The flair of the Higgsflare

Raquel Gomez-Ambrosio

https://arxiv.org/abs/2204.01763

in collaboration with F. Llanes-Estrada, A. Salas-Bernardez, and JJ. Sanz-Cillero

The flair of the Higgsflare: motivation

flair

noun

UK /fleəʳ/ **US** /fler/

C1 [S]

natural ability to do something well:

- *He has a flair* ***for*** *languages.*

$$\mathscr{F}(h) = \left(1 + a_1\frac{h}{v} + a_2\frac{h^2}{v^2} + a_3\frac{h^3}{v^3} + \ldots + a_n\frac{h^n}{v^n}\right)$$

(Some) Earlier works on EWChL HEFT

* Madrid UCM and UAM

  * Strongly coupled theories beyond the Standard Model. Antonio Dobado, Domènec Espriu.
    Prog.Part.Nucl.Phys. 115 (2020) 103813

  * Unitarity, analyticity, dispersion relations, and resonances in strongly interacting WL WL, ZL ZL, , and hh scattering. R.Delgado , A Dobado, F Llanes-Estrada.
    Phys.Rev.D 91 (2015) 7, 075017

  * Production of vector resonances at the LHC via WZ-scattering: a unitarized EChL analysis. R.L. Delgado, A. Dobado, D. Espriu, C. Garcia-Garcia, M.J. Herrero et al. JHEP 11 (2017) 098

  * One-loop $\gamma\gamma \to$ WL WL and $\gamma\gamma \to$ ZL ZL from the Electroweak Chiral Lagrangian with a light Higgs-like scalar. R.L. Delgado, A. Dobado, M.J. Herrero, J.J. Sanz-Cillero. JHEP 07 (2014) 149

And refs therein…

Recent works highlighting the EFT geometry

* 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].

And refs therein…

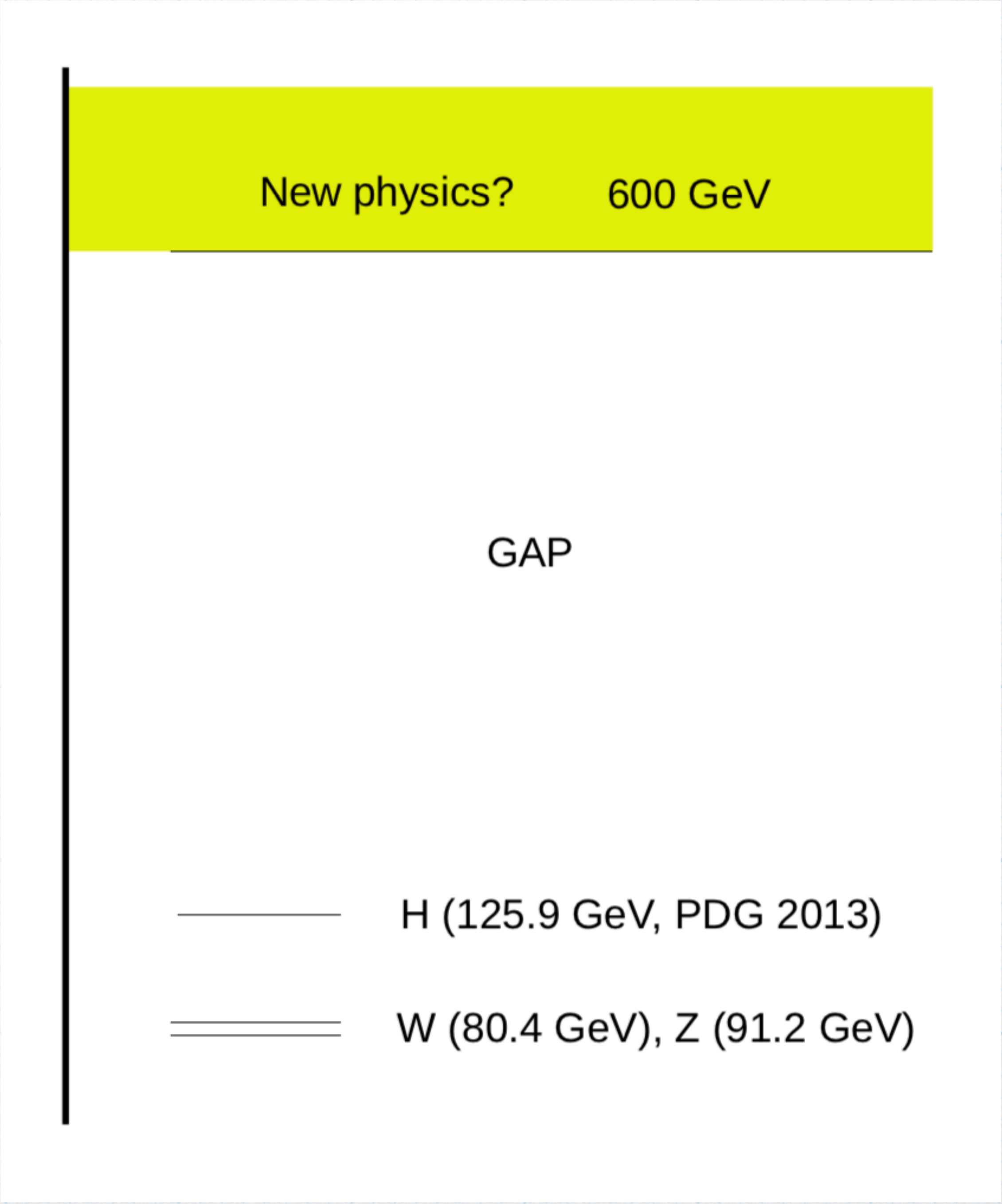
* These works show us that SMEFT vs HEFT is more than linear vs nonlinear realisations…
    * SMEFT exists if: $\exists h^* \to \mathscr{F}(h) = 0$
    * And $\mathscr{F}(h)$ is analytic in a certain region
* Consequences:
    * $\exists F(h) \implies \mathscr{F}(h) = F(h)^2$
    * Double 0 of $\mathscr{F}(h)$
    * Odd derivatives vanish (even derivatives of $F(h)$)

