Cross-section measurements for the production of a Z boson in association with high-transverse-momentum jets in pp collisions at √s = 13 TeV with the ATLAS detector

The ATLAS Collaboration

DOI
10.1007/JHEP06(2023)080

Publication date
2023

Document Version
Final published version

Published in
Journal of High Energy Physics

License
CC BY

Citation for published version (APA):
Cross-section measurements for the production of a $Z$ boson in association with high-transverse-momentum jets in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: Cross-section measurements for a $Z$ boson produced in association with high-transverse-momentum jets ($p_T \geq 100$ GeV) and decaying into a charged-lepton pair ($e^+e^-, \mu^+\mu^-$) are presented. The measurements are performed using proton–proton collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 139 fb$^{-1}$ collected by the ATLAS experiment at the LHC. Measurements of angular correlations between the $Z$ boson and the closest jet are performed in events with at least one jet with $p_T \geq 500$ GeV. Event topologies of particular interest are the collinear emission of a $Z$ boson in dijet events and a boosted $Z$ boson recoiling against a jet. Fiducial cross sections are compared with state-of-the-art theoretical predictions. The data are found to agree with next-to-next-to-leading-order predictions by NNLOjet and with the next-to-leading-order multi-leg generators MadGraph5_AMC@NLO and Sherpa.

KEYWORDS: Electroweak Interaction, Hadron-Hadron Scattering

ArXiv ePrint: 2205.02597
1 Introduction

The measurement of Z-boson production\(^1\) in association with jets, Z + jets, constitutes a powerful test of perturbative quantum chromodynamics (QCD) \([1, 2]\) and, in the case of high-energy jets, it provides a way to probe the interplay between QCD and higher-order electroweak (EW) processes \([3–6]\). The large Z + jets production cross section and the easily identifiable decays of the Z boson to charged-lepton final states offer a clean experimental signature which can be measured precisely. Such processes also constitute non-negligible backgrounds in measurements of the Higgs boson \([7, 8]\) and in searches for new phenomena \([9–11]\), which often exploit the presence of high-\(p_T\) jets to enrich a data sample with potential signal. In those studies, predictions are used to extrapolate Z + jets backgrounds from control regions to the signal regions and to model the distributions of the final discriminants.

In the calculations of Z + 1-jet production at leading order (LO), the Z boson recoils against a quark or a gluon. At next-to-leading order (NLO), real and virtual QCD and EW effects play a role in Z + jets production, such as in topologies corresponding to dijet events where a real Z boson is emitted from an incoming or outgoing quark leg \([3–6]\).

\(^1\)Throughout this paper, Z/\(\gamma^*\)-boson production is simply referred to as Z-boson production.
Example Feynman diagrams for LO and NLO $Z$ + jets production processes are shown in figure 1. The latter case can lead to production rate enhancements proportional to $\alpha_s \ln^2(p_{T,j1}/m_Z)$, where $\alpha_s$ is the strong coupling constant, $p_{T,j1}$ the transverse momentum of the leading jet, and $m_Z$ the mass of the $Z$ boson, and thus the effect can become very large for events with high-$p_T$ jets. These events exhibit a collinear enhancement in the distribution of the angular distance between the $Z$ boson and the closest jet. Although the enhancement can be probed in the region of small angular separation, this region also contains contributions where the $Z$ boson is produced in association with larger numbers of jets, which must be included in the predictions. The measurements presented in this paper target QCD-only $Z$ + jets production, treating EW $Z$ + 2-jets ($EWZjj$) production [12] as a background. Measurements where the EW $Zjj$ contribution is treated as signal and not subtracted as background are also performed and published in the HEPData entry [13] of this measurement.

The ATLAS Collaboration [14] at the Large Hadron Collider (LHC) [15] first measured angular distributions in high-$p_T W$ boson production with jets ($W$+jets) in the 8 TeV $pp$-collision data set [16]. The first similar measurement in $Z$ + jets events was published by the CMS Collaboration and used a partial 13 TeV data set corresponding to 35.9 fb$^{-1}$ [17]. Both measurements highlight the fact that the collinear region, where the angular separation between the $W/Z$ boson and the closest jet is small, represents a major challenge for contemporary Monte Carlo (MC) generators. The measurements presented in this paper include a wide range of new observables sensitive to the presence of high-$p_T$ jets and to the collinear emission of a $Z$ boson in dijet events. The statistical power of the full LHC Run-2 data set makes it possible to tighten the collinear selection, and to measure key observables separately for collinear and non-collinear topologies.

This publication focuses on events that contain a $Z$-boson candidate reconstructed from either an $e^+e^-$ or $\mu^+\mu^-$ pair in association with hadronic jets defined as jets having transverse momentum greater than or equal to 100 GeV. The phase-space region with at least one associated jet is labelled as the inclusive region. In this region, the measured quantities are the transverse momentum of the leading jet ($p_{T,j1}$), the transverse momentum of the $Z$ boson ($p_{T,\ell\ell}$), the scalar sum of the transverse momentum of all selected jets and leptons ($H_T$), and the jet multiplicity. A high-$p_T$ region is selected by requiring the presence of a jet with $p_T \geq 500$ GeV. To test the prediction that this region is composed of two characteristic topologies, the soft radiation of a $Z$ boson from a jet (collinear topology) and the hard scatter of a $Z$ boson against a jet (back-to-back topology), the high-$p_T$ region is split to cover different ranges of the angle between the $Z$ boson and the closest jet, and selected key observables are measured separately for each region. In the high-$p_T$ region, the following observables sensitive to the presence of collinear $Z$-boson emission are studied:

- $\Delta R_{Z,j}^{\text{min}}$, the angular distance$^2$ between the $Z$ boson and the closest jet. Real $Z$-boson radiation is expected to be enhanced at low values of $\Delta R_{Z,j}^{\text{min}}$. At large values of

$^2$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 $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle
Figure 1. Representative Feynman diagrams for the production of a $Z$ boson in association with high-$p_T$ jets. The $Z+1$-jet events (left) are expected to populate the back-to-back region where the $Z$ boson is balanced against a single high-$p_T$ jet. In dijet events (right), the $Z$ boson is expected to be radiated from the quark leg, with kinematics leading to small values of the angular distance between the $Z$ boson and the closest jet, $\Delta R_{Z,j}^{\text{min}}$, and therefore populating the collinear region.

$\Delta R_{Z,j}^{\text{min}}$, the $Z$ boson is balanced by a recoiling jet and large virtual EW corrections are expected. To enrich these two topologies, collinear and back-to-back regions are constructed by requiring $\Delta R_{Z,j}^{\text{min}} \leq 1.4$ and $\Delta R_{Z,j}^{\text{min}} \geq 2.0$, respectively.

- $r_{Z,j}$, the ratio of the $Z$-boson $p_T$ to the closest-jet $p_T$, defined as
  \[ r_{Z,j} \equiv \frac{p_T,\ell\ell}{p_T(\text{closest jet})}. \]

Collinear $Z$-boson radiation is expected to be dominated by soft $Z$ bosons, resulting in very small values for this ratio.

- $N_{\text{jets}}$, the jet multiplicity. The back-to-back region is expected to be dominated by $Z+1$-jet events, whereas the collinear region would be dominated by $Z+2$-jets events.

The measurements of jet multiplicity and $r_{Z,j}$ are performed both in the full high-$p_T$ region and separately in the collinear and back-to-back regions.

Measurements of jet multiplicity and $\Delta R_{Z,j}^{\text{min}}$ are also performed in an alternative high-energy region, constructed by requiring the scalar sum of the transverse momentum of all selected jets, $S_T$, to be at least 600 GeV. This alternative region probes high-energy events but does not depend on the presence of a single very energetic object. In this region, called the high-$S_T$ region, a large fraction of the events have higher jet multiplicity.

Predictions from the most recent generators combine NLO multi-leg matrix elements (ME) with a parton shower (PS) and hadronisation model [18–21]. Fixed-order parton-level theoretical predictions for $Z+\text{jets}$ production at next-to-next-to-leading order (NNLO) are available for up to one associated jet [22–25]. In this paper, the cross-section measurements are compared with state-of-the-art multi-leg ME+PS generators and NNLO fixed-order

\[ \theta \] as $\eta = -\ln \tan(\theta/2)$. The angular distance is defined as $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$. When dealing with massive jets and particles, the rapidity $y = (1/2) \ln ((E + p_z)/(E - p_z))$ is used, where $E$ is the jet/particle energy and $p_z$ is the z-component of the jet/particle momentum.
Z + jets predictions from NNLOjet [24, 25]. Virtual EW corrections were made available recently [26, 27] and are included in one of the SHERPA [19] predictions studied in this paper.

The paper is organised as follows. Section 2 contains a brief overview of the ATLAS detector. The data and simulated samples, as well as additional predictions used in the analysis, are described in section 3. The object definition and the event reconstruction at detector level are presented in section 4, while section 5 describes the background modelling and presents a comparison of measured and predicted yields at detector level. After background subtraction, the data are unfolded to particle level in a fiducial phase space with a procedure described in section 6. The experimental and theoretical systematic uncertainties are estimated in section 7. Section 8 presents the unfolded cross-section results and the comparisons with predictions. Conclusions are provided in section 9.

2 ATLAS detector

The ATLAS experiment at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range |η| < 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 (|η| < 1.7). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to |η| = 4.9. The muon spectrometer 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 tracking chambers 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 kHz on average depending on the data-taking conditions. An extensive software suite [28] is used 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 set and simulated event samples

The data used in this analysis were recorded with the ATLAS detector from 2015 to 2018 in pp collisions at \( \sqrt{s} = 13 \) TeV (full Run-2 data set) and correspond to a total integrated luminosity of 139 fb\(^{-1} \) [29]. The mean number of pp interactions per bunch crossing, including the hard scattering and other interactions in the same and neighbouring bunch crossings (pile-up), was \( \langle \mu \rangle = 34 \).
Table 1. Summary of the programs used to produce the signal and the various background samples.

