

Role of the top Yukawa coupling in triple Higgs production at the LHC

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In this Letter, I quantify the effects of varying the top Yukawa coupling in the process of the production of three Higgs bosons at the LHC. Modifications of the coupling within experimentally observed ranges have a sizeable impact on the total cross section, but they do not have large effects on the distributions of the invariant mass of the three-Higgs system and other global observables.

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Introduction. The determination of the parameters of the Higgs boson is a key aspect in high-energy physics [1,2]. The couplings associated with the Higgs self-interactions are, in this context, the subject of an intense investigation, both theoretical and experimental. Measuring their values would be crucial to understanding the fundamental properties of the Higgs boson and the nature of the electroweak phase transition [3,4].

Two processes are fundamental for this quest: namely, the production of two and of three Higgs bosons. Any observed deviation from the Standard Model (SM) expectation could provide precious insights about possible new-physics scenarios [5]. While the former process is sensitive to the trilinear self-interaction of the Higgs boson, the latter is sensitive to both trilinear and quadrilinear interactions. A combination of measurements for these processes can then be used to precisely determine the corresponding couplings. Furthermore, when considering higher orders or effective field theory operators, the single-Higgs and double-Higgs processes can be used to constrain the trilinear [6–9] and quadrilinear [10,11] couplings, respectively. It is worth mentioning that while double- and triple-Higgs production both dominantly occur via gluon fusion (ggF), they can also be realized via vector-boson fusion (VBF), opening the possibility to probe Higgs couplings with SM gauge bosons as well [12–15].

For this reason, multiple studies have appeared in literature to provide predictions, interpretation, and phenomenological aspects for HH [3,16–27] and HHH [5,28–40]

at the LHC or future colliders. From the experimental side, many searches have started to probe the HH process [41–54] and, more recently, the HHH one [55–57]. While no observation has been made so far, constraints have been obtained on the Higgs self-coupling modifiers, defined as $\kappa_{3,4} = \lambda_{3,4}/\lambda_{3,4}^{\text{SM}}$, as well as on other coupling modifiers in the κ framework [58,59].

One aspect which, to my knowledge, has been so far neglected in triple-Higgs production searches is the dependence of the results on the value of the Yukawa couplings, and in particular, the top one, y_t . The large mass of the top quark with respect to all the other particles of the SM makes it one of the most likely candidates to probe new-physics scenarios. Its mass might receive contributions from new sectors (such as new scalars or mixing with vectorlike top partners), potentially disentangling the SM correspondence between m_t and y_t —i.e., $y_t^{\text{SM}} = \sqrt{2}m_t/v$, where v is the Higgs vacuum expectation value. It is thus reasonable to relax the assumption that the coupling between the Higgs boson and the top quark corresponds to the SM prediction and consider y_t as a free parameter within its measured uncertainty windows. In the HHH process, y_t appears in multiple topologies: considering pentagon and box diagrams, for example, the squared amplitudes are proportional to y_t^6 and $\lambda_3^2 y_t^4$, respectively, and their interference is proportional to $\lambda_3 y_t^5$. Any deviation from the SM value will therefore potentially affect in a sizeable way the cross section and the kinematical properties of the three Higgs bosons being produced.

The dependence of results on the top Yukawa has been largely explored for single- and double-Higgs production [60–66]. For triple Higgs, a study has been performed in the context of a large set of anomalous interactions [67]. Estimating the impact of variations of y_t on the triple-Higgs cross section, on the measured bounds on $\kappa_{3,4}$, and on the shape of relevant kinematical distribution is the scope of this study.

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Model and analysis strategy. In order to isolate and analyze the relative contributions of set of diagrams, and to greatly simplify the determination of results for different values of the couplings, I will use the deconstruction method already introduced in Refs. [68,69] for studying new-physics contributions to the di-Higgs process. This method consists in writing the cross section of the process as a weighted sum of contributions proportional to unique products of couplings and simulating separately each term of the sum, such that the same Monte Carlo (MC) samples can be used to reconstruct the cross sections and kinematical distributions for different values of the couplings using a semi-analytical approach and without further simulations. For the triple-Higgs process, in the absence of new-physics particles propagating in the topologies, the only couplings which appear are those in the Higgs potential, λ_3 and λ_4 , kept as free parameters, and the Yukawa couplings y_t and y_b . However, as will be shown in the following, deviations in y_b within experimental uncertainties give negligible contributions to the HHH cross section, and therefore they will be neglected in this analysis.

