

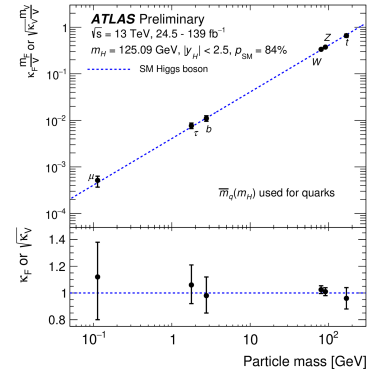
Anomalous Couplings in Higgs plus Jet Production

High Precision for Hard Processes 2024

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Motivation - Higgs Physics

- Run2 measured couplings of Higgs to heavy fermions
- Run3 and HL-LHC are expected to give even more precise measurements
- Precise theoretical predictions needed
- Want to distinguish BSM effects from higher-order uncertainties in Higgs p_T spectrum



[ATLAS '20]

Effective Field Theory - Formulae

Linear EFT - Standard Model Effective Field Theory (SMEFT)

- SM symmetries - Poincaré and gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Higgs part of $SU(2)_L$ doublet
- ordering via canonical mass dimension

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_i \frac{c_i^{(7)}}{\Lambda^3} \mathcal{O}_i^{(7)} + \sum_i \frac{c_i^{(8)}}{\Lambda^4} \mathcal{O}_i^{(8)} + \mathcal{O}\left(\frac{1}{\Lambda^5}\right)$$

Non-linear EFT - Higgs Effective Field Theory (HEFT)

- EW symmetry breaking is realised non-linearly
- Scalar doublet splits into EW singlet h and Goldstone Bosons, which satisfy $SU(2)$
- counting via chiral dimension: $d_\chi(A^\mu, \phi, h, v) = 0$, $d_\chi(\partial^\mu, \bar{\Psi}\Psi, g, Y) = 1$,
- Weinbergs Power counting formula [Weinberg 1979]: $d_\chi = 2 + (D - 2)L + \sum_{k=1}^{\infty} 2(k - 1)V_{2k}$

Effective Operators for Higgs plus Jet

Effective operators up to $d_\chi = 4$:

- Rescaling of top Yukawa coupling (c_t): $O_t = -m_t \frac{\hbar}{v} \bar{t} t$
- Effective Higgs-gluon coupling (c_g): $O_g = \frac{\alpha_s}{8\pi} \frac{\hbar}{v} G_{\mu\nu}^a G^{a,\mu\nu}$

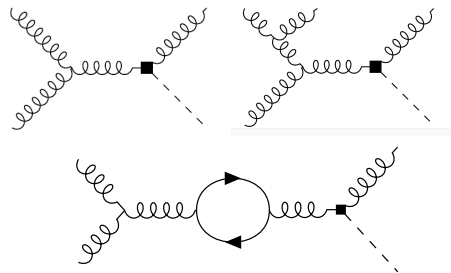
$$\kappa_g = 3/2 c_g : \quad \frac{\sigma_{\text{incl}}(c_t, c_g)}{\sigma_{\text{incl}}^{SM}} = (c_t + \kappa_g)^2 + \mathcal{O}\left(\frac{\kappa_g}{c_t + \kappa_g} \frac{m_h^2}{4m_t^2}\right)^1$$

$c_t + \kappa_g \approx 1 \pm 10\%$ Measured in inclusive Higgs production in gluon fusion

¹[Grojean et al. 2014]

Heavy Top Limit (HTL) vs HEFT

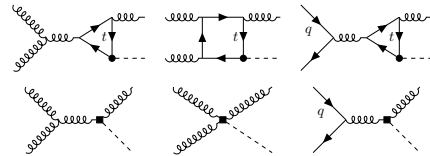
- c_g diagrams not just rescaled HTL-diagrams!
- Only at Born level and for real radiation
- Virtual corrections can have top-loops!
- HTL corresponds to $c_g = 2/3$ excluding virtual top-loops.



