PROCEEDINGS OF SCIENCE

Di-Higgs searches at CMS

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This proceeding presents the CMS searches for the nonresonant production of Higgs boson pairs in proton–proton collisions at a centre-of-mass energy of 13 TeV. The analyses use the full Run 2 dataset collected with the CMS detector during 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. Several final states with complementary sensitivities are explored, including $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$, $bbWW$, $bbZZ$, multilepton, $WW\gamma\gamma$, and $\tau\tau\gamma\gamma$, together with a dedicated search for the associated production $VHH \rightarrow Vbbbb$ included in the global interpretation.

The observed (expected) upper limit on the inclusive Higgs boson pair production cross section relative to the Standard Model prediction is 3.5 (2.5) at 95% confidence level. Assuming all other Higgs boson couplings take their Standard Model values, the trilinear self-coupling modifier κ_λ is constrained to $-1.35 \leq \kappa_\lambda \leq 6.37$ at 95% confidence level. For the quartic vector-boson–Higgs coupling modifier, $\kappa_{2V} = 0$ is excluded with a significance of 6.6 standard deviations, with an allowed interval of $0.64 \leq \kappa_{2V} \leq 1.40$ at 95% confidence level.

The results are interpreted within the Higgs Effective Field Theory, setting upper limits across established benchmarks and on the contact-interaction coefficient. An extrapolation to the integrated luminosity expected after the High-Luminosity LHC upgrade illustrates the projected improvement in sensitivity to nonresonant HH production and to the Higgs boson self-coupling. Combining single- and double-Higgs measurements further refines the determination of the trilinear coupling, with $-1.2 < \kappa_\lambda < 7.5$ when other couplings are fixed and $-1.4 < \kappa_\lambda < 7.8$ when they are allowed to vary.

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1. Introduction

Since the discovery of the Higgs boson by the ATLAS and CMS Collaborations in 2012 [1, 2], determining the structure of the Higgs potential and testing whether the Higgs mechanism alone accounts for electroweak symmetry breaking have become central objectives of the LHC physics programme. The Higgs boson self-interactions define the potential and are essential for understanding the nature of the electroweak phase transition, vacuum stability, and the dynamics of the early Universe. The trilinear self-coupling λ_3 governs the shape of the potential and provides the leading collider probe through Higgs boson pair (HH) production, directly testing the self-interaction of the Higgs field and potential extensions of the Standard Model (SM).

In the SM, nonresonant HH production proceeds mainly via gluon fusion (ggF) through top-quark loops, where a triangle diagram proportional to λ_3 interferes destructively with a box diagram proportional to the top Yukawa coupling, suppressing the cross section by roughly three orders of magnitude compared to single-Higgs production. Additional contributions arise from vector-boson fusion (VBF), which probes the quartic $VVHH$ interaction, and from associated VHH production, which provides complementary sensitivity due to its distinct interference structure.

CMS has performed a comprehensive set of searches for HH production in proton–proton collisions at $\sqrt{s}$ = 13 TeV using the full Run 2 data set of 138 fb^{-1}. The analyses target multiple final states with complementary strengths: $bbbb$ [3, 4], $bb\tau\tau$ [5], $bb\gamma\gamma$ [6], $bbWW$ [7, 8], $bbZZ$ [9], multilepton [10], and rarer modes such as $WW\gamma\gamma$ [11], $\tau\tau\gamma\gamma$ [12], and associated $VHH \rightarrow Vbbbb$ production [13]. Each channel probes different kinematic regimes and background compositions, and their statistical combination provides the most sensitive CMS test to date of Higgs boson pair production and the Higgs self-coupling. The results are interpreted within the coupling modifier framework, where the trilinear coupling modifier $\kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$ quantifies deviations of the Higgs boson trilinear self-coupling from its Standard Model expectation, and the quartic vector-boson–Higgs coupling modifier κ_{2V} controls the strength of the $VVHH$ interaction. These results can further be interpreted in the framework of the Higgs Effective Field Theory (HEFT), which parameterises possible deviations from the SM predictions through higher-dimensional operators affecting the Higgs–top, Higgs–gluon, and vector-boson–Higgs interactions.

