Search for new phenomena in the $Z \rightarrow \ell \ell + E_T^{\text{miss}}$ final state at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

A study of the $\ell \ell + E_T^{\text{miss}}$ ($\ell = e, \mu$) final state is performed using 13.3 fb$^{-1}$ of 13 TeV proton-proton collision data collected by the ATLAS experiment. The collisions were produced by the Large Hadron Collider in 2015 and the first half of 2016. The analysis is optimised to address three searches: 1) the search for new heavy resonances decaying to $ZZ \rightarrow \ell \ell \nu \nu$, 2) the search for dark matter in association with a leptonically decaying Z boson and 3) the search for an invisibly decaying Higgs boson in the channel $ZH$, $Z \rightarrow \ell \ell$. New physics is searched for as an excess over the Standard Model predictions in the $ZZ$ transverse mass distribution and in the missing transverse momentum distribution. Results are found to be compatible with Standard Model expectations.

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1 Introduction

Events characterised by leptons and large missing transverse momentum ($E_T^{miss}$) not only constitute a distinct signature for many Standard Model (SM) processes, but are also particularly interesting in the searches for new physics, thanks to the clean final state and the relatively low background contamination. The searches for new particles at the Large Hadron Collider (LHC) benefit from the increased centre-of-mass energy available in Run-II proton-proton ($pp$) collisions; the expected larger data sample would allow to extend the sensitivity of these searches improving Run-I results [1–3].

This note describes the study of $\ell\ell+E_T^{miss}$ final states in 13 TeV $pp$ collisions, using an integrated luminosity of $13.3\text{ fb}^{-1}$ collected by the ATLAS detector in 2015 and part of 2016. Three searches are addressed and discussed in more detail in the following paragraphs: 1) the search for a new heavy resonance decaying to two $Z$ bosons in the channel $ZZ \rightarrow \ell\ell\nu\nu$, 2) the search for the production of a leptonically decaying $Z$ boson in association with a pair of dark matter particles, called Mono-$Z(\rightarrow \ell\ell)$ production in the following, and 3) the search for an invisibly decaying Higgs boson in association with a leptonically decaying $Z$ boson, $Z(\rightarrow \ell\ell)H(\rightarrow$ invisible). They share the same experimental signature of $\ell\ell+E_T^{miss}$ as well as the same background composition.

Some extensions of the SM predict the existence of additional heavy resonances with properties similar to those of the recently discovered Higgs boson [4, 5]. Among these, the two-Higgs-doublet (2HDM) [6] and the electroweak-singlet model [7] are two of the more popular models in the searches for a spin-0 particle decaying to two on-shell $Z$ bosons. In this note additional heavy Higgs bosons are searched for through the $ZZ \rightarrow \ell\ell\nu\nu$ decay in the mass range $300 < m_H < 1000$ GeV. As already shown in Run-I [1], the $\ell\ell\nu\nu$ channel provides complementary sensitivity to the searches in the other $H \rightarrow ZZ$ channels, particularly in the region above 500 GeV, due to the larger branching fraction with respect to $\ell\ell\ell\ell$, and the cleaner event topology than $\ell\ellqq$ and $\nu\nuqq$. The search is performed in the Narrow Width Approximation (NWA), which assumes a resonance with a width narrower than the experimental detector resolution. Limits at 95% confidence level (CL) are set on the production cross section of the Higgs boson times the branching fraction (BF) to $Z$ boson pairs as a function of $m_H$. Using the same $\ell\ell\nu\nu$ final state, limits are also set on the production of a spin-2 Kaluza-Klein (KK) graviton expected in the Randall-Sundrum (RS) framework with a warped extra dimension (RS1) [8]. This analysis follows closely the previous 13 TeV ATLAS result [9].

Several astrophysical observations point to the existence of Dark Matter (DM), a non-baryonic component of the universe whose nature is still unknown. Given the inadequacy of the SM particles to describe DM, the existence of new still undiscovered particles is usually inferred; among these, weakly interacting massive particles (WIMP) are the most promising candidates. At hadron colliders, DM production is predicted to occur mainly in pairs of particles, which are not seen by the detector, but can be detected as an excess of events showing an imbalance in transverse momentum conservation. To detect the events, the presence of an easily-tagged SM particle against which the invisible particles recoil, is crucial. In this note a search for DM through the Mono-$Z(\rightarrow \ell\ell)$ production is performed. The results of the analysis are interpreted in terms of Simplified Models [10], where an additional Beyond Standard Model (BSM) vector particle is introduced to mediate the interaction between WIMP and SM particles.

The SM Higgs boson with a measured mass by the ATLAS and CMS collaborations of $m_H = 125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV is predicted to have a small BF to invisible particles, $\sim 0.1\%$ in the $H \rightarrow ZZ \rightarrow \nu\nu\nu\nu$ channel [11], which is far below the experimental sensitivity of the current analyses. However, this BF can be enhanced if the Higgs boson is allowed to decay to a pair of stable or
long-lived particles [12–14], such as DM candidates, identified through $E_T^{\text{miss}}$. In this note a search for $Z(\rightarrow \ell\ell)H(\rightarrow \text{invisible})$ is performed. The $\ell\ell+E_T^{\text{miss}}$ final states are used either to set an upper limit on the BF of the $H \rightarrow \text{invisible}$ decay, assuming the SM $ZH$ production cross section for the SM Higgs boson, or to place limits on the cross section times BF for $Z(\rightarrow \ell\ell)H(\rightarrow \text{invisible})$ production.

Given the similarity of the event topology along with the common phase space to which the analyses are sensitive to, the $Z(\rightarrow \ell\ell)H(\rightarrow \text{invisible})$ and the Mono-$Z(\rightarrow \ell\ell)$ searches are commonly referred to as the “Low Mass” (LM) analysis, and share the same event selection. The search for a new $ZZ$ resonance will be called the “High Mass” (HM) analysis in this note.

The note is organised as follows. In Section 2 an overview of the ATLAS detector is given, while Section 3 describes the dataset as well as the Monte Carlo (MC) samples used to model signal and background processes. The reconstruction, identification and selection of the leptons, jets and $E_T^{\text{miss}}$ as used in the analyses are presented in Section 4. Section 5 details the event selection for both the HM and LM analyses, while the background estimation is described in Section 6. The assessment of systematic uncertainties is discussed in Section 7. Results and their interpretations in terms of BSM and DM models are provided in Section 8, and the conclusions are given in Section 9. Finally, the Appendix provides additional figures and displays of two reconstructed $\ell\ell\nu\nu$ candidate events.

2 ATLAS detector

The ATLAS detector [15] at the LHC [16] covers nearly the entire solid angle around the collision point, and consists of an inner tracking detector surrounded by a thin superconducting solenoid magnet producing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large toroid magnet assemblies. The inner detector (ID) consists of a high-granularity silicon pixel detector, including the newly-installed Insertable B-layer (IBL) [17], and a silicon microstrip tracker, together providing precision tracking in the pseudorapidity $|\eta| < 2.5$, complemented by a transition radiation tracker providing tracking and electron identification information for $|\eta| < 2.0$. A lead liquid-argon (LAr) electromagnetic calorimeter covers the region $|\eta| < 3.2$, and hadronic calorimetry is provided by steel/scintillating tile calorimeters for $|\eta| < 1.7$ and by copper/LAr hadronic calorimeters for $1.5 < |\eta| < 3.2$. The forward region extending to $|\eta| = 4.9$ is covered by additional LAr calorimeters with copper and tungsten absorbers. An extensive muon spectrometer with an air-core toroid magnet system surrounds the calorimeters. The muon spectrometer consists of precision tracking chambers covering the region $|\eta| < 2.7$, and separate trigger chambers covering $|\eta| < 2.4$. A two-level trigger system, using custom hardware followed by a software-based level, is used to reduce the event rate to around 1 kHz for offline storage.

\footnote{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector. The positive x-axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive y-axis pointing upwards, while the beam direction defines the z-axis. Pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan \theta/2$, and transverse momentum and energy are defined relative to the beamline as $p_T = p \sin \theta$ and $E_T = E \sin \theta$. The azimuthal angle around the beam line is denoted by $\phi$, and distances in $(\eta, \phi)$ space by $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.}
3 Data and simulated samples

The data sample used in the analyses corresponds to 13.3 fb$^{-1}$ of $pp$ collisions collected by the ATLAS experiment at $\sqrt{s} = 13$ TeV during 2015 and part of the 2016 data taking. Data are required to satisfy specific quality conditions; only data runs in which all relevant sub-detectors were working with a high efficiency are considered.

