HEFT (AND SMEFT) MULTI-HIGGS PREDICTIONS

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1st COMETA Meeting, Wednesday 28th February, 2024

Alexandre Salas-Bernárdez

UNIVERSITY OF BAKIRÇAY

Outline

1. Introduction and motivation.

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2. Distinction of HEFT and SMEFT.

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See also: 2204.01763 (Phys. Rev. D) and 2207.09848 (Comm. Th. Phys.)

Introduction

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The Electroweak Sector

One of the most uncharted and promising sectors in SM

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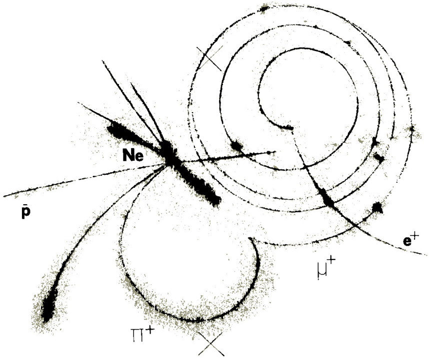
- Nature of Higgs boson and EW gauge bosons? Composite or not?

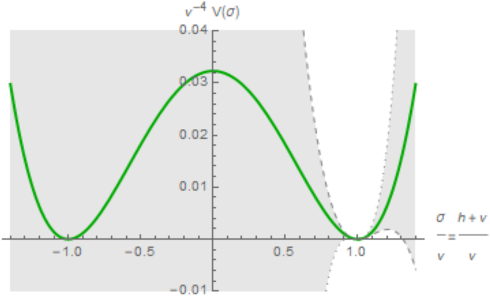
- Could EW Goldstone bosons (ω_is) resemble a π (pion)?
- SUSY? 2HDM?, etc.



The Electroweak SB Sector

One of the most uncharted and promising sectors in SM

- Nature of Higgs boson and EW gauge bosons? Composite or not?
- Measurable: Higgs self interaction and its coupling to electroweak gauge bosons.



$SMEFT \subset HEFT$

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“Two” EW EFT candidates

- Standard Model Effective Field Theory (SMEFT)

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$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_{n=5}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}(H) \ .$$

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- Higgs Effective Field Theory (HEFT):
  Chiral Lagrangian

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{1}{2}\mathcal{F}(h)\partial_\mu \omega^i \partial^\mu \omega^j \left(\delta_{ij} + \frac{\omega^i \omega^j}{v^2 - \omega^2}\right) \ .$$

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What is their relation?

In a few words...

Basically, SMEFT assumes the SM EWSB structure, where the Higgs boson is part of an $SU(2)_L$ doublet.

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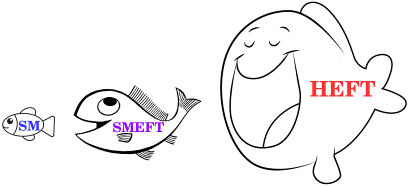
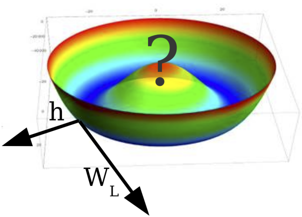


Geometric distinction HEFT/SMEFT

- Several works have provided field-redefinition invariant criteria to distinguish SMEFT from HEFT:
  - R. Alonso, E. E. Jenkins, and A. V. Manohar,
    "A Geometric Formulation of Higgs Effective Field Theory: Measuring the Curvature of Scalar Field Space," Phys. Lett. B754 (2016) 335–342, arXiv:1511.00724 [hep-ph].
    "Sigma Models with Negative Curvature," Phys.Lett.B756,358(2016),arXiv:1602.00706 [hep-ph].
    "Geometry of the Scalar Sector," JHEP 08 (2016) 101, arXiv:1605.03602 [hep-ph]."
    (Cohen et al., 2021, p. 95)
  - T. Cohen, N. Craig, X. Lu, and D. Sutherland:
    "Is SMEFT Enough?", JHEP 03, 237, arXiv:2008.08597 [hep-ph].
    "Unitarity Violation and the Geometry of Higgs EFTs",
    (2021), arXiv:2108.03240 [hep- ph].