Looking for Physics Beyond the SM

* SMEFT: LHC's favourite

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)}$$

$$\mathscr{L}_{SMEFT} = A(|H|^2)|\partial H|^2 + \frac{1}{2}B(|H|^2)(\partial |H|^2)^2 - V(|H|^2) + \mathscr{O}(\partial^4)$$



Alternatively: HEFT

* Take EwChL, enhanced by a flare function:

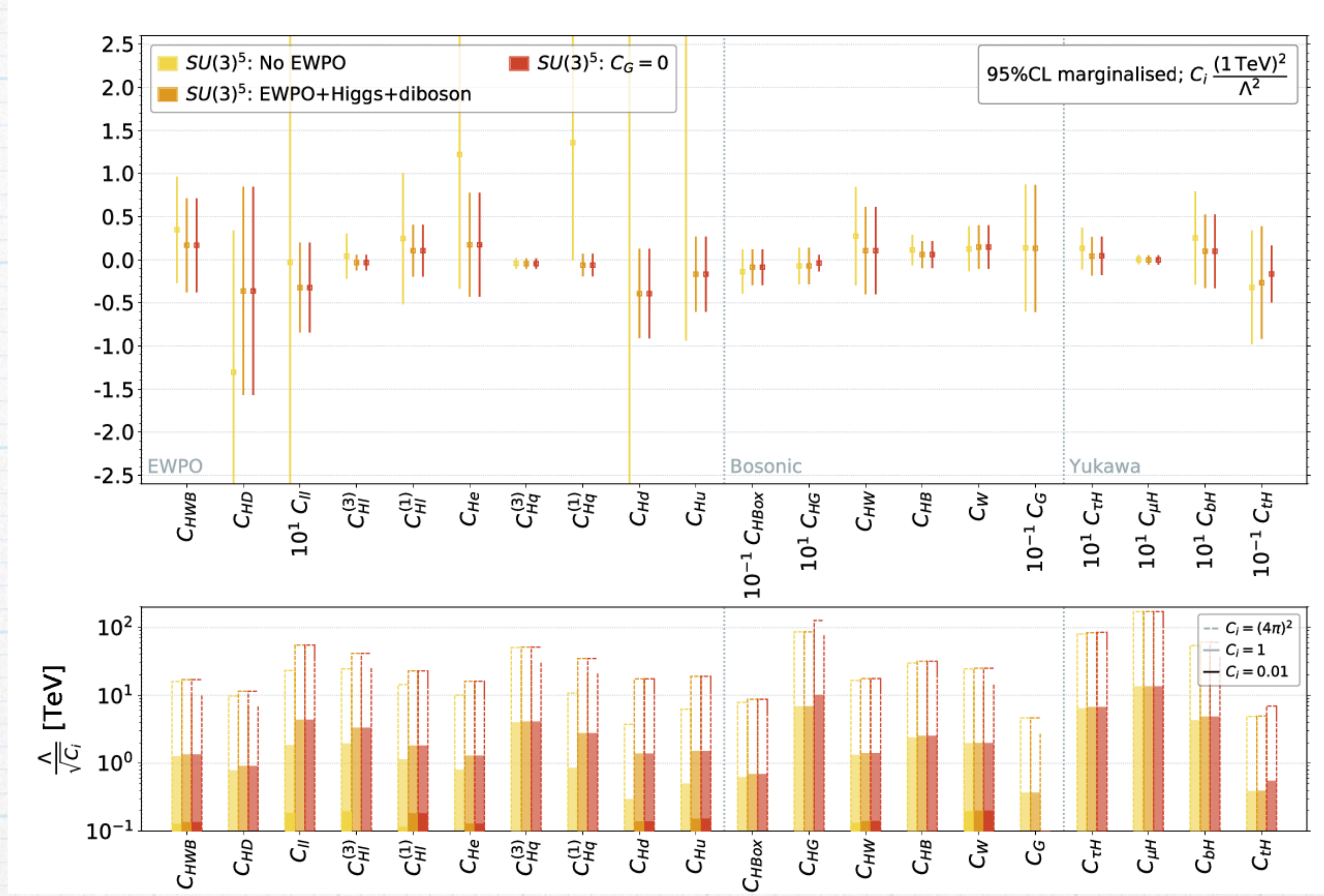
$$\mathscr{L}_{HEFT} = \frac{1}{2}\partial_\mu h \partial_\mu h - V(h) + \frac{1}{2}\mathscr{F}(h)\, \partial_\mu w^i \partial^\mu w^j \left(\delta_{ij} + \frac{w_i w_j}{v^2 - \mathrm{w}^2}\right)$$

