Nonstandard Yukawa Couplings

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Workshop "The CP nature of the Higgs boson"

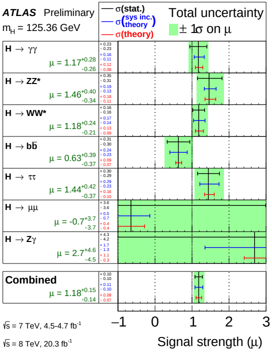
Amherst Center for Fundamental Interactions – May 2, 2015

Motivation – NP at LHC

- We have found New Physics (NP) at the LHC! $\Rightarrow$ The Higgs
- Yet, we still need to find NP beyond the Standard Model (BSM)
- The discovery of the/a Higgs boson opens a new window to NP BSM
- CP violation
  - In the quark sector consistent with SM
  - Already probe scales of up to $\mathcal{O}(10^4)$ TeV
  - CP violation in the Higgs sector?
- Interesting for electroweak baryogenesis

Motivation – SM Higgs

- Higgs couplings completely determined in the SM
- SM Yukawas are
  - flavor-diagonal
  - real (CP-conserving)
- Experimentally, we know nearly nothing about the light-fermion Yukawas



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 $\to$ CP violation
- More generally, we write:

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

Motivation – baryogenesis

[Huber, Pospelov, Ritz, hep-ph/0610003]

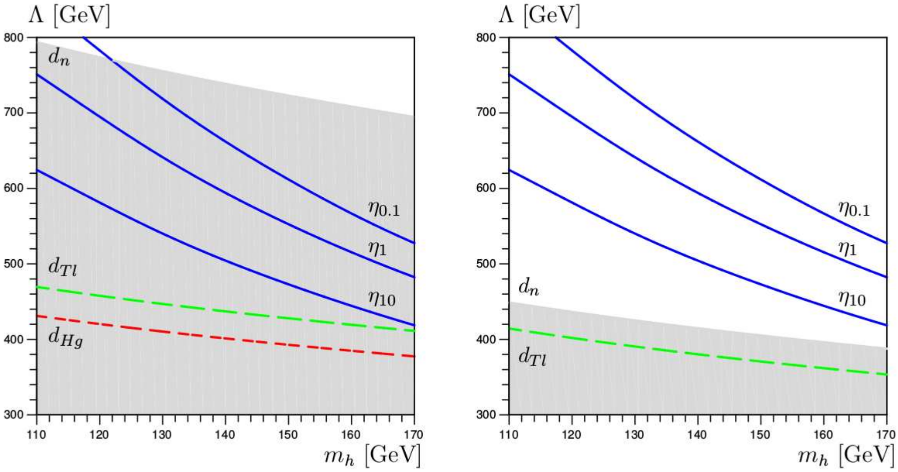
- A minimal setup for baryogenesis:

$$\mathcal{L} = \frac{1}{\Lambda^2}(H^\dagger H)^3 + \frac{Z_t}{\Lambda^2}(H^\dagger H)\bar{Q}_3 H^c t_R$$

- $\Lambda \sim 500 - 800\,\mathrm{GeV}$ gives correct η_b
- In principle there are more operators
- Simple UV completion: Second heavy Higgs doublet H_h
- $\Lambda \sim M_{H_h}$

Motivation – EDM constraints on baryogenesis

[Huber, Pospelov, Ritz, hep-ph/0610003]

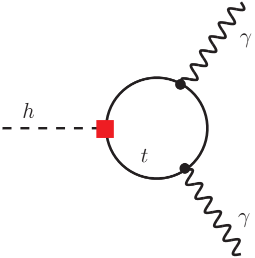


Outline

- CPV Yukawa couplings
- Light-fermion Yukawas
- Flavor changing Higgs couplings

CP-violating Yukawa couplings

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



- In the SM, Yukawa coupling to fermion f is

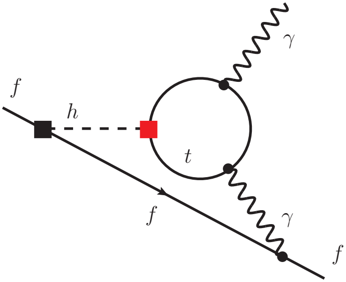
$$\mathcal{L}_Y = -\frac{y_f}{\sqrt{2}} \bar{f} f \, h$$

