Projected sensitivity to non-resonant Higgs boson pair production in the $b\bar{b}b\bar{b}$ final state using proton–proton collisions at HL-LHC with the ATLAS detector

The ATLAS Collaboration

Abstract

Estimates of the sensitivity to non-resonant Higgs boson pair production using the $HH \to b\bar{b}b\bar{b}$ channel with the full High-Luminosity LHC dataset of 3000 fb$^{-1}$ of proton–proton collisions at $\sqrt{s} = 14$ TeV are presented. These estimates are based on the extrapolation of current results obtained with the 2016 dataset, comprising $\int L dt = 10.1$ fb$^{-1}$ of proton–proton collisions at $\sqrt{s} = 13$ TeV. In the absence of any signal and without (with) systematics, cross-sections 1.5 times (5.2 times) greater than the Standard Model prediction are excluded at the 95% confidence level. The Higgs boson self-coupling, $\lambda_{HHH}$ can be constrained to $0.2 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 7.0$ ($-3.5 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 11$). The sensitivity of the analysis to increasing trigger thresholds has been studied. The jet $p_T$ requirement of the projected High-Luminosity LHC trigger increases the cross-section limit by a factor 1.3 (2.2).
1 Introduction

The observation of Higgs boson pair production is a principal goal of the High-Luminosity LHC (HL-LHC) programme [1], because it would enable measurement of the Higgs self-coupling, $\lambda_{HHH}$. Since this is related to the form of the Higgs potential, it could lead to experimental confirmation of the Standard Model (SM) prediction of spontaneous symmetry breaking in the Higgs sector.

At the LHC, the SM predicts that gluon-fusion is the dominant mechanism by which Higgs boson pairs are produced. The process is described at leading order by the two Feynman diagrams shown in Figure 1. Figure 1(a) contains a Higgs boson self-coupling vertex, $\lambda_{HHH}$, and interferes destructively with Figure 1(b) which has no dependence on $\lambda_{HHH}$. The small cross-section of $\sigma(p p \rightarrow HH) = 39.5^{+2.9}_{-3.2} \text{ fb}$ at $\sqrt{s} = 14 \text{ TeV}$ [2] necessitates the analysis of the large HL-LHC dataset for observation of Higgs boson pair production and motivates the use of the dominant $H \rightarrow b\bar{b}$ decay mode to search for Higgs boson pair production in the $b\bar{b}b\bar{b}$ final state.

![Feynman diagrams](image)

Figure 1: Feynman diagrams describing Higgs boson pair production at leading order.

The $HH \rightarrow b\bar{b}b\bar{b}$ channel was the most sensitive channel to Higgs boson pair production in ATLAS during Run-1 [3] and so far in Run-2 [4, 5]. No evidence for a signal was obtained, but these analyses consistently obtained the world’s best exclusion limits: in Run-1, a signal strength of $\mu = \sigma / \sigma_{SM} \geq 57$ was excluded at 95% confidence level (C.L.) [3] and in 13.3 fb$^{-1}$ of Run-2 data, a signal strength upper limit of $\mu = 29$ was obtained [5].

The projections presented in this note are extrapolations of the recent results obtained by ATLAS using the Run-2 dataset [5]. In making these extrapolations, the assumption is made that the planned upgrades to the ATLAS detector [6, 7] and improvements to reconstruction algorithms will mitigate the effects of higher instantaneous luminosity and detector aging, leading to performance matching the present day’s in jet reconstruction and b-quark jet identification (b-tagging). Jet transverse momentum ($p_T$) thresholds, determined by the trigger requirement, will likely increase for HL-LHC running. The effect of raising jet thresholds is studied below. Furthermore, the assumption is made that the analysis will be unchanged in terms of selection and statistical analysis technique – a rather pessimistic assumption given that the analysis will be improved to use new techniques and optimised to make best use of larger datasets.

