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Measurement of the cross-sections of the electroweak and total production of a $Z\gamma$ pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

This Letter presents the measurement of the fiducial and differential cross-sections of the electroweak production of a $Z\gamma$ pair in association with two jets. The analysis uses 140 fb^{-1} of LHC proton–proton collision data taken at $\sqrt{s}$=13 TeV recorded by the ATLAS detector during the years 2015–2018. Events with a Z boson candidate decaying into either an e^+e^- or $\mu^+\mu^-$ pair, a photon and two jets are selected. The electroweak component is extracted by requiring a large dijet invariant mass and by using the information about the centrality of the system and is measured with an observed and expected significance well above five standard deviations. The fiducial $pp \to Z\gamma jj$ cross-section for the electroweak production is measured to be 3.6 ± 0.5 fb. The total fiducial cross-section that also includes contributions where the jets arise from strong interactions is measured to be $16.8^{+2.0}_{-1.8}$ fb. The results are consistent with the Standard Model predictions. Differential cross-sections are also measured using the same events and are compared with parton-shower Monte Carlo simulations. Good agreement is observed between data and predictions.

Contents

1. Introduction

The study of the electroweak (EW) production of two vector bosons associated with two jets is a powerful test of the Standard Model (SM) due to its sensitivity to the gauge-boson self-interactions, related to the non-Abelian structure of the elec-

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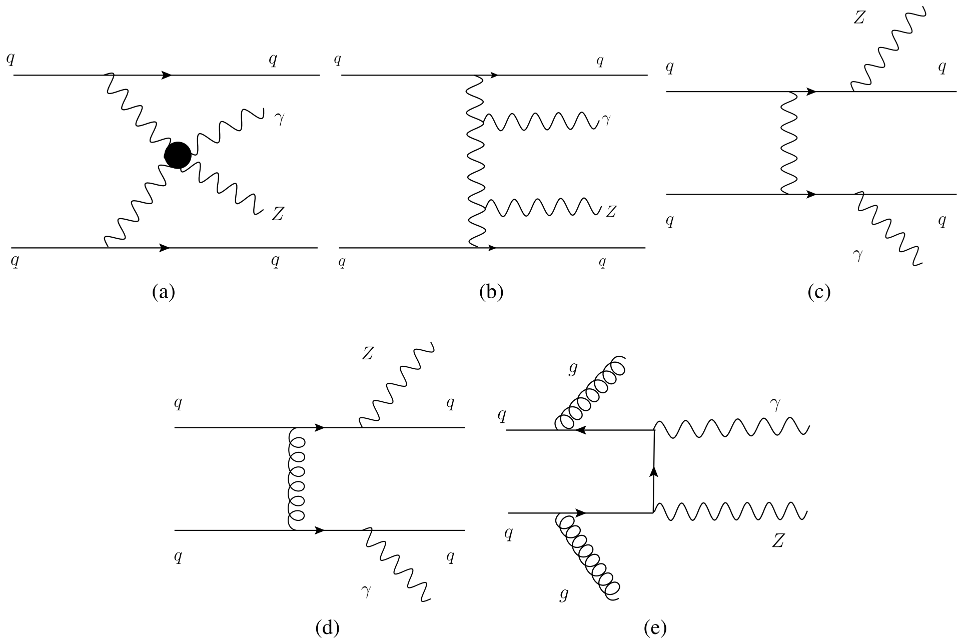


Fig. 1. Representative Feynman diagrams of the processes relevant to this analysis: (a) quartic gauge coupling VBS, (b) triple gauge coupling VBS, (c) electroweak non-VBS, QCD-induced process with (d) gluon exchange or (e) gluon radiation.

troweak interaction. It provides the means to investigate vector-boson scattering (VBS) processes ($VV \to VV$ with $V = W$, Z or γ), which directly probe the electroweak symmetry breaking sector of the SM [1], and to extract constraints on anomalous gauge-boson couplings [2]. Improved constraints probe scales of new physics in the multi-TeV range and provide a way to look for signals of new physics in a model-independent way.

In particular, the study of the EW production of a $Z\gamma$ pair associated with two jets (referred to as $EW - Z\gamma jj$) is interesting because it probes the neutral quartic gauge couplings, as for the ZZ production but with a larger expected cross-section. These couplings are forbidden at the lowest order in the SM. The EW production of the $Z\gamma jj$ final state, shown in the top row of Fig. 1, consists of both VBS processes directly sensitive to triple and quartic gauge couplings, and non-VBS processes, which incorporate other EW contributions.

In the VBS process two jets are typically present, one in the forward direction and the other in the backward direction, while the vector-boson pair is more centrally produced [3]. For such events the scattered quarks are not colour connected and little hadronic activity is expected in the gap between the two jets. This topology allows VBS production to be distinguished statistically from the production of $Z\gamma jj$ final states via mixed EW and quantum chromodynamics (QCD) mechanisms, referred to as $QCD - Z\gamma jj$. The bottom row of Fig. 1 shows examples of some $QCD - Z\gamma jj$ diagrams where the strong interaction acts between the initial quarks, or where the jets arise from the strong interaction. The $Z\gamma jj$ production via EW and QCD mechanisms interfere constructively when the initial and final states are the same, with an interference term at the level of 7%.

Previous experimental results of $EW - Z\gamma jj$ production with the Z decaying into charged leptons were published by the ATLAS and CMS collaborations using data collected at $\sqrt{s}$ = 8 TeV [4,5]. Evidence of the process was reported by both experiments using partial data sets collected at $\sqrt{s}$ = 13 TeV using 36 fb^{-1} [6,7], and the process has been observed by CMS [8] using the full Run 2 data sample. The measurement of the total $Z\gamma jj$ cross-section has been reported recently by ATLAS [9]. The results presented here complement this previous paper by providing a measurement of the total $Z\gamma jj$ cross section in a VBS-like region, which is useful to obtain a detailed characterization of this process in a region sensitive to new physics.

The analysis described here exploits the full data sample collected with the ATLAS detector in Run 2 at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV corresponding to an integrated luminosity of 140 fb^{-1}. This Letter reports the observation by ATLAS of the $EW - Z\gamma jj$ process, where the Z boson decays into either e^+e^- or $\mu^+\mu^-$ pairs, and its fiducial and differential cross-section measurements in several observables: the transverse momentum of the leading lepton (p_{T}^{l}, sensitive to process modelling), the transverse momentum of the jets (p_{T}^{j}), the invariant mass of and absolute rapidity difference between the two leading jets (m_{jj} and $|\Delta y|$, sensitive to the $EW - Z\gamma jj$ and $QCD - Z\gamma jj$ kinematic differences), the transverse momentum of the photon and $Z\gamma$ systems and the absolute azimuthal difference between the $Z\gamma$ system and the two leading jets (E_{T}^{γ}, $p_{\mathrm{T}}^{Z\gamma}$ and $|\Delta\phi(Z\gamma, jj)|$, potentially sensitive to new physics effects).

The fiducial and differential cross-sections that include the $QCD - Z\gamma jj$ contribution are also reported for the same observables, in addition to the Z boson transverse momentum ($p_{\mathrm{T}}^{\mathrm{Z}}$) and the centrality of the $Z\gamma jj$ system ($\zeta(Z\gamma)$, described in Section 4).

The measurement of the EW and total fiducial cross-sections presented in this Letter improves upon the precision of the previous ATLAS result [6] and several variables are measured for the first time differentially in these processes ($p_{\mathrm{T}}^{Z\gamma}$, $|\Delta\phi(Z\gamma, jj)|$, $p_{\mathrm{T}}^{\mathrm{Z}}$ and $\zeta(Z\gamma)$).

The layout of the Letter is as follows: the ATLAS detector is briefly described in Section 2, the data sample and the simulated signal and background Monte Carlo (MC) samples used in the analysis are presented in Section 3, while the event reconstruction and selection are reported in Section 4. The determination of the background and event yields are discussed in Section 5 and the experimental and theoretical uncertainties are presented in Section 6. The procedure to extract the signal and to measure the differential cross-sections are described in Sections 7 and 8. Finally, Section 9 presents the cross-section measurements, and conclusions are drawn in Section 10.

2. ATLAS detector

The ATLAS detector [10] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry[1] and nearly 4π coverage in solid angle. It consists of an inner tracking detector (ID), electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID, surrounded by a thin superconducting solenoid delivering a 2 T magnetic field, provides precision tracking of charged particles and momentum measurements in the pseudorapidity range of $|\eta| < 2.5$. A high-granularity electromagnetic (EM) sampling calorimeter covers the pseudorapidity range of $|\eta| < 3.2$, and a coarser granularity calorimeter up to $|\eta| = 4.9$. The hadronic calorimeter system covers the entire pseudorapidity range up to $|\eta| = 4.9$. The MS consists of three large superconducting toroids each containing eight coils, a system of trigger chambers, and precision tracking chambers, which provide trigger and tracking capabilities in the range $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively. A two-level trigger system [11] is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information. This is followed by the software-based high-level trigger system, which runs offline reconstruction.