- We will look at modification

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

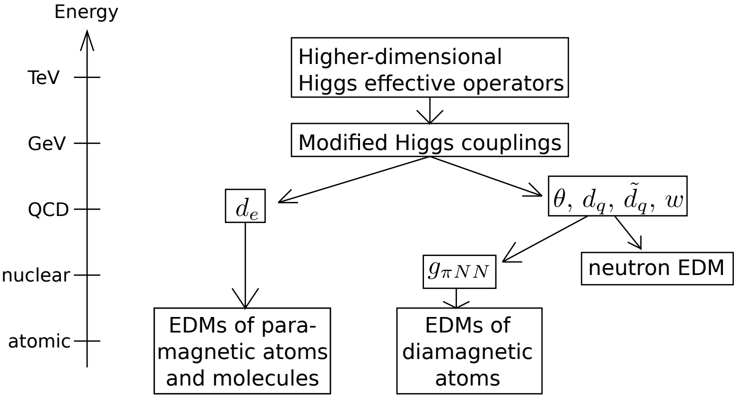
- New contributions will modify Higgs production cross section and decay rates

. . . 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



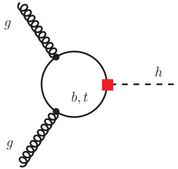
[Adapted from Pospelov et al., 2005]

CPV in htt couplings

Constraints from $gg \to h$

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

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



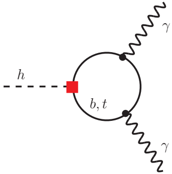
- c_g, $\tilde{c}_g$ given in terms of loop functions
- $\kappa_g \equiv c_g / c_{g,\text{SM}}$, $\tilde{\kappa}_g \equiv 3\tilde{c}_g / 2c_{g,\text{SM}}$

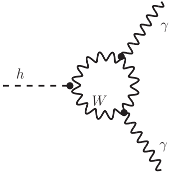
$$\frac{\sigma(gg \to h)}{\sigma(gg \to h)_{\text{SM}}} = |\kappa_g|^2 + |\tilde{\kappa}_g|^2 = \kappa_t^2 + 2.6\,\tilde{\kappa}_t^2 + 0.11\,\kappa_t\,(\kappa_t - 1)$$

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
- $\kappa_\gamma \equiv c_\gamma / c_{\gamma,\text{SM}}$, $\tilde{\kappa}_\gamma \equiv 3\tilde{c}_\gamma / 2c_{\gamma,\text{SM}}$

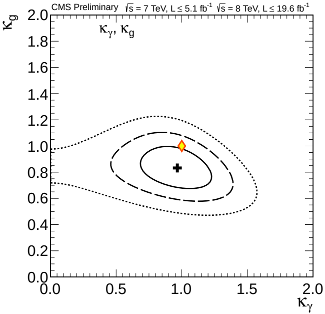
$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\text{SM}}} = |\kappa_\gamma|^2 + |\tilde{\kappa}_\gamma|^2 = (1.28 - 0.28\,\kappa_t)^2 + (0.43\,\tilde{\kappa}_t)^2$$

LHC input

- Naive weighted average of ATLAS, CMS

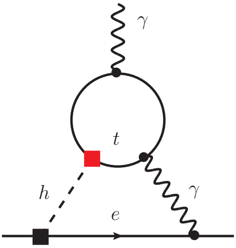
$$\kappa_{g,\text{WA}} = 0.91 \pm 0.08\,, \quad \kappa_{\gamma,\text{WA}} = 1.10 \pm 0.11$$

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



[CMS-PAS-HIG-13-005]

