

Harnessing Higgs boson kinematics for HEFT constraints

Christoph Englert^{1,*}, Tom Ingebrechtsen Carlson^{2,†}, Jörgen Sjölin^{2,‡} and Michael Spannowsky^{3,§}

¹*School of Physics & Astronomy, University of Glasgow, Glasgow G12 8QQ, United Kingdom*

²*Department of Physics, Stockholm University, 106 91 Stockholm, Sweden*

³*Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, United Kingdom*



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We present a momentum-dependent reweighting strategy to extend current LHC di-Higgs analyses within the κ framework and Standard Model effective field theory into the bosonic sector of the Higgs effective field theory (HEFT). Unlike Standard Model effective field theory, where symmetry constraints tightly correlated multi-Higgs processes, HEFT allows for a broader range of momentum-dependent deviations that can substantially impact di-Higgs kinematics and offer a powerful probe of nonlinear Higgs dynamics. We generalize the interpretation of existing experimental analyses by integrating HEFT operators up to chiral dimension 4 into differential Monte Carlo reweighting. We quantify the sensitivity to representative HEFT operators using multidimensional likelihoods for Run 3 and project the reach at the high-luminosity LHC. Particular emphasis is placed on how different exclusive final states, such as $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$, respond to momentum enhancements and how their complementary event selections drive exclusion limits. We further explore how rare final states, especially four-top production, can provide orthogonal constraints on HEFT-induced modifications, thereby enhancing global sensitivity to new physics effects in the Higgs sector.

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I. INTRODUCTION

As constraints on new physics from Higgs signal strength measurements and exotics' production are becoming increasingly tight at the Large Hadron Collider (LHC), limits on the production of multiple Higgs bosons are still relatively far away from sensitivity to the prediction of the Standard Model (SM). With largely SM-consistent measurements at the energy frontier of the LHC so far, this highlights di-Higgs production as a critical tool for the discovery of phenomena beyond the SM (BSM) in a phenomenological arena where deviations could still be sizable. The dominant gluon fusion mode $gg \rightarrow hh$ is also the most promising avenue to get a direct handle on the Higgs boson's self-coupling, which is understood to be one of the key parameters that could connect the electroweak scale to a more fundamental theory of particle interactions.

Modifications of di-Higgs final states are predicted in many concrete BSM scenarios where coupling modifications are typically accompanied by new resonance structures in the hh final states (see, e.g., [1–4]). Among a range of exclusive final states, the statistically most promising channels are $b\bar{b}b\bar{b}$ [5,6], $b\bar{b}\tau^+\tau^-$ [7], and $b\bar{b}\gamma\gamma$ [8]. Searches for resonant extensions of the SM [9] are complemented by nonresonant effective field theory (EFT) analyses, especially applying Standard Model effective field theory (SMEFT) [10,11], which constructs BSM interactions from the SM particle content, in particular relying on operators derived from the Higgs doublet Φ . In this “linear” framework, the value of Higgs pair production is somewhat limited; SM gauge symmetry tightly correlates the phenomenological implications across different Higgs boson multiplicities. For SM-consistent single-Higgs measurements, $gg \rightarrow hh$ dominantly singles out interactions $\sim(\Phi^\dagger\Phi)^3$ (Φ denotes the SM Higgs doublet), which manifests itself in the departure of the Higgs boson's trilinear coupling from its SM predicted value. [The latter is fixed by the electroweak vacuum expectation value (the W mass) and the observed Higgs mass.] Put differently, “kappa” framework modifications [12] of the Higgs trilinear interaction can be mapped transparently to SMEFT di-Higgs studies when single Higgs boson observables are consistent with the SM.

The expectation of these correlations has continuously shaped the experimental analyses program, principally

*Contact author: christoph.englert@glasgow.ac.uk

†Contact author: tom.ingebrechtsen-carlson@fysik.su.se

‡Contact author: sjolin@fysik.su.se

§Contact author: michael.spannowsky@durham.ac.uk

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through identifying particular signal regions of the mentioned exclusive hh final states and their direct experimental value when viewed against rescaling of the Higgs self-coupling. As motivated as this approach might appear, given the current experimental outcome at the LHC, the imposed theoretical bias could distract from unexpected modifications of the Higgs sector, and this is in the very channel where deviations could be most telling. This may explain the growing interest in “nonlinear” (or Higgs EFT, HEFT) effects in the Higgs sector (e.g., [13–17]) in the recent literature, especially because they provide unique opportunities for the LHC BSM Higgs physics agenda. HEFT highlights the Higgs boson’s properties as a custodial singlet, *a priori* unrelated to the mechanism of electroweak symmetry breaking in a theoretically consistent manner. Several calculations [18–23] have highlighted the flexibility and theoretical appeal of this framework in interpreting Higgs physics data and the correlation of Higgs measurements across different processes. In this context, Higgs pair production is uniquely placed as the first phenomenological instance that could tension the Higgs multiplicity correlations predicted in SMEFT. Are these correlations experimentally observed? And if there is a deviation in the hh pair production approaching the high luminosity (HL) LHC phase, can it clarify its linear vs nonlinear nature? This work aims to provide a step toward finding answers to these questions. We clarify how HEFT-like interactions highlight different exclusive channels to set constraints on momentum-dependent modifications of Higgs self-interactions that do not follow the dominant SMEFT paradigm. Capitalizing on differential reweighting techniques [24], we demonstrate how bosonic HEFT interactions can be straightforwardly included in the existing experimental workflow. Without significant overhead, this enables the generalization of the existing di-Higgs measurement effort toward a more comprehensive study of Higgs interactions that goes beyond the current coupling rescalings. In passing, we also highlight HEFT-specific correlations with other rare LHC final states that could clarify HEFT-like properties beyond Higgs pair production, with a focus on four top production, motivated by Higgs propagator considerations [25].

