Multi-Higgs production from VBS in HEFT

Javier Martínez-Martín[1]

[1]In collaboration with Rafael L. Delgado, Raquel Gómez-Ambrosio, Alexandre Salas-Bernárdez and Juan J. Sanz-Cillero - 2311.04280v2 - JHEP 03 (2024) 037

The 21st Workshop of the LHC Higgs Working Group
19 November 2024

Outline

Motivation

- Understanding the SM as the leading order of an EFT, we would like to find new terms.
- At the current energies, both SMEFT and HEFT are valid descriptions of the currently available LHC data.
- Multi-Higgs measurements at HL-LHC and beyond are crucial to check their validity range.

Framework

- We used the Equivalence theorem approximation where $W_L^a \quad !^a$.
- Assuming $m_h^2 \quad m_W^2 \quad s \quad \Lambda^2$.
- Using only derivative terms of the Lagrangian up to 2 derivatives (which scale with the energy).
- As a first approximation, only one SMEFT operator is needed (at each EFT dimenson).

Higgs Effective Field Theory
Canonical form

HEFT Lagrangian[1]
[Appelquist et al. - Phys. Rev. D 22 (1980) 200 , Longhitano et al. - Phys. Rev. D 22 (1980) 1166]

$$L_{\text{HEFT}} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}F(h)\,\partial_\mu \omega^a \partial^\mu \omega^a + O(\partial^4)$$

Flare function[2]
[Gómez-Ambrosio, Llanes-Estrada, Salas-Bernárdez and Sanz-Cillero - 2204.01762]

$$F(h) = 1 + a_1\frac{h}{v} + a_2\left(\frac{h}{v}\right)^2 + a_3\left(\frac{h}{v}\right)^3 + a_4\left(\frac{h}{v}\right)^4 + O(h^5)$$

$$a \equiv \frac{a_1}{2}\,;\, a_2 \equiv b \quad \text{with} \quad a_{1,\text{SM}} = 2\,;\, a_{2,\text{SM}} = 1\,;\, a_{3,\text{SM}} = 0\,;\, a_{4,\text{SM}} = 0$$

[1] We only focus on the EW sector. In the conditions where, under the Goldstone equivalence theorem, longitudinal VBS is approximated by Goldstone scattering.

[2] Where a_n is the effective coupling of $\omega\omega$ with nh. This can be done similarly for the Yukawa sector through the study of $t\bar{t} \to n\,h$ processes, see:
Englert et al. - 2308.11722 , Gómez-Ambrosio et al. - 2207.09848

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Higgs Effective Field Theory

Check: Rede ned form

Calculations have also been checked with:

Redefined HEFT Lagrangian

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Redefined Flare function[3]

$$\hat{F}(h) = 1 + \hat{a}_2\left(\frac{h}{v}\right)^2 + \hat{a}_3\left(\frac{h}{v}\right)^3 + \hat{a}_4\left(\frac{h}{v}\right)^4 + \mathcal{O}(h^5)$$

$$\hat{a}_2 = b - a^2; \quad \hat{a}_3 = a_3 - \frac{4a}{3}\left(b - a^2\right); \quad \hat{a}_4 = a_4 - \frac{3}{2}a\,a_3 + \frac{5}{3}a^2\left(b - a^2\right)$$

[3] This rede nition gives a more direct interpretation of the results, see: L. Delgado et al. 2311.04280v2

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Relation to SMEFT
SMEFT

SMEFT lagrangian
[Gómez-Ambrosio, Llanes-Estrada, Salas-Bernárdez and Sanz-Cillero - 2207.09848]

$$L_{\text{SMEFT}} = L_{\text{SM}} + \sum_{n=5}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} O_i^{(n)}$$

O_H operator

$$O_H^{(6)} = (H^\dagger H) \Box (H^\dagger H); \quad O_H^{(8)} = (H^\dagger H)^2 \Box (H^\dagger H); \quad \Box \equiv \partial^2$$

SMEFT parameters

$$d = \frac{2v^2 c_H^{(6)}}{\Lambda^2} \quad ; \quad = \frac{c_H^{(8)}}{2(c_H^{(6)})^2}$$

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Relation to SMEFT

Relation between parameters

Relation with canonical parameters[4]

