Precision Constraints on Higgs and Z couplings

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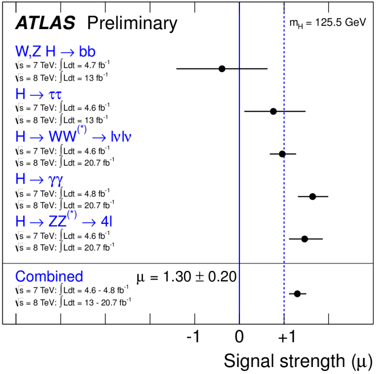
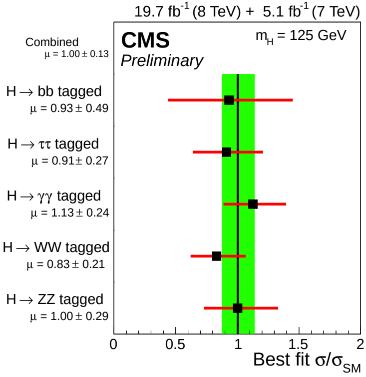
With Ulrich Haisch, Jure Zupan – JHEP 1311 (2013) 180 [arXiv:1310.1385]
With Admir Grelio, Emmanuel Stamou, Patipan Uttayarat – arXiv:1408.0792

What do we know about the Higgs couplings?





[ATLAS-CONF-2013-034]

[CMS-PAS-HIG-14-009]

Outline

- Anomalous Higgs couplings
  - ttH
  - bbH
  - $\tau\tau H$
- Anomalous ttZ couplings
- Conclusion

SM EFT

- No BSM particles at LHC $\Rightarrow$ use EFT with only SM fields
  [See, e.g., Buchmüller et al. 1986, Grzadkowski et al. 2010]

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

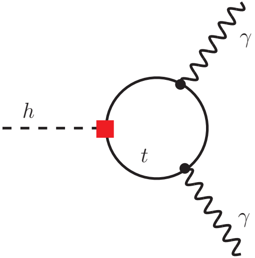
For instance,

$$y_f(\bar{Q}_L t_R H) + \text{h.c.} \quad \xrightarrow{\text{EWSB}} \quad m_t = \frac{y_t v}{\sqrt{2}}$$

$$\frac{H^\dagger H}{\Lambda^2}(\bar{Q}_L t_R H) + \text{h.c.} \quad \xrightarrow{\text{EWSB}} \quad \delta m_t \propto \frac{(v/\sqrt{2})^3}{\Lambda^2}\,, \quad \delta y_t \propto 3\frac{(v/\sqrt{2})^2}{\Lambda^2}$$

- If both terms are present, mass and Yukawa terms are independent

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



- In the SM, Yukawa coupling to fermion f is

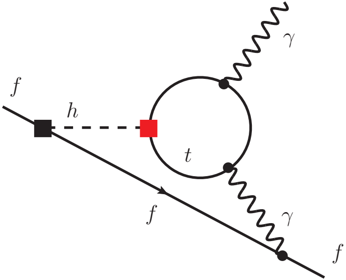
$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \bar{f} f \, h$$

- We will look at modification

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

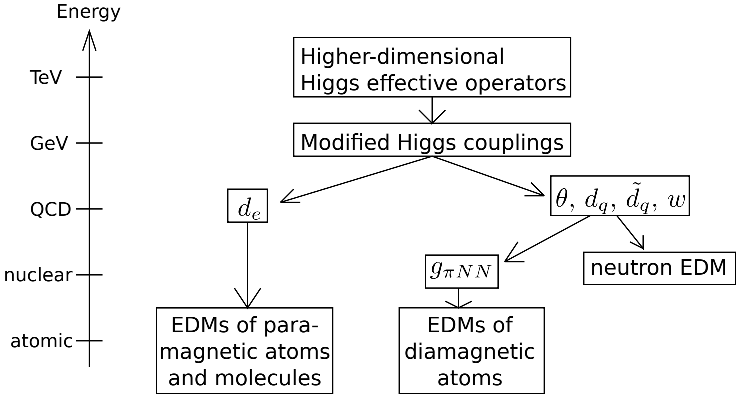
- New contributions will modify Higgs production cross section and decay rates

