Measurement of the cross-section for electroweak production of dijets in association with a Z boson in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

DOI
10.1016/j.physletb.2017.10.040

Publication date
2017

Document Version
Final published version

Published in
Physics Letters B

License
CC BY

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Measurement of the cross-section for electroweak production of dijets in association with a $Z$ boson in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

1. Introduction

At the Large Hadron Collider (LHC) events containing a $Z$ boson and at least two jets ($Zjj$) are produced predominantly via initial-state QCD radiation from the incoming partons in the Drell–Yan process (QCD-$Zjj$), as shown in Fig. 1(a). In contrast, the production of $Zjj$ events via $t$-channel electroweak gauge boson exchange (EW-$Zjj$ events), including the vector-boson fusion (VBF) process shown in Fig. 1(b), is a much rarer process. Such VBF processes for vector-boson production are of great interest as a ‘standard candle’ for other VBF processes at the LHC: e.g., the production of Higgs bosons or the search for weakly interacting particles beyond the Standard Model.

The kinematic properties of $Zjj$ events allow some discrimination between the QCD and EW production mechanisms. The emission of a virtual $W$ boson from the quark in EW-$Zjj$ events results in the presence of two high-energy jets, with moderate transverse momentum ($p_T$), separated by a large interval in rapidity ($y$) and therefore with large dijet mass ($m_{jj}$) that characterises the EW-$Zjj$ signal. A consequence of the exchange of a vector boson in Fig. 1(b) is that there is no colour connection between the hadronic systems produced by the break-up of the two incoming protons. As a result, EW-$Zjj$ events are less likely to contain additional hadronic activity in the rapidity interval between the two high-$p_T$ jets than corresponding QCD-$Zjj$ events.

The first studies of EW-$Zjj$ production were performed [1] in $pp$ collisions at a centre-of-mass energy ($\sqrt{s}$) of 7 TeV by the CMS Collaboration, where the background-only hypothesis was rejected at the 2.6σ level. The first observation of the EW-$Zjj$ process was performed by the ATLAS Collaboration at a centre-of-mass energy ($\sqrt{s}$) of 8 TeV [2]. The cross-section measurement is in agreement with predictions from the Powheg-box event generator [3–5] and allowed limits to be placed on anomalous triple gauge couplings. The CMS Collaboration has also observed and measured [6] the cross-section for EW-$Zjj$ production at 8 TeV. This Letter presents measurements of the cross-section for EW-$Zjj$ production and inclusive $Zjj$ production at high dijet invariant mass in $pp$ collisions at $\sqrt{s} = 13$ TeV using data corresponding to an integrated luminosity of 3.2 fb$^{-1}$ collected by the ATLAS detector at the LHC. These measurements allow the dependence of the cross-section on $\sqrt{s}$...
to be studied. The increased $\sqrt{s}$ allows exploration of higher dijet masses, where the EW-$Zjj$ contribution to the total $Zjj$ rate becomes more pronounced.

2. ATLAS detector

The ATLAS detector is described in detail in Refs. [7,8]. It consists of an inner detector for tracking, surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnet systems. The inner detector is immersed in a 2T axial magnetic field and provides charged-particle tracking in the range $|\eta|<2.5$.

Electromagnetic calorimetry is provided by barrel and end-cap lead/liquid-argon (LAr) calorimeters in the region $|\eta|<3.2$. Within $|\eta|<2.47$ the calorimeter is finely segmented in the lateral direction of the showers, allowing measurement of the energy and position of electrons, and providing electron identification in conjunction with the inner detector. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta|<1.7$, and two hadronic end-cap calorimeters. A copper/LAr hadronic calorimeter covers the $1.5<|\eta|<3.2$ region, and a forward copper/tungsten/LAr calorimeter with electromagnetic-shower identification capabilities covers the $3.1<|\eta|<4.9$ region.

The muon spectrometer comprises separate trigger and high-precision tracking chambers. The tracking chambers cover the region $|\eta|<2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in part of the forward region, where the hit rate is highest. The muon trigger system covers the range $|\eta|<2.4$ with resistive plate chambers in the barrel region, and thin gap chambers in the end-cap regions.

A two-level trigger system is used to select events of interest [9]. The Level-1 trigger is implemented in hardware and uses a subset of the detector information to reduce the event rate to around 100 kHz. This is followed by the software-based high-level trigger system which reduces the event rate to about 1 kHz.

3. Monte Carlo samples

The production of EW-$Zjj$ events was simulated at next-to-leading-order (NLO) accuracy in perturbative QCD using the POWHEG-BOX v1 Monte Carlo (MC) event generator [4,5,10] and, alternatively, at leading-order (LO) accuracy in perturbative QCD using the SHARPE 2.2.0 event generator [11]. For modelling of the parton shower, hadronisation and underlying event (UEPS), POWHEG-BOX was interfaced to PYTHIA 8 [12] with a dedicated set of parton-shower-generator parameters (tune) denoted AZNLO [13] and the CT10 NLO parton distribution function (PDF) set [14]. The renormalisation and factorisation scales were set to the Z boson mass. SHARPE predictions used the COMIX [15] and OpenLoops [16] matrix element event generators, and the CKKW method was used to combine the various final-state topologies from the matrix element and match them to the parton shower [17]. The matrix elements were merged with the SHARPE parton shower [18] using the ME+PS@NLO prescription [19,20], and using SHARPE’s native dynamical scale-setting algorithm to set the renormalisation and factorisation scales. SHARPE predictions used the NNPDF30NLO PDF set [21].

The production of QCD-$Zjj$ events was simulated using three event generators, SHARPE 2.2.1, ALPGEN 2.14 [22] and MadGraph5_aMC@NLO 2.2.2 [23]. SHARPE provides $Z+n$-parton predictions calculated for up to two partons at NLO accuracy and up to four partons at LO accuracy in perturbative QCD. SHARPE predictions used the NNPDF30NLO PDF set together with the tuning of the UEPS parameters developed by the SHARPE authors using the ME+PS@NLO prescription [19,20]. ALPGEN is an LO event generator which uses explicit matrix elements for up to five partons and was interfaced to PYTHIA 6.426 [24] using the Perugia2011C tune [25] and the CTEQ6L1 PDF set [26]. Only matrix elements for light-flavour production in ALPGEN are included, with heavy-flavour contributions modelled by the parton shower, MadGraph5_aMC@NLO 2.2.2 (MG5_aMC) uses explicit matrix elements for up to four partons at LO, and was interfaced to PYTHIA 8 with the A14 tune [27] and using the NNPDF23LO PDF set [28]. For reconstruction-level studies, total $Z$ boson production rates predicted by all three event generators used to produce QCD-$Zjj$ predictions are normalised using the next-to-next-to-leading-order (NNLO) predictions calculated with the FEWZ 3.1 program [29–31] using the CT10 NNLO PDF set [14]. However, when comparing particle-level theoretical predictions to detector-corrected measurements, the normalisation of quoted predictions is provided by the event generator in question rather than an external NNLO prediction.