[Gómez-Ambrosio, Llanes-Estrada, Salas-Bernárdez and Sanz-Cillero - 2207.09848]

$$
\begin{aligned}
a_1{=}2 &= a = 1 + \frac{d}{2} + \frac{d^2}{2}\left(\frac{3}{4} + \quad\right) + O\left(d^3\right) \\
a_2 &= b = 1 + 2d + 3d^2(1 + \quad) + O\left(d^3\right) \\
a_3 &= \frac{4}{3}d + d^2\left(\frac{14}{3} + 4 \quad\right) + O\left(d^3\right) \\
a_4 &= \frac{1}{3}d + d^2\left(\frac{11}{3} + 3 \quad\right) + O\left(d^3\right)
\end{aligned}
$$

[4] a_5 and a_6 can be found in L. Delgado et al. 2311.04280v2.
a_n for n 7 vanishes at order $1{=}\ ^4$.

! ! ! 2h

The following results in this section are calculated in the massless limit.

Amplitude[5]

$$T_{\omega\omega\to 2h} \overset{\text{HEFT}}{=} \frac{\hat{a}_2 s}{v^2} = $$
$$\overset{\text{SMEFT}}{=} \frac{s}{v^2} \; d + 2d^2 (1 + \;\;) \; + O \;\; d^3$$

Cross section

$$_{\omega\omega\to 2h} \overset{\text{HEFT}}{=} \frac{8 \;\; ^3 \hat{a}_2^2}{s} \;\; \frac{s}{16 \;\; ^2 v^2} \;^2 =$$
$$\overset{\text{SMEFT}}{=} \frac{8 \;\; ^3}{s} \; d^2 + 4d^3 \; (1 + \;\;) \;\; \frac{s}{16 \;\; ^2 v^2} \;^2 + O \;\; d^4$$

[5] Compatible with previous analysis in e.g. Arganda et al. - 1807.09763, Dobado et al. - 1711.10310.

! ! ! 3h

Amplitude[6]

$$T_{!\,!\,\;!\,3h} \overset{\text{HEFT}}{=} \frac{3\hat{a}_3 s}{v^3} =$$

$$\overset{\text{SMEFT}}{=} \frac{4s}{v^3} d^2 (1 + \quad) + O \quad d^3$$

Cross section

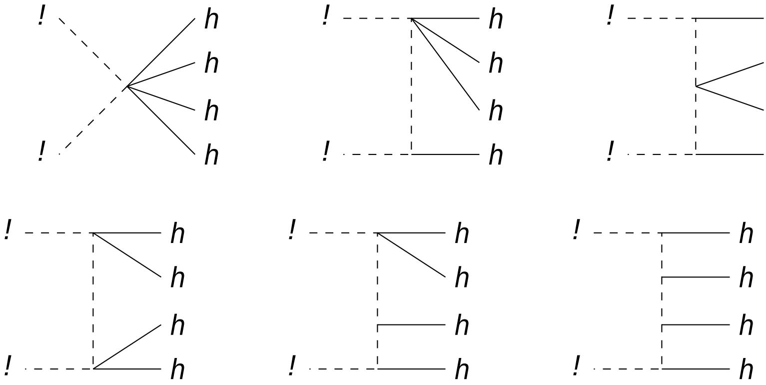
$$_{!\,!\,\;!\,3h} \overset{\text{HEFT}}{=} \frac{12 \quad ^3 \hat{a}_3^2}{s} \quad \frac{s}{16 \quad ^2 v^2} \quad ^3 =$$

$$\overset{\text{SMEFT}}{=} \frac{64 \quad ^3}{3s} d^4 (1 + \quad)^2 \quad \frac{s}{16 \quad ^2 v^2} \quad ^3 + O \quad d^5$$

[6] Previous analysis with modi cations in e.g. Gonzalez-Lopez et al. - 2011.13915, Chen et al. - 2105.11500.

