Search for heavy resonances decaying to a Z boson and a photon in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

DOI
10.1016/j.physletb.2016.11.005

Publication date
2017

Document Version
Final published version

Published in
Physics Letters B

License
CC BY

Citation for published version (APA):
Search for heavy resonances decaying to a $Z$ boson and a photon in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration*

1. Introduction

Many models of physics beyond the Standard Model (SM) introduce new bosons through either an extension of the Higgs sector or additional gauge fields. This suggests that a broad experimental survey of physics beyond the SM can be made by searching for new massive bosons. Some models predict that these bosons decay to final states containing the SM electroweak $W$ or $Z$ bosons or photons [1,2]. Attractive decays from an experimental perspective are to $\gamma\gamma$ [3–6], $Z\gamma$ [7,8] or $ZZ$ [9,10] final states, since both the $Z$ bosons and photons in pair production can be measured well with relatively low backgrounds. If such new bosons were produced, the complete reconstruction of these final states could be used to precisely measure their properties, such as their mass.

This Letter presents a search for $X \rightarrow Z\gamma$ resonances using an integrated luminosity of 3.2 $fb^{-1}$ of proton–proton ($pp$) collisions at a centre-of-mass energy $\sqrt{s}$ of 13 TeV, collected with the ATLAS detector at the Large Hadron Collider (LHC) in 2015. To enhance the sensitivity of the search, both the leptonic ($Z \rightarrow \ell^+\ell^-$, $\ell = e, \mu$)\(^1\) and hadronic ($Z \rightarrow q\bar{q}$) decay modes of the $Z$ boson are used. The combined selection captures about 77% of all $Z$ boson decays. In the following, the search based on the selection of $\ell\ell\gamma$ final states is also referred to as the leptonic analysis, while the search based on the selection of $q\bar{q}\gamma$ final state is also referred to as the hadronic analysis.

The leptonic analysis uses events collected using lepton triggers and is performed in the $X$ boson mass ($m_X$) range 250 GeV–1.5 TeV. The hadronic analysis is performed in the $m_X$ range 700 GeV–2.75 TeV. Due to the large value of $m_X$, the $Z$ bosons from $X \rightarrow Z\gamma$ are highly boosted and the two collimated sprays of energetic hadrons, called jets in the following, that are produced in $Z \rightarrow q\bar{q}$ decays are merged into a single, large-radius, jet $J$. The events used for the hadronic analysis are collected using single-photon triggers. Due to the larger $Z$ boson branching ratio to hadrons, the boosted hadronic analysis dominates the sensitivity at high $m_X$, where the number of events is very small, while the leptonic analysis, with its higher signal-to-background ratio, dominates the sensitivity at low $m_X$.

Previous searches for non-SM bosons decaying into $Z\gamma$ final states were carried out at the Tevatron and the LHC. The D0 Collaboration set limits [11] on $X \rightarrow Z\gamma$ production using $pp$ collisions at $\sqrt{s} = 1.96$ TeV. At the LHC, the ATLAS Collaboration used $pp$ collisions collected in 2011 and 2012 at $\sqrt{s}$ = 7 and 8 TeV to extend the mass range and sensitivity of $X \rightarrow Z\gamma$ searches [7,8]. The analyses assumed a narrow width for the $X$ boson and used $e^+e^-$ and $\mu^+\mu^-$ decays of the $Z$ boson. No signals were observed and limits on the product of the production cross section $\sigma(pp \rightarrow X)$ times the branching ratio $BR(X \rightarrow Z\gamma)$ were determined for values of $m_X$ in the range $\approx 200$ to 1600 GeV.

The analyses presented here search for a localized excess in the reconstructed invariant mass distribution of the final state, either a photon and two leptons or a photon and a heavy, large-radius jet. In the leptonic analysis, the main background arises from continuum production of a $Z$ boson in association with a photon, or, to a lesser extent, with a hadronic jet misidentified as a photon. In the hadronic analysis, the background is dominated by non-resonant SM production of $\gamma +$ jet events, with smaller contributions from dijet events with a jet misidentified as a photon, and from SM

---

*E-mail address: atlas.publications@cern.ch.

\(^1\) In the following, $\ell\ell$ final states are referred to as $\ell\ell$ for simplicity.
\(V + \gamma\) events \((V = W, Z)\). The invariant mass distribution of the background should be smoothly and steeply decreasing with the mass. It is parameterized by a smooth function with free parameters, which are adjusted to the data. The intrinsic width of the heavy boson is assumed to be small compared to the experimental resolution. The boson is assumed to be a spin-0 particle produced via gluon fusion.

2. The ATLAS detector

The ATLAS detector is a multi-purpose particle detector with approximately forward–backward symmetric cylindrical geometry.\(^2\) Its original design [12] has been complemented with the installation, prior to the 2015 data-taking, of a new innermost silicon pixel layer [13].