For every process the name of the program used is indicated in the second column. The third column reports the order of the QCD calculation in the matrix elements, where $n_p$ denotes the number of real parton emissions. The Sherpa 2.2.11 $Z + \text{jets}$ processes include virtual electroweak corrections.

MC simulation samples are used to estimate most of the contributions from background events, to unfold the data to particle level, and in comparisons with the unfolded data distributions. The generated samples were processed using the Geant4-based ATLAS detector simulation [30, 31] and the same event-reconstruction algorithms are used for both the MC samples and the data. A summary of the MC generators and calculations used for the simulation of signal and background processes is provided in table 1.

The production of $Z$ bosons in association with jets was simulated with the ATLAS configuration of Sherpa 2.2.11 [19], which includes matrix elements for up to five partons at LO and up to two partons at NLO. They are calculated with the Comix [32] and OpenLoops [33–35] libraries and matched with the Sherpa parton shower [36] using the MEPS@NLO prescription [37–40] with a set of tuned parameters (‘tune’) developed by the Sherpa authors. In contrast to Sherpa 2.2.1 [18], used previously in ATLAS publications, it includes a modified Catani–Seymour subtraction scheme [41], the Hessian NNPDF3.0nnlo PDF set [42] is used, and an analytic enhancement technique has been introduced [19]. The cross section in the high-$p_T$ region has been considerably reduced relative to the prediction from the previous Sherpa version by switching to an improved matching scheme with a different treatment of unordered histories [40]. Sherpa 2.2.11 is also the only sample used in this paper which includes NLO virtual EW corrections [34, 35]. The samples were produced using three options for the combination of NLO EW and QCD corrections: an additive, a multiplicative, and an exponential scheme. The nominal prediction is derived via the additive scheme; a systematic uncertainty band is derived...
from the envelope of all schemes. In contrast to virtual EW corrections, EW parton showers are not included in any of the generators used in this paper. The SHERPA 2.2.11 Z + jets samples are used for the nominal unfolding of the data distributions, to estimate the systematic uncertainties and in comparisons with the cross-section measurements.

A second Z + jets sample, referred to as MG5_AMC+Py8 FxFx [19], was produced by using the MADGRAPH5_AMC@NLO 2.6.5 [43] program to generate matrix elements at NLO accuracy in QCD for up to three additional partons in the final state. The NNPDF3.1nnlo set [42] was used in the generation. The parton showering and subsequent hadronisation was performed using PYTHIA 8.240 [21] with the A14 tune [44] and the NNPDF2.3LO PDF set [45]. The jet multiplicities were merged using the FxFx prescription [20]. This prediction is compared with the unfolded cross-section measurements.

A third sample of Z + jets events and an event sample from W + jets processes were produced with the SHERPA 2.2.1 [18] generator using NLO matrix elements for up to two partons, and LO matrix elements for up to four partons, calculated with the Comix and OPENLOOPS libraries. They were matched with the SHERPA parton shower using the MEPS@NLO prescription with a set of tuned parameters developed by the SHERPA authors. The MC replica version of the NNPDF3.0nnlo set of PDFs was used. The SHERPA 2.2.1 Z + jets sample is used in comparisons with the unfolded cross-section measurements, as it was used as a standard in previous ATLAS Run-2 publications.

A fourth Z + jets sample, referred to as MG5_AMC+Py8 CKKWL, was generated using LO-accurate matrix elements with up to four final-state partons calculated by MADGRAPH5_AMC@NLO 2.2.2 [43]. The ME calculation employed the NNPDF3.0nlo PDF set and was interfaced to PYTHIA 8.186 [46] for the modelling of the parton shower, hadronisation, and underlying event. The overlap between matrix element and parton shower emissions was removed using the CKKW-L merging procedure [47, 48]. The A14 tune of PYTHIA was used with the NNPDF2.3LO PDF set. This sample is used to validate the unfolding method and in comparisons with the unfolded cross-section measurements.

Two additional Z + jets samples were generated with the NNLOJET program [24, 25], which computes fixed-order parton-level predictions for inclusive jet processes at higher orders in QCD. The NLO and NNLO predictions, referred to as NNLOJET@NLO and NNLOJET@NNLO, respectively, were calculated as higher-order corrections to the parton-level LO process of Z + 1-jet production. The NNPDF3.1nnlo set was used with a central scale choice of \( \mu_0 = \frac{1}{2}(E_{T,Z} + \sum_{i \in \text{partons}} p_{T,i}) \) with \( E_{T,Z} = \sqrt{p_{T,Z}^2 + m_{\ell\ell}^2} \). These samples are pure QCD predictions at parton level. To match the fiducial selection of the measurement (see section 6), scale factors to correct from the Born level to the dressed-lepton level are computed and applied to these predictions. The slightly different overlap-removal procedure for jets and leptons used in these samples, due to the NNLOJET program design, is addressed by overlap-removal correction scale factors. Both sets of scale factors, deviating from unity at the percent level and computed separately for each bin of the measured observables, are published in the HEPData entry [13] of this measurement. Non-perturbative corrections are found to be consistent with zero when \( p_{T,j} \) exceeds 100 GeV and are not needed to match the fiducial selection of these measurements. These samples are used in comparisons with the unfolded cross-section measurements.
The EW $Zjj$ process is defined by the $t$-channel exchange of a weak boson and at tree level is calculated at $\mathcal{O}(\alpha_{em}^2)$ when including the decay of the $Z$ boson [12]. In contrast, the strong $Zjj$ process, which is covered by the $Z +$ jets samples, has no weak boson exchanged in the $t$-channel and at tree level is calculated at $\mathcal{O}(\alpha_{em}^2 \alpha_s^2)$ when including the decay of the $Z$ boson. The EW $Zjj$ samples were produced in the vector-boson fusion (VBF) approximation with HERWIG 7.1.5 [49, 50] at NLO accuracy in the strong coupling, using VBFNLO 3.0.0 [51] to provide the loop amplitude. The MMHT2014lo PDF set [56] was used along with the default set of tuned parameters for parton showering, hadronisation and the underlying event. To account for the interference between strong $Zjj$ and EW $Zjj$ processes, a uniform modelling uncertainty of 25% in the EW $Zjj$ cross section (40% in the collinear region), determined from simulation with MadGraph5_aMC@NLO 2.9.5, is applied [12].

The $t\bar{t}$ background in this measurement is derived with a data-driven method as described in section 5. The MC $t\bar{t}$ events used for intermediate steps of the method were modelled using the POWHEG BOX v2 [52–55] generator at NLO with the NNPDF3.0nlo PDF set and the $h_{\text{damp}}$ parameter\(^3\) set to 1.5 $m_{\text{top}}$ [57]. The events were interfaced to PYTHIA 8.230 [21] to model the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune and using the NNPDF2.3lo set of PDFs. The $t\bar{t}$ sample is normalised to the cross-section prediction at NNLO accuracy, including the resummation of next-to-next-to-leading logarithmic (NNLL) soft-gluon terms calculated with Top++ 2.0 [58–64].

Single top quark production in the $s$-channel, in the $t$-channel, and in association with a $W$ boson ($tW$) was modelled using the POWHEG BOX v2 generator at NLO in QCD with the five-flavour scheme and the NNPDF3.0nlo set of PDFs. The diagram-removal scheme [65] was used to remove interference and overlap with $t\bar{t}$ production. The $tW$ cross section is corrected to the theory prediction at approximate NNLO accuracy [66, 67], while the $s$- and $t$-channel cross sections are corrected to the prediction at NLO accuracy [68, 69].

Samples of diboson final states ($VV$) were produced with the SHERPA 2.2.1 or SHERPA 2.2.2 generator depending on the process, including off-shell effects and Higgs boson contributions where appropriate. Fully leptonic final states and semileptonic final states, where one boson decays leptonically and the other hadronically, were generated using matrix elements at NLO accuracy in QCD for up to one additional parton and at LO accuracy for up to three additional parton emissions. The matrix element calculations were matched and merged with the SHERPA parton shower as detailed above for SHERPA 2.2.1, and the NNPDF3.0nnlo set of PDFs was used.

The production of $V + \gamma$ final states was simulated with the SHERPA 2.2.8 [18] generator. Matrix elements at NLO QCD accuracy for up to one additional parton and LO accuracy for up to three additional parton emissions were matched and merged with the SHERPA parton shower as detailed above for SHERPA 2.2.1, and the NNPDF3.0nnlo set of PDFs was used.

\(^3\)The $h_{\text{damp}}$ parameter is a resummation damping factor and one of the parameters that control the matching of POWHEG matrix elements to the parton shower and thus effectively regulates the high-$p_T$ radiation against which the $t\bar{t}$ system recoils.
Background events involving semileptonic decays of heavy quarks, hadrons misidentified as leptons, and, in the case of the electron channel, electrons from photon conversions are referred to collectively as ‘multijet events’. The multijet background is estimated using data-driven techniques, as described in section 5.

For bottom and charm hadron decays, the EvtGen 1.7.0 program \cite{70} was used for MG5_AMC+PY8 FxFX samples, and EvtGen 1.2.0 was used for all other MadGraph and POWHEG samples. The effect of multiple interactions in the same and neighbouring bunch crossings (pile-up) was modelled by overlaying the simulated hard-scattering event with inelastic pp events generated with PYTHIA 8.186 \cite{46} using the NNPDF2.3lo PDF and the A3 tune \cite{71}. The small differences in lepton reconstruction, isolation, and trigger efficiencies between simulation and data are corrected in the simulation on an event-by-event basis by applying efficiency scale factors for each lepton \cite{72–74}.

4 Event reconstruction

Events are used if they were recorded during stable beam conditions and if they satisfy detector and data-quality requirements \cite{75}. They are required to have a primary vertex, defined as the vertex with the highest sum of track $p_T^2$, with at least two associated tracks with $p_T > 500\text{ MeV}$ \cite{76}. Events are selected using triggers \cite{77–79} that require at least two electrons or two muons, or the combination of at least one electron and one muon; the efficiencies for these triggers plateau in the region of $p_T > 25\text{ GeV}$.

