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 – JHEP 1502 (2015) 141 [arXiv:1408.0792]

With Wolfgang Altmannshofer, Martin Schmaltz – arXiv:1503.04830

Introduction

The goal of Particle Physics

What is $\mathcal{L}$?

- Current knowledge contained in the “Standard Model of Particle Physics”
- Good agreement with collider and precision experiments

(Selected) problems of the SM

- Dark Matter?
- Neutrino masses?
- Flavor structure? (14 of 19 parameters in the flavor sector!)
- Sakharov conditions:
  - B violation
  - C, CP violation
  - Thermal non-equilibrium
- More specific questions:
  - Are the gauge boson interactions as in the SM?
  - Are the Higgs boson interactions as in the SM?
  - Are there additional sources of CP violation?

Outline

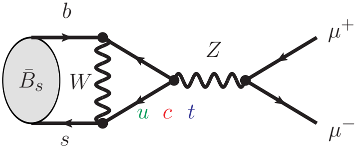
- Anomalous ttZ couplings
- CP-violating Higgs couplings to top and bottom quarks
- What do we know about the electron Yukawa?

Indirect searches for new physics

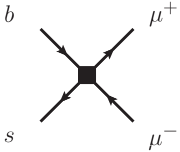
- Strategy for the search for new physics:
  - Choose process that is suppressed in the SM
  - E.g., FCNC transition; one-loop + GIM
  - New particles can contribute via loops
  - General parameterisation by EFT
- Two steps:
  - Precise SM prediction
  - Comparison with experiment
- Complements direct searches for new physics ("high-p_T")

Example: Rare B and K decays

- Rare decays with theory uncertainty $\mathcal{O}(1\%)$:
- $\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.65(23) \times 10^{-9}$ [Bobeth et al., arXiv:1311.0903]
- $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = 7.81(75)(29) \times 10^{-11}$ [Brod et al., arXiv:1009.0947]
- $\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu}) = 2.43(39)(6) \times 10^{-11}$ [Brod et al., arXiv:1009.0947]



$\Leftrightarrow$



- Look for new physics in $b \to s$ ($s \to d$) transistions

One more step

- What we have learned from LHC:
  - There is a "SM-like" Higgs particle
  - Other new particles are most likely very heavy ($M \gg v$)
- All SM particles are then light in comparison
- Construct all operators using SM fields ⇒ "SM-EFT"
  [See, e.g., Buchmüller et al. 1986, Grzadkowski et al. 2010]
- $SU(2) \times U(1)$ gauge invariance explicit

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

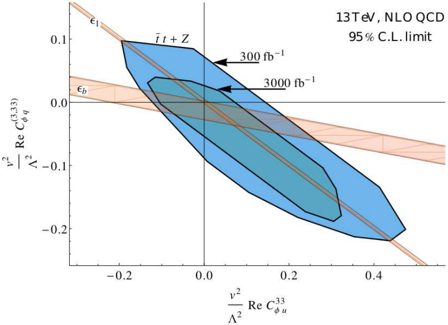
- Higher orders suppressed by powers of v/M
- Explicit examples follow!

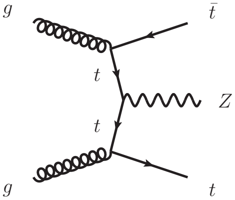
Anomalous $t\bar{t}Z$ Couplings

Anomale ttZ-Kopplungen

- Direct searches at LHC extremely difficult
- Unconventional example for the sensitivity of rare decays
  - (. . . and the application of SM-EFT)

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

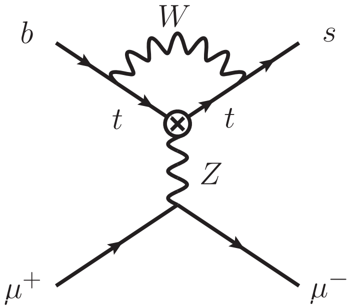




- ttZ production at NLO
  [Röntsch, Schulze, arXiv:1404.1005]
- $\approx 20\% - 30\%$ deviation from SM still allowed even with 3000 fb^{-1}

Basic idea

- Can we constrain anomalous $t\bar{t}Z$ couplings by precision observables?
- Yes – using mixing via electroweak loops



Assumption I: Operators in the UV

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

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

- 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

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

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

- LEP data on $Z \to b\bar{b}$: $g_L'' \sim 10^{-3}$
- $C_{Hq}^{(3)}(\Lambda) + C_{Hq}^{(1)}(\Lambda) = 0$
- 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
- Comment later on deviations from that assumption

