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Letter

Observation of $W^+W^-\gamma$ production in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector and constraints on anomalous quartic gauge-boson couplings

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ABSTRACT

This Letter reports the observation of $W^+W^-\gamma$ triboson production in 140 fb^{-1} of data collected by the ATLAS detector from proton–proton collisions at a centre-of-mass energy of $\sqrt{s}$ = 13 TeV at the LHC. Events with an opposite-charge $e\mu$ pair, a high transverse-momentum photon, and significant missing transverse momentum are considered. The observed (expected) significance of the signal is 5.9 (6.0) standard deviations. The measured fiducial cross-section, defined for the $W^+W^-\gamma \to e^\pm\mu^\mp\nu\bar{\nu}\gamma$ final state is 6.2 ± 0.8 (stat.) ± 0.6 (sys.) fb, in good agreement with the Standard Model prediction of $6.1^{+1.0}_{-0.7}$ fb. Constraints on the Wilson coefficients of 13 dimension-8 operators describing physics beyond the Standard Model through anomalous quartic gauge-boson couplings are derived using the effective field theory framework.

1. Introduction

In the Standard Model (SM), the electroweak interaction is based on the non-Abelian $\mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$ gauge group. This leads to couplings among the electroweak gauge bosons (the W and Z bosons and the photon) through triple and quartic vertices [1]. Measurements of triboson production processes allow stringent tests of the gauge structure and offer sensitivity to physics beyond the SM.

The ATLAS [2] and CMS [3] collaborations at the Large Hadron Collider (LHC) [4] investigated both the $WW\gamma$ and $WZ\gamma$ processes [5,6] using datasets collected at a centre-of-mass energy ($\sqrt{s}$) of 8 TeV and integrated luminosities ($\mathcal{L}$) of 20.2 fb^{-1} and 19.7 fb^{-1}, respectively. The CMS Collaboration has since observed the $WW\gamma$ process at $\sqrt{s}$ = 13 TeV using its full Run-2 dataset corresponding to $\mathcal{L} = 138$ fb^{-1} [7]. Many triboson production processes have been studied by both the ATLAS and CMS collaborations using their full Run-2 datasets, including WWW [8,9], $W\gamma\gamma$ [10,11], $Z\gamma\gamma$ [11,12], $WZ\gamma$ [13,14], and WVZ, where V refers to W or Z bosons [9,15]. Both the ATLAS and CMS collaborations have set constraints on anomalous quartic gauge-boson coupling (aQGC) parameters.

This Letter reports the observation of $WW\gamma$ production by examining the $e^\pm\mu^\mp\nu\bar{\nu}\gamma$ final state in 140 fb^{-1} [16] of data from proton–proton collisions at $\sqrt{s}$ = 13 TeV collected by the ATLAS detector at the LHC. Events with an opposite-charge $e\mu$ pair, a photon, and missing transverse momentum are selected. The photon in a $WW\gamma$ event can originate from three processes: direct coupling to a W boson – either triple gauge-boson coupling (TGC) or quartic gauge-boson coupling (QGC); initial-state radiation (ISR) from an initial quark; or emission as final-state radiation (FSR). In the case of FSR, the photon is emitted either by a lepton from a W boson decay or by an associated quark. Fig. 1 shows examples of the lowest-order Feynman diagrams for $WW\gamma$ production where the photon arises from a QGC vertex, a TGC vertex, or is radiated directly from a quark without involving interactions between electroweak force carriers.

The fiducial cross-section is measured using a binned maximum-likelihood fit performed on the output distribution of a boosted decision tree, which was trained to enhance the separation between signal and background. Limits on aQGCs are also derived, by performing an analysis in which deviations from the SM predictions are parameterised using effective field theory (EFT) [17].

2. ATLAS detector

The ATLAS experiment [2] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] It consists of an inner tracking de-

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[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 pipe. 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 plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in

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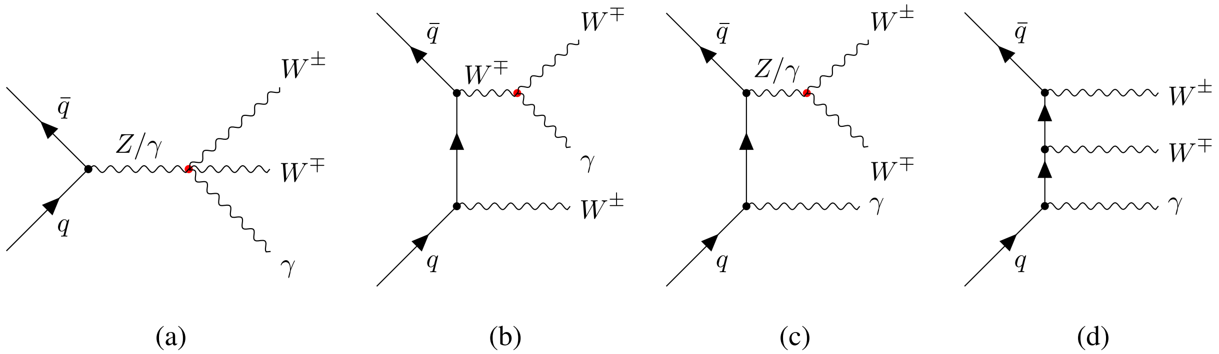

Fig. 1. Representative leading-order Feynman diagrams for the $WW\gamma$ production process with a triple or quartic gauge-boson coupling vertex shown in red: (a) diagram featuring a QGC vertex (b,c) diagrams with a TGC vertex, and (d) a diagram showing photon radiation from an initial-state quark. Additional contributions arise from other diagrams not shown here.

tector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A steel/scintillator-tile hadron calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T · m across most of the detector. The muon spectrometer includes a system of precision chambers for tracking and fast detectors for triggering. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1.25 kHz on average depending on the data-taking conditions. A software suite [18] 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. Data and MC simulation

This measurement uses $140\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 13$ TeV proton–proton collision data collected by the ATLAS detector from 2015 to 2018 [16]. The selected data were collected during periods with stable LHC beam conditions and a fully functioning ATLAS detector [19]. Events were required to satisfy a single-electron or single-muon trigger [20,21]. Single-lepton triggers with low transverse momentum (p_T) thresholds and isolation requirements were combined with triggers applying higher p_T thresholds, looser identification criteria, and no isolation requirements, resulting in an efficiency of almost 100 % for events satisfying the analysis selection criteria. The lowest p_T threshold ranged from 24 GeV to 26 GeV for single-electron triggers and from 20 GeV to 26 GeV for single-muon triggers. The average number of collisions per bunch crossing (pile-up) ranged from 13 to 38 during the 2015–2018 data-taking periods.

Monte Carlo (MC) simulated event samples are used to model the signal and irreducible backgrounds. The MC events were passed through a GEANT4-based simulation of the ATLAS detector [22,23] to account for detector resolution and acceptance effects. For some samples used in the evaluation of systematic uncertainties, a faster parameterised shower simulation was employed in place of the full GEANT4 model. Inelastic collisions were simulated using the PYTHIA 8.186 [24] MC event generator with the A3 set of tuned parameters [25] and the NNPDF2.3LO [26] set of parton distribution functions (PDFs) and overlaid on simulated signal and background events. Correction factors are applied to account for differences between data and simulation in the amount of pile-up and in the reconstruction, particle identification, and trigger efficiencies.

Signal $WW\gamma$ events including up to two light-flavour jets were generated using SHERPA 2.2.11 [27] and the NNPDF3.0NNLO PDF set [28], together with the default SHERPA tuning of parton-shower parameters. The $WW\gamma$ + 0-jet events were simulated at next-to-leading order (NLO) in QCD, and combined with $WW\gamma$ + 1-jet and $WW\gamma$ + 2-jet event samples, which were simulated at leading order (LO) using matrix elements from the Comix [29] and OPENLOOPS [30–32] libraries. The partons were matched with the SHERPA parton shower [33] using the ME + PS@NLO prescription [34–37] with the set of tuned parameters developed by the SHERPA authors. The $WW\gamma$ process was simulated in the $\ell\nu\ell\nu\gamma$ ($\ell = e, \mu, \tau$) final state, including contributions from off-shell W bosons and lepton pairs not originating from W boson decays such as $ZZ\gamma \to \ell\ell\nu\nu\gamma$. Photons radiated from initial- or final-state charged particles were included. A minimum photon energy of 7 GeV and a separation of $\Delta R > 0.1$ between the photon and charged leptons were required. Processes with a b-quark in the initial or final state are excluded because they are dominated by top-quark contributions rather than diagrams with gauge-boson couplings. This procedure also removes small $b\bar{b}$-induced signal contributions that are free of top quarks, but the impact on the total cross-section is less than 1 %, as evaluated with SHERPA for $WW\gamma$ + 0-jet production at LO in QCD.