Conditions on $\mathcal{F} = F^2$ for SMEFT's validity

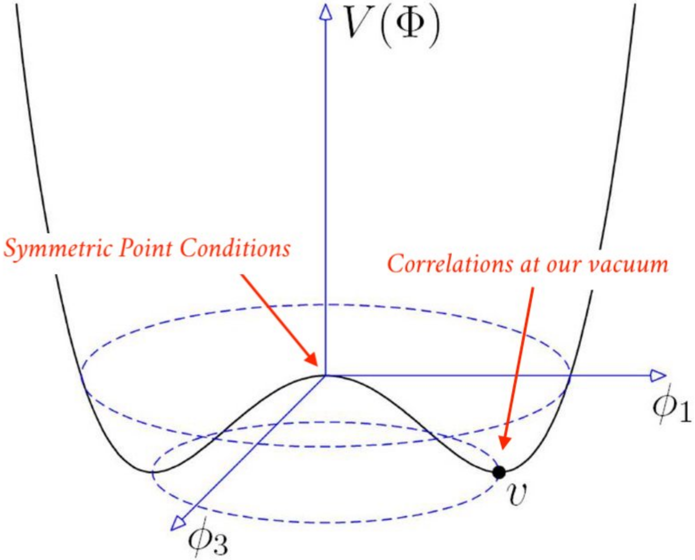
In 2204.01763 we found an easier analytical criterion for SMEFT to be valid:

1. $\boxed{\mathcal{F}(h_1^*) = 0}$ must have a double zero.
2. At that point h_1^*,

$$\boxed{\mathcal{F}'(h_1^*) = 0\ ,\ \mathcal{F}''(h_1^*) = \frac{2}{v^2}}\ .$$

3. Analyticity of the SMEFT Lagrangian: all even derivatives to vanish at the symmetric point, $F^{(\ell)}(h_1^*) = 0$ for even ℓ. From the point of view of $\mathcal{F}$ this implies the vanishing of all odd derivatives, $\boxed{\mathcal{F}^{(2\ell+1)}(h_1^*) = 0}$.

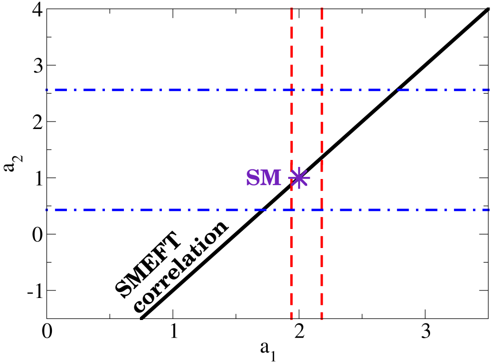
Origin of SMEFT correlations: just match two Taylor exp.



SMEFT assumption ⇒ HEFT parameters correlation

Correlations among HEFT parameters due to SMEFT structure:

(Bands from single Higgs production at ATLAS (ATLAS-CONF-2020-027) and Higgs Pair production at CMS 2202.09617) $\boxed{\mathcal{F}(h) = 1 + a_1 h/v + a_2 h^2/v^2 + \ldots}$,



Same game with the potential $V(h)$ and the Yukawas... (see 2207.09848)

Amplitudes and Cross sections

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High energy measurements

In the TeV region the potential is subleading. The flare function $\mathcal{F}$ encodes relevant physics (it accompanies the GB kinetic term)

$$\mathcal{F}(h_{\mathrm{HEFT}}) = 1 + \sum_{n=1}^{\infty} a_n \left(\frac{h_{\mathrm{HEFT}}}{v}\right)^n .$$

At high energies (Equivalence Theorem) $\omega \simeq \boldsymbol{W_L}$

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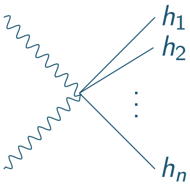
$\Rightarrow \omega\omega \to n \times h$ can test SMEFT framework.