The signal production is modelled using MC simulation. Heavy-Higgs boson samples are generated up to next-to-leading order (NLO) in $\alpha_S$ using POWHEG-BOX v2 [18, 19]. All of the POWHEG-BOX and other samples mentioned in this section are interfaced to PYTHIA8.186 [20] for parton shower and hadronisation, and to EvtGen v1.2.0 [21] for the simulation of $b$ and $c$-hadron decays. The exceptions are the top quark samples, which are interfaced to PYTHIA6.428 [22], and all the samples generated with SHERPA, which has its own parton showering [23]. The CT10 parton distribution function (PDF) set [24] is used. Samples are generated for different mass values of the scalar resonance in the $m_H$ interval of 300-1000 GeV. The heavy Higgs boson width is fixed to 4.07 MeV as narrow-width approximation. Samples are generated in the gluon-gluon fusion (ggF) production mode.

The RS graviton ($G^*$) production [25] is generated with MadGraph5_aMC@NLO v2.2.2 [26]. The A14 set of generator-parameter values (tune) [27] and the NNPDF2.3LO PDF set [28] are used. The model is characterised by a dimensionless coupling constant $\kappa/\sqrt{M_{Pl}}$, where $\kappa$ is the curvature of the warped extra-dimensions and $\sqrt{M_{Pl}}$ is the reduced Planck mass. For $\kappa/\sqrt{M_{Pl}} = 1$, the graviton has a width relative to its mass of approximately 3.7% at 500 GeV and 5.5% at 1 TeV. The corresponding branching fractions, $\text{BF}(G^* \rightarrow ZZ)$, are about 18.0% and 9.5%, respectively.

The Mono-$Z(\rightarrow \ell\ell)$ production is simulated using MadGraph5 [29] in the context of the simplified models. These are BSM theory models which describe the interaction of Dirac fermions WIMP particles $\chi$ with SM particles, through the introduction of an unknown massive mediator $\eta$. The model that has been considered in this analysis following the prescriptions of the ATLAS/CMS Dark Matter Forum [30] is the Vector-mediator model, where the DM candidate is produced via the exchange of a neutral spin-1 mediator in the $s$-channel. Together with the mass of the mediator $m_{\text{med}}$ and the mass of the WIMP $m_{\chi}$, the other parameters needed to completely specify the model are the mediator width $\Gamma$, the coupling $g_{\chi}$ between the mediator and the WIMP, and the coupling $g_{\eta}$ between the mediator and the SM particles. The coupling parameters have been set to $g_{\chi} = 1.0$ and $g_{\eta} = 0.25$. Various $m_{\text{med}}$ and $m_{\chi}$ hypotheses are used in the simulation. In particular, $m_{\text{med}}$ has been varied in the interval (10, 10000) GeV, while $m_{\chi}$ in (1, 1000) GeV. In all cases, the cross section is evaluated at leading order (LO). The NNPDF3.0 [28] PDF set is used.

The production of the SM Higgs boson in association with a $Z$ boson, and its decay to invisible particles are modelled with POWHEG-BOX v2. To emulate the invisible decay, the Higgs boson is forced to decay as $H \rightarrow \nu\nu\nu\nu$ with a branching fraction of 100%. The process is simulated at NLO in perturbation theory using the MiNLO [31] program but next-to-next-to-leading-order (NNLO) QCD and NLO electroweak (EW) corrections are accounted for in the cross section computation. The cross section for the $ZH$, $Z \rightarrow \ell\ell$ process, as well as its uncertainties, are taken from Ref. [11, 32, 33], and correspond to 89.31 $^{+3.86}_{-3.0}$% (QCD scale) $\pm$ 3% (PDF) fb. The $gg \rightarrow ZH$ box-diagram occurs as a part of NNLO QCD correction and it is included in the total cross section, although not simulated as part of the signal sample.

MC simulations are also used to model many of the SM backgrounds affecting the searches. The $ZZ^{(*)}$ continuum constitutes the dominant background in both the HM and LM searches. POWHEG-BOX v2 is
used for the quark-antiquark annihilation mode (qqZZ) while gg → H∗ → ZZ events (ggZZ), including the off-shell SM ggF Higgs boson signal, the continuum background, and the interference contributions are generated at LO in perturbative quantum chromodynamics (QCD) using αs2v3.1.6 [34, 35] but corrected to higher order calculations. The CT10nlo set is used in qqZZ events simulation as PDF of the hard-processing while the CTEQL1 [36] PDF set is used for the parton shower. The non-perturbative effects are modelled using the A2nlo [37] tune. For the ggZZ mode the CT10 PDF set is used instead. The NNLO QCD [38] and NLO EW corrections extended to the ℓℓνν final state by the authors of Ref. [39] are considered for the quark-initiated ZZ as a function of mZZ, using the same procedure as described in Ref. [40]. A K-factor of 1.7 is applied on the ggZZ to account for higher order QCD effects, based on the studies in Ref. [41]. Other di-boson processes such as WZ and WW are also simulated with POWHEG-BOX v2.

Events containing a Z boson associated with jets are simulated with MadGraph5_AMC@NLO and the A14 tune is used together with the NNPDF2.3LO PDF set. The Z+jets background dominates in the low jet multiplicity regions and at low EmissT, and the simulation considered has been found to provide a good description of the jet-related kinematic variables in the phase space of interest for these analyses. However, a mis-modelling has been observed in describing some of the variables used for the event selection, such as the transverse momentum pT of the Z boson and the angular distance between the two leptons in (η, φ) space \( \Delta R_{\ell\ell} = \sqrt{\Delta \phi_{\ell\ell}^2 + \Delta \eta_{\ell\ell}^2} \). To correct for this effect, a bin-by-bin reweighting of the Z boson pT distribution to the data is performed. The W production associated with jets is simulated with POWHEG-BOX v2. Both Z+jets and W+jets cross sections are normalised to the NNLO prediction.

Production of top-quark pairs is modelled with POWHEG-BOX v2 and the cross section is normalised to the cross section calculated at NNLO with the soft gluon resummation at next-to-next-to-leading-log (NNLL) using Top++ [42]. Single top production in the s-, t-, and Wt-channels are also simulated with POWHEG-BOX v2.

Other minor background processes are the tri-boson WWW, WZZ, WWZ and ZZZ backgrounds, simulated in multi-leptonic final states using Sherpa2.1.1, except for the \( t\bar{t}V \), \( V = W, Z \) and the \( t\bar{t}WW \) production, for which MadGraph+PYTHIA 8 is used.

Generated events are processed through the ATLAS detector simulation [43] within the Geant4 framework [44] except for the RS graviton and the Mono-Z(→ ℓℓ) samples where a fast simulation is used for the calorimeter part. Multiple overlaid pp collisions (pile-up) are simulated with the soft QCD processes of PYTHIA8.186 using the A2 tune [45] and the MSTW2008LO PDF [46]. The simulated samples are reweighted to match the pile-up conditions in the data. The MC simulation is corrected for the differences with respect to the data in lepton energy scale and resolution as well as lepton reconstruction, identification and selection efficiencies.

## 4 Objects selection

For lepton candidates a looser selection, referred to as “baseline”, is defined and used to veto the presence of any additional leptons in the event, besides the two leptons coming from the Z boson decay, named “signal”, on which a tighter selection is applied.

Electron candidates in the central region of the detector (|η| < 2.47) are reconstructed from energy deposits in the electromagnetic calorimeter (EM) matched to a track reconstructed in the ID. Baseline electrons are
identified with a loose likelihood, based on the shapes of electromagnetic showers in the calorimeter as well as tracking and track-to-cluster matching quantities [47]; a transverse momentum of \( p_T > 7 \) GeV is also required. The electron must satisfy a \( p_T \)-dependent loose cone-based isolation criteria defined using both the calorimeter and tracker information. Signal leading (sub-leading) electrons are required to pass a medium likelihood identification and have \( p_T > 30 \) (20) GeV.

