Multi-Higgs production and chiral effective Lagrangians

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JHEP 03 (2024) 037; PRD 106 (2022) 5, 5; Commun.Theor.Phys. 75 (2023) 9, 095202

+ forthcoming pheno work

Outline

- SM, SMEFT and HEFT : basic considerations
- $\omega\omega \to n \times h$ scattering : compact expressions
- Understanding $T_{\omega\omega\to n\times h}$: field redefinitions
- SMEFT pheno : suppressed multi-H production wrt HEFT

- **SM:**
  - Complex doublet H
  - Renormalizable (canonical dim. $D \leq 4$)

$$\mathcal{L}_{SM} = \mathcal{L}_{D\leq 4}$$

- **SMEFT:**
  - Complex doublet H
  - Non-renormalizable (canonical dim. expan.)

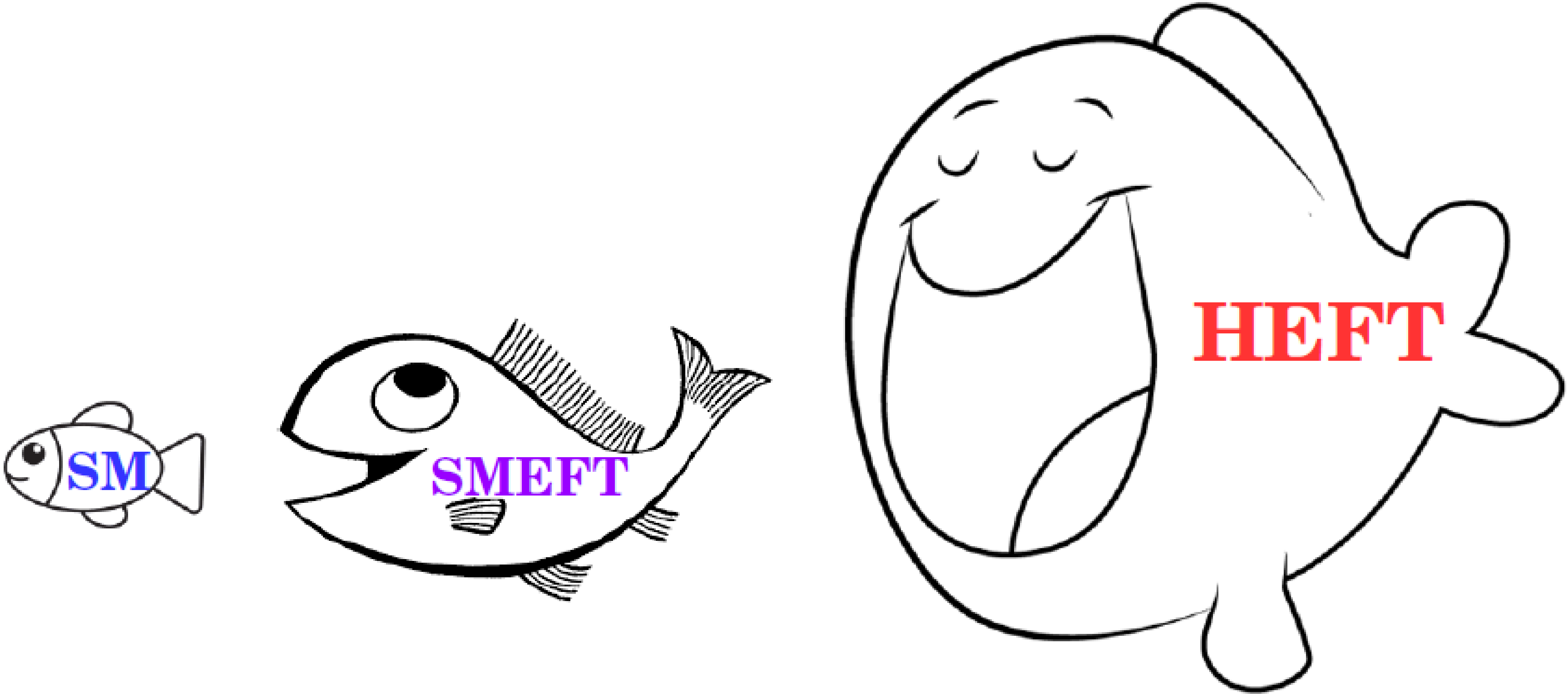
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{n,i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)}$$

- **HEFT** (= EWChL = EWET)
  - 3 EW Goldstones + 1 singlet Higgs h (indep.)
  - Non-renormalizable (chiral expan.)

$$\mathcal{L}_{HEFT} = \mathcal{L}_{p^2} + \mathcal{L}_{p^4} + \ \ldots$$

[w/ $\mathcal{L}_{SM} \subset \mathcal{L}_{p^2}$]

[by Felipe J. Llanes-Estrada]



(x) See, e.g., Alonso,Jenkins,Manohar, PLB 754 (2016) 335-342; PLB 756 (2016) 358-364; JHEP 08 (2016) 101; Cohen,Craig,Lu,Sutherland, JHEP 03 (2021) 237; JHEP 12 (2021) 003; Brivio,Corbett,Éboli,Gavela,González-Fraile,González-García,Merlo,Rigolin, JHEP 03 (2014) 024; Agrawal,Saha,Xu,Yu,Yuan, PRD 101 (2020) 7, 075023; Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC, PRD 106 (2022) 5, 5; Commun.Theor.Phys. 75 (2023) 9, 095202; Dawson,Fontes,Quezada-Calonge,SC, 2311.16897 [hep-ph]; PRD 108 (2023) 5, 055034; Arco,Domenech,Herrero,Morales, PRD 108 (2023) 9, 095013;

HEFT: $W_L W_L \to 2h, 3h, 4h \ldots$

- kinematics well over WW threshold: $s \gg m_W^2 \sim m_h^2$

- Mass corrections neglected

- Chiral LO: only $O(\partial^2)$ derivative operators

- Equivalence theorem appr.: $W_L W_L \to n \times h \approx \omega\omega \to n \times h$

[I know: 3h, 4h, etc. looks like science-fiction nowadays]

- Specific $\omega\omega \to n \times h$ stand-alone Mathematica code [link]
- FeynRules + FeynCalc chiral model file @ LO + NLO [link1] [link2]

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

F_π from χPT ➔ EW vev $v = \left(\sqrt{2}G_F\right)^{-1} = 246$ GeV

- Relevant HEFT Lagrangian at LO, O(p^2):

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathcal{F}(h)\,\mathrm{Tr}\left\{\partial_\mu U^\dagger \partial^\mu U\right\}$$

w/ the SU(2)-singlet “Flare” function,

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

Other usual notation in the bibliography: $\boldsymbol{\kappa_V} \equiv a \equiv a_1/2\,,\ \ \boldsymbol{\kappa_{2V}} \equiv b \equiv a_2$

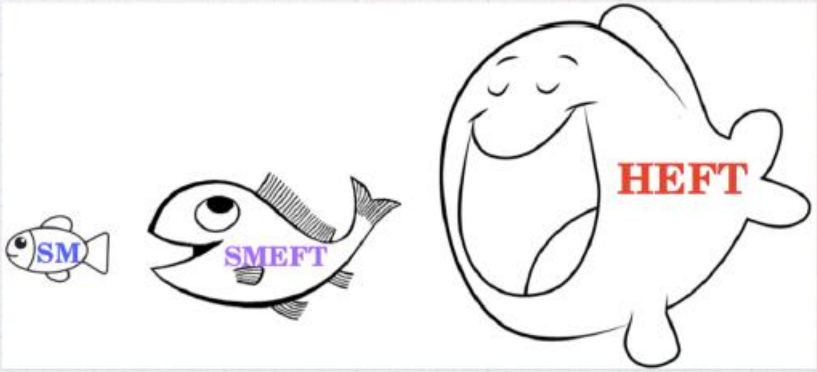
- Non-linear Goldstone realization: $U(\omega) = 1 + i\sigma^a\omega^a/v + \mathcal{O}(\omega^2)$

The Flare Function

* In HEFT: $\mathscr{F}(h)_{HEFT} = 1 + a_1 \frac{h}{v} + a_2 \left(\frac{h}{v}\right)^2 + a_3 \left(\frac{h}{v}\right)^3 + \ldots$
* In the SM: $\mathscr{F}(h)_{SM} = \left(1 + \frac{h}{v}\right)^2$
* In SMEFT?

* Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC,
PRD 106 (2022) 5, 5;
Commun.Theor.Phys. 75 (2023) 9, 095202

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



$$\omega\omega \to 2h$$

$$T_{\omega\omega\to 2h} = -\frac{\hat{a}_2 s}{v^2}$$

$$\sigma_{\omega\omega\to 2h} = \frac{8\pi^3\,\hat{a}_2^2}{s}\left(\frac{s}{16\pi^2 v^2}\right)^2$$

- Relevant combination: $\hat{a}_2 = a_2 - a_1^2/4 = b - a^2$

- Pure s-wave (J=0) ➔ critical angular information

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

(x) Gonzalez-Lopez,Herrero,Martinez-Suarez, EPJC 81 (2021) 3, 260

$$\omega\omega \to 3h$$

$$T_{\omega\omega\to 3h} = -\frac{3\hat{a}_3 s}{v^3}$$

$$\sigma_{\omega\omega\to 3h} = \frac{12\pi^3\,\hat{a}_3^2}{s}\left(\frac{s}{16\pi^2 v^2}\right)^3$$

- Relevant combination: $\hat{a}_3 = a_3 - \frac{2}{3}a_1\left(a_2 - a_1^2/4\right) = a_3 - \frac{4}{3}a\left(b - a^2\right)$

- Pure s-wave (J=0) ➔ critical angular information

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

$\omega\omega \to 4h$

1-crossed-propagator
dimensionless angular function
[BACKUP SLIDES]

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

$$\sigma_{\omega\omega\to 4h} = \frac{8\pi^3}{9s}\left(\frac{s}{16\pi^2 v^2}\right)^4 \left[\left(3\hat{a}_4 - \hat{a}_2^2\right)^2 + 2\left(3\hat{a}_4 - \hat{a}_2^2\right)\hat{a}_2^2\chi_1 + \hat{a}_2^4\chi_2\right]$$

numerical integration constants $\chi_{1,2}$: MaMuPaXS [link]

- Relevant combination:

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

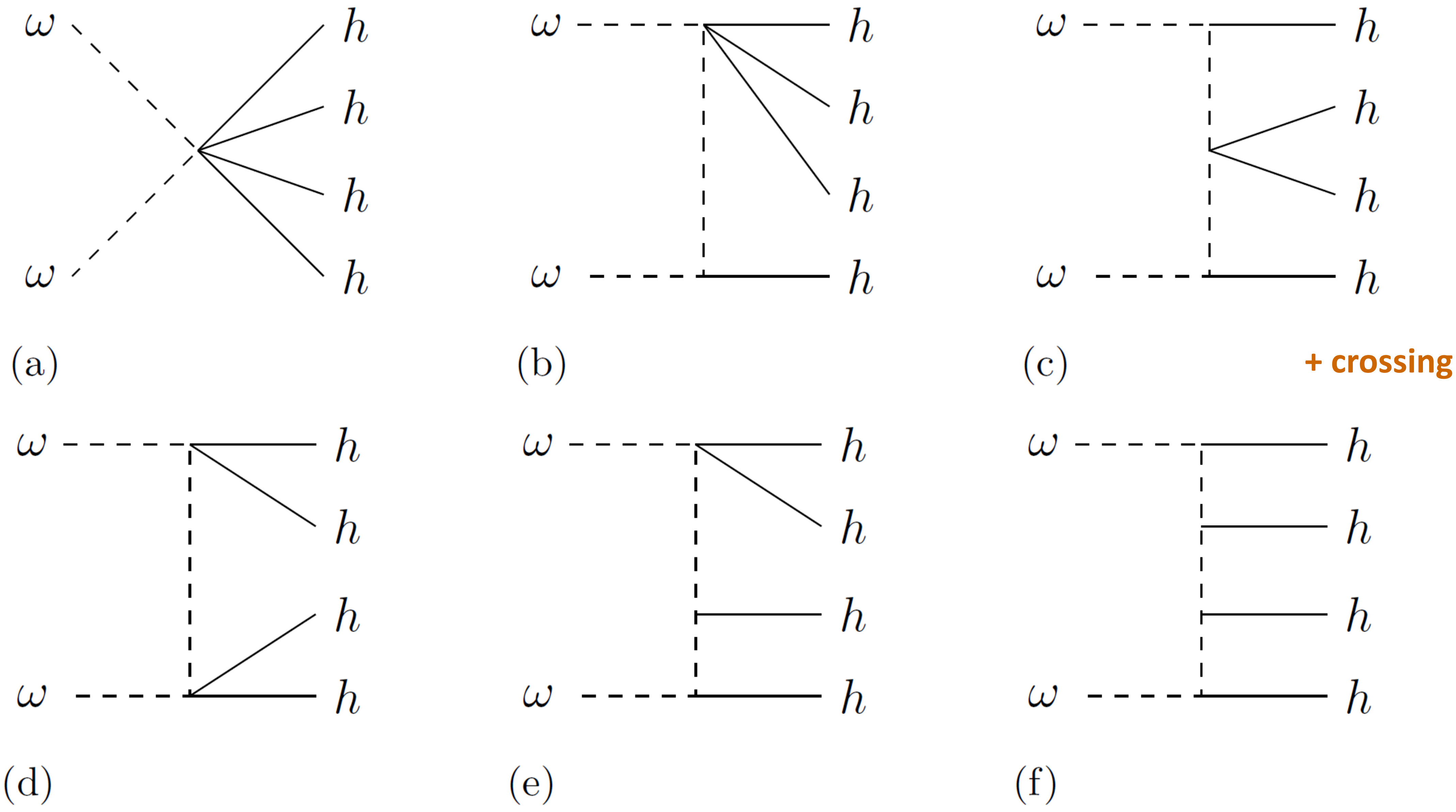
$$\hat{a}_2 = a_2 - a_1^2/4 = b - a^2$$

[exactly same combination as in $\omega\omega \to 2h$]

- Almost s-wave (J=0) [$\chi_1 = -0.12,\ \chi_2 = 0.019$] ➔ critical angular information

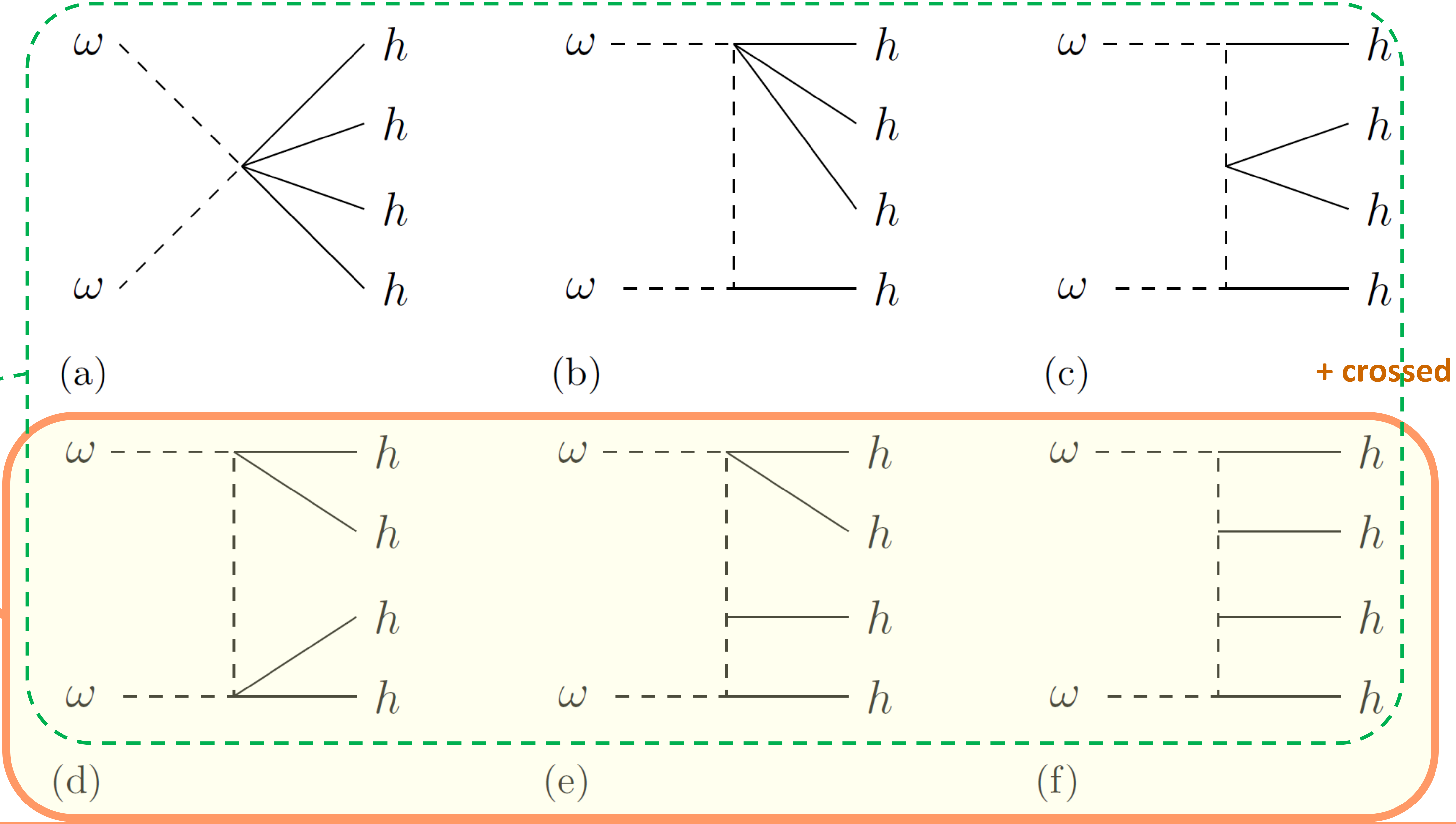
* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

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



[with permutations: 75 diagrams]

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



Understanding the $T_{\omega\omega\to n\times h}$ structure: field redefinitions

HEFT Lagrangian[1]

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

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\mathcal{F}(h)\,\partial_\mu \omega^a \partial^\mu \omega^a \; + \mathcal{O}(\omega^4)$$

Flare function[2]

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

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

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

HEFT lagrangian

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\mathcal{F}(h)\,\partial_\mu \omega^a \partial^\mu \omega^a \; + \; \mathcal{O}(\omega^4)$$

Field redefinition

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

Redefined HEFT Lagrangian for $g'(h) = -2\mathcal{N}/[v\,\mathcal{F}(h)]$

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\hat{\mathcal{F}}(h)\,\partial_\mu \omega^a \partial^\mu \omega^a + \mathcal{O}(\omega^4)$$

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

Redefined HEFT lagrangian

$$\mathcal{L}_{\mathrm{HEFT}} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\hat{\mathcal{F}}(h)\,\partial_\mu \omega^a \partial^\mu \omega^a + \mathcal{O}(\omega^4)$$

Redefined flare function

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

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

- For a general normalization $\mathcal{N}$ and solution of $g'(h) = -2\mathcal{N}/[v\,\mathcal{F}(h)]$:

$$g(h) = -\frac{2\mathcal{N}}{v}\int_0^h \frac{ds}{\mathcal{F}(s)} = \mathcal{N}\left(-2\frac{h}{v}+2a\frac{h^2}{v^2}+\frac{2}{3}(b-4a^2)\frac{h^3}{v^3}+\frac{1}{2}(a_3-4ab+8a^3)\frac{h^4}{v^4}+\mathcal{O}(h^5)\right)$$

$$\hat{\mathcal{F}}(h) = \mathcal{F}(h)\Big(1+g(h)\Big)^2$$

- However, for the particular normalization $\mathcal{N} = \frac{a_1}{4} = \frac{a}{2}$:

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

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

Redefined parameters ($\hat{a}_1 = 0$)

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

$$\hat{a}_3 = a_3 - \frac{4a}{3}\left(b - a^2\right)$$

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

Exactly the same effective combinations found

before in the $\omega\omega \to\ n \times h$ scattering amplitudes !!!

