**Effective Field Theory in Multiboson Production Workshop ,Padova, 10-11 June 2024**

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# Exploring HH and HHH at colliders with the Bosonic-HEFT

## Content of this talk based on results in:

HH and HHH within HEFT at *pp*

**2011.13195, EPJC 81 (2021)3, 260, González-López, Herrero, Martínez-Suárez Preliminar. Cepeda, Domenech, Garcia-Mir, Herrero. Work in progress (2024) 2312.03877, EPJC 84 (2024)5, 503, Davila, Domenech, Herrero, Morales**  $\mathsf{NLO}(\eta, \delta)$ 2208.05452, Phys. Rev. D 106 (2022)11, 115027, Domenech, Herrero, Morales, Ramos LO NLO  $(\kappa_V, \kappa_{2V})$ (*η*, *δ*)  $(\kappa_V, \kappa_{2V})$  **Preliminar. Domenech, Herrero, Morales. Work in progress (2024) 2405.05385 Anisha, Domenech, Englert, Herrero, Morales (gg to HH and HHH)**  via 1PIs **2208.05900, Phy.Rev.D 106(2022)7, 073008, Herrero, Morales** Renorm.  $\mathbf{i}$ **n**  $R_{\xi}$ Matching Amplitudes **2307.15693, Phys.Rev.D <sup>108</sup> (2023)9, 095013, Arco, Domenech, Herrero, Morales**  Tools used: FeynArts, FeynRules, FormCalc, Looptools, MG5, VBFNLO, HEFT model file included

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HH and HHH within HEFT at  $e^+e^-$ 

Rad. corrections

Matching HEFT-2HDM









# Main motivation: HH and HHH production at colliders



Correlations within SM :  $V_{HWW} = vV_{HHWW}$  $V$ <sub>HHH</sub> =  $vV$ <sub>HHHH</sub>



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What about BSM?

Do we learn anything comparing HH and HHH production?







[1]ATLAS, Phys. Rev. D **101** (2020) [1909.02845] [24]UIVIS, PLB 842, 137331 (2023) [2200.09401] [3a]ATLAS (PLB 843 (2023)137745 [2a]CMS, PLB 842,137531 (2023) [2206.09401] (2b) CMS, PRL129, 081802(2022) [2202.09617] (2c) ATLAS, PRD108, 052003(2023) [2301.03212]

María Herrero, EFT Multiboson, Padova 10 June 2024 (20) ATLAS, PRIJTU8, USZUU3(ZUZ3) [Z3UT.U3ZTZ] 4

$$
\mathbf{H} \quad \mathbf{W}_{\mu}^{\text{F}} = \frac{V^2}{4} \left[ 1 + \mathcal{R} \left( \frac{H}{V} \right) + \mathcal{D} \left( \frac{H}{V} \right)^2 + c \left( \frac{H}{V} \right)^3 \right] \text{Tr} \left[ D_{\mu} U^{\dagger} D^{\mu} U \right]
$$
\n
$$
\text{SM: } \mathbf{a} = \mathbf{b} = \kappa_3 = \kappa_4 = 1 \quad \text{LECs-Anomalous couplings: parametrize possible BSM effects}
$$
\n
$$
W_{\mu}^{\text{F}} \quad \gamma_{\mu} \quad \mathbf{a} = \kappa_V \qquad W_{\mu}^{\text{F}} \quad \gamma_{\mu} \quad \mathbf{b} = \kappa_{2V}
$$
\n
$$
W_{\mu}^{\text{F}} \quad \gamma_{\mu} \quad \mathbf{b} = \kappa_{2V}
$$
\n
$$
W_{\mu}^{\text{exp}} \quad \mathbf{a}^{\text{exp}} \in [0.97, 1.13]^{[11]} \quad \mathbf{a} = \mathbf{b} \quad W_{\nu}^{\text{F}} \quad \mathbf{b}^{\text{exp}} \quad \mathbf{b}^{\text{exp}} \in [0.0, 2.1]
$$
\n
$$
H \quad \mathbf{b} = \kappa_{2V}
$$
\n
$$
H \quad \mathbf{b}^{\text{exp}} \in [0.02, 2.1]
$$
\n
$$
H \quad \mathbf{b}^{\text{exp}} \in [-0.1, 2.2]
$$
\n
$$
H \quad \mathbf{b}^{\text{exp}} \in [-0.03, 2]
$$
\n
$$
H \quad \mathbf{b}^{\text{exp}} \in [-0.03, 2]
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H \quad \mathbf{b}^{\text{exp}} \in [-0.03, 2]
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H \quad \mathbf{b}^{\text{exp}} \in [-0.03, 2]
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H \quad \mathbf{b}^{\text{exp}} \in [-0.03, 2]
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$$
H \quad \mathbf{b}^{\text{exp}} \in [-0.03, 2]
$$
\n
$$
H \quad \mathbf{b}
$$

[3b]CMS (Nature 607, 7917, 2022)



We focus on *WW* ! *HH*:

either or there is the strip way of the coupling of the coupling of the also have the two we also have a triple  $\mathbb{R}$ 



### interactions, respectively. We will omit the analytical result of the corresponding amplitudes for shortness. WW—>HHH gives access to  $\kappa_3$   $\bullet$  and  $\kappa_4$   $\bullet$  (LO-HEFT)



Figure 38: Diagrams contributing to the *<sup>W</sup>W*<sup>+</sup> ! *HHH* subprocess in the unitary gauge. Less available phase space ——-> smaller cross sections than for WW —>HH: But yet possible access to large BSM *κ*′*s*

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Very small SM ( $\kappa_3 = \kappa_4 = 1$ ) rates:  $\sigma^{\rm SM}(pp \to HHHjj)(14 \,\rm TeV) = 10^{-7} \,\rm pb$   $\sigma^{\rm SM}(e^+e^- \to HHH \nu \bar{\nu})(3 \,\rm TeV) = 3 \times 10^{-7} \,\rm pb$ 













 $\frac{1}{\sqrt{2}}$ <sup>√</sup>*<sup>s</sup>* <sup>=</sup> 1000 GeV (upper right) and <sup>√</sup>*<sup>s</sup>* <sup>=</sup> 3000 GeV (lower). In these plots we explore the BSM effects from *a* and *b* and

HHH : Similar behavior at large  $\sqrt{s}$  as in the SM (shifted upwards) **No unitarity constraints on**  $κ_3$ **,**  $κ_4$ Max sensitivity to  $\kappa_3$  close to  $3 m_H$ put in the putting from the previous at 1 *<sup>s</sup>* <sup>−</sup> <sup>4</sup>*m*<sup>2</sup> *H* tarity constraints on *s* + 4<sup>m</sup><sub>2</sub> where  $\mathcal{S}$ set  $\overline{\phantom{a}}$ inited in the number of the SM is an example. We also include the SM is a set of the SM is  $\mathbb{R}^n$  $\sqrt{ }$  comparison with respect to the comparison with respect to the comparison with respect to the total value of  $\sqrt{ }$  $\bigvee S$  as in . The SM prediction gives a parabola with two maxima at <br>The SM prediction gives at two maxima at No unitarity constraints on  $\lambda$ cos de la India<br>De la India prediction in the BSM prediction in the BSM prediction in the HEFT prediction in the HEFT predictio Max sensitivity to  $\kappa_2$  close to larger energies (1 and 3 TeV) symmetrically at both sides of

 $\tau$  differential cross section with respect to cos  $\tau$ 

set one particular correlation given by \$*b* = \$*a/*2 for def-

HH : Strong enhancement at large  $\sqrt{s}$  for  $b \neq a^2$ Pert. unitarity viol above few TeV  $\kappa_{2V}^{}=0$  viol unit. above  $\,$  2.4 TeV ! Max sensitivity to  $\kappa_3$  close to  $2m_H$ are not allowed by present LHC constraints. Therefore,  $\mathbf{H}^{\text{H}}$ can conclude from the concluder from the particular conclude from the particular to particular that a set of t at large  $\sqrt{s}$  for  $v \neq a$ **Fert.** unitd  $\kappa_{2V}^{}=0$  viol unit. above [2.4] lev ! Max sensitivity to  $\kappa_3$  close to  $2 m_H$ cos θ = 0*.* In contrast, the BSM prediction in the HEFT develops two minima which manifest in the plots with the Pert. unitarity viol above few TeV Right plot assumes *<sup>a</sup>*<sup>2</sup> <sup>=</sup> *<sup>b</sup>.* The shaded region denotes the region of perturbative unitarity violation where |*a*0| *>* 1 predictions within the HEFT for this differential cross sec $k_{2V} = 0$  viol unit. above 2.4  $f(x_2)$   $\sigma$  violentic above  $\epsilon$ . In these plots we explore the BSM effects from *a* and *b* and