Muon candidates are reconstructed in the region \( |\eta| < 2.5 \) of the detector through a combined fit of tracks reconstructed independently in the ID and in the MS [48]. Baseline muons are identified with a loose selection and are required to have a momentum \( p_T > 7 \) GeV. The muons are also required to satisfy the same \( p_T \)-dependent cone-based isolation criteria as the electrons. Signal leading (sub-leading) muons are required to pass a medium identification and have \( p_T > 30 \) (20) GeV.

Jets are reconstructed with the anti-\( k_T \) algorithm [49] with radius parameter \( R = 0.4 \) using as input topological clusters of calorimeter cell energies [50]. Selected jets must have \( p_T > 20 \) GeV and \(|\eta| < 4.5\). A dedicated calibration scheme is employed to correct the jet energy measured with the calorimeter to the true energy of the jet [51]. To reduce the probability of selecting a pile-up jet, additional requirements are applied on the fraction of tracks in the jet coming from the primary vertex [52], for jets with \( p_T < 60 \) GeV and \(|\eta| < 2.4\).

Jets containing \( b \)-hadrons (\( b \)-jets) may be distinguished due to the long lifetime, high mass and decay multiplicity of \( b \)-hadrons. In this analysis \( b \)-jets are selected using an algorithm that achieves an identification efficiency of about 85% in simulated \( t\bar{t} \) events, on average, and a rejection factor for light flavor jets of about 34 [53–55].

Object reconstruction may result in an ambiguity between several objects that needs to be resolved. Electrons are removed if they share the same ID track as a muon, jets close to electrons and muons are always removed except for the case in which the muon is recognised as coming from a pile-up jet.

The missing transverse momentum \( \vec{E}_T^{\text{miss}} \), with magnitude \( E_T^{\text{miss}} \), is computed as the negative of the global vector sum of all the calibrated selected physics objects (electrons, muons, jets). Tracks with \( p_T > 0.5 \) GeV, \(|\eta| < 2.5\), compatible with the primary vertex, and not matched to any of those objects are included in the reconstruction as the so-called “track soft term (TST)” [56]. The \( E_T^{\text{miss}} \) reconstruction using the TST minimises the effect of pile-up which causes a degradation in the \( E_T^{\text{miss}} \) performance.

5 Event selection

Despite the fact that the HM and LM searches target different physical interpretations, the common experimental signature of two high-\( p_T \) leptons from a \( Z \) boson decay and appreciable \( E_T^{\text{miss}} \) results in a very similar event selection. The optimal selection criteria for each of the two analyses were chosen through a maximum significance scan and are detailed below.

A common event pre-selection is applied to reject non-collision background events and pile-up jets [57], which can give rise to fake \( E_T^{\text{miss}} \) and consequently a degradation of the \( E_T^{\text{miss}} \) performance. The presence of a primary vertex (PV) with at least two associated tracks with \( p_T > 400 \) MeV is required, where the PV is defined as the vertex with the greatest \( \Sigma p_T^2 \) reconstructed in the event. At least one out of the two selected leptons must have fired a single \( e \) or \( \mu \) trigger. The values of the lower \( p_T \) trigger thresholds are 20 (24) GeV for \( \mu \) (\( e \)) in the 2015 data sample, but were raised as high as 26 GeV for both \( e \) and \( \mu \) as
a function of the instantaneous luminosity in 2016 data [58]. The chosen trigger configuration assures a trigger efficiency of the order of 98% or higher for signal events passing the full event selection.

Events are accepted if they contain only two opposite-charge same-flavour leptons. Events with additional \( p_T > 7 \) GeV leptons are vetoed, to reject WZ background. To select events in which the two opposite-charge electrons or muons come from a Z boson decay, the invariant mass of the two leptons \( m_{\ell\ell} \) is required to be within 15 GeV of the Z boson mass.

The presence of neutrinos or DM particles is inferred through the requirement of significant \( E_T^{\text{miss}} \) in the event. A lower requirement at 90 (120) GeV is applied in the LM (HM) analysis, which significantly reduces the Z+jets background. The \( E_T^{\text{miss}} \) distribution after the di-lepton invariant mass selection is shown in Figure 1(a). The uncertainty band in the ratio plot, showing the uncertainty on the background, is widest in the region dominated by the steeply falling Z+jets background. The dominant contributions to this uncertainty come from jets and \( E_T^{\text{miss}} \)-related systematic uncertainties as described in Section 7.

The large \( E_T^{\text{miss}} \) value selects events topologies with a boosted Z boson. The boost implies that the charged leptons are produced with small angular separation \( \Delta R \). A \( \Delta R_{\ell\ell} < 1.8 \) cut allows to effectively suppress not only the Z+jets background but also the di-boson backgrounds.

In the absence of initial or final state radiation, the Z boson in the signal events is expected to be produced back-to-back to the \( E_T^{\text{miss}} \), in the azimuthal plane. For this reason, the azimuthal angle \( \Delta \phi (p_T^{\ell\ell}, E_T^{\text{miss}}) \) between the vectorial sum of the two lepton momenta, \( \vec{p}_T^{\ell\ell} \), and the \( E_T^{\text{miss}} \) is required to be greater than 2.7.

For the same reason, the \( E_T^{\text{miss}} \) is expected to be balanced against the \( p_T \) of the Z boson. Any possible imbalance is accounted for in the fractional \( p_T \) difference, defined as \( |p_T^{\text{miss,jet}} - p_T^{\ell\ell}|/p_T^{\ell\ell} \), is required to be less than 20\%, where \( p_T^{\text{miss,jet}} = |E_T^{\text{miss}} + \sum_{\text{jet}} p_T^{\text{jet}}| \).

Two additional selection criteria are introduced to further reduce the Z+jets background. One is the \( \Delta \phi (E_T^{\text{miss}}, \text{jets}) \), defined as the minimum distance between the \( E_T^{\text{miss}} \) and the jets in the event, where the lower jet \( p_T \) threshold is \( p_T > 25 \) (100) GeV for the LM (HM) analysis respectively. The \( \Delta \phi (E_T^{\text{miss}}, \text{jets}) \) is introduced to reduce events that originate from the mis-measurement of jets. A minimum requirement of 0.4 (0.7) is applied in the LM (HM) analysis.

The other selection criterion introduced is the \( p_T^{\ell\ell}/m_T \), which helps to reject events with fake \( E_T^{\text{miss}} \) as well as events where the \( E_T^{\text{miss}} \) is poorly determined due to the momentum resolution of high-\( p_T \) muons. Here \( m_T \) is the transverse mass of the event, whose definition differs in the HM and LM analyses; the definition of the former explicitly requires a ZZ resonance as in Equation 1, while the latter uses the formula in Equation 2.

\[
(m^{ZZ}_T)^2 \equiv \left( \sqrt{m_Z^2 + |p_T^{\ell\ell}|^2} + \sqrt{m_Z^2 + |E_T^{\text{miss}}|^2} \right)^2 - |\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}}|^2, \tag{1}
\]

\[
m_T = \sqrt{2 p_T^{\ell\ell} E_T^{\text{miss}}} \left[ 1 - \cos \Delta \phi \left( p_T^{\ell\ell}, E_T^{\text{miss}} \right) \right]. \tag{2}
\]

The event topology of the signal selects preferably events with \( p_T^{\ell\ell}/m_T \sim 0.5 \). A 0.7 (0.9) upper cut is applied in the HM (LM) analysis, which is more stringent in the HM analysis due to the larger boost.
expected for a heavy resonance. The $m_{\ell\ell}^{ZZ}$ distribution after the di-lepton invariant mass cut is applied, is depicted in Figure 1(b).

Finally, events with a $b$-jet with $p_T > 20$ GeV and $|\eta| < 2.5$ are rejected to reduce the top quark background contribution. The distributions of the variables used for the event selection are shown in the Figures 10 and 11 of the Appendix. The data/MC agreement is shown in events with two opposite sign leptons after the di-lepton invariant mass and the $E_T^{miss} > 90$ GeV cuts are applied.