Electron candidates are reconstructed from inner-detector tracks which come from the primary vertex and are matched to clusters of energy deposits in the EM calorimeter. To fulfil the primary-vertex condition, the electron track’s transverse impact parameter significance must satisfy $|d_0|/\sigma(d_0) < 5.0$, where $d_0$ is the transverse impact parameter and $\sigma(d_0)$ its uncertainty, and the longitudinal impact parameter $z_0$ must satisfy $|z_0\sin(\theta)| < 0.5 \text{ mm}$, where $\theta$ is the angle of the track to the beamline. Electron candidates must satisfy the ‘Medium’ likelihood-based identification requirements \cite{72} based on EM shower shapes, track quality, and track–cluster matching. They must also satisfy the ‘PflowLoose’ \cite{72} isolation requirement. Electron candidates are used in the analysis if they have $p_T \geq 25\text{ GeV}$ and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$.

Muon candidates are identified by matching inner-detector tracks from the primary vertex to either full tracks or track segments reconstructed in the muon spectrometer. The candidates must satisfy the following primary-vertex requirements: the transverse impact parameter significance must satisfy $|d_0|/\sigma(d_0) < 3.0$ and the longitudinal impact parameter must satisfy $|z_0\sin(\theta)| < 0.5 \text{ mm}$, where $d_0$, $\sigma(d_0)$, $z_0$ and $\theta$ are as defined above for the electrons. Muons are required to pass ‘Medium’ identification requirements \cite{73, 74} based on quality criteria applied to the inner-detector and muon-spectrometer tracks. Muon candidates with $p_T \geq 300\text{ GeV}$ must satisfy tighter identification requirements in the muon spectrometer in order to improve the muon-$p_T$ resolution. Muons must also satisfy the ‘PflowLoose’ isolation requirement, built from tracking and calorimeter information, with a muon-$p_T$-dependent variable cone size $\Delta R$ \cite{74}. Muon candidates are used in the analysis if they have $p_T \geq 25\text{ GeV}$ and $|\eta| < 2.4$. 
Jets of hadrons are reconstructed using a particle-flow algorithm \cite{80} based on noise-suppressed positive-energy topological clusters in the calorimeter. Energy deposited in the calorimeter by charged particles is subtracted and replaced by the momenta of tracks which are matched to those topological clusters. The jets are clustered using the anti-$k_t$ \cite{81} algorithm implemented in the FastJet package \cite{82} with a radius parameter $R = 0.4$. They are further calibrated according to in situ measurements of the jet energy scale \cite{83}. Analysis jets are required to have a calibrated $p_T \geq 100 \text{ GeV}$ and $|y| < 2.5$.

Electrons, muons and jets are reconstructed and identified independently. An overlap-removal procedure is then applied to uniquely identify these objects in an event. For the lepton–jet overlap removal, softer jets with $p_T \geq 30 \text{ GeV}$ and $|y| < 2.5$ are considered. Preselected jets with a high probability to have been initiated by an electron or a radiated photon such that $\Delta R$ between the jet and a lepton is smaller than 0.2 are removed. In a second step, leptons closer than $\Delta R = 0.4$ to any remaining jet are removed.

Events are selected if they contain a $Z$-boson candidate reconstructed from two same-flavour, opposite-charge leptons ($\ell = e, \mu$) and with dilepton invariant mass $71 \text{ GeV} \leq m_{\ell\ell} \leq 111 \text{ GeV}$. The selected events are also required to contain at least one analysis jet. Events which satisfy the above selection requirements define the inclusive $Z + \text{jets}$ region. A dedicated high-$p_T$ region is created by requiring the leading jet to have $p_{T,j1} \geq 500 \text{ GeV}$. This latter region is split into the collinear region, where the angular distance between the $Z$ boson and the closest jet must be $\Delta R_{Z,j}^{\text{min}} \leq 1.4$, and the back-to-back region that requires $\Delta R_{Z,j}^{\text{min}} \geq 2.0$. An alternative phase space is also defined by requiring $S_T \geq 600 \text{ GeV}$, labelled as the high-$S_T$ region, where $S_T$ is defined as the scalar sum of the $p_T$ of the analysis jets.

5 Background estimation

Backgrounds from single-boson, diboson and single-top-quark processes are estimated using the MC samples described in section 3, while top-pair production and ‘multijet event’ contributions from semileptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversions are estimated from data. A summary of the composition and relative importance of the backgrounds in the various signal regions is given in table 2. The overall purity of the $Z + \text{jets}$ selections (defined as the expected fraction of signal events after the final selection) ranges from 94% in the inclusive region to 87%, 86%, 87% and 88% in the high-$p_T$, collinear, back-to-back and high-$S_T$ regions, respectively. Backgrounds are dominated by $t\bar{t}$, diboson and EW $Zjj$ processes, with fractions of 2%–5%, 2%–6% and 1%–5%, respectively. The fraction of events arising from $Z \rightarrow \tau^+\tau^-$, $W + \text{jets}$, $V + \gamma$, and multijet backgrounds is below the percent level in all signal regions.

The $t\bar{t}$ background is evaluated with a data-driven methodology. A $t\bar{t}$-enriched control region is constructed with the same event selection as the signal region, but with $e^\pm\mu^\mp$ final states instead of the same-flavour $e^+e^-$ or $\mu^+\mu^-$ pairs. This control region contains only percent-level contributions from $Z + \text{jets}$, $W + \text{jets}$, diboson, single-top and $Z \rightarrow \tau^+\tau^-$ events. The prediction for the $t\bar{t}$ distributions in the signal region is obtained by multiplying the corresponding measured distributions in the control region (after subtracting the non-$t\bar{t}$
Table 2. Event yields in the different $Z +$ jets signal regions in the electron and muon channels. Uncertainties correspond to the statistical and experimental systematic uncertainties added in quadrature. The $Z +$ jets prediction is computed with Sherpa 2.2.11. The number of multijet events is negligible and not included.

<table>
<thead>
<tr>
<th>$Z \rightarrow e^+e^-$</th>
<th>Inclusive</th>
<th>High-$p_T$</th>
<th>Collinear</th>
<th>Back-to-back</th>
<th>High-$S_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z +$ jets</td>
<td>1171000 ± 49000</td>
<td>6150 ± 310</td>
<td>2520 ± 120</td>
<td>2520 ± 150</td>
<td>18300 ± 800</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>44000 ± 1300</td>
<td>209 ± 16</td>
<td>136 ± 13</td>
<td>472 ± 7.5</td>
<td>917 ± 41</td>
</tr>
<tr>
<td>Diboson</td>
<td>19530 ± 750</td>
<td>428 ± 29</td>
<td>183 ± 16</td>
<td>167 ± 16</td>
<td>1008 ± 53</td>
</tr>
<tr>
<td>EW $Zjj$</td>
<td>13270 ± 500</td>
<td>312 ± 23</td>
<td>102 ± 11</td>
<td>135 ± 14</td>
<td>789 ± 43</td>
</tr>
<tr>
<td>Single-top</td>
<td>2430 ± 160</td>
<td>27.9 ± 5.5</td>
<td>14.0 ± 3.8</td>
<td>9.8 ± 3.2</td>
<td>54.2 ± 8.2</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>515 ± 37</td>
<td>4.6 ± 4.2</td>
<td>1.6 ± 2.1</td>
<td>2.2 ± 1.7</td>
<td>10.6 ± 6.2</td>
</tr>
<tr>
<td>$W^+ +$ jets</td>
<td>93 ± 16</td>
<td>3.4 ± 1.9</td>
<td>0.3 ± 0.6</td>
<td>2.9 ± 1.7</td>
<td>3.4 ± 1.9</td>
</tr>
<tr>
<td>$V + \gamma$</td>
<td>1413 ± 83</td>
<td>14.2 ± 4.3</td>
<td>6.5 ± 2.6</td>
<td>5.1 ± 2.3</td>
<td>34.1 ± 7.3</td>
</tr>
<tr>
<td>Total predicted</td>
<td>1252000 ± 51000</td>
<td>7150 ± 350</td>
<td>2970 ± 130</td>
<td>2890 ± 170</td>
<td>21100 ± 880</td>
</tr>
<tr>
<td>Data</td>
<td>1312145</td>
<td>7539</td>
<td>2955</td>
<td>3231</td>
<td>21746</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$Z \rightarrow \mu^+\mu^-$</th>
<th>Inclusive</th>
<th>High-$p_T$</th>
<th>Collinear</th>
<th>Back-to-back</th>
<th>High-$S_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z +$ jets</td>
<td>1537000 ± 63000</td>
<td>6700 ± 300</td>
<td>2950 ± 130</td>
<td>2420 ± 120</td>
<td>23110 ± 920</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>55400 ± 1300</td>
<td>209 ± 16</td>
<td>142 ± 12</td>
<td>39.1 ± 6.6</td>
<td>1058 ± 41</td>
</tr>
<tr>
<td>Diboson</td>
<td>24160 ± 870</td>
<td>438 ± 27</td>
<td>198 ± 16</td>
<td>157 ± 14</td>
<td>1149 ± 55</td>
</tr>
<tr>
<td>EW $Zjj$</td>
<td>17020 ± 580</td>
<td>328 ± 22</td>
<td>113 ± 12</td>
<td>134 ± 13</td>
<td>915 ± 45</td>
</tr>
<tr>
<td>Single-top</td>
<td>3110 ± 190</td>
<td>29.1 ± 5.5</td>
<td>13.6 ± 3.8</td>
<td>11.2 ± 3.5</td>
<td>70.0 ± 9.2</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>460 ± 33</td>
<td>3.5 ± 4.0</td>
<td>1.1 ± 2.3</td>
<td>1.8 ± 1.5</td>
<td>8.8 ± 5.4</td>
</tr>
<tr>
<td>$W^+ +$ jets</td>
<td>128 ± 14</td>
<td>1.9 ± 1.4</td>
<td>0.3 ± 0.5</td>
<td>1.5 ± 1.3</td>
<td>2.7 ± 2.0</td>
</tr>
<tr>
<td>$V + \gamma$</td>
<td>1273 ± 90</td>
<td>2.5 ± 2.4</td>
<td>0.9 ± 0.7</td>
<td>2.2 ± 1.5</td>
<td>22.4 ± 5.5</td>
</tr>
<tr>
<td>Total predicted</td>
<td>1638000 ± 64000</td>
<td>7710 ± 330</td>
<td>3420 ± 140</td>
<td>2770 ± 140</td>
<td>26300 ± 1000</td>
</tr>
<tr>
<td>Data</td>
<td>1673057</td>
<td>7896</td>
<td>3372</td>
<td>3059</td>
<td>26567</td>
</tr>
</tbody>
</table>

Contributions (by $ee/e\mu$ and $\mu\mu/e\mu$ scale factors [84]. These factors are computed bin by bin in the signal region for each distribution using simulation.