. . . to electric dipole moments



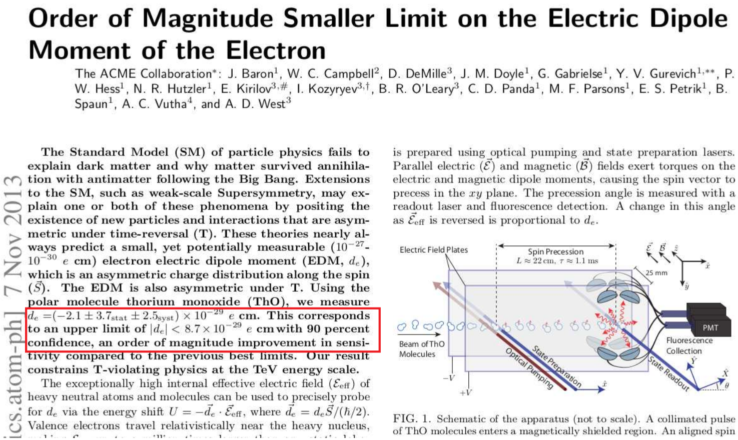
- Attaching a light fermion line leads to EDM
- Indirect constraint on *CP*-violating Higgs coupling
- SM "background" enters at three- and four-loop level
- Complementary to collider measurements
- Constraints depend on additional assumptions

Electric Dipole Moments (EDMs) – Generalities



[Adapted from Pospelov and Ritz, hep-ph/0504231]

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.

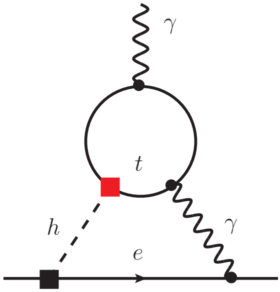
FIG. 1. Schematic of the apparatus (not to scale). A collimated pulse of ThO molecules enters a magnetically shielded region. An aligned spin

- Expect order-of-magnitude improvements!

Anomalous ttH couplings

Electron EDM

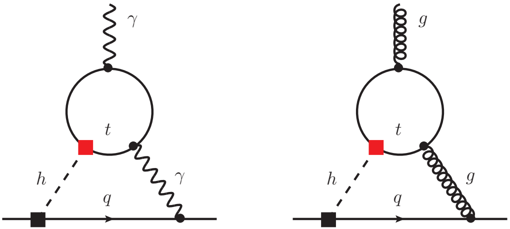
$$\mathcal{L}_{\text{eff}} = -d_e \, \frac{i}{2} \, \bar{e} \, \sigma^{\mu\nu} \gamma_5 \, e \, F_{\mu\nu}$$



- EDM induced via "Barr-Zee" diagrams [Weinberg 1989, Barr & Zee 1990]
- $\frac{d_e}{e} = \frac{16}{3} \frac{\alpha}{(4\pi)^3} \sqrt{2} G_F \, m_e \, \kappa_e \tilde{\kappa}_t \, f_1\left(\frac{m_t^2}{M_h^2}\right)$
- $|d_e/e| < 8.7 \times 10^{-29}$ cm (90% CL) [ACME 2013] with ThO molecules
- Constraint on $\tilde{\kappa}_t$ vanishes if Higgs does not couple to electron

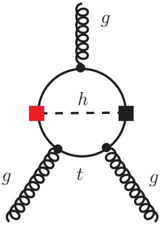
Neutron EDM – EDM and CEDM

$$\mathcal{L}_{\rm eff} \supset -d_q \frac{i}{2} \bar{q}\sigma^{\mu\nu}\gamma_5 q F_{\mu\nu} - \tilde{d}_q \frac{ig_s}{2} \bar{q}\sigma^{\mu\nu} T^a \gamma_5 q G^a_{\mu\nu}$$



- $d_q(\mu_W) = -\frac{16}{3} e Q_q \frac{\alpha}{(4\pi)^3} \sqrt{2} G_F m_q \kappa_q \tilde{\kappa}_t f_1\left(\frac{m_t^2}{M_h^2}\right)$
- $\tilde{d}_q(\mu_W) = -2 \frac{\alpha_s}{(4\pi)^3} \sqrt{2} G_F m_q \kappa_q \tilde{\kappa}_t f_1\left(\frac{m_t^2}{M_h^2}\right)$

Neutron EDM – The Weinberg Operator



- Here the Higgs couples only to the top quark
- Get bound even if light-quark couplings are zero
- $w(\mu_W) = \frac{g_s}{4} \frac{\alpha_s}{(4\pi)^3} \sqrt{2} G_F \kappa_t \tilde{\kappa}_t f_3\left(\frac{m_t^2}{M_h^2}\right)$

Neutron EDM – RG Running

- Need to run from $\mu_W \sim M_W$ to hadronic scale $\mu_H \sim 1$ GeV
- Operators will mix: $\mu \frac{d}{d\mu}\mathcal{C}(\mu) = \gamma^T \mathcal{C}(\mu)$

$$\gamma = \frac{\alpha_s}{4\pi} \begin{pmatrix} \frac{32}{3} & 0 & 0 \\ \frac{32}{3} & \frac{28}{3} & 0 \\ 0 & -6 & 14 + \frac{4N_f}{3} \end{pmatrix}$$