! ! ! 4h

Contributing diagrams



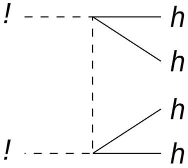
With permutations of external particles, there are a total of 75 diagrams

! ! ! 4h

Amplitude

$$T_{!\,!\;\;!\,4h} \overset{\text{HEFT}}{=} \frac{4s}{v^4}\left(3\hat{a}_4 + \hat{a}_2^2\,(B \quad 1)\right) =$$

$$\overset{\text{SMEFT}}{=} \frac{4s}{v^4} d^2\,(1 + \quad + B) + O\;\; d^3$$



Cross section

$$!\;!\;!\;4h \overset{\text{HEFT}}{=} \frac{8\;\;^3}{9s}\;\; \frac{s}{16\;\;^2 v^2}\;\;^4 \text{"}\; 3\hat{a}_4 \quad \hat{a}_2^2\;\;^2 + 2\;\; 3\hat{a}_4 \quad \hat{a}_2^2\;\; \hat{a}_2^2\;\; _1 + \hat{a}_2^4\;\; _2 =$$

$$\overset{\text{SMEFT}}{=} \frac{8\;\;^3}{9s}\;\; \frac{s}{16\;\;^2 v^2}\;\;^4\; d^4\;\; (1 + \quad)^2 + 2(1 + \quad)\;\; _1 + \quad _2\;\; + O(d^5)$$

! ! ! 4h

Parameters

Definitions[7]

$$B = f_1 f_2 f_3 f_4 \quad B_{1234} + B_{1324} + B_{1423} + B_{2314} + B_{2413} + B_{3412}$$

$$B_{ijk`} = \frac{z_{ij} z_{k`}}{2 f_i f_j z_{ij} \quad f_i z_i \quad f_j z_j}\,; \quad z_{ij} = z_{ji} = \frac{q^2 (p_i p_j)}{(q p_i)(q p_j)} \overset{\text{CM}}{=} 2\sin^2(\;_{ij}=2)$$

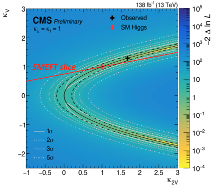
$$f_i = \frac{q p_i}{q^2} \overset{\text{CM}}{=} k p_i k = \sqrt{s}\,; \quad z_i = \frac{2 k_1 p_i}{q p_i} \overset{\text{CM}}{=} 2\sin^2(\;_i=2)$$

$$q = k_1 + k_2 = p_1 + p_2 + p_3 + p_4$$

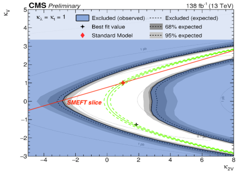
$$_n = V_4^{\;1} \int d\Pi_4\, B^n\,; \quad _1 = 0{:}124984\,(10)\,; \quad _2 = 0{:}0193760\,(16)$$

[7] Numerical values computed with a personal code, see: https://github.com/mamupaxs/mamupaxs

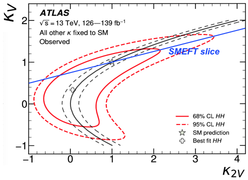
Previous CMS and ATLAS data



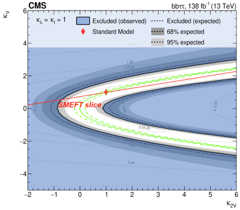
(a)



(b)



(c)

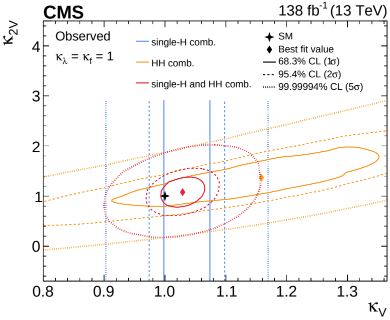


(d)

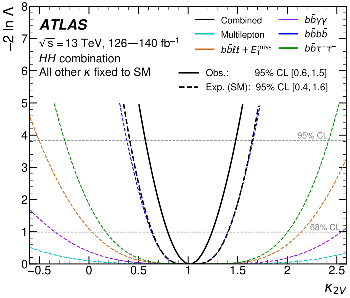
Figure: **(a)** Phys. Rev. Lett. 131 (2023) 041803 [2205.06667] **(b)** CMS-PAS-HIG-21-005 **(c)** ATLAS-CONF-2022-050 **(d)** Phys. Lett. B 842 (2023) 137531 [2206.09401].

- a_1 is relatively well known from Higgs decays at LHC. Close to the SM, up to $O(10\%)$.
- $v = a = \frac{a_1}{2}$
  $2v = a_2$
- Superimposed SMEFT correlation: $a_2 = 2a_1 \quad 3$
- Plotted parabolas:
  $\hat{a}_2 \quad a_2 \quad \frac{a_1^2}{4} = 0$
  $\hat{a}_2 = \quad 0{:}2$

Latest CMS and ATLAS data



(a)



(b)

Figure: **(a)** Submitted to Phys. Lett. B [2407.13554] **(b)** Phys. Rev. Lett. 133 (2024) 101801 [2406.09971].