Figure 1: $E_T^{miss}$ (a) and $m_{\ell\ell}^{ZZ}$ (b) distribution after the invariant mass cut on the di-lepton system. Distributions are drawn for the combination of events with two electrons and with two muons, which are linearly summed. Stacked histograms represent the SM background predictions while data points are drawn as black dots. Backgrounds are normalised to MC expectations for 13.3 fb$^{-1}$. The error band in the ratio plot shows the statistical plus systematic uncertainty on the background. The last bin is the overflow bin, summing up all the events that are found outside the x-axis range of the plot.

Table 1 summarises the definition of the High Mass Signal Region (HMSR) and of the Low Mass Signal Region (LMSR).

Tables 2 and 3 show the acceptance times efficiency for the HM and LM signals respectively, obtained with the event selection described in this section. The overlap between the two SRs has been checked in the data sample and it is found to be 42% (28%) in the HMSR (LMSR). However, the HM and LM searches are performed independently, and no combination of the two is performed.

6 Background estimates

Various processes can result in background events containing a reconstructed di-lepton pair and $E_T^{miss}$ that satisfy the signal selection criteria. ZZ production can lead to a true $\ell\ell\nu\nu$ final state through decays of the Z bosons and therefore constitutes the dominant and irreducible background in this search. The second largest background comes from WZ production with the charged lepton from the W decay escaping detection or decaying hadronically in the case of $W \to \tau\nu$. Background events with a di-electron or di-muon pair from Z boson decays and one or more accompanying jets in the final state ($Z+\text{jets}$) can contribute to the signal region due to poorly reconstructed $E_T^{miss}$. This background is largely suppressed
Event Selection

Exactly one $ee$ or $\mu\mu$ pair

$p_T(e/\mu) > 30(20)$ GeV for leading (sub-leading) lepton

<table>
<thead>
<tr>
<th>Selection</th>
<th>High Mass</th>
<th>Low Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>m_{ll} - m_Z</td>
<td>&lt;$ 15 GeV</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>&gt; 120 GeV</td>
<td>&gt; 90 GeV</td>
</tr>
<tr>
<td>$\Delta R_{\ell\ell}$</td>
<td>&lt; 1.8</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi(p_T^{\ell\ell}, E_T^{\text{miss}})</td>
<td>$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi(E_T^{\text{miss}}, \text{jets})</td>
<td>$</td>
</tr>
<tr>
<td>$p_T^{\text{miss, jet}} / p_T^{\ell\ell}$</td>
<td>&gt; 0.2</td>
<td></td>
</tr>
<tr>
<td>Number of $b$-jets</td>
<td>= 0</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Event Selection for the High Mass Signal Region and Low Mass Signal Region definition.

<table>
<thead>
<tr>
<th>High Mass SR</th>
<th>ggF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_H$ [GeV]</td>
<td>600</td>
</tr>
<tr>
<td>Acc. x Eff.</td>
<td>47% (ee) 47% ($\mu\mu$)</td>
</tr>
</tbody>
</table>

Table 2: Acceptance times efficiency (Acc. x Eff.) for the $ee$ and $\mu\mu$ final states in the HMSR for a heavy Higgs signal of $m_H = 600$ and 1000 GeV assuming a narrow intrinsic width.

<table>
<thead>
<tr>
<th>Low Mass SR</th>
<th>ZH</th>
<th>Mono-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Model</td>
<td>$qqZH$</td>
<td>$(m_\chi, m_{\text{med}}) = (1, 10)$ GeV</td>
</tr>
<tr>
<td>Acc. x Eff.</td>
<td>18% (ee) 19% ($\mu\mu$)</td>
<td>2% (ee) 2% ($\mu\mu$)</td>
</tr>
</tbody>
</table>

Table 3: Acceptance times efficiency (Acc. x Eff.) for the LM signal samples with the corresponding event selection. Numbers are given for the $ZH$ as well as for different DM particle and mediator mass hypotheses for the Mono-Z($\rightarrow \ell\ell$) signals. Both the $ee$ and $\mu\mu$ acceptances are provided.
by imposing strict cuts on $E_T^{\text{miss}}$-related kinematic variables. Additional backgrounds with a genuine dilepton pair not directly coming from resonant $Z$ boson decays (the non-resonant-$\ell\ell$ background), such as $WW$, $t\bar{t}$, $Wt$, and $Z \rightarrow \tau\tau$ processes, contribute to a small fraction of the data sample after the full selection. Backgrounds from $W+\text{jets}$, semi-leptonically decaying $t\bar{t}$, single top-quark ($s$- and $t$-channel), and multi-jet processes with at least one jet misidentified as an electron or muon are very small, and denoted as fake-lepton background in this note. There are also very small contributions from $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}WW$, and tri-boson background events ($t\bar{t}V/VVV$ background). Details about the estimation of each backgrounds are given in later subsections, and finally, the estimated background contributions in the HM and LM signal regions are presented in Table 4 and 5, respectively.

<table>
<thead>
<tr>
<th>High Mass Signal Region</th>
<th>$ee$</th>
<th>$\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>147</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 4: Observed data yields, signal expectations and estimated background contribution corresponding to $13.3 \text{ fb}^{-1}$ in the High Mass signal region. The first and second errors represent the statistical and systematic uncertainties, respectively. The systematic uncertainties of the MC-based predictions include the luminosity uncertainty. The total background prediction is given in the last row. The statistical uncertainty of the total background prediction is calculated as the quadratic sum of the statistical uncertainties from each background processes. To mimic the actual level of correlation between systematic uncertainties of each processes, in the calculation of the systematic uncertainty of the total background estimate, the systematic uncertainties of MC-based estimates of the $qqZZ$ and $t\bar{t}V/VVV$ backgrounds are first summed linearly and then quadratically combined with that of predictions of other background processes.

### 6.1 Estimation of the ZZ background

The ZZ background consists of two sub-processes, one from the dominant quark-antiquark initial state ($qqZZ$) and the other from gluon-gluon interaction ($ggZZ$). Both the $qqZZ$ and $ggZZ$ processes are estimated from MC simulation, and the MC predictions are scaled to match the state-of-the-art predictions of the production cross sections.

For the $qqZZ$ background, the differential $m_{ZZ}$ cross sections in the total phase-space are corrected to the NNLO QCD and NLO EW predictions using separate $K$-factors, as described in Section 3. The NNLO QCD correction increases the normalisation by about $13\%$ for $m_{ZZ} = 300$ GeV, and by about $30\%$ for $m_{ZZ}$.
Table 5: Observed data yields, signal expectations and estimated background contribution corresponding to 13.3 fb$^{-1}$ in the Low Mass signal region. The first and second errors represent the statistical and systematic uncertainties, respectively. The systematic uncertainties of the MC-based predictions include the luminosity uncertainty. The total background prediction is given in the last row. The statistical uncertainty of the total background prediction is calculated as the quadratic sum of the statistical uncertainties from each background processes. To mimic the actual level of correlation between systematic uncertainties of each processes, in the calculation of the systematic uncertainty of the total background estimate, the systematic uncertainties of MC-based estimates of the $qqZZ$ and $t\bar{t}V/VVV$ backgrounds are first summed linearly and then quadratically combined with that of predictions of other background processes.

\[
\begin{array}{|c|c|c|}
\hline
\text{Low Mass Signal Region} & ee & \mu\mu \\
\hline
\text{Data} & 220 & 236 \\
\hline
\text{Signals} & & \\
ZH (m_H = 125 \text{ GeV}) \text{ with BF}(H \rightarrow \text{invisible})=100\% & 40.5 \pm 1.2 \pm 4.1 & 41.7 \pm 1.2 \pm 4.4 \\
Mono-Z (m_t = 1 \text{ GeV}, m_{\text{med}} = 10 \text{ GeV}) & 175 \pm 24 \pm 14 & 169 \pm 21 \pm 22 \\
Mono-Z (m_t = 50 \text{ GeV}, m_{\text{med}} = 300 \text{ GeV}) & 43.7 \pm 2.3 \pm 2.8 & 49.1 \pm 2.6 \pm 4.2 \\
\hline
\text{Backgrounds} & & \\
qqZZ \text{ (MC-based)} & 95.0 \pm 1.5 \pm 5.8 & 102.1 \pm 1.6 \pm 8.0 \\
\text{ggZZ }\text{(MC-based)} & 5.6 \pm 0.1 \pm 3.3 & 5.7 \pm 0.1 \pm 3.4 \\
WZ \text{ (Data-driven)} & 44.0 \pm 1.1 \pm 3.3 & 50.5 \pm 1.2 \pm 3.3 \\
Z(\rightarrow ee,\mu\mu)+\text{jets }\text{(Data-driven)} & 23 \pm 5 \pm 11 & 16.9 \pm 5.2 \pm 6.7 \\
\text{non-resonant-}\ell\ell \text{ (Data-driven)} & 16.9 \pm 2.8 \pm 1.0 & 20.7 \pm 3.4 \pm 1.2 \\
\text{fake-lepton }\text{(Data-driven)} & 0.18 \pm 0.04 \pm 0.03 & 0.36 \pm 0.46 \pm 0.08 \\
tV/VVV \text{ (MC-based)} & 0.44 \pm 0.02 \pm 0.06 & 0.43 \pm 0.02 \pm 0.06 \\
\hline
\text{Total background} & 185 \pm 6 \pm 13 & 196 \pm 7 \pm 12 \\
\hline
\end{array}
\]

