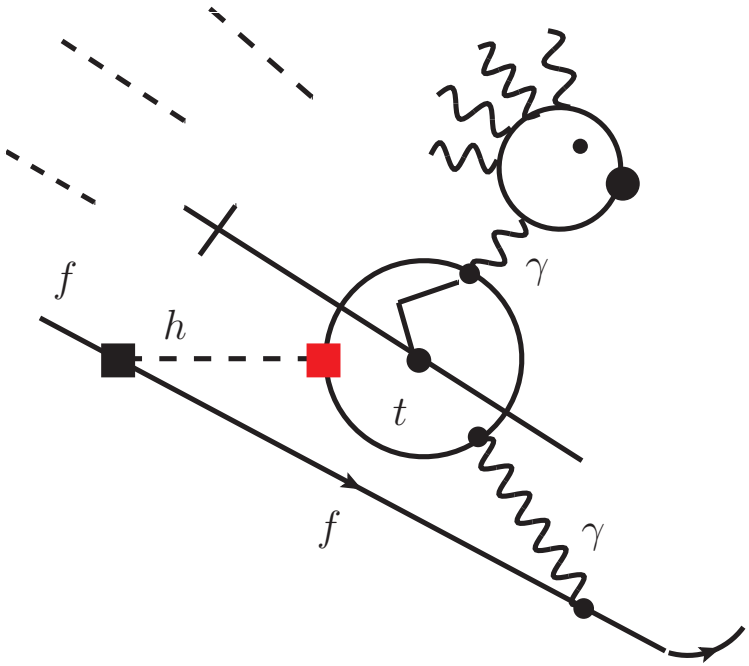
- New contributions can lead to CP-violating Higgs decays, will modify Higgs production cross section and decay rates

. . . to electric dipole moments



- Dipole moments of elementary spin-1/2 particles violate T
- SM "background" enters at three- and four-loop level
- Complementary to collider measurements
- Need to make assumptions

Rumor has it . . .



- . . . that certain higher-order contributions are considered at the 2014 Aspen winter conference

Outline

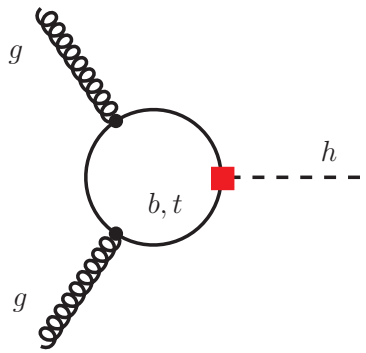
- Constraints on the top coupling
  - LHC
  - EDMs
- Constraints on the bottom and τ couplings
  - LHC
  - EDMs

Constraints on the top coupling

Constraints from $gg \to h$

- $gg \to h$ generated at one loop
- Have effective potential

$$V_{\rm eff} = -c_g \, \frac{\alpha_s}{12\pi} \, \frac{h}{v} \, G^a_{\mu\nu} \, G^{\mu\nu,a} - \tilde{c}_g \, \frac{\alpha_s}{8\pi} \, \frac{h}{v} \, G^a_{\mu\nu} \, \widetilde{G}^{\mu\nu,a}$$



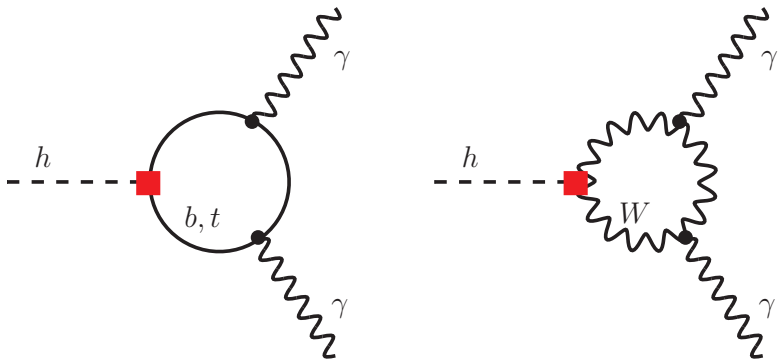
- c_g, $\tilde{c}_g$ given in terms of loop functions
- $\kappa_g \equiv c_g / c_{g,\rm SM}$, $\tilde{\kappa}_g \equiv 3\tilde{c}_g / 2 c_{g,\rm SM}$

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

Constraints from $h \to \gamma\gamma$

- $h \to \gamma\gamma$ generated at one loop
- Have effective potential

$$V_{\rm eff} = -c_\gamma \, \frac{\alpha}{\pi} \, \frac{h}{v} \, F_{\mu\nu} \, F^{\mu\nu} - \tilde{c}_\gamma \, \frac{3\alpha}{2\pi} \, \frac{h}{v} \, F_{\mu\nu} \, \widetilde{F}^{\mu\nu}$$