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

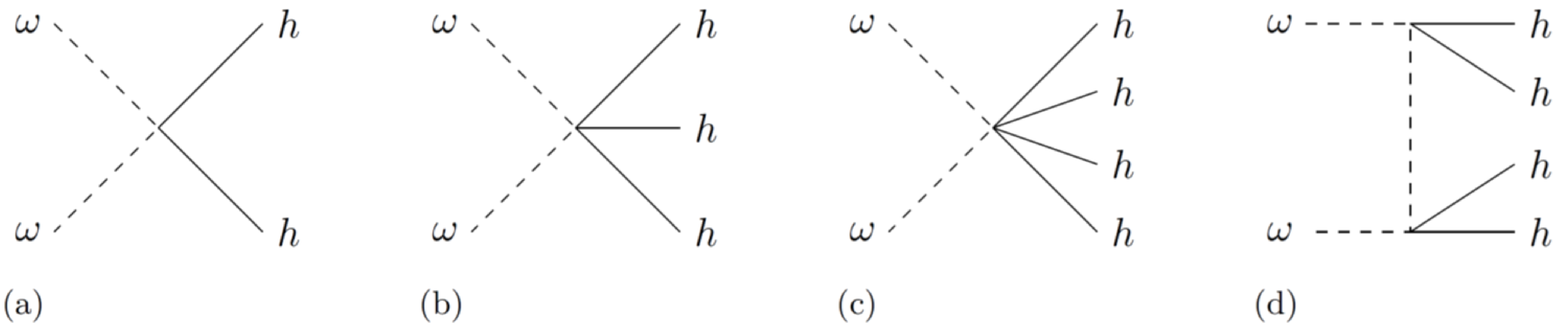


Figure 10. a) Only diagram contributing to the process $\omega\omega \to 2h$. **b)** Only diagram contributing to the process $\omega\omega \to 3h$. **c-d)** Only two diagrams contributing to the process $\omega\omega \to 4h$. We have used the simplified Lagrangian (C.6) to generate these amplitudes, so every $\omega\omega h^n$ vertex carries an $\hat{a}_n$ effective coupling. Note that, in addition, one needs to consider all possible permutations for the assignment of the external particles.

To make yourself an idea of the important simplification:

$\lambda\varphi^4$ theory is simpler to compute than $\lambda\varphi^3$

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

SMEFT theory: $\omega\omega \to 2h, 3h, 4h$ ... suppression

- SMEFT⇔HEFT relations for the relevant combinations:

$$\hat{a}_2 = d + 2d^2(1+\rho) + \mathcal{O}(d^3)$$
$$\hat{a}_3 = \frac{4}{3}d^2(1+\rho) + \mathcal{O}(d^3)$$
$$\hat{a}_4 = \frac{1}{3}d^2(1+\rho) + \mathcal{O}(d^3)$$

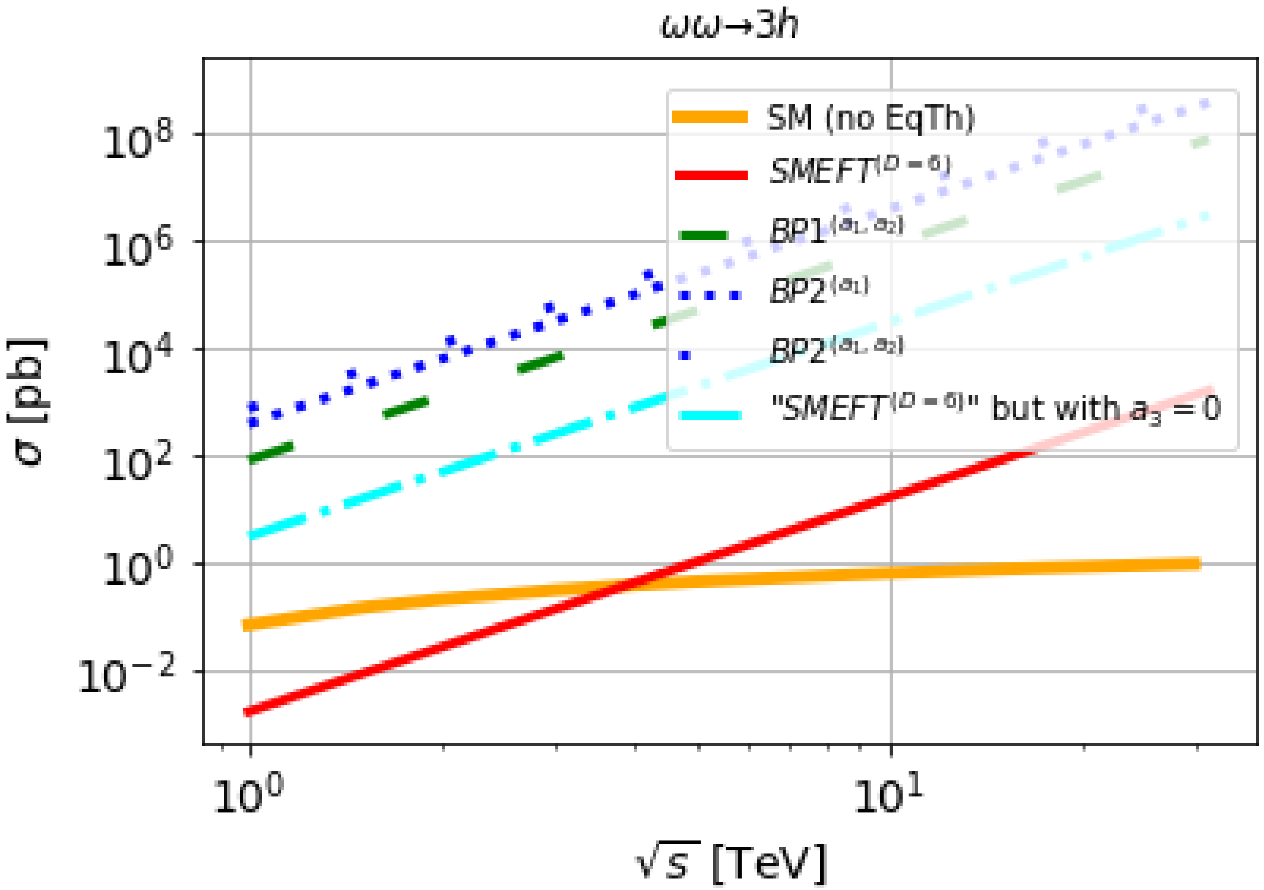
$$d = \frac{2v^2 c^{(6)}_{H\Box}}{\Lambda^2} \quad , \quad \rho = \frac{c^{(8)}_{H\Box}}{2(c^{(6)}_{H\Box})^2}$$

- Multi-Higgs fine-tuned suppression in SMEFT

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

SMEFT pheno: $\omega\omega \to 2h, 3h, 4h$ … suppression

• **An illustrative example:** $\omega\omega \to 3h$



* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

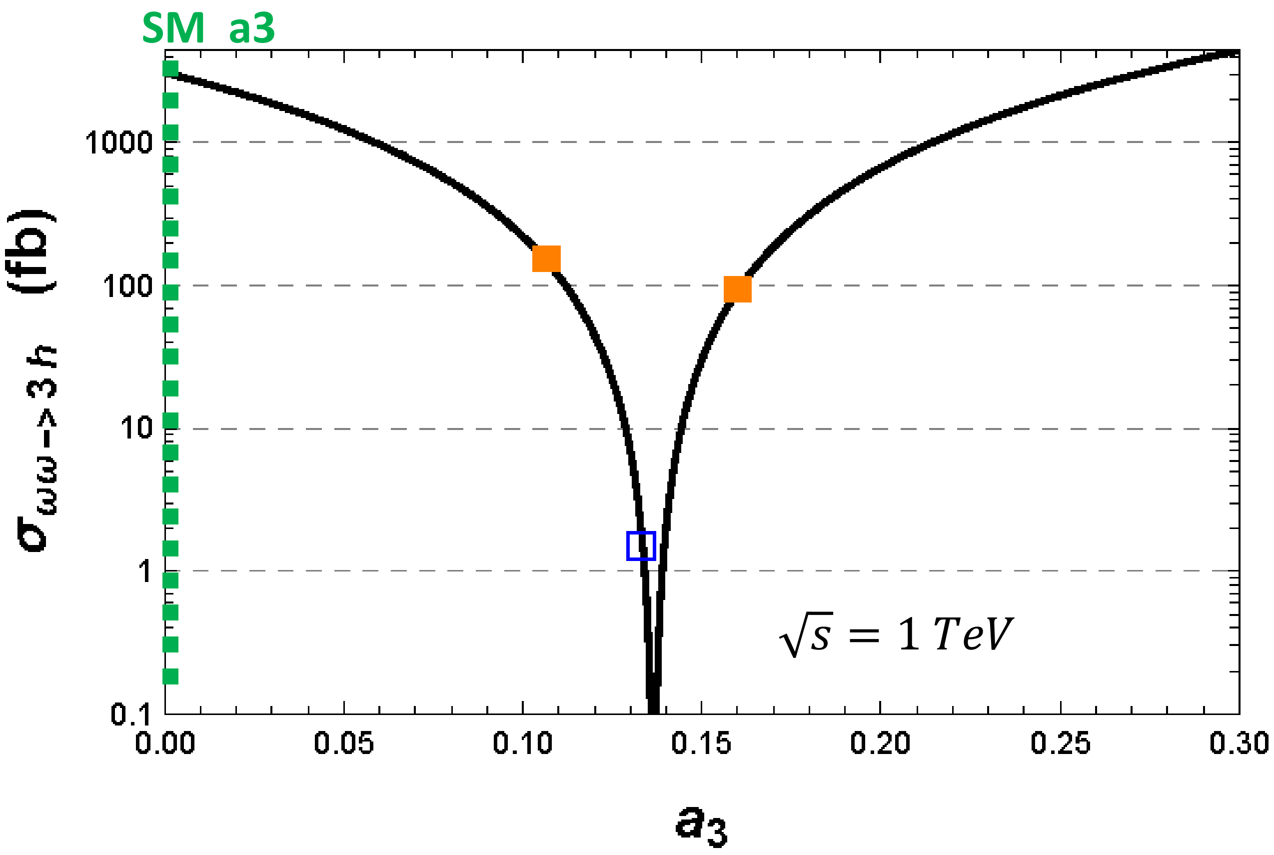
Scanning of the $\omega\omega \to 3h$ cross section predictions for $\sqrt{s} = 1$ TeV:

- Empty blue square - SMEFT$^{(D=6)}$ -BP $(d = 0.1)$:

$$a = a_1/2 = a^{SMEFT(D=6)} = 1.05, \qquad b = a_2 = a_2^{SMEFT\,(D=6)} = 1.2, \qquad a_3 = a_3^{SMEFT\,(D=6)} = 0.1\hat{3}$$

- Full Orange square - HEFT:

$$a = a_1/2 = a^{SMEFT(D=6)} = 1.05, \qquad b = a_2 = a_2^{SMEFT\,(D=6)} = 1.2, \qquad a_3 = a_3^{SMEFT\,(D=6)} \times (1 \;\pm \mathbf{20\%}\;)$$



- Analogous to previous $a_2 = b = \kappa_{2V}$ scannings for LHC and FCC analyses:

(x) Englert,Naskar,Sutherland, JHEP 11 (2023) 158

Conclusions

- **Compact structure for $W_L W_L \to n \times h$ scattering:**

  [Ruled by very particular combinations, $\hat{\kappa}_{2V} \equiv \hat{a}_2$ for $2h$, $\hat{a}_3$ for $3h$, etc.]

- **Field redefinitions helps us to understand this simplicity**

- **Strong multi-Higgs suppression in SMEFT** wrt to HEFT

  –Even for small O(10%) deviations in SMEFT $a_{1,2,3,4\ldots}$–

  –Much larger XS in pure HEFT–

BACKUP

- Various public code repositories created:

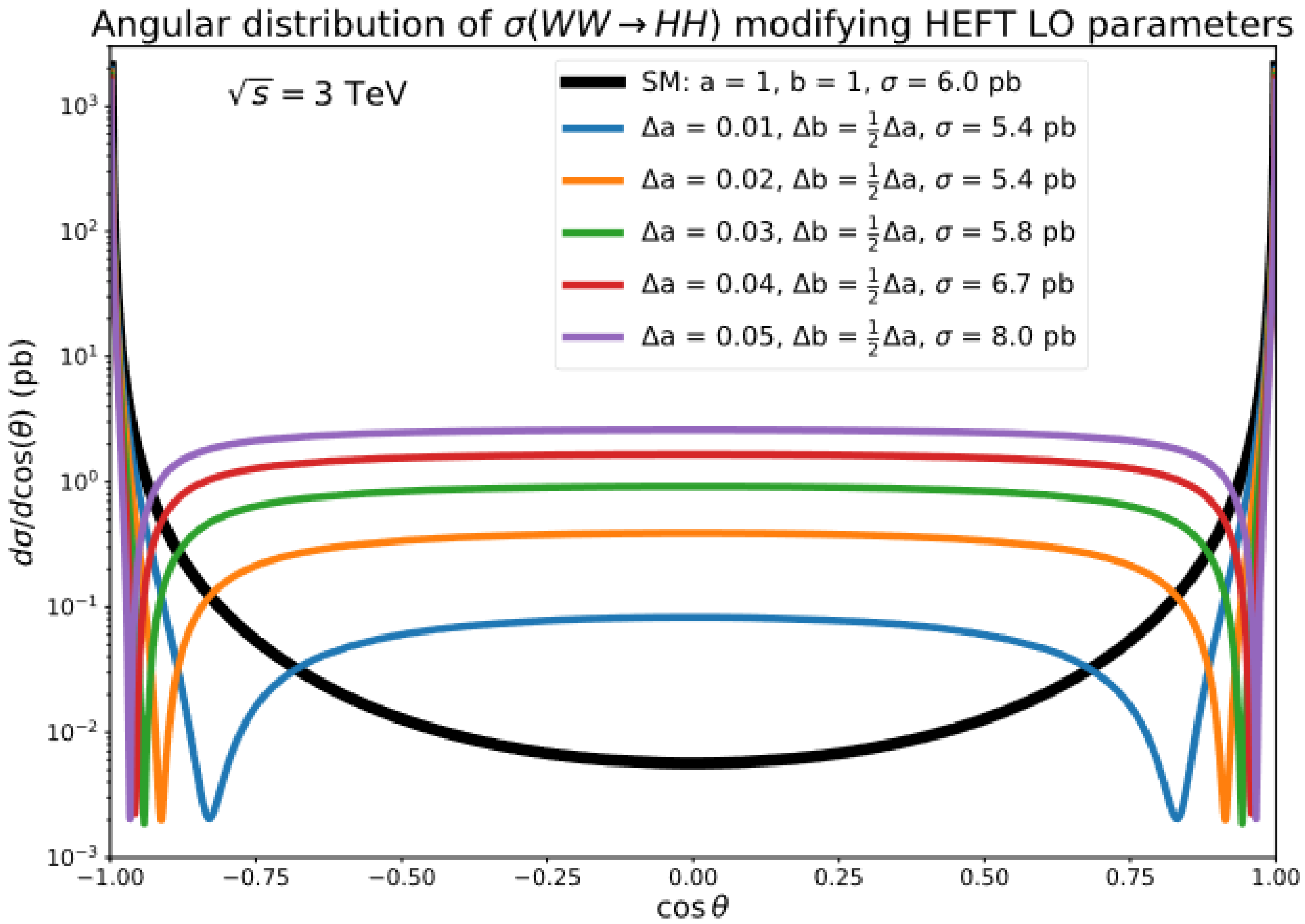
  - Specific Mathematica stand-alone code for $\omega\omega \to n \times h$

    https://github.com/alexandresalasb/WWtonHcalculator

  - General FeynRules model file https://github.com/Javomar99/EWET implementing $O(p^2)$ and $O(p^4)$ HEFT Lagrangian

  - New fast Massless Particle Phase-Space Integrator MaMuPaXS https://github.com/mamupaxs/mamupaxs

- **IR finite**
- Equiv. Theorem implies a **pure s-wave**
- This HEFT behaviour approximately observed with **real W's** (x) [vs **SM** angular distribution]



(x) Dávila,Domenech,Herrero,Morales, EPJC 84 (2024) 5, 503

Calculations have also been checked with:

Redefined HEFT Lagrangian

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h + \frac{1}{2}\hat{\mathcal{F}}(h)\,\partial_\mu \omega^a \partial^\mu \omega^a \; + \mathcal{O}(\omega^4)$$

Redefined Flare function[3]

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

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

[3] This redefinition gives a more direct interpretation

SMEFT: $\omega\omega \to 2h, 3h, 4h \ldots$ VERTEX suppression

- SMEFT⇔HEFT relations for the Higgs couplings:

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

[4] a_5 and a_6 can be found in the paper. a_n for $n \geq 7$ vanishes at order $1/\Lambda^4$.

$$
d = \frac{2v^2 c_{H\Box}^{(6)}}{\Lambda^2} \quad , \quad \rho = \frac{c_{H\Box}^{(8)}}{2(c_{H\Box}^{(6)})^2}
$$

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

SMEFT-like model. Benchmark points[7]

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

$$d = 0.1$$
$$a = a_1/2 = 1.05\,, \quad b = a_2 = 1.20$$
$$a_3 = 0.1\widehat{3}\,, \quad a_4 = 0.0\widehat{3}$$

$\mathrm{SMEFT}^{(D=8)}$ BP

$$d = 0.1\,, \quad \rho = 1$$
$$a = a_1/2 \approx 1.06\,, \quad b = a_2 = 1.26$$
$$a_3 = 0.22\,, \quad a_4 = 0.10$$

[7] d is compatible with the SM deviation range of ATLAS and CMS and crucial for the convergence. ρ is non relevant as long as it's order 1.

