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Institute for Theoretical Physics

Anomalous Couplings in Higgs plus Jet Production

Young Scientist Meeting

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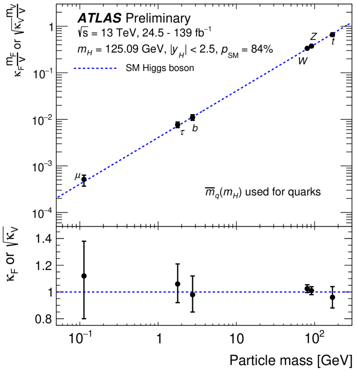
Motivation - Higgs Physics

- 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]

History

Has been studied by

- [Grojean et al. 2014]
- [Battaglia et al. 2021]
- [Maltoni, Ventura, and Vryonidou 2024]
- [Di Noi, Gröber, and Mandal 2024]

but not at NLO with full top mass dependence!

Effective Field Theory - Formulae

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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 for Higgs plus Jet

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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): $O_g = \frac{\alpha_s}{8\pi} \frac{h}{v} G^a_{\mu\nu} G^{a,\mu\nu}$

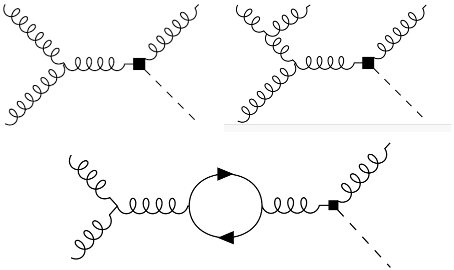
$$\kappa_g = 3/2 c_g : \quad \frac{\sigma_{\mathrm{incl}}(c_t, c_g)}{\sigma^{SM}_{\mathrm{incl}}} = (c_t + \kappa_g)^2 + \mathcal{O}(\frac{\kappa_g}{c_t + \kappa_g} \frac{m_h^2}{4 m_t^2})^1$$

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

[1] [Grojean et al. 2014]

Heavy Top Limit (HTL) vs HEFT

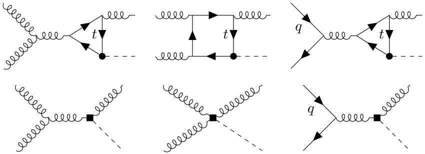
- c_g diagrams not just rescaled HTL-diagrams!
- Only at Born level and for real radiation
- Virtual corrections can have top-loops!
- HTL corresponds to $c_g = 2/3$ excluding virtual top-loops.



Calculation

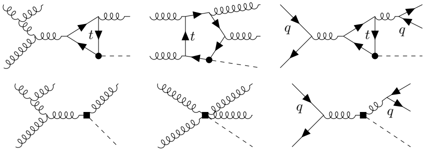
Leading Order

- 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

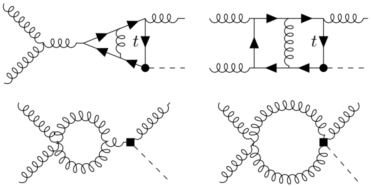
- calculated with `GoSam`, `ninja` [Peraro 2014] and `OneLOop` [Hameren 2011]
- Implemented into `POWHEG-BOX-V2` (does subtraction of IR divergences, PS integration) [Nason 2004; Frixione, Nason, and Oleari 2007; Alioli et al. 2010]



Calculation

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

$p_{T,h}$ cut [GeV]	$\sigma_{\rm cut}(c_t = 0.9, c_g = 1/15)$ [fb]		$\sigma_{\rm cut}(\rm SM)$ [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	$0.28^{+0.13}_{-0.08}$	$0.57^{+0.07}_{-0.11}$	$0.20^{+0.10}_{-0.06}$	$0.41^{+0.04}_{-0.08}$

