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HH non-resonant and self-coupling at ATLAS and CMS

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Measuring Higgs pair production (HH) will provide information about the Higgs self coupling, which is key to determine the shape of the Higgs potential at higher order. The leading HH production mode at the Large Hadron Collider is gluon gluon fusion and the sub-leading production mode is vector boson fusion. Given the small cross section, Higgs pair production has not yet been observed. However, competitive upper limits on the HH production cross section and Higgs self coupling modifier κ_λ are set by the ATLAS and CMS Collaborations.

Searches for HH production in a final state where one Higgs boson decays to a pair of b quarks, and the other Higgs boson decays either to two photons, two b quarks or four leptons, with the full Run 2 proton-proton collision data set at $\sqrt{s}$ = 13 TeV from the ATLAS and CMS experiments, are presented. Combinations of HH searches and Higgs self coupling measurements with partial Run 2 data are also presented.

Competitive upper limits on the HH cross section are obtained by the ATLAS and CMS HH searches in the $b\bar{b}\gamma\gamma$ final state. However, the CMS HH search in the $b\bar{b}b\bar{b}$ final state sets the current most stringent observed upper limit on the HH production cross section of 3.6 times the Standard Model expectation at 95% confidence level. The current most stringent limits on κ_λ are obtained by the ATLAS HH search in the $b\bar{b}\gamma\gamma$ final state, which sets observed (expected) limits of -1.5 (-2.4) $< \kappa_\lambda <$ 6.7 (7.7) at 95% confidence level.

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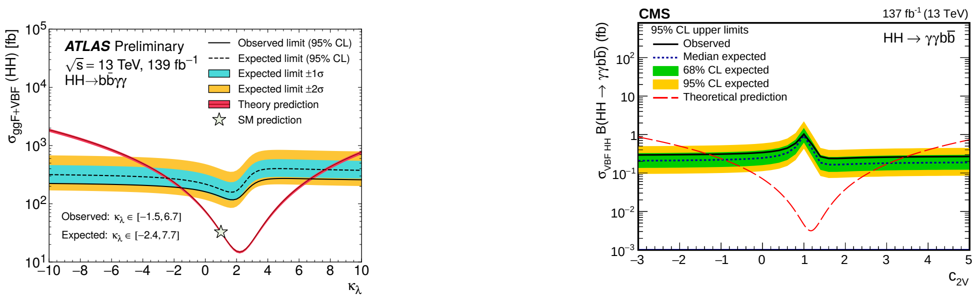
1. Introduction

Searches for Higgs pair production (HH) with full Run 2 data by the ATLAS [4] and CMS [5] experiments in multiple final states and combinations with partial Run 2 data are presented.

2. $HH \to b\bar{b}\gamma\gamma$

The CMS [6] and the ATLAS [7] $HH \to bb\gamma\gamma$ searches use boosted decision trees (BDT) to discriminate the HH signal from the background. To ensure sensitivity to multiple SM and beyond SM (BSM) scenarios, the $\tilde{M}_X = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 2m_h$ distribution is used together with the BDT score to define multiple signal regions (SRs). The CMS search is optimised for both ggF and VBF HH while the ATLAS search is optimised solely for ggF HH production. Both searches estimate the non-resonant background from data by exploiting the Higgs mass resonance through a fit to the $m_{\gamma\gamma}$ invariant mass side bands. Furthermore, in the CMS search a fit to the $m_{b\bar{b}}$ distribution is also performed. A joint maximum likelihood fit is performed to the multiple SRs.

Observed (expected) limits are set at 95% CL by both experiments on the HH cross section and κ_λ. ATLAS sets upper limits of $\sigma^{HH}_{ggF+VBF} < 4.1\ (5.5) \times \sigma^{HH\ SM}_{ggF+VBF}$ and $-1.5\ (-2.4) < \kappa_\lambda < 6.7\ (7.7)$ as shown in Fig. 1a. The latter are the most stringent limits on the Higgs self coupling strength modifier κ_λ. The corresponding CMS limits are $\sigma^{HH}_{ggF+VBF} < 7.7\ (5.2) \times \sigma^{HH\ SM}_{ggF+VBF}$ and $-3.3\ (-2.5) < \kappa_\lambda < 8.5\ (8.2)$. The CMS limits on σ^{HH}_{VBF} and κ_{2V}, $\sigma^{HH}_{VBF} < 225\ (208) \times \sigma^{HH\ SM}_{VBF}$ and $-1.3\ (-0.9) < \kappa_{2V} < 3.5\ (3.1)$, are shown in Fig. 1b. Limits on $\sigma^{HH\ BSM}_{ggF}$ for 12 Higgs EFT shape benchmarks and two-dimensional scans in the (κ_t,κ_λ) and (κ_{2V},κ_λ) planes are also performed by CMS.