- At hadronic scale μ_H need to evaluate hadronic matrix elements
- Use QCD sum rule techniques [Pospelov, Ritz, hep-ph/0504231]
- There are large $\mathcal{O}(100\%)$ uncertainties
    - E.g. excited states, higher terms in OPE, ambiguity in nuclear current. . .
- In the future, lattice might provide more reliable estimates

Neutron EDM – Bounds

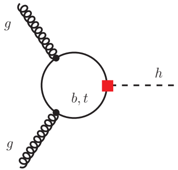
$$\frac{d_n}{e} = \Big\{(1.0 \pm 0.5)\left[-5.3\,\kappa_q\tilde{\kappa}_t + 5.1\cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\right] + (22 \pm 10)\,1.8\cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\Big\}\cdot 10^{-25}\,\mathrm{cm}\,.$$

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

Constraints from $gg \to h$

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

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



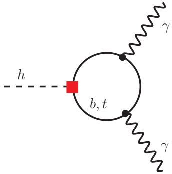
- c_g, $\tilde{c}_g$ given in terms of loop functions
- $\kappa_g \equiv c_g/c_{g,\text{SM}}$, $\tilde{\kappa}_g \equiv 3\tilde{c}_g/2c_{g,\text{SM}}$

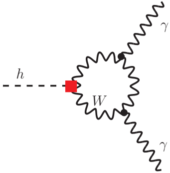
$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\text{SM}}} = |\kappa_g|^2 + |\tilde{\kappa}_g|^2 = \kappa_t{}^2 + 2.6\,\tilde{\kappa}_t{}^2 + 0.11\,\kappa_t\,(\kappa_t - 1)$$

Constraints from $h \to \gamma\gamma$

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

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





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

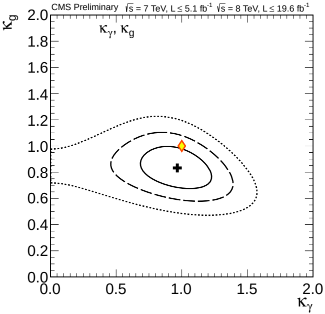
$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\text{SM}}} = |\kappa_\gamma|^2 + |\tilde{\kappa}_\gamma|^2 = (1.28 - 0.28\,\kappa_t)^2 + (0.43\,\tilde{\kappa}_t)^2$$

LHC input

- Naive weighted average of ATLAS, CMS

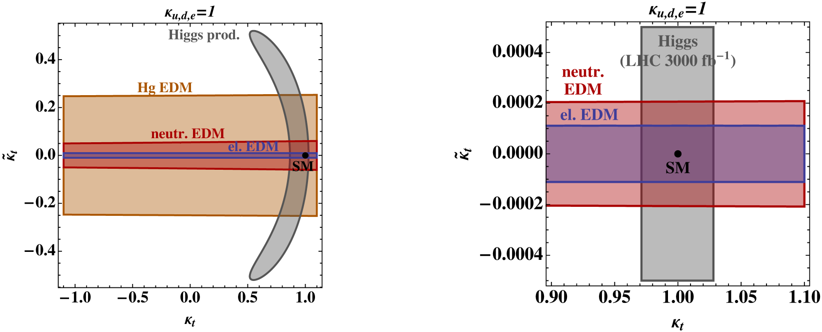
$$\kappa_{g,\text{WA}} = 0.91 \pm 0.08\,, \qquad \kappa_{\gamma,\text{WA}} = 1.10 \pm 0.11$$

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



[CMS-PAS-HIG-13-005]

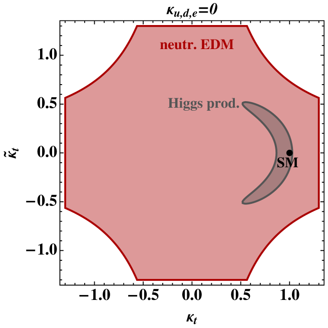
Combined constraints on top coupling

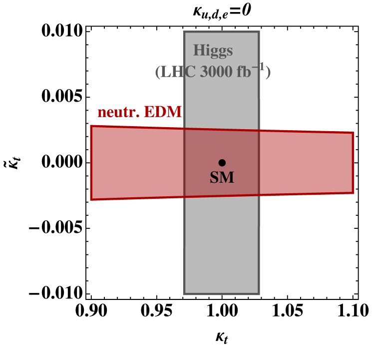


- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
  [J. Olsen, talk at Snowmass Energy Frontier workshop]
- Factor 90 (300) improvement on electron (neutron) EDM
  [Fundamental Physics at the Energy Frontier, arXiv:1205.2671]