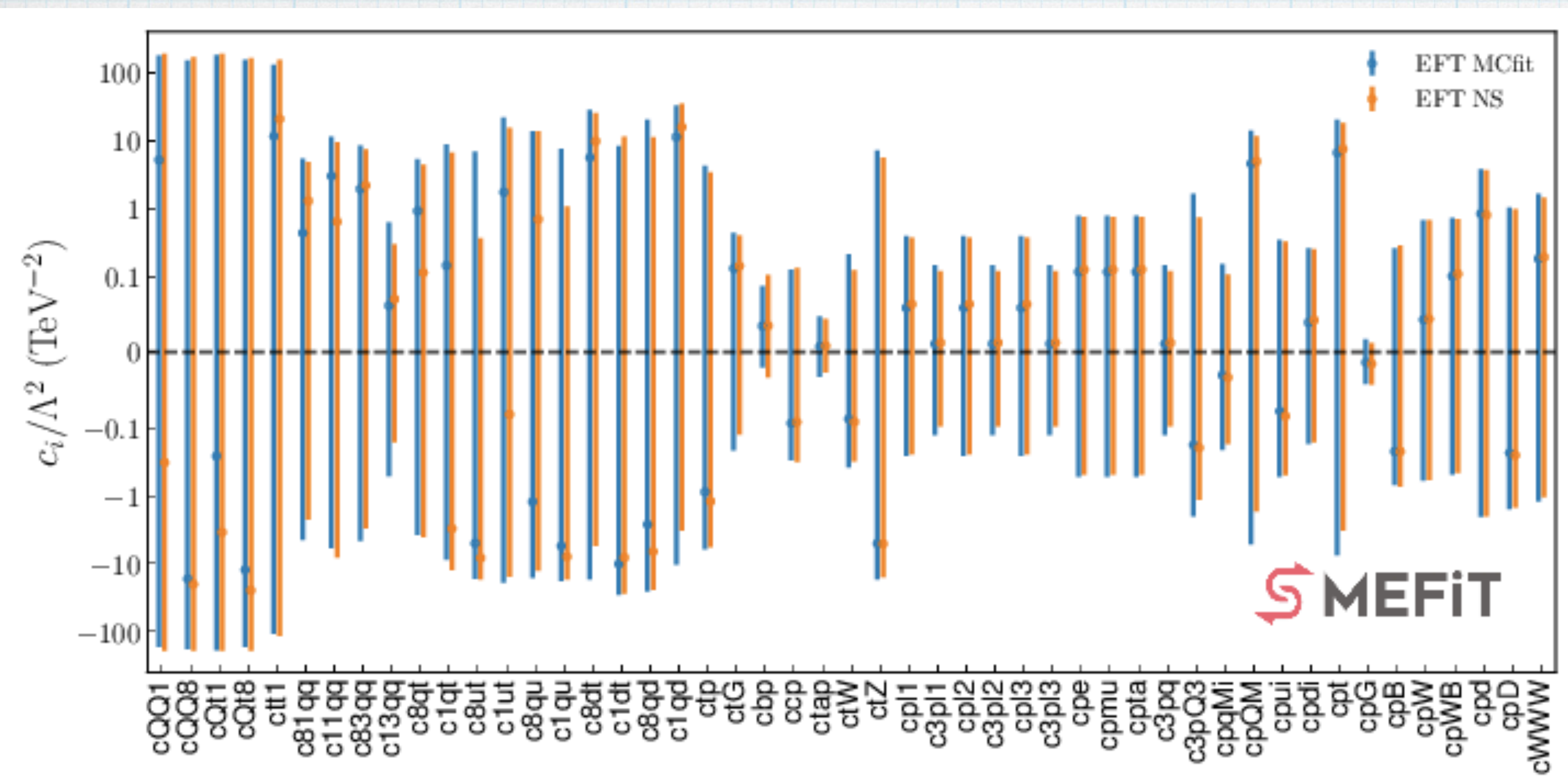
$$\mathscr{F}(h) = 1 + \sum a_n \left(\frac{h}{v}\right)^n$$

In HEFT, h and w's are independent

LHC Global fits

* In the absence of new particles, our main effort goes into constraining SMEFT coefficients





fitmaker, smefit, et al.

The SM is falsified by finding a nonzero Wilson coefficient

How is the SMEFT falsified?

SMEFT vs HEFT

* A deviation from the SM, if small enough, can always be parametrised by the Warsaw basis

SMEFT vs HEFT

* A deviation from the SM, if small enough, can always be parametrised by the Warsaw basis

