Constraints on new physics: EDM vs Higgs production

Emanuele Mereghetti

with: Y. T. Chien, V. Cirigliano, W. Dekens, J. de Vries

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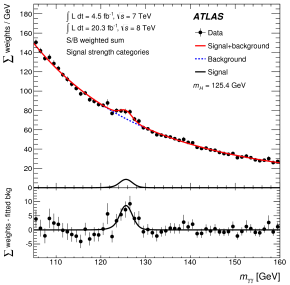
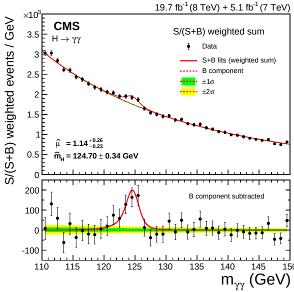
Intersections of BSM Phenomenology and QCD for New Physics Searches

Los Alamos NATIONAL LABORATORY EST. 1943

- the Standard Model works just fine



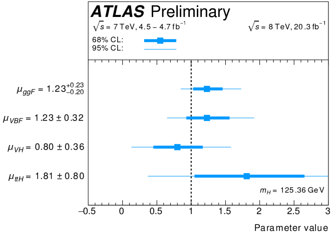
ATLAS collaboration, '14.

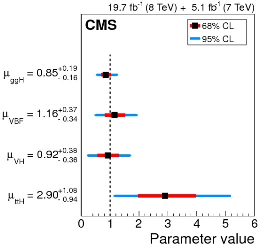


CMS collaboration, '14.

- last missing piece discovered @ LHC

- the Standard Model works just fine

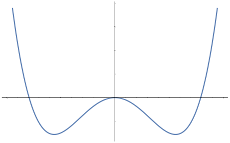




- last missing piece discovered @ LHC
- SM-like, so far

Introduction

1. what's the nature of the Higgs



elementary or composite?
what protects its mass?

2. baryogenesis

why matter and not antimatter?

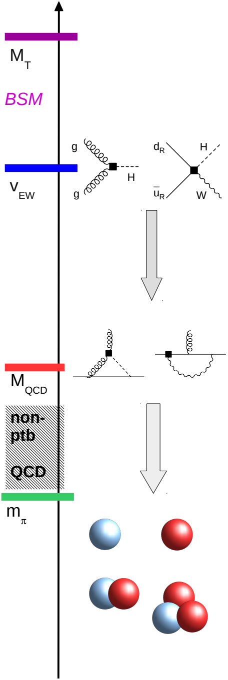
unsolved puzzles

3. dark matter

is it particle? how does it interact?

interplay of high and low energy probes!

Introduction



- experiments on large variety of scales
- expect signals both at colliders and low energy

The Problem(s)

1. uniform framework

   able to follow BSM physics every step down in energy
2. deal with non-perturbative QCD

   reliably estimate/compute hadronic and nuclear matrix elements
3. identify minimal number of observables

Framework

Assumptions:

1. the scale of new physics is much larger than EW scale

$$M_{\not{T}} \gg v = 246\,\mathrm{GeV}$$

2. there are not new light degrees of freedom
3. new physics is captured by a linearly realized EFT

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   include all operators that

   - are written in terms of SM fields
   - have the same symmetries as SM $SU_c(3) \times SU_L(2) \times U_{\text{em}}(1)$

4. most important effects from minimal $d > 4$ in our case, $d = 6$

$$\mathcal{L}_{\not T} = \sum \frac{c_{i,6}}{M_{\not T}^2} \mathcal{O}_{6\,i} + \sum \frac{c_{i,7}}{M_{\not T}^7} \mathcal{O}_{7\,i} + \dots$$

Dimension 6 operators

- full set of dimension 5 and 6 operator known

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

- 1 dimension 5 operator, responsible for neutrino masses & mixing
- 32 CP-even, 27 CP-odd dimension 6 operators
  1350 and 1149 if include flavor-changing...

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

Grzadkowski *et al.* '10

Framework

- pseudoscalar Yukawa & θ'

$$\mathcal{L} = -\theta' \frac{\alpha_s}{16\pi} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} \left(\varphi^\dagger \varphi\right) + \sqrt{2}\varphi^\dagger \varphi \ \left(\bar{q}_L Y'_u \, \tilde{\varphi} u_R + \bar{q}_L Y'_d \, \varphi d_R\right) + \text{ h.c.}$$

- top CEDM

$$\mathcal{L} = -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \, \tilde{\Gamma}_t t^a g_s G^a_{\mu\nu} \frac{\tilde{\varphi}}{v} t_R + \text{h.c.}$$

- (weak) dipole operators & W right handed currents

$$\begin{aligned} \mathcal{L} \quad = \quad & -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left(\Gamma^u_B g' B_{\mu\nu} + g \Gamma^u_W \tau^i W^i_{\mu\nu}\right) \frac{\tilde{\varphi}}{v} \, u_R \\ & -\frac{1}{\sqrt{2}} \bar{q}_L \sigma^{\mu\nu} \left(\Gamma^d_B g' B_{\mu\nu} + g \Gamma^d_W \tau^i W^i_{\mu\nu}\right) \frac{\varphi}{v} d_R + \bar{u}_R \Xi \gamma^\mu d_R \ \tilde{\varphi}^\dagger i D_\mu \varphi \end{aligned}$$

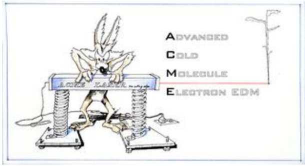
- all modify Higgs properties

Connection to EDMs

- electron EDM
  (via ThO energy levels)

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

ACME collaboration, '14.