$$= -\frac{n! a_n}{2 v^n}\, s$$

Measure $\mathcal{F}$ expansion in multi-Higgs final states

$$T_{\omega\omega\to h} = -\frac{a_1 s}{2v}$$

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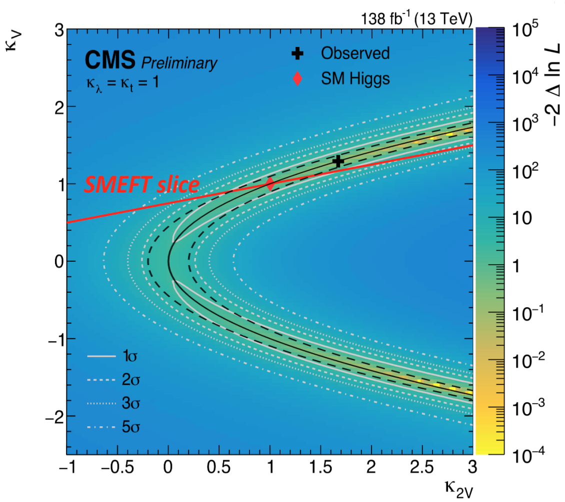
$$T_{\omega\omega\to hh} = -\frac{s}{v^2}\left(a_2 - \frac{a_1^2}{4}\right),$$

Detour: how well does the Eq. Th. perform?



Remember $T_{\omega\omega\to hh} = -\frac{s}{v^2}\left(k_2 - \frac{k_1^2}{4}\right)$

CMS-B2G-22-003

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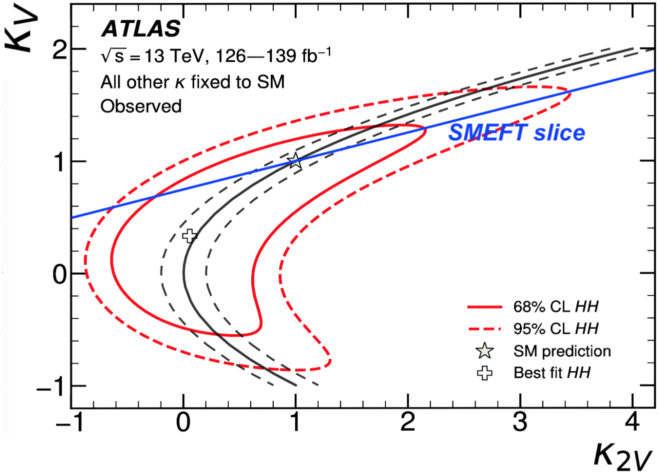

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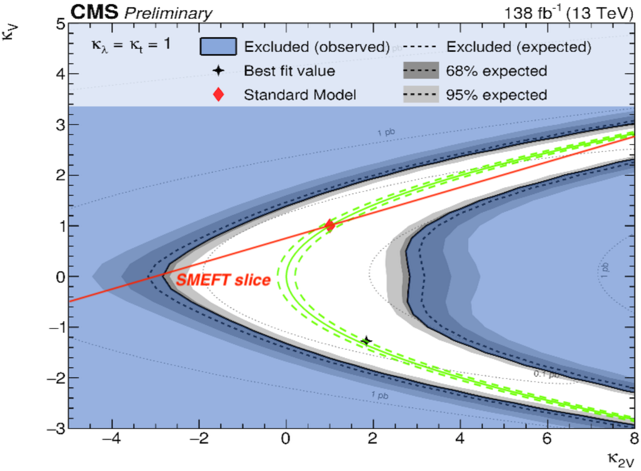

CMS-PAS-HIG-21-005 (with one Higgs boson decaying to $\bar{b}b$ and the other one to W^+W^-)

