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Measurements of Four-Lepton Production at the Z Resonance in \(pp\) Collisions at \(\sqrt{s} = 7\) and 8 TeV with ATLAS

G. Aad et al.

(ATLAS Collaboration)

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Measurements of four-lepton (4\(\ell\), \(\ell = e, \mu\)) production cross sections at the Z resonance in \(pp\) collisions at the LHC with the ATLAS detector are presented. For dilepton and four-lepton invariant mass regions \(m_{\ell^+\ell^-} > 5\) GeV and \(80 < m_{4\ell} < 100\) GeV, the measured cross sections are \(76 \pm 18\) (stat) \(\pm 4\) (syst) \(\pm 1.4\) (lumi) fb and \(107 \pm 9\) (stat) \(\pm 4\) (syst) \(\pm 3.0\) (lumi) fb at \(\sqrt{s} = 7\) and 8 TeV, respectively. By subtracting the nonresonant 4\(\ell\) production contributions and normalizing with \(Z \rightarrow \mu^+\mu^-\) events, the branching fraction for the Z boson decay to 4\(\ell\) is determined to be \((3.20 \pm 0.25\) (stat) \(\pm 0.13\) (syst)) \(\times 10^{-6}\), consistent with the standard model prediction.

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This Letter presents measurements of the cross sections for the inclusive production of four leptons (4\(\ell\), \(\ell = e, \mu\)) at the Z resonance in \(pp\) collisions at \(\sqrt{s} = 7\) and 8 TeV using data recorded by the ATLAS detector [1] at the LHC [2]. In the standard model (SM), 4\(\ell\) production in the Z resonance region occurs dominantly via an s-channel diagram such as that shown in Fig. 1(a) where the Z boson decay to charged leptons includes the production of an additional lepton pair from the internal conversion of a virtual Z or \(\gamma\). A small fraction of 4\(\ell\) events is produced in a t-channel process such as that shown in Fig. 1(b), which includes Z production with internal conversion of initial-state radiation. The process \(gg \rightarrow Z(\rightarrow \ell^+\ell^-)\rightarrow 4\ell\) accounts for only about \(10^{-3}\) of the total 4\(\ell\) event rate around the Z resonance [3]. A resonant peak around the Z mass in the 4\(\ell\) invariant mass spectrum is observed along with the nearby peak from the Higgs boson decay \(H \rightarrow 4\ell\) [4,5]. A measurement of the 4\(\ell\) production cross section at the Z resonance provides a test of the SM and a cross-check of the detector response to the 4\(\ell\) final state from Higgs decays.

Since the interference between the resonant and nonresonant (t-channel and gg) production mechanisms is expected to be small around the Z resonance, the branching fraction of the rare decay \(Z \rightarrow 4\ell\) can be determined by subtracting the expected nonresonant 4\(\ell\) contributions from the measured 4\(\ell\) rate. For simplicity, inclusive 4\(\ell\) production around the Z resonance, including the nonresonant contributions, is denoted as \(Z \rightarrow 4\ell\) from here on, except that the branching fraction \(\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z\) refers to the s-channel contribution alone. The CMS Collaboration has observed the \(Z \rightarrow 4\ell\) resonance in \(\sqrt{s} = 7\) TeV data and determined a branching fraction, summed over the 4e, 4\(\mu\), and \(2e2\mu\) final states, of \(\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z = (4.2^{+0.9}_{-0.8}\) (stat) \(\pm 0.2\) (syst)) \(\times 10^{-6}\), where \(80 < m_{4\ell} < 100\) GeV and \(m_{4\ell} > 4\) GeV for all pairs of leptons [6]. The results presented here include the first cross-section measurement of the 4\(\ell\) production at the Z resonance at \(\sqrt{s} = 8\) TeV, and a determination of \(\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z\) with improved statistical precision in a final phase-space region defined by the dilepton and four-lepton invariant mass requirements \(m_{\ell^+\ell^-} > 5\) GeV and \(80 < m_{4\ell} < 100\) GeV, where \(\ell^+\ell^-\) denotes all same-flavor lepton pairs with opposite charge.

The ATLAS detector has a cylindrical geometry [7] and consists of an inner tracking detector (ID) surrounded by a 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) with a toroidal magnetic field. The ID provides precision tracking for charged particles for \(|\eta| < 2.5\). It consists of silicon pixel and strip detectors surrounded by a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range \(|\eta| < 4.9\). For \(|\eta| < 2.5\), the liquid-argon electromagnetic calorimeter is finely segmented and plays an important role in electron identification. The MS includes fast-trigger chambers (\(|\eta| < 2.4\)) and high-precision tracking chambers covering \(|\eta| < 2.7\).