The production of a pair of EW vector bosons (bosiboson), where one decays leptonically and the other hadronically, or where both decay leptonically and are produced in association with two or more jets, through $WZ$ or $ZZ$ production with at least one $Z$ boson decaying to leptons, was simulated separately using SHARPE 2.1.1 and the CT10 NLO PDF set.

The largest background to the selected $Zjj$ samples arises from $t\bar{t}$ and single-top ($Wt$) production. These were generated using POWHEG-BOX v2 and PYTHIA 6.428 with the Perugia2012 tune [25], and normalised using the cross-section calculated at NNLO+$NNLL$ (next-to-next-to-leading log) accuracy using the Top++2.0 program [32].

All the above MC samples were fully simulated through the GEANT 4 [33] simulation of the ATLAS detector [34]. The effect of additional $pp$ interactions (pile-up) in the same or nearby bunch crossings was also simulated, using PYTHIA v8.186 with the A2 tune [35] and the MSTW2008LO PDF set [36]. The MC samples were reweighted so that the distribution of the average number of pile-up interactions per bunch crossing matches that observed in data. For the data considered in this Letter, the average number of interactions is 13.7.

4. Event preselection

The $Z$ bosons are measured in their dielectron and dimuon decay modes. Candidate events are selected using triggers requiring at least one identified electron or muon with transverse momentum thresholds of $p_{T}>24$ GeV and $20$ GeV respectively, with additional isolation requirements imposed in these triggers. At higher transverse momenta, the efficiency of selecting candidate events is improved through the use of additional electron and
muon triggers without isolation requirements and with thresholds of \( p_T = 60 \) GeV and \( 50 \) GeV respectively.

Candidate electrons are reconstructed from clusters of energy in the electromagnetic calorimeter matched to inner-detector tracks [37]. They must satisfy the Medium identification requirements described in Ref. [37] and have \( p_T > 25 \) GeV and \( |\eta| < 2.47 \), excluding the transition region between the barrel and end-cap calorimeters at \( 1.37 < |\eta| < 1.52 \). Candidate muons are identified as tracks in the inner detector matched and combined with track segments in the muon spectrometer. They must satisfy the Medium identification requirements described in Ref. [38], and have \( p_T > 25 \) GeV and \( |\eta| < 2.4 \). Candidate leptons must also satisfy a set of isolation criteria based on reconstructed tracks and calorimeter activity. Events are required to contain exactly two leptons of the same flavour but of opposite charge. The dilepton invariant mass must satisfy \( 81 < m_{\ell\ell} < 101 \) GeV.

Candidate hadronic jets are required to satisfy \( p_T > 25 \) GeV and \( |\eta| < 4.4 \). They are reconstructed from clusters of energy in the calorimeter [39] using the anti-\( k_t \) algorithm [40,41] with radius parameter \( R = 0.4 \). Jet energies are calibrated by applying \( p_T \)- and \( \gamma \)-dependent corrections derived from Monte Carlo simulation with additional in situ correction factors determined from data [42]. To reduce the impact of pile-up contributions, all jets with \( |\eta| < 2.4 \) and \( p_T < 60 \) GeV are required to be compatible with having originated from the primary vertex (the vertex with the highest sum of track \( p_T^2 \)), as defined by the jet vertex tagger algorithm [43]. Selected electrons and muons are discarded if they lie within \( \Delta R = 0.4 \) of a reconstructed jet. This requirement is imposed to remove non-prompt non-isolated leptons produced in heavy-flavour decays or from the decay in flight of a kaon or pion.

5. Measurement of inclusive \( Zj\bar{j} \) fiducial cross-sections

5.1. Definition of particle-level cross-sections

Cross-sections are measured for inclusive \( Zj\bar{j} \) production that includes the EW-\( Zj\bar{j} \) and QCD-\( Zj\bar{j} \) processes, as well as diboson events. The particle-level production cross-section for inclusive \( Zj\bar{j} \) production in a given fiducial region \( f \) is given by

\[
\sigma^f = \frac{N^f_{\text{obs}} - N^f_{\text{bkg}}}{L \cdot C^f},
\]

where \( N^f_{\text{obs}} \) is the number of events observed in the data passing the selection requirements of the fiducial region under study at detector level, \( N^f_{\text{bkg}} \) is the corresponding number of expected background (non-\( Zj\bar{j} \)) events, \( L \) is the integrated luminosity corresponding to the analysed data sample, and \( C^f \) is a correction factor applied to the observed data yields, which accounts for experimental efficiency and detector resolution effects, and is derived from MC simulation with data-driven efficiency and energy/momentum scale corrections. This correction factor is calculated as:

\[
C^f = \frac{N^f_{\text{det}}}{N^f_{\text{particle}}},
\]

where \( N^f_{\text{det}} \) is the number of signal events that satisfy the fiducial selection criteria at detector level in the MC simulation, and \( N^f_{\text{particle}} \) is the number of signal events that pass the equivalent selection but at particle level. These correction factors have values between 0.63 and 0.77, depending on the fiducial region.