2 ATLAS Detector

The projected sensitivities presented in this paper are calculated by extrapolating results obtained with data collected with the present ATLAS detector. The present detector is described followed by a summary...
of the upgrades foreseen for the HL-LHC detector.

2.1 Present ATLAS Detector

The ATLAS experiment [8] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle.\footnote{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. Cylindrical coordinates $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.} It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon micro-strip, and transition radiation tracking detectors. An additional pixel detector layer [9], inserted at a mean radius of 3.3 cm, is used in the Run-2 data-taking. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic energy measurements. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for both EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer (MS) surrounds the calorimeters and includes three large superconducting air-core toroids. The field integral of the toroids ranges between 2.0 and 6.0 T m for most of the detector. The MS includes a system of precision tracking chambers and fast detectors for triggering. A dedicated trigger system is used to select events [10]. The first-level (L1) trigger is implemented in hardware and uses the calorimeter and muon detectors to reduce the accepted event rate to 100 kHz. This is followed by a software-based high-level trigger (HLT) that reduces the accepted event rate to 1 kHz on average.

2.2 HL-LHC ATLAS Detector

The HL-LHC will collide protons with a levelled instantaneous luminosity of up to $L = 7.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. This leads to an average number of $\sim 175$ proton–proton collisions per bunch-crossing (compared to $\sim 25$ in 2016 data-taking at $L \sim 1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$). Upgrades of the ATLAS detector are necessary to maintain its performance in the higher luminosity environment and to mitigate the impact of radiation damage and detector aging.

The inner detector will be completely replaced for HL-LHC, using an all-silicon design ("ITk") with increased granularity, higher read-out bandwidth and reduced material budget. It will be extended to provide tracking in the region $|\eta| < 4$. The performance of the ITk will be as good, and in most cases better, than the existing ID in an environment with significantly higher pile-up [7]. All of the calorimeters except for the forward calorimeters will maintain their current performance and will not be replaced, although the readout electronics will be replaced to enable improved triggering. A new high granularity calorimeters may also be installed in the forward regions to reduce occupancy in the high-pile-up HL-LHC environment. The muon detector will be upgraded in order to: extend coverage for muon identification to $|\eta| < 4$; permit the use of precision tracking for early trigger decisions; reduce the fake trigger rate in the forward region while preserving high efficiency; and increase trigger acceptance by eliminating gaps. The trigger and data acquisition systems will be improved to preserve high signal acceptance in the high rate, high occupancy HL-LHC environment. The improvements will include: higher bandwidth readout; using high
granularity measurements earlier in the trigger; and using tracking information earlier in the trigger. The L1 trigger accept rate is planned to be 400-1000 kHz, while the HLT accept rate will be 10 kHz.

The $b$-jet efficiency and light-quark rejection of the projected HL-LHC ATLAS detector are similar to that of the current detector. The $c$-jet rejection of the projected HL-LHC detector is about a factor of two lower than that of the current detector.

3 Data and Simulated Samples

3.1 Data

This analysis is performed on the LHC $pp$ collision dataset collected during March-July 2016 at $\sqrt{s} = 13$ TeV. After requiring that the data were collected during stable beam conditions and that all relevant detector systems were functional, the integrated luminosity was measured to be 10.1 fb$^{-1}$, with a preliminary uncertainty of ±3.7% found using $x - y$ beam-separation scans performed in May 2016, following a methodology similar to that detailed in Ref. [11, 12].

Events were selected from these datasets for analysis using a set of four triggers. These triggers require events to have either: one $b$-tagged jet with $p_T > 275$ GeV, one $b$-tagged jet with $p_T > 75$ GeV and three additional jets with $p_T > 75$ GeV, two $b$-tagged jets with $p_T > 55$ GeV and an additional jet with $p_T > 100$ GeV, or two $b$-tagged jets with $p_T > 35$ GeV and two additional jets with $p_T > 35$ GeV. The combination of these triggers give a total the signal efficiency of 86%.