The deconstruction method requires us to identify deviations from the SM parameters through separate terms in the Lagrangian, which then reads

$$\mathcal{L} \supset (\lambda^{\text{SM}} + \delta\lambda_3)vh^3 + \frac{1}{4}(\lambda^{\text{SM}} + \delta\lambda_4)h^4 + (y_t^{\text{SM}} + \delta y_t)h\bar{t}t + \text{H.c.}, \quad (1)$$

where λ^{SM} and y_t^{SM} are, respectively, the SM values of the coupling in front of the $(\Phi^\dagger\Phi)^2$ operator in the Higgs potential and of the top Yukawa coupling, while the quantities labeled with δ are the deviations associated with the corresponding quantities. The mapping in terms of coupling modifiers in the κ framework is trivial: $\kappa_{3,4} = 1 + \delta\lambda_{3,4}/\lambda^{\text{SM}}$ and $\kappa_t = 1 + \delta y_t/y_t^{\text{SM}}$.

With this formalism, the triple-Higgs cross section is deconstructed into

$$\sigma_{HHH} = \sum_{i=0}^6 \sum_{j=0}^4 \sum_{k=0}^2 (\delta y_t)^i (\delta\lambda_3)^j (\delta\lambda_4)^k \hat{\sigma}_{ijk}, \quad (2)$$

where $\hat{\sigma}_{ijk}$ are reduced cross sections obtained by setting all δ couplings to 1, and the $i = j = k = 0$ term corresponds to the SM cross section. If any of the coupling modifications is equal to 0, the convention $0^0 \equiv 1$ is assumed to account for the absence of that modification in the amplitude squared. The indices in the sums correspond in practice to the number of vertices associated with each coupling in the amplitudes squared, and one term of the sum can correspond to multiple subprocesses. For example, the term $(\delta y_t)^2 (\delta\lambda_3) (\delta\lambda_4) \hat{\sigma}_{211}$ corresponds to different interference contributions, such as those represented in Fig. 1. The upper limits of the sum represent the maximum number of times a given coupling can appear in any amplitude squared.

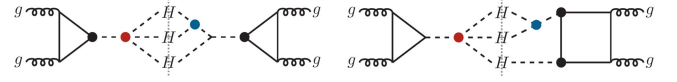


FIG. 1. Examples of interference topologies associated with the deconstruction term $(\delta y_t)^2 (\delta\lambda_3) (\delta\lambda_4) \hat{\sigma}_{211}$. The couplings which receive modifications are explicitly indicated.

From a technical point of view, each term of the deconstruction can be individually simulated with MG5_aMC [70,71], using a UFO [72] model in which each new coupling is associated with a different coupling order and using a specific syntax, such as those described in Refs. [68,69].¹ Each simulation has been performed at 13 TeV using the NNPDF4.0 set of PDFs at LO [73,74], with 10^5 MC events per term. Considering that not all the terms in Eq. (2) are allowed (for example, there cannot be a term with one trilinear and two quadrilaterals in the amplitude squared), this leads to a total of just 40 MC event samples (which increases to 108 when including modifications to the bottom Yukawa), which have been used to perform the analysis for any value of the coupling modifiers. The table of cross sections used for this study is available as an auxiliary file in the Supplemental Material [75].

Results. Computing the cross sections by varying the top Yukawa within the 2σ windows of the ATLAS and CMS fits [1,2,76], it is possible to evaluate how the κ_3 and κ_4 bounds are modified. This is shown in Fig. 2.

When the Yukawa coupling becomes larger than the observed central values, the bounds on the parameters of the Higgs potential get stronger, and their contour shrinks toward the SM values, but while the bounds on the triple-Higgs production still remain rather weak, variations due to the top Yukawa are significant. To better assess the impact of such variations, the HHH bound obtained by applying a K -factor of 1.7 to the SM central value, corresponding to QCD NNLO corrections [36], is also shown for comparison. The uncertainties on the top Yukawa couplings have a comparable effect to applying higher-order corrections, and are therefore worth being included in future searches.

On the other hand, the bound on the cross section for di-Higgs production strongly limits the allowed region for κ_3 . In Fig. 2, an estimate of the κ_t -dependent variations of the κ_3 bound derived from the di-Higgs cross section upper limit reported in Ref. [45] is included. The variations of the HH bound have been obtained using the deconstructed samples for the ggF di-Higgs production process produced for Refs. [68,69] with the same method described above.²

¹The model is available in the FeynRules repository at https://github.com/FeynRules/Models/tree/main/HHH_deconstruction.

²The ATLAS search [45] sums the ggF and VBF channels, but since the VBF is relatively small, I applied their upper limit only to the ggF process to estimate the impact of κ_t on the κ_3 constraint.