Electron EDM

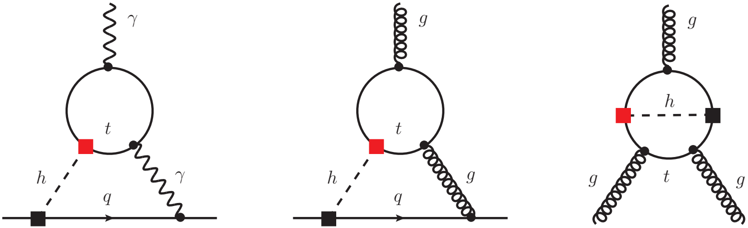


- EDM induced via "Barr-Zee" diagrams [Weinberg 1989, Barr & Zee 1990]
- $|d_e/e| < 8.7 \times 10^{-29}\,\text{cm}$ (90% CL) [ACME 2013] with ThO molecules

$$|\tilde{\kappa}_t| < 0.01$$

- Constraint on $\tilde{\kappa}_t$ vanishes if Higgs does not couple to electron

Neutron EDM



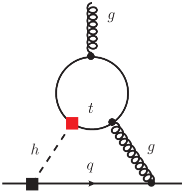
- Three operators; will mix, need to perform RGE analysis

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

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

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

Mercury EDM

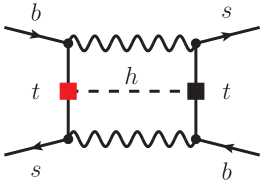


- Diamagnetic atoms also provide constraints
- $|d_{\mathrm{Hg}}/e| < 3.1 \times 10^{-29}\,\mathrm{cm}$ (95% CL) [Griffith et al., 2009]
- Dominant contribution from CP-odd isovector pion-nucleon interaction

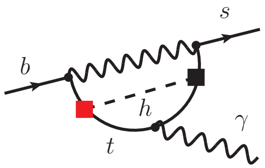
$$\frac{d_{\mathrm{Hg}}}{e} = -\left(4^{+8}_{-2}\right)\,\left[3.1\,\tilde{\kappa}_t - 3.2 \cdot 10^{-2}\,\kappa_t\tilde{\kappa}_t\right] \cdot 10^{-29}\,\mathrm{cm}$$

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

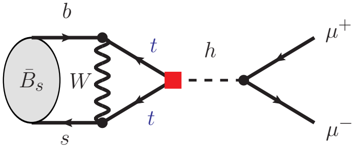
Other low-energy constraints



- No effects in dim. six operators

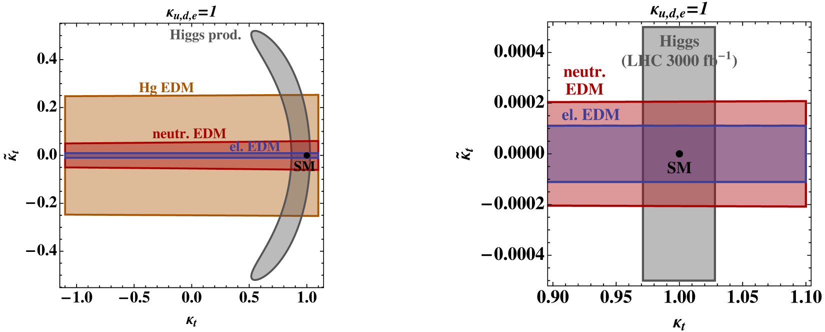


- $\mathcal{O}(100)$ effects allowed by data



- $\mathcal{O}(100)$ effects allowed by data

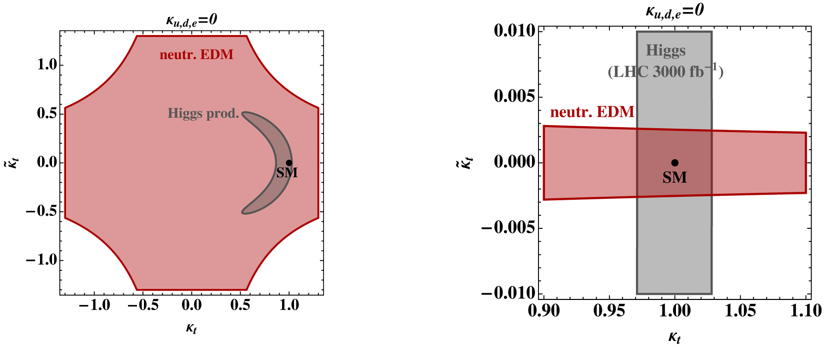
Combined constraints on top coupling



- 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



CPV in *hbb* 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

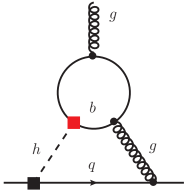
$$\mathrm{Br}(h \to b\bar{b}) = \frac{\left(\kappa_b^2 + \tilde{\kappa}_b^2\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