FIG. 1. Examples of (a) s-channel and (b) t-channel Feynman diagrams for 4\(\ell\) production in \(pp\) collisions.
The data sets for this analysis are recorded using single-lepton and dilepton triggers. The transverse momentum ($p_T$) thresholds of these triggers vary from 20 to 24 GeV for the single-lepton triggers and from 8 to 13 GeV for the dilepton triggers, depending on lepton flavor and data-taking period. The overall trigger efficiency for selected $Z \rightarrow 4\ell$ events ranges from 94 to 99%.

After removing the short data-taking periods having problems that affect the lepton reconstruction, the total integrated luminosity used in the analysis is 4.5 fb$^{-1}$ at 7 TeV and 20.3 fb$^{-1}$ at 8 TeV. The overall uncertainty on the integrated luminosity is 1.8% [8] and 2.8% [9] for the $\sqrt{s} = 7$ and 8 TeV data sets, respectively.

The POWHEG Monte Carlo (MC) program [10–12], used to calculate the signal cross sections, includes perturbative QCD corrections to next-to-leading order. The calculation also includes the interference terms between the $s$-channel and the $t$-channel as well as the interference terms between the $Z$ and the $\gamma^*$ diagrams. The CT10 [13] set of parton distribution functions (PDFs) and QCD renormalization and factorization scales of $\mu_R, \mu_F = m_{4\ell}$ are used. In the $m_{4\ell} > 5$ GeV and $80 < m_{4\ell} < 100$ GeV phase space, the production cross sections calculated by POWHEG are 53.4 $\pm$ 1.2 fb (45.8 $\pm$ 1.1 fb) for the sum of the $4e$ and $4\mu$ final states, and 51.5 $\pm$ 1.2 fb (44.2 $\pm$ 1.1 fb) for the $2e2\mu$ final state at 8 TeV (7 TeV). The cross sections for $4e$ and $4\mu$ are larger than for $2e2\mu$ due to the interference between the two same-flavor lepton pairs. The cross-section uncertainties reflect theoretical uncertainties from the choice of QCD scales and PDFs. The scales are varied independently from 0.5 to 2.0 times the nominal $\mu_R, \mu_F = m_{4\ell}$. The PDF uncertainties are estimated by taking the sum in quadrature of the deviations of the cross section for each PDF error set (52 CT10 eigenvectors varied by one standard deviation) and for an alternative PDF set, MSTW2008 [14], with respect to the nominal one. The expected fraction of $4\ell$ events produced via the $t$-channel process is $(3.35 \pm 0.02\%$ and $(3.90 \pm 0.02\%$ for same-flavor ($4e, 4\mu$) and mixed-flavor ($2e2\mu$) final states, respectively, for both 7 and 8 TeV. The $gg \rightarrow ZZ \rightarrow 4\ell$ process is modeled by gg2ZZ [15], and the $4\ell$ event fraction from this process is calculated to be around 0.1%. The overall nonresonant fraction ($f_{nr}$) from the $t$-channel and $gg$ contributions combined is $(3.45 \pm 0.02\%$ and $(4.00 \pm 0.02\%$ for the same-flavor and mixed-flavor final states, respectively. To generate MC events with a simulation of the detector to determine the signal acceptance, POWHEG is interfaced to PYTHIA6 [16] or PYTHIA8 [17] for showering and hadronization and to PHOTOS [18] for radiated photons from charged leptons.

The MC generators used to simulate the reducible background contributions are MC@NLO [19] (to model top productions) and ALPGEN [20] (to model Z boson production in association with jets, referred to as $Z +$ jets). These generators are interfaced to HERWIG [21] and JIMMY [22] for parton showering and underlying-event simulations. The diboson background processes $WZ$ and $ZZ$, and $Z^{(*)}\rightarrow 4\ell$ decays involving $\tau \rightarrow e/\mu + 2\nu$, are modeled by POWHEG (interfaced to PYTHIA for parton showering) and SHERPA [23].

The detector response simulation [24] is based on the GEANT4 program [25]. Additional inelastic $pp$ interactions (referred to as pile-up) are included in the simulation, and events are reweighted to reproduce the observed distribution of the average number of collisions per bunch crossing in the data.

The $Z \rightarrow 4\ell$ event selection closely follows the $H \rightarrow ZZ^* \rightarrow 4\ell$ analysis [26] with muon $p_T$ and dilepton invariant mass requirements loosened to increase the acceptance for the $Z \rightarrow 4\ell$ process.