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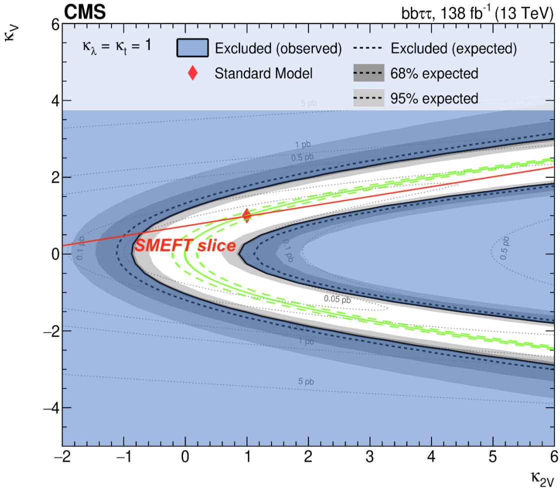

CMS 2206.09401 (with Higgs bosons $b\bar{b}\tau^+\tau^-$ final states)

Measure $\mathcal{F}$ expansion in multi-Higgs final states

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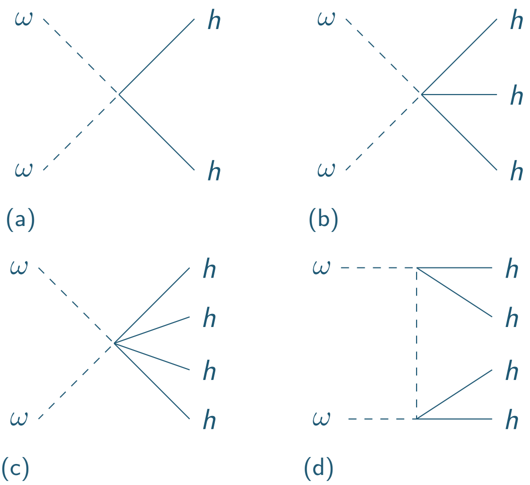
$$T_{\omega\omega\to 4h} = -\frac{4s}{v^4}\left(3\hat{a}_4 + \hat{a}_2^2\,(B-1)\right),$$

where $\hat{a}_2 = a_2 - a_1^2/4$ and $\hat{a}_4 = a_4 - \frac{3}{4}a_1 a_3 + \frac{5}{12}a_1^2\left(a_2 - a_1^2/4\right)$.

Effective $h^n\omega\omega$ vertices (see 2401.18002)

In we found a very nice field redefinition that eliminated the $h\omega\omega$ vertex. Leaving only the contributing diagrams:



SMEFT vs HEFT phenomenology

Dimension 6 (8) SMEFT operators contributing to $\mathcal{F}(h)$ are $|H|^{2(4)}\Box|H|^2/\Lambda^{2(4)}$

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

with,

$$
d = \frac{2v^2 c^{(6)}_{H\Box}}{\Lambda^2} , \qquad \rho = \frac{c^{(8)}_{H\Box}}{2(c^{(6)}_{H\Box})^2} .
$$

Benchmark Points for the comparison: SMEFT BP

SMEFT BP (the choice of ρ is not really relevant):

$$d = \frac{2v^2 c^{(6)}_{H\Box}}{\Lambda^2} = 0.1\,, \qquad \rho = \frac{c^{(8)}_{H\Box}}{2(c^{(6)}_{H\Box})^2} = 1\,.$$

within the most precise experimental determinations up to date from **ATLAS 2207.00092**, $a = \kappa_V = 1.035 \pm 0.031$, and **CMS 2207.00043**, $a = \kappa_V = 1.014 \pm 0.029$.

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$\Rightarrow \boxed{\frac{a_1}{2} = 1.05}$ and $\boxed{a_2 = 1.20}$.

