Search for heavy $ZZ$ resonances in the $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A search for heavy resonances decaying into a pair of $Z$ bosons leading to $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states, where $\ell$ stands for either an electron or a muon, is presented. The search uses proton–proton collision data at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 36.1 fb$^{-1}$ collected with the ATLAS detector during 2015 and 2016 at the Large Hadron Collider. The mass range of the hypothetical resonances considered is between 200 GeV and 2000 GeV depending on the final state, and the model considered. The results are interpreted as upper limits on the production cross section of a spin-0 or spin-2 resonance. The upper limits for the spin-0 resonance are translated to exclusion contours in the context of Type-I and Type-II two-Higgs-doublet models, while those for the spin-2 resonance are used to constrain the Randall–Sundrum model with an extra dimension giving rise to spin-2 graviton excitations.
1 Introduction

In 2012, the ATLAS and CMS collaborations at the LHC discovered a new particle [1, 2], an important milestone in the understanding of the mechanism of electroweak (EW) symmetry breaking [3–5]. The experiments have confirmed that the spin, parity and couplings of the new particle are consistent with those predicted for the Standard Model (SM) Higgs boson [6–8] (denoted as $h$ throughout this paper), measured its mass to be $m_h = 125.09 \pm 0.21\text{(stat)} \pm 0.11\text{(syst)}$ GeV [9] and reported recently on a combination of measurements of its couplings to other SM particles [10].

One important question is whether the newly discovered particle is part of an extended scalar sector as postulated by various extensions to the Standard Model such as the two-Higgs-doublet model (2HDM) [11]. These models predict additional Higgs bosons, motivating searches in an extended range of mass.

This paper reports on two searches for a heavy resonance decaying into two SM $Z$ bosons, encompassing the final states $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ and $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ where $\ell$ stands for either an electron or a muon and $\nu$ stands for all three neutrino flavours. These final states are referred to as $\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ respectively.

It is assumed that an additional Higgs boson would be produced predominantly via gluon fusion (ggF) and vector boson fusion (VBF) processes, but that the ratio of the two production mechanisms is unknown in the absence of a specific model. For this reason, the results are interpreted separately for ggF and VBF production modes, with events being classified into ggF- and VBF-enriched categories in both final states, as discussed in Sections 5 and 6. With good mass resolution and high signal-to-background ratio, the $\ell^+\ell^-\ell^+\ell^-$ final state is well-suited to search for a narrow resonance with mass $m_H$ between 200 GeV and 1200 GeV. The $\ell^+\ell^-\nu\bar{\nu}$ search covers the $300 \text{ GeV} < m_H < 1400 \text{ GeV}$ range and dominates at high masses due to its larger branching ratio.

These searches look for an excess in the four–lepton invariant mass, $m_{4\ell}$, for the $\ell^+\ell^-\ell^+\ell^-$ final state, and the transverse invariant mass, $m_T$, for $\ell^+\ell^-\nu\bar{\nu}$ final state, as the escaping neutrinos do not allow the full reconstruction of the final state. The $m_T$ is defined as:

$$m_T \equiv \sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_{T}^{\text{miss}})^2} - |p_T^{\ell\ell} + E_{T}^{\text{miss}}|$$

where $m_Z$ is the mass of the $Z$ boson, $p_T^{\ell\ell}$ is the transverse momentum of the lepton pair, $E_{T}^{\text{miss}}$ is the missing transverse momentum and $E_{T}^{\text{miss}}$ is the missing transverse momentum magnitude. In the absence of such excess, limits on the production rate of different signal hypotheses are obtained from a simultaneous likelihood fit to the two mass distributions. The first hypothesis is the ggF and VBF production of a heavy Higgs boson (spin-0 resonance) under the Narrow Width Approximation (NWA). The upper limits on a heavy Higgs boson are then translated into exclusion contours in the context of the two-Higgs-doublet model. As several theoretical models favour non-negligible natural widths, Large Width Assumption (LWA) models, widths of 1%, 5% and 10% of the resonance mass are also studied. The interference between the heavy scalar and the SM Higgs boson as well as the heavy scalar and the $gg \rightarrow ZZ$ continuum background are taken into account in this study. Limits are also set on the Randall–Sundrum (RS) model [12, 13] with a warped extra dimension giving rise to a spin-2 graviton excitation $G_{KK}$. The results of this paper extend previous results published by the ATLAS collaboration on the search for an additional heavy Higgs boson [14] performed with the LHC data collected at centre-of-mass energy of $\sqrt{s} = 8$ TeV. Similar results on the data collected at the LHC with $\sqrt{s} = 8$ TeV have also been reported by the CMS collaboration [15].
2 ATLAS detector

The ATLAS experiment is described in detail in Ref. [16]. ATLAS is a multi-purpose detector with a forward–backward symmetric cylindrical geometry and a solid angle coverage of nearly $4\pi$. The inner tracking detector (ID), covering the region $|\eta| < 2.5$, consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The innermost layer of the pixel detector, the insertable B-layer (IBL) [17], was installed between Run 1 and Run 2 of the LHC. The inner detector is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by a finely segmented lead/liquid-argon (LAr) electromagnetic calorimeter covering the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter provides coverage in the central region $|\eta| < 1.7$. The end-cap and forward regions, covering the pseudorapidity range $1.5 < |\eta| < 4.9$, are instrumented with electromagnetic and hadronic LAr calorimeters, with steel, copper or tungsten as the absorber material. A muon spectrometer (MS) system incorporating large superconducting toroidal air-core magnets surrounds the calorimeters. Three layers of precision wire chambers provide muon tracking in the range $|\eta| < 2.7$, while dedicated fast chambers are used for triggering in the region $|\eta| < 2.4$. The trigger system, composed of two stages, was upgraded [18] before Run 2. The Level-1 trigger system, implemented with custom hardware, uses information from calorimeters and muon chambers to reduce the event rate from about 40 MHz to a maximum of 100 kHz. The second stage, called the High-Level Trigger (HLT), reduces the data acquisition rate to about 1 kHz on average. The HLT is software–based and runs reconstruction algorithms similar to those used in the offline reconstruction.

3 Data and Monte Carlo samples

The proton–proton ($pp$) collision data used in these searches were collected by the ATLAS detector at a centre-of-mass energy of 13 TeV with a 25 ns bunch spacing configuration during 2015 and 2016. The data are subjected to quality requirements: if any relevant detector component is not operating correctly during a period in which an event is recorded, the event is rejected. After these quality requirements, the total accumulated data sample corresponds to an integrated luminosity of 36.1 fb$^{-1}$.

Simulated events are used to determine signal acceptance and some of the background contributions to these searches. The particle-level events produced by each event generator are processed through the ATLAS detector simulation [19] within the Geant 4 framework [20]. Additional $pp$ interactions in the same or nearby bunch crossings (pile-up) are simulated using inelastic $pp$ collisions and overlaid on the simulated events. The Monte Carlo (MC) generator used for this is PYTHIA 8.212 [21] with either the A14 [22] set of tuned parameters and NNPDF23 [23] for the parton density functions (PDF) set, or the AZNLO [24] tuned parameters and CTEQL1 [25] PDF when the Powheg-Box [26, 27] generator is used for the hard process. The simulated events are weighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data (pile-up reweighting). The properties of the bottom and charm hadron decays are simulated by the EvtGen v1.2.0 program [28].

Heavy spin-0 resonance production is simulated using the Powheg-Box MC event generator with the Higgs mass parameter set to the heavy resonance mass. Gluon fusion and vector boson fusion production modes

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1 The ATLAS experiment 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 upward. 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 $\eta = -\ln \tan(\theta/2)$. 

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are calculated separately with matrix elements up to next-to-leading order (NLO) in QCD. Powheg-Box is interfaced to Pythia 8.212 for decaying the Higgs boson into the $H \rightarrow ZZ \rightarrow ℓ^+ℓ^−ℓ^+ℓ^−$ or $H \rightarrow ZZ \rightarrow ℓ^+ℓ^−ν\bar{ν}$ final states. The CT10 [29] PDF set is used for the hard process. Events from ggF and VBF production are generated separately in the $300 < m_H < 1600$ GeV mass range under the NWA, using a step of 100 (200) GeV up to (above) 1000 GeV in mass. For the $ℓ^+ℓ^−ℓ^+ℓ^−$ final state, due to the sensitivity of the analysis at lower masses, events are also generated for $m_H = 200$ GeV. In addition, events from ggF production with a width of 5%, 10% and 15% of the scalar mass $m_H$ are generated with MadGraph5_aMC@NLO [30] for both final states. For the $ℓ^+ℓ^−ℓ^+ℓ^−$ final state, the $m_{4ℓ}$ distribution is parametrised analytically as described in Section 5.3, and the samples with a width of 15% of $m_H$ are used to validate the parametrisation. For the $ℓ^+ℓ^−ν\bar{ν}$ final state, a reweighing procedure as described in Section 6.3 is used on fully simulated events to obtain the reconstructed $m_{T}$ distribution at any value of mass and width tested. To have a better description of the jet multiplicity, MadGraph5_aMC@NLO is also used to generate events for the process $pp \rightarrow H+ ≥ 2$ jets at NLO QCD accuracy with the FxFx merging scheme [31]. The fraction of the ggF events that enter into the VBF-enriched category is estimated from the MadGraph5_aMC@NLO simulation.