3.2 Simulated Samples

Simulated 13 TeV Monte Carlo (MC) event samples are used in this analysis to model signal production and the background from $t\bar{t}$ events. The dominant multi-jet background is modelled using data-driven techniques.

Non-resonant SM $pp \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ signal events were generated via the gluon-fusion process at next-to-leading order in QCD with MG5_aMC@NLO using form factors for the top-quark loop from HPAIR [13, 14]. The mass of the Higgs boson ($m_H$) was set to 125.0 GeV. The matrix-element-level events were generated using the CT10 PDF set [15]. They were passed to Herwig++ 2.7.1 for parton showering, hadronization and simulation of the underlying event. For this step, the CTEQ6L1 PDF set [16] was used along with the UE-EE-5-CTEQ6L1 set of tuned underlying event parameters [17]. The cross-section times branching ratio to the $b\bar{b}b\bar{b}$ final state, evaluated at next-to-next-to-leading order with the summation of logarithms at next-to-next-to-leading-logarithm accuracy and including top-quark mass effects at next-to-leading order [18] is $11.3^{+0.9}_{-1.0}$ fb [2]. The uncertainty includes the effects due to renormalization and factorization scales, PDF set, $\alpha_S$, and the $H \rightarrow b\bar{b}$ branching ratio. Additional $pp \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ signal samples with $\lambda_{HHH}/\lambda_{SM} = 0, 2$ and 10 were also generated. Recent results [19] indicate that the di-Higgs invariant mass distribution in $HH$ production may differ from the NLO predictions in some bins by up to 15%. This has not been accounted for in this analysis.

Generation of $t\bar{t}$ events was performed with Powheg-box v1 [20] using the CT10 PDF set. The parton shower, hadronization, and the underlying event were simulated using Pythia 6.428 [21] with the CTEQ6L1 PDF set and the corresponding Perugia 2012 set of tuned underlying-event parameters [22].
The top-quark mass was set to 172.5 GeV. Higher-order corrections to \( t\bar{t} \) cross section were computed with Top++ 2.0 [23]. These incorporate next-to-next-to-leading order corrections in QCD, including resummation of next-to-next-to-leading logarithmic soft gluon terms.

For all simulated samples, charm-hadron and bottom-hadron decays were handled by EvtGen 1.2.0 [24]. To simulate the impact of multiple \( pp \) interactions that occur within the same or nearby bunch crossings, minimum-bias events generated with Pythia 8 are overlaid on top of the hard scatter event. The detector response was simulated with Geant 4 [25, 26] and the events were processed with the same reconstruction software as that used for the data.

4 Run-2 Analysis

The extrapolation of the \( HH \rightarrow b\bar{b}b\bar{b} \) sensitivity is based on the “resolved analysis” of the 2016 dataset documented in Ref. [5]. This analysis reconstructs each b-quark from the Higgs boson decays as a distinct jet and has been optimised to search for low-mass and non-resonant Higgs boson pairs. The mass of the two Higgs boson candidate system (\( m_{4j} \)) is used as the final discriminant between Higgs boson pair production and the backgrounds. Non-resonant production would result in an excess in the tail of the \( m_{4j} \) spectrum. The remainder of this section briefly summarises this analysis. The reader is directed to the reference above for more detail.

4.1 Event Reconstruction

Higgs boson kinematic properties are reconstructed using pairs of \( R = 0.4 \) anti-\( k_t \) jets [27] built from topological clusters of energy deposits in calorimeters cells [28]. The clusters are calibrated at the electromagnetic scale. The directions of jets are corrected to point back to the identified hard-scatter proton–proton collision vertex. The jets are corrected for additional energy due to pile-up using an area-based correction [29], with a further, small correction based on the number of \( pp \) collisions in the bunch-crossing that removes any residual energy offset. Jets are then calibrated using \( p_T \)- and \( \eta \)-dependent calibration factors derived from MC simulation, before global sequential calibration [30] is applied, which reduces flavour-dependent differences in calorimeter response. Final calibration is performed based on in-situ measurements in real collision data [31]. Jets with a majority of their energy arising from these pile-up interactions are suppressed using tracking information as detailed in Ref. [32].