A two-level trigger system [14] selects events to be recorded for offline analysis. The first-level trigger is hardware-based, while the second, high-level trigger is implemented in software and employs algorithms similar to those used offline to identify lepton and photon candidates.

3. Data sample

Data were collected in 2015 during \(pp\) collisions at a centre-of-mass energy of 13 TeV. The bunch spacing was 25 ns and the average number of inelastic interactions per bunch crossing was 13.

The search in the \(\ell \ell \gamma\) final state is performed in events recorded using the lowest-threshold unprescaled single-lepton or dilepton triggers. The single-muon trigger has a nominal transverse momentum \((p_T)\) threshold of 20 GeV and a loose requirement on the track isolation. This quantity, defined as the sum of the transverse momenta of the tracks in the inner detector \((ID)\) found in a cone of size \(\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.2\) around the muon, excluding the muon track itself, is required to be less than 12% of the muon \(p_T\). Only tracks with longitudinal impact parameter \(z_0\) within 6 mm of that from the muon track are considered in the calculation. An additional single-muon trigger with a higher \(p_T\) threshold (50 GeV) but no isolation requirement is also used. The dimuon trigger has a \(p_T\) threshold of 10 GeV for both muon candidates and applies no isolation criteria. The single-electron (di-electron) trigger has a nominal \(p_T\) threshold of 24 GeV (12 GeV). Electron candidates are required to satisfy likelihood-based identification criteria looser than those applied offline and described in Section 5. The electron identification likelihood is computed from both the properties of the track reconstructed in the ID and the energy deposited in the electromagnetic \((EM)\) calorimeter.

The search in the \(J \gamma\) final state uses events recorded by the lowest-\(p_T\) threshold unprescaled single-photon trigger. This trigger requires at least one photon candidate with \(p_T > 120\) GeV passing loose identification requirements based on the shape of the shower in the electromagnetic calorimeter and on the energy leaking into the hadronic calorimeter [15].

The trigger efficiency for events satisfying the offline selection criteria described in Section 5 is greater than 99% in the \(ee\gamma\) and \(J \gamma\) channels and is about 96% in the \(\mu \mu \gamma\) channel due to the reduced geometric acceptance of the muon trigger system.

The integrated luminosity after the trigger and data quality requirements is \(L_{\text{int}} = 3.2\) fb\(^{-1}\).

4. Monte Carlo simulation

Simulated signal and background samples were generated with a Monte Carlo (MC) technique. They are used to optimize the selection criteria and to quantify the signal efficiency of the final selection. Each MC sample is also used to test the analytic parameterization of the \(Z\gamma\) invariant mass spectra of signal and background, while the estimate of the background yield after the selection is estimated in situ from the data.

All MC samples are generated assuming a centre-of-mass \(pp\) collision energy of 13 TeV. The samples are passed through a detailed simulation of the ATLAS detector response [16] based on the GEANT4 [17]. Multiple inelastic proton–proton collisions (referred to as pile-up) are simulated with the soft QCD processes of PYTHIA 8.186 [18] using the A2 set of tuned parameters (A2 tune) [19] and the MSTW2008LO parton distribution function (PDF) set [20], and are overlaid on each MC event. The distribution of the number of pile-up interactions in the simulation is reweighted to match the data. The simulated signals in the detector are passed through the event reconstruction algorithms used for the data. The simulation is tuned to take into account small differences with data. These include corrections to photon, lepton and jet reconstruction and selection efficiencies, and their energy or momentum resolution and scale. The corrections are obtained either from control samples selected in early \(\sqrt{s} = 13\) TeV data or from 8 TeV data with additional systematic uncertainties introduced to cover the different conditions between the 2012 and 2015 data-taking.

In the signal simulation, a scalar boson \(X\) is produced in \(pp\) collisions via gluon fusion, and decays to a photon and a \(Z\) boson. Monte Carlo samples are produced for different \(m_X\) hypotheses between 200 GeV and 3 TeV. The width of the boson \(X\) is set to 4 MeV, which is much smaller than the experimental resolution, regardless of the resonance mass. Due to the assumed narrow width of the \(X\) boson and the small contribution of gluon fusion to the non-resonant SM production of \(Z + \gamma\) [21], the interference between the \(gg \to X \to Z\gamma\) signal process and the SM \(gg \to Z\gamma\) background is neglected in the simulation. The signal samples are generated with POWHEG-BOX [22,23] interfaced to PYTHIA 8.186 for the underlying event, parton showering and hadronization. The CT10 [24] PDF set and the AZNLO tune [25] of the underlying event are used.

