Determination of the off-shell Higgs boson signal strength in the high-mass ZZ final state with the ATLAS detector

The ATLAS Collaboration

Abstract

The measurement of the ZZ final state in the mass range above the $2m_Z$ threshold provides a unique opportunity to measure the off-shell coupling strength of the observed Higgs boson. In this note a determination of the off-shell Higgs boson signal strength in the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ final states is presented. The result is based on the data collected by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at a collision energy of $\sqrt{s} = 8$ TeV. The 95% confidence level upper $CL_s$ limit on the off-shell signal strength $\mu_{\text{off-shell}}$ is in the range 5.6–9.0 when varying the unknown $gg \rightarrow ZZ$ background K-factor from higher-order QCD corrections between half and twice the known signal K-factor, with an expected range of 6.6–10.7. Assuming no energy-scale dependence of the relevant Higgs boson couplings, a combination with the on-shell measurement of $\mu_{\text{on-shell}}$ in the $H \rightarrow ZZ \rightarrow 4\ell$ channel yields an observed (expected) 95% confidence level upper limit on $\Gamma_H/\Gamma_H^{\text{SM}}$ in the range 4.8–7.7 (7.0–12.0) under the same variations of the background K-factor.
1 Introduction

The observation of a new particle in the search for the Standard Model (SM) Higgs boson at the LHC, reported by the ATLAS [1] and CMS [2] Collaborations, is a milestone in the quest to understand electroweak symmetry breaking. Precision measurements of the properties of the new boson are of critical importance. Among its key properties are the couplings to each of the SM fermions and bosons, for which ATLAS presented results in Refs. [3, 4] and spin/CP properties, for which ATLAS presented results in Ref. [5].

The studies in Refs. [6–9] have shown that the high-mass off-peak regions of the $H \to ZZ$ and $H \to WW$ channels above the $2m_V \ (V = W, Z)$ threshold have sensitivity to Higgs boson production through off-shell and background interference effects, which presents a novel way of characterising the properties of the Higgs boson in terms of the off-shell signal strength and the associated off-shell Higgs boson couplings. This approach was used by the CMS collaboration [10] to set an indirect limit on the total width.

This note presents an analysis of the off-shell signal strength in the $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ final states ($\ell = e, \mu$). It is structured as follows: Section 2 presents the analysis concept and some key theoretical considerations for this analysis. Section 3 discusses the simulation of the main signal and background processes. Sections 4 and 5 give details for the analysis in the $ZZ$ final states, respectively. The dominant systematic uncertainties are discussed in Section 6. Finally the results of the $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ analysis and their combination are presented in Section 7.

The ATLAS detector is described in Ref. [11]. The present analysis is performed on data corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at a collision energy of $\sqrt{s} = 8$ TeV.

2 Off-shell signal and theoretical considerations

The recent interest in the cross section for the off-shell Higgs boson production $gg \to (H^\ast \to)VV^1$, $\sigma_{gg\to H^\ast\to VV}^{\text{off-shell}}$ for high-mass $WW$ and $ZZ$ final states was sparked by the novel approach to Higgs boson couplings measurements possible in this region. This could provide sensitivity to new physics that alters the interactions between the Higgs boson and other fundamental particles in the high-mass region [12–15].

The cross section for the off-shell signal strength $\sigma_{gg\to H^\ast\to ZZ}^{\text{off-shell}}$ is proportional to the Higgs boson couplings for production and decay. However, unlike the on-shell Higgs boson production, $\sigma_{gg\to H^\ast\to ZZ}^{\text{off-shell}}$ is independent of the total Higgs boson decay width $\Gamma_H$ [6, 7]. Using the framework of Higgs boson coupling deviations as in Ref. [16] this proportionality can be expressed as:

$$\frac{\sigma_{gg\to H^\ast\to ZZ}^{\text{off-shell}}}{\sigma_{gg\to H^\ast\to ZZ}^{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = k_{g,\text{off-shell}} \cdot k_{V,\text{off-shell}} \cdot \Gamma_H$$

where $\mu_{\text{off-shell}}$ is the off-shell signal strength in the high-mass region above the $2m_Z$ threshold and $k_{g,\text{off-shell}}$ and $k_{V,\text{off-shell}}$ are the off-shell coupling scale factors associated with the $gg \to H^\ast$ production and the $H^\ast \to ZZ$ decay, respectively. The off-shell Higgs boson signal cannot be treated independently from the $gg \to ZZ$ background, as sizeable negative interference effects appear [6]. The interference term is proportional to $\sqrt{\mu_{\text{off-shell}}} = k_{g,\text{off-shell}} \cdot k_{V,\text{off-shell}}$.

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In the following notation $gg \to (H^\ast \to)ZZ$ is used for the full signal+background process for $ZZ$ production, including the Higgs boson signal $gg \to H^\ast \to ZZ$ process, the continuum background $gg \to ZZ$ process and their interference. For Vector Boson Fusion (VBF) production, the analogous notation VBF $(H^\ast \to)ZZ$ is used for the full signal plus background process, with VBF $H^\ast \to ZZ$ representing the Higgs boson signal and VBF $ZZ$ for the background.
In contrast, the on-shell process $gg \rightarrow H \rightarrow ZZ$ allows a measurement of the ratio:

$$\frac{\sigma_{gg \rightarrow H \rightarrow ZZ} \text{on-shell}}{\sigma_{gg \rightarrow H \rightarrow ZZ} \text{on-shell, SM}} = \mu_{\text{on-shell}} = \frac{k_{g,\text{on-shell}}^2 \cdot k_{\gamma,\text{on-shell}}^2}{\Gamma_H / \Gamma_{\text{SM} H}}$$  \hspace{1cm} (2)

where the total width $\Gamma_H$ appears in the denominator. The combination of both on- and off-shell measurements promises a significantly higher sensitivity to the total width $\Gamma_H$ than previously believed possible at the LHC through direct measurements of the on-shell line shape.

Several theory considerations have to be taken into account for this analysis:

- The determination of $\mu_{\text{off-shell}}$ is valid under the assumption that any new physics which modifies the off-shell couplings $k_{i,\text{off-shell}}^2$ does not modify the expectation for the SM backgrounds (including higher-order QCD and electroweak (EW) corrections to the SM signal and background predictions) nor does it produce other sizeable signals in the search region of this analysis unrelated to an enhanced off-shell signal strength. This assumption is similar in structure to the assumptions needed for the Higgs boson coupling scale factor framework in Ref. [16] and a $\mu_{\text{off-shell}}$ measurement should be regarded as a search for a deviation from the SM expectation. The observation of a deviation is independent of any assumptions, but the interpretation of the deviation as a non-standard Higgs boson off-shell coupling relies on the assumption above.

- The interpretation of $\mu_{\text{off-shell}}$ as a measurement of $\Gamma_H$ requires a combination with the on-shell signal strength measurements from the $\sim 125.5$ GeV Higgs boson peak. This interpretation is valid under the assumption $k_{i,\text{on-shell}} = k_{i,\text{off-shell}}$. This assumption is particularly relevant to the running of the effective coupling $k_g$ for the loop induced $gg \rightarrow H$ production process, as it is sensitive to new physics that enters at higher mass scales and could be probed in the high-mass $m_{Z'Z'}$ signal region of this analysis. More details are given in Refs. [12–15].

- While higher-order QCD and EW corrections are known for the off-shell signal process [17] in the form of a next-to-next-to-leading-order (NNLO) K-factor $K_{\text{NNLO}}(m_{Z'Z'}) = \sigma_{\text{NNLO}}^{gg \rightarrow H \rightarrow ZZ} / \sigma_{\text{LO}}^{gg \rightarrow H \rightarrow ZZ}$, no higher-order QCD calculations are available for the leading-order (LO) $gg \rightarrow ZZ$ background process. In Ref. [18] a soft-collinear approximation is used to estimate the next-to-leading-order (NLO) and NNLO corrections to the $gg \rightarrow WW$ background process, indicating that the signal $K$-factor may also be applied to the signal-background interference term at the cost of adding an additional uncertainty of $\sim 30\%$. Details can be found in Section 6.

- Although the NNLO/LO K-factor $K_{\text{NNLO}}(m_{Z'Z'})$ is known for the signal [17] as a function of $m_{Z'Z'}$, it is calculated inclusively, meaning that it is integrated over all jet multiplicities or non-zero $p_T(ZZ)$ values that are induced by the higher order QCD corrections, and may no longer be accurate if event selections which bias the jet multiplicity or transverse momentum $p_T(ZZ)$ are applied. Consequently, the impact of any direct or indirect selections in jet multiplicity or $p_T(ZZ)$, must be assessed by simulating the additional QCD activity with a parton shower MC to approximate the missing higher order matrix element contributions. This will lead to correspondingly larger acceptance uncertainties.

As a consequence of these considerations, the primary goal of this analysis is to provide a limit on the off-shell signal strength $\mu_{\text{off-shell}}$. The experimental analysis was designed to be as inclusive as possible with respect to additional QCD activity, to minimize additional acceptance-related uncertainties on the $gg \rightarrow (H^+ \rightarrow ZZ)$ process. Finally, results will be given as a function of the K-factor ratio $K_{gg \rightarrow ZZ} / K_{gg \rightarrow H^+ \rightarrow ZZ}$ to make their dependence on this unknown K-factor explicit. Following Ref. [18], the central value is obtained with the background K-factor taken from the Higgs boson signal calculation.
3 Monte Carlo event simulation

The dominant processes contributing to the high-mass signal region in the \( ZZ \rightarrow 4\ell \) and \( ZZ \rightarrow 2\ell 2\nu \) final states are: the \( gg \rightarrow H^* \rightarrow ZZ \) off-shell signal, the \( gg \rightarrow ZZ \) background, the interference between them, \( ZZ \) production through VBF and \( VH \)-like production modes \( pp \rightarrow ZZ + 2j \) (s-, t- and u-channel) and finally the \( q\bar{q} \rightarrow ZZ \) background. In the following a Higgs boson mass of \( m_H = 125.5 \) GeV, close to the ATLAS measured Higgs boson mass value of 125.36 GeV [19], is assumed for the signal processes. However, the expected value for the off-shell production rate is only very weakly dependent on the Higgs boson mass value. The detector simulation for all generated Monte Carlo (MC) event samples is done with Geant4 [20, 21].

