Evidence for Electroweak Production of $W^\pm W^\mp jj$ in $pp$ Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

G. Aad et al.*

(ATLAS Collaboration)

(Received 23 May 2014; published 3 October 2014)

This Letter presents the first study of $W^\pm W^\mp jj$, same-electric-charge diboson production in association with two jets, using 20.3 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded by the ATLAS detector at the Large Hadron Collider. Events with two reconstructed same-charge leptons ($e^\pm e^\pm$, $e^\pm \mu^\pm$, and $\mu^\pm \mu^\pm$) and two or more jets are analyzed. Production cross sections are measured in two fiducial regions, with different sensitivities to the electroweak and strong production mechanisms. First evidence for $W^\pm W^\mp jj$ production and electroweak-only $W^\pm W^\mp jj$ production is observed with a significance of 4.5 and 3.6 standard deviations, respectively. The measured production cross sections are in agreement with standard model predictions. Limits at 95% confidence level are set on anomalous quartic gauge couplings.

DOI: 10.1103/PhysRevLett.113.141803 PACS numbers: 14.70.Fm, 12.60.Cn, 13.38.Be, 13.85.Fb

The scattering of two massive vector bosons (VBS), $VV \rightarrow VV$ with $V = W$ or $Z$, is a key process to probe the nature of electroweak symmetry breaking [1,2]. In the absence of a standard model (SM) Higgs boson, the longitudinally polarized VBS amplitude increases as a function of the center-of-mass energy $\sqrt{s}$ and violates unitarity at energies around 1 TeV [3-5]. The recent discovery of a 125 GeV SM-like Higgs boson at the Large Hadron Collider (LHC) [6,7] provides a plausible explanation for the mechanism that unitarizes this process. However, many physics scenarios predict enhancements in VBS either from additional resonances or if the observed SM-like Higgs boson only partially unitarizes this amplitude [8,9]. There is no previous evidence for a process involving a $VVVV$ vertex.

At hadron colliders VBS can be idealized as an interaction of gauge bosons radiated from initial state quarks yielding a final state with two bosons and two jets ($VVjj$) in a purely electroweak process [10]. VBS diagrams are not separately gauge invariant and must be studied in conjunction with additional Feynman graphs leading to the same $VVjj$ final state [11]. Two classes of physical processes give rise to $VVjj$ final states. The first process, which includes VBS contributions, involves exclusively weak interactions at Born level (of order $\alpha^2_{\text{EW}}$ without considering the boson decay, where $\alpha_{\text{EW}}$ is the electroweak force coupling constant) and is referred to as electroweak production. The second process involves both the strong and electroweak interactions at Born level (of order $\alpha^2 \alpha_{\text{EW}}^2$, where $\alpha_s$ is the strong force coupling constant) and is referred to as strong production. In the case of same-electric-charge $WW$ production ($W^\pm W^\mp jj$), the strong production cross section does not dominate the electroweak cross section, making this channel an ideal choice for initial studies on VBS.

This Letter presents the first evidence for electroweak $W^\pm W^\mp jj$ production, where both $W$ bosons decay leptonically ($W^\pm \rightarrow \ell^\pm \nu$, $\ell = e$, $\mu$), using $pp$ collision data at $\sqrt{s} = 8$ TeV collected by the ATLAS detector at the LHC. This process has a distinct experimental signature of two same-electric-charge leptons and two jets.