Bulk Randall-Sundrum graviton events are generated with MadGraph5_aMC@NLO at leading order (LO) in QCD. The dimensionless coupling $k/M_{Pl}$, where $M_{Pl} = M_{Pl}/\sqrt{8\pi}$ is the reduced Planck scale and $k$ is the curvature scale of the extra dimension, is set to 1.0. In this configuration, the width of the resonance is expected to be ~ 6% of its mass. Mass points between 600 GeV and 2 TeV with 200 GeV spacing are generated for the $ℓ^+ℓ^−ν\bar{ν}$ final state. These samples are produced with a fast simulation that uses a parametrisation of the response of electromagnetic and hadronic calorimeters.

The $q\bar{q} \rightarrow ZZ$ background for the $ℓ^+ℓ^−ν\bar{ν}$ final state is simulated by the Powheg-Box v2 generator [32], interfaced to the Pythia 8.186 [33] parton shower model. The CT10NLO [29] PDF set is used for hard scattering processes. Next-to-next-to-leading-order (NNLO) QCD and NLO electroweak (EW) corrections are included [34–37] as a function of the invariant mass of the ZZ system $m_{ZZ}$. For the $ℓ^+ℓ^−ℓ^+ℓ^−$ final state, this background is simulated with the Sherpa 2.2 [38–40] generator, with the NNPDF3.0 [41] NNLO PDF set for the hard scattering process. NLO accuracy is achieved in the matrix element calculation for 0-, and 1-jet final states and LO accuracy for 2- and 3-jet final states. The merging is performed with the Sherpa parton shower [42] using the MePs@NLO prescription [43]. NLO EW corrections are applied as a function of $m_{ZZ}$ [36, 44]. In addition, Sherpa 2.2 is used for the $ℓ^+ℓ^−ν\bar{ν}$ final state to scale the fraction of events in the VBF-enriched category obtained from Powheg-Box simulation, because the Sherpa generator calculates matrix elements up to one parton at NLO and up to three partons at LO. The EW production of the vector boson scattering with two jets down to $O(α_{W}^0)$ is generated using Sherpa, where the process $ZZZ \rightarrow 4ℓqq$ is also taken into account.

The $gg \rightarrow ZZ$ production is modelled by Sherpa 2.2 at LO in QCD for the $ℓ^+ℓ^−ℓ^+ℓ^−$ final state and by gg2VV [45] for the $ℓ^+ℓ^−ν\bar{ν}$ final state, both including the off-shell $h$ contribution and the interference between the $h$ and the ZZ background. The k-factor accounting for higher order QCD effects for the $gg \rightarrow ZZ$ continuum production is calculated for massless quark loops [46, 47] in the heavy top-quark approximation [48], including the $gg \rightarrow H^* \rightarrow ZZ$ process [49]. Based on these studies, a constant k-factor of 1.7 is used, and a relative uncertainty of 60% on the normalisation is applied to both searches.

The $WW$ and $WZ$ diboson events are simulated by Powheg-Box, using the CT10NLO PDF set and Pythia 8.186 for parton showering.

Events containing $Z$ bosons with associated jets are simulated using the Sherpa 2.2 generator. Matrix elements are calculated for up to two partons at NLO and four partons at LO using the Comix [39] and
OpenLoops [40] matrix element generators and merged with the Sherpa parton shower [42] using the ME+PS@NLO prescription [43]. The NNPDF3.0 NNLO PDF set is used in conjunction with dedicated parton shower tuning developed by the Sherpa authors. The $Z +$ jets events are normalised to the NNLO cross sections [50].

The tri-boson backgrounds $ZZZ$, $WZZ$, and $WWZ$ with four or more prompt leptons are modelled using Sherpa 2.1. For the fully leptonic $t\bar{t} + Z$ background, with four prompt leptons originating from the top-quark and $Z$-boson decays, MadGraph5_aMC@NLO is used. The $t\bar{t}$ background as well as the single top and $Wt$ production, is modelled using Powheg-Box interfaced to Pythia 6 [51] for parton shower and hadronisation, to PHOTOS [52] for QED radiative corrections and to Tauola [53, 54] for the simulation of $\tau$ lepton decays.

In order to study the interference treatment for the LWA case, samples containing the $gg \rightarrow ZZ$ continuum background ($B$) as well as its interference ($I$) with a hypothetical heavy scalar ($S$) have been used and are referred to as $SBI$ samples hereafter. In the $\ell^+\ell^-\ell^+\ell^-$ final state the MCFM [55] NLO generator, interfaced to Pythia 8.212 for parton showering and hadronisation is used, to produce $SBI$ samples where the width of the heavy scalar is set to 15\% of its mass, for masses of 200, 300, 400, 500, 600, 800, 1000, 1200 and 1400 GeV. Background-only samples are also generated with the MCFM generator, and are used to extract the signal plus interference term ($SI$) by subtracting them from the aforementioned $SBI$ samples. For the $\ell^+\ell^-\nu\bar{\nu}$ final state, the $SBI$ samples were generated with the gc2VV generator. The samples include signal events with a scalar mass of 400, 700, 900, 1200 and 1500 GeV.

### 4 Object reconstruction

Electrons are reconstructed using information from the ID and the electromagnetic calorimeter [56]. Electron candidates are clusters of energy associated with ID tracks, where the final track-cluster matching is performed after the tracks have been fitted with a Gaussian-sum filter (GSF) to account for bremsstrahlung energy losses. Background rejection relies on the longitudinal and transverse shapes of the electromagnetic showers in the calorimeters, track-cluster matching and properties of tracks in the ID (e.g. hit requirement in the IBL). All of this information, except for the one related to track hits, is combined into a likelihood discriminant. The selection used combines the likelihood with the number of track hits and defines two working points (WP) which are used in the analyses presented here. The $\ell^+\ell^-\ell^+\ell^-$ analysis uses a “loose” WP, with an efficiency ranging from 90\% for transverse energy $p_T = 20$ GeV to 96\% for $p_T > 60$ GeV. A “medium” WP has been chosen for the $\ell^+\ell^-\nu\bar{\nu}$ analysis with an efficiency increasing from 82\% at $p_T = 20$ GeV to 93\% for $p_T > 60$ GeV. The electron transverse energy is computed from the cluster energy and the track direction at the interaction point.

Muons are formed from tracks reconstructed in the ID and MS, and their identification is primarily based on the presence of the track or track segment (tag) in the MS [57]. If the ID and MS full track information is present, a combined muon track is formed by a global fit using the hit information from both the ID and MS detectors (combined muon), otherwise the momentum is measured using the ID, and the partial MS track serves as identification (segment-tagged muon). The segment-tagged muon is limited to the centre of the barrel region ($|\eta| < 0.1$) which has reduced MS geometrical coverage. Furthermore in this central region, an ID track with $p_T > 15$ GeV is identified as a muon if its calorimetric energy deposition is consistent with a minimum ionising particle (calorimeter-tagged muon). In the forward region ($2.5 < |\eta| < 2.7$) with limited or no ID coverage, the MS track is either used alone (standalone muon) or combined with silicon hits, if found in the forward ID (combined muon). The ID tracks associated with the muons are
required to have a minimum number of associated hits in each of the ID sub-detectors to ensure good
track reconstruction. The standalone muon candidates are required to have hits in each of the three MS
stations they traverse. A “loose” muon identification WP, which uses all muon types and has an efficiency
of 98.5%, is adopted by the $\ell^+\ell^-\ell^+\ell^-$ analysis. For the $\ell^+\ell^-\nu\bar{\nu}$ analysis a “medium” WP is used, which
only includes combined muons and has an efficiency of 97%.

Jets are reconstructed using the anti-$k_t$ algorithm [58] with a radius parameter $R = 0.4$, and positive-energy
clusters of calorimeter cells as input. The algorithm suppresses noise and pile-up by keeping only cells
with a significant energy deposit and their neighbouring cells. Jets are calibrated using a dedicated scheme
designed to adjust, on average, the energy measured in the calorimeter to that of the true jet energy [59].
The jets used in this analysis are required to satisfy $p_T > 20$ GeV and $|\eta| < 4.5$. To reduce the number of
jet candidates originating from pile-up vertices, jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are required to pass
the jet vertex tagger selection [60].

Jets containing $b$-hadrons, referred to as $b$-jets, are identified by the long lifetime, high mass and decay
multiplicity of $b$-hadrons, as well as the hard $b$-quark fragmentation function. The $\ell^+\ell^-\nu\bar{\nu}$ analysis
identifies $b$-jets of $p_T > 20$ GeV and $|\eta| < 2.5$ using an algorithm that achieves an identification efficiency
of about 85% in simulated $t\bar{t}$ events, with a rejection factor for light flavour jets of about 33 [61, 62].

