

Constraining top-Higgs couplings at high and low energy

Emanuele Mereghetti

XIIth Quark Confinement and the Hadron Spectrum

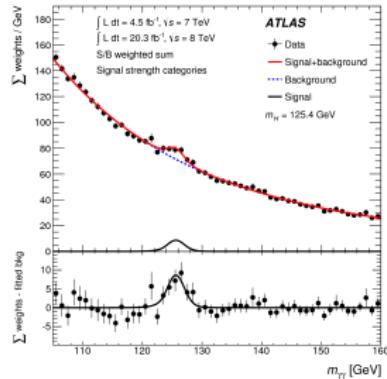
August 28th, 2016

with V. Cirigliano, W. Dekens (LANL) and J. de Vries (NIKHEF)



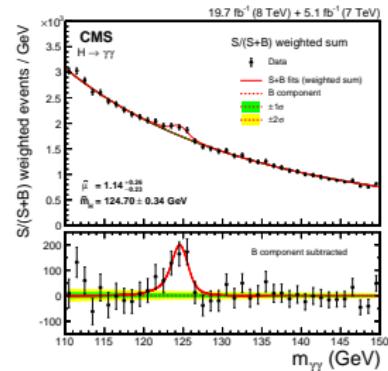
Introduction

- the Standard Model works just fine



ATLAS collaboration, '14.

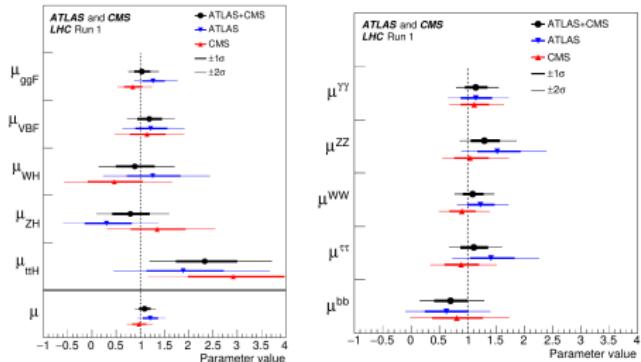
- last missing piece discovered @ LHC



CMS collaboration, '14.

Introduction

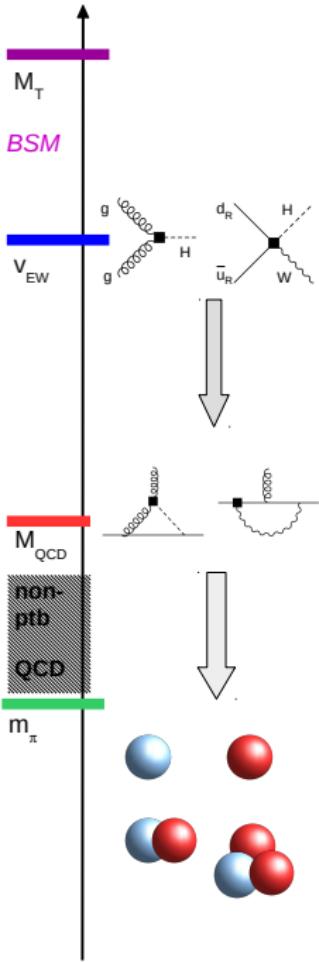
- the Standard Model works just fine



- last missing piece discovered @ LHC
- SM-like, so far . . . with large uncertainties
- is there room for deviations?

look at top-Higgs couplings

Framework: the linear SM-EFT



Theory Framework: linear SM-EFT

- full set of dimension 5 and 6 operator known

Buchmuller & Wyler '86, Weinberg '89, de Rujula *et al.* '91, Grzadkowski *et al.* '10 . . .

- focus on subset that:
- involve top & Higgs

- have CP-breaking component

X^3	φ^6 and $\varphi^4 D^2$	$\psi^2 \varphi^3$
Q_G	$f^{ABC} G_\mu^{Av} B_\nu^{B\mu} G_\rho^{C\mu}$	Q_{φ} $(\varphi^\dagger \varphi)^3$
$Q_{\bar{G}}$	$f^{ABC} \bar{G}_\mu^{Av} G_\nu^{B\mu} G_\rho^{C\mu}$	$Q_{\varphi \square}$ $(\varphi^\dagger \varphi) \square (\varphi^\dagger \varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$ $(\varphi^\dagger D^\mu \varphi)^*$ $(\varphi^\dagger D_\mu \varphi)$
$Q_{\bar{W}}$	$\varepsilon^{IJK} \bar{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$ $(\varphi^\dagger D^\mu \varphi)^*$ $(\varphi^\dagger D_\mu \varphi)$

$X^2 \varphi^2$	$\psi^2 X \varphi$	$\psi^2 \varphi^2 D$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{\mu\nu}$	Q_{eW} $(\bar{l}_\mu \sigma^{\mu\nu} e_\nu)^T \varphi W_\nu^I$
$Q_{\varphi \bar{G}}$	$\varphi^\dagger \varphi \bar{G}_{\mu\nu}^A G^{\mu\nu}$	Q_{eS} $(\bar{l}_\mu \sigma^{\mu\nu} e_\nu)_\tau \varphi B_{\nu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W^{I\mu}$	$Q_{\bar{e}G}$ $(\bar{q}_\mu \sigma^{\mu\nu} T^A u_\nu)_\tau \bar{\varphi} G_{\mu\nu}^A$
$Q_{\varphi \bar{W}}$	$\varphi^\dagger \varphi \bar{W}_\mu^I W^{I\mu}$	$Q_{\bar{e}W}$ $(\bar{q}_\mu \sigma^{\mu\nu} u_\nu)^T \tilde{\varphi} W_\nu^I$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{\bar{e}B}$ $(\bar{q}_\mu \sigma^{\mu\nu} u_\nu)_\tau \tilde{\varphi} \bar{B}_{\mu\nu}$
$Q_{\varphi \bar{B}}$	$\varphi^\dagger \varphi \bar{B}_{\mu\nu} B^{\mu\nu}$	Q_{dG} $(\bar{q}_\mu \sigma^{\mu\nu} T^A d_\nu)_\tau \varphi G_{\mu\nu}^A$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_\mu^I B^{\mu\nu}$	Q_{dW} $(\bar{q}_\mu \sigma^{\mu\nu} d_\nu)^T \varphi W_\nu^I$
$Q_{\varphi \bar{WB}}$	$\varphi^\dagger \tau^I \varphi \bar{W}_\mu^I B^{\mu\nu}$	$Q_{d\bar{B}}$ $(\bar{q}_\mu \sigma^{\mu\nu} d_\nu)_\tau \varphi B_{\mu\nu}$