Diboson backgrounds are dominated by two contributions: semileptonic $WZ$ and $ZZ$ final states, and fully leptonic diboson final states where the decay products of a gauge boson are reconstructed as jets. The measured kinematics of the boson decay products, as well as the production of one or two additional jets, agrees with predictions from Sherpa, as demonstrated in refs. [85–89] within the modelling uncertainties described in section 7. The simulation of the EW $Zjj$ events done with HERWIG+VBFNLO agrees with measurements performed in $(Z \rightarrow \ell^+\ell^-)$-enriched phase spaces [12]. Due to their good performance in previous measurements, simulations are used to describe the diboson and EW $Zjj$ backgrounds in this analysis.

Multijet events are assessed with a data-driven approach using a template fit of the $m_{\ell\ell}$ distribution. The $m_{\ell\ell}$ template for this background is derived from data in a multijet-enriched control region, which is defined by either inverting or dropping the lepton selection requirements associated with isolation, identification and charge. The sub-percent contributions to the multijet template that do not originate from the multijet background are evaluated and subtracted using simulation. The fit is performed over the range
Figure 2. Distributions of the leading-jet $p_T$ in the inclusive region in the electron channel (left) and the angular distance between the $Z$ boson and the closest jet, $\Delta R_{Z,j}$, in the high-$p_T$ region in the muon channel (right). The signal and background samples are stacked to produce the figures. The $W+\text{jets}$, $Z\to\tau^+\tau^+$ and $V+\gamma$ processes are combined and labelled ‘Other’. The bottom panel shows the ratio of the data to the total prediction. Experimental uncertainties (described in section 7) for the signal and background distributions are combined in the hatched band, and the data statistical uncertainty is shown as error bars.

51 GeV $\leq m_{\ell\ell} \leq$ 151 GeV. The contribution from multijet events in the analysis is then estimated in the invariant-mass interval of the signal region (71 GeV $\leq m_{\ell\ell} \leq$ 111 GeV). The resulting fraction of multijet events is at the sub-percent level and so is neglected in this analysis.

Figure 2 shows the data and predicted event yields as a function of $p_{T,j1}$ in the electron channel and as a function of $\Delta R_{Z,j}$ in the high-$p_T$ region in the muon channel. The Sherpa 2.2.11 predictions agree with the data in general, but do not describe it precisely in the full range of the measurements. The distributions are discussed in more detail in section 8.

6 Unfolding of detector effects

The cross-section measurements presented in this paper (see section 1) are performed within the fiducial acceptance region defined by the following requirements:

- Two same-flavour, opposite-charge leptons with $p_T \geq 25$ GeV and $|\eta| < 2.5$
- 71 GeV $\leq m_{\ell\ell} \leq$ 111 GeV
- At least one jet, where jets must have $p_T \geq 100$ GeV and $|y| < 2.5$.

The high-$p_T$, collinear, back-to-back, and high-$S_T$ signal regions are defined in analogy to the detector-level definitions.
The cross sections are defined at particle level, corresponding to ‘dressed’ electrons and muons. A dressed lepton is defined as the four-vector combination of a prompt lepton (that does not originate from the decay of a hadron or a $\tau$-lepton, or from a photon conversion) and all prompt photons within a surrounding cone of size $\Delta R = 0.1$. The particle level also includes jets found by applying the anti-$k_t$ algorithm with radius parameter $R = 0.4$ to final-state particles with decay length $c\tau > 10$ mm, excluding dressed $Z$-boson decay products. Overlap removal is also applied at particle level: jets with $p_T \geq 30$ GeV within $\Delta R = 0.2$ of a dressed lepton are removed, followed by the removal of leptons within $\Delta R = 0.4$ of the remaining jets. This overlap removal is applied at particle level in order to best match the detector response, especially in the collinear region where the detector is not able to discriminate easily between nearby objects.

The fiducial cross sections are evaluated from the reconstructed kinematic observables for events that pass the selection described in section 4. The expected background components, as described in section 5, are subtracted from the distributions in data.

An iterative unfolding technique [90] with two iterations, as implemented in the RooUnfold package [91], is used to unfold the background-subtracted data to the particle level, thereby accounting for the impact of detector inefficiencies and resolution [72–74, 80, 83]. Before entering the iterative unfolding, the background-subtracted data are corrected for the expected fraction of events passing the detector-level selection but not the particle-level selection. The unfolding is carried out with the response matrices constructed from the SHERPA 2.2.11 $Z + \text{jets}$ samples. The unfolded event yields are divided by the integrated luminosity of the data sample to provide the final fiducial cross sections [92]. The electron and muon channels are unfolded separately and then combined to measure the production cross section for a $Z$ boson decaying into a single charged-lepton flavour ($Z \rightarrow \ell^+\ell^-$).

The binning of all observables is optimised to keep the statistical uncertainty below 10% and to maximize the purity, or the fraction of reconstructed events where the reconstructed and truth values fall in the same bin. The latter is kept above 60%, with typical values of $70 - 90\%$. In order to mitigate the modelling uncertainty due to migration effects across the lower edge of the $p_T,j_1$ distribution, this observable is unfolded using two underflow bins within $60$ GeV $\leq p_T,j_1 < 100$ GeV. In a similar fashion, an underflow bin is added for the $p_T,\ell\ell$, $H_T$ and jet multiplicity distributions for events where the leading jet does not pass the $p_T \geq 100$ GeV selection but instead has $60$ GeV $\leq p_T,j_1 \leq 100$ GeV. The unfolding of $r_{Z,j}$ is performed in two dimensions using three bins for the $p_T$ of the closest jet for each bin of $r_{Z,j}$.

7 Systematic uncertainties

Theory modelling uncertainties. Theoretical modelling uncertainties from the MC predictions are considered when unfolding the data and in the comparisons with the cross-section measurements.

Modelling uncertainties are taken into account by varying the QCD scales, the PDFs and, in the case of SHERPA 2.2.11, the virtual EW corrections. The effect of QCD scale uncertainties is defined by the envelope of variations resulting from changing the renormal-
isation ($\mu_r$) and factorisation ($\mu_f$) scales by factors of two with an additional constraint of $0.5 \leq \mu_r/\mu_f \leq 2$. Uncertainties due to the PDF parameterisation are evaluated using sets of PDF variations [93]. The PDF uncertainties also include a comparison with the nominal MMHT2014nnlo [56] PDF and the CT14nnlo [94] PDFs. For Sherpa $Z +$ jets and diboson processes, the PDF uncertainties also include a consistent variation of $\alpha_s$ in the PDF and in the hard scatter based on NNPDF3.0nlo [42]. The prediction from Sherpa 2.2.11 also considers uncertainties related to the NLO virtual EW corrections, derived from the envelope of the additive, multiplicative and exponentiated EW correction schemes [19]. The uncertainties associated with the virtual EW corrections are maximal and amount to 5% where the EW corrections are largest: in the back-to-back region with large $p_T^{\ell\ell}$ and $\Delta R_{Z,j}^\text{min} \approx \pi$. In comparison, the effect of QCD scale uncertainties on Sherpa 2.2.11 predictions ranges between 10% and 60%, with average values near 25%. The corresponding range in MG5_aMC+Py8 FxFx is between 5% and 20%. The differences between these two generators and their uncertainties are further explored in ref. [19]. In the NNLOjet predictions, the QCD scale uncertainties are typically in the range between 5% and 10% and constitute the dominant systematic component. Due to computational limitations in the NNLOjet program, the predictions do not include PDF uncertainties.

The diboson predictions used in the background subtraction from data include PDF and scale uncertainties. The EW $Zjj$ prediction includes the effects of scale, PDF and interference uncertainties, which amount to normalisation uncertainties of 9%, 2% and 25%–40% respectively (see section 3). The effects of scale and PDF uncertainties on the single-top predictions amount to a total normalisation uncertainty of about 4%, primarily from the normalisation to theory predictions at NNLO and NLO accuracies.

**Systematic uncertainties in cross-section measurements.** Systematic uncertainties in the measured cross sections stem from experimental, MC-modelling and unfolding uncertainties. The uncertainties are propagated to the data cross sections by varying the subtracted background and the MC inputs to the unfolding procedure (response matrix, fraction of unmatched events, reconstruction efficiency). They are treated as being correlated over kinematic regions, over distributions of observables and, where applicable, over channels and between signal and background processes.

**Experimental uncertainties specific to each leptonic final state ($Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$):** Systematic uncertainties in the lepton-candidate selection are related to the reconstruction, identification, isolation, and trigger [72, 73]. Uncertainties in the lepton calibrations can cause changes in the acceptance, owing to the migration of events across the $p_T$ threshold and the $m_{\ell\ell}$ boundaries. The uncertainties in the electron energy scale and resolution are taken into account [95], as are those related to the muon momentum scale, inner-detector and muon-spectrometer resolution, and sagitta-bias correction [73].