Events from SM processes containing a photon and a \(Z\) or \(W\) boson \((V + \gamma)\), a \(Z\) boson produced in association with jets, or a prompt photon produced in association with jets \((\gamma + \text{jets})\) are simulated using the SHERPA 2.1.1 [26] generator. The matrix elements for SM \(V + \gamma\) \((\gamma + \text{jets})\) production are calculated for real emission of up to three \((\text{four})\) partons at leading order \((\text{LO})\) in the strong coupling constant \(\alpha_S\) and are merged with the SHERPA parton shower [27] using the ME+PS@LO prescription [28]. The matrix elements of events containing \(Z\) bosons with associated jets are calculated for up to two partons at next-to-leading order \((\text{NLO})\) and four partons at LO and merged with the parton shower using the ME+PS@NLO prescription [29]. The matrix elements are calculated using the Comix [30] and OpenLoops [31] generators. For all the background samples, the CT10 PDF set is used in conjunction with dedicated parton shower tuning developed by the SHERPA authors. The \(\gamma + \text{jets}\) and \(V + \gamma\) samples are generated in binned ranges of the transverse momentum of the photon to ensure precise predictions over the full spectrum relevant for these analyses. Similarly, \(Z + \text{jets}\) events are generated in binned ranges of the dilepton pair \(p_T\) from the \(Z\) boson decays.
5. Event selection

Events with at least one primary vertex candidate with two or more tracks with \( p_T > 400 \) MeV are selected. In each event, the primary vertex candidate with the largest sum of the \( p_T^2 \) of the associated tracks is chosen as the hard interaction primary vertex.

Events are required to contain at least one photon candidate and one \( Z \) boson candidate. In the leptonic analysis, the \( Z \) boson candidate is formed from a pair of opposite-sign, same-flavour electrons or muons. In the hadronic analysis, \( Z \) bosons are required to recoil against a high-momentum photon (\( p_T > 250 \) GeV); as a consequence of the \( Z \) boson’s large Lorentz boost, the two jets from the hadronization of the two quarks are reconstructed as a single, relatively heavy, large-radius jet. Jet-substructure variables and the jet mass are then used to discriminate between a \( Z \) boson decay and jets from single quarks or gluons [32]. Events with one or more electron or muon candidates satisfying the selection described below are vetoed in the hadronic analysis. In the following, the selection of photons, leptons, large-radius jets and of the final \( X \to Z\gamma \) candidates is described.

Unconverted photons, photon conversions to electron-positron pairs, and electrons are reconstructed from clusters of energy deposits in the EM calorimeter cells found by a sliding-window algorithm and from tracks reconstructed in the ID and extrapolated to the calorimeter [33,34].

Photon candidates are required to have a pseudorapidity within the regions \( |\eta| < 1.37 \) or \( 1.52 < |\eta| < 2.37 \), where the first calorimeter layer has high granularity. In the leptonic analysis, the transverse momentum of photon candidates is initially required to pass a loose preselection, \( p_T > 15 \) GeV, whereas the final photon \( p_T \) requirement is applied when a \( Z\gamma \) candidate is reconstructed, as described later. In the hadronic analysis, the photon transverse momentum is required to be larger than 250 GeV. To reduce background from hadronic jets, photon candidates are required to satisfy a set of requirements on the shower leakage in the hadronic calorimeter and on the transverse shower profile measured with the first two layers of the electromagnetic calorimeter [33]. The requirements were optimized using simulated samples of photons and hadronic jets produced in 13 TeV pp collisions. The efficiency of the identification criteria is about 98% for converted photon candidates and 94% for unconverted photon candidates with \( p_T > 100 \) GeV. Background from hadronic jets is further reduced by requiring the transverse energy measured in the calorimeter in a cone of size \( \Delta R = 0.4 \) around the photon direction (\( E_{T,\text{iso}} \) [35], also called calorimeter isolation in the following) to be less than \( 2.45\text{GeV} + 0.022 \times p_T \).

Electron candidates are required to have \( p_T > 10 \) GeV and \( |\eta| < 2.47 \), excluding the transition region between the barrel and endcaps in the EM calorimeter (\( 1.37 < |\eta| < 1.52 \)). To suppress background from hadronic jets, electron candidates are required to satisfy likelihood-based identification criteria [36]. Such requirements provide approximately 85% identification efficiency for electrons with a transverse momentum of 20 GeV, increasing to 95% for \( p_T > 80 \) GeV.

Muons with \( |\eta| < 2.5 \) are reconstructed by combining tracks in the ID with tracks in the muon spectrometer (MS) [37]. The acceptance is extended to the region \( 2.5 < |\eta| < 2.7 \) by also selecting muons whose trajectory is reconstructed only in the MS. Muon candidates are required to have transverse momentum above 10 GeV. Background muons, originating mainly from pion and kaon decays, are rejected by applying a set of quality requirements on the number of hits in the muon spectrometer and (for \( |\eta| < 2.5 \)) on the compatibility between the ID and MS momentum measurements. The muon identification efficiency is around 97% for transverse momenta above 10 GeV.