The trilinear coupling modifier κ_λ also affects single-Higgs observables through electroweak loop corrections. A simultaneous fit to single- and double-Higgs measurements can therefore exploit this complementarity to obtain a more model-independent determination of κ_λ by profiling other Higgs coupling modifiers.

This proceeding summarises the CMS Run 2 results on nonresonant Higgs boson pair production, incorporating recent updates from individual analyses, the Run 2 legacy combination of all final states [14], as well as the combined analysis of single- and double-Higgs measurements [15].

2. Data and Analysis Overview

The analyses use the full CMS Run 2 data set of proton–proton collisions at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} collected under stable detector and beam conditions.

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A suite of dedicated analyses targets the nonresonant production of Higgs boson pairs in multiple final states, each optimised for distinct experimental signatures, branching fractions, and mass resolutions. The $HH \to bbbb$ channel, with the largest branching fraction, achieves the highest single-channel sensitivity through resolved and boosted topologies using advanced b-tagging and multivariate discriminants. The $HH \to bb\tau\tau$ analysis combines several τ-decay categories with dedicated mass reconstruction algorithms, while $HH \to bb\gamma\gamma$ benefits from excellent diphoton mass resolution for a clean two-dimensional signal extraction. Leptonic final states such as $HH \to bbWW$, $HH \to bbZZ(4\ell)$, and the inclusive multilepton analysis extend the sensitivity to high-purity regions with reduced hadronic backgrounds. Additional rare modes, including $HH \to WW\gamma\gamma$, $HH \to \tau\tau\gamma\gamma$, and the associated $VHH \to Vbbbb$ production, probe distinctive kinematics and provide complementary coverage of the Higgs coupling structure.

All analyses are combined across ggF, VBF, and associated VHH production modes, ensuring orthogonal event categories and a coherent treatment of correlated uncertainties. This combination serves as the baseline for the Effective Field Theory interpretation and for projections to the High-Luminosity LHC. A complementary simultaneous fit of single- and double-Higgs measurements includes a subset of the most sensitive HH channels together with precision single-Higgs measurements in $H \to \gamma\gamma$, ZZ, and WW decays, yielding an improved and less model-dependent constraint on κ_λ.

3. Statistical Framework and Interpretation

The combined results are obtained from a global maximum-likelihood fit using the asymptotic $\mathrm{CL_s}$ method, profiling correlated experimental and theoretical uncertainties across all analyses and data-taking years. Signal templates are derived from simulated samples, and background processes are modelled using Monte Carlo predictions or data control regions as defined in the individual analyses. Systematic uncertainties are implemented as nuisance parameters with appropriate correlations, including theoretical variations in QCD scales, parton distribution functions, and branching fractions, as well as experimental effects related to luminosity, pileup, trigger efficiencies, lepton and photon identification, b-tagging, and jet energy calibration. Uncertainties from limited simulation statistics and detector stability are treated consistently with dedicated nuisance terms.

Confidence intervals and upper limits are derived from the profile-likelihood-ratio test statistic, profiling all nuisance parameters. One-dimensional scans are performed for κ_λ, and two-dimensional contours are obtained for $(\kappa_\lambda, \kappa_{2V})$, where κ_{2V} quantifies the quartic interaction strength between two vector bosons and two Higgs bosons. Other couplings are fixed to their Standard Model values unless stated otherwise. The same statistical framework is employed for the simultaneous H+HH fit, which adds likelihood terms from single-Higgs precision measurements, enabling a consistent determination of κ_λ when other couplings are profiled.