**Experimental uncertainties common to the electron and muon final states:** Systematic uncertainties associated with jet reconstruction are addressed via jet-energy-scale (JES) variations in a 29-nuisance-parameter scheme and jet-energy-resolution (JER) variations in a 13-nuisance-parameter scheme [96, 97]. Imperfect modelling of the effects of pile-up leads to acceptance changes for different jet multiplicities. To assess this uncertainty,
the average number of pile-up interactions is varied in simulation. The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [98], obtained using the LUCID-2 detector [99] for the primary luminosity measurements.

**Modelling uncertainties:** Distribution-shape variations from PDF, scale and EW uncertainties in the SHERPA 2.2.11 $Z + \text{jets}$ simulation, computed as described above, are propagated to the unfolded cross sections via the response matrices and associated unmatched-events and efficiency corrections. Although the uncertainties in the simulation can be large, their effect on the cross-section measurement is minimised by the unfolding technique used. The systematic uncertainties in the modelling of background MC samples are propagated to the unfolded cross section via the background subtraction in the signal regions. The background-modelling uncertainty comes mainly from the diboson and EW $Zjj$ backgrounds.

**Systematic uncertainties associated with the unfolding procedure:** Systematic uncertainties account for possible residual biases in the unfolding procedure, such as those due to the modelling of the signal events or the finite bin width used in each distribution. The limited size of a simulation sample can also create biases in the distribution used in the unfolding procedure. The following uncertainties from the unfolding procedure are considered:

- The statistical uncertainties of the MC inputs to the unfolding procedure are propagated to the unfolded cross sections with a ‘toy’ simulation method based on 1000 ensembles (pseudo-experiments) of unfolding inputs.

- The effects of the mismodelling of the data by the MC simulation on the results of unfolding procedure are derived by reweighting the SHERPA 2.2.11 $Z + \text{jets}$ MC simulation at particle level for each unfolded observable, such that the MC simulation distribution matches the background-subtracted data at the reconstruction level. The reweighted MC simulation is unfolded with the non-reweighted response matrix and the uncertainty is obtained by comparing the unfolded result against the reweighted distribution at particle level (non-closure).

- An additional uncertainty is derived to account for more subtle differences between the SHERPA 2.2.11 and MG5\_AMC+Py8 CKKW\_L generators (e.g. hadronisation models, additional soft objects, distributions in other kinematic dimensions) which are not accounted for by the previous method. A non-closure test is performed where the MG5\_AMC+Py8 CKKW\_L samples are first reweighed to match SHERPA 2.2.11 particle-level distributions for each observable in turn and subsequently unfolded with SHERPA 2.2.11. The uncertainty is evaluated by comparing the unfolded result and the reweighted distribution at particle level.

The total fractional uncertainties of the unfolded differential cross sections in $p_{T,1}$ and $\Delta R_{Z,j}$ for the combined $Z \rightarrow \ell^+ \ell^-$ measurement, performed as detailed in section 8, are shown in figure 3. Table 3 shows the breakdown of the total relative statistical and systematic uncertainties in the measured integrated cross sections for $Z + \text{jets}$ production in the five kinematic search regions. In the inclusive and high-$S_T$ regions, jet uncertainties
Fractional uncertainties in the measured differential cross-sections in $p_{T,\ell}$ in the inclusive region (left) and in $\Delta R_{Z,j}$ in the high-$p_T$ region (right) from the combined $Z \rightarrow \ell^+\ell^-$ measurement.

Table 3. Relative statistical and systematic uncertainties (in %) in the measured integrated cross sections for $Z +$ jets production in the five search regions, computed by integrating over the respective jet-multiplicity distribution.

<table>
<thead>
<tr>
<th>Uncertainty source [%]</th>
<th>Inclusive</th>
<th>High-$p_T$</th>
<th>Collinear</th>
<th>Back-to-back</th>
<th>High-$S_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES/JER</td>
<td>2.6</td>
<td>3.2</td>
<td>2.8</td>
<td>3.6</td>
<td>2.8</td>
</tr>
<tr>
<td>Lepton</td>
<td>0.9</td>
<td>1.6</td>
<td>1.4</td>
<td>2.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.1</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.5</td>
<td>1.0</td>
<td>1.1</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Background modelling</td>
<td>0.5</td>
<td>2.0</td>
<td>2.0</td>
<td>1.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>0.5</td>
<td>1.2</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Total syst. uncertainty</td>
<td>3.4</td>
<td>4.8</td>
<td>4.4</td>
<td>5.3</td>
<td>4.2</td>
</tr>
<tr>
<td>Data stat. uncertainty</td>
<td>0.1</td>
<td>2.1</td>
<td>2.9</td>
<td>2.7</td>
<td>1.2</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>3.4</td>
<td>5.3</td>
<td>5.3</td>
<td>5.9</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Results

The integrated and differential fiducial cross sections are measured in the electron and muon channels separately, and the compatibility of the results from the two channels is tested. These results are then combined using the Best Linear Unbiased Estimate (BLUE)
method [100]. In the combination, all systematic uncertainties except the lepton-related experimental uncertainties are treated as correlated between the electron and muon channels. Data and MC statistical uncertainties are treated as uncorrelated between channels. The combined measurements are consistent with both individual decay channels for the full set of observables. In general, the uncertainties in the measured cross sections are dominated by the systematic uncertainties and are smaller than the uncertainties in the predictions, except for NNLOJET@NNLO, which matches or exceeds the precision of the measurements in some kinematic regions.

Integrated fiducial cross sections for $Z + \text{jets}$ production are evaluated in the inclusive, high-$p_T$, collinear, back-to-back and high-$S_T$ signal regions (see section 6) by summing over the respective unfolded jet-multiplicity distributions. The measured cross sections are compared with the predictions from Sherpa 2.2.11, MG5\_AMC+Py8 FxFx, Sherpa 2.2.1 and with NNLO and NLO predictions from NNLOJET in table 4 and in figure 4. The prediction from Sherpa 2.2.11 uniquely includes NLO virtual EW corrections (see section 3). When these virtual corrections are removed from the Sherpa 2.2.11 prediction, its total cross sections for the inclusive, high-$p_T$, collinear, back-to-back and high-$S_T$ regions increase by 0.065\%, 6.9\%, 3.8\%, 11\% and 3.0\%, respectively. The cross sections predicted by the three generators and the NNLOJET predictions agree with the measured values within the theory uncertainties.

Differential cross sections are measured and compared in figures 5–11 with predictions from Sherpa 2.2.1, MG5\_AMC+Py8 CKKWL, and the next-generation MC generators Sherpa 2.2.11 and MG5\_AMC+Py8 FxFx, and with NLO and NNLO $Z + \text{jets}$ calculations from NNLOJET. In general, NNLOJET@NNLO and MG5\_AMC+Py8 FxFx provide the most precise predictions.

The $Z$-boson and jet transverse momenta (two correlated quantities) are fundamental observables of the $Z + \text{jets}$ process and probe perturbative QCD over a wide range of scales. Moreover, understanding the kinematics of jets in events with vector bosons produced in association with several jets is essential for the modelling of backgrounds for other SM processes and searches beyond the SM. Figure 5 shows the differential cross section as a function of $p_T, \ell\ell$ and $p_T,j_1$. The high-$p_T,\ell\ell$ region is dominated by the back-to-back topology and receives significant negative corrections due to EW effects. In contrast, events with a high-$p_T$ jet typically result in both back-to-back and collinear topologies. The Sherpa 2.2.1 and MG5\_AMC+Py8 CKKWL generators predict a harder $p_T,j_1$ distribution than seen in the data, resulting in an overestimation of the cross section for high $p_T,j_1$. In contrast, Sherpa 2.2.11 and MG5\_AMC+Py8 FxFx show significantly better modelling of the $p_T,j_1$ spectrum and are also in good agreement with the measured $p_T,\ell\ell$ spectrum. The smaller cross section from Sherpa 2.2.11 relative to Sherpa 2.2.1 in the high-$p_T$ region is attributed to the improved matching scheme with a different treatment of unordered histories [19]. The prediction from MG5\_AMC+Py8 FxFx models the data more precisely, due to the inclusion of NLO matrix elements with three partons. The NNLOJET@NNLO predictions describe the data very precisely, except for very large values of $p_T,\ell\ell$ (and $p_T,j_1$), where negative NLO virtual EW corrections of 10\%-20\% are expected and the QCD-only calculation overestimates the data.
### Inclusive $Z + \text{jets}$

