Is SMEFT enough for di-Higgs production?

Lorenzo Tiberi

Department of Physics & Geology, University of Perugia & INFN

Work in progress with Iñigo Asiáin and Ramona Gröber

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Outline

1. Effective field theories for the Higgs boson:
   - H pair production.
   - SM $\subseteq$ SMEFT $\subseteq$ HEFT.
   - Loryons.
2. Scalar singlet model:
   - Model.
   - Matching to SMEFT and HEFT.
   - Results.
3. Colored Scalar:
   - Model.
   - 1-loop matching.
   - Results
4. Conclusion.

Introduction (items 1)

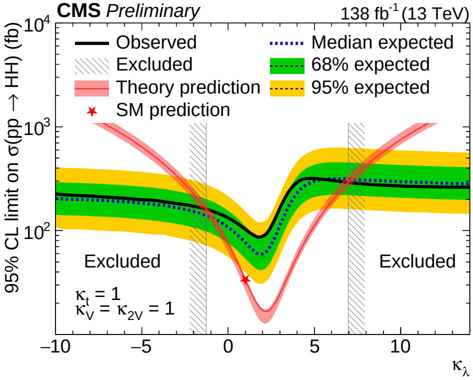
Our work (items 2–3)

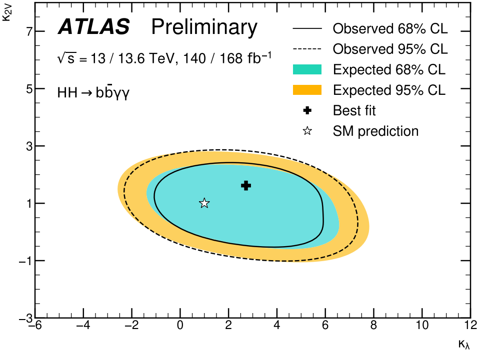
Sorry for incomplete and/or biased bibliography...

Motivations

Higgs pair production gives access to the Higgs self coupling λ, which is loosely bounded.

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \Rightarrow \frac{1}{2} m^2 h^2 + \lambda v h^3 + \frac{\lambda}{8} h^4 + \ldots ?$$

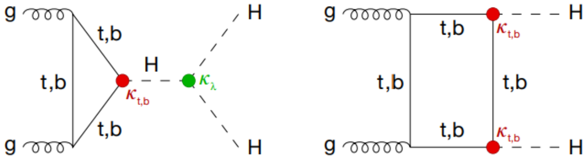




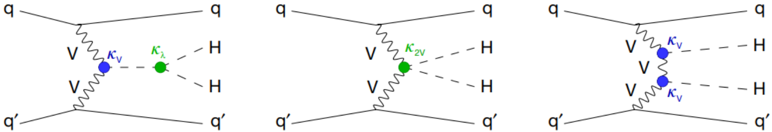
[Aram Hayrapetyan et al. (2024)](left) [Georges Aad et al. (2025)] (right).

Di-Higgs production

Largest contributions from gluon gluon fusion (ggF) and vector boson fusion (VBF).
$\sqrt{s} = 13\text{TeV}$, $\sigma_{\text{ggF}} = 31.1\text{fb}$ [D. de Florian et al. (2016)].



$\sqrt{s} = 13\text{TeV}$, $\sigma_{\text{VBF}} = 1.72\text{fb}$ [D. de Florian et al. (2016)].



For more on HH see *talk by Stefano Moretti*! We focus on two *inequivalent* effective field theories to describe new physics.

Scalar sector

$\mathcal{L}_{\rm SM} \supset (\partial_\mu H)^\dagger \partial^\mu H - V(H)$ is $O(4)$ invariant and **by assumption** h is part of the doublet:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix} \to \vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ v+h \end{pmatrix} .$$

Linear transformation under $O(4)$:

$$\vec{\phi} \to O\vec{\phi}\,, \qquad O \in O(4)\,, \qquad \boxed{\text{SMEFT}}.$$

Local isomorphism in group theory $O(4) \simeq SU(2)_L \otimes SU(2)_R$:

$$\Sigma \equiv \left(\tilde{H}, H\right), \quad \Sigma(x) = \frac{v+h(x)}{\sqrt{2}} U(x), \quad U(x) = e^{i\frac{\pi^a \sigma^a}{v}} .$$

Transformation under chiral symmetry:

$$h \to h, \qquad U \to LUR^\dagger, \quad L/R \in SU(2)_{L/R}\,, \qquad \boxed{\text{HEFT}}.$$

Always possible to go SMEFT $\to$ HEFT, viceversa is not [Timothy Cohen et al. (2021)].