Two fiducial regions are defined. The first region or “inclusive region” is defined to study the combination of electroweak and strong production mechanisms, and in this region both processes are referred to as the signal. It is defined at particle level as follows. Exactly two prompt charged leptons ($\tau$ leptons and leptons originating from $\tau$ decays are excluded) are required with the same electric charge, transverse momentum $p_T > 25$ GeV, $|\eta| < 2.5$ [12], invariant mass $m_{\ell\ell} > 20$ GeV, and angular separation $\Delta R_{\ell\ell} \equiv \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} > 0.3$. At least two jets reconstructed with the anti-$k_T$ algorithm [13] with jet size $R = 0.4$ and with $p_T > 30$ GeV, $|\eta| < 4.5$, and separated from the leptons by $\Delta R_{jj} > 0.3$ are also required. The invariant mass of the two jets with the largest $p_T$ ($m_{jj}$) must be larger than 500 GeV, and the magnitude of the missing transverse momentum ($E_T^{\text{miss}}$) calculated using all neutrinos in the final state must be greater than 40 GeV. To reduce the dependence on QED radiation, lepton momenta include contributions from photons within $\Delta R = 0.1$ of the lepton direction. The second region or “VBS region” is a subset of the inclusive region that also requires the two jets with largest $p_T$ to be separated in rapidity [14] by $|\Delta y_{jj}| > 2.4$. This enhances the purity of electroweak $W^\pm W^\mp jj$ by removing most of the strong $W^\pm W^\pm jj$ events, which are considered as a background in this region.

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.

0031-9007/14/113(14)/141803(19) 141803-1 © 2014 CERN, for the ATLAS Collaboration
The expected production cross sections for the $pp \rightarrow W^\pm W^{\mp} jj$ process in the two fiducial regions (“fiducial cross sections”) are calculated using POWHEGBOX [15,16], with CT10 parton distribution functions (PDFs) [17], interfaced with PYTHIA8 [18,19] for parton showering, hadronization, and underlying event modeling. The contribution from nonresonant production of the same leptonic final state is also considered, but is strongly suppressed [16]. The cross section for the electroweak $W^\pm W^{\mp} jj$ process is predicted to be $1.00 \pm 0.06$ fb in the inclusive region and $0.88 \pm 0.05$ fb in the VBS region. The cross section for the strong $W^\pm W^{\mp} jj$ process is $0.35 \pm 0.05$ fb in the inclusive region and $0.098 \pm 0.018$ fb for the VBS region. The uncertainty on these predictions include 68% confidence level PDF uncertainties [20], parton shower, and hadronization modeling uncertainties estimated by comparing PYTHIA8 and HERWIG++ plus JIMMY [21,22], the independent variation of renormalization and factorization scales by a factor of 2, the difference between the predictions from POWHEGBOX and VBFNLO [23], and the integration error. The parton shower and generator uncertainties are dominant for electroweak production, while scale variations are dominant for strong production. Interference between electroweak and strong production is studied at leading-order accuracy using SHERPA [24] and is found to increase the combined strong and electroweak $W^\pm W^{\mp} jj$ cross section by $(12 \pm 6)\%$ in the inclusive region and $(7 \pm 4)\%$ in the VBS region. The total SM signal cross-section prediction in the inclusive region is $1.52 \pm 0.11$ fb, while the sum of electroweak and interference contributions in the VBS region is $0.95 \pm 0.06$ fb.

The ATLAS detector described in Ref. [25] is a multipurpose particle physics detector. It consists of an inner tracking detector (ID) surrounded by a calorimeter and a muon spectrometer (MS). Events for this analysis are selected with single-lepton ($e$ or $\mu$) triggers. After applying data quality requirements, the remaining data set has a total integrated luminosity of $20.3 \pm 0.6$ fb$^{-1}$ [26].

Electron candidates are reconstructed from a combination of a cluster of energy deposits in the electromagnetic calorimeter and a track in the ID. They are required to have $p_T > 25$ GeV and $|\eta| < 2.47$, excluding the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$). Candidate electrons must satisfy the tight quality definition described in Ref. [27] and reoptimized for 2012 data taking. Muon candidates are reconstructed by combining tracks in the ID and MS [28]. The combined track is required to have $p_T > 25$ GeV and $|\eta| < 2.4$. Leptons are required to originate from the same interaction vertex and, to reduce nonprompt production, calorimeter and tracker isolation requirements are applied within a cone of size $\Delta R = 0.3$.