(a) Limits on κ_λ (ATLAS)

(b) Limits on κ_{2V} (CMS)

Figure 1: Limits from ATLAS [7] and CMS [6] $HH \to bb\gamma\gamma$ searches with full Run 2 data.

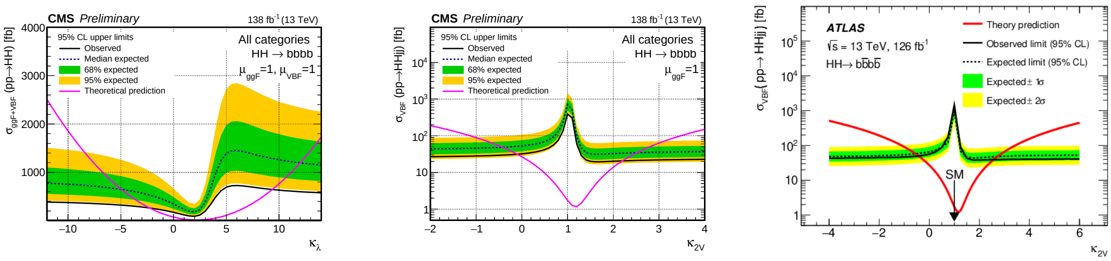
3. $HH \to b\bar{b}b\bar{b}$

The CMS $HH \to b\bar{b}b\bar{b}$ search [8] targets both ggF and VBF HH production. Higgs candidates and their invariant masses (m_H) are reconstructed from the 4 b jets and events are divided into a SR and a control region (CR) based on $\chi = \sqrt{(m_{H_1} - 125)^2 + (m_{H_2} - 120)^2}$. The VBF HH candidates are selected by requiring 2 additional non-b jets and a BDT trained to separate VBF from

PoS(LHCP2021)072

ggF events is used to reduce the mis-classification of ggF events. To enhance sensitivity to both SM and BSM scenarios, the m_{HH} distribution, a dedicated ggF BDT and the VBF-vs-ggF BDT distributions are used to define a total of 4 SRs. The large multi-jet background is estimated from data and a binned maximum likelihood fit is simultaneously performed in all SRs. The observed (expected) limits at 95% CL, shown in Fig. 2a and 2b , are $\sigma^{HH}_{ggF+VBF} < 3.6\ (7.3) \times \sigma^{HH\ SM}_{ggF+VBF}$, $-2.3\ (-5.0) < \kappa_\lambda < 9.4\ (12.0)$ and $-0.1\ (-0.4) < \kappa_{2V} < 2.2\ (2.5)$.

The ATLAS $HH \to b\bar{b}b\bar{b}$ search [9] targets VBF HH production as signal and therefore considers ggF HH events as background. The strategy consists of reconstructing the leading and sub-leading di-jet invariant masses (m_{2b}) and defining concentric signal, validation and side-band regions from the leading and sub-leading m_{2b} distributions. The large multi-jet and all-hadronic backgrounds are estimated from data through a fit in the side band region. The observed (expected) limits at 95% CL, shown in Fig. 2c, are $\sigma^{HH}_{VBF} < 1000\ (540) \times \sigma^{HH\ SM}_{VBF}$ and $-0.43\ (-0.55) < \kappa_{2V} < 2.56\ (2.72)$.



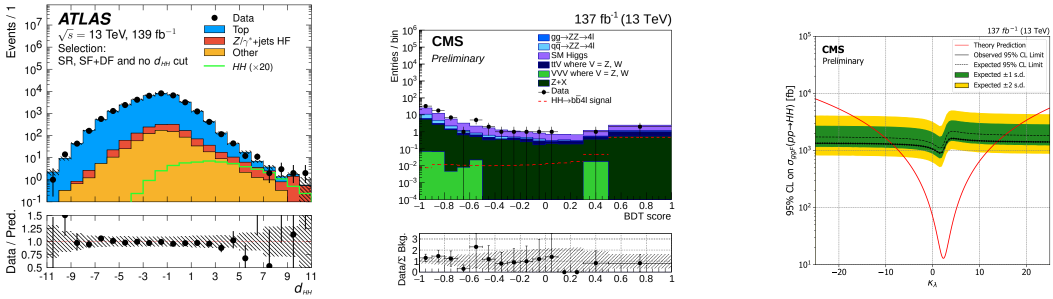
(a) Limits on κ_λ (CMS) **(b)** Limits on κ_{2V} (CMS) **(c)** Limits on κ_{2V} (ATLAS)

Figure 2: Limits from CMS [8] and ATLAS [9] $HH \to b\bar{b}b\bar{b}$ searches with full Run 2 data.