An extensive software suite [12] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Simulated event samples

MC simulated samples are used to model the $EW - Z\gamma jj$ signal and a variety of background processes. The signal process was generated at leading-order (LO) accuracy (at order α_{EW}^4, where α_{EW} is the electroweak coupling constant) using MadGraph5_aMC@NLO 2.6.5 [13] with the default dynamical scale choice and the NNPDF3.1 LO parton distribution function (PDF) set [14]. Pythia 8.240 [15] with the 'dipoleRecoil' option turned on, and configured with the A14 set of tuned parameters (tune) [16], was used to add parton-showering, hadronisation and underlying event activity. The signal MC was also interfaced with Herwig ++ 2.7.1 [17,18] for parton showering, hadronisation and underlying event activity. The comparison between the two samples is used to estimate the uncertainties due to the choice of the parton showering and underlying event models.

The dominant background in the cross-section measurement of the EW production of $Z\gamma jj$ events is represented by the $QCD - Z\gamma jj$ process. Two sets of MC samples are used to model this final state. The nominal sample was produced with Sherpa 2.2.11 [19,20], where matrix elements were calculated with up to one additional parton at next-to-leading order (NLO) and up to three additional partons at LO. The matrix element calculation included all diagrams at order α_{EW}^2. The virtual QCD corrections for matrix elements at NLO accuracy were provided by the OpenLoops library [21]. The merging of the matrix element and parton shower (PS) was performed with MEPS@NLO [22,23]. The NNPDF3.0 next-to-next-to-leading-order (NNLO) PDF was used in conjunction with a dedicated PS tuning developed by the Sherpa authors. An alternative sample was produced with MadGraph5_aMC@NLO 2.3.3 and used for cross checks. This sample has the default dynamical scale using the NNPDF3.0 NLO PDF set. The matrix element calculation in this sample includes all diagrams at order α_{EW}^2 and the emission of up to two extra final-state partons, where up to one additional final-state parton is at NLO.

Additionally, for the evaluation of the theoretical uncertainty, a set of four samples was generated at particle level using Sherpa 2.2.11 with the NNPDF3.0 NNLO PDF set, as well all other generation parameters being the same as the nominal Sherpa 2.2.11 sample, in order to provide results with alternative merging and resummation scales. Two samples were produced with merging scale variations (QCUT=15 GeV and QCUT=30 GeV) and two samples with resummation scale factors (QSF=0.25 and QSF=4).[2]

Interference between the EW and QCD processes was estimated at LO accuracy using the MadGraph5_aMC@NLO 2.3.3 MC event generator with the NNPDF3.0 LO PDF set including contributions to the sum of the amplitudes of the matrix element squared at order $\alpha_S \alpha_{EW}^3$. These interference effects are found to be positive and about 7% of the $EW - Z\gamma jj$ cross-section in the fiducial phase space studied. This effect is included as a systematic uncertainty in the signal prediction.

In all samples described above, photon isolation criteria were imposed at parton level making use of the smooth-cone isolation prescription introduced in Ref. [24]. This procedure removes contributions in which the photon is produced from quark or gluon fragmentation in an infrared safe way to all orders of perturbation theory. The chosen isolation parameters are $\delta_0 = 0.1$, $\epsilon = 0.1$ and $n = 2$.

The second-largest background, arising from the Z+jets process with one of the jets misidentified as a photon, is estimated with a data-driven method. A MC sample is only used to estimate a correlation factor between different control regions as explained in Section 5. This sample was produced with Powheg Box v1 [25–27] at NLO accuracy with the CT10 [28] NLO PDF set, interfaced to Pythia 8.210 [15] with the AZNLO tune [29].

The third-largest background, arising from the $t\bar{t}\gamma$ process was generated at LO accuracy with MadGraph5_aMC@NLO using the NNPDF 2.3 LO PDF set [30] and was interfaced to the Pythia 8.212 generator, configured with the A14 tune [16]. An NLO factor of 1.44 was applied, based on the value found in an analysis of $t\bar{t}\gamma$ production at $\sqrt{s} = 13$ TeV by the ATLAS Collaboration [31], which normalizes the LO prediction from this MC sample to an NLO calculation in the fiducial phase-space region used in the $t\bar{t}\gamma$ analysis in the dilepton channel. The predicted contribution from this background is validated using an $e\mu\gamma$ control region as explained in Section 5.

All other backgrounds are smaller and are estimated with MC simulation. The background process $QCD - WZ(l\nu ll)$ was generated with Sherpa 2.2.2 at NLO with up to one additional parton, using the NNPDF3.0 NNLO PDF set. The $EW - WZ(l\nu ll)jj$ background was generated with MadGraph5_aMC@NLO 2.6.2 at LO accuracy, using the NNPDF3.0 LO PDF set and interfaced to Pythia 8.235. The $WW\gamma$ background is only considered in the $e\mu\gamma$ control region study and was generated with Sherpa 2.2.5 at NLO, using the NNPDF3.0 NNLO PDF set.

The simulated samples are overlaid with additional proton-proton interactions (pile-up) generated with Pythia 8.186 using the A3 tune [32] and the NNPDF2.3LO PDF set [30]. MC events are reweighted to better reproduce the distribution of the mean number of interactions per bunch crossing observed in data. All generated events were passed through the ATLAS detector simulation [33] based on Geant4 [34] and processed using the same

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam direction. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

[2] QCUT indicates the scale for the calculation of the overlap between jets from the matrix element and the parton shower and is nominally 20 GeV, and QSF represents the scale used for the resummation of the soft gluon emissions and is nominally 1.

reconstruction software as for data. Scale factors are applied to the simulated events to correct for small differences between them and data in the trigger, reconstruction, identification and isolation efficiencies for photons, electrons and muons. Furthermore, in simulated events electron, photon and jet energy and the muon momentum are smeared to account for the small differences in resolution between data and simulation.

4. Event reconstruction and selection

The data were collected between 2015 and 2018 during proton–proton collisions at $\sqrt{s}$ = 13 TeV. The integrated luminosity of the sample used for the analysis is 140 fb^{-1}. The sample only includes data recorded with stable beam conditions and with all relevant subdetector systems operational [35].

Events were selected using unprescaled single lepton and dilepton triggers [36,37] with transverse momentum (p_T) thresholds that depended on the lepton flavour and running period. In 2015 a single-electron or muon trigger, with p_T above 24 and 20 GeV respectively, was required while in the following years these thresholds were set to 26 GeV for both flavours of leptons. Additional single-lepton triggers with higher p_T thresholds but with looser identification criteria were also used to increase the total data-taking efficiency. Events with a pair of electron candidates with $p_T > 12$ GeV, or a pair of muon candidates satisfying $p_T > 18$ GeV and $p_T > 8$ GeV for the leading and subleading muons, were also selected at trigger level in 2015. In the following years these dilepton trigger thresholds were increased up to 24 GeV for the dielectron case and 22 (8) GeV for the leading (subleading) muon for the dimuon case. The trigger efficiency for events satisfying all the selection criteria described below is about 99%.

Events are required to have at least one collision vertex reconstructed from at least two tracks, where the tracks must have a p_T larger than 500 MeV. The hard-interaction vertex of the event is chosen as the one with the largest value of the sum of the squared transverse momentum of the associated tracks.

Electron candidates, reconstructed from topological clusters of energy deposited in the EM calorimeter that are matched to an ID track, are required to satisfy the medium likelihood identification criterion of Ref. [38]. This is based on a combination of shower shape information from the EM calorimeter and tracking information from the ID. Electron candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.47$ but excluding the transition region between the barrel and endcap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$). The overall efficiency of the electron reconstruction and identification is about 80% for electrons with $p_T \approx 20$ GeV and increases with p_T.

Muon candidates, reconstructed by matching tracks in the ID with tracks in the MS, are required to satisfy the medium identification criterion of Ref. [39]. This includes requirements on the number of hits matched to the tracks reconstructed in the ID and in the MS, and on the probability that the ID and MS momentum measurements are compatible. Muon candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. The overall efficiency of the muon reconstruction and identification is above 97% with no strong dependence on p_T.

Electron and muon candidates are required to originate from the primary vertex. The significance of the transverse impact parameter, defined as the absolute value of the track transverse impact parameter, $|d_0|$, measured relative to the hard-interaction vertex and divided by its uncertainty, is required to be less than five for electrons and less than three for muons. Furthermore, for both electrons and muons the difference Δz_0 between the value of the z coordinate of the point on the track at which d_0 is defined, and the z position of the primary vertex, is required to satisfy $|\Delta z_0 \cdot \sin\theta| < 0.5$ mm (where θ is the track polar angle).

