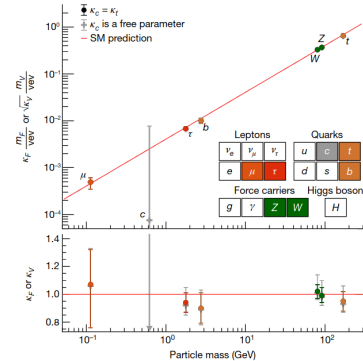# Anomalous Couplings in Higgs plus Jet Production

Higgs (2024) Uppsala

Benjamin Campillo, Gudrun Heinrich, Matthias Kerner, Lucas Kunz | 06.11.2024

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 '22]

History

Standard Model

- NLO study with full top mass [Bonciani et al. 2023; Jones, Kerner, and Luisoni 2018; Neumann 2018]
- several NNLO calculations in HTL [Boughezal, Caola, et al. 2013; Chen, Gehrmann, Glover, and Jaquier 2015; Boughezal, Caola, et al. 2015; Boughezal, Focke, et al. 2015; Caola, Melnikov, and Schulze 2015; Chen, Gehrmann, Glover, and Huss 2019; Campbell, Ellis, and Seth 2019]

Effective Field Theory

- LO Study in [Grojean et al. 2014; Schlaffer et al. 2014]
- NLL study [Battaglia et al. 2021]
- LO + RGE running study [Maltoni, Ventura, and Vryonidou 2024]
- 2-loop RGE running [Di Noi, Gröber, and Mandal 2024]
- NLO in HTL [Grazzini et al. 2017]

but not at NLO with full top mass dependence!

Effective Field Theory - Formulae

Linear EFT - Standard Model Effective Field Theory (SMEFT)

- SM symmetries - Poincaré and gauge group $SU(3)_{\mathrm{C}} \times SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}}$
- Higgs part of $SU(2)_{\mathrm{L}}$ doublet
- ordering via canonical mass dimension

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

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: $d_\chi(A^\mu, \phi, h, v) = 0$, $d_\chi(\partial^\mu, \overline{\Psi}\Psi, g, Y) = 1$,
- Weinbergs Power counting formula [Weinberg 1979]: $d_\chi = 2 + (D-2)L + \sum_{k=1}^{\infty} 2(k-1)V_{2k}$

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

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

$$\kappa_g = 3/2 c_g : \quad \frac{\sigma_{\mathrm{incl}}(c_t, c_g)}{\sigma_{\mathrm{incl}}^{SM}} = (c_t + \kappa_g)^2 + \mathcal{O}(\frac{\kappa_g}{c_t + \kappa_g} \frac{m_h^2}{4m_t^2})^1$$
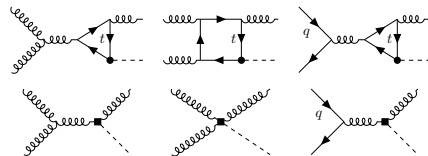
$c_t + \kappa_g \approx 1 \pm 10\%$ Measured in inclusive Higgs production in gluon fusion
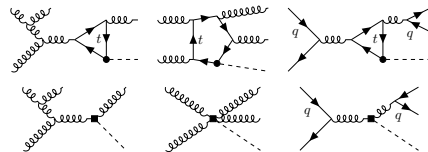
[1][Grojean et al. 2014]

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]

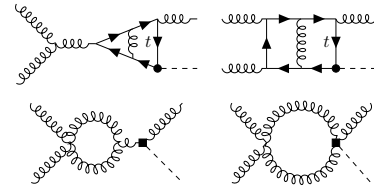**Real Radiation**

- calculated with `GoSam`, `ninja` [Peraro 2014] and `OneLOop` [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]

Virtual Corrections

- one-loop part done with `GoSam`, `ninja` and `OneLOop`
- 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: $d\sigma^V \sim 2\Re\left[\left(\mathcal{M}^{2L}_{c_t} + \mathcal{M}^{1L}_{c_g}\right) \cdot \left(\mathcal{M}^{1L}_{c_t} + \mathcal{M}^{0L}_{c_g}\right)^\dagger\right]$

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

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

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

- Use neural network to interpolate $\left[\mathcal{M}^{2L}_{c_t} \cdot \left(\mathcal{M}^{1L}_{c_t} + \mathcal{M}^{0L}_{c_g}\right)^\dagger\right]$