Jets are reconstructed from clusters of energy in the calorimeter, using the anti-$k_T$ algorithm with jet-size parameter $R = 0.4$ and calibrated using techniques from Ref. [29]. Only jets with $p_T > 30$ GeV and $|\eta| < 4.5$ are considered. Jets containing $b$ hadrons (“$b$ jet”) with $|\eta| < 2.5$ are identified by combining information on the impact parameter significances of their tracks and explicit secondary vertex reconstruction [30]. The measurement of $E_T^{\text{miss}}$ [31] is based on the energy collected by the electromagnetic and hadronic calorimeters, and muon tracks reconstructed by the ID and MS.

Candidate $W^\pm W^{\mp} jj$ events are required to have exactly two leptons (electrons or muons) with the same electric charge and at least two jets satisfying the above selection criteria. Three different final states (“channels”) are considered based on the lepton flavor, namely, $e^+e^-$, $e^\pm\mu^\mp$, and $\mu^+\mu^-$. To reduce the contributions from $WZ/\gamma^* +$ jets and $ZZ +$ jets production, events are removed if they contain additional leptons reconstructed with looser isolation requirements, $p_T > 7$ GeV (6 GeV) for electrons (muons) and loose quality definition for electrons [27]. The two leptons must have $m_{\ell\ell} > 20$ GeV. The dielectron invariant mass must not be within 10 GeV of the $Z$ boson mass to reduce $Z +$ jets background from electron charge misidentification. Events are also required to have $E_T^{\text{miss}} > 40$ GeV, and in order to reject backgrounds from nonprompt leptons, mainly $t\bar{t} \rightarrow e\nu jjbb$, events must not contain a $b$ jet. To further reduce $t\bar{t}$ and $WZ/\gamma^* +$ jets backgrounds, events in the inclusive region are required to have $m_{jj} > 500$ GeV. In addition, in the VBS region $|\Delta y_{jj}| > 2.4$ is required.

Monte Carlo (MC) simulation is used to estimate the expected signal events. The $W^\pm W^{\mp} jj$ processes are generated with SHERPA, using up to three jets in the matrix-element and parton shower model [24], and normalized using the expected cross section in each fiducial region (see above). Generated events are processed with the full detector simulation [32] based on GEANT4 [33], and the standard ATLAS reconstruction software.

Several SM processes enter the $W^\pm W^{\mp} jj$ signal regions as irreducible physics processes or through instrumental effects. About 90% of the expected prompt lepton background originates from $WZ/\gamma^* \rightarrow \ell^\pm \ell'^\mp \nu \nu$ production that passes signal region selections when one lepton is outside of the experimental acceptance or does not satisfy the lepton identification criteria. Up to 20% of the expected $WZ/\gamma^*$ contribution comes from electroweak production. Smaller contributions from $ZZ +$ jets and $t\bar{t} + WZ$ are also considered. These “prompt lepton backgrounds” are estimated using MC simulation. In the VBS region strong $W^\pm W^{\mp} jj$ is estimated using simulation and normalized to the SM prediction for the fiducial cross section described above. Correction factors for lepton and jet efficiencies, additional $pp$ interactions (pile-up), and beam-spot location are applied to the simulation to account for differences with data. Furthermore, the simulation is tuned to reproduce the calorimeter response and the muon momentum scale and resolution observed in data. Systematic uncertainties on the
signal yield and backgrounds estimated from MC simulation are derived from uncertainties on the correction factors, energy smearing parameters, the $E_T^{miss}$ modeling, and the $b$-tagging efficiency and mistag rate [30].

SHERPA is used to produce $WZ/\gamma^* +$ jets events, taking into account both the strong and electroweak production mechanisms. This sample is normalized to the next-to-leading-order calculation in QCD from VBFNLO in each fiducial region [34,35], with an accuracy of 14% in the inclusive region and 11% in the VBS region. The SHERPA extrapolation from the inclusive region to the VBS region differs from the VBFNLO calculation by 3%. The main sources of uncertainties on the VBFNLO normalization are from the PDF, from factorization and renormalization scale dependence, and from the parton shower model. The small $t\bar{t}Z$ component in this sample is estimated using the SHERPA prediction.

