PROCEEDINGS OF SCIENCE

Non-resonant Higgs boson pair production and self-coupling determination with the ATLAS experiment

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Higgs boson pair production (HH) plays a central role in probing the Higgs boson self-interactions, which are key to understanding the shape of the Higgs potential and the mechanism of electroweak symmetry breaking. This talk presents the latest results from the ATLAS experiment on non-resonant Higgs boson pair production, based on the full Run 2 dataset collected at $\sqrt{s}$ = 13 TeV, with the inclusion of available Run 3 results where relevant. These analyses provide sensitivity to the Higgs boson self-coupling and the quartic VVHH coupling, offering key tests of the Higgs sector beyond single-Higgs measurements. Constraints are also derived from higher-order electroweak corrections to single Higgs boson production, and a combination of single and di-Higgs results is used to obtain the most precise determination of the self-coupling to date. The talk further includes projections for future sensitivity at the High-Luminosity LHC, outlining the expected improvements and challenges ahead.

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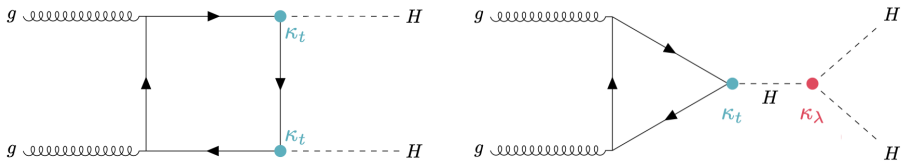


Figure 1: Leading order Feynman diagrams for ggF production.

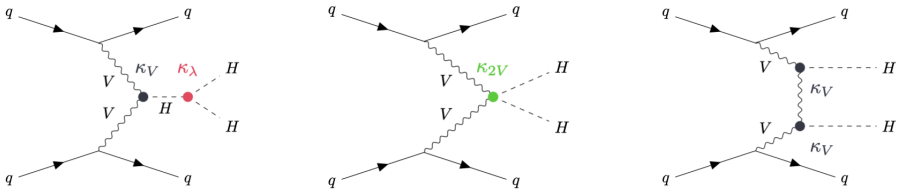


Figure 2: Leading order Feynman diagrams for VBF production.

1. Introduction

The discovery of the Higgs boson in 2012 completed the Standard Model (SM) and confirmed the mechanism of electroweak symmetry breaking. However, the precise shape of the Higgs potential remains largely untested. The scalar potential can be written as:

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_{hhh} v H^3 + \lambda_{hhhh} H^4 + \ldots, \tag{1}$$

where m_H is the Higgs mass, v is the vacuum expectation value, and λ_{hhh} and λ_{hhhh} represent the trilinear and quartic self-coupling terms, respectively. Any deviation of λ_{hhh} from its SM prediction would signal new physics in the scalar sector.

The measurement of Higgs pair production provides the only direct access to the trilinear coupling, while indirect constraints arise from loop corrections to single-Higgs processes. The production of HH final states proceeds dominantly via gluon–gluon fusion (ggF), with a next-to-next-to-leading order (NNLO) SM cross section of approximately 30.8 fb at $\sqrt{s}$ = 13 TeV. The subleading vector-boson-fusion (VBF) process contributes about 1.69 fb (also at 13 TeV). Despite the small cross section, this process is uniquely sensitive to modifications of the Higgs self-coupling and the quartic $HHVV$ coupling. Feynman diagrams for ggF and VBF are shown in Figure 1 and Figure 2, respectively. Within the κ-framework, deviations from the SM couplings are parameterized through scaling factors such as κ_λ (Higgs self-coupling), κ_t (top-Yukawa), and κ_V (gauge-Higgs couplings). The generalization of it is the Higgs Effective Field Theory (HEFT), where operators such as c_{tthh}, c_{gghh}, and c_{hhh} are additionally introduced; example diagrams with them are shown in Figure 3. Both frameworks are utilized in the analyses summarized here. These analyses use the pp collision datasets collected by the ATLAS detector at $\sqrt{s}$ = 13 and 13.6 TeV. The ATLAS detector [1] at the LHC is a multipurpose apparatus optimized for measuring final states with photons, leptons, and jets.

