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

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Abstract

This note describes a search for new resonances with mass larger than 250 GeV, decaying to a $Z$ boson and a photon. The dataset consists of 3.2 fb$^{-1}$ of $pp$ collisions collected at $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider. The $Z$ bosons are identified through their decays either to charged, light lepton pairs ($e^+e^-,\mu^+\mu^-$) or to hadrons. The data are consistent with the expected background in the whole mass range investigated and upper limits are set on the production cross section times decay branching ratio to $Z\gamma$ of a narrow scalar boson with mass between 250 GeV and 2.75 TeV.
1. Introduction

Many models of physics beyond the Standard Model (SM) introduce new bosons through either an extension of the Higgs sector or through 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 these will decay to final states containing the SM electroweak $W$ or $Z$ bosons or photons [1, 2]. Attractive decays from an experimental perspective are to $\gamma\gamma$, $Z\gamma$ or $ZZ$ final states, since both $Z$ bosons and photons can be well measured with relatively low backgrounds. If such new bosons were produced, the complete reconstruction of these final states could be used to measure precisely their properties, such as their mass. Recently, there have been a large number of theory papers exploring models that include new neutral bosons $X$ decaying to $\gamma\gamma$ and $Z\gamma$.

This report presents a search for $X \rightarrow Z\gamma$ resonances using $3.2 \text{ fb}^{-1}$ of proton–proton collisions at a center of mass energy of 13 TeV, collected with the ATLAS detector at the Large Hadron Collider (LHC) in 2015. To improve the sensitivity of the search, both leptonic and hadronic decay modes of the $Z$ boson are used. Events in which the $Z$ boson decays to $\ell^+\ell^-$ ($\ell = e, \mu$) are collected using lepton triggers. Events in which the $Z$ boson decays to hadrons are collected using single-photon triggers. This allows the use of offline detector information to identify boosted $Z$ bosons from the merged di-jet cluster reconstructed as a single, large-radius, jet $J$. The combined selection captures about 77% of the $Z$ boson decay branching ratio. In the following, the search based on the selection of $\ell\ell\gamma$ final states will also be referred to as the leptonic analysis, while the search based on the selection of $J\gamma$ final state will also be denoted as the hadronic analysis.

Previous searches for non-SM bosons decaying into $Z\gamma$ final states were carried out at the Tevatron and the LHC. The D0 collaboration [4] set limits on $X \rightarrow Z\gamma$ production using $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. At the LHC, the ATLAS [5, 6] and CMS [7] collaborations 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. The analyses assumed a narrow width of the $X$ boson and used $e^+e^-$ and $\mu^+\mu^-$ decays of the $Z$ boson. No signals were observed and limits on $\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$ were determined for values of the $X$ boson mass $m_X$ in the range $\approx 200$ to 1000 GeV.

The analyses presented here search for a localized, high-mass excess in the reconstructed invariant mass distribution of the final state, either a photon and two leptons or a photon and a large-radius jet. In the leptonic analysis, the main background arises from continuum production of a $Z$ boson in association with a photon, with a smaller contribution from inclusive $Z$ boson production events in which a hadronic jet is misidentified as a photon. In the hadronic $Z$ boson final state, the background is dominated by non-resonant SM production of $\gamma$+jet events, with smaller contributions from di-jet events with a jet misidentified as a photon, and from SM $V + \gamma$ events ($V = W, Z$). The invariant mass distribution of the background is 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 boson is assumed to be small compared to the experimental resolution. The search is performed in the $X$ mass range 250 GeV–1.5 TeV using leptonic $Z$ boson decays and 720 GeV–2.75 TeV using hadronic $Z$ boson decays. Beyond 1.5 TeV the $Z$ boson is sufficiently boosted to produce two leptons that have a typical angular separation $\Delta R \approx 0.3$ or less and the efficiency of the lepton selection requirements applied in the leptonic analysis decreases. The boson is assumed to be a Higgs-like spin-0 particle produced via gluon fusion.

\footnote{See for example Ref. [3] and references there in.}

\footnote{In the following $\ell^+\ell^-$ final states are be referred to as $\ell\ell$ for simplicity}
The document is organized as follows. Section 2 contains a brief description of the ATLAS detector. The data and simulation samples used in this study are summarized in sections 3 and 4, respectively. The event selection is presented in section 5. The signal and background modelling are discussed in section 6. Section 7 illustrates the systematic uncertainties. In section 8 the statistical procedures used to estimate the signal yield in the selected sample, to quantify its significance and to set limits on the signal production cross section are presented. The final results are given in section 9.