- neutron EDM

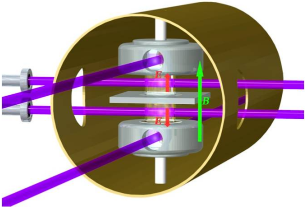
$$|d_n| \leq 2.9 \cdot 10^{-13}\, e\,\text{fm}$$

Baker *et al*, '06.

- Hg EDM

$$|d_{^{199}\text{Hg}}| \leq 2.6 \cdot 10^{-16}\, e\,\text{fm}$$

Griffith *et al*, '09.



Connection to EDMs

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

$$
\begin{aligned}
\mathcal{L}_{4+6} \quad = \quad & \frac{d_e}{2}\bar{e}i\sigma^{\mu\nu}\gamma_5 e\, F_{\mu\nu} \\
& + \cancel{m_*\bar{\theta}\bar{q}i\gamma_5 q} + \frac{d_W}{6} f^{abc}\epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} \\
& - \sum_{q=u,d,s} \frac{\bar{m}_q d_q}{2} \bar{q}i\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \sum_{q=u,d,s} \frac{\bar{m}_q \tilde{d}_q}{2} \bar{q}i\sigma^{\mu\nu}\gamma_5 \lambda^a q\, g_s G^a_{\mu\nu} \\
& + \ \ldots
\end{aligned}
$$

- 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 ...)

Hadronic uncertainties. d_n

d_n	$m_u d_u(1\,\mathrm{GeV})$	$m_d d_d(1\,\mathrm{GeV})$	$m_s d_s(1\,\mathrm{GeV})$
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 d_s

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

Hadronic uncertainties. d_n

d_n	$em_u \tilde{d}_u(1\,\text{GeV})$	$e\,m_d\tilde{d}_d(1\,\text{GeV})$	$e\,m_s\tilde{d}_s(1\,\text{GeV})$	$e\,d_W(1\,\text{GeV})$
central	-0.55	-1.1	xxx	± 50 MeV
uncertainties	0.28	0.55	xxx	40 MeV
method	Sum Rules†	Sum Rules†		Sum Rules/NDA

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- qCEDM: 50% errors?
- situation not settled for $\tilde{d}_s$ (might be large)

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† M. Pospelov and A. Ritz, '05.

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- qCEDM: 50% errors?
- situation not settled for $\tilde{d}_s$ (might be large)
- gCEDM: 100% errors

† M. Pospelov and A. Ritz, '05.

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

	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	$\{0.063,\ 0.63\}$	$\{-0.38,\ 1.14\}$	$\{-5, 15\}\,\bar{m}\tilde{d}_0^*$	$\{10, 60\}\,\bar{m}\tilde{d}_3^*$

$^*\ \bar{m}d_{0,3} = m_u d_u \pm m_d d_d$ Engel, '13; M. Pospelov and A. Ritz, '05.

- d_{Hg} has several components

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

- screening factor $\mathcal{A} = -(2.8 \pm 0.6) \cdot 10^{-4}\mathrm{fm}^{-2}$
- two-body component
  determined by $\not{T}$ one-pion-exchange potential
- one-body component

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

Dmitriev and Sen'kov, '03.

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

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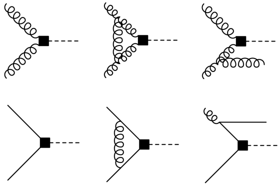
Hadronic and nuclear uncertainties

We give bounds in two scenarios:

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

- with current theory knowledge, bounds are widely different

θ' and Im Y'_q. Collider

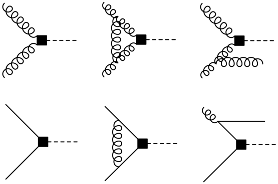


- after EWSB

$$\mathcal{L} = -v^2\theta'\left(\frac{1}{2}+\frac{h}{v}\right)\frac{\alpha_s}{16\pi}\varepsilon^{\mu\nu\alpha\beta}G^a_{\mu\nu}G^a_{\alpha\beta} + \frac{1}{2}\sum_q v^2 \mathrm{Im}Y'_q\left(1+\frac{h}{v}+2\frac{h}{v}\right)\bar{q}\,i\gamma_5 q.$$

- no Higgs: correct QCD $\bar{\theta}$ term & quark mass phase
  killed by PQ
- one Higgs: correct gluon fusion production cross section
  dominant SM mechanism!