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

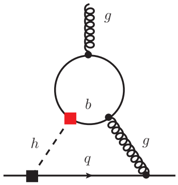




Anomalous bbH couplings

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
- For neutron EDM, extra scale $m_b \ll M_h$ important



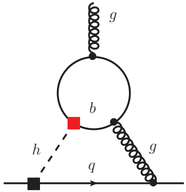
$$d_q(\mu_W) \simeq -4\, e\, Q_q\, N_c\, Q_b^2 \frac{\alpha}{(4\pi)^3} \sqrt{2} G_F\, m_q\, \kappa_q \tilde{\kappa}_b \frac{m_b^2}{M_h^2} \left(\log^2 \frac{m_b^2}{M_h^2} + \frac{\pi^2}{3} \right) ,$$

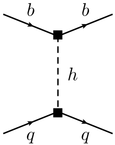
$$\tilde{d}_q(\mu_W) \simeq -2 \frac{\alpha_s}{(4\pi)^3} \sqrt{2} G_F\, m_q\, \kappa_q \tilde{\kappa}_b \frac{m_b^2}{M_h^2} \left(\log^2 \frac{m_b^2}{M_h^2} + \frac{\pi^2}{3} \right) ,$$

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

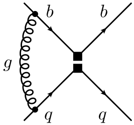
RGE analysis of the b-quark contribution to EDMs

- ≈ 3 scale uncertainty in CEDM Wilson coefficient
- Two-step matching at M_h and m_b:

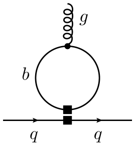




- Integrate out Higgs
- $\mathcal{O}_1^q = \bar{q}q\,\bar{b}i\gamma_5 b$



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



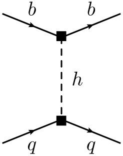
- Matching onto
- $\mathcal{O}_6^q = -\frac{i}{2}\frac{m_b}{g_s}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G^a_{\mu\nu}$

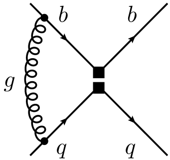
RG Running

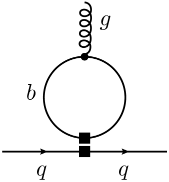
- Above $\mu_b \sim m_b$ have 10 operators which mix:

$$\gamma^{(0)} = \begin{pmatrix}
-16 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 2 & -\frac{4}{9} & -\frac{5}{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -96 & \frac{16}{3} & 0 & 0 & 0 & -48 & 0 & 0 & 0 & 0 \\
-\frac{64}{3} & -40 & 0 & -\frac{38}{3} & 0 & 0 & 0 & -8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -10 & -\frac{1}{6} & 0 & 0 & 4 & 4 & 0 \\
0 & 0 & 0 & 0 & 40 & \frac{34}{3} & 0 & 0 & -112 & -16 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -\frac{14}{3} & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & \frac{32}{3} & -6 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\frac{14}{3} & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \frac{32}{3} & -6 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -6 & 0 & -6 & \frac{16}{3}
\end{pmatrix}.$$

CEDM operator

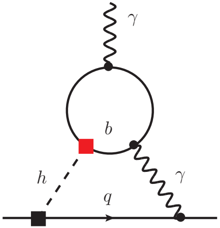






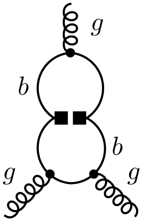
- $\mathcal{C}_{\tilde{d}_q}(\mu_b) = \frac{432}{2773\,\eta_5^{9/23}} + \frac{0.07501}{\eta_5^{1.414}} + 9.921 \cdot 10^{-4}\,\eta_5^{0.7184} - \frac{0.2670}{\eta_5^{0.6315}} + \frac{0.03516}{\eta_5^{0.06417}}$
  - $\eta_5 \equiv \alpha_s(\mu_W)/\alpha_s(\mu_b)$
- Expand: $\mathcal{C}_{\tilde{d}_q}(\mu_b) \simeq \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}}{8}\,\log^2\frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)$

EDM operator



- $\mathcal{C}_{d_q}(\mu_b) = -4\,\frac{\alpha\,\alpha_s}{(4\pi)^2}\,Q_q\log^2\frac{m_b^2}{M_h^2} + \left(\frac{\alpha_s}{4\pi}\right)^3\frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}\gamma_{87}^{(0)}}{48}\,\log^3\frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^4)$
- QCD mixing term dominates by a factor of $\approx 4.5(-9.0)$!