Muons are identified by tracks reconstructed in the MS and are matched to tracks reconstructed in the ID ($|\eta| < 2.5$). The muon momentum is calculated by combining the information from the tracking systems, correcting for the energy lost in the calorimeters. In the region $2.5 < |\eta| < 2.7$, muons can also be identified by an MS track alone (denoted stand-alone muons). The identified muons described above are required to have $p_T > 4$ GeV. In the MS gap region ($|\eta| < 0.1$) muons are identified by an ID track with $p_T > 15$ GeV associated with a compatible calorimeter energy deposit (denoted calorimeter-tagged muons).

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter matched to a track in the ID [27]. Tracks associated with electromagnetic clusters are fitted using a Gaussian sum filter [28], which allows bremsstrahlung energy losses to be taken into account. For $\sqrt{s} = 8$ TeV data, improved electron discrimination from jets is obtained using a likelihood function formed from parameters characterizing the shower shape and track association, resulting in a reduction of the electron misidentification rate by more than a factor of two compared to that at 7 TeV. Electron candidates are required to have $p_T > 7$ GeV and $|\eta| < 2.47$.

Collision events are selected by requiring at least one reconstructed vertex with at least three charged particle tracks with $p_T > 0.4$ GeV. If more than one vertex satisfies the selection requirement, the primary vertex is chosen as the one with the highest $\sum p_T^2$, summed over all tracks associated with the vertex.

In order to reject electrons and muons from jets, only isolated leptons are selected, requiring the scalar sum of the transverse momenta, $\sum p_T$, of other tracks inside a cone size of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the lepton to be less than 15% of the lepton $p_T$. In addition, the $\sum E_T$ deposited in calorimeter cells inside a cone size of $\Delta R = 0.2$ around the lepton direction, excluding the transverse energy due to the lepton and corrected for the expected pileup contribution, is required to be less than 30% of the lepton $p_T$, reduced to 20% for electrons in the 8 TeV data.
The fiducial region, defined at the MC generator level, requires the leading lepton pair, with mass $m_{12}$, and the subleading lepton pair, with mass $m_{34}$, to be a stand-alone muon or a calorimeter-tagged muon. For all same-flavor lepton pairs, $m_{12} > 20$ GeV and $m_{34} > 5$ GeV. In the $4\ell$ and $4\mu$ channels all the $\ell^+\ell^-$ pairs are required to have $m_{\ell^+\ell^-} > 5$ GeV, to reject events containing $J/\psi \rightarrow \ell^+\ell^-$ decays. The $4\ell$ invariant mass is restricted to $80 < m_{4\ell} < 100$ GeV. A total of 21 and 151 $Z \rightarrow 4\ell$ candidate events are selected in the 7 and 8 TeV data sets, respectively. The distributions of $m_{12}$, $m_{34}$, and $m_{4\ell}$ are shown in Fig. 2. The number of events observed in each channel is shown in Table I, where the labeling $\ell^+\ell^- + \ell^+\ell^-$ indicates the leading and subleading lepton pairs.

The overall signal selection efficiency is the product of efficiency and acceptance factors, $C_{4\ell}$ and $A_{4\ell}$, respectively. The efficiency factor $C_{4\ell}$ is the ratio of the number of $Z \rightarrow 4\ell$ events passing the reconstructed event selections to the number in the fiducial region, and is determined using the signal MC samples after the detector simulation. The fiducial region, defined at the MC generator level using the lepton four-momenta, requires $p_T > 20, 15, 10$ (8), 7(4) GeV and $|\eta| < 2.5(2.7)$ of the $p_T$-ordered $e(\mu)$, $\Delta R(\ell, \ell') > 0.1(0.2)$ for all same(different)-flavor lepton pairs, $m_{\ell^+\ell^-} > 20$ GeV for at least one lepton pair, $m_{\ell^+\ell^-} > 5$ GeV for all same-flavor lepton pairs, and $80 < m_{4\ell} < 100$ GeV. The four-momenta of all final-state photons within $\Delta R = 0.1$ of a lepton are summed into the four-momentum of that lepton. The acceptance factor $A_{4\ell}$ is the fraction of $Z \rightarrow 4\ell$ events in the final phase space which falls into the fiducial region. The $C_{4\ell}$ uncertainty is mostly experimental and the $A_{4\ell}$ uncertainty is entirely theoretical. The $A_{4\ell}$ and $C_{4\ell}$ values are listed in Table I for each channel and data set. The $C_{4\ell}$ values for 8 TeV are larger than for 7 TeV due to a variety of factors, including electron identification improvements with better bremsstrahlung treatment and additional muon detector coverage.