Non-SMEFT-like models[8]. Benchmark points

$\mathrm{BP1}^{(a_1)}$

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

$$a_2 = 2.205\,,\ a_3 \approx 1.54\,,\ a_4 \approx 0.81$$

$\mathrm{BP2}^{(a_1)}$

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

$$a_2 \approx 3.31\,,\ a_3 \approx 4.63\,,\ a_4 = 6.08$$

$\mathrm{BP1}^{(a_1,a_2)}$

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

$$a_3 \approx -0.57\,, \quad a_4 \approx -0.90$$

$\mathrm{BP2}^{(a_1,a_2)}$

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

$$a_3 \approx -2.01\,,\ a_4 \approx -4.53$$

---

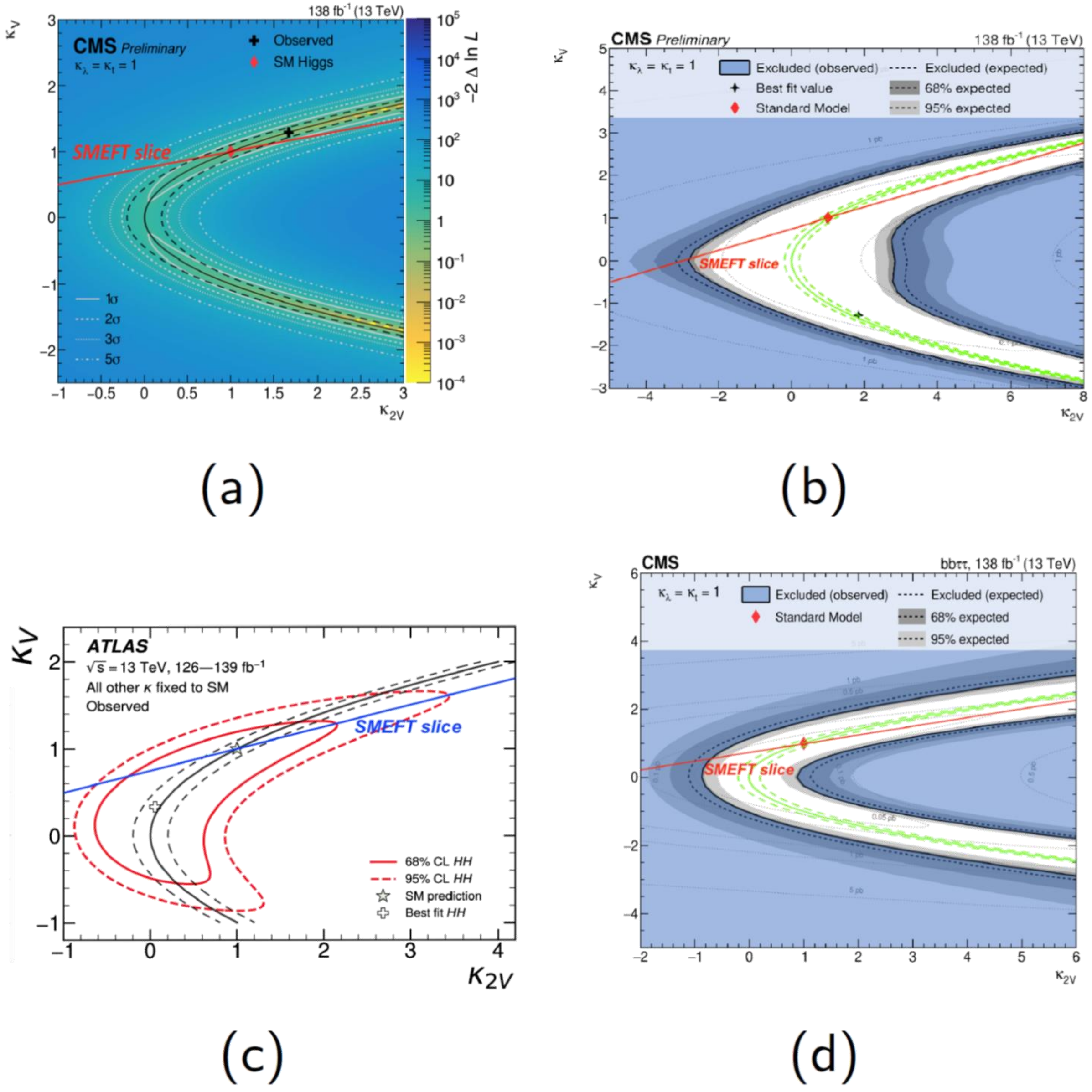
[8] This flare functions have no real zeros [Cohen et al. - 2008.08597, Manohar et al. 1605.03602] but fulfil the postivity requirements in Gómez-Ambrosio et al. - 2204.01763

ATLAS and CMS analyses on multi-Higgs:
Where are we standing?

- Uncertainty in $\boldsymbol{k_V} = a = a_1/2$ $(h \to \omega\omega$ vertex): O(10%)

- Uncertainty in $\boldsymbol{k_{2V}} = b = a_2$ $(hh \to \omega\omega$ vertex): **O(100%)**

- **BUT,** in the relevant $\omega\omega \to hh$ amp. combination $\widehat{\boldsymbol{k}}_{\boldsymbol{2V}} = \hat{a}_2$: O(10%)



... + some recente important improvement from HH + H:

CMS PAS HIG-23-006

- Exp. data on hh-production at LHC show an important correlation between (a, b)

[notation: $a = a_1/2 = \kappa_V,\ \ b = a_2 = \kappa_{2V}$]

- NOTE we have superimposed:

  - Parabolles w/ constant $\hat{a}_2 = a_2 - \frac{a_1^2}{4}$

  - D=6 SMEFT prediction $a_2 = 2\,a_1 - 3$

(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]. NOTE: $\kappa_V = a_1/2$, $\kappa_{2V} = a_2$.

(a)

$$a_2 = 2a_1 - 3$$

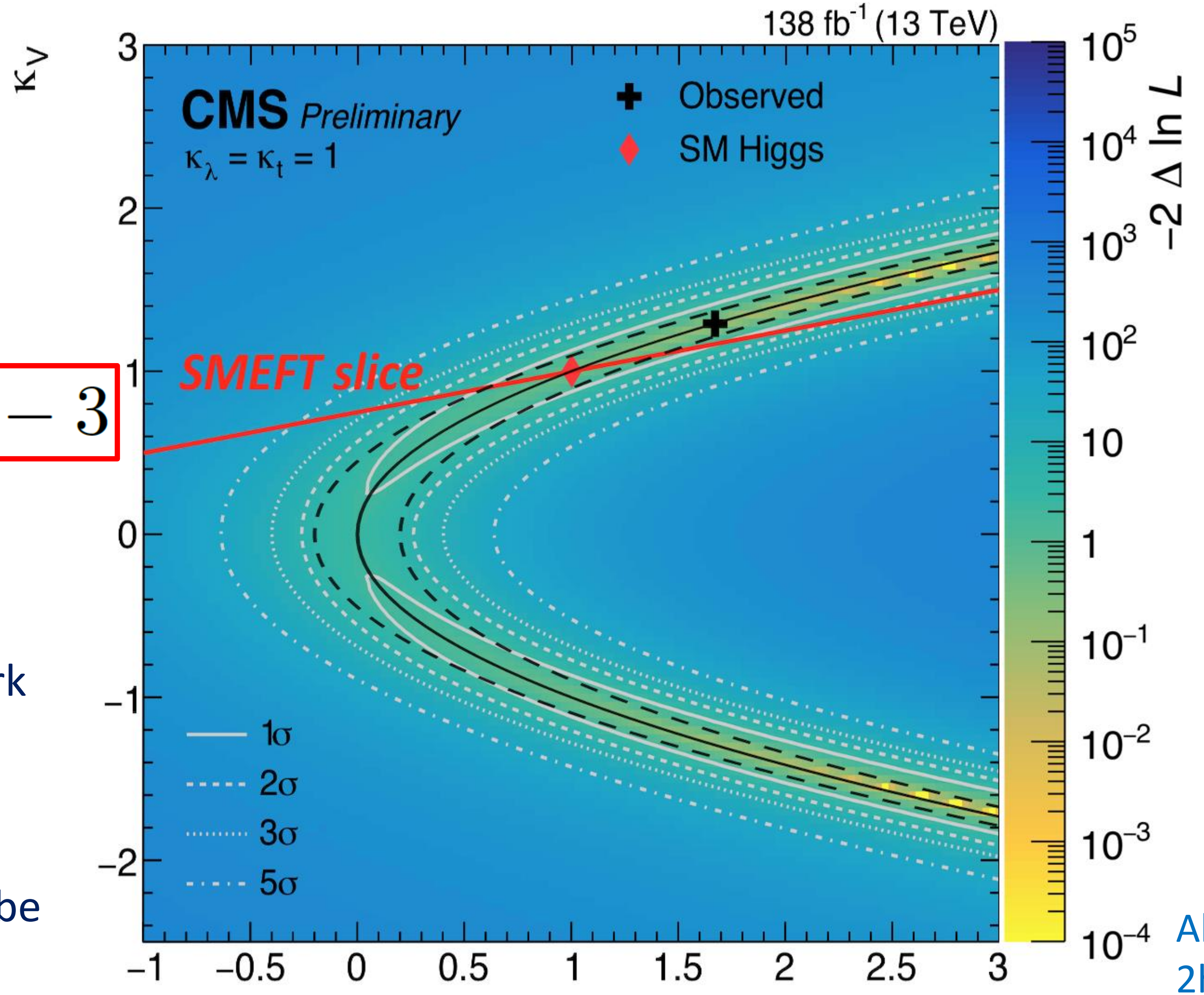


Figure 2. a) CMS experimental confidence regions for the hWW coupling $\kappa_V = a = a_1/2$ and for the $hhWW$ coupling $\kappa_{2V} = b = a_2$, from a non-resonant hh production search with each Higgs boson decaying into a highly boosted $b\bar{b}$ pair [77] (white lines and colour map in figure 11 from the additional material in CMS-B2G-22-003). b) CMS confidence regions from processes with one Higgs boson

$$\hat{a}_2 = \pm 0.2$$

The equivalence theorem approximations in this work seem to be in agreement with hh-production data

Indications that we might be O(10%) close to the SM in (a, b)

Also previous theoretical 2h-production for LHC* noted important correlations between (κ_V, κ_{2V})

["banana" plots, as M.J. Herrero calls them]

(a) Phys. Rev. Lett. 131 (2023) 041803 [2205.06667]

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

* Anisha, Atkinson, Bhardwaj, Englert, Stylianou, JHEP 10 (2022) 172

- We will actually compute the Goldstone-Goldstone scattering,

$$T_{\omega\omega\to n\times h}$$

and extract the corresponding cross section:

$$\sigma_{\omega\omega\to n\times h} = \frac{1}{n!}\frac{1}{2s}\int \left|T_{\omega\omega\to n\times h}\right|^2 d\Pi_n$$

$$\omega^+(k_1)\,\omega^-(k_2) \;\to\; h(p_1)\,h(p_2)\,h(p_3)\,h(p_4)$$

$$B = f_1 f_2 f_3 f_4 \left(\mathcal{B}_{1234} + \mathcal{B}_{1324} + \mathcal{B}_{1423} + \mathcal{B}_{2314} + \mathcal{B}_{2413} + \mathcal{B}_{3412} \right)$$

$$\mathcal{B}_{ijk\ell} = \frac{z_{ij} z_{k\ell}}{2 f_i f_j z_{ij} - f_i z_i - f_j z_j}$$

where $f_i = qp_i/q^2$, $z_i = 2k_1 p_i/qp_i$, $z_{ij} = z_{ji} = q^2\,(p_i p_j)/[(qp_i)\,(qp_j)]$

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

(CM)

$$f_i = \|\vec{p}_i\|/\sqrt{s} \;\; (s = 4\|\vec{k}_1\|^2)$$

$$z_i \; = \; 2\sin^2(\theta_i/2)$$

$$z_{ij} = 2\sin^2(\theta_{ij}/2)$$

$$\sigma_{\omega\omega\to 4h} = \frac{8\pi^3}{9s}\left(\frac{s}{16\pi^2 v^2}\right)^4 \left[\left(3\hat{a}_4 - \hat{a}_2^2\right)^2 + 2\left(3\hat{a}_4 - \hat{a}_2^2\right)\hat{a}_2^2\chi_1 + \hat{a}_2^4\chi_2\right]$$

$$\chi_n = \mathcal{V}_4^{-1}\int d\Pi_4\, B^n\,,$$

$$\mathcal{V}_4 = \int d\Pi_4 = s^2\left(24(4\pi)^5\right)^{-1}$$

$$\chi_1 = -0.124984\,(10)$$

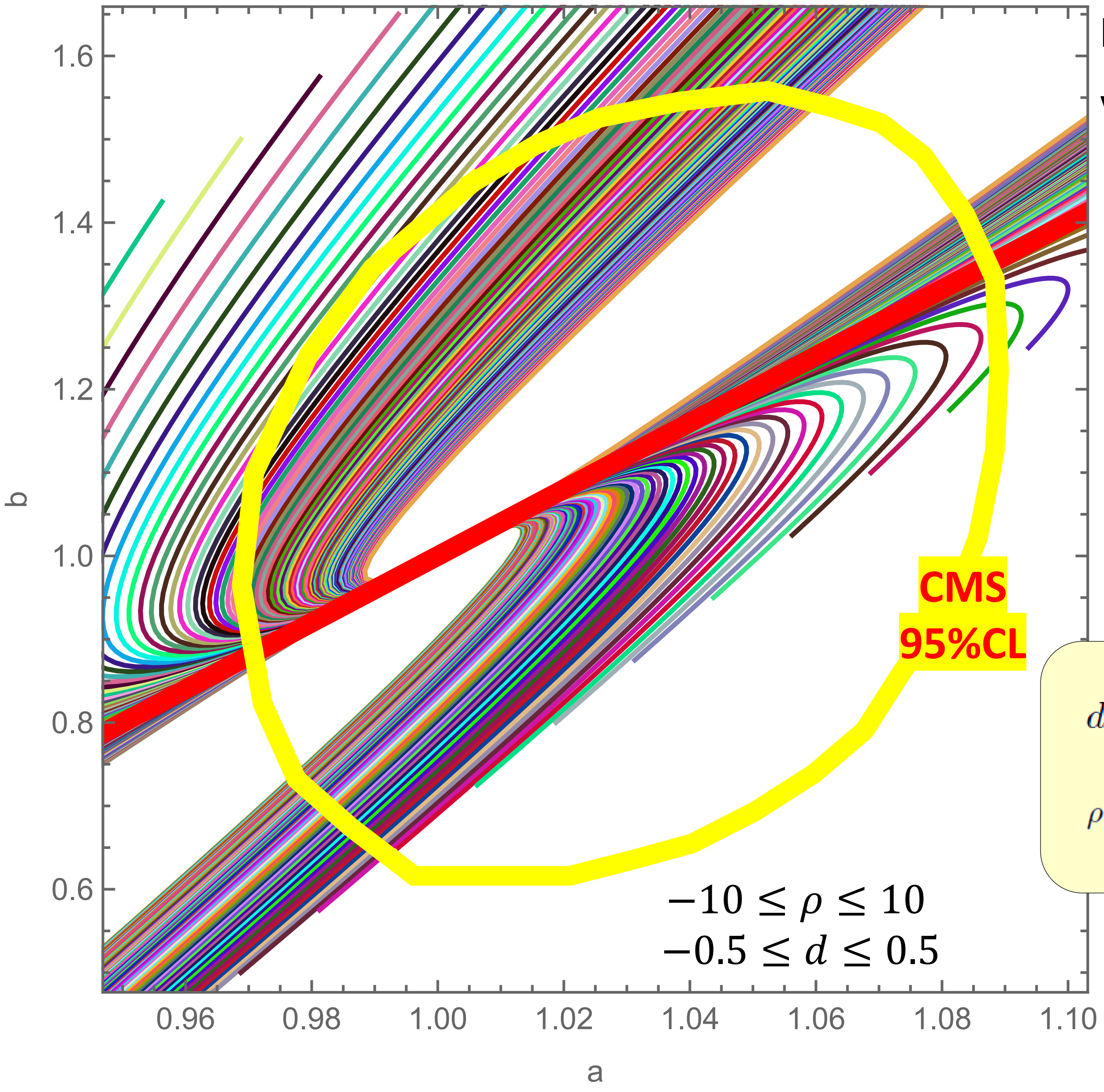
$$\chi_2 = 0.0193760\,(16)$$

our phase-space integration code (MaMuPaXS)

What about D=8 corrections to SMEFT? ➔ The line turns into a “thick line”/area

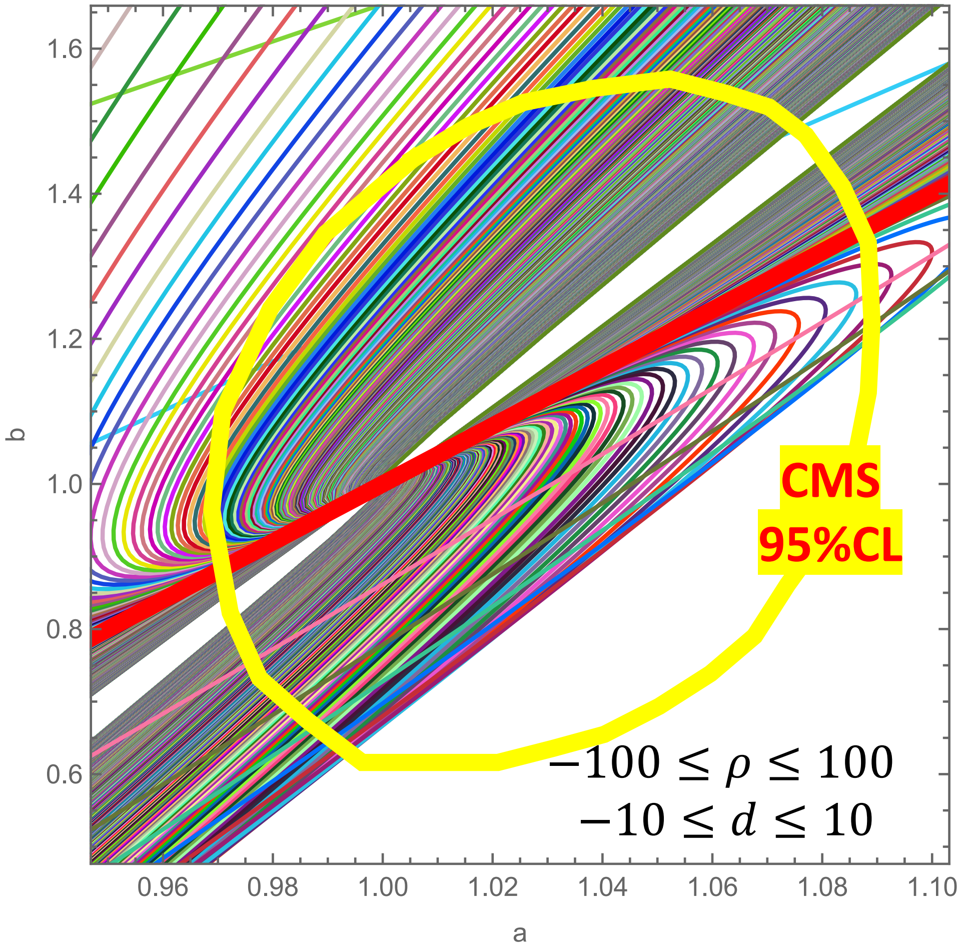
but still can’t go everywhere.

