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Non-Resonant Di-Higgs Searches at the Large Hadron Collider with the CMS Experiment †

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Abstract: Investigating the production of Higgs boson pairs (HH) at the LHC provides critical insights into the self-interaction properties of the Higgs boson, representing an essential verification of the Standard Model and contributing to our understanding of the Higgs boson properties. This work highlights the latest findings from the CMS collaboration on HH production measurements. These searches include different final states and integrate data collected by the CMS experiment at a center-of-mass energy of 13 TeV.

Keywords: high-energy particle physics; Higgs physics; CMS; HH; self-coupling

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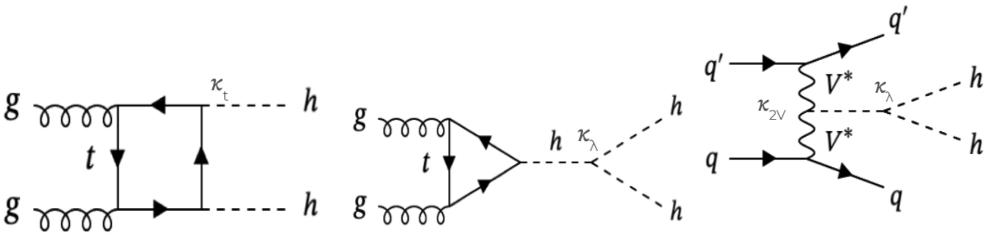
1. Introduction

The discovery of the Higgs boson in 2012 [1,2] marked a major achievement in the field of particle physics, confirming the existence of the Higgs field and providing a mechanism for understanding how elementary particles acquire mass. This discovery, while a cornerstone of the Standard Model (SM) of particle physics, raised many other questions: many of its properties remain poorly understood, particularly the self-coupling of the Higgs field, which governs the interactions between Higgs bosons.

The Higgs self-coupling is a key parameter in the Higgs potential [3], a function that describes the energy configuration of the Higgs field. Di-Higgs production, in which two Higgs bosons are produced simultaneously, is a direct way to probe the Higgs self-coupling. Although this process is rare, it provides a unique opportunity to measure the self-coupling parameter λ_{HHH}, which describes the interaction between two Higgs bosons. Theoretical models, such as those involving supersymmetry or other extensions of the SM, predict possible modifications to the Higgs self-coupling, making this a good area of investigation.

To explore these deviations, a coupling modifier κ_λ is introduced. It scales the strength of the Higgs self-interaction λ_{HHH} relative to its SM value, where $\kappa_\lambda = 1$ corresponds to the SM prediction. Any deviation from this value could indicate Beyond Standard Model (BSM) contributions. The SM calculation for this coupling gives a value of $\lambda_{HHH} \approx 0.13$.

The primary mechanism for Higgs boson pair production at the LHC is gluon fusion, with two leading-order Feynman diagrams contributing to this process, shown in Figure 1. These include a box diagram (Figure 1a) and a triangle diagram (Figure 1b), the latter of which is sensitive to the λ_{HHH} coupling and the top-quark Yukawa coupling, mediated via a top-quark loop. In the SM, these diagrams interfere destructively, yielding a gluon-gluon Higgs–Higgs production cross-section of 31.05 fb at 13 TeV center-of-mass energy. The next most significant production mechanism is vector-boson fusion (Figure 1c), with a production cross section of approximately 1.73 fb at 13 TeV. The inclusive HH production cross section (around 32 fb) is thus quite small, making it difficult to measure this process at the LHC.



(**a**) (**b**) (**c**)

Figure 1. The main Feynman diagrams for the production of two Higgs bosons. (**a**) Box diagram; (**b**) triangle diagram; and (**c**) vector fusion process.

Searches for this process at CMS have focused on measuring the di-Higgs production cross-section using both resonant and non-resonant search strategies. Resonant searches look for potential new particles decaying into Higgs boson pairs, while non-resonant searches aim to measure the SM cross-section and put limits on κ_λ while exploring possible deviations from it. However, significant challenges remain, including the rarity of di-Higgs production events at the LHC energy and the need for increasingly precise measurements.

This work summarizes the current efforts to probe the Higgs self-coupling through di-Higgs production, focusing on the ongoing non-resonant research at the LHC with the CMS experiment. I will review the key channels being explored and outline future research directions in this area.