This work is organized as follows. In Sec. II, we provide details on di-Higgs production in the bosonic HEFT, up to chiral dimension 4. We sketch an implementation of reweighting techniques [24] that enables the experimental

communities to carry out similar analyses with little overhead, using their existing Monte Carlo toolchains. In Sec. III, we turn to expected results by carefully reproducing existing LHC analyses and recasting them in the bosonic HEFT. Special attention is given to representative momentum-dependent enhancements not expected in dimension-6 SMEFT. We also provide an extrapolation to the HL-LHC phase and highlight the relevance of additionally sensitive rare final states for HEFT-like analyses, specifically focusing on four top productions. We provide conclusions in Sec. IV.

II. HEFT HIGGS INTERACTIONS FOR HH PRODUCTION

HEFT interactions have been considered in a range of theoretical studies, in particular after the Higgs boson discovery [17,26,27]. Radiative corrections within this framework have been scrutinized [18,22,23,28–32]. We will focus on Higgs pair production, for which phenomenological studies so far typically restrict interactions to the dominant chiral-dimension two operators. The relation with the SMEFT and, chiefly, the departure from these interactions in the di-Higgs mode, are well documented. In this work, we will present an extended analysis of di-Higgs production with a particular focus on how nontrivial HEFT momentum dependencies can sculpt the experimentally used paradigms that have been established through chiral dimension-2 studies. We aim to clarify the sensitivity potential that can be achieved when such interactions are present, and how experimental analyses beyond SMEFT correlations add value to LHC data interpretation across different channels, in particular in concert with other di-Higgs observation modes such as $pp \rightarrow t\bar{t}t\bar{t}$.

Within the bosonic HEFT, the three-point function that is typically associated with κ_H rescalings receives corrections from a multitude of operators, in particular when chiral dimension 4 interactions are included (see, e.g., [22,32] for overviews). In approaches tailored to experimental analyses based on momentum-dependent interpolations [24], changes to the Higgs two-point and three-point vertices, relevant for the *reducible* three-point function entering the $gg \rightarrow hh$ subamplitudes, can be obtained by a momentum-dependent replacement of the self-coupling

$$h(q^2 \neq m_h^2) \text{---} c_{hhh} \text{---} h \rightarrow \text{---} h \text{---} \text{---} h \text{---} \text{---} h + \text{---} h \text{---} \text{---} h \text{---} \text{---} h, \quad (2.1)$$

where the light-shaded regions denote the 1-PI irreducible insertions and we consider interactions up to chiral dimension 4 (in the on-shell scheme) without including radiative chiral dimension-2 corrections (the impact of these have been comprehensively discussed in [31,32]).¹ Both vertex and propagator contributions, due to their scalar nature, can be effectively parametrized as a momentum-dependent redefinition

$$\begin{aligned}
c_{hh\chi^4}^{\text{HEFT}} = & c_{hhh} \left(1 - \frac{e^2}{2s_W^2} \frac{q^2 + m_h^2}{m_W^2} a_{\square\square} \right) \\
& + \frac{e^2}{12c_W^2 s_W^2} \frac{1}{m_h^2 m_W^2} \{ (q^2 + 2m_h^2) m_W^2 a_{ddZ} \\
& + c_W^2 (q^4 a_{dd\square} + 2m_h^2 [m_W^2 a_{ddW} + m_h^2 (a_{h\square\square} + a_{hdd})] \\
& + q^2 (m_W^2 a_{ddW} + m_h^2 [4a_{h\square\square} + a_{hdd} - 4a_{dd\square}]) \} \},
\end{aligned} \tag{2.2}$$

where on-shell kinematics for two Higgs legs have been enforced as required for the $gg \rightarrow hh$ process. Here, the various a_i are the HEFT coefficients that arise due to nonminimal HEFT operators (the operator structures are explicitly listed in Table 1 of Ref. [32]).

The only relevant scale is therefore the invariant di-Higgs mass $q^2 = m_{hh}^2$. Note that within the bosonic HEFT, this modification, including the specific choice of kinematics, can be imported globally into higher-order QCD corrections (see, e.g., [33]) or leading order jet-merged approaches without loss of generality.

Although the interactions arise from different HEFT coefficients a_i , as it becomes apparent from Eq. (2.2), there are flat directions when their impact on the Higgs-trilinear self-coupling is considered. These cannot be disentangled via Higgs pair production alone. As we are predominantly interested in the impact of non-SM momentum dependences, we will investigate representative choices of a_i that parametrize the different momentum dependencies. Most notably, $a_{\square\square}$ induces a new momentum dependence $\sim q^4$ into the Higgs self-energy, which can significantly shift the results away from the SM(EFT) expectation, see also [34,35]. Further, $a_{dd\square}$ is a prime candidate to introduce telltale momentum enhancements in the hh final states. It is the combination of these operators that will enable us to track the importance of different experimental selections in setting HEFT limits in the future.²

¹In the spirit of EFT each HEFT coefficient needs to be treated as an independent input parameter. Our results can therefore also be understood as a qualitative representation of the value of di-Higgs measurements and their nonstandard momentum dependence in such a comprehensive program going beyond SMEFT.