Volunteers can play with D=10 corrections



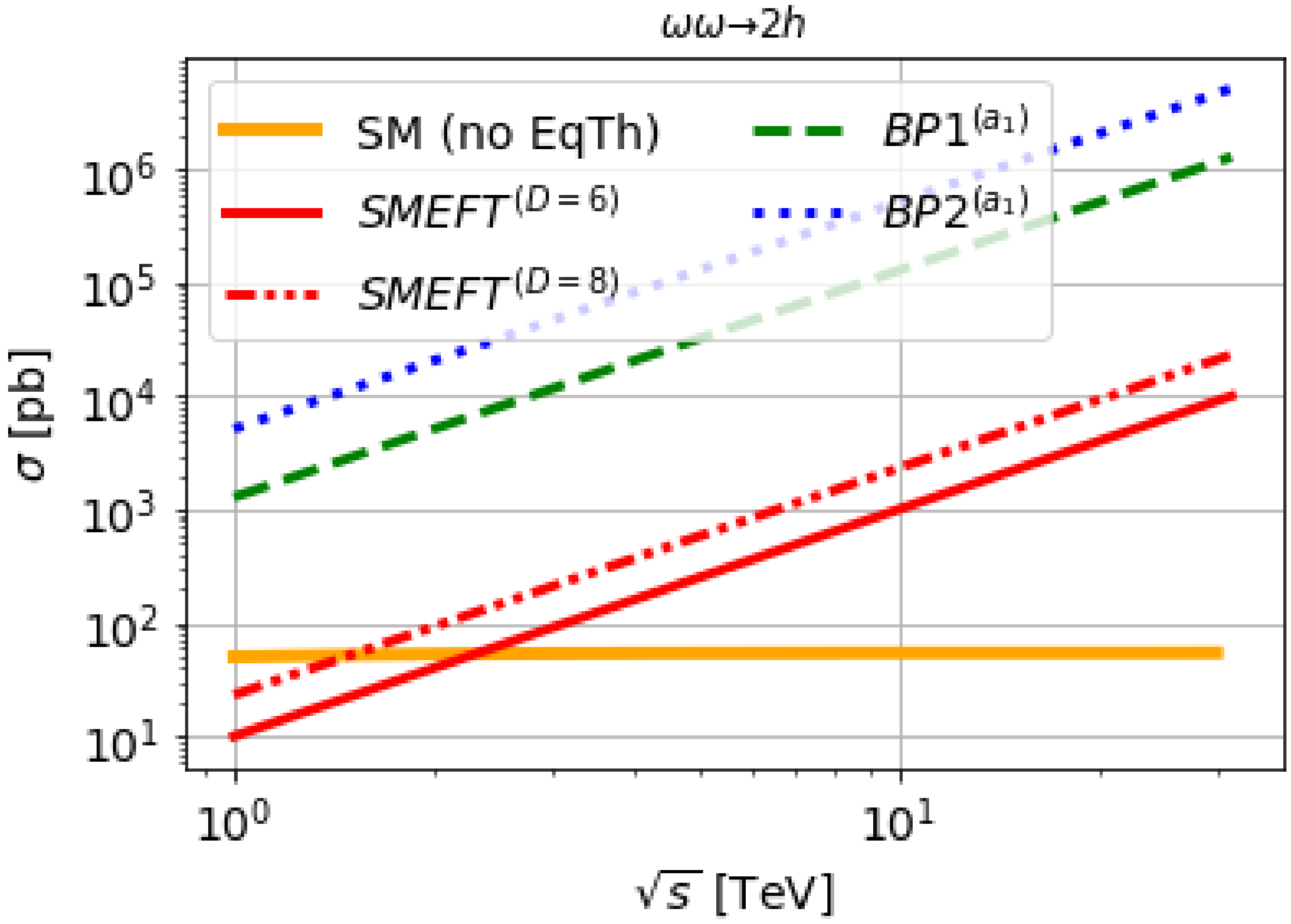
$$d = \frac{2v^2 c_{H\Box}^{(6)}}{\Lambda^2}$$

$$\rho = \frac{c_{H\Box}^{(8)}}{2\left(c_{H\Box}^{(6)}\right)^2}$$



BP study

2H



* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

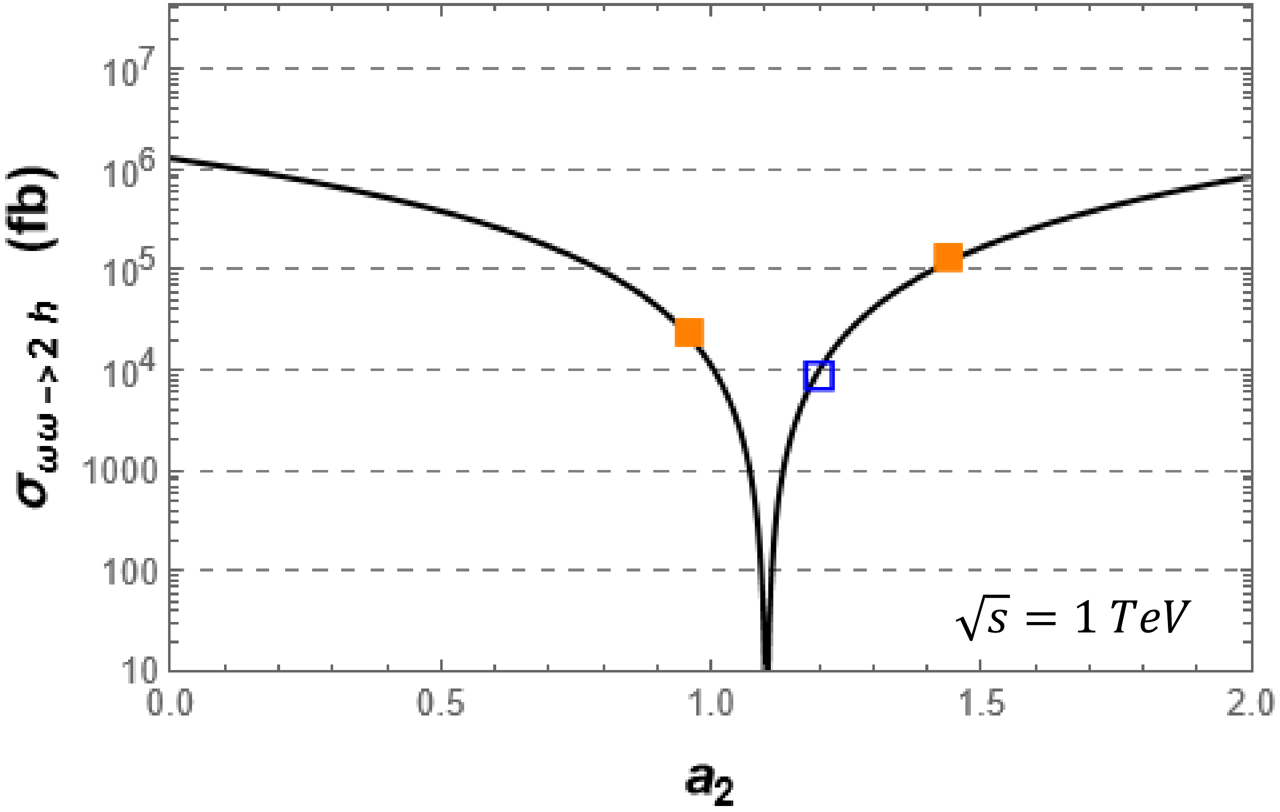
Scanning of the $\omega\omega \to 2h$ cross section predictions for $\sqrt{s} = 1$ TeV:

- Empty blue square - SMEFT$^{(D=6)}$ -BP $(d = 0.1)$:

$$a = a_1/2 = a^{SMEFT(D=6)} = 1.05, \qquad b = a_2 = a_2^{SMEFT\,(D=6)} = 1.2$$

- Full Orange square - HEFT:

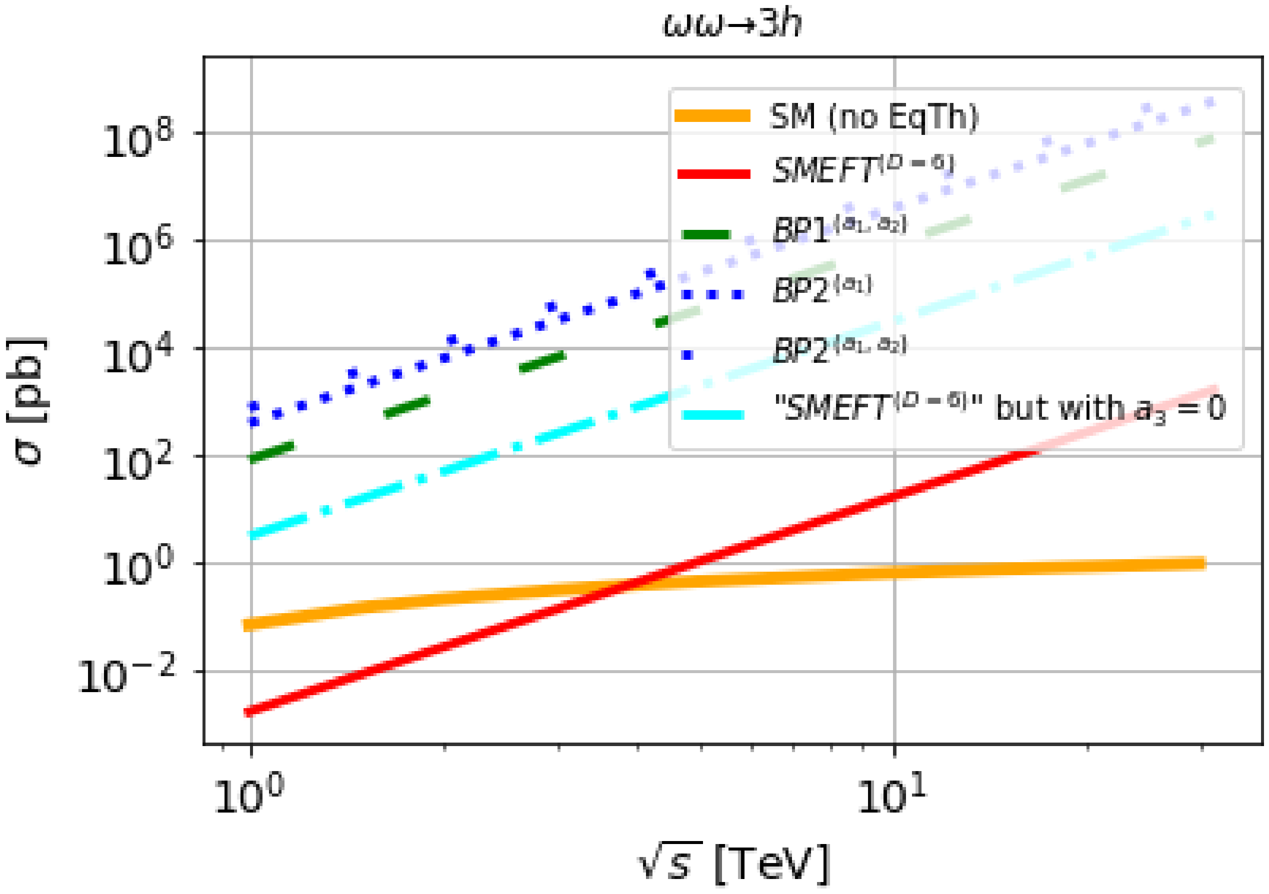
$$a = a_1/2 = a^{SMEFT(D=6)} = 1.05, \qquad b = a_2 = a_2^{SMEFT\,(D=6)} = 1.2 \times (1 \pm 20\%\ )$$

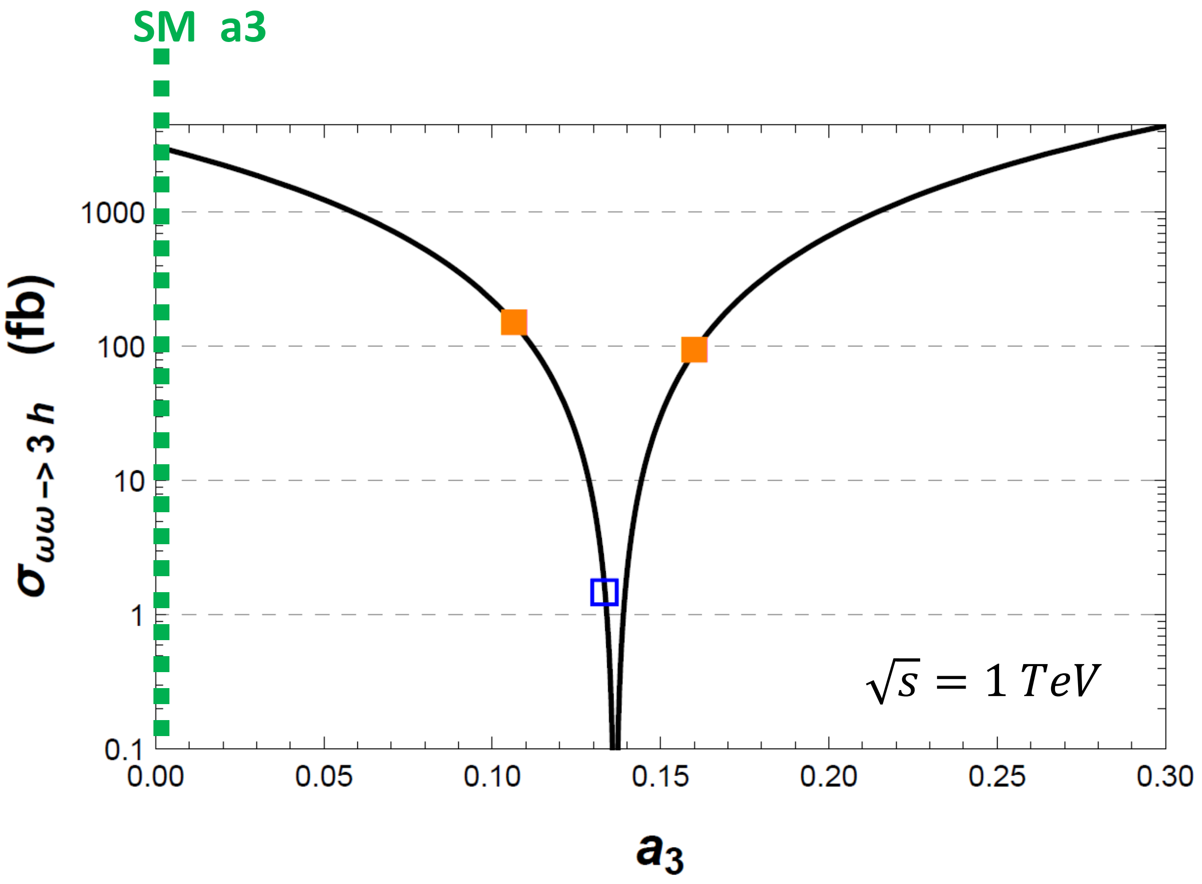


- Analogous to previous $a_2 = b = \kappa_{2V}$ scannings for LHC and FCC analyses:

(x) Englert,Naskar,Sutherland, JHEP 11 (2023) 158

BP study
3H





* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

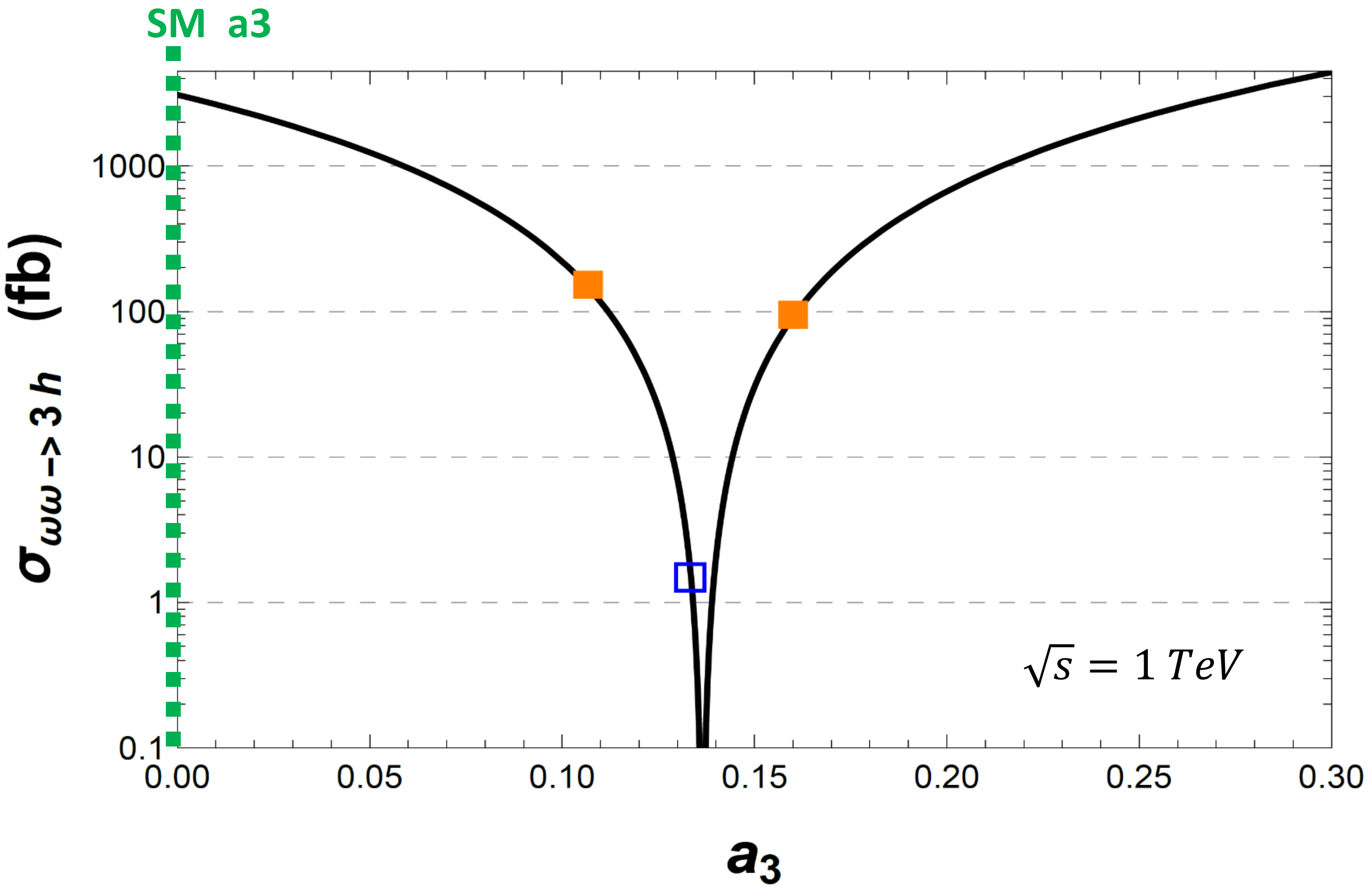
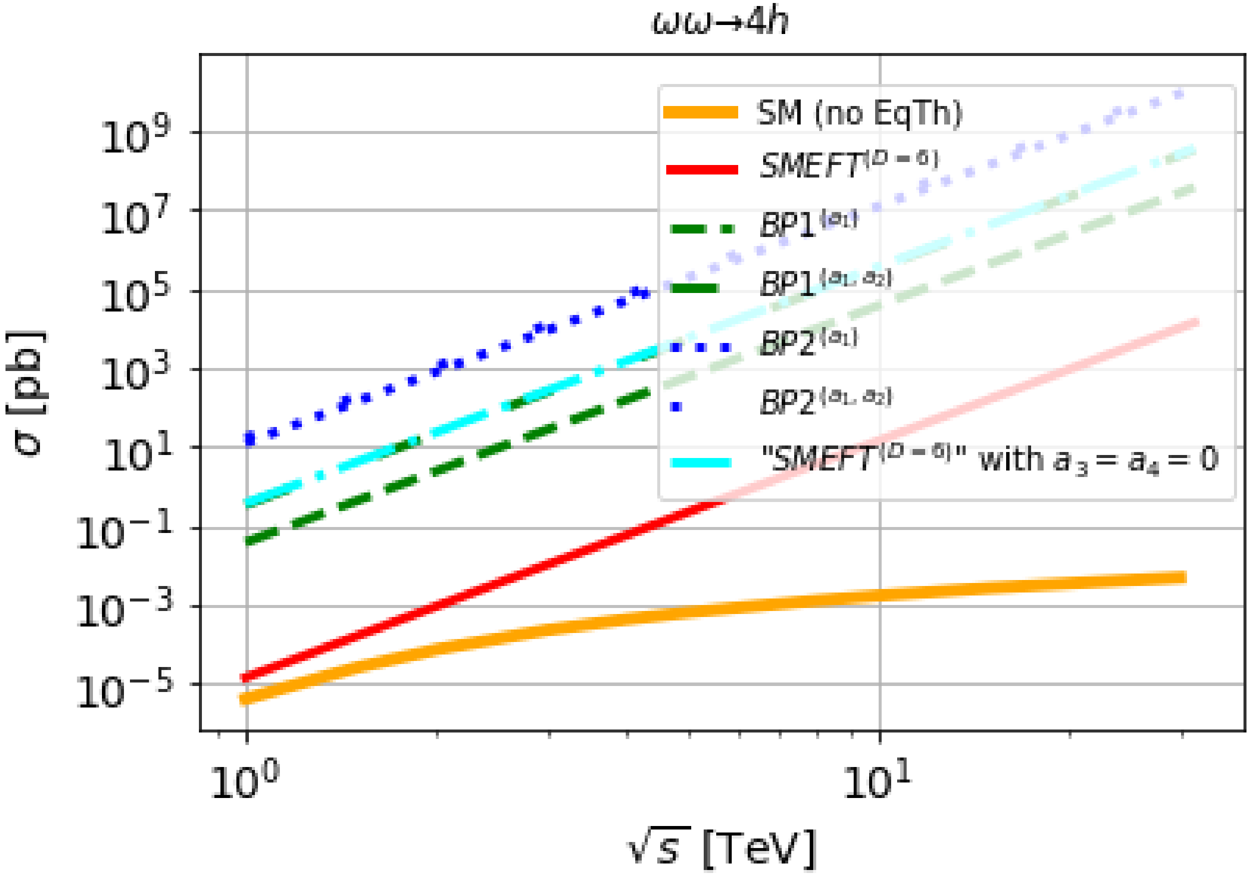


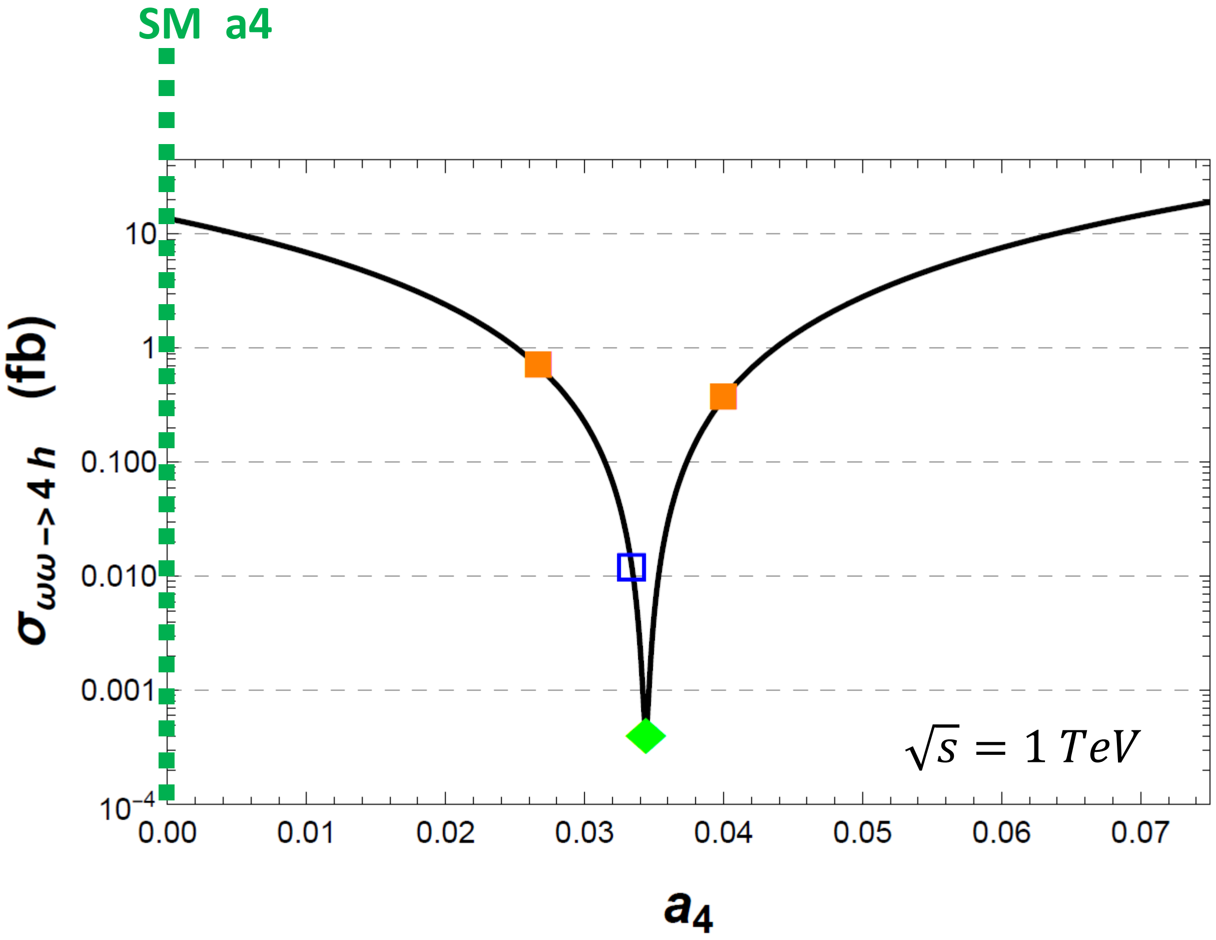
Figure 5. Scan of the $\omega\omega \to 3h$ cross section predictions in terms of a_3 at $\sqrt{s} = 1$ TeV. The inputs $a_1 = a_1^{\rm SMEFT(D=6)} = 2.1$ and $a_2 = a_2^{\rm SMEFT(D=6)} = 1.2$ are taken from (4.2), the SMEFT$^{\rm (D=6)}$ BP. We have marked a few especial points: $a_3 = a_3^{\rm SMEFT(D=6)} = 0.1\widehat{3}$ (empty blue square) and their 20% deviations (full orange squares), $a_3 = 80\% \times a_3^{\rm SMEFT(D=6)}$ and $a_3 = 120\% \times a_3^{\rm SMEFT(D=6)}$. We note that, in between, $\sigma_{\omega\omega\to 3h}$ vanishes at $a_3 = \frac{2}{3}a_1\left(a_2 - \frac{1}{4}a_1^2\right) = 0.1365$.

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

BP study

4H





* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

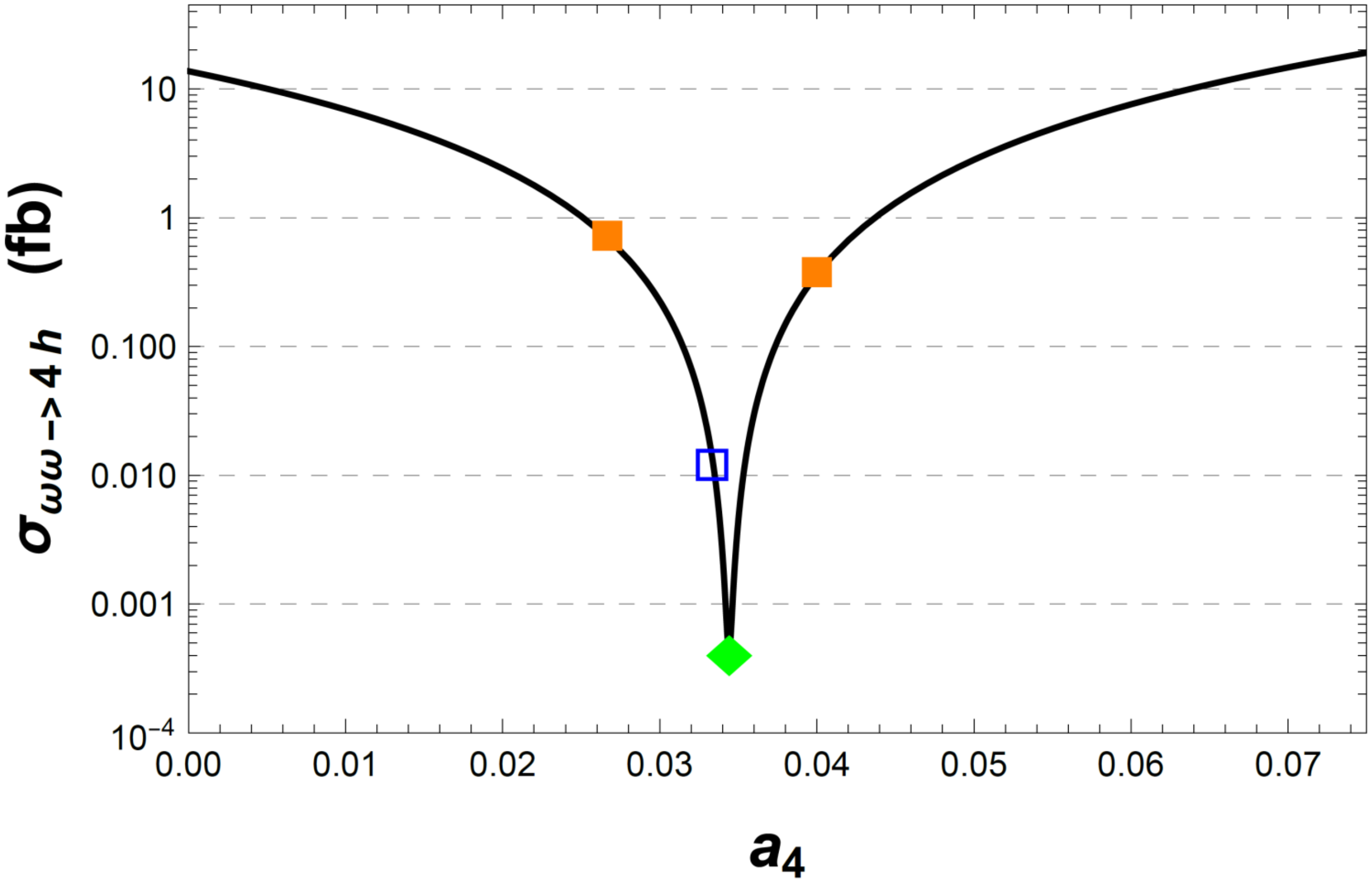
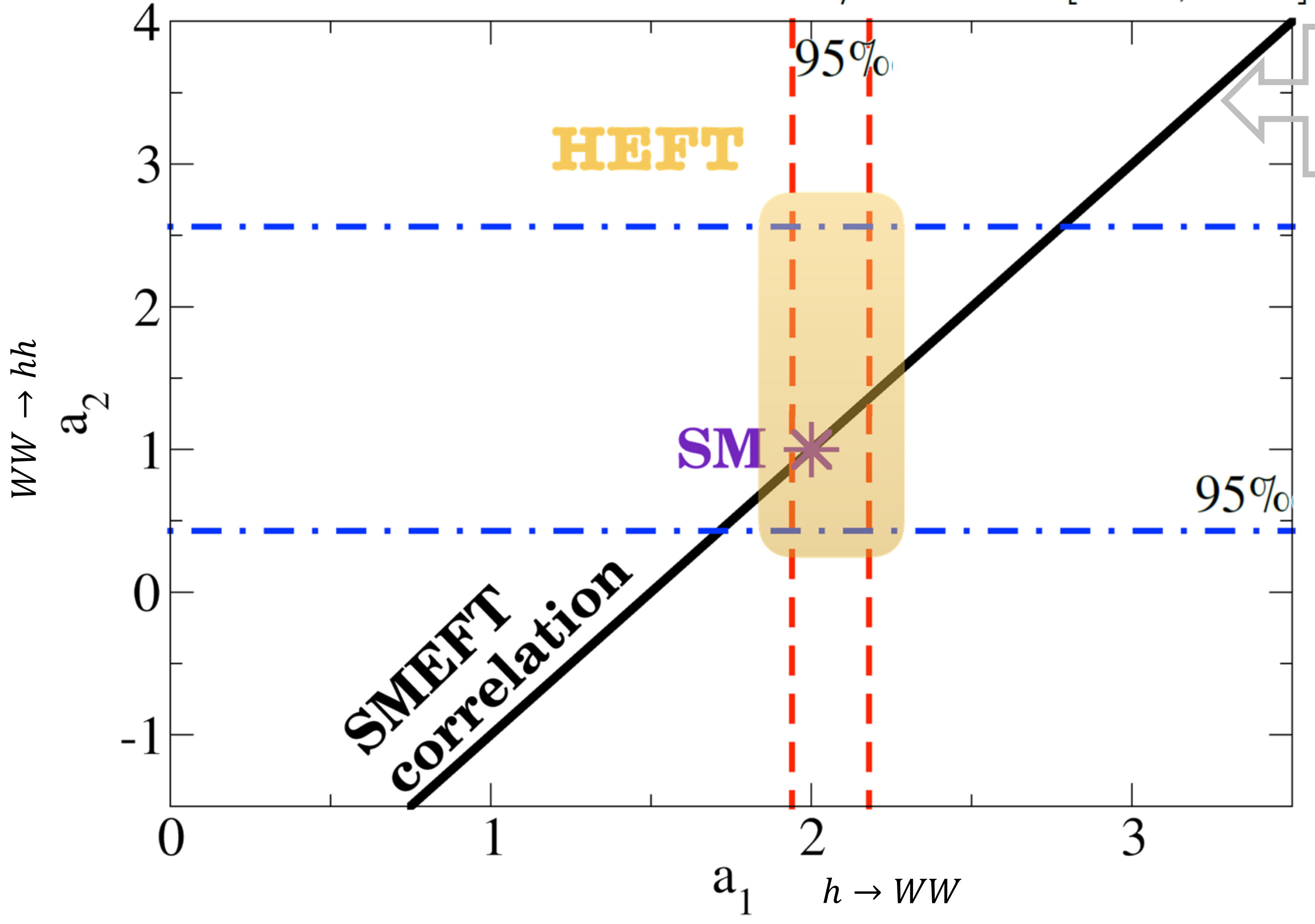


Figure 7. Scanning of the $\omega\omega \to 4h$ cross section predictions in terms of a_4 at $\sqrt{s} = 1$ TeV. The inputs $a_1 = a_1^{\text{SMEFT(D=6)}} = 2.1$, $a_2 = a_2^{\text{SMEFT(D=6)}} = 1.2$ and $a_3 = a_3^{\text{SMEFT(D=6)}} = 0.1\widehat{3}$ are taken from (4.2), the SMEFT$^{\text{(D=6)}}$ BP. We have marked a few especial points: $a_4 = a_4^{\text{SMEFT(D=6)}} = 0.0\widehat{3}$ (empty blue square) and their 20% deviations (full orange squares), $a_4 = 80\% \times a_4^{\text{SMEFT(D=6)}}$ and $a_4 = 120\% \times a_4^{\text{SMEFT(D=6)}}$. The cross section's minimum is not zero this time and it is found at $a_4 = \frac{3}{4}a_1a_3 - \frac{5}{12}a_1^2\hat{a}_2 + \frac{1}{3}\hat{a}_2^2(1-\chi_1) \approx 0.0344$ (filled green diamond).