$(\bar{L}L)(LL)$	$(\bar{R}R)(RR)$	$(\bar{L}L)(RR)$
Q_{ll} $(\bar{l}_\mu \gamma_\mu l_\tau)_\tau (\bar{l}_\nu \gamma^\mu l_\tau)$	Q_{ee} $(\bar{e}_\mu \gamma_\mu e_\tau)_\tau (\bar{e}_\nu \gamma^\mu e_\tau)$	Q_{le} $(\bar{l}_\mu \gamma_\mu l_\tau)_\tau (\bar{e}_\nu \gamma^\mu e_\tau)$
$Q_{l\bar{q}}^{(1)}$ $(\bar{q}_\mu \gamma_\mu q_\nu)_\tau (\bar{q}_\lambda \gamma^\mu q_\lambda)$	Q_{lu} $(\bar{u}_\mu \gamma_\mu u_\nu)_\tau (\bar{u}_\lambda \gamma^\mu u_\lambda)$	$Q_{l\bar{u}}$ $(\bar{l}_\mu \gamma_\mu l_\tau)_\tau (\bar{u}_\nu \gamma^\mu u_\tau)$
$Q_{\bar{q}q}^{(3)}$ $(\bar{q}_\mu \gamma_\mu \tau^I q_\nu)_\tau (\bar{q}_\lambda \gamma^\mu \tau^I q_\lambda)$	Q_{ld} $(\bar{d}_\mu \gamma_\mu d_\nu)_\tau (\bar{d}_\lambda \gamma^\mu d_\lambda)$	$Q_{l\bar{d}}$ $(\bar{l}_\mu \gamma_\mu l_\tau)_\tau (\bar{d}_\nu \gamma^\mu d_\lambda)$
$Q_{lq}^{(1)}$ $(\bar{l}_\mu \gamma_\mu l_\tau)_\tau (\bar{q}_\nu \gamma^\mu q_\lambda)$	Q_{ce} $(\bar{e}_\mu \gamma_\mu e_\tau)_\tau (\bar{u}_\lambda \gamma^\mu u_\tau)$	Q_{qc} $(\bar{q}_\mu \gamma_\mu q_\nu)_\tau (\bar{e}_\lambda \gamma^\mu e_\tau)$
$Q_{lq}^{(3)}$ $(\bar{l}_\mu \gamma_\mu \tau^I l_\tau)_\tau (\bar{q}_\nu \gamma^\mu \tau^I q_\lambda)$	Q_{cd} $(\bar{e}_\mu \gamma_\mu e_\tau)_\tau (\bar{d}_\lambda \gamma^\mu d_\lambda)$	Q_{qu} $(\bar{q}_\mu \gamma_\mu q_\nu)_\tau (\bar{u}_\lambda \gamma^\mu u_\tau)$
<i>B-violating</i>		
$Q_{lqq\bar{q}}$ $(\bar{l}_\mu^2 \tau_\tau)_\tau (\bar{d}_\lambda^2 d_\lambda)$	Q_{duq} $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(\bar{d}_\mu^{\alpha})^T C u_\nu^\beta \right] \left[(q_\lambda^{\gamma j})^T C l_\tau^k \right]$	
$Q_{q\bar{q}qd}^{(1)}$ $(\bar{q}_\mu^1 \tau_\tau)_\tau \varepsilon_{jk} (\bar{q}_\lambda^2 d_\lambda)$	Q_{qqu} $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \left[(\bar{q}_\mu^{\alpha})^T C q_\nu^{\beta k} \right] \left[(u_\lambda^{\gamma j})^T C e_\tau \right]$	
$Q_{q\bar{q}qd}^{(3)}$ $(\bar{q}_\mu^2 \tau_\tau^A)_\tau \varepsilon_{jk} (\bar{q}_\lambda^3 T^A d_\lambda)$	$Q_{qqg}^{(1)}$ $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{\mu\nu} \left[(\bar{q}_\mu^{\alpha})^T C q_\nu^{\beta k} \right] \left[(q_\lambda^{\gamma m})^T C l_\tau^n \right]$	
$Q_{lqq\bar{q}}$ $(\bar{l}_\mu^2 \tau_\tau)_\tau \varepsilon_{jk} (\bar{q}_\lambda^2 u_\tau)$	$Q_{q\bar{q}q}$ $\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} (T^I \varepsilon)_{jk} (T^I \varepsilon)_{mn} \left[(q_\mu^{\alpha i})^T C q_\nu^{\beta k} \right] \left[(q_\lambda^{\gamma m})^T C l_\tau^n \right]$	
$Q_{lqq\bar{q}}$ $(\bar{l}_\mu^2 \tau_\tau)_\tau \varepsilon_{jk} (\bar{q}_\lambda^2 u_\tau)$	$Q_{d\bar{q}u}$ $\varepsilon^{\alpha\beta\gamma} \left[(\bar{d}_\mu^{\alpha})^T C u_\nu^\beta \right] \left[(u_\lambda^{\gamma j})^T C e_\tau \right]$	

Grzadkowski *et al.* '10

Theory Framework: linear SM-EFT

- full set of dimension 5 and 6 operator known
Buchmuller & Wyler ‘86, Weinberg ‘89, de Rujula *et al.* ‘91, Grzadkowski *et al.* ‘10 . . .
- focus on subset that:
 - involve top & Higgs
 - have CP-breaking component
 - top Yukawa C_Y

$$\mathcal{L}_6 = -y_t(v^2 C_Y) \bar{t}_L t_R h \left(1 + \frac{3}{2} \frac{h}{v} + \frac{1}{2} \frac{h^2}{v^2} \right)$$

$$C_\alpha = c_\alpha + i\tilde{c}_\alpha$$

gauge invariance

$$v^2 C_\alpha = \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$$

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- focus on subset that:
- involve top & Higgs
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- top Yukawa C_Y
- gluon and photon dipoles, C_g & C_γ

$$\mathcal{L}_6 = -y_t \left[(v^2 C_\gamma) \frac{e Q_t}{2v} \bar{t}_L \sigma_{\mu\nu} F^{\mu\nu} t_R + (v^2 C_g) \frac{g_s}{2v} \bar{t}_L \sigma_{\mu\nu} G^{\mu\nu} t_R \right] \left(1 + \frac{h}{v} \right)$$

$$C_\alpha = c_\alpha + i \tilde{c}_\alpha$$

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- focus on subset that:
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 - have CP-breaking component

- top Yukawa C_Y
- gluon and photon dipoles, C_g & C_γ
- weak dipoles, C_{Wt} & C_{Wb}

$$\mathcal{L}_6 = - \left[y_t(v^2 C_{Wt}) \frac{g}{\sqrt{2}v} \bar{b}'_L \sigma^{\mu\nu} t_R W_{\mu\nu}^- + y_b(v^2 C_{Wb}) \frac{g}{\sqrt{2}v} \bar{t}'_L \sigma^{\mu\nu} b_R W_{\mu\nu}^+ \right] \left(1 + \frac{h}{v} \right)$$

$$C_\alpha = c_\alpha + i\tilde{c}_\alpha$$

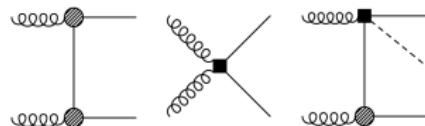
gauge invariance

$$v^2 C_\alpha = \mathcal{O}\left(\frac{v^2}{\Lambda^2}\right)$$

Strategy

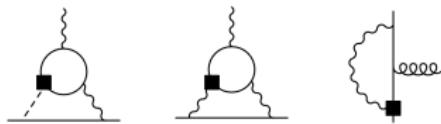
1. effects of C_α on collider processes w. top quarks & Higgs

- $t\bar{t}$ @ 7, 8 & 13 TeV
- single top @ 7, 8 & 13 TeV
- $t\bar{t}h$ @ 7, 8 TeV