- c_γ, $\tilde{c}_\gamma$ given in terms of loop functions
- $\kappa_\gamma \equiv c_\gamma / c_{\gamma,\rm SM}$, $\tilde{\kappa}_\gamma \equiv 3\tilde{c}_\gamma / 2 c_{\gamma,\rm SM}$

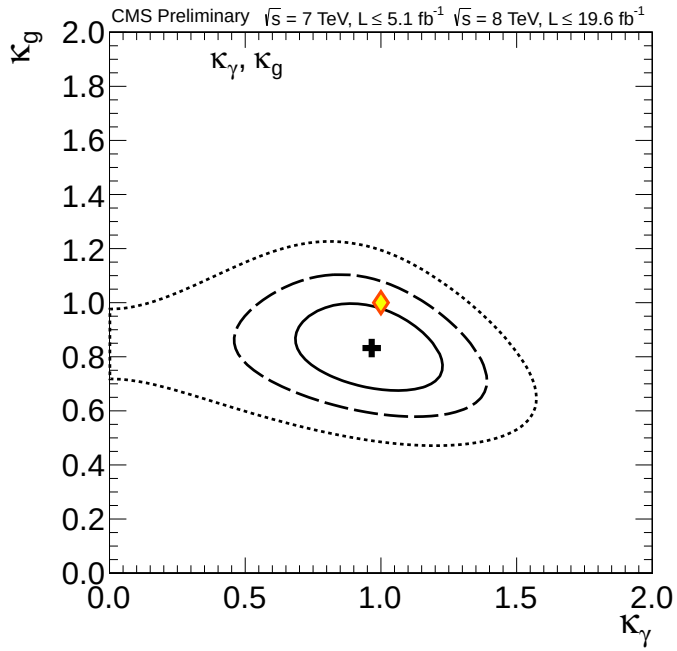
$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\rm SM}} = |\kappa_\gamma|^2 + |\tilde{\kappa}_\gamma|^2 = (1.28 - 0.28\,\kappa_t)^2 + (0.43\,\tilde{\kappa}_t)^2$$

LHC input

- Naive weighted average of ATLAS, CMS

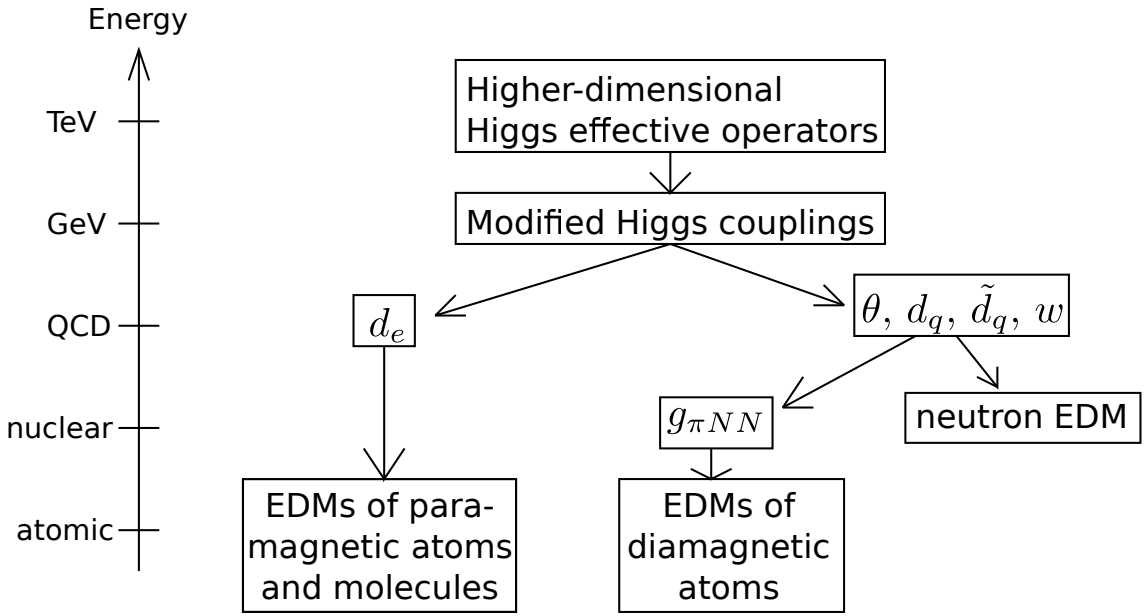
$$\kappa_{g,\mathrm{WA}} = 0.91 \pm 0.08\,, \quad \kappa_{\gamma,\mathrm{WA}} = 1.10 \pm 0.11$$