ATLAS-CONF-2020-027 $a_1/2 = a \in [0.97, 1.09]$



SMEFT at order $1/\Lambda^2$ predicts correlation $a_2 = 2a_1 - 3$

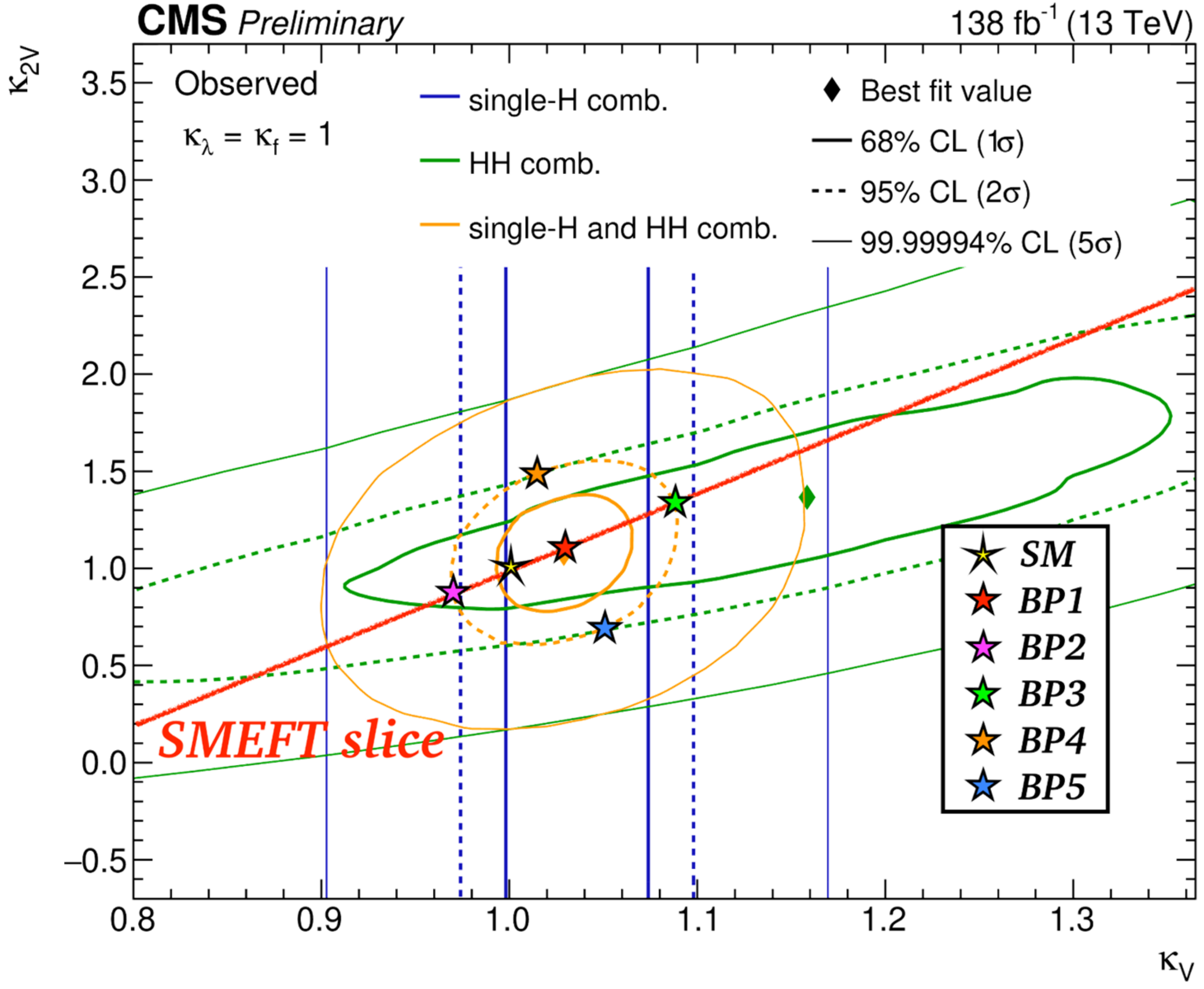
$a_2 = b = \kappa_{2V} \in [-0.1, 2.2]$

CMS-HIG-20-005

Blue and red: best available exp. bounds

(*) Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC, PRD 106 (2022) 5, 5; arXiv: 2207.09848 [hep-ph]

CMS PAS HIG-23-006



Correlations accurate at order Λ^{-2}	Correlations accurate at order Λ^{-4}	Λ^{-4} Assuming SMEFT perturbativity
$\Delta a_2 = 2\Delta a_1$		$\lvert\Delta a_2\rvert \leq 5\lvert\Delta a_1\rvert$
$a_3 = \frac{4}{3}\Delta a_1$	$\left(a_3 - \frac{4}{3}\Delta a_1\right) = \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}\left(\Delta a_1\right)^2$	
$a_4 = \frac{1}{3}\Delta a_1$	$\left(a_4 - \frac{1}{3}\Delta a_1\right) = \frac{5}{3}\Delta a_1 - 2\Delta a_2 + \frac{7}{4}a_3 = \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{7}{12}\left(\Delta a_1\right)^2$	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
$a_6 = 0$ SMEFT	$a_6 = \frac{1}{6}a_5$ SMEFT	SMEFT

$$\Delta a_1 := a_1 - 2 = 2a - 2$$
$$\Delta a_2 := a_2 - 1 = b - 1$$

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

(*) Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC, PRD 106 (2022) 5, 5; arXiv: 2207.09848 [hep-ph]

Consistent SMEFT range at order Λ^{-2}	Consistent SMEFT range at order Λ^{-4}	Perturbativity of Λ^{-4} SMEFT $\lvert\Delta a_2\rvert \leq 5\lvert\Delta a_1\rvert$
$\Delta a_2 \in [-0.12, 0.36]$ $a_3 \in [-0.08, 0.24]$ $a_4 \in [-0.02, 0.06]$ $a_5 = 0$ $a_6 = 0$	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 $a_3 \in [-3.1, 1.7]$ $a_4 \in [-3.3, 1.5]$ $a_5 \in [-1.5, 0.6]$ $a_6 = a_5$

$a_1/2 = a \in [0.97, 1.09]$ [67]

- ATLAS

$a_2 = b = \kappa_{2V} \in [-0.43, 2.56]$ [69]

- CMS

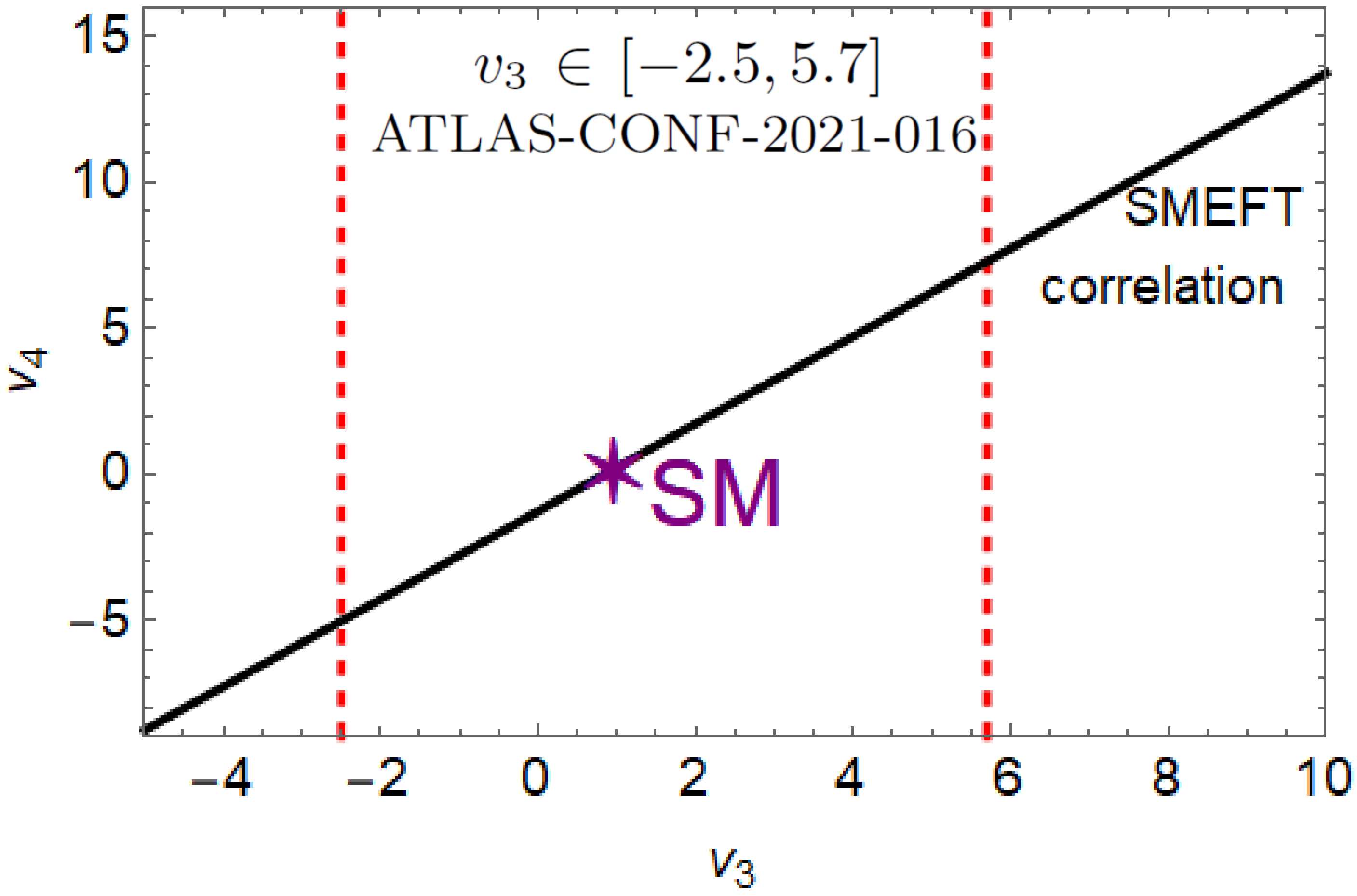
$a_2 = b = \kappa_{2V} \in [-0.1, 2.2]$ [68]

(*) Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC, 2204.01763 [hep-ph]

Other correlations: Higgs potential

$$V_{\rm HEFT} = \frac{m_h^2 v^2}{2}\left[\left(\frac{h_{\rm HEFT}}{v}\right)^2 + v_3\left(\frac{h_{\rm HEFT}}{v}\right)^3 + \right.$$
$$\left. + v_4\left(\frac{h_{\rm HEFT}}{v}\right)^4 + \dots\right],$$

with $v_3 = 1$, $v_4 = 1/4$ and $v_{n\geq 5} = 0$ in the SM



SMEFT	
$\Delta v_4 = \frac{3}{2}\Delta v_3 - \frac{1}{6}\Delta a_1$	$\Delta v_4 \in [-3.8, 8.6]$
$v_5 = 6v_6 = \frac{3}{4}\Delta v_3 - \frac{1}{8}\Delta a_1$	$v_5 = 6v_6 \in [-1.9, 4.3]$

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

(*) Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC, PRD 106 (2022) 5, 5; arXiv: 2207.09848 [hep-ph]

Correlations in the potential

HEFT correlations from the Custodial preserving SMEFT operators

$$\mathcal{O}_H := (H^\dagger H)^3 \,, \quad \mathcal{O}_{H\Box} := (H^\dagger H)\Box(H^\dagger H) \,.$$

$$v_3 = 1 + \frac{3v^2 c_{H\Box}}{\Lambda^2} + \frac{\mu^2 c_H}{\lambda^2\Lambda^2}\,, \quad v_4 = \frac{1}{4} + \frac{25 v^2 c_{H\Box}}{6\Lambda^2} + \frac{3}{2}\frac{\mu^2 c_H}{\lambda^2\Lambda^2}\,,$$

$$v_5 = \frac{2v^2 c_{H\Box}}{\Lambda^2} + \frac{3}{4}\frac{\mu^2 c_H}{\lambda^2\Lambda^2}\,, \quad v_6 = \frac{v^2 c_{H\Box}}{3\Lambda^2} + \frac{1}{8}\frac{\mu^2 c_H}{\lambda^2\Lambda^2}\,,$$

$$v_{n\geq 7} = 0\,,$$

with $m_h^2 = -2\mu^2 \left(1 + \frac{2c_{H\Box}v^2}{\Lambda^2} + \frac{3}{4}\frac{\mu^2 c_H}{\lambda^2\Lambda^2}\right)$,

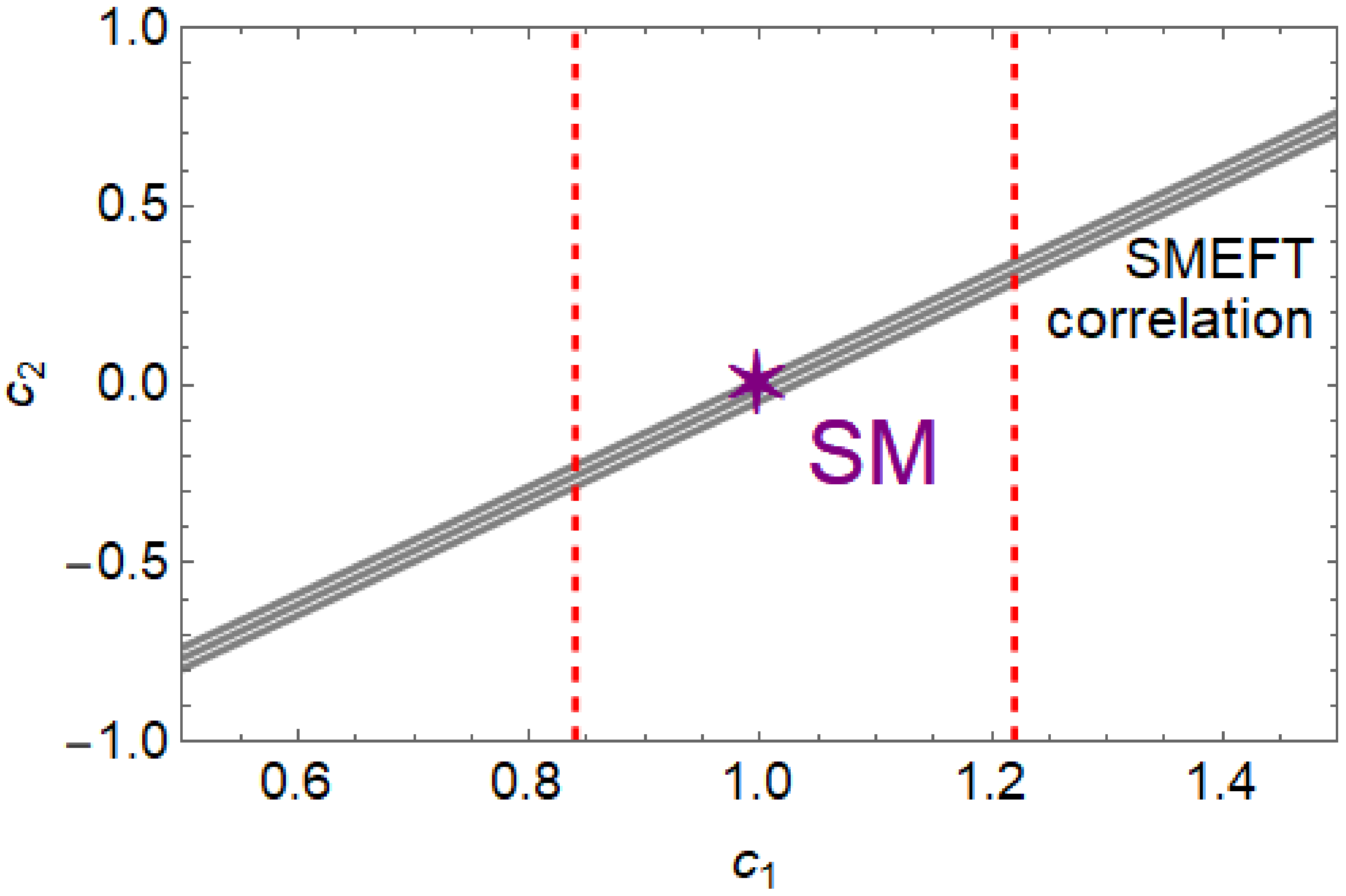
$$2\langle |H|^2\rangle = v^2 = -\frac{\mu^2}{\lambda}\left(1 - \frac{3}{4}\frac{\mu^2 c_H}{\lambda^2\Lambda^2}\right).$$

Other correlations: Yukawa's

$$\mathcal{L}_Y = -\mathcal{G}(h) M_t \bar{t} t \sqrt{1 - \frac{\omega^2}{v^2}} + \ldots$$

$$\mathcal{G}(h_{\rm HEFT}) = 1 + c_1 \frac{h_{\rm HEFT}}{v} + c_2 \left(\frac{h_{\rm HEFT}}{v}\right)^2 + \ldots$$

(with $c_1 = 1$, $c_{i\geq 2} = 0$ in the Standard Model)



SMEFT

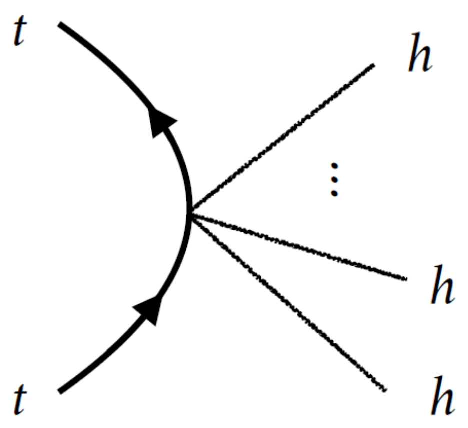
$$c_2 = 3c_3 = \frac{3}{2}(c_1 - 1) - \frac{1}{4}\Delta a_1 \quad \Rightarrow \quad c_2 = 3c_3 \in [-0.27, 0.35]$$

(*) Gómez-Ambrosio,Llanes-Estrada,Salas-Bernárdez,SC, PRD 106 (2022) 5, 5; arXiv: 2207.09848 [hep-ph]

Correlations in the top-Yukawa

The Yukawa Lagrangian in HEFT:

$$\mathcal{L}_Y = -\mathcal{G}(h) M_t \bar{t} t \sqrt{1 - \frac{\omega^2}{v^2}} \,,$$



with the function

$$\mathcal{G}(h_{\rm HEFT}) = 1 + c_1 \frac{h_{\rm HEFT}}{v} + c_2 \left(\frac{h_{\rm HEFT}}{v}\right)^2 + \ldots$$

(with $c_1 = 1$, $c_{i\geq 2} = 0$ in the Standard Model).