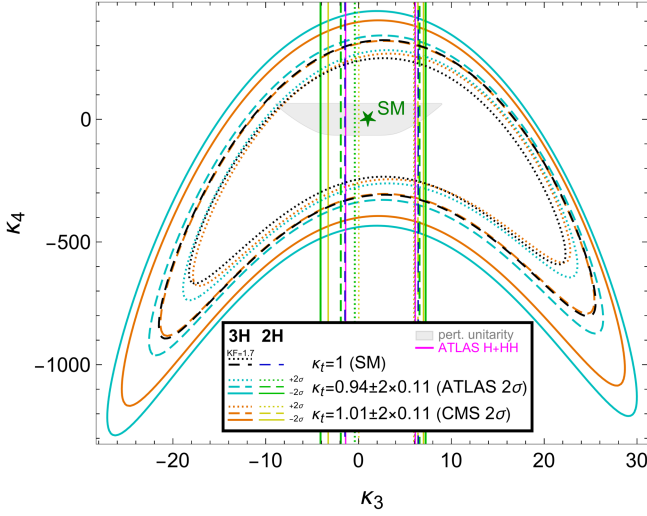


FIG. 2. Bounds for the κ_3 and κ_4 coupling modifiers for variations of the top Yukawa couplings within the 2σ windows of the ATLAS and CMS fits [1,2,76], for the triple-Higgs production process, using the 59 fb upper limit on the HHH cross section from Ref. [55]. Estimates of the limits for κ_3 as functions of the top Yukawa, using the results of Ref. [45] for HH , are shown as vertical lines. For both HHH and HH , the bounds obtained assuming $k_t = 1$ (unmodified SM value) are shown for reference. For HHH , the $k_t = 1$ bound is also shown assuming a QCD NNLO K -factor of 1.7 [36]. The bounds on κ_3 obtained by ATLAS by combining H and HH measurements with relaxed assumptions about all κ modifiers [77] are also shown. The perturbative unitarity region [38,78] is overlaid.

The ATLAS Collaboration has also determined the limits on κ_3 using a combination of H and HH production [77]. This result is also shown because it is obtained by relaxing the assumptions of $\kappa_{t,b,\tau,V} = 1$, effectively probing the full parameter space in the Higgs couplings.

Examples of cross sections for specific benchmarks—i.e., the SM central point and the four corners of the perturbative unitarity window [38,78]—are shown in Table I.

It is interesting to notice the large differences for the $\kappa_{3,4} = 1$ point. An increase of 20% from $\kappa_t = 1$ leads to a

TABLE I. Cross sections in fb for specific choices of $\kappa_{3,4}$, at the corners of the perturbative unitarity window and at the SM central point, for variations of κ_t around 20% of the central value. The percent differences of the cross sections relative to the values with $\kappa_t = 1$ are shown in parentheses.

$\{\kappa_3, \kappa_4\}$	κ_t		
	0.8	1	1.2
$\{-8, 50\}$	15.950 (−45%)	29.196	49.073 (68%)
$\{6, 50\}$	1.862 (−20%)	2.338	2.661 (14%)
$\{1, 1\}$	0.007 (−80%)	0.034	0.122 (255%)
$\{-5, -50\}$	0.695 (−62%)	1.845	4.186 (127%)
$\{3, -50\}$	1.125 (−44%)	2.002	3.235 (62%)

much larger cross section, which might even lead to some visible events in the high-luminosity phase of the LHC (HL-LHC). On the other hand, if the top Yukawa is smaller than its SM prediction, it will be very challenging to observe this process before the construction of a future collider. As mentioned previously, variations of the bottom Yukawa coupling lead to negligible effects. For example, variations of κ_b in the range $\{0.8, 1.2\}$ with all the other modifiers set to 1 lead to relative variations of the cross section with respect to the SM central value in the range $\{-0.04\%, 0.03\%\}$.

Deviations from the SM value of y_t also have a potential effect on differential distributions, by changing the weights of the terms proportional to δy_t in Eq. (2). It is useful to quantify the size of such effects in order to help in designing future searches which might be sensitive to potentially different kinematic properties of the final states.