Beyond the κ framework, the HH combination is interpreted in the Higgs Effective Field Theory, introducing higher-dimensional, gauge-invariant operators that modify Higgs interactions with top quarks and gluons. Event-level reweighting is performed across the parameter space (κ_λ, κ_t, c_2, c_g, c_{2g}), where κ_t is the top-quark Yukawa coupling modifier, c_2 denotes the contact interaction between two Higgs bosons and a top-quark pair, and c_g (c_{2g}) parameterises effective couplings of one (two) Higgs bosons to gluons. Two benchmark grids, corresponding to the

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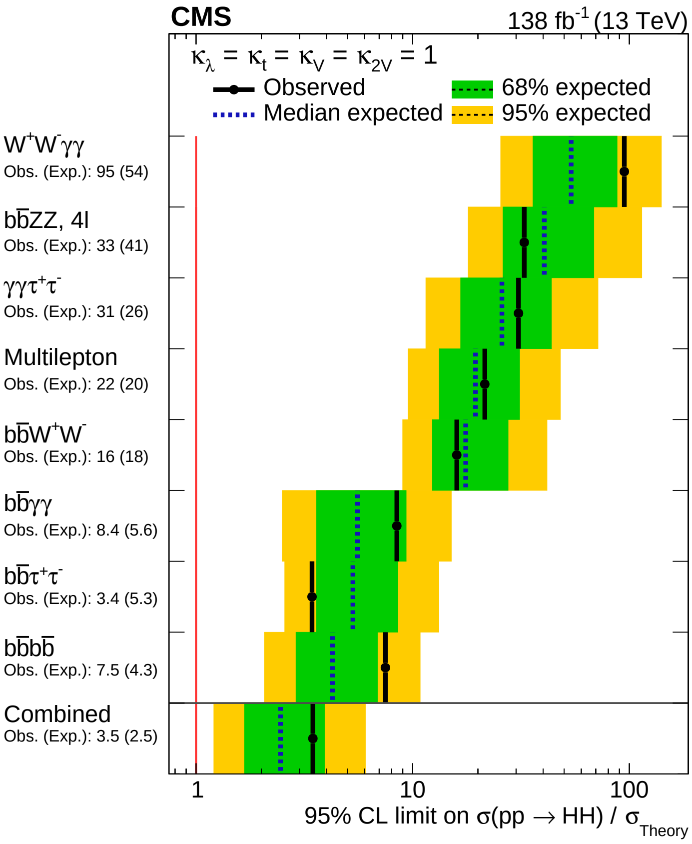

Figure 1: The upper limits at 95% CL on the HH production cross section for each channel and their combination. The inner (green) and outer (yellow) bands indicate the 68 and 95% CL intervals, respectively, under the background-only hypothesis. The individual contributions within the $bbbb$ and $bbWW$ channels have been combined in order to simplify the presentation of results.

parameterisations defined in Refs. [16, 17], are used to evaluate the experimental sensitivity to deviations from the Standard Model predictions.

4. Results

The combination of all Run 2 CMS analyses provides the most sensitive test to date of nonresonant Higgs boson pair production and the Higgs boson self-interaction. Figure 1 summarises the observed and expected 95% confidence level upper limits on the Higgs boson pair production cross section in each individual final state and in their statistical combination. The combined analysis yields an observed (expected) upper limit of 3.5 (2.5) times the Standard Model prediction. The $bbbb$, $bb\gamma\gamma$, and $bb\tau\tau$ channels provide the leading sensitivity, while other final states contribute complementary coverage.

The one-dimensional likelihood scans for the trilinear Higgs self-coupling modifier κ_λ and the quartic vector-boson–Higgs coupling κ_{2V} are shown in Fig. 2. The best-fit value of the trilinear coupling is $\kappa_\lambda = 1.51$, consistent with the Standard Model expectation within uncertainties. The couplings are constrained to $-1.35 < \kappa_\lambda < 6.37$ and $0.64 < \kappa_{2V} < 1.40$ at 95% CL, with the