2. The CMS Detector

The analyses discussed in this work are based on data collected by the CMS experiment [4] at the LHC between 2016 and 2018, corresponding to an integrated luminosity of 138 fb^{-1} at a center-of-mass energy of 13 TeV. The CMS detector is a general purpose experiment, featuring a 3.8 T superconducting solenoid, silicon trackers ($|\eta| < 2.5$), electromagnetic and hadronic calorimeters ($|\eta| < 3$), forward calorimeters ($|\eta| < 5$), and muon chambers ($|\eta| < 2.4$). A two-level trigger system, including a hardware-based Level-1 trigger and a High-Level Trigger employing fast reconstruction algorithms, reduces the event rate to 1 kHz. The data are analyzed using simulations that incorporate pileup, parton shower [5–7], and detector response [8]. Sophisticated algorithms are employed to reconstruct events and identify particles [9].

3. Di-Higgs Searches

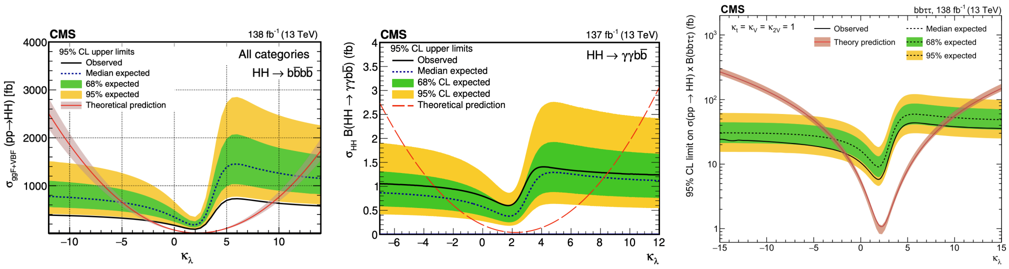
3.1. Key Non-Resonant Channels

The sensitivity to non-resonant di-Higgs production is driven by three channels, namely, $HH \to bbbb$, $HH \to bb\tau\tau$, and $HH \to bb\gamma\gamma$. These channels are particularly effective due to their relatively large branching ratios and clean experimental signature, which allow for better separation from background processes, making them ideal for probing the Higgs self-coupling.

- HH→4b channel: This channel, where both Higgs bosons decay to bottom quarks, has a large branching ratio of 33%. However, it is limited by significant background interference from multi-jet and $t\bar{t}$ processes. Advanced techniques such as DeepJet [10] b-tagging and fitting methods allowed one to reduce the background and place the 95% CL limits on κ_λ between −2.3 and 9.4 [11], as shown in Figure 2a.
- HH→bb$\gamma\gamma$ channel: With a smaller branching ratio of 0.26%, this channel benefits from a cleaner signature, thanks to the excellent mass resolution of the diphoton

system. Techniques like Deep Neural Networks (DNNs) and Boosted Decision Trees (BDTs) are used to suppress the background. The 95% CL limits for this channel are between -3.3 and 8.5 [12], as shown in Figure 2b.

- HH→bb$\tau\tau$ channel: With a branching ratio of 7.3%, this channel is sensitive but faces background from DY, $t\bar{t}$, and QCD multi-jet events. The limits on κ_λ in this channel are observed to be between -1.7 and 8.7 at 95% CL [13], as shown in Figure 2c.



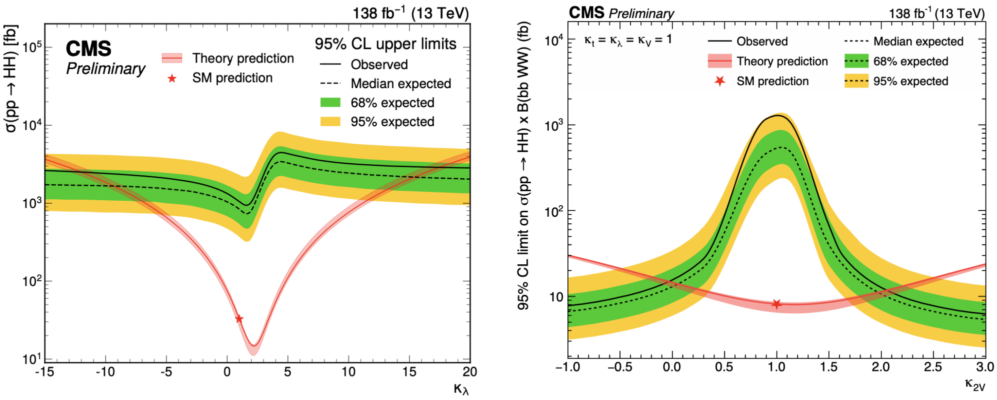
(**a**) (**b**) (**c**)

Figure 2. Cross−section dependence on κ_λ for the key non-resonant di-Higgs production channels. (**a**) $4b$ channel [11]; (**b**) $bb\gamma\gamma$ channel [12]; and (**c**) $bb\tau\tau$ channel [13].