Weinberg operator



- $\mathcal{C}_w(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{5,11}^{(1)}}{2} \log\frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)$
- Linear log requires two-loop running

Neutron EDM at the hadronic scale

- Below $\mu_b \sim m_b$, analysis is analogous to case of top quarks

$$\frac{d_n}{e} = \left\{ (1.0 \pm 0.5) \left[-18.1\, \tilde{\kappa}_b + 0.15\, \kappa_b \tilde{\kappa}_b \right] + (22 \pm 10)\, 0.48\, \kappa_b \tilde{\kappa}_b \right\} \cdot 10^{-27}\, \mathrm{cm}\,.$$

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

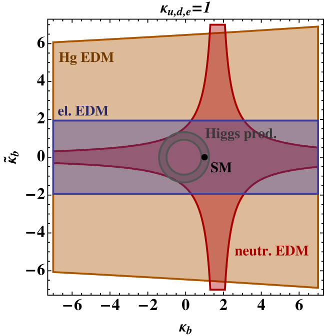
$$\mathrm{Br}(h \to b\bar{b}) = \frac{\left({\kappa_b}^2 + {\tilde{\kappa}_b}^2\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}{1 + \left({\kappa_b}^2 + {\tilde{\kappa}_b}^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

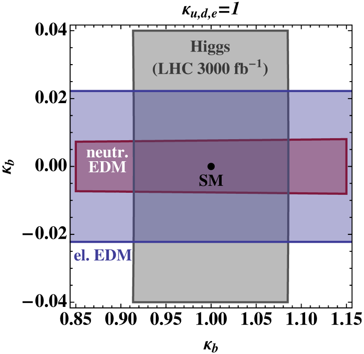
$$\mathrm{Br}(h \to X) = \frac{\mathrm{Br}(h \to X)_{\mathrm{SM}}}{1 + \left({\kappa_b}^2 + {\tilde{\kappa}_b}^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

- 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

Combined constraints on bottom couplings

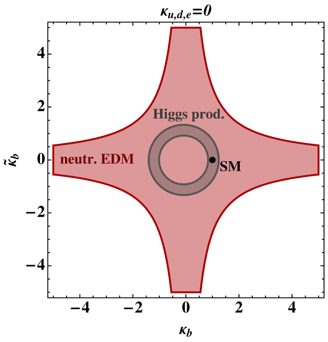


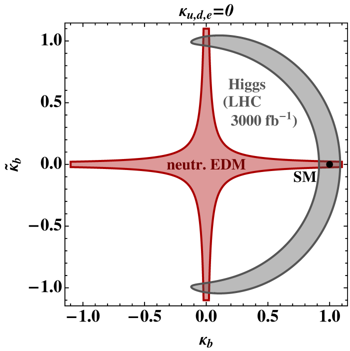


- Assume SM couplings to electron and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
- Factor 90 (300) improvement on electron (neutron) EDM

Combined constraints on bottom couplings

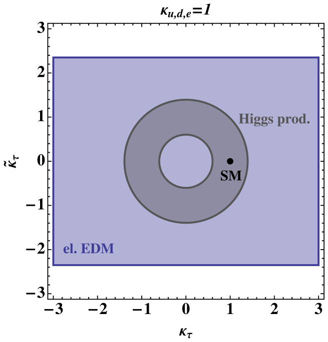
- Set couplings to electron and light quarks to zero
- Contribution of Weinberg operator will lead to competitive constraints in the future scenario

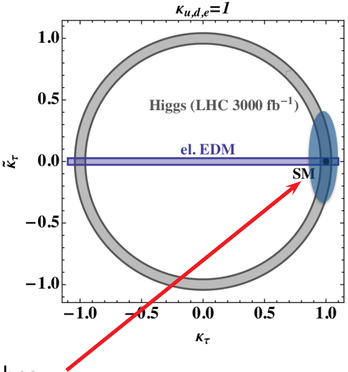




Combined constraints on τ couplings

- Effect of modified $h\tau\tau$ coupling on κ_γ, $\tilde{\kappa}_\gamma$ again subleading
- Get simple constraint from modification of branching ratios



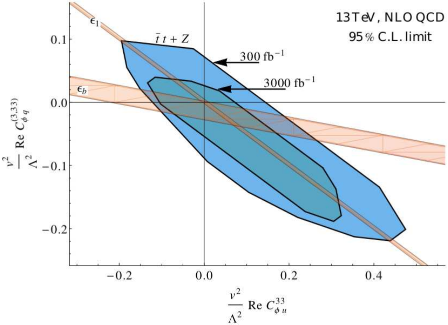


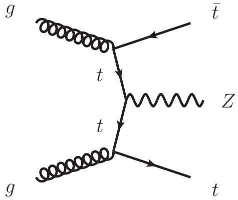
- Shaded region shows reach for direct searches

  [Harnik et al., Phys.Rev. D88 (2013) 7, 076009 [arXiv:1308.1094[hep-ph]]]