FALSE

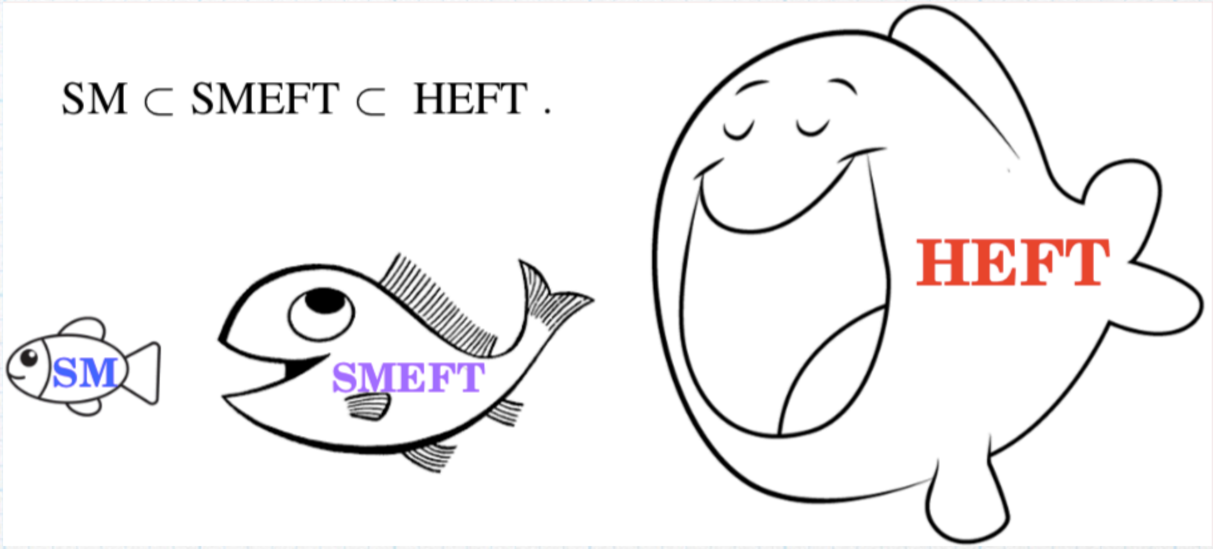
SMEFT vs HEFT

* A deviation from the SM, if small enough, can always be parametrised by the Warsaw basis

NOT STRICTLY TRUE

Here is where HEFT kicks in

Write SMEFT
in HEFT form:



$$|\partial H|^2 + \frac{1}{2}B(|H|)^2(\partial(|H|^2))^2 \;\rightarrow\; \frac{v^2}{4}\mathscr{F}(h)\langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}(\partial h_{HEFT})^2$$

$$\boxed{dh_{HEFT} = \sqrt{1+(v+h_{SMEFT})^2 B(h_{SMEFT})}\;\; dh_{SMEFT}}$$

Falsifying SMEFT

* Relevant SMEFT operators for the Higgs sector (dim 6):

* $$\mathcal{O}_H = (H^\dagger H)^3\,, \qquad \mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)\,,$$
  $$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,.$$

    * At high energies they decouple and only one survives: $\mathcal{O}_{H\Box}$

Alonso & West 2109.13290

The role of cHBox in SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \frac{1}{2}\left(1 - \frac{2c_{H\Box}v^2}{\Lambda^2}\right)\partial_\mu h \partial^\mu h + \ldots$$

$$\frac{\sigma_{H,\,\text{SMEFT}}}{\sigma_{H,\,\text{SM}}} \propto \frac{\Gamma_{H,\,\text{SMEFT}}}{\Gamma_{H,\,\text{SM}}} \propto 1 + 2\frac{c_{H\Box}v^2}{\Lambda^2} = 1 + 0.12 c_{H\Box}\,,$$

Current Bounds
(SMEFiT and Fitmaker)

$$c_{H\Box} \simeq -0.3 \pm 0.7 \;\; \text{(individual)}$$
$$c_{H\Box} \simeq -1 \pm 2 \;\; \text{(marginalized)}\,.$$

The Flare function in SMEFT

$$\mathcal{L}_{\rm SMEFT} = \frac{v^2}{4}\left(1+\frac{h_1}{v}\right)^2 \langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}\left(1-\frac{2c_{H\Box}(h_1+v)^2}{\Lambda^2}\right)(\partial_\mu h_1)^2 \; - \; V(h_1)$$

$$= \frac{v^2}{4}\mathcal{F}(h_1)\langle D_\mu U^\dagger D^\mu U\rangle + \frac{1}{2}(\partial_\mu h_1)^2 - V(h) - \frac{c_{H\Box}\left[(v+h_1)^3 \; - \; v^3\right]}{3\Lambda^2}V'(h_1)\,.$$

$$\mathcal{F}(h_1) = \left(1+\frac{h_1}{v}\right)^2 + \frac{2v^3 c_{H\Box}}{\Lambda^2}\left(1+\frac{h_1}{v}\right)\left(\frac{h_1^3}{3v^3}+\frac{h_1^2}{v^2}+\frac{h_1}{v}\right) + \mathcal{O}\left(\frac{c_{H\Box}^2}{\Lambda^4}\right) =$$

$$= 1 + \left(\frac{h_1}{v}\right)\left(2+2\frac{c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h_1}{v}\right)^2\left(1+4\frac{c_{H\Box}v^2}{\Lambda^2}\right) +$$

$$+ \left(\frac{h_1}{v}\right)^3\left(8\frac{c_{H\Box}v^2}{3\Lambda^2}\right) + \left(\frac{h_1}{v}\right)^4\left(2\frac{c_{H\Box}v^2}{3\Lambda^2}\right)\,,$$

$$a_1 = 2a = 2\left(1+v^2\frac{c_{H\Box}}{\Lambda^2}\right)\,,\quad a_2 = b = 1+4v^2\frac{c_{H\Box}}{\Lambda^2}\,,\quad a_3 = \frac{8v^2}{3}\frac{c_{H\Box}}{\Lambda^2}\,,\quad a_4 = \frac{2v^2}{3}\frac{c_{H\Box}}{\Lambda^2}\,.$$