SMEFT

Linear realization of EWSB, this EFT power counting is based on inverse powers of NP scale Λ (really a multiscale problem):

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{c^{(5)}}{\Lambda_{\text{LNV}}}\mathcal{O}_{\text{Weinberg}} + \sum_{d\geq 6}\frac{c_i^d}{\Lambda^{(d-4)}}\mathcal{O}_i^{(d)},$$

Key properties of SMEFT:

- Λ can be taken arbitrarily high, in collider physics we choose $\Lambda \sim \mathcal{O}(\text{TeV})$.
- well defined power counting in terms of inverse powers of Λ.
- Lorentz invariant operators which are invariant uder SM gauge group.

In this work $d = 4, 6$ terms, the famous **Warsaw-basis** [B. Grzadkowski et al. (2010)]$\Rightarrow$ [See *Manuel Drees talk*]

EWSB in SMEFT requires: vev redefinifion, canonical normalization of the h field, mass shifts in the gauge boson sector and the Yukawa sector.

HEFT

H can also be described in a non-linear realization. Formally adopting CCWZ formalism:

$$H \to \frac{v+h}{\sqrt{2}}\boldsymbol{U}, \qquad \boldsymbol{U} = e^{\frac{i\sigma_i \pi^i}{v}},$$

Here we restrict to LO EW chiral Lagrangian ($d_\chi = 2$) [F. Feruglio (1993), G. Buchalla and O. Cata (2012)], also NLO basis in literature [I. Brivio et al. (2014), H. Sun and Jiang-Hao Xiao Ming-Lei Yu (2023)]:

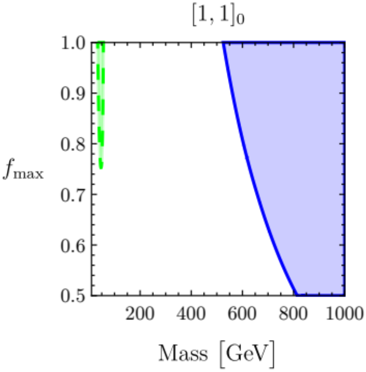
$$\begin{aligned}\mathcal{L}_0 = & -\frac{1}{4}G^a_{\mu\nu}G^{a\,\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\partial_\mu h\,\partial^\mu h - \lambda v^4\mathcal{V}(h) - \frac{v^2}{4}\mathrm{Tr}(\mathbf{V}_\mu\mathbf{V}^\mu)\,\mathcal{F}_C(h) \\ & + c_T\,\frac{v^2}{4}\mathrm{Tr}(\mathbf{T}\mathbf{V}_\mu)^2\,\mathcal{F}_T(h) + i\bar{Q}_L \not{D} Q_L + i\bar{Q}_R \not{D} Q_R + i\bar{L}_L \not{D} L_L \\ & + i\bar{L}_R \not{D} L_R - \frac{v}{\sqrt{2}}(\bar{Q}_L\,\mathbf{U}\,\mathcal{Y}_Q(h)\,Q_R + \text{h.c.}) - \frac{v}{\sqrt{2}}(\bar{L}_L\,\mathbf{U}\,\mathcal{Y}_L(h)\,L_R + \text{h.c.})\end{aligned}$$

HEFT power counting based on the number of loops, a more difficult counting where couplings count. A lower upper bound $4\pi v$ where this EFT breaks down.

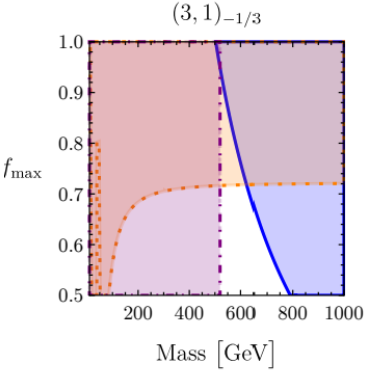
Loryons

Loryons [I. Banta et al. (2022)]are hypothetical **non-decoupling BSM particles** that: get most of their mass from EWSB and/or introduce additional source of EWSB. Loryons live in the quotient space HEFT/SMEFT. A necessary matching into HEFT is required if:

$$f = \lambda_{H\Phi}/(\lambda_{H\Phi} + \lambda_{ex}) \geq 0.5\,, \quad \lambda_{ex} = 2m_{ex}^2/v^2\,, \quad m_{ex}\ \textbf{non EWSB mass.}$$



(a) Scalar singlet [I. Banta et al. (2022)].