2. The ATLAS detector

The ATLAS detector [8] is a multi-purpose particle detector with approximately forward-backward symmetric cylindrical geometry. The inner tracking detector (ID) covers |η| < 2.5 and consists of a silicon pixel detector (including the newly installed innermost pixel layer [9]), a silicon microstrip detector, and a straw-tube transition radiation tracker (TRT). The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field and by a high-granularity lead/liquid-argon (LAr) sampling electromagnetic (EM) calorimeter. The EM calorimeter measures the energy and the position of electromagnetic showers with |η| < 3.2. It includes a presampler (for |η| < 1.8) and three sampling layers, longitudinal in shower depth, up to |η| = 2.5. The hadronic calorimeter, surrounding the electromagnetic one and covering |η| < 4.9, is a sampling calorimeter which uses either scintillator tiles or LAr as the active medium, and steel, copper or tungsten as the absorber material. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroid magnets, each with eight coils, a system of precision tracking chambers (|η| < 2.7), and fast tracking chambers for triggering (|η| < 2.4). Precision tracking in the MS volume is provided by three layers of Monitored Drift Tube Chambers (MDT); for |η| > 2, the inner layer is instrumented with a quadruplet of Cathode Strip Chambers (CSC) instead of MDTs. Muon triggering capability is provided by Resistive Plate chambers (RPC) for |η| < 1.05 and Thin Gap Chambers (TGC) for 1.0 < |η| < 2.4.

A two-level trigger system 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 by the ATLAS detector in 2015 during pp collisions at a center-of-mass energy of 13 TeV. The bunch spacing was 25 ns and the average number of inelastic interactions per bunch crossing was 13. Events with data quality problems are not considered.

The search in the ℓℓγ final state is performed on events recorded using the lowest-threshold unprescaled single-lepton or di-lepton triggers. The single-muon trigger has a nominal transverse momentum (p_T) threshold of 20 GeV and a loose requirement on the track isolation of the muon. This quantity, defined as the sum of the transverse momenta of the inner detector tracks found in a cone of ΔR = √((Δφ)^2 + (Δη)^2) < 0.2 around the muon, excluding the muon track itself, is required to be less than 12% of the muon p_T. Only

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3 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as η = −ln tan(θ/2).
tracks within 6 mm from the muon track along the beam line are considered in the calculation. An additional single-muon trigger with higher $p_T$ threshold (50 GeV) but no isolation requirement is also used. The di-muon trigger has a transverse momentum threshold of 10 GeV for both muon candidates and applies no isolation criteria. The single-electron (di-electron) trigger has a nominal transverse momentum threshold of 24 GeV (12 GeV). Electron candidates are required to pass likelihood-based identification criteria looser than those applied offline and described in Sec. 5, based on information from both the track reconstructed in the ID and the energy deposited in the electromagnetic 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 transverse momentum above 120 GeV and passing loose identification requirements based on the lateral shape of the shower in the EM calorimeter and on the energy leaking into the hadronic calorimeter [10].

The trigger efficiency for events satisfying the offline selection criteria described in Sec. 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 in the $|\eta| < 1.05$ and $|\eta| > 2.4$ regions.

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

4. Monte Carlo simulation

Simulated signal and background event samples are 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. Such MC samples are also used to test the analytic parametrization used for the $Z\gamma$ invariant mass spectra of signal and background.

All MC samples are generated assuming a center-of-mass $pp$ collision energy of 13 TeV. The samples are passed through a detailed simulation of the ATLAS detector response [11] based on GEANT4 [12]. Multiple inelastic proton–proton collisions (denoted pile-up) are simulated with the soft QCD processes of PYTHIA8.186 using the A2 set of tuned parameters (tune) [13] and the MSTW2008LO parton distribution function (PDF) set [14], and are overlaid to each MC event. The distribution of the number of pile-up events in the simulation reproduces the one observed in data. The resulting detector simulation outputs are passed through the same event reconstruction algorithms as used for the data. The simulation is corrected to take into account data-MC differences in photon, lepton and jet efficiencies and energy or momentum resolution, and muon momentum scale. The corrections are obtained either from control samples selected in early $\sqrt{s} = 13$ TeV data or from 8 TeV ATLAS data with additional systematic uncertainties introduced to cover the different conditions between the 2012 and 2015 setups.