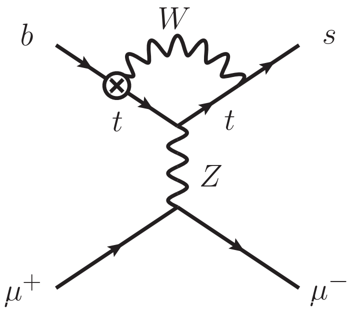
A Comment on the Literature

- 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 $\Lambda \sim M_W$:

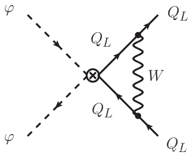
$$\mathcal{A} = \frac{g^2}{16\pi^2}\left(A + B \log \frac{\mu_W}{\Lambda}\right)$$

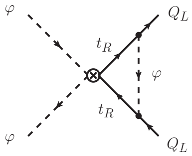
- Note that the finite part A is renormalization-scheme dependent!

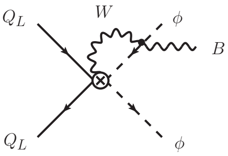


Operator Mixing

- Weak gauge boson and Higgs exchange 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







Analytic result

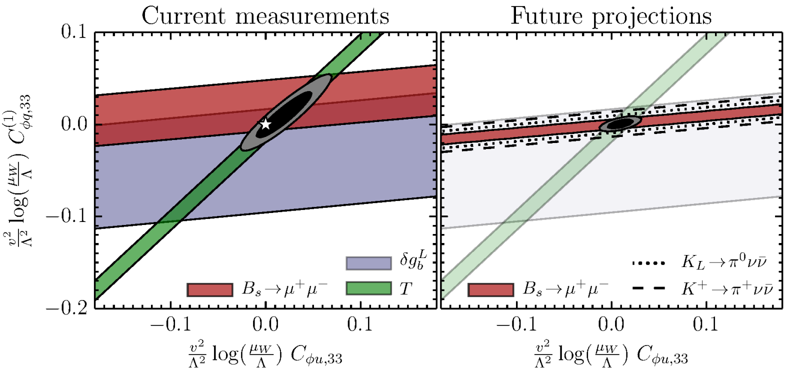
$$\delta g_L^b = -\frac{e}{2s_w c_w}\frac{\alpha}{4\pi}\left\{ V_{33}^* V_{33}\left[\frac{x_t}{2s_w^2}\left(8C_{\phi q,33}^{(1)} - C_{\phi u}\right) + \frac{17c_w^2 + s_w^2}{3s_w^2 c_w^2} C_{\phi q,33}^{(1)}\right] \right.$$

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

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

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

Numerical result



T	$0.08 \quad \pm 0.07$	[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?

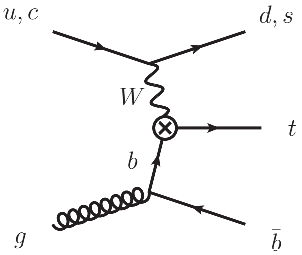
- A generic NP model can generate FCNC transitions in the up sector
- Consider models with large enhancement of the bottom Yukawa (2HDM...)
- Assume MFV – e.g., now, have $\bar{Q}_L(Y_u Y_u^\dagger + Y_d Y_d^\dagger)Q_L$
- Large bottom Yukawa induces flavor off-diagonal operators in the up sector
- They will contribute to FCNC top decays and $D - \bar{D}$ mixing
- These effects are suppressed by powers of $\lambda \equiv |V_{us}| \approx 0.22$
- $D - \bar{D}$ mixing is suppressed by $\lambda^{10} \approx 10^{-7}$
- FCNC top-quark decays:

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

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

t-channel single top production

- $\sqrt{\sigma(t)/\sigma_{\text{SM}}(t)} = 0.97(10)$
  [ATLAS-CONF-2014-007]
- $\sqrt{\sigma(t)/\sigma_{\text{SM}}(t)} = 0.998(41)$ [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]



$t\bar{t}Z$: Summary and outlook

- Strong constraints from rare B and K decays
- Bounds on other interaction are possible: e.g. WWZ
  [Bobeth, Haisch, arxiv:1503.04829]
- Use other decays that get a Z-penguin contribution: e.g. $B \to K^* \ell\ell$
- More generally: Global $SU(2)$-invariant analysis of flavor and electroweak precision data
  [See also Alonso, Grinstein, Camalich, arXiv:1407.7044]

CP-violating Higgs Couplings

CP-violating Higgs couplings

- The discovery of the Higgs particle opened a new window for the search for new physics!
  - CP Violation in Higgs-fermion couplings?
- Difficult to measure at LHC
- Elektric dipole moments (EDM) of electron and neutron very sensitive to CP violation
  - SM background many orders of magnitude below experimental limits

How can we change the Higgs couplings?