Benchmark Points for the comparison: First HEFT BP

BP1$^{(\mathrm{a}_1)}$: Simplest exponential flare function that matches the $D = 6$ SMEFT prediction for a_1:

$$\mathcal{F}(h) = \exp\left\{a_1 \frac{h}{v}\right\} \qquad \Longrightarrow$$

$$a_2 = \frac{a_1^2}{2!} = 2.205\,, \quad a_3 = \frac{a_1^3}{3!} \approx 1.54\,, \quad a_4 = \frac{a_1^4}{4!} \approx 0.81\,.$$

BP1$^{(\mathrm{a}_1,\,\mathrm{a}_2)}$: Simplest exponential flare function that matches the $D = 6$ SMEFT prediction for a_1 and a_2:

$$\mathcal{F}(h) = \exp\left\{a_1 \frac{h}{v} + \left(a_2 - \frac{a_1^2}{2}\right)\frac{h^2}{v^2}\right\} \qquad \Longrightarrow$$

$$a_3 = \left(a_1 a_2 - \frac{a_1^3}{3}\right) \approx -0.57\,, \qquad a_4 = \left(\frac{a_2^2}{2} - \frac{a_1^4}{12}\right) \approx -0.90\,.$$

Benchmark Points for the comparison: Second HEFT BP

BP2$^{(a_1)}$: Simplest rational flare function that matches the $D=6$ SMEFT prediction for a_1:

$$\mathcal{F}(h) = \left(1 - \frac{a_1}{2}\frac{h}{v}\right)^{-2} \qquad \Longrightarrow$$

$$b = \frac{3}{4}a_1^2 \approx 3.31\,, \qquad a_3 = \frac{1}{2}a_1^3 \approx 4.63\,, \qquad a_4 = \frac{5}{16}a_1^4 \approx 6.08\,,$$

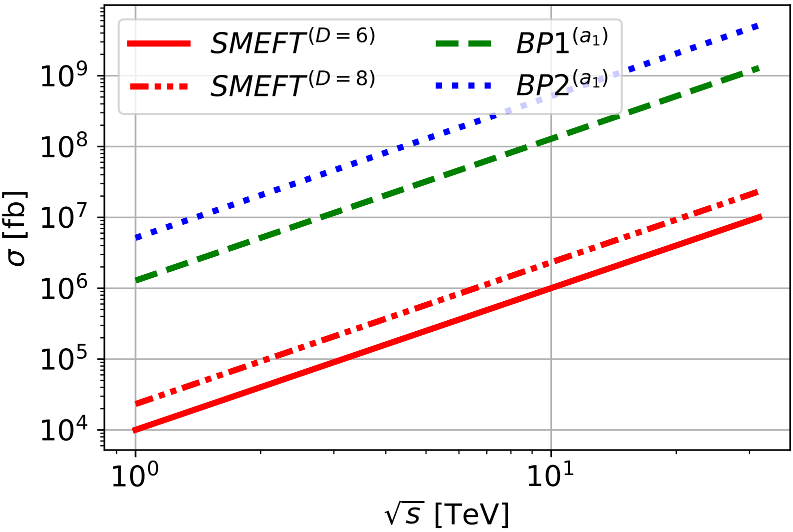
BP2$^{(a_1,\,a_2)}$: Simplest rational flare function that matches the $D=6$ SMEFT prediction for a_1 and a_2:

$$\mathcal{F}(h) = \left(1 - \frac{a_1}{2}\frac{h}{v} - \left(\frac{a_2}{2} - \frac{3a_1^2}{8}\right)\frac{h^2}{v^2}\right)^{-2} \qquad \Longrightarrow$$

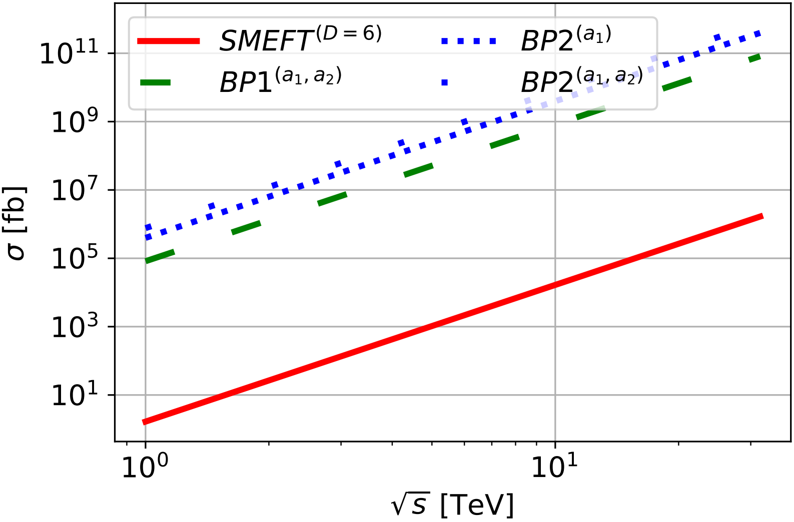
$$a_3 = \frac{1}{8}\left(-5a_1^3 + 12a_1a_2\right) \approx -2.01\,,$$