The missing transverse momentum $\vec{E}_{\text{T}}^\text{miss}$, which accounts for the imbalance of visible momenta in the
plane transverse to the beam axis, is computed as the negative vector sum of the transverse momenta of all
identified physics objects (electrons, muons, jets) as well as a “soft term”, accounting for unclassified soft
tracks and energy clusters in the calorimeters [63]. The presented analysis uses a track-based “soft term”,
which is built combining the information provided by the ID and the calorimeter, in order to minimise the
effect of pile-up which causes a degradation of the $\vec{E}_{\text{T}}^\text{miss}$ performance. The “soft term” is computed using the
momenta of the tracks associated to the primary vertex, while the momenta of the hard objects are
computed at the calorimeter level to allow the inclusion of neutral particles. Jet-muon overlap handling
is enabled in the $E_{\text{T}}^\text{miss}$ calculation. This corrects for fake jets due to pile-up close to muons and double
counted jets from muon energy losses.

Selected events are required to have at least one vertex with two associated tracks with $p_T > 400$ MeV, and
the primary vertex is chosen to be the vertex reconstructed with the largest $\sum p_T^2$. As different objects can
be reconstructed from the same detector information, an overlap ambiguity resolution is applied. For an
electron and a muon which share the same ID track, the muon is selected except for a calorimeter-tagged
muon which does not have a MS track, or a segment tagged muon, in which case the electron is selected. The
reconstructed jets which overlap with electrons (muons) in a cone of size $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2(0.1)$ are removed.

5 $H \rightarrow ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ event selection and background estimation

5.1 Event selection

Four-lepton events are selected and initially classified according to the lepton flavours: $4\mu$, $2e2\mu$, $4e$
called channels hereafter. They are selected with single-lepton, di-lepton and tri-lepton triggers, with the
di-lepton and tri-lepton ones including electron(s)-muon(s) triggers. Single-electron triggers apply “me-
dium” and “tight” likelihood identification, whereas multi-electron triggers apply “loose” and “medium”
identification. For the bulk of the data, recorded in 2016, the lowest $p_T$ threshold for the single-electron
(muon) triggers used is set to 26 (26) GeV, for the di-electron (muon) triggers to 15 (10) GeV and for the tri-electron (muon) triggers to 12 (6) GeV. For the data collected in 2015, the instantaneous luminosity was lower so the trigger thresholds were lower; this increases the signal efficiency by less than 1%. Globally, the trigger efficiency for signal events passing the final selections is about 98%.

Four-lepton candidates are formed by selecting in each channel, a lepton-quadruplet made out of two same-flavour, opposite-sign lepton pairs, selected as described in Section 4. Each electron (muon) must satisfy $p_T > 7 (5) \text{ GeV}$ and be measured in the pseudorapidity range of $|\eta| < 2.47 \quad (|\eta| < 2.7)$. The highest-$p_T$ lepton in the quadruplet must satisfy $p_T > 20 \text{ GeV}$, and the second (third) lepton in $p_T$ order must satisfy $p_T > 15 \text{ GeV} \quad (p_T > 10 \text{ GeV})$. In case of muons, at most one calorimeter-tagged or segment-tagged muon or a muon in the forward region ($2.5 < |\eta| < 2.7$) is allowed per quadruplet.

In case of ambiguity in the lepton-to-pair assignment, only one quadruplet per channel is selected by keeping the quadruplet with the lepton pairs closest (leading pair) and second closest (sub-leading pair) to the $Z$ boson mass, with invariant masses referred to as $m_{12}$ and $m_{34}$ respectively. In the selected quadruplet, the $m_{12}$ is required to be $50 < m_{12} < 106 \text{ GeV}$, while the $m_{34}$ is required to be less than 115 GeV and greater than a threshold, that is $12 \text{ GeV}$ for $m_{4\ell} \leq 140 \text{ GeV}$, rises linearly from 12 to 50 GeV with $m_{4\ell}$ in the interval of $[140 \text{ GeV}, 190 \text{ GeV}]$ and is fixed to 50 GeV for $m_{4\ell} > 190 \text{ GeV}$.

Selected quadruplets are required to have their leptons separated by $\Delta R > 0.1$ from each other if they are of the same flavour and $\Delta R > 0.2$ otherwise. For $4\mu$ and $4e$ quadruplets, if an opposite-charge same-flavour lepton pair is found with $m_{\ell\ell}$ below 5 GeV, the quadruplet is removed to suppress the contamination from $J/\psi$.

The $Z + \text{jets}$ and $t\bar{t}$ background contributions are reduced by applying impact parameter requirements as well as track- and calorimeter-based isolation requirements on the leptons. The transverse impact parameter significance, defined as the impact parameter calculated with respect to the measured beam line position in the transverse plane divided by its uncertainty, $|d_0|/\sigma_{d_0}$, for all muons (electrons) is required to be lower than 3 (5). The normalised track isolation discriminant, defined as the sum of the transverse momenta of tracks, inside a cone of size $\Delta R = 0.3 \quad (0.2)$ around the muon (electron) candidate excluding the lepton track, divided by the lepton $p_T$, is required to be smaller than 0.15. The larger muon cone size corresponds to that used by the muon trigger. Contributions from pile-up are suppressed by requiring tracks in the cone to originate from the primary vertex. To retain efficiency at higher $p_T$, the track isolation cone size is reduced linearly by 10 GeV/$p_T$ for $p_T$ above 33 (50) GeV for muons (electrons).

The relative calorimetric isolation is computed as the sum of the cluster transverse energies $E_T$, in the electromagnetic and hadronic calorimeters, with a reconstructed barycentre inside a cone of size $\Delta R = 0.2$ around the candidate lepton, divided by the lepton $p_T$. The clusters used for the isolation are the same as those for reconstructing jets. The relative calorimetric isolation is required to be smaller than 0.3 (0.2) for muons (electrons). The measured calorimeter energy around the muon (inside a cone of size $\Delta R = 0.1$) and the cells within $0.125 \times 0.175$ in $\eta \times \phi$ around the electron barycentre are excluded from the respective sums. The pile-up and underlying event contribution to the calorimeter isolation is subtracted event by event [64]. For both the track- and calorimeter-based isolation requirements any contribution arising from other leptons of the quadruplet is subtracted.

An additional requirement based on a vertex-reconstruction algorithm, which fits the four-lepton candidates under the assumption that they originate from a common vertex, is applied in order to reduce further the $Z + \text{jets}$ and $t\bar{t}$ background contributions. A loose cut of $\chi^2/\text{ndof} < 6$ for $4\mu$ and $< 9$ for the other channels is applied, which retains a signal efficiency larger than 99% in all channels.
The QED process of radiative photon production in $Z$ boson decays is well modelled by simulation. Some of the final-state radiation (FSR) photons can be identified in the calorimeter and incorporated into the $\ell^+\ell^-\ell^+\ell^-$ analysis. The strategy to include FSR photons into the reconstruction of $Z$ bosons is the same as in Run 1 \cite{14}. It consists of a search for collinear (for muons) and non-collinear FSR photons (for both muons and electrons) with only one FSR photon allowed per event. After the FSR correction, the lepton four-momenta of both dilepton pairs are recomputed by means of a $Z$-mass-constrained kinematic fit. The fit uses a Breit-Wigner $Z$ line shape and a single Gaussian per lepton to model the momentum response function with the Gaussian width set to the expected resolution for each lepton. The $Z$-mass constraint is applied to both $Z$ candidates, and improves the $m_{4\ell}$ resolution by about 15%.

In order to be sensitive to the VBF production mode, events are classified into four categories: one for the VBF production mode and three for the ggF production mode based on the three channels. If an event has two or more jets with $p_T$ greater than 30 GeV, with the two leading jets being well separated in $\eta$, $\Delta\eta_{jj} > 3.3$, and having a large invariant mass $m_{jj}$, $m_{jj} > 400$ GeV, this event is classified into the VBF-enriched category; otherwise the event is classified into one of the ggF-enriched categories. Such classification is used only in the search for a heavy scalar produced with the NWA.

The signal acceptance, defined as the ratio of the number of reconstructed events passing the analysis requirements to the number of simulated events in each category, is shown in Table 1, for the ggF and VBF production modes as well as different resonance masses. The contribution from final states with $\tau$ leptons decaying to electrons or muons is found to be negligible.

Table 1: The signal acceptance for the $\ell^+\ell^-\ell^+\ell^-$ analysis, for both the ggF and VBF production modes and resonance masses of 300 and 600 GeV. The acceptance is defined as the ratio of the number of reconstructed events after all selection requirements to the number of simulated events for each channel/category.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Production mode</th>
<th>$4\mu$ channel</th>
<th>ggF- enriched categories</th>
<th>$4e$ channel</th>
<th>VBF- enriched category</th>
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</thead>
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<td>300 GeV</td>
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<td>48%</td>
<td>40%</td>
<td>1%</td>
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<tr>
<td></td>
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<td>36%</td>
<td>30%</td>
<td>24%</td>
<td>21%</td>
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<tr>
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<td>ggF</td>
<td>64%</td>
<td>56%</td>
<td>48%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>VBF</td>
<td>36%</td>
<td>34%</td>
<td>32%</td>
<td>26%</td>
</tr>
</tbody>
</table>

5.2 Background estimation

The main background component in the $H \to ZZ \to \ell^+\ell^-\ell^+\ell^-$ final state, accounting for 97% of the total expected background events, is the non-resonant ZZ production. This arises from quark-antiquark annihilation (86%), gluon-gluon induced production (10%) and a small contribution from EW vector boson scattering (1%). The latter is more important in the VBF-enriched category, where it accounts for 16% of the total expected background. These backgrounds are all modelled by MC simulation as described in Section 3. Additional background comes from the $Z$ + jets and $t\bar{t}$ processes, which contribute at the percent level and decrease more rapidly than the non-resonant ZZ production as a function of $m_{4\ell}$. These backgrounds are estimated using data where possible, following slightly different approaches for final states with a di-muon ($\ell\ell + \mu\mu$) or a di-electron ($\ell\ell + ee$) sub-leading pair \cite{65}.
The $\ell\ell + \mu\mu$ non-$ZZ$ background is comprised of mostly $t\bar{t}$ and $Z + \text{jets}$ events, where in the latter case the muons arise mostly from heavy-flavour semileptonic decays and to a lesser extent from $\pi/K$ in-flight decays. The contribution from single-top production is negligible. The normalisations for the $Z + \text{jets}$ and $t\bar{t}$ backgrounds are determined using fits to the invariant mass of the leading lepton pair in dedicated data control regions. The control regions are formed by relaxing the $\chi^2$ requirement on the vertex fit, and by inverting and relaxing isolation and/or impact-parameter requirements on the subleading muon pair. An additional control region ($e\mu\mu\mu$) is used to improve the $t\bar{t}$ background estimate. Transfer factors to extrapolate from the control regions to the signal region are obtained separately for $t\bar{t}$ and $Z + \text{jets}$ using simulated events.