Calculation

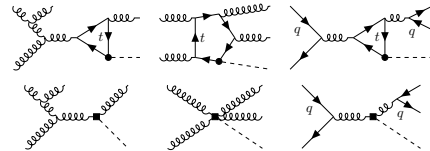
Leading Order

- calculated analytically
- one-loop part based on SM calculation [Baur and Glover 1990]
- cross-checked via GoSam [Cullen et al. 2012; Cullen et al. 2014]



Real Radiation

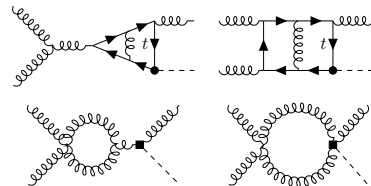
- calculated with GoSam, ninja [Peraro 2014] and OneL0op [Hameren 2011]
- Implemented into POWHEG-BOX-V2 (does subtraction of IR divergences, PS integration) [Nason 2004; Frixione, Nason, and Oleari 2007; Alioli et al. 2010]



Calculation

Virtual Corrections

- one-loop part done with GoSam , ninja and OneL0op
- two-loop part based on SM calculation
[\[Jones, Kerner, and Luisoni 2018\]](#) using REDUZE [\[Manteuffel and Studerus 2012\]](#) and SECDEC-3 [\[Borowka et al. 2015\]](#)



Calculation

Two-Loop Virtuals

- two-loop form factors computed in [\[Jones, Kerner, and Luisoni 2018\]](#) for 2000 points

- Use: $d\sigma^V \sim 2\Re \left[\left(\mathcal{M}_{c_t}^{2L} + \mathcal{M}_{c_g}^{1L} \right) \cdot \left(\mathcal{M}_{c_t}^{1L} + \mathcal{M}_{c_g}^{0L} \right)^\dagger \right]$

$$= 2\Re \left[\mathcal{M}_{c_t}^{2L} \cdot \left(\mathcal{M}_{c_t}^{1L} + \mathcal{M}_{c_g}^{0L} \right)^\dagger + \mathcal{M}_{c_g}^{1L} \cdot \left(\mathcal{M}_{c_t}^{1L} + \mathcal{M}_{c_g}^{0L} \right)^\dagger \right]$$

- $\mathcal{M}_{c_t} = c_t \mathcal{M}_{\text{SM}}$

- \Rightarrow Rescale [\[Jones, Kerner, and Luisoni 2018\]](#) by c_t and add Born c_g form factors

- Add two-loop part $\left[\mathcal{M}_{c_t}^{2L} \cdot \left(\mathcal{M}_{c_t}^{1L} + \mathcal{M}_{c_g}^{0L} \right)^\dagger \right]$ at the end to the rest

- Calculate $\mathcal{M}_{c_g}^{1L} \cdot \left(\mathcal{M}_{c_t}^{1L} + \mathcal{M}_{c_g}^{0L} \right)^\dagger$ via GoSam and implement into POWHEG-BOX-V2

Results - Cross Section

$p_{T,h}$ cut [GeV]	$\sigma_{\text{cut}}(c_t = 0.9, c_g = 1/15)$ [fb]		$\sigma_{\text{cut}}(\text{SM})$ [fb]	
	LO	NLO	LO	NLO
50	$(4.6^{+0.2}_{-0.1}) \cdot 10^3$	$(9.3^{+0.2}_{-1.7}) \cdot 10^3$	$(4.6^{+0.2}_{-0.1}) \cdot 10^3$	$(9.3^{+0.0}_{-1.7}) \cdot 10^3$
400	13^{+6}_{-4}	28^{+2}_{-6}	12^{+5}_{-3}	$25^{+1.5}_{-5}$
600	$1.6^{0.7}_{-0.5}$	$3.3^{+0.4}_{-0.7}$	$1.3^{+0.6}_{-0.4}$	$2.7^{+0.2}_{-0.5}$
800	$0.28^{+0.13}_{-0.08}$	$0.57^{+0.07}_{-0.11}$	$0.20^{+0.10}_{-0.06}$	$0.41^{+0.04}_{-0.08}$

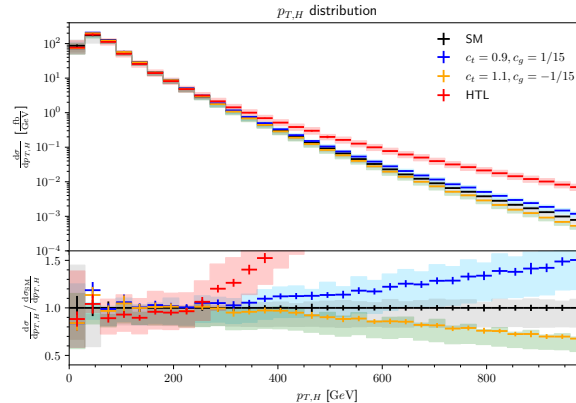
- Scale given by: $\mu_0 = \frac{H_T}{2} = \frac{1}{2} \left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}| \right)$, (sum i over final state partons)
- Difference only exceeds scale uncertainties for highly boosted Higgs bosons, $p_{T,H} > 600\text{GeV}$

Results - Cross Section

$p_{T,H}$ cut [GeV]	$\sigma_{\text{cut,HEFT}}/\sigma_{\text{cut,SM}}$	
	LO	NLO
50	0.9966 ± 0.0006	0.99 ± 0.03
400	1.118 ± 0.007	1.11 ± 0.01
600	1.251 ± 0.012	1.23 ± 0.01
800	1.407 ± 0.016	1.37 ± 0.02

- Ratio increases for higher cuts
- Monte-Carlo uncertainties

Results - Transverse Momentum Distribution



- Only for boosted Higgs is BSM outside SM scale uncertainty
- Cannot use HTL!