θ' and Im Y'_q. Collider



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θ'. Collider

$$\sigma_{ggH} = (17.45^{+1.9}_{-1.5} \pm 1.12) + (39.8^{+4.2}_{-3.4} \pm 2.6)(v^2\theta')^2 \text{ pb}$$

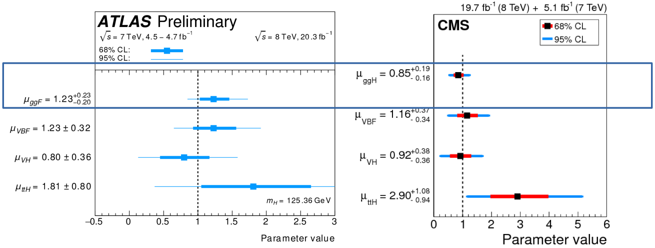
$$\mu_{ggH} = \frac{\sigma^{SM}_{ggH} + \sigma^{\theta'}_{ggH}}{\sigma^{SM}_{ggH}} = 1 + (2.28 \pm 0.01)(v^2\theta')^2$$

- using N^2LO short distance cross sections

R. V. Harlander and W. B. Kilgore, ‘02 & ‘03
C. Anastasiou and K. Melnikov, ‘02 & ‘03

- GG and $G\tilde{G}$ have $\sim 10\%$ errors from scale variations & PDF
- errors cancel out in ratio

Collider bounds on θ'



- LHC Run 1 agrees with SM

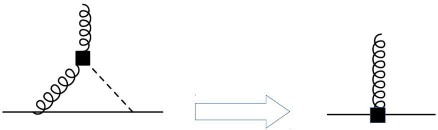
$$|v^2\theta'|_{ATLAS} < 0.52 \qquad |v^2\theta'|_{CMS} < 0.27$$

at 90% CL

- LHC Run 2 projects a reduction to 10% (theory dominated!)

$$|v^2\theta'| < 0.20$$

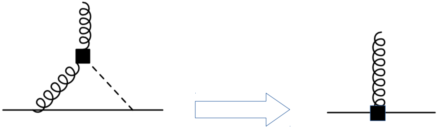
EDM bounds on θ'



- θ' mixes with the qCEDM for scales larger than m_h

$$\mu\frac{d}{d\mu}\begin{pmatrix} d_q/Q_q \\ \tilde{d}_q \\ d_W/g_s \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 \\ 0 & 16C_F - 4N_c & 2N_c & -1/4\pi^2 \\ 0 & 0 & N_c + 2n_f + \beta_0 & 0 \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/Q_q \\ \tilde{d}_q \\ d_W/g_s \\ \theta' \end{pmatrix}$$

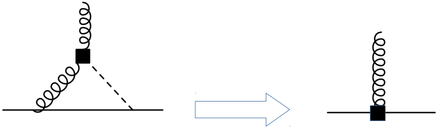
EDM bounds on θ'



- θ' mixes with the qCEDM for scales larger than m_h
- d_q, $\tilde{d}_q$ and d_W keep running below m_h

$$\mu \frac{d}{d\mu} \begin{pmatrix} d_q/Q_q \\ \tilde{d}_q \\ d_W/g_s \end{pmatrix} = \frac{\alpha_s}{4\pi} \begin{pmatrix} 8C_F & -8C_F & 0 \\ 0 & 16C_F - 4N_c & 2N_c \\ 0 & 0 & N_c + 2n_f + \beta_0 \end{pmatrix} \begin{pmatrix} d_q/Q_q \\ \tilde{d}_q \\ d_W/g_s \end{pmatrix}$$

EDM bounds on θ'



- θ' mixes with the qCEDM for scales larger than m_h
- d_q, $\tilde{d}_q$ and d_W keep running below m_h
- at $\Lambda_\chi = 1$ GeV

$$\tilde{d}_q(\Lambda_\chi) = 1.7 \cdot 10^{-4}\,\theta' \qquad d_q(\Lambda_\chi)/Q_q = 1.4 \cdot 10^{-4}\theta',$$
$$d_W(\Lambda_\chi) = -7.3 \cdot 10^{-6}\,\theta'$$

EDM bounds on θ'

$v^2\theta'$	d_n	$d_{\rm Hg}$	CMS	ATLAS
central	0.06	0.04	0.27	0.52
minimized	0.23	×	0.27	0.52
minimized + improved theory	0.05		0.27	0.52

central

- stronger bound from $d_{^{199}\rm Hg}$

minimized

- neutron bound gets weaker
- × ^{199}Hg bound disappears!
- EDM & collider much closer

minimized + better theory

if d_W, d_s with 50% uncertainty
& $\tilde{d}_u$ and $\tilde{d}_d$ with 25% uncertainty

bounds go back to central

Pseudoscalar Yukawa Couplings

$M_{\not T} = 1$ TeV	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_b$
central	$3.9 \cdot 10^{-7}$	$3.0 \cdot 10^{-7}$	$1.1 \cdot 10^{-3}$	$4.3 \cdot 10^{-4}$	$8.4 \cdot 10^{-3}$
minimized	$2.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$6.3 \cdot 10^{-3}$	0.42	$4.1 \cdot 10^{-2}$
collider (CMS)	$0.6 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$