With the exception of background from multijet and \( W+j \) jets processes (henceforth referred to together simply as multijet processes), contributions to \( N^f_{\text{bkg}} \) are estimated using the Monte Carlo samples described in Section 3. Background from multijet events is estimated from the data by reversing requirements on lepton identification or isolation to derive a template for the contribution of jets mis-reconstructed as lepton candidates as a function of dilepton mass. Non-multijet background is subtracted from the template using simulation. The normalisation is derived by fitting the nominal dilepton mass distribution in each fiducial region with the sum of the multijet template and a template comprising signal and background contributions determined from simulation. The multijet contribution is found to be less than 0.3% in each fiducial region. The contribution from \( W+j \) jets processes was checked using MC simulation and found to be much smaller than the total multijet background as determined from data. At particle level, only final-state particles with proper lifetime \( \tau > 10 \) mm are considered. Prompt leptons are dressed using the four-momentum combination of an electron or muon and all photons (not originating from hadron decays) within a cone of size \( \Delta R = 0.1 \) centred on the lepton. These dressed leptons are required to satisfy \( p_T > 25 \) GeV and \( |\eta| < 2.47 \). Events are required to contain exactly two dressed leptons of the same flavour but of opposite charge, and the dilepton invariant mass must satisfy \( 81 < m_{\ell\ell} < 101 \) GeV. Jets are reconstructed using the anti-\( k_t \) algorithm with radius parameter \( R = 0.4 \). Prompt leptons and the photons used to dress these leptons are not included in the particle-level jet reconstruction. All remaining final-state particles are included in the particle-level jet clustering. Prompt leptons with a separation \( \Delta R_{j,\ell} < 0.4 \) from any jet are rejected.

The cross-section measurements are performed in the six phase-space regions defined in Table 1. These regions are chosen to have varying contributions from EW-\( Zj\bar{j} \) and QCD-\( Zj\bar{j} \) processes.

5.2. Event selection

Following Ref. [2], events are selected in six detector fiducial regions. As far as possible, these are defined with the same kinematic requirements as the six phase-space regions in which the cross-section is measured (Table 1). This minimises systematic uncertainties in the modelling of the acceptance.

The baseline fiducial region represents an inclusive selection of events containing a leptonically decaying \( Z \) boson and at least two jets with \( p_T > 45 \) GeV, at least one of which satisfies \( p_T > 55 \) GeV. The two highest-\( p_T \) (leading and sub-leading) jets in a given event define the dijet system. The baseline region is dominated by QCD-\( Zj\bar{j} \) events. The requirement of \( 81 < m_{\ell\ell} < 101 \) GeV suppresses other sources of dilepton events, such as \( tt \) and \( Z \rightarrow \tau\tau \), as well as the multijet background.

Because the energy scale of the dijet system is typically higher in events produced by the EW-\( Zj\bar{j} \) process than in those produced by the QCD-\( Zj\bar{j} \) process, two subsets of the baseline region are defined which probe the EW-\( Zj\bar{j} \) contribution in different ways: in the high-mass fiducial region a high value of the invariant mass of the dijet system \( (m_{jj} > 1 \text{ TeV}) \) is required, and in the high-\( p_T \) fiducial region the minimum \( p_T \) of the leading and sub-leading jets is increased to 85 GeV and 75 GeV respectively. The EW-\( Zj\bar{j} \) process typically produces harder jet transverse momenta and results in a harder dijet invariant mass spectrum than the QCD-\( Zj\bar{j} \) process.

Three additional fiducial regions allow the separate contributions from the EW-\( Zj\bar{j} \) and QCD-\( Zj\bar{j} \) processes to be measured. The EW-enriched fiducial region is designed to enhance the EW-\( Zj\bar{j} \) contribution relative to that from QCD-\( Zj\bar{j} \), particularly at high \( m_{jj} \). The EW-enriched region is derived from the baseline region requiring \( m_{jj} > 250 \) GeV, a dilepton transverse momentum of \( p_T^\ell > 20 \) GeV, and that the normalised transverse momentum balance between the two leptons and the two highest transverse
Table 1

Summary of the particle-level selection criteria defining the six fiducial regions (see text for details).

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Object</th>
<th>Baseline</th>
<th>High-mass</th>
<th>High-$p_T$</th>
<th>EW-enriched</th>
<th>EW-enriched, $m_{jj} &gt; 1$ TeV</th>
<th>QCD-enriched</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptons</td>
<td></td>
<td>$</td>
<td>y</td>
<td>&lt; 2.47$, $p_T &gt; 25$ GeV, $\Delta R_{\ell j} &gt; 0.4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dilepton pair</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p_T^{\ell} &gt; 20$ GeV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$</td>
<td>y</td>
</tr>
<tr>
<td>Dijet system</td>
<td>$m_{jj} &gt; 1$ TeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interval jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$N_{\text{jet}} (p_T &gt; 25$ GeV) $= 0$</td>
<td></td>
</tr>
<tr>
<td>$Zjj$ system</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p_T^{\text{balance}} &gt; 0.15$</td>
<td></td>
</tr>
</tbody>
</table>

Two dilepton channels are in agreement within statistical uncertainties. The numbers of selected events in data and expectations from total signal plus background estimates are also given for each region. The largest discrepancy between observed and expected yields is seen in the high-mass region, and results from a mismodeling of the $m_{jj}$ spectrum in the QCD-$Zjj$ MC simulations used, which is discussed below and accounted for in the assessment of systematic uncertainties in the measurement.

5.4. Systematic uncertainties in the inclusive $Zjj$ fiducial cross-sections

Experimental systematic uncertainties affect the determination of the $C^j$ correction factor and the background estimates. The dominant systematic uncertainty in the inclusive $Zjj$ fiducial cross-sections arises from the calibration of the jet energy scale and resolution. This uncertainty varies from around 4% in the EW-enriched region to around 12% in the QCD-enriched region. The larger uncertainty in the QCD-enriched region is due to the higher average jet multiplicity (an average of 1.7 additional jets in addition to the leading and sub-leading jets) compared with the EW-enriched region (an average of 0.4 additional jets). Other experimental systematic uncertainties arising from lepton efficiencies related to reconstruction, identification, isolation and trigger, and lepton energy/momentum scale and resolution as well as from the effect of pile-up, amount to a total of around 1–2%, depending on the fiducial region.

In the baseline region, 30686 events are selected in the dielectron channel and 36786 events are selected in the dimuon channel. The total observed yields are in agreement with the expected yields within statistical uncertainties in each dilepton channel. The largest deviation across all fiducial regions is a 2$\sigma$ (statistical) difference between the expected to observed ratio in the electron versus muon channel in the high-$p_T$ region.