3.1 \( gg \rightarrow H^* \rightarrow ZZ \) signal and \( gg \rightarrow ZZ \) background

To generate the \( gg \rightarrow H^* \rightarrow ZZ \) and \( gg \rightarrow ZZ \) processes, including the interference, the leading-order MC generators gg2VV [6, 22] and MCFM [8] are used, and they yield identical results. The QCD renormalisation and factorisation scales are set to \( m_{ZZ}/2 \) [8]. The CT10 NNLO PDF set [23] is used, as the LO \( gg \rightarrow ZZ \) process is part of the NNLO calculation for \( pp \rightarrow ZZ \). Figure 1 shows the \( m_{4j} \) distribution for the \( gg \rightarrow (H^* \rightarrow ZZ) \rightarrow 2\ell 2\mu \) processes\(^2\), applying the event selections in the \( ZZ \rightarrow 4\ell \) channel (see Section 4) on generator level quantities. For low masses \( m_{ZZ} < 2m_Z \) the off-shell signal is negligible, while it becomes comparable to the continuum \( gg \rightarrow ZZ \) background for masses above the \( 2m_t \) threshold. The interference between the \( gg \rightarrow H^* \rightarrow ZZ \) signal and the \( gg \rightarrow ZZ \) background is negative over the whole mass range.

The default parton showering and hadronization option for the events processed with the full detector simulation is Pythia8 [25] with the “power shower” parton shower option.

3.1.1 Higher-order QCD corrections

In Ref. [17] the NNLO/LO K-factor \( K_{NNLO}(m_{ZZ}) = \frac{\sigma_{gg\rightarrow H^*\rightarrow ZZ}^{\text{NNLO}}}{\sigma_{gg\rightarrow H^*\rightarrow ZZ}^{\text{LO}}} \) and associated uncertainties are calculated for the \( pp \rightarrow gg \rightarrow H^* \rightarrow ZZ \) signal\(^3\) with \( m_H \sim 125.5 \) GeV, as a function of the Higgs boson virtuality \( m_{ZZ} \), using the MSTW2008 PDF set [26]. The K-factor also accounts for NLO EW corrections. This K-factor approximately doubles the expected off-shell signal yield in the high-mass region and is applied to the LO \( gg \rightarrow H^* \rightarrow ZZ \) MC events after reweighting the K-factor to the CT10 NNLO PDF set which is used for the \( gg \rightarrow H^* \rightarrow ZZ \) MC sample.

For the \( gg \rightarrow ZZ \) continuum processes, NLO and NNLO QCD calculations are not available. However, the effect of the NLO and NNLO QCD corrections are studied for the WW final state in Ref. [18] in the soft-collinear approximation, which is considered suitable for the Higgs boson production at high-mass. This approximation to the \( gg \rightarrow WW \) background process is compared to the same approximation for the \( gg \rightarrow H \rightarrow WW \) signal process, where the full NNLO QCD corrections are available, leading to the conclusion that the signal K-factor may also be applied to the signal-background interference term as an approximation to higher-order QCD corrections. This same approximation should also apply to the \( ZZ \) final state and the off-shell Higgs process.

As discussed in Section 2, the results in this note are given as a function of the unknown K-factor ratio \( K_{gg}(m_{ZZ})/K_{gg}(m_{ZZ}) \) between the \( gg \rightarrow ZZ \) background and the \( gg \rightarrow H^* \rightarrow ZZ \) off-shell signal. Ref. [17] considers only the gluon-initiated part \( K_{gg}(m_{ZZ}) \) of the full NNLO Higgs boson

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\(^2\)In this illustration, all four lepton final states (2e2\(\mu\), 4e and 4\(\mu\)) are identical, as final state interference effects from same lepton flavours are negligible in the high-mass region [24].

\(^3\)In the following the shorter \( gg \rightarrow X \) notation is used also in the context of QCD higher-order calculations where \( gg \) and \( qq \) initial states contribute to the full \( pp \rightarrow gg \rightarrow X \) process.
**Figure 1:** (a) Differential cross-sections for the $gg \rightarrow (H^* \rightarrow ZZ \rightarrow 2e2\mu)$ channel at the parton level, for the $gg \rightarrow H^* \rightarrow ZZ$ signal (red solid line), $gg \rightarrow ZZ$ continuum background (thick brown dotted line), $gg \rightarrow (H^* \rightarrow ZZ)$ with SM Higgs coupling (magenta long dashed line) and $gg \rightarrow (H^* \rightarrow ZZ)$ with $\mu_{\text{off-shell}} = 10$ (blue long dashed line). (b) Differential cross-section as a function of $m_{4l}$ for the $gg \rightarrow H^* \rightarrow ZZ \rightarrow 2e2\mu$ signal (solid red line) and its interference with the $gg \rightarrow ZZ \rightarrow 2e2\mu$ continuum background (black dashed line).

K-factor for the interference term\(^4\). This approach is adopted here for both the interference term and the background, hence the more precise definition for the K-factor ratio above is:

$$R_{H^*}^{B} = \frac{K(gg \rightarrow ZZ)}{K(gg \rightarrow H^* \rightarrow ZZ)} = \frac{K_{gg}^{B}(m_{ZZ})}{K_{H^*}^{B}(m_{ZZ})},$$

where $K_{gg}^{B}(m_{ZZ})$ is the mass dependent K-factor for the $gg \rightarrow ZZ$ background. As the K-factor $K_{gg}^{H^*}(m_{ZZ})$ is almost constant as a function of $m_{ZZ}$ in the relevant region of phase space, no mass dependence on $R_{H^*}^{B}$ is assumed.

### 3.1.2 Dependence of off-shell signal and background interference on the signal strength

An event sample $MC_{gg \rightarrow (H^* \rightarrow ZZ); \mu_{\text{off-shell}}}$ for the $gg \rightarrow (H^* \rightarrow ZZ)$ process with an arbitrary value of the off-shell Higgs boson signal strength $\mu_{\text{off-shell}}$ can be constructed from the MC sample for the SM Higgs boson signal $gg \rightarrow H^* \rightarrow ZZ$ ($MC_{gg \rightarrow H^* \rightarrow ZZ}^{\text{SM}}$), the $gg \rightarrow ZZ$ continuum background MC sample ($MC_{gg \rightarrow ZZ}^{\text{cont}}$) and a full SM Higgs boson signal plus background $gg \rightarrow (H^* \rightarrow ZZ)$ MC sample.

\(^4\)Numerically, $K_{gg}^{H^*}(m_{ZZ})$ differs from $K_{gg}^{H^*}(m_{ZZ})$ by $\sim 2\%$ as the higher-order QCD contribution from $gg$ and $qq$ production is small. However, $K_{gg}^{H^*}(m_{ZZ})$ has substantially larger uncertainties than $K_{gg}^{H^*}(m_{ZZ})$.\)
(MC\textsuperscript{SM} \textit{gg→H'→ZZ}) using the following weighting function:

\[
\text{MC}_{\text{gg→H'→ZZ}}(\mu_{\text{off-shell}}) = \frac{K^{H'}(m_{ZZ}) \cdot \mu_{\text{off-shell}} \cdot \text{MC}_{\text{gg→H'→ZZ}}}{\sqrt{R_H^B \cdot \mu_{\text{off-shell}}} + K^B(m_{ZZ}) \cdot \text{MC}_{\text{cont}}^{\text{gg→ZZ}}} \]

\[
\text{MC}_{\text{Interference}}^{\text{gg→ZZ}} = \text{MC}_{\text{SM}}^{\text{gg→H'→ZZ}} - \text{MC}_{\text{SM}}^{\text{gg→H'→ZZ}} - \text{MC}_{\text{cont}}^{\text{gg→ZZ}},
\]

where MC\textsuperscript{Interference} \textit{gg→ZZ} represents a MC sample for the interference term between signal and background as defined in Equation (5). The K-factors are calculated inclusively without any selections.

As a direct simulation of an interference MC sample is not possible, Equation (5) and R\textit{H}B can be used to obtain:

\[
\text{MC}_{\text{gg→H'→ZZ}}(\mu_{\text{off-shell}}) = \left( K^{H'}(m_{ZZ}) \cdot \mu_{\text{off-shell}} - K^B(m_{ZZ}) \cdot \sqrt{R_H^B \cdot \mu_{\text{off-shell}}} \right) \cdot \text{MC}_{\text{SM}}^{\text{gg→H'→ZZ}}
\]

\[
+ K^B(m_{ZZ}) \cdot \left( R_H^B - \sqrt{R_H^B \cdot \mu_{\text{off-shell}}} \right) \cdot \text{MC}_{\text{cont}}^{\text{gg→ZZ}},
\]

### 3.2 \textit{q̅q} → \textit{ZZ} and \textit{q̅q} → \textit{WZ} background

The \textit{q̅q} → \textit{ZZ} and \textit{q̅q} → \textit{WZ} background are simulated with Powheg [27, 28] in NLO QCD using dynamic QCD renormalisation and factorisation scales of \textit{m}_{\text{VZ}} and the CT10 NLO PDF set. Parton showering and hadronization is done with Pythia8. The interference with the \textit{q̅q} → \textit{WW} process for the 2\ell2\nu final state is neglected [28].

#### 3.2.1 NNLO QCD correction to \textit{q̅q} → \textit{ZZ}

The cross section for the \textit{q̅q} → \textit{ZZ} process is calculated in Ref. [29] for two on-shell Z in the final state at NNLO QCD accuracy, which makes this calculation applicable to the high-mass region. This calculation already contains the \textit{gg} → \textit{ZZ} process as part of the NNLO calculation. Excluding the \textit{gg} → \textit{ZZ} component, the cross section in the high-mass region is increased by approximately 4% compared to the NLO calculation.

A differential K-factor in \textit{m}_{ZZ} which can be directly applied to the Powheg NLO \textit{q̅q} → \textit{ZZ} sample, using dynamic QCD renormalisation and factorisation scales of \textit{m}_{ZZ}/2 and the CT10 NNLO PDF set, but removing the \textit{gg} → \textit{ZZ} component:

\[
K(m_{ZZ}) = \frac{\sigma_{\text{NLO}}^{\text{NNLO}}(m_{ZZ}/2, \text{CT10 NNLO}) - \sigma_{\text{NLO}}^{\text{LO}}(m_{ZZ}/2, \text{CT10 NNLO})}{\sigma_{\text{NLO}}^{\text{NNLO}}(m_{ZZ}, \mu = m_{ZZ}/2, \text{CT10 NNLO})},
\]

has been calculated by the authors of Ref. [29] and is used for this analysis.

#### 3.2.2 NLO EW corrections

Electroweak higher-order corrections are not taken into account by Powheg or any officially released generator, but were calculated in Ref. [30, 31] for on-shell outgoing vector bosons and found to be approximately −10% in the high-mass \textit{ZZ} region of this analysis. These NLO EW corrections are taken into account in the analysis by reweighting the Powheg events based on the kinematics of the diboson system. The required quantities are derived from the initial state quarks and the outgoing vector bosons and a reweighting procedure comparable to that described in Ref. [32] is applied.
3.3 EW ZZ production through VBF and VH-like production modes (s-, t- and u-channel)

The EW \( pp \rightarrow ZZ + 2j \) processes are simulated using MadGraph5 [33]. The QCD renormalisation and factorisation scales are set to \( m_W \) following the recommendation in Ref. [24] and the CTEQ6L1 PDF set [34] is used. Pythia6 [35] is used for parton showering and hadronisation. Phantom [36] was used as cross-check for MadGraph5 and validation showed good agreement between them in the high-mass region.