In Fig. 3, the normalized distributions for the invariant mass of the tri-Higgs system and the scalar sum of the transverse momenta of the three Higgs bosons before their

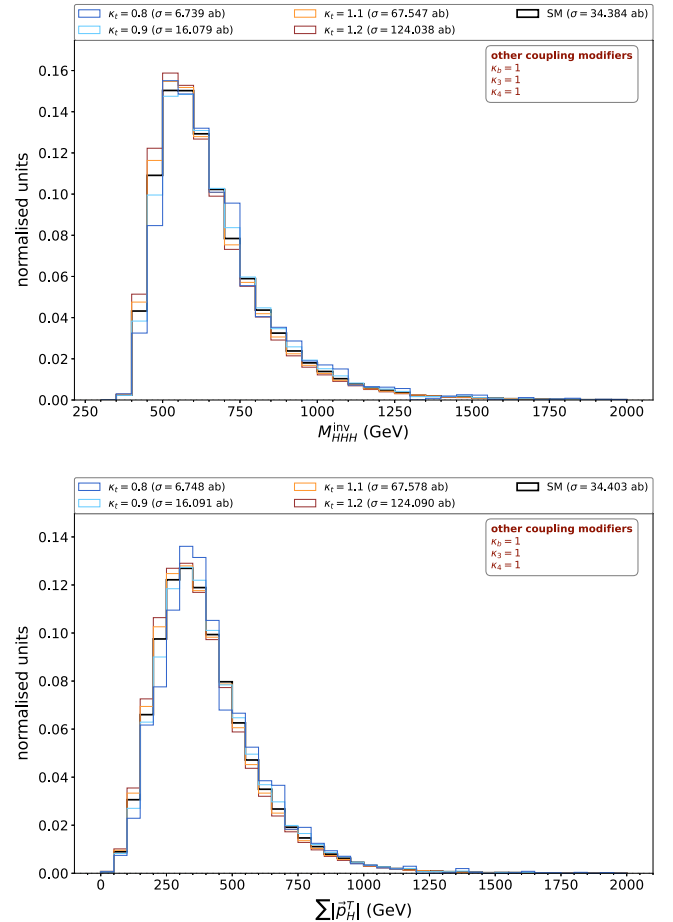


FIG. 3. Normalized differential distributions for the invariant mass of the tri-Higgs system (left) and the scalar sum of their transverse momenta (right), for different values of the top Yukawa coupling around $\pm 20\%$ of its SM value, and with all other couplings set to the SM value.

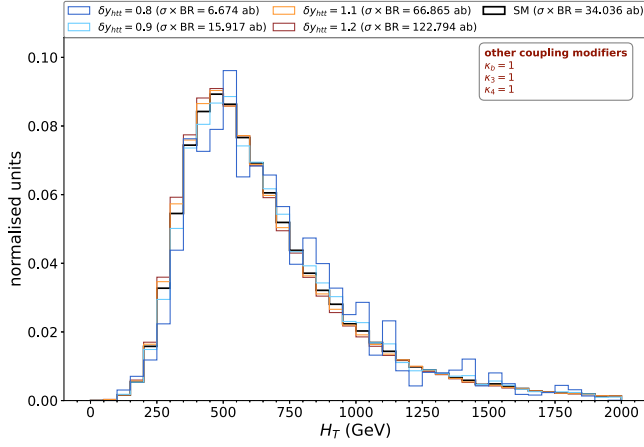


FIG. 4. Normalized differential distributions for the scalar sum of the transverse momenta of hadronic objects in the final state after Higgs decays for $\kappa_t = 1 \pm 0.2$ and $\kappa_{b,3,4} = 1$.

decays are shown for different values of the top Yukawa coupling modifiers κ_t , with a $\pm 20\%$ variation around the SM central value, while keeping all the other coupling modifiers at 1.

The number of expected physical events at a given luminosity can be easily calculated for each distribution from the cross sections provided in the legends. At the HL-LHC with a 3 ab^{-1} integrated luminosity, for example, more than 300 tri-Higgs events would be generated if the top Yukawa were 20% larger than the SM value. What matters here, however, is that the shapes of the distributions are not largely different, meaning that the kinematics of the final state is not strongly affected if the top Yukawa deviates from its central value within the measured uncertainties. There is a slight tendency for a faster-rising distribution when the Yukawa is larger than the SM value in both distributions, but this difference is rather mild. The main effect of varying y_t is thus a rescaling of the distribution with $y_t = y_t^{\text{SM}}$. The shape of the distributions depends in a much stronger way on the coupling modifiers associated with the Higgs potential, $\kappa_{3,4}$, but varying the top Yukawa in the same 20% range around a given choice of these parameters (at least within the perturbative unitarity region [38,78]) does not significantly change the shapes. Therefore, at LO, the dependence on the top Yukawa coupling is mostly limited to an almost flat rescaling of the M_{HHH}^{inv} and $\sum |\vec{p}_H^T|$ distributions.