For the EFT interpretation described in Section 9, MC samples were generated with non-zero Wilson coefficients for the $\mathcal{O}_{\mathrm{M0}}$, $\mathcal{O}_{\mathrm{M1}}$, $\mathcal{O}_{\mathrm{M2}}$, $\mathcal{O}_{\mathrm{M3}}$, $\mathcal{O}_{\mathrm{M4}}$, $\mathcal{O}_{\mathrm{M5}}$, $\mathcal{O}_{\mathrm{M7}}$, $\mathcal{O}_{\mathrm{T0}}$, $\mathcal{O}_{\mathrm{T1}}$, $\mathcal{O}_{\mathrm{T2}}$, $\mathcal{O}_{\mathrm{T5}}$, $\mathcal{O}_{\mathrm{T6}}$, and $\mathcal{O}_{\mathrm{T7}}$ operators in the Eboli model [17] at LO in QCD using MADGRAPH5_AMC@NLO 2.9.9 [38], interfaced with PYTHIA 8.3, and employing the NNPDF3.0NNLO PDF set. These samples include only on-shell W bosons and no additional partons in the matrix element (ME). The Wilson coefficients were set to $1\,\mathrm{TeV}^{-4}$ in all EFT samples. In addition, a SM $WW\gamma$ event sample was generated using the same MADGRAPH5_AMC@NLO + PYTHIA setup. The ratio of SHERPA to MADGRAPH5_AMC@NLO SM predictions was used to derive $p_\mathrm{T}(\gamma)$-dependent corrections for the EFT samples, with a correction factor of approximately 2.3 observed in the high-$p_\mathrm{T}(\gamma)$ region, $p_\mathrm{T}(\gamma) > 500$ GeV.

Simulated event samples containing prompt photons and leptons are used to model background processes with final states similar to the signal. These include $t\bar{t}\gamma$, $tW\gamma$, $Z\gamma$, $WZ\gamma$ and $ZZ\gamma$ productions.

MC $t\bar{t}\gamma$ background events with photons from ISR were generated at NLO in QCD with MADGRAPH5_AMC@NLO 2.7.3 [38] using the NNPDF3.0NLO PDF set [28] interfaced to PYTHIA 8.240 [39], which

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terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

used the A14 set tune [40] and the NNPDF2.3LO PDF set for the parton shower (PS). Top quarks were decayed at LO in QCD using MADSPIN [41,42]. With the same setup, a second $t\bar{t}\gamma$ sample with photons from FSR was generated as a $2 \to 2$ process with on-shell top quarks at LO precision, where the photon originates from the charged decay products of the top quarks. The normalisation of this sample is corrected by a NLO/LO inclusive k-factor of 1.5 obtained in Ref. [43]. The production of $tW\gamma$ was simulated at LO in QCD with MADGRAPH5_AMC@NLO interfaced to PYTHIA 8.212 using the A14 tune and the NNPDF2.3LO PDF set. Two samples were generated: one where the photon originates from the initial state or from radiative tW production, and another where the photon arises from the decay of the top quark, the W boson, or their charged decay products.

The $Z\gamma$ MC event sample was generated as $\ell\ell\gamma$ ($\ell = e, \mu, \tau$) with SHERPA 2.2.8 [27]. The $Z\gamma$ events with two or three light-flavour jets were simulated at LO in QCD, whereas $Z\gamma$ + 0,1-jet events were simulated at NLO in QCD. Background $WZ\gamma$ and $ZZ\gamma$ (referred to as $VZ\gamma$) MC events were generated at NLO in QCD as $\ell\nu\ell\ell\gamma$ and $\ell\ell\ell\ell\gamma$ ($\ell = e, \mu, \tau$) final states with SHERPA 2.2.11. Those with one or two additional light-flavour jets were simulated at LO in QCD and combined with the $WZ\gamma$ + 0-jet and $ZZ\gamma$ + 0-jet NLO samples. The NNPDF3.0NNLO PDF set [28] was used for these samples. Events with off-shell W or Z bosons were included, as were those with a photon radiated from an initial- or final-state charged particle.

Background events in which at least one lepton or photon is not prompt or is due to misidentification, referred to as fake-lepton and fake-photon backgrounds, can also mimic the signal. These contributions are estimated using MC samples, with their normalisation and shape corrected using data-driven methods and dedicated control regions. The contributing processes include diboson (VV), $t\bar{t}$, tW and Z + jets production.

The diboson samples were generated with SHERPA 2.2.12 using the same setup as the signal, i.e. the NNPDF3.0NNLO PDF set and the dedicated parton-shower tuning provided by the SHERPA authors. The $t\bar{t}$ and tW event samples were generated at NLO in QCD with POWHEG BOX V2 [44–47] with the NNPDF3.0NLO PDF set and the h_{damp} parameter[2] set to $1.5\,m_{\mathrm{top}}$ [48]. Both samples were interfaced to PYTHIA 8.230 [39], which used the A14 tune and the NNPDF2.3LO PDF set. The Z + jets MC sample was generated with SHERPA 2.2.1 [27], using NLO QCD matrix elements for up to two partons and LO QCD matrix elements for three or four partons, together with the NNPDF3.0NNLO PDF set.

4. Object reconstruction and event selection

A primary vertex [49] is constructed by requiring at least two tracks consistent with a pp collision at the interaction point. The primary vertex with the highest sum of the squared transverse momenta of all associated tracks with $p_{\mathrm{T}} > 500$ MeV is selected.

Electron candidates are reconstructed from energy clusters in the EM calorimeter and matched to reconstructed tracks in the ID [50,51]. Electrons are also required to meet the `TightLH` identification and `PLVTight` isolation criteria, and to satisfy $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.47$, excluding the transition region $1.37 < |\eta| < 1.52$ between the calorimeter barrel and endcaps. Electron tracks must also be consistent with originating from the primary vertex by satisfying $|d_0|/\sigma_{d_0} < 5$ and $|z_0 \cdot \sin\theta| < 0.5$ mm. Here, d_0 denotes the transverse impact parameter with respect to the beamline, σ_{d_0} is its associated uncertainty, z_0 is the longitudinal impact parameter with respect to the primary vertex, and θ is the polar angle of the track.

Photon candidates are reconstructed from energy clusters in the EM calorimeter [50]. Photon energy clusters must be within $|\eta| < 2.37$, excluding the transition region $1.37 < |\eta| < 1.52$ between the barrel and endcaps. Photon candidates are required to meet the `Tight` identification and `FixedCutTight` isolation criteria and have $p_{\mathrm{T}} > 20$ GeV [50].

Muon candidates are reconstructed by combining a track reconstructed in the ID with one reconstructed in the MS [52] and are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. Several quality requirements are imposed to reject non-prompt muon candidates, which originate primarily from pion and kaon decays. Muons are required to meet `Medium` identification and `Tight` isolation criteria [52]. Muon tracks are also required to be consistent with originating from the primary vertex by satisfying $|d_0|/\sigma_{d_0} < 3$ and $|z_0 \cdot \sin\theta| < 0.5$ mm.