The production of $ZZ +$ jets is modeled with SHERPA, while for $t\bar{t} + W/Z$ processes MADGRAPH [36] with PYTHIA8 is used. The theoretical uncertainties on the production cross sections of these processes are ±19% and ±30%, respectively, dominated by the jet multiplicity modeling and the scale uncertainties.

Contributions from $W\gamma$ production, including electroweak production of $W\gamma jj$, where the photon converts to an electron-positron pair inside the detector is included in the “conversion background.” It is estimated using ALPGEN [37] with HERWIG plus JIMMY and SHERPA (for electroweak $W\gamma jj$) MC samples with a total theory uncertainty of ±17%.

The remaining conversion background originates from processes that produce oppositely charged prompt leptons where one lepton’s charge is misidentified, primarily because one electron has undergone hard bremsstrahlung and subsequent photon conversion. This background is estimated from data. The dominant origins of this background are $t\bar{t} \rightarrow e\ell vv b\bar{b}$ and Drell-Yan lepton pair production. The electron charge misidentification rate is measured using $Z/\gamma^* \rightarrow ee$ events. The muon charge misidentification rate is found to be negligible. The background is estimated by applying the electron charge misidentification rate to data selected using all signal selection criteria except for the electric charges of the leptons, which are instead required to be opposite sign. The dominant systematic uncertainties arise from possible method bias (studied in simulation) and the statistical uncertainty in the charge misidentification rate. The total uncertainty is between 15% and 32% depending on signal region and channel.

Contributions from SM processes that produce at least one nonprompt lepton from hadron decays in jets ($W +$ jets, $t\bar{t}$, single top or multijet production, denoted by “other nonprompt background”) are estimated from data events that contain one lepton passing all selections and one nonisolated or loose-quality lepton. These events, which are dominated by the nonprompt background, are scaled by a “fake rate” to predict the nonprompt background. The fake rate is the efficiency for nonprompt leptons to pass the nominal lepton selections with respect to the looser isolation and quality requirements. The fake rate for nonprompt leptons is measured in a dijet sample. The uncertainty on the nonprompt background estimate is between 39% and 52% depending on region and channel, dominated by prompt-lepton contamination in the dijet sample and the uncertainty on the extrapolation of fake rates into the signal region.

Contributions from double parton scattering [38] arise mainly in $WZ/\gamma^*$ and dijet production. However, simulation shows they are negligible after the requirement of $m_{jj} > 500$ GeV.

Background predictions are tested in several same-electric-charge dilepton control regions summarized in Table I. The MC modeling of prompt backgrounds is tested in a trilepton control region defined by inverting the third-lepton veto and removing the $|\Delta y_{jj}|$ and $m_{jj}$ selections. Conversion and prompt backgrounds are tested in a region with at most one jet ($\leq$ 1 jet, in Table I). In this sample the $e^+e^-$ channel is dominated by $Z \rightarrow ee$ events, the $\mu^+\mu^-$ channel is dominated by prompt processes, and the $e^+\mu^-$ channel has a mixture of prompt, nonprompt, and conversion backgrounds. Backgrounds from nonprompt leptons originating from $t\bar{t} \rightarrow \ell\nu jj b\bar{b}$ are tested in a control region that requires at least one of the jets to be identified as a $b$ jet. Finally, the combined background model is tested by inverting the $m_{jj}$ selection.