- The constraint on a_2 is driven by the HH categories enriched in VBF HH events.
- The observed (expected) 95% CL interval: $0{:}6 < a_2 < 1{:}5$ ($0{:}4 < a_2 < 1{:}6$).

Benchmark points

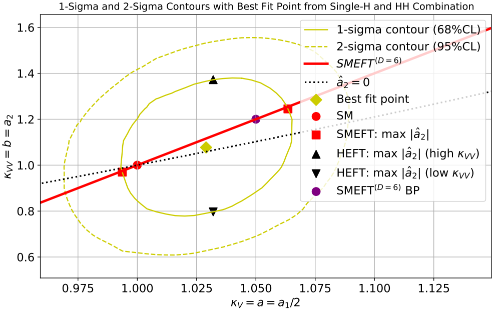


Figure: https://www.hepdata.net/record/ins2808928.

$SMEFT^{(D=6)}$ BP

$$d = 0.1$$

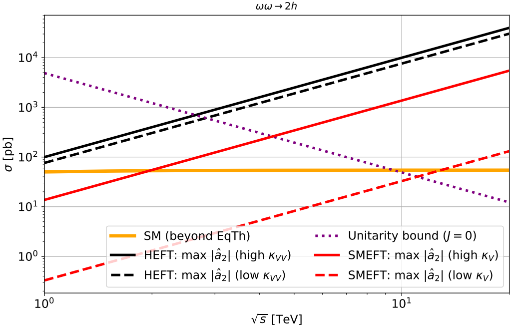
$$a = a_1/2 = 1.05\,; \quad b = a_2 = 1.20$$

$$a_3 = 0.19\,; \quad a_4 = 0.09$$

- d is compatible with the SM deviation range of ATLAS and CMS, $\Delta a = a \quad 1 \quad 0.05$ with $a \quad 1 + d/2$.
- d is crucial for the convergence of the expansion.
- $a_{1,SM} = 2\,;\ a_{2,SM} = 1$
  $a_{3,SM} = 0\,;\ a_{4,SM} = 0$

BP study

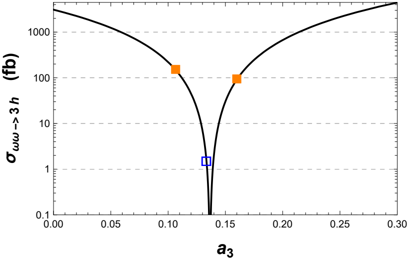
! ! ! 2h (Preliminary)

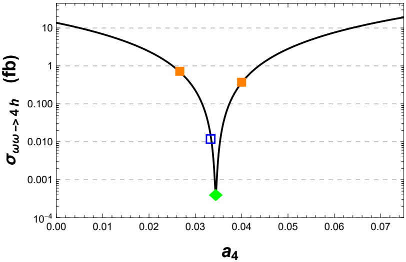


- SMEFT is suppressed by 1 order of magnitude.
- All of the SM needs to be considered.
- Unitarity studied for pure s-wave.

BP study

! ! ! 3h & ! ! ! 4h





- a_1 and a_2 are set to their SMEFT$^{(D=6)}$ values. $\sqrt{s} = 1$ TeV.
- SMEFT is a particular value (blue).
- A 20% variation on a_3 varies the XS by 2 orders of magnitude (SM: $a_3 = 0$).
- The XS vanishes for a particular value.

- a_1, a_2 and a_3 are set to their SMEFT$^{(D=6)}$ values. $\sqrt{s} = 1$ TeV.
- SMEFT is a particular value (blue).
- A 20% variation on a_4 varies the XS by 2 orders of magnitude (SM: $a_4 = 0$).
- The XS doesn't vanish.

State of the art

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Our next steps

Work in progress

- Include the complete SM.
- Calculating processes with W_L and masses.
- Adding the PDFs for the full processes.
- Partial waves and unitarity study.

Possible future works

- Higgs self-interactions.
- Final-state particles decay.
- New-physics models for these couplings.
- Beyond VBS processes.