Jet-related variables play an important role in this analysis. A veto on jets originating from b-quarks (b-jets) is primarily used to suppress backgrounds from top-quark processes, and additional jet-related observables are used in the boosted decision tree to enhance signal–background separation. Jets are reconstructed from particle-flow objects [53], using the anti-k_t algorithm [54,55] with a radius parameter of $R = 0.4$. Jets are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. Jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.5$ must fulfil the requirement of a likelihood tagger called the Jet Vertex Tagger (`JVT`) to reduce the impact of pile-up [56]. A `JVT` requirement that has 92 % efficiency while rejecting 98 % of jets from pile-up and noise is imposed. Identification of b-jets is based on reconstructing secondary vertices formed by tracks associated with jets and combining their spatial-parameter values with lifetime-related information. The `DL1r` b-tagging algorithm [57–59] is used at a working point with an 85 % b-jet-tagging efficiency, independent of b-jet p_{T} and calibrated using simulated $t\bar{t}$ events. The rejection rates for light-flavour jets and c-jets are p_{T}-dependent, and on average are 40 and 3, respectively.

The missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, provides a measure of the transverse momentum imbalance due to escaping neutrinos. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated as the magnitude of the negative vector sum of the transverse momenta of all reconstructed electrons, muons, photons, and jets in the event, plus a term to account for soft hadronic activity, built from tracks associated with the hard-scattering vertex but not matched to any of the reconstructed objects [60].

Object reconstruction is followed by an overlap removal procedure applied to electrons, photons, muons and jets to remove possible duplication due to individual physical objects being reconstructed as two different entities in the detector [61].

The $WW\gamma$ process yields several different final states depending on the decay modes of the W bosons. In this measurement, the targeted final state contains an electron and a muon of opposite electric charge, accompanied by missing transverse momentum and exactly one photon. This selection defines the $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ signal region (SR). The $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ final state, together with a veto on events containing b-jets, is chosen in order to suppress background contributions, particularly from $t\bar{t}\gamma$, $Z\gamma$, and $tW\gamma$ production. Throughout this analysis, ℓ refers exclusively to electrons or muons.

Events must have exactly one muon and one electron satisfying the requirements described above. At least one lepton must have $p_{\mathrm{T}} >$ 27 GeV to satisfy the trigger threshold, and be matched to the lepton that was accepted by the trigger. Exactly one photon is required, meeting the identification and isolation requirements specified previously. In addition, events are required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV. A Z-boson veto is applied mainly to reduce contributions from $WZ \to \mu^{\pm}\nu e^{+}e^{-}$, where one electron from the $Z \to e^{+}e^{-}$ decay is reconstructed as a prompt photon. This is achieved by requiring $|m(e\gamma) - m_Z| > 5$ GeV. Additionally, events containing b-jets are vetoed to reduce $t\bar{t}\gamma$ and $tW\gamma$ background contributions. These signal event requirements are summarised in Table 1.

5. Background estimation

The background yields are estimated using a combination of MC simulations and data-driven methods, and are constrained using statistically

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[2] The h_{damp} parameter is a resummation damping factor and one of the parameters that controls the matching of the POWHEG BOX ME to the PS and thus effectively regulates the high-p_{T} radiation against which the $t\bar{t}$ system recoils.

Table 1
Signal and control regions used in the analysis. The Z-boson mass m_Z is taken to be 90 GeV. Selections shown in boldface correspond to differences with respect to the SR, chosen both to enhance the targeted background and to ensure orthogonality between regions.

Common selections
Leading lepton $p_T > 27$ GeV
Subleading lepton $p_T > 20$ GeV
Exactly 1 photon with $p_T > 20$ GeV
$E_T^{miss} > 20$ GeV

SR $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$	CR $t\bar{t}\gamma$	CR1 $Z\gamma$	CR2 $Z\gamma$	CR $e \to \gamma$
$e^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$	**$e^+e^-/\mu^+\mu^-$**	**$e^+e^-/\mu^+\mu^-$**	$e^{\pm}\mu^{\mp}$
$\lvert m(e\gamma) - m_Z \rvert > 5$ GeV	$\lvert m(e\gamma) - m_Z \rvert > 5$ GeV	**–**	**–**	**$\lvert m(e\gamma) - m_Z \rvert < 5$ GeV**
–	–	**$m(\ell\ell\gamma) < 100$ GeV**	**$m(\ell\ell\gamma) > 100$ GeV**	–
0 b-jets	**1 b-jet**	0 b-jets	0 b-jets	0 b-jets

independent control regions (CRs). Table 1 summarises the event selection criteria and defines the CRs used to estimate the normalisation of the major backgrounds.

The modelling of prompt backgrounds, such as those due to the $t\bar{t}\gamma$ and $Z\gamma$ processes, is based on MC simulations, with their normalisations determined by a maximum-likelihood fit using dedicated $t\bar{t}\gamma$ and $Z\gamma$ CRs. The $t\bar{t}\gamma$ CR matches the kinematic properties of the signal region, but requires exactly one b-jet. Two $Z\gamma$ CRs are constructed, each selecting $\ell\ell\gamma$ events with a $e^+e^-/\mu^+\mu^-$ lepton pair. The $Z\gamma$ CR1 requires $m(\ell\ell\gamma) < 100$ GeV, whereas $Z\gamma$ CR2 requires $m(\ell\ell\gamma) > 100$ GeV, resulting in an approximately 30 % contribution from jets or neutral hadrons misidentified as photons ($j \to \gamma$), making it well suited to constrain this background. An additional control region (the $e \to \gamma$ CR) is defined by requiring $|m_{e\gamma} - m_Z| < 5$ GeV, in order to constrain backgrounds from electrons misidentified as photons ($e \to \gamma$). This region is dominated by WZ events, where an electron from the Z-boson decay is reconstructed as a photon.

These $j \to \gamma$ background events stem from processes without prompt photons, typically $t\bar{t}$, Z + jets, or diboson (VV), where jets occasionally satisfy the photon identification and isolation criteria. Samples of MC events from these processes are used to estimate the $j \to \gamma$ misidentification background. An overlap-removal procedure ensures orthogonality between prompt- and non-prompt-photon MC samples [62]. Events with photons from initial- or final-state radiation (ISR/FSR) are included in prompt-photon samples (e.g. $t\bar{t}\gamma$), while jet-induced photon-like objects remain in non-prompt-photon samples (e.g. $t\bar{t}$). Discrepancies between MC simulation and data are minimised by applying two-dimensional scale factors (SFs) derived as functions of the scalar sum of jet transverse momenta, Σp_T(jet), and the transverse mass of the dilepton–E_T^{miss} system, $m_T(\ell\ell, E_T^{miss})$. The use of these variables, sensitive to event kinematics and the presence of jets and leptons, effectively addresses modelling mismatches.

The correction SFs are calculated in a statistically independent region enriched in $j \to \gamma$ events, where SR selection requirements other than the photon isolation criterion are applied. The photon candidate fails the `FixedCutTight` isolation requirement [50], but passes a looser selection, in which the sum of track p_T within a cone of $\Delta R = 0.2$ around the photon is less than 5 % of $p_T(\gamma)$, and the calorimeter-based isolation requirement is reversed. This region is kinematically similar to the SR, allowing the scale factors to be applied reliably. The SFs are computed by normalising the $j \to \gamma$ MC event yields to data after subtracting contributions from prompt backgrounds. The resulting scale factors typically range between 0.8 and 1.5. The associated uncertainties, arising from limited numbers of data and MC events, range from ±0.2 to ±0.7 and are treated as additional systematic uncertainties.

The $j \to \gamma$ background estimate is cross-checked using a two-dimensional sideband technique [10]. Four non-overlapping regions are defined by using two uncorrelated variables: photon identification and photon isolation. The SR requires photons to satisfy both the `Tight` identification and the `FixedCutTight` isolation criteria. Three CRs are constructed by inverting the identification and/or isolation criteria to enhance the contribution from misidentified jets. This is done by selecting events with a photon candidate that passes the `Loose` photon identification requirement but fails at least two of the EM shower-shape requirements used in `Tight` identification; these photons are denoted by T'. For isolation (I), the photon candidate must pass the track-isolation requirement but fail the calorimeter-isolation requirement (I'). The $j \to \gamma$ yield in the SR is then estimated as $TI = T'I \cdot TI'/T'I'$. As an additional cross-check, the procedure is repeated with photon identification paired with the requirement of same-sign lepton events instead of the $e^{\pm}\mu^{\mp}$ selection. The two $j \to \gamma$ estimates, obtained from the sideband and scale-factor methods, differ by 30 %, which is assigned as an additional systematic uncertainty on the $j \to \gamma$ background in the SR.