The observed number of events is compared in Table II to the expected background and signal yield with systematic uncertainties for the three channels in both the inclusive and VBS signal regions. In the VBS region strong $W^\pm Z^\pm jj$ is considered as background using the SM prediction and its experimental and theoretical uncertainties. The systematic uncertainty on the background prediction is about 20%, dominated by the jet reconstruction uncertainties (11%–15%) and theory uncertainties (4%–11%). An excess of events over the background expectation is observed in both signal regions and in all three channels; the combined significance over the background-only

---

**Table I.** Expected numbers of events (exp) and measured data counts are shown by channel for each control region described in the text. The uncertainty shown is the systematic uncertainty on the expected yield.

<table>
<thead>
<tr>
<th>Control region</th>
<th>Trilepton</th>
<th>$\leq$ 1 jet</th>
<th>$b$-tagged</th>
<th>Low $m_{jj}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^+e^-$</td>
<td>exp</td>
<td>36 ± 6</td>
<td>278 ± 28</td>
<td>40 ± 6</td>
</tr>
<tr>
<td></td>
<td>data</td>
<td>40</td>
<td>288</td>
<td>46</td>
</tr>
<tr>
<td>$e^+\mu^-$</td>
<td>exp</td>
<td>110 ± 18</td>
<td>288 ± 42</td>
<td>75 ± 13</td>
</tr>
<tr>
<td></td>
<td>data</td>
<td>104</td>
<td>328</td>
<td>82</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>exp</td>
<td>60 ± 10</td>
<td>88 ± 14</td>
<td>25 ± 7</td>
</tr>
<tr>
<td></td>
<td>data</td>
<td>48</td>
<td>101</td>
<td>36</td>
</tr>
</tbody>
</table>

---
TABLE II. Estimated background yields, observed number of data events, and predicted signal yields for the three channels are shown with their systematic uncertainty. Contributions due to interference are included in the $W^\pm W^\pm jj$ electroweak prediction.

<table>
<thead>
<tr>
<th>Region</th>
<th>$e^+e^+$</th>
<th>$e^+\mu^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+e^+$</th>
<th>$e^+\mu^-$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt</td>
<td>3.0 ± 0.7</td>
<td>6.1 ± 1.3</td>
<td>2.6 ± 0.6</td>
<td>2.2 ± 0.5</td>
<td>4.2 ± 1.0</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>Conversions</td>
<td>3.2 ± 0.7</td>
<td>2.4 ± 0.8</td>
<td>…</td>
<td>2.1 ± 0.5</td>
<td>1.9 ± 0.7</td>
<td>…</td>
</tr>
<tr>
<td>Other nonprompt</td>
<td>0.61 ± 0.30</td>
<td>1.9 ± 0.8</td>
<td>0.41 ± 0.22</td>
<td>0.50 ± 0.26</td>
<td>1.5 ± 0.6</td>
<td>0.34 ± 0.19</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Strong</td>
<td>0.89 ± 0.15</td>
<td>2.5 ± 0.4</td>
<td>1.42 ± 0.23</td>
<td>0.25 ± 0.06</td>
<td>0.71 ± 0.14</td>
<td>0.38 ± 0.08</td>
</tr>
<tr>
<td>$W^\pm W^\pm jj$ Electroweak</td>
<td>3.07 ± 0.30</td>
<td>9.0 ± 0.8</td>
<td>4.9 ± 0.5</td>
<td>2.55 ± 0.25</td>
<td>7.3 ± 0.6</td>
<td>4.0 ± 0.4</td>
</tr>
<tr>
<td>Total background</td>
<td>6.8 ± 1.2</td>
<td>10.3 ± 2.0</td>
<td>3.0 ± 0.6</td>
<td>5.0 ± 0.9</td>
<td>8.3 ± 1.6</td>
<td>2.6 ± 0.5</td>
</tr>
<tr>
<td>Total predicted</td>
<td>10.7 ± 1.4</td>
<td>21.7 ± 2.6</td>
<td>9.3 ± 1.0</td>
<td>7.6 ± 1.0</td>
<td>15.6 ± 2.0</td>
<td>6.6 ± 0.8</td>
</tr>
<tr>
<td>Data</td>
<td>12</td>
<td>26</td>
<td>12</td>
<td>6</td>
<td>18</td>
<td>10</td>
</tr>
</tbody>
</table>