<table>
<thead>
<tr>
<th>Data</th>
<th>$13.90 \pm 0.01$ (stat)</th>
<th>$\pm 0.47$ (syst)</th>
<th>pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHERPA 2.2.11</td>
<td>13.3</td>
<td>$-0.2$ (PDF)</td>
<td>$+1.8$ (Scale)</td>
</tr>
<tr>
<td>MG5_AMC+Py8 FxFx</td>
<td>14.5</td>
<td>$-0.1$ (PDF)</td>
<td>$+0.8$ (Scale)</td>
</tr>
<tr>
<td>SHERPA 2.2.1</td>
<td>13.8</td>
<td>$-0.5$ (PDF)</td>
<td>$+2.2$ (Scale)</td>
</tr>
<tr>
<td>NNLOJET@NNLO</td>
<td>13.83</td>
<td>$+0.18$ (PDF)</td>
<td>$-0.27$ (Scale)</td>
</tr>
<tr>
<td>NNLOJET@NLO</td>
<td>13.5</td>
<td>$+1.1$ (PDF)</td>
<td>$-0.9$ (Scale)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High-$p_T$: $p_T, j_1 \geq 500$ GeV</th>
<th>72.3</th>
<th>$\pm 1.5$ (stat)</th>
<th>$\pm 3.5$ (syst)</th>
<th>fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHERPA 2.2.11</td>
<td>69</td>
<td>$^+2^-1$ (PDF)</td>
<td>$^+2^-1$ (Scale)</td>
<td>$^+2^-2$ (EW)</td>
</tr>
<tr>
<td>MG5_AMC+Py8 FxFx</td>
<td>78</td>
<td>$^+1^-1$ (PDF)</td>
<td>$^+4^-1$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>SHERPA 2.2.1</td>
<td>95</td>
<td>$^+4^-3$ (PDF)</td>
<td>$^+5^-2$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NNLO</td>
<td>76</td>
<td>$^-2^-1$ (PDF)</td>
<td>$^-2^-1$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NLO</td>
<td>71</td>
<td>$^+14^-1$ (PDF)</td>
<td>$^+7^-1$ (Scale)</td>
<td>fb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Collinear: High-$p_T$ and $\Delta R_{Z, j}^{min} \leq 1.4$</th>
<th>27.9</th>
<th>$\pm 0.8$ (stat)</th>
<th>$\pm 1.2$ (syst)</th>
<th>fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHERPA 2.2.11</td>
<td>28</td>
<td>$^+1^-2$ (PDF)</td>
<td>$^+4^-2$ (Scale)</td>
<td>$\pm 1$ (EW)</td>
</tr>
<tr>
<td>MG5_AMC+Py8 FxFx</td>
<td>29.6</td>
<td>$^-3^-0.3$ (PDF)</td>
<td>$^+4^-3$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>SHERPA 2.2.1</td>
<td>30</td>
<td>$^+2^-1$ (PDF)</td>
<td>$^+3^-1$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NNLO</td>
<td>27.0</td>
<td>$^+5^-2$ (PDF)</td>
<td>$^+7^-2$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NLO</td>
<td>24.1</td>
<td>$^+7^-2$ (PDF)</td>
<td>$^+7^-2$ (Scale)</td>
<td>fb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Back-to-back: High-$p_T$ and $\Delta R_{Z, j}^{min} \geq 2.0$</th>
<th>31.6</th>
<th>$\pm 0.8$ (stat)</th>
<th>$\pm 1.7$ (syst)</th>
<th>fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHERPA 2.2.11</td>
<td>28.1</td>
<td>$^+0.8^-2$ (PDF)</td>
<td>$^+3^-1$ (Scale)</td>
<td>$^+14^-2$ (EW)</td>
</tr>
<tr>
<td>MG5_AMC+Py8 FxFx</td>
<td>34.4</td>
<td>$^-2^-0$ (PDF)</td>
<td>$^-2^-0$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>SHERPA 2.2.1</td>
<td>38</td>
<td>$+2^-1$ (PDF)</td>
<td>$^+2^-1$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NNLO</td>
<td>35.3</td>
<td>$^+1^-0.3$ (PDF)</td>
<td>$^+1^-0.3$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NLO</td>
<td>36.0</td>
<td>$^+1^-0.3$ (PDF)</td>
<td>$^+1^-0.3$ (Scale)</td>
<td>fb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>High-$S_T$: $S_T \geq 600$ GeV</th>
<th>236.0</th>
<th>$\pm 2.6$ (stat)</th>
<th>$\pm 9.5$ (syst)</th>
<th>fb</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHERPA 2.2.11</td>
<td>220</td>
<td>$^+10^-10$ (PDF)</td>
<td>$^+110^-10$ (Scale)</td>
<td>$\pm 10$ (EW)</td>
</tr>
<tr>
<td>MG5_AMC+Py8 FxFx</td>
<td>247</td>
<td>$^+10^-10$ (PDF)</td>
<td>$^+30^-10$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>SHERPA 2.2.1</td>
<td>280</td>
<td>$^+10^-10$ (PDF)</td>
<td>$^+130^-80$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NNLO</td>
<td>223</td>
<td>$^+4^-2$ (PDF)</td>
<td>$^+4^-2$ (Scale)</td>
<td>fb</td>
</tr>
<tr>
<td>NNLOJET@NLO</td>
<td>168</td>
<td>$^+45^-43$ (PDF)</td>
<td>$^+45^-43$ (Scale)</td>
<td>fb</td>
</tr>
</tbody>
</table>

### Table 4

Measured integrated fiducial cross sections for $Z + \text{jets}$ production in the five signal regions and predictions from SHERPA 2.2.11, MG5\_AMC+Py8 FxFx, SHERPA 2.2.1, NNLOJET@NNLO and NNLOJET@NLO. Systematic uncertainties in the measured and predicted cross sections are calculated as described in section 7.

Jet-multiplicity distributions provide an excellent probe of QCD. Whereas the $Z + 1$-jet bin is most sensitive to PDF effects, those with higher jet multiplicities are more sensitive to perturbative QCD effects [101]. Jet-multiplicity distributions also probe the validity of predictions in the presence of jet vetoes, which are frequently used in searches that require a specific number of jets in the selection. These vetoes create additional logarithmic terms, which are not explicitly included in the theoretical predictions presented in this paper. Figure 6 shows the differential cross section as a function of the jet multiplicity in the inclusive and high-$p_T$ regions. As expected [101], the jet multiplicity in the inclusive phase
Figure 4. Summary of integrated fiducial cross-section results. The measured cross sections are shown with black points and the error bars represent the total uncertainty. Data are compared with predictions from MC generators and fixed-order calculations. The uncertainties in the predictions are found by adding in quadrature the uncertainties from the variations of the PDF (excluding NNLOJET predictions), QCD scales and, for SHERPA 2.2.11, virtual EW contributions, as explained in section 7.

space follows a downward staircase pattern, whereas in the high-$p_T$ phase space, the cross section increases between 1-jet and 2-jet events followed by a downward pattern for higher jet multiplicities. While SHERPA 2.2.1 and MG5_aMC+PY8 CKKWL tend to overestimate the cross section for higher jet multiplicities, SHERPA 2.2.11 and MG5_aMC+Py8 FxFx agree with the data for both the inclusive and high-$p_T$ regions, the latter generator at a higher level of precision. The NNLOJET predictions agree with the data in the inclusive and high-$p_T$ phase spaces at high precision when it is expected from the order of the calculation, and at lower precision when the order of the calculation is exceeded.

The angular distance between the Z boson and the closest jet, $\Delta R_{Z,j}^{\text{min}}$, and the ratio of the Z-boson transverse momentum to the closest-jet transverse momentum, $r_{Z,j}$, provide a way to distinguish between the presence of collinear Z-boson emission and back-to-back topologies. In the high-$p_T$ selection, the collinear region is sensitive to logarithmic enhancements in production proportional to $\alpha_s \ln^2(p_{T,j1}/m_Z)$, whereas the back-to-back region receives non-negligible virtual EW corrections. Figure 7 shows the differential cross sections as a function of $\Delta R_{Z,j}^{\text{min}}$ and $r_{Z,j}$ in the high-$p_T$ region. Both distributions show
Figure 5. Differential cross section as a function of the transverse momentum of the $Z$ boson (left) and of the transverse momentum of the leading jet (right) in the inclusive region. The unfolded data are shown with the black points where the statistical uncertainty is given as an error bar and the total uncertainty as a hatched region. The data are compared with predictions from MC generators and fixed-order calculations. In the ratio panels, the error bars correspond to the statistical uncertainty of the prediction and solid triangles indicate that the prediction is outside the vertical-axis range, while the total uncertainty of the unfolded data is represented as the hatched region. The uncertainties in the predictions, dominated by the scale uncertainties, are shown only in the ratio panels, except for MG5\_aMC+Py8 CKKWL which is not included. They are found by adding in quadrature the uncertainties from the variations of the PDF (excluding NNLOJET predictions), QCD scales and, for SHERPA 2.2.11, virtual EW contributions, as explained in section 7.

an accumulation of events at low and high values of these two quantities: collinear events populate the figures at values $\Delta R_{ZJ} \lesssim 1.4$ and $r_{ZJ} \lesssim 0.4$, while the back-to-back events are observed with $\Delta R_{ZJ} \approx \pi$ and $r_{ZJ} \approx 1.0$. The collinear events are expected to be dominated by diagrams corresponding to the EW radiation of a $Z$ boson from one of the legs of a dijet event. Consequently, they are expected to correspond to the accumulation of events with low values of $r_{ZJ}$. This hypothesis is validated in figure 8, which shows the measurement of the $r_{ZJ}$ distribution for the subset of collinear events defined by $\Delta R_{ZJ} \leq 1.4$ where only the accumulation of low-$r_{ZJ}$ events is observed. In contrast, the measurement of the $r_{ZJ}$ distribution for the back-to-back selection defined by $\Delta R_{ZJ} \geq 2.0$ is populated by events with $r_{ZJ} \approx 1$. The jet multiplicity is also measured separately for the collinear and back-to-back topologies as shown in figure 9. It is found that the collinear region is dominated by dijet events whereas the back-to-back region is dominated by $Z + 1$-jet events.

Figures 7–9 show that while still marginally in agreement with data within modelling uncertainties of up to 50%, SHERPA 2.2.1 central values increasingly overestimate the cross section with decreasing values of $\Delta R_{ZJ}$. A similar trend is observed for
Figure 6. Differential cross section as a function of the jet multiplicity in the *inclusive* region (left) and *high-\(p_T\) region* (right). In each case, the last bin is inclusive in higher jet multiplicities. Further details are provided in the caption of figure 5.

MG5\_AMC+Py8 CKKWL. The modelling is improved by the state-of-the-art generators MG5\_AMC+Py8 FxFx and Sherpa 2.2.11. Good agreement of MG5\_AMC+Py8 FxFx and Sherpa 2.2.11 with data even for very collinear events indicates that resummation of the additional logarithmic terms, e.g. via EW showers, is not needed at the present level of theoretical and experimental precision in the experimentally accessible kinematic regime. The NNLOjet@NNLO prediction models the data distribution in both the collinear and the *back-to-back* regions with high precision. The good performance in the *collinear* phase space is remarkable, as this region contains a large fraction of events with at least three jets, which are simulated only at LO in NNLOjet@NNLO and not at all by NNLOjet@NLO. The QCD-only calculation overestimates the cross section for exact *back-to-back* events in the *high-\(p_T\)* region, dominated by *high-\(p_{T,\ell}\)\(,\ell\) events, consistent with the pattern observed in figure 5.