Photon candidates are reconstructed and identified using algorithms based on the expected shapes of showers developing in the electromagnetic calorimeter [38]. Both converted and unconverted candidates[3] are retained. Photon candidates are selected if they are reconstructed within the fiducial volume of the central calorimeter ($|\eta| < 2.37$) and outside the transition region between the barrel and endcap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$).

Photon, electron and muon candidates are required to be isolated from other particles. In all cases, the isolation criteria are based on the sum, p_T^{iso}, of the scalar transverse momenta of tracks with $p_T > 1$ GeV, and on the sum, E_T^{iso}, of the transverse energy of topological clusters, within cones of size ΔR around the photon or lepton candidates, excluding the contribution of the candidates themselves. The calorimeter isolation is also corrected on an event-by-event basis for the contribution from the underlying event and pile-up. Electron candidates are required to satisfy the *FCLoose* isolation criteria of Ref. [38] with a cone of size $\Delta R = 0.2$. The efficiency of the isolation criteria is greater than 95% for electrons with $p_T > 20$ GeV. Muon candidates are required to satisfy the *PflowLoose_FixedRad* isolation criteria of Ref. [39] with a cone of size $\Delta R = 0.2$. The efficiency of the isolation criteria is greater than 90% for muons with $p_T > 20$ GeV.

Photon candidates are required to satisfy the *FixedCutLoose* isolation criteria of Ref. [38]. The photon isolation criterion employs a cone of size $\Delta R = 0.2$ for both the track and calorimeter isolation, and requires $p_T^{iso}/E_T^{\gamma} < 0.05$ and $E_T^{iso}/E_T^{\gamma} < 0.065$, where E_T^{γ} is the photon transverse energy.

At least one isolated photon, satisfying tight identification requirements is required. The efficiency of the tight photon identification criterion, for isolated photons, ranges from 80−85% for photons of transverse energy $E_T^{\gamma} \approx 25$ GeV depending on the pseudorapidity region of the detector and on the conversion status of the candidate.

Jets are clustered using the anti-k_t algorithm [40,41] with a radius parameter of $R = 0.4$. The inputs to the algorithm are obtained with a particle flow procedure using topological clusters in the calorimeter and reconstructed tracks [42].

Jets are calibrated and corrected for detector effects using a combination of simulated events and in situ methods. Jet candidates are required to have $p_T > 25$ GeV and rapidity $|y| < 4.4$. Jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are required to be consistent with originating from the primary vertex using the tight working point of the jet vertex tagging algorithm of Ref. [43].

A procedure to remove ambiguities in the particle reconstruction is applied: jet candidates are removed if they overlap with electron or photon candidates, i.e. $\Delta R(j,e) < 0.2$ or $\Delta R(j,\gamma) < 0.4$, then leptons are removed if they are close to a jet candidate, i.e. $\Delta R(\ell, j) < 0.4$ (ℓ = e, μ), photons are removed if they are close to a lepton candidate, i.e. $\Delta R(\gamma,\ell) < 0.4$ and finally electron candidates are removed if they overlap with muon candidates i.e. $\Delta R(\mu, e) < 0.2$.

Events are required to have exactly two leptons of same flavour and opposite charge, at least one photon and at least two jets. One of the electrons or muons in the lepton pair must be matched to the electron or muon that triggered the event. Events are further selected by requiring that the leading lepton has $p_T > 30$ GeV and that the leading photon has $p_T > 25$ GeV and satisfies isolation and tight identification requirements. To remove contributions from low-mass resonances, the invariant mass $m(\ell\ell)$ of the opposite-charge, same-flavour lepton pair must be larger than 40 GeV.

[3] For the converted candidates, the photon cluster is matched to a reconstructed conversion vertex formed either from two oppositely charged-particle tracks or from a single track consistent with having originated from a photon conversion. For the unconverted photons the photon cluster is matched to neither a conversion vertex nor an electron track.

To suppress events originating from leptonic Z decays where one of the leptons has radiated a photon, the sum of $m_{\ell\ell}$ and the invariant mass of the $\ell^+\ell^-\gamma$ system, $m_{\ell^+\ell^-\gamma}$, formed from the lepton pair and the highest-E_T^γ photon candidate, must be larger than 182 GeV, approximately twice the mass of the Z boson, as adopted in previous publications [4,6].

Furthermore, to enhance the VBS topology, events must have at least two jets with p_T^j above 50 GeV and a rapidity difference between them, $|\Delta y| > 1$. The invariant mass of this pair of jets, m_{jj}, is required to be larger than 150 GeV for the total $Z\gamma jj$ process measurements, and larger than 500 GeV for the $Z\gamma jj$ EW process measurements. This selection significantly reduces the number of events with three bosons in the final state in first case, and the number of QCD $Z\gamma jj$ background events in the second case. Events containing b-tagged jets are rejected. The b-tagging algorithm provides a working point with a 70% selection efficiency for b-jets in an inclusive $t\bar{t}$ MC sample and rejection factors of ≈ 10 and 400 for charm- and light-flavour jets, respectively [44]. The two highest-p_T jets satisfying these conditions are referred to as VBS tagged jets. Events with additional jets of transverse momentum above 25 GeV in the rapidity gap between the two VBS tagged jets are rejected. The centrality of the $\ell^+\ell^-\gamma$ system relative to the VBS tagged jets (j_1 and j_2) defined as

$$\zeta(Z\gamma) = \left| \frac{y_{Z\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|, \quad (1)$$

where y indicates the rapidity, is required to be less than 5.

For the EW $Z\gamma jj$ signal extraction, within the $m_{jj} > 500$ GeV region, the selected events are further split into a signal region (SR, $\zeta(Z\gamma) < 0.4$) and a QCD control region (CR, $\zeta(Z\gamma) > 0.4$) as explained in Section 7. For the measurements of the full $Z\gamma jj$ process, within the relaxed $m_{jj} > 150$ GeV region, only the region $\zeta(Z\gamma) < 0.4$ is used, referred to as 'Extended SR'. This variable has been chosen to build the signal and control regions because it has been found to be almost uncorrelated with m_{jj}.

The observed total number of events in the $m_{jj} > 500$ GeV SR and CR is 562 and 274 respectively. In the $m_{jj} > 150$ GeV Extended SR phase space, the observed total number of events is 1461.

5. Background estimation

The main source of background in the cross-section measurement of the EW production of $Z\gamma jj$ final states consists of $Z\gamma jj$ events from QCD-induced processes. The shape of this background is estimated from simulation and the normalisation is determined simultaneously with the signal strength via a maximum-likelihood fit to the m_{jj} data distribution in the SR and CR that are defined in Section 4. A $QCD - Z\gamma jj$ normalisation parameter, together with the signal normalisation is extracted and the CR is used to constrain the systematic uncertainties in both $QCD{-}Z\gamma jj$ and $EW - Z\gamma jj$ processes. The fit procedure is described in Section 7.

The second-largest background (and largest background for the total $Z\gamma jj$ cross-section measurements) arises from the Z+jets process with a jet misidentified as a photon and is referred to as non-prompt photon background. This contribution is estimated in data separately in the SR, Extended SR and CR using a two-dimensional sideband method [45] similar to that applied in the previous analyses [4,6] and includes the background deriving from both EW and QCD Z+jets induced processes. In this procedure the selection criteria that define the SR, Extended SR and CR are applied to data except for the photon identification and calorimeter isolation requirements. Photon candidates are split into those that satisfy the tight ID requirements and those that do not. The candidates that fail to satisfy the tight identification requirements are required to satisfy a non-tight selection criterion that removes requirements on four of the nine EM calorimeter shower shape variables required for tight photons. These two samples are further split according to whether the photon satisfies the calorimeter isolation criteria or not. A prompt photon region and three control regions are then defined using this method. The number of Z+jets events in SR, CR and Extended SR is obtained from the number of events in the three control regions by assuming that the ratio of non-prompt isolated and non-isolated photon candidates is the same for tightly identified photons and for photons failing to satisfy the tight identification criteria. The small residual correlation between the two variables and the leakage of prompt photon candidates into the non-prompt photon region are estimated from simulation. The correlation is also estimated in data using a control region where the photon fails track isolation and the difference between the MC and data results are included in the systematic uncertainty (Section 6). The shape of this background is obtained from both control regions where the photon candidate fails to satisfy the tight identification criteria. Comparisons with different control regions show that this choice does not introduce any bias to the shape of the distributions.

Table 1
Summary of the observed number of events after the fit in EW signal ($N_{EW-Z\gamma jj}$), QCD $Z\gamma jj$ ($N_{QCD-Z\gamma jj}$), $Z\gamma jj$ ($N_{Z\gamma jj}$), in background ($N_{Z+\text{jets}}$, $N_{t\bar{t}\gamma}$, N_{WZjj}), and in data (N_{obs}). The quoted uncertainty corresponds to the post-fit statistical and systematic uncertainties and includes the covariance. The individual uncertainties can be correlated and do not necessarily add in quadrature to equal the total uncertainty.