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

Results - Cross Section

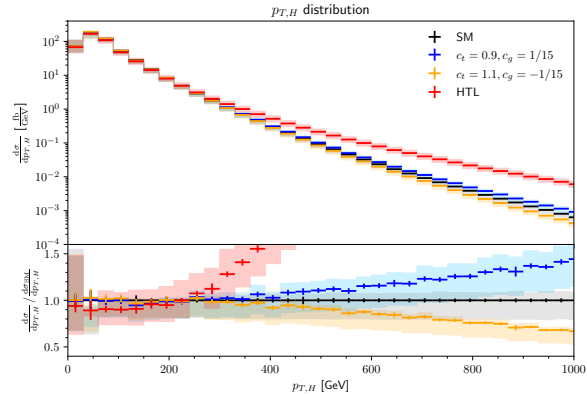| $p_{T,H}^{\text{cut}}$ [GeV]	$\sigma_{\text{cut}}(c_t = 0.9,\ c_g = 1/15)$ [fb]		$\sigma_{\text{cut}}(\text{SM})$ [fb]	
	LO	NLO	LO	NLO
50	$\left(4.5^{+1.8}_{-1.2}\right) \cdot 10^3$	$\left(9.1^{+0.1}_{-1.6}\right) \cdot 10^3$	$\left(4.5^{+1.8}_{-1.2}\right) \cdot 10^3$	$\left(9.1^{+0.0}_{-1.4}\right) \cdot 10^3$
400	13^{+6}_{-4}	28^{+2}_{-6}	12^{+5}_{-3}	$25^{+1.6}_{-5}$
600	$1.6^{0.7}_{-0.5}$	$3.3^{+0.3}_{-0.7}$	$1.3^{+0.6}_{-0.4}$	$2.7^{+0.2}_{-0.5}$
800	$0.29^{+0.14}_{-0.09}$	$0.60^{+0.07}_{-0.12}$	$0.21^{+0.10}_{-0.06}$	$0.43^{+0.04}_{-0.09}$

- 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

$p_{T,H}^{\text{cut}}$ [GeV]	$\sigma_{\text{cut.HEFT}}/\sigma_{\text{cut,SM}}$	
	LO	NLO
50	0.9966 ± 0.0006	1.00 ± 0.04
400	1.119 ± 0.007	1.10 ± 0.01
600	1.250 ± 0.012	1.22 ± 0.01
800	1.410 ± 0.016	1.37 ± 0.01

- Ratio increases for higher $p_{T,H}$ cuts
- Monte-Carlo uncertainties

Results - Transverse Momentum Distribution

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

- $\sigma = c_t^2 A + 2c_t c_g B + c_g^2 C \quad , \quad \sigma_{\mathrm{SM}} = A$
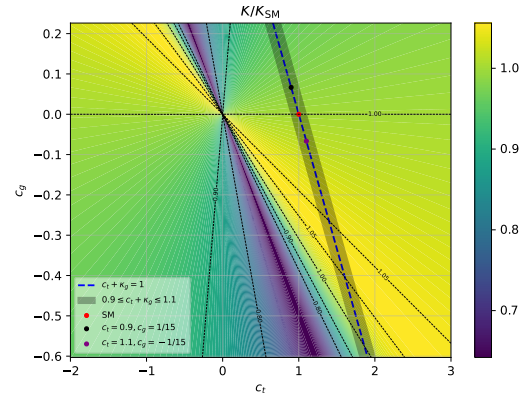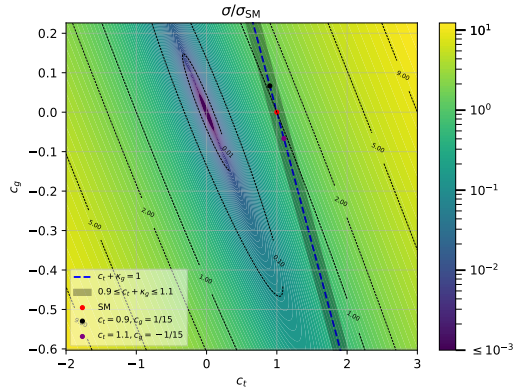
Results - Fits

$$\sigma = c_t^2 A + 2 c_t c_g B + c_g^2 C \quad , \quad \sigma_{\rm SM} = A$$

$p_{T,H}^{\rm cut}$	A	B	C
50	9.13 ± 0.12	13.1 ± 0.3	18.9 ± 0.5
400	$(2.54 \pm 0.01) \cdot 10^{-2}$	$(5.65 \pm 0.08) \cdot 10^{-2}$	$(13.7 \pm 0.1) \cdot 10^{-2}$
600	$(2.73 \pm 0.01) \cdot 10^{-3}$	$(8.37 \pm 0.11) \cdot 10^{-3}$	$(28.9 \pm 0.2) \cdot 10^{-3}$
800	$(4.33 \pm 0.02) \cdot 10^{-4}$	$(17.5 \pm 0.2) \cdot 10^{-4}$	$(80.6 \pm 0.5) \cdot 10^{-4}$