The main background in the $\ell\ell + ee$ process arises from the misidentification of light-flavour jets as electrons, photon conversions and the semi-leptonic decays of heavy-flavour hadrons. The $\ell\ell + ee$ control-region selection requires the electrons in the subleading lepton pair to have the same charge, and relaxes the identification and isolation requirements on the electron candidate, denoted $X$, with the lowest transverse momentum. The heavy-flavour background is completely determined from simulation, whereas the light-flavour and photon conversion background is obtained with the sPlot \cite{66} method, based on a fit to the number of hits in the innermost ID layer $n_{\text{IBL}}$ in the data control region. Transfer factors for the light-flavour jets and converted photons, obtained from simulated samples, are corrected using a $Z + X$ control region and then used to extrapolate the extracted yields to the signal region. Both the yield extraction and the extrapolation are performed in bins of the transverse momentum of the electron candidate and the jet multiplicity.

The $WZ$ production is included in the data-driven estimates for the $\ell\ell + ee$ final states, while it is added from simulation for the $\ell\ell + \mu\mu$ final states. The contributions from $tV$ (where $V$ stands for either a $W$ or a $Z$ boson) and tri-boson processes are minor and taken from simulated samples.

### 5.3 Signal and background modelling

The parametrisation of the reconstructed four-lepton invariant mass $m_{4\ell}$ distribution for signal and background is based on the MC simulation and afterwards used to fit the data.

In the case of a narrow-width resonance, the width in $m_{4\ell}$ is determined by the detector resolution, which can be modelled by the sum of a Crystal Ball ($CB$) function \cite{67,68} and a Gaussian ($G$):

$$P_s(m_{4\ell}) = f_{CB} \times CB(m_{4\ell}; \mu, \sigma_{CB}, \alpha_{CB}, n_{CB}) + (1 - f_{CB}) \times G(m_{4\ell}; \mu, \sigma_{G}).$$

The $CB$ and the Gaussian function share the same peak value of $m_{4\ell} (\mu)$, but acquire different parameters for the resolution, $\sigma_{CB}$ and $\sigma_{G}$. The $\alpha_{CB}$ and $n_{CB}$ parameters control the shape and position of the non-Gaussian tail and the parameter $f_{CB}$ ensures the relative normalisation of the two probability density functions. To improve the stability of the parametrisation in the full mass range considered, the parameter $n_{CB}$ is set to constant. The bias on the extraction of signal yields introduced by using the analytical function is below 1.5%. The function parameters are determined separately for each final state using signal simulation, and fitted to first- and second-degree polynomials in scalar mass $m_H$ to interpolate between the generated mass points. The use of this parametrisation for the function parameters introduces an extra bias on the signal yield and $m_H$ extraction of about 1%. An example of this parametrisation is illustrated in Figure 1, where the left plot shows the mass distribution for simulated samples at $m_H = 300, 600, 900$ GeV and the right plot shows the RMS of the $m_{4\ell}$ distribution in the range considered for this search.
In the case of LWA, the particle-level line-shape of $m_{4\ell}$ is derived from a theoretical calculation, as described in Ref. [69], and then is convolved with the detector resolution, using the same procedure as for the modelling of the narrow-width resonance.

The $m_{4\ell}$ distribution for the ZZ continuum background is taken from MC simulation, and parametrised by an empirical function for both the quark- and gluon-induced processes:

$$ f_{qqZZ/ggZZ}(m_{4\ell}) = (f_1(m_{4\ell}) + f_2(m_{4\ell})) \times H(m_0 - m_{4\ell}) \times C_0 + f_3(m_{4\ell}) \times H(m_{4\ell} - m_0) $$

(2)

where:

$$ f_1(m_{4\ell}) = \exp(a_1 + a_2 \cdot m_{4\ell}), $$

$$ f_2(m_{4\ell}) = \left\{ \frac{1}{2} + \frac{1}{2} \text{erf}\left(\frac{m_{4\ell} - b_1}{b_2}\right) \right\} \times \frac{1}{1 + \exp\left(\frac{m_{4\ell} - b_3}{b_4}\right)}, $$

$$ f_3(m_{4\ell}) = \exp(c_1 + c_2 \cdot m_{4\ell} + c_3 \cdot m_{4\ell}^2 + c_4 \cdot m_{4\ell}^3), $$

$$ C_0 = \frac{f_3(m_0)}{f_1(m_0) + f_2(m_0)}. $$

(3)

The first part of the function $f_1$ covers the low mass part of the spectrum where one of the Z bosons is off-shell, while $f_2$ models the ZZ threshold around 2-$m_Z$ and $f_3$ describes the high mass tail. The transition between low mass and high mass parts is performed by the Heaviside step function $H(x)$ around $m_0 = 240$ GeV. The continuity of the function around the $m_0$ is ensured by the normalisation factor $C_0$ that is applied to the low mass part. Finally, $a_i$, $b_i$ and $c_i$ are shape parameters which are obtained by fitting the $m_{4\ell}$ distribution in simulation for each category. The uncertainties on these parameters from the fitting are found negligible. The MC statistical uncertainties on the high mass tail are taken into account by introducing 1% uncertainty on $c_4$. 

Figure 1: (a) Parametrisation of the four-lepton invariant mass ($m_{4\ell}$) spectrum for various resonance mass ($m_H$) hypotheses in the NWA. Markers show the simulated $m_{4\ell}$ distribution for three specific values of $m_H$ (300, 600, 900 GeV) and the dashed lines show the parametrisation used in the $\ell^+\ell^-\ell'^+\ell'^-$ final state for these mass points as well as for intervening ones. (b) RMS of the four-lepton invariant mass distribution as a function of $m_H$. 

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*ATLAS Simulation Preliminary*

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*ATLAS Simulation Preliminary*
The $m_{4\ell}$ shapes are extracted from simulation for most background components ($t\bar{t}V$, $VVV$, $\ell\ell + \mu\mu$ and heavy-flavour hadron component of the $\ell\ell + ee$), except for the light-flavour jets and photon conversions in the case of $\ell\ell + ee$ background, which is taken from the control region as described in section 5.2.

5.3.1 Interference modelling

The gluon-initiated production of a heavy scalar $H$, the SM $h$ and the $gg \rightarrow ZZ$ continuum background all share the same initial and final state, and thus lead to interference terms in the total amplitude. Theoretical calculations described in Ref. [70] have shown that the effect of the interference could modify the integrated cross section by up to $O(10\%)$, and this effect is enhanced as the width of the heavy scalar increases. Therefore a search for a heavy scalar Higgs boson in the LWA case must properly account for two interference effects: the interference between the heavy scalar and the SM Higgs boson (denoted as $H-h$) and between the heavy scalar and the $gg \rightarrow ZZ$ continuum (denoted as $H-B$).

Assuming that $H$ and $h$ have similar properties, they have the same production and decay amplitudes and therefore the only difference in the signal and interference term in the production cross section comes from the propagator. Hence, the acceptance and resolution of the signal and interference terms are expected to be the same. The $H-h$ interference is obtained by reweighting the particle-level line-shape of generated signal events using the following formula:

$$w(m_{4\ell}) = 2 \cdot \text{Re} \left[ \frac{\frac{1}{s-s_H} \cdot \frac{1}{(s-s_h)^\ast}}{\frac{1}{|s-s_H|^2}} \right]$$

(4)

where $\frac{1}{s-s_H(\alpha)}$ is the propagator for a scalar ($H$ or $h$). The particle-level line-shape is then convolved with the detector resolution function and the acceptance of the signal and the interference is assumed to be the same.

In order to extract the $H-B$ interference contribution, signal-only and background-only samples have been subtracted from the generated SBI samples. The extracted particle-level $m_{4\ell}$ distribution for the $H-B$ interference term is then convolved with the detector resolution.

Figure 2 shows the overlay of the signal, both interference effects and the total line-shape for different mass and width hypotheses assuming the SM-like couplings for the heavy Higgs boson. As it can be seen, the two interference effects tend to cancel out, and the total interference yield is for the most part positive, enhancing the signal.