- collider bounds exclude Im $Y'_q > 3y_b$
- μ_{ggH} at LHC Run 2 will not improve these bounds
  but direct study $h \to b\bar{b}$, $h \to c\bar{c}$ could
- collider not competitive on Y'_u, Y'_d
- collider wins on Y'_s and Y'_b

$\mathbf{Y}'_s$

- artifact of our ignorance

$$d_n = (0.01 \pm 0.01) d_s + (???) \tilde{d}_s$$

$\mathbf{Y}'_b$

- several same-size contribs. to d_n

Pseudoscalar Yukawa Couplings

$M_{\not T} = 1$ TeV	$v^2 \text{Im}\, Y'_u$	$v^2 \text{Im}\, Y'_d$	$v^2 \text{Im}\, Y'_c$	$v^2 \text{Im}\, Y'_s$	$v^2 \text{Im}\, Y'_b$
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Future Min.	$1.9 \cdot 10^{-6}$	$0.97 \cdot 10^{-6}$	$2.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-4}$	$1.1 \cdot 10^{-2}$
collider (CMS)	$0.6 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$1.6 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$3.6 \cdot 10^{-2}$

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$\mathbf{Y'_s}$

- artifact of our ignorance

$$d_n = (0.01 \pm 0.01) d_s + (???) \tilde{d}_s$$

$\mathbf{Y'_b}$

- several same-size contribs. to d_n not improved much by more theory

Bounds on θ' and Yukawa. Future

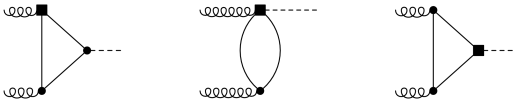
	$v^2\mathrm{Im}\,Y_c'$	$v^2\mathrm{Im}\,Y_s'$	$v^2\mathrm{Im}\,Y_b'$	$v^2\,\theta'$
Current	$6.3\cdot 10^{-3}$	$42\cdot 10^{-2}$	$4.1\cdot 10^{-2}$	0.23
Current+Th.	$2.2\cdot 10^{-3}$	$8.7\cdot 10^{-4}$	$1.1\cdot 10^{-2}$	0.052
$d_n + d_{\mathrm{ThO}}$	$2.3\cdot 10^{-5}$	$2.4\cdot 10^{-2}$	$2.4\cdot 10^{-3}$	$8.0\cdot 10^{-4}$
$d_n + d_{\mathrm{ThO}}$+Th.	$8.4\cdot 10^{-6}$	$3.5\cdot 10^{-6}$	$8.9\cdot 10^{-5}$	$3.3\cdot 10^{-4}$
collider (CMS)	$1.6\cdot 10^{-2}$	$2.0\cdot 10^{-2}$	$3.6\cdot 10^{-2}$	0.27

$d_n + d_{\mathrm{Th0}}$ assume $d_n < 10^{-15}$ e fm & $d_e < 5\cdot 10^{-17}$ e fm

Theory 50% uncertainty on d_n from d_W, d_s
25% uncertainty on d_n from $\tilde{d}_u$, $\tilde{d}_d$
50 % uncertainty on $\bar{g}_{0,1}$ & a_0, a_1

- EDM theory as important as improved experiments!
- EDM theory only is enough to beat LHC Run 1 & Run 2
- EDM theory + improved experiments unbeatable

Top CPV couplings

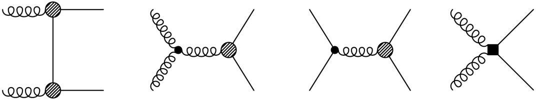


$$\mathcal{L} = v^2 \mathrm{Im} Y_t' \, \bar{t} i \gamma_5 t - \frac{i}{2} \tilde{d}_t \, \bar{t} g_s \sigma \cdot G \gamma_5 t \left(1 + \frac{h}{v}\right)$$

Richer collider phenomenology:

1. indirect contribution to ggH
2. total $t\bar{t}$ cross section
3. associated production of h and a $t\bar{t}$ pair

Top CPV couplings



$$\mathcal{L} = v^2 \mathrm{Im} Y_t' \, \bar{t} i \gamma_5 t - \frac{i}{2} \tilde{d}_t \, \bar{t} g_s \sigma \cdot G \gamma_5 t \left(1 + \frac{h}{v}\right)$$

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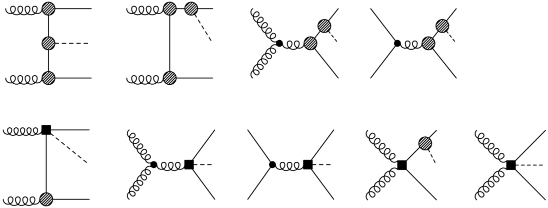