Results - Fits

- $\sigma = c_t^2 A + 2c_t c_g B + c_g^2 C$, $\sigma_{\text{SM}} = A$, $\sigma_{\text{HTL}} = (2/3)^2 C_{\text{HTL}}$

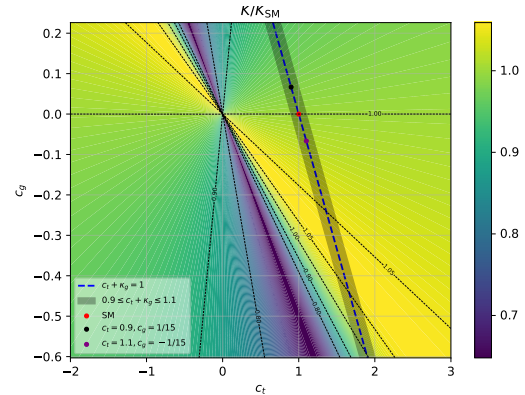
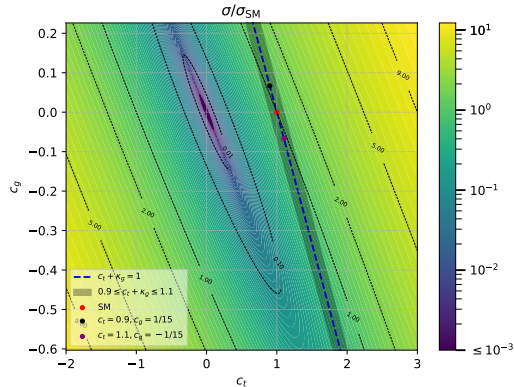
Results - Fits

$$\sigma = c_t^2 A + 2c_t c_g B + c_g^2 C \quad , \quad \sigma_{\text{SM}} = A \quad , \quad \sigma_{\text{HTL}} = (2/3)^2 C_{\text{HTL}}$$

$\rho_{T,h}$ cut [GeV]	$A[\text{pb}]$	$B[\text{pb}]$	$C[\text{pb}]$	$C_{\text{HTL}}[\text{pb}]$
50	9.35 ± 0.13	13.4 ± 0.3	19.2 ± 0.6	18.9 ± 0.4
400	$(2.54 \pm 0.01) \cdot 10^{-2}$	$(5.61 \pm 0.08) \cdot 10^{-2}$	$(13.6 \pm 0.1) \cdot 10^{-2}$	$(13.6 \pm 0.4) \cdot 10^{-2}$
600	$(2.66 \pm 0.01) \cdot 10^{-3}$	$(8.19 \pm 0.11) \cdot 10^{-3}$	$(28.3 \pm 0.2) \cdot 10^{-3}$	$(28.2 \pm 0.3) \cdot 10^{-3}$
800	$(4.14 \pm 0.02) \cdot 10^{-4}$	$(16.8 \pm 0.2) \cdot 10^{-4}$	$(78.3 \pm 0.5) \cdot 10^{-4}$	$(77.7 \pm 0.2) \cdot 10^{-4}$

- $C > B > A$
- C/A increases with cut
- $C_{\text{HTL}} \approx C$

Results - Heat Maps



- Bounds inspired by [\[Celada et al. 2024\]](#)
- Higgs p_T cut of 400GeV
- $\sigma = c_t^2 A + 2c_t c_g B + c_g^2 C$, $C > B > A$

- Ratios can vary considerably
- Inside grey band: Negative c_g : Lower ratio, higher K-factors
Positive c_g : Higher ratio, lower K-factors

Conclusion and Outlook

Higgs plus jet at NLO QCD

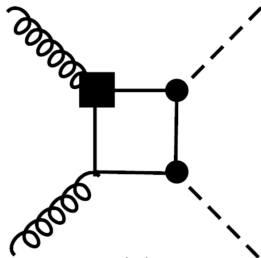
- First study of NLO Higgs plus jet production with HEFT operators and full top mass dependence.
- Studied the total cross section and transverse momentum ($p_{T,h}$) differential distribution
 - Shown that high $p_{T,h}$ regime is very sensitive to BSM effects
 - Still a lot hidden in scale uncertainties
- Studied heat maps of ratio to SM
 - Fit of coupling coefficients allows for fast evaluation of cross section

Outlook

- Higher order HEFT operators
- Higher order QCD corrections
- Other SM uncertainties

Thank you for your attention!