If SMEFT applies, $\mathcal{G}(h)$ must have only odd powers of $(h - h^*)$ around the symmetric point h^*), we obtain the correlations

$$c_2 = 3c_3 = \frac{3}{2}(c_1 - 1) - \frac{1}{4}\Delta a_1 \qquad c_2 = 3c_3 \in [-0.27, 0.35]$$

$c_1 \in [0.84, 1.22]$ J. de Blas et al., JHEP 07 (2018), 048

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.*

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

See 2204.01763

22

Low-energy EFT (SM + …): representations

- Higgs field representation: SMEFT vs HEFT, a matter of taste? (+)

1) Linear* (SMEFT): in terms of a doublet $\phi = (1+h/v)\, U(\omega^a) \langle\phi\rangle$

$$\mathcal{L}^{L}_{EFT} = (D_\mu\phi)^\dagger D_\mu\phi - \frac{1}{\Lambda^2}(\phi^\dagger\phi)\Box(\phi^\dagger\phi) + \ldots$$
$$= \frac{(v+h)^2}{4}\langle (D_\mu U)^\dagger D_\mu U\rangle + \frac{1}{2}(1+P(h))\,(\partial_\mu h)^2 + \ldots$$

$$\frac{dh^{NL}}{dh^{L}} = \sqrt{1+P(h^L)}$$

$$h^{NL} = \int_0^{h^L}\sqrt{1+P(h)}\,dh$$

? ? ?

$$\frac{v^2}{2}\mathcal{F}_C(h^{NL}) = \frac{(v+h^L)^2}{2} = \phi^\dagger\phi$$

if there exists an $SU(2)_L \times SU(2)_R$ fixed point $\mathcal{F}_C(h^*)=0$ (x)

$$\mathcal{L}^{NL}_{EFT} = \frac{v^2}{4}\mathcal{F}_c(h)\langle (D_\mu U)^\dagger D_\mu U\rangle + \frac{1}{2}(\partial_\mu h)^2 + \ldots$$

$$\mathcal{F}_C(h) = 1 + \frac{2ah}{v} + \frac{bh^2}{v^2} + \mathcal{O}(h^3)$$

2) Non-linear* (HEFT or EWχL): in terms of 1 singlet h + 3 NGB in $U(\omega^a)$

(+) SC, arXiv:1710.07611 [hep-ph]; PoS EPS-HEP2017 (2017) 460
* Jenkins,Manohar,Trott, JHEP 1310 (2013) 087
* LHCHXSWG Yellow Report [1610.07922]

(x) Transformations:
Giudice,Grojean,Pomarol,Rattazzi, JHEP 0706 (2007) 045
Alonso,Jenkins,Manohar, JHEP 1608 (2016) 101

SMEFT lagrangian

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

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

$\mathcal{O}_{H\Box}$ operator

$$\mathcal{O}_{H\Box}^{(6)} = (H^\dagger H)\Box(H^\dagger H)\,, \quad \mathcal{O}_{H\Box}^{(8)} = (H^\dagger H)^2\Box(H^\dagger H)\,, \quad \partial^2 \equiv \Box$$

SMEFT parameters

$$d = \frac{2v^2 c_{H\Box}^{(6)}}{\Lambda^2} \quad , \quad \rho = \frac{c_{H\Box}^{(8)}}{2(c_{H\Box}^{(6)})^2}$$

Exclusion plots

$$\sigma_{\omega\omega\to 2h} = \frac{8\pi^3}{s}\, d^2 \left(\frac{s}{16\pi^2 v^2}\right)^2 ,$$

$$\sigma_{\omega\omega\to 3h} = \frac{64\pi^3}{3s}\, d^4 (1+\rho)^2 \left(\frac{s}{16\pi^2 v^2}\right)^3 ,$$

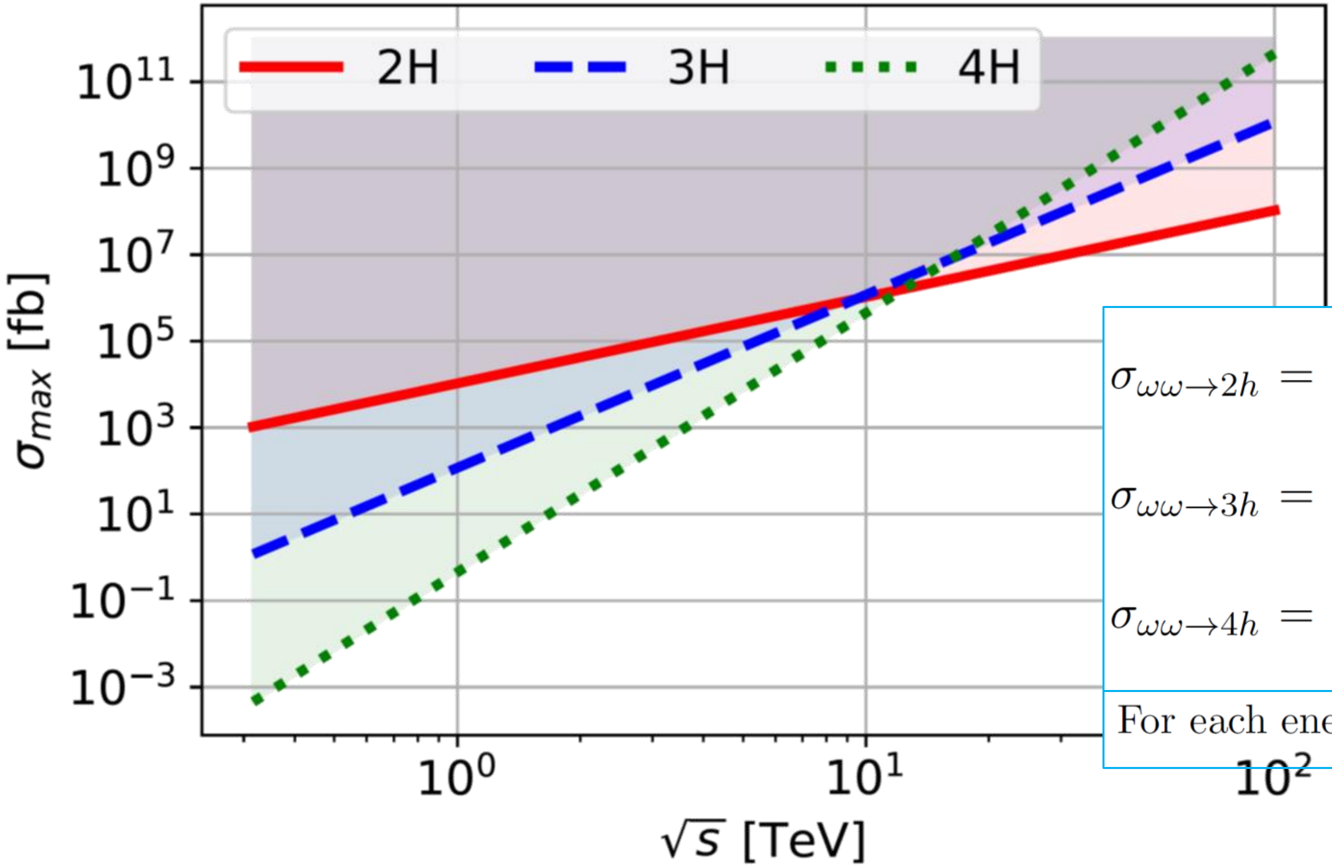
$$\sigma_{\omega\omega\to 4h} = \frac{8\pi^3}{9s} \left(\frac{s}{16\pi^2 v^2}\right)^4 d^4 \left[(1+\rho)^2 + 2(1+\rho)\chi_1 + \chi_2\right]$$

$$\sigma^{\max}_{\omega\omega\to hh} = \frac{8\pi^3}{s}\, d^2_{\max} \left(\frac{s}{16\pi^2 v^2}\right)^2 ,$$

$$\sigma^{\max}_{\omega\omega\to 3h} = \frac{64\pi^3}{3s}\, d^4_{\max} (1+\rho_{\max})^2 \left(\frac{s}{16\pi^2 v^2}\right)^3 ,$$

$$\sigma^{\max}_{\omega\omega\to 4h} = \frac{8\pi^3}{9s} \left(\frac{s}{16\pi^2 v^2}\right)^4 d^4_{\max} \left[(1+\rho_{\max})^2 + 2(1+\rho_{\max})\chi_1 + \chi_2\right]$$

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037



$$|d| \leq d_{\max} = 0.1\,, \qquad |\rho| \leq \rho_{\max} = 1$$

$$\sigma_{\omega\omega\to 2h} = \frac{8\pi^3}{s}\, d^2 \left(\frac{s}{16\pi^2 v^2}\right)^2 ,$$

$$\sigma_{\omega\omega\to 3h} = \frac{64\pi^3}{3s}\, d^4\, (1+\rho)^2 \left(\frac{s}{16\pi^2 v^2}\right)^3 ,$$

$$\sigma_{\omega\omega\to 4h} = \frac{8\pi^3}{9s} \left(\frac{s}{16\pi^2 v^2}\right)^4 d^4 \left[(1+\rho)^2 + 2(1+\rho)\chi_1 + \chi_2\right]$$

For each energy the cross section maxima are reached for $d = d_{\max}$

Figure 8. SMEFT exclusion plot for the cross sections for 2, 3 and 4 Higgs bosons with $|d| \leq d_{\max} = 0.1$ and $|\rho| \leq \rho_{\max} = 1$. The regions above the solid, dashed and dotted lines can be safely excluded if the Wilson coefficients are within the considered range. Notice that the EFT perturbativity condition is not considered in this figure, as the EFT expansion breaks down on the region past the crossing point.

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

- What if we require that, at a given energy, the couplings must always be small enough so the EFT power expansion is still convergent at that E_{CM} ?

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

$$\left|\frac{c^{(6)}_{H\Box}\, s}{\Lambda^2}\right| = \left|\frac{d\, s}{2v^2}\right| \leq \epsilon \ll 1$$

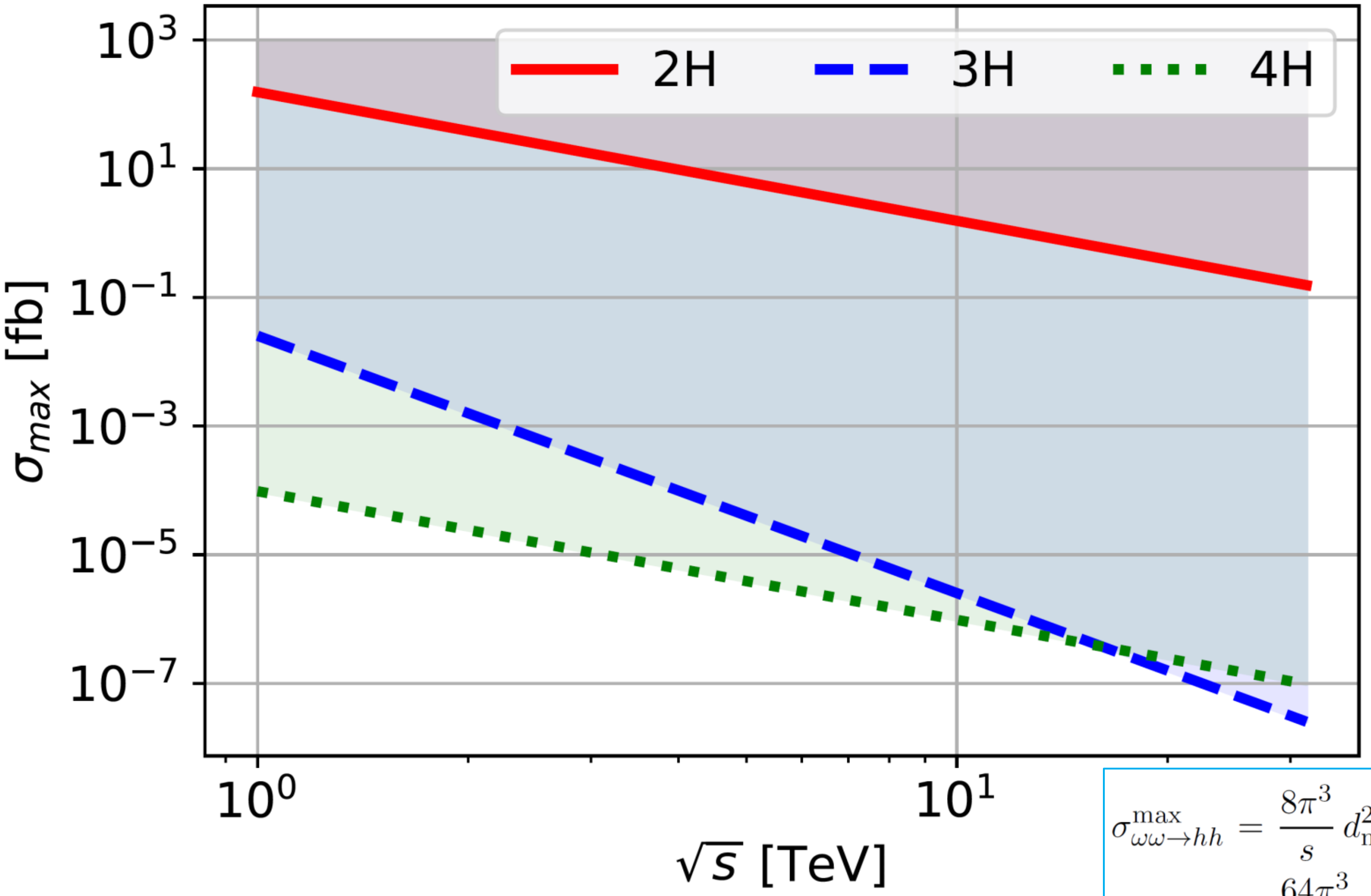
$$|d| \leq d_{\rm max}(s) = \frac{2v^2}{s}\,\epsilon$$

$$\sigma^{\rm EFT-max}_{\omega\omega\to hh} = \frac{\epsilon^2}{8\pi s}\,,$$

$$\sigma^{\rm EFT-max}_{\omega\omega\to 3h} = \left(\frac{v^2}{16\pi^2\, s}\right)\frac{4\epsilon^4}{3\pi s}\,(1+\rho_{\rm max})^2\,,$$

$$\sigma^{\rm EFT-max}_{\omega\omega\to 4h} = \left(\frac{1}{16\pi^2}\right)^2\frac{\epsilon^4}{18\pi s}\,((1+\rho_{\rm max})^2 + 2(1+\rho_{\rm max})\chi_1 + \chi_2)$$

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

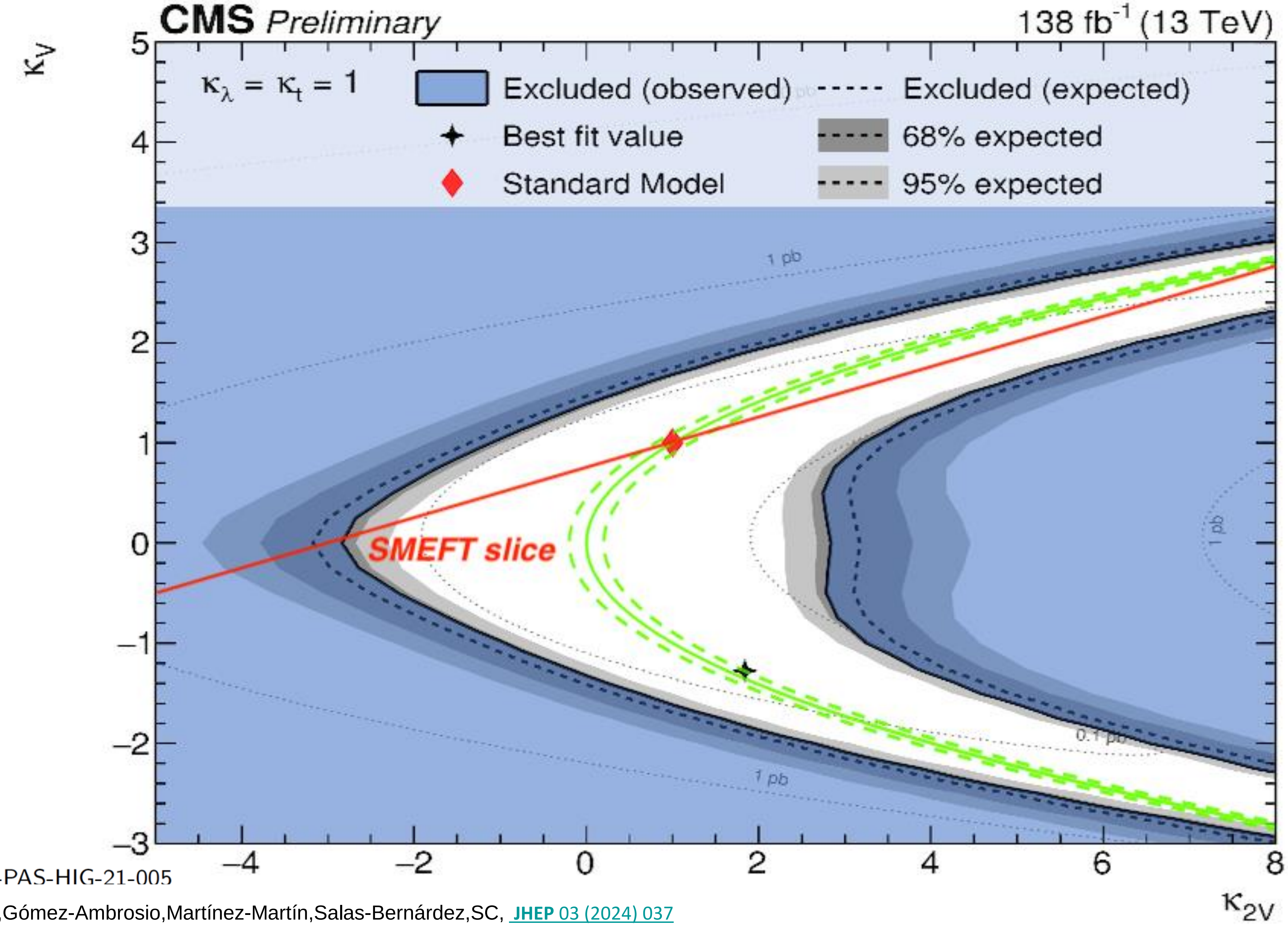


$$\sigma^{\rm max}_{\omega\omega\to hh} = \frac{8\pi^3}{s}\, d^2_{\rm max} \left(\frac{s}{16\pi^2 v^2}\right)^2 ,$$
$$\sigma^{\rm max}_{\omega\omega\to 3h} = \frac{64\pi^3}{3s}\, d^4_{\rm max}\,(1+\rho_{\rm max})^2 \left(\frac{s}{16\pi^2 v^2}\right)^3 ,$$
$$\sigma^{\rm max}_{\omega\omega\to 4h} = \frac{8\pi^3}{9s} \left(\frac{s}{16\pi^2 v^2}\right)^4 d^4_{\rm max} \left[(1+\rho_{\rm max})^2 + 2(1+\rho_{\rm max})\chi_1 + \chi_2\right]$$

Figure 9. Exclusion plot for the maximum value of the cross sections for 2, 3 and 4 Higgs bosons with the constraint $|\rho| \leq \rho_{\rm max} = 1$ and EFT-expansion tolerance $\epsilon = 0.1$.