If two electron candidates share the same track, or have clusters in the calorimeter separated by \( |\Delta \eta| < 0.075 \) and \( |\Delta \phi| < 0.125 \), only the candidate with the higher energy measured by the calorimeter is kept. In addition, if the track associated with an electron candidate is within a distance \( \Delta R = 0.02 \) from the track associated with a muon candidate, the electron candidate is rejected.

Track and calorimeter isolation requirements are further applied to the selected leptons. For electrons, combined criteria are applied to the calorimeter isolation, \( E_{T,\text{iso}} \), in a cone of radius \( \Delta R = 0.2 \), and to the track isolation, \( \sum_{\text{tracks}} p_T \), in a cone of radius \( \Delta R = 0.2 \) for electron transverse momenta \( p_T < 50 \) GeV and of radii \( \Delta R = (10 \text{ GeV})/p_T \) for \( p_T > 50 \) GeV. In the calculation of the track isolation, the contribution from the electron track itself is not included. The criteria are chosen to provide an efficiency of about 99% independent of the electron transverse momentum and pseudorapidity, as determined in a control sample of \( Z \to ee \) decays selected with a tag-and-probe technique [36]. For muons, combined criteria are imposed on \( E_{T,\text{iso}} \) in a cone of radius \( \Delta R = 0.2 \) and on \( \sum_{\text{tracks}} p_T \) inside a cone of radius \( \Delta R = 0.3 \) for muon transverse momenta \( p_T < 33 \) GeV and of radius \( \Delta R = (10 \text{ GeV})/ p_T \) for \( p_T > 33 \) GeV. The efficiency of these criteria increases with the muon transverse momentum, reaching 95% at 25 GeV and 99% at 60 GeV, as measured in \( Z \to \mu\mu \) events selected with a tag-and-probe method [37].

In the hadronic analysis, topological clusters of energy in the calorimeter that were locally calibrated and assumed to be massless [38] are used as inputs to reconstruct large-radius jets, based on the anti-\( k_T \) algorithm [39] with radius parameter \( R = 1.0 \) [40]. Within the large-radius jets, smaller “subjets” are reconstructed using the \( k_T \) algorithm [41,42] with a radius parameter \( R = R_{\text{sub}} = 0.2 \). The large-radius jet is trimmed [43] by removing subjets that carry fractional \( p_T \) less than \( f_{\text{cut}} = 5\% \) of the \( p_T \) of the original jet. The pseudorapidity, energy and mass of these trimmed large-radius jets are calibrated using a simulation-based calibration scheme [44]. The large-radius jets are required to have \( p_T > 200 \) GeV and \( |\eta| < 2.0 \). Large-radius jets within \( \Delta R = 1.0 \) from selected photons are discarded. A \( p_T \)-dependent requirement on the substructure observable \( D_2^{b=1} \) [45], defined as the ratio \( e_2^{b=1}\langle e_2^{b=1}\rangle^{-1} \) of \( N \)-point energy correlation functions \( e_2^{b=1} \) of the jet constituents [46], is used to select hadronically decaying bosons while rejecting jets from single quarks or gluons. The ratio makes use of the sensitivity of the \( e_2 \) functions to the “pronginess” character of the jet. In particular, it relies on the sensitivity of \( e_2 \) to radiation around a single hard core, and of \( e_3 \) to radiation with two cores. The powers of the \( e_2 \) and \( e_3 \) functions in the ratio are chosen to optimize the discrimination between one- and two-prong jets following an analysis of the \((e_2, e_1)\) phase-space of these two types of jets.

The jet mass \( m_j \), computed from its topological cluster constituents that remain after the trimming procedure, is required to be in the range \( 80 \text{ GeV} < m_j < 110 \text{ GeV} \). The jet is required to be associated with less than 30 tracks with \( p_T > 500 \) MeV originating from the hard-interaction primary vertex (before trimming). The efficiency of the \( D_2^{b=1}, m_j \) and number-of-track requirements is around 22% for the signal jet and 2.2% for jets from single quarks or gluons.

After the selection of photons, leptons and large-radius jet candidates, the \( Z\gamma \) candidate is chosen. If an event has multiple photon or jet candidates, only the photon or jet candidate with highest transverse momentum is kept. In the leptonic analysis, only \( Z \to \ell\ell \) candidates with invariant mass \( m_{\ell\ell} \) within \( \pm 15 \) GeV of the \( Z \) boson mass [47] are retained; in case of multiple dilepton candidates, only the one with invariant mass closest to the \( Z \) bo-
son mass is kept. Moreover, the triggering leptons are required to match one, or both in the case of events collected with dilepton triggers, of the Z boson candidate’s leptons.