Jets containing \( b \)-hadrons are identified using a multivariate \( b \)-tagging algorithm [33]. This algorithm is applied to a set of charged-particle tracks associated to each jet that satisfy quality and impact parameter criteria. Tracks are associated with jets using a \( p_T \)-dependent \( \Delta R \) requirement. The \( b \)-tagging requirements result in an efficiency of 70% for jets containing \( b \)-hadrons as determined in a sample of simulated \( t\bar{t} \) events. The corresponding efficiencies for c-hadron jets and light-quark or gluon jets are 7.8% and 0.4%, respectively.

4.2 Event Selection

The selection begins with the requirement that the event contains at least four \( b \)-tagged anti-\( k_t \), \( R = 0.4 \) jets with \( p_T > 30 \) GeV and \( |\eta| < 2.5 \). The acceptance times efficiency \( (A \cdot \epsilon) \) of this requirement is 7.2%. The four jets with the highest \( b \)-tagging score are paired to construct two Higgs boson candidates.
as described in Ref [5]. After requiring events to contain two Higgs boson candidates satisfying these criteria the cumulative $A \cdot \varepsilon$ is 6.4%.

Higgs boson pairs are reconstructed over a wide range of masses, $200 \text{ GeV} \lesssim m_{4j} \lesssim 1300 \text{ GeV}$. Event selection criteria that vary as a function of the reconstructed mass are used to enhance the analysis sensitivity across this range. Mass-dependent requirements are made on the leading Higgs boson candidate $p_T$, the sub-leading Higgs boson $p_T$, and the pseudorapidity difference between the two Higgs boson candidates. Following this mass-dependent selection, a further requirement is made that the two Higgs boson candidates must be separated in $\Delta R$, demanding $\Delta R (H, H) > 1.5$. After the mass-dependent selection and Higgs separation requirements, the cumulative $A \cdot \varepsilon = 4.3\%$.

Finally, a requirement on the Higgs boson candidates’ masses is made:

$$X_{HH} = \sqrt{\left(\frac{m_{2j}^{\text{lead}} - 120 \text{ GeV}}{0.1 m_{2j}^{\text{lead}}}\right)^2 + \left(\frac{m_{2j}^{\text{subl}} - 115 \text{ GeV}}{0.1 m_{2j}^{\text{subl}}}\right)^2} < 1.6$$

(1)

where the $0.1 m_{2j}$ terms represent the widths of the leading and sub-leading Higgs boson candidate mass distributions. The acceptance times efficiency of the full event selection, including this requirement and the trigger, is $A \cdot \varepsilon = 1.8\%$.

The final analysis discriminant, $m_{4j}$, is simply the invariant mass of the selected four-jet system. No correction is made based on the known Higgs boson mass.

### 4.3 Background Estimation

After the full event selection, $\sim 95\%$ of the background consists of multijet events. It is difficult to model this background accurately using Monte Carlo simulation, partly due to complexity of the large number of processes contributing to the background, but mainly due to the need for an extremely large number of events as a result of the large cross-section and high background rejection factor. As a result, the multijet background is modelled using a data-driven method, as described in Ref. [5]. Several high-purity, high-statistics control regions are defined using mass sidebands in the $m_{2j}^{\text{lead}}$-$m_{2j}^{\text{subl}}$ plane. This allows the data-driven multijet background to be derived and tested using independent data samples that have background composition kinematics similar to the signal region.

The remaining 5% is $t\bar{t}$ production, which is modelled using MC simulation. There is negligible background from all other sources – including processes involving Higgs bosons.

### 4.4 Systematic Uncertainties

Systematic uncertainties on the modelling of signal and background processes are evaluated. The modelling of signals and $t\bar{t}$ backgrounds share common sources of systematic uncertainty because they depend on MC simulation: detector modelling uncertainties and theoretical uncertainty in the acceptance.