Theoretical uncertainties due to the choice of QCD renormalisation and factorisation scales ($\mu_r$ and $\mu_f$) and the eigenvector uncertainty of the CT10 PDF set at 68\% CL are estimated using the NLO+PS MC events and found to be about 4\% and 3\%, respectively, of the $qqZZ$ background. The QCD scales are individually varied by a factor of two or one half, excluding two extreme cases of $\mu_r/\mu_f = 4$ or 0.25, and the maximum difference between the resulting $qqZZ$ estimates in each scenario and that with the nominal scale choice ($\mu_r = \mu_f = m_{ZZ}$) is assigned as the QCD scale uncertainty. The same approach is used to derive the QCD scale and PDF uncertainties for the WZ background and the signal processes, specified in Sections 6.2 and 7, respectively. The non-perturbative uncertainty is evaluated by comparing the estimate from the nominal MC sample to that from an alternative sample generated with POWHEG-BOX interfaced to HERWIG++ [59], and the impact on the $qqZZ$ estimate is found to be around 1\%. The uncertainty due to the NLO EW correction is evaluated using the approach adopted in Ref. [40] and found to have a small impact. Variations of PDF and QCD scales not only affect the normalisation of the $qqZZ$ background, but can also slightly change the slope of the corresponding $E_T^{\text{miss}}$ and $m_{ZZ}$ distribution. Because of this, a shape uncertainty is additionally included. Experimental uncertainties, due to luminosity and reconstruction of leptons, jets and $E_T^{\text{miss}}$, are also taken into account and found to have about 6\% impact on the $qqZZ$ background.

The higher order (HO) QCD correction to the $qqZZ$ background is expected to be sizable. Efforts have been made to calculate HO cross sections of the constituents of the $qqZZ$ background [60–64], however,
a complete calculation for the whole $ggZZ$ process is not yet available. The $ggZZ$ estimate from the LO MC sample is scaled by a $K$-factor of 1.7, the size of the HO correction calculated for the continuum $ggZZ$ process [60], to account for HO effects to the $ggZZ$ background, and a conservative relative uncertainty of 60% [60] is assigned to cover the QCD scale uncertainty and any potential bias. Both the theoretical uncertainty on the $K$-factor and the experimental uncertainties are included for the estimates.

6.2 Estimation of the WZ background

The WZ process constitutes about 25% of the total background in both the HM and LM signal regions. It is modelled with the NLO POWHEG-BOX generator, and the NNLO QCD correction to the total WZ production cross section is found to be at the level of 10% according to a recent calculation [65]. In addition, the WZ production cross sections were measured about 15% higher than the POWHEG-BOX estimate, which is assigned as an additional uncertainty. The theoretical and experimental uncertainties on the extrapolation factor from the 3ℓ control region to the final states. The maximal difference between the average $f_{WZ}$ and the various values in each final states is taken as the systematic uncertainty. This procedure yields $f_{WZ} = 1.25\pm 0.04\text{(stat)}\pm 0.05\text{(syst)}$. The theoretical and experimental uncertainties on the extrapolation factor from the 3ℓ control region to the signal region, $N_{WZ,MC}^{SR}/N_{WZ,MC}^{SR}$, are found to be below 1% and are therefore neglected in this search. WZ production with three charged leptons ($e$ or $\mu$) from decays of the bosons ($WZ \rightarrow 3\ell$) can contribute to the signal region if one of the leptons fails the selection criteria. The efficiency of vetoing one lepton in the $WZ \rightarrow 3\ell$ events is computed from MC simulation. An alternative calculation is performed by taking into account a correction derived from data on the efficiency of a lepton within the detector acceptance to fail the selection criteria. The two different calculations yield a difference of about 4% in the total WZ background estimate, which is assigned as an additional uncertainty. The $m_{T}^{WZ}$ and $E_{T}^{miss}$ distributions for the WZ background in the signal region are taken from MC, and the shape systematic uncertainty from theory and experimental uncertainties is also included. The theoretical
shape uncertainty is evaluated by varying QCD scales and PDF eigenvectors, and found to be small (below 2%).

![Figure 2](image.png)

**Figure 2**: Kinematic distributions comparing the data and MC predictions in the 3ℓ control region used to determine the normalisation factor for the WZ background, combining eee, eeµ, µe, and µµµ final states: a) for \( E_T^{miss} \) and b) for \( m_W^{WZ} \) distributions. The variable \( m_W^{WZ} \) is calculated following Equation 1, and the lepton from the W decay is treated as part of \( E_T^{miss} \). The WZ background is already scaled by the \( f_{WZ} \). Other background expectations as well as a band corresponding to the combined statistical and systematic uncertainties.

### 6.3 Estimation of the Z+jets background

The Z+jets background has no genuine \( E_T^{miss} \) in the final state, but it can contribute to the signal region due to mis-measurements of jets and leptons. The mis-measurements are difficult to model in MC, and therefore it is crucial to determine the Z+jets contribution from data. A so-called ABCD method is used in this search to estimate the Z+jets background. The method uses two nearly uncorrelated variables, the fractional \( p_T \) difference and \( \Delta \phi (p_T^\ell, E_T^{miss}) \), to define four non-overlapping regions: region A with fractional \( p_T \) difference < 0.2 and \( |\Delta \phi (p_T^\ell, E_T^{miss})| > 2.7 \) corresponding to the signal region selections, region B with reversed cut on the fractional \( p_T \) difference, region C with reversed cut on \( \Delta \phi (p_T^\ell, E_T^{miss}) \), and region D with both cuts reversed. Figure 3 and 12 shows the \( E_T^{miss} \) and \( m_T^{ZZ} \) distributions, respectively, in the different regions after the cut on \( m_H \) is applied. Regions B, C and D are enriched in the Z+jets background, and the Z+jets contribution to the signal region can be calculated as

\[
N_{SR}^{Z+jets} = N_{data-nonZ}^C \times \frac{N_{data-nonZ}^B}{N_{data-nonZ}^D}, \tag{4}
\]

where \( N_{data-nonZ}^B, N_{data-nonZ}^C, \) and \( N_{data-nonZ}^D \) are the observed data events subtracting the non-Z+jets contribution in region B, C and D, respectively. Data-driven estimates of the WZ background are used to subtract their contamination in the B, C and D regions, while the contribution estimated from MC simulation is used to remove other backgrounds. Due to the harsh cuts adopted in this search to suppress the Z+jets background, regions B and D are left with insufficient data statistics after applying the full event...
selection; and therefore the ratio $\frac{N_{\text{data}} - N_{\text{MC}}}{N_{\text{MC}}}$ is evaluated with a looser selection, which has only the di-lepton mass requirement but no other selection criteria. Its dependence on the selection is assessed using MC events and considered as one source of systematic uncertainty. Equation 4 is applied to the $Z+\text{jets}$ MC events, and the discrepancy between the MC prediction in the signal region and the estimated MC yields from the method is assigned as the non-closure uncertainty of the method. An additional uncertainty due to the subtraction of the non-$Z$+jets backgrounds is also taken into account. The total fractional uncertainty on the $Z+\text{jets}$ estimate in the signal regions amounts to about 80%.