The same conclusion holds when considering kinematical distributions after object reconstruction. To test this, the

MC events have been hadronized through Pythia8 [79], the object reconstruction has been made with FastJet [80] via MadAnalysis5 [81], and various distributions have been tested, including the invariant mass of the six bottom final-state and other global observables, such as the scalar sum of the transverse momenta of hadronic objects (shown in Fig. 4) or the missing transverse energy, and no significant dependence has been observed.

A detailed analysis for different final states after the decay of the Higgs bosons, with detector effects and comparison with the backgrounds, is beyond the explorative nature of this letter, and it is left for studies of HHH for future colliders.

Conclusions. This analysis explored the role of the top Yukawa coupling in the process of production of three Higgs bosons at the LHC. Variations of the coupling within the 2σ windows around the measured values from global fits of Higgs observations by ATLAS and CMS lead to sizeable corrections to the HHH cross section, which significantly modify the current constraints on the trilinear and quadrilinear self-couplings of the Higgs boson. By setting all Higgs couplings to their SM values, if the top Yukawa is larger than the SM value by a factor 1.2, the HHH LO cross section increases from 0.034 fb to 0.12 fb, a +255% variation, while it drops to 7 ab (−80%) if the Yukawa is 0.8 smaller. Investigating the differential distribution of the invariant mass of the three-Higgs system and the distributions of other global observables, also at object reconstruction level after the decays of the Higgs bosons, revealed that modifications of the top Yukawa do not lead to sizeable shape deviations, at least at LO. This simple study shows that increasing the precision of the top Yukawa determination is paramount for assessing the possibility to observing the HHH process at HL-LHC or future hadron colliders, and for improving the precision on the determination of the Higgs self-couplings through this process.

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Data availability. The data that support the findings of this article are openly available [75].