Backgrounds such as diboson events with electron-to-photon ($e \to \gamma$) misidentification are significantly suppressed by rejecting events with $m(e\gamma)$ within the Z-boson mass window. The remaining $e \to \gamma$ “fake rate” is estimated using a data-driven reweighting method, as described in Refs. [10,63]. The rate estimate is derived from $Z \to e^+e^-$ events reconstructed as $e\gamma$ final states, using two dedicated regions. An $e\gamma$ region is defined by requiring one electron and one photon with an invariant mass within 35 GeV of the Z-boson mass, and the photon p_T to be less than the electron p_T (to make the photon more likely to be fake). An e^+e^- region is defined by selecting events with two oppositely charged electrons with an invariant mass within 35 GeV of the Z-boson mass. In both regions, events containing b-jets are removed.

The invariant mass distributions in the $e\gamma$ and e^+e^- control regions are modelled using a single-sided Crystal Ball function [64] for the Z-boson resonance and a fifth-order Bernstein polynomial for non-resonant background processes. The yields $N_{e\gamma}$ and N_{ee} are binned in p_T and $|\eta|$ of the fake photon, and fake-factors are then defined as the ratio $N_{e\gamma}/N_{ee}$. The correction scale factors, typically between 0.71 and 1.26, are derived as the MC-to-data ratio of the fake-factors, and are used to reweight MC samples that include $e \to \gamma$ misidentification events. A systematic uncertainty is assigned to account for the limited number of data and MC events used in the evaluation of the scale factors, ranging from ±0.01 to ±0.21. An additional background uncertainty is included to account for the choice of parameterisation.

Finally, contributions from fake leptons are found to be negligible in the regions considered. Photon contributions from pile-up are evaluated following the method described in Ref. [65] and are found to be well modelled in the MC simulation, with no additional treatment required.

The predicted yield of $WW\gamma$ events in the SR after the likelihood fit (post-fit) is 250 ± 40, constituting 26 % of the expected total number of events. The quoted uncertainty includes both statistical and systematic components from the likelihood fit to data, as described in Section 8. Most of the background in the $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ SR comes from sources with prompt photons, including $t\bar{t}\gamma$ (45 %), $Z\gamma$ (13 %) and $VZ\gamma$ (3 %). The

Table 2
Input variables used to train the BDT in the $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ SR, ordered by feature importance. For jet-related observables, values are set to −99 if the required number of jets is not reconstructed: $\Delta R(jj)$ and $p_{\mathrm{T}}(j_2)$ for fewer than two jets, and $p_{\mathrm{T}}(j_1)$ for zero jets.

Variable	Feature importance	Definition
$m_{\mathrm{T}}(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$	13 %	Transverse mass of the leading lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$.
$\Delta R(jj)$	11 %	ΔR between the leading and subleading jets.
$m(\ell\ell)$	11 %	Invariant mass of the two-lepton system in the event.
$p_{\mathrm{T}}(j_2)$	11 %	p_{T} of the subleading jet.
$\Sigma\lvert p_{\mathrm{T}}(j)\rvert$	10 %	Scalar sum of the p_{T} of all jets in the event.
$m_{\mathrm{T}}(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	10 %	Transverse mass of the subleading lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$.
$p_{\mathrm{T}}(j_1)$	10 %	p_{T} of the leading jet.
N(jets)	9 %	Number of jets in the event.
$\Sigma\lvert p_{\mathrm{T}}(\ell)\rvert$	9 %	Scalar sum of the p_{T} of the two leptons in the event.
$m(\ell_2\gamma)$	6 %	Invariant mass of the subleading lepton and photon.

remaining background contributions are due to non-prompt or misidentified photons, and include events where an electron is misidentified as a photon ($e \to \gamma$, 3.5 %) and events where a jet is misidentified as a photon ($j \to \gamma$, 9.5 %).

6. Multivariate analysis

To improve the separation between signal and background events, the `XGBoost` [66] package is used to train a boosted decision tree (BDT), which constructs a discriminant that takes correlations among the input variables into account, resulting in a single continuous output variable in the interval $[0, 1]$. The BDT is implemented with hyperparameters optimised for performance and stability, using 120 trees with a maximum depth of four.

The BDT is trained using MC events from the SR, where all signal and background processes are included in the training and weighted according to their expected event yields. The $e \to \gamma$ and $j \to \gamma$ backgrounds are scaled using the MC correction scale factors described in Section 5. A 5-fold cross-validation strategy [67,68] is used to improve the statistical stability of the trained BDT by training five independent models. The resulting BDT output distributions from the five held-out sets are added to form the final BDT distribution used in the statistical fit.

Only variables that provide good signal-background separation and are well modelled are used in the BDT training. The ten input variables with the highest feature importance are selected, and the full list is shown in Table 2. The feature importance is calculated using the Gain method [66].

The distributions of the four variables contributing the most to the BDT, shown after the likelihood fit described in Section 8, are presented in Fig. 2. The jet-related variables provide good separation between the $WW\gamma$ and $t\bar{t}\gamma$ processes. In contrast, the remaining BDT input variables provide discrimination power between the signal and the $Z\gamma$ and $VZ\gamma$ backgrounds.

7. Systematic uncertainties

Systematic uncertainties related to the efficiency of reconstructing the $WW\gamma$ signal and major backgrounds, and the normalisation of the $VZ\gamma$ background contribution, are taken into account. Experimental and theoretical uncertainties affecting the kinematic distributions used in the analysis are also included, with correlations across the analysis regions applied.

Reconstruction efficiency and calibration uncertainties: Systematic uncertainties affecting the reconstruction efficiency, energy calibration, and identification of electrons, photons, muons and jets are propagated through the analysis. Each source contributes only at the few-percent level to the total uncertainty in the measured signal cross-section.

Differences between electron (muon) trigger, reconstruction and selection efficiencies in data and those in MC simulation are minimised by applying scale factors derived from dedicated $Z \to e^+e^-$ ($Z \to \mu^+\mu^-$) enriched control samples using a tag-and-probe method [50,52]. Similarly, corrections and associated uncertainties for photon reconstruction and identification efficiencies are derived as described in Ref. [50].

The jet energy scale (JES) was derived using test-beam data, LHC collision data, and simulation information. The JES calibration [69] includes corrections that account for detector problems, jet fragmentation, the impact of pile-up, and differences between data and MC simulation. The impact of the uncertainty in the jet energy resolution (JER) [69] is evaluated by smearing the jet energy in the MC and data samples accordingly. An additional uncertainty arises from the correction applied to simulated events associated with the `JVT` selection [70].

The b-tagging efficiencies and mistagging rates are measured in data as described in Refs. [57,58,71], with the systematic uncertainties associated with the b-tagging efficiency and the mistagging rates estimated separately. The impact of the uncertainties in the b-tagging calibration is evaluated separately for b-jets, c-jets and light-flavour jets in the MC samples.

E_T^{miss}: The uncertainty in $E_{\mathrm{T}}^{\mathrm{miss}}$ due to a possible miscalibration of the soft-track component of the $E_{\mathrm{T}}^{\mathrm{miss}}$ is derived from data–MC comparisons of the p_{T} balance between the hard and soft $E_{\mathrm{T}}^{\mathrm{miss}}$ components [60]. The uncertainties associated with the leptons, jets and photons are propagated from their energy/momentum scale and resolution uncertainties, and are grouped with other uncertainties associated with those objects.