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e 2024 The largest sensitivity to k3 and k4 occurs in ggF, gg —>HH(HHH), see later 7 production via WBF preserve perturbative unitarity at the in ggr, igg —>HH(HHH), see later

 $b \neq a^2$  $\blacksquare$ PERTURBATIVE  $a = 1.5, b = 0.5$  $a = 0.5$ , b = 1.5 UNITARITY VIOLATION  $a = 0.5, b = 0.5$  $a = 1, b = 0$  $\sqrt{\frac{1500}{5}}$  (GeV) Eur. Phys. J. C (2024) 84:503 Page 7 of 23 503  $b = a^2$  $h = a^2$  $\boldsymbol{\nu} - \boldsymbol{\mu}$ **a** = 1 (SM<br> **a** = 0.5<br> **a** = 0.9 PERTURBATIVE UNITARITY VIOLATION  $\begin{array}{r} \n\begin{array}{c}\n\hline\na = 2 \\
a = 5 \\
a = 10\n\end{array}$ the highest cross sections. Concretely for *(a, b)* = *(*1*.*5*,* 0*.*5*)*  $\mathcal{F}_{10^0}$  $t_{\rm s}$  , the total comes from the total cross section comes from the problematic interval *MH H* ∈ *(*1800*,* 3000*)* GeV. **1**  $\sum_{i=1}^{n}$  **b**  $\sum_{i=1}^{n}$  **a** perturbative unitarity violation is very different. As can be different to the can be different. As can be different to the can be different. As can be different to the can be different. As can be different to the can be d see **10<sup>-2</sup>,** *a*  $\overline{\phantom{a}}$  **b**  $\overline{\phantom{a}}$  energy changes leading to a flat plateau at large energies that is below the unitarity crossing line. The only exception is for  $\sqrt{\frac{1500}{5}}(\text{GeV})$ 

### Appendices **A DIEGO DIAGRAMS CONTRIGHTMENT CONTRIGHTMENT CONTRIGHTMENT CONTRIGHTMENT CONTRIGHTMENT CONTRIGHTMENT CONTRIGHTMENT** are neglectron mass in the generation of t are automatically generated by MadGraph and using the UFO file with our HEFT model. They 1 contain the diagrams with WBF configuration, diagrams 5, 6, 7 and 8, which are the ones where  $\eta$ <sup>T</sup> $\rho$ <sup>+</sup> + +  $\eta$ <sup>+</sup>  $\$  $\rho \circ \rho$  bosons. Note that  $\rho \circ \rho \rightarrow H$  $\sim$  is done contribution from the contribution from the contribution from the coloured dots in the coloure dots in the coloure of  $\sim$ h has the same of th 4  $\sqrt{1}$ h 1  $\ket{\mathbf{N}}$  $\cdot$ 6 Our Bosonic-HEFT model file is implemented in MG5 e-HH production: testing a= $\kappa_V$ , b= $\kappa_{2V}$  together at colliders (LO-HEFT)  $e^+e^- \rightarrow HH\nu\bar{\nu}$  **LHC**  $q_1\bar{q}_2 \rightarrow HHq_3\bar{q}_4$  (+ diags for  $\bar{q}\bar{q}$  and for  $qq$  ) Our Bosonic-HEFT model file is implemented in MC  $c^{\frac{1}{2}}$  a  $r^{\frac{1}{2}}$  a  $r^{\frac{1}{2}}$  and  $r^{\frac{1}{2}}$  and  $r^{\frac{1}{2}}$  and  $r^{\frac{1}{2}}$  $e^+e^- \rightarrow H H \nu \nu$ rates found for the final (*b*¯*bb*¯*b*⌫⌫¯) events, are approximately equal to the *HH*⌫⌫¯ rates multiplied by . The production:  ${\sf testing}$  a= ${\sf k}_{V}$ , b= ${\sf k}_{2V}$  together at  $\rho + \rho = 2$ contrast, the event rates from **H**<sub>192</sub>, and  $\mathbf{y}_1 \mathbf{y}_2$ *e*+*e* − e- $\bm{U}$ h eulays l  $\prime$   $\Delta$ h e- $\overline{\phantom{a}}$



Diagrams made by MadGraph5\_aMC@NLO Diagrams made by MadGraph5\_aMC@NLO BSM signals means deviations in *σ* and in *dσ*′*s* respect the SM rates. We also explore correlations. Explore in *HH*  $\bm{\mathrm{Explore}}$  in  $\mathit{HH}\mathit{\cancel{\mathbb{E}}_T}$  events. We require  $\mathit{\cancel{\mathbb{E}}_T}>20\,\mathrm{GeV}$  $T_{\text{cubic}}$  is the propertum and  $T_{jj}$  are section.  $M_{jj}$  > 500 GeV transverse energy from the second term the **P**<br>**RSM** signals means deviations in  $\sigma$  and in  $d\sigma$ 's respe separations in previous in products in previous that a strategies of the *b-jets. The cuts that are used* in the *b*-jets. The *b*-jets. The cuts that are used in this control of **b**-jets. The *b-jets. B*-jets. B-jets. B-j events. We require Explore in *HHjj* events. We require WBF  $\frac{1}{2}$  Explore in  $HH\not\!\!E_T$  events. We require  $\not\!\!E_T>20\,{\rm GeV}$ **The subseteral areas are the transverse momentum and the property of the property of the property of the missing of the property of the missing of the missin**  $\text{Cuts, } \Delta \eta_{jj} > 4, \text{ } M_{jj} > 300 \text{ GeV}$ <br>
RCM signals researce deviations in a small in delayer sensor the CNA retor signal and the and used in parations in and and in angle between the bivindus.<br>Maria Herrero, EET Multiboson Padova 10 June 2024  $\mathcal{U}_l$  $\frac{1}{2}$ 3 diagram 3  $\sim$ diagram  $\alpha$ 3  $\overline{a}$   $\overline{a}$   $\overline{b}$   $\overline{c}$   $\overline{d}$   $\overline{$  $\ddotsc$  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$  $\overline{\phantom{a}}$ ve~  $\overline{\phantom{a}}$  and  $\overline{\phantom{a}}$ 6 1 3  $Z_3^2$  $\alpha = 1$   $\alpha = 0, \alpha = 0, \alpha$ e+ w+  $q_l$ ve~ 6 1 diagram 9 NP=0, QCD=0, QED=4 diagram 10 NP=0, QCD=0, QED=4 Diagrams made by MadGraph5\_aMC@NLO 6 1  $\cdots$  $\cdots$  $\cdots$ ve~  $\overline{a}$ 1  $\bar{q}_j$  $\bar{q}_j$  $\bar{q}_j$  $\bar{q}_j$ *Z*  $\bar{q}_l$ *H Z*  $\bar{q}_l$ *Z*  $\bar{\bar{q}}_l$ *Z*



### the (*a, b*) = (1*,* 1) point marked here with a star. The dashed white line in each plot represents the correlation between the Hera parameters are a *accest sensitivity expected if*  $\blacksquare$ Largest sensitivity expected if process within the region of the (*a, b*) parameter space explored in this figure is in general larger  $a^2 \neq b$  $a^- \neq b$

for the larger energy colliders, reaching size at  $\mathcal{A}$  $F$ xpected censitivity at  $c_1$  10.  $\Lambda h \sim (0.11)^{-1}$ . Expected sensitivity at CLIC.:  $\Delta b \sim \mathcal{O}(10^{-1})$  $\mathcal{L}$ uts:  $\not\hspace{-.1cm}E_{T}>20\,{\rm GeV}$  (see also ILC 0.5 and 1 TeV in paper)

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Figure 7. Predictions from the HEFT for the contourlines of cross section (*e*<sup>+</sup>*e* ! *HH*⌫⌫¯) (in pb) in the 2312.03877 Davila, Domenech, Herrero, Morales, EPJC 84 (2024)5, 503