²These operators are also the most important ones contributing to the structures of Eq. (2.2).

III. IMPLICATIONS FOR THE LHC

A. Toward experimental analyses of HEFT hh shapes

The momentum dependencies introduced by HEFT operators are capable of sculpting the m_{hh} distribution in ways that extend beyond, e.g., the benchmarking that has been performed in the context of the Higgs Cross Section Working Group [12]. Representative shape examples are provided in Fig. 1, demonstrating a wide range of phenomenological outcomes that should predominantly inform the following discussion rather than be considered realistic HEFT parameter choices from the point of view of perturbativity.

As a proxy for more inclusive selection, we focus in the following on the $b\bar{b}\gamma\gamma$ mode, which we contrast with $b\bar{b}b\bar{b}$. $b\bar{b}b\bar{b}$ relies on harder selections to combat backgrounds and is therefore a good candidate to highlight correlation changes that become relevant in HEFT. Throughout, we focus on gluon fusion and neglect weak boson fusion (for a recent analysis in the context of HEFT, we refer the reader to [23,31,36,37]).

As a $2 \rightarrow 2$ process, the hard scattering of $gg \rightarrow hh$ is described by the Mandelstam parameters s (the invariant di-Higgs mass m_{hh}) and t (scattering angle). The HEFT interactions considered here dominantly modify the s dependence; however, the interference with box Feynman topologies can imply nontrivial, correlated t sensitivity. Close to the threshold, angular information that relates to t does not give rise to additional discriminating sensitivity, Fig. 2, but angular dependencies become more relevant for larger invariant masses, Fig. 3, and the $b\bar{b}b\bar{b}$ channel that accesses this boosted regime by construction.

Focussing on $b\bar{b}\gamma\gamma$ first, we base our analysis on the results of Ref. [38]. We have validated³ our results against the reported Run 2 results, on which [38] itself builds as detailed in Ref. [40]. A flat signal efficiency, computed as the average of the signal efficiency for SM and $\kappa_\lambda = 10$, is applied. These points for evaluating the signal efficiency are chosen because they are provided by ATLAS in Refs. [40,41], and their adequacy is evaluated by reproducing the reported limits. Further, we consider systematic uncertainties of 7% and 10% related to the background. These values are chosen as they reproduce the ATLAS Run 2 and HL projections and are consistent with the uncertainties quoted in the corresponding data tables of [41,42].

Our analysis framework is binned with two bins as $m_{hh} \in [250, 350, 1400]$ GeV and two bins in $|\cos\theta^*|$ with edges $[0, 0.5, 1.0]$. The bins in $|\cos\theta^*|$ are considered to enable better compatibility with the limits from ATLAS

³As part of this validation, we have regenerated the dominant $b\bar{b}\gamma\gamma$ continuum background with MadGraph5_aMC@NLO [39], rescaled to have the same signal yield as the ATLAS result a function of m_{hh} as given in the paper after all selections. This enables us to go beyond m_{hh} as a single discriminant, see below.

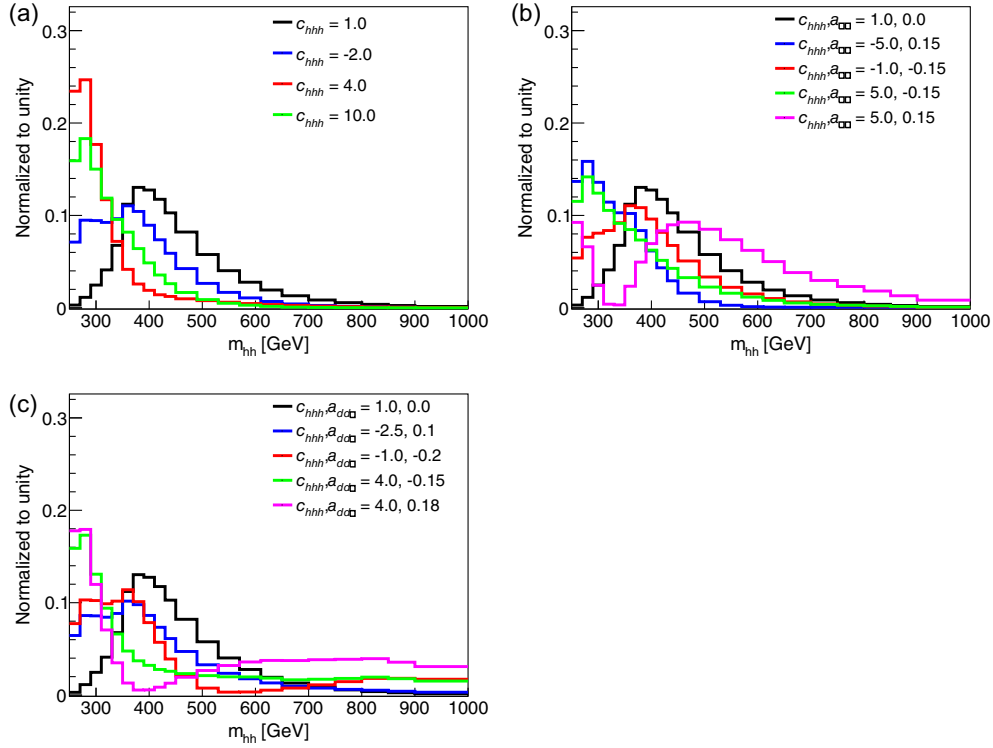


FIG. 1. Representative distributions for different values of the (phenomenology-dominating) HEFT coefficients of Eq. (2.2), demonstrating that a wide range of momentum-dependent shape modifications of the crucial m_{hh} distribution can be achieved.