The expected composition of the selected data samples in the six $Zjj$ fiducial regions is summarised in Table 2, averaging across the dielectron and dimuon channels as these compositions in the two dilepton channels are in agreement within statistical uncertainties. The numbers of selected events in data and expectations from total signal plus background estimates are also given for each region. The largest discrepancy between observed and expected yields is seen in the high-mass region, and results from a mismodeling of the $m_{jj}$ spectrum in the QCD-$Zjj$ MC simulations used, which is discussed below and accounted for in the assessment of systematic uncertainties in the measurement.
radiation (generated with the PERUGIA2012RadoalH[Lo tunes [25]], or using an alternative top-quark production sample from MadGraph5_aMC@NLO interfaced to HERWIG++ v.2.71 [23,46].

The systematic uncertainty in the integrated luminosity is 2.1%. This is derived following a methodology similar to that detailed in Ref. [47], from a calibration of the luminosity scale using x-y beam-separation scans performed in June 2015.

5.5. Inclusive Zjj results

The measured cross-sections in the dielectron and dimuon channels are combined and presented here as a weighted average (taking into account total uncertainties) across both channels. These cross-sections are determined using each of the correction factors derived from the six combinations of the three QCD-Zjj (ALPGEN, MG5_aMC, and SHERPA) and two EW-Zjj (POWHEG and SHERPA) MC samples. For a given fiducial region (Table 1) the cross-section averaged over all six variations is presented in Table 3. The envelope of variation between QCD-Zjj and EW-Zjj models is assigned as a source of systematic uncertainty (1% in all regions except the EW-enriched region where the variation is 3% and the high-mass region where the variation is 2%).

The theoretical predictions from SHERPA (QCD-Zjj) + POWHEG (EW-Zjj), MG5_aMC (QCD-Zjj) + POWHEG (EW-Zjj), and ALPGEN (QCD-Zjj) + POWHEG (EW-Zjj) are found to be in agreement with the measurements in most cases. The uncertainties in the theoretical predictions are significantly larger than the uncertainties in the corresponding measurements.

The largest differences between predictions and measurement are in the high-mass and EW-enriched (mjj > 250 GeV and > 1 TeV) regions. Predictions from SHERPA (QCD-Zjj) + POWHEG (EW-Zjj) and MG5_aMC (QCD-Zjj) + POWHEG (EW-Zjj) exceed measurements in the high-mass region by 54% and 34% respectively, where the predictions have relative uncertainties with respect to the measurement of 36% and 32%. For the EW-enriched region, SHERPA (QCD-Zjj) + POWHEG (EW-Zjj) describes the observed rates well, but MG5_aMC (QCD-Zjj) + POWHEG (EW-Zjj) overestimates measurements by 28% with a relative uncertainty of 11%. In the EW-enriched (mjj > 1 TeV) region the same predictions overestimate measured rates by 32% and 57%, with relative uncertainties of 16% and 15%. Some of these differences arise from a significant mismodelling of the QCD-Zjj contribution, as investigated and discussed in detail in Section 6.1. Predictions from ALPGEN (QCD-Zjj) + POWHEG (EW-Zjj) are in agreement with the data for the high-mass and EW-enriched (mjj > 250 GeV and > 1 TeV) regions.

6. Measurement of EW-Zjj fiducial cross-sections

The EW-enriched fiducial region (defined in Table 1) is used to measure the production cross-section of the EW-Zjj process. The EW-enriched region has an overall expected EW-Zjj signal fraction of 4.8% (Table 2) and this signal fraction grows with increasing mjj to 26.1% for mjj > 1 TeV. The QCD-enriched region has an overall expected EW-Zjj signal fraction of 1.6% increasing to 4.4% for mjj > 1 TeV. The dominant background to the EW-Zjj cross-section measurement is QCD-Zjj production. It is subtracted in the same way as non-Zjj backgrounds in the inclusive measurement described in Section 5. Although diboson production includes contributions from purely EW processes, in this measurement it is considered as part of the background and is estimated from simulation.

A particle-level production cross-section measurement of EW-Zjj production in a given fiducial region f is thus given by

$$\sigma_{EW}^f = \frac{N_{obs}^f - N_{QCD-Zjj}^f - N_{bkg}^f}{L \cdot c_{EW}^f},$$

with the same notations as in Eq. (1) and where N_{QCD-Zjj}^f is the expected number of QCD-Zjj events passing the selection requirements of the fiducial region at detector level, N_{bkg}^f is the expected number of background (non-Zjj and diboson) events, and c_{EW}^f is a correction factor applied to the observed background-subtracted data yields that accounts for experimental efficiency and detector resolution effects, and is derived from EW-Zjj MC simulation with data-driven efficiency and energy/momentum scale corrections. For the mjj > 250 GeV (mjj > 1 TeV) region the correction factor is determined to be 0.66 (0.67) when using the SHERPA EW-Zjj prediction, and 0.67 (0.68) when using the POWHEG EW-Zjj prediction.

Detector-level comparisons of the mjj distribution between data and simulation in (a) the EW-enriched region and (b) the QCD-enriched region are shown in Fig. 2. It can be seen in Fig. 2(a)
that in the EW-enriched region the EW-$Zjj$ component becomes prominent at large values of $m_{jj}$. However, Fig. 2(b) demonstrates that the shape of the $m_{jj}$ distribution for QCD-$Zjj$ production is poorly modelled in simulation. The same trend is seen for all three QCD-$Zjj$ event generators listed in Section 3. ALPGEN provides the best description of the data over the whole $m_{jj}$ range. In comparison, MG5_aMC and Sherpa overestimate the data by 80% and 120% respectively, for $m_{jj} = 2$ TeV, well outside the uncertainties on these predictions described in Table 3. These discrepancies have been observed previously in $Zjj$ [2,48] and Wjj [49–51] production at high dijet invariant mass and at high jet rapidities. For the purpose of extracting the cross-section for EW-$Zjj$ production, this mismodelling of QCD-$Zjj$ is corrected for using a data-driven approach, as discussed in the following.