Sample	Ext. SR, $m_{jj} > 150$ GeV	SR, $m_{jj} > 500$ GeV	CR, $m_{jj} > 500$ GeV
$N_{\text{EW}-Z\gamma\text{jj}}$		269 ± 27	25 ± 6
$N_{\text{QCD}-Z\gamma\text{jj}}$		245 ± 21	224 ± 18
$N_{Z\gamma\text{jj}}$	1292 ± 50		
$N_{Z+\text{jets}}$	78 ± 30	21 ± 8	16 ± 5
$N_{t\bar{t}\gamma}$	73 ± 11	16 ± 2	8 ± 1
N_{WZ}	17 ± 3	9 ± 2	4 ± 1
Total	1461 ± 38	560 ± 23	277 ± 17
N_{obs}	1461	562	274

The third-largest background arises from the $t\bar{t}\gamma$ process. It is estimated from simulation and checked by comparing predictions with data using an $e\mu\gamma$ data sample where the same selections are applied as those that define the SR, Extended SR and CR, except that a different-flavour lepton pair is chosen instead of a same-flavour pair. The very small number of non-$t\bar{t}\gamma$ events in this sample is estimated either from simulated events, for events with a prompt photon, or with the procedure described above for events with a jet misidentified as a photon. Predictions are compared with data in the control regions $e\mu\gamma$_SR, $e\mu\gamma$_Extended_SR and $e\mu\gamma$_CR, before or after requiring that the events have at least one b-jet. In both cases it is found that predictions must be scaled by a factor of 1.44± 0.22 (i.e., an uncertainty of ± 15%) to describe the data well, in agreement with previous studies [31].

The background contribution due to $WZjj$ events is minor and is evaluated from simulation while the contribution from other processes is found to be negligible. In the SR, it is estimated that 48% of the events come from $EW - Z\gamma jj$ and 44% from $QCD - Z\gamma jj$, compared to 9% and 81% for $EW - Z\gamma jj$ and $QCD - Z\gamma jj$ in the CR, respectively. In the Extended SR, it is estimated that 88% of events come from $Z\gamma jj$.

The yields of the different sources of background, after the fit to extract the signal is performed, are shown in Table 1.

6. Systematic uncertainties

The overall uncertainties in the differential cross-section measurements are dominated by the statistical uncertainty in the data, and the inclusive cross-section measurement uncertainties are shared equally between the statistical and systematic uncertainties.

Systematic uncertainties that affect the acceptance and the shape of the m_{jj} distribution for the fiducial cross-section measurement and of the other observables for the differential cross-section measurements for both signal and backgrounds are considered. The $EW-Z\gamma jj$ and $QCD-Z\gamma jj$ normalisations are extracted from a likelihood fit. Systematic uncertainties in the shapes and normalisation of distributions are only considered if they are found to make an impact on the result, which is translated into a threshold for only considering the uncertainties that are larger than 0.5% for all measurements except for the $EW-Z\gamma jj$ differential cross-section for which the threshold is 1%, due to larger statistical uncertainties in this measurement. Uncertainties that are smaller than these thresholds are found to make no difference to the results when added to the fit.

The experimental systematic uncertainties that are accounted for in the analysis include uncertainties in the energy scale and resolution of jets, photons and electrons, in the scale and resolution of the muon momentum and uncertainties in the scale factors applied to simulation to reproduce the trigger, reconstruction, identification, and isolation efficiencies measured in data. Uncertainties due to the suppression of pile-up jets and to the b-jet veto are also considered.

The largest of these experimental uncertainties, in all cross-section measurements, are related to the jet energy calibration and response, and are at the level of 3% in most of the measured bins, but can reach 7% in highest bin of the m_{jj} differential measurement. The dominant uncertainties associated with photons are due to the identification and isolation efficiencies [46], which are both about 1% with a negligible dependence on m_{jj}, but can reach 3% in the highest bin of p_T^{γ} differential cross-section measurement. Uncertainties in the lepton reconstruction, identification, isolation, trigger efficiency, energy/momentum scale and resolution are determined using $Z\rightarrow\ell\ell$ events [38,39,47]. The dominant contribution comes from the electron identification efficiency, which is about 1% with a negligible dependence on m_{jj}, but can reach about 4% in the highest bin of the p_T^{l} differential measurement. The uncertainty associated with the pile-up modelling depends on m_{jj} and is 2% on average. The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [48], obtained using van der Meer beam separation scans during dedicated running periods.

The overall uncertainty related to the background estimation is the second largest experimental uncertainty in the cross-section measurements, at the level of 1-2% depending on the variable or process measured. A 35% uncertainty on the normalisation of the Z+jets background is used.

It is extracted along with the data-driven procedure described in Section 5 and it accounts for the uncertainty in the number of events in the two-dimensional sideband method used to estimate this background (statistical component). It also includes the uncertainty related to the estimate of the correlation between the photon identification and isolation requirements and to the leakage of the prompt photons into the non-prompt regions. The statistical component dominates. The uncertainty derived from the evaluation of the shape of the Z+jets background in different observables is found to be negligible. A 15% and a 20% yield uncertainty, derived from the data-driven normalisation correction (see Section 5) and from QCD scales and PDF variations, is assigned to the estimate of the normalisation of the $t\bar{t}\gamma$ and $W^{\pm}Z\rightarrow lll\nu$ backgrounds, respectively. Other sources of background, including one due to the superposition of pile-up events, are found to be negligible and therefore the related uncertainties are neglected.

The main theoretical uncertainties that are considered in the analysis are related to the scale and PDF set choices in the MC generation of the signal and the $QCD-Z\gamma jj$ background. The effect of missing higher orders is estimated by changing the default values of the renormalisation and factorisation scales, μ_R and μ_F, by a factor of 0.5 and 2.0 with the constraint that the ratio $0.5\le\mu_R/\mu_F\le 2$. The maximal change in the shape of distributions from these variations is taken as the associated uncertainty. This procedure is performed for the $EW-Z\gamma jj$ and $QCD-Z\gamma jj$ processes using the nominal MadGraph5_aMC@NLO and Sherpa 2.2.11 samples, respectively. The uncertainties due to the choice of PDF in the shape of distributions for the $EW-Z\gamma jj$ and $QCD-Z\gamma jj$ processes are evaluated using the eigenvalues of the PDF set following the PDF4LHC prescription [49]. To account for the uncertainties related to the modelling of $QCD-Z\gamma jj$, the impact of the merging and resummation scale is derived using the five Sherpa 2.2.11 samples with different QCUT and QSF scales as described in Section 3. Signal uncertainties due to the choice of the parton showering and the underlying event model are estimated by interfacing the signal MC to either Pythia or Herwig and the five up and down eigenvariations of the A14 tune. The parton shower uncertainty from taking the difference between Herwig and Pythia is dominant and has a strong shape component. Parton shower and underlying event uncertainties are uncorrelated. The underlying event uncertainty is obtained by taking the envelope of the maximum variations bin by bin.

The interference between the EW signal and the $QCD-Z\gamma jj$ background is not included as part of the EW signal in the fit that extracts the EW signal. Instead this contribution is directly computed with MadGraph5_aMC@NLO and the size and shape of the interference contribution is taken as an extra template uncertainty on the signal. The overall size effect is 7% in the phase space dedicated to the signal measurement and the shape varies depending on the variable studied, with typically larger interference effect where the $QCD-Z\gamma jj$ background dominates. Another source of uncertainty arises from the finite size of the MC (at the level of 1%) and the data samples (ranging from 9% to 22% depending on the measurement, variable and bin considered).

The implementation of these uncertainties in the various measurements performed are described in Sections 7 and 8 and their final impact on the measurements is discussed in Section 9. Table 3 provides a breakdown of the uncertainties in the final measurement.