Backup - Chromomagnetic Operator



(c)

$$d_\chi = 6$$

non-hermitian ($\bar{L}R$)

6: $\psi^2 XH + \text{h.c. [LG]}$			
$Q_{eW} (\bar{\ell}_p \sigma^{\mu\nu} e_r) \tau^I H W_{\mu\nu}^I$	$Q_{uG} (\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{H} G_{\mu\nu}^A$	$Q_{dG} (\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G_{\mu\nu}^A$	
$Q_{eB} (\bar{\ell}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{uW} (\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{H} W_{\mu\nu}^I$	$Q_{dW} (\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I H W_{\mu\nu}^I$	
	$Q_{uB} (\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{H} B_{\mu\nu}$	$Q_{dB} (\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$	

Table taken from [Isidori, Wilsch, and Wyler 2024]

LG = Loop generated

Backup - Form Factors for $g(p_1)g(p_2) \rightarrow g(p_3)h(p_4)$

$$M^{\mu\nu\tau} = F_a T_a^{\mu\nu\tau} + F_b T_b^{\mu\nu\tau} + F_c T_c^{\mu\nu\tau} + F_d T_d^{\mu\nu\tau}$$

$$T_a^{\mu\nu\tau} = (s_{12}g^{\mu\nu} - 2p_2^\mu p_1^\nu)(s_{23}p_1^\tau - s_{13}p_2^\tau) \frac{1}{2s_{13}}$$

$$T_b^{\mu\nu\tau} = (s_{23}g^{\nu\tau} - 2p_3^\nu p_2^\tau)(s_{13}p_2^\mu - s_{12}p_3^\mu) \frac{1}{2s_{12}}$$

$$T_c^{\mu\nu\tau} = (s_{13}g^{\tau\mu} - 2p_1^\tau p_3^\mu)(s_{12}p_3^\nu - s_{23}p_1^\nu) \frac{1}{2s_{23}}$$

$$T_d^{\mu\nu\tau} = [g^{\mu\nu}(s_{23}p_1^\tau - s_{13}p_2^\tau) + g^{\nu\tau}(s_{13}p_2^\mu - s_{12}p_3^\mu) + g^{\tau\mu}(s_{12}p_3^\nu - s_{23}p_1^\nu) + 2p_3^\mu p_1^\nu p_2^\tau - 2p_2^\mu p_3^\nu p_1^\tau] \frac{1}{2}$$

Backup - Form Factors for $g(p_1)g(p_2) \rightarrow g(p_3)h(p_4)$

$$P_{k, \mu\nu\tau} M^{\mu\nu\tau} = F_k$$

$$P_a^{\mu\nu\tau} = \frac{1}{(D-3) s_{23}} \left(-\frac{Ds_{13}}{s_{12}^2 s_{23}} T_a^{\mu\nu\tau} + \frac{D-4}{s_{23}^2} T_b^{\mu\nu\tau} + \frac{D-4}{s_{12} s_{13}} T_c^{\mu\nu\tau} + \frac{D-2}{s_{12} s_{23}} T_d^{\mu\nu\tau} \right)$$

$$P_b^{\mu\nu\tau} = \frac{1}{(D-3) s_{12}} \left(\frac{D-4}{s_{12} s_{23}} T_a^{\mu\nu\tau} - \frac{Ds_{12}}{s_{13} s_{23}^2} T_b^{\mu\nu\tau} + \frac{D-4}{s_{13}^2} T_c^{\mu\nu\tau} + \frac{D-2}{s_{13} s_{23}} T_d^{\mu\nu\tau} \right)$$

$$P_c^{\mu\nu\tau} = \frac{1}{(D-3) s_{13}} \left(\frac{D-4}{s_{12}^2} T_a^{\mu\nu\tau} + \frac{D-4}{s_{13} s_{23}} T_b^{\mu\nu\tau} - \frac{Ds_{23}}{s_{12} s_{13}^2} T_c^{\mu\nu\tau} + \frac{D-2}{s_{12} s_{13}} T_d^{\mu\nu\tau} \right)$$

$$P_d^{\mu\nu\tau} = \frac{D-2}{(D-3) s_{12} s_{13} s_{23}} \left(\frac{s_{13}}{s_{12}} T_a^{\mu\nu\tau} + \frac{s_{12}}{s_{23}} T_b^{\mu\nu\tau} + \frac{s_{23}}{s_{13}} T_c^{\mu\nu\tau} + \frac{D}{D-2} T_d^{\mu\nu\tau} \right)$$