# $\frac{1}{2\pi\sqrt{2\pi}}$  in  $\frac{1}{2\pi\sqrt{2\pi}}$  in  $\frac{1}{2\pi\sqrt{2\pi}}$  in  $\frac{1}{2\pi\sqrt{2\pi}}$  is  $\frac{1}{2\pi\sqrt{2\pi}}$  in  $\frac{1}{2\pi\sqrt{2\pi}}$  is  $\frac{1}{2\pi\sqrt{2\pi}}$ *HH jj HHH jj*

p p > h h h j j cross section (QCD=0) 0.030 0.010  $a \qquad | \qquad$   $\Box$   $a$ 0.006  $\sigma$  (pb) 0.004 0.002 0.000  $-0.5$  $0.0$  $0.5$  $1.0\,$  $-1.0$  $1.0$  $1.5$ a **PRELIMINARY** p p > h h h j j cross section (QCD=0) 0.010  $\boldsymbol{b}$  **b b b b**  $rac{2}{6}$  0.02 0.004  $\begin{array}{ccc} \text{Largest sensitivity expected if} \end{array}$ 0.002 0.000  $0.00$  $1.5$  $-0.5$  $0.0$  $-1.0$  $0.5$  $1.0$  $-1.0$  $-0.5$  $0.0$  $0.5$  $1.0$  $1.5$  $2.0$ b Interesting correlation in b !!  $M_{ii} > 500 \,\text{GeV}$  **Except for factor suppression HHH/HH due to phase space**   $2 < \eta_j < 5$  ,  $\eta_{j1} \times \eta_{j2} < 0$  $P_{Tj} > 20\,{\rm GeV}\;$  ,  $\Delta R_{jj} > 0.4\;$  Work in progress: Herrero with Morales, Domenech, …Englert, Anisha…

**WBF cuts:** 





### $F_{\text{Y}}$  phenomenological consequences  $(\kappa, \kappa_{\text{Y}})$  at  $e^+e^- \rightarrow HH_1\bar{\nu}$  in  $d\sigma/dM_{\text{Y}}$  $e^+e^-(3 \text{ TeV})$  Dávila, Domenech, Herrorism Dávila, D Exploring correlations  $(\kappa_V, \kappa_{2V})$  at  $e^+e^- \rightarrow HH\nu\bar{\nu}$  in  $d\sigma/dM_{HH}$ *e*+*e*<sup>−</sup> **Dávila, Domenech, Herrero, Morales [**2312.03877**] EPJC 84 (2024)5, 503** (3 TeV)

# $\epsilon$  Except close to  $\kappa_{2V} = \kappa_V^2$

miani conore Minimum sensitivity if

 $\kappa_{2V} = \kappa_{\bar{V}}$  $\kappa_{2V} = \kappa_V^2$ 

 $\Delta \kappa_{2V} = 2\Delta \kappa_V$ 

 $(\Delta b = 2\Delta a)$ 



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 $\alpha$  distributions the distribution distribution  $\alpha$  $\sim$   $\sim$   $\mu$  $\sim$   $\mu$  $\sim$   $\mu$  $\sim$   $\sim$   $\mu$  $\sim$   $\sim$ 

In general going BSM with  $\kappa_{2V} \neq 1$  ;  $\kappa_V \neq 1$  distorts the dist. in  $M_{HH}$  producing bumps,

Maximum sensitivity if

$$
\kappa_{2V} \neq \kappa_V^2
$$







 $\sigma(e^+ e^-$  -> H H v  $\overline{v}$ ) at  $\sqrt{s} = 3$  TeV



 $-(3 \text{ TeV})$ *e*+*e*−(3 TeV)



larger  $(\kappa_V^2 - \kappa_{2V}) \neq 0 \rightarrow$  higher peaks  $\rightarrow$  more transverse Higgs !!! **Very characteristic BSM examples, with**  $q_3 q_4^2 - \kappa_{2V}) \neq 0$  Dávila, Domenech, Herrero, Morales [2312.03877] EPJC (2024)

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### *j* **.**<br>, <u>.</u> . **WBF** jets !!

**Cepeda, Domenech, Garcia-Mir, Herrero (Work in progress) It looks promising : now we are including pythia and Delphes for a more realistic simulation**

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 $--- 3/ab$ , 3 TeV

 $-5/ab$ , 3 TeV



much higher sensitivity to  $\kappa_3$  expected Future expected sensitivity to  $\kappa_4$  yet poor plot on the right shows a zoomed-in version.

$$
e^+e^- \to 6b + E_T^{\text{mis}}
$$

 $\kappa_3 \ge 2 \; (\kappa_4 = 1)$ <br> $\kappa_4 \ge 4 \; (\kappa_3 = 1)$  $\kappa_3$   $\kappa_4$ CLIC (3 TeV) where BSM/SM  $\geq 10$  for  $\kappa_3 \geq 2$  ( $\kappa_4 = 1$ ) BSM/SM  $\geq 10$  for  $\kappa_4 \geq 4$  ( $\kappa_3 = 1$ )  $\sigma^{\text{SM}}(e^+e^- \to HHH\nu\bar{\nu})$  (3 TeV) = 3 × 10<sup>-7</sup> pb



Conclusions

 *<sup>m</sup>*<sup>2</sup> <sup>2</sup> *a*˜*<sup>H</sup>VV v*  $\frac{1}{2}$ and that for the second operator is (*addVV*<sup>2</sup> + (*a/*2)*add*⇤) which we rename as (*addVV*2). ators list given in the literature (see, for instance, Brivio et al 13 I<sub>n</sub> the Lagrangian with dimps dimensional parameters and *Lagrange*-fixing  $\sigma$ Full operators list given in the literature (see, for instance, "brivio et

### Full operators list given in the literature (see, for instance, Brivio et al 1311.1823)  $\sim$ coecients in *L*2, *a*, *b* and <sup>3</sup> (<sup>4</sup> does not enter in this process) and 9 coecients in *L*4, *addVV*1, *addVV*2, *ad*2, *aHd*2, *aHdd*, *aHWW* , *aHHWW* , *aHVV* and *aHHVV*. Notice, that other scattering processes *<sup>V</sup><sup>µ</sup>V<sup>µ</sup> <sup>m</sup>*<sup>2</sup> <sup>4</sup> *a*˜*HHVV <sup>v</sup>* <sup>2</sup> Tr *<sup>V</sup><sup>µ</sup>V<sup>µ</sup>* + ˜*aHdd v* 2 *v* @*<sup>µ</sup>H* @*µH* + *...*

summarized by:  $a_{dd}v_{v1} \leftrightarrow c_8$ ,  $a_{dd}v_{v2} \leftrightarrow c_{20}$ ,  $a_{11} \leftrightarrow c_9$ ,  $a_{HWW} \leftrightarrow a_W$ ,  $a_{HHWW} \leftrightarrow b_W$ ,  $a_{d2} \leftrightarrow c_5$ ,  $a_{Hd2} \leftrightarrow a_5$ ,  $a_{\Box\mathcal{V}\mathcal{V}} \leftrightarrow c_7$ ,  $a_{H\Box\mathcal{V}\mathcal{V}} \leftrightarrow a_7$ ,  $a_{d3} \leftrightarrow c_{10}$ ,  $a_{Hd3} \leftrightarrow a_{10}$ ,  $a_{\Box\Box} \leftrightarrow c_{\Box H}$ ,  $a_{H\Box\Box} \leftrightarrow a_{\Box H}$  $a_{dd\Box} \leftrightarrow c_{\Delta H}, a_{HVV} \leftrightarrow a_C \text{ and } a_{HHVV} \leftrightarrow b_C.$ 

coecients in *L*2, *a*, *b* and <sup>3</sup> (<sup>4</sup> does not enter in this process) and 9 coecients in *L*4, *addVV*1, State in the control of the María Herrero, EFT Multiboson, Padova 10 June 2024

 $\mathcal{V}_\mu \,=\, (D_\mu U) U^\dagger$ 

$$
\Box H = -m_h^2 H - \frac{3}{2} \kappa_3 m_h^2 \frac{H^2}{v} \n- \frac{a}{2} v \text{Tr} \left[ \mathcal{V}^\mu \mathcal{V}_\mu \right] - \frac{b}{2} H \text{Tr} \left[ \mathcal{V}^\mu \mathcal{V}_\mu \right] \n\text{Tr} \left[ \tau^j \mathcal{D}_\mu \mathcal{V}^\mu \right] = -\text{Tr} \left[ \tau^j \mathcal{V}^\mu \right] \frac{2a}{v} \partial_\mu H
$$

$$
e.o.m
$$

### NLO-HEFT Higgs operators involved in (EW) HH production *<sup>µ</sup>*⌫ = @*µW* where *W* ˆ *<sup>µ</sup>* = *gW<sup>a</sup> <sup>µ</sup>* ⌧ *<sup>a</sup>/*2, and *B* ˆ maximum of two *H* or two *W* gauge bosons in the operator: <sup>H</sup>*<sup>H</sup>* <sup>3</sup> *H*<sup>2</sup> i *b* h i <sup>2</sup>7 | |:<br>2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 2009 | 20 2*g* <sup>0</sup> <sup>2</sup> Tr<sup>h</sup> + *LGF* + *LF P ,* (2.6) and the relevant chiral dimension four Lagrangian for *WW* ! *HH* is