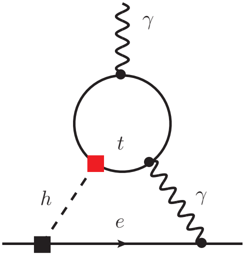
Operator	Mass term	Higgs-fermion coupling
$y_t(\bar{Q}_L t_R H^c) + \text{h.c.}$	$m_t = \frac{y_t v}{\sqrt{2}}$	$\frac{y_t}{\sqrt{2}}$
$\frac{H^\dagger H}{\Lambda^2}(\bar{Q}_L t_R H^c) + \text{h.c.}$	$\delta m_t \propto \frac{(v/\sqrt{2})^3}{\Lambda^2}$	$\delta y_t \propto 3\frac{(v/\sqrt{2})^2}{\Lambda^2}$

- Mass and Yukawa term become independent
- Relative complexe phase → CP violation
- More generally, we write:

$$\mathcal{L}'_Y = -\frac{y_f}{\sqrt{2}}(\kappa_f + i\tilde{\kappa}_f)\,\bar{f}_L f_R h + \text{h.c.}$$

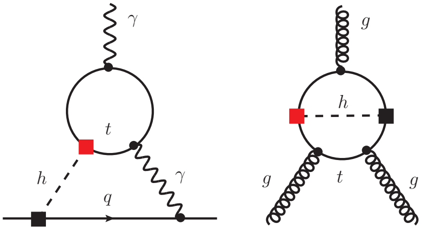
CP-violating $t\bar{t}H$ Couplings

Electron EDM



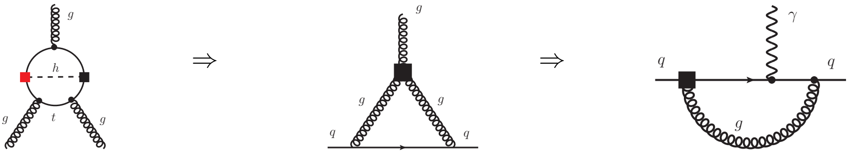
- "Barr-Zee" diagrams induce EDM [Weinberg 1989, Barr & Zee 1990]
- $|d_e/e| < 8.7 \times 10^{-29}\,\text{cm}$ (90% CL) [ACME 2013]
- $\Rightarrow |\tilde{\kappa}_t| < 0.01$
- Constraint on $\tilde{\kappa}_t$ vanishes if the Higgs does not couple to the electron

Neutron EDM – The Weinberg Operator



- Barr-Zee diagrams similar as in electron case
- Contribution of the Weinberg Operator: Higgs couples only to top quark
- Get constraint even if couplings to light quarks vanish

Neutron EDM – RG running



- Operator mixing: $\mu \frac{d}{d\mu}\mathcal{C}(\mu) = \gamma^T \mathcal{C}(\mu)$

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

- Hadronic matrix element are evaluated at $\mu_H \sim 1$ GeV
- QCD sum rules (large $\mathcal{O}(1)$ uncertainties!)
  [Pospelov, Ritz, hep-ph/0504231]

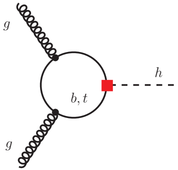
Neutron EDM – Constraints

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

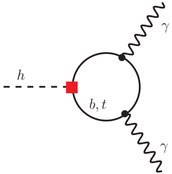
$$+ (22 \pm 10)\,1.8\cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\Big\}\cdot 10^{-25}\,\mathrm{cm}\,.$$

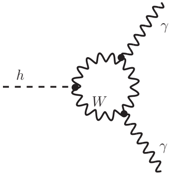
- terms $\propto \kappa_t\tilde{\kappa}_t$ subdominant, but proportional only to top Yukawa
- $|d_n/e| < 2.9 \times 10^{-26}\,$cm (90% CL) [Baker et al., 2006]
  - $|\tilde{\kappa}_t| \lesssim 0.1$ – SM couplings to light quarks
  - $|\tilde{\kappa}_t| \lesssim 0.7$ – only coupling to top quark