6 $H \rightarrow ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ event selection and background estimation

6.1 Event selection

The analysis is designed to select $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ events (with $\ell = e, \mu$), where the missing neutrinos are identified by a large $E_T^{\text{miss}}$, and to discriminate against the large $Z +$ jets, $WZ$ and top-quark backgrounds.

Events are required to pass either a single electron or muon trigger, where different $p_T$ thresholds are used depending on the instantaneous luminosity of the LHC. For the 2015 data the electron and muon triggers have $p_T$ thresholds of 24 and 20 GeV respectively, while for 2016 the muon trigger threshold is increased...
**Figure 2**: Particle-level four-lepton mass $m_{4\ell}$ model for signal only (red), $H-h$ interference (green), $H-B$ interference (blue) and the sum of the three processes (black). Three values of the resonance mass $m_H$ ($400$, $600$, $800$ GeV) are chosen, as well as three values of the resonance width $\Gamma_H$ ($1\%$, $5\%$, $10\%$ of $m_H$). The signal cross section which determines the relative contribution of the signal and interference is taken to be the cross section of the expected limit for each combination of $m_H$ and $\Gamma_H$. The full model (black) is finally normalised to unity and the other contributions are scaled accordingly.
to 24 GeV. For both triggers, the lower threshold is set to 26 GeV when the instantaneous luminosity exceeds the value of $10^{34}$ cm$^{-2}$s$^{-1}$. The trigger efficiency for signal events passing the final selection is about 99%.

Events are selected if they contain exactly two opposite-charge leptons of the same flavour and “medium” identification, with the more energetic lepton having $p_T > 30$ GeV and the other one having $p_T > 20$ GeV. The same impact parameter significance criteria as defined in Section 5.1 are applied to the selected leptons. Track- and calorimeter-based isolation criteria as defined in Section 5.1 are also applied to the leptons, but in this analysis the criteria are optimised such that by adjusting the isolation threshold the selection efficiency of the isolation criteria is 99%. If an additional lepton with $p_T > 7$ GeV and “loose” identification is found then the event is rejected, to reduce the amount of the $WZ$ background. In order to select leptons originating from the decay of a $Z$ boson, the invariant mass of the pair is required to be in the range 76 to 106 GeV. Moreover, since a $Z$ boson originating from the decay of a high-mass particle will be boosted, the two leptons are required to be produced with a small angular separation $\Delta R_{\ell\ell} < 1.8$.

Events with neutrinos in the final state are selected by imposing $E_T^{\text{miss}} > 120$ GeV, and this requirement heavily reduces the amount of $Z +$ jets background. In signal events with no initial- or final-state radiation the $Z$ boson is expected to be produced back-to-back with respect to the missing transverse momentum, and this characteristic is used to further suppress the $Z +$ jets background. The azimuthal angle between the dilepton system and the missing transverse momentum ($\Delta \phi (\ell \ell, E_T^{\text{miss}})$) is thus required to be greater than 2.7 and the fractional $p_T$ difference, defined as $|p_{T,\text{miss,jet}} - p_{T,\ell \ell}|/p_{T,\ell \ell}$, to be less than 20%, where $p_{T,\text{miss,jet}} = |E_T^{\text{miss}} + \sum p_{T,jet}|$.

Additional selection criteria are applied to keep only events with $E_T^{\text{miss}}$ originating from neutrinos rather than detector inefficiencies, poorly reconstructed high-$p_T$ muons or mis-measurements in the hadronic calorimeter. If at least one reconstructed jet has a $p_T$ greater than 100 GeV, the azimuthal angle between the highest-$p_T$ jet and the missing transverse momentum is required to be greater than 0.4. Similarly, if $E_T^{\text{miss}}$ is found to be less than 40% of the scalar sum of the transverse momenta of leptons and jets in the event ($H_T$), the event is rejected. Finally, to reduce the $t\bar{t}$ background, events are rejected whenever a $b$-jet is found.

The sensitivity of the analysis to the VBF production mode is increased by creating a dedicated category of VBF-enriched events. An optimisation procedure based on the significance obtained by using signal and background MC samples is performed and the selection criteria require the presence of at least two jets with $p_T > 30$ GeV checking that the two highest-$p_T$ jets are widely separated in $\eta$, $\Delta \eta_{jj} > 4.4$, and have a large combined invariant mass $m_{jj}$ greater than 550 GeV.

The signal acceptance, defined as the ratio of the number of reconstructed events passing the analysis requirements to the number of simulated events in each category, for the $\ell^+\ell^-\nu\bar{\nu}$ analysis is shown in Table 2, for the ggF and VBF production modes as well as for different resonance masses.

The $\ell^+\ell^-\nu\bar{\nu}$ search starts only from 300 GeV because this is where it begins to improve the combined sensitivity as the acceptance increases due to a kinematic threshold coming from the Emiss selection criteria, also seen from Table 2.

### 6.2 Background estimation

The dominant and irreducible background for this search is the non-resonant ZZ production which accounts for about 60% of the expected background events. The second largest background comes from
Table 2: Signal acceptance for the $\ell^+\ell^-\nu\bar{\nu}$ analysis, for both the ggF and VBF production modes and resonance masses of 300 and 600 GeV. The acceptance is defined as the ratio of the number of reconstructed events after all selection requirements to the number of simulated events for each channel/category.

<table>
<thead>
<tr>
<th>Mass</th>
<th>Production mode</th>
<th>ggF-enriched categories</th>
<th>VBF-enriched category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\mu^+\mu^-$ channel</td>
<td>$e^+e^-$ channel</td>
</tr>
<tr>
<td>300 GeV</td>
<td>ggF</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>VBF</td>
<td>2.6%</td>
<td>2.4%</td>
</tr>
<tr>
<td>600 GeV</td>
<td>ggF</td>
<td>44%</td>
<td>44%</td>
</tr>
<tr>
<td></td>
<td>VBF</td>
<td>27%</td>
<td>27%</td>
</tr>
</tbody>
</table>

WZ production (~30%) followed by $Z+\text{jets}$ production with poorly reconstructed $E_T^{\text{miss}}$ (~6%). Other sources of background are the $WW$, $t\bar{t}$, $Wt$ and $Z\rightarrow\tau\tau$ processes (~3%). Finally, a small contribution comes from $W+\text{jets}$, $t\bar{t}$, single-top quark and multi-jet processes, with at least one jet mis-identified as an electron or muon, as well as from $t\bar{t}VV$ events.

The $ZZ$ production, the dominant background, both in the ggF- and in the VBF-enriched signal regions, is modelled using Monte Carlo simulation and normalised to SM predictions, as explained in Section 3. The remaining backgrounds are mostly estimated using control samples in data.

The $WZ$ background is modelled using simulation but a correction factor for its normalisation is extracted as the ratio of data to simulated events in a dedicated control region, after subtracting from data the non-$WZ$ background contributions. The $WZ$ enriched control sample, called the $3\ell$ control region, is built by selecting $Z\rightarrow\ell\ell$ candidates with an additional electron or muon. This additional lepton is required to pass all selection criteria used for the other two leptons, with the only difference that its transverse momentum is required to be greater than 7 GeV. The contamination from $Z+\text{jets}$ and $t\bar{t}$ events is reduced by vetoing events with at least one reconstructed $b$-jet and by requiring the transverse mass of the $W$ boson ($m_W^{\text{T}}$), built using the additional lepton and the $E_T^{\text{miss}}$, to be greater than 60 GeV. The distribution of the missing transverse momentum for data and simulated events in the $3\ell$ control region is shown in Figure 3(a). The correction factor derived in the $3\ell$ control region is found to be $1.29\pm0.09$, where the uncertainty includes effects from the statistics of the control region as well as from experimental systematic uncertainties. Due to poor statistics when applying all the VBF selection requirements to the $WZ$ enriched control sample, the estimate for the VBF-enriched category is performed by including in the $3\ell$ control region only the requirement of at least two jets with $p_T > 30$ GeV. Finally, a transfer factor is derived from Monte Carlo simulation by calculating the probability of events passing all analysis selection criteria and containing two jets with $p_T > 30$ GeV to satisfy the $\Delta y_{jj} > 4.4$ and $m_{jj} > 550$ GeV requirements.