- [1] G. Aad *et al.* (ATLAS Collaboration), A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery, *Nature (London)* **607**, 52 (2022).
- [2] A. Tumasyan *et al.* (CMS Collaboration), A portrait of the Higgs boson by the CMS experiment ten years after the discovery, *Nature (London)* **607**, 60 (2022).
- [3] A. Noble and M. Perelstein, Higgs self-coupling as a probe of electroweak phase transition, *Phys. Rev. D* **78**, 063518 (2008).
- [4] L. Biermann, C. Borschensky, C. Englert, M. Mühlleitner, and W. Naskar, Double and triple Higgs boson production to probe the electroweak phase transition, *Phys. Rev. D* **110**, 095012 (2024).
- [5] H. Abouabid *et al.*, HHH whitepaper, *Eur. Phys. J. C* **84**, 1183 (2024).
- [6] G. Degrandi, P. P. Giardino, F. Maltoni, and D. Pagani, Probing the Higgs self coupling via single Higgs production at the LHC, *J. High Energy Phys.* **12** (2016) 080.
- [7] M. Gorbahn and U. Haisch, Indirect probes of the trilinear Higgs coupling: $gg \rightarrow h$ and $h \rightarrow \gamma\gamma$, *J. High Energy Phys.* **10** (2016) 094.
- [8] W. Bizon, M. Gorbahn, U. Haisch, and G. Zanderighi, Constraints on the trilinear Higgs coupling from vector boson fusion and associated Higgs production at the LHC, *J. High Energy Phys.* **07** (2017) 083.
- [9] F. Maltoni, D. Pagani, A. Shivaji, and X. Zhao, Trilinear Higgs coupling determination via single-Higgs differential measurements at the LHC, *Eur. Phys. J. C* **77**, 887 (2017).
- [10] W. Bizoń, U. Haisch, and L. Rottoli, Constraints on the quartic Higgs self-coupling from double-Higgs production at future hadron colliders, *J. High Energy Phys.* **10** (2019) 267.
- [11] S. Borowka, C. Duhr, F. Maltoni, D. Pagani, A. Shivaji, and X. Zhao, Probing the scalar potential via double Higgs boson production at hadron colliders, *J. High Energy Phys.* **04** (2019) 016.
- [12] A. Belyaev, A. C. A. Oliveira, R. Rosenfeld, and M. C. Thomas, Multi Higgs and vector boson production beyond the standard model, *J. High Energy Phys.* **05** (2013) 005.
- [13] E. Arganda, C. Garcia-Garcia, and M. J. Herrero, Probing the Higgs self-coupling through double Higgs production in vector boson scattering at the LHC, *Nucl. Phys.* **B945**, 114687 (2019).
- [14] A. S. Belyaev, P. B. Schaefer, and M. C. Thomas, Precise test of Higgs boson properties via triple Higgs boson production in vector boson fusion at future colliders, *Phys. Rev. D* **99**, 015030 (2019).
- [15] F. A. Dreyer and A. Karlberg, Vector-boson fusion Higgs pair production at N³LO, *Phys. Rev. D* **98**, 114016 (2018).
- [16] E. W. N. Glover and J. J. van der Bij, Higgs boson pair production via gluon fusion, *Nucl. Phys.* **B309**, 282 (1988).
- [17] D. A. Dicus, C. Kao, and S. S. D. Willenbrock, Higgs boson pair production from gluon fusion, *Phys. Lett. B* **203**, 457 (1988).
- [18] T. Plehn, M. Spira, and P. M. Zerwas, Pair production of neutral Higgs particles in gluon-gluon collisions, *Nucl. Phys.* **B479**, 46 (1996).
- [19] S. Dawson, S. Dittmaier, and M. Spira, Neutral Higgs boson pair production at hadron colliders: QCD corrections, *Phys. Rev. D* **58**, 115012 (1998).
- [20] S. Kanemura, S. Kiyoura, Y. Okada, E. Senaha, and C. P. Yuan, New physics effect on the Higgs self-coupling, *Phys. Lett. B* **558**, 157 (2003).
- [21] J. Baglio, A. Djouadi, R. Gröber, M. M. Mühlleitner, J. Quevillon, and M. Spira, The measurement of the Higgs self-coupling at the LHC: Theoretical status, *J. High Energy Phys.* **04** (2013) 151.
- [22] M. J. Dolan, C. Englert, and M. Spannowsky, New physics in LHC Higgs boson pair production, *Phys. Rev. D* **87**, 055002 (2013).
- [23] S. Borowka, N. Greiner, G. Heinrich, S. P. Jones, M. Kerner, J. Schlenk *et al.*, Higgs boson pair production in gluon fusion at next-to-leading order with full top-quark mass dependence, *Phys. Rev. Lett.* **117**, 012001 (2016).
- [24] M. Grazzini, G. Heinrich, S. Jones, S. Kallweit, M. Kerner, J. M. Lindert *et al.*, Higgs boson pair production at NNLO with top quark mass effects, *J. High Energy Phys.* **05** (2018) 059.
- [25] J. Alison *et al.*, Higgs boson potential at colliders: Status and perspectives, *Rev. Phys.* **5**, 100045 (2020).
- [26] M. L. Mangano, G. Ortona, and M. Selvaggi, Measuring the Higgs self-coupling via Higgs-pair production at a 100 TeV p-p collider, *Eur. Phys. J. C* **80**, 1030 (2020).
- [27] J. Baglio, F. Campanario, S. Glaus, M. Mühlleitner, J. Ronca, M. Spira, and J. Streicher, Higgs-pair production via gluon fusion at hadron colliders: NLO QCD corrections, *J. High Energy Phys.* **04** (2020) 181.
- [28] T. Plehn and M. Rauch, The quartic Higgs coupling at hadron colliders, *Phys. Rev. D* **72**, 053008 (2005).
- [29] T. Binoth, S. Karg, N. Kauer, and R. Ruckl, Multi-Higgs boson production in the standard model and beyond, *Phys. Rev. D* **74**, 113008 (2006).
- [30] B. Fuks, J. H. Kim, and S. J. Lee, Probing Higgs self-interactions in proton-proton collisions at a center-of-mass energy of 100 TeV, *Phys. Rev. D* **93**, 035026 (2016).
- [31] A. Papaefstathiou and K. Sakurai, Triple Higgs boson production at a 100 TeV proton-proton collider, *J. High Energy Phys.* **02** (2016) 006.
- [32] C.-Y. Chen, Q.-S. Yan, X. Zhao, Y.-M. Zhong, and Z. Zhao, Probing triple-Higgs productions via $4b2\gamma$ decay channel at a 100 TeV hadron collider, *Phys. Rev. D* **93**, 013007 (2016).
- [33] B. Fuks, J. H. Kim, and S. J. Lee, Scrutinizing the Higgs quartic coupling at a future 100 TeV proton-proton collider with taus and b-jets, *Phys. Lett. B* **771**, 354 (2017).
- [34] W. Kilian, S. Sun, Q.-S. Yan, X. Zhao, and Z. Zhao, New physics in multi-Higgs boson final states, *J. High Energy Phys.* **06** (2017) 145.
- [35] A. Papaefstathiou, G. Tetlalmatzi-Xolocotzi, and M. Zaro, Triple Higgs boson production to six b -jets at a 100 TeV proton collider, *Eur. Phys. J. C* **79**, 947 (2019).
- [36] D. de Florian, I. Fabre, and J. Mazzitelli, Triple Higgs production at hadron colliders at NNLO in QCD, *J. High Energy Phys.* **03** (2020) 155.
- [37] M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini, and X. Zhao, Measuring the quartic Higgs self-coupling at a multi-TeV muon collider, *J. High Energy Phys.* **09** (2020) 098.
- [38] P. Stylianou and G. Weiglein, Constraints on the trilinear and quartic Higgs couplings from triple Higgs production at the LHC and beyond, *Eur. Phys. J. C* **84**, 366 (2024).