An alternative way to select a high-energy phase space is by requiring a large value of \(H_T\) or \(S_T\). The former is often used as a dynamical scale choice, whereas the latter is more suited to selecting a phase space similar to the *high-\(p_T\)* region. Figure 10 shows the differential cross section as a function of \(H_T\). The central values from Sherpa 2.2.1 increasingly overestimate the cross section with increasing \(H_T\), while still marginally agreeing with the data within modelling uncertainties of up to 50%. The prediction from MG5\_AMC+Py8 CKKWL shows a similar trend. In contrast, the state-of-the-art predictions from Sherpa 2.2.11, MG5\_AMC+Py8 FxFx and NNLOjet@NNLO model the data well, the last with higher precision. Figure 11 shows the differential cross section as a function of \(\Delta R_{Z,j}^{\text{min}}\) and jet multiplicity in the *high-\(S_T\)* region. The *high-\(S_T\)* region probes high-energy events where the energy is typically shared by several jets. Compared to the *high-\(p_T\)* region, the jet multiplicity distribution is shifted towards higher values, and the
Figure 7. Differential cross section as a function of angular distance between the $Z$ boson and the closest jet, $\Delta R_{Z,j}^{\text{min}}$ (left) and of the ratio of $Z$-boson to closest-jet transverse momenta $r_{Z,j}$ (right) in the high-$p_T$ region. For the NNLOJET predictions, the bins around $r_{Z,j} = 1$ are merged to be insensitive to the singularity in the fixed-order calculation. Further details are provided in the caption of figure 5.

Figure 8. Differential cross section as a function of the ratio of $Z$-boson to closest-jet transverse momenta $r_{Z,j}$ in the collinear $\Delta R_{Z,j}^{\text{min}} \leq 1.4$ region (left) and in the back-to-back $\Delta R_{Z,j}^{\text{min}} \geq 2.0$ region (right). For the NNLOJET predictions, the bins around $r_{Z,j} = 1$ are merged to be insensitive to the singularity in the fixed-order calculation. Further details are provided in the caption of figure 5.

back-to-back peak in the $\Delta R_{Z,j}^{\text{min}}$ distribution is suppressed relative to events where a jet is in closer proximity to the $Z$ boson. As in the high-$p_T$ region, SHERPA 2.2.1 is marginally consistent with the data within a large theoretical uncertainty, with the overestimation of the central values most pronounced in the collinear region and for higher jet multiplicity.
Figure 9. Differential cross section as a function of the jet multiplicity in the collinear $\Delta R_{Z,j}^{\min} \leq 1.4$ region (left) and in the back-to-back $\Delta R_{Z,j}^{\min} \geq 2.0$ region (right). In each case, the last bin is inclusive in higher jet multiplicities. In data, no events with exactly one jet are selected in the collinear region. Further details are provided in the caption of figure 5.

Figure 10. Differential cross section as a function of the transverse momenta scalar sum $H_T$ in the inclusive region. Further details are provided in the caption of figure 5.

ties, with MG5\_AMC+Py8 CKKWL showing a similar trend. Both Sherpa 2.2.11 and MG5\_AMC+Py8 FxFx are consistent with the data, the latter at higher precision. The NNLOjet@NNLO prediction models this region well and with high precision, even though the fraction of events with at least three jets is larger than in the high-$p_T$ phase space.
9 Conclusions

This paper presents measurements of cross sections for a $Z$ boson produced in association with high-transverse-momentum jets and decaying into a charged-lepton pair. The data were collected from $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC during 2015–2018 and correspond to an integrated luminosity of 139 fb$^{-1}$. Measurements were performed on events that contain a $Z$-boson candidate reconstructed from an $e^+e^-$ pair or a $\mu^+\mu^-$ pair in association with hadronic jets defined as jets having transverse momentum greater than or equal to 100 GeV. Primarily, only the QCD component of $Z + \text{jets}$ production is measured, treating the EW $Zjj$ processes as a background. The paper focuses on selections with very high leading-jet $p_T$ ($p_{T,j1} \geq 500$ GeV) and very high $S_T$ ($S_T \geq 600$ GeV), which are used to study two populations of events – collinear events and back-to-back events – with distinct patterns in distributions of $\Delta R_{Z,j}^{\text{min}}$, $r_{Z,j}$, and jet multiplicity.

The data distributions were unfolded to the particle level and compared with state-of-the-art generator predictions and fixed-order calculations. Both SHERPA 2.2.1 and MG5\_AMC+PY8 CKKWL overestimate the cross sections for large values of $p_{T,j1}$, $H_T$ and $S_T$. The predictions from MG5\_AMC+PY8 FxFx, with matrix elements for up to three partons at NLO, offer a significant improvement over MG5\_AMC+PY8 CKKWL (which models up to four partons at LO) and in general match the data with high precision. Similarly, SHERPA 2.2.11, with the addition of a fifth parton at LO in the matrix element, the addition of NLO virtual EW corrections, and a different treatment of unordered histories in the parton shower, shows a significant improvement over SHERPA 2.2.1 and agrees with the data. The NNLO calculations at fixed order from NNLOJET describe the data...
cross sections at a very high level of precision, including in high-$p_T$ regions where a sizeable fraction of the events have more than two jets. The calculation exhibits a harder $p_{T,\ell\ell}$ spectrum than the data in a region where larger negative EW corrections are expected.

Acknowledgments

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [102].

A HepData material

The following tables will be included in the HEPData entry (link to entry):

1. Differential cross section of $p_{T,\ell\ell}$ in the inclusive region
2. Differential cross section of $p_{T,j_1}$ in the inclusive region
3. Differential cross section of jet multiplicity in the inclusive region
4. Differential cross section of jet multiplicity in the high-$p_T$ region
5. Differential cross section of $\Delta R_{Z,j}^{\text{min}}$ in the high-$p_T$ region
6. Differential cross section of $r_{Z,j}$ in the high-$p_T$ region
7. Differential cross section of $r_{Z,j}$ in the collinear region
8. Differential cross section of $r_{Z,j}$ in the back-to-back region
9. Differential cross section of jet multiplicity in the collinear region
10. Differential cross section of jet multiplicity in the back-to-back region
11. Differential cross section of $H_T$ in the inclusive region
12. Differential cross section of $\Delta R_{Z,j}^{\text{min}}$ in the high-$S_T$ region
13. Differential cross section of jet multiplicity in the high-$S_T$ region
14. Relative bin-by-bin systematic uncertainties of $p_T,\ell\ell$ in the inclusive region
15. Relative bin-by-bin systematic uncertainties of $p_{T,j_1}$ in the inclusive region
16. Relative bin-by-bin systematic uncertainties of jet multiplicity in the inclusive region
17. Relative bin-by-bin systematic uncertainties of jet multiplicity in the high-$p_T$ region
18. Relative bin-by-bin systematic uncertainties of $\Delta R_{Z,j}^{\text{min}}$ in the high-$p_T$ region
19. Relative bin-by-bin systematic uncertainties of $r_{Z,j}$ in the high-$p_T$ region
20. Relative bin-by-bin systematic uncertainties of $r_{Z,j}$ in the collinear region
21. Relative bin-by-bin systematic uncertainties of $r_{Z,j}$ in the back-to-back region
22. Relative bin-by-bin systematic uncertainties of jet multiplicity in the collinear region
23. Relative bin-by-bin systematic uncertainties of jet multiplicity in the back-to-back region
24. Relative bin-by-bin systematic uncertainties of $H_T$ in the inclusive region
25. Relative bin-by-bin systematic uncertainties of $\Delta R_{Z,j}^{\text{min}}$ in the high-$S_T$ region
26. Relative bin-by-bin systematic uncertainties of jet multiplicity in the high-$S_T$ region
27. Bin-by-bin Born to dressed level leptons correction scale factor for $p_{T,\ell\ell}$ in the inclusive region
28. Bin-by-bin Born to dressed level leptons correction scale factor for $p_{T,j_1}$ in the inclusive region
29. Bin-by-bin Born to dressed level leptons correction scale factor for the jet multiplicity in the inclusive region
30. Bin-by-bin Born to dressed level leptons correction scale factor for the jet multiplicity in the high-$p_T$ region
31. Bin-by-bin Born to dressed level leptons correction scale factor for $\Delta R_{Z,j}^{\text{min}}$ in the high-$p_T$ region
32. Bin-by-bin Born to dressed level leptons correction scale factor for $r_{Z,j}$ in the high-$p_T$ region
33. Bin-by-bin Born to dressed level leptons correction scale factor for $r_{Z,j}$ in the collinear region
34. Bin-by-bin Born to dressed level leptons correction scale factor for $r_{Z,j}$ in the back-to-back region
35. Bin-by-bin Born to dressed level leptons correction scale factor for the jet multiplicity in the collinear region
36. Bin-by-bin Born to dressed level leptons correction scale factor for the jet multiplicity in the back-to-back region
37. Bin-by-bin Born to dressed level leptons correction scale factor for $H_T$ in the inclusive region
38. Bin-by-bin Born to dressed level leptons correction scale factor for $\Delta R_{Z,j}^{\text{min}}$ in the high-$S_T$ region
39. Bin-by-bin Born to dressed level leptons correction scale factor for the jet multiplicity in the high-$S_T$ region
40. Bin-by-bin overlap removal correction scale factor for $p_{T,\ell\ell}$ in the inclusive region
41. Bin-by-bin overlap removal correction scale factor for $p_{T,j1}$ in the inclusive region
42. Bin-by-bin overlap removal correction scale factor for the jet multiplicity in the inclusive region
43. Bin-by-bin overlap removal correction scale factor for the jet multiplicity in the high-$p_T$ region
44. Bin-by-bin overlap removal correction scale factor for $\Delta R_{Z,j}^{\text{min}}$ in the high-$p_T$ region
45. Bin-by-bin overlap removal correction scale factor for $r_{Z,j}$ in the high-$p_T$ region
46. Bin-by-bin overlap removal correction scale factor for $r_{Z,j}$ in the collinear region
47. Bin-by-bin overlap removal correction scale factor for $r_{Z,j}$ in the back-to-back region
48. Bin-by-bin overlap removal correction scale factor for the jet multiplicity in the collinear region
49. Bin-by-bin overlap removal correction scale factor for the jet multiplicity in the back-to-back region
50. Bin-by-bin overlap removal correction scale factor for $H_T$ in the inclusive region
51. Bin-by-bin overlap removal correction scale factor for $\Delta R_{Z,j}^{\text{min}}$ in the high-$S_T$ region
52. Bin-by-bin overlap removal correction scale factor for the jet multiplicity in the high-$S_T$ region
53. Differential cross section of $p_{T,\ell\ell}$ in the inclusive region, where the EW Zjj contribution is not subtracted as background
54. Differential cross section of $p_{T,j1}$ in the inclusive region, where the EW Zjj contribution is not subtracted as background
55. Differential cross section of jet multiplicity in the inclusive region, where the EW Zjj contribution is not subtracted as background
56. Differential cross section of jet multiplicity in the high-$p_T$ region, where the EW Zjj contribution is not subtracted as background
57. Differential cross section of $\Delta R_{Z,j}^{\text{min}}$ in the high-$p_T$ region, where the EW Zjj contribution is not subtracted as background
58. Differential cross section of $r_{Z,j}$ in the high-$p_T$ region, where the EW Zjj contribution is not subtracted as background
59. Differential cross section of $r_{Z,j}$ in the collinear region, where the EW Zjj contribution is not subtracted as background
60. Differential cross section of $r_{Z,j}$ in the back-to-back region, where the EW Zjj contribution is not subtracted as background
61. Differential cross section of jet multiplicity in the collinear region, where the EW Zjj contribution is not subtracted as background
62. Differential cross section of jet multiplicity in the back-to-back region, where the EW Zjj contribution is not subtracted as background
63. Differential cross section of $H_T$ in the inclusive region, where the EW Zjj contribution is not subtracted as background
64. Differential cross section of $\Delta R_{Z,j}^{\min}$ in the high-$S_T$ region, where the EW Zjj contribution is not subtracted as background
65. Differential cross section of jet multiplicity in the high-$S_T$ region, where the EW Zjj contribution is not subtracted as background
66. Relative bin-by-bin systematic uncertainties of $p_{T,\ell\ell}$ in the inclusive region, where the EW Zjj contribution is not subtracted as background
67. Relative bin-by-bin systematic uncertainties of $p_{T,j1}$ in the inclusive region, where the EW Zjj contribution is not subtracted as background
68. Relative bin-by-bin systematic uncertainties of jet multiplicity in the inclusive region, where the EW Zjj contribution is not subtracted as background
69. Relative bin-by-bin systematic uncertainties of jet multiplicity in the high-$p_T$ region, where the EW Zjj contribution is not subtracted as background
70. Relative bin-by-bin systematic uncertainties of $\Delta R_{Z,j}^{\min}$ in the high-$p_T$ region, where the EW Zjj contribution is not subtracted as background
71. Relative bin-by-bin systematic uncertainties of $r_{Z,j}$ in the high-$p_T$ region, where the EW Zjj contribution is not subtracted as background
72. Relative bin-by-bin systematic uncertainties of $r_{Z,j}$ in the collinear region, where the EW Zjj contribution is not subtracted as background
73. Relative bin-by-bin systematic uncertainties of $r_{Z,j}$ in the back-to-back region, where the EW Zjj contribution is not subtracted as background
74. Relative bin-by-bin systematic uncertainties of jet multiplicity in the collinear region, where the EW Zjj contribution is not subtracted as background
75. Relative bin-by-bin systematic uncertainties of jet multiplicity in the back-to-back region, where the EW Zjj contribution is not subtracted as background
76. Relative bin-by-bin systematic uncertainties of $H_T$ in the inclusive region, where the EW Zjj contribution is not subtracted as background
77. Relative bin-by-bin systematic uncertainties of $\Delta R_{Z,j}^{\min}$ in the high-$S_T$ region, where the EW Zjj contribution is not subtracted as background
78. Relative bin-by-bin systematic uncertainties of jet multiplicity in the high-$S_T$ region, where the EW Zjj contribution is not subtracted as background
Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited. SCOAP³ supports the goals of the International Year of Basic Sciences for Sustainable Development.