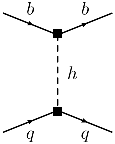
$$\mathrm{Br}(h \to X) = \frac{\mathrm{Br}(h \to X)_{\mathrm{SM}}}{1 + \left(\kappa_b^2 + \tilde{\kappa}_b^2 - 1\right)\mathrm{Br}(h \to b\bar{b})_{\mathrm{SM}}}$$

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

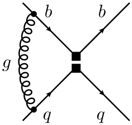
RGE analysis of the *b*-quark contribution to EDMs

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

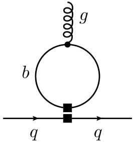




- Integrate out Higgs
- $\mathcal{O}_1^q = \bar{q}q\,\bar{b}i\gamma_5 b$

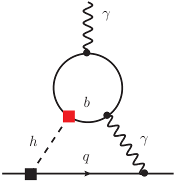


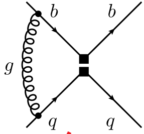
- Mixing into
- $\mathcal{O}_4^q = \bar{q}\sigma_{\mu\nu}T^a q\,\bar{b}i\sigma^{\mu\nu}\gamma_5 T^a b$



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

RGE analysis of the b-quark contribution to EDMs

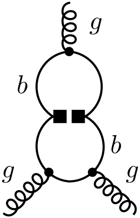




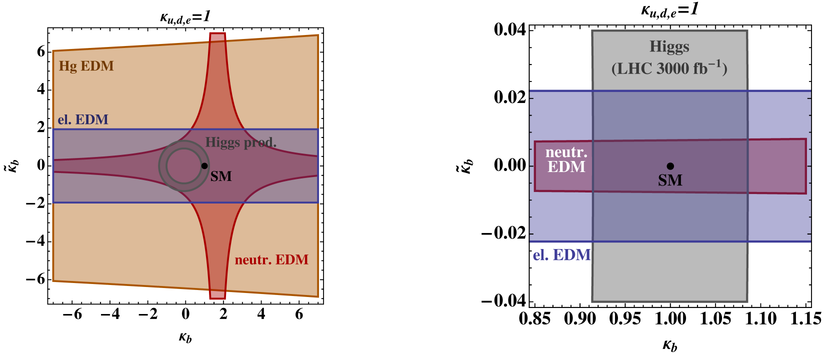
- $\mathcal{C}_5^q(\mu_b) = -4\,\frac{\alpha\,\alpha_s}{(4\pi)^2}\,Q_q \log^2\frac{m_b^2}{M_h^2} + \left(\frac{\alpha_s}{4\pi}\right)^3 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}\gamma_{87}^{(0)}}{48}\,\log^3\frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^4)\,,$

- $\mathcal{C}_6^q(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{14}^{(0)}\gamma_{48}^{(0)}}{8}\,\log^2\frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)\,,$

- $\mathcal{C}_7(\mu_b) = \left(\frac{\alpha_s}{4\pi}\right)^2 \frac{\gamma_{5,11}^{(1)}}{2}\,\log\frac{m_b^2}{M_h^2} + \mathcal{O}(\alpha_s^3)\,.$



Combined constraints on bottom couplings



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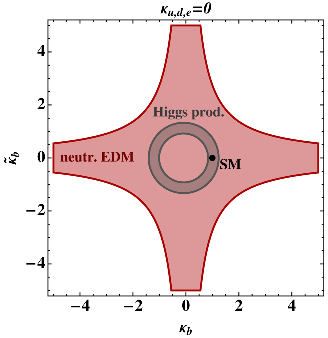
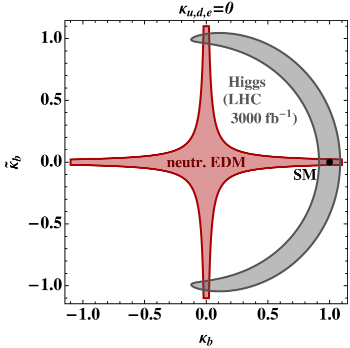
Combined constraints on bottom couplings