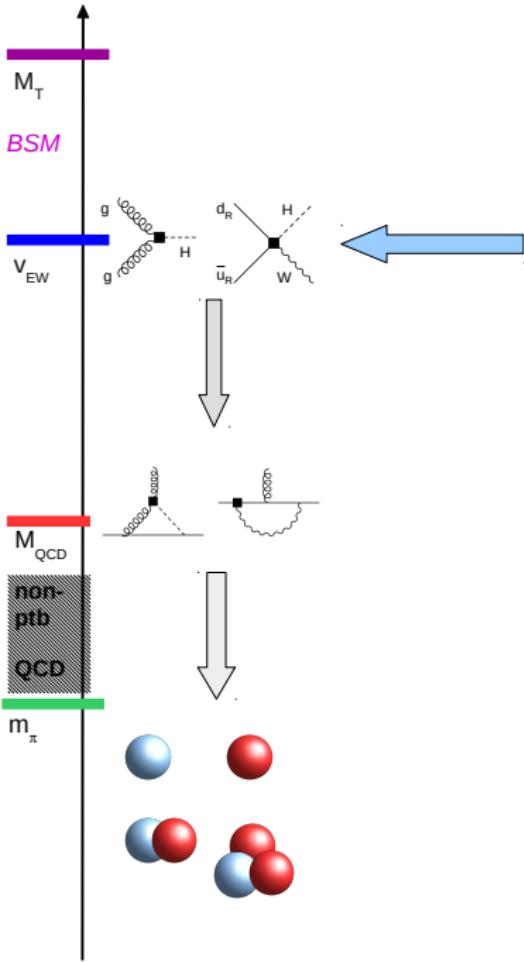


2. “indirect probes”: loop-induced processes with small SM background

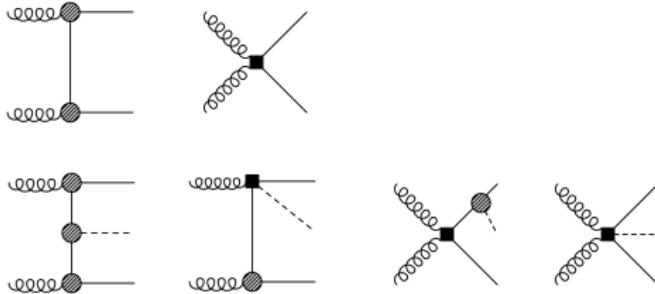
- Higgs production & decays
- rare B decays, $b \rightarrow s\gamma$
- electric dipole moments



Dimension 6 operators at Collider



C_Y , C_g and C_γ . Direct Probes

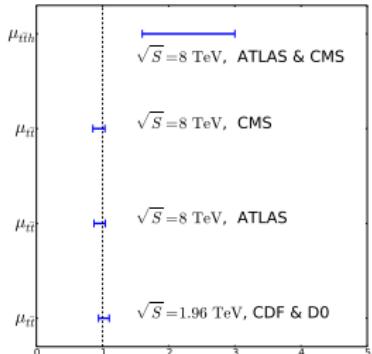


- C_g contributes to $t\bar{t}$ production & $t\bar{t}h$ production ✓
- C_Y affects $t\bar{t}h$ production ✓
- C_γ affects $t\bar{t}Z$, $t\bar{t}\gamma$ ✗ not very sensitive yet

$$\mu_{\bar{t}}(8 \text{ TeV}) = \frac{\sigma_{t\bar{t}}}{\sigma_{SM}} = 1 - 1.3(v^2 c_g) + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

$$\mu_{\bar{t}h}(8 \text{ TeV}) = \frac{\sigma_{t\bar{t}h}}{\sigma_{SM}} = (1 + v^2 c_Y)^2 - 7.1(v^2 c_g) + \mathcal{O}\left(\frac{v^4}{\Lambda^4}\right)$$

C_Y , C_g and C_γ . Direct Probes



$$v^2 c_Y \sim 1$$

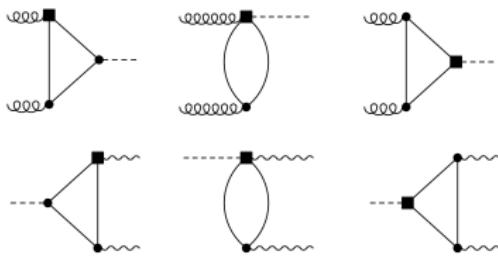
$$v^2 c_g \sim 0.10$$

- C_g contributes to $t\bar{t}$ production & $t\bar{t}h$ production ✓
 - C_Y affects $t\bar{t}h$ production ✓
 - C_γ affects $t\bar{t}Z$, $t\bar{t}\gamma$ ✗ not very sensitive yet

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C_Y , C_g and C_γ . Higgs production and decay

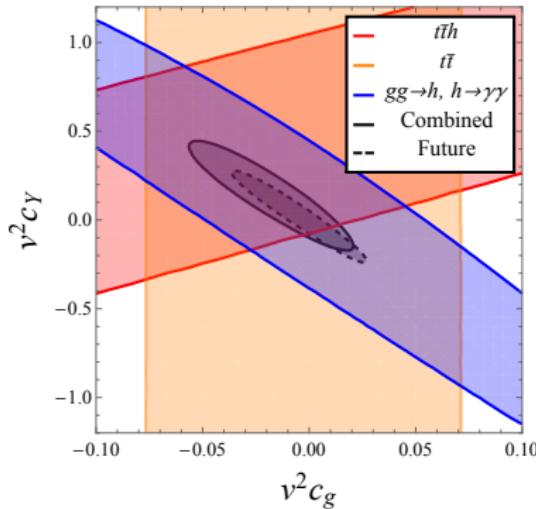


	$X^2\varphi^2$	$\psi^2 X \varphi$
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$(\bar{q}_p \sigma^{\mu\nu} e_r) \tilde{\varphi} B_{\mu\nu}$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$

- $gg \rightarrow h$ and $h \rightarrow gg, h \rightarrow \gamma\gamma$ are loop-induced in the SM
- C_g, C_γ mix onto $X^2\varphi^\dagger\varphi$ operators
- mixing is large, large corrections to SM!

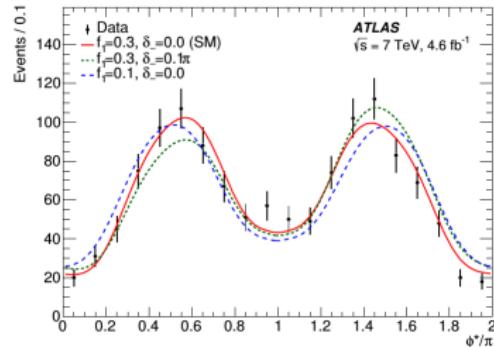
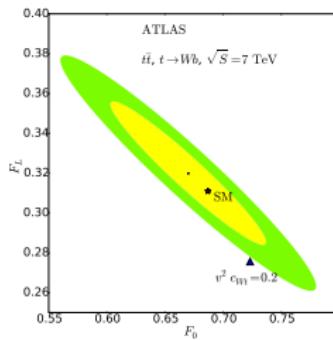
$$\begin{aligned}\mu_{gg \rightarrow h}(8 \text{ TeV}) &= (1 + v^2 c_Y + 7.6 v^2 c_g)^2 \\ \frac{\Gamma_{h \rightarrow \gamma\gamma}}{\Gamma_{h \rightarrow \gamma\gamma}^{SM}} &= (1 - 0.27 v^2 c_Y + 2.0 v^2 c_\gamma)^2\end{aligned}$$

C_Y , C_g and C_γ



- c_g very well constrained \sim few percent level
- c_γ well constrained $\sim \mathcal{O}(10\%)$
- large corrections to the top Yukawa still possible
- Higgs observables very competitive with direct probes

C_{Wt} and C_{Wb}



C_{Wt}

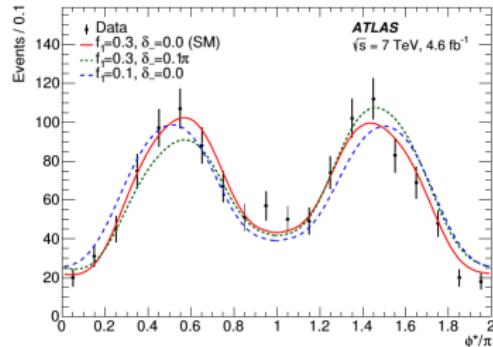
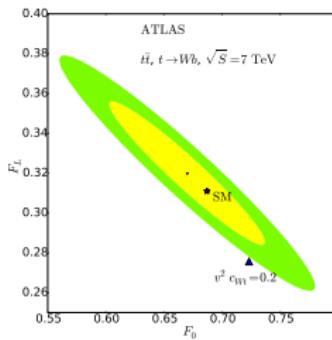
- (t-channel) single top ✓
with NLO corrections
- W boson polarization in t decay ✓
- phase δ^- in single top decay ✓

$$v^2 c_{Wt}, v^2 \tilde{c}_{Wt} \sim 0.2$$

$$\delta^- \propto J_t \cdot (p_e \times p_\nu)$$

analog of D coeff. in β decay
sensitive to the phase of C_{Wt}

C_{Wt} and C_{Wb}



C_{Wt}

- (t-channel) single top ✓ with NLO corrections
- W boson polarization in t decay ✓
- phase δ^- in single top decay ✓