 $\overline{1}$ 

ICLION LO 9  $u_i$ s in LO coefficients entering fillowing  $\rightarrow$   $\pi\pi$ Reduction to 9  $a_i's$  NLO coefficients entering into  $WW \rightarrow HH$ is encoded in the chiral coecients *a*, *b*, <sup>3</sup> and <sup>4</sup> of *L*<sup>2</sup> when they are di↵erent from one, and in

$$
\mathscr{L}_{\text{HEFT}}^{\text{NLO}} = \dots - a_{dd\nu\nu1} \frac{\partial^{\mu} H \partial^{\nu} H}{\partial^2} \text{Tr} \left[ \mathcal{V}_{\mu} \mathcal{V}_{\nu} \right] - a_{dd\nu\nu2} \frac{\partial^{\mu} H \partial_{\mu} H}{\partial^2} \text{Tr} \left[ \mathcal{V}^{\nu} \mathcal{V}_{\nu} \right] + a_{11} \text{Tr} \left[ \mathcal{D}_{\mu} \mathcal{V}^{\mu} \mathcal{D}_{\nu} \mathcal{V}^{\nu} \right] - \frac{m_H^2}{4} \left( 2a_{H \nu \nu} \frac{H}{v} + a_{H \mu \nu \nu} \frac{H^2}{v^2} \right) \text{Tr} \left[ \mathcal{V}^{\mu} \mathcal{V}_{\mu} \right] - \left( a_{H \nu W} \frac{H}{v} + a_{H \mu \nu W} \frac{H^2}{v^2} \right) \text{Tr} \left[ \hat{W}_{\mu \nu} \hat{W}^{\mu \nu} \right] + i \left( a_{d2} + a_{H d2} \frac{H}{v} \right) \frac{\partial^{\nu} H}{v} \text{Tr} \left[ \hat{W}_{\mu \nu} \mathcal{V}^{\mu} \right] + \left( a_{\text{D}\nu} + a_{H \text{D}\nu} \mathcal{V}_{\nu} \frac{H}{v} \right) \frac{\Box H}{v} \text{Tr} \left[ \mathcal{V}_{\mu} \mathcal{V}^{\mu} \right] + a_{d3} \frac{\partial^{\nu} H}{v} \text{Tr} \left[ \mathcal{V}_{\nu} \mathcal{D}_{\mu} \mathcal{V}^{\mu} \right] + \left( a_{\text{D}\Box} + a_{H \text{D}\Box} \frac{H}{v} \right) \frac{\Box H \Box H}{v^2} + a_{dd\Box} \frac{\partial^{\mu} H \partial_{\mu} H \Box H}{v^3} + a_{H dd} \frac{m_H^2}{v^2} \frac{H}{v} \partial^{\mu} H \partial_{\mu} H - \left( a_{\text{D}\Box} + a_{H \text{D}\Box} \frac{H}{v} \right) \frac{\Box H \Box H}{v^2} + a_{d4\Box} \frac{\partial^{\mu} H
$$

$$
\mathscr{L}_{\text{HFFT}}^{\text{NLO + e.o.m}} = \dots \underbrace{-a_{ddvv}}_{-4} \underbrace{\partial^{\mu} H \partial^{\nu} H}_{2} \text{Tr} \left[ \nu_{\mu} \nu_{\nu} \right] - \underbrace{a_{ddvv}}_{v^{2}} \underbrace{\partial^{\mu} H \partial_{\mu} H}_{v^{2}} \text{Tr} \left[ \nu^{\nu} \nu_{\nu} \right]}_{v^{2}} \text{Tr} \left[ \nu^{\mu} \nu_{\mu} \right] + a_{Hdd} \underbrace{\frac{m_{\text{H}}^{2}}{v^{2}} \frac{H}{v} \partial^{\mu} H \partial_{\mu} H}_{v^{2}} - \underbrace{\left( a_{HWW} \frac{H}{v} + a_{HHWW} \frac{H^{2}}{v^{2}} \right) \text{Tr} \left[ \hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] + i \left( a_{d2} + a_{Hd2} \frac{H}{v} \right) \underbrace{\frac{\partial^{\nu} H}{v} \text{Tr} \left[ \hat{W}_{\mu\nu} \nu^{\mu} \right]}_{v^{2}} \text{ The most relevant}
$$
\n
$$
\text{Reduction to 9 } a_{i}^{\prime} \text{S NLO coefficients entering into } WW \rightarrow HH \qquad \text{and}
$$

The most relevant  
are  

$$
a_{ddVV1} \equiv \eta \ , \ a_{ddVV2} \equiv \delta
$$







# **Accessibility to NLO-HEFT**  $(n, \delta)$  at  $e^+e^-$  (4b+ETmiss)



María Herrero, EFT Multiboson, Padova 10 June 2024





Developed a practical program to include one-loop HEFT radiative corrections via insertions of 1PI's





# **Including radiative corrections within bosonic-HEFT**

- **H** Developed a practical program to include one-loop HEFT radiative corrections via insertions of 1PI's<br>.
	-
- Easy to implement in physical scattering procceses

Based on computation of one-loop FDs (graphical/intuitive) easy to implement with usual tools FeynRules, FormCalc, Looptools etc.. These latter are the shift are needed in the shift and are needed in the shift of a *a*<sup>*i*</sup> and are needed in the shift *a*<sup>*i*</sup> and are needed in the shift and are





Renormalization of the involved 1PI Green functions in generic  $R_\varepsilon$  gauges, with generic off-shell legs  $\,$ (renormalization of the Lagrangian is not enough, running Wilson coffs. is not enough) *Rξ* remove the extra diverse the extra divergences are divergences and the looptoons etc..<br>Renormalization of the involved 1PI Green functions in generic  $R_\varepsilon$  gauges, with generic off-shell legs renormanzation of the Eagrangian is not enough, ruming wilson cons. Is not enough,<br>
Master, equation for renormalized 1PI function within NI O HFFT



Master equation for renormalized 1PI function within NLO HEFT









mension i te



*H*





*g*  $t$   $\overrightarrow{H}$ *t*

*H*

Renormalized one-loop 1PIs  $\hat{\Gamma}_{\rm HEFT}^{\rm NLO}$  computed in Feynman 'tHooft gauge = shaded balls inserted in the FDs ̂ HEFT  $\hat{\mathbf{r}}$ Renormalized one-loop TPIs I  $_{\mathrm{HET}}^{\mathrm{YLO}}$  computed in Feynman 'tHooft gauge = shaded "balls inserted in the FDs  $=$  s<sub>*i*</sub>  $i$  aded balls *m*<sup>2</sup> H *v* 2  $\overline{\phantom{a}}$ 4  $\boldsymbol{\varTheta}$ *m*<sup>2</sup> H *m*<sup>2</sup> H ) t ✓*Z*⇡  $\overline{5}$   $\overline{1}$ *v v* 。<br>◆

 $\overline{g}$ 

### (EW) Radiative corrections in  $gg \to _\ast HH$  and in  $gg \to HHH$ Anísha, D.Domenech, C. Englert, M.J. Herrero, R.A<sup>.n</sup>Morales<sup>y</sup>, 2405.05385 +*OHdd* + *OHHdd* + *OddW* + *OHddW* + *OddZ* + *OHddZ ,* (2.1b) *H H* ralert. M.I. Herrero. R.A.Morales<sup>H</sup>. 2405.0 *H H H H*  $\binom{6}{4}$ *H*  $H_{\text{max}}$  boson in HEFT, and the cancels explicitly.  $HEX \rightarrow HHH$ with similar cancellations of gauge dependencies in the gauge dependence in the gauge boson sector  $\mathcal{Z}$  $with VBFNLO)$ **H** *H* **A** *H* **A** *H* **A** *H***<b>A** *H* **H**  $\sim$  100.00  $\frac{1}{2}$ *H H H* (a) (b) (c) *H*  $H$  *Morales<sup>H</sup>*, 2405, 05385 *H H H H H H H H* = *i*ˆ*HHHH*(*p*1*, p*2*, p*3*, p*4) **(numerical estimates with VBFNLO)**

 $\frac{y}{g}$ 

*g*

*g*

*t*

*t*





4) *H H t g H t*

*t*

*t*

*t*

*t*

16⇡<sup>2</sup>

— 16

# Size of the corrections in  $gg \rightarrow HH$  and in  $gg \rightarrow HHH$

 $\overline{\phantom{0}}$  LO



 $\text{CDF}$  relative to the relative to the relative to the relative to the reference LO expectation, cf.  $\ell$  $\sigma_{\text{LO}}^{\text{SM}}(HH) = \sigma_{\text{LO}}^{\text{ref}}(HH) = 17.40 \,\text{fb}$ ;  $\sigma_{\text{LO}}^{\text{SM}}(HHH) = \sigma_{\text{LO}}^{\text{ref}}(HHH) = 0.041 \,\text{fb}$ 