Experimentalists' next steps. HEFT Wishlist

Experimentalists' next steps. HEFT Wishlist

Experimentalists' next steps. HEFT Wishlist

Conclusions

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- We studied longitudinal VBS using the Goldstone equivalence theorem, the massless approximation, and $\mathcal{O}(\partial^2)$.
- We computed the analytic expressions for h, $2h$ and $4h$ production at tree level for SMEFT and HEFT.
- We found multi-Higgs production is very suppressed in SMEFT but not in general HEFT scenarios.
- There are lots of steps left to take.
- This is a very hot topic being worked on nowadays.

THANK YOU SO MUCH!

Outline

Back up 1. Rede nition of HEFT

Fields rede nition

Fields rede nition

$$! ^{a} ! \quad ! ^{a} + g(h) ! ^{a} ; \qquad h ! \quad h + N \, (1 + g(h)) \, \frac{! ^{a} ! ^{a}}{v} $$

Back up 1. Rede nition of HEFT

Fields rede nition

Fields rede nition

$$\omega^a \to \omega^a + g(h)\,\omega^a; \qquad h \to h + N\,(1 + g(h))\,\frac{\omega^a \omega^a}{v}$$

HEFT lagrangian

$$L_{HEFT} = \frac{1}{2}\partial h \partial h + \frac{1}{2}F(h)\,\partial\omega^a \partial\omega^a + O(\omega^4)$$

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Fields rede nition

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Rede ned HEFT lagrangian

$$L_{HEFT} = \frac{1}{2} @h @h + \frac{1}{2}\hat{F}(h)\, @!^a @!^a + O(!^4)$$

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Fields rede nition

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Rede ned are function

$$\hat{F}(h) = \left(F(h)\,\left(1 + g(h)\right) \right)^2$$

Appendix 1. Rede nition of HEFT

Flare function rede nition

Normalization

$$N = \frac{a}{2}$$

$$g(h) = a\frac{h}{v} + a^2\frac{h^2}{v^2} + \frac{1}{3}a(b \quad 4a^2)\frac{h^3}{v^3} + \frac{1}{4}a(a_3 \quad 4ab + 8a^3)\frac{h^4}{v^4} + O(h^5)$$

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Flare function

$$F(h) = 1 + a_1\frac{h}{v} + a_2\left(\frac{h}{v}\right)^2 + a_3\left(\frac{h}{v}\right)^3 + a_4\left(\frac{h}{v}\right)^4 + O(h^5)$$

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Rede ned are function

$$\hat{F}(h) = 1 + \hat{a}_2\left(\frac{h}{v}\right)^2 + \hat{a}_3\left(\frac{h}{v}\right)^3 + \hat{a}_4\left(\frac{h}{v}\right)^4 + O(h^5)$$

Back up 1. Rede nition of HEFT

Parameters rede nition

Rede ned parameters

$$\hat{a}_2 = b \quad a^2$$

$$\hat{a}_3 = a_3 \quad \frac{4a}{3} \; b \quad a^2$$

$$\hat{a}_4 = a_4 \quad \frac{3}{2} a \, a_3 + \frac{5}{3} a^2 \; b \quad a^2$$

Back up 2. HEFT-SMEFT parameters relation

Parameters

SMEFT parameters

$$d = \frac{2v^2 c_H^{(6)}}{\Lambda^2} \qquad ; \qquad = \frac{c_H^{(8)}}{2(c_H^{(6)})^2}$$

Back up 2. HEFT-SMEFT parameters relation

Relation with canonical parameters

Relation with canonical parameters

$$a_1/2 = a = 1 + \frac{d}{2} + \frac{d^2}{2}\left(\frac{3}{4} + \right) + O\left(d^3\right)$$

$$a_2 = b = 1 + 2d + 3d^2(1 + \ ) + O\left(d^3\right)$$

$$a_3 = \frac{4}{3}d + d^2\left(\frac{14}{3} + 4\ \right) + O\left(d^3\right)$$

$$a_4 = \frac{1}{3}d + d^2\left(\frac{11}{3} + 3\ \right) + O\left(d^3\right)$$

Back up 2. HEFT-SMEFT parameters relation

Relation with rede ned parameters

Relation with redefined parameters

$$\hat{a}_2 = d + 2d^2(1 + \ ) + O(d^3)$$

$$\hat{a}_3 = \frac{4}{3}d^2(1 + \ ) + O(d^3)$$

$$\hat{a}_4 = \frac{1}{3}d^2(1 + \ ) + O(d^3)$$