(b) Colored scalar [I. Banta et al. (2022)].

Scalar singlet

Renormalizable UV completion adds $\Phi \sim (1,1,0)$ to SM, tree level mixing present.

$$\mathcal{L}_{UV} = \mathcal{L}_{SM} + (D_\mu H)^\dagger (D^\mu H) + \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi - \mu_1^2 H^\dagger H$$
$$- \frac{\mu_2^2}{2}\Phi^2 - \lambda_1 (H^\dagger H)^2 - \frac{\lambda_2}{4}\Phi^4 - \frac{\lambda_3}{2}\Phi^2 (H^\dagger H) - \mu_4 H^\dagger H \Phi - \frac{\mu_3}{3}\Phi^3 \,.$$

Motivations:

- Loryon list.
- Generates $C_{H\Box}$ at tree level [J. de Blas et al. (2018)] generates a deviation to the Higgs couplings to vector bosons and fermions when performing a field redefintion to canconically normalise the Higgs kinetic term.
- Resonant di-Higgs production, distinctive signature expected.

Matching (Scalar singlet)

SMEFT matching

SMEFT :
$$C_{H\Box} = -\frac{\mu_4^2}{2\mu_2^2}\,, \qquad C_H = -\frac{\lambda_3\,\mu_4^2}{2\mu_2^2} + \frac{\mu_3\,\mu_4^3}{3\mu_2^4}\,.$$
[Ulrich Haisch et al. (2020)]

HEFT matching

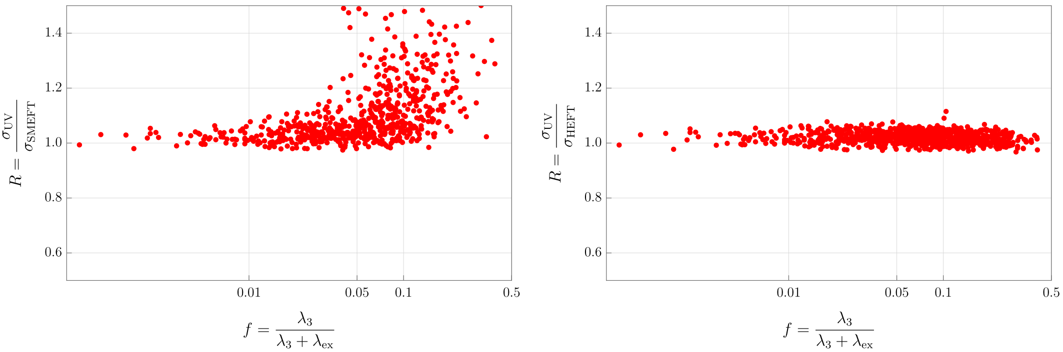
HEFT :
$$c_{tth} = \cos(\theta)\,, \qquad c_{tthh} = -\frac{\sin(\theta)\,v\,d_2}{M^2}\,, \qquad \kappa_\lambda = \frac{2v}{m^2}d_1\,,$$
$$\kappa_{hVV} = \cos(\theta)\,, \qquad \kappa_{hhVV} = \cos(\theta)^2 - 2\sin(\theta)\frac{v\,d_2}{M^2}\,.$$

where SMEFT and HEFT coincides (scalar singlet)

	HEFT	SMEFT
c_{hVV}	$1-\frac{1}{2}\theta^2$	$1-\frac{1}{2}\theta^2+\frac{v_S v_H \lambda_3}{m_2^2}\theta$
c_{hhVV}	$1-2\theta^2$	$1-2\theta^2+\frac{4v_S v_H \lambda_3}{m_2^2}\theta$
c_{hhh}	$1-\frac{3}{2}\theta^2+\frac{\lambda_3 v_H^2}{m_1^2}\theta^2$	$1-\frac{3}{2}\theta^2+\frac{\lambda_3 v_H^2}{m_1^2}\theta^2+\frac{3v_H v_S \lambda_3}{m_2^2}\theta$
c_t	$1-\frac{1}{2}\theta^2$	$1-\frac{1}{2}\theta^2+\frac{v_S v_H \lambda_3}{m_2^2}\theta$
c_{2t}	$-\frac{1}{2}\theta^2$	$-\frac{1}{2}\theta^2+\frac{v_S v_H \lambda_3}{m_2^2}\theta$

Scalar singlet results: ggF

Coupling coefficients are sensitive to **field redefinitions** $\rightarrow$rely on observable quantities, which, according to the S-matrix theorem, remain invariant under such transformations.
In particular, we compute the inclusive cross section for the process $pp \rightarrow hhjj$.