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



[CMS-PAS-HIG-13-005]

Electric Dipole Moments (EDMs) – Generalities

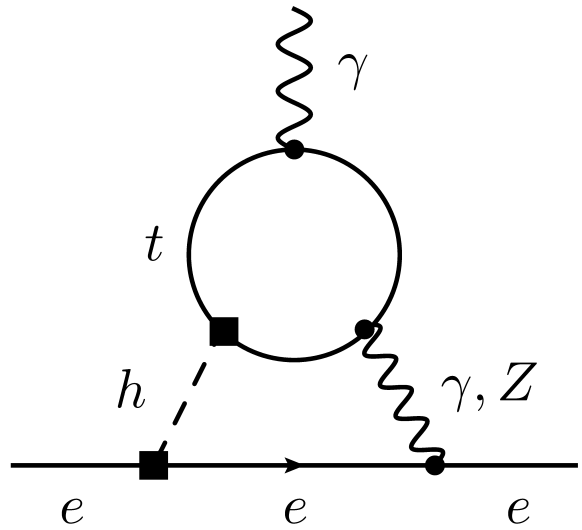


[Adapted from Pospelov et al., 2005]

- Three types of EDMs
- Neglect CP-odd electron-nucleon coupling
- Assume some solution of strong CP problem
- QCD uncertainties

Electron EDM

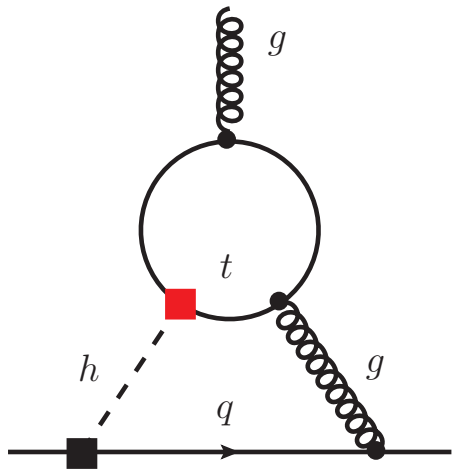
$$\mathcal{L}_{\text{eff}} = -d_e \frac{i}{2} \bar{e} \sigma^{\mu\nu} \gamma_5 e F_{\mu\nu}$$

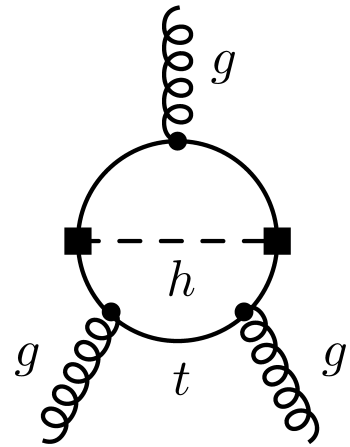


- EDM induced via "Barr-Zee" diagrams [Weinberg 1989, Barr & Zee 1990]
- $|d_e/e| < 8.7 \times 10^{-29}$ cm (90% CL) [ACME 2013] with ThO molecules
- Constraint on $\tilde{\kappa}_t$ vanishes if Higgs does not couple to electron

Neutron EDM

$$\mathcal{L}_{\text{eff}} = -d_q \frac{i}{2} \bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu}$$
$$- \tilde{d}_q \frac{ig_s}{2} \bar{q}\sigma^{\mu\nu} T^a \gamma_5 q\, G^a_{\mu\nu}$$
$$- w \frac{1}{3} f^{abc}\, G^a_{\mu\sigma} G^{b,\sigma}_{\nu} \widetilde{G}^{c,\mu\nu}$$



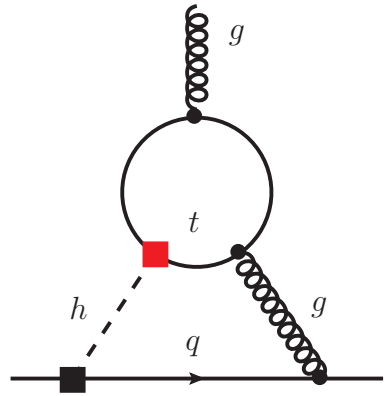


- Three operators; will mix, need to perform RGE analysis

$$\frac{d_n}{e} = \Big\{ (1.0 \pm 0.5) \left[-5.3\, \kappa_q \tilde{\kappa}_t + 5.1 \cdot 10^{-2}\, \kappa_t \tilde{\kappa}_t \right]$$
$$+ (22 \pm 10)\, 1.8 \cdot 10^{-2}\, \kappa_t \tilde{\kappa}_t \Big\} \cdot 10^{-25}\, \text{cm}\,.$$