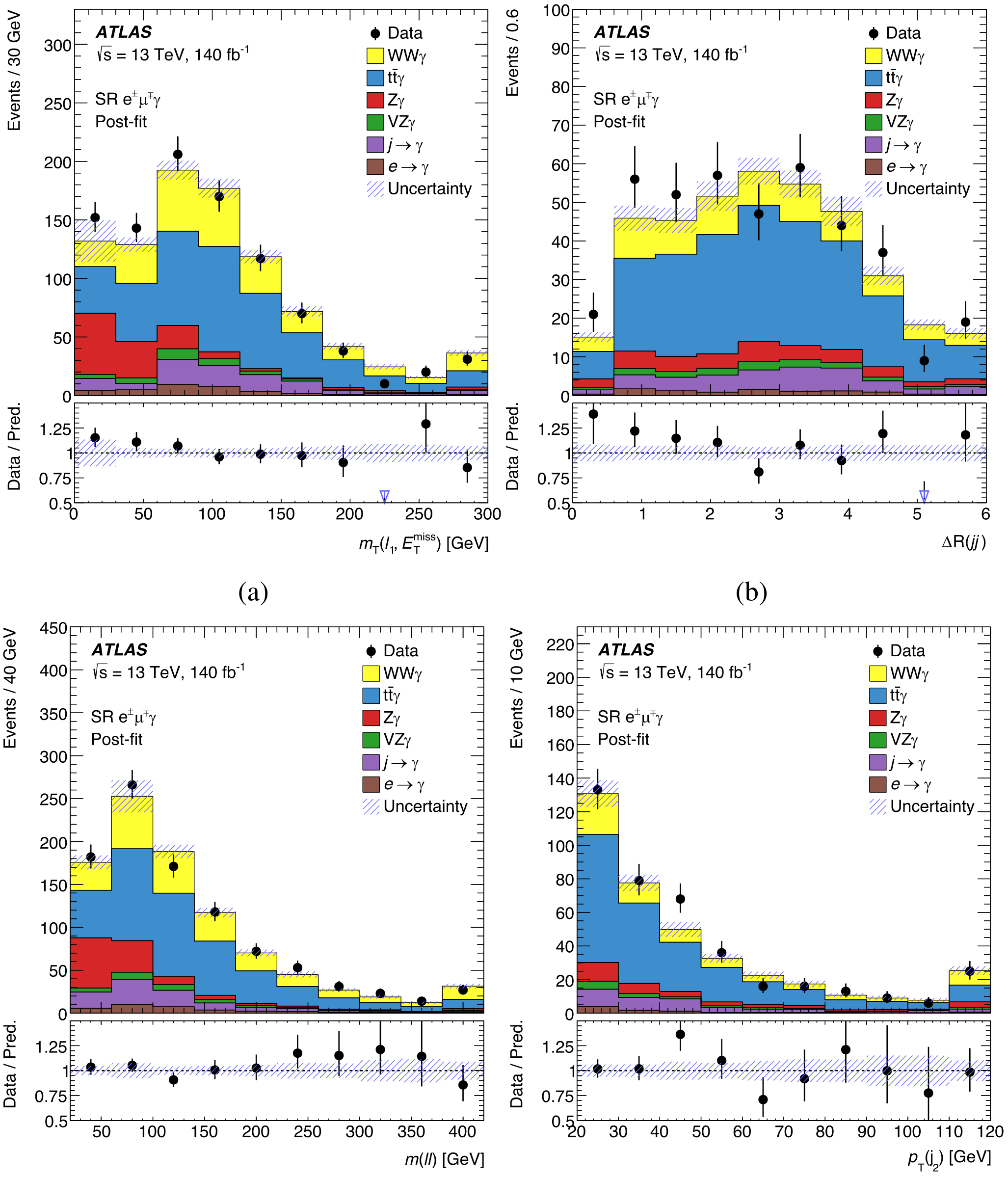
Luminosity: The uncertainty in the combined 2015–2018 integrated luminosity is 0.83 % [16], obtained using the LUCID-2 detector [72] for the primary luminosity measurements.

Uncertainty in pile-up modelling: The uncertainty in pile-up modelling is accounted for by varying the reweighting of the MC samples to the data pile-up conditions by the uncertainty in the average number of interactions per bunch crossing.

Signal and background modelling: The systematic uncertainties in the $WW\gamma$ and $Z\gamma$ modelling are estimated using the internal SHERPA 2.2.11 weights. These correspond to independently varying the renormalisation scale (μ_{r}) up and down by a factor of 2 while keeping μ_{f} fixed, and vice versa for the factorisation scale (μ_{f}). The PDF uncertainties are estimated using the nominal and variation weights provided for the PDF4LHC PDF set [73]. The resulting uncertainty is applied to the nominal signal sample. The uncertainty from the strong coupling constant, α_{s}, is evaluated for the $WW\gamma$ process, using the NNPDF3.0 PDF set with varied α_{s} values. The variations in μ_{r}, μ_{f}, the PDFs, and α_{s} are applied simultaneously to both the matrix-element calculation and the parton shower.

The systematic uncertainties associated with the renormalisation and factorisation scales of the $t\bar{t}\gamma$ and $tW\gamma$ processes are estimated by raising and lowering μ_{r} and μ_{f} by a factor of 2 in MADGRAPH5_AMC@NLO. The PDF uncertainties are evaluated with the NNPDF2.3LO PDF set [26] following the PDF4LHC prescription [73]. The systematic uncertainty associated with the parton shower and hadronisation modelling is estimated by comparing samples generated with MADGRAPH5_AMC@NLO 2.3.3 and interfaced with either PYTHIA 8.212 or HERWIG 7. For the $t\bar{t}\gamma$ process, an additional systematic uncertainty due to initial- and final-state radiation modelling and α_{s} is estimated by varying the “Var3c” parameter [40] in the A14 tune of PYTHIA 8.

Data-driven background: For the $j \to \gamma$ background, a systematic uncertainty is included to account for the limited numbers of data and MC events in the regions used to derive the estimate. This uncertainty is applied separately to each MC process contributing to the estimate, i.e.



(a)

(b)

(c)

(d)

Fig. 2. Comparison between data and prediction ("Pred.") for the four most discriminating BDT input variables after the fit to data ("Post-Fit") under the signal-plus-background hypothesis, shown in the SR. The variables displayed are (a) $m_T(\ell_1, E_T^{\text{miss}})$, (b) $\Delta R(jj)$, (c) $m(\ell\ell)$, and (d) $p_T(j_2)$. The uncertainty band includes both the statistical and systematic uncertainties as obtained from the fit. The rightmost bin includes overflow events. The lower panels show the ratio of data to prediction. Open markers indicate data points lying outside the vertical range of the plot.

$t\bar{t}$, Z + jets, and $VV\gamma$ as detailed in Section 5, and contributes approximately 2.5 % to the measurement uncertainty.