The $m_T^{ZZ}$ and $E_T^{\text{miss}}$ distributions for the $Z+\text{jets}$ background in the signal regions are taken from MC. The MC distributions nearly vanish in the high $m_T^{ZZ}$ or $E_T^{\text{miss}}$ regions due to the stringent cuts as well as the insufficient MC statistics. MC shapes produced with a looser selection, which give larger fraction of tail events, are used to assign a conservative shape uncertainty to the nominal shapes.

Figure 3: $E_T^{\text{miss}}$ distributions after the di-lepton mass requirement in Regions A (a), B (b), C (c) and D (d), which are defined in the estimation of the $Z+\text{jets}$ background. The stacked histograms represent the background predictions from simulation. The bottom panel shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined statistical and systematic uncertainties.
6.4 Estimation of the non-resonant-\(\ell\ell\) background

The non-resonant-\(\ell\ell\) background consists of multiple processes (WW, \(Wt\), \(t\bar{t}\), and \(Z \rightarrow \tau\tau\)), which have two leptons and \(E_T^{\text{miss}}\) in the final state, but the di-lepton pair is not directly produced from the decay of a \(Z\) boson. One important characteristic of this background is the possibility to produce not only same-flavour di-lepton pairs (ee or \(\mu\mu\)) but also \(e\mu\) pairs; their rates depend on the respective branching fractions as well as the reconstruction efficiencies of electrons and muons. By requiring an \(e\mu\) pair, the contamination from the \(Z+\text{jets}\) background is dramatically reduced, and the resulting event sample, namely the \(e\mu\) control sample, is dominated by the non-resonant-\(\ell\ell\) background. Figure 4 shows the distributions of \(E_T^{\text{miss}}\) and \(m_{\text{ZZ}}\) in the \(e\mu\) control region after the \(E_T^{\text{miss}}\) cut is applied. The contribution of the non-resonant-\(\ell\ell\) background in the signal regions can be estimated from this \(e\mu\) control region by correcting for the efficiency difference between electrons and muons. The procedure is described by the following equation:

\[
N_{\text{SR}}^{\text{non-resonant-}\ell \ell} = \frac{1}{2} \times \epsilon_{\text{corr}} \times N_{\text{data-other}}^{e\mu}\tag{5}
\]

where \(N_{\text{data-other}}^{e\mu}\) is the number of observed data events subtracting contamination from other processes (\(Z+\text{jets}\), ZZ and WZ) estimated from MC simulation in the \(e\mu\) control region, \(\epsilon_{\text{corr}}\) is a correction factor scaling the efficiency of selecting \(e\mu\) events to that of selecting di-electron or di-muon events, and the factor \(
\frac{1}{2}
\) corrects the branching fraction from \(e\mu\) to the di-electron or di-muon final state. The efficiency difference between selecting electrons and muons is evaluated in a \(Z \rightarrow \ell\ell\) data sample, and calculated as the square-root of the number of \(Z \rightarrow ee\) events divided by the number of \(Z \rightarrow \mu\mu\) events, denoted as \(\epsilon_\text{diff} = \sqrt{ \frac{N_{ee}}{N_{\mu\mu}} }\). The efficiency correction factor is then defined as \(\epsilon_{\text{corr}} = \epsilon_{\text{diff}}\) and \(\epsilon_{\text{corr}} = \frac{1}{\epsilon_{\text{diff}}}\) for the \(ee\) and \(\mu\mu\) channels, respectively.

MC predictions of the non-resonant-\(\ell\ell\) background in the signal regions are compared to the estimates resulting from applying this method to MC events, and the two are found to be consistent within the statistical uncertainty of the MC sample; therefore no specific uncertainty is assigned.
The efficiency correction factor estimated from the simulated non-resonant-$\ell\ell$ events is found to be about 8% larger than that calculated using the MC $Z \rightarrow \ell\ell$ events, and this difference is assigned as a systematic uncertainty. The final non-resonant-$\ell\ell$ estimates in the signal regions have a systematic uncertainty of O(10%) and a statistical uncertainty of 20-50% due to the limited size of the $e\mu$ data sample.

The kinematic distributions in the signal regions for the non-resonant-$\ell\ell$ background are taken from MC simulation.

6.5 Estimation of other small backgrounds

The fake-lepton background is estimated from data using the fake-factor method [68]. This method defines a control region enriched in the fake-lepton background by requiring one baseline lepton and one “loose” lepton, which fails the lepton identification or the isolation requirement in the baseline selection. The fake-lepton contribution in the signal region is then estimated by multiplying the number of observed data events after subtracting the non-fake contributions using MC simulation with a “fake factor”. The “fake factor” is measured in a $Z$+jets data sample as number of jets passing the baseline lepton selection divided by number of jets satisfying the “loose” selection. This background is found to be very small and have an overall uncertainty of 30-100%, consisting of uncertainties due to limited data statistics in the control region, estimation of the fake factors, and subtraction of the non-fake contributions from the control region.

The contribution from the $t\bar{t}V/VVV$ background is estimated from MC simulation, and found to be very small in the signal regions. A 10% uncertainty is assigned to cover theoretical uncertainties on the NLO cross sections of the $t\bar{t}V/VVV$ processes. The experimental uncertainties on the estimated $t\bar{t}V/VVV$ contribution and on the kinematic shapes of $E_T^{\text{miss}}$ and $m_{ZZ}$ are also taken into account.

7 Systematic uncertainties

Several sources of systematic uncertainties have been considered in this search. They include experimental uncertainties due to the luminosity measurement and the event reconstruction, theory uncertainties in the evaluation of the ZZ and WZ backgrounds, uncertainties originating from the data-driven background estimations, and theoretical uncertainties for the signal processes. Some of these uncertainties affect only the normalisation, while others impact both the normalisation and shape of the $m_{TT}$ and $E_T^{\text{miss}}$ distributions, which are used as the discriminating variables to search for new phenomena in the HM and LM analyses, respectively.

The preliminary uncertainty on the combined 2015+2016 integrated luminosity is 2.9%. It is derived, following a methodology similar to that detailed in Ref. [69], from a preliminary calibration of the luminosity scale using $x-y$ beam-separation scans performed in August 2015 and May 2016. The uncertainty due to pile-up is estimated by reweighting the MC distributions of the average number of interactions per bunch crossing to alternative distributions which are shifted from that observed in the data by a conservative factor.

Major experimental systematic uncertainties come from the determination of electron energy scale and resolution, efficiencies of electron reconstruction, identification, isolation and trigger selections [47, 58],
energy scale and resolution of jets [51] and $E_T^\text{miss}$ soft terms [56], and $b$-tagging efficiency [70]. Uncertainties due to the muon reconstruction [48] are found to be small in the low-$p_T$ region, while they give a larger impact in the searches for high mass resonances, where high-$p_T$ muons are present. As discussed in Section 3, the uncertainties due to lepton energy scale and resolution and lepton selection efficiencies are accounted for on the corresponding data-driven corrections applied to the MC simulation. The uncertainties due to lepton and jet energy scale and resolution are propagated to the uncertainty on the $E_T^\text{miss}$.

Systematic uncertainties occurring in the estimation of each background process are detailed in Section 6. The experimental uncertainties on both the normalisation and shape are included for processes estimated from MC simulation (signal, ZZ, $t\bar{t}V$/VVV), while for the WZ background, only the shape uncertainty is accounted for, since the normalisation has been derived from the 3$\ell$ control region. The total experimental uncertainty for processes estimated from MC simulation is found to have a similar size (about 5%).

Theoretical uncertainties on the acceptance calculation and on the $E_T^\text{miss}$ and $m_{ZZ}^\text{T}$ shapes are taken into account for the signal processes. The theoretical cross-section uncertainties are additionally considered in the determination of the $H \rightarrow$ invisible branching fraction. The theoretical acceptance uncertainty for the heavy Higgs signal accounts for the PDF and QCD scale uncertainties as well as the uncertainty due to variation of the eigenvectors in the underlying event model in PYTHIA 8, and it ranges from 0.5% to 4% depending on the mass of the heavy Higgs boson. The acceptance of the Mono-Z($\rightarrow \ell\ell$) signals is found to have $\leq 5$% uncertainty due to PDF and QCD scales, and a constant acceptance uncertainty of 5% (2.2%) is assigned for the RS graviton ($ZH$) process. The $ZH$ production cross section has a relative 5% total uncertainty [32]. In addition, a study is performed to examine the impact on the $ZH$ acceptance due to the fact that the $gg \rightarrow ZH$ process is not included in the simulated MC sample, and this results in an additional 5% uncertainty assigned to cover the estimated bias.