Anomalous ttZ couplings

Direct bounds on anomalous $t\bar{t}Z$ couplings

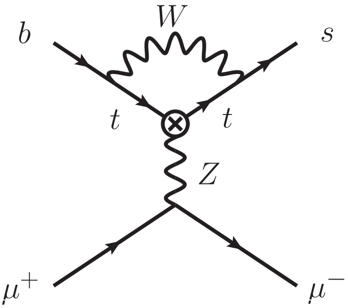




- ttZ production at NLO
  [Röntsch, Schulze, arXiv:1404.1005]
- $\approx 20\% - 30\%$ deviation from SM still allowed even with 3000 fb^{-1}

Basic idea

- Can we constrain anomalous $t\bar{t}Z$ couplings by precision observables?
- Yes – using mixing via electroweak loops
- Need to make (only a few) assumptions



Assumption I: Operators in the UV

- At NP scale Λ, only the following operators have nonzero coefficients:

$$Q_{Hq}^{(3)} \equiv (H^\dagger i \overset{\leftrightarrow}{D}{}^a_\mu\, H)(\bar{Q}_{L,3}\gamma^\mu \sigma^a Q_{L,3})\,,$$
$$Q_{Hq}^{(1)} \equiv (H^\dagger i \overset{\leftrightarrow}{D}_\mu\, H)(\bar{Q}_{L,3}\gamma^\mu Q_{L,3})\,,$$
$$Q_{Hu} \equiv (H^\dagger i \overset{\leftrightarrow}{D}_\mu\, H)(\bar{t}_R\gamma^\mu t_R)\,.$$

- Here, $Q_{L,3}^T = (t_L, V_{ti} d_{L,i})$
- Only these operators induce tree-level $t\bar{t}Z$ couplings

Assumption II: LEP bounds

- After EWSB these operators induce

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

$$g_R' \propto C_{Hu}, \qquad g_L' \propto C_{Hq}^{(3)} - C_{Hq}^{(1)}, \qquad g_L'' \propto C_{Hq}^{(3)} + C_{Hq}^{(1)}, \qquad k_L \propto C_{Hq}^{(3)}$$

- LEP data on $Z \to b\bar{b}$ constrain $g_L'' = 0$ within permil precision
- $C_{Hq}^{(3)}(\Lambda) + C_{Hq}^{(1)}(\Lambda) = 0$
- This scenario could be realized with vector-like quarks
  [del Aguila et al., hep-ph/0007316]

Assumption III: Only top Yukawa

- Only the top-quark Yukawa is nonvanishing
- Neglect other Yukawas in RGE
- Our basis then comprises the leading operators in MFV counting
  - E.g. $\bar{Q}_L Y_u Y_u^\dagger Q_L$
- Comment later on deviations from that assumption

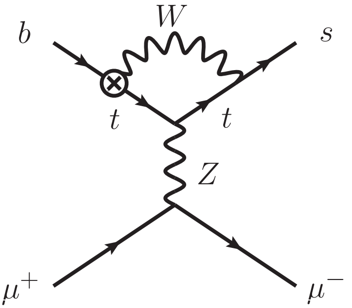
A Comment on the Literature

- In [arxiv:1112.2674, arxiv:1301.7535, arxiv:1109.2357] indirect bounds on qtZ, tbW couplings have been derived using a similar approach

- They calculated the diagrams, with $\Lambda \sim M_W$:

$$\mathcal{A} = \frac{g^2}{16\pi^2}\left(A + B \log \frac{\mu_W}{\Lambda}\right)$$

- Note that the finite part A is scheme dependent!



Getting the bounds: RG Mixing

- The RG induces mixing into [Jenkins et al., 2013; see also Brod et al. 2014]
  - $Q^{(3)}_{\phi q,ii} \equiv (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{Q}_{L,i}\gamma^\mu \sigma^a Q_{L,i}) \to b\bar{b}Z$
  - $Q^{(1)}_{\phi q,ii} \equiv (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\bar{Q}_{L,i}\gamma^\mu Q_{L,i}) \to b\bar{b}Z$
  - $Q^{(3)}_{lq,33jj} \equiv (\bar{Q}_{L,3}\gamma_\mu \sigma^a Q_{L,3})(\bar{L}_{L,j}\gamma^\mu \sigma^a L_{L,j}) \to$ rare K / B
  - $Q^{(1)}_{lq,33jj} \equiv (\bar{Q}_{L,3}\gamma_\mu Q_{L,3})(\bar{L}_{L,j}\gamma^\mu L_{L,j}) \to$ rare K / B
  - $Q_{\phi D} \equiv \left|\phi^\dagger D_\mu \phi\right|^2 \to$ T parameter