The \( pp \rightarrow ZZ + 2j \) process contains both VBF-like events and \( VH \)-like events. The high-mass range selected by the analysis receives Higgs boson signal induced events through:

- the off-shell VBF \( H \rightarrow ZZ \) process (this process scales with \( \kappa_V \) and is independent of \( \Gamma_H \)),
- VBF-like ZZ processes with a t-channel Higgs boson exchange (this process scales with \( \kappa_V \) and is independent of \( \Gamma_H \)),
- \( WH \) and \( ZH \) events with an on-shell Higgs boson, with decays \( Z \rightarrow \ell \ell \) or \( W \rightarrow \ell \nu \) and \( H \rightarrow 2\ell 2j \) or \( H \rightarrow \ell \nu 2j \) (this process scales with \( \kappa_V^2/\Gamma_H \)).

As the events with an on-shell Higgs boson behave differently from the off-shell events with respect to a measurement of off-shell Higgs boson couplings or the total width, these two populations need to be separated in the analysis by applying a cut on the generated Higgs boson mass \( |m_H^{gen} - 125.5 \text{ GeV}| < 1 \text{ GeV} \). In this context the \( VH \) events behave more like a background than like a signal. A K-factor of 1.08 is applied to the \( VH \) events to scale to the NNLO QCD corrected cross section as in Ref. [16].

3.3.1 Dependence of the off-shell signal and the background interference on the off-shell signal strength

A MC event sample for the EW \( pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j \) process with an arbitrary value of the off-shell Higgs boson signal strength \( \mu_{\text{off-shell}} \) can be constructed from a pure \( pp \rightarrow ZZ + 2j \) continuum background MC sample, a full SM Higgs boson signal plus background \( pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j \) MC sample and a third Higgs boson signal plus background \( pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j \) MC sample with \( \mu_{\text{off-shell}} = \kappa_V^2 = \Gamma_H/\Gamma_H^{SM} = 10 \). Using \( \Gamma_H/\Gamma_H^{SM} = 10 \) for the last sample ensures that the on-shell \( VH \) events are generated with SM-like signal strength. Within the context of this analysis \( \mu_{\text{off-shell}} = \kappa_g^2 \cdot \kappa_V^2 = \kappa_V^4 \) is assumed for the sub-dominant VBF-like component.

The following weighting function is used:

\[
MC_{pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j(\mu_{\text{off-shell}})} = \mu_{\text{off-shell}} \cdot MC_{pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j}^{SM} + \sqrt{\mu_{\text{off-shell}}} \cdot MC_{pp \rightarrow ZZ + 2j}^{\text{Interference}} + MC_{pp \rightarrow ZZ + 2j}^{\text{cont}},
\]

where the signal and interference samples are implicitly defined through the SM \( pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j \) MC sample

\[
MC_{pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j}^{SM} = MC_{pp \rightarrow H^* + 2j \rightarrow ZZ + 2j}^{SM} + MC_{pp \rightarrow ZZ + 2j}^{\text{Interference}} + MC_{pp \rightarrow ZZ + 2j}^{\text{cont}}
\]

and a \( \mu_{\text{off-shell}} = 10 \) MC sample:

\[
MC_{pp \rightarrow (H^* + 2j \rightarrow)ZZ + 2j}^{\kappa_V^4=10} = 10 \cdot MC_{pp \rightarrow H^* + 2j \rightarrow ZZ + 2j}^{SM} + \sqrt{10} \cdot MC_{pp \rightarrow ZZ + 2j}^{\text{Interference}} + MC_{pp \rightarrow ZZ + 2j}^{\text{cont}}.
\]
Solving for the generated MC samples yields:

\[
\text{MC}_{pp \to (H^* + \ell^+ \ell^- \ell^+ \ell^-)} = \frac{\mu_{\text{off-shell}}^{10} - \sqrt{10}\mu_{\text{off-shell}}^{10}}{10 - \sqrt{10}} \text{MC}_{pp \to (H^* + \ell^+ \ell^- \ell^+ \ell^-)}^{10} + \frac{10\sqrt{10}\mu_{\text{off-shell}}^{10} - \sqrt{10}\mu_{\text{off-shell}}^{10}}{10 - \sqrt{10}} \text{MC}_{pp \to (H^* + \ell^+ \ell^- \ell^+ \ell^-)}^{\text{SM}} + \frac{(\mu_{\text{off-shell}}^{10} - 1) \cdot (\mu_{\text{off-shell}}^{10} - \sqrt{10})}{\sqrt{10}} \text{MC}_{pp \to (H^* + \ell^+ \ell^- \ell^+ \ell^-)}^{\text{Cont}}
\]

4 Analysis in the ZZ \( \to 4\ell \) final state

4.1 Event selection and background estimations

The analysis in the ZZ \( \to 4\ell \) channel follows closely the Higgs boson measurements in the same final states in Ref. [19], with the same event selections in the off-peak region of 220 GeV < m_{4\ell} < 1000 GeV. To avoid the dependence of the qg \( \to ZZ \) kinematics on higher-order QCD effects, the analysis is performed inclusively, ignoring the number of jets in the events. The analysis is split into the same 4 lepton final states (\( 2\mu 2e, 2e2\mu, 4e, 4\mu \)) as in Ref. [19]. The same background estimation procedures are applied for the qg \( \to ZZ \) and reducible backgrounds.

To enhance the sensitivity, a matrix element based kinematic discriminant (ME-based discriminant) is used, exploiting the full kinematics in the centre-of-mass frame of the 4\ell system, to be discussed in Section 4.2. For the nominal result, a binned maximum likelihood fit to the ME-based discriminant distribution is performed. As a cross-check, a cut-and-count analysis is also performed, by counting events in an enriched signal region, defined to be 400 GeV < m_{4\ell} < 1000 GeV.

Table 1 shows the expected number of events for the signal and background processes in the inclusive off-peak region and the cut-based signal region. In both regions data are found to be consistent with the SM expectation. The dominant background comes from the qg \( \to ZZ \) process. The contribution of reducible backgrounds, such as Z+jets and top-quark production, is only about 0.5% of the total background in the full off-peak region and in the signal-enriched region. These backgrounds are not included in the final analysis.

4.2 Matrix element based kinematic discriminant

A matrix element based discriminant is constructed to enhance the sensitivity to the qg \( \to H^* \to ZZ \) signal in the off-shell region, with respect to the qg \( \to ZZ \) and qg \( \to ZZ \) backgrounds. It fully exploits the event kinematics in the centre-of-mass frame of the 4\ell system, based on eight observables: \( [m_{4\ell}, m_{Z_1}, m_{Z_2}, \cos \theta_1, \cos \theta_2, \phi, \cos \theta', \phi_1] \), defined in Ref. [19]. These observables are used to create the four-momenta of the leptons and incoming partons, which are then used to calculate matrix elements for different processes, provided by the MCFM program [8]. The following matrix elements are calculated for each event:

- \( P_{qg} \): matrix element for the qg \( \to ZZ \) \( \to 4\ell \) process,
- \( P_{gg} \): matrix element for the gg \( \to (H^* \to ZZ) \to 4\ell \) process including the Higgs boson (\( m_H = 125.5 \) GeV) with SM couplings, continuum background and their interference,
- \( P_H \): matrix element for for the gg \( \to H^* \to ZZ \to 4\ell \) process (\( m_H = 125.5 \) GeV).
The peak around -2.5 corresponds to the $gg$ analysis in the $ZZ$ between -4.5 and 0.5 are used in the final analysis. $gg$ corresponds mainly to the $gg$ discriminant values, compared to the $q$ ($220$ GeV $< m_{4\ell} < 1000$ GeV). The definitions of the reconstructed physics objects momentum are used. but some of the kinematic cuts have been optimised for the current analysis, as described below.

The analysis in the $ZZ$ is an empirical constant, chosen to be 0.1, to approximately balance the overall cross-sections $H$ processes. The expected events for the $gg \rightarrow (H^{*} \rightarrow ZZ$ and VBF $(H^{*} \rightarrow ZZ$ processes, including the Higgs boson signal, background and interference, are reported for both the SM predictions and $R_{Z}$ background K-factor of $R_{Z} = 1$ is assumed. The uncertainties in the number of expected events include the statistical uncertainties from MC samples and systematic uncertainties.

The kinematic discriminant is defined as in Ref. [8]:

$$ ME = \log_{10}\left(\frac{P_{H}}{P_{gg} + c \cdot P_{q\bar{q}}}\right), $$

where $c$ is an empirical constant, chosen to be 0.1, to approximately balance the overall cross-sections of the $q\bar{q} \rightarrow ZZ$ and $gg \rightarrow (H^{*} \rightarrow ZZ$ processes. The value of $c$ has a very small effect on the overall sensitivity.

Figure 2 shows the shape comparisons of the key input variables to the ME-based discriminant: $m_{4\ell}$, $m_{4\ell} < 1000$ GeV). Figure 3 shows the shape comparisons of the ME-based discriminant for the $gg \rightarrow H^{*} \rightarrow ZZ$ signal, $q\bar{q} \rightarrow ZZ$ background, $gg \rightarrow (H^{*} \rightarrow ZZ$ with SM $\mu_{off-shell}$ and $gg \rightarrow (H^{*} \rightarrow ZZ$ with $\mu_{off-shell} = 10$, for the full off-peak region $220$ GeV $< m_{4\ell} < 1000$ GeV). The $gg \rightarrow H^{*} \rightarrow ZZ$ signal events have on average larger ME-based discriminant values, compared to the $q\bar{q} \rightarrow ZZ$ background and the $gg \rightarrow ZZ$ background dominated $gg \rightarrow (H^{*} \rightarrow ZZ$ events. The $gg \rightarrow (H^{*} \rightarrow ZZ$ events with $\mu_{off-shell} = 10$ have a double-peak structure. The peak around -2.5 corresponds to the $gg \rightarrow ZZ$ background component, while the peak around -0.5 corresponds mainly to the $gg \rightarrow H^{*} \rightarrow ZZ$ component. Events with ME-based discriminant values between -4.5 and 0.5 are used in the final analysis.