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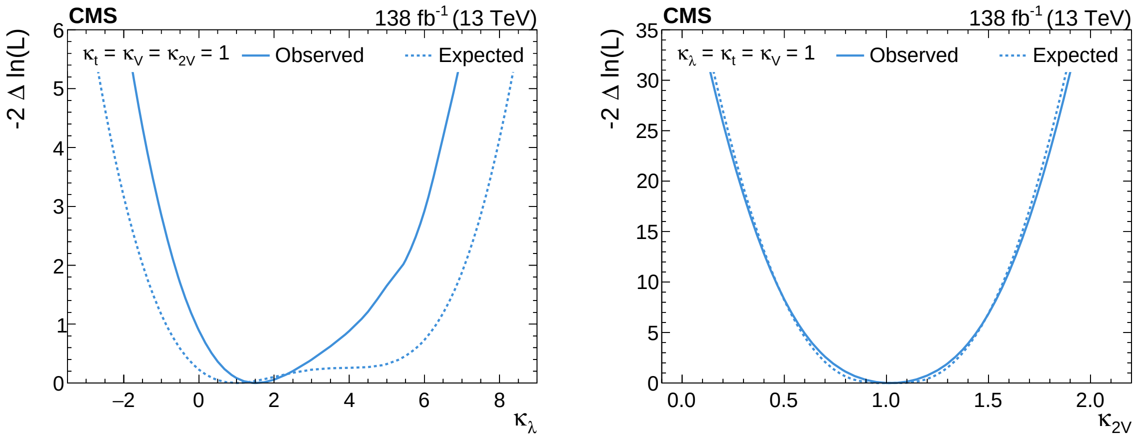

Figure 2: The $-2\Delta\ln(\mathcal{L})$ scans as functions of the coupling modifiers κ_λ (left) and κ_{2V} (right) for the combination of all channels when all the other parameters are fixed to their SM values.

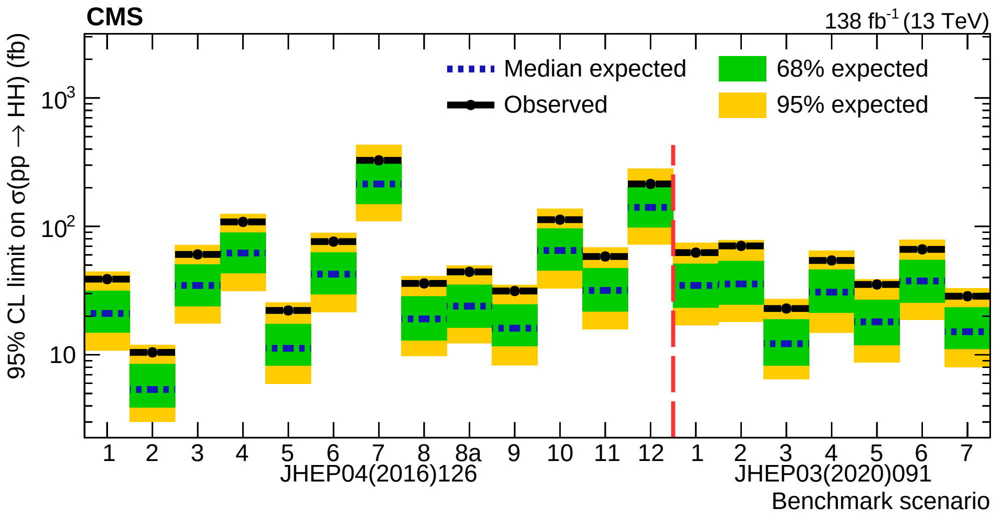

Figure 3: The upper limits at 95% CL on the HH production cross section for the two sets of HEFT benchmarks.

$\kappa_{2V} = 0$ hypothesis excluded at 6.6 standard deviations. The two-dimensional contour in the $(\kappa_\lambda, \kappa_t)$ plane illustrates the interplay between the trilinear and top–Higgs Yukawa couplings, with the SM point lying within the 68% CL contour and thus fully consistent with the predicted correlations.