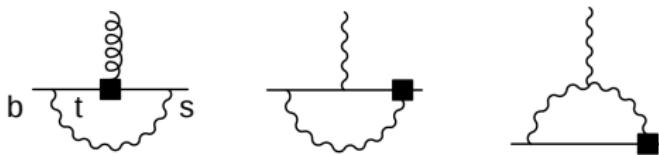
$$\delta^- \propto J_t \cdot (p_e \times p_\nu)$$

C_{Wb}

- suppressed by y_b
- no sensitive collider observables

analog of D coeff. in β decay
sensitive to the phase of C_{Wt}

$b \rightarrow s\gamma$



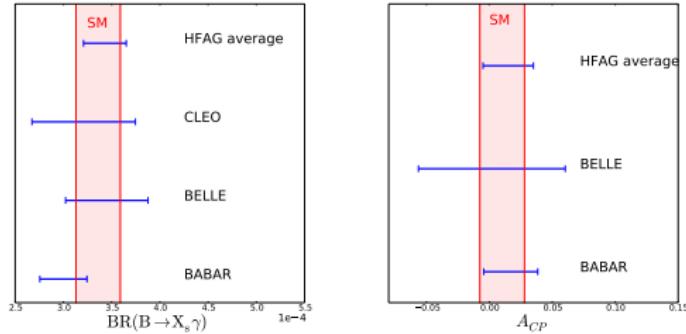
- $b \rightarrow s\gamma$ induced by flavor changing dipoles

$$\mathcal{L}_{b \rightarrow s\gamma} = -\frac{4G_F m_b}{\sqrt{2}} \frac{V_{tb} V_{ts}^*}{(4\pi)^2} \left\{ e C_7 \bar{s}_L \sigma_{\mu\nu} F^{\mu\nu} b_R - g_s C_8 \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu} b_R \right\}$$

- C_g, C_γ, C_{Wt} and C_{Wb} mix onto C_7, C_8

$$C_7 \sim \{C_\gamma, C_{Wt}, C_{Wb}\} \log \frac{m_t}{\Lambda}, \quad C_8 \sim C_g \log \frac{m_t}{\Lambda}$$

$b \rightarrow s\gamma$

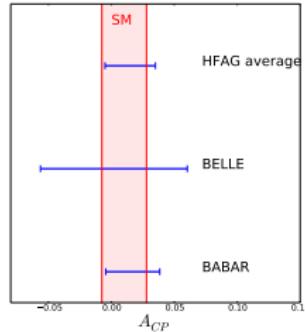
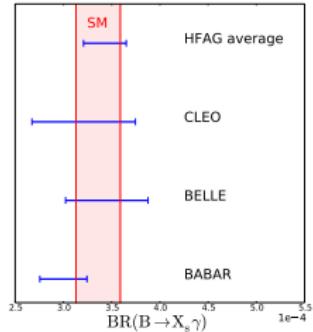


$$\text{BR}(B \rightarrow X_s \gamma) = (3.36 \pm 0.23) \cdot 10^{-4} \left[1 + \text{Re} \left((-2.14 + 0.20i)C_7 + (-0.75 - 0.19i)C_8 \right) \right]$$

$\text{BR}(B \rightarrow X_s \gamma)$

- 5-20% bounds on c_γ, c_{Wt}, c_{Wb}
- weaker bounds on c_g

$b \rightarrow s\gamma$



$$A_{CP}(B \rightarrow X_s \gamma) = \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_{\bar{s}} \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_{\bar{s}} \gamma)}$$

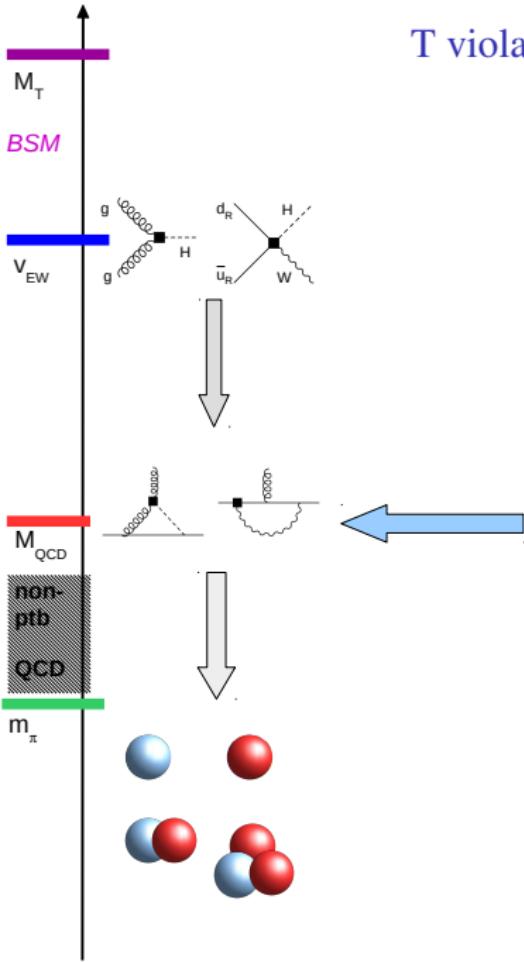
$\text{BR}(B \rightarrow X_s \gamma)$

- 5-20% bounds on c_γ, c_{Wt}, c_{Wb}
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$A_{CP}(B \rightarrow X_s \gamma)$

- sensitive to imaginary parts
- larger non-perturbative errors

T violation at 1 GeV & Connection to EDMs

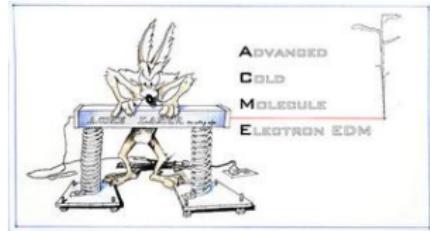


EDMs. Experimental status

- electron EDM
(via ThO energy levels)

$$|d_e| \leq 8.7 \cdot 10^{-16} e \text{ fm}$$

ACME collaboration, '14.



- neutron EDM

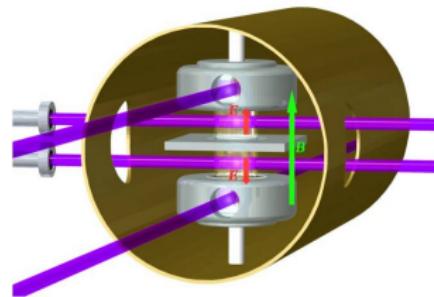
$$|d_n| \leq 2.9 \cdot 10^{-13} e \text{ fm}$$

Baker *et al*, '06.

- Hg EDM

$$|d_{^{199}\text{Hg}}| \leq 6.2 \cdot 10^{-17} e \text{ fm}$$

Graner *et al*, '16.