$$a_4 = \frac{1}{64}\left(-25a_1^4 + 24a_1^2a_2 + 48a_2^2\right) \approx -4.53\,,$$

Cross section comparison: two Higgses



Cross section comparison: three Higgses



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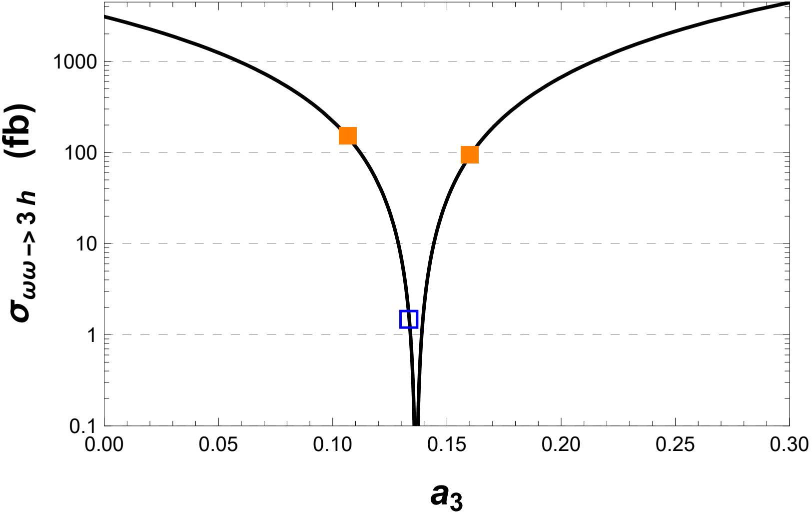
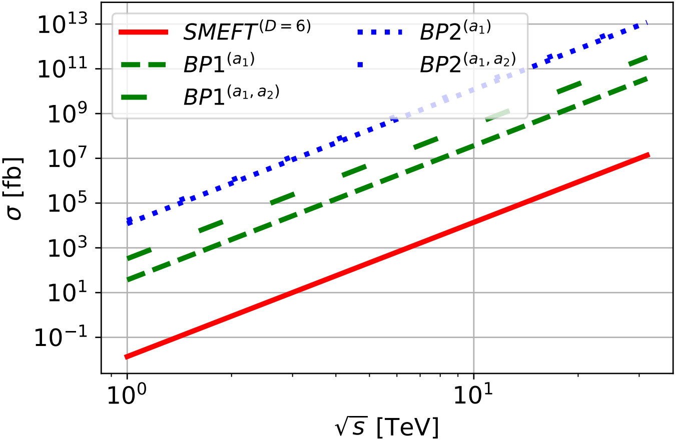


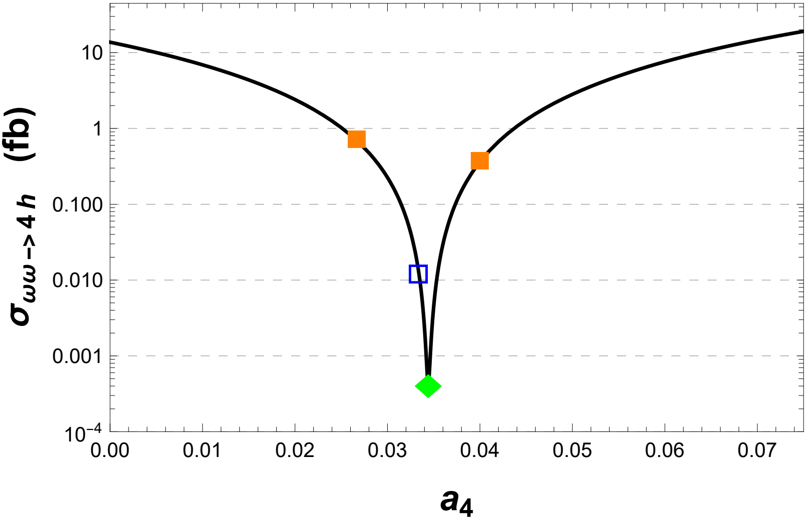
Deviating a_3 only 10% of SMEFT value drastically changes XS.