6.1. Corrections for mismodelling of QCD-$Zjj$ production and fitting procedure

The normalisation of the QCD-$Zjj$ background is extracted from a fit of the QCD-$Zjj$ and EW-$Zjj$ $m_{jj}$ simulated distributions to the data in the EW-enriched region, after subtraction of non-$Zjj$ and diboson background, using a log-likelihood maximisation [52]. Following the procedure adopted in Ref. [2], the data in the EW-enriched region are used to evaluate detector-level shape correction factors for the QCD-$Zjj$ MC predictions bin-by-bin in $m_{jj}$. These data-to-simulation ratio correction factors are applied to the simulation-predicted shape in $m_{jj}$ of the QCD-$Zjj$ contribution in the EW-enriched region. This procedure is motivated by two observations:

(a) the QCD-enriched region and EW-enriched region are designed to be kinematically very similar, differing only with regard to the presence/absence of jets reconstructed within the rapidity interval bounded by the dijet system,
(b) the contribution of EW-$Zjj$ to the region of high $m_{jj}$ is suppressed in the QCD-enriched region (4.4% for $m_{jj} > 1$ TeV) relative to that in the EW-enriched region (26.1% for $m_{jj} > 1$ TeV) (also illustrated in Fig. 2); the impact of the residual EW-$Zjj$ contamination in the QCD-enriched region is assigned as a component of the systematic uncertainty in the QCD-$Zjj$ background.

The shape correction factors in $m_{jj}$ obtained using the three different QCD-$Zjj$ MC samples are shown in Fig. 3(a). These are derived as the ratio of the data to simulation in bins of $m_{jj}$ after normalisation of the total yield in simulation to that observed.

Table 3

Measured and predicted inclusive $Zjj$ production cross-sections in the six fiducial regions defined in Table 1. For the measured cross-sections, the first uncertainty given is statistical, the second is systematic and the third is due to the luminosity determination. For the predictions, the statistical uncertainty is added in quadrature to the systematic uncertainties arising from the PDFs and factorisation and renormalisation scale variations.

<table>
<thead>
<tr>
<th>Fiducial region</th>
<th>Inclusive $Zjj$ cross-sections [pb]</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td></td>
</tr>
<tr>
<td></td>
<td>value ± stat. ± syst. ± lumi.</td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>13.9 ± 0.1 1.1 ± 0.3</td>
<td>13.5 ± 1.9 15.2 ± 2.2 11.7 ± 1.7</td>
</tr>
<tr>
<td>High-P_T</td>
<td>4.77 ± 0.05 0.27 ± 0.10</td>
<td>4.7 ± 0.8 5.5 ± 0.9 4.2 ± 0.7</td>
</tr>
<tr>
<td>EW-enriched</td>
<td>2.77 ± 0.04 0.13 ± 0.06</td>
<td>2.7 ± 0.2 3.6 ± 0.3 2.4 ± 0.2</td>
</tr>
<tr>
<td>QCD-enriched</td>
<td>1.34 ± 0.02 0.17 ± 0.03</td>
<td>1.5 ± 0.4 1.4 ± 0.3 1.1 ± 0.3</td>
</tr>
<tr>
<td>High-mass</td>
<td>0.30 ± 0.01 0.03 ± 0.01</td>
<td>0.46 ± 0.11 0.40 ± 0.09 0.27 ± 0.06</td>
</tr>
<tr>
<td>EW-enriched ($m_{jj} &gt; 1$ TeV)</td>
<td>0.118 ± 0.008 ± 0.006 ± 0.002</td>
<td>0.156 ± 0.019 0.185 ± 0.023 0.120 ± 0.015</td>
</tr>
</tbody>
</table>

Fig. 2. Detector-level comparisons of the dijet invariant mass distribution between data and simulation in (a) the EW-enriched region and (b) the QCD-enriched region, for the dielectron and dimuon channel combined. Uncertainties shown on the data are statistical only. The EW-$Zjj$ simulation sample comes from the Powheg event generator and the QCD-$Zjj$ MC sample comes from the Sherpa event generator. The lower panels show the ratio of simulation to data for three QCD-$Zjj$ models, from ALPGEN, MG5_aMC, and Sherpa. The hatched band centred at unity represents the size of statistical and experimental systematic uncertainties added in quadrature.
in data in the QCD-enriched region. A binned fit to the correction factors derived in dijet invariant mass is performed with a linear fit function (and also with a quadratic fit function) to produce a continuous correction factor. The linear fit is illustrated overlaid on the binned correction factors in Fig. 3(a). The nominal value of the EW-Zjj cross-section corresponding to a particular QCD-Zjj event generator template is determined using the correction factors from the linear fit. The change in resultant EW-Zjj cross-section from using binned correction factors directly is assessed as a systematic uncertainty. The change in the extracted EW-Zjj cross-section when using a quadratic fit was found to be negligible. The variations observed between event generators may be partly due to differences in the modelling of QCD radiation within the rapidity interval bounded by the dijet system, which affects the extrapolation from the central-jet-enriched QCD-enriched region to the central-jet-suppressed EW-enriched region. The variation between event generators is much larger than the effect of PDF and scale uncertainties in a particular prediction (indicated in Fig. 3(a) by a shaded band on the predictions from Sherpa). Estimating the uncertainties associated with QCD-Zjj mismodelling from PDF and scale variations around a single generator prediction would thus result in an underestimate of the true theoretical uncertainty associated with this mismodelling. In this measurement, the span of resultant EW-Zjj cross-sections extracted from the use of each of the three QCD-Zjj templates is assessed as a systematic uncertainty. The variation in the EW-Zjj cross-section measurement due to a change in the EW-Zjj signal template used in the derivation of the mjj correction factors (from Powheg to Sherpa) is found to be negligible.

To test the dependence of the QCD-Zjj correction factors on the modelling of any additional jet emitted in the dijet rapidity interval, the QCD-enriched control region is divided into pairs of mutually exclusive subsets according to the \(|y|\) of the highest \(p_T\) jet within the rapidity interval bounded by the dijet system, the \(p_T\) of that jet, or the value of \(N_{\text{jet}}(p_T>25\text{ GeV})\). The continuous correction factors are determined from each subregion using both a linear and a quadratic fit to the data. Correction factors derived in the subregions using quadratic fits result in the largest variation in the extracted cross-sections. These fits are shown in Fig. 3(b) for the Alpgen QCD-Zjj sample, which displays the largest variation between subregions of the three event generators used to produce QCD-Zjj predictions. Within statistical uncertainties the measured EW-Zjj cross-sections are not sensitive to the definition of the control region used.