The Flare function in SMEFT

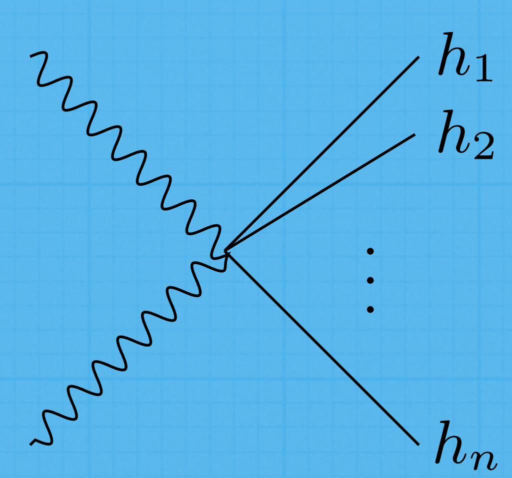
$$
\begin{aligned}
\mathcal{F}(h_1) = 1 &+ \left(\frac{h_1}{v}\right)\left(2 + 2\frac{c_{H\Box}^{(6)}v^2}{\Lambda^2} + 3\frac{(c_{H\Box}^{(6)})^2 v^4}{\Lambda^4} + 2\frac{c_{H\Box}^{(8)}v^4}{\Lambda^4}\right) + \\
&+ \left(\frac{h_1}{v}\right)^2\left(1 + 4\frac{c_{H\Box}^{(6)}v^2}{\Lambda^2} + 12\frac{(c_{H\Box}^{(6)})^2 v^4}{\Lambda^4} + 6\frac{c_{H\Box}^{(8)}v^4}{\Lambda^4}\right) + \\
&+ \left(\frac{h_1}{v}\right)^3\left(8\frac{c_{H\Box}^{(6)}v^2}{3\Lambda^2} + 56\frac{(c_{H\Box}^{(6)})^2 v^4}{3\Lambda^4} + 8\frac{c_{H\Box}^{(8)}v^4}{\Lambda^4}\right) + \\
&+ \left(\frac{h_1}{v}\right)^4\left(2\frac{c_{H\Box}^{(6)}v^2}{3\Lambda^2} + 44\frac{(c_{H\Box}^{(6)})^2 v^4}{3\Lambda^4} + 6\frac{c_{H\Box}^{(8)}v^4}{\Lambda^4}\right) + \\
&+ \left(\frac{h_1}{v}\right)^5\left(88\frac{(c_{H\Box}^{(6)})^2 v^4}{15\Lambda^4} + 12\frac{c_{H\Box}^{(8)}v^4}{5\Lambda^4}\right) + \\
&+ \left(\frac{h_1}{v}\right)^6\left(44\frac{(c_{H\Box}^{(6)})^2 v^4}{45\Lambda^4} + 2\frac{c_{H\Box}^{(8)}v^4}{5\Lambda^4}\right) + \mathcal{O}(\Lambda^{-6})\,.
\end{aligned}
$$

Naturally extend to dim8 and further, and to quadratic terms

Multihiggs production

* At high energies ($\leq \approx 1\mathrm{TeV}$) we can rely on the equivalence theorem

$$T_{\omega\omega\to n\times h} = \frac{s}{v^n}\sum_{i=1}^{p(n)}\left(\psi_i(q_1,q_2,\{p_k\})\prod_{j=1}^{|\mathrm{IP}[n]_i|} a_{\mathrm{IP}[n]_i^j}\right)$$



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

Falsifying SMEFT

* Two approaches

    1. Ratios of total cross sections of $w_L w_L \to nh$

    2. Correlations between flare coefficients

Tabulated amplitudes for ww -> nh available on request

Falsifying SMEFT: Ratios of XSECS

In HEFT:

$$T_{\omega\omega\to nh} = f(a_1, \ldots, a_n)$$

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

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

$$T_{\omega\omega\to nh} \propto \left(\frac{s}{v^{n-2}\Lambda^2}\right) c_{H\Box} \quad \text{in SMEFT up to } \mathcal{O}\left(\Lambda^{-2}\right)$$

$$\boxed{\frac{\sigma(\omega\omega\to nh)}{\sigma(\omega\omega\to mh)} = \text{independent of } c_{H\Box}}$$