 $\Delta$ ll All simulations done with BVFNLO

Most important message:  $\longrightarrow$  NLO  $\longrightarrow$  NLO<sup>2</sup> (EW) radiative corrections within NLO-HEFT change the sensitivity to  $\kappa_3$  and  $\kappa_4$  in HH and HHH production at LHC The most relevant change is in  $\kappa_3$ For  $\kappa_3$ <0, we find relevant enhancements in the NLO/LO prediction  $\overline{\phantom{0}}$  LO  $\sigma(HH)$  of  $~\sim 10\,\%$  $\longrightarrow$  NLO and in  $\sigma(HHH)$  of  $~\sim 30\,\%$  (  $\sim 80\,\%$  if  $\rm NLO^2$ )

> Also large changes in *κ*4 For  $\kappa_4$  > 0, we find relevant reductions in the NLO/LO prediction  $\sigma(HHH)$  of  $\sim 50\,\%$





Corrections at LHC (13 TeV) cross sections

**Anisha, D.Domenech, C. Englert, M.J. Herrero, R.A.Morales , 2405.05385**

## **Large effects from NLO coefficients**





The largest effects are from operators with higher number of derivatives:  $a_{dd}$ <sub> $\Box$ </sub>,  $a_{H\Box}$ ,  $a_{ddd}$ ...

> For instance, for  $a_{H\Box\Box} = 0.1$  and  $\kappa_3 = 1$  $\sigma^{\text{HEFT}}(HH) \sim 1.5 \,\sigma^{\text{SM}}(HH)$  (50%)  $\sigma^{\text{HEFT}}(HHH) \sim 1.8 \sigma^{\text{SM}}(HHH)$  (80%)





**Anisha, D.Domenech, C. Englert, M.J. Herrero, R.A.Morales , 2405.05385**



# Conclusions

 Multiple Higgs production at colliders (HH, HHH,..) will test the Higgs potential and BSM Higgs couplings to gauge bosons. Some correlations could also be tested:  $V_{\text{HWW}}/V_{\text{HHWW}}$ ,  $\lambda_{\text{HHH}}/ \lambda_{\text{HHHH}}$ ,...uncorrelated in HEFT because H is a singlet but correlated in other specific scenarios. In particular: 2HDM, SMEFT, …. where H is part of a doublet

 Both HL-LHC (14 TeV) and CLIC (3TeV) will give access to LO and NLO HEFT coefficients. Studying specific difxsections will help in  $\epsilon$  exploring potential correlations: Ex.  $d\sigma/d\eta_H$  for  $\kappa_V^2 \leftrightarrow \kappa_{2V}$ 



Including radiative corrections within HEFT predictions is important

**Back up slides**

# $\epsilon$  Best prospects for *κ*<sub>3</sub> are at future  $e^+e^-$  colliders

- *Proposed* high-energy linear  $e^+e^-$  colliders: ILC and CLIC
- Projected sensitivity to  $\kappa_3$  from  $hhZ$  and  $hh\nu\bar{\nu}$  (better than HL-LHC!):

500 GeV (4 ab-1)  $+ 1$  TeV  $(5 \times ab^{-1})$ :  $\pm 10\%$ 

### At ILC:

Until we have these machines ... Plenty of room for BSM physics! Best expected sensitivities Δ*κ*<sup>3</sup> ∼ 0.1



![](_page_25_Figure_11.jpeg)

![](_page_25_Picture_12.jpeg)

![](_page_25_Picture_13.jpeg)

### line). Negative (positive) values of <sup>3</sup> are shown in the left (right) panel.  $\mathbf{H} = \mathbf{H} \cdot \mathbf{H$  $t_{\rm ISNN} > 10$  tor  $\kappa_{\rm 2}$ that in the *HHH* channel, similarly to the *HH* channel, the di↵erence with respect to the  $BSM/SM \geq 10$  for  $\kappa_4 \geq 4$  ( $\kappa_3 = 1$ ) associated *Z* production subprocess disappears as we separate from <sup>3</sup> = 1, showing once The best expectations are for CLIC (3 TeV) where **BSM/SM**  $\geq 10$  for  $\kappa_3 \geq 2$  ( $\kappa_4 = 1$ )

Figure 26: Left: Contour levels for the total cross section of the *<sup>e</sup>*+*e* ! *HHH*⌫*e*⌫¯*<sup>e</sup>* process Higher sensitivity to  $\kappa_3$  than to  $\kappa_4$ !!

![](_page_26_Figure_7.jpeg)

## Sensitivity to *κ*<sub>3</sub> and *κ*<sub>4</sub> in  $e^+e^-$  → *HHHvv*

![](_page_26_Figure_2.jpeg)

# di↵erent values of the CM energy p*s*. The plot on the right shows a zoom around the dip region.

 $E_{\text{pred}}$ , bomenedi, bardia mir, menero noon, in progress.<br>IVIOQUIS WITH  $a = b$  very difficult to test to the value of the value of the anomalous constants a constant of the data of  $\mathcal{C}$  is the data line of data line  $\mathcal{C}$ denotes all points relative by a sections with specific variables (angular, rapidity et Models with  $a^2 = b$  very difficult to test Exploring correlations at LHC more difficult than at  $e^+e^-$  but yet possible by studying differential xsections with specific variables (angular, rapidity etc..see next) **Cepeda, Domenech, Garcia-Mir, Herrero (Work in progress)**

*T j<sup>i</sup>* = 20 GeV, ⌘*j*<sup>1</sup> ⇥ ⌘*j*<sup>2</sup> *<sup>&</sup>lt;* 0, 2 *<sup>|</sup>*⌘*j<sup>i</sup> <sup>|</sup>* 5, *<sup>M</sup>min* María Herrero, EFT Multiboson, Padova 10 June 2024

# Sensitivity to  $a=x_V$ ,  $b=x_V$  in  $pp \rightarrow HHj_1j_2$  (LHC, 14TeV)

![](_page_27_Figure_1.jpeg)

 $\Delta$ pplied cuts:  $P_{Tj}^{\min} = 20\,GeV$  ,  $\eta_{j1}\eta_{j2} < 0$  ,  $2 \leq |\eta_j| \leq 5$  ,  $M_{jj}^{\min} = 500GeV$  ,  $\Delta R_{jj}^{\min} = 0.4$ 

(1) CMS, PRL129, 081802(2022) [2202.09617] (2) ATLAS, PRD108, 052003(2023) [2301.03212]

![](_page_27_Picture_8.jpeg)