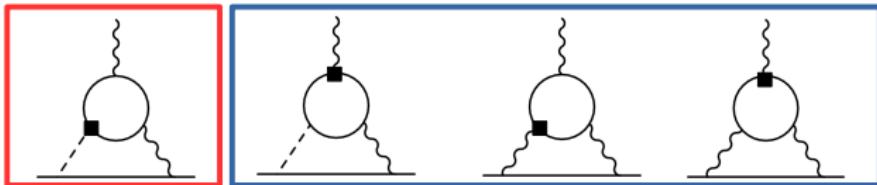
T violation at 1 GeV

- after EWSB & integrating out SM heavy particles (W, Z, H, \dots)

$$\begin{aligned}\mathcal{L}_{4+6} = & -\frac{m_e \tilde{c}_\gamma^{(e)}}{2} \bar{e} i \sigma^{\mu\nu} \gamma_5 e \, e F_{\mu\nu} \\ & + \cancel{m_s \bar{q} i \gamma_5 q} + \frac{C_{\tilde{G}}}{6} f^{abc} \epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}^a G_{\mu\rho}^b G_{\nu}^{c\rho} \\ & - \sum_{q=u,d,s} \frac{\bar{m}_q \tilde{c}_\gamma^{(q)}}{2} \bar{q} i \sigma^{\mu\nu} \gamma_5 q \, e F_{\mu\nu} - \sum_{q=u,d,s} \frac{\bar{m}_q \tilde{c}_g^{(q)}}{2} \bar{q} i \sigma^{\mu\nu} g_s G_{\mu\nu} \gamma_5 q \\ & + \dots\end{aligned}$$

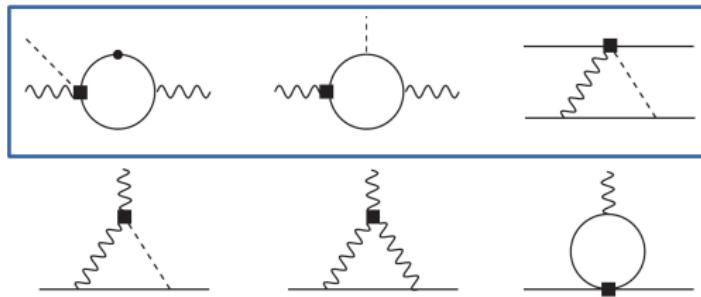
- assume Peccei-Quinn to get rid of $\bar{\theta}$ term
- 7 \not{T} hadronic operators
 - Weinberg operator (gCEDM)
 - u, d, s EDM and chromo-EDM
- neglect 4-quarks operators
(... nothing known on matrix elements ...)

Matching & Running. Electron EDM



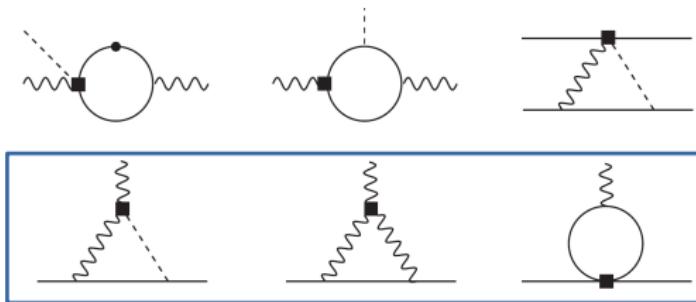
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- C_{Wt}, C_γ : log divergences
- leading log through a two-step path:

Matching & Running. Electron EDM



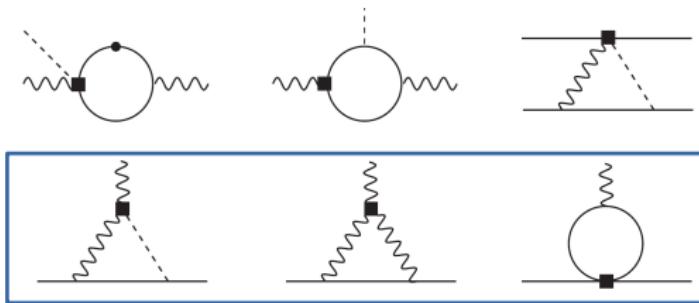
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 1. C_{Wt}, C_γ mix onto $\varphi^\dagger \varphi B\tilde{B}$, $\varphi^\dagger \varphi W\tilde{W}$, $\varphi^\dagger \tau \varphi B\tilde{W}$ & four-fermion

Matching & Running. Electron EDM



- C_Y gives a finite, threshold correction
- C_{Wt}, C_γ : log divergences
- leading log through a two-step path:
 1. C_{Wt}, C_γ mix onto $\varphi^\dagger \varphi B\tilde{B}$, $\varphi^\dagger \varphi W\tilde{W}$, $\varphi^\dagger \tau \varphi B\tilde{W}$ & four-fermion
 2. $\varphi^\dagger \varphi B\tilde{B}$, $\varphi^\dagger \varphi W\tilde{W}$, $\varphi^\dagger \tau \varphi B\tilde{W}$ & four-fermion mix into $\tilde{c}_\gamma^{(e)}$

Matching & Running. Electron EDM

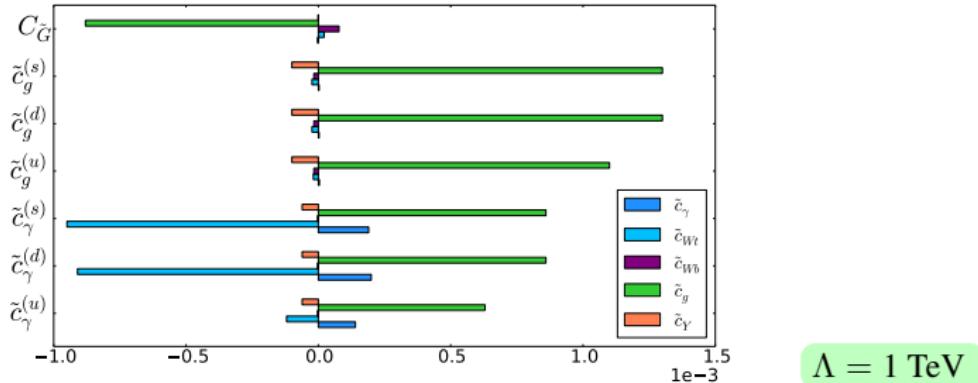


- C_Y gives a finite, threshold correction
- C_{Wt}, C_γ : log divergences
- leading log through a two-step path:

$$d_e = e \frac{m_e}{v^2} (v^2 \tilde{c}_\gamma^{(e)}) = 1.6 \cdot 10^{-9} (v^2 \tilde{c}_\gamma^{(e)}) e \text{ fm}$$
$$\frac{\tilde{c}_\gamma^{(e)}}{\tilde{c}_\gamma} \simeq \frac{6g^2 m_t^2}{(4\pi)^4 v^2} \left(1 + 7t_W^2\right) \log^2 \frac{\Lambda}{m_t} \sim 4 \cdot 10^{-4}$$

$$\tilde{c}_\gamma < 10^{-3} !$$

Matching & Running. Quark - gluon operators



Two qualitative cases:

1. $\tilde{c}_\gamma, \tilde{c}_{Wt}$ mainly induce light quark EDMs

hadronic uncertainties under control
good bound from neutron EDM

2. \tilde{c}_g, \tilde{c}_Y and \tilde{c}_{Wb} give comparable contributions to several operators

lots of room for cancellations
strong dependence on treatment of theory input

EDMs. Theory status. d_n

d_n	$em_u Q_u \tilde{c}_\gamma^{(u)}(1 \text{ GeV})$	$em_d Q_d \tilde{c}_\gamma^{(d)}(1 \text{ GeV})$	$em_s Q_s \tilde{c}_\gamma^{(s)}(1 \text{ GeV})$
central	-0.22	0.74	0.008
uncertainties	0.03	0.07	0.010
method	LQCD*	LQCD*	LQCD*

Table: Central values and ranges of nucleon-EDM matrix elements.