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. MC 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 corresponds to that of a SM Higgs boson with a mass of 125 GeV, regardless of the resonance mass. The interference between the $gg \rightarrow X \rightarrow Z\gamma$ process and the non-resonant SM production of $Z + \gamma$ is neglected in the simulation. The signal samples are generated with POWHEG-box [15, 16] interfaced with PYTHIA8 for the underlying event, parton showering and hadronization. The CT10 [17] PDF set and the AZNLO tune [18] of the underlying event are used.
Events from SM processes containing either a photon and a $Z$ boson, a $Z$ boson produced in association with jets, or a prompt photon produced in association with jets ($\gamma+$jet) are simulated using the Sherpa 2.1.1 [19] generator. The matrix elements for SM $Z + \gamma$ ($\gamma+$jet) production are calculated for real emission of up to 3 (4) partons at leading order (LO) in the strong coupling constant $\alpha_s$ and merged with the Sherpa parton shower [20] using the ME+PS@LO prescription [21]. The matrix elements of events containing $Z$ bosons with associated jets are calculated for up to 2 partons at next-to-leading order (NLO) and 4 partons at LO and merged with the parton shower using the ME+PS@NLO prescription [22]. The matrix elements are calculated using the Comix [23] and OpenLoops [24] 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 $\gamma+$jet and $Z + \gamma$ samples are binned in the photon transverse momentum to cover the full spectrum relevant to this analysis. Similarly, $Z+$jet events are binned in the transverse momentum of the di-lepton pair produced in 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 leptons. In the hadronic analysis, $Z$ bosons are required to recoil against a high-momentum photon ($p_T > 250$ GeV); as a consequence of their large Lorentz boost the two jets from the hadronization of the two quarks from the $Z$ boson decay are reconstructed as a single, large-radius jet. Jet-substructure quantities and the jet invariant mass are then used to discriminate between a $Z$ boson decay and jets from single quarks or gluons [25]. Events with at least one good electron or muon candidate are vetoed by the hadronic analysis. In the following, the selection of photons, leptons, large-radius jet candidates and of the final $X \rightarrow Z\gamma$ candidates is described.

Photons 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 inner detector and extrapolated to the calorimeter [26, 27].

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 backgrounds from hadronic jets, photon candidates are required to satisfy a set of requirements on the hadronic leakage and on the transverse shower profile measured with the first two layers of the electromagnetic calorimeter [10]. The requirements were optimized using simulated samples of photons and hadronic jets produced in 13 TeV $pp$ collisions. Background from hadronic jets is further reduced by requiring the transverse isolation energy $E_{T,iso}$ [28] of the photon candidates in a cone of $\Delta R = 0.4$ around the photon direction (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 transverse momentum $p_T > 10$ GeV and pseudorapidity $|\eta| < 2.47$, excluding the transition region between the barrel and endcaps in the LAr calorimeter (1.37 <
|\eta| < 1.52). To suppress background from hadronic jets misidentified as electrons, electron candidates are required to pass likelihood-based identification criteria [29]. The quantities used as inputs for the calculation of the likelihood are the longitudinal and transverse shower profiles in the electromagnetic calorimeter, measures of track and track-cluster matching quality, and the transition radiation detected in the TRT. The electron identification requirements provide approximately 85% identification efficiency for electrons with a transverse momentum of 20 GeV.

Muons with |\eta| < 2.5 are reconstructed by combining ID and MS tracks that have consistent trajectories and curvatures [30]. The acceptance is extended in the region 2.5 < |\eta| < 2.7 by selecting also muons whose trajectory is reconstructed only in the MS. Muon candidates are required to have transverse momentum above 10 GeV. Background muons coming mainly from pion and kaon decays, as well as hadrons reconstructed as muons, 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 have identical track parameters, or have clusters in the calorimeter closer than |\Delta\eta| < 0.075 and |\Delta\phi| < 0.125, only the candidate with the highest energy measured by the calorimeter is kept. In addition, if the track associated to an electron candidate is within a distance \Delta R < 0.02 from the track associated to a muon candidate, the electron candidate is rejected. In the leptonic analysis, photon candidates that are within \Delta R < 0.3 of a selected electron or muon candidate are rejected, thus suppressing background from final-state-radiation (FSR) Z + \gamma events.

Track and calorimeter isolation requirements are further applied to the selected leptons. For electrons, combined criteria are applied on the calorimeter isolation \text{E}_{\text{T,iso}} in a cone of radius \Delta R = 0.2 and on the track isolation \sum_{\text{tracks}} p_T inside a variable-size cone around the electron of radius \Delta R = 0.2 for transverse momenta below 50 GeV and of radius \Delta R = (10 \text{ GeV})/p_T above 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% independently of the electron transverse momentum and pseudorapidity, as determined on a control sample of Z \rightarrow ee decays selected with a tag-and-probe technique. For muons, combined criteria are applied on \text{E}_{\text{T,iso}} in a cone of radius \Delta R = 0.2 and on \sum_{\text{tracks}} p_T inside a variable-size cone of radius \Delta R = 0.3 for p_T < 33 GeV and of \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 \rightarrow \mu\mu events selected with a tag-and-probe method.