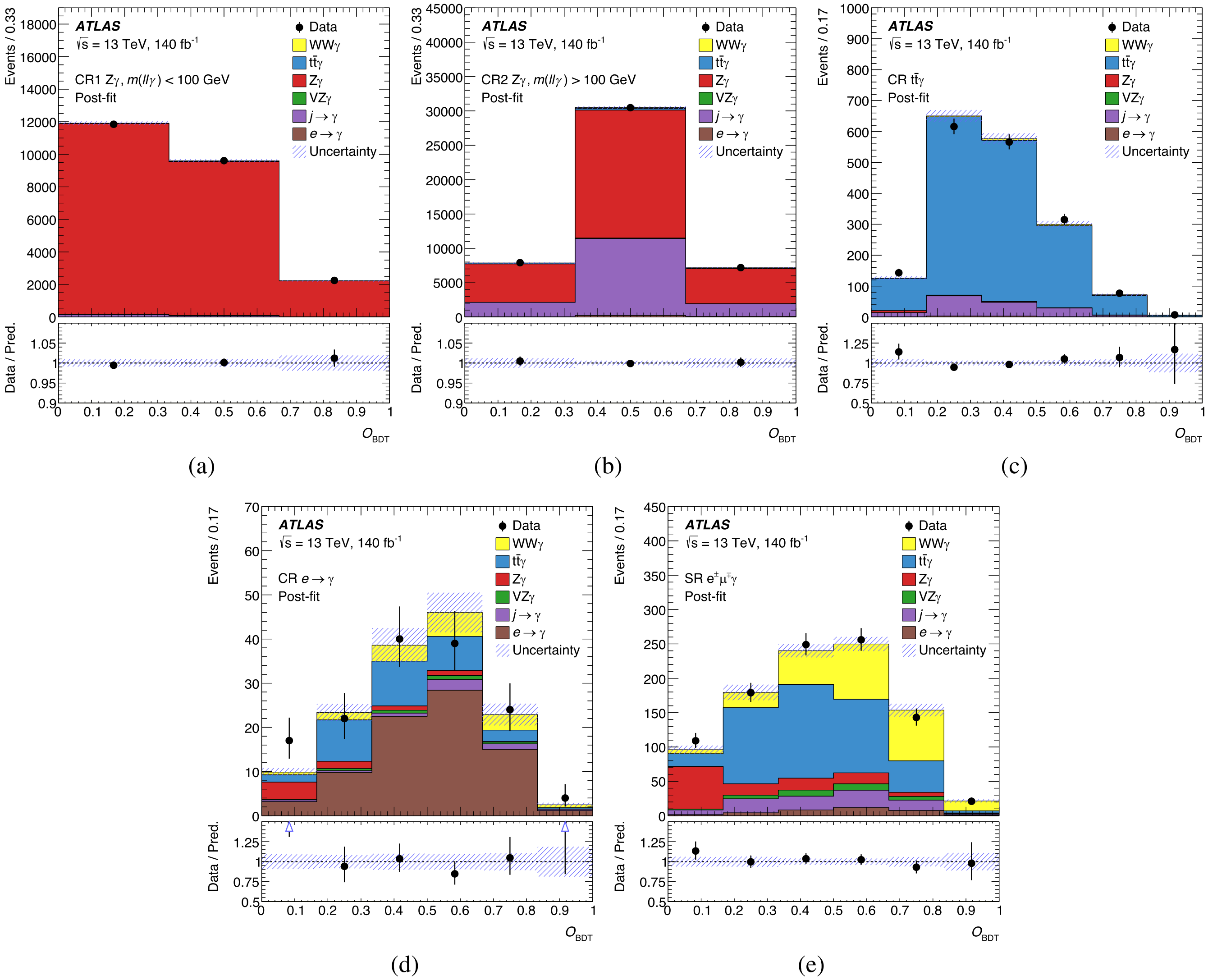
An additional uncertainty associated with the $j \to \gamma$ misidentification is applied separately to processes involving light-flavour jets, such as Z + jets and VV, and to those involving heavy-flavour jets, such as $t\bar{t}$ and tW. The total contribution from $j \to \gamma$ misidentification to the overall uncertainty is approximately 4.5 %.

A systematic uncertainty is assigned to the $e \to \gamma$ background to account for the limited numbers of data and MC events in the $e\gamma$ and $e^{\pm}e^{\mp}$ regions. An additional uncertainty, estimated by using the alternative non-resonant background model described in Section 5, affects the measurement uncertainty by less than 1 %. In total, the data-driven background estimate contributes a 5.4 % uncertainty to the measurement.

Background rate uncertainty: For the $VZ\gamma$ process, a 20 % normalisation uncertainty is applied, motivated by the $WZ\gamma$ measurement [13]. This accounts for uncertainties from the PDFs, renormalisation and factorisation scale variations, and other possible missing higher-order QCD corrections.

8. Results

To extract the $WW\gamma$ signal strength, a simultaneous binned maximum-likelihood fit is performed on the BDT output distributions in the $WW\gamma$ SR and the $t\bar{t}\gamma$, $Z\gamma$ and $e \to \gamma$ CRs. The fit is implemented using the `TRExFitter` framework [74], which builds upon `HistFactory` [75] and `RooFit` [76].



(a) (b) (c)

(d) (e)

Fig. 3. Comparison between data and the post-fit prediction (“Pred.”), under the signal-plus-background hypothesis, from the distributions of the boosted decision tree output (O_{BDT}) in the (a) $Z\gamma$ CR1, (b) $Z\gamma$ CR2, (c) $t\bar{t}\gamma$ CR, (d) $e \to \gamma$ CR, and (e) $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ SR. The uncertainty band includes both the statistical and systematic uncertainties as obtained from the fit.The lower panels show the ratio of data to prediction. The open markers indicate data points lying outside the vertical range of the lower panel in (d).

The BDT trained in the SR is evaluated on the events selected in the corresponding CRs. Five unconstrained fit parameters corresponding to the $WW\gamma$, $t\bar{t}\gamma$, $Z\gamma$, $j \to \gamma$, and $e \to \gamma$ normalisations are included. Nuisance parameters are included in the fit to account for each systematic uncertainty described in Section 7.

Fig. 3 compares the BDT output distribution for the data with those for the post-fit signal and backgrounds. The numbers of fitted signal and background events are compared with the data in Table 3. The normalisation of the $WW\gamma$ signal is $1.03^{+0.22}_{-0.21}$, in good agreement with the SM prediction, and includes the uncertainty from the predicted fiducial cross-section. The measured normalisation parameters for the backgrounds are also consistent with the SM predictions within uncertainties.

To obtain the $WW\gamma$ fiducial production cross-section, a fiducial volume is defined at particle level to closely match the selection criteria of the SR. Events are selected if they contain at least one photon, and one muon and one electron with opposite electric charges. Electrons and muons, excluding those originating from τ-lepton decays, are “dressed” by adding all nearby photons within a cone of size $\Delta R = 0.1$. The dressed leptons are then required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. Final-state photons must be prompt, with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.37$, and satisfy a particle-level isolation requirement: the scalar sum of the transverse energy (E_{T}) of all stable particles, excluding neutrinos, within $\Delta R = 0.2$ of the photon must be less than 7 % of the photon E_{T}, i.e. $E_{\mathrm{T}}^{\mathrm{iso}}/E_{\mathrm{T}}^{\gamma} < 0.07$. Photons within $\Delta R = 0.4$ of a selected muon or electron are discarded.

Table 3
Predicted and observed event yields in the signal region (SR) and control regions (CR). The signal and background predictions are shown after the fit to data. The uncertainties include the statistical and systematic uncertainties of the yields, and also the correlations among nuisance parameters, as well as correlations across signal and background processes because of shared systematic effects.

	SR $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$	CR $t\bar{t}\gamma$	CR1 $Z\gamma$	CR2 $Z\gamma$	CR $e \to \gamma$
$WW\gamma$	250 ± 40	17.7 ± 3.4	42 ± 6	290 ± 40	15.5 ± 2.4
$VZ\gamma$	31 ± 6	3.7 ± 0.8	35 ± 7	123 ± 25	2.7 ± 0.5
$Z\gamma$	119 ± 7	10.7 ± 1.2	$23{,}390 \pm 180$	$29{,}300 \pm 800$	7.7 ± 0.7
$t\bar{t}\gamma$	422 ± 34	1530 ± 90	38.9 ± 3.3	418 ± 33	31.8 ± 2.9
$j \to \gamma$	89 ± 34	160 ± 90	220 ± 80	$15{,}100 \pm 800$	5.5 ± 1.6
$e \to \gamma$	34 ± 5	8.1 ± 1.3	4.4 ± 0.8	330 ± 50	80 ± 13
Total	941 ± 29	1730 ± 40	$23{,}730 \pm 160$	$45{,}560 \pm 230$	143 ± 12
Data	957	1724	23707	45570	146

Table 4

The impact of systematic uncertainties on the measured $WW\gamma$ fiducial cross-section, decomposed into their major categories. For each category, the contribution is obtained by summing in quadrature the impacts of its nuisance parameters. The total systematic uncertainty is calculated similarly by combining all nuisance parameter impacts in quadrature. The statistical uncertainty is calculated as the square root of the difference of the squares of the total uncertainty and the total systematic uncertainty.