Constraints from Higgs production and decay



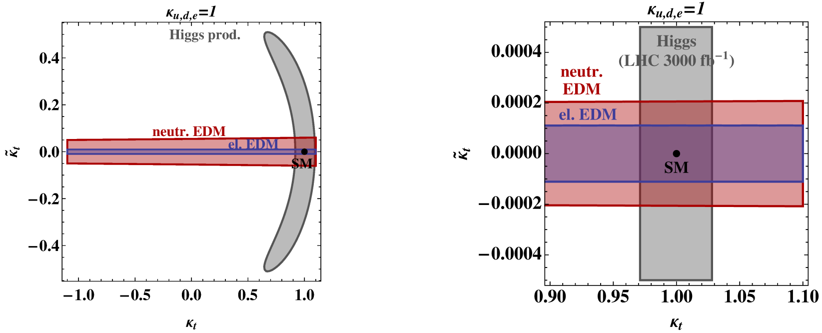
$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\mathrm{SM}}} = {\kappa_t}^2 + 2.6\,{\tilde{\kappa}_t}^2 + 0.11\,\kappa_t\,(\kappa_t - 1)$$





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

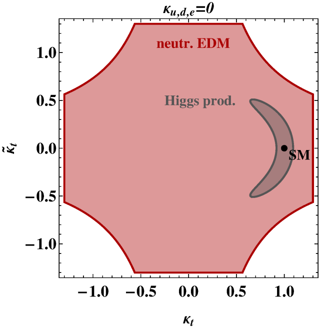
Combined bounds – SM couplings to light fermions

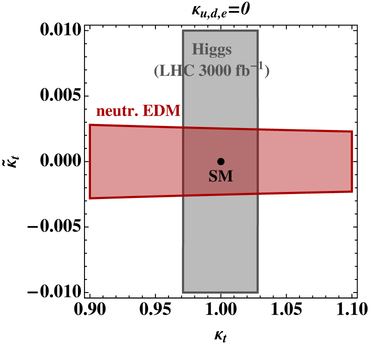


- Assume SM couplings to electrons and light quarks
- Future projection for 3000fb^{-1} @ high-luminosity LHC
  [J. Olsen, talk at Snowmass Energy Frontier workshop]
- Factor 90 (300) improvement on electron (neutron) EDM
  [Fundamental Physics at the Energy Frontier, arXiv:1205.2671]

Combined bounds – only top Yukawa

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

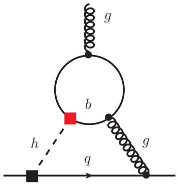




CP-violating $b\bar{b}H$ Couplings

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



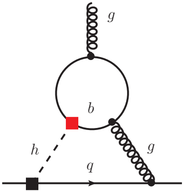
$$d_q(\mu_W) \simeq -4\,e\,Q_q\,N_c\,Q_b^2\,\frac{\alpha}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

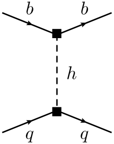
$$\tilde{d}_q(\mu_W) \simeq -2\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,m_q\,\kappa_q\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log^2\frac{m_b^2}{M_h^2}+\frac{\pi^2}{3}\right),$$

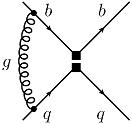
$$w(\mu_W) \simeq -g_s\,\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F\,\kappa_b\tilde{\kappa}_b\,\frac{m_b^2}{M_h^2}\left(\log\frac{m_b^2}{M_h^2}+\frac{3}{2}\right).$$

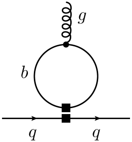
RGE analysis of the b-quark contribution to EDMs

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

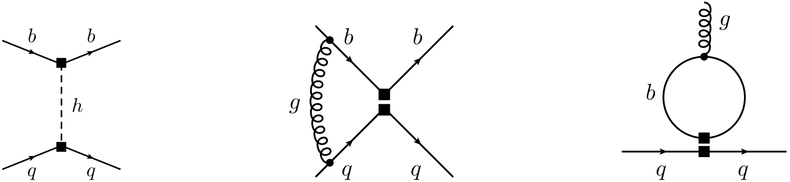
- Matching onto
- $\mathcal{O}_6^q = -\frac{i}{2}\frac{m_b}{g_s}\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q G_{\mu\nu}^a$