The measured fiducial cross section for strong and electroweak $W^\pm W^\pm jj$ production in the inclusive region

FIG. 1 (color online). The $m_{jj}$ distribution for events passing the inclusive region selections except for the $m_{jj}$ selection indicated by the dashed line. The black hatched band in the upper plot represents the systematic uncertainty on the total prediction. On the lower plot the shaded band represents the fractional uncertainty of the total background while the solid line and hatched band represents the ratio of the total prediction to background only and its uncertainty. The $W^\pm W^\pm jj$ prediction is normalized to the SM expectation.

FIG. 2 (color online). The $|\Delta y_{jj}|$ distribution for events passing all inclusive region selections. The $|\Delta y_{jj}|$ selection is indicated by a dashed line. The $W^\pm W^\pm jj$ prediction is normalized to the SM expectation.

We interpret the excess over background as $W^\pm W^\pm jj$ production, and the fiducial cross sections in the two regions ($\sigma_{\text{fid}}$) are measured by combining the three decay channels in a likelihood function. Systematic uncertainties are taken into account with nuisance parameters.

The measured fiducial cross section for strong and electroweak $W^\pm W^\pm jj$ production in the inclusive region
is \( \sigma_{\text{fid}} = 2.1 \pm 0.5\,\text{(stat)} \pm 0.3\,\text{(syst)} \) fb. The measured fiducial cross section for electroweak \( W^\pm W^\pm jj \) production, including interference with strong production in the VBS region, is \( \sigma_{\text{fid}} = 1.3 \pm 0.4\,\text{(stat)} \pm 0.2\,\text{(syst)} \) fb. The measured cross sections are in agreement with the respective SM expectations of 1.52 \pm 0.11 fb and 0.95 \pm 0.06 fb.

Additional contributions to \( W^\pm W^\pm jj \) production can be expressed in a model-independent way using higher-dimensional operators leading to anomalous quartic gauge boson couplings (AQGCs). The measured cross section in the VBS fiducial region is used to set limits on AQGCs affecting vertices with four interacting \( W \) bosons. The WHIZARD event generator [39] is used to generate \( W^\pm W^\pm jj \) events with AQGCs using a \( K \)-matrix unitarization method [40]. Following existing notations [40,41], deviations from the SM (which includes a SM Higgs with \( m_H = 126 \) GeV) are parametrized in terms of two parameters (\( \alpha_4, \alpha_5 \)).

The reconstruction efficiency is derived using simulated WHIZARD samples combined with PYTHIA8. The difference with respect to SHERPA for the SM case is taken as additional systematic uncertainty. The reconstruction efficiency increases with increasing \( \alpha_{4,5} \) values, but the effect is small compared to the increase in the fiducial cross sections in the same parameter space. The expected and observed 95% confidence intervals derived from the profile likelihood function are shown in Fig. 3. The one-dimensional projection at \( \alpha_{4,5} = 0 \) is, respectively, \(-0.14 < \alpha_4 < 0.16 \) and \(-0.23 < \alpha_5 < 0.24 \), compared to an expected \(-0.10 < \alpha_4 < 0.12 \) and \(-0.18 < \alpha_5 < 0.20 \).

In conclusion, a significant excess of events over background predictions is found using 20.3 fb\(^{-1}\) of \( pp \) collision data at \( \sqrt{s} = 8 \) TeV recorded by the ATLAS detector at the LHC. This excess is consistent with SM \( W^\pm W^\mp jj \) production. Two fiducial cross sections are measured in regions with different sensitivities to the electroweak and strong \( W^\pm W^\pm jj \) processes. The measured cross sections are in good agreement with SM predictions. In addition, the first limits on the \( \alpha_{4,5} \) AQGC parameters are set.