In the hadronic analysis, massless topological clusters which have been locally calibrated [31] are used as inputs to reconstruct large-radius jets, based on the anti-
\text{k}_{\text{T}} algorithm [32] with radius parameter R = 1.0 [33]. Within the large-radius jets, smaller “subjets” are reconstructed using the \text{k}_{\text{T}} algorithm [34, 35] with a radius parameter R = R_{\text{sub}} = 0.2. The large-radius jet is trimmed 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. The jets are required to have transverse momentum p_T > 200 GeV and pseudorapidity |\eta| < 2.0. Large-radius jets within \Delta R < 1.0 from selected photons are discarded. The substructure observable \text{D}^{\beta=1}_2, which is the ratio of energy correlation functions \text{e}^{\beta=1}_3/\left(\text{e}^{\beta=1}_2\right)^3, is used to select hadronically decaying bosons while rejecting quark- or gluon-like jets [36, 37]. The energy correlation functions \text{e}^{\beta=1}_n measure the n-point correlation of the energy within a set of particles, without reference to any jet algorithm. The ratio \text{D}^{\beta=1}_2 is useful for identifying jets with two-prong substructure. The jet mass m_J, computed from its topocluster constituents that remain after the trimming procedure, is required to be within 15 GeV of the reconstructed Z boson mass peak (80 GeV < m_J < 110 GeV). The jet is required to be isolated from
additional hadronic activity by allowing at most 30 tracks (before trimming) to be associated to it and to originate from the hard interaction primary vertex. The efficiency of the $D_{(\beta=1)}^{J\gamma}$, $m_J$ and track isolation requirements is around 22% for the signal jet and 2.2% for quark and gluon jets.

After the selection of photons, leptons and large-radius jet candidates, the $Z\gamma$ candidate is chosen. In case of 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 ±15 GeV of the $Z$ boson mass are retained; in case of multiple di-lepton candidates, only the one with invariant mass closest to the $Z$ boson mass is kept. Moreover, the triggering leptons are required to match one (or both in the case of events collected with di-lepton triggers) of the $Z$ candidate’s leptons.

The invariant mass $m_{\text{inv}}$ of the selected $Z\gamma$ candidates is computed from the four-momenta of the photon candidate and of either the selected leptons or the jet ($m_{\text{inv}} = m_{ee\gamma}$, $m_{\mu\mu\gamma}$ or $m_{J\gamma}$). In the leptonic analysis, the four-momentum of the photon is recalculated using the identified primary vertex as the photon’s origin, and the four-momenta of the leptons are corrected for collinear FSR (muons only) and are finally recomputed by means of a $Z$-mass-constrained kinematic fit [38]. The $Z\gamma$ 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 $m_{\text{inv}}$, significantly suppressing background at large invariant mass while keeping a good 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 the signal+background model to the invariant mass distribution of the selected data events. Both the signal and background models are described in this section, while the full likelihood function and the statistical procedures used to obtain the results are given in section 8.

6.1. Signal model

Figure 1 illustrates the distributions of $m_{\mu\mu\gamma}$, $m_{ee\gamma}$ and $m_{J\gamma}$ 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, thus the reconstructed distributions are completely determined by the detector response. The invariant mass resolution of $\ell\ell\gamma$ events, combining $ee\gamma$ and $\mu^+\mu^-\gamma$ events, ranges between 2 GeV for $m_X = 200$ GeV and 15 GeV for $m_X = 1500$ GeV (1% relative resolution). The $J\gamma$ invariant mass resolution ranges between 22 GeV for $m_X = 750$ GeV (3%) and 50 GeV for $m_X = 3$ TeV (1.7%).

The $m_{\ell\ell\gamma}$ distribution is modelled with a double-sided Crystal Ball function (a Gaussian function with power-law tails on both sides). The $m_{J\gamma}$ distribution is modelled with the sum of a Crystal Ball function (a Gaussian function with a power-law tail on the left side) and a small, wider Gaussian component. The fraction of signal $J\gamma$ events described by the Crystal Ball function is above 90% for resonance masses up to 1.8 TeV and decreases with $m_X$ reaching 85% for $m_X = 3$ TeV. Polynomial parameterizations of the signal shape parameters as a function of the resonance mass $m_X$ are obtained from a simultaneous fit to the invariant mass distributions of all the simulated signal samples, for each $Z$ boson decay channel.
Figure 1: Invariant mass distribution for $X \rightarrow Z\gamma$, $Z \rightarrow ee$ (a), $Z \rightarrow \mu\mu$ (b) or $Z \rightarrow J$ (c) events in a simulation of a resonance $X$ with a mass of 800 GeV and narrow intrinsic width (4 MeV) produced in a gluon-fusion process in $\sqrt{s} = 13$ TeV $pp$ collisions. All selection requirements have been applied. The solid lines represent the fits of the points with a double-sided Crystal Ball function (a, b) or with the sum of a Crystal Ball and a Gaussian function (c).
Figure 2 shows the signal detection efficiency versus the mass $m_X$ of the signal. The efficiency as a function of $m_X$ is computed in the leptonic analysis by interpolating the efficiencies of all the simulated signal samples up to $m_X = 1.5$ TeV with a function of the form $a + be^{cm_X}$. In the hadronic analysis the efficiency at any value of $m_X$ is obtained through a linear interpolation between the efficiencies obtained from the two simulated signal samples with masses closest to $m_X$. The signal detection efficiency of the leptonic analysis ranges between 28% for $m_X = 250$ GeV and 43% for $m_X = 1.5$ TeV, while that of the hadronic analysis increases from 11% for $m_X = 720$ GeV to 15% at $m_X = 3$ TeV. Taking into account $BR(Z \rightarrow \ell\ell) = 6.7\%$ and $BR(Z \rightarrow q\bar{q}) = 70\%$, the efficiency of the two analyses for $pp \rightarrow X \rightarrow Z\gamma$ events is between 1.9% and 2.9% for the leptonic final state and between 7.7% and 11% for the hadronic one.