3.2. Less Sensitive Searches

Rarer decay channels have also been explored to extend the reach of the search:

- HH→$\tau\tau\gamma\gamma$ channel: This channel, with a very small branching ratio of 0.027%, combines the clean diphoton signature with the relatively larger branching ratio of Higgs boson to tau decays. Backgrounds are modeled using analytic fits, and a double Crystal Ball function is used to describe the signal. A simultaneous maximum likelihood fit is performed on the $m_{\gamma\gamma}$ distributions in the analysis categories. The observed 95% CL constraints on κ_λ exclude values outside the interval $[-13, 18]$, as shown in Figure 3a. These results are complementary to those found in alternative final states, such as the search with two bottom quarks and two photons, where the observed upper limit was 7.7 times the SM prediction. The inclusion of the $\tau\tau\gamma\gamma$ channel further strengthens the overall search sensitivity and provides valuable constraints in combination with other final states studied by CMS [14].
- HH→bbVV channel: Involving the decay of one Higgs to bottom quarks and the other to vector bosons, this channel benefits from a branching ratio of 13%. Despite challenges from QCD multi-jet background processes, the use of novel event classification methods, such as the Particle Transformer [15], provides promising limits on the κ_{2V} parameter. Specifically, the analysis utilizes a binned maximum likelihood fit to the observed m_{bb} distributions, performed simultaneously in both the signal and background dominated regions. The signal shapes are interpolated using a linear combination of simulations with varying couplings, allowing one to constrain the κ_{2V} parameter more precisely. These results show that the κ_{2V} coupling modifier is constrained within the ranges $[-0.04, 2.05]$ at 95% CL, as shown in Figure 3b. This focus on κ_{2V}, rather than κ_λ, arises because this channel is more sensitive to the vector boson–Higgs coupling, which is modulated by κ_{2V}, making it a key parameter to probe in the context of this analysis [16].

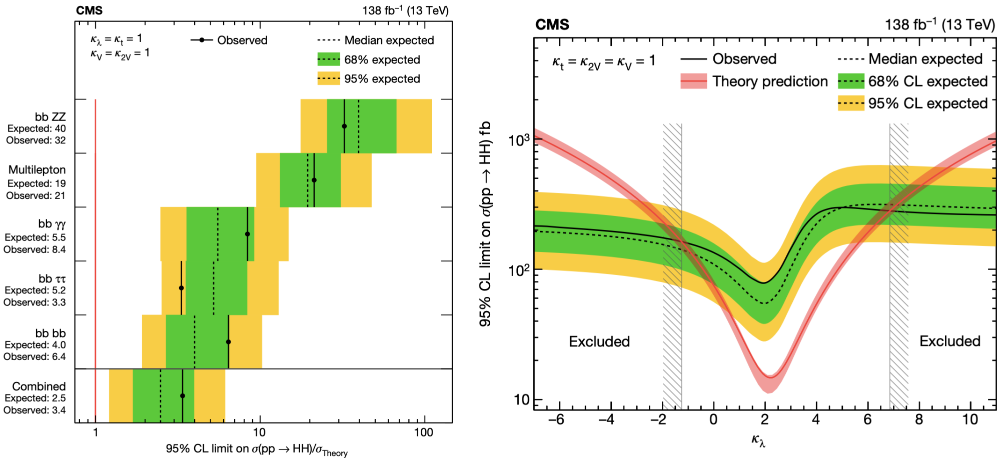


(**a**) (**b**)

Figure 3. Expected and observed 95% CL upper limits on the nonresonant HH production cross section. (**a**) Dependence on κ_λ in the $\tau\tau\gamma\gamma$ channel [14]; (**b**) dependence on κ_{2V} in the $bbVV$ channel [16].

3.3. Run 2 Combined Results

The combination of the results of several channels from Run 2 is shown in Figure 4. It provides an upper limit 95% C.L. of 2.5 times the SM prediction, a significantly improved result compared to what was expected from early Run2 results [17], when scaled with luminosity. This is largely due to the implementation of advanced machine learning techniques, such as jet tagging, tau identification, and more efficient triggers.