The latest ATLAS results, which are reviewed in this document, are:

- Run-2 combinations: all HH channels [2] and the H+HH combination [3],

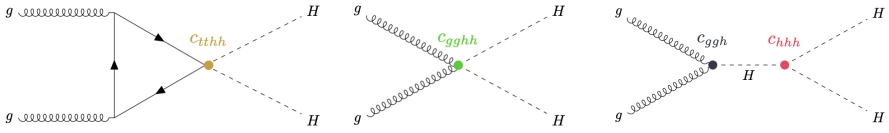


Figure 3: Feynman diagrams involving HEFT operators.

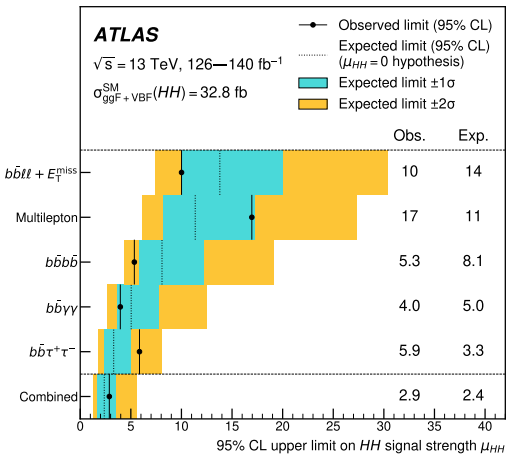


Figure 4: Observed and expected 95% CL upper limits on the signal strength for inclusive ggF HH and VBF HH production from the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, and multilepton decay channels, and their statistical combination [2].

- the $b\bar{b}\gamma\gamma$ analysis including data up to 2024 [6]; and
- HL-LHC projections of Run-2 analyses: ATLAS alone [4] and a combined ATLAS+CMS projection [5].

2. Run-2 combinations

All Run-2 non-resonant HH channels have been combined, including the $b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $b\bar{b}\gamma\gamma$, and multilepton final states. The combination yields an observed (expected) 95% confidence level (CL) upper limit of 2.9 (2.4)×SM, as shown in Figure 4. The constraint (95% CL, observed) on the self-coupling is found to be: $-1.2 < \kappa_\lambda < 7.2$, as shown in Figure 5. Constraint on the quartic coupling modifier is found to be $0.6 < \kappa_{2V} < 1.5$, also shown in Figure 5. Two-dimensional HEFT interpretation results are shown in Figure 6.

Indirect sensitivity to κ_λ can be obtained from electroweak corrections affecting single-Higgs production and decay rates . A combined fit of single- and double-Higgs channels improves the precision on κ_λ by approximately 5–7% relative to the HH-only combination. The combined analysis demonstrates that the inclusion of single-Higgs information helps to break degeneracies between κ_t and κ_λ, as shown in Figure 7a.

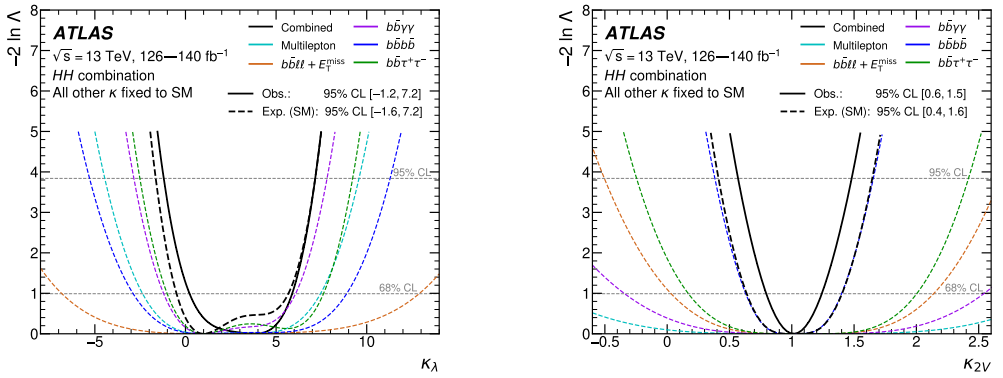


Figure 5: Observed and expected profile likelihood scan of κ_λ and κ_{2V} [2].