The invariant mass of the selected Z candidate is computed from the four-momenta of the photon candidate and either the selected leptons or the jet (mZ = mT or mJ). In the leptonic analysis, the four-momenta of the photon is recalculated using the identified primary vertex as the photon’s origin, while the four-momenta of the leptons are first corrected for collinear FSR (muons only) and then recomputed by means of a Z-mass-constrained kinematic fit [48]. The Z invariant mass is required to be larger than 200 (640) GeV for the leptonic (hadronic) analysis, to be sufficiently far from the kinematic turn-on due to the Z boson mass and the photon transverse momentum requirement.

Finally, the leptonic analysis only retains candidates in which the photon transverse momentum is larger than 30% of mZ, significantly suppressing background at large invariant mass while maintaining high efficiency over a large range of signal masses.

6. Signal and background models

The final discrimination between signal and background events in the selected sample is achieved by means of an unbinned maximum-likelihood fit of a signal + background model to the invariant mass distribution of the selected data events. Both the signal and background models are described in this section.

6.1. Signal model

Fig. 1 illustrates the distributions of mT and mJ for simulated signal events for a resonance mass of 800 GeV. The intrinsic width of the simulated resonance (4 MeV) is negligible compared to the experimental resolution. The mT distribution ranges between 2 GeV at mX = 200 GeV and 15 GeV at mX = 1500 GeV (1% relative resolution). The mJ distribution ranges between 22 GeV at mX = 750 GeV (3%) and 50 GeV at mX = 3 TeV (1.7%).

The mT distribution is modelled with a double-sided Crystal Ball function (a Gaussian function with power-law tails on both sides). The mJ distribution is modelled with the sum of a Crystal Ball function [49] (a Gaussian function with a power-law tail on one side) and a second small, wider Gaussian component. The fraction of signal Jγ events described by the Crystal Ball function is near 90% for resonance masses up to 1.8 TeV and decreases with mX, reaching 85% at mX = 3 TeV. Polynomial parameterizations of the signal shape parameters as a function of the resonance mass mX are obtained from a simultaneous fit to the invariant mass distributions of all the simulated signal samples, for each Z boson decay channel.

The signal detection efficiency (including the acceptance of the kinematic criteria) of the leptonic analysis is produced by interpolating the efficiencies predicted by all the simulated signal samples up to mX = 1.5 TeV with a function of the form e−bzmX. In the hadronic analysis, the efficiency at any value of mX is obtained through a linear interpolation between the efficiencies obtained from the two simulated signal samples with masses closest to mX. The signal detection efficiency of the leptonic analysis ranges between 28% at mX = 250 GeV and 43% at mX = 1.5 TeV, while that of the hadronic analysis increases from 11% at mX = 700 GeV to 15% at mX = 3 TeV, as shown in Fig. 2.

6.2. Background model

In both the leptonic and hadronic final states, the total background exhibits a smoothly falling spectrum as a function of the invariant mass mZ of the final-state products. The mZ distribution of the background is parameterized with a function similar to the one used in previous searches in the γ + jet and diphoton final states [5,50]:

\[ f_{bg}(m_{Z}) = N(1 - x^{k})p_{1}+t_{2}x^{p_{2}}. \]  

Here \( N \) is a normalization factor, \( x = m_{Z}/\sqrt{\xi} \), the exponent \( k \) is 1/3 for the leptonic analysis and 1 for the hadronic analysis, and \( p_{1} \) and \( p_{2} \) are dimensionless shape parameters that are fitted to the data. The constant \( \xi \) is set to zero in the leptonic analysis and to the value (ten) that minimizes the correlation between the maximum-likelihood estimates of \( p_{1} \) and \( p_{2} \) in a fit to the background simulation for the hadronic analysis.

These parameterizations were chosen since they satisfy the following two requirements: (i) the bias in the fitted signal due to the
choice of this functional form is estimated to be sufficiently small compared to the statistical uncertainties from the background, and (ii) the addition of further degrees of freedom to Eq. (1) does not lead to a significant improvement in the goodness of the fit to the data distribution.

The bias is checked by performing signal+background fits to large background control samples, scaled to the luminosity of the data. A functional form is retained if the absolute value of the fitted signal yield $N_{\text{sig}}$ (spurious signal in the following) is less than 20% (25%) of its statistical uncertainty in the leptonic (hadronic) analysis [51].