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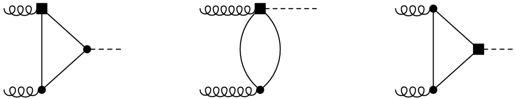
Gluon Fusion



- Y_t' gives a threshold correction to θ'

$$\theta'(m_t^-) = \theta'(m_t^-) - \frac{v}{m_t}\mathrm{Im}\, Y_t'(m_t)$$

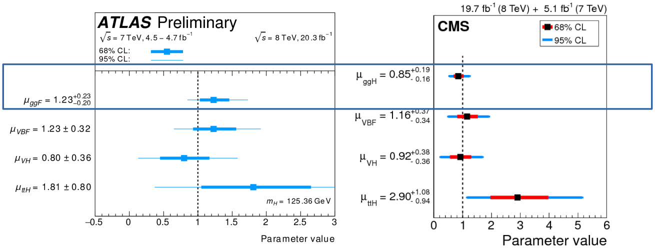
- $\tilde{d}_t$ mixes with θ' ... pretty strongly

$$\mu\frac{d}{d\mu}\begin{pmatrix}\tilde{d}_q\\ \theta'\end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix}16C_F - 4N_c & -1/4\pi^2\\ -8\frac{4\pi}{\alpha_s}y_q^2 & 0\end{pmatrix}\begin{pmatrix}\tilde{d}_q\\ \theta'\end{pmatrix}$$

- at the top scale

$$\frac{\tilde{d}_t}{m_t}(m_t) \approx 0.9\frac{\tilde{d}_t}{m_t}(1\,\mathrm{TeV}), \qquad \theta'(m_t) \approx 5.2\frac{\tilde{d}_t}{m_t}(1\,\mathrm{TeV})$$

Gluon Fusion

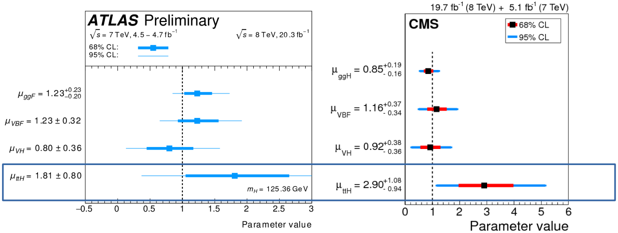


- LHC Run 1 agrees with SM

$$|v^2\tilde{d}_t/m_t|_{ATLAS} < 0.10 \qquad |v^2\tilde{d}_t/m_t|_{CMS} < 0.05$$
$$|v^2 \mathrm{Im}Y_t'|_{ATLAS} < 0.30 \qquad |v^2 \mathrm{Im}Y_t'|_{CMS} < 0.15$$

at 90% CL

- small improvements possible at LHC Run 2

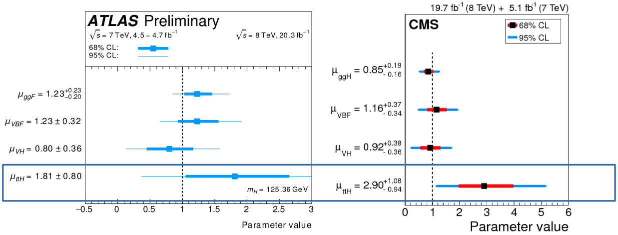


- total $t\bar{t}$ cross section measured with 5% accuracy
  predicted with 8% accuracy (N^2LO!)

$$|v^2 \tilde{d}_t / m_t| < 0.23$$

- $t\bar{t}h$ is known less precisely

$$\mu_{t\bar{t}h}(8\,\text{TeV}) = 1 + (248 \pm 24)(m_t \tilde{d}_t)^2 + (0.67 \pm 0.04)\left(v^2 \text{Im}\, Y_t'\right)^2 + (0.41 \pm 0.54)(v^2 m_t\, \tilde{d}_t \text{Im}\, Y_t'),$$



- total $t\bar{t}$ cross section measured with 5% accuracy

  predicted with 8% accuracy (N^{2}LO!)

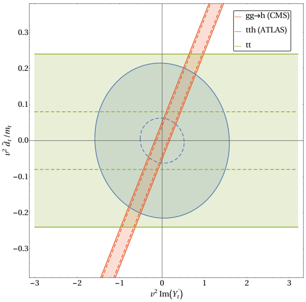
$$|v^2 \tilde{d}_t/m_t| < 0.23$$

- $t\bar{t}h$ is known less precisely

$$v^2 \, |\tilde{d}_t/m_t|_{ATLAS} < 0.21, \qquad 0.07 < |v^2 \tilde{d}_t/m_t|_{CMS} < 0.27.$$

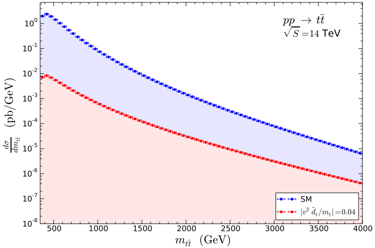
competitive with $t\bar{t}$!