Results – Useless Form

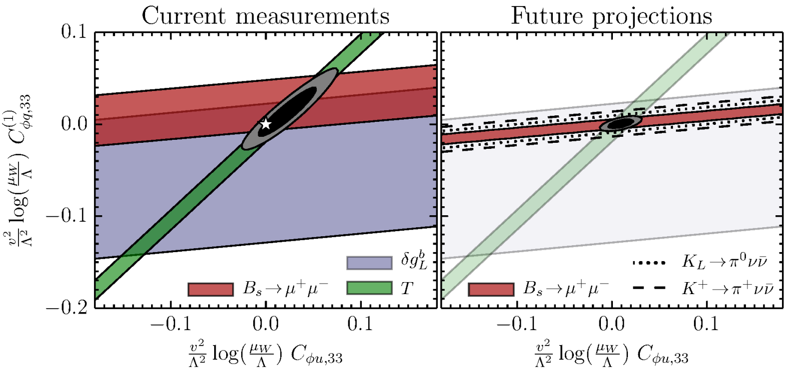
$$\delta g_L^b = -\frac{e}{2s_w c_w}\frac{v^2}{\Lambda^2}\frac{\alpha}{4\pi}\Bigg\{ V_{33}^* V_{33}\left[\frac{x_t}{2s_w^2}\left(8C_{\phi q,33}^{(1)} - C_{\phi u}\right) + \frac{17c_w^2 + s_w^2}{3s_w^2 c_w^2} C_{\phi q,33}^{(1)}\right]$$

$$+ \left[\frac{2s_w^2 - 18c_w^2}{9s_w^2 c_w^2} C_{\phi q,33}^{(1)} + \frac{4}{9c_w^2} C_{\phi u}\right]\Bigg\} \log\frac{\mu_W}{\Lambda}\,.$$

$$\delta T = -\frac{v^2}{\Lambda^2}\left[\frac{1}{3\pi c_w^2}\left(C_{\phi q,33}^{(1)} + 2C_{\phi u,33}\right) + \frac{3x_t}{2\pi s_w^2}\left(C_{\phi q,33}^{(1)} - C_{\phi u,33}\right)\right] \log\frac{\mu_W}{\Lambda}\,.$$

$$\delta Y^{\mathrm{NP}} = \delta X^{\mathrm{NP}} = \frac{x_t}{8}\left(C_{\phi u} - \frac{12 + 8x_t}{x_t} C_{\phi q,33}^{(1)}\right)\frac{v^2}{\Lambda^2} \log\frac{\mu_W}{\Lambda}\,,$$

Results – Useful Form



T	0.08 ± 0.07	[Ciuchini et al., arxiv:1306.4644]
δg_L^b	0.0016 ± 0.0015	[Ciuchini et al., arxiv:1306.4644]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [CMS]	$(3.0^{+1.0}_{-0.9}) \times 10^{-9}$	[CMS, arxiv:1307.5025]
$\mathrm{Br}(B_s \to \mu^+\mu^-)$ [LHCb]	$(2.9^{+1.1}_{-1.0}) \times 10^{-9}$	[LHCb, arxiv:1307.5024]
$\mathrm{Br}(K^+ \to \pi^+\nu\bar\nu)$	$(1.73^{+1.15}_{-1.05}) \times 10^{-10}$	[E949, arxiv:0808.2459]

How general are our results?

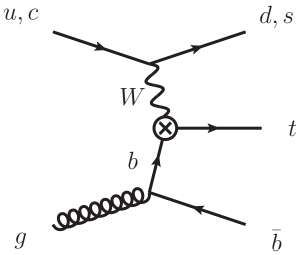
- A generic NP model can generate FCNC transitions in the up sector
- Consider models with large enhancement of the bottom Yukawa (2HDM...)
- Assume MFV – e.g., now, have $\bar{Q}_L(Y_u Y_u^\dagger + Y_d Y_d^\dagger)Q_L$
- Large bottom Yukawa induces flavor off-diagonal operators in the up sector
- They will contribute to FCNC top decays and $D - \bar{D}$ mixing
- These effects are suppressed by powers of $\lambda \equiv |V_{us}|$
- $D - \bar{D}$ mixing is suppressed by $\lambda^{10} \approx 10^{-7}$
- top-FCNC decays:

$$\mathrm{Br}(t \to cZ) \simeq \frac{\lambda^4 v^4}{\Lambda^4} \left[\left(C_{\phi q,33}^{(3)} - C_{\phi q,33}^{(1)} \right)^2 + C_{\phi u,33}^2 \right] .$$