- $C > B > A$
- C/A increases with cut; A scales as $1/p_{T,H}^2$, C as $1/p_{T,H}$ [Caola, Forte, et al. 2016]
  - Uncertainties = Monte-Carlo + Fit

Results - Heat Maps

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

- 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
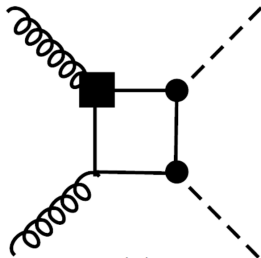
Higgs plus jet at NLO QCD

- 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 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
- Code will be available on the POWHEG-BOX-V2

Outlook

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

Thank you for your attention!

(c)

$d_\chi = 6$

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

Table taken from [Isidori, Wilsch, and Wyler 2024]
LG = Loop generated

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

$$
\begin{aligned}
T_a^{\mu\nu\tau} &= \left(s_{12}g^{\mu\nu} - 2p_2^\mu p_1^\nu\right)\left(s_{23}p_1^\tau - s_{13}p_2^\tau\right)\frac{1}{2s_{13}} \\
T_b^{\mu\nu\tau} &= \left(s_{23}g^{\nu\tau} - 2p_3^\nu p_2^\tau\right)\left(s_{13}p_2^\mu - s_{12}p_3^\mu\right)\frac{1}{2s_{12}} \\
T_c^{\mu\nu\tau} &= \left(s_{13}g^{\tau\mu} - 2p_1^\tau p_3^\mu\right)\left(s_{12}p_3^\nu - s_{23}p_1^\nu\right)\frac{1}{2s_{23}} \\
T_d^{\mu\nu\tau} &= \left[g^{\mu\nu}\left(s_{23}p_1^\tau - s_{13}p_2^\tau\right) + g^{\nu\tau}\left(s_{13}p_2^\mu - s_{12}p_3^\mu\right) + g^{\tau\nu}\left(s_{12}p_3^\nu - s_{23}p_1^\nu\right)\right. \\
&\quad \left. + 2p_3^\mu p_1^\nu p_2^\tau - 2p_2^\mu p_3^\nu p_1^\tau\right]\frac{1}{2}
\end{aligned}
$$

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

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

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

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

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

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

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

$$
\begin{aligned}
T_1 &= \overline{u}(p_1)\,p\!\!\!/_3\,v(p_2)\,(p_2 \cdot \epsilon_3) - \overline{u}(p_1)\,\epsilon\!\!\!/_3\,v(p_2)\,(p_2 \cdot p_3) \\
T_2 &= \overline{u}(p_1)\,p\!\!\!/_3\,v(p_2)\,(p_1 \cdot \epsilon_3) - \overline{u}(p_1)\,\epsilon\!\!\!/_3\,v(p_2)\,(p_1 \cdot p_3)
\end{aligned}
$$

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

$$
\begin{aligned}
P_1 &= \frac{D-2}{2(D-3)s_{12}s_{13}^2} T_1^\dagger - \frac{D-4}{2(D-3)s_{12}s_{13}s_{23}} T_2^\dagger \\
P_2 &= -\frac{D-4}{2(D-3)s_{12}s_{13}s_{23}} T_1^\dagger + \frac{D-2}{2(D-3)s_{12}s_{23}^2} T_2^\dagger
\end{aligned}
$$

Backup - Scale dependency of couplings

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

$$\partial_t c_t = -4\frac{m_t^2}{v^2}\, a_s\, c_{tg}\,,$$

$$\partial_t c_g = \frac{m_t^2}{2v^2}\, c_{tg}\,,$$

$$\partial_t c_{tg} = \frac{7a_s}{6}\, c_{tg}\,.$$

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

$$
\begin{aligned}
\mathcal{L}_2 = \quad & - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} G^b_{\mu\nu} G^{b,\mu\nu} + \sum_{\Psi = Q_L, L_L, U_R, D_R, E_R} \overline{\Psi}\, i \slashed{D}\, \Psi \\
& + \frac{v^2}{4} \mathrm{Tr} \left[D_\mu \Omega^\dagger D^\mu \Omega \right] (1 + F_\Omega(h)) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h) - V(h) \\
& - v \left[\overline{Q}_L \left(Y_u + \sum_{n=1}^\infty Y_u^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega\, P_+\, Q_R + \overline{Q}_L \left(Y_d + \sum_{n=1}^\infty Y_d^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega\, P_-\, Q_R \right. \\
& \left. \quad + \overline{L}_L \left(Y_e + \sum_{n=1}^\infty Y_e^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega\, P_-\, L_R + h.c. \right]
\end{aligned}
$$

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

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

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