In the leptonic analysis, the goodness of the chosen signal model and of the parameters returned by the simultaneous fit is estimated by computing the bias on the signal yield in signal+background fits to the invariant mass distribution of Asimov pseudodata, in which all statistical fluctuations are suppressed [39]. These datasets are built by combining a background-only dataset, generated using the same background model used for the fit (and described in the next section), and a signal-only dataset, containing the signal invariant mass distribution predicted by the simulation. The study is repeated by embedding signals corresponding to different values of $m_X$ spanning the full range under study. The signal yield returned by the fit deviates from the true value by less than 1%.

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 $m_{inv}$ of the final state products. The $m_{inv}$ distribution of the background
is parameterized with a function similar to the one used in previous searches in the $\gamma$+jet and di-photon
final states [40, 41]:

$$f_{\text{bkg}}(m_{\text{inv}}) = N(1 - x^k)^{p_1 + \xi p_2} x^{p_2}. \quad (1)$$

Here $N$ is a normalization factor, $x = m_{\text{inv}}/\sqrt{s}$, the exponent $k$ is $1/3$ for the leptonic analysis and $1$ for
the hadronic one, $p_1$ 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 (approximately 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 have been chosen since they satisfy the following two requirements: (i) the bias
on 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 high-statistics background control samples,
scaled to the luminosity of the data. The fitted signal yield $N_{\text{spur}}$, called spurious signal in the following, is
required to be less than $20\%$ ($25\%$) of its statistical uncertainty in the leptonic (hadronic) analysis [42].

For the leptonic analysis, the control sample for the spurious signal study is obtained by summing together
the invariant mass distributions of $Z + \gamma$ and $Z$+jet simulated events, normalized according to their relative
fractions measured in data ($90\%$ and $10\%$, respectively). These fractions are determined by means of a
two-dimensional sideband method based on the numbers of $\ell\ell\gamma$ candidates in which the photon either
passes anti-isolation requirements, anti-identification requirements, or both [10]. The resulting fractions
are cross-checked with an alternative technique based on a simultaneous fit of the calorimeter isolation
distributions of the photon candidates passing or failing the identification requirements. To increase the
statistics 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 [43]. The $m_{\text{inv}}$ distribution of the lower-statistics simulated $Z + \gamma$ events described in Sec. 4
agrees well with that of this parametric simulation. The $m_{\text{inv}}$ distribution of $Z$+jet events is obtained by
reweighting that of the high-statistics $Z + \gamma$ sample by a second-order polynomial function. The parameters
of this function are determined from a fit to the ratio of the $m_{\text{inv}}$ distributions of simulated $Z$+jet events
(Sec. 4) and of the parameterized simulation of $Z + \gamma$.

For the hadronic analysis, the spurious signal is studied on control samples consisting in a background-only
sample of $\gamma$+jet events (which are estimated to contribute around $93\%$ of the total background), simulated
with SHHERPA (Sec. 4), as well as of collision data enriched in jets not originating from $Z$ boson decays.
This second control sample passes the selection described in Sec. 5, with the exception that the jet mass
$m_J$ is either between 50 GeV and 65 GeV, or between 110 GeV and 140 GeV.

Tests to check whether the chosen function accurately describes the background distribution in data or
whether more degrees of freedom are needed 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 $\Lambda_{12}$ 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 distribution of this test statistic is computed by generating
an ensemble of pseudodata according to the background model $f_1$ with fewer degrees of freedom, fitting
it with both models and calculating the value of $\Lambda_{12}$ for each pseudodata sample. The simpler model $f_1$ is
then rejected in favor of $f_2$ if the probability of finding values of $\Lambda_{12}$ 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 measured $\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$ is affected by the systematic uncertainties on the integrated luminosity of the analysed data $L_{\text{int}}$, on the estimated signal yield $N_{\text{sig}}$, and on the signal efficiency $\varepsilon$.

The integrated luminosity uncertainty ($\pm 5\%$) is derived, following a methodology similar to that detailed in Ref. [44], from a preliminary calibration of the luminosity scale using $x - y$ beam-separation scans performed in August 2015.