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

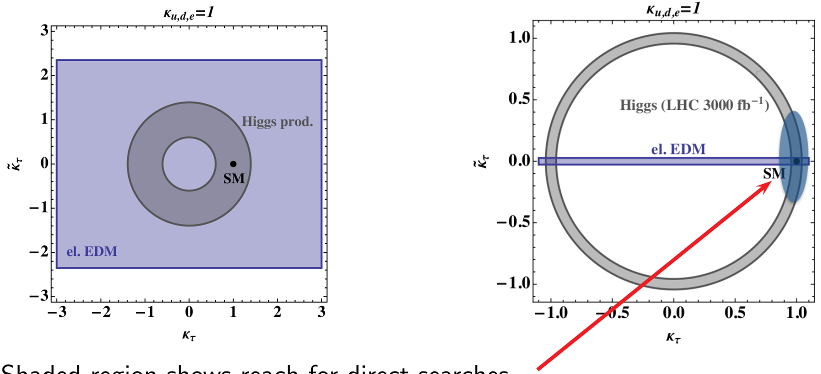




CPV in $h\tau\tau$ couplings

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

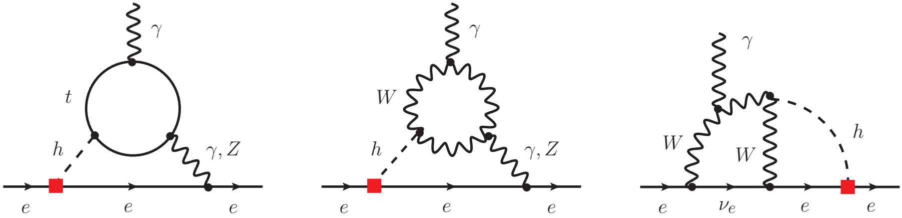


- Shaded region shows reach for direct searches

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

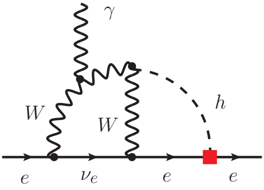
CPV in light-fermion Yukawas

Electron Yukawa



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

Light-quark Yukawas



- In principle have all ingredients for light quarks:
- Combine complete analytic two-loop result and RGE evolution
- $|d_e/e| < 8.7 \times 10^{-29}$ cm (90% CL) [ACME 2013]
- ... leads to $|\tilde{\kappa}_q| < 0.1$??? [work in progress]

What do we know about the light-fermion Yukawas?

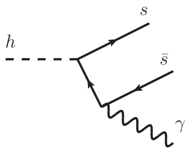
Electron Yukawa – Collider bounds

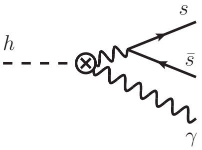
$$\mathrm{Br}(h \to e^+e^-) = \frac{\left(\kappa_e^2 + \tilde{\kappa}_e^2\right)\mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}}}{1 + \left(\kappa_e^2 + \tilde{\kappa}_e^2 - 1\right)\mathrm{Br}(h \to e^+e^-)_{\mathrm{SM}}}$$

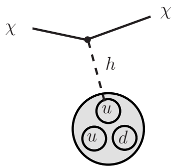
- CMS limit $\mathrm{Br}(h \to e^+e^-) < 0.0019$ [CMS, arxiv:1410.6679]
- leads to $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} < 611$ [Altmannshofer, Brod, Schmaltz, arxiv:1503.04830]
- Gain one order of magnitude at a 100 TeV hadron collider with 3000/fb
- Measure up to a order of a few at a dedicated electron-positron collider

(How) Can we probe the light-quark Yukawas?