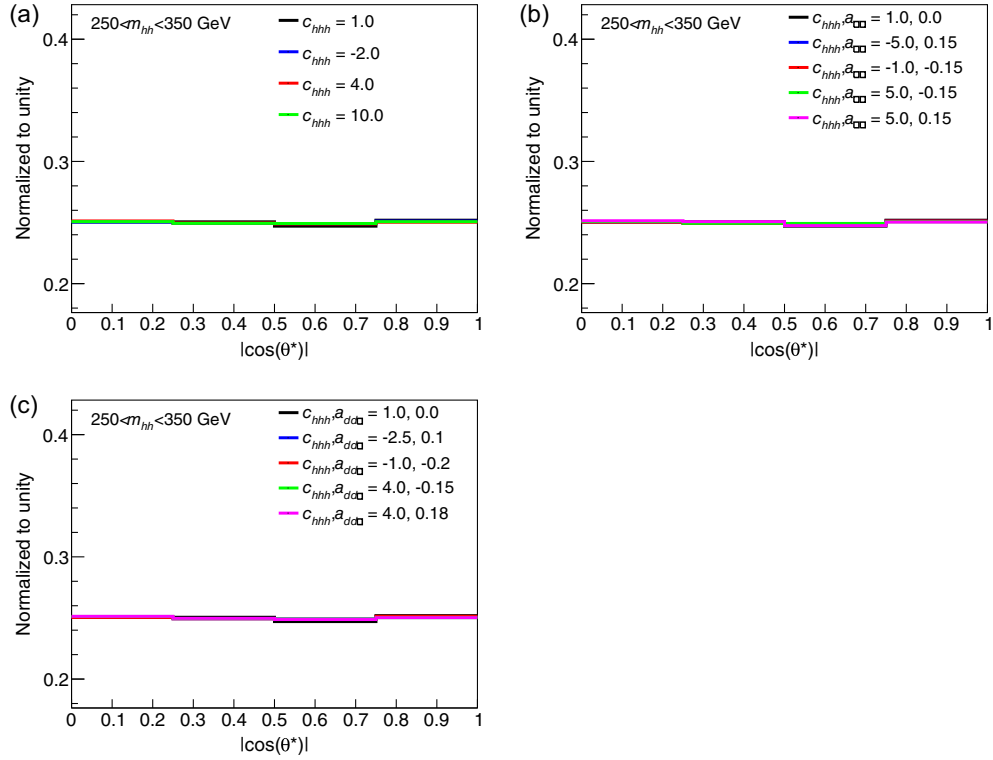


FIG. 2. Representative distributions of the h scattering angle for different values of the (phenomenology-dominating) HEFT coefficients of Eq. (2.2), similar to Fig. 1. Here we focus on the threshold region of the hh system that drives inclusive sensitivity. No discernible variation is visible as a function of the HEFT coefficients considered in this work.