The uncertainties on the signal yield arise from the choice of the functional forms used to describe the signal and the background in the final fit to $m_{\text{inv}}$, as well as on the parameters of the signal model, which are determined from the simulation. The former are computed from the bias studies described in the previous section. The latter arise from the uncertainties on the energy scales and resolutions of the final state particles (photons, electrons, muons, and large-radius jets).

The uncertainty on $\varepsilon$ arises from uncertainties on the efficiency of the trigger, reconstruction, identification and isolation requirements of the final state particles. An additional contribution originates from the efficiency of the kinematic requirements due to the uncertainties on the energy scale and resolution of the final state particles.

The effects of the lepton and photon trigger, reconstruction, identification and isolation efficiency uncertainties are estimated by varying the MC-to-data efficiency correction factors within 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 position and the width of the invariant mass distribution of the signal after varying these quantities within their uncertainties in the simulation.

The uncertainties on the jet $p_T$, mass and $D^{\beta=1}_2$ scales and resolutions are evaluated by comparing the ratio of calorimeter-based to track-based measurements in dijet data and simulation [25, 45]. 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 $D^{\beta=1}_2$ scales and the resolutions within their uncertainties.

In the leptonic analysis, the systematic uncertainties give an overall small contribution to the final result, which is dominated by the large statistical uncertainties originating from the small size of the selected sample. The main contributions arise from the uncertainty on the photon and electron resolution, from the spurious signal and from the luminosity uncertainty. They increase the expected 95% confidence-level limit on the signal cross section respectively by only 0.5%–4%, 2%–3% and 0.5%.

In the hadronic analysis, the dominant systematic uncertainties originate from the jet mass resolution, which leads to an uncertainty of 15% on the signal efficiency, and from the jet and photon energy resolutions, which lead to uncertainties of about 25% and 5% respectively on the $m_{J\gamma}$ resolution. The overall effect of the systematic uncertainties on the expected limit in the hadronic analysis decreases with $m_X$ from 20% at 750 GeV to 8% at 1.5 TeV, and to 2% at 2.75 TeV, where the results are dominated by statistical uncertainties.
8. Statistical interpretation

A profile-likelihood-ratio method [39] is used to search for an excess over the SM background in the $m_{\text{inv}}$ distribution of the data, to quantify its significance or to set limits on the signal cross section. The extended likelihood function $L(\theta)$ is given by the product of a Poisson term built from the number $n$ of observed events and the expected event yield $N$, and of the values $f(m_{\text{inv}}^i, \theta)$ of the probability density function (pdf) of the invariant mass distribution for each candidate event $i$:

$$L(\theta|m_{\text{inv}}^i_{i=1..n}) = \frac{e^{-N(\theta)}N(\theta)^n}{n!} \prod_{i=1}^{n} f(m_{\text{inv}}^i, \theta) \times G(\theta).$$  (2)

The set $\theta$ of parameters of the likelihood function includes the parameter of interest, $\sigma \times BR$, as well as other parameters, called nuisance parameters. The function $G(\theta)$ represents a set of constraints on some of the nuisance parameters, as described in the following.

The number of expected candidates $N$ is the sum of the number of signal events $N_{\text{sig}} = \sigma \times BR \times L_{\text{int}} \times \varepsilon$, the number of background events $N_{\text{bkg}}$, and the spurious signal yield $N_{\text{spur}}$ fitted on background-only samples as described in the previous section.

The total pdf is built from the probability density functions $f_{\text{sig}}$ and $f_{\text{bkg}}$ describing the signal and background $m_{\text{inv}}$ distributions:

$$f(m_{\text{inv}}^i, \theta) = \frac{1}{N} \left[ \left( (\sigma \times BR)(m_X) \times L_{\text{int}} + N_{\text{spur}}(m_X) \times \theta_{\text{spur}} \right) \times f_{\text{sig}}(m_{\text{inv}}^i, \theta_{\text{sig}}) 
+ N_{\text{bkg}} \times f_{\text{bkg}}(m_{\text{inv}}^i, \theta_{\text{bkg}}) \right].$$  (3)

In this expression $\theta_{\text{sig}}$ are the nuisance parameters that implement the systematic uncertainties affecting the signal efficiency and invariant mass distribution, $\theta_{\text{spur}}$ is the nuisance parameter corresponding to the systematic uncertainty from the choice of background model, and $\theta_{\text{bkg}}$ are the background shape parameters.

Apart from the spurious signal, systematic uncertainties with an estimated size $\delta$ are incorporated into the likelihood by multiplying the relevant parameter of the statistical model by a factor $(1 + \delta \theta)$, or by $e^{\delta \theta}$ when negative values of the corresponding model parameter are not allowed. For all systematic uncertainties the likelihood is then multiplied by a constraint term $G(\theta)$ which is a standard normal distribution for $\theta$, centered at zero.