<table>
<thead>
<tr>
<th>Process</th>
<th>$220$ GeV $&lt; m_{4\ell} &lt; 1000$ GeV</th>
<th>$400$ GeV $&lt; m_{4\ell} &lt; 1000$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \rightarrow H^{*} \rightarrow ZZ$ (S)</td>
<td>2.2 ± 0.5</td>
<td>1.1 ± 0.3</td>
</tr>
<tr>
<td>$gg \rightarrow ZZ$ (B)</td>
<td>30.7 ± 7.0</td>
<td>2.7 ± 0.7</td>
</tr>
<tr>
<td>$gg \rightarrow (H^{*} \rightarrow ZZ$</td>
<td>29.2 ± 6.7</td>
<td>2.3 ± 0.6</td>
</tr>
<tr>
<td>$gg \rightarrow (H^{*} \rightarrow ZZ$ ($\mu_{off-shell} = 10$)</td>
<td>40.2 ± 9.2</td>
<td>9.0 ± 2.5</td>
</tr>
<tr>
<td>VBF $H^{*} \rightarrow ZZ$ (S)</td>
<td>0.2 ± 0.0</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>VBF ZZ (B)</td>
<td>2.2 ± 0.1</td>
<td>0.7 ± 0.0</td>
</tr>
<tr>
<td>VBF $(H^{*} \rightarrow ZZ$</td>
<td>2.0 ± 0.1</td>
<td>0.6 ± 0.0</td>
</tr>
<tr>
<td>VBF $(H^{*} \rightarrow ZZ$ ($\mu_{off-shell} = 10$)</td>
<td>3.0 ± 0.2</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow ZZ$</td>
<td>168 ± 13</td>
<td>21.3 ± 2.1</td>
</tr>
<tr>
<td>Reducible backgrounds</td>
<td>1.4 ± 0.1</td>
<td>0.1 ± 0.0</td>
</tr>
<tr>
<td>Total Expected (SM)</td>
<td>200 ± 15</td>
<td>24.3 ± 2.2</td>
</tr>
<tr>
<td>Observed</td>
<td>182</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 1: Expected and observed number of events in the $ZZ \rightarrow 4\ell$ channel in the full off-peak region ($220$ GeV $< m_{4\ell} < 1000$ GeV) and the cut-based analysis signal region ($400$ GeV $< m_{4\ell} < 1000$ GeV). The reducible background includes contributions from the $Z$+jets and top quark processes. The expected events for the $gg \rightarrow (H^{*} \rightarrow ZZ$ and VBF $(H^{*} \rightarrow ZZ$ processes, including the Higgs boson signal, background and interference, are reported for both the SM predictions and $\mu_{off-shell} = 10$. A relative $gg \rightarrow ZZ$ background K-factor of $R_{Z} = 1$ is assumed. The uncertainties in the number of expected events include the statistical uncertainties from MC samples and systematic uncertainties.

5 Analysis in the $ZZ \rightarrow 2\ell 2\nu$ final state

The analysis in the $ZZ \rightarrow 2\ell 2\nu$ channel follows similar strategies to those used in the invisible Higgs boson search in the $ZH$ channel [37]. The definitions of the reconstructed physics objects are identical, but some of the kinematic cuts have been optimised for the current analysis, as described below.

\footnote{For the $ZZ \rightarrow 2\ell 2\nu$ analysis electrons, muons, jets, missing transverse momentum, and track-based missing transverse momentum are used.}
Figure 2: Distributions of the key input variables to the ME-based discriminant, for all lepton final states combined, normalised to unit area for shape comparisons, for the full off-peak region (220 GeV < $m_{4l}$ < 1000 GeV). The thick black dotted line represents the $q\bar{q} \to ZZ$ background, the red solid line the $gg \to H^* \to ZZ$ signal with SM couplings, the magenta long-dashed line the $gg \to (H^* \to ZZ)$ with SM off-shell, and the blue dashed line is for $gg \to (H^* \to ZZ)$ with $\mu_{\text{off-shell}} = 10$. 
Figure 3: Distributions of the ME-based discriminant in the four lepton final states normalised to unit area to show the shape comparisons, for the full off-peak region ($220 \text{ GeV} < m_4l < 1000 \text{ GeV}$). The thick black dotted line represents the $q\bar{q} \to ZZ$ background, the red solid line the $gg \to H^* \to ZZ$ signal with SM couplings, the magenta long-dashed line the $gg \to (H^* \to ZZ$ with SM $\mu_{\text{off-shell}}$, and the blue dashed line is for $gg \to (H^* \to ZZ$ with $\mu_{\text{off-shell}} = 10$. 

(a) $2\mu 2\mu$

(b) $2\mu 2e$

(c) $4e$

(d) $4\mu$
As the neutrinos in the final state do not allow for a kinematic reconstruction of the mass $m_{ZZ}$, the transverse mass ($m_T$) reconstructed from the momentum of the di-lepton system ($p_T^{\ell\ell}$) and the magnitude of the missing transverse momentum ($E_T^{\text{miss}}$):

$$m_T^2 = \left[ \sqrt{m_Z^2 + [p_T^{\ell\ell}]^2} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2} \right]^2 - \left[ p_T^{\ell\ell} + E_T^{\text{miss}} \right]^2,$$

is chosen as the discriminating variable to enhance sensitivity to the $gg \rightarrow H^* \rightarrow ZZ$ signal.

The analysis cuts are optimised to maximize the signal significance with respect to the main backgrounds $ZZ$, $WZ$, $WW$, top-quark events, and $W+$jets as described in Section 5.1. The selection cuts are also chosen to minimize the contributions of systematic uncertainties arising from the jet kinematics. After the optimisation, the following event selection is adopted (any requirements not listed here are identical to those used in Ref [37]):

- Opposite-charge di-electron or di-muon in the $Z$ mass window ($76 < m_{\ell\ell} < 106$ GeV),
- No third lepton (e or $\mu$) identified in the event using looser identification criteria for the electrons and a lower $p_T$ threshold of 7 GeV,
- $E_T^{\text{miss}} > 150$ GeV,
- $350$ GeV $< m_T < 1000$ GeV,
- $b$-jet [38] veto ($p_T > 20$ GeV, $|\eta| < 2.5$),
- Requirement on the fractional $p_T$ difference:
  $$\left| \frac{E_T^{\text{miss}}}{p_T^{\ell\ell}} + \sum_{\text{jet}} \frac{p_T^{\text{jet}}}{p_T^{\ell\ell}} \right| < 0.3,$$

  where $p_T^{\text{jet}}$ is the 2-dimensional vector of the jet momentum in the transverse plane,
- Requirement on the azimuthal angular difference of the directions of the $E_T^{\text{miss}}$ and track-based missing transverse momentum ($p_T^{\text{miss}}$):
  $$d\phi(E_T^{\text{miss}}, p_T^{\text{miss}}) < 0.5.$$

### 5.1 Background estimation

The dominant background is the SM $q\bar{q} \rightarrow ZZ$ production, followed by the SM $q\bar{q} \rightarrow WZ$ production. Background contributions from events with a genuine isolated lepton pair, not originating from a $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ decay arise from the $WW$, $t\bar{t}$, $Wt$, and $Z \rightarrow \tau\tau$ processes. The remaining backgrounds are from $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ with badly reconstructed $E_T^{\text{miss}}$, and from events with at least one fake electron or muon coming from $W+$jets, semi-leptonic top decays ($t\bar{t}$ and single top), and multi-jet events.

#### 5.1.1 ZZ and WZ backgrounds

The $WZ$ background is estimated with the MC and validated with data in a three-lepton control region. The theoretical prediction of the ZZ production agrees with the ATLAS cross-section measurement [39]. The Powheg samples are used as mentioned in Section 3.2, and the Sherpa samples are compared to Powheg as a cross-check. The NLO EW correction is applied to the Powheg simulation, which reduces the yields by about 8% for ZZ and 6% for WZ. The data and MC agree in all control regions within the statistical and systematic uncertainties.
5.1.2 WW, ℓℓ, Wt, and Z → ττ backgrounds

The WW, ℓℓ, Wt, and Z → ττ backgrounds are inclusively estimated with data using the flavour symmetry in an eμ control region. The following equations show how these backgrounds in the signal region can be estimated with the eμ events:

\[ N_{\text{ee}}^{\text{bkg}} = \frac{1}{2} N_{\text{e}}^{\text{data,sub}} \times \alpha, \]
\[ N_{\mu\mu}^{\text{bkg}} = \frac{1}{2} N_{\mu}^{\text{data,sub}} \times \frac{1}{\alpha}, \]

where \( N_{\text{ee}}^{\text{bkg}} \) and \( N_{\mu\mu}^{\text{bkg}} \) are the number of di-electron and di-muon events in the signal region. \( N_{\text{e}}^{\text{data,sub}} \) is the number of events in the eμ control region with non-WW, ℓℓ, Wt, and Z → ττ backgrounds subtracted using simulation. The different e and μ efficiencies are taken into account as \( \alpha \), which is an efficiency correction factor given by Equation 18:

\[ \alpha = \frac{N_{\text{data,Z}}^{\text{ee}}}{N_{\text{data,Z}}^{\mu\mu}}. \]

where \( N_{\text{ee}}^{\text{data,Z}} \) and \( N_{\mu\mu}^{\text{data,Z}} \) are the numbers of di-electron and di-muon events after the Z mass requirement. The value of \( \alpha \) is 0.939 ± 0.006, where the systematic uncertainty is included to take into account the small difference between data and MC. The other source of systematic uncertainty comes from the subtraction of non-Z backgrounds in the eμ control region using the MC.

5.1.3 Z → ee, μμ backgrounds

Imperfect modeling of detector non-uniformities and \( E_T^{\text{miss}} \) response could lead to additional Z background in the signal region. The Z background is estimated with data using the two dimensional sideband regions constructed by reversing one or both of the fractional \( p_T \) difference and \( \Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss}}) \) selections [37] shown in Equations 14 and 15. When a cut is reversed, the threshold is also increased by 0.1 (i.e. 0.6 for \( \Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss}}) \) and 0.4 for the fractional \( p_T \) difference) to reduce the contamination of non-Z background. The main uncertainty on the mis-measured Z background arises from the differences in shape of the \( E_T^{\text{miss}} \) and \( m_T \) distributions in the signal and sideband regions and the small correlation between the above two variables. Other systematic uncertainties originate from the subtraction of the non-Z backgrounds in the sideband regions, and uncertainties coming from the \( \Delta \phi(E_T^{\text{miss}}, p_T^{\text{miss}}) \) resolution.

5.1.4 W+jets and multi-jet backgrounds

The fake lepton background is estimated from data using the fake-factor method [37]. The expected background with a looser \( E_T^{\text{miss}} \) cut applied at 100 GeV, and without the \( M_T \) cut is 0.04 ± 0.01 events. No event remains after applying the full event selection for both the data-driven method and MC samples, and hence this background is negligible.