7. Signal extraction procedure

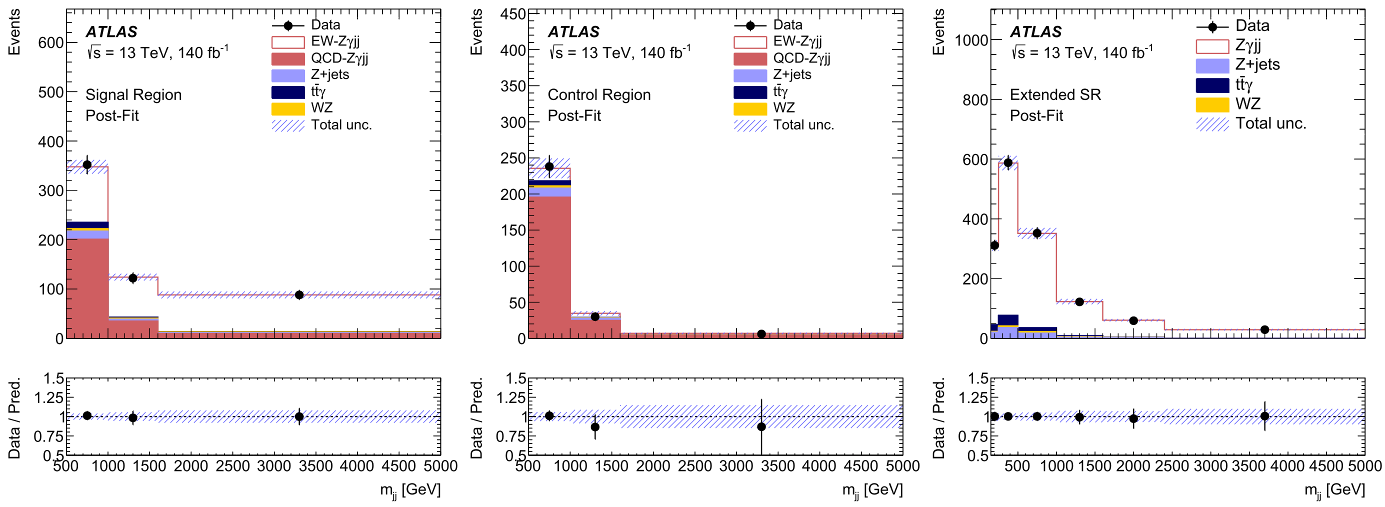
To extract the $EW-Z\gamma jj$ cross-section, the signal strength parameter defined as

$$\mu_{EW}=\sigma^{EW}_{meas}/\sigma^{EW}_{exp} \quad (2)$$

is introduced in both the SR and CR, and obtained with a maximum-likelihood fit simultaneously to the data m_{jj} distributions in both regions using template MC distributions. In Eq. (2) the numerator indicates the measured $EW-Z\gamma jj$ cross-section and the denominator is the expected $EW-Z\gamma jj$ cross-section. An unconstrained normalisation parameter is introduced in the SR and CR for the $QCD-Z\gamma jj$ contribution and is extracted simultaneously with μ_{EW}.

The significance of observing the $EW-Z\gamma jj$ process is estimated by using a profile likelihood ratio of the background only hypothesis ($\mu_{EW}=0$) and the best fit result ($\mu_{EW}=\hat{\mu}$) [50]. The $EW-Z\gamma jj$ cross-section is obtained from the signal strength by multiplying it by the MC cross-section prediction in the SR region defined at particle level.

The extraction of the full $Z\gamma jj$ cross-section is performed in a very similar manner, adding together the relative fractions of the $EW-Z\gamma jj$ and $QCD-Z\gamma jj$ m_{jj} templates, as predicted from MC, and defining the signal strength $\mu_{Z\gamma}$ as parameter of interest of the fit. No CR is used in this fit, and a wider region (with



(a) (b) (c)

Fig. 2. Post-fit m_{jj} distributions in (a) the $m_{jj} > 500$ GeV SR (b) the $m_{jj} > 500$ GeV CR and (c) the $m_{jj} > 150$ GeV Extended SR. The uncertainty band around the expectation includes all systematic uncertainties (including MC statistical uncertainty) and takes into account their correlations as obtained from the fit. The error bar around the data points represents the data statistical uncertainty. Events beyond the upper limit of the histogram are included in the last bin.

$m_{jj} > 150$ GeV, the Extended SR) is used. The $Z\gamma jj$ cross-section is obtained by multiplying the signal strength by the MC cross-section prediction in the Extended SR defined at particle level.

In these two measurements, the electron and muon channels are combined directly in the input histograms, by summing the two contributions, such that a single template is used. Probability density functions are built for the m_{jj} templates in the SR, Extended SR and CR based on a Poisson distribution and are combined in an extended likelihood. Each source of uncertainty is implemented in these functions as a nuisance parameter of the likelihood fit with a Gaussian constraint, except for the MC statistical uncertainty that is implemented with a Poisson constraint.

The uncertainties from the Z+jets, WZ and $t\bar{t}\gamma$ backgrounds are treated as correlated between regions. All systematic uncertainties except for the theoretical ones are correlated between processes and between the two regions. The PDF and scale uncertainties are not correlated between processes, and for the $EW-Z\gamma jj$ process they are also not correlated between regions. Choosing a different correlation scheme does not change the result. The normalisation part of PDF and scale uncertainties are subtracted to consider only acceptance effects on the signal. The interference, parton shower and underlying event uncertainties in the $EW-Z\gamma jj$ contribution are also not correlated between regions. The merging and resummation scale uncertainties in the $QCD-Z\gamma jj$ contribution are correlated between regions.

For the $EW-Z\gamma jj$ measurement, the difference in the predicted m_{jj} shape between two different $QCD-Z\gamma jj$ MCs is the same in the SR and CR within modelling uncertainties; therefore, the m_{jj} shape in the CR is used to validate the m_{jj} shape of the $QCD-Z\gamma jj$ background in the SR, and to constrain the correlated systematic uncertainties.

Table 1 shows the observed total number of events and expected number of signal and background events in the SR, Extended SR and CR, after the fit is performed. The post-fit m_{jj} distributions are displayed in Fig. 2.

8. Differential cross-sections

The procedure to extract the $EW-Z\gamma jj$ and the $Z\gamma jj$ differential cross-sections of the variables discussed in Section 1 is explained below.

Table 2
Summary of selection criteria applied at particle level.

Lepton	$p_T^{\ell} > 20, 30$(leading) GeV, $\lvert\eta_\ell\rvert < 2.5$
	$N_\ell \geq 2$
Photon	$E_T^{\gamma} > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$
	$E_T^{\text{cone20}} < 0.07 E_T^{\gamma}$
	$\Delta R(\ell, \gamma) > 0.4$
Jet	$p_T^{j} > 50$ GeV, $\lvert y_j\rvert < 4.4$
	$\lvert\Delta y\rvert > 1.0$
	$m_{jj} > 150$ GeV or $m_{jj} > 500$ GeV
	Remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV
	$m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV
	$\zeta(Z\gamma) < 0.4$
	$N_{\text{jets}}^{\text{gap}} = 0$

8.1. Phase space definition

To define the phase space of the measurement, selection criteria, which closely mimic the detector-level selection are applied at particle level to the simulated signal. This selection is shown in Table 2.

Only particles with a mean lifetime $c\tau > 10$ mm (referred to as stable particles) are considered. Only photons and leptons that do not originate from the decay of hadrons (or, for the leptons, from τ-lepton decays) are selected. They are referred to as prompt photons and leptons, respectively. Contributions from photons within $\Delta R = 0.1$ of a lepton are summed together to correct the lepton's four-momentum, a procedure known as 'dressing'.

At least one isolated photon with transverse momentum $p_T > 25$ GeV and $\lvert\eta\rvert < 2.37$ is required. The photon isolation requires that the scalar sum of p_T for all stable particles (except neutrinos, muons and the photon itself) within a cone of radius $\Delta R = 0.2$ around the photon, E_T^{cone20} is less than 7% of the photon p_T. This criterion is found to be closest to the detector level isolation criteria used in the analysis.

The angular distance between the highest p_T photon and each of the two charged leptons selected is required to be $\Delta R > 0.4$.

Jets are reconstructed using the anti-k_t algorithm with radius parameter $R = 0.4$ using stable particles, excluding neutrinos and prompt electrons, muons and photons. Jets are considered if their angular distance relative to each of the two charged leptons selected above is $\Delta R(j,\ell) > 0.3$ and if the angular distance relative to the highest p_{T} isolated photon is $\Delta R(j,\gamma) > 0.4$.

The rejection of events containing b-tagged jets as described in Section 4 is not applied in the fiducial phase space. Applying this selection would reduce the predicted $EW - Z\gamma jj$ fiducial cross-section by less than 1% in both SR and CR, and the predicted $QCD - Z\gamma jj$ fiducial cross-section event yield by about 7% in the Extended SR, with no kinematic dependence within the uncertainties of the measurements. The assumption is made that the simulation is correctly extrapolating from reconstructed to fiducial phase space.

8.2. Unfolding procedure

To obtain the $EW - Z\gamma jj$ and the $Z\gamma jj$ cross-sections at particle level in the fiducial volume discussed above, an unfolding procedure is performed to correct for detector effects (signal efficiency and acceptance effects). The unfolding procedure is the same as described in Refs. [51,52] and based on a profile-likelihood approach.

The procedure is applied to the observed number of data events per bin i N_i^{reco} in the SR and Extended SR, and is related to the number of events at fiducial level in bin j N_j^{fid} by:

$$N_i^{\mathrm{reco}} = \frac{1}{A_i}\sum_j e_j M_{ij} N_j^{\mathrm{fid}} \quad (3)$$

where M_{ij} is the migration matrix (where each entry represents the normalised fraction of events at particle level in a bin j that are reconstructed at detector level in a bin i), A_i the acceptance correction (fraction of detector-level events that are found both in the fiducial volume and in the detector-level selection) and e_j the efficiency correction (fraction of events that are in the fiducial volume that are found both in the fiducial volume and in the detector-level selection). For the $Z\gamma jj$ measurement, the migration matrix is built after having summed the EW and QCD contributions.