- qEDM: 10% accuracy
- but no signal for $\tilde{c}_\gamma^{(s)}$

* T. Bhattacharya *et al*, '15.

EDMs. Theory status. d_n

d_n	$e m_u \tilde{c}_g^{(u)}(1 \text{ GeV})$	$e m_d \tilde{c}_g^{(d)}(1 \text{ GeV})$	$e m_s \tilde{c}_g^{(s)}(1 \text{ GeV})$	$e C_{\tilde{G}}(1 \text{ GeV})$
central	-0.55	-1.1	xxx	$\pm 50 \text{ MeV}$
uncertainties	0.28	0.55	xxx	40 MeV
method	Sum Rules [†]	Sum Rules [†]		Sum Rules/NDA

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(might be large)

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- situation not settled for $\tilde{c}_g^{(s)}$
(might be large)
- gCEDM: 100% errors

central gCEDM large w.r.t $\tilde{c}_g^{(u,d)}$
... but large interval

Hadronic and nuclear uncertainties

Give bounds in two scenarios:

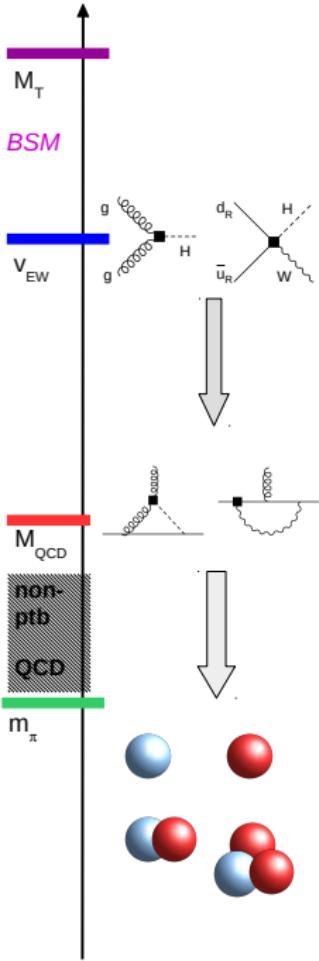
- **central:** take the central value of hadronic and nuclear matrix elements
- **R(ange) fit:** vary the matrix elements within their allowed range and choose matrix elements that minimize the total χ^2 of the set of EDM experiments.

“Rfit” procedure in CKM fits

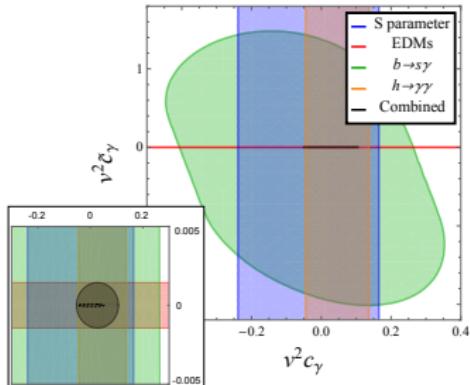
A. Hocker, H. Lacker, S. Laplace, F. Le Diberder, ‘11

- with current theory knowledge, bounds are widely different
- which matrix elements is crucial to improve? and how?

Bounds on top-Higgs couplings



Single coupling analysis. C_γ & C_{Wt}

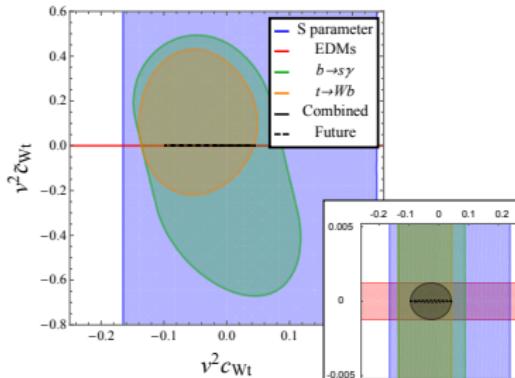


Re	R-fit
$v^2 c_\gamma$	$[-5.3, 11] \cdot 10^{-2}$
Im	
$v^2 \tilde{c}_\gamma$	$[-1.4, 1.4] \cdot 10^{-3}$

- $h \rightarrow \gamma\gamma$ dominates bound on c_γ
- electron EDM strongly constrains \tilde{c}_γ

1000 times better than $b \rightarrow s\gamma$!

Single coupling analysis. C_γ & C_{Wt}



Re	R-fit
$v^2 c_\gamma$	$[-5.3, 11] \cdot 10^{-2}$
$v^2 c_{Wt}$	$[-9.5, 4.2] \cdot 10^{-2}$
Im	
$v^2 \tilde{c}_\gamma$	$[-1.4, 1.4] \cdot 10^{-3}$
$v^2 \tilde{c}_{Wt}$	$[-1.2, 1.2] \cdot 10^{-3}$

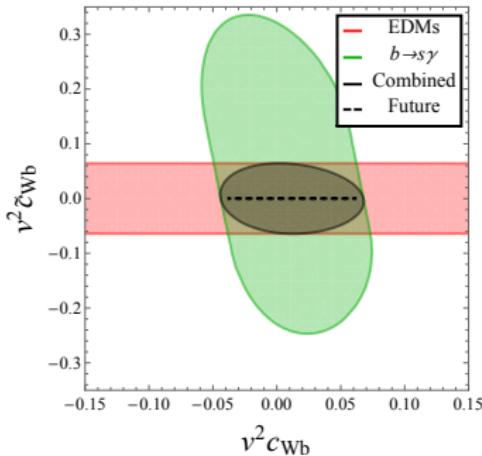
- $h \rightarrow \gamma\gamma$ dominates bound on c_γ
- electron EDM strongly constrains \tilde{c}_γ

1000 times better than $b \rightarrow s\gamma$!

- W helicity fractions dominate bound on c_{Wt}
- electron EDM strongly constrains \tilde{c}_{Wt}

400 times better than δ^- & $b \rightarrow s\gamma$!

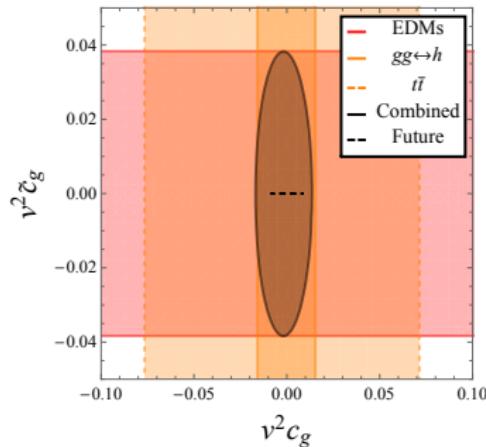
Single coupling analysis. C_{Wb} , C_g & C_Y



Re	R-fit
$v^2 c_{Wb}$	$[-4.4, 6.7] \cdot 10^{-2}$
Im	
$v^2 \tilde{c}_{Wb}$	$[-6.4, 6.4] \cdot 10^{-2}$

- c_{Wb} : no collider observable can compete with $b \rightarrow s\gamma$
- \tilde{c}_{Wb} : neutron EDM 5 times better than $b \rightarrow s\gamma$

Single coupling analysis. C_{Wb} , C_g & C_Y

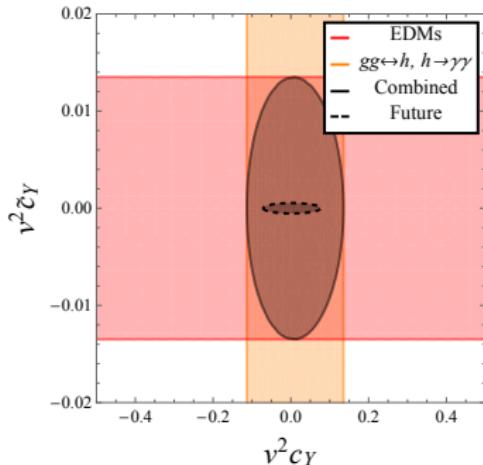


	R-fit
$v^2 c_{Wb}$	$[-4.4, 6.7] \cdot 10^{-2}$
$v^2 c_g$	$[-1.7, 1.4] \cdot 10^{-2}$
	Im
$v^2 \tilde{c}_{Wb}$	$[-6.4, 6.4] \cdot 10^{-2}$
$v^2 \tilde{c}_g$	$[-3.8, 3.8] \cdot 10^{-2}$