5.1.5 Summary of the expected signal and background yields

The expected signals and backgrounds with statistical and systematic uncertainties are summarised in Table 2. The observed event yields agree with the total expected ones from the SM within the uncertainties.
6 Systematic uncertainties

The largest systematic uncertainties for this analysis arise from theoretical uncertainties on the $gg \to H^* \to ZZ$ signal process and the $gg/q\bar{q} \to ZZ$ background processes. Compared to the theoretical uncertainties, the experimental uncertainties are small in the $ZZ \to 2\ell 2\nu$ analysis and close to negligible in the $ZZ \to 4\ell$ analysis.

6.1 Systematic uncertainties on $gg \to (H^* \to ZZ)$

6.1.1 Uncertainty on the $gg \to H^* \to ZZ$ signal

The uncertainty from missing higher-order QCD and EW corrections to the off-shell $gg \to H^* \to ZZ$ signal is estimated in Ref. [17] as a function of the Higgs boson virtuality $m_{ZZ}$ and adopted for this analysis. The uncertainty is ~20-30% for the high-mass region used in this analysis.

The PDF uncertainty for the $gg \to (H^* \to ZZ$ process as a function of $m_{ZZ}$ is found to be ~10-20% in the high-mass region used in this analysis. This is consistent with an earlier study at $\sqrt{s} = 7$ TeV [24].

6.1.2 Treatment of the $gg \to ZZ$ continuum background uncertainty

For the $gg \to ZZ$ continuum background processes, NLO and NNLO QCD calculations are not available. As discussed in Section 3.1.1 the gluon-induced part of the signal K-factor $K_{gg}^{H^*}(m_{ZZ})$ is applied to the background and results are then given as a function of the unknown K-factor ratio $R_{gg}^{H^*}$ between background and signal. As the uncertainty on $K_{gg}^{H^*}(m_{ZZ})$ is larger than the uncertainty on $K_{gg}^{H^*}(m_{ZZ})$, because some parts of the full signal NNLO QCD K-factor are not present in $K_{gg}^{H^*}(m_{ZZ})$, the following correlation

<table>
<thead>
<tr>
<th>Process</th>
<th>ee</th>
<th>$\mu\mu$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$gg \to H^* \to ZZ (S)$</td>
<td>$2.6 \pm 0.03 \pm 0.8$</td>
<td>$2.2 \pm 0.02 \pm 0.7$</td>
<td>$4.8 \pm 0.04 \pm 1.5$</td>
</tr>
<tr>
<td>$gg \to ZZ (B)$</td>
<td>$4.8 \pm 0.06 \pm 1.4$</td>
<td>$4.3 \pm 0.05 \pm 1.3$</td>
<td>$9.2 \pm 0.8 \pm 2.7$</td>
</tr>
<tr>
<td>$gg \to (H^* \to ZZ)$</td>
<td>$3.8 \pm 0.05 \pm 1.1$</td>
<td>$3.5 \pm 0.05 \pm 1.1$</td>
<td>$7.4 \pm 0.1 \pm 2.2$</td>
</tr>
<tr>
<td>$gg \to (H^* \to ZZ) (\mu_{\text{off-shell}} = 10)$</td>
<td>$18.7 \pm 0.1 \pm 5.6$</td>
<td>$16.0 \pm 0.1 \pm 4.8$</td>
<td>$34.7 \pm 0.2 \pm 10.4$</td>
</tr>
<tr>
<td>VBF $H^* \to ZZ (S)$</td>
<td>$0.3 \pm 0.05 \pm 0.01$</td>
<td>$0.2 \pm 0.05 \pm 0.01$</td>
<td>$0.5 \pm 0.07 \pm 0.02$</td>
</tr>
<tr>
<td>VBF ZZ (B)</td>
<td>$1.0 \pm 0.1 \pm 0.03$</td>
<td>$0.8 \pm 0.1 \pm 0.03$</td>
<td>$1.8 \pm 0.1 \pm 0.1$</td>
</tr>
<tr>
<td>VBF $(H^* \to ZZ)$</td>
<td>$0.8 \pm 0.1 \pm 0.03$</td>
<td>$0.6 \pm 0.1 \pm 0.03$</td>
<td>$1.4 \pm 0.1 \pm 0.1$</td>
</tr>
<tr>
<td>VBF $(H^* \to ZZ) (\mu_{\text{off-shell}} = 10)$</td>
<td>$2.2 \pm 0.1 \pm 0.09$</td>
<td>$1.6 \pm 0.1 \pm 0.05$</td>
<td>$3.7 \pm 0.2 \pm 0.1$</td>
</tr>
<tr>
<td>$q\bar{q} \to ZZ$</td>
<td>$28.0 \pm 0.7 \pm 3.0$</td>
<td>$26.4 \pm 0.6 \pm 2.8$</td>
<td>$54.4 \pm 0.9 \pm 5.7$</td>
</tr>
<tr>
<td>WW, $t\bar{t}$, $Wt$, and $Z \to \tau\tau$</td>
<td>$10.5 \pm 0.5 \pm 1.2$</td>
<td>$10.6 \pm 0.5 \pm 1.2$</td>
<td>$21.1 \pm 0.7 \pm 2.3$</td>
</tr>
<tr>
<td>$Z \to ee, \mu\mu$</td>
<td>$1.3 \pm 1.1 \pm 0.1$</td>
<td>$1.5 \pm 1.3 \pm 0.1$</td>
<td>$2.8 \pm 1.7 \pm 0.2$</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>$5.3 \pm 2.6 \pm 2.1$</td>
<td>$4.3 \pm 2.4 \pm 1.9$</td>
<td>$9.6 \pm 3.5 \pm 4.0$</td>
</tr>
<tr>
<td>Total Expected (SM)</td>
<td>$51.3 \pm 3.0 \pm 5.0$</td>
<td>$48.8 \pm 2.8 \pm 4.6$</td>
<td>$100 \pm 4 \pm 10$</td>
</tr>
<tr>
<td>Observed</td>
<td>$54$</td>
<td>$50$</td>
<td>$104$</td>
</tr>
</tbody>
</table>

Table 2: The expected yields for signals and backgrounds, with statistical and systematic uncertainties, in the $H \to ZZ \to 2\ell 2\nu$ channel corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at a collision energy of $\sqrt{s} = 8$ TeV. The expected events for the $gg \to (H^* \to ZZ$ and VBF $(H^* \to ZZ)$ processes, including the Higgs boson signal, background and interference, are reported for both the SM predictions and $\mu_{\text{off-shell}} = 10$. A relative $gg \to ZZ$ background K-factor of $R_{gg}^{H^*}=1$ is assumed. The uncertainties in the number of expected events are split into the statistical uncertainties from MC samples (or data statistical uncertainties for data-driven background estimations) and systematic uncertainties.
treatment of uncertainties is applied: the uncertainty of the signal K-factor\( K^H(m_{ZZ}) \) is applied as a correlated uncertainty to\( K^H(m_{gg}) \). The quadratic difference between the uncertainty on\( K^H(m_{ZZ}) \) and\( K^H(m_{gg}) \) is added as an uncorrelated uncertainty component only to\( K^H(m_{gg}) \).

A range between 0.5 and 2 is chosen for the variation of the K-factor ratio\( R^B_H \) in order to include the full correction from the signal K-factor\( K^H(m_{zz}) \sim 2 \) in the variation range. With respect to the LO\( gg \rightarrow ZZ \) process, this corresponds to an absolute variation in the range 1 to 4.

### 6.1.3 Treatment of the \( gg \rightarrow (H^* \rightarrow ZZ) \) interference uncertainty

In Ref. [18], a soft-collinear approximation is used for the\( gg \rightarrow WW \) background to calculate with \( \sim 10\% \) accuracy a higher-order QCD approximation for the sum of a heavy Higgs boson\( (gg \rightarrow H \rightarrow WW) \) and its interference with the background. This corresponds to an uncertainty of \( \sim 30\% \) on the interference alone. The calculations yield a similar K-factor for the sum of signal and interference as for the signal alone.

Within the ansatz of using an unknown K-factor ratio between background and signal (see Equation (4)), this additional uncertainty of \( \sim 30\% \) on the interference term can be represented by a \( \sim 60\% \) variation of the K-factor ratio\( R^B_H \) for the background around the nominal value of 1. The approximation of scaling the interference term in Equation 4 with the square root of an inclusive background K-factor\( K^B \) is valid only if the variation of this K-factor over the phase-space being integrated in the analysis is sufficiently small to be factorised out of the integration.

For the Higgs boson signal component, Ref. [18] suggests that the soft-collinear approximation is expected to account for the dominant part of the full signal K-factor and shows little variation across phase space. Hence, this approximation is justified for the signal. It is estimated that this is also the case for the background, but this can only be confirmed once a full NLO calculation for the background is available. Therefore the variation of\( R^B_H \) from 0.5 to 2 should cover both the leading corrections and uncertainties for the interference and the background component taken individually.

However, with respect to the expected results shown in Tables 1 and 2 and the values\( \mu^95\%_{\text{off-shell}} \) for the various expected limits at 95\% CL presented in Section 7 the uncertainty on the negative interference component given by the\( \sqrt{R^B_H} \) variation and the uncertainty on the positive background component given by the\( R^B_H \) variation cancel each other to a large extent.

This raises the question whether the chosen ansatz of scaling the interference term with\( \sqrt{R^B_H} \), although apparently a good approximation, is sufficient. Additional uncertainties on the interference component, which are not covered by the soft-collinear approximation could have an impact on the analysis. Therefore, in order to conservatively account for these additional contributions, the 30\% uncertainty on the interference derived in Ref. [18] is applied to the interference component in addition to, and uncorrelated with, the\( \sqrt{R^B_H} \) variation.

Finally it should be noted that Ref. [17] derives a maximum variation of \( \sim 50\% \) for the sum of signal and interference between the different options presented in Ref. [17] to treat the missing higher-order uncertainties. This should be viewed as the most conservative approach for the sum of signal and interference. At least part of this should be covered by the two independent sources of variation given by\( R^B_H \) and the additional 30\% uncertainty on the interference contribution.

### 6.1.4 Treatment of the \( gg \rightarrow (H^* \rightarrow ZZ) \) acceptance uncertainties

The\( ZZ \rightarrow 4\ell \) analysis is inclusive in QCD observables and no further acceptance uncertainties are assigned. Although the\( ZZ \rightarrow 2\ell 2\nu \) analysis does not apply dedicated jet categories, the selections described in Section 5 have an indirect influence on jet emissions and the transverse momentum\( p_T(ZZ) \).
of the ZZ system which may induce additional QCD acceptance uncertainties. As the MC generation is
done at leading-order in QCD there is no clear recipe to estimate these uncertainties. The approach taken
was to compare several parton shower and hadronization options using the LO matrix element:

- Pythia8 “power shower” parton shower including a matrix element correction on the first jet emis-
- Pythia8 “power shower” parton shower without a matrix element correction,
- Pythia8 “wimpy shower” parton shower without a matrix element correction,
- Herwig [40] in combination with Jimmy [41],

and compare these to high-mass Powheg NLO $gg \rightarrow H \rightarrow ZZ$ event samples with Higgs boson masses
between 300 and 800 GeV and a Sherpa+OpenLoops [42–44] $gg \rightarrow ZZ$ background sample using
merged 0-jet and 1-jet matrix element calculations. The normalised $p_T(ZZ)$ distribution for these sam-
ple is shown in Figure 4 for the restricted mass range $345 < m_{4\ell} < 415$ GeV in order to ensure a similar
mass of the hard interaction system.