The non-resonant background includes mainly $WW$, $t\bar{t}$ and $Wt$ processes, but also $Z\rightarrow\tau\tau$ events in which the $\tau$ leptons produce light leptons and $E_T^{\text{miss}}$. It is estimated by using a control sample of events with lepton pairs of different flavour ($e^+\mu^-$), passing all analysis selection criteria. Figure 3(b) shows the missing transverse momentum distribution for $e^+\mu^-$ events in data and simulation after applying the dilepton invariant mass selection but before applying the other selection requirements. The non-resonant background in the $e^+e^-$ and $\mu^+\mu^-$ channels is estimated by applying a scale factor ($f$) to the selected
Figure 3: Missing transverse momentum distribution (a) for events in the $3\ell$ control region as defined in the text and (b) for $e^\pm\mu^\mp$ lepton pairs after applying the dilepton invariant mass selection. The backgrounds are determined following the description in Section 6.2 and the last bin includes the overflow. The error bars on the data points indicate the statistical uncertainty, while the systematic uncertainty on the prediction is shown by the hatched band. The bottom part of the figures shows the ratio of data over expectation.

events in the $e^\pm\mu^\mp$ control region, such that:

$$\begin{align*}
N_{ee}^{\text{bkg}} &= \frac{1}{2} \times N_{\text{data,sub}}^{e\mu} \times f, \\
N_{\mu\mu}^{\text{bkg}} &= \frac{1}{2} \times N_{\text{data,sub}}^{e\mu} \times \frac{1}{f},
\end{align*}$$

(5)

where $N_{ee}^{\text{bkg}}$ and $N_{\mu\mu}^{\text{bkg}}$ are the numbers of electron and muon pair events estimated in the signal region and $N_{\text{data,sub}}^{e\mu}$ is the number of events in the $e^\pm\mu^\mp$ control sample with $ZZ$, $WZ$ and other small backgrounds subtracted using simulation. The factor $f$ takes into account the different selection efficiency of $e^+e^-$ and $\mu^+\mu^-$ pairs at the level of the $Z \rightarrow \ell\ell$ selection, and is measured from data as $f^2 = N_{ee}^{\text{data}} / N_{\mu\mu}^{\text{data}}$, where $N_{ee}^{\text{data}}$ and $N_{\mu\mu}^{\text{data}}$ are the number of events passing the $Z$ boson mass requirement ($76 < m_{\ell\ell} < 106$ GeV) in the electron and muon channel respectively. As no events survive in the $e^\pm\mu^\mp$ control region after applying the full VBF selection, the background estimate is performed by including only the requirement of at least two jets with $p_T > 30$ GeV. The efficiency of the remaining selection criteria on $\Delta\eta_{jj}$ and $m_{jj}$ is obtained from simulated events.

The number of $Z +$ jets background events in the signal region is estimated from data, using a so-called ABCD method [71], since events with no genuine $E_T^{\text{miss}}$ in the final state are difficult to model using simulation. The method combines the selection requirements presented in Section 6.1 (with $n_{b\text{-jets}}$ representing the number of $b$-jets in the event) into two Boolean discriminants, $V_1$ and $V_2$, defined as:
\[ V_1 \equiv E_T^{\text{miss}} > 120 \text{ GeV} \quad \text{and} \quad E_T^{\text{miss}}/H_T > 0.4, \quad (6) \]
\[ V_2 \equiv |p_T^{\text{miss, jet}} - p_T^{\ell \ell}|/p_T^{\ell \ell} < 0.2 \quad \text{and} \quad \Delta \phi(\ell \ell, E_T^{\text{miss}}) > 2.7 \quad \text{and} \quad \Delta R_{\ell \ell} < 1.8 \quad \text{and} \quad n_{b-jets} = 0, \quad (7) \]

with all events required to pass the trigger and dilepton invariant mass selections. The signal region (A) is thus obtained by requiring both \( V_1 \) and \( V_2 \) to be true, control regions B and C require only one of the two booleans to be false (\( V_1 \) and \( V_2 \) respectively) and finally control region D is defined by requesting both \( V_1 \) and \( V_2 \) to be false. With this definition, an estimate of the number of events in region A is given by \[ N_{\text{est}}^A = N_{\text{obs}}^C \times \left( \frac{N_{\text{obs}}^B}{N_{\text{obs}}^D} \right) \]
where \( N_{\text{obs}}^X \) is the number of events observed in region X after subtracting non-Z-boson backgrounds. This relation holds as long as the correlation between \( V_1 \) and \( V_2 \) is small, and this is obtained by introducing two additional requirements on control regions B and D, namely \( E_T^{\text{miss}} > 30 \text{ GeV} \) and \( E_T^{\text{miss}}/H_T > 0.1 \). The estimation of the \( Z + \text{jets} \) background was cross-checked with another approach in which a control region is defined by inverting the analysis selection on \( E_T^{\text{miss}}/H_T \) and then using \( Z + \text{jets} \) Monte Carlo simulation to perform the extrapolation to the signal region, yielding results compatible with the ABCD method. Finally, the estimate for the VBF-enriched category is performed by extrapolating the inclusive result obtained with the ABCD method to the VBF signal region, extracting the efficiency of the two-jet, \( \Delta \eta_{jj} \) and \( m_{jj} \) selection criteria from \( Z + \text{jets} \) simulation.

The \( W + \text{jets} \) and multi-jet backgrounds are estimated from data using a so-called fake factor method [72]. A control region enriched in fake leptons is designed by requiring one lepton to pass all analysis requirements (baseline selection) and the other one to fail either the lepton “medium” identification or the isolation criteria (inverted selection). The background in the signal region is then derived using a transfer factor, measured in a data sample enriched in \( Z + \text{jets} \) events, as the ratio of jets passing the baseline selection to those passing the inverted selection.

Finally, the background from the \( t \bar{t}V \) and \( VVV \) processes is estimated using MC simulation.

### 6.3 Signal and background modelling

The modelling of the transverse invariant mass \( m_T \) distribution for signal and background is based on templates derived from fully simulated events and afterwards used to fit the data. In the case of a narrow width resonance, simulated MC events generated at fixed mass hypotheses as described in Section 3 are used as the inputs in the moment morphing technique [73] to obtain the \( m_T \) distribution for any other mass hypothesis.

The extraction of the interference terms for the LWA case is performed in the same way as in the \( \ell^+ \ell^- \ell^+ \ell^- \) final state, as described in Section 5.3. In the case of the \( \ell^+ \ell^- \nu \bar{\nu} \) final state a correction factor, extracted as a function of \( m_{ZZ} \), is used to reweight the interference distributions obtained at particle-level to account for reconstruction effects. The final expected LWA \( m_T \) distribution is obtained from the combination of the interference distributions with simulated \( m_T \) distributions, which are interpolated between the simulated mass points with a weighting technique using the Higgs propagator, a similar method to that used for the interference.
7 Systematic uncertainties

The systematic uncertainties can be classified into experimental and theoretical uncertainties. The first category relates to the reconstruction and identification of the physics objects (leptons and jets), their energy scale and resolution, and the integrated luminosity. Systematic uncertainties on the data-driven background estimates are also included in this category. The second category includes uncertainties on the theoretical description of the signal and background processes.

In both cases the uncertainties are implemented as additional nuisance parameters (NP) that are constrained by a Gaussian distribution in the profile likelihood ratio, as discussed in Section 8.1. The uncertainties affect the signal acceptance, its selection efficiency and the discriminant distributions as well as the background estimates for both final states. Each source of uncertainties is either fully correlated or anti-correlated among the different channels and categories.

7.1 Experimental uncertainties

The uncertainty on the combined 2015 and 2016 integrated luminosity is 3.2%. This is derived from a preliminary calibration of the luminosity scale using x–y beam-separation scans performed in May 2016, following a methodology similar to that detailed in Ref. [74].

The lepton identification and reconstruction efficiency and energy/momentum scale and resolution are derived from data using large samples of $J/\psi \rightarrow \ell\ell$ and $Z \rightarrow \ell\ell$ decays. The uncertainties on the reconstruction performance are computed following the method described in Ref. [57] for muons and Ref. [56] for electrons. Typical uncertainties on the identification efficiency are in the range 0.5–3.0% for muons and 1.0–1.7% for electrons. The uncertainties on the electron energy scale, the muon momentum scale and their resolutions are small, and are fully correlated between the two searches ($\ell^+\ell^-\ell^+\ell^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states).

The uncertainties on the jet energy scale and resolution have several sources, including uncertainties on the absolute and relative in situ calibration, the correction for pile-up, the flavour composition and response. These uncertainties are separated into independent components, which are fully correlated between the two searches. They vary from 4.5% for jets with transverse momentum $p_T = 20$ GeV, decreasing to 1% for jets with $p_T = 100$–1500 GeV and increasing again to 3% for jets with higher $p_T$, for the average pile-up conditions of the 2015 and 2016 data taking period.

Uncertainties on the lepton and jet energy scales are propagated to the uncertainty on the $E_T^{\text{miss}}$. Additionally, the uncertainties from the momentum scale and resolution of the tracks that are not associated with any identified physics object contribute 8% and 3% respectively to the uncertainty on the $E_T^{\text{miss}}$.

The efficiency for the lepton triggers in events with reconstructed leptons are nearly 100%, and hence the related uncertainties are negligible.

7.2 Theoretical uncertainties

For simulated signal and backgrounds, theoretical modelling uncertainties associated with PDF, missing QCD higher order corrections (via variations of factorisation and renormalisation scales), and parton showering uncertainties are considered.
For various signal hypotheses, the dominant theoretical modelling uncertainties are due to the missing QCD higher order corrections and to the parton showering. The missing QCD higher order corrections for the events from the ggF production that fall into the VBF-enriched category are evaluated using MadGraph5_aMC@NLO and affect the signal acceptance by 10%. Parton showering uncertainties are of order 10% and are evaluated by comparing Pythia 8.212 to HERWIG7 [75] generators.

For the $q\bar{q} \to ZZ$ background, the effect of the PDF uncertainties in the full mass range varies between 2% and 5% in all categories, and that of missing QCD higher order corrections is about 10% in the ggF-enriched categories and 30% in the VBF-enriched category. The parton showering uncertainties result in less than 1% impact in the ggF-enriched categories and about 10% impact in the VBF-enriched category.