In this procedure, the particle-level bins j are treated as separate subsamples that are multiplied by their respective entries in the response matrix and freely floating parameters (μ^j_{EW} or $\mu^j_{Z\gamma}$, the signal strengths defined in Section 7 applied in bin j) are assigned to each of these subsamples at detector level. In the $EW - Z\gamma jj$ unfolding, the CR is fitted simultaneously with the SR to extract the $QCD - Z\gamma jj$ bin by bin correction, together with μ^j_{EW}. In this measurement, since the signal contamination is smaller than 1% in the CR, an approximation is made whereby the signal is treated as an additional background, and no response matrix for the signal is built in the CR. Each bin in the particle-level distribution is then 'folded' through the migration matrix via Eq. (3) to the same number of bins at detector level. In the unfolding procedure, no regularisation is applied.

For the $EW - Z\gamma jj$ unfolding, the fraction of events in the diagonal elements of the migration matrix ranges between 80% ($|\Delta\phi(Z\gamma, jj)|$) and 99% ($E_T^{\gamma}$, $p_T^{Z\gamma}$, p_T^{l}, $|\Delta y|$). The acceptance corrections are on average around 89% improving as the variable increases, for all variables except $|\Delta y|$ for which there is no obvious dependence. The efficiency corrections are at a level of 47% on average, and show similar trends as observed for the acceptance corrections.

For the $Z\gamma jj$ unfolding, the fraction of events in the diagonal elements of the migration matrix ranges between 82% ($|\Delta\phi(Z\gamma, jj)|$) and 98% ($|\Delta y|$ and p_T^{γ}). The acceptance corrections are on average around 76% improving as the variable increases, for all variables except $|\Delta y|$ and $\zeta(Z\gamma)$ for which there is no obvious dependence. The efficiency corrections are at a level of 40% on average, and show similar trends as observed for the acceptance corrections.

The systematic uncertainties considered for the unfolded results are the same as for the results at detector level (see Section 6) and are calculated via the migration matrices. Several checks are performed to verify the robustness of the procedure: an injection test with non-SM cross-section values to check if this can be recovered in the unfolding procedure, the use of alternative MC predictions for the $QCD - Z\gamma jj$ process and data-driven reweighting of the MC templates using the same observables or alternative ones. None of these checks show any noticeable effect on the unfolding results, and thus no additional uncertainty is assigned to the unfolding procedure.

9. Results

The $EW - Z\gamma jj$ measured signal strength is

$$\mu_{\mathrm{EW}} = 1.02 \pm 0.09\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}) = 1.02^{+0.13}_{-0.12}.$$

There is a clear observation of the signal, with a background-only hypothesis rejected with a significance well above 5 standard deviations. The normalisation parameter of the $QCD - Z\gamma jj$ background, constrained by data in the SR and CR is measured to be 1.18 ± 0.10.

The fiducial cross-section for the electroweak $pp \to Z\gamma jj$ process in the phase space defined in Section 8 is obtained by computing the product of the signal strength and the predicted cross-section. The result is:

$$\sigma_{\mathrm{EW}} = 3.6 \pm 0.5\ \mathrm{fb}$$

to be compared with he predicted value from MadGraph5_aMC@NLO 2.6.5 (interfaced with Pythia) (see Section 3), which gives:

$$\sigma^{pred}_{\mathrm{EW}} = 3.5 \pm 0.2\ \mathrm{fb}.$$

The PDF and scale theoretical uncertainties in the prediction are evaluated using the procedure described in Section 6.

The breakdown of the systematic uncertainties in the $EW - Z\gamma jj$ cross-section is shown in Table 3.

The total cross-section of the process $pp \to Z\gamma jj$ in the fiducial phase space, which includes the $QCD - Z\gamma jj$ and the $EW - Z\gamma jj$ contributions, is obtained by multiplying the signal strength value $\mu_{Z\gamma\mathrm{jj}}$ by the predicted total $Z\gamma jj$ cross-section in the Extended SR, where $\mu_{Z\gamma\mathrm{jj}} = 1.07 \pm 0.12$. The measured total $Z\gamma jj$ cross-section is thus:

$$\sigma_{Z\gamma} = 16.8^{+2.0}_{-1.8}\ \mathrm{fb},$$

to be compared with the sum of predictions of MadGraph5_aMC@NLO 2.6.5 interfaced with Pythia (EW contribution) and Sherpa 2.2.11 (QCD contribution):

$$\sigma^{pred}_{Z\gamma} = 15.7^{+5.0}_{-2.6}\ \mathrm{fb}.$$

The PDF and scale theoretical uncertainties in the prediction are evaluated using the procedure described in Section 6. Uncertainties are treated as uncorrelated between the $EW - Z\gamma jj$ and $QCD - Z\gamma jj$ contributions.

The breakdown of the systematic uncertainties in the $Z\gamma jj$ cross-section is shown in Table 3. The differential cross-sections are shown in Figs. 3, 4, 5 and 6.

In the SR phase space, the following variables are measured in two or three bins: p_{T}^{l}, p_{T}^{j}, E_{T}^{γ}, $p_{\mathrm{T}}^{Z\gamma}$, m_{jj}, $|\Delta y|$ and $|\Delta\phi(Z\gamma, jj)|$.

Table 3
The breakdown of the systematic uncertainties in the $EW - Z\gamma jj$ and $Z\gamma jj$ cross-sections. The "Background" component includes uncertainties on Z+jets, $t\bar{t}\gamma$ and WZ backgrounds. The "Reco" component includes uncertainties from electrons, photons, muons, jets, flavour tagging and pileup. The "EW mod." component includes interference, parton shower, underlying event, PDF and QCD scale uncertainties in the $EW - Z\gamma jj$ process. The "QCD mod." component includes merging scale, resummation scale, PDF and QCD scale uncertainties in the $QCD - Z\gamma jj$ process.

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	± 9	± 1	± 1	± 4	$^{+8}_{-6}$	± 2	± 13
$\Delta\sigma_{Z\gamma}/\sigma_{Z\gamma}$ [%]	± 3	± 1	± 2	$^{+4}_{-3}$	$^{+7}_{-6}$	± 9	$^{+12}_{-11}$