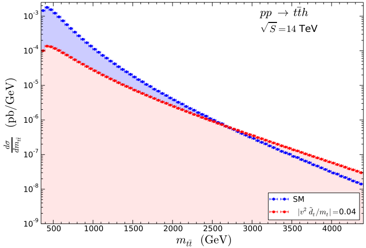
Top CPV couplings



- at the moment, gluon fusion gives the strongest constraint
- $t\bar{t}h$ already competitive with $t\bar{t}$
- $t\bar{t}$ and $t\bar{t}h$ have more chance of improving at Run 2 will catch up with ggH

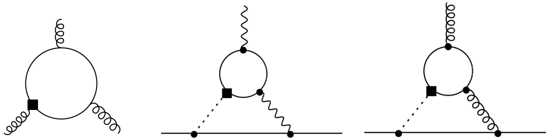
Top CPV couplings





- relative contribution to $t\bar{t}h$ is larger
- and takes over for $m_{t\bar{t}} > 2.5$ TeV
- but number of events is small
  225 + 130 events with 300 fb^{-1},
  with $h \to b\bar{b}$, at least one W decays leptonically

Top CPV couplings. EDM bounds



- Im Y_t': threshold correction to d_e, $\tilde{d}_q$, d_q
- $\tilde{d}_t$: threshold correction to d_W, mixing with $\tilde{d}_q$, d_q
- Yukawa

$$|v^2 \text{Im}\, Y_t'| < 7.8 \cdot 10^{-3}$$

dominated by electron!

- top CEDM

central

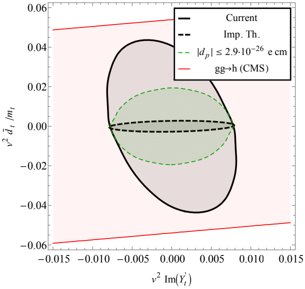
$$|v^2 \tilde{d}_t / m_t| < 1.0 \cdot 10^{-3}$$

minimized

$$|v^2 \tilde{d}_t / m_t| < 4.2 \cdot 10^{-2}$$

dominated by d_n
necessary to improve Weinberg!

Top CPV couplings. EDM bounds

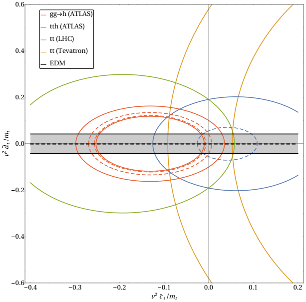


- collider not competitive on Im Y_t' thanks d_e!
- bounds on $\tilde{d}_t$ are comparable

EDM constraints pull away if:

- determine Weinberg matrix element with 50% error
- improve d_n by to 10^{-15} fm, or d_p to 10^{-13} fm

top CMDM



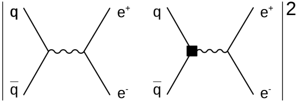
- the top chromo-magnetic moment contributes to ggH, $t\bar{t}$, $t\bar{t}h$
- best constraints from loop contribution to ggH
- . . . but $t\bar{t}$ and $t\bar{t}h$ are not too far

Weak EDMs and Ξ. Drell-Yan

- after EWSB

$$
\begin{aligned}
\mathcal{L}_{q^2\varphi X} \quad = \quad & -\left(1+\frac{h}{v}\right)\left(\frac{g\mathrm{Im}\Gamma^u_Z}{2\cos\theta_W}\,\bar{u}i\sigma^{\mu\nu}\gamma_5 u\, Z_{\mu\nu}+\dots\right) \\
& +\left(1+\frac{h}{v}\right)^2 \frac{v^2\Xi}{4}\frac{g}{\sqrt{2}}\,\left(\bar{d}\gamma^\mu\left(1+\gamma_5\right)uW_\mu+(u\to d)\right)
\end{aligned}
$$

- modify $pp\to e^+e^-$ and $pp\to e\nu$ (Drell-Yan)



- modify production only
  neglect $\not{T}$ leptonic operators
- no interference with the SM

- after EWSB

$$\mathcal{L}_{q^2\varphi X} = -\left(1+\frac{h}{v}\right)\left(\frac{g\,\mathrm{Im}\Gamma^u_Z}{2\cos\theta_W}\,\bar{u}i\sigma^{\mu\nu}\gamma_5 u\, Z_{\mu\nu} + \dots\right) + \left(1+\frac{h}{v}\right)^2 \frac{v^2\Xi}{4}\frac{g}{\sqrt{2}}\left(\bar{d}\gamma^{\mu}\left(1+\gamma_5\right)uW_{\mu} + (u\to d)\right)$$

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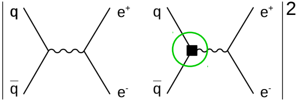

- modify production only
  neglect $\not{T}$ leptonic operators
- no interference with the SM