For $gg \to ZZ$ background, as described in Section 3, a 60% relative uncertainty on the inclusive cross section is considered, while a 100% uncertainty is assigned in the VBF-enriched category.

8 Results and Interpretations

8.1 Statistical procedure

The statistical treatment of the data follows the procedure for the Higgs boson search combination [76, 77], and is implemented with RooFit [78] and RooStats [79]. The test statistic employed for hypothesis testing and limit setting is the profiled likelihood ratio $\Lambda(\alpha, \theta)$, which depends on one or more parameters of interest $\alpha$, and additional nuisance parameters $\theta$. The parameter of interest is the cross section times branching ratio for a heavy resonance production, assumed to be correlated for both searches. The nuisance parameters represent the estimates of the systematic uncertainties and are constrained by a Gaussian distribution. For each category of each search, a likelihood fit to the kinematic distribution of a discriminating variable is used to further separate signal from background. The $\ell^+\ell^-\ell^+\ell^-$ final state uses $m_{4\ell}$ as the discriminant in each category, while the $\ell^+\ell^-\nu\bar{\nu}$ final state uses $m_T$ in each category except for the VBF-enriched one where only the overall event counts are used.

As discussed in Section 7, the signal acceptance uncertainties, and many of the background theoretical and experimental uncertainties, are treated as fully correlated between the searches. A given correlated uncertainty is modelled in the fit by using a nuisance parameter common to all of the searches. The impact of a systematic uncertainty on the result depends on the production mode and the mass hypothesis. For the ggF production, at lower masses the luminosity uncertainty, the modelling uncertainty of the $Z$ boson with associated jets background and the statistical uncertainty in the $e\mu$ control region of the $\ell^+\ell^-\nu\bar{\nu}$ final state dominate, and at higher masses the uncertainties on the electron isolation efficiency become important, as seen also in the VBF production. For the VBF production, the dominant uncertainties come from the theoretical predictions of the $ZZ$ events in the VBF category. Additionally at lower masses, the pileup reweighting and the jet energy resolution uncertainties are also important. Table 3 shows the impact of the leading systematic uncertainties on the signal cross section, which is set to the expected upper limit (shown in Figure 6), for ggF production and VBF production. The impact of the uncertainty on the integrated luminosity, 3.2%, enters both in the normalisation of the fitted number of signal events as well as in the background expectation from simulation. This leads to a luminosity uncertainty which varies from 4% to 7% across the mass distribution, depending on the signal to background ratio.
Table 3: Impact of the leading systematic uncertainties on the predicted signal event yield which is set to the expected upper limit, expressed as a percentage of the cross section for the ggF (left) and VBF (right) production modes at $m_H = 300, 600,$ and $1000$ GeV.

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>ggF production Impact [%]</th>
<th>VBF production Impact [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>m$_H$ = 300 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$)</td>
<td>3.3</td>
<td>Jet energy scale 4</td>
</tr>
<tr>
<td>Parton showering</td>
<td>3.2</td>
<td>Luminosity 4</td>
</tr>
<tr>
<td>$e\mu$ statistical uncertainty $\ell^+\ell^-\nu\bar{\nu}$</td>
<td>3.2</td>
<td>$q\bar{q} \rightarrow ZZ$ QCD scale (VBF-enriched category) 4</td>
</tr>
</tbody>
</table>

| m$_H$ = 600 GeV   |                           |                           |
| Luminosity        | 6                         | 6                         |
| Pileup reweighting| 5                         | Pileup reweighting 6      |
| Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$) | 4                         | Jet energy scale 6        |
| QCD scale of $q\bar{q} \rightarrow ZZ$ | 3.1                        | Luminosity 4              |

| m$_H$ = 1000 GeV  |                           |                           |
| Luminosity        | 4                         | 6                         |
| QCD scale of $gg \rightarrow ZZ$ | 2.3                        | Jet energy scale 5        |
| Jet vertex tagger | 1.9                       | Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$) 4 |
| Z+jets modeling ($\ell^+\ell^-\nu\bar{\nu}$) | 1.8                        | Luminosity 4              |

8.2 General results

The numbers of observed candidate events for each of the four categories with mass above 130 GeV along with the background yields are presented in Table 4 for the $\ell^+\ell^-\ell^+\ell^-$ analysis. The $m_{4\ell}$ spectrum for the ggF-enriched and VBF-enriched categories is shown in Figure 4.

Table 5 contains the number of observed candidate events along with the background yields for the $\ell^+\ell^-\nu\bar{\nu}$ analysis, while Figure 5 shows the $m_T$ distribution for the electron and muon channels with the ggF-enriched and VBF-enriched categories combined.

Table 4: $\ell^+\ell^-\ell^+\ell^-$ search: Number of expected and observed events for $m_{4\ell} > 130$ GeV, together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

<table>
<thead>
<tr>
<th>Process</th>
<th>$4\mu$ channel</th>
<th>ggF-enriched categories</th>
<th>VBF-enriched category</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td>297 ± 1 ± 40</td>
<td>480 ± 1 ± 60</td>
<td>193 ± 1 ± 25</td>
</tr>
<tr>
<td>ZZ (EW)</td>
<td>1.92 ± 0.11 ± 0.19</td>
<td>3.36 ± 0.14 ± 0.33</td>
<td>1.88 ± 0.12 ± 0.20</td>
</tr>
<tr>
<td>Z + jets/tt/WZ</td>
<td>3.7 ± 0.1 ± 0.8</td>
<td>7.8 ± 0.1 ± 1.1</td>
<td>4.4 ± 0.1 ± 0.8</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>5.1 ± 0.1 ± 0.6</td>
<td>8.7 ± 0.1 ± 1.0</td>
<td>4.0 ± 0.1 ± 0.5</td>
</tr>
<tr>
<td>Total background</td>
<td>308 ± 1 ± 40</td>
<td>500 ± 1 ± 60</td>
<td>203 ± 1 ± 25</td>
</tr>
<tr>
<td>Observed</td>
<td>357</td>
<td>545</td>
<td>256</td>
</tr>
</tbody>
</table>

In the $\ell^+\ell^-\ell^+\ell^-$ search, two excesses are observed in the data for $m_{4\ell}$ around 240 and 700 GeV, each
Figure 4: Four-lepton invariant mass distribution in the $\ell^+\ell^-\ell^+\ell^-$ search for (a) the ggF-enriched category and (b) the VBF-enriched category. The backgrounds are determined following the description in Section 5.2 and the last bin includes the overflow. The error bars on the data points indicate the statistical uncertainty, while the systematic uncertainty on the prediction is shown by the hatched band. The bottom part of the figures shows the ratio of data over expectation.

Table 5: $\ell^+\ell^-\nu\bar{\nu}$ search: Number of expected and observed events together with their statistical and systematic uncertainties, for the ggF- and VBF-enriched categories.

<table>
<thead>
<tr>
<th>Process</th>
<th>ggF-enriched categories</th>
<th>VBF-enriched category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e^+e^-$ channel</td>
<td>$\mu^+\mu^-$ channel</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>177 ± 3 ± 21</td>
<td>180 ± 3 ± 21</td>
</tr>
<tr>
<td>$WZ$</td>
<td>93 ± 2 ± 4</td>
<td>99.5 ± 2.3 ± 3.2</td>
</tr>
<tr>
<td>$WW/tt/We/Z \rightarrow \tau\tau$</td>
<td>9.2 ± 2.2 ± 1.4</td>
<td>10.7 ± 2.5 ± 0.9</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>17 ± 1 ± 11</td>
<td>19 ± 1 ± 17</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>1.12 ± 0.04 ± 0.08</td>
<td>1.03 ± 0.04 ± 0.08</td>
</tr>
<tr>
<td>Total background</td>
<td>297 ± 4 ± 24</td>
<td>311 ± 5 ± 27</td>
</tr>
<tr>
<td>Observed</td>
<td>320</td>
<td>352</td>
</tr>
</tbody>
</table>
Figure 5: Transverse invariant mass distribution in the \( \ell^+\ell^-\nu\bar{\nu} \) search for (a) the electron channel and (b) the muon channel, including events from both the ggF-enriched and the VBF-enriched categories. The backgrounds are determined following the description in Section 6.2 and the last bin includes the overflow. The error bars on the data points indicate the statistical uncertainty and markers are drawn at the bin centre. The systematic uncertainty on the prediction is shown by the hatched band. The bottom part of the figures shows the ratio of data over expectation.

with a local significance of 3.6 \( \sigma \) estimated under the asymptotic approximation, assuming the signal comes only from ggF production. The global significance is of 2.2 \( \sigma \) and is calculated, for each excess individually, under the NWA, in the range of 200 GeV \( < m_H < 1200 \) GeV using pseudo-experiments. The excess at 240 GeV is observed mostly in the 4\( e \) channel, while the one at 700 GeV is observed in all channels and categories. No significant deviation with respect to the background expectation is observed in the \( \ell^+\ell^-\nu\bar{\nu} \) final state analysis. The excess observed on the \( \ell^+\ell^-\ell^+\ell^- \) search at a mass around 700 GeV is excluded at 95\% confidence level by the \( \ell^+\ell^-\nu\bar{\nu} \) search which is more sensitive in this mass range. The excess at 240 GeV is not covered by the \( \ell^+\ell^-\nu\bar{\nu} \) search, the sensitivity of which starts from 300 GeV. When combining the results from the two final states, the largest deviation with respect to the background expectation is observed around 700 GeV with a global significance of less than 1 \( \sigma \) and a local significance of about 2 \( \sigma \). The combined yield of the two final states leads to 1870 events observed in data compared to 1643 \( \pm 164 \) (combined statistical and systematic uncertainty) for the background expectation. This corresponds to a 1.3 \( \sigma \) global excess in data. Since no significant excess is found, the results are interpreted as upper limits on the production cross section of a spin-0 or spin-2 resonance.