For the leptonic analysis, the control sample for the spurious signal study is obtained by summing the invariant mass distributions of $Z + \gamma$ and $Z + \text{jets}$ simulated events, normalized according to their relative fractions measured in data (90% and 10% respectively). These fractions are determined by means of a simultaneous fit of the $E_{\text{T}}\text{miss}$ distributions of the photon candidates passing or failing the identification requirements. To increase the number of $Z + \gamma$ MC events, a very large (up to one thousand times more events than in data) simulated sample is obtained by passing the events generated by SHHERPA through a fast simulation of the calorimeter response [52]. The agreement of the $m_{Z\gamma}$ distribution in the parametric simulation with that of the full-simulation $Z + \gamma$ sample described in Section 4 was evaluated with a $\chi^2$ test. The $\chi^2$ was found to be 23 for 28 degrees of freedom, corresponding to a $p$-value of 75%, indicating that the shapes agree well within statistical uncertainties. The $m_{Z\gamma}$ distribution of $Z + \text{jets}$ events is obtained by reweighting that of the large $Z + \gamma$ sample by a second-order polynomial function. The parameters of this function are determined from a fit to the ratio of the $m_{Z\gamma}$ distributions of a $Z + \text{jets}$-enriched data control sample to that of the parametrized simulation of $Z + \gamma$.

For the hadronic analysis, the spurious signal is studied in a data control sample enriched in jets not originating from Z boson decays. This sample passes the selection described in Section 3, with the exception that the jet mass $m_J$ is either between 50 GeV and 85 GeV, or between 110 GeV and 140 GeV. Based on simulation and data-driven studies, the $m_{J\gamma}$ distribution of $\gamma + \text{jets}$ events has a similar shape to that of the total background in the signal region, where the latter also includes contributions at the 10% level from $V + \gamma$ and dijet events. Thus, this control region (dominated by $\gamma + \text{jets}$ events) can be used to study the background in the hadronic $Z\gamma$ signal region.

Tests to check whether the degrees of freedom of the chosen function are sufficient to accurately describe the background distribution in data are performed by comparing the goodness of the fits to the data using either the nominal background function or a function with one or two additional degrees of freedom. A test statistic $\Lambda_{1,2}$ to discriminate between two background models $f_1$ and $f_2$ is built. This uses either the $\chi^2$ and number of degrees of freedom computed from a binned comparison between the data and the fit (leptonic analysis) or directly the maximum value of the likelihood (hadronic analysis), for the fits performed to data using either $f_1$ or $f_2$. The simpler model $f_1$ is then rejected in favour of $f_2$ if the probability of finding values of $\Lambda_{1,2}$ more extreme than the one measured in data is lower than 5%. No significant improvement in goodness of fit over the model of Eq. (1) is found when adding one or two extra degrees of freedom to it.

7. Systematic uncertainties

The systematic uncertainty in the measured $\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$ has contributions from uncertainties in the integrated luminosity $L_{\text{int}}$ of the analyzed data, in the estimated signal yield $N_{\text{sig}}$, and in the signal efficiency $\varepsilon$.

An integrated-luminosity uncertainty of $\pm 5\%$ is derived, following a methodology similar to that detailed in Ref. [53], from a preliminary calibration using $x$-$y$ beam-separation scans performed in August 2015.

The uncertainties in the signal yield arise from the choice of functional forms used to describe the signal and the background in the final fit to $m_{Z\gamma}$, as well as from the parameters of the signal model, which are determined from the simulation. Uncertainties due to the parameterization of the signal distribution chosen in Section 6.1 are negligible compared to the other uncertainties. Effects of spurious signals from the choice of background function on the signal are included as described in Section 6.2. The uncertainties in the signal model parameters arise from the uncertainties in the energy scales and resolutions of the final-state particles (photons, electrons, muons, and large-radius jets).

Contributions to the uncertainty in the signal detection efficiency $\varepsilon$ originate from the trigger and the reconstruction, identification and isolation requirements of the selected final-state particles. There is also a contribution from the kinematic requirements used to select the final-state particles due to uncertainties in the energy scale and resolution. The effects of the lepton and photon trigger, reconstruction, identification and isolation efficiency uncertainties are estimated by varying the simulation-to-data efficiency correction factors by their $\pm 1\sigma$ uncertainties and recalculating the signal efficiency. The impact of the lepton and photon energy scale and resolution uncertainties is estimated by computing the relative change in efficiency and in the peak position and the width of the invariant mass distribution of the signal after varying these quantities by their uncertainties in the simulation.

The uncertainties in the jet $p_T$, mass and $D_2^{2n-1}$ scales and resolutions are evaluated by comparing the ratio of calorimeter-based to track-based measurements in dijet data and simulation [32, 54]. Their effect is estimated by recomputing the efficiency of the hadronic $Z$ boson selection and the signal $m_{J\gamma}$ distribution after varying the $p_T$, mass and $D_2^{2n-1}$ scales and resolutions by their uncertainties. The requirement on the number of primary-vertex tracks associated with the jet induces a 6% systematic uncertainty in the corresponding efficiency, as estimated from the comparison of simulation and control samples of data.