The uncertainties on the acceptance comprise: missing higher-order terms in the matrix elements and PDF set, as well as modelling of the underlying event, hadronic showers, initial- and final-state radiation. The total theoretical uncertainty is dominated by the uncertainties associated with the modelling of the initial- and final-state radiation.
The following detector modelling uncertainties are evaluated: uncertainties in the jet energy scale (JES) and resolution (JER), and uncertainties in the $b$-tagging efficiency. The MC simulated samples also share common luminosity uncertainties described in Section 3.

Systematic uncertainties in the normalization and shape of the multijet background model were assessed using data. The largest yield discrepancy observed among several control region variations is $\pm 5\%$, which is assigned as the normalisation uncertainty. Uncertainties were also assigned to cover possible mis-modelling of the $m_{4j}$ shape in the kinematic turn-on, peak and high-mass tail of the distribution.

The derivation of all of these uncertainties is described in Ref. [5].

### 4.5 2016 Results

The predicted background in the signal region, the observed data, and the predicted yield for SM non-resonant Higgs boson pair production are shown in Figure 2. The observed data is in agreement with the predicted background.

![Figure 2: Distributions of $m_{4j}$ in the signal region for data, compared to the predicted backgrounds, reproduced from Ref. [5] (Figure 5b). The hatched band shown in the data/background ratio in the bottom panel represents the combined statistical and systematic uncertainties in the total background estimate. The expected signal distributions for SM non-resonant $HH$ production and $G_{KK}$ resonances with masses of 300 and 800 GeV are also shown.](image-url)
5 Extrapolation Method

The statistical framework used to produce the Run-2 results documented in Ref. [5] is extended to assess
the sensitivity of the analysis to non-resonant Higgs boson pair production with larger datasets. A test
statistic based on the profile likelihood ratio [34] is used to test hypothesised values of the global signal
strength factor, \( \mu = \sigma / \sigma_{\text{theory}} \), for the SM non-resonant \( HH \) signal model. Systematic uncertainties are
treated using Gaussian or log-normal constraint terms in the definition of the likelihood function. The
extended framework is used to produce \( m_{4j} \) distributions for the signal and background, which have been
modified to represent different integrated luminosities. These distributions are used to set upper limits on
the cross sections for the signal process using a signal plus background fit to the background-only \( m_{4j} \)
distribution. Exclusion limits are based on the value of the statistic \( CL_s \) [35], with a value of \( \mu \) regarded as
excluded at the 95% C.L. when \( CL_s \) is less than 5%. The distributions can also be modified to investigate
different assumptions and scenarios, for example assumptions related to the evolution of the systematic
uncertainties.

The signal distributions are taken directly from MC simulation. Since the statistical uncertainties associ-
ated with this distribution are determined by the size of the MC sample (10^6 events) these are treated as
constant with respect to integrated luminosity. As a result, the distribution and its uncertainties are simply
scaled by the factor:

\[
s = \frac{\left( \int L dt \right)_{\text{target}}}{\left( \int L dt \right)_{2016}}.
\]

The systematic uncertainties related to detector-modelling – JES, JER, \( b \)-tagging, luminosity – are them-
selves largely set by the systematic uncertainties of the methods used to determine them. As such, these
are not expected to improve much with higher integrated luminosity and are also treated as constant.

The multijet and \( t\bar{t} \) distributions have uncertainties associated with their normalisation and shape that are
treated as nuisance parameters in the statistical analysis. In order to use the best models of these back-
grounds in the dataset extrapolation process, a signal plus background fit is performed to the 2016 data
(assuming \( \mu = 1 \)) and the best fit values of the nuisance parameters extracted. Background distributions
are then generated to represent different integrated luminosities, using these best fit nuisance parameter
values. The statistical uncertainties on the data-driven multijet model are set to follow Poisson statistics
corresponding to the dataset size, while the systematic uncertainties are left unchanged (additional con-
straints coming from the fit to 2016 data are ignored). Different assumptions regarding the evolution of
the background uncertainties are explored in Section 6.