mplitude leve

## **Matching amplitudes**

- We do matching at amplitude level (more useful to compare with data).  $\frac{1}{2}$
- In contrast to other approaches: matching Lagrangians, matching Effective Actions …etc natching Effective Actions ...etc tching Effec
	- $(S_{\text{at}})$  $1.0$ ,  $1.1$   $1.0$ ,  $1.0$
	- Setting the n-loop order  $\mathscr{O}(\hbar^n)$ , same in both sides  $\mathcal{L} = \mathcal{L} \mathcal$  $\int$  Setting the n-loop order  $\mathcal{O}(h^{\prime\prime})$ , same in both sides
		- Setting the input parameters, in both sides ers in both sides
	- Setting the proper large mass expansion in the UV theory  $4$  Analytical results of the amplitudes 11  $\alpha$  amplitudes 11  $\alpha$  amplitudes 11  $\alpha$  $\vert$  Setting the proper large mass expansion in the UV theory Head experision in the OV theory
	- ${\sf LO} \quad h \to WW^* \to W f \bar{f}' \quad \quad {\sf tree}$  $\left\{\n\begin{array}{c}\n\text{L}_0 \rightarrow ZZ^* \rightarrow Zf\bar{f} \\
	\text{L}_1 \rightarrow ZZ^* \rightarrow Zf\bar{f}\n\end{array}\n\right.\n\text{Here}$  $W^+W^- \rightarrow hh$  $\mathsf{LO}$   $\overline{ZZ} \to hh$  tree  $\mathsf{L}\mathsf{O}\qquad h h\to h h\qquad\qquad\qquad\mathsf{tree}$  $\begin{array}{ccc} \text{110} & \text{1010} \\ \text{121} & \text{122} \\ \text{131} & \text{133} \\ \text{241} & \text{242} \\ \text{251} & \text{263} \\ \text{264} & \text{274} \\ \text{275} & \text{284} \\ \text{286} & \text{274} \\ \text{296} & \text{284} \\ \text{207} & \text{274} \\ \text{218} & \text{284} \\ \text{228} & \text{296} \\ \text{218} & \text{207} \\ \text{2$  $\begin{array}{ccc} \text{NLO} & \text{if } \mathcal{T} & \mathcal{P} \end{array}$ 5.1 Amples for large *m*<br>3.1 Amples for the 20theavier in the matter in the matter of the matter and solutions to the matter and solutions<br>2011 Mercury 20theavier 20theavier 20theavier 20theavier 20theavier 20theavier 20th  $\frac{1}{2}$  Hert coefficients from non-decoupling heavy Higgs bosons 233  $\mu$ ching several amplitudes:  $\begin{pmatrix} 1 & \mathsf{LO} & h \to WW^* \to Wff' & \mathsf{tree} \end{pmatrix}$  $\left\{ \mu_1, m_N, m_Z, c'_i \right\}$   $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{array} \right\}$   $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{array} \right\}$   $\left\{ \begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{array} \right\}$ 4.3 *ZZ* ! *hh* 13  $h_1$ ,  $m_1$ ,  $m_2$ ,  $m_1$ <sub>2</sub> (light)  $\Box$   $hh \rightarrow hh$  tree  $H, {}^{\textstyle m}\!A, {}^{\textstyle m}\!H^\pm$  (heavy)  $\bigcap$  NLO  $h \to \gamma\gamma$   $R_\varepsilon$  1-loop  $n\,\beta,\ \cos(\beta-\alpha)$  (free)  $\big\{$   $\mathsf{NLO}$   $h\rightarrow \gamma Z$   $R_\xi^{\mathsf{s}}$  1-loop arge mass expansion is in  $\left(\frac{1}{m_{\rm heavy}}\right)$  . Other parameters are derived  $(\lambda_{h_i h_j h_{k'}} ....)$ 4 Analytical results of the amplitudes 11  $h \rightarrow ZZ^* \rightarrow Zf f$  tree  $W^+W^- \to hh$  tree  $ZZ \rightarrow hh$  tree  $h h \rightarrow h h$  tree  $\begin{array}{ccc} \text{O} & h\to\gamma\gamma & R_{\xi} & \text{1-loop} \end{array}$  $\mathcal{D} \longrightarrow \gamma Z$   $R_{\xi}^{3}$  1-loop Other parameters are derived  $(\lambda_{h_i h_j h_k'}....)$ LO LO LO LO NLO  $\tan \beta$ ,  $\cos(\beta - \alpha)$  (free)  $\setminus$  NLO  $h \to \gamma Z$   $K_{\xi}$  1-loop  $m_h$ ,  $m_W$ ,  $m_Z$ ,  $m_{12}$  (light) Proper large mass expansion is in  $\big(\frac{1}{m} \big)$  . Other parameters are derived  $(\lambda_{h_i h_j h_{k'}} ....)$ *m*light *<sup>m</sup>*heavy) *n*  $\lambda_{h_i h_j h_k}$ (free) *Rξ Rξ*

![](_page_28_Figure_2.jpeg)

![](_page_28_Figure_11.jpeg)

## **Solution to the matching equations: HEFT versus 2HDM**

$$
(a = 1 - \Delta a, b = 1 - \Delta b, \kappa_3 = 1 - \Delta \kappa_3, \kappa_4 = 1 - \Delta \kappa_4)
$$
  
\n
$$
\Delta a_{2\text{HDM}} = 1 - s_{\beta-\alpha},
$$
  
\n
$$
\Delta b_{2\text{HDM}} = -c_{\beta-\alpha}^2 (1 - 2c_{\beta-\alpha}^2 + 2c_{\beta-\alpha}s_{\beta-\alpha}\cot 2\beta),
$$
  
\n
$$
\Delta \kappa_3|_{2\text{HDM}} = 1 - s_{\beta-\alpha}(1 + 2c_{\beta-\alpha}^2) - c_{\beta-\alpha}^2 \left(-2s_{\beta-\alpha}\frac{m_{12}^2}{m_{h}^2 s_{\beta} c_{\beta}} + 2c_{\beta-\alpha}\cot 2\beta \left(1 - \frac{m_{12}^2}{m_{h}^2 s_{\beta} c_{\beta}}\right)\right),
$$
  
\n
$$
\Delta \kappa_4|_{2\text{HDM}} = -\frac{c_{\beta-\alpha}^2}{3} \left(-7 + 64c_{\beta-\alpha}^2 - 76c_{\beta-\alpha}^4 + 12\left(1 - 6c_{\beta-\alpha}^2 + 6c_{\beta-\alpha}^4\right)\frac{m_{12}^2}{m_{h}^2 s_{\beta} c_{\beta}} + 4c_{\beta-\alpha}s_{\beta-\alpha}\cot 2\beta \left(-13 + 38c_{\beta-\alpha}^2 - 3(-5 + 12c_{\beta-\alpha})\frac{m_{12}^2}{m_{h}^2 s_{\beta} c_{\beta}}\right)\right),
$$
  
\n
$$
+ 4c_{\beta-\alpha}^2 \cot^2 2\beta \left(3c_{\beta-\alpha}^2 - 16s_{\beta-\alpha}^2 + 3(-1 + 6s_{\beta-\alpha}^2)\frac{m_{12}^2}{m_{h}^2 s_{\beta} c_{\beta}}\right),
$$
  
\n
$$
s_{\beta-\alpha}
$$

$$
a_{h\gamma\gamma}|_{\text{2HDM}} = -\frac{s_{\beta-\alpha}}{48\pi^2},
$$
  

$$
a_{h\gamma Z}|_{\text{2HDM}} = -\frac{(2c_{\text{w}}^2 - 1)s_{\beta-\alpha}}{96c_{\text{w}}^2 \pi^2}.
$$

Summarize the Non-Decoupling effects of the heavy Higgs bosons at low energies Figure that in the previous  $\sim$  remarks that in the previous  $\sim$  some simple correlations of  $\sim$ among the LO-HEFT coefficients that we find the LO-HEFT comments that we find in the  $\Gamma$ *a|* qal le neavy Higgs bosons at low energies

 $\overline{\mathcal{L}}$ *m*light *<sup>m</sup>*heavy)

> They are valid for arbitrary 2 They are a ior anditrary<br>*c*

**(quasi-alignement)** previous that in the previous correlations of the previous correlations of the previous some simple correlations of the previous some simple correlations of the correlations of the correlations of the correlations of the c <u>|</u><br>|
|
|

 $\Delta a|^{\rm gal}_{\rm 2H}$  $\frac{\text{qal}}{2\text{HDM}} = -\frac{1}{2}$ 2  $\Delta a^{\text{qal}} = -\frac{1}{2}\Delta b^{\text{qal}}$ 

### These contributions are

*m*<sup>2</sup>

 $\overline{\phantom{a}}$ 

when  $c_{\beta-\alpha}\ll 1$  is required The first one is independent on *m*<sup>12</sup> and tan . Notice the di↵erent correlation between these two 's here in the 2DDM and in the SMEFT when  $c_{\scriptscriptstyle B} \ll 1$  is required at the result of Section 2. For the results in the regarding the 's in Eq. (5.16) the correlation gets further simplified if *m*<sup>12</sup> = 0:

$$
t_\beta,c_{\beta-\alpha}
$$

Se non-decoupling effects from the neavy posons.<br>The previous formulas we have used and previous formulations of previous designs and all and the previous designs of are not optained in the sivier in the compact with the exting correlations round and the 2HDM increase of the v<br>Where all effects are decoupling *s*, *c* and conclusion in Eq. (3.12) show the first conclusion in all the first c These non-decoupling effects from the heavy bosons are not obtained in the SMEFT where all effects are decoupling

![](_page_29_Picture_19.jpeg)

$$
\left(\frac{m_{\text{light}}}{m_{\text{heavy}}}\right)^n, n \ge 2
$$

Solving the matching equations implies identifying all momenta and Lorentz structures involved and extracting the corresponding  $\,$  HEFT  $c_i^{\prime}s\,$  coeffs  $\,$ 

3*|*

 $^{\rm 0}$  Leading terms in the large  $\ m_{\rm heavy}$  expansion

14

 $2\Delta\kappa_3|_{2\mathrm{H}}^\mathrm{qal}$  $^{\rm qal}_{\rm 2HDM}+\Delta\kappa_4$  $(4)$ 4*|* qal  $= -\frac{2}{3}c_{\beta}^{2}$  $\sigma$  $2\Delta\kappa_3|_{\rm 2HDM}^{\rm gal}+\Delta\kappa_4|_{\rm 2HDM}^{\rm gal}=-\frac{2}{3}c_{\beta-\alpha}^2$  ,  $\frac{\text{qal}}{2\text{HDM}}=-\frac{2}{3}$ 3  $c_{\beta-\alpha}^2$ 

which is interesting because it is independent on the value of  $\mathcal{A}$  and tan . Then, from Eq. (5.14) and Eq. (5.14) and Eq.