In the leptonic analysis, the systematic uncertainties have a small effect on the final results, which are dominated by the statistical uncertainties originating from the small size of the selected sample. The main contributions arise from the uncertainty in the photon and electron resolution, from the spurious signal and from the luminosity uncertainty. They worsen the search sensitivity by only 4.0%–0.5%, 3.0%–2.0% and 0.5% respectively, over the $m_X$ range from 250 GeV to 1.5 TeV.

In the hadronic analysis, the systematic uncertainties are dominated by estimates of the jet mass resolution and the jet energy resolution. The search sensitivity worsens by 4.3% (5.3%), 4.3% (1.1%) and 2.1% (1.0%) at $m_{J\gamma}$ masses of 0.7 TeV, 1.5 TeV and 2.7 TeV, from the effects of the jet mass resolution (jet energy resolution) uncertainty. The degradation of the search sensitivity due to the uncertainty in the efficiency of the requirement on the number of tracks associated with the large-radius jet is less than 1% at all tested masses.

8. Statistical procedure

A profile-likelihood-ratio method [55] is used to search for a localized excess over a smoothly falling background in the $m_{Z\gamma}$ distribution of the data, as well as to quantify its significance and estimate its production cross section. The extended likelihood function $L(\alpha, \theta)$ is given by the product of a Poisson term, the
values of the probability density function \( f_{\text{tot}}(m_{Z'Y}, \alpha, \theta) \) of the invariant mass distribution for each candidate event \( i \) and constraint terms \( G(\theta) \):

\[
L\left( \alpha, \theta \right| m_{Z'Y}, \gamma \right) = \frac{e^{-N(\alpha, \theta)} N(\alpha, \theta)}{n!} \prod_{i=1}^{n} f_{\text{tot}}(m_{Z'Y}, \alpha, \theta) \times G(\theta).
\]

(2)

In this expression \( \alpha \) represents the parameter of interest, \( \alpha = \sigma (pp \rightarrow X) \times BR(X \rightarrow Z') \), \( \theta \) are nuisance parameters, \( n \) is the observed number of events, and the expected event yield \( N \) is the sum of the number of signal events \( N_{\text{sig}} = L_{\text{int}} \times (\sigma \times BR) \times \epsilon \), the number of background events \( N_{\text{bkg}} \), and the spurious signal yield \( N_{\text{spur}} \) described in Section 6.2. The function \( f_{\text{tot}}(m_{Z'Y}, \alpha, \theta) \) is built from the signal and background probability density functions of \( m_{Z'Y} \), \( N_{\text{sig}} \) and \( f_{\text{bkg}} \):

\[
f_{\text{tot}}(m_{Z'Y}, \alpha, \theta) = \frac{1}{N} \left[ (N_{\text{sig}}(m_X, \alpha, \theta_{\text{sig}}) + N_{\text{spur}}(m_X) \times \theta_{\text{spur}}) \right.
\]

\[
\times f_{\text{sig}}(m_{Z'Y}, \theta_{\text{sig}}) + N_{\text{bkg}} \times f_{\text{bkg}}(m_{Z'Y}, \theta_{\text{bkg}}) \].
\]

(3)

The uncertainties in the signal parameterization, efficiency and bias in the signal yield due to the choice of the background model are included in the fit via nuisance parameters which are constrained with Gaussian or log-normal penalty terms for signal modelling and a Gaussian penalty term for the spurious signal uncertainty.

The significance of the signal is estimated by computing the \( p \)-value of the compatibility of the data with the background-only hypothesis \( \langle p_0 \rangle \). A modified frequentist (CL) method \([56]\) is used to set upper limits on the signal cross section times branching ratio at 95\% confidence level (CL), by identifying the value of \( \sigma \times BR \) for which \( CL_s \) is equal to 0.05.

Closed-form asymptotic formulæ \([55]\) are used to derive the results. Due to the small size of the selected dataset and of the expected background for large values of \( m_X \), the results for some values of \( m_X \), spread over the full tested range, are checked using ensemble tests. The results obtained using the asymptotic formulæ are in good agreement (differences on the cross-section limits < 10\%) with those from the ensemble tests for most of the \( m_X \) range, except at high \( m_X \) where the differences on the cross-section limits can be as large as 30\%.

9. Results

In the data, there are 382 \( Z(\rightarrow \ell\ell)/Y \) candidates with \( m_{Z'Y} > 200 \) GeV and 534 \( Z(\rightarrow jj)/Y \) candidates with \( m_{Z'Y} > 640 \) GeV. The candidates with largest invariant mass in the leptonic and hadronic analyses have \( m_{\ell\ell}/Y = 1.47 \) TeV and \( m_{jj}/Y = 2.58 \) TeV respectively.

The invariant mass distributions of the selected \( Z'Y \) candidates in data in the leptonic and hadronic final states are shown in Fig. 3. The solid lines represent the results of a background-only fit.