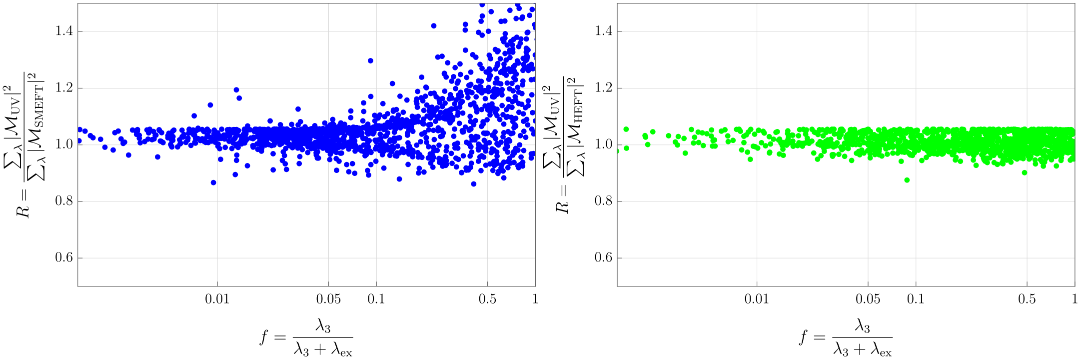


SMEFT is poorly convergent for $f \geq 0.1$, while both EFTs do the job in low f region!!

Scalar singlet results: VBF

Partonic level the convergence of EFT matching as a function of f (set $M \in [1, 3]$ TeV):

$$R_{UV/EFT} = \sum_{\lambda,\lambda'} \mathcal{M}^{\lambda}_{\text{UV}} \mathcal{M}^{*,\lambda'}_{\text{UV}} \Big/ \sum_{\lambda,\lambda'} \mathcal{M}^{\lambda}_{\text{EFT}} \mathcal{M}^{*\lambda'}_{\text{EFT}} , \qquad \text{EFT} = \{\text{SMEFT}, \text{HEFT}\} .$$



Colored scalar

Renormalizable UV completion adding $\omega_1 \sim (3, 1, -\frac{1}{3})$ to the SM spectrum:

$$\begin{aligned} \mathcal{L}'_{UV} =& \mathcal{L}_{SM} + (D_\mu \omega_1)^\dagger D^\mu \omega_1 - M_{ex}^2 \omega_1^\dagger \omega_1 - \frac{c_{\lambda h}}{2} \omega_1^\dagger \omega_1 H^\dagger H \,, \\ D_\mu \omega_1 =& \left(\partial_\mu - i g_3 G_\mu^a T^a - i g_1 Y B_\mu \right) \omega_1 \,. \end{aligned}$$

Motivations:

- ω_1 is in the Loryon list.
- generates effective couplings between gluons and higgs h.
- does not produce a new resonance in di-Higgs production.

Physical mass has an explicit contribution plus v.e.v. dependent part:

$$M_{Loryon}^2 = M_{ex}^2 + \frac{c_{\lambda h}}{4} v^2 = M_{ex}^2 + \Delta M_{Loryon}^2 \,.$$

Matching (Colored Scalar)

- SMEFT: adopt a functional matching procedure

$$\Gamma_{EFT}\left[H, \Psi_{SM}\right] = \Gamma_{UV}\left[H, \Psi_{SM}\right] .$$

$$c_{ggh}^{\text{SMEFT}} = \frac{c_{\lambda h} v^2}{24 M_{ex}^2} , \qquad c_{gghh}^{\text{SMEFT}} = \frac{c_{\lambda h} v^2}{48 M_{ex}^2} .$$

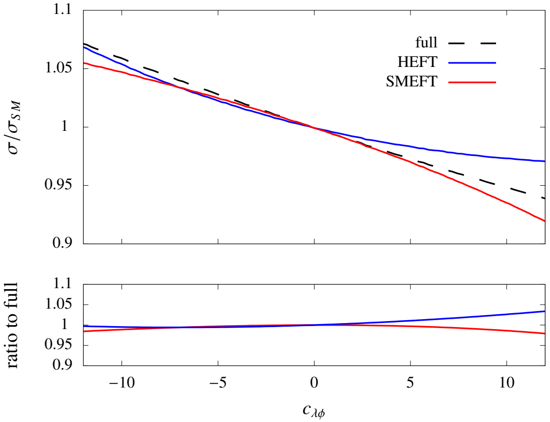
- HEFT: adopt a diagrammatic matching procedure →***non-linear coupling relations!***