Cross section comparison: four Higgses



Integration performed through new open-source code MaMuPaXS
github.com/mamupaxs

Cross section comparison: four Higgses



Deviating a_4 only 10% of SMEFT value drastically changes XS.

Collider estimate and SMEFT limits

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SMEFT exclusion bounds

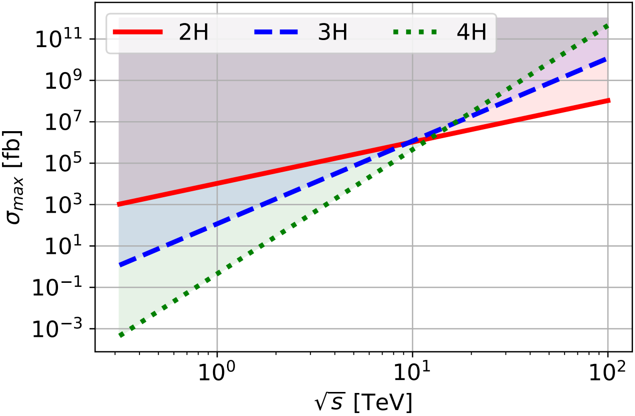


Figure 1: SMEFT exclusion plot for the cross sections for 2, 3 and 4 Higgs bosons with $|d| \leq d_{\max} = 0.1$ and $|\rho| \leq \rho_{\max} = 1$.

Exclusion plot: EFT perturbativity

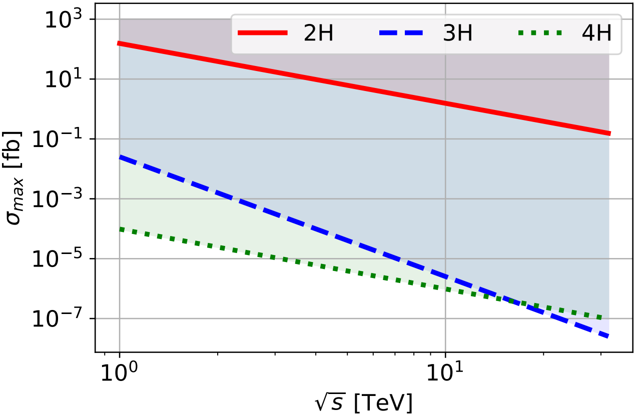


Figure 2: Exclusion plot for the maximum value of the cross sections for 2, 3 and 4 Higgs bosons with the constraint $|\rho| \leq \rho_{\max} = 1$ and EFT-expansion tolerance $\epsilon = 0.1$. $\left|\frac{c^{(6)}_{H\Box} s}{\Lambda^2}\right| = \left|\frac{d\, s}{2v^2}\right| \leq \epsilon \ll 1$

The Effective W approximation

In the Effective W approximation (EWA), W_L are radiated collinear to initial particles (expected to dominate XS).