- Processes with off-shell Higgs and external SM particles difficult:
  - Scalar Higgs current competes with neutral currents induced by g, γ, Z
- Two options:
  - On-shell Higgs decays (e.g. $h \to \phi\gamma$) [Kagan et al., arxiv:1406.1722]
  - New probes: DM

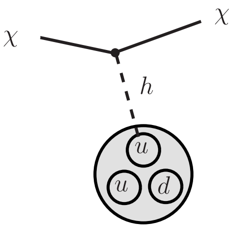


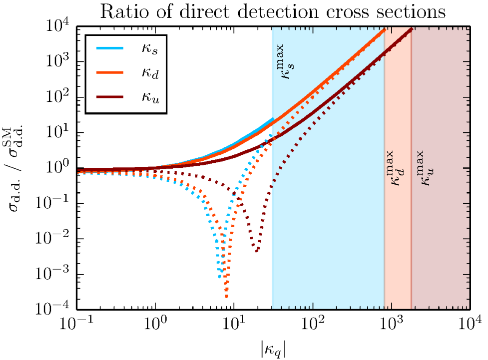




Direct detection – Yukawa dependence

[Bishara, Brod, Uttayarat, Zupan, arXiv:1504.04022]



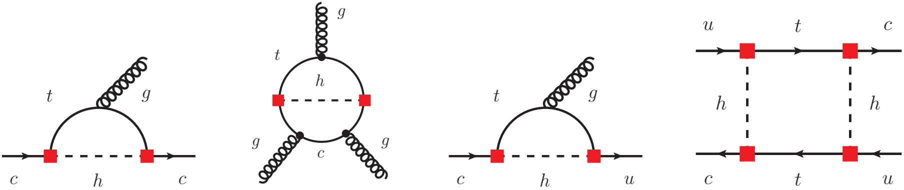


Flavor-changing Higgs couplings

$$\mathcal{L} \supset -Y_{tq}\bar{t}_L q_R - Y_{qt}\bar{q}_L t_R + \text{h.c.}$$

Hadronic

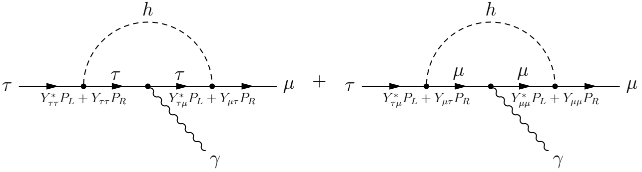
[Gorbahn, Haisch, arxiv:1404.4873]

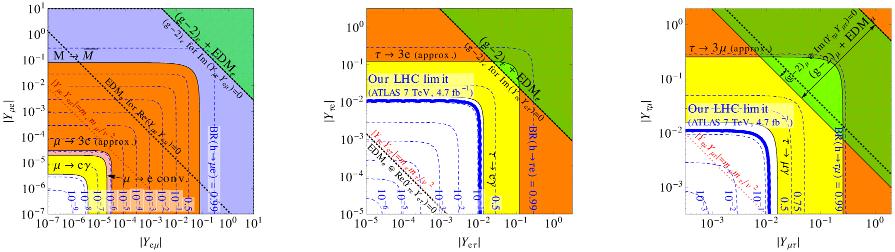


Observable	Coupling	Present bound	Future sensitivity
$t \to ch$	$\sqrt{\lvert Y_{tc}\rvert^2 + \lvert Y_{ct}\rvert^2}$	0.14	$2.8 \cdot 10^{-2}$
$t \to uh$	$\sqrt{\lvert Y_{tu}\rvert^2 + \lvert Y_{ut}\rvert^2}$	0.13	$2.8 \cdot 10^{-2}$
d_n	$\lvert \mathrm{Im}\,(Y_{tc} Y_{ct})\rvert$	$5.0 \cdot 10^{-4}$	$1.7 \cdot 10^{-6}$
	$\lvert \mathrm{Im}\,(Y_{tu} Y_{ut})\rvert$	$4.3 \cdot 10^{-7}$	$1.5 \cdot 10^{-9}$
ΔA_{CP}	$\lvert \mathrm{Im}\,(Y_{ut}^* Y_{ct})\rvert$	$4.0 \cdot 10^{-4}$	—
$D - \bar{D}$ mixing	$\sqrt{\lvert \mathrm{Im}\,(Y_{tc}^* Y_{ut}^* Y_{tu} Y_{ct})\rvert}$	$4.1 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$

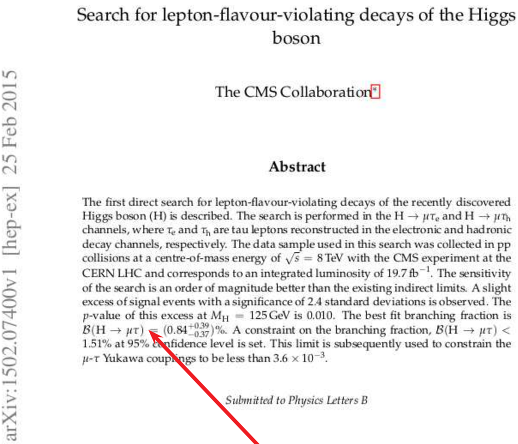
Leptonic

[Harnik, Kopp, Zupan, arxiv:1209.1397]





A hint of new physics?