and Eq. (5.18) it is immediate to check that the following relation among the four 's holds in the

The first one is independent on the distribution on  $\mathcal{A}$  and tan . Notice the distribution between the distribution be

here in the 2HDM and in the 2HDM and in the SMEFT was commented at the end of Section 2. For the end of Section 2. For the result of Section 2. For the end of Section 2. For the result of Section 2. For the result of Secti

Interesting correlations found

 **2307.15693, Phys.Rev.D 108 (2023)9, 095013, Arco, Domenech, Herrero, Morales** 

### **Matching amplitudes: HEFT versus SMEFT** DOMENECH, HERRERO, MORALES, and RAMOS PHYS. REV. D 106, 115027 (2022) than in that reference. The relation among the two sets addv $\mathbf{W}$ 20, a11  $\mathbf{W}$  of  $\mathbf{U}$ corresponding contributions from the different channels: the S-channel S-channel, the U-channel, the U-channel, the U-channel, the U-channel, the U-channel, the U-channel, and the U-channel, the U-channel, the U-channel, the U-channel, and the U-channel, the U-channel, and the U contact term. Notice that in this section we use capital letters for the s, t, and u Mandelstam variables. The oneles: HEFT vers i þ **MEFT** a<sup>ð</sup>2<sup>Þ</sup> FIG. 9. Total unpolarized cross section prediction in the HEFT at subprocess level for different parameter values of addVV<sup>1</sup> (left) and FIG. 9. Total unpolarized cross section prediction in the HEFT at subprocess level for different parameter values of addVV<sup>1</sup> (left) and addVV<sup>2</sup> (right). The SM prediction (black) is shown for comparison and corresponds to vanishing EChL coefficients. The energy for which unitarity is also shown. Notice that it only occurs in the second parameter values of  $\mathcal{C}^{\text{max}}$

2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Mo  $\mathsf{False}, \mathsf{Ramos}$ 2208.05452. Phus. Rev. D 106 (2022) 115027. Domenech. Herrero. Morales. Ramos  $,w$  ,  $\nu$  only occurs in the it only occurs in the set  $\alpha$  parameter values of  $\alpha$ . 2208.05452, Phys. Rev. D 106 (2022) 115027, Domenech, Herrero, Morales, Ramos  $\,$ 

A½6&

### Requiring matching of the amplitudes for WW—>HH (similar for ZZ —>HH) Requiring matching of the amplitudes for MMAL HEFT at NLO is given by:  $\lambda$  tching of the amplitudes for WW—>HH (similar for ZZ —>HH) and identifying all momenta and Lore a<br>Uversing<br>Oversing a<br>|
|
| □ <sup>↔</sup> <sup>c</sup>Δ<sup>H</sup>, aHVV <sup>↔</sup> aC, and aHHVV <sup>↔</sup> bC. Here and in the following of the following of the northern formulation  $\mathbf{r}$ the momenta assignments and Lorentz indexes involved in ν απα πασπτη<sub>β</sub>  $\lim_{n \to \infty}$  of the ampl where the chiral-dim  $\mathbf{y}$  and chiral-dim 4 contributions are dim 4 contributions are distributions are distrib given, respectively, by: g un montendo und Lorence scructures inverved  $\rightarrow$ H  $\mathbf{r}$  $H$ IG OF the amplitudes for vvvv—>nn (simil addy comparison is shown for comparison to vanishing  $\mathcal{L}$ above, the suppression in the suppression of  $\mathbf{I}$  and  $\mathbf{I}$  and  $\mathbf{I}$  and  $\mathbf{I}$ dimension d > 4. The complete nonredundant basis of dim THE REF. IN REF. In Ref. 2015 because it is a variation of the Lagrangian  $\mathcal{I}$ Lorentz structures invo of the emplitudes for  $MM/$   $>$  UU (similar for 77  $>$  UU) The two-derivative dim 8 operators in the Lagrangian dim 8 operators in the Lagrangian dim 8 operators in the iomenta and Lorentz structures involved our interest as the dim 6 operators but their contributions ionicita a tz etructures invol for our declined in the local state and the local state model in the local state in the l addavidation is the SM prediction (black) is shown to vanish the shown for contraction  $\sim$ Un discription of version of the political is coefficients addVV<sup>1</sup> and addVV2. <u>————</u> focus on operators that affect mostly the longitudinal  $\mathsf{F}$  $\mathbf{u}$  and  $\mathbf{c}$  are  $\mathbf{u}$  $P_{\text{L}}$  is also shown. Notice that it only occurs in the two ECHL is mainly determined by the two ECHL is ma  $t$ or WW $/$ STRUCTURAS L LES SURCLUIT ES INVOIVEU  $\mathbf{r}$  at the TeV domain. Hence, we have the text of the TeV domain. Hence, we have the text of the TeV domain. Hence, we have imilar tors  $\sqrt{2}$  $\mathbf{u}$ muditude and  $\mathbf{u}$ coefficients addVV<sup>1</sup> and addVV2. I \9III.IIIC A. The relevant SMEFT Lagrangian The SMEFT content is built upon the same field content and the same field content and the same field content a the subsetting  $\epsilon$  $77 \times 1111$  $LL \rightarrow$  $\blacksquare$ The SMET  $\mu$  is  $\mu$ metry as the SM. Contrarily to the SM. Contrarily to the HEFT, and identifying all momenta and Lorentz structures involved 1H) □

5  $\frac{1}{2}$ 

$$
\mathcal{A}^{(2)}|_{S} = \frac{g^{2}}{2} 3 a \kappa_{3} \frac{m_{\text{H}}^{2}}{S - m_{\text{H}}^{2}} \epsilon_{+} \cdot \epsilon_{-}
$$
\n
$$
\mathcal{A}^{(2)}|_{T} = g^{2} a^{2} \frac{m_{\text{W}}^{2} \epsilon_{+} \cdot \epsilon_{-} + \epsilon_{+} \cdot k_{1} \epsilon_{-} \cdot k_{2}}{T - m_{\text{W}}^{2}}
$$
\n
$$
\mathcal{A}^{(2)}|_{U} = g^{2} a^{2} \frac{m_{\text{W}}^{2} \epsilon_{+} \cdot \epsilon_{-} + \epsilon_{+} \cdot k_{2} \epsilon_{-} \cdot k_{1}}{U - m_{\text{W}}^{2}}
$$
\n
$$
\mathcal{A}^{(2)}|_{C} = \frac{g^{2}}{2v^{2}} b \epsilon_{+} \cdot \epsilon_{-}
$$
\n
$$
\mathcal{A}^{(4)}|_{S} = \frac{g^{2}}{2v^{2}} \frac{1}{S - m_{\text{H}}^{2}} (3 \kappa_{3} a_{2} m_{\text{H}}^{2} (S \epsilon_{+} \cdot \epsilon_{-} - 2 \epsilon_{+} \cdot p_{-} \epsilon_{-} \cdot p_{+})
$$
\n
$$
+ 6 \kappa_{3} a_{HW} m_{\text{H}}^{2} ((S - 2 m_{\text{W}}^{2}) \epsilon_{+} \cdot \epsilon_{-} - 2 \epsilon_{+} \cdot p_{-} \epsilon_{-} \cdot p_{+}) - (3 \kappa_{3} a_{H V} v m_{\text{H}}^{4} + a a_{H d d} m_{\text{H}}^{2} (S + 2 m_{\text{H}}^{2})) \epsilon_{+} \cdot \epsilon_{-})
$$
\n
$$
\mathcal{A}^{(4)}|_{T} = \frac{g^{2}}{2v^{2}} \frac{a}{T - m_{\text{W}}^{2}} (a_{a2} (4 m_{\text{W}}^{2} m_{\text{H}}^{2} \epsilon_{+} \cdot \epsilon_{-} + 2 (T + 3 m_{\text{W}}^{2} - m_{\text{H}}^{2}) \epsilon_{+} \cdot k_{1} \epsilon_{-} \cdot k_{2})
$$
\n
$$
- 4 m_{\text{W}}^{2} (\epsilon_{+} \cdot k_{1} \epsilon_{-} \cdot
$$

Solutions to the matching:  $\begin{bmatrix} a-1 & -\frac{1}{4} \end{bmatrix}$ 

$$
\text{3olutions to the matching:} \quad\n \begin{aligned}\n a - 1 &= \frac{1}{4} \frac{v^2}{\Lambda^2} \delta a_{\phi D} & a_{HWW} &= -\frac{v^2}{2m_W^2} \frac{v^2}{\Lambda^2} a_{\phi W} \\
 b - 1 &= \frac{v^2}{\Lambda^2} \delta a_{\phi D} & a_{HHWW} &= -\frac{v^2}{4m_W^2} \frac{v^2}{\Lambda^2} a_{\phi W}\n \end{aligned}
$$