### 8 Results and interpretations

The observed data yields, signal expectations and estimated background contributions in the HM and LM signal regions are given in Table 4 and Table 5, respectively. No significant excess of events is observed above the background expectations in both signal regions. Figure 5 shows the $m_{ZZ}^\text{T}$ distributions in the HM signal region in the $ee$, $\mu\mu$ and combined $ee + \mu\mu$ channels, respectively. Figure 6 depicts the $E_T^\text{miss}$ distributions in the LM signal region in the respective channels. As an example, two of the candidate events in the HM signal region are displayed in Figures 13 and 14.

In the absence of a significant excess, limits are set on the existence of the new physics processes considered in this search. More specifically, upper limits on the production cross-sections of the heavy Higgs boson and RS graviton are derived at 95% CL as a function of the resonance mass using the HM signal region, and the LM signal region is used to place the 95% CL limits on the production cross-section ($\sigma$) of the Mono-Z signatures with different DM and mediator masses and the $ZH$ signal process with the $Z \rightarrow \ell\ell$ and $H \rightarrow$ invisible decays. The cross section limit on the production of an invisibly decaying Higgs boson associated with a Z boson is further interpreted as the upper limit on the branching fraction of the $H \rightarrow$ invisible decay with $m_H = 125$ GeV.

The $m_{ZZ}^\text{T}$ and $E_T^\text{miss}$ distributions are used to set limits in the HM and LM signal regions, respectively. In each case, a profile-likelihood-ratio test statistic [71] is used to check the compatibility between the data and predictions containing an injected signal contribution. Then the 95% CL upper limits on the
Figure 5: $m_{ZZ}^2$ distributions in the High Mass signal region for the $ee$ (a), $\mu\mu$ (b) and combined $ee + \mu\mu$ (c) channels. The stacked histograms represent the background predictions, while the blue, pink and cyan curves give the predicted signal distributions for a heavy Higgs boson with $m_H = 300, 600,$ and $1000$ GeV, respectively. The total uncertainty of the background expectation is shown in the grey shaded band. The number of entries in each bin corresponds to the number of events per 50 GeV in that region.
Figure 6: $E_T^{miss}$ distributions in the Low Mass signal region for the $ee$ (a), $\mu\mu$ (b) and combined $ee + \mu\mu$ (c) channels. The stacked histograms represent the background predictions, while the blue, pink and cyan curves give the predicted signal distributions for the $Z(\rightarrow \ell\ell)H(\rightarrow$ invisible) process ($m_H = 125$ GeV), and the Mono-$Z(\rightarrow \ell\ell)$ signatures with ($m_\chi = 1$ GeV, $m_{med} = 10$ GeV) and ($m_\chi = 50$ GeV, $m_{med} = 300$ GeV), respectively. The total uncertainty of the background expectation is shown in the grey shaded band. The number of entries in each bin corresponds to the number of events per 10 GeV in that region.
production $\sigma$ of the new physics processes are derived using a frequentist method with the CL$_s$ formalism [72]. The likelihood function used in the test statistic is the product of Poisson probability density functions over the considered kinematic bins and analysed decay channels ($ee$ and $\mu\mu$), in which the production cross-section $\sigma$ of the new physics process is the free parameter and systematic uncertainties are considered as nuisance parameters (NPs) each constrained with a Gaussian distribution. Apart from the normalisation and shape uncertainties discussed in Section 7, additional shape uncertainty due to MC statistical fluctuations are implemented for processes with shapes determined from MC simulation. In most cases, a common NP is used to account for a systematic uncertainty for all the kinematic bins in both the $ee$ and $\mu\mu$ channels, and the single NP is applied to all the processes relevant to this uncertainty. The $Z+$jets background uncertainty is considered uncorrelated between the $ee$ and $\mu\mu$ channels, and therefore two separate NPs are implemented. Finally, multiple NPs are assigned for the MC statistical uncertainty, which is treated fully uncorrelated between all the kinematic bins, decay final states and processes.

The limits on $\sigma(pp \rightarrow H) \times BF(H \rightarrow ZZ)$ at 95% CL as a function of $m_{H}$ from 300 GeV to 1 TeV are presented in Figure 7(a). The expected upper limits at 95% CL on $\sigma(pp \rightarrow H) \times BF(H \rightarrow ZZ)$ of a narrow-width scalar boson decaying into ZZ are 107 and 53 fb at $m_{H} = 600$ GeV and 1 TeV, respectively. The observed limits are 69 and 37 fb for the respective mass points, and found to be consistent with the expectation within about one standard deviation. The results are also interpreted as a search for a RS graviton. The limits on $\sigma(pp \rightarrow G^*) \times BF(G^* \rightarrow ZZ)$ at 95% CL as a function of $m_{G^*}$ from 600 GeV to 1.2 TeV are shown in Figure 7(b). The predicted $G^*$ cross sections are also given in the figure, and the production of this particle is excluded up to 1.03 TeV using data and 1 TeV using the background-only expectation.

Figure 8 gives the exclusion limits for the Mono-$Z(\rightarrow \ell\ell)$ signals with a vector mediator and coupling parameters $g_\chi = 1.0$ and $g_q = 0.25$ in 2-dimensional phase spaces of dark matter and mediator masses ($m_\chi$ and $m_{med}$). The 2-dimensional contours are produced by interpolating between the cross-section limits derived from a limited number of MC samples, and this causes the resulting contours to be slightly non-smooth.

Table 6 shows the 95% CL upper limits on the production cross-section of the $Z(\rightarrow \ell\ell)H(\rightarrow$ invisible) process and the $H \rightarrow$ invisible decay branching fraction. Figure 9 presents a distribution of the confidence levels corresponding to each value of upper limits on $\sigma(Z(\rightarrow \ell\ell)H(\rightarrow$ invisible)) divided by the SM prediction of the $ZH$ production cross-section (with $m_{H}=125$ GeV) scanned from 0 to 1.4. The shown confidence levels can be interpreted as that on the upper limits of $BF(H \rightarrow$ invisible), for the region with the x-axis value less than one. The expected and observed upper limit on $BF(H \rightarrow$ invisible) at 95% CL is 65% and 98%, respectively. The observed limit is larger than the expectation, and this is caused by the moderate data excess in the $E_T^{miss}$ distributions in both the $ee$ and $\mu\mu$ channels, as shown in Figure 6.

The statistical uncertainty of the data dominates in the searches discussed in this note, and therefore systematic uncertainties have a relatively small impact on the expected and observed limits. To assess the importance of a systematic uncertainty, expected limits are derived with only the statistical uncertainty of the data and then compared to that computed considering the specific uncertainty.

The impact from the total systematic uncertainty on the expected cross section limits for a heavy Higgs boson or a RS graviton with resonance mass above 600 GeV is only about 1-2%, while the impact is larger on the limits for lower mass resonances and found to be about 10% for a heavy Higgs boson with $m_{H} = 300$ GeV. In the searches for the invisible decay of the Higgs boson and the Mono-$Z(\rightarrow \ell\ell)$ signatures in the LM signal region, systematic uncertainties are found to have a larger impact (up to 30%) on the limits. The impact of the systematic uncertainty varies in the different searches performed in this
analysis, mainly depending on the signal to background ratio and the size of the data sample in the phase space the new physics process is searched for.

Among the sources of systematic uncertainties, the uncertainties related to the background estimations dominate, and the experimental uncertainties due to luminosity, and jet energy scale and resolution, also constitute a nontrivial part of the total systematic impact. For example, uncertainties that give a sizable impact on the expected limit of $\text{BF}(H \rightarrow \text{invisible})$ are those related to luminosity (6.2%), estimation of $Z+\text{jets}$ (6.3%), $ggZZ$ (6.4%), $qqZZ$ (4.5%), and $WZ$ (3.0%), and jet energy scale and resolution (3.6%), where the impacts from each individual sources on the expected limits are given in the parenthesis.