- $w \propto \kappa_t \tilde{\kappa}_t$ subdominant, but does not vanish if Higgs does not couple to light quarks
- $|d_n/e| < 2.9 \times 10^{-26}\,\text{cm}$ (90% CL) [Baker et al., 2006]

Mercury EDM

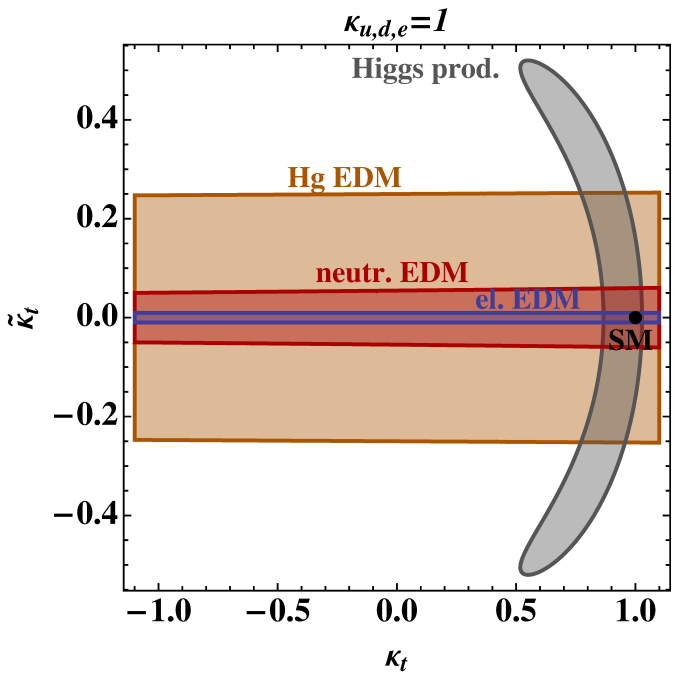


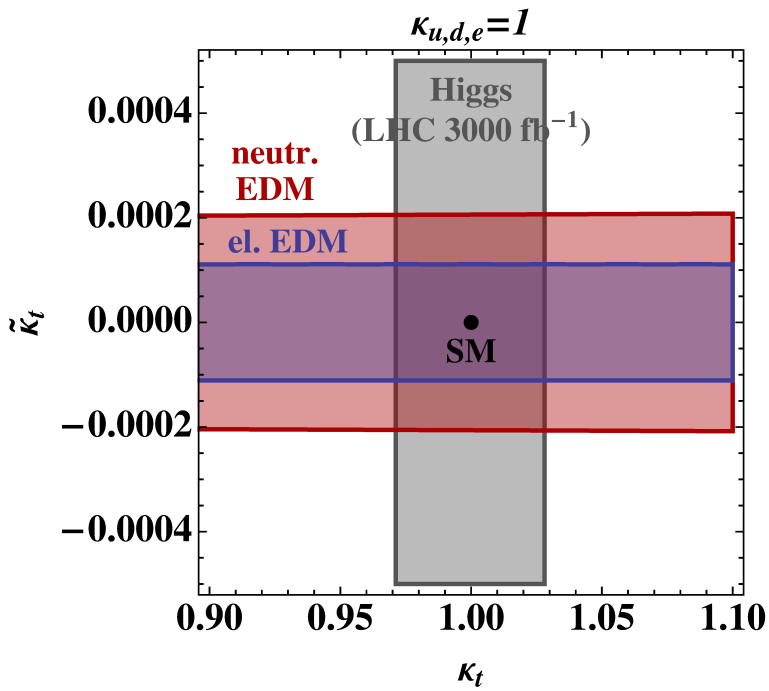
- Diamagnetic atoms also provide constraints
- $|d_{\mathrm{Hg}}/e| < 3.1 \times 10^{-29}\,\mathrm{cm}$ (95% CL) [Griffith et al., 2009]
- Dominant contribution from CP-odd isovector pion-nucleon interaction