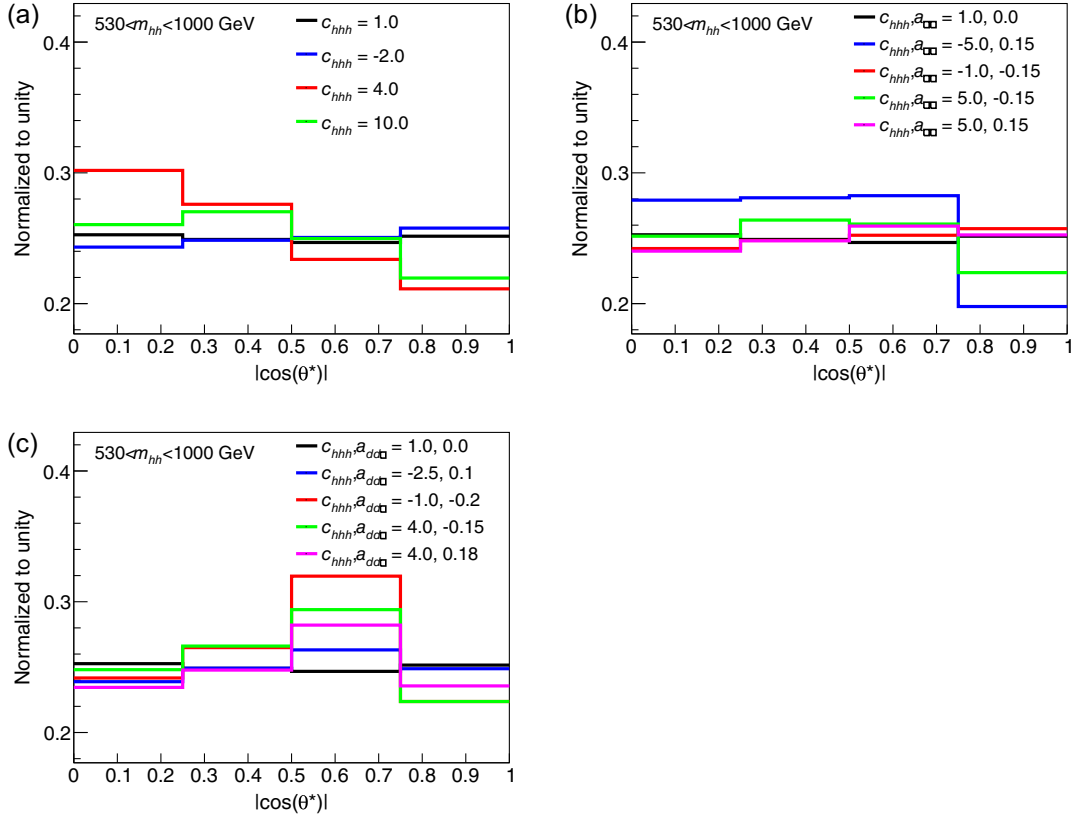


FIG. 3. Identical to Fig. 2, but focusing on the boosted h region at large invariant di-Higgs masses. Correlations probe the interplay of the triangle diagrams with the box topologies for $gg \rightarrow hh$ production at one loop, thus providing additional sensitivity that can be exploited in a multidimensional likelihood approach.

when performing the validations; however, they do not have a big impact beyond achieving a better validation of the inclusive selection. For the HL $b\bar{b}\gamma\gamma$ projections, the cross section of the background and the signal is scaled by a factor 1.18 according to Ref. [41], in accordance with Large Hadron Collider (LHC) Working Group recommendations.

Turning to $b\bar{b}b\bar{b}$, we again validate our analysis against Ref. [43], reproducing the relevant Run 2 results. We also performed cross-checks against Ref. [44]. Similar to $b\bar{b}\gamma\gamma$, we consider a two-dimensional likelihood build from binned m_{hh} and $|\Delta\eta_{hh}|$ distributions.⁴ A flat signal efficiency, calculated based on the average SM and for $\kappa_\lambda = 6$ signal efficiency, is applied, similar to $b\bar{b}\gamma\gamma$. We apply a flat signal efficiency, averaging the SM and $\kappa_\lambda = 6$ efficiencies as detailed above. Systematic uncertainties of 1% or 2.5% are assigned to the background. As for our choices in the $b\bar{b}\gamma\gamma$ channel, these values reproduce the ATLAS Run 2 and HL projections. For the HL-LHC signal and background are rescaled by 1.18 [44].

⁴The variable X_{hh} used in [43] is omitted because it is a reconstruction-level quantity not suitable for the analysis presented here.

Throughout this work, we obtain limits from a likelihood-ratio test based on Wilks's theorem [45]. The likelihoods are assumed to be Gaussian, and the histogram bins are treated as uncorrelated. This approach largely emulates procedures on the experimental side (see, e.g., [40,43] for additional information and discussion). For this work, we will limit ourselves to reporting the results of the statistical analysis.

As the bosonic HEFT can be implemented technically via a replacement of c_{hhh} , we can expect approximate cancelations when we compare momentum-dependent modifications with momentum-independent ones. Depending on the search channel, the event count is characterized by an average invariant di-Higgs mass, which can then lead to cancelations in the limit setting. We demonstrate this in Fig. 4. In particular, $a_{\square\square}$ can be canceled by an appropriate choice of c_{hhh} , leaving a wide area unconstrained when hh is considered in isolation at Run 3. The relatively enhanced momentum dependence imparted by $a_{dd\square}$ makes such cancelations less efficient. As expected, the harder $b\bar{b}b\bar{b}$ selection compared to the more inclusive $b\bar{b}\gamma\gamma$ makes it particularly effective in setting limits on momentum-enhanced contributions. This comes at the price of a slightly higher impact from systematics,