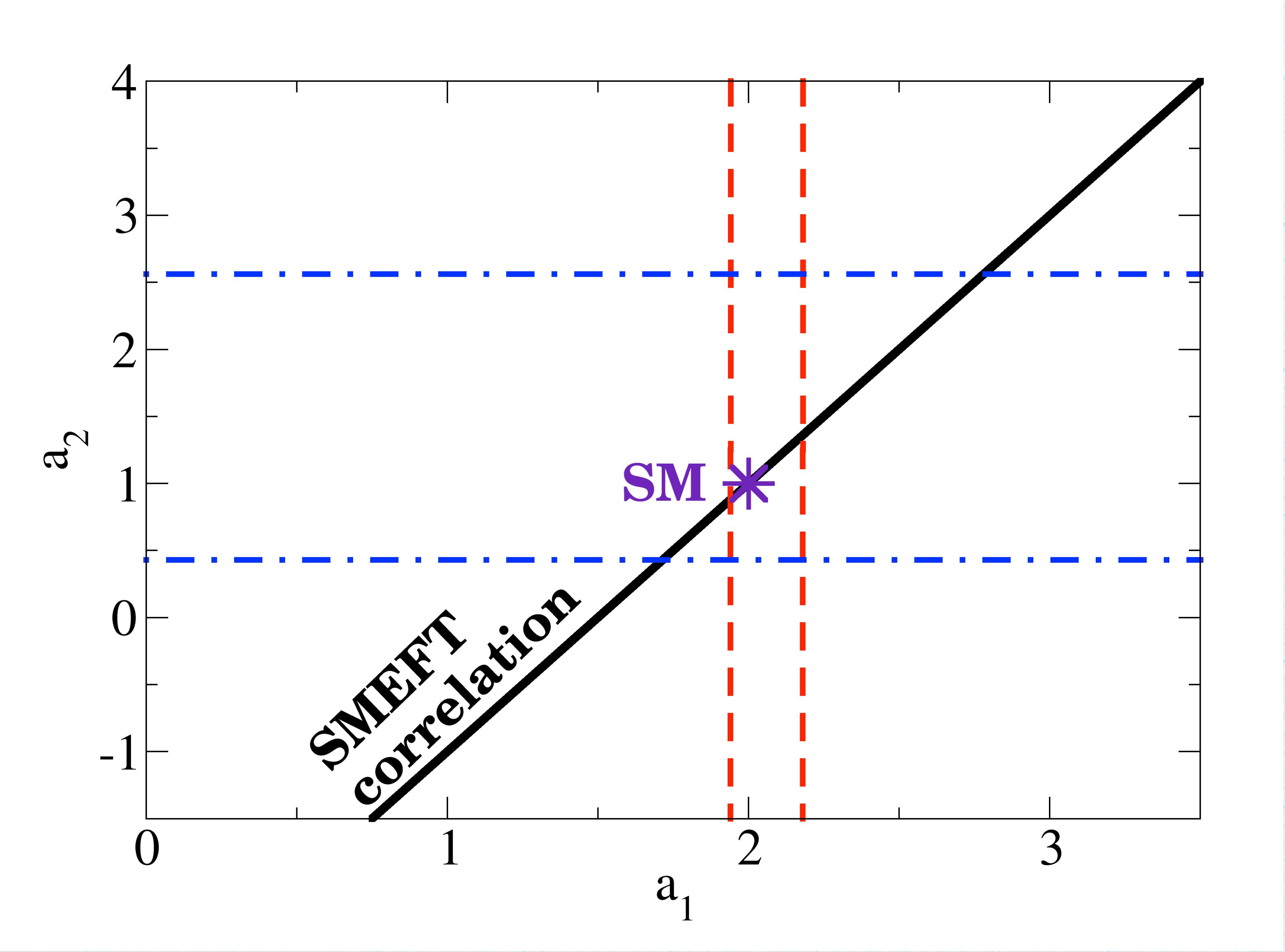
Work in progress....

Falsifying SMEFT: correlations

Correlations accurate at order Λ^{-2}	**Correlations** accurate at order Λ^{-4}	Λ^{-4} **Assuming SMEFT perturbativity**
$\Delta a_2 = 2\Delta a_1$		$\lvert\Delta a_2\rvert \le 5\lvert\Delta a_1\rvert$
$a_3 = \frac{4}{3}\Delta a_1$	$\left(a_3 - \frac{4}{3}\Delta a_1\right) = \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}\left(\Delta a_1\right)^2$	
$a_4 = \frac{1}{3}\Delta a_1$	$\left(a_4 - \frac{1}{3}\Delta a_1\right) = \frac{5}{3}\Delta a_1 - 2\Delta a_2 + \frac{7}{4}a_3 =$ $= \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{7}{12}\left(\Delta a_1\right)^2$	those for a_3, a_4, a_5, a_6
$a_5 = 0$	$a_5 = \frac{8}{5}\Delta a_1 - \frac{22}{15}\Delta a_2 + a_3 =$ $= \frac{6}{5}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}\left(\Delta a_1\right)^2$	all the same
$a_6 = 0$	$a_6 = \frac{1}{6}a_5$	

$$a_1 = \left(2 + 2\frac{c^{(6)}_{H\Box}v^2}{\Lambda^2} + 3\frac{(c^{(6)}_{H\Box})^2 v^4}{\Lambda^4} + 2\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right) \qquad a_2 = \left(1 + 4\frac{c^{(6)}_{H\Box}v^2}{\Lambda^2} + 12\frac{(c^{(6)}_{H\Box})^2 v^4}{\Lambda^4} + 6\frac{c^{(8)}_{H\Box}v^4}{\Lambda^4}\right).$$

Falsifying SMEFT



Blue and red:
Best available bounds

Experimental application

* Ideally future colliders will be able to measure multihiggs production at a good enough accuracy to test these correlations.
* Already a measurement of double H production at HL-LHC would provide greater insight on the a1/a2 values.