**Requiring matching of the amplitudes for WW—PHI (similar for ZZ—HH)**

\nand identifying all momenta and Lorentz structures involved

\n
$$
\mathcal{A}(WW \to HH)|_{\text{HEFT}} = \mathcal{A}^{(2)} + \mathcal{A}^{(4)} \iff \mathcal{A}(WW \to HH)_{\text{SMEFT}} = \mathcal{A}_{\text{SM}} + \mathcal{A}^{[6]} + \mathcal{A}^{[8]}
$$
\n
$$
\mathcal{A}^{(1)} = \frac{\sum_{k=1}^{n} a_{k} \sum_{k=1}^{n} a_{k} \sum_{k=1}^{n}
$$

![](_page_30_Figure_7.jpeg)

![](_page_30_Figure_8.jpeg)

 $\epsilon$  . The largest contributions to the process under process under the proce

<sup>Λ</sup><sup>2</sup> <sup>δ</sup>aϕ<sup>D</sup>

2m<sup>2</sup> W v2

addinastic Control Co

### from the tadpole tadpole tadpole tadpole tadpole tadpole tadpole tadpole tad not repeat them here. The main  $\sim$  TMMMM δολαμβάν, δολαμβάν,<br>Το διαθέτερα της διαθέτερας του διαθέτερα της δολαμβάν, δολαμβάν, δολαμβάν, δολαμβάν, δολαμβάν, δολαμβάν, δολα NIO WW $\rightarrow$  HH ar CTs in NLO  $WW \rightarrow HH$  and derived RGEs scattering amplitude, and on the other hand it also acts as a source of new counterterms in order to remove the extra

 $M_{\cdot}$ *)*. He M.J. Herrero and R.A Morales, PRD106,073008(2022) 2208.05900  $M$ l Herrero and  $R$  $m_{ij}$ . There is a simple redefinition of the simple redefi

**CTS in NLO** 
$$
WW \rightarrow HH
$$
 and  $6.9$  respectively.  
\n
$$
\delta_{\mu}a = \frac{\Delta_{r-1}}{16\pi^2 2r^3}((a^2 - b)(a - c_4)m_0^2 + a((1 - 3a^2 + 2b)m_W^2 + (1 - a^2)m_2^2)).
$$
\n
$$
\delta_{\mu}b = -\frac{\Delta_{r-1}}{16r^2 2r^3}((a^2 - b)(8a^2 - 2b - 12ax_3 - 3x_4)m_W^2 + (1 - a^2)m_2^2)).
$$
\n
$$
\delta_{\mu}b = -\frac{\Delta_{r-1}}{16r^2 2r^3}((a^2 - b)(8a^2 - 2b - 12ax_3 - 3x_4)m_W^2 + (1 - a^2)x_3m_W^2 + (1 - a^2)x_4m_1^2m_2^2).
$$
\n
$$
\delta_{\mu}c_{\mu}c_{\mu} = -\frac{\Delta_{\mu}c^2}{16r^2 2r^3}((a^2 - b + 9a_0^2 - 6b^2m_W), a^2 - 6b^2m_W),
$$
\n
$$
\delta_{\mu}c_{\mu}c_{\mu} = -\frac{1}{16r^2} \frac{1}{2m_1^2r^2}((a^2 - b + 9a_0^2 - 6a_1)m_W^4 - 3(1 - a^2)x_4m_1^2(m_W^2 + m_2^2))
$$
\n
$$
\delta_{\mu}a_{\mu}c_{\mu} = -\frac{1}{2}(a_2b + 2a^2x_3 + bx_3)(2m_W^2 + m_2^2)),
$$
\n
$$
\delta_{\mu}a_{\mu}c_{\mu} = -\frac{1}{2}(a^2 - b^2)x_4m_1^2 + (1 - a^2)x_4m_1^2(m_W^2 + m_2^2).
$$
\n
$$
\delta_{\mu}a_{\mu} = -\frac{1}{2}(a^2 - b^2)x_4m_1^2 + (1 - a^2)x_4m_1^2 + (1 - a^2)x_4m
$$

 $\alpha$  *Comment:*  $\delta_{\epsilon}$  $\kappa_4$  *and others*  $\delta_{\epsilon}a_i's$  *are fixed in NLO*  $gg \to HH$  *and*  $gg \to HHH$  *(see next)* 

spin limit  $m_W = m$ <br>Others were u<br>before our work  $\sum_{W}$  (before our work) not study study study study study study study to the total study study study of the total study study of the t renormalization of the Lagrangian of the Lagrangian of the Lagrangian. In particular, the Lagrangian of the La renormalization of the ECH was studied in the path of the path  $\sim$ Others were unknown aiðμÞ ¼ ai <sup>þ</sup> <sup>γ</sup>ai before our work (see paper) eri<br>1 Othe <sup>3</sup> <sup>6</sup>4)*m*<sup>4</sup> m known<br>...

![](_page_31_Figure_8.jpeg)

### Comparing SMEFT and HEFT : LO and NLO  $\sim$  relevant sub-process at the relevant sub-process at the relevant sub-particular, in this approximation, we only have  $\sim$ to comparing sivier i and neri: LO and NLO ww **if Comparing SMEFT and HEFT : LO and NLO** WW corrections, or corrections, or considering trees in the constant of our aim is to anal- $WW \rightarrow HH$  subprocess

come prelimin Some prelíminar results (D. Domenech, M. Herrero, R. Morales, M. Ramos, 2022)

$$
\mathcal{L}_{6} \supset c_{\phi^{6}}(\phi^{\dagger}\phi)^{3} + c_{\phi\Box}(\phi^{\dagger}\phi)\Box(\phi^{\dagger}\phi) + c_{\phi D}(\phi^{\dagger}D_{\mu}\phi)((D^{\mu}\phi)^{\dagger}\phi) + c_{\phi W}(\phi^{\dagger}\phi)W^{a}_{\mu\nu}W^{a\mu\nu}
$$

 $\mathcal{L}_8 \supset c_{\mathcal{A}4}^{(1)}(D_{\mu}\phi^{\dagger}D_{\nu}\phi)(D^{\nu}\phi^{\dagger}D^{\mu}\phi) + c_{\mathcal{A}4}^{(2)}(D_{\mu}\phi^{\dagger}D_{\nu}\phi)(D^{\mu}\phi^{\dagger}D^{\nu}\phi) + c_{\mathcal{A}4}^{(3)}(D_{\mu}\phi^{\dagger}D_{\mu}\phi)(D^{\nu}\phi^{\dagger}D^{\nu}\phi) + \dots$  $\varphi$  are the operators which grow with the energy see table 1.1  $\varphi$  and the energy see table 1.1  $\varphi$  $\mathcal{L}_8 \supset c$ (1)  $\frac{(1)}{\phi^4}(D_\mu \phi^\dagger D_\nu \phi)(D^\nu \phi^\dagger D^\mu \phi)+c_{\phi^4}^{(2)}$ 

Agam: the largest boivi deviations in Longitudinal modes  $w_L w_L \rightarrow \pi \pi$  inansverse for the classes  $\Lambda$ modes are less affected. At TeV: dim8 compete with dim6 !! Again: the largest BSM deviations in Longitudinal modes  $W_LW_L\to HH$  Transverse

in each class. Now, the first operator does not grow with the energy so it is interested by interested by inte<br>The first operator does not grow with the energy so it is interested by interested by interested by interested If matching in amplitudes according to behavior with energy: SMEFT dim 8 (6) <—> HEFT chi-dim 4 (2)

![](_page_32_Picture_10.jpeg)

![](_page_32_Picture_12.jpeg)

![](_page_32_Figure_5.jpeg)

- $D_\mu \phi) ((D^\mu \phi)$  $\phi^{\dagger}(\phi) + c_{\phi W}(\phi^{\dagger}\phi)W_{\mu\nu}^{a}W^{a\mu\nu}$  $c_i \equiv a_i / \Lambda^2$
- $\frac{(2)}{\phi^4}(D_\mu \phi^\dagger D_\nu \phi)(D^\mu \phi^\dagger D^\nu \phi) + c^{(3)}_{\phi^4}$  $\frac{d^{(3)}}{\phi^4}(D_\mu \phi^\dagger D_\mu \phi)(D^\nu \phi^\dagger D^\nu \phi) + \dots$  $c_i \equiv a_i / \Lambda^4$ 
	-