Uncertainty source	$\Delta\sigma/\sigma$ [%]
Non-prompt-photon background modelling	5.4
Jet energy scale and resolution	4.1
Jet flavour tagging	3.0
MC statistics	2.9
Signal modelling	2.8
Pile-up modelling	2.5
Lepton reconstruction and calibration	2.3
Prompt-photon background modelling	2.1
Photon reconstruction and calibration	2.0
$E_{\text{T}}^{\text{miss}}$ reconstruction and calibration	1.1
Luminosity	0.9
Total systematic uncertainty	9.6
Statistical uncertainty	12
Total uncertainty	16

Additionally, at least one muon or electron must have $p_{\text{T}} > 27$ GeV. Finally, events with particle-level jets containing b-hadrons are removed, where jets are required to have $p_{\text{T}} > 20$ GeV and $|\eta| < 4.5$. This requirement rejects about 1 % of events when evaluated on the $WW\gamma$ samples. The fiducial cross-section includes non-resonant and off-shell $WW\gamma$ contributions, which amount to <1 % of the predicted fiducial cross-section. Using the signal MC sample described in Section 3, the predicted fiducial cross-section is $\sigma_{\text{fid}} = 6.1^{+1.0}_{-0.7}$ fb. Renormalisation and factorisation scale uncertainties contribute $^{+17}_{-11}$%, evaluated from the envelope of seven-point scale variations where the scales are raised or lowered by a factor of two, excluding combinations where one scale is raised and the other lowered. The PDF uncertainty contributes 0.13 %, evaluated using the RMS of the 100 replicas in the NNPDF3.0NNLO PDF set. An uncertainty of 0.8 % arises from varying the strong coupling constant α_{s} by ± 0.001 via the PDFs named NNPDF30_nnlo_as_119 and NNPDF30_nnlo_as_117.

The measured $WW\gamma$ fiducial production cross-section is $6.2 \pm 0.8\,(\text{stat.}) \pm 0.6\,(\text{sys.})\,\text{fb} = 6.2 \pm 1.0\,\text{fb}$, which corresponds to a total uncertainty of 16 %. The total systematic uncertainty is calculated by combining all nuisance parameter impacts in quadrature. The impact of a nuisance parameter on the signal strength is quantified by the corresponding off-diagonal element of the post-fit covariance matrix [77]. In the case of nuisance parameters representing the MC statistical uncertainty in each bin, their impacts are evaluated by dividing their post-fit off-diagonal elements by their corresponding pre-fit uncertainties. The uncertainty of the measured cross-section is dominated by a statistical uncertainty of 12 %, calculated as the square root of the difference of the squares of the total uncertainty and the total systematic uncertainty. The impact of systematic uncertainties on the measured signal strength is grouped into categories and summarised in Table 4.

The probability of the background processes alone producing a signal-like excess at least as large as that seen in data is derived using the profile-likelihood-ratio test statistic in the asymptotic approximation [78]. The significance of the observed signal is 5.9σ, compared to an expected significance of 6.0σ.

9. EFT interpretation

Potential deviations from the SM predictions, such as in cross-section values or kinematic distributions, are modelled using an EFT framework, which extends the SM Lagrangian to include higher-dimensional operators that parameterise new physics at energy scales beyond the SM. In this analysis, the Eboli parameterisation [17] is used, focusing exclusively on dimension-8 operators acting on quartic gauge-boson couplings. Dimension-6 operators relevant to triple gauge-boson couplings have already been tightly constrained by ATLAS [79–82] and CMS [83–89] analyses of diboson processes. Since the $WW\gamma$ channel offers substantially weaker sensitivity compared with existing diboson measurements, the contributions of dimension-6 operators are not investigated in this analysis.

The $WW\gamma\gamma$ and $WWZ\gamma$ vertices are sensitive to 13 dimension-8 operators defined in Ref. [17], called $\mathcal{O}_{\text{M0}}$, $\mathcal{O}_{\text{M1}}$, $\mathcal{O}_{\text{M2}}$, $\mathcal{O}_{\text{M3}}$, $\mathcal{O}_{\text{M4}}$, $\mathcal{O}_{\text{M5}}$, $\mathcal{O}_{\text{M7}}$, $\mathcal{O}_{\text{T0}}$, $\mathcal{O}_{\text{T1}}$, $\mathcal{O}_{\text{T2}}$, $\mathcal{O}_{\text{T5}}$, $\mathcal{O}_{\text{T6}}$, and $\mathcal{O}_{\text{T7}}$. Each operator is associated with a Wilson coefficient (f_i), which parametrises the strength of the corresponding higher-dimensional interaction. These operators correspond to two classes of mixed-scalar operators, consisting of two covariant derivatives of the Higgs field and two field-strength tensors, and tensor-type operators, consisting of four field-strength tensors.

The effects of higher-dimensional beyond-the-SM (BSM) operators are more pronounced at high photon p_{T}. To enhance the sensitivity of the analysis to such effects, the SR used for the SM $WW\gamma$ measurement is split into two regions: a one-bin high-$p_{\text{T}}(\gamma)$ signal region with $p_{\text{T}}(\gamma) > 500$ GeV, and a CR with $p_{\text{T}}(\gamma) < 500$ GeV, where the BDT distribution is used. The threshold at 500 GeV is chosen to optimise the expected signal-to-background ratio for BSM contributions, resulting in negligible BSM sensitivity in all CRs including the low-$p_{\text{T}}(\gamma)$ CR, while maximising it in the high-$p_{\text{T}}(\gamma)$ bin. The photon p_{T} distribution used to define these regions is provided in the Appendix A. The expected yield, including the SM $WW\gamma$ contribution, in the high-$p_{\text{T}}(\gamma)$ region is 2.24 ± 0.31, whereas one event is observed in data.

A simultaneous binned maximum-likelihood fit is performed for each dimension-8 operator independently, neglecting possible interference between operators, and using the high-$p_{\text{T}}(\gamma)$ EFT region together with the CRs, following the same set-up as in the $WW\gamma$ measurement. The SM background normalisations, including that of SM $WW\gamma$, are treated as free parameters in the likelihood fit. Additional unconstrained fit parameter is defined such that f_i^2 is the normalisation factor of events arising from BSM contributions, while events arising from interference between SM and BSM amplitudes are scaled by f_i. Additional modelling uncertainties for the BSM contributions are taken into account, including those from the PDF, μ_{r} and μ_{f}. A one-dimensional 95 % confidence interval (CI) for each Wilson coefficient is derived from the profile-likelihood curves using the criterion $-2 \cdot \Delta \ln \mathcal{L} = 3.84$, as prescribed by Wilks' theorem [90].

The expected and observed 95 % CIs for the Wilson coefficients are presented in Table 5. The sensitivity is statistically limited: including all systematic uncertainties changes the expected interval widths by less than 1 %. These limits are comparable to limits obtained from vector-boson scattering measurements and $Z(\nu\nu)\gamma$ [65], $W\gamma jj$ [91] and VVZ productions [15].

Limits on the dimension-8 Wilson coefficients are also evaluated as functions of a cut-off scale, $\sqrt{\hat{s}}$, using the clipping technique [92]. For events with $\sqrt{\hat{s}}$ greater than the cut-off, the EFT contribution is set to zero. The unitarity bounds for aQGC operators, as derived in Ref. [93], are formulated for 2-to-2 scattering processes in proton-proton collisions. To extend these bounds to $WW\gamma$ production, $\sqrt{\hat{s}}$ is set to the maximum of the three diboson invariant mass combinations, $\max(m_{V_iV_j})$.

The most stringent limit respecting unitarity is found at the intersection of the calculated limits with the unitarity bounds. Among the 13 coefficients investigated, four coefficients exhibit a range of values that respect unitarity: $[-9.5, 9.5]$ TeV^{-4} at $\sqrt{\hat{s}} = 1.9$ TeV for f_{M3}/Λ^4, $[-10, 10]$ TeV^{-4} at 2.0 TeV for f_{M5}/Λ^4, $[-4, 4]$ TeV^{-4} at 1.5 TeV for f_{T6}/Λ^4, and $[-10.5, 10.5]$ TeV^{-4} at 1.5 TeV for f_{T7}/Λ^4. Fig. 4 shows the 95 % CI for the f_{M3}/Λ^4 Wilson coefficient as a function of the cut-off scale applied to restore unitarity.

Table 5
Expected and observed non-unitarised 95 % CIs for the 13 dimension-8 Wilson coefficients The expected CIs are derived from an Asimov dataset constructed in two steps: first, the control regions, including the SM $WW\gamma$ CR, are fitted assuming no EFT contribution to extract the background normalisations; second, a signal-plus-background fit is performed using an Asimov dataset built from these fitted normalisations.