$$\mathcal{M}_{HEFT}(gg \to hh) = \mathcal{M}_{UV}(gg \to hh) .$$

$$c_{ggh} = \frac{\Delta M_{\text{Loryon}}^2}{6 M_{\text{Loryon}}^2} + \mathcal{O}\left(\frac{s \Delta M_{\text{Loryon}}^2}{M_{\text{Loryon}}^4}\right) ,$$

$$c_{gghh} = \frac{\Delta M_{\text{Loryon}}^2}{12 M_{\text{Loryon}}^2} - \frac{\Delta M_{\text{Loryon}}^4}{6 M_{\text{Loryon}}^4} + \mathcal{O}\left(\frac{s \Delta M_{\text{Loryon}}^2}{M_{\text{Loryon}}^4}\right) .$$

ggF for ω_1



Deviation with respect to SM too small for observation, both SMEFT and HEFT work reasonably well.

Conclusions

Our conclusion:

- Differences between SMEFT and HEFT show up when considering processes with more than 1 Higgs boson.
- Loryon models converge better in HEFT rather than in SMEFT this is particularly clear for scalar singlet model.
- we have studied the most interesting ones: others are strongly constrained by EWPTs, fermionic Loryons are strongly constrained and loop-suppressed.

Ways to go from here:

- Higher in precision: dimension 8, one loop-matching (many subtleties).
- Study more models.

Thank you!

Backup slides

SMEFT vs HEFT

- Correlation of couplings in Higgs Flare functions for a multi-Higgs process[R. Gómez-Ambrosio et al. (2022)]:

$$\mathcal{F}(h) = 1 + 2a\frac{h}{v} + b\left(\frac{h}{v}\right)^2 + \dots, \quad \text{in SM:} \quad a = b = 1\,,$$

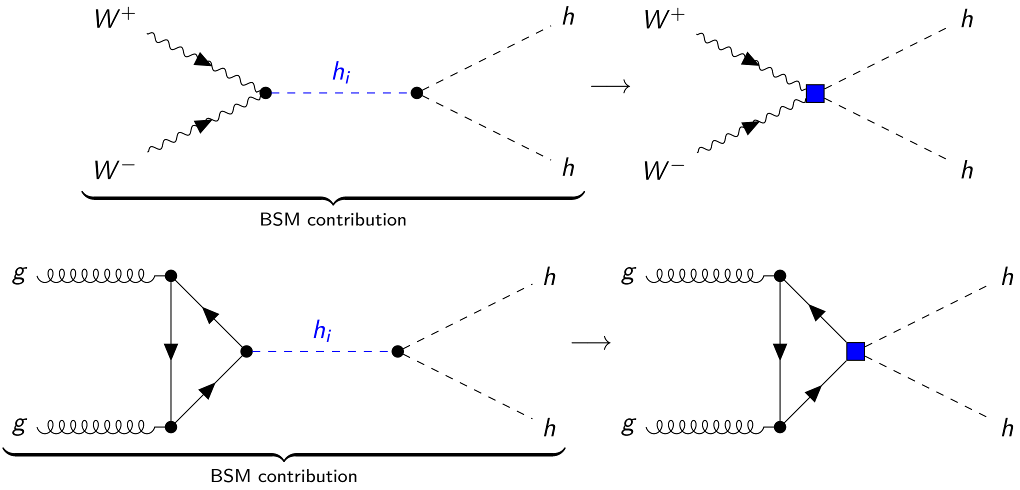
  SMEFT is "locking" coefficients in linear relation, any deviations from these constraints being a smoking gun of HEFT.
- Geometric formulation of the scalar sector. Scalar sector is a manifold where field are viewed as coordinates:

$$\mathcal{L} \supset \frac{1}{2} g^{IJ}(\phi)\partial_\mu \phi^I \partial^\mu \phi^J\,,$$

  If the manifold has on $O(4)$ invariant point then HEFT can be rewritten as SMEFT [R. Alonso, Elizabeth E. Jenkins, and Aneesh V. Manohar (2016)], see also [Adam Falkowski and Riccardo Rattazzi (2019)].