The normalisations of the corrected QCD-Zjj templates and the EW-Zjj templates are allowed to vary independently in a fit to the background-subtracted \(m_{jj}\) distribution in the EW-enriched region. The measured electroweak production cross-section is determined from the data minus the QCD-Zjj contribution determined from these fits (Eq. (3)). As the choice of EW-Zjj template can influence the normalisation of the QCD-Zjj template in the EW-enriched region fit, the measured EW-Zjj cross-section determination is repeated for each QCD-Zjj template using either the Powheg or Sherpa EW-Zjj template in the fit. The central value of the result quoted is the average of the measured EW-Zjj cross-sections determined with each of the six combinations of the three QCD-Zjj and two EW-Zjj templates, with the envelope of measured results from these variations taken as an uncertainty associated with the dependence on the modelling of the templates in the EW-enriched region. Separate uncertainties are assigned for the determination of the QCD-Zjj correction factors in the QCD-enriched region and their propagation into the EW-enriched region. The measurement of the EW-Zjj cross-section in the EW-enriched region for \(m_{jj}>1\text{ TeV}\) is extracted from the same fit procedure, with data and QCD-Zjj yields integrated for \(m_{jj}>1\text{ TeV}\).

Fig. 4(a) shows a comparison in the EW-enriched region of the fitted EW-Zjj and mjj-reweighted QCD-Zjj templates to the background-subtracted data, from which the measured EW-Zjj cross-section is extracted. Fig. 4(b) demonstrates how the data in the EW-enriched region is modelled with the fitted EW-Zjj and mjj-reweighted QCD-Zjj templates, for the three different QCD-Zjj event generators (and their corresponding correction factors derived in the QCD-enriched region shown in Fig. 3(a)). Despite significantly different modelling of the \(m_{jj}\) distribution between event generators, and different models for additional QCD radiation, the results of the combined correction and fit procedure give a consistent description of the data.

6.2. Systematic uncertainties in the EW-Zjj fiducial cross-section

The total systematic uncertainty in the cross-section for EW-Zjj production in the EW-enriched fiducial region is 17% (16% in the EW-enriched \(m_{jj}>1\text{ TeV}\) region). The sources and size of each systematic uncertainty are summarised in Table 4.

Systematic uncertainties associated with the EW-Zjj signal template used in the fit and EW-Zjj signal extraction are obtained from the variation in the measured cross-section when using either of the individual EW-Zjj MC samples (Powheg and Sherpa).
The ATLAS Collaboration / Physics Letters B 775 (2017) 206–228

Fig. 4. (a) Comparison in the EW-enriched region of the sum of EW-$Zjj$ and $m_{jj}$-rewighted QCD-$Zjj$ templates to the data (minus the non-$Zjj$ backgrounds). The normalisation of the templates is adjusted to the results of the fit (see text for details). The EW-$Zjj$ MC sample comes from the Powheg event generator and the QCD-$Zjj$ MC sample comes from the Alpgen event generator. (b) The ratio of the sum of the EW-$Zjj$ and $m_{jj}$-rewighted QCD-$Zjj$ templates to the background-subtracted data in the EW-enriched region, for three different QCD-$Zjj$ MC predictions. The normalisation of the templates is adjusted to the results of the fit. Error bars represent the statistical uncertainties in the data and combined QCD-$Zjj$ plus EW-$Zjj$ MC samples added in quadrature. The hatched band represents experimental systematic uncertainties in the $m_{jj}$ distribution.

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative systematic uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$m_{jj}&gt;250$ GeV</td>
</tr>
<tr>
<td>EW-$Zjj$ signal modelling (QCD scales, PDF and UEPS)</td>
<td>± 7.4</td>
</tr>
<tr>
<td>EW-$Zjj$ template statistical uncertainty</td>
<td>± 0.5</td>
</tr>
<tr>
<td>EW-$Zjj$ contamination in QCD-enriched region</td>
<td>−1.1</td>
</tr>
<tr>
<td>QCD-$Zjj$ modelling ($m_{jj}$ shape constraint / third-jet veto)</td>
<td>± 11</td>
</tr>
<tr>
<td>Stat. uncertainty in QCD control region constraint</td>
<td>± 6.2</td>
</tr>
<tr>
<td>QCD-$Zjj$ signal modelling (QCD scales, PDF and UEPS)</td>
<td>± 4.5</td>
</tr>
<tr>
<td>QCD-$Zjj$ template statistical uncertainty</td>
<td>± 2.5</td>
</tr>
<tr>
<td>QCD-EW interference</td>
<td>± 1.3</td>
</tr>
<tr>
<td>$t\bar{t}$ and single-top background modelling</td>
<td>± 1.0</td>
</tr>
<tr>
<td>Diboson background modelling</td>
<td>± 0.1</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>± 2.3</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>+5.3/-4.1</td>
</tr>
<tr>
<td>Lepton identification, momentum scale, trigger, pile-up</td>
<td>+1.3/-2.5</td>
</tr>
<tr>
<td>Luminosity</td>
<td>± 2.1</td>
</tr>
<tr>
<td>Total</td>
<td>± 17</td>
</tr>
</tbody>
</table>

Table 4

Systematic uncertainties contributing to the measurement of the EW-$Zjj$ cross-sections for $m_{jj}>250$ GeV and $m_{jj}>1$ TeV. Uncertainties are grouped into EW-$Zjj$ signal modelling, QCD-$Zjj$ background modelling, QCD-EW interference, non-$Zjj$ backgrounds, and experimental sources.

Compared to the average of the two, taken as the central value. Uncertainties in the EW-$Zjj$ templates due to variations of the QCD scales, of the PDFs, and of the UEPS model are also included as are statistical uncertainties in the templates themselves.

Following the extraction of the EW-$Zjj$ cross-section in the EW-enriched regions, the normalisations of the EW-$Zjj$ MC samples are modified to agree with the measurements and the potential EW contamination of the QCD-enriched region is recalculated, which leads to a modification of the QCD-$Zjj$ correction factors. The EW-$Zjj$ cross-section measurement is repeated with these modified QCD-$Zjj$ templates and the change in the resultant cross-sections is assigned as a systematic uncertainty associated with the EW-$Zjj$ contamination of the QCD-enriched region.