As the $p_T(ZZ)$ distributions for the Powheg and Sherpa samples are very similar and should provide
the best prediction, the acceptance of the $gg \rightarrow (H^+ \rightarrow)ZZ$ process in the $ZZ \rightarrow 2\ell 2\nu$ channel is re-
weighted to the Powheg sample. Because the default samples are generated with the LO $gg \rightarrow (H^+ \rightarrow)ZZ$
matrix element with Pythia8 using the “power shower” parton shower option, and this sample shows the
largest deviation from Powheg and Sherpa, the full difference is taken as a systematic uncertainty. For
the $ZZ \rightarrow 2\ell 2\nu$ analysis selection this amounts to $\sim 5\%$. 

![Figure 4: Generator-level distribution of $p_T(ZZ)$ for the $gg \rightarrow (H^+ \rightarrow ZZ$ process, comparing the NLO
generator Powheg showered with Pythia8, the LO generator $gg2VV$ with Pythia8 using a matrix element
correction to the first jet, the power shower or the wimpy shower, the LO generator $gg2VV$ showered
with Jimmy+Herwig and a Sherpa+OpenLoops $gg \rightarrow ZZ$ sample with a matched 0-jet + 1-jet matrix
element. All samples are restricted to the range $345 < m_{4\ell} < 415$ GeV in order to ensure a similar mass
of the hard interaction system.](image-url)
In Ref. [45] the jet-veto efficiency for $gg \rightarrow (H^* \rightarrow)WW$ is calculated at next-to-leading-log (NLL) accuracy. This type of calculation can allow more exclusive event selections without large increases in systematic uncertainties, and hence lead to higher sensitivity in future analyses.

6.1.5 Summary of the $gg \rightarrow (H^* \rightarrow)ZZ$ systematic uncertainties

The common uncertainties on the signal, background and interference components of the $gg \rightarrow (H^* \rightarrow)ZZ$ process arise from the missing higher-order uncertainties on the K-factors $K_H^{gg}(m_{ZZ})$ and $K_H^H(m_{ZZ})$, the PDF uncertainties and the acceptance uncertainties. Instead of applying ad-hoc uncertainties on the unknown $gg \rightarrow ZZ$ background K-factor, the results are presented as a function of the unknown ratio $R^B_H$ between the background and signal K-factor in the range $R^B_H \in [0.5, 2]$. To be conservative, the additional uncertainty of 30% discussed in Section 6.1.3 is also applied to the interference component.

6.2 Systematic uncertainties on $q\bar{q} \rightarrow ZZ$

The missing higher-order and PDF uncertainties for the $q\bar{q} \rightarrow ZZ$ background, as a function of $m_{ZZ}$, are taken from Ref. [24], based on NLO 7 TeV calculations using a fixed scale of $m_Z$. Identical systematic uncertainties are found for 8 TeV using a dynamic scale of $m_{ZZ}/2$. Both the QCD scale uncertainty and the PDF uncertainty are \( \sim 5\text{-}10\% \) for the high-mass region used in this analysis. The NNLO calculation in Ref. [29] does not yield a significantly reduced QCD scale systematic uncertainty.

An evaluation of the PDF uncertainty correlations shows that the $q\bar{q} \rightarrow ZZ$ background PDF uncertainties are anti-correlated with the PDF uncertainties for the $gg \rightarrow (H^* \rightarrow)ZZ$ process, and this is taken into account in the analysis.

Acceptance uncertainties on the $q\bar{q} \rightarrow ZZ$ background are evaluated by comparing Pythia and Herwig samples and found to be negligible.

6.2.1 Systematic uncertainty on the EW correction

The EW corrections for the $q\bar{q} \rightarrow ZZ$ process described in Section 3.2.2 are only strictly valid for the LO QCD $q\bar{q} \rightarrow ZZ$ process above the di-boson production threshold and when both vector bosons are on-shell, which is the case for both analyses after final selections.

The EW corrections are computed at LO QCD because the mixed QCD-EW corrections have not yet been calculated. In events with high QCD activity, an additional systematic uncertainty is considered by studying the variable $\rho = \left( \frac{\sum_i \vec{T}_{i,T} + \vec{E}_{miss}^T}{\sum_i |\vec{T}_{i,T}| + |\vec{E}_{miss}^T|} \right)$ introduced in equation (4.4) of Ref. [32]. A phase space region with $\rho < 0.3$ is selected where both the LO and NLO QCD predictions are dominated by recoiling vector bosons and therefore the corrections are applicable without additional uncertainty. For events with $\rho > 0.3$ the correction is applied with a 100% systematic uncertainty since mixed QCD-EW corrections of the same order of magnitude are expected, but not yet calculated.

The applied corrections are partial in that they only include virtual corrections, and do not include polarisation effects. The sum of both effects is $O(1\%)$ [32] and is neglected in this analysis.

6.3 Systematic uncertainties on $q\bar{q} \rightarrow WZ$

The PDF, QCD scale, and EW correction uncertainties are considered in the same way as for the $q\bar{q} \rightarrow ZZ$ process. Both the QCD scale uncertainty and the PDF uncertainty are estimated to be \( \sim 5\text{-}10\% \) for the high-mass region used in this analysis. The impact of the NLO EW correction uncertainty is about 1% for the $ZZ \rightarrow 2\ell 2\nu$ channel. To be conservative, these uncertainties are considered correlated between the $q\bar{q} \rightarrow ZZ$ and $q\bar{q} \rightarrow WZ$ processes.
6.4 Systematic uncertainties on EW ZZ signal and background production in association with two jets

As the electroweak production modes give only a small signal contribution and missing higher-order and PDF uncertainties are estimated to be small for VH-like and VBF-like processes $pp \rightarrow ZZ + 2j$, these uncertainties are neglected.

6.5 Experimental systematic uncertainties

For the $ZZ \rightarrow 4\ell$ analysis the same sources of experimental uncertainties are evaluated as in Ref. [19]. In the off-shell Higgs boson region, the leptons come from the decay of on-shell $Z$ bosons, hence the lepton related systematic uncertainties are small, compared to the leptons from on-shell Higgs boson production. The leading, but still very small, experimental systematic uncertainties are due to the electron and muon reconstruction efficiency uncertainties.

For the $2\ell2\nu$ channel the same source of experimental uncertainties are evaluated as in Ref. [37]. The electron energy scale, electron identification efficiency, muon reconstruction efficiency, jet energy scale, and systematic uncertainties from the data-driven $Z$ background estimates are the main sources of the experimental systematic uncertainties. These experimental uncertainties affect the expected sensitivity of the $\mu_{\text{off-shell}}$ measurement only at the percent level.

7 Results

In this section the results for the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell2\nu$ analyses and their combination are presented. In the $ZZ \rightarrow 4\ell$ channel, a binned maximum likelihood fit to the ME-based discriminant distribution is performed to extract the limits on the off-shell Higgs boson signal strength. The fit model accounts for signal and background processes, including $gg \rightarrow (H^* \rightarrow)ZZ$, VBF($H^* \rightarrow)ZZ$ and $q\bar{q} \rightarrow ZZ$. The probability density functions (pdf) of the signal-related processes $gg \rightarrow \ell\ell$ZZ and VBF ($H^* \rightarrow)ZZ$ are parametrised as a function of both the off-shell Higgs boson signal strength $\mu_{\text{off-shell}}$ and the unknown background K-factor ratio $R_H^b$, as given in Equations (6) and (11). Normalisation and shape systematic uncertainties on the signal and background processes are taken into account as described in Section 6.1.3, with correlations between different components and processes as indicated therein. A cut-based analysis, comparing the event yield in a signal-enriched region to data, is also performed as a cross-check and to enable the re-interpretation of the results in models where the ME-based discriminant cannot be applied.

In the $ZZ \rightarrow 2\ell2\nu$ channel, a similar maximum likelihood fit is performed, comparing the event yield in the signal enriched region in data with the expectations. The fit model accounts for signal and all background processes mentioned in Table 2. The modelling of the dominant signal and background processes is the same as in the $ZZ \rightarrow 4\ell$ channel.

Assuming the same coupling strength for on-shell and off-shell Higgs boson production and decay, the measurement of the on-shell signal strength $\mu_{\text{on-shell}}$ in the low mass $H \rightarrow ZZ \rightarrow 4\ell$ channel can be re-interpreted as a limit on the total width $\Gamma_H/\Gamma_H^{\text{SM}}$ of the observed Higgs boson. The on-shell signal strength $\mu_{\text{on-shell}}$ is obtained from a simultaneous fit to the $H \rightarrow ZZ \rightarrow 4\ell$ on-shell region in Ref. [19] and the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell2\nu$ off-shell regions, taking into account the proper correlations between the systematic uncertainties.

In both measurements for $\mu_{\text{off-shell}}$ and for the total width $\Gamma_H/\Gamma_H^{\text{SM}}$ upper limits are derived using the $CL_s$ method [46], based on the following ratio of $p$-values: $CL_s(x) = p_s/(1-p_1)$ where $p_s$ is the $p$-value for testing a given $x = \mu_{\text{off-shell}}$ or $x = \Gamma_H/\Gamma_H^{\text{SM}}$ (null hypothesis\(^6\)) and $p_1$ is the $p$-value derived

---

\(^6\)Please note that “null hypothesis” is taken from the statistics literature and refers to the hypothesis to be excluded, i.e. the case with large $\mu_{\text{off-shell}}$ or large $\Gamma_H/\Gamma_H^{\text{SM}}$. 

17
from the same test statistic under the alternative hypothesis of $\mu_{\text{off-shell}} = 1$ in the first case and either $\Gamma_H/\Gamma_{H}^{\text{SM}} = 1$ or $\Gamma_H/\Gamma_{H}^{\text{SM}} = \mu_{\text{on-shell}} = 1$ in the second case\footnote{In the context of this analysis the alternative hypothesis is given by the standard model value(s) either only for the parameter of interest or for all relevant parameters of the fit model.}. The 95\% CL upper limit is found by solving for $CL_x(x) = 5\%$. Values $x > x_{95\%}$ are regarded as excluded at 95\% confidence level (CL). A detailed prescription of the implementation of the $CL_x$ procedure can be found in Ref. [47].