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

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

Combined constraints on top coupling





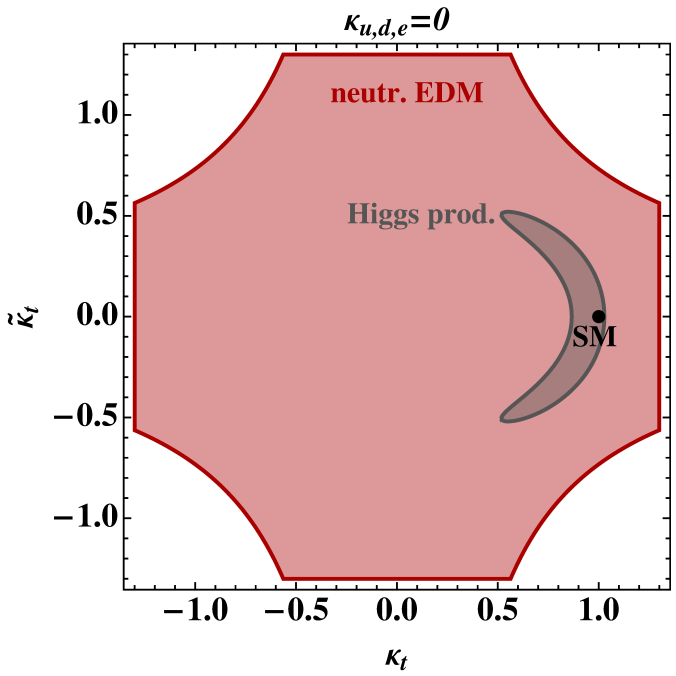
- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC

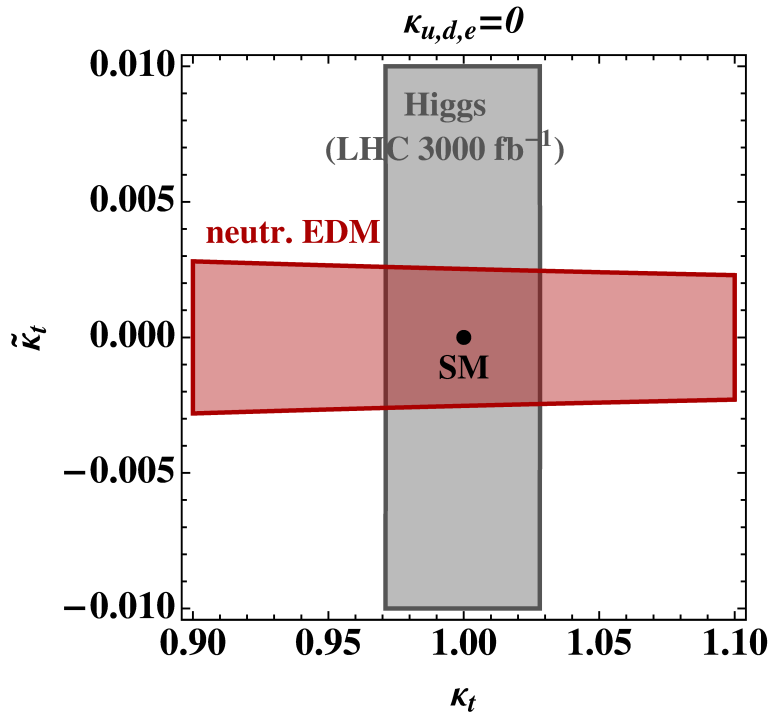
  [J. Olsen, talk at Snowmass Energy Frontier workshop]
- Factor 90 (300) improvement on electron (neutron) EDM

  [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 and τ 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

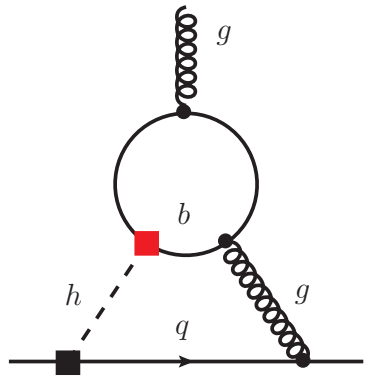
$$\mathrm{Br}(h \to b\bar{b}) = \frac{\left(\kappa_b^2 + \tilde{\kappa}_b^2\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

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

- 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

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



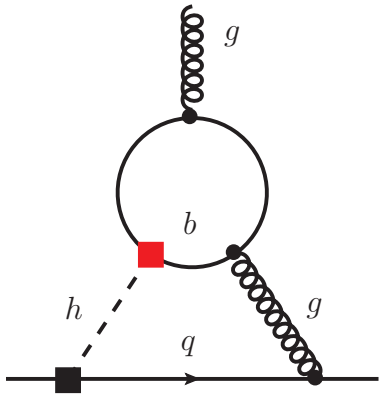
$$d_q(\mu_W) \simeq -4\,e\,Q_q\,N_c\,Q_b^2\,\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

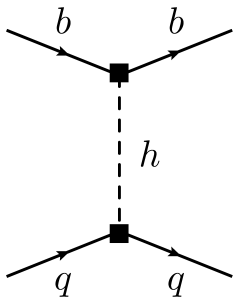
$$\tilde{d}_q(\mu_W) \simeq -2\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