As discussed in Section 6.1, the use of a QCD-enriched region provides a way to correct for QCD-$Zjj$ modelling issues and also constrains theoretical and experimental uncertainties associated with observables constructed from the two leading jets. Nevertheless, the largest contribution to the total uncertainty arises from modelling uncertainties associated with propagation of the $m_{jj}$ correction factors for QCD-$Zjj$ in the QCD-enriched region into the EW-enriched region, and these correction factors depend on the modelling of the additional jet activity in the QCD-$Zjj$ MC samples used in the measurement. The uncertainty is assessed by repeating the EW-$Zjj$ cross-section measurement with $m_{jj}$-rewighted QCD-$Zjj$ MC templates from Alpgen, MG5_aMC, and Sherpa, and assigning the variation of the measured cross-sections from the central EW-$Zjj$ result as a systematic uncertainty. Statistical uncertainties from data and simulation in the $m_{jj}$ correction factors derived in the QCD-enriched region are also propagated through to the measured EW-$Zjj$ cross-section as a systematic uncertainty. Uncertainties associated with QCD renormalisation and factorisation scales, PDF error sets, and UEPS modelling are assessed by studying the change in the extracted EW-$Zjj$ cross-sections when repeating the measurement procedure, including rederiving...
$m_{jj}$ correction factors in the QCD-enriched region and repeating fits in the EW-enriched region, using modified QCD-$Z_{jj}$ MC templates. Statistical uncertainties in the QCD-$Z_{jj}$ template in the EW-enriched region are also propagated as a systematic uncertainty in the EW-$Z_{jj}$ cross-section measurement.

Potential quantum-mechanical interference between the QCD-$Z_{jj}$ and EW-$Z_{jj}$ processes is assessed using MG5_aMC to derive a correction to the QCD-$Z_{jj}$ template as a function of $m_{jj}$. The impact of interference on the measurement is determined by repeating the EW-$Z_{jj}$ measurement procedure twice, either applying this correction to the QCD-$Z_{jj}$ template only in the QCD-enriched region or only in the EW-enriched region and taking the maximum change in the measured EW-$Z_{jj}$ cross-section as a symmetrised uncertainty. This approach assumes the interference affects only one of the two fiducial regions and therefore has a maximal impact on the signal extraction. Potential interference between the $Z_{jj}$ and diboson processes was found to be negligible.

Normalisation and shape uncertainties in the estimated background from top-quark and diboson production are assessed with varied background templates as described in Section 5.4, albeit with significantly larger uncertainties in the EW-enriched fiducial region compared to the baseline region.

Experimental systematic uncertainties arising from the jet energy scale and resolution, from lepton efficiencies related to reconstruction, identification, isolation and trigger, and lepton energy/momentum scale and resolution, and from pile-up modelling, are independently assessed by repeating the EW-$Z_{jj}$ measurement procedure using modified QCD-$Z_{jj}$ and EW-$Z_{jj}$ templates. Here, the QCD-enriched QCD-$Z_{jj}$ template constraint procedure described in Section 6.1 has the added benefit of significantly reducing the jet-based experimental uncertainties, as can be seen in Table 4 from their small impact on the total systematic uncertainty.

6.3. Electroweak $Z_{jj}$ results

As in the inclusive $Z_{jj}$ cross-section measurements, the quoted EW-$Z_{jj}$ cross-section measurements are the average of the cross-sections determined with each of the six combinations of the three QCD-$Z_{jj}$ MC templates and two EW-$Z_{jj}$ MC templates. The measured cross-sections for the EW production of a leptonically decaying $Z$ boson and at least two jets satisfying the fiducial requirements for the EW-enriched regions as given in Table 1 with the requirements $m_{jj} > 250$ GeV and $m_{jj} > 1$ TeV are shown in Table 5, where they are compared to predictions from POWHEG+PYTHIA. The use of a differential template fit in $m_{jj}$ to extract the EW-$Z_{jj}$ signal allows systematic uncertainties on the EW-$Z_{jj}$ cross-section measurements to be constrained by the bins with the most favourable balance of EW-$Z_{jj}$ signal purity and minimal shape and normalisation uncertainty. For the $m_{jj} > 250$ GeV region, although all $m_{jj}$ bins contribute to the fit, the individually most-constraining $m_{jj}$ interval is the 900–1000 GeV bin. The use of this method results in very similar relative systematic uncertainties in the EW-$Z_{jj}$ cross-section measurements at the two different $m_{jj}$ thresholds, despite the measured relative EW-$Z_{jj}$ contribution to the total $Z_{jj}$ rate for $m_{jj} > 1$ TeV being more than six times the relative contribution of EW-$Z_{jj}$ for $m_{jj} > 250$ GeV.

The EW-$Z_{jj}$ cross-sections at $\sqrt{s} = 13$ TeV are in agreement with the predictions from POWHEG+PYTHIA for both $m_{jj} > 250$ GeV and $m_{jj} > 1$ TeV. The effect on the measurement of inclusive $Z_{jj}$ production rates (Section 5.5) from correcting the EW-$Z_{jj}$ production rates predicted by POWHEG+PYTHIA to the measured rates presented here was found to be negligible. Modifications to the $m_{jj}$ distribution shape are already accounted for as a systematic uncertainty in the inclusive $Z_{jj}$ measurements.

Fig. 5 shows a summary of the fiducial cross-sections for a leptonically decaying $Z$ boson and at least two jets at 13 TeV compared to equivalent results at 8 TeV [2] and to theoretical predictions with their uncertainties. A significant rise in cross-section is observed between $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV within each fiducial region. In the EW-enriched region, for $m_{jj}$ thresholds of 250 GeV and 1 TeV, the measured EW-$Z_{jj}$ cross-sections at 13 TeV are found to be respectively 2.2 and 3.2 times as large as those measured at 8 TeV, as illustrated in Fig. 6.
7. Summary