While the final 95\% CL limits are given as a function of the unknown background K-factor ratio $R_{B}^{H}$, comparisons between the observed data and MC expectations, and values in other figures and tables, are given assuming $R_{B}^{H} = 1$.

7.1 Results for the $ZZ \rightarrow 4\ell$ analysis

Figure 5 shows the observed and expected distributions of $m_{4\ell}$ and of the ME-based discriminant, combining all lepton final states in the ME-based discriminant analysis region. A small deficit of the order of 1$\sigma$ is observed when comparing data with the SM expectations. This leads to a more stringent observed limit on $\mu_{\text{off-shell}}$ compared to the expected limit. Figure 6 shows the scan of the negative log-likelihood, $-2\ln \Lambda$, as a function of $\mu_{\text{off-shell}}$ for data and the expected curve for a SM Higgs boson for the ME-based discriminant analysis. Table 3 and Figure 7 show the observed and expected 95\% CL upper limit on $\mu_{\text{off-shell}}$ as a function of $R_{B}^{H}$ for both analyses, where the observed data are consistent with the SM expectation.

![Figure 5](image)

(a) ATLAS Preliminary

$H \rightarrow ZZ \rightarrow 4\ell$

$\sqrt{s} = 8$ TeV, $L_{\text{int}} = 20.3 \, \text{fb}^{-1}$

Data

$gg$+VBF+$H^{*} \rightarrow ZZ$

Background $q\bar{q}$+ZZ

Background $Z$+jets, $t\bar{t}$

All contributions ($\mu_{\text{off-shell}}^{10}$)

![Figure 6](image)

(b) ATLAS Preliminary

$H \rightarrow ZZ \rightarrow 4\ell$

$CL_x = 20.3 \, \text{fb}^{-1}$

Data

$gg$+VBF+$H^{*} \rightarrow ZZ$

Background $q\bar{q}$+ZZ

Background $Z$+jets, $t\bar{t}$

All contributions ($\mu_{\text{off-shell}}^{10}$)

Figure 5: Observed distributions for $m_{4\ell}$ (a) and the ME-based discriminant (b) combining all lepton final states for the ME-based analysis signal region, compared to the expected contributions from the SM including the Higgs boson (stack). The dashed line corresponds to the total expected yield, including all backgrounds, for the Higgs boson with $\mu_{\text{off-shell}} = 10$ and interference. A relative $gg \rightarrow ZZ$ background K-factor of $R_{B}^{H} = 1$ is assumed.

To understand the impact of the systematic uncertainties, each of them is added independently with the corresponding expected upper limits of $\mu_{\text{off-shell}}$ shown in Table 4. The leading systematic impact
Table 3: The observed and expected 95% CL upper limits on $\mu_{\text{off-shell}}$ in the cut-based and the ME-based discriminant analyses in the 4\ell channel, within the range of $0.5 < R_{HH}^B < 2$. The bold numbers correspond to the limit assuming $R_{HH}^B = 1$. The upper limits are evaluated using the CL$_S$ method, with the alternative hypothesis $R_{HH}^B = 1$ and $\mu_{\text{off-shell}} = 1$.

<table>
<thead>
<tr>
<th>$R_{HH}^B$</th>
<th>Observed</th>
<th>Median expected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
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</tr>
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<td>cut-based</td>
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<td><strong>12.2</strong></td>
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<td>ME-based</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>6.1</td>
<td><strong>7.2</strong></td>
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</tbody>
</table>

Figure 6: Scan of the negative log-likelihood, $-2\ln\Lambda$, as a function of $\mu_{\text{off-shell}}$ in the ZZ → 4\ell channel in the ME-based discriminant analysis. The black solid (dashed) line represents the observed (expected) value including all systematic uncertainty, while the red dotted line is for the expected value without systematic uncertainties. A relative $gg \to ZZ$ background K-factor of $R_{HH}^B = 1$ is assumed.
Figure 7: The observed and expected 95% CL upper limit on \( \mu_{\text{off-shell}} \) as a function of \( R_{H^*} \), for the cut-based (a) and ME-based discriminant (b) analyses in the 4\( \ell \) channel. The upper limits are evaluated using the \( CL_s \) method, with the alternative hypothesis \( R_{H^*} = 1 \) and \( \mu_{\text{off-shell}} = 1 \).

comes from the higher-order QCD corrections to the \( gg \to ZZ \) processes. The impact of the experimental uncertainties on the expected sensitivity is small.

<table>
<thead>
<tr>
<th>Source of systematic uncertainties</th>
<th>95% CL on ( \mu_{\text{off-shell}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale for ( gg \to ZZ )</td>
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</tr>
<tr>
<td>QCD scale for the ( gg \to (H^* \to ZZ) ) interference</td>
<td>9.2</td>
</tr>
<tr>
<td>QCD scale for ( q\bar{q} \to ZZ )</td>
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</tr>
<tr>
<td>PDF for ( pp \to ZZ )</td>
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<tr>
<td>EW for ( q\bar{q} \to ZZ )</td>
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<tr>
<td>Luminosity</td>
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<td>electron efficiency</td>
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<tr>
<td>( \mu ) efficiency</td>
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<tr>
<td>No systematic</td>
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</table>

Table 4: The expected 95% CL upper limit on \( \mu_{\text{off-shell}} \) in the ME-based discriminant analysis in the 4\( \ell \) channel, with a ranked listing of each systematic uncertainty individually, comparing with no systematic uncertainty or all systematic uncertainties. The upper limits are evaluated using the \( CL_s \) method, assuming \( R_{H^*} = 1 \).

7.2 Results for the \( ZZ \to 2\ell 2\nu \) analysis

Figure 8 shows the observed distributions of \( m_T \) for the \( ee \) and \( \mu\mu \) modes in the signal region, compared to the expected contributions from the SM as well as to a Higgs boson with \( \mu_{\text{off-shell}} = 10 \).

Figure 9 shows the scan of the negative log-likelihood, \( -2 \ln \Lambda \), as a function of \( \mu_{\text{off-shell}} \) for data and
Figure 8: Observed distributions of $m_T$ for the $ZZ \to 2\ell 2\nu$ analysis in the signal region compared to the expected contributions from $gg + VBF \to (H^* \to ZZ)$ SM and with $\mu_{\text{off-shell}} = 10$ (dashed) in the $2e2\nu$ (left) and $2\mu2\nu$ (right) channels. The last bin in each distribution contains the overflow. A relative $gg \to ZZ$ background K-factor of $R_B = 1$ is assumed.

Table 5 shows the impact of theoretical and experimental uncertainties on the limits of $\mu_{\text{off-shell}}$ in the $2\ell 2\nu$ channel, where each of the uncertainties is considered one by one as was done in Table 4. The dominant effects come from the theoretical uncertainties, especially the higher-order QCD corrections to the $gg \to ZZ$ processes, as is the case for the $4\ell$ channel.

<table>
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<tr>
<th>$R_B^{H^*}$</th>
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<th>11.3</th>
<th>12.8</th>
<th>Median expected</th>
<th>8.6</th>
<th>9.9</th>
<th>12.9</th>
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<tr>
<td>0.5</td>
<td>Median expected</td>
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<td></td>
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</tbody>
</table>

Table 5: The observed and expected 95% CL upper limit on $\mu_{\text{off-shell}}$ in the $2\ell 2\nu$ channel, within the range of $0.5 < R_B^{H^*} < 2$. The bold numbers correspond to the limit assuming $R_B^{H^*} = 1$. The upper limits are evaluated using the $CL_s$ method, with the alternative hypothesis $R_B^{H^*} = 1$ and $\mu_{\text{off-shell}} = 1$. The expected number of events varies with $R_B^{H^*}$, while the observed number of data events is constant.
Figure 9: Likelihood scan for the $ZZ \rightarrow 2\ell 2\nu$ analysis with and without systematic uncertainties being considered. The black dashed (red dotted) line indicates the expected value with (without) systematic uncertainties considered, and the black solid line shows the observed value. A relative $gg \rightarrow ZZ$ background K-factor of $R_{B}^{H} = 1$ is assumed.

Figure 10: The observed and expected 95% CL upper limit on the signal strength $\mu_{\text{off-shell}}$ as a function of $R_{H}^{B}$ for the $ZZ \rightarrow 2\ell 2\nu$ analysis. The upper limit is evaluated using the $CL_s$ method, with the alternative hypothesis $R_{H}^{B} = 1$ and $\mu_{\text{off-shell}} = 1$. 
7.3 Results for the combination of $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$

The $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$ channels are combined in a simultaneous binned maximum likelihood fit to extract the off-shell signal strength $\mu_{\text{off-shell}}$. In this combination the ME-based discriminant analysis from the $ZZ \to 4\ell$ channel is used.

Assuming the on-shell and off-shell couplings are identical, this likelihood fit is extended to include the $H \to ZZ \to 4\ell$ analysis in the low mass region [19] to simultaneously measure the on-shell and off-shell signal strength $\mu_{\text{on-shell}}$ and $\mu_{\text{off-shell}}$. The experimental systematic uncertainties are treated as correlated between the on-shell and off-shell $H \to ZZ \to 4\ell$ analysis. Also the QCD scale uncertainties on the $gg \to H$ signal and the $q\bar{q} \to ZZ$ background are treated as correlated, while PDF uncertainties are treated as uncorrelated, since the different energy-scales of the two measurements result in an almost complete decorrelation of these uncertainties. As the off-shell measurement constrains the Higgs boson production and decay couplings, this allows the interpretation of the on-shell measurement in terms of the Higgs boson total width $\Gamma_H/\Gamma_H^{\text{SM}} = \mu_{\text{off-shell}}/\mu_{\text{on-shell}}$ relative to the SM expectation. The free parameters in the measurement of $\Gamma_H/\Gamma_H^{\text{SM}}$ are chosen as $\Gamma_H/\Gamma_H^{\text{SM}}$ and $\mu_{\text{on-shell}}$, with $\mu_{\text{off-shell}}$ re-expressed as $\mu_{\text{off-shell}} = \mu_{\text{on-shell}} \cdot \Gamma_H/\Gamma_H^{\text{SM}}$.