Experimental application: state of the art

- Measurements by ATLAS and CMS have produced bounds on a1 and a2:

$$a_1/2 = a \in [0.97, 1.09]$$

$$a_2 \in [-0.43, 2.56](\mathrm{AT})$$

$$\in [-0.1, 2.2](\mathrm{CMS})$$

Consistent SMEFT range at order Λ^{-2}	**Consistent SMEFT range at order Λ^{-4}**	**Perturbativity of Λ^{-4} SMEFT**
$\Delta a_2 \in [-0.12, 0.36]$ $a_3 \in [-0.08, 0.24]$ $a_4 \in [-0.02, 0.06]$ $a_5 = 0$ $a_6 = 0$	ATLAS $a_3 \in [-4.1, 4.0]$ $a_4 \in [-4.2, 3.9]$ $a_5 \in [-1.9, 1.8]$ $a_6 = a_5$	ATLAS $a_3 \in [-3.1, 1.7]$ $a_4 \in [-3.3, 1.5]$ $a_5 \in [-1.5, 0.6]$ $a_6 = a_5$
	CMS $a_3 \in [-3.2, 3.0]$ $a_4 \in [-3.3, 3.0]$ $a_5 \in [-1.5, 1.3]$ $a_6 = a_5$	CMS $a_3 \in [-3.1, 1.7]$ $a_4 \in [-3.3, 1.5]$ $a_5 \in [-1.5, 0.6]$ $a_6 = a_5$

Conclusions and outlook

* The Higgs potential is a big open question at LHC

* We have shown here a procedure to rule out the SMEFT, independent of the finding of new particles

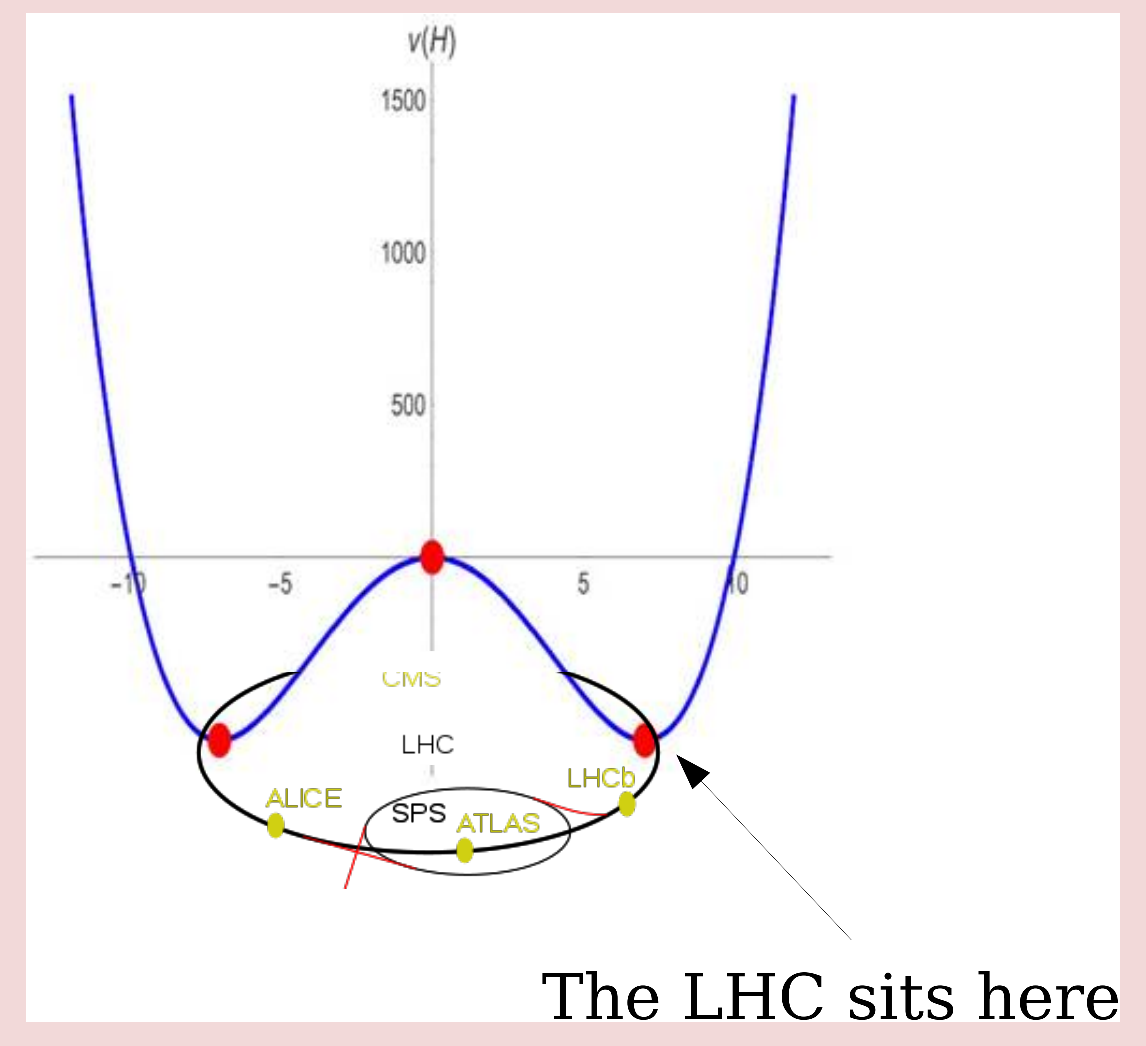
* A first clue might be accessible at HL-LHC (through double H production)

* We can use properties of the flare function to extract further insights on low energy physics (see paper)