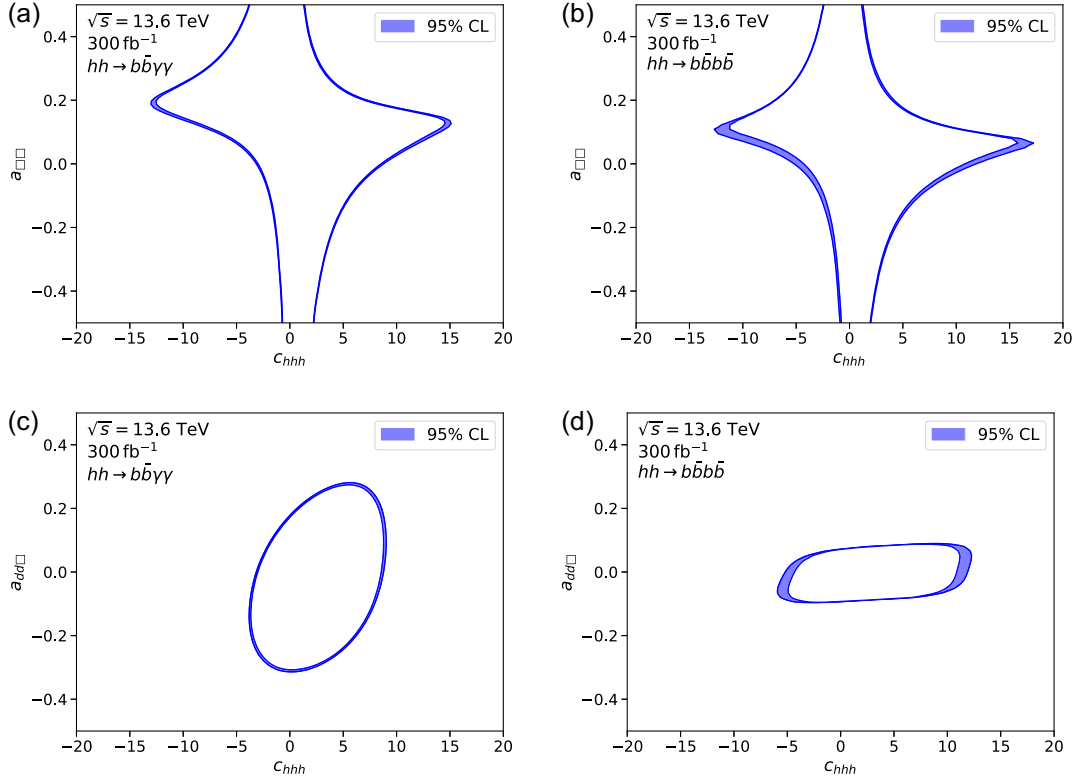


FIG. 4. Expected exclusion contours resulting from our analysis for the LHC Run 3 in the c_{hhh} and $a_{\square\square}$, $a_{dd\square}$ planes, respectively, for inclusive $b\bar{b}\gamma\gamma$ (including systematics ranging from 7% to 10%) (a),(c) and $b\bar{b}b\bar{b}$ (systematics varying from 1% for 2.5% (b),(d) (for details see the main text).

which we represent by the width of the exclusion contour in Fig. 4.

The systematics do limit the sensitivity somewhat, but statistical uncertainties play a more dominant role for Run 3. This also becomes apparent from Tables I and II, which provide individual limits for comparison. The latter

improves significantly when we turn to the HL-LHC phase (Tables III and IV), where we see a broad improvement in sensitivity in Fig. 5. Constraints will improve by factors of up to two, particularly highlighting the boosted regime accessed in $b\bar{b}b\bar{b}$ that comes under better statistical control for the 3/ab data set.

TABLE I. Run 3 one-dimensional 95% CL limits and systematic uncertainties for $b\bar{b}\gamma\gamma$.

Coefficient	95% CL limit	σ_{syst}
$a_{\square\square}$	$[-1.17, 0.50]$	7%
$a_{\square\square}$	$[-1.19, 0.52]$	10%
$a_{dd\square}$	$[-0.27, 0.17]$	7%
$a_{dd\square}$	$[-0.28, 0.17]$	10%

TABLE II. Run 3 one-dimensional 95% CL limits and systematic uncertainties for $b\bar{b}b\bar{b}$.

Coefficient	95% CL limit	σ_{syst}
$a_{\square\square}$	$[-0.97, 0.50]$	1%
$a_{\square\square}$	$[-0.99, 0.54]$	2.5%
$a_{dd\square}$	$[-0.081, 0.063]$	1%
$a_{dd\square}$	$[-0.081, 0.063]$	2.5%

TABLE III. HL one-dimensional 95% CL limits and systematic uncertainties for $b\bar{b}\gamma\gamma$.

Coefficient	95% CL limit	σ_{syst}
$a_{\square\square}$	$[-0.91, 0.26]$	7%
$a_{\square\square}$	$[-0.96, 0.31]$	10%
$a_{dd\square}$	$[-0.20, 0.10]$	7%
$a_{dd\square}$	$[-0.21, 0.11]$	10%

TABLE IV. HL one-dimensional 95% CL limits and systematic uncertainties for $b\bar{b}b\bar{b}$.

Coefficient	95% CL limit	σ_{syst}
$a_{\square\square}$	$[-0.63, 0.23]$	1%
$a_{\square\square}$	$[-0.67, 0.32]$	2.5%
$a_{dd\square}$	$[-0.045, 0.025]$	1%
$a_{dd\square}$	$[-0.045, 0.025]$	2.5%