There is no significant excess with respect to the background-only hypothesis, and the largest deviations are observed around \( m_X = 350 \) GeV in the leptonic analysis (2.0σ local significance) and around \( m_X = 1.9 \) TeV in the hadronic analysis (1.8σ local significance).

For a narrow scalar boson \( X \) of mass \( m_X \), 95\% CL upper limits on \( \sigma (pp \rightarrow X) \times BR(X \rightarrow Z') \) are set for \( m_X \) between 250 GeV and 1.5 TeV in the leptonic analysis and between 700 GeV and 2.75 TeV in the hadronic analysis. In the \( m_X \) range between 700 GeV and 1.5 TeV the results of the two analyses are then combined. The observed limits range between 295 fb for \( m_X = 340 \) GeV and 8.2 fb for \( m_X = 2.15 \) TeV, while the expected limits range between 230 fb for \( m_X = 250 \) GeV and 10 fb for \( m_X = 2.75 \) TeV. The observed and expected limits as a function of \( m_X \) are shown in Fig. 4.

10. Conclusion

A search for new resonances with masses between 250 GeV and 2.75 TeV decaying to a photon and a Z boson has been performed using 3.2 fb\(^{-1}\) of proton–proton collision data at a centre-of-mass energy of \( \sqrt{s} = 13 \) TeV collected by the ATLAS detector at the Large Hadron Collider. The Z bosons were reconstructed through their decays either to charged, light, lepton pairs \((e^-e^+, \mu^-\mu^+)\) or to boosted quark–antiquark pairs giving rise to a single, large-radius, heavy jet of hadrons.

No significant excess in the invariant-mass distribution of the final-state particles due to a scalar boson with a narrow width (4 MeV) was found over the smoothly falling background.

Limits at 95\% CL using a profile-likelihood ratio method were set on the production cross section times decay branching ratio to \( ZY \) of such a boson. The observed limits range between 295 fb for \( m_X = 340 \) GeV and 8.2 fb for \( m_X = 2.15 \) TeV, while the expected limits range between 230 fb for \( m_X = 250 \) GeV and 10 fb for \( m_X = 2.75 \) TeV.
Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not have been operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; FWF, Flanders; FNRS and FOM, Belgium; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MINEYA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, Canarie, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; HERALICOS, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSF, BSF, GIF and Minerva, Israel; BRF, Norway; Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully. In particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [57].

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States
7 Department of Physics, University of Arizona, Tucson AZ, United States
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografos, Greece
11 Department of Physics, The University of Texas at Austin, Austin TX, United States
12 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
13 Instituto de Física d’Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
14 Institute of Physics, University of Belgrade, Belgrade, Serbia
15 Department for Physics and Technology, University of Bergen, Bergen, Norway
16 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States
17 Department of Physics, Humboldt University, Berlin, Germany
18 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
19 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
20 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (d) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
21 Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
22 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Accademia di Astronomia, Università di Bologna, Bologna, Italy
23 Physikalisches Institut, University of Bonn, Bonn, Germany
24 Department of Physics, Boston University, Boston MA, United States
25 Department of Physics, Brandeis University, Waltham MA, United States
26 (a) Universidade Federal do Rio de Janeiro COPPE/EE/F, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of São João del Rey (UFJS), São João del Rey; (d) Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
27 Physics Department, Brookhaven National Laboratory, Upton NY, United States
28 (a) Transilvania University of Brașov, Brașov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
29 Departamento de Física; Universidad de Buenos Aires, Buenos Aires, Argentina
30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
31 Department of Physics, Carleton University, Ottawa ON, Canada
32 CERN, Geneva, Switzerland
33 Enrico Fermi Institute, University of Chicago, Chicago IL, United States
34 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
35 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Hefei; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
36 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
37 Nevis Laboratory, Columbia University, Irvington NY, United States
38 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
39 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
40 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
41 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
42 Physics Department, Southern Methodist University, Dallas TX, United States
43 Physics Department, University of Texas at Dallas, Richardson TX, United States
44 DESY, Hamburg and Zeuthen, Germany
45 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
46 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
47 Department of Physics, Duke University, Durham NC, United States
48 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
49 INFN Laboratori Nazionali di Frascati, Frascati, Italy
50 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
51 Section de Physique, Université de Genève, Geneva, Switzerland
52 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
53 (a) I. I. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
54 IF Physikalisches Institut, Justus-Liebig-Universität Gießen, Gießen, Germany
55 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
56 IF Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
57 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
58 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at School of Physics, Shandong University, Shandong, China.

Also at Department of Physics, California State University, Sacramento CA, United States of America.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Eotvos Lorand University, Budapest, Hungary.

Also at Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at National Research Nuclear University MEPhI, Moscow, Russia.

Also at Department of Physics, Stanford University, Stanford CA, United States of America.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Flensburg University of Applied Sciences, Flensburg, Germany.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also affiliated with PKU-CHEP.

* Deceased.