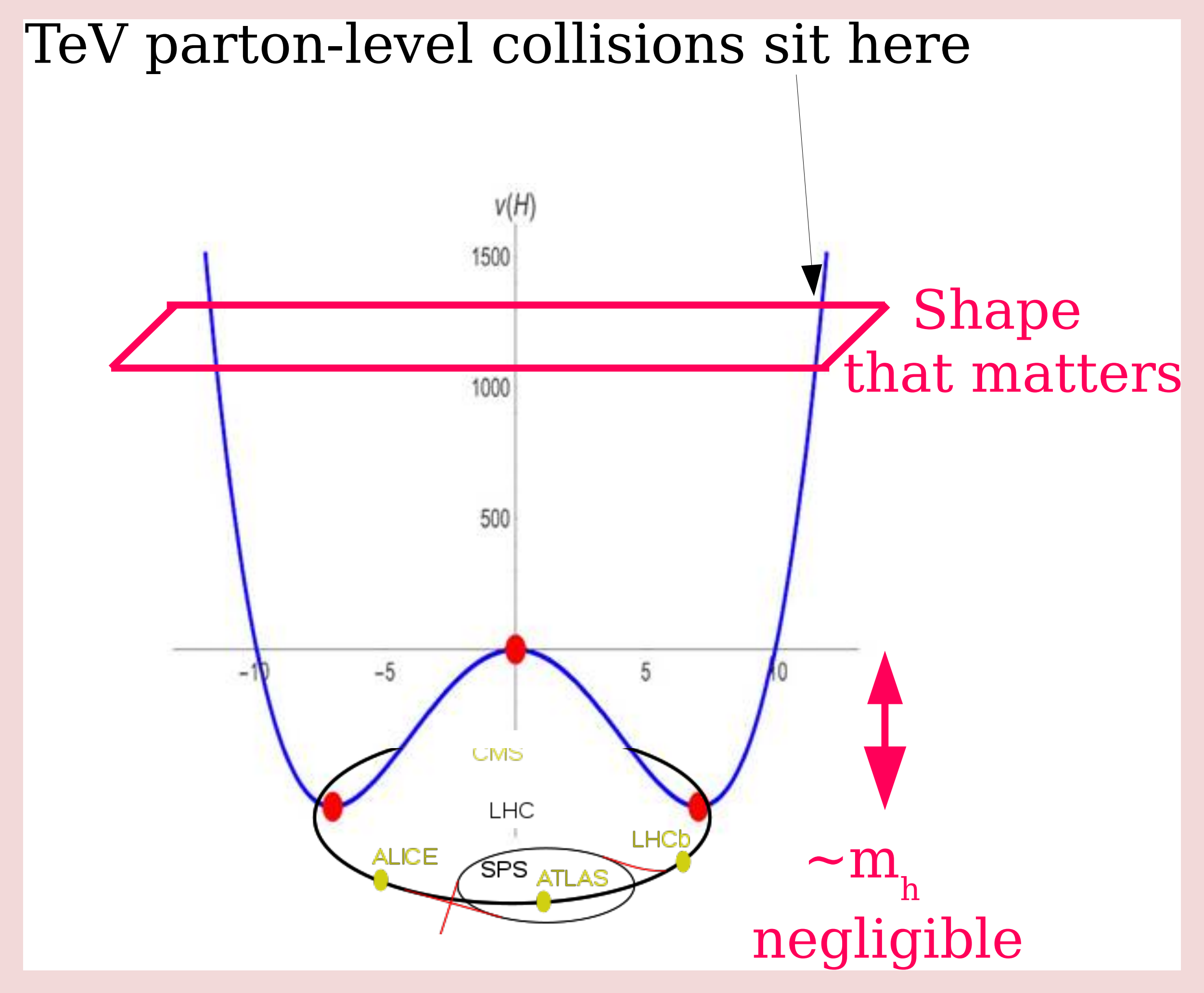
* We can associate the flare function being HEFT-like or SMEFT-like with concrete BSM scenarios

Supported by **spanish MICINN** PID2019-108655GB-I00 grant, and **Universidad Complutense de Madrid** under research group 910309 and the **IPARCOS** institute; **ERC** Starting Grant REINVENT-714788; UCM CT42/18-CT43/18; the **Fondazione Cariplo** and **Regione Lombardia**, grant 2017-2070.

Backup



v(H)
1500
1000
500
-10
-5
5
10
CMS
LHC
ALICE
SPS
ATLAS
LHCb
The LHC sits here



TeV parton-level collisions sit here
v(H)
1500
1000
500
-10
-5
5
10
Shape
that matters
CMS
LHC
ALICE
SPS
ATLAS
LHCb
~m$_h$
negligible

Measurements of a1/a2

A combination of measurements of Higgs boson production and decay using up to 139 fb^{-1} of proton–proton collision data at 13 TeV collected with the ATLAS experiment, (2020).

A. Tumasyan et al. (CMS), Search for Higgs boson pair production in the four b quark final state in proton-proton collisions at 13 TeV, (2022), arXiv:2202.09617 [hep-ex].

G. Aad et al. (ATLAS), Search for the HH → bbbb process via vector-boson fusion production using proton-proton collisions at s = √ 13 TeV with the ATLAS detector, JHEP **07**, 108, [Erratum: JHEP 01, 145 (2021), Erratum: JHEP 05, 207 (2021)], arXiv:2001.05178