All distributions are corrected to account for the increase in collision energy from \( \sqrt{s} = 13 \) TeV to \( \sqrt{s} =
14 \) TeV. For simplicity this is done by scaling the number of expected events by 1.18, which accounts for
the increase in cross-sections due to the change in gluon-luminosity. Possible effects on the \( m_{4j} \) shape are
neglected for this study. The same factor is applied to both the SM signal and background.

The \( m_{4j} \) distributions extrapolated to 3000 fb\(^{-1}\) are shown in Figure 3. These distributions are used in the
statistical analysis, along with others corresponding to systematic uncertainty variations. The pseudo-data
used in the extrapolation is taken to be the sum of the background distributions.
6 Results

The expected 95% C.L. upper limit on the global signal strength as a function of integrated luminosity is shown in Figure 4 for the best possible scenario where systematic uncertainties are entirely negligible and for the conservative scenario where the uncertainties remain as they were for the 2016 analysis. The potential benefit of reducing the systematic uncertainties are significant and become even more pronounced with larger datasets: the sensitivity with the current systematic uncertainties is 3.5 times worse than when systematic uncertainties are negligible with 3000 fb$^{-1}$.

If systematic uncertainties were entirely eliminated, the excluded signal strength would be 1.5.

Table 1 summarises the impact of the uncertainties on the 95% C.L. exclusion limit with 3000 fb$^{-1}$, showing the change in excluded signal strength when the named systematic uncertainty is ignored in the statistical analysis. Uncertainties in the background model are dominant, with a large impact on the exclusion limit. The multi-jet uncertainties were determined in 2016 by studying the background modeling in control regions defined using mass sidebands. The $t\bar{t}$ uncertainty is determined from MC simulation and is dominated by uncertainties in detector modelling, statistical uncertainties and theoretical uncertainties in the cross-section and acceptance. Despite being a smaller background, $t\bar{t}$ has a larger impact on the limit. This is a result of larger relative uncertainties on $t\bar{t}$ and the fact that it has a harder $m_{4j}$ distribution which is closer in shape to the $HH$ signal.
Figure 4: Expected 95% C.L. upper limit on the cross-section $\sigma \left( HH \rightarrow b\bar{b}b\bar{b} \right) / \sigma_{SM}$, as a function of the integrated luminosity of the search. The red line shows the upper limit when evaluated without systematic uncertainties, while the green line assumes that the systematic uncertainties remain as they were in 2016. The lower panel shows the ratio between these two limits. The extrapolated sensitivity is shown using a jet $p_T$ threshold of 30 GeV.

Table 1: Summary of changes induced in the 95% C.L. exclusion limit (expressed in units of signal strength, $\mu = \sigma / \sigma_{SM}$) when the named systematic uncertainties are ignored in the analysis. All other systematic uncertainties are included.

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta \mu$</th>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Jet Energy</td>
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</tr>
<tr>
<td>$b$-tagging</td>
<td>0.34</td>
</tr>
<tr>
<td>Theoretical</td>
<td>0.10</td>
</tr>
<tr>
<td>Multijet</td>
<td>1.85</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>2.83</td>
</tr>
</tbody>
</table>

6.1 Impact of Reducing Background Modelling Uncertainties

The impact of potential reductions in the background modelling uncertainties is shown in Figure 5.