References


ATLAS collaboration, Modelling and computational improvements to the simulation of single vector-boson plus jet processes for the ATLAS experiment, JHEP 08 (2022) 089 [arXiv:2112.09588] [inSPIRE].


A. Gehrmann-De Ridder et al., The NNLO QCD corrections to Z boson production at large transverse momentum, JHEP 07 (2016) 133 [arXiv:1605.04295] [inSPIRE].

S. Kallweit et al., NLO QCD+EW predictions for V + jets including off-shell vector-boson decays and multijet merging, JHEP 04 (2016) 021 [arXiv:1511.08692] [inSPIRE].


[99] G. Avoni et al., The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS, 2018 *JINST* **13** P07017 [nsPIRE].


22 (a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; (b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
23 (c) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; (d) INFN Sezione di Bologna; Italy
24 Physikalisches Institut, Universität Bonn, Bonn; Germany
25 Department of Physics, Boston University, Boston MA; United States of America
26 Department of Physics, Brandeis University, Waltham MA; United States of America
27 (a) Transilvania University of Brasov, Brasov; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e) University Politehnica Bucharest, Bucharest; (f) West University in Timisoara, Timisoara; Romania
28 (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
29 Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
30 Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
31 California State University, CA; United States of America
32 Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
33 (a) Department of Physics, University of Cape Town, Cape Town; (b) iThemba Labs, Western Cape; (c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; (d) National Institute of Physics, University of the Philippines Diliman (Philippines); (e) University of South Africa, Department of Physics, Pretoria; (f) University of Zululand, KwaDlangezwa; (g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa
34 Department of Physics, Carleton University, Ottawa ON; Canada
35 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Énergies — Université Hassan II, Casablanca; (b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat; (f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
36 CERN, Geneva; Switzerland
37 Affiliated with an institute covered by a cooperation agreement with CERN
38 Affiliated with an international laboratory covered by a cooperation agreement with CERN
39 Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
40 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
41 Nevis Laboratory, Columbia University, Irvington NY; United States of America
42 Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
43 (a) Dipartimento di Fisica, Università della Calabria, Rende; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
44 Physics Department, Southern Methodist University, Dallas TX; United States of America
45 Physics Department, University of Texas at Dallas, Richardson TX; United States of America
46 National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece
47 (a) Department of Physics, Stockholm University; (b) Oskar Klein Centre, Stockholm; Sweden
48 Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
49 Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
50 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
51 Department of Physics, Duke University, Durham NC; United States of America
52 SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
53 INFN e Laboratori Nazionali di Frascati, Frascati; Italy
54 Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
55 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
</tr>
<tr>
<td>131</td>
</tr>
<tr>
<td>132</td>
</tr>
<tr>
<td>133</td>
</tr>
<tr>
<td>134</td>
</tr>
<tr>
<td>135</td>
</tr>
<tr>
<td>136</td>
</tr>
<tr>
<td>137</td>
</tr>
<tr>
<td>138</td>
</tr>
<tr>
<td>139</td>
</tr>
<tr>
<td>140</td>
</tr>
<tr>
<td>141</td>
</tr>
<tr>
<td>142</td>
</tr>
<tr>
<td>143</td>
</tr>
<tr>
<td>144</td>
</tr>
<tr>
<td>145</td>
</tr>
<tr>
<td>146</td>
</tr>
<tr>
<td>147</td>
</tr>
<tr>
<td>148</td>
</tr>
<tr>
<td>149</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>151</td>
</tr>
<tr>
<td>152</td>
</tr>
<tr>
<td>153</td>
</tr>
<tr>
<td>154</td>
</tr>
<tr>
<td>155</td>
</tr>
<tr>
<td>156</td>
</tr>
<tr>
<td>157</td>
</tr>
<tr>
<td>158</td>
</tr>
<tr>
<td>159</td>
</tr>
<tr>
<td>160</td>
</tr>
<tr>
<td>161</td>
</tr>
<tr>
<td>162</td>
</tr>
<tr>
<td>163</td>
</tr>
<tr>
<td>164</td>
</tr>
<tr>
<td>165</td>
</tr>
<tr>
<td>166</td>
</tr>
<tr>
<td>167</td>
</tr>
<tr>
<td>168</td>
</tr>
</tbody>
</table>
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany

Department of Physics, Yale University, New Haven CT; United States of America

a Also Affiliated with an institute covered by a cooperation agreement with CERN
b Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America
c Also at Bruno Kessler Foundation, Trento; Italy
d Also at Center for High Energy Physics, Peking University; China
e Also at Centro Studi e Ricerche Enrico Fermi; Italy
f Also at CERN, Geneva; Switzerland

g Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
h Also at Departament de Fisica de la Universitat Autònoma de Barcelona, Barcelona; Spain
i Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece
j Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
k Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America
l Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel
m Also at Department of Physics, California State University, East Bay; United States of America
n Also at Department of Physics, California State University, Sacramento; United States of America
o Also at Department of Physics, King’s College London, London; United Kingdom
p Also at Department of Physics, University of Fribourg, Fribourg; Switzerland
q Also at Department of Physics, University of Thessaly; Greece
r Also at Department of Physics, Westmont College, Santa Barbara; United States of America
s Also at Hellenic Open University, Patras; Greece
t Also at Institut Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain
u Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany
v Also at Institute of Particle Physics (IPP); Canada
w Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
x Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia
y Also at Lawrence Livermore National Laboratory, Livermore; United States of America
z Also at Physics Department, An-Najah National University, Nablus; Palestine
aa Also at The City College of New York, New York NY; United States of America
ab Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China
ac Also at TRIUMF, Vancouver BC; Canada
ad Also at Università di Napoli Parthenope, Napoli; Italy
ae Also at University of Chinese Academy of Sciences (UCAS), Beijing; China
af Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America
ag Also at Yeditepe University, Physics Department, Istanbul; Türkiye

* Deceased