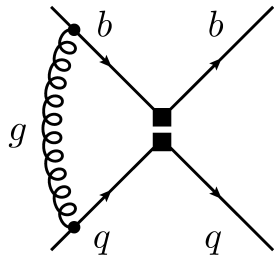
$$w(\mu_W) \simeq -g_s\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,\kappa_b\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log\frac{m_b^2}{M_h^2}+\frac{3}{2}\right).$$

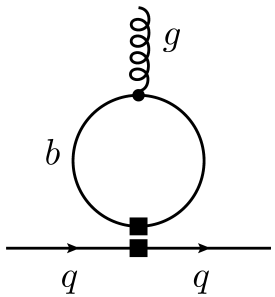
RGE analysis of the b-quark contribution to EDMs

- Integrating out the bottom together with the Higgs introduces $\mathcal{O}(3)$ uncertainty in CEDM Wilson coefficient
- Two-step matching at M_h and m_b:









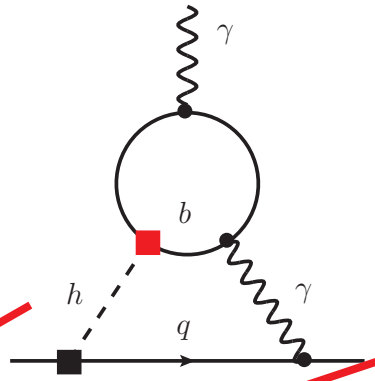
- Integrate out Higgs
- $\mathcal{O}_1^q = \bar{q}q\,\bar{b}i\gamma_5 b$

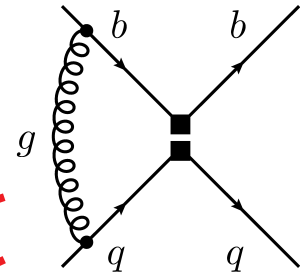
- Mixing into
- $\mathcal{O}_4^q = \bar{q}\sigma_{\mu\nu}T^a q\,\bar{b}i\sigma^{\mu\nu}\gamma_5 T^a b$

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

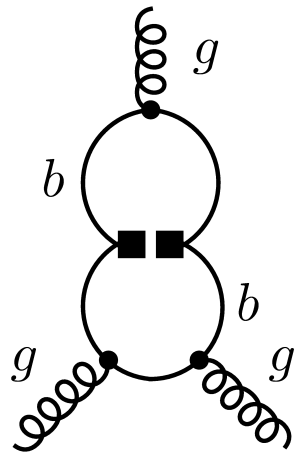
RGE analysis of the b-quark contribution to EDMs