8.3 Spin-0 resonance interpretation

Limits from the combination of the two searches in the context of a spin-0 resonance are described below.
Figure 6: The upper limits at 95% confidence level on the cross section times branching ratio for (a) the ggF production mode ($\sigma_{ggF} \times BR(H \rightarrow ZZ)$) and (b) for the VBF production mode ($\sigma_{VBF} \times BR(H \rightarrow ZZ)$) in the case of NWA. The green and yellow bands represent the ±1σ and ±2σ uncertainties on the expected limits. The dashed coloured lines indicate the expected limits obtained from the individual searches.

### 8.3.1 NWA interpretation

Upper limits on the cross section times branching ratio ($\sigma \times BR(H \rightarrow ZZ)$) for a heavy resonance are obtained as a function of $m_H$ with the $CL_s$ procedure [80] in the asymptotic approximation from the combination of the two final states. It is assumed that an additional heavy scalar would be produced predominantly via the ggF and VBF processes but that the ratio of the two production mechanisms is unknown in the absence of a specific model. For this reason, fits for the ggF and VBF production processes are done separately, and in each case the other process is allowed to float in the fit as an additional nuisance parameter. Figure 6 presents the expected and observed limits at 95% confidence level on $\sigma \times BR(H \rightarrow ZZ)$ of a narrow-width scalar for the ggF (left) and VBF (right) production modes, as well as the expected limits from the $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ searches. This result is valid for models in which the width is less than 0.5% of $m_H$. When combining both final states, the 95% CL upper limits range from 0.68 pb at $m_H = 242$ GeV to 11 fb at $m_H = 1200$ GeV for the gluon fusion production mode and from 0.41 pb at $m_H = 236$ GeV to 13 fb at $m_H = 1200$ GeV for the vector boson fusion production mode. Compared with the results presented in Run 1 [14] where all four final states of ZZ decays were combined, the exclusion region presented here is significantly extended, depending on the heavy scalar mass tested.

### 8.3.2 LWA interpretation

In the case of the LWA, limits on the cross section for the ggF production mode times branching ratio ($\sigma_{ggF} \times BR(H \rightarrow ZZ)$) are set for different widths of the heavy scalar. The interference between the heavy scalar and the SM Higgs boson, $H \rightarrow h$, as well as the heavy scalar and the $gg \rightarrow ZZ$ continuum, $H \rightarrow B$, are modelled by either analytical functions or reweighting the signal-only events as explained in Sections 5.3 and 6.3. Figures 7(a), 7(b), and 7(c) show the limits for a width of 1%, 5% and 10% of $m_H$ respectively. The limits are set for masses of $m_H$ higher than 400 GeV.
The ratio of the vacuum expectation values of the two doublets $(\tan \beta)$, the mixing angle between the CP-even Higgs bosons, and the potential parameter $m_{12}^2$ that mixes the two Higgs doublets. The two Higgs doublets $\Phi_1$ and $\Phi_2$ can couple to leptons and up- and down-type quarks in several ways. In the Type-I model, $\Phi_2$ couples to all quarks and leptons, whereas for Type-II, $\Phi_1$ couples to down-type quarks and leptons and $\Phi_2$ couples to up-type quarks. The ‘lepton-specific’ model is similar to Type-I except for the fact that the leptons couple to $\Phi_1$, instead of $\Phi_2$; the ‘flipped’ model is similar to Type-II except that the leptons couple to $\Phi_2$, instead of $\Phi_1$. In all these models, the coupling of the heaviest CP-even Higgs boson to vector bosons is proportional to $\cos(\beta - \alpha)$. In the limit $\cos(\beta - \alpha) \to 0$ the light CP-even Higgs boson, is indistinguishable from a SM Higgs boson with the same mass. In the context of $H \to ZZ$ decays there is no direct coupling of the Higgs boson to leptons, and so only the Type-I and -II interpretations are
Figure 8: The exclusion contour in the 2HDM (a) Type-I and (b) Type-II models for $m_H = 200$ GeV shown as a function of the parameters $\cos(\beta - \alpha)$ and $\tan \beta$. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The hatched area shows the observed exclusion.

8.4 Spin-2 resonance interpretation

The results are also interpreted in the context of a search for a RS graviton excitation, $G_{KK}$, using the $\ell^+\ell^-\nu\bar{\nu}$ final state as the $\ell^+\ell^-\ell^+\ell^-$ final state has negligible sensitivity for this type of models. The limits on $\sigma \times BR(G_{KK} \rightarrow ZZ)$ at 95% CL as a function of the graviton mass, $m(G_{KK})$, are shown in Figure 10 together with the predicted $G_{KK}$ cross section. A spin-2 graviton is excluded up to a mass of 1300 GeV. These limits have been extracted using the asymptotic approximation, and their accuracy has been verified to be correct within about 2% using pseudo-experiments.
Figure 9: The exclusion contour in the 2HDM (a) Type-I and (b) Type-II models for $\cos(\beta - \alpha) = -0.1$, shown as a function of the heavy scalar mass $m_H$ and the parameter $\tan \beta$. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties on the expected limits. The hatched area shows the observed exclusion.

Figure 10: Limits on $\sigma \times BR(G_{KK} \rightarrow ZZ)$ for a RS graviton produced with $k/\bar{M}_{Pl} = 1$. The green and yellow bands give the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties of the expected limits. The predicted production cross section as a function of the $G_{KK}$ mass $m(G_{KK})$ is shown by the red solid line.
9 Summary

A search is presented for heavy resonances decaying into a pair of \( Z \) bosons which decay subsequently to \( \ell^+\ell^-\ell^+\ell^- \) and \( \ell^+\ell^-\nu\bar{\nu} \) final states. The search uses proton–proton collision data collected with the ATLAS detector during 2015 and 2016 at the Large Hadron Collider at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 36.1 fb\(^{-1}\). The results of the search are interpreted as upper limits on the production cross section of a spin-0 or spin-2 resonance. The mass range of the hypothetical resonances considered is between 200 GeV and 2000 GeV depending on the final state, and the model considered. The spin-0 resonance is assumed to be a heavy scalar, whose dominant production modes are gluon fusion and vector boson fusion. In a model independent approach the spin-0 resonance is studied in the Narrow Width Approximation and the Large Width Assumption. In the case of the Narrow Width Approximation, limits on the production rate of a heavy scalar decaying into two \( Z \) bosons are set separately for gluon fusion and vector boson fusion production modes. Combining both final states, 95\% CL upper limits range from 0.68 pb at \( m_H = 242 \) GeV to 11 fb at \( m_H = 1200 \) GeV for the gluon fusion production mode and from 0.41 pb at \( m_H = 236 \) GeV to 13 fb at \( m_H = 1200 \) GeV for the vector boson fusion production mode. The results are also interpreted in the context of Type-I and Type-II two-Higgs-doublet models, with exclusion contours given in the \( \cos(\beta - \alpha) \) versus \( \tan \beta \) (for \( m_H = 200 \) GeV) and \( m_H \) versus \( \tan \beta \) planes. This \( m_H \) value is chosen so that the assumption of a narrow-width Higgs boson is valid over most of the parameter space and the experimental sensitivity is maximum. The limits on the production rate of a large-width scalar are obtained for widths of 1\%, 5\% and 10\% of the mass of the resonance, with the interference between the heavy scalar and the SM Higgs boson as well as the heavy scalar and the \( gg \to ZZ \) continuum taken into account. In the framework of the Randall-Sundrum model with one warped extra dimension a graviton excitation spin-2 resonance with \( m(G_{KK}) < 1300 \) GeV is excluded at 95\% CL.
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Appendix
Figure 11: The distribution of the four-lepton invariant mass, $m_{4\ell}$, in the $\ell^+\ell^-\ell^+\ell^-$ final state in the ggF-enriched (a) $4\mu$, (b) $4e$ and (c) $2\mu2e$ categories. The error bars on the data points indicate the statistical uncertainty. The systematic uncertainty on the prediction is shown by the hatched band. The last bin includes the overflow. The bottom part of the figures shows the ratio of data over expectation.
Figure 12: Distributions of local p-value for the $\ell^+\ell^-\ell^+\ell^-$ (blue, dashed line) and $\ell^+\ell^-\nu\bar{\nu}$ (red, dotted line) final states as well as for their combination (black line) derived for a narrow width resonance and assuming the signal comes only from ggF production, as a function of the resonance mass $m_H$ between 200 GeV and 1200 GeV. Also shown are local (dot-dashed line) significance levels.