The multijet background modelling uncertainties were determined in 2016 by examining the agreement between the background model and data in control regions. The uncertainties were essentially limited by the statistical precision of these comparisons. As more data is accumulated, the statistical precision of these comparisons will increase and a reduction in the modelling uncertainties should be possible. A
6.2 Limits on Higgs Boson Self-coupling

Variations in the Higgs boson self-coupling, \( \lambda_{HHH} \), change both the total cross-section of \( pp \to hh \) and the \( m_{HH} \) distribution. To assess the sensitivity of the \( HH \to b\bar{b}b\bar{b} \) analysis to \( \lambda_{HHH} \), \( m_{HH} \) distributions were generated using the morphing technique documented in Ref. [36] for \(-20 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 20\). These distributions were then used to set 95% C.L. upper limit on the cross-sections, as shown in Figure 6. If systematic uncertainties were negligible, the Higgs boson self-coupling would be constrained at 95% C.L. to \( 0.2 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 7.0 \). If the systematic uncertainties remain as they were for the 2016 analysis, the constraint would be \(-3.5 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 11\).

The exclusion limits grow worse in the range \( 3 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 5 \) as the \( m_{HH} \) distribution skews to lower values of \( m_{HH} \) where the background is larger. Figure 1(a) has a softer \( m_{HH} \) distribution than Figure 1(b): as \( \lambda_{HHH} \) increases, the self-coupling diagram becomes dominant, leading to a shift to lower \( m_{HH} \).
The high number of pile-up events at HL-LHC cause difficulties in maintaining high acceptance when triggering on multijet final states. Jets produced in the pile-up events cause high trigger rates, necessitating a rise in jet $p_T$ thresholds, which is exacerbated by the deterioration in trigger $p_T$ turn-on curves caused by the additional soft energy deposited in the calorimeters.

The impact of increasing the multijet trigger $p_T$ thresholds has been examined by repeating the analysis using different minimum jet $p_T$ requirements on the constituent jets of the Higgs boson candidates. The expected 95% C.L. upper limit on the cross-section $\sigma \left( HH \to b\bar{b}b\bar{b} \right)$ as a function of the minimum jet $p_T$ required is shown in Figure 7. Ref. [7] proposes a trigger menu with a multijet trigger that requires four jets, all satisfying a minimum $p_T$ threshold equivalent to demanding $p_T > 75$ GeV for jets reconstructed offline. This degrades the sensitivity by $\sim 30\%$ relative to the current analysis threshold of $p_T > 30$ GeV and is equivalent to reducing the integrated luminosity of the final dataset by 1000 fb$^{-1}$.

The expected 95% C.L. upper limit on the SM cross-section $\sigma \left( HH \to b\bar{b}b\bar{b} \right)$ as a function of integrated luminosity is shown in Figure 8, when the minimum jet $p_T > 75$ GeV is required. Two scenarios are shown: the best possible scenario where systematic uncertainties are entirely negligible and for the conservative scenario where the uncertainties remain as they were for the 2016 analysis. It can be seen that sensitivity is lost for all integrated luminosities compared to the analysis with minimum jet $p_T > 30$ GeV and that the detrimental impact of the systematic uncertainties is increased.

Demanding a higher minimum jet $p_T > 75$ GeV has a significant impact on the sensitivity of the analysis to $\lambda_{HHH}$, as shown in Figure 9. The Higgs boson self-coupling would be constrained more loosely.
Figure 7: Expected 95% C.L. upper limit on the cross-section \( \sigma \left( HH \rightarrow b\bar{b}b\bar{b} \right) / \sigma_{SM} \), as a function of the minimum jet \( p_T \) required of the four Higgs boson candidate constituent jets.

assuming that systematic uncertainties are negligible, \(-3.4 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 12\), while if current systematic uncertainties are used, \(-7.4 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 14\).

Table 2 summarises the various extrapolations made under different assumptions presented above.

Table 2: Summary of the constraints on \( \sigma \left( HH \rightarrow b\bar{b}b\bar{b} \right) / \sigma_{SM} \) and \( \lambda_{HHH}/\lambda_{HHH}^{SM} \) extrapolated to 3000 fb\(^{-1}\) under various assumptions.