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

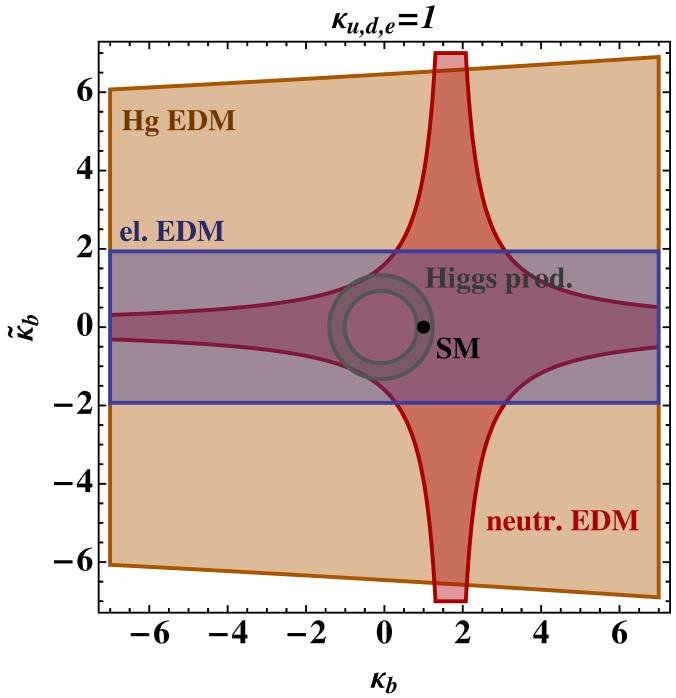


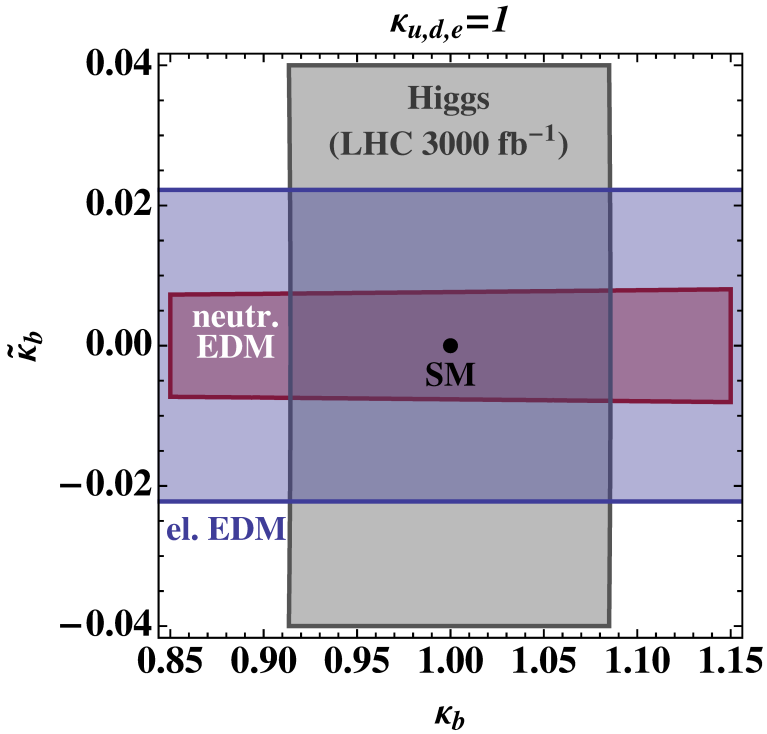


- $\mathcal{C}_5^q(\mu_b) = -4 \frac{\alpha \alpha_s}{(4\pi)^2} Q_q \log^2 \frac{m_b^2}{M_h^2} + \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{\gamma_{14}^{(0)} \gamma_{48}^{(0)} \gamma_{87}^{(0)}}{48} \log^3 \frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^4)\,,$
- $\mathcal{C}_6^q(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2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



Combined constraints on bottoms couplings





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- Future projection for 3000fb^{-1} @ high-luminosity LHC
- Factor 90 (300) improvement on electron (neutron) EDM