- very similar to SM
  $\hat{\sigma} \sim s^{-1}$

- after EWSB

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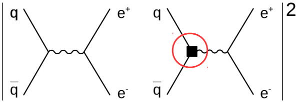
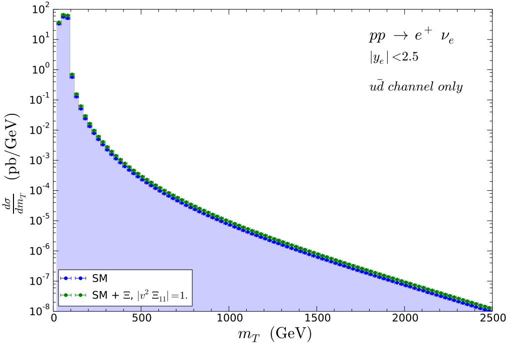
- modify $pp \to e^+e^-$ and $pp \to e\nu$ (Drell-Yan)



- modify production only
  neglect $\not{T}$ leptonic operators
- no interference with the SM

- very similar to SM
  $\hat{\sigma} \sim s^{-1}$
- different s dependence
  $\hat{\sigma} \sim s^0$

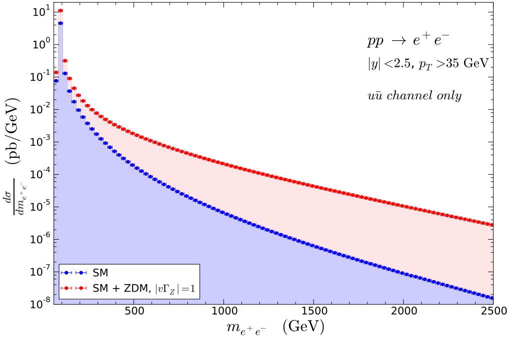
$\not{T}$ operators at colliders. Drell-Yan



Y. T. Chien, V. Cirigliano,W. Dekens, J. de Vries, EM *in progress*

- Ξ has same shape as SM
- dipole decrease more slowly with s
- in both cases, large peak at m_W, m_Z

$\not{T}$ operators at colliders. Drell-Yan



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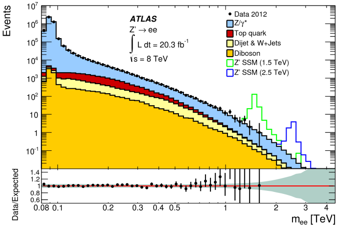
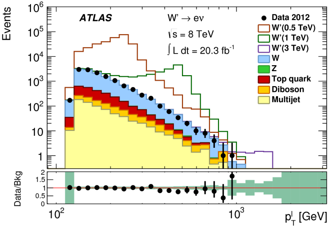
Bounds from LHC





ATLAS, PRD **90** 052005 (2014), ATLAS, JHEP **09** (2014) 037

- ATLAS and CMS are in good agreement with SM

Bounds from LHC

	$v\Gamma_W^{u,d}$	$v\Gamma_W^{c,s}$	$v\Gamma_Z^{u}$	$v\Gamma_Z^{d}$	$v\Gamma_Z^{s}$	$v\Gamma_Z^{c}$	$v\Gamma_Z^{b}$
ATLAS	0.03	0.16	0.08	0.10	0.25	0.39	0.63
CMS	0.05	1.01					
	$v^2\Xi_{ud}$	$v^2\Xi_{us}$	$v^2\Xi_{uc}$	$v^2\Xi_{cd}$	$v^2\Xi_{cs}$	$v^2\Xi_{cb}$	
ATLAS	0.19	0.24	0.39	0.38	0.66	1.14	
CMS	0.88	1.32	5.06	5.84	7.63	14.50	

Table : 90% confidence bounds on the coefficients of the WDM and right-handed current from Drell-Yan.

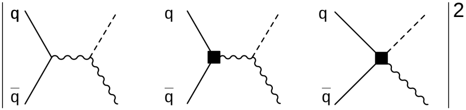
Y. T. Chien, V. Cirigliano,W. Dekens, J. de Vries, EM *in progress*

- ATLAS and CMS are in good agreement with SM
- bounds are better for dipole operators (different shape)
- bounds get worse for heavier quark (pdf suppression)

$$M_{\not T} \sim (1-10)v$$

$\not{T}$ operators at colliders. Higgs Couplings

- associated production of Higgs and a W/Z boson (VH)

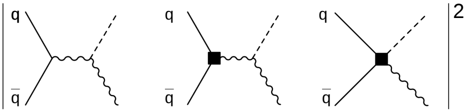


- gauge invariance!
- contributions to DY and VH are related
- there exist a contact quark-Higgs-Z/W vertex

SM and dim. 6 operators have very different s dependence!