The significance of the signal is estimated by computing the $p$-value of the compatibility of the data with the background-only hypothesis ($p_0$). A modified frequentist ($CL_s$) method [46] 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 formulae [39] are used to derive the results. Due to the small size of the selected dataset and of the expected background for large values of $m_X$, a few results are checked using ensemble tests. The results obtained using the asymptotic formulae agree with those from the ensemble tests within 1\sigma of the expected distribution of $CL_s$. 

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9. Results

In the data there are 382 $Z(\rightarrow \ell\ell)\gamma$ candidates with invariant mass above 200 GeV and 534 $Z(\rightarrow J)\gamma$ candidates with invariant mass larger than 640 GeV. The candidates with largest invariant mass have $m_{\ell\ell\gamma} = 1.47$ TeV and $m_{J\gamma} = 2.58$ TeV respectively.

The invariant mass distributions of selected $Z\gamma$ 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.

![Graph showing invariant mass distribution](image)

(a) Distribution of the reconstructed $Z\gamma$ invariant mass in events in which the $Z$ boson decays to electrons and muons (a) or to hadrons reconstructed as a single, large-radius jet (b). The solid lines show the results of background-only fits to the data. The residuals of the data points with respect to the fit are also shown.

No significant excess with respect to the background is visible. The observed $p_0$ is shown in Fig. 4, and is compatible with the data being composed of background only, in the hypothesis of a signal with narrow width. The largest deviations from the background hypothesis are found for $m_X = 350$ GeV in the leptonic analysis ($2\sigma$ local significance) and for $m_X = 1.9$ TeV in the hadronic analysis ($1.8\sigma$ local significance).

Observed and expected upper limits on the $pp \rightarrow X$ cross section times $X \rightarrow Z\gamma$ branching ratio are derived at 95% CL, as shown in Fig. 5, for a narrow scalar boson $X$ of mass $m_X$. 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.

Figure 6 shows the observed and expected 95% CL limits for the two analyses overlaid on the same figure for comparison.

Both the $p$-values and the exclusion limits are computed as a function of $m_X$ in fixed steps of 5 GeV (10 GeV) for the leptonic (hadronic) analysis.
Figure 4: Observed $p_0$ (compatibility of the data with the background-only hypothesis) as a function of the mass of a narrow scalar boson decaying to $Z\gamma$, using $Z$ bosons reconstructed in decays to electrons and muons (a) or hadrons (b).

Figure 5: Observed (solid line) and median expected (dashed line) 95% CL upper limits on the product of the production cross section of a narrow scalar boson $X$ times its decay branching ratio to a $Z$ boson and a photon. The $Z$ boson is reconstructed using either (a) $Z \rightarrow \ell\ell$ or (b) $Z \rightarrow q\bar{q}$ decays. The green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals for the expected exclusion limit, respectively.
Figure 6: Observed (solid lines) and median expected (dashed lines) 95% CL limits on the product of the production cross section times the branching ratio for the decay to a $Z$ boson and a photon of a narrow scalar boson $X$, as a function of the boson mass $m_X$. The black lines correspond to the limits set with the $J\gamma$ final state, the blue lines correspond to the limits set with the $\ell\ell\gamma$ final state. The dark green and dark yellow hatched bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals for the expected exclusion limit, respectively, set with the $J\gamma$ final state. The green and yellow solid bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals for the expected exclusion limit, respectively, set with the $\ell\ell\gamma$ final state.

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 with a center-of-mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS detector at the Large Hadron Collider. The $Z$ bosons have been reconstructed either through their decays to charged, light lepton pairs ($e^+e^-$, $\mu^+\mu^-$) or to a boosted quark-antiquark pair giving rise to a single, large-radius jet of hadrons in the detector.

No significant excess in the data in the invariant mass distribution of the final state particles was found over the smoothly falling background from SM processes. The largest deviations from the background-only hypothesis were found for masses of 350 GeV and 1.9 TeV and correspond to a local significance of $2\sigma$ and $1.8\sigma$, respectively, for a narrow boson produced in a gluon fusion process.

Limits at 95% CL using a profile likelihood method have been set on the production cross section times decay branching ratio to $Z\gamma$ 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.
References


[16] E. Bagnaschi et al., 


A. Appendix

A.1. Signal distributions

Figure 7 shows the calibrated jet mass distributions for signal events of masses between 750 GeV and 2.5 TeV.

Figure 7: Comparison of calibrated jet mass distributions for the MC $gg \rightarrow X \rightarrow Z\gamma \rightarrow J\gamma$ signal events, generated for three different $m_X$ hypotheses: $m_X = 750$ GeV (black points), $m_X = 1500$ GeV (red squares), $m_X = 2500$ GeV (green triangles). Events passing the photon and jet kinematic analysis selection criteria are used.