Search for lepton-flavour-violating decays of the Higgs boson

The CMS Collaboration[*]

Abstract

The first direct search for lepton-flavour-violating decays of the recently discovered Higgs boson (H) is described. The search is performed in the $H \to \mu\tau_e$ and $H \to \mu\tau_h$ channels, where τ_e and τ_h are tau leptons reconstructed in the electronic and hadronic decay channels, respectively. The data sample used in this search was collected in pp collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of 19.7 fb^{-1}. The sensitivity of the search is an order of magnitude better than the existing indirect limits. A slight excess of signal events with a significance of 2.4 standard deviations is observed. The p-value of this excess at $M_H = 125$ GeV is 0.010. The best fit branching fraction is $\mathcal{B}(H \to \mu\tau) = (0.84^{+0.39}_{-0.37})\%$. A constraint on the branching fraction, $\mathcal{B}(H \to \mu\tau) < 1.51\%$ at 95% confidence level is set. This limit is subsequently used to constrain the μ-τ Yukawa couplings to be less than 3.6×10^{-3}.

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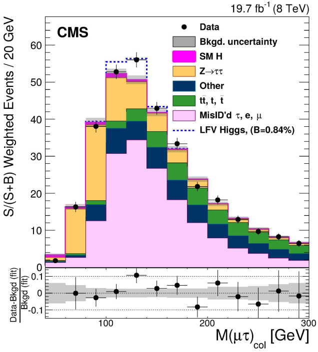
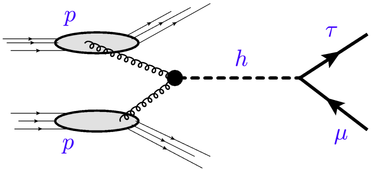
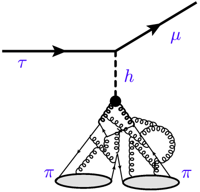


$$\mathrm{BR}(h \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$$

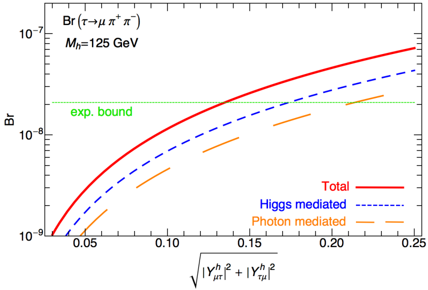
Rare τ decays

[Celis, Cirigliano, Passemar, arxiv:1309.3564]





- $\tau \to \mu\gamma$ can get large dipole contribution
- $\tau \to \mu\pi\pi$ gives more direct constraint



Summary

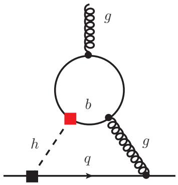
- EDMs give strong bounds on Higgs CP violation (and FC transitions)
  - Complementary to collider constraints
  - . . . but depend on additional assumptions
- We don't know much about the light-fermion Yukawas

Appendix

CP violation – reminder

- In the SM, only CP violation comes from electroweak sector (CKM phase)
- Switch off weak interactions:
  $K_1 = \frac{1}{\sqrt{2}}(K^0 + \bar{K}^0)$, $K_2 = (K^0 - \bar{K}^0)/\sqrt{2}$
  are CP-even / CP-odd eigenstates
- Weak interactions lead to a superposition via box diagrams – K_L and K_S
- They are not CP eigenstates
- Analogy would be scalar h^0 and pseudoscalar A^0 Higgs in 2HDM
- If Higgs potential is not CP symmetric, lightest mass eigenstate is superposition $p\, h^0 + q\, A^0$