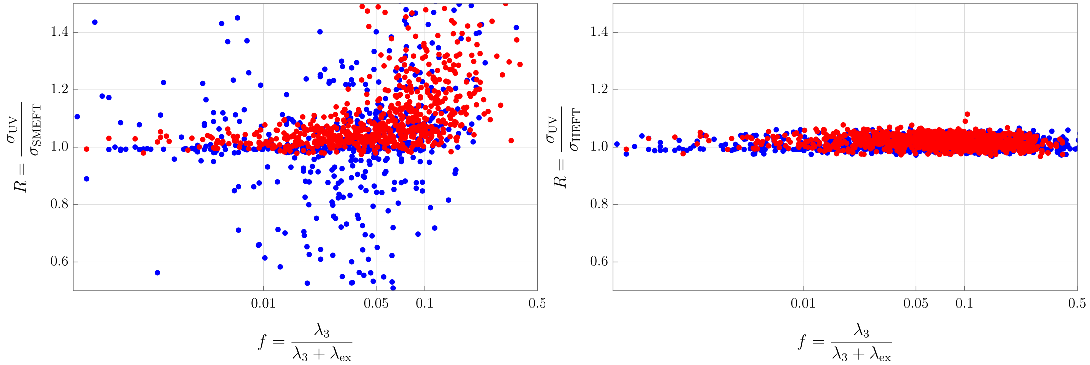
Idea: The difference between the EFTs is more than a field redefinition connecting linear and non-linear realization of EWSB. Try to show it at the level of observables.

Diagrams in the UV



Scalar singlet results: ggF

We compute the inclusive cross section of H pair production plus two jets.



On the right (left) panel we display ratio of $\sigma_{\rm UV}$ over the same quantity computed in HEFT (SMEFT) framework. Red (blue) points refer to scan 1 with $v_s \in [0.02, 0.2\, v_H]$(scan 2, with $v_s \in [0.01, 5\, v_H]$) while .

SMEFT vs HEFT in 2HDM

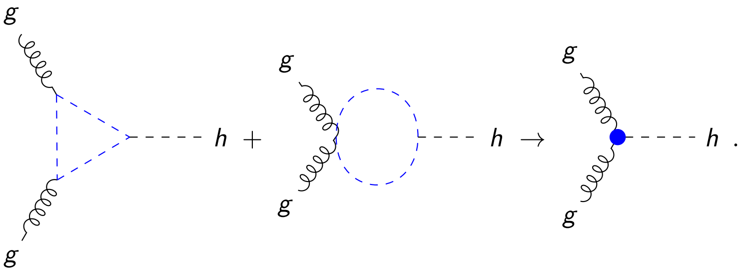
A second doublet Φ_2 is added on top of SM spectrum, a $\mathcal{Z}_2$ symmetry is also imposed $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$. Rotation to *Higgs basis* $(\Phi_1, \Phi_2) \to (H_1, H_2)$.

	HEFT	SMEFT
c_{hhh}	$1 - 2\frac{M^2}{m_h^2} c^2_{\beta-\alpha}$	$1 - 2\frac{m_H^2}{m_h^2} c^2_{\beta-\alpha}$
c_t	$1 + \frac{c_{\beta-\alpha}}{t_\beta}$	$1 + \frac{c_{\beta-\alpha}}{t_\beta}$
c_{2t}	$4\frac{M^2}{m_H^2}\frac{c_{\beta-\alpha}}{t_\beta} - \frac{c_{\beta-\alpha}}{t_\beta}$	$3\frac{c_{\beta-\alpha}}{t_\beta}$

The physical masses of the heavy higgs bosons $m_{H^\pm}$, m_A and m_H are taken degenerate:

$$m_H^2 = M^2 + \tilde{\Lambda} v^2 = M^2 + \Delta m_H^2 \,.$$

Feynman diagrams involved in the matching for single Higgs production in the colored scalar case :



$$i\mathcal{M}_{HEFT}(g(p_1)g(p_2) \to h(p3)) = i\mathcal{M}^{(2)}_{UV}(g(p_1)g(p_2) \to h(p_3)),$$

$$i\frac{\alpha_S}{\pi}\epsilon^a_\mu\epsilon^b_\nu\delta^{ab}\frac{1}{v}c_{ggh}\left(p_1^\nu p_2^\mu - p_1 p_2 g^{\mu\nu}\right) = i\frac{\alpha_S}{\pi}\epsilon^a_\mu\epsilon^b_\nu\delta^{ab}\frac{1}{v}\frac{c_{\lambda_h}v^2}{6(4M_{ex}^2 + c_{\lambda_h}v^2)}\left(p_1^\nu p_2^\mu - p_1 p_2 g^{\mu\nu}\right).$$

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