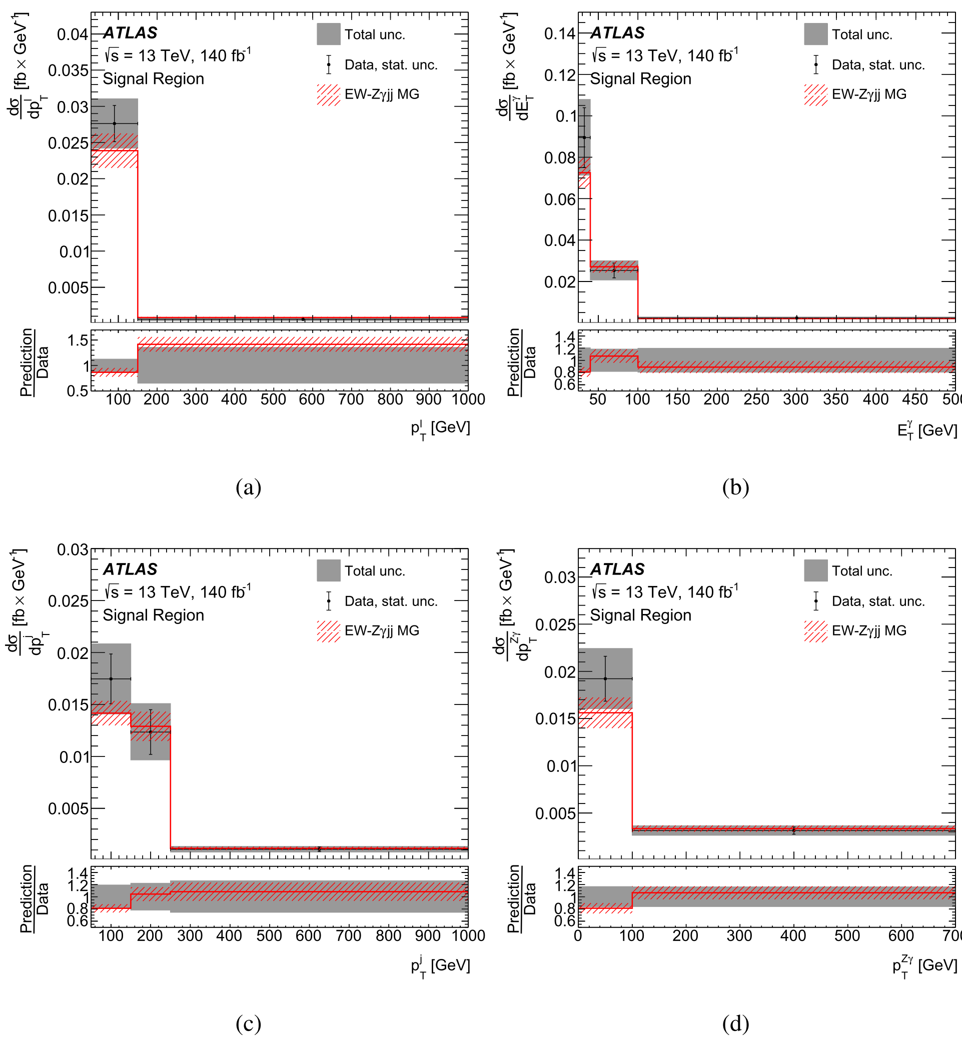
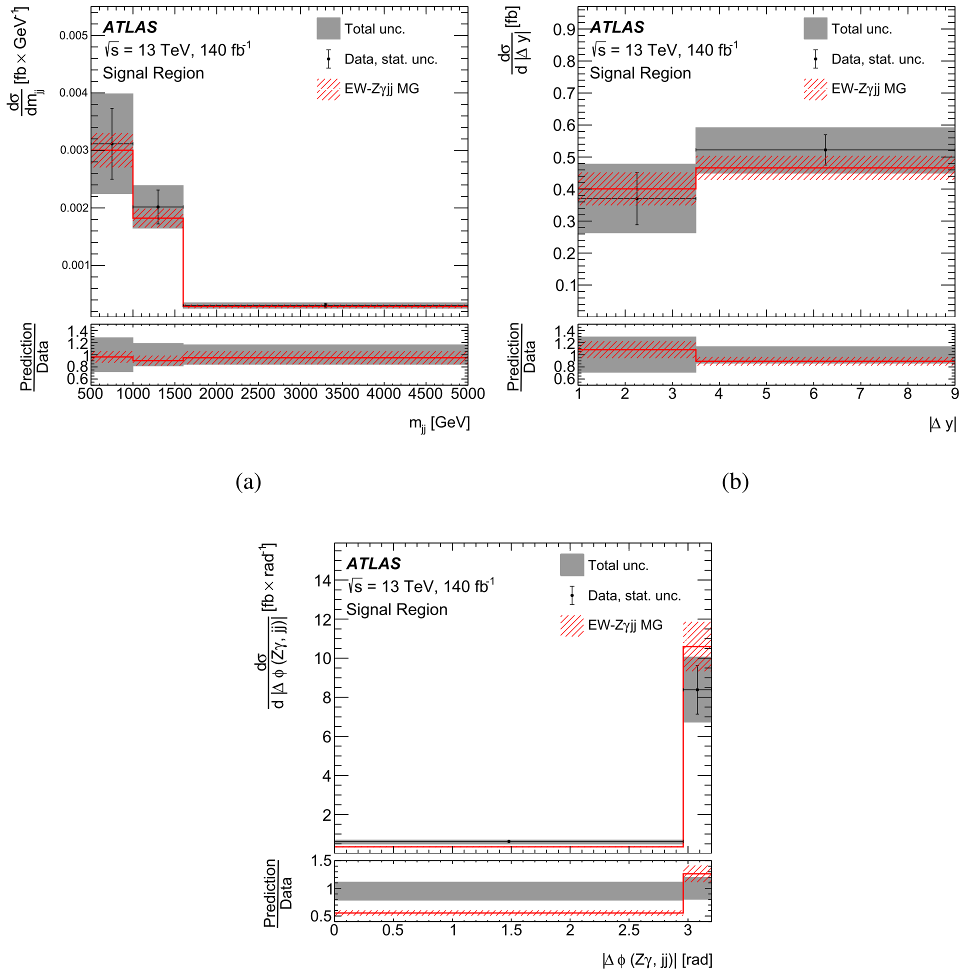


Fig. 3. The $EW - Z\gamma jj$ differential cross-section in the Signal Region as a function of (a) the leading lepton p_T, (b) the leading photon p_T, (c) the leading jet p_T and (d) the $Z\gamma$ system p_T. The lower panels show the ratios of the MC predictions to the data. The band around the unfolded data represents the total uncertainty (including statistical uncertainty) and takes into account the correlations as obtained from the fit. The hatched area represents the uncertainty in the prediction. Events beyond the upper limit of the histogram are included in the last bin.

The variables $|\Delta y|$ and m_{jj} are particularly sensitive to the kinematic difference between $QCD - Z\gamma jj$ and $EW - Z\gamma jj$ events (highest bins being dominated by $EW - Z\gamma jj$ events), which make them important variables for VBS studies. They are measured with a precision ranging from about 25% (lowest bin) to about 15% (the highest bin, covering the range 1.5 TeV to 5 TeV for m_{jj} and 3.5 to 9 for $|\Delta y|$). The variables $p_{\mathrm{T}}^{Z\gamma}$, E_{T}^{γ} and $|\Delta\phi(Z\gamma, jj)|$ are usually studied for their sensitivity to new physics effects [4,8,53]. They are measured in the ranges of 0–700 GeV, 25–500 GeV and 0–π, respectively, with a precision of 15–20% depending on bins and variables. The variables $p_{\mathrm{T}}^{Z\gamma}$ and ($|\Delta\phi(Z\gamma, jj)|$) are in addition measured differentially for the first time at the LHC. Transverse momentum p_{T}^{l} and p_{T}^{j} are also measured in the ranges of 30–1000 GeV and 50–1000 GeV respectively with a precision of around 25–30% in the last bin. The MadGraph5_aMC@NLO predictions reproduce the data well everywhere within uncertainties, except for $|\Delta\phi(Z\gamma, jj)|$ where a ~two standard deviation discrepancy in the lowest bin of $EW - Z\gamma jj$ measurement is seen. In the Extended SR phase space, the same variables are measured in the same ranges for the total $Z\gamma jj$ process with five bins in most cases, except for m_{jj} where the lower range is extended to 150 GeV, and p_{T}^{l} and $p_{\mathrm{T}}^{Z\gamma}$ for which the higher range is reduced to 500 GeV. The measurements in this process are also more precise, on average around 10%, ranging from ~7% to ~20% for lowest



(a) (b) (c)

Fig. 4. The $EW - Z\gamma jj$ differential cross-section in the Signal Region as a function of (a) the dijet invariant mass, (b) the dijet rapidity difference and (c) the $Z\gamma$ and dijet azimuthal difference. The lower panels show the ratios of the MC predictions to the data. The band around the unfolded data represents the total uncertainty (including statistical uncertainty) and takes into account the correlations as obtained from the fit. The hatched area represents the uncertainty in the prediction. Events beyond the upper limit of the histogram are included in the last bin.

to highest p_T bins typically. In addition, p_T^Z (from 0 to 800 GeV) and $\zeta(Z\gamma)$ (from 0 to 0.4) are measured. These two variables are also measured for the first time at the LHC for this process, with a precision of about 10%. The sum of MadGraph5_aMC@NLO (for $EW - Z\gamma jj$) and Sherpa 2.2.11 (for $QCD - Z\gamma jj$) predictions reproduce the measurements well within uncertainties.

10. Conclusions

This Letter presents a study of the production of events with a Z boson, decaying into either an e^+e^- or $\mu^+\mu^-$ pair, a photon and two jets. The analysis uses 140 fb^{-1} of LHC proton–proton collision data recorded at $\sqrt{s}$ = 13 GeV by the ATLAS detector during the years 2015–2018. The data sample is enriched in events from the $EW - Z\gamma jj$ process by requiring a large dijet invariant mass and by using the information about the centrality of the system. These selections characterise the signal region of the analysis. The $EW - Z\gamma jj$ signal is extracted from a maximum-likelihood fit to the m_{jj} distributions in data simultaneously using this signal region and a control region and relying on template MC distributions.

The $EW - Z\gamma jj$ process is observed by ATLAS in its charged leptonic decay with a significance well above 5 standard deviations by combining the electron and muon channels. The cross-section of the $EW - Z\gamma jj$ process is measured with a precision of 13% to be 3.6± 0.5 fb in the signal phase space defined in the analysis, with $m_{jj} > 500$ GeV, to be compared with the predicted value from MadGraph5_aMC@NLO 2.6.5 which gives 3.5± 0.3 fb. The $(EW + QCD) - Z\gamma jj$ cross-section, which also includes contributions where the jets arise from the strong interaction, is obtained with a precision of 12%, in the $m_{jj} > 150$ GeV phase space. In the signal phase space of the analysis, the measured $(EW + QCD) - Z\gamma jj$ cross-section is $16.8^{+2.0}_{-1.8}$ fb to be compared with the sum of predictions of MadGraph5_aMC@NLO 2.6.5 and Sherpa 2.2.11 which gives $15.7^{+5.0}_{-2.6}$ fb. These results are thus consistent with the SM predictions. Differential cross-section measurements as a function of the transverse momentum of the leading lepton, jet, photon, and $Z\gamma$ system, the invariant mass of and absolute rapidity difference between the two leading jets, the azimuthal difference between $Z\gamma$ system and the two leading jets, the Z boson transverse momentum, and the centrality of the $Z\gamma jj$ system are measured for the $EW - Z\gamma jj$ and $Z\gamma jj$ processes with precision around 20% and 10% on average respectively, and all of them are found to be consistent with the SM predictions.