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

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

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

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

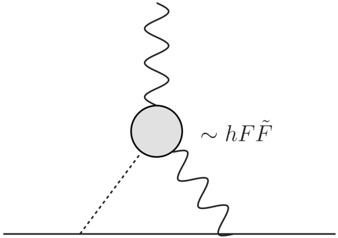
Some models

Model	κ_t	$\kappa_{c(u)}/\kappa_t$	$\tilde{\kappa}_t/\kappa_t$	$\tilde{\kappa}_{c(u)}/\kappa_t$
SM	1	1	0	0
NFC	$V_{hu}\, v_W/v_u$	1	0	0
MSSM	$\cos\alpha/\sin\beta$	1	0	0
GL	$1+\mathcal{O}(\epsilon^2)$	$\simeq 3(7)$	$\mathcal{O}(\epsilon^2)$	$\mathcal{O}(\kappa_{c(u)})$
GL2	$\cos\alpha/\sin\beta$	$\simeq 3(7)$	$\mathcal{O}(\epsilon^2)$	$\mathcal{O}(\kappa_{c(u)})$
MFV	$1+\frac{\text{Re}(a_u v_W^2+2b_u m_t^2)}{\Lambda^2}$	$1-\frac{2\text{Re}(b_u)m_t^2}{\Lambda^2}$	$\frac{\Im(a_u v_W^2+2b_u m_t^2)}{\Lambda^2}$	$\frac{\Im(a_u v_W^2)}{\Lambda^2}$
RS	$1-\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$	$1+\mathcal{O}\left(\frac{v_W^2}{m_{KK}^2}\bar{Y}^2\right)$
pNGB	$1+\mathcal{O}\left(\frac{v_W^2}{f^2}\right)+\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$1+\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$	$\mathcal{O}\left(y_*^2\lambda^2\frac{v_W^2}{M_*^2}\right)$

Electron Yukawa

Limits from electron EDM

- Constraint on $y_e \cdot \tilde{c}$ from electron EDM

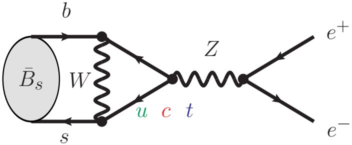


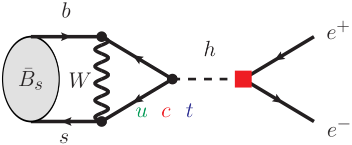
- $\tilde{c} \lesssim 10^{-3}$ for SM electron Yukawa [McKeen et al., Phys.Rev. D86 (2012) 113004 [arXiv:1208.4597[hep-ph]] – updated with new ACME result]
- Vanishes if Higgs does not couple to electron, or if there are cancellations

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

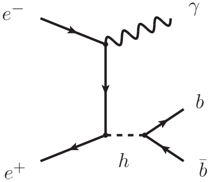
Indirect bounds: Real part – rare B decays

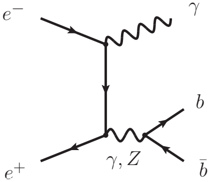




- SM prediction [Bobeth et al., arXiv:1311.0903]
  - $\mathrm{Br}(B_s \to e^+e^-)_{\mathrm{SM}} = (8.54 \pm 0.55) \times 10^{-14}$
  - $\mathrm{Br}(B_d \to e^+e^-)_{\mathrm{SM}} = (2.48 \pm 0.21) \times 10^{-15}$
- Current bounds [CDF 2009]
  - $\mathrm{Br}(B_s \to e^+e^-) < 2.8 \times 10^{-7}$
  - $\mathrm{Br}(B_d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

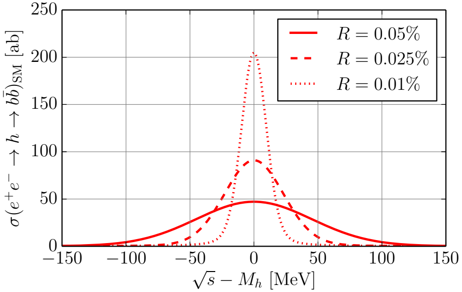
Collider bounds: LEP II





- 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: 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 $\sqrt{\kappa_e^2 + \tilde{\kappa}_e^2} \sim 15$