- [39] U. Haisch, A. Sankar, and G. Zanderighi, A new probe of the quartic Higgs self-coupling, [arXiv:2505.20463](#).
- [40] B. Fuks, A. Papaefstathiou, and G. Tetlalmatzi-Xolocotzi, Extracting Higgs self-coupling constraints through triple Higgs boson production at future hadron colliders, *Eur. Phys. J. C* **85**, 1309 (2025).
- [41] G. Aad *et al.* (ATLAS Collaboration), Search for nonresonant pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state in pp collisions at $s = 13$ TeV with the ATLAS detector, *Phys. Rev. D* **108**, 052003 (2023).
- [42] G. Aad *et al.* (ATLAS Collaboration), Search for non-resonant Higgs boson pair production in the $2b + 2\ell + E_T^{\text{miss}}$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* **02** (2024) 037.
- [43] G. Aad *et al.* (ATLAS Collaboration), Search for the nonresonant production of Higgs boson pairs via gluon fusion and vector-boson fusion in the $b\bar{b}\tau^+\tau^-$ final state in proton-proton collisions at $s = 13$ TeV with the ATLAS detector, *Phys. Rev. D* **110**, 032012 (2024).
- [44] G. Aad *et al.* (ATLAS Collaboration), Search for non-resonant Higgs boson pair production in final states with leptons, taus, and photons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* **08** (2024) 164.
- [45] G. Aad *et al.* (ATLAS Collaboration), Combination of searches for Higgs boson pair production in pp collisions at $s = 13$ TeV with the ATLAS detector, *Phys. Rev. Lett.* **133**, 101801 (2024).
- [46] G. Aad *et al.* (ATLAS Collaboration), Search for pair production of boosted Higgs bosons via vector-boson fusion in the $b\bar{b}b\bar{b}$ final state using pp collisions at $s = 13$ TeV with the ATLAS detector, *Phys. Lett. B* **858**, 139007 (2024).
- [47] G. Aad *et al.* (ATLAS Collaboration), Study of Higgs boson pair production in the $HH \rightarrow b\bar{b}\gamma\gamma$ final state with 308 fb $^{-1}$ of data collected at $\sqrt{s} = 13$ TeV and 13.6 TeV by the ATLAS experiment, [arXiv:2507.03495](#).
- [48] A. M. Sirunyan *et al.* (CMS Collaboration), Combination of searches for Higgs boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **122**, 121803 (2019).
- [49] A. M. Sirunyan *et al.* (CMS Collaboration), Search for nonresonant Higgs boson pair production in final states with two bottom quarks and two photons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **03** (2021) 257.
- [50] A. Tumasyan *et al.* (CMS Collaboration), Search for Higgs boson pair production in the four b quark final state in proton-proton collisions at $s = 13$ TeV, *Phys. Rev. Lett.* **129**, 081802 (2022).
- [51] A. Tumasyan *et al.* (CMS Collaboration), Search for Higgs boson pairs decaying to WW^*WW^* , $WW^*\tau\tau$, and $\tau\tau\tau\tau$ in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2023) 095.
- [52] A. Tumasyan *et al.* (CMS Collaboration), Search for nonresonant Higgs boson pair production in final state with two bottom quarks and two tau leptons in proton-proton collisions at $s = 13$ TeV, *Phys. Lett. B* **842**, 137531 (2023).
- [53] A. Hayrapetyan *et al.* (CMS Collaboration), Search for Higgs boson pair production in the $b\bar{b}W^+W^-$ decay mode in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2024) 293.
- [54] CMS Collaboration, Combination of searches for nonresonant Higgs boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV, [arXiv:2510.07527](#).
- [55] G. Aad *et al.* (ATLAS Collaboration), Search for triple Higgs boson production in the $6b$ final state using pp collisions at $s = 13$ TeV with the ATLAS detector, *Phys. Rev. D* **111**, 032006 (2025).
- [56] CMS Collaboration, Search for nonresonant triple Higgs boson production in the six b -quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV, Report No. CMS-PAS-HIG-24-012, 2025.
- [57] CMS Collaboration, Search for triple Higgs production in Run 2 data of CMS using 4 $b2\gamma$ final state, Report No. CMS-PAS-HIG-24-015, 2025.
- [58] A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. Passarino *et al.* (LHC Higgs Cross Section Working Group), LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle, [arXiv:1209.0040](#).
- [59] J. R. Andersen *et al.* (LHC Higgs Cross Section Working Group), Handbook of LHC Higgs cross sections: 3. Higgs properties, [arXiv:1307.1347](#).
- [60] G. Li, L.-X. Xu, B. Yan, and C. P. Yuan, Resolving the degeneracy in top quark Yukawa coupling with Higgs pair production, *Phys. Lett. B* **800**, 135070 (2020).
- [61] J. Davies, G. Mishima, K. Schönwald, M. Steinhauser, and H. Zhang, Higgs boson contribution to the leading two-loop Yukawa corrections to $gg \rightarrow HH$, *J. High Energy Phys.* **08** (2022) 259.
- [62] M. Mühlleitner, J. Schlenk, and M. Spira, Top-Yukawa-induced corrections to Higgs pair production, *J. High Energy Phys.* **10** (2022) 185.
- [63] G. Heinrich, S. Jones, M. Kerner, T. Stone, and A. Vestner, Electroweak corrections to Higgs boson pair production: The top-Yukawa and self-coupling contributions, *J. High Energy Phys.* **11** (2024) 040.
- [64] A. M. Sirunyan *et al.* (CMS Collaboration), Measurements of $t\bar{t}H$ production and the CP structure of the Yukawa interaction between the Higgs boson and top quark in the diphoton decay channel, *Phys. Rev. Lett.* **125**, 061801 (2020).
- [65] G. Aad *et al.* (ATLAS Collaboration), CP properties of Higgs boson interactions with top quarks in the $t\bar{t}H$ and tH processes using $H \rightarrow \gamma\gamma$ with the ATLAS detector, *Phys. Rev. Lett.* **125**, 061802 (2020).
- [66] G. Aad *et al.* (ATLAS Collaboration), Probing the CP nature of the top-Higgs Yukawa coupling in $t\bar{t}H$ and tH events with $H \rightarrow b\bar{b}$ decays using the ATLAS detector at the LHC, *Phys. Lett. B* **849**, 138469 (2024).
- [67] A. Papaefstathiou and G. Tetlalmatzi-Xolocotzi, Multi-Higgs boson production with anomalous interactions at current and future proton colliders, *J. High Energy Phys.* **06** (2024) 124.
- [68] S. Moretti, L. Panizzi, J. Sjölin, and H. Waltari, Deconstructing squark contributions to di-Higgs production at the LHC, *Phys. Rev. D* **107**, 115010 (2023).