$\not{T}$ operators at colliders. Higgs Couplings

- associated production of Higgs and a W/Z boson (VH)

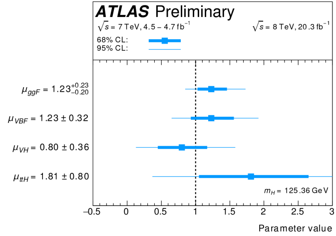


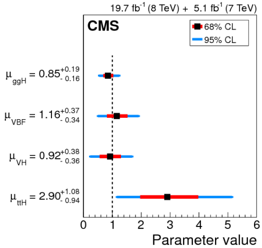
$$\frac{m_Z^2}{s - m_Z^2} \qquad \frac{m_Z^2}{s - m_Z^2} \qquad 1$$

- gauge invariance!
- contributions to DY and VH are related
- there exist a contact quark-Higgs-Z/W vertex

SM and dim. 6 operators have very different s dependence!

$\not{T}$ operators at colliders. Higgs Couplings





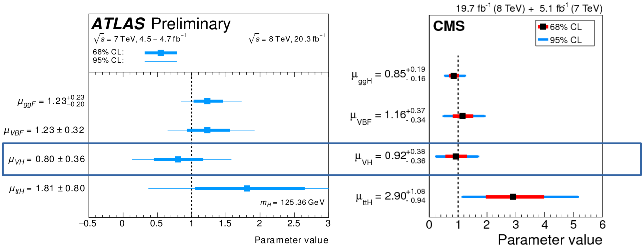
- relative contribution to VH and DY very different

$$\mu_{DY} = 1 + \frac{\sigma^{\mathrm{BSM}}(pp \to e^+\nu_e)}{\sigma^{\mathrm{SM}}(pp \to e^+\nu_e)} = 1 + 0.17(v\Gamma_W^{u,d})^2 + 0.6(v^2\Xi_{ud})^2 + \ldots$$

$$\mu_{WH} = 1 + \frac{\sigma^{\mathrm{BSM}}(pp \to WH)}{\sigma^{\mathrm{SM}}(pp \to WH)} = 1 + 94.7(v\Gamma_W^{u,d})^2 + 112.9(v^2\Xi_{ud})^2 + \ldots$$

- tough VH cross section is known much worse than DY, competitive bounds!

$\not{T}$ operators at colliders. Higgs Couplings



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$\not{T}$ operators at colliders. Higgs Couplings

		$v\Gamma_W^{u,d}$	$v\Gamma_W^{s,c}$	$v\Gamma_Z^u$	$v\Gamma_Z^d$	$v\Gamma_Z^s$	$v\Gamma_Z^c$	$v\Gamma_Z^b$
DY	ATLAS	0.03	0.16	0.08	0.10	0.25	0.39	0.63
	CMS	0.05	1.01					
VH	ATLAS	0.08	0.36	0.09	0.11	0.34	0.56	0.92
	CMS	0.09	0.42	0.10	0.14	0.40	0.67	1.09

Table : 90% confidence bounds on the coefficients of the ZDM from Higgs associated production.

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$\not{T}$ operators at colliders. Higgs Couplings

		$v^2\Xi_{ud}$	$v^2\Xi_{us}$	$v^2\Xi_{ub}$	$v^2\Xi_{cd}$	$v^2\Xi_{cs}$	$v^2\Xi_{cb}$
DY	ATLAS	0.19	0.24	0.39	0.38	0.66	1.14
	CMS	0.88	1.32	5.06	5.84	7.63	14.50
VH	ATLAS	0.07	0.10	0.16	0.17	0.33	0.56
	CMS	0.08	0.11	0.18	0.19	0.39	0.66

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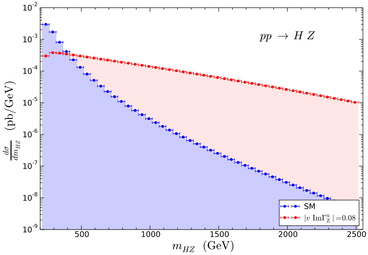

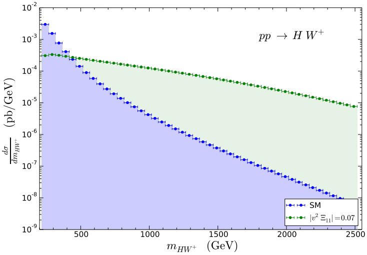

Y. T. Chien, V. Cirigliano, W. Dekens, J. de Vries, EM *in progress*

- BSM operators dominate at large *s*

- more precision for total cross section
- & measurement of differential distributions

greatly improve bounds!
with current luminosities

Conclusion

- Higgs production observables and EDMs show complementarity
- EDMs have potentially a large edge
- weakened by large uncertainties on nuclear matrix elements
  e.g. lose d_{Hg} bounds

Goal

- 50% uncertainty on d_n from d_W, d_s
- 25% uncertainty on d_n from $\tilde{d}_u$, $\tilde{d}_d$
- 50 % uncertainty on $\bar{g}_{0,1}$
- 50 % uncertainty on a_0, a_1

EDM hard to beat!

but

- try to be smarter at collider
  construct genuine $\not{T}$ observables