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

(b)



(b) CMS-PAS-HIG-21-005

$$a_2 = 2a_1 - 3$$

$$\hat{a}_2 = \pm 0.2$$

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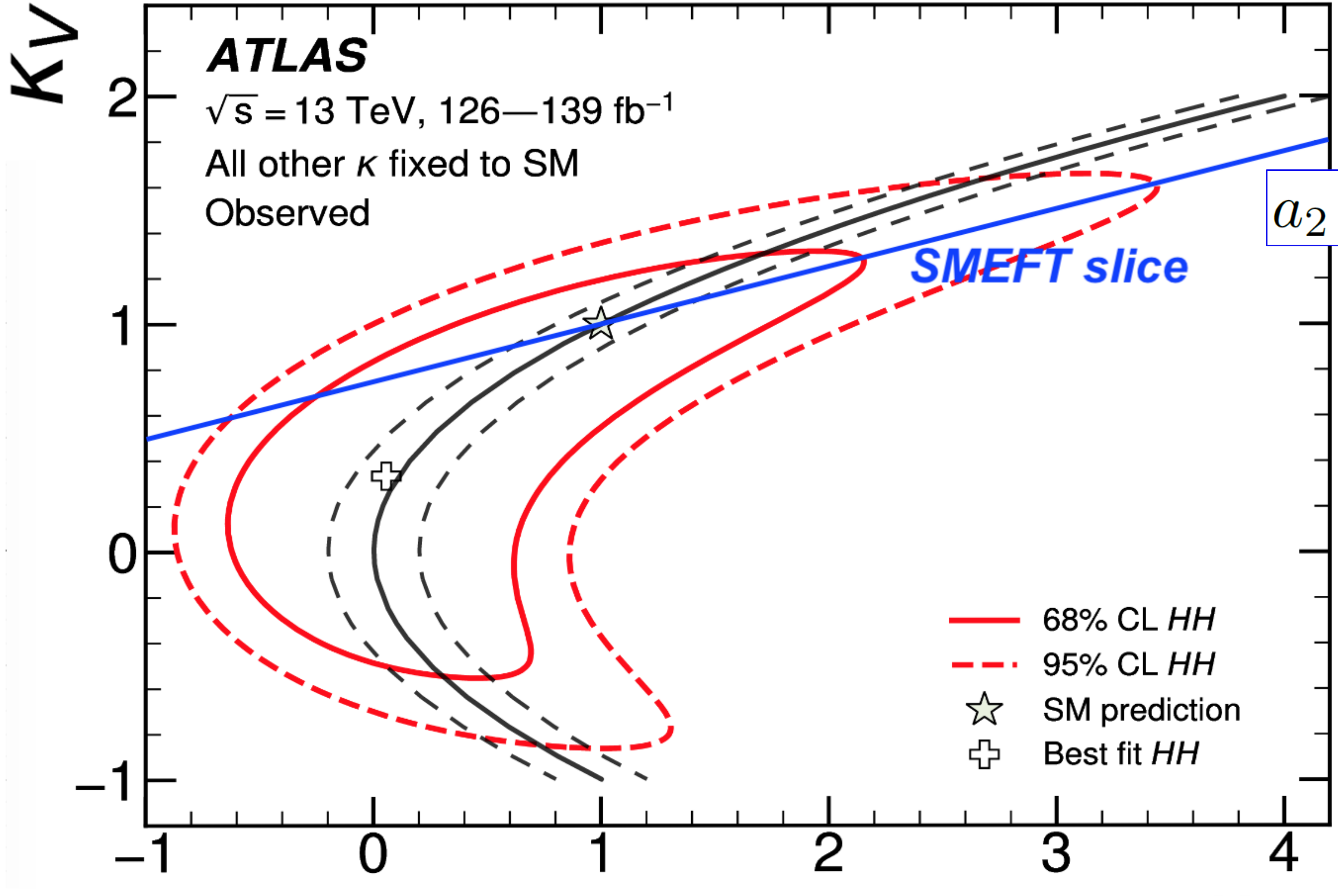
(c)



$$\hat{a}_2 = \pm 0.2$$

$$a_2 = 2a_1 - 3$$

(c) ATLAS-CONF-2022-050

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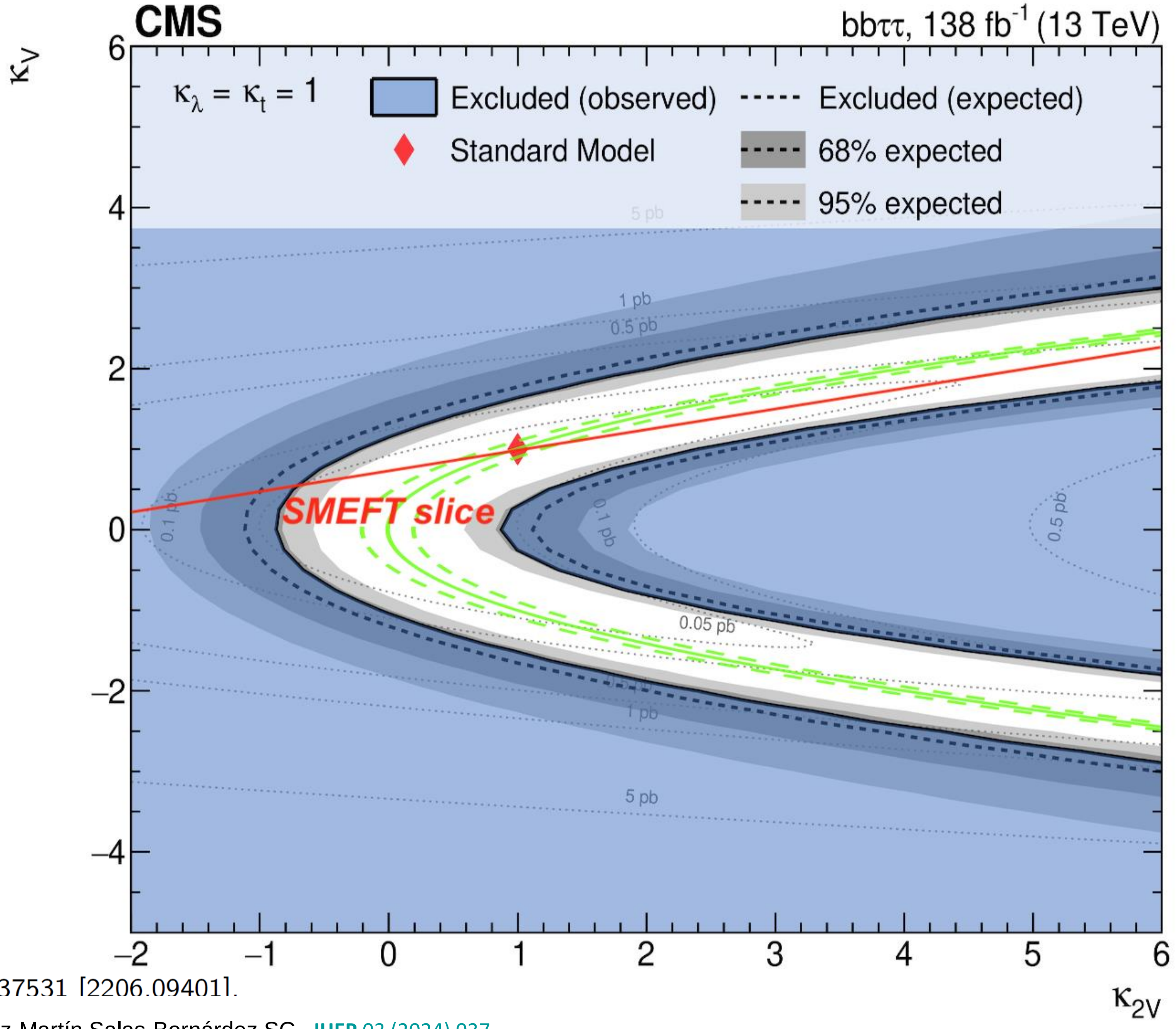
(d)



$$a_2 = 2a_1 - 3$$

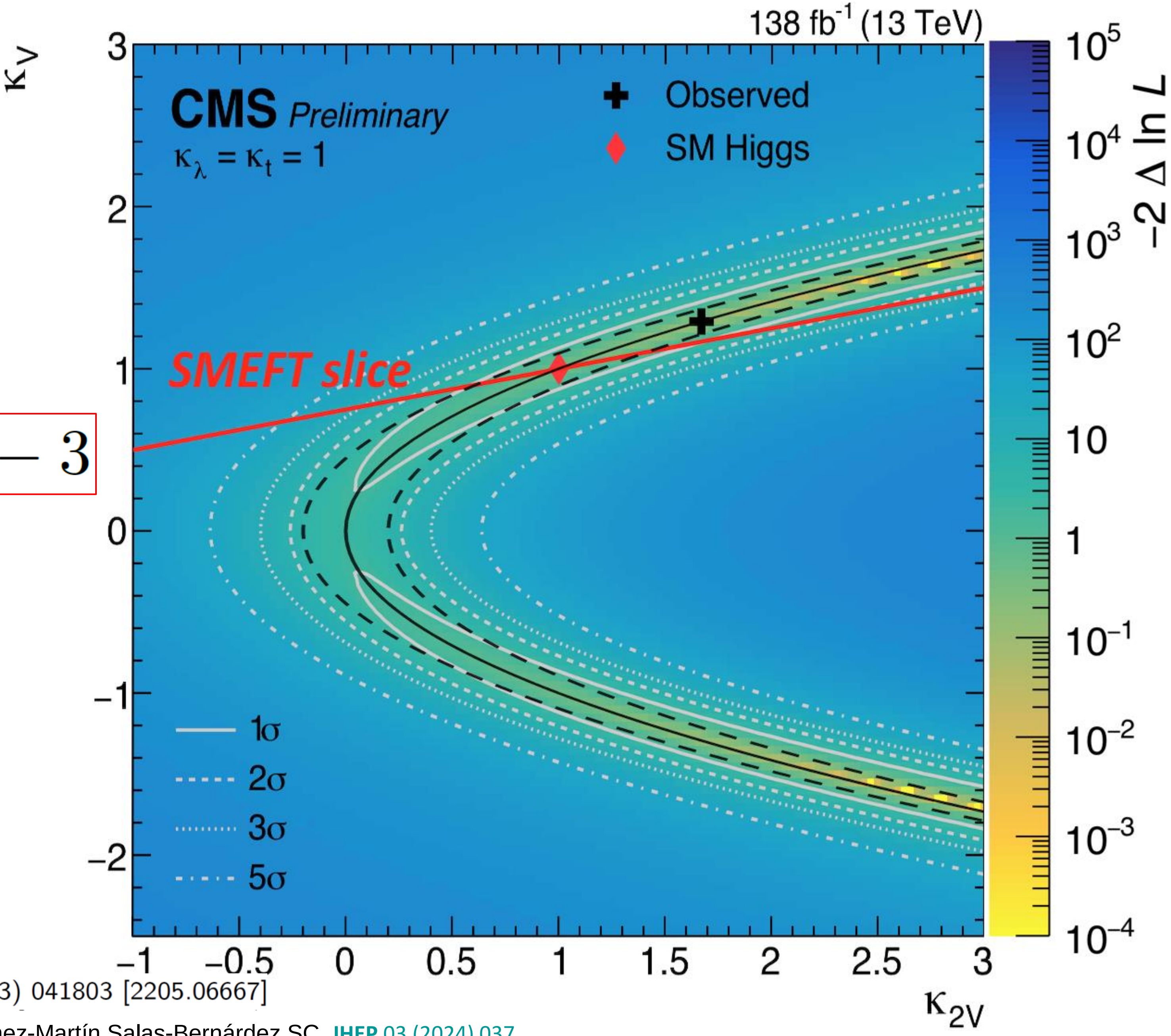
$$\hat{a}_2 = \pm 0.2$$

(d) Phys. Lett. B 842 (2023) 137531 [2206.09401].

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037

(a)

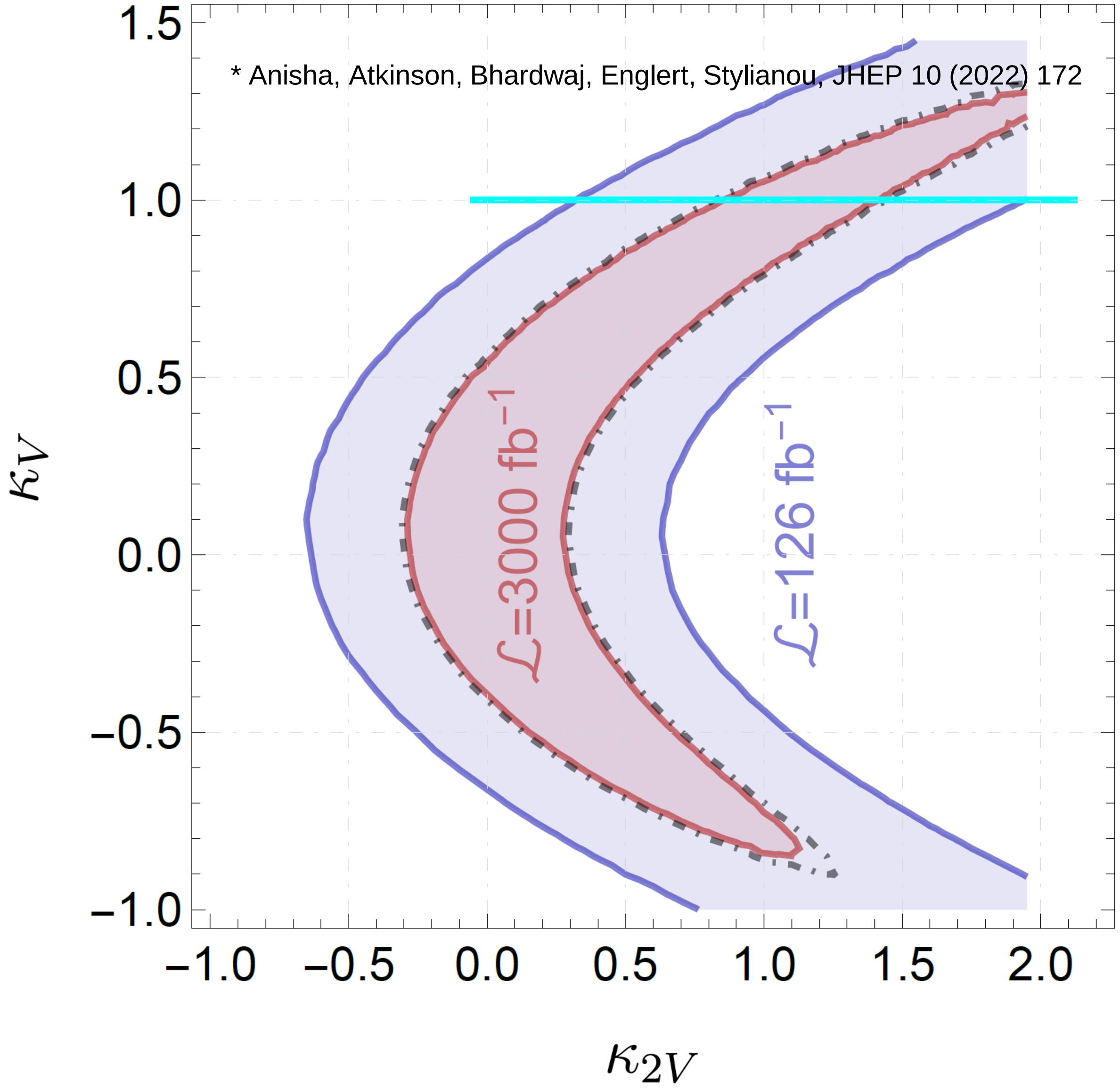
$$a_2 = 2a_1 - 3$$



$$\hat{a}_2 = \pm 0.2$$

(a) Phys. Rev. Lett. 131 (2023) 041803 [2205.06667]

* Delgado,Gómez-Ambrosio,Martínez-Martín,Salas-Bernárdez,SC, JHEP 03 (2024) 037



- Also previous theoretical hh-production simulations for LHC* noted an important correlation between (a, b)

["banana" plots, as M.J. Herrero calls them]