- [69] S. Moretti, L. Panizzi, J. Sjölin, and H. Waltari, Deconstructing resonant Higgs boson pair production at the LHC: Effects of colored and neutral scalars in the NMSSM test case, *Phys. Rev. D* **112**, 055005 (2025).
- [70] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [71] R. Frederix, S. Frixione, V. Hirschi, D. Pagani, H. S. Shao, and M. Zaro, The automation of next-to-leading order electroweak calculations, *J. High Energy Phys.* **07** (2018) 185.
- [72] C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, and T. Reiter, UFO—The universal FeynRules output, *Comput. Phys. Commun.* **183**, 1201 (2012).
- [73] R. D. Ball *et al.* (NNPDF Collaboration), The path to proton structure at 1% accuracy, *Eur. Phys. J. C* **82**, 428 (2022).
- [74] A. Buckley, J. Ferrando, S. Lloyd, K. Nordström, B. Page, M. Rüfenacht, M. Schönherr, G. Watt, LHAPDF6: Parton density access in the LHC precision era, *Eur. Phys. J. C* **75**, 132 (2015).
- [75] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/5ssz-3nh7> for hhh deconstructed cross sections.
- [76] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [77] G. Aad *et al.* (ATLAS Collaboration), Constraints on the Higgs boson self-coupling from single- and double-Higgs production with the ATLAS detector using pp collisions at $s = 13$ TeV, *Phys. Lett. B* **843**, 137745 (2023).
- [78] L. Di Luzio, R. Gröber, and M. Spannowsky, Maxi-sizing the trilinear Higgs self-coupling: How large could it be?, *Eur. Phys. J. C* **77**, 788 (2017).
- [79] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, P. Ilten, and C. O. Rasmussen, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [80] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, *Eur. Phys. J. C* **72**, 1896 (2012).
- [81] E. Conte, B. Fuks, and G. Serret, MadAnalysis5 5, a user-friendly framework for collider phenomenology, *Comput. Phys. Commun.* **184**, 222 (2013).