- c_{Wb} : no collider observable can compete with $b \rightarrow s\gamma$
- \tilde{c}_{Wb} : neutron EDM 5 times better than $b \rightarrow s\gamma$
- c_g : $gg \rightarrow h$ significantly stronger than $t\bar{t}$
- \tilde{c}_g : with Rfit, no bound from d_n !

cancellations between Weinberg
& light quark CEDM

Single coupling analysis. C_{Wb} , C_g & C_Y



Re	R-fit
$v^2 c_{Wb}$	$[-4.4, 6.7] \cdot 10^{-2}$
$v^2 c_g$	$[-1.7, 1.4] \cdot 10^{-2}$
$v^2 \tilde{c}_Y$	$[-12, 14] \cdot 10^{-2}$
Im	
$v^2 \tilde{c}_{Wb}$	$[-6.4, 6.4] \cdot 10^{-2}$
$v^2 \tilde{c}_g$	$[-3.8, 3.8] \cdot 10^{-2}$
$v^2 \tilde{c}_Y$	$[-1.3, 1.3] \cdot 10^{-2}$

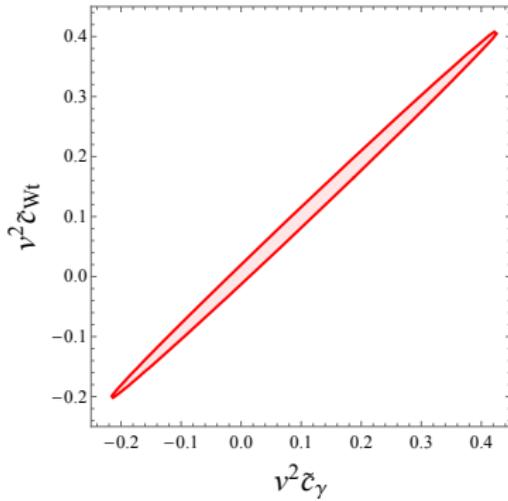
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- c_g : $gg \rightarrow h$ significantly stronger than $t\bar{t}$
- \tilde{c}_g : with Rfit, no bound from d_n !
- c_Y : $gg \rightarrow h$ significantly stronger than $t\bar{t}h$
- \tilde{c}_Y : dominated by d_e

Single coupling analysis. Role of hadronic uncertainties.

Imaginary	R-fit	Central	
$v^2 \tilde{c}_\gamma$	$[-1.4, 1.4] \cdot 10^{-3}$	$[-1.4, 1.4] \cdot 10^{-3}$	d_e
$v^2 \tilde{c}_{Wt}$	$[-1.2, 1.2] \cdot 10^{-3}$	$[-1.2, 1.2] \cdot 10^{-3}$	d_e
$v^2 \tilde{c}_{Wb}$	$[-6.4, 6.4] \cdot 10^{-2}$	$[-4.2, 4.4] \cdot 10^{-3}$	d_n
$v^2 \tilde{c}_g$	$[-3.8, 3.8] \cdot 10^{-2}$	$[-2.9, 2.9] \cdot 10^{-4}$	d_n
$v^2 \tilde{c}_Y$	$[-1.3, 1.3] \cdot 10^{-2}$	$[-1.3, 1.3] \cdot 10^{-2}$	d_e

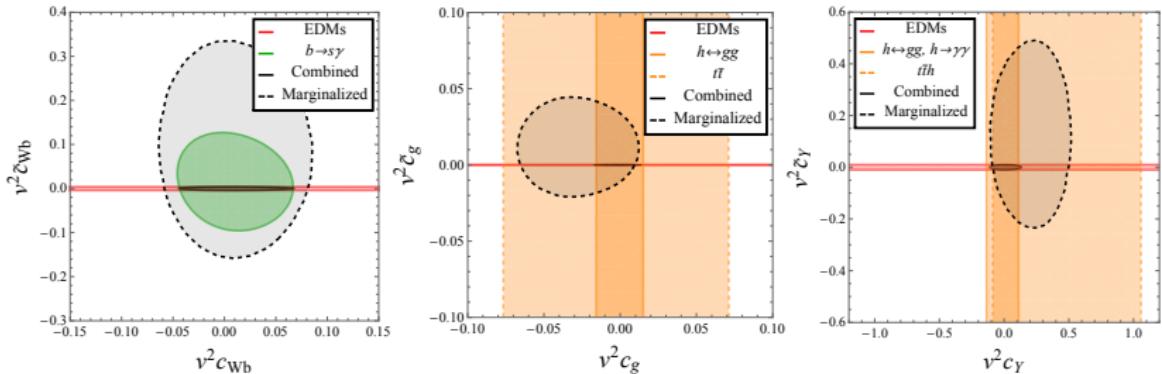
- bounds on \tilde{c}_g & \tilde{c}_{Wb} are strongly affected by hadronic ME
weakened by a factor of 100 and 10!
 1. poor knowledge of Weinberg ME
allowing Weinberg to vary within uncertainty
causes large cancellations with qCEDMs
 2. poor knowledge of mercury EDMs
in Rfit it is always possible to cancel d_{Hg}

Global Analysis



- turn on all couplings at $\Lambda = 1$ TeV & gauge the effects of fine tunings
 - c_γ and c_{Wt} are barely affected
 - bounds on \tilde{c}_{Wt} and \tilde{c}_γ much weaker
 - but \tilde{c}_{Wt} and \tilde{c}_γ are strongly correlated
 - non trivial constraint on model-building

Global Analysis



- all bounds get weaker
- strong correlation between c_g and c_Y

both constrained by $gg \rightarrow h$

improve with more $t\bar{t}$
and $t\bar{t}h$ measurements

- weak bounds on \tilde{c}_Y , $v^2 \tilde{c}_Y \sim 0.5$

need CPV observables
at collider

Top-Higgs Couplings. Conclusion

- chirality-flipping top anomalous couplings are well determined by a combination of direct and indirect probes

Real part

- Higgs production & decay very sensitive to top Yukawa, magnetic and chromo-magnetic dipoles

better than direct probes $t\bar{t}$, $t\bar{t}h$

Imaginary part

- in the single coupling analysis, EDMs dominate the bounds

bounds on top EDM, weak EDM
1000 times stronger than collider & flavor

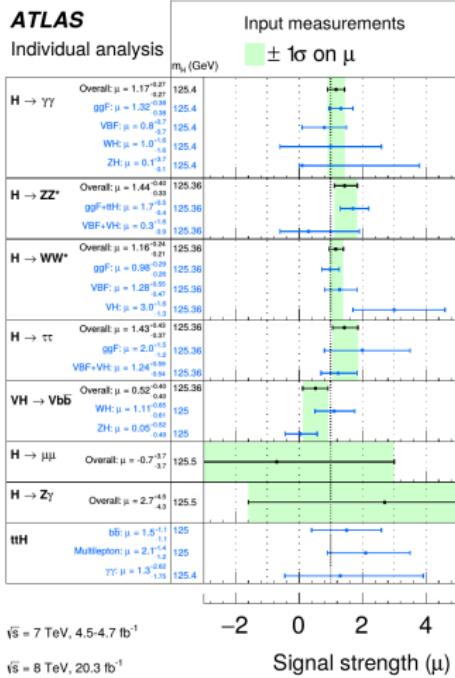
- to avoid bounds: detailed cancellations between the couplings
- large hadronic uncertainties limit the constraining power of hadronic/nuclear EDMs