RG Running

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

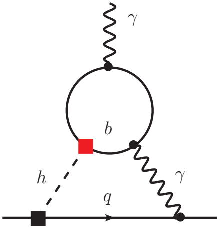
$$\gamma^{(0)} = \begin{pmatrix} -16 & 0 & 0 & -2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2 & -\frac{4}{9} & -\frac{5}{6} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -96 & \frac{16}{3} & 0 & 0 & 0 & -48 & 0 & 0 & 0 & 0 \\ -\frac{64}{3} & -40 & 0 & -\frac{38}{3} & 0 & 0 & 0 & -8 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -10 &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

CEDM operator



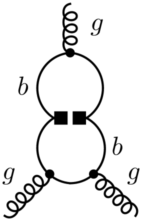
- $\mathcal{C}_{\tilde{d}_q}(\mu_b) = \frac{432}{2773\,\eta_5^{9/23}} + \frac{0.07501}{\eta_5^{1.414}} + 9.921 \cdot 10^{-4}\,\eta_5^{0.7184} - \frac{0.2670}{\eta_5^{0.6315}} + \frac{0.03516}{\eta_5^{0.06417}}$
  - $\eta_5 \equiv \alpha_s(\mu_W)/\alpha_s(\mu_b)$
- Expand: $\mathcal{C}_{\tilde{d}_q}(\mu_b)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

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



- $\mathcal{C}_w(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma^{(1)}_{5,11}}{2} \log \frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)$
- 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

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

Collider constraints

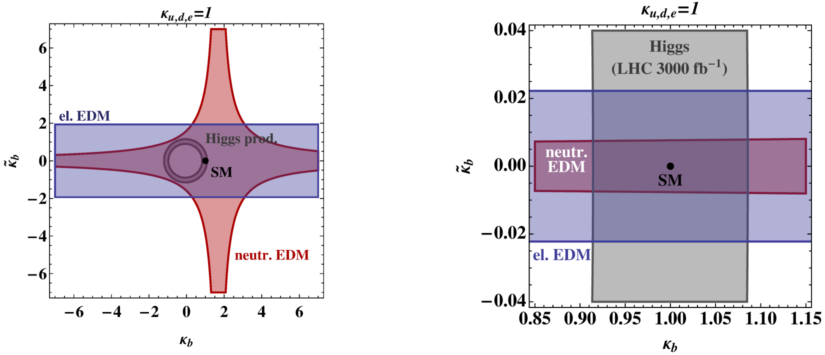
- Modifications of $gg \to h$, $h \to \gamma\gamma$ due to $\kappa_b \neq 1$, $\tilde{\kappa}_b \neq 0$ are subleading
- $\Rightarrow$ Main effect: modifications of branching ratios / total decay rate

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

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

- 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

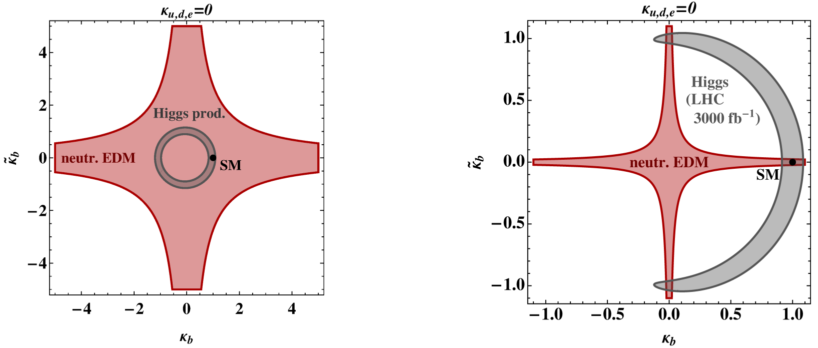
Combined bounds: SM couplings to light fermions



- 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 bounds: only bottom Yukawa

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

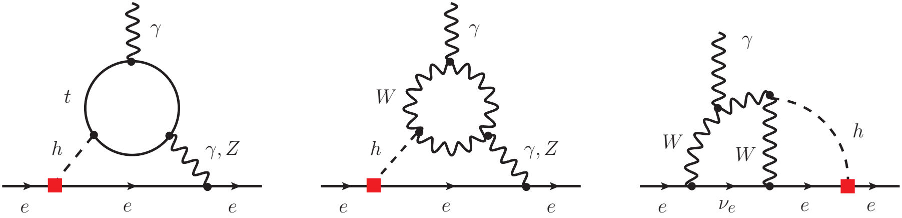


What do we know about the electron Yukawa?