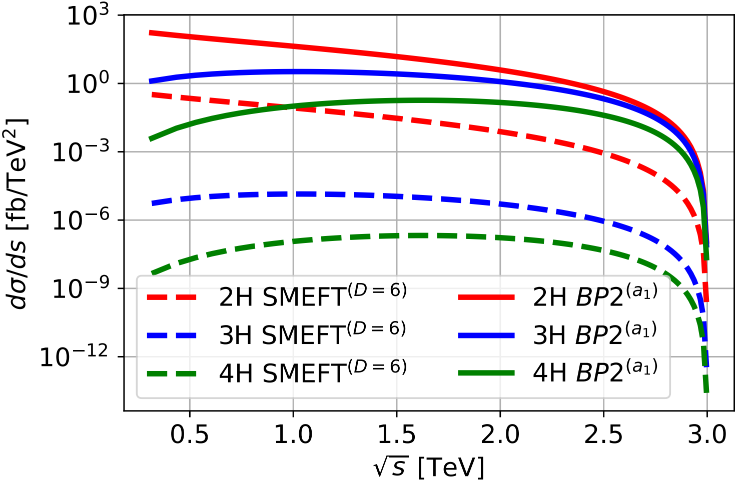
Collider estimate: 3 TeV CLIC e^+e^-

In the EWA factorization, the total cross section, σ_{tot}, is provided by the hard subprocess cross section times an appropriate W_L–luminosity function of the form,

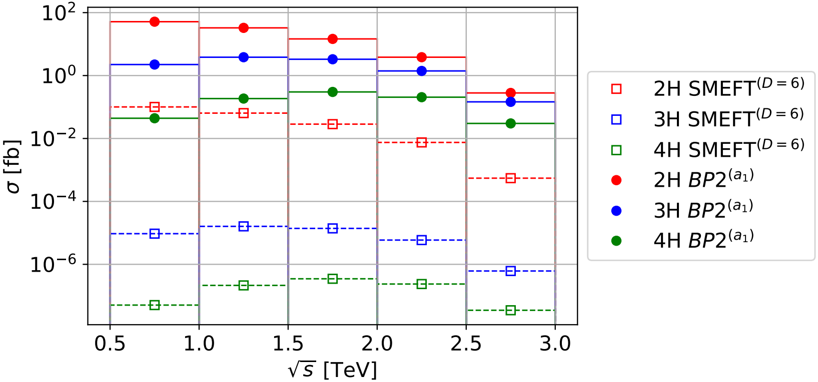
$$\frac{d\sigma_{tot}}{ds} = \frac{\alpha^2}{8\pi^2 s \; s_{\theta_W}^2} \left[2\left(\frac{s}{s^{\mathrm{tot}}} - 1\right) - \left(\frac{s}{s^{\mathrm{tot}}} + 1\right)\log\frac{s}{s^{\mathrm{tot}}}\right] \times \sigma(s)\Big|_{W_L^+ W_L^- \to n\times h}$$

1508.03544

Differential XS in the EWA



$e^+e^- \to e^+e^- + n \times h$ cross section in the EWA



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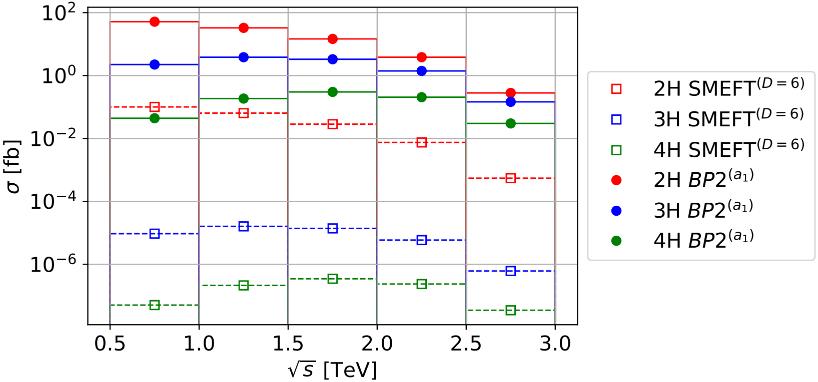

CLIC at 3 TeV expected to have $5000 fb^{-1}$ luminosity. 1812.02093

Conclusions

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2. Computed $\omega\omega \to hhh$ and $\omega\omega \to hhhh$ at LO HEFT amplitudes and cross sections.
3. HEFT cross sections can be both small and big. SMEFT ones are usually suppressed.
4. Observation of three and four hs final states at CLIC 3 TeV e^+e^- could signal SMEFT is not enough.

Aknowledgments

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