In the case of a data excess in some kinematic regions, the NPs that correspond to the main systematic uncertainties in these regions may be fixed to non-zero values ("pull") in the derivation of the observed limits. The pulls of NPs help to improve the agreement between the data and post-fit predictions, but decrease the best-fit signal production cross-sections as well as their upper limits. As a result of this, the overall impact of the corresponding systematic uncertainties on the observed limits can decrease. In the searches performed in the LM region, only the NP related to the $Z+\text{jets}$ uncertainty gets a significant pull in the fits to the data. This is due to the fact that there is a moderate discrepancy between the data and prediction in the low $E_T^{\text{miss}}$ bins shown in Figure 6, and the $Z+\text{jets}$ contribution and its uncertainty play an important role in that region. As a result, the impact of the total systematic uncertainty on the observed $\text{BF}(H \rightarrow \text{invisible})$ limit is found to be about 10%, and similar effects are found in the search for Mono-$Z(\rightarrow \ell\ell)$ signals. On the other hand, no obvious pulls of NPs are found in the search for heavy resonances in the HM region, and therefore the observed impact of systematic uncertainties is similar to the expectation.

Figure 7: Limits on $\sigma(pp \rightarrow X) \times \text{BF}(X \rightarrow ZZ)$ ($X = H, G^*$) at 95% CL for a narrow-width, heavy-Higgs boson produced via gluon-gluon fusion (a) and for a RS graviton produced with $\kappa/\bar{M}_{\text{Pl}} = 1$ (b). The green and yellow bands give the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties of the expected limits, respectively. The predicted production cross-sections as a function of the $G^*$ mass are shown in the blue solid line.
Figure 8: Exclusion limits for Mono-\(Z(\rightarrow \ell\ell)\) dark matter signals with vector mediator and coupling parameters \(g_\chi = 1.0\) and \(g_q = 0.25\) in the 2-dimensional phase spaces of dark matter and mediator masses \((m_\chi\text{ and } m_{\text{med}})\). The dashed grey line indicates the kinematic threshold where the mediator can decay on-shell into dark matter. The region below the dashed blue line is excluded at 95% CL based on the background only expectation, and the green band gives the 1\(\sigma\) uncertainty of the expected exclusion limits. The phase space circled by the solid black line is excluded using data at 95% CL. The 2-dimensional contours are produced by interpolating between the cross-section limits derived from a limited number of MC samples, and this causes the resulting contours to be slightly non-smooth.

<table>
<thead>
<tr>
<th>Central Value</th>
<th>Limits on (\sigma(Z(\rightarrow \ell\ell)H(\rightarrow \text{invisible}))) [fb]</th>
<th>Limits on BF((H \rightarrow \text{invisible}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td>58</td>
<td>88</td>
</tr>
<tr>
<td>((-1\sigma, +1\sigma))</td>
<td>(41, 83)</td>
<td></td>
</tr>
<tr>
<td>((-2\sigma, +2\sigma))</td>
<td>(30, 115)</td>
<td></td>
</tr>
</tbody>
</table>

Table 6: The 95% CL upper limits on \(\sigma(Z(\rightarrow \ell\ell)H(\rightarrow \text{invisible}))\) and branching fraction of the \(H \rightarrow \text{invisible}\) decay. Both expected and observed limits are given, and the \(\pm 1\sigma\) and \(\pm 2\sigma\) variations of the expected limits are provided as well.
Figure 9: Confidence levels corresponding to upper limits on $\sigma_{ZH} \times \text{BF}(H \rightarrow \text{inv.}) / \sigma_{SM}^{ZH}$ (with $m_H=125$ GeV) scanned from 0 to 1.4. The expected and observed confidence levels are shown as the dashed black and solid black lines, respectively. The green and yellow bands give the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties of the expected confidence levels, respectively. The shown confidence levels can be interpreted as those on the upper limits of $\text{BF}(H \rightarrow \text{invisible})$, for the region with the $x$-axis value less than one. The 95% CL upper limit on $\text{BF}(H \rightarrow \text{invisible})$ can be read from the crossing points between the dashed blue “95% CL” line and the respective confidence level curve.
9 Conclusion

This note presents a search for new phenomena in the $Z(\rightarrow \ell \ell)+E_T^{\text{miss}}$ final state using 13 TeV $pp$ collision data with an integrated luminosity of 13.3 fb$^{-1}$ collected with the ATLAS detector in both 2015 and part of 2016. No significant deviation from the SM expectation is observed in the high mass and low mass signal regions. Upper limits on the production cross section of a heavy scalar particle with a width smaller than the detector resolution have been derived as a function of its mass, and the observed 95% CL limits is more stringent than the limits obtained in Run-I. Upper limits on the production cross-section of a RS graviton are also computed, and comparing to the theoretical cross section predictions, RS gravitons with mass smaller than 1.03 TeV are excluded at 95% CL using the data. In addition, limits are set on the production cross-section of a invisibly decaying SM Higgs boson associated with a $Z$ boson as well as the branching fraction of the $H \rightarrow \text{invisible}$ decay. Finally, exclusion limits are placed on the dark matter production through a vector mediator in a 2-dimensional phase space of dark matter and mediator masses.

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Appendix

Figure 10: Distributions after the $E_{\text{T}}^{\text{miss}} > 90$ GeV requirement, for the combined $ee$ and $\mu\mu$ selection. The di-lepton $p_T$ distribution is shown in (a), and the number of jets in (b). The stacked histograms represent the background predictions from simulation. The bottom panel shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined statistical and systematic uncertainties.
Figure 11: Distributions after the $E^\text{miss} > 90$ GeV requirement, for the combined $ee$ and $\mu\mu$ selection. The angular separation between the leptons $\Delta R_{ll}$ is shown in (a), the angle between the di-lepton system and the $E^\text{miss}$ $\Delta\phi(p_T^{miss}, E^\text{miss})$ in (b), the fractional $p_T$ balance $|p_{T,\text{miss,jet}}^{\text{had}} - p_{T,\text{miss}}^{\text{had}}|/p_{T,\text{miss}}^{\text{had}}$ in (c), the angle between the $E^\text{miss}$ and the nearest jet $\Delta\phi(E^\text{miss}_1, jets)$ in (d), $p_T^{\text{had}}/m_T$ in (e), and the number of $b$-jets in (f). The stacked histograms represent the background predictions from simulation. The bottom panel shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined statistical and systematic uncertainties.
Figure 12: $m_{ZZ}$ distributions after the di-lepton mass requirement in Regions A (a), B (b), C (c) and D (d), which are defined in the estimation of the $Z$+jets background. The stacked histograms represent the background predictions from simulation. The bottom panel shows the ratio of the data to the combined background expectations as well as a band corresponding to the combined statistical and systematic uncertainties.
Figure 13: Event display for a candidate high mass ZZ resonance event from proton-proton collisions recorded by ATLAS with LHC stable beams at a collision energy of 13 TeV. The candidate is reconstructed in the two electrons plus $E_T^{miss}$ final state. In the left display, the transverse section and the side view of the ATLAS detector are shown. The red dotted line shows the $E_T^{miss}$ found in the event, while the green lines represent the paths of the two electrons together with the energy deposit in the electromagnetic calorimeter, in yellow. As shown in the lego plot on the right, the electrons have a transverse momentum of 110 and 30 GeV. The $E_T^{miss}$ is found to be of about 222 GeV and the reconstructed ZZ transverse mass equals to 477 GeV.
Figure 14: Event display for a candidate high mass ZZ resonance event from proton-proton collisions recorded by ATLAS with LHC stable beams at a collision energy of 13 TeV. The candidate is reconstructed in the two muons plus $E_T^{\text{miss}}$ final state. In the left display, the transverse section and the side view of the ATLAS detector are shown. The red dotted line shows the $E_T^{\text{miss}}$ found in the event, while the red lines represent the paths of the two muons from the inner detector to the muon spectrometer. As shown in the lego plot on the right, the muons have a transverse momentum of 115 and 90 GeV. The $E_T^{\text{miss}}$ is found to be of about 254 GeV and the reconstructed ZZ transverse mass equals to 545 GeV.