Figure 11 shows the scans of the negative log-likelihood, $-2\ln \Lambda$, as a function of $\mu_{\text{off-shell}}$ and $\Gamma_H/\Gamma_H^{\text{SM}}$. The best fit values and uncertainties extracted from the likelihood scan are $\mu_{\text{off-shell}} = 0.4^{+2.1}_{-0.4}$ and $\Gamma_H/\Gamma_H^{\text{SM}} = 0.3^{+1.4}_{-0.3}$, where in both cases the negative error corresponds to $\mu_{\text{off-shell}} = 0$ and $\Gamma_H/\Gamma_H^{\text{SM}} = 0$, respectively, as a negative value for these measurements is not defined. Both measurements are compatible with $\mu_{\text{off-shell}} = 1$ and $\Gamma_H/\Gamma_H^{\text{SM}} = 1$, respectively, within 1$\sigma$. The best fit value for the on-shell signal strength is $\mu_{\text{on-shell}} = 1.54^{+0.40}_{-0.34}$ in the combination with the $\Gamma_H/\Gamma_H^{\text{SM}}$ measurement, consistent with Ref. [19]. Table 7 and Figure 12 show the observed and expected 95% $CL_s$ upper limits on $\mu_{\text{off-shell}}$ and $\Gamma_H/\Gamma_H^{\text{SM}}$ varying the background K-factor ratio $R^B_H$ in the range $0.5 < R^B_H < 2$.

![Figure 11: Scan of the negative log-likelihood, $-2\ln \Lambda$, as a function of $\mu_{\text{off-shell}}$ (a) and $\Gamma_H/\Gamma_H^{\text{SM}}$ (b), combining the $ZZ \to 4\ell$ and $ZZ \to 4\nu$ channels. The black (red) dashed line represents the expected value with (and without) systematic uncertainties, while the solid black line indicates the observed value. A relative $gg \to ZZ$ background K-factor of $R^B_H = 1$ is assumed.](image)

Two choices of alternative hypotheses depending on the assumed value of $\mu_{\text{on-shell}}$ are used for the
### Source of systematic uncertainties

<table>
<thead>
<tr>
<th>Source of systematic uncertainties</th>
<th>95% CL on $\mu_{\text{off-shell}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale for $gg \rightarrow ZZ$</td>
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</tr>
<tr>
<td>QCD scale for the $gg \rightarrow (H^{*} \rightarrow ZZ$ interference</td>
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</tr>
<tr>
<td>QCD scale for $q\bar{q} \rightarrow ZZ$</td>
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</tr>
<tr>
<td>PDF for $pp \rightarrow ZZ$</td>
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</tr>
<tr>
<td>EW for $q\bar{q} \rightarrow ZZ$</td>
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</tr>
<tr>
<td>Parton showering</td>
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<tr>
<td>Z BG systematic</td>
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<td>No systematic</td>
<td>7.1</td>
</tr>
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</table>

Table 6: The expected 95% CL upper limit on $\mu_{\text{off-shell}}$ in the $2\ell 2\nu$ channel, with a ranked listing of each systematic uncertainty individually, and comparing to including no systematic uncertainty or all systematic uncertainties. The upper limits are evaluated using the $CL_s$ method, assuming $R_{BH}^{H} = 1$.

### Table 7

<table>
<thead>
<tr>
<th>$R_{BH}^{H}$</th>
<th>Observed</th>
<th>Median expected</th>
<th>Alternative hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
<td>1.0</td>
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<tr>
<td></td>
<td>5.6</td>
<td>6.7</td>
<td>9.0</td>
</tr>
<tr>
<td>$\Gamma_{H}/\Gamma_{SM}^{H}$</td>
<td>4.1</td>
<td>4.8</td>
<td>6.0</td>
</tr>
<tr>
<td>$\Gamma_{H}/\Gamma_{SM}^{H}$</td>
<td>4.8</td>
<td>5.7</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Table 7: The observed and expected 95% CL upper limit on $\mu_{\text{off-shell}}$ and $\Gamma_{H}/\Gamma_{SM}^{H}$ within the range of $0.5 < R_{BH}^{H} < 2$, combining the ZZ $\rightarrow 4\ell$ and ZZ $\rightarrow 2\ell 2\nu$ channels. The bold numbers correspond to the limit assuming $R_{BH}^{H} = 1$. The upper limits are evaluated using the $CL_s$ method, including all systematic uncertainties, with the alternative hypothesis as indicated in the last column. The two measurements of $\Gamma_{H}/\Gamma_{SM}^{H}$ differ only in the choice of the alternative hypothesis. In particular, $\mu_{\text{on-shell}}$ is treated as an auxiliary measurement in both cases in the fit and hence takes a value close to the observed value of $\mu_{\text{on-shell}} \sim 1.5$. 

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24
Figure 12: The observed and expected 95% CL upper limits on $\mu_{\text{off-shell}}$ (a) and $\Gamma_H/\Gamma_H^{\text{SM}}$ (b) and (c), as a function of $R^B_{H^+}$, combining the $ZZ \rightarrow 4\ell$ and $ZZ \rightarrow 2\ell 2\nu$ channels. The upper limits are evaluated using the $CL_s$ method including all systematic uncertainties. The alternative hypothesis for the measurement of $\mu_{\text{off-shell}}$ in (a) is $R^B_{H^+} = \mu_{\text{off-shell}} = 1$, while results for two choices of alternative hypothesis are provided for the measurement of $\Gamma_H/\Gamma_H^{\text{SM}}$: (b) $R^B_{H^+} = 1, \Gamma_H/\Gamma_H^{\text{SM}} = 1$ with $\mu_{\text{on-shell}} = 1.51$ as measured in data and (c) $R^B_{H^+} = 1, \Gamma_H/\Gamma_H^{\text{SM}} = 1$ with $\mu_{\text{on-shell}} = 1$ as expected in the SM. The two measurements of $\Gamma_H/\Gamma_H^{\text{SM}}$ in (b) and (c) differ only in the choice of the alternative hypothesis. In particular, $\mu_{\text{on-shell}}$ is treated as an auxiliary measurement in both cases in the fit and hence takes a value close to the observed value of $\mu_{\text{on-shell}} \sim 1.5$. 

25
results on $\Gamma_{H}/\Gamma_{H}^{\text{SM}}$: (i) the fitted data $\mu_{\text{on-shell}}$ value under the $\Gamma_{H}/\Gamma_{H}^{\text{SM}} = 1$ hypothesis i.e. $\mu_{\text{on-shell}} = 1.51$ and (ii) $\mu_{\text{on-shell}} = 1$ as expected in the SM. The alternative hypothesis is only used for the expected results and the evaluation of the compatibility of the alternative hypothesis with the data used in the $p_1$ calculation. As the ATLAS Higgs boson measurements [3–5] indicate compatibility with the SM, the more conservative alternative hypothesis with $\mu_{\text{on-shell}} = 1$ is used as the nominal result.

Under the assumption of $R_{H}^{B} = 1$ an observed CL$_{s}$ limit of $\mu_{\text{off-shell}} < 6.7$ and $\Gamma_{H}/\Gamma_{H}^{\text{SM}} < 5.7$ at 95\% CL ($\mu_{\text{off-shell}} < 7.9$ and $\Gamma_{H}/\Gamma_{H}^{\text{SM}} < 8.5$ expected) is found. Both limits are slightly better than expected, but compatible with the expectation within 1\sigma.

To understand the impact of the systematic uncertainties on the combined results for $\mu_{\text{off-shell}}$, each of them is included independently and shown with the corresponding expected upper limits on $\mu_{\text{off-shell}}$ in Table 8. The leading systematic impact comes from the missing higher-order uncertainties to the $gg \rightarrow ZZ$ and $pp \rightarrow ZZ$ processes.

<table>
<thead>
<tr>
<th>Source of systematic uncertainties</th>
<th>95% CL on $\mu_{\text{off-shell}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale for $gg \rightarrow ZZ$</td>
<td>6.7</td>
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<tr>
<td>QCD scale for $gg \rightarrow (H^* \rightarrow ZZ)$ interference</td>
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<td>QCD scale for $q\bar{q} \rightarrow ZZ$</td>
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<td>PDF for $pp \rightarrow ZZ$</td>
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Table 8: The expected 95\% CL upper limit on $\mu_{\text{off-shell}}$ in the combination of the 4\ell and 2\ell2\nu channels, with a ranked listing of each systematic uncertainty individually, compared with no systematic uncertainty or all systematic uncertainties. The upper limits are evaluated using the CL$_{s}$ method assuming $R_{H}^{B} = 1$. Only the sources of systematic uncertainty that increase the limit by one significant digit are shown.

8 Conclusion

A determination of the off-shell signal strength $\mu_{\text{off-shell}}$ in the high-mass $H^* \rightarrow ZZ \rightarrow 4\ell$ and $H^* \rightarrow ZZ \rightarrow 2\ell2\nu$ analysis is presented, using $pp$ collision data corresponding to an integrated luminosity of 20.3 fb$^{-1}$ at $\sqrt{s} = 8$ TeV.

The analysis in the 4\ell channel uses a likelihood fit to the distribution of a matrix element discriminant, while the analysis in the 2\ell2\nu channel counts events in a $H^* \rightarrow ZZ$ enriched signal region with high transverse missing momentum and high transverse mass. As no NLO QCD calculation is available for the $gg \rightarrow ZZ$ continuum background, the results are presented as a function of the K-factor ratio $R_{H}^{B}$ between the $gg \rightarrow ZZ$ continuum background and the $gg \rightarrow H^* \rightarrow ZZ$ signal.

The combination of both analyses leads to a 95\% CL limit on $\mu_{\text{off-shell}}$ in the range $5.6 < \mu_{\text{off-shell}}^{95\%} < 9.0$ when varying the unknown background K-factor ratio in the range $0.5 < R_{H}^{B} < 2$. The expected exclusion range is $6.6 < \mu_{\text{off-shell}}^{95\%} < 10.7$. Assuming the identical coupling strength for on- and off-shell Higgs boson production and decay, the measurement of the on-shell signal strength $\mu_{\text{on-shell}}$ in the low mass $H \rightarrow ZZ \rightarrow 4\ell$ channel is reinterpreted as a constraint on the total width $\Gamma_{H}/\Gamma_{H}^{\text{SM}}$ of the observed Higgs boson. Within the range of $0.5 < R_{H}^{B} < 2$, the observed (expected) 95\% CL limit on $\Gamma_{H}/\Gamma_{H}^{\text{SM}}$ is $4.8 < \Gamma_{H}^{95\%}/\Gamma_{H}^{\text{SM}} < 7.7$ ($7.0 < \Gamma_{H}^{95\%}/\Gamma_{H}^{\text{SM}} < 12.0$).
Assuming the K-factor for the $gg \rightarrow ZZ$ background is the same as the K-factor for the $gg \rightarrow H^* \rightarrow ZZ$ signal, a 95% CL limit of $\mu_{\text{off-shell}} < 6.7$ on the off-shell signal strength with an expected limit of $\mu_{\text{off-shell}} < 7.9$ is set. Under the same assumption an observed (expected) 95% CL upper limit on $\Gamma_H/\Gamma_H^{\text{SM}}$ of 5.7 (8.5) is found.

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References