Figure 8 shows the angular separation between the two leptons in MC $gg \rightarrow X \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events for masses $m_X$ between 200 GeV and 2 TeV, before reconstruction.

Figure 9 shows the transverse momentum distributions of photons in MC $X \rightarrow Z\gamma \rightarrow \ell\ell\gamma$ events for masses $m_X$ between 200 GeV and 2 TeV, before reconstruction. The distributions of the transverse momentum divided by $m_{\ell\ell\gamma}$ are also shown.
Figure 8: $\Delta R$ separation at generator-level between the two leptons from the decays of the $Z$ bosons from $X \rightarrow Z \gamma$ in signal samples of with mass $m_X$ between 200 GeV and 2 TeV.
Figure 9: Generator-level distributions of the photon transverse momentum before (a) or after (b) dividing it by the three-body mass $m_{\ell\ell\gamma}$, in $X \rightarrow Z\gamma$ decays.
A.2. Signal efficiency

Figure 10 shows the overall signal efficiency of the leptonic and hadronic selection for simulated $pp \rightarrow X \rightarrow Z\gamma$ events, including the branching ratios of the $Z$ boson decays to $\ell\ell$ (6.7%) and $q\bar{q}$ (70%).

Figure 10: Efficiency as a function of the resonance mass $m_X$ of the lepton selection (filled circles) and of the hadronic selection (open squares), for simulated $X \rightarrow Z\gamma$ events in which the $Z$ bosons decay inclusively. The solid and dashed lines represent an interpolation with a smooth function (of the type $a + be^{c m_X}$) and a linear, piece-wise interpolation of the efficiencies of the leptonic and hadronic selections, respectively.
A.3. Data-MC comparisons

Figures 11 and 12 show a comparison between data and simulation of the calibrated jet mass distributions and the $J\gamma$ invariant mass distributions, respectively. The data is compared to the dominant background from $\gamma$+jet events. In addition, the jet mass distribution for a signal with a mass of 750 GeV is also shown in Fig. 11.

Figure 11: Calibrated jet mass distribution for data events (black points), MC $\gamma$+jet events (red solid histogram) and MC $gg \rightarrow X \rightarrow Z\gamma \rightarrow J\gamma$ signal events with $m_X = 750$ GeV (green hollow histogram), passing the photon and jet kinematic analysis selection criteria. Both the MC $\gamma$+jet and signal yields are normalized to the data for illustration purpose. The shape of the jet mass distribution in data and in the $\gamma$+jet simulation are in good agreement as illustrated by the data/MC ratio plot shown at the bottom of the figure.
Figure 12: $m_{J\gamma}$ distribution in data and in MC $\gamma$+jet for events passing the analysis selection criteria. The MC $\gamma$+jet yield is normalized to the data. The shape of the $m_{J\gamma}$ distribution in data and in $\gamma$+jet MC are in good agreement as illustrated by the data/MC ratio plot shown at the bottom of the figure.
A.4. Additional limit plots

Figure 13 shows the observed and expected 95% CL limits for the two analyses in logarithmic vertical scale.

Figure 13: Observed (solid line) and median expected (dashed line) 95% CL upper limits on the product of the production cross section times the branching ratio for the decay to a Z boson and a photon of a narrow scalar boson $X$. The limits are set as a function of the boson mass $m_X$, using either Z bosons reconstructed in decays to electrons and muons (a) or hadrons (b). The green and yellow bands correspond to the ±1σ and ±2σ intervals for the expected exclusion limit, respectively.
A.5. Event displays

Figures 14–16 show the event display of some interesting ℓℓγ candidates.

Figure 14: Event display of the highest invariant mass μμγ candidate passing the event selection. The transverse momenta of the photon (in green) and of the two muons (in red) are 491, 488, and 48 GeV, respectively. The di-muon invariant mass is 93.9 GeV and the μμγ invariant mass is 1030 GeV. Only inner-detector tracks with $p_T > 1$ GeV and calorimeter cells with energy deposits larger than 250 MeV are shown.
Figure 15: Event display of the highest-invariant mass $e e \gamma$ candidate passing the event selection. The transverse momenta of the photon (green bar) and of the two electrons (blue bars) are 795, 528, and 135 GeV, respectively. The di-electron invariant mass is 91.7 GeV and the $e e \gamma$ invariant mass is 1470 GeV. Only inner-detector tracks with $p_T > 5$ GeV and calorimeter cells with energy deposits larger than 250 MeV are shown.
Figure 16: Event display of the highest-invariant mass $ee\gamma$ candidate passing the event selection (lateral view). The transverse momenta of the photon and of the two electrons are 795, 528, and 135 GeV, respectively. The di-electron invariant mass is 91.7 GeV and the $ee\gamma$ invariant mass is 1470 GeV. Only inner-detector tracks with $p_T > 5$ GeV and calorimeter cells with energy deposits larger than 250 MeV are shown.