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; STSC, 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, DNSRC, and Lundbeck Foundation, Denmark; EPLANET and ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and CCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSDT, Serbia; MSSR, Slovakia; AARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NIS, Taiwan; TAEK, Turkey; STFC, the Royal Society, and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and 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) and in the Tier-2 facilities worldwide.

Rapidity is defined as
\[
y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right).
\]

The pseudorapidity is defined in terms of the polar angle \( \theta \) as
\[
\eta = -\ln \tan(\theta/2).
\]

Transverse projections are defined relative to the beam axis.
Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA
Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington, IN, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
Department of Physics and Astronomy, Iowa State University, Ames, IA, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
Department of Physics, Indiana University, Bloomington, IN, USA
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
Department of Physics and Astronomy, Iowa State University, Ames, IA, USA
Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Science, Kyoto University, Kyoto, Japan
Kyoto University of Education, Kyoto, Japan
Department of Physics, Kyushu University, Fukuoka, Japan
Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, United Kingdom
INFN Sezione di Lecce, Italy
Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
Department of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston, LA, USA
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lunds universitet, Lund, Sweden
Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
Institut für Physik, Universität Mainz, Mainz, Germany
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, MA, USA
Department of Physics, McGill University, Montreal QC, Canada
School of Physics, University of Melbourne, Victoria, Australia
Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
INFN Sezione di Milano, Italy
Dipartimento di Fisica, Università di Milano, Milano, Italy
B. I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, USA
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P. N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
D. V. Skobeltsyn Institute of Nuclear Physics, M. V. Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
INFN Sezione di Napoli, Italy
Dipartimento di Fisica, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
Department of Physics, Northern Illinois University, DeKalb, IL, USA
Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
Department of Physics, New York University, New York, NY, USA
Ohio State University, Columbus, OH, USA
Faculty of Science, Okayama University, Okayama, Japan
151 School of Physics, University of Sydney, Sydney, Australia
152 Institute of Physics, Academia Sinica, Taipei, Taiwan
153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
158 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
159 Department of Physics, University of Toronto, Toronto ON, Canada
160 TRIUMF, Vancouver BC, Canada
161 Department of Physics and Astronomy, York University, Toronto ON, Canada
162 Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
163 Department of Physics and Astronomy, Tufts University, Medford, MA, USA
164 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
165 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA
166 INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
167 ICTP, Trieste, Italy
168 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
169 Department of Physics, University of Illinois, Urbana, IL, USA
167 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
168 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
169 Department of Physics, University of British Columbia, Vancouver BC, Canada
170 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
171 Department of Physics, University of Warwick, Coventry, United Kingdom
172 Waseda University, Tokyo, Japan
173 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
174 Department of Physics, University of Wisconsin, Madison, WI, USA
175 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
176 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
177 Department of Physics, Yale University, New Haven, CT, USA
178 Yerevan Physics Institute, Yerevan, Armenia
179 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

a Deceased.
b Also at Department of Physics, King’s College London, London, United Kingdom.
c Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
d Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
e Also at TRIUMF, Vancouver, BC, Canada.
f Also at Department of Physics, California State University, Fresno, CA, USA.
g Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
h Also at Universitá di Napoli Parthenope, Napoli, Italy.
i Also at Institute of Particle Physics (IPP), Canada.
j Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
k Also at Chinese University of Hong Kong, China.
l Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
m Also at Louisiana Tech University, Ruston, LA, USA.
n Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
o Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
p Also at CERN, Geneva, Switzerland.
q Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
r Also at Manhattan College, New York, NY, USA.
s Also at Novosibirsk State University, Novosibirsk, Russia.
t Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
u Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
w Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
x Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
y Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
z Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
a Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA.
bb Also at Section de Physique, Université de Genève, Geneva, Switzerland.
c Also at International School for Advanced Studies (SISSA), Trieste, Italy.
dd Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.
e Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
f Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
g Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
hh Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
i Also at Department of Physics, Oxford University, Oxford, United Kingdom.
j Also at Department of Physics, Nanjing University, Jiangsu, China.
k Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
l Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA.
m Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.