Fiducial cross-sections for the electroweak production of two jets in association with a leptonically decaying Z boson in proton-proton collisions are measured at a centre-of-mass energy of 13 TeV, using data corresponding to an integrated luminosity of 3.2 fb\(^{-1}\) recorded with the ATLAS detector at the Large Hadron Collider. The EW-Zjj cross-section is extracted in a fiducial region chosen to enhance the EW contribution relative to the dominant QCD-Zjj process, which is constrained using a data-driven approach. The measured fiducial EW cross-section is \(\sigma_{EW} = 119 \pm 16\) (stat.) \(\pm 20\) (syst.) \(\pm 2\) (lumi.) fb for dijet invariant mass greater than 250 GeV, and 34.2 \(\pm 5.8\) (stat.) \(\pm 5.5\) (syst.) \(\pm 0.7\) (lumi.) fb for dijet invariant mass greater than 1 TeV. A comparison with previously published measurements at \(\sqrt{s} = 8\) TeV is presented, with measured EW-Zjj cross-sections at \(\sqrt{s} = 13\) TeV found to be 2.2 (3.2) times as large as those measured at \(\sqrt{s} = 8\) TeV in the low (high) dijet mass EW-enriched regions. Relative to measurements at \(\sqrt{s} = 8\) TeV, the increased \(\sqrt{s}\) allows a region of higher dijet mass to be explored, in which the EW-Zjj signal is more prominent. The Standard Model predictions are in agreement with the EW-Zjj measurements.

The inclusive \(Zjj\) cross-section is also measured in six different fiducial regions with varying contributions from EW-Zjj and QCD-Zjj production. At higher dijet invariant masses (> 1 TeV), particularly crucial for precision measurements of EW-Zjj production and for searches for new phenomena in vector-boson fusion topologies, predictions from SHERPA (QCD-Zjj) + POWHEG (EW-Zjj) and MG5\_aMC (QCD-Zjj) + POWHEG (EW-Zjj) are found to significantly overestimate the observed \(Zjj\) production rates in data. A\_L\_P\_G\_EN (QCD-Zjj) + POWHEG (EW-Zjj) provides a better description of the \(m_{jj}\) shape.

Acknowledgements

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/Irfu, France; SRNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR, MESTD, Serbia; MSSR, Slovakia; ARRS and MIŽS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Knut and Alice Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, Canarie, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes cofunded by EU-ESF and the Greek NSRF; BRF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [53].

References

The ATLAS Collaboration

The ATLAS Collaboration / Physics Letters B 775 (2017) 206–228
40. INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; 41. Dipartimento di Fisica, Università della Calabria, Rende, Italy
42. AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; 43. Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
44. Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
45. Physics Department, Southern Methodist University, Dallas TX, United States
46. Physics Department, University of Texas at Dallas, Richardson TX, United States
47. DESY, Hamburg and Zeuthen, Germany
48. Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
49. Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
50. Department of Physics, Duke University, Durham NC, United States
51. SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
52. INFN - Laboratori Nazionali di Frascati, Frascati, Italy
53. Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
54. Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
55. INFN Sezione di Genova; 56. Dipartimento di Fisica, Università di Genova, Genova, Italy
56. E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
57. High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
58. II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
59. SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
60. II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
61. Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
62. Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States
63. Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
64. Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
65. Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
66. Department of Physics, The Chinese University of Hong Kong, Shatin, N.T.; 67. Department of Physics, The University of Hong Kong; 68. Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
69. Department of Physics, National Tsing Hua University, Taiwan
70. Department of Physics, Indiana University, Bloomington IN, United States
71. Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
72. University of Iowa, Iowa City IA, United States
73. Department of Physics and Astronomy, Iowa State University, Ames IA, United States
74. Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
75. KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
76. Graduate School of Science, Kobe University, Kobe, Japan
77. Faculty of Science, Kyoto University, Kyoto, Japan
78. Kyoto University of Education, Kyoto, Japan
79. Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
80. Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
81. Physics Department, Lancaster University, Lancaster, United Kingdom
82. INFN Sezione di Lecce; 83. Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
84. Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
85. Department of Experimental Particle Physics, Jozef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
86. School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
87. School of Physics, Royal Holloway University of London, Surrey, United Kingdom
88. Department of Physics and Astronomy, University College London, London, United Kingdom
89. Louisiana Tech University, Ruston LA, United States
90. Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
91. Fysiska institutionen, Lunds universitet, Lund, Sweden
92. Departamento de Física Teórica C-15, Universidad Autonoma de Madrid, Madrid, Spain
93. Institut für Physik, Universität Mainz, Mainz, Germany
94. School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
95. CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
96. Department of Physics, University of Massachusetts, Amherst MA, United States
97. Department of Physics, McGill University, Montreal QC, Canada
98. School of Physics, University of Melbourne, Victoria, Australia
99. Department of Physics, The University of Michigan, Ann Arbor MI, United States
100. Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States
101. INFN Sezione di Milano; 102. Dipartimento di Fisica, Università di Milano, Milano, Italy
103. B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
104. Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
105. Group of Particle Physics, University of Montreal, Montreal QC, Canada
106. P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
107. Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
108. National Research Nuclear University MEPhI, Moscow, Russia
109. D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
110. Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
111. Max-Planck-Institut für Physik [Werner-Heisenberg-Institut], München, Germany
112. Nagasaki Institute of Applied Science, Nagasaki, Japan
113. Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
114. INFN Sezione di Napoli; 115. Dipartimento di Fisica, Università di Napoli, Napoli, Italy
116. Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States
117. Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
118. Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
119. Department of Physics, Northern Illinois University, DeKalb IL, United States
120. Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
121. Department of Physics, New York University, New York NY, United States
122. Ohio State University, Columbus OH, United States
123. Faculty of Science, Okayama University, Okayama, Japan
124. Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States
125. Department of Physics, Oklahoma State University, Stillwater OK, United States
Also at Physics Department, An-Najah National University, Nablus, Palestine.

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

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.

Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal.

Also at Tomsk State University, Tomsk, Russia.

Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.

Also at Università di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America.

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.

Also at Louisiana Tech University, Ruston LA, United States of America.

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

Also at Graduate School of Science, Osaka University, Osaka, Japan.

Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.

Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.

Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.

Also at Institute of Theoretical Physics, Ila State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Georgian Technical University (GTU), Tbilisi, Georgia.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York NY, United States of America.

Also at Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago, Chile.

Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.

Also at The City College of New York, New York NY, United States of America.

Also at Departamento de Física Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Portugal.

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

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

Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.

Also at Institut de Fisica d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.

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

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

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

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

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

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

Also at Giresun University, Faculty of Engineering, Turkey.

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

Also at Department of Physics, Nanjing University, Jiangsu, China.

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

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

Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.

Also at PKU-CHEP.

* Deceased.