<table>
<thead>
<tr>
<th>Jet Threshold [GeV]</th>
<th>Background Systematics</th>
<th>( \sigma/\sigma_{SM} ) 95% Exclusion</th>
<th>( \lambda_{HHH}/\lambda_{HHH}^{SM} ) Lower Limit</th>
<th>( \lambda_{HHH}/\lambda_{HHH}^{SM} ) Upper Limit</th>
</tr>
</thead>
<tbody>
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<td>30 GeV</td>
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<td>0.2</td>
<td>7</td>
</tr>
<tr>
<td>30 GeV</td>
<td>Current</td>
<td>5.2</td>
<td>-3.5</td>
<td>11</td>
</tr>
<tr>
<td>75 GeV</td>
<td>Negligible</td>
<td>2.0</td>
<td>-3.4</td>
<td>12</td>
</tr>
<tr>
<td>75 GeV</td>
<td>Current</td>
<td>11.5</td>
<td>-7.4</td>
<td>14</td>
</tr>
</tbody>
</table>
Figure 8: Expected 95% C.L. upper limit on the cross-section $\sigma\left(HH \rightarrow b\bar{b}b\bar{b}\right)/\sigma_{SM}$, as a function of the integrated luminosity of the search. The red line shows the upper limit when evaluated without systematic uncertainties, while the green line assumes that the systematic uncertainties remain as they were in 2016. The lower panel shows the ratio between these two limits. The extrapolated sensitivity is shown using a jet $p_T$ threshold of 75 GeV.

Figure 9: Expected 95% C.L. upper limit on the cross-section $\sigma\left(HH \rightarrow b\bar{b}b\bar{b}\right)/\sigma_{SM}$, as a function of the Higgs self-coupling constant $\lambda_{HHH}$ when the selection demands four b-tagged jets with $p_T > 75$ GeV. (a) systematic uncertainties are assumed to be negligible and (b) systematic uncertainties are assumed to remain at their current values. The cross-section exclusion limit grows less stringent in the range $3 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 5$ due to the shift of $m_{HH}$ towards lower values where the analysis acceptance is decreased and the backgrounds are higher. The extrapolated sensitivities are shown using a jet $p_T$ threshold of 75 GeV.
7 Conclusions

The results of the $HH \rightarrow b\bar{b}b\bar{b}$ analysis documented in [5] have been extrapolated to the 3000 fb$^{-1}$ of the HL-LHC dataset. The projected sensitivity from extrapolating the current analysis is insufficient for the $HH \rightarrow b\bar{b}b\bar{b}$ channel alone to observe SM non-resonant Higgs boson pair production, but it offers sensitivity comparable to that forecast for the $b\bar{b}\gamma\gamma$ [37] and $b\bar{b}\tau^+\tau^-$ [38] channels and so the prospects for a combination of these channels appear promising. In addition, analysis improvements and optimization allowed for with larger datasets may further improve the sensitivity of the $HH \rightarrow b\bar{b}b\bar{b}$ channel.

The projected 95% C.L. upper limit on $\sigma(HH \rightarrow b\bar{b}b\bar{b})$ is equivalent to $\mu = \sigma/\sigma_{SM} = 1.5$ if the effect of systematic uncertainties is ignored. The upper limit increases to $\mu = 5.2$ if the systematic uncertainties remain as large as in 2016. The Higgs boson self-coupling will be constrained to $0.2 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 7.0$ without systematic uncertainties, or $-3.5 < \lambda_{HHH}/\lambda_{SM}^{HHH} < 11$ with the 2016 systematic uncertainties. It is not expected that the systematic uncertainties will worsen with luminosity, but rather there will be improvements due to the enlarged dataset and better understanding. These two limits then serve to bound the possible result, while emphasizing the importance of reducing systematic uncertainties as much as possible. The sensitivity of the analysis to increasing trigger thresholds has also been studied. Increasing the jet $p_T$ requirement to thresholds to 75 GeV increases the di-Higgs cross-section limit by a factor 1.3 (2.2), when ignoring (including) the current systematic uncertainties.
References

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[2] LHC Higgs Cross Section Working Group, 2016,
url: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG.