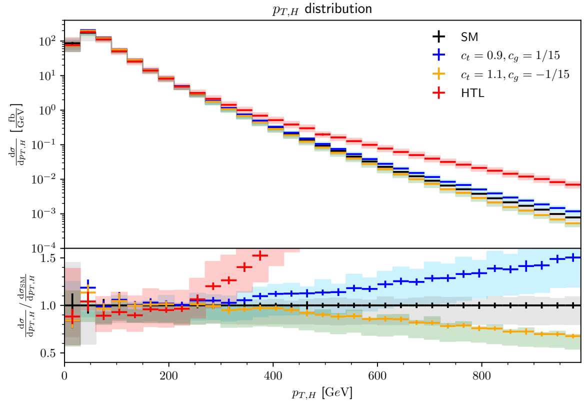
- Scale given by: $\mu_0 = \frac{H_T}{2} = \frac{1}{2}\left(\sqrt{m_H^2 + p_{T,H}^2} + \sum_i |p_{T,i}|\right)$, (sum i over final state partons)
- Difference only exceeds scale uncertainties for highly boosted Higgs bosons, $p_{T,H} > 600\text{GeV}$

Results - Cross Section

$p_{T,H}$ cut [GeV]	$\sigma_{\text{cut,HEFT}}/\sigma_{\text{cut,SM}}$ LO	$\sigma_{\text{cut,HEFT}}/\sigma_{\text{cut,SM}}$ 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

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

Results - Fits

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

$p_{T,h}$ cut [GeV]	A[pb]	B[pb]	C[pb]	C_{HTL}[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
- $C_{\mathrm{HTL}} \approx C$
- Uncertainties = Monte-Carlo + Fit

Results - Heat Maps

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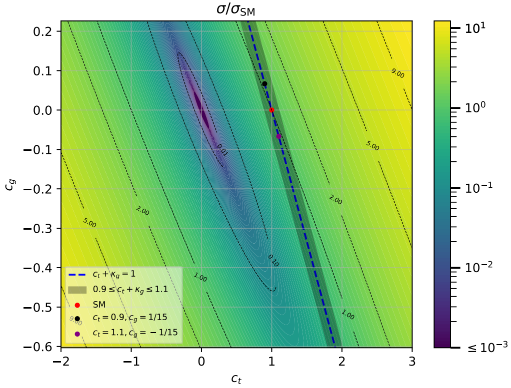
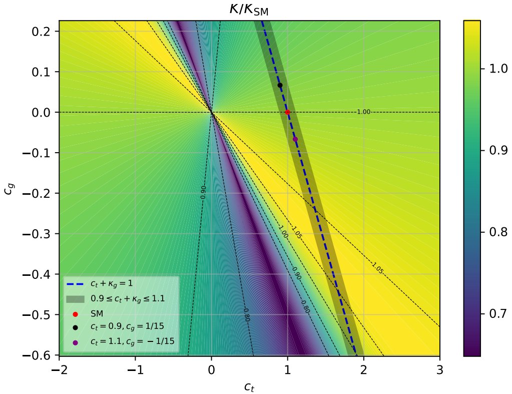




- Bounds inspired by [Celada et al. 2024]
- Higgs p_T cut of $400\mathrm{GeV}$
- $\sigma = c_t^2 A + 2c_t c_g B + c_g^2 C, \quad C > B > A$
- Ratios can vary considerably
- Inside grey band: Negative c_g: Lower ratio, higher K-factors
  Positive c_g: Higher ratio, lower K-factors

Conclusion and Outlook

Higgs plus jet at NLO QCD

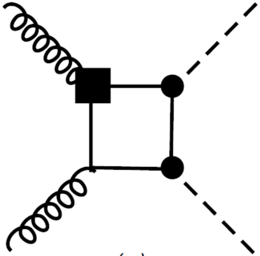
- First study of NLO Higgs plus jet production with HEFT operators and full top mass dependence.
- Studied the total cross section and transverse momentum ($p_{T,h}$) differential distribution
  - Shown that high pTH regime is very sensitive to BSM effects
  - Still a lot hidden in scale uncertainties
- 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: $\psi^2 XH$ + h.c. [LG]					
Q_{eW}	$(\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H} G^A_{\mu\nu}$	Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H G^A_{\mu\nu}$
Q_{eB}	$(\bar{\ell}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H} W^I_{\mu\nu}$	Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H W^I_{\mu\nu}$
		Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H} B_{\mu\nu}$	Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H B_{\mu\nu}$