Backup

Higgs Signal Strengths

ATLAS

Individual analysis



$$\mu_{i \rightarrow h \rightarrow f}^{\mathcal{O}} = \mu_i^{\mathcal{O}} \mu_f^{\mathcal{O}}$$

$$= \left(1 + \frac{\sigma_{i \rightarrow h}^{\mathcal{O}}}{\sigma_{i \rightarrow h}^{SM}} \right) \frac{1 + \frac{\Gamma_{h \rightarrow f}^{\mathcal{O}}}{\Gamma_{h \rightarrow f}^{SM}}}{1 + \frac{\Gamma_{tot}^{\mathcal{O}}}{\Gamma_{tot}^{SM}}}$$

$\sigma_{i \rightarrow h}^{\mathcal{O}}$: correction to i prod. channel

$gg \rightarrow h$

$\Gamma_{h \rightarrow f}^{\mathcal{O}}$: correction to f decay channel

$h \rightarrow \gamma\gamma$

$\Gamma_{tot}^{\mathcal{O}}$: correction to total width

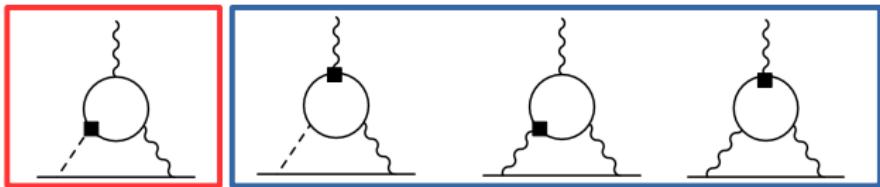
$h \rightarrow gg$

$$\begin{aligned}
 \frac{A_{CP}(B \rightarrow s\gamma)}{\pi} &\equiv \frac{1}{\pi} \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_{\bar{s}} \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_{\bar{s}} \gamma)} \\
 &\approx \left[\left(\frac{40}{81} - \frac{40}{9} \frac{\Lambda_c}{m_b} \right) \frac{\alpha_s}{\pi} + \frac{\Lambda_{17}^c}{m_b} \right] \text{Im} \frac{C_2}{C_7} - \left(\frac{4\alpha_s}{9\pi} + 4\pi\alpha_s \frac{\Lambda_{78}}{3m_b} \right) \text{Im} \frac{C_8}{C_7} \\
 &\quad - \left(\frac{\Lambda_{17}^u - \Lambda_{17}^c}{m_b} + \frac{40}{9} \frac{\Lambda_c}{m_b} \frac{\alpha_s}{\pi} \right) \text{Im} \left(\frac{V_{ub} V_{us}^*}{V_{tb} V_{ts}^*} \frac{C_2}{C_7} \right),
 \end{aligned}$$

- CP asymmetry depends on the scale $\Lambda_c \simeq 0.38$ GeV
- and on three HQET matrix elements

$$\begin{aligned}
 \Lambda_{17}^u &\in [-0.33, 0.525] \text{ GeV}, & \Lambda_{17}^c &\in [-0.009, 0.011] \text{ GeV}, \\
 \Lambda_{78} &\in [-0.017, 0.19] \text{ GeV}
 \end{aligned}$$

Matching & Running. Electron EDM and Muon $g - 2$



- solving the RGEs ($\Lambda = 1 \text{ TeV}$)

$$d_e = \left(3.8(v^2 \tilde{c}_\gamma) - 4.4(v^2 \tilde{c}_{Wt}) + 0.1(v^2 \tilde{c}_g) + 0.4(v^2 \tilde{c}_Y) \right) 1.6 \cdot 10^{-13} e \text{ fm}$$

- real part of diagrams \implies anomalous magnetic moments

$$\Delta a_l = 2 \frac{m_l^2}{v^2} (v^2 c_\gamma^{(l)})$$

$$\Delta a_\mu = \left(13.8 (v^2 c_\gamma) + 0.51 (v^2 c_g) - 16.0 (v^2 c_{Wt}) + 1.5 (v^2 c_Y) \right) \cdot 10^{-11}$$

$$\ll (\Delta a_\mu)_{\text{meas}} = 288(63)(49) \cdot 10^{-11}$$

Hadronic and nuclear uncertainties. $d_{^{199}\text{Hg}}$

	Estimated ranges of $a_{0,1}$		Estimated ranges of $g_{0,1}$	
	a_0	a_1	\bar{g}_0 (fm $^{-1}$)	\bar{g}_1 (fm $^{-1}$)
^{199}Hg	{0.063, 0.63}	{−0.38, 1.14}	{−5, 15} $\bar{m}\tilde{c}_g^{(0)}$ *	{10, 60} $\bar{m}\tilde{c}_g^{(3)}$ *

$$* \bar{m}\tilde{c}_g^{(0,3)} = m_u\tilde{c}_g^{(u)} \pm m_d\tilde{c}_g^{(d)}$$

J. Engel, M. Ramsey-Musolf, U. van Kolck, '13;
M. Pospelov and A. Ritz, '05.

- d_{Hg} has several components

$$d_{^{199}\text{Hg}} = \mathcal{A} \left((a_0\bar{g}_0 + a_1\bar{g}_1) e \text{ fm}^3 + (\alpha_n d_n + \alpha_p d_p) \text{ fm}^2 \right)$$

- screening factor $\mathcal{A} = -(2.8 \pm 0.6) \cdot 10^{-4} \text{ fm}^{-2}$
- two-body component
determined by \mathcal{T} one-pion-exchange potential
- one-body component

$$\alpha_n = 1.9 \pm 0.1 \quad \alpha_p = 0.20 \pm 0.06$$

Dmitriev and Sen'kov, '03.

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Dmitriev and Sen'kov, '03.

Single coupling analysis. Role of hadronic uncertainties.

Imaginary	R-fit	Central	R-fit + theory
$v^2 \tilde{c}_\gamma$	$[-1.4, 1.4] \cdot 10^{-3}$	$[-1.4, 1.4] \cdot 10^{-3}$	$[-1.4, 1.4] \cdot 10^{-3}$
$v^2 \tilde{c}_{Wt}$	$[-1.2, 1.2] \cdot 10^{-3}$	$[-1.2, 1.2] \cdot 10^{-3}$	$[-1.2, 1.2] \cdot 10^{-3}$
$v^2 \tilde{c}_{Wb}$	$[-6.4, 6.4] \cdot 10^{-2}$	$[-4.2, 4.4] \cdot 10^{-3}$	$[-1.7, 1.7] \cdot 10^{-2}$
$v^2 \tilde{c}_g$	$[-3.8, 3.8] \cdot 10^{-2}$	$[-2.9, 2.9] \cdot 10^{-4}$	$[-3.2, 3.2] \cdot 10^{-3}$
$v^2 \tilde{c}_Y$	$[-1.3, 1.3] \cdot 10^{-2}$	$[-1.3, 1.3] \cdot 10^{-2}$	$[-1.3, 1.3] \cdot 10^{-2}$

Rfit + theory improvements

- 50% uncertainty on the Weinberg EDM

$$d_n = \pm(50 \pm 25) C_{\tilde{G}} \text{ eMeV}$$

- 50% uncertainty on mercury EDM

Weinberg on the lattice
prel. work in progress

$$a_0 = 0.13 \pm 0.065, \quad a_1 = 0.25 \pm 0.125,$$

- modest theory improvements can have big impact
- w/o theory $d_n \sim 10^{-15} \text{ e fm}$ does not improve bounds