4. $HH \to b\bar{b}$+leptons

The ATLAS $HH \to bbl\nu l\nu$ search [10] targets ggF $HH \to bbWW^*$, $bbZZ^*$ and $bb\tau\tau$ in a final state with two b jets, two leptons ($l = e, \mu$) and missing transverse energy. Due to its larger branching ratio, the strategy consists of using a multi-class classification Neural Network to differentiate the ggF $HH \to bbWW^*$ signal from the SM backgrounds. The main discriminant shown in Fig. 3a is defined as $d_{HH} = \ln(p_{HH}/p_{\mathrm{Top}} + p_{Z-ll} + p_{Z-\tau\tau})$ where p_i are the NN outputs that represent the probability of an event to belong to a class i. A counting experiment is performed using the targeted HH decays as signal. The observed (expected) limits obtained are $\sigma^{HH}_{ggF} < 40\ (29) \times \sigma^{HH\ SM}_{ggF}$ at 95% CL.

The CMS $HH \to bbllll$ search [11] targets the ggF $HH \to bbZZ^*$ in a final state with two b jets and four leptons. The analysis strategy consists of using the 4-lepton invariant mass ($m(4l)$) to define a CR for the $Z + X$ background and a SR with $m(4l) \sim m_H$. For further discrimination in the SR, a total of 9 BDTs are trained (for each data taking year and leptonic final state). The irreducible single Higgs background is estimated from simulation and a multi-dimensional binned fit to data of the BDT distribution, shown in Fig. 3a, is performed. The search sets observed (expected) limits at 95% CL of $\sigma^{HH}_{ggF} < 30\ (37) \times \sigma^{HH\ SM}_{ggF}$ and $-9\ (-10.5) < \kappa_\lambda < 14\ (15.5)$ as shown in Fig. 3c.

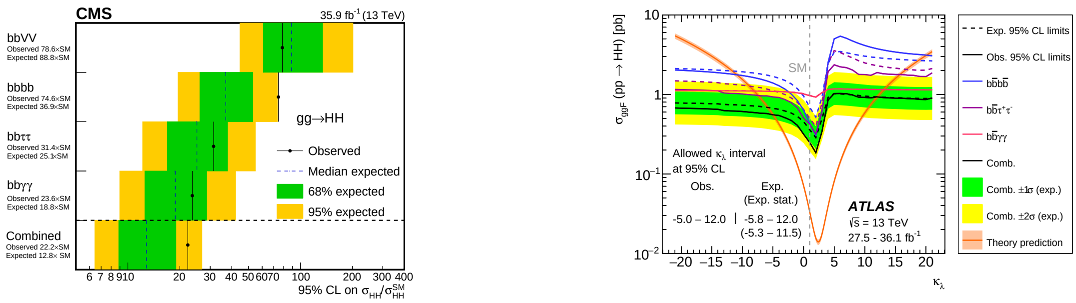


(a) d_{HH} ($HH \to bbl\nu l\nu$) **(b)** BDT score ($HH \to bbllll$) **(c)** Limits on κ_λ ($HH \to bbllll$)

Figure 3: Discriminants and limit for the $HH \to b\bar{b}$+leptons searches [10], [11] with full Run 2 data.

5. Combinations

In order to increase the sensitivity, searches using complementary decay modes are combined. The latest results of combined HH searches with partial Run 2 data from ATLAS [12] and CMS [13] are shown in Fig. 4. The ATLAS HH combination sets observed (expected) limits at 95% CL of $\sigma_{ggF}^{HH} < 6.9\,(10) \times \sigma_{ggF}^{HH\ SM}$ while the CMS combination sets slightly looser upper limits of $\sigma_{ggF}^{HH} < 12.8\,(22.2) \times \sigma_{ggF}^{HH\ SM}$. The ATLAS combination set limits of $-5\,(-5.8) < \kappa_\lambda < 12\,(12.0)$, while the CMS combination sets limits of $-11.8\,(-7.1) < \kappa_\lambda < 18.8\,(13.6)$.



(a) Combined limits on $\sigma_{ggF}^{HH}/\sigma_{ggF}^{HH\ SM}$ (CMS) **(b)** Combined limits on κ_λ (ATLAS)

Figure 4: Combined limits from the CMS [13] and ATLAS [12] HH searches with partial Run 2 data.

These limits can be improved by combining the single Higgs and HH searches because even though κ_λ enters at tree level in HH production, it is also present for single Higgs production at loop level giving the single Higgs cross section a dependence on κ_λ. The ATLAS single Higgs and HH combination [14] combines multiple production and decay modes to set the tightest combined limits on κ_λ of $-2.5\,(-5.1) < \kappa_\lambda < 10.3\,(11.2)$. These combined limits have already been surpassed by the limits from the individual $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}b\bar{b}$ searches with full Run 2 data and therefore even more stringent limits are expected from the combinations of the searches with full Run 2 data.

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PoS(LHCP2021)072