It's small and real! (In the SM.)

$$y_e^{\mathrm{SM}} = \sqrt{2}\frac{m_e}{v} \simeq 2.9 \times 10^{-6}$$

Indirect bounds: Imaginary part – electron EDM

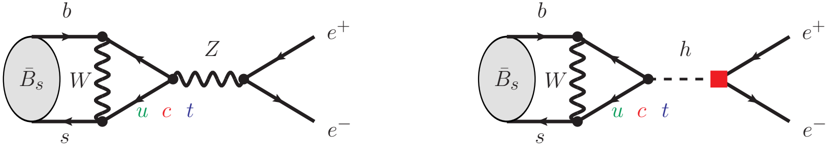


- $\ldots +$ 117 more two-loop diagrams
- Complete analytic result [Altmannshofer, Brod, Schmaltz, arxiv:1503.04830]
- $|d_e/e| < 8.7 \times 10^{-29}\,\text{cm}$ (90% CL) [ACME 2013]
- $\ldots$ leads to $|\tilde{\kappa}_e| < 0.017$

Indirect bounds: Real part – $(g-2)_e$

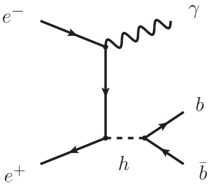
- Usually, the measurement of $a_e \equiv (g-2)_e/2$ is used to extract α
- Using independent α measurement, can make a prediction for a_e
  [cf. Giudice et al., arXiv:1208.6583]
- With
  - $\alpha = 1/137.035999037(91)$ [Bouchendira et al., arXiv:1012.3627]
  - $a_e = 11596521807.3(2.8) \times 10^{-13}$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

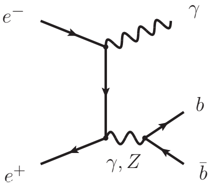
Indirect bounds: Real part – rare B decays



- SM prediction [Bobeth et al., arXiv:1311.0903]
  - $\text{Br}(B_s \to e^+e^-)_{\text{SM}} = (8.54 \pm 0.55) \times 10^{-14}$
  - $\text{Br}(B_d \to e^+e^-)_{\text{SM}} = (2.48 \pm 0.21) \times 10^{-15}$
- Current bounds [CDF 2009]
  - $\text{Br}(B_s \to e^+e^-) < 2.8 \times 10^{-7}$
  - $\text{Br}(B_d \to e^+e^-) < 8.3 \times 10^{-8}$
- ... leads to $|\kappa_e| = \mathcal{O}(10^6)$

Collider bounds: LEP II





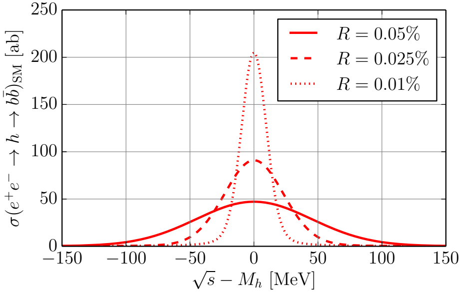
- LEP / LEP II did not run on the Higgs resonance
- They collected $\sim 500/\text{pb}$ per experiment between $\sqrt{s} = 189 \ldots 207$ GeV
- A bound could be obtained via "radiative return" to the Z pole
- Requiring $N_{\text{r.r.}}/\sqrt{N_{\text{bkg.}}} = 1$ we find $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \lesssim 2000$
- A dataset at $\sqrt{s} = 130$ GeV leads a similar bound

Collider bounds: CMS

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

- CMS limit $\mathrm{Br}(h \to e^+e^-) < 0.0019$ [CMS, arxiv:1410.6679]
  leads to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} < 611$
- Estimated future sensitivities at hadron colliders:
  - 14 TeV LHC with 3000/fb: $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 150$
  - 100 TeV collider with 3000/fb: $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 75$

Collider bounds: Future e^+e^- machines



- A future e^+e^- machine...
  - collecting 100 fb^{-1} on the Higgs resonance
  - assuming 0.05% beam-energy spread
- ...would be sensitive to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 15$

Summary

- Precision observables can often yield constraints that are compatible or stronger than bounds from direct searches
- EMDs yield strong constraints on CP-violating Yukawa couplings
- FCNC down-sector transitions yield strong constraints on up-sector diagonal couplings
- The electron Yukawa will likely never be measured precisely