Backup - Form Factors for $q(p_1)\bar{q}(p_2) \rightarrow g(p_3)h(p_4)$

$$M^{\rho} \epsilon_{\rho} = F_1 T_1 + F_2 T_2$$

$$T_1 = \bar{u}(p_1) \not{p}_3 v(p_2) (p_2 \cdot \epsilon_3) - \bar{u}(p_1) \not{\epsilon}_3 v(p_2) (p_2 \cdot p_3)$$

$$T_2 = \bar{u}(p_1) \not{p}_3 v(p_2) (p_1 \cdot \epsilon_3) - \bar{u}(p_1) \not{\epsilon}_3 v(p_2) (p_1 \cdot p_3)$$

$$\sum_{\text{spins}} P_i M^{\rho} \epsilon_{\rho} = F_i$$

$$P_1 = \frac{D-2}{2(D-3)s_{12}s_{13}^2} T_1^{\dagger} - \frac{D-4}{2(D-3)s_{12}s_{13}s_{23}} T_2^{\dagger}$$

$$P_2 = -\frac{D-4}{2(D-3)s_{12}s_{13}s_{23}} T_1^{\dagger} + \frac{D-2}{2(D-3)s_{12}s_{23}^2} T_2^{\dagger}$$

Backup - Scale dependency of couplings

- Why is there no scale dependency in the anomalous couplings?
- \Rightarrow Only at LL and without c_{tg} .

$$\begin{aligned}\partial_t c_t &= -4 \frac{m_t^2}{v^2} a_s c_{tg}, \\ \partial_t c_g &= \frac{m_t^2}{2v^2} c_{tg}, \\ \partial_t c_{tg} &= \frac{7a_s}{6} c_{tg}.\end{aligned}$$

Taken from [\[Battaglia et al. 2021\]](#) where $t = \log(Q^2/\mu^2)$

Backup - HEFT Lagrangian

$$\begin{aligned}
 \mathcal{L}_2 = & - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a,\mu\nu} - \frac{1}{4} G_{\mu\nu}^b G^{b,\mu\nu} + \sum_{\Psi=Q_L, L_L, U_R, D_R, E_R} \bar{\Psi} i \not{D} \Psi \\
 & + \frac{v^2}{4} \text{Tr} [D_\mu \Omega^\dagger D^\mu \Omega] (1 + F_\Omega(h)) + \frac{1}{2} (\partial_\mu h)(\partial^\mu h) - V(h) \\
 & - v \left[\bar{Q}_L \left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega P_+ Q_R + \bar{Q}_L \left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega P_- Q_R \right. \\
 & \quad \left. + \bar{L}_L \left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega P_- L_R + h.c. \right]
 \end{aligned}$$

Backup - HEFT Lagrangian

Goldstone Bosons: $\Omega = \exp\left(2i \frac{\phi^a \sigma_a}{v}\right)$ with $D_\mu \Omega = \partial_\mu \Omega + igW_\mu \Omega - ig'B_\mu \Omega \sigma_3$

Right-handed Doublets: $Q_R = \begin{pmatrix} U_R \\ D_R \end{pmatrix}$, $L_R = \begin{pmatrix} 0 \\ E_R \end{pmatrix}$ with $P_+ = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$, $P_- = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$

Higgs Potential: $F_\Omega(h) = \sum_{n=1}^{\infty} f_{\Omega,n} \left(\frac{h}{v}\right)^n$, $V(h) = v^4 \sum_{n=2}^{\infty} f_{V,n} \left(\frac{h}{v}\right)^n$

Standard Model: $f_{\Omega,1} = 2$, $f_{\Omega,2} = 1$, $f_{V,2} = f_{V,3} = \frac{m_h^2}{2v^2}$, $f_{V,4} = \frac{m_h^2}{8v^2}$, $Y_f^{(1)} = Y_f$

Chiral Dimension: $d_\chi(A^\mu, \phi, h, v, f_{\Omega,n}) = 0$, $d_\chi(\partial^\mu, \bar{\Psi}\Psi, g, Y) = 1$, $d_\chi(f_{V,n}) = 2$