The results are further interpreted in the Higgs Effective Field Theory. Two benchmark sets, corresponding to the configurations defined in Refs. [16, 17], are used to sample this four-dimensional parameter space. As shown in Fig. 3, no significant deviations from the SM expectations are observed across the benchmark points. Small upward fluctuations at the level of 1–2 standard deviations appear in several high-sensitivity regions, consistent with statistical variations. For the contact-interaction coefficient c_2, the best-fit value is 0.40 with 68% (95%) CL intervals of [0.20, 0.52] and [−0.29, 0.63], respectively.

Projections to the High-Luminosity LHC are derived using the Run 2 combination as a baseline,

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scaled to an integrated luminosity of 2 or 3 ab^{-1} at $\sqrt{s}$ = 14 TeV. Signal and background yields are extrapolated assuming detector performance comparable to Run 2 and systematically improved uncertainties. Three uncertainty scenarios are considered, with the nominal one (S2) corresponding to reduced theoretical and experimental systematics. Under this scenario, the expected 95% CL upper limit on the inclusive HH production cross section reaches about 0.5–0.6 times the SM rate. The combined significance for observing the SM HH signal increases from about 3.5σ at 2 ab^{-1} to 4.2σ at 3 ab^{-1}, and up to 4.8σ in the statistical-only case. The precision on the trilinear self-coupling improves substantially, with the expected uncertainty on κ_λ reducing from approximately $^{+80\%}_{-60\%}$ at 2 ab^{-1} to $^{+60\%}_{-50\%}$ at 3 ab^{-1}. These projections indicate that the HL-LHC will establish evidence for Higgs boson pair production and significantly tighten the precision on the Higgs self-coupling within the SM framework.

The H+HH combination resolves the degeneracy present in HH-only scans arising from the quadratic dependence of the gluon-fusion amplitude on κ_λ. It yields improved sensitivity with a 95% CL interval of $-1.4 < \kappa_\lambda < 7.8$ when all other couplings are profiled, and $-1.2 < \kappa_\lambda < 7.5$ when they are fixed to their SM values. The two-dimensional likelihood contours in $(\kappa_\lambda, \kappa_t)$ and (κ_V, κ_{2V}) show a significant reduction of the allowed parameter space compared to the HH-only combination, demonstrating the complementarity between single- and double-Higgs measurements in probing the Higgs potential.

5. Conclusions and Outlook

The CMS experiment has performed a comprehensive set of searches for nonresonant Higgs boson pair production using the full Run–2 data set of proton–proton collisions at $\sqrt{s}$ = 13 TeV, corresponding to 138 fb^{-1}. All major final states—$bbbb$, $bb\tau\tau$, $bb\gamma\gamma$, $bbWW$, $bbZZ$, and multileptons—together with rarer modes such as $WW\gamma\gamma$, $\tau\tau\gamma\gamma$, and $VHH \to Vbbbb$, are statistically combined to probe the Higgs self-interactions through gluon-fusion, vector-boson-fusion, and associated production. No significant deviation from the Standard Model is observed. The inclusive 95% confidence level upper limit on the production rate is 3.5 (2.5) times the Standard Model prediction, with allowed ranges $-1.35 < \kappa_\lambda < 6.37$ and $0.64 < \kappa_{2V} < 1.40$ at 95% CL, excluding $\kappa_{2V} = 0$ beyond five standard deviations. Interpretations in the Higgs Effective Field Theory also show consistency with the Standard Model. A joint H+HH combination incorporating single-Higgs precision measurements further refines the determination of the trilinear coupling to $-1.2 < \kappa_\lambda < 7.5$ (fixed others) and $-1.4 < \kappa_\lambda < 7.8$ (profiling others). Looking ahead to the High-Luminosity LHC, with 3 ab^{-1} at $\sqrt{s}$ = 14 TeV, CMS is expected to reach sensitivity close to the SM rate and measure κ_λ with a precision around 50%, marking the transition of Higgs pair production from a search into a precision test of the Higgs potential and electroweak symmetry breaking.

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