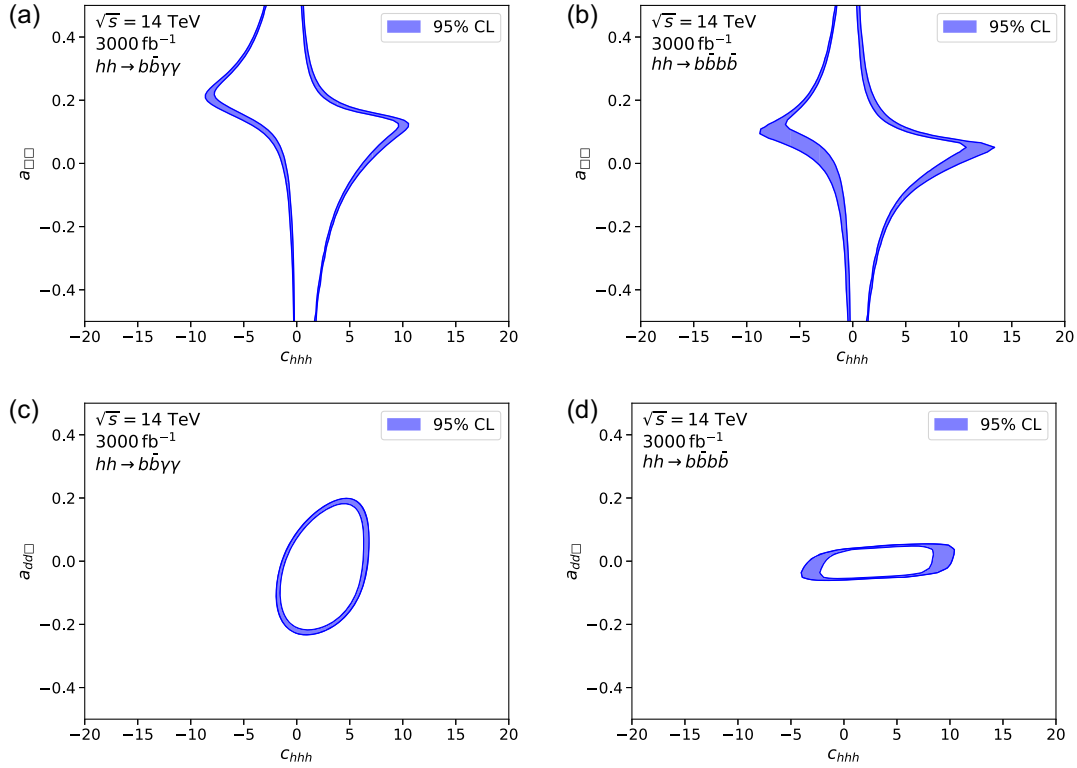


FIG. 5. Expected exclusion contours resulting from our analysis for the HL-LHC in the c_{hhh} and $a_{\square\square}$, $a_{dd\square}$ planes, respectively, for inclusive $b\bar{b}\gamma\gamma$ (including systematics ranging from 7% to 10%) (a),(c) and $b\bar{b}b\bar{b}$ (systematics varying from 1% for 2.5% (b),(d) (for details see the main text).

B. Relevance of four top production

As the bosonic HEFT introduces considerably more parameters to the hh final states, additional complementary information needs to be included to tighten constraints. With $a_{\square\square}$ modifying Higgs propagation off-shell, two LHC processes are singled out, where such a behavior is observable. Firstly, in $gg \rightarrow ZZ$, the Higgs contribution remains sizable even for large ZZ invariant masses due to unitarity cancellations expected in the SM [46,47]. This provides an avenue for setting constraints on $a_{\square\square}$ as discussed recently in [35]. Notably, momentum enhancements of a similar type in SMEFT cancel to leading order in this final state [25]. The second process is four top production, which is particularly sensitive to electroweak contributions [48] and has been highlighted as a versatile tool for BSM discovery [49–54]. We can expect four top production to reach good sensitivity toward the HL-LHC phase as it is currently systematics limited with experiments displaying impressive progress in enhancing their sensitivity beyond naive extrapolations (see also [55]). Hence, we expect to reach very good sensitivity to $a_{\square\square}$ when these processes are scrutinized from this angle, and we will consider their interplay with the $gg \rightarrow hh$ discussion above in more detail.

Obtaining the four top estimate using MadGraph5_aMC@NLO [39] through a modified Helas

implementation [56] that evaluates the Higgs two-point function in the on-shell scheme [22,23]. Our analysis of four top quark production is based on Ref. [57], and we combine hh and $t\bar{t}t\bar{t}$ final states to obtain constraints in the c_{hhh} , $a_{\square\square}$ plane, Figs. 6 and 7. Both at the LHC Run 3, as well as for the HL-LHC phase, we see good sensitivity improvements compared to hh in isolation: The vertical $a_{\square\square}$ direction gets tightly constrained even for the $b\bar{b}\gamma\gamma$ selection, where such constraints are not achievable in hh alone at the HL-LHC.⁵ This highlights four top production not only as a very relevant channel in determining more general deviations from the SM than modeled by SMEFT at dimension 6, but also its interplay in setting constraints on more general new physics models when considered in concert with other processes that will unfold their full statistical power in the HL phase, such as hh production.

A relevant question in this context arises when we view the constraints against the requirement of unitarity. Put differently, if the constraints reside in the nonperturbative coupling choice regime, they will not constrain theories that are linked to the HEFT parameter space via a *perturbative* matching. To enable the latter, the relevant amplitude parts tested in the particular collider process under consideration

⁵It is worthwhile pointing out that the constraints obtained this way on $a_{\square\square}$ are tighter than the one obtained from $gg \rightarrow ZZ$ [35].

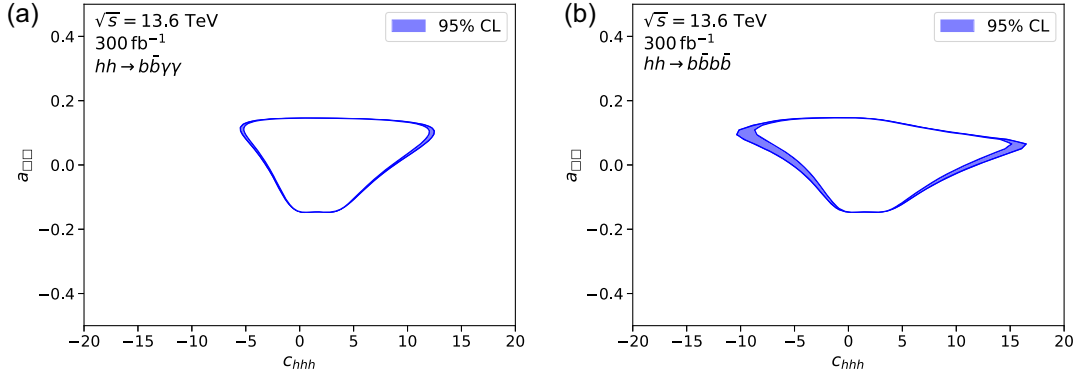


FIG. 6. Similar to Fig. 4, but including constraints from four top measurements at Run 3. The external constraint from the four tops on $a_{\square\square}$ is included as a Gaussian constraint with $\sigma = 0.06$ centered at zero.