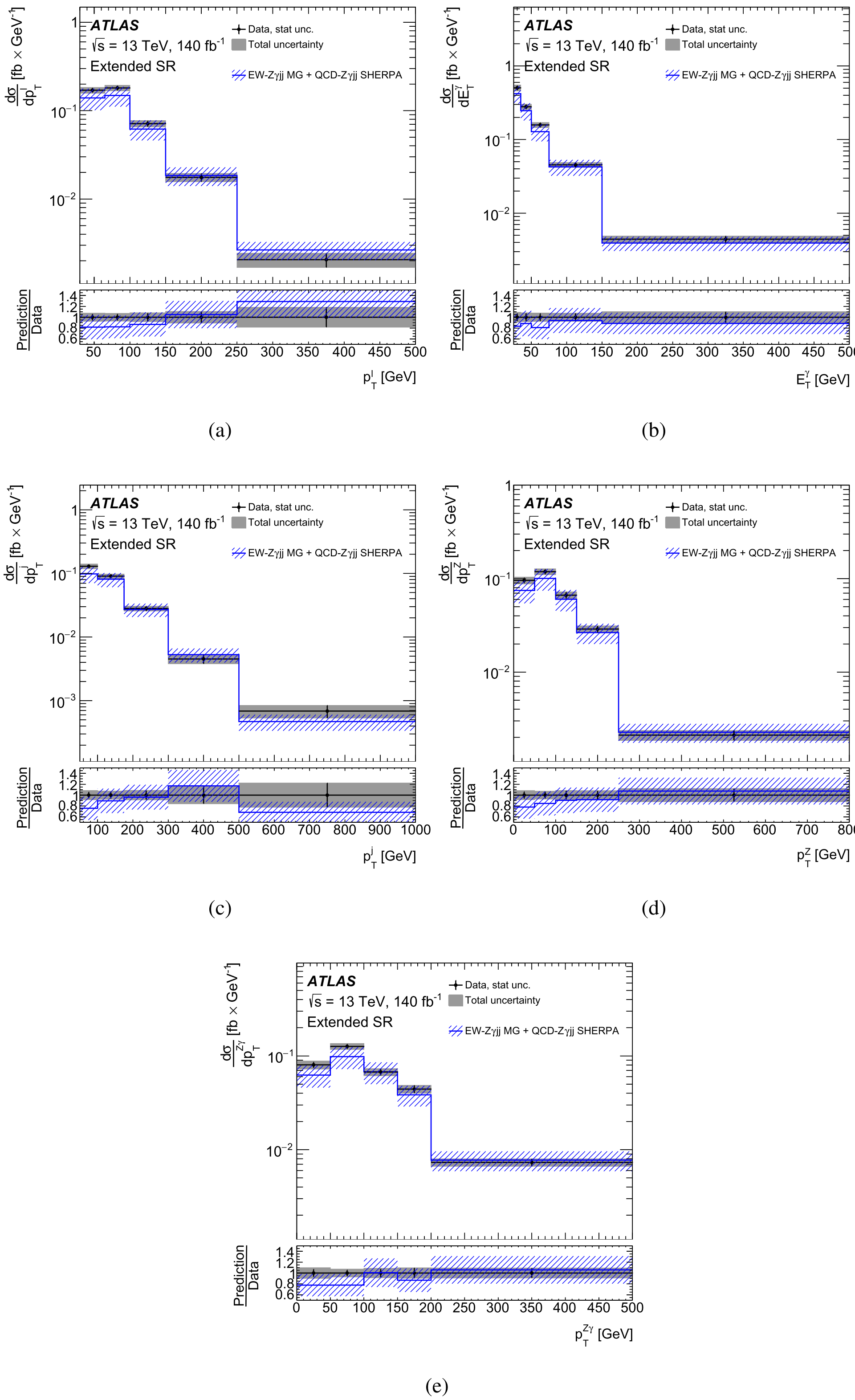


Fig. 5. The total $Z\gamma jj$ differential cross-section in the Extended SR as a function of (a) the leading lepton p_T, (b) the leading photon p_T, (c) the leading jet p_T, (d) the Z boson p_T and (e) the $Z\gamma$ system p_T. The lower panels show the ratios of the MC predictions to the data. The band around the unfolded data represents the total uncertainty (including statistical uncertainty) and takes into account the correlations as obtained from the fit. The hatched area represents the uncertainty in the prediction. Events beyond the upper limit of the histogram are included in the last bin.

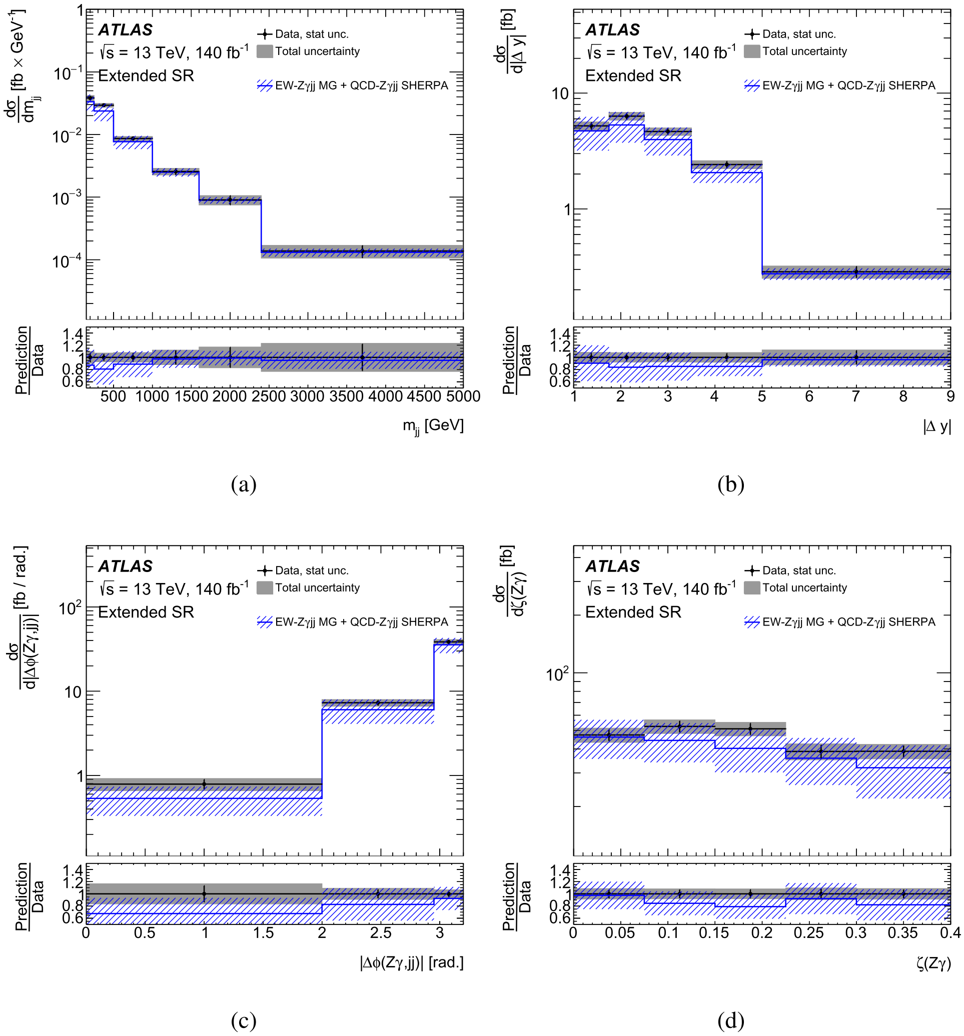


Fig. 6. The total $Z\gamma jj$ differential cross-section in the Extended SR as a function of (a) the dijet invariant mass, (b) the dijet rapidity difference, (c) the $Z\gamma$ and dijet azimuthal difference and (d) the centrality of the system $\zeta(Z\gamma)$. The lower panels show the ratios of the MC predictions to the data. The band around the unfolded data represents the total uncertainty (including statistical uncertainty) and takes into account the correlations as obtained from the fit. The hatched area represents the uncertainty in the prediction. Events beyond the upper limit of the histogram are included in the last bin.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (https://hepdata.cedar.ac.uk)

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