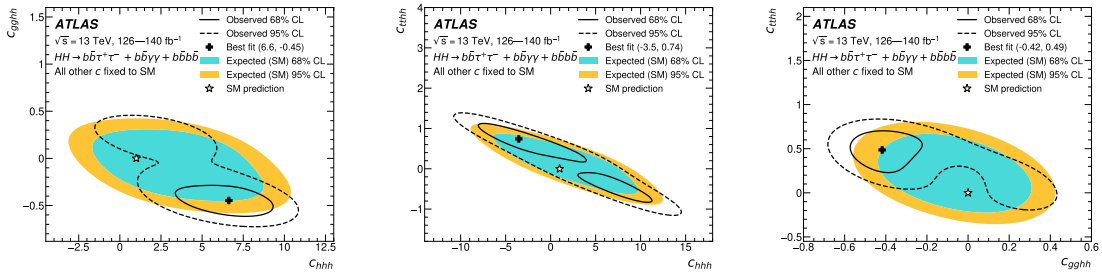
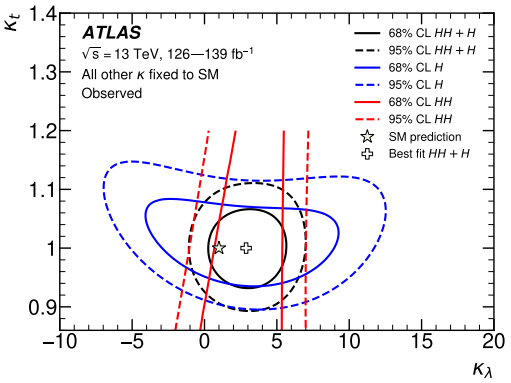
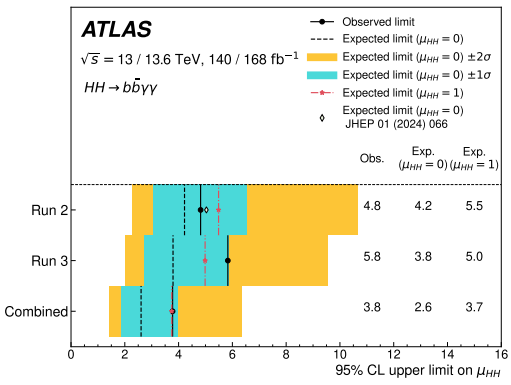


Figure 6: Two-dimensional test-statistic contours at 68% CL (solid line) and 95% CL (dashed line) in the c_{gghh}–c_{hhh}, c_{tthh}–c_{hhh}, and c_{tthh}–c_{gghh} HEFT parameter spaces, with c_{tthh}, c_{gghh}, and c_{hhh} fixed to their SM values, respectively. The corresponding SM expected contours are shown by the inner and outer shaded regions. The SM prediction is indicated by the star, while the best-fit value is shown by the cross [2].



(a) Observed constraints in the $\kappa_\lambda - \kappa_t$ plane from single-Higgs (blue) and double-Higgs (red) analyses, and their combination (black) [3].



(b) The 95% CL upper limits on the signal strength [6], obtained with separate fits to Run-2 and Run-3 data as well as their combination.

Figure 7

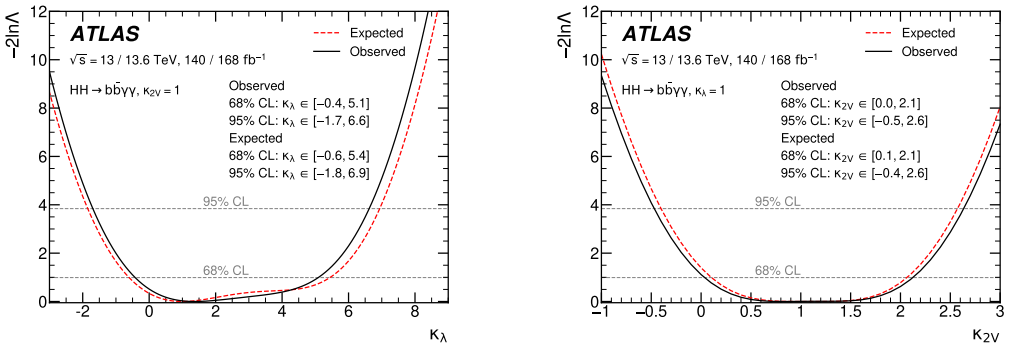


Figure 8: Observed and expected profile likelihood scan of κ_λ and κ_{2V} [6].