EFT operator	Expected 95 % CI [TeV^{-4}]	Observed 95 % CI [TeV^{-4}]
$f_{\mathrm{M0}}/\Lambda^4$	[−8, 8]	[−6, 6]
$f_{\mathrm{M1}}/\Lambda^4$	[−13, 13]	[−10, 10]
$f_{\mathrm{M2}}/\Lambda^4$	[−3.1, 3.1]	[−2.5, 2.5]
$f_{\mathrm{M3}}/\Lambda^4$	[−5, 5]	[−4, 4]
$f_{\mathrm{M4}}/\Lambda^4$	[−8, 8]	[−6, 6]
$f_{\mathrm{M5}}/\Lambda^4$	[−6, 6]	[−5, 5]
$f_{\mathrm{M7}}/\Lambda^4$	[−26, 26]	[−21, 21]
$f_{\mathrm{T0}}/\Lambda^4$	[−1.4, 1.4]	[−1.1, 1.1]
$f_{\mathrm{T1}}/\Lambda^4$	[−1.7, 1.7]	[−1.4, 1.3]
$f_{\mathrm{T2}}/\Lambda^4$	[−4, 4]	[−3.1, 3.0]
$f_{\mathrm{T5}}/\Lambda^4$	[−1.1, 1.1]	[−0.9, 0.9]
$f_{\mathrm{T6}}/\Lambda^4$	[−1.3, 1.3]	[−1.1, 1.1]
$f_{\mathrm{T7}}/\Lambda^4$	[−3.0, 3.0]	[−2.4, 2.4]

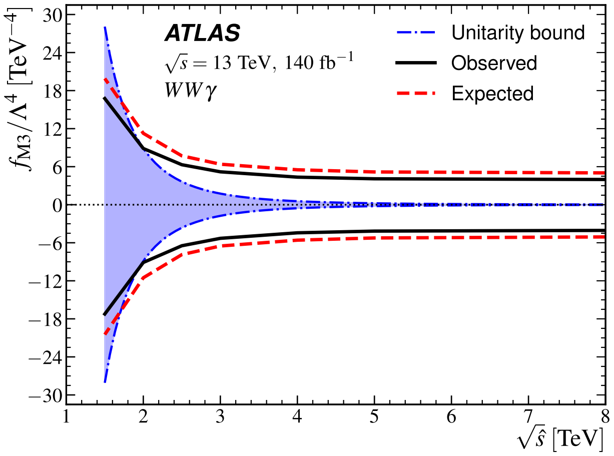


Fig. 4. The 95 % confidence interval of the $f_{\mathrm{M3}}/\Lambda^4$ Wilson coefficient as a function of the energy threshold used in the clipping method to restore unitarity. The blue dash-dotted lines indicate the unitarity bound. The black solid lines show the observed upper and lower limits, while the red dashed lines show the expected upper and lower limits.

10. Conclusion

The production of $WW\gamma$ events is observed with a significance of 5.9σ, compared to an expected significance of 6.0σ, using the $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ final state and 140 fb^{-1} of data from 13 TeV proton–proton collisions recorded by the ATLAS detector at the LHC between 2015 and 2018.

The measured fiducial cross-section in the $e^{\pm}\mu^{\mp}\nu\bar{\nu}\gamma$ final state is $6.2 \pm 0.8\,(\mathrm{stat.}) \pm 0.6\,(\mathrm{sys.})$ fb $= 6.2 \pm 1.0$ fb, corresponding to a total uncertainty of 16 %. This measurement is in good agreement with the SM prediction of $6.1^{+1.0}_{-0.7}$ fb, calculated at NLO in QCD for $WW\gamma$ + 0-jet events and at LO for events with one or two additional jets.

In addition, constraints at the 95 % confidence level are set on 13 dimension-8 EFT Wilson coefficients within the effective field theory framework. These constitute the first limits from the $WW\gamma$ channel, probing aQGC at high photon transverse momentum. They are complementary to existing multiboson results and provide valuable input to the global EFT interpretation of QGC.

Declaration of interests

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.

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Appendix A.

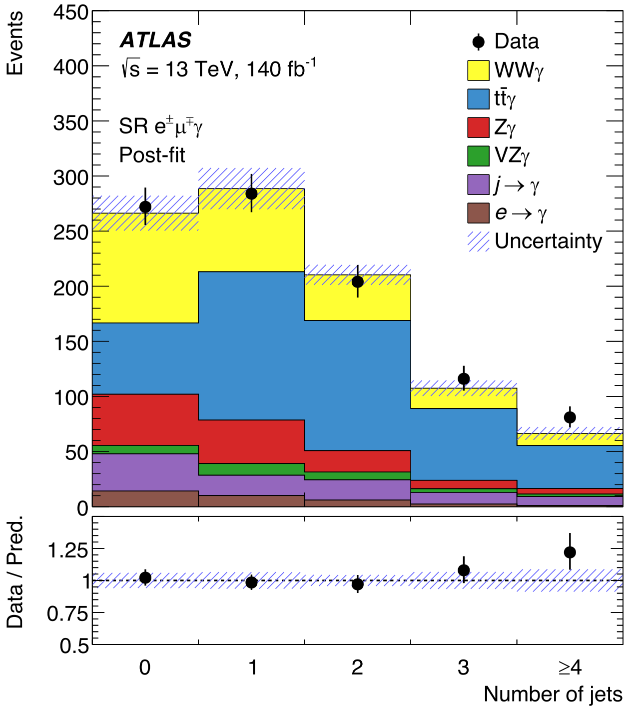

Fig. A.5. Comparison between data and prediction ("Pred.") for the jet multiplicity distribution after the fit to data ("Post-Fit") under the signal-plus-background hypothesis, shown in the SR. The uncertainty band includes both statistical and systematic uncertainties as obtained from the fit. The rightmost bin includes overflow events.

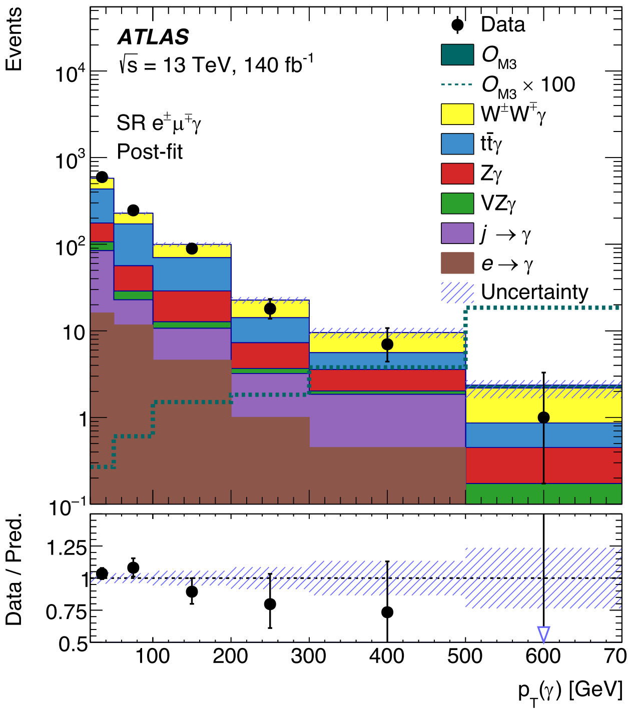

Fig. A.6. Comparison between data and prediction ("Pred.") for the photon p_{T} distribution after the fit to data ("Post-fit") under the signal-plus-background hypothesis including $\mathcal{O}_{\mathrm{M3}}$ operator, shown in the $WW\gamma$ SR. The uncertainty band includes both statistical and systematic uncertainties as obtained from the fit.The rightmost bin includes overflow events.The contribution of the Wilson coefficient $f_{\mathrm{M3}}/\Lambda^4$ is shown as shaded teal area and is normalised to the prediction for a coefficient value of 1 TeV^{-4}. The dashed teal line corresponds to the same prediction multiplied by a factor of 100. The EFT sensitivity is enhanced when the photon p_{T} is above 500 GeV.

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