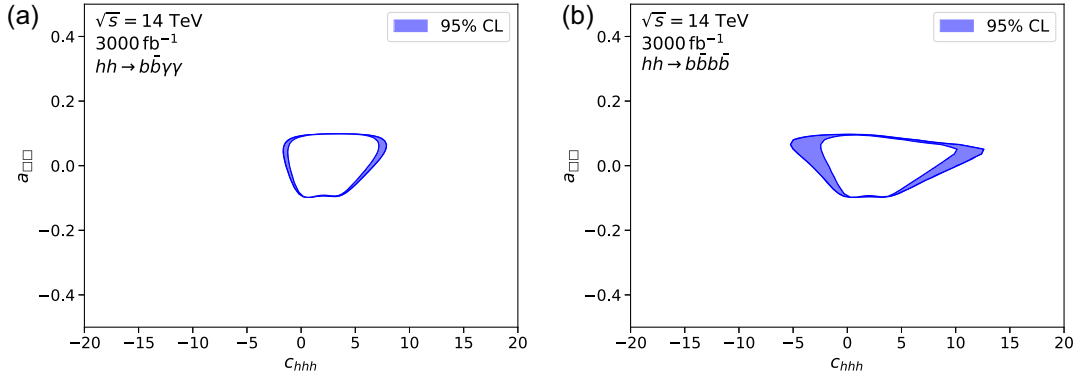


FIG. 7. Similar as Fig. 5, but including constraints from four top measurements at HL. The external constraint from four tops on $a_{\square\square}$ is included as a Gaussian constraint with $\sigma = 0.04$ centered at zero.

must stay within perturbative limits over the energy range that is probed experimentally by this very process. This then enables a perturbative matching at the maximum scale probed by the experiment. By performing a partial wave analysis, we have verified that the $th \rightarrow th$ subamplitudes giving rise to Fig. 5 remain unitary for the constrained parameter region up to an energy of around 1.7 TeV unless cancellations are probed at large (and unrealistic) values $a_{\square\square} > 0.2$. ($a_{dd\square}$ is more susceptible to unitarity violation as it sources highly non-SM momentum dependencies.) This invariant mass will not be efficiently probed at the HL-LHC in nonresonant hh final state searches, related to elastic th scattering via crossing. In the SM, we expect around three events in the $b\bar{b}b\bar{b}$ channel in this region before acceptance cuts and detector effects are taken into account. We can therefore be confident that the constraints obtained at the HL-LHC can be used perturbatively; however, of course, strongly depending on the scenario that they are used to put limits on.

IV. SUMMARY AND CONCLUSIONS

Di-Higgs final states, particularly in the dominant gluon fusion production mode, remain a central target for probing the structure of the Higgs sector and searching for new

physics beyond the Standard Model. While SMEFT and κ -framework approaches have guided most current experimental strategies, these frameworks impose rigid correlations between Higgs interactions across different multiplicities. In contrast, HEFT allows for more general, momentum-dependent deformations that can decouple di-Higgs observables from single-Higgs measurements and thereby offer a richer phenomenological landscape.

In this work, we proposed and implemented a momentum-dependent reweighting scheme that enables the inclusion of bosonic HEFT interactions up to chiral dimension 4 into existing Monte Carlo workflows. This strategy allows for the reinterpretation of current and future di-Higgs searches in a more general EFT framework, without requiring significant changes to experimental analyses. We showed that HEFT operators, particularly $a_{\square\square}$ and $a_{dd\square}$, can introduce substantial shape modifications to the di-Higgs invariant mass distribution m_{hh} , especially in boosted regimes. These modifications can result in differential sensitivities across final states such as $b\bar{b}b\bar{b}$ and $b\bar{b}\gamma\gamma$, which we analyzed using a multidimensional likelihood approach.

For LHC Run 3, we provided one-dimensional 95% confidence level bounds on key HEFT coefficients, demonstrating that momentum-enhanced operators like $a_{dd\square}$ can

be effectively constrained in channels with harder event selections. In contrast, $a_{\square\square}$, which can partially mimic standard κ -type modifications, remains more challenging to isolate in inclusive channels unless accompanied by shape-sensitive observables. These challenges are alleviated at the HL-LHC, where improved statistical precision and access to boosted kinematic regimes—particularly in the $b\bar{b}b\bar{b}$ final state—lead to significantly tighter bounds. For example, the HL-LHC can constrain $a_{dd\square}$ at the percent level, highlighting the potential to resolve nonlinear dynamics in the Higgs sector.

Moreover, we emphasized the value of combining di-Higgs measurements with other rare LHC final states. In particular, four-top production $pp \rightarrow t\bar{t}t\bar{t}$ provides sensitivity to HEFT coefficients such as $a_{\square\square}$, which enter via modified Higgs propagators. We showed that including current and projected four-top constraints significantly improves exclusion contours in the $(c_{hhh}, a_{\square\square})$ plane, even in channels where di-Higgs sensitivity is limited. This underscores the complementarity of rare processes in building a comprehensive picture of BSM Higgs interactions.

Thus, the study shows that general momentum-dependent effects encoded in HEFT can leave distinctive imprints in di-Higgs kinematics accessible with current experimental tools. Furthermore, we outline a strategy to

explore nonlinear Higgs dynamics at the LHC and beyond by utilizing simple reweighting techniques and combining information across multiple final states and rare processes. Applying this strategy to a high-luminosity extrapolation, the LHC will provide a relatively detailed picture of nonlinear effects in the Higgs sector, in particular when viewed in concert with other rare final states such as four top production that highlight off-shell Higgs properties.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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