3. Run-2 + partial Run-3 $HH \to b\bar{b}\gamma\gamma$ analysis

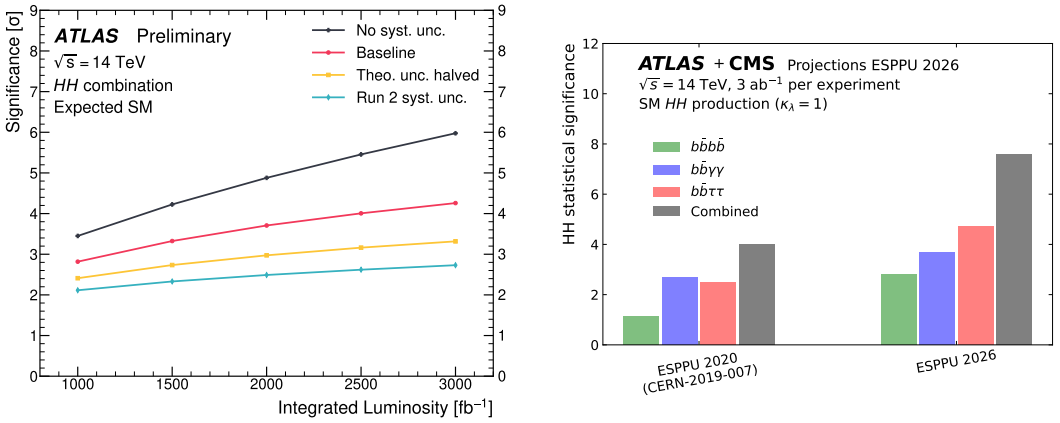
The $b\bar{b}\gamma\gamma$ final state remains one of the golden channels for HH searches owing to the excellent di-photon mass resolution and manageable backgrounds despite a small branching ratio. The first ATLAS result including including Run-3 data collected in 2024 was reported in [6]. The analysis employs improved photon identification, a novel GN2 b-tagger with 85% working point efficiency, and a dedicated kinematic fit to enhance the $m_{b\bar{b}}$ and $m^*_{b\bar{b}\gamma\gamma}$ resolution. Events are categorized using two boosted decision tree (BDT) discriminants, leading to a simultaneous fit across seven event regions in both Run-2 and Run-3 datasets.

The observed (expected) significance for the SM HH signal is 0.8 (1.0)σ. The corresponding 95% CL upper limit on the cross section is 3.8 (2.6)× the SM prediction, as shown in Figure 7b. Expected limit is comparable to whole previous Run-2 combination [2]. Expected limits (95% CL) on κ_λ (κ_{2V}) are improved by 30%(20%) compared to previous analysis. Expected and observed profile likelihood curves are shown in Figure 8.

4. Projections for the HL-LHC

Projections for the HL-LHC are based on scaling the Run-2 analyses yields by an overall luminosity (up to 3000 fb^{-1}) factor and a process-dependent $\sigma = f(E_{CM})$ factor, assuming unchanged selection efficiencies and improved theoretical and experimental systematics. Four scenarios are considered: Run-2 systematic uncertanties, halved theoretical uncertainties, the baseline HL-LHC scenario with reduced experimental systematics, and the no-systematics limit. Under the baseline scenario, as can be seen in Figure 9a, the expected significance for SM HH production reaches 4.3σ. The projected 68% CL constraints on the coupling modifiers are $0.58 < \kappa_\lambda < 1.48$ (75% improvement over previous projection) and $0.85 < \kappa_{2V} < 1.18$.

Combining ATLAS and CMS data, the overall significance is expected to exceed 5σ, corresponding to an observation of SM-like Higgs pair production, as shown in Figure 9b.



(a) Expected HH significance under the SM hypothesis, with 3000 fb^{-1} of data at $\sqrt{s}$ = 14 TeV in the different uncertainty scenarios [4].

(b) Comparison of the ESPPU 2020 and ESPPU 2026 projected 3 ab-1 HH sensitivities from various final states, and their combinations. [5].

Figure 9

5. Conclusion

The measurement of non-resonant Higgs boson pair production is a fundamental test of the the Standard Model. The ATLAS Collaboration has released a comprehensive combination of all Run-2 HH decay channels, establishing stringent limits on the Higgs self-coupling and quartic gauge-Higgs interaction modifiers. The inclusion of single-Higgs information provides additional sensitivity to κ_λ, while forthcoming $b\bar{b}\gamma\gamma$ partial Run-3 analysis demonstrate steady progress toward observation. HL-LHC projections indicate that ATLAS alone should reach a 4.3σ sensitivity, and the combined ATLAS+CMS result is expected to bring discovery-level significance.

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[4] ATLAS Collaboration, *ATL-PHYS-PUB-2025-006* (2025).

[5] ATLAS Collaboration, *ATL-PHYS-PUB-2025-018* (2025).

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