- $\mathrm{Br}(t \to cZ) < 0.05\%$ [CMS, arxiv:1312.4194] $\Rightarrow$ not competitive

t-channel single top production

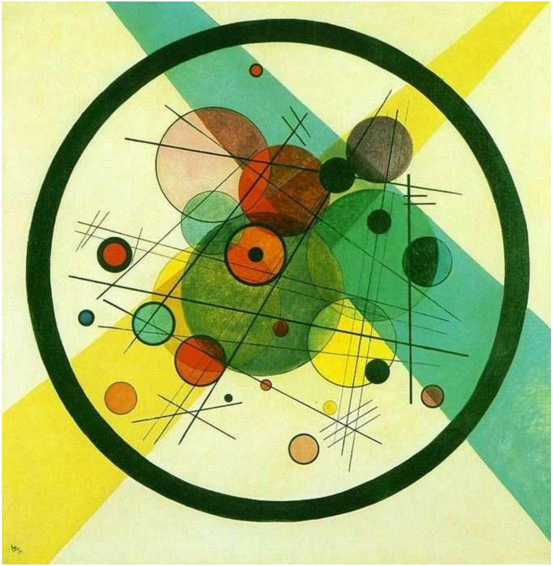
- $\sqrt{\sigma(t)/\sigma_{\rm SM}(t)} = 0.97(10)$
  [ATLAS-CONF-2014-007]
- $\sqrt{\sigma(t)/\sigma_{\rm SM}(t)} = 0.998(41)$ [CMS, arxiv:1403.7366]
- t-channel single top production constrains
  $v^2 C_{Hq}^{(3)}/\Lambda^2 = -0.006 \pm 0.038$ [arxiv:1408.0792]



Summary

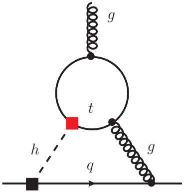
- LHC experiments and precision observables put complementary constraints on anomalous Higgs and Z couplings
- EMDs yield strong constraints on CP-violating Yukawa couplings
- FCNC down-sector transitions yield strong constraints on up-sector diagonal couplings
- Most bounds will improve in the future
- What about the small (e, u, d, ...) Yukawa couplings? [work in progress]

Outlook



Appendix

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

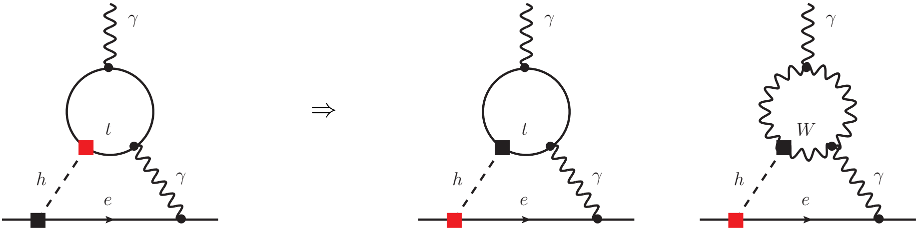
$$\frac{d_{\rm Hg}}{e} = -\left(4^{+8}_{-2}\right) \left[3.1\,\tilde\kappa_t - 3.2 \cdot 10^{-2}\,\kappa_t\tilde\kappa_t\right] \cdot 10^{-29}\,\mathrm{cm}$$

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

What do we know about the electron Yukawa?

Indirect bounds: electron EDM

- A different look at Barr & Zee:



- $|d_e/e| < 8.7 \times 10^{-29}\,\text{cm}$ (90% CL) [ACME 2013]
- leads to $|\tilde{\kappa}_e| < 0.0013$ (for $\kappa_t = 1$)

Indirect bounds: electron $g - 2$

- Usually, measurement of $a_e \equiv (g-2)_e/2$ used to extract α
- Using independent α masurement, can make a prediction for a_e
  [Giudice et al., arXiv:1208.6583]
- With
  - $\alpha = 1/137.035999037(91)$ [Bouchendira et al., arXiv:1012.3627]
  - $a_e = 11596521807.3(2.8) \times 10^{-13}$ [Gabrielse et al. 2011]
- ... I find $|\kappa_e| \lesssim 3000$
- Bound expected to improve by a factor of 10

Direct collider bounds

$$\text{Br}(h \to e^+e^-) = \frac{\left(\kappa_e^2 + \tilde{\kappa}_e^2\right)\text{Br}(h \to e^+e^-)_{\text{SM}}}{1 + \left(\kappa_e^2 + \tilde{\kappa}_e^2 - 1\right)\text{Br}(h \to e^+e^-)_{\text{SM}}}$$

- CMS limit $\text{Br}(h \to e^+e^-) < 0.0019$ [CMS, arxiv:1410.6679] leads to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} < 611$
- LEP bound (via radiative return) probably not competitive
- A future e^+e^- machine...
  - collecting 100 fb^{-1} on the Higgs resonance
  - assuming 25 MeV beam energy spread
- ...can push the limit to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \lesssim 10$