(**a**) (**b**)

Figure 4. (**a**) Limits on Higgs boson pair production. The observed and expected upper limits at 95%CL on the ratio of the measured cross-section to the Standard Model prediction ($\sigma/\sigma_{\mathrm{SM}}$) are shown for individual final states and their combination. (**b**) Limits on the di-Higgs production cross section for different values of κ_λ are also shown [17].

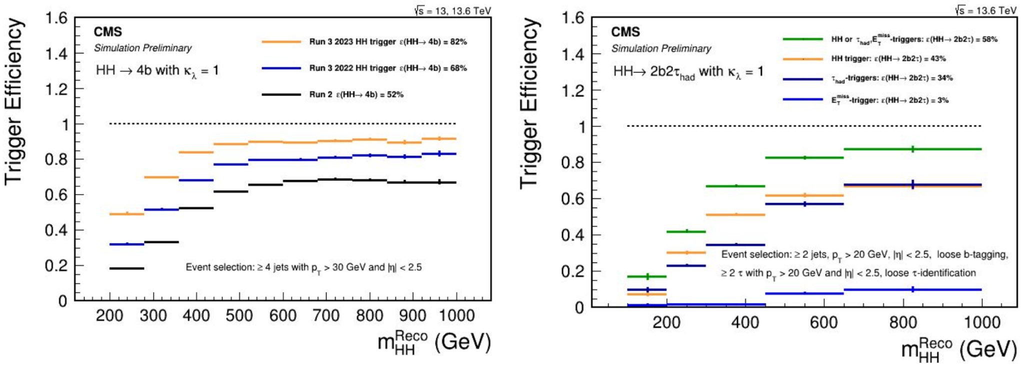
By combining single Higgs and di-Higgs measurements [18], tighter constraints were placed on the Higgs self-coupling modifier κ_λ. The results suggest that values of κ_λ outside the interval $(-1.2, 7.5)$ are excluded at 95% confidence level.

4. Discussion

The study of Higgs self-coupling is a cornerstone of understanding the Higgs potential and the fundamental interactions of the SM. The results obtained during Run 2 provide valuable constraints on the Higgs self-coupling parameter, κ_λ. The combination of different search channels, despite their varying challenges, has led to a consistent picture that is compatible with the SM, with no significant deviations [17].

However, the results also highlight the current limitations of the experimental sensitivity. The background processes, particularly from QCD multi-jet events, and the small branching ratios of some of the decay channels remain significant challenges. Nevertheless, the application of advanced machine learning techniques, such as DNNs and BDTs, has significantly improved the ability to distinguish signal from background, allowing us to achieve limits close to few times the SM expectation.

Looking ahead, the ongoing Run 3 and the upcoming High-Luminosity LHC (HL-LHC) offer exciting prospects. With new triggers [19] designed specifically for di-Higgs production, as shown in Figure 5, and improvements in tau identification via the DeepTau [20] algorithm, an even greater sensitivity is expected to be achieved. These improvements, combined with the increased data volume, will bring us closer to the goal of a 5σ discovery of di-Higgs production.



(**a**) (**b**)

Figure 5. Trigger efficiency as a function of the invariant mass m_{HH} for the simulated SM HH production ($\kappa_\lambda = 1$) with two different final states: $HH \to 4b$ (left) and $HH \to 2b2\tau_{\text{had}}$ (right). (**a**) For the $4b$ process, the efficiency is shown for Run 2 (black), Run 3 2022 (blue), and Run 3 2023 (orange) triggers, with an overall efficiency of 82%, improved by 57% compared to Run 2 and 20% compared to 2022. (**b**) For the $2b2\tau_{\text{had}}$ process, the efficiency is shown for Run 3 hadronic τ triggers (blue), Run 3 2023 HH trigger (orange), and a combination of both (green). By combining the two triggers with the missing transverse energy trigger, the resulting trigger efficiency is 58% [19].

5. Conclusions

In conclusion, the study of Higgs self-coupling remains one of the most exciting and important areas of particle physics. The results from Run 2 have provided strong constraints on the Higgs potential, in line with the SM. However, the full potential of this search is yet to be realized. The anticipated upgrades in Run 3, along with the new data we will obtain with the HL-LHC, will offer an opportunity to explore the Higgs sector more deeply.

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Conflicts of Interest: The authors declare no conflicts of interest.

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