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

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

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

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

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

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

$$\begin{aligned}
P_a^{\mu\nu\tau} &= \frac{1}{(D-3)\,s_{23}}\left(-\frac{Ds_{13}}{s_{12}^2 s_{23}}\,T_a^{\mu\nu\tau} + \frac{D-4}{s_{23}^2}\,T_b^{\mu\nu\tau} + \frac{D-4}{s_{12}s_{13}}\,T_c^{\mu\nu\tau} + \frac{D-2}{s_{12}s_{23}}\,T_d^{\mu\nu\tau}\right)\\
P_b^{\mu\nu\tau} &= \frac{1}{(D-3)\,s_{12}}\left(\frac{D-4}{s_{12}s_{23}}\,T_a^{\mu\nu\tau} - \frac{Ds_{12}}{s_{13}s_{23}^2}\,T_b^{\mu\nu\tau} + \frac{D-4}{s_{13}^2}\,T_c^{\mu\nu\tau} + \frac{D-2}{s_{13}s_{23}}\,T_d^{\mu\nu\tau}\right)\\
P_c^{\mu\nu\tau} &= \frac{1}{(D-3)\,s_{13}}\left(\frac{D-4}{s_{12}^2}\,T_a^{\mu\nu\tau} + \frac{D-4}{s_{13}s_{23}}\,T_b^{\mu\nu\tau} - \frac{Ds_{23}}{s_{12}s_{13}^2}\,T_c^{\mu\nu\tau} + \frac{D-2}{s_{12}s_{13}}\,T_d^{\mu\nu\tau}\right)\\
P_d^{\mu\nu\tau} &= \frac{D-2}{(D-3)\,s_{12}\,s_{13}\,s_{23}}\left(\frac{s_{13}}{s_{12}}\,T_a^{\mu\nu\tau} + \frac{s_{12}}{s_{23}}\,T_b^{\mu\nu\tau} + \frac{s_{23}}{s_{13}}\,T_c^{\mu\nu\tau} + \frac{D}{D-2}\,T_d^{\mu\nu\tau}\right)
\end{aligned}$$

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

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

$$\begin{aligned} T_1 &= \overline{u}(p_1)\, \not{p}_3\, v(p_2)\ (p_2 \cdot \epsilon_3) - \overline{u}(p_1)\, \not{\epsilon}_3\, v(p_2)\ (p_2 \cdot p_3) \\ T_2 &= \overline{u}(p_1)\, \not{p}_3\, v(p_2)\ (p_1 \cdot \epsilon_3) - \overline{u}(p_1)\, \not{\epsilon}_3\, v(p_2)\ (p_1 \cdot p_3) \end{aligned}$$

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

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

Backup - Scale dependency of couplings

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- Why is there no scale dependency in the anomolous 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

$$
\begin{aligned}
\mathcal{L}_2 = \quad & - \quad \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a,\mu\nu} - \frac{1}{4} G^b_{\mu\nu} G^{b,\mu\nu} + \sum_{\Psi = Q_\mathrm{L}, L_\mathrm{L}, U_\mathrm{R}, D_\mathrm{R}, E_\mathrm{R}} \overline{\Psi}\, i \not{D}\, \Psi \\
& + \quad \frac{v^2}{4} \mathrm{Tr}\left[D_\mu \Omega^\dagger D^\mu \Omega \right] (1 + F_\Omega(h)) + \frac{1}{2} (\partial_\mu h)(\partial^\mu h) - V(h) \\
& - \quad v \Bigg[\overline{Q}_\mathrm{L} \left(Y_u + \sum_{n=1}^{\infty} Y_u^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega\, P_+\, Q_\mathrm{R} + \overline{Q}_\mathrm{L} \left(Y_d + \sum_{n=1}^{\infty} Y_d^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega\, P_-\, Q_\mathrm{R} \\
& \qquad + \overline{L}_\mathrm{L} \left(Y_e + \sum_{n=1}^{\infty} Y_e^{(n)} \left(\frac{h}{v} \right)^n \right) \Omega\, P_-\, L_\mathrm{R} + h.c. \Bigg]
\end{aligned}
$$

Backup - HEFT Lagrangian

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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: $Q_\mathrm{R} = \begin{pmatrix} U_\mathrm{R} \\ D_\mathrm{R} \end{pmatrix}$, $L_\mathrm{R} = \begin{pmatrix} 0 \\ E_\mathrm{R} \end{pmatrix}$ 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: $d_\chi(A^\mu, \phi, h, v, f_{\Omega,n}) = 0$, $d_\chi(\partial^\mu, \overline{\Psi}\Psi, g, Y) = 1$, $d_\chi(f_{V,n}) = 2$