Combined constraints on bottom couplings

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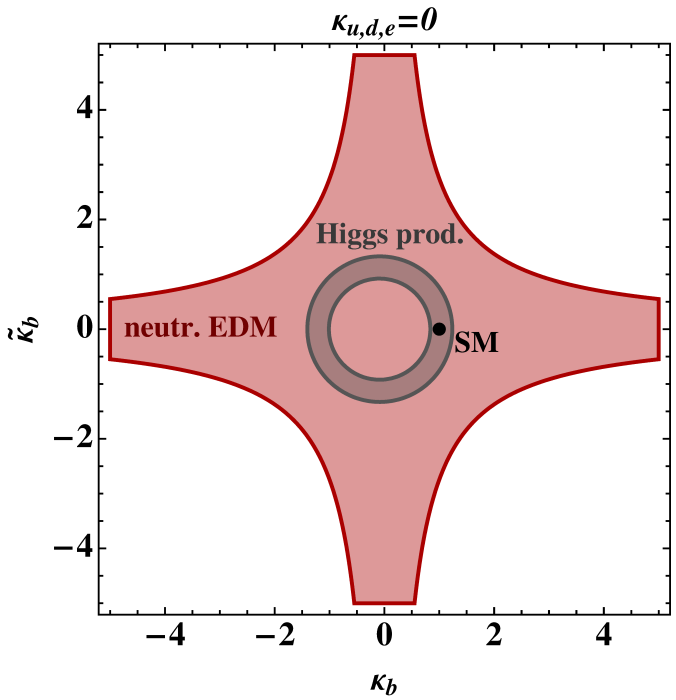
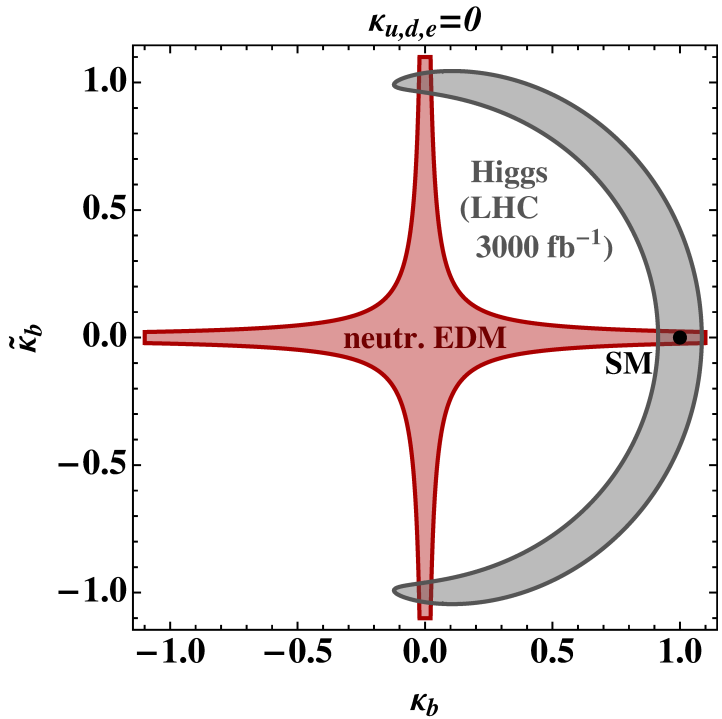
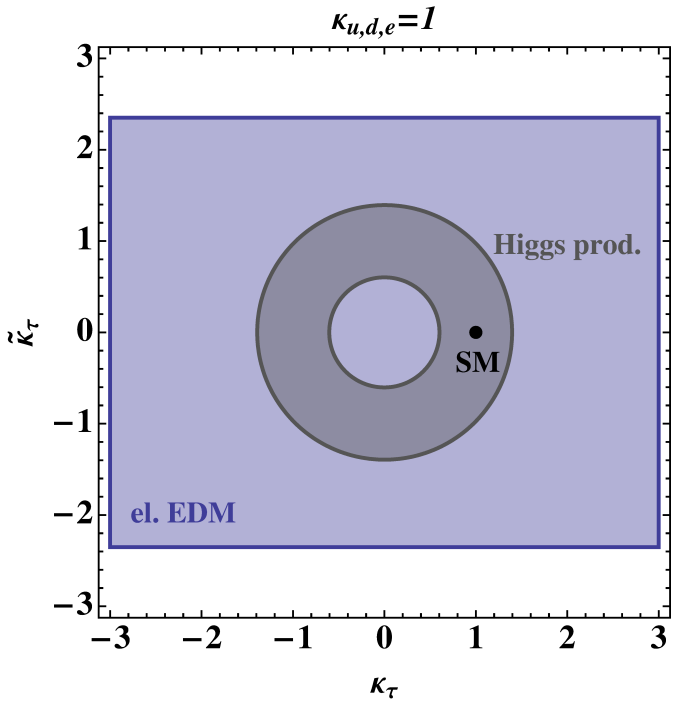
- Contribution of Weinberg operator will lead to competitive constraints in the future scenario

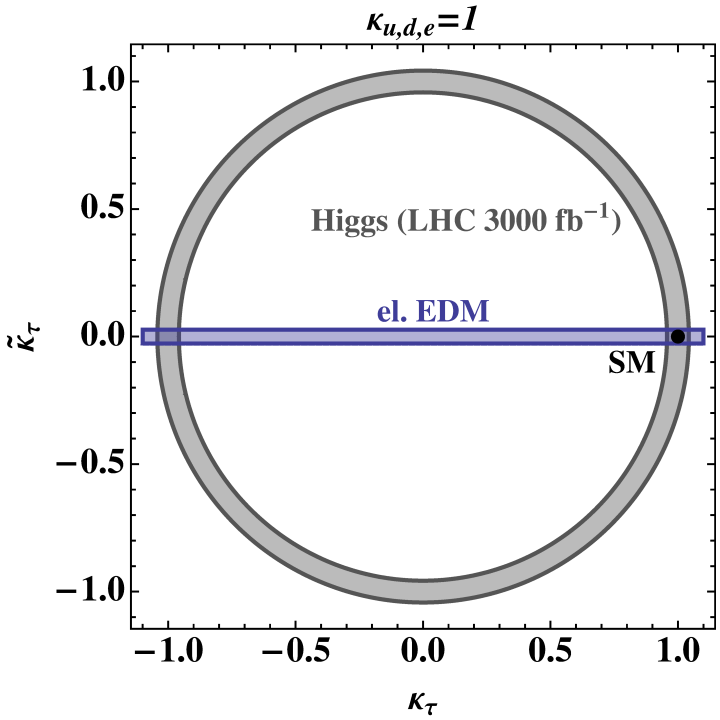




Combined constraints on τ couplings

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





- Weaker constraint from angular correlations in $h \to \tau\tau$, but does not rely on coupling to light fermions [see next talk by Reinard Primulando]

Outlook

- Need to understand the properties of the newly discovered Higgs boson
- LHC experiments and EDMs put constraints on CP-violating Higgs couplings
- EDM constraints will become strong in particular in the future

Outlook