The MC lepton identification and trigger efficiencies are corrected based on studies performed in data control regions. The energy and momentum scales and resolutions of the MC events are calibrated to reproduce data from $Z \rightarrow \ell^+\ell^-$ and $J/\psi \rightarrow \ell^+\ell^-$ decays. The uncertainties on the $Z \rightarrow 4\ell$ signal detection efficiency are determined by varying the nominal calibrations (including lepton energy and momentum resolutions and scales, and the trigger, reconstruction, and identification efficiencies) in the MC samples by one standard deviation. For the 8 TeV ($7 \text{ TeV}$) analysis, the relative uncertainties on the $C_{4\ell}$ factors are 2.7% (2.7%), 3.7% (4.9%), 6.2% (9.8%), and 9.4% (14.9%) for $\mu + \mu$, $ee + \mu$, $\mu + ee$, and $ee + ee$, respectively. The major uncertainty contributions come from the lepton reconstruction and identification efficiencies. The relative uncertainties on the $A_{4\ell}$ factors, evaluated using POWHEG MC samples with the same approach for QCD scale and PDF uncertainties as described earlier, range from 1.3% to 1.7% depending on the channel.

The overall background in the selected $4\ell$ event sample is estimated to be below 1%, as shown in Table I. The background contributions from diboson production are estimated, using MC simulations, to be $0.06 \pm 0.01$ and $0.49 \pm 0.04$ events in the 7 and 8 TeV data sets.
respectively. Background contributions from $Z + jets$ and top-production processes are estimated from data. Such background events may contain two isolated leptons from $Z$ decays or from $W$ decays in top events, together with additional activity such as heavy-flavor jets or misidentified components of jets yielding reconstructed leptons. These backgrounds are estimated using a background-enriched control sample of $\ell\ell j_{\ell}\ell j_{\ell}$ events, selected with the standard signal requirements except that lepton-like jets, $j_{\ell}$, are selected in place of two of the signal leptons. Electron-like jets, $j_{e}$, in the $\ell\ell j_{\ell}\ell j_{\ell}$ control sample are obtained from electromagnetic clusters matched to tracks in the ID that do not satisfy the identification criteria or isolation requirements. Muon-like jets, $j_{\mu}$, are defined as muon candidates that fail the requirements on isolation. These backgrounds in the signal sample are estimated by scaling each event in the $\ell\ell j_{\ell}\ell j_{\ell}$ control sample by $f_{j_{i}} \times f_{j_{2}}$, where the factor $f_{j_{i}}$ ($i = 1, 2$) for each of the two lepton-like jets depends on lepton flavor and $p_T$. The factor $f$ is the ratio of the probability for a jet to satisfy the signal lepton selection criteria to the probability for the jet to satisfy the lepton-like jet criteria, and is obtained from independent jet-enriched data samples dominated by $Z + jets$ or $tt$ events. The background from $Z + jets$ and top processes, for all 4$\ell$ channels combined, is estimated to be $0.38 \pm 0.14$ and $0.49 \pm 0.10$ events for the 7 and 8 TeV data, respectively.

The number of signal events predicted by MC simulation are $23.8 \pm 1.2$ and $145 \pm 7$ for 7 and 8 TeV, respectively. The data and MC predictions, as shown in Fig. 2, are in good agreement. Denoting the integrated luminosity by $L$, the measured fiducial cross sections ($\sigma_{Z4\ell}^{fid}$), determined by $(N_{Z4\ell}^{obs} - N_{Z4\ell}^{bkg}) / (L \times C_{4\ell})$, are given in Table I. The cross section in the final phase space for each channel is calculated by $\sigma_{Z4\ell}^{fid} / A_{4\ell}$. The cross sections obtained for the $ee + ee$ and $\mu\mu + \mu\mu$ channels, and for the $2e + 2\mu$ and $2\mu + 2e$ channels, are compatible within errors and are combined using $2 \times 2$ covariance matrices. The total 4$\ell$ cross section is a sum of the two combined cross sections, and the uncertainty includes correlations between the four channels. These cross sections in the final phase space are also given in Table I.

The $Z \rightarrow 4\ell$ branching fraction, $\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z$, is determined by subtracting the nonresonant contributions to the selected events and normalizing the resulting yield to the observed number of $Z \rightarrow \mu^+\mu^-$ events in the same data set,

$$
\frac{\Gamma_{Z \rightarrow 4\ell}}{\Gamma_Z} = \frac{\Gamma_{Z \rightarrow \mu\mu}}{\Gamma_Z} \frac{(N_{Z4\ell}^{obs} - N_{Z4\ell}^{bkg})(1 - f_{\mu\mu})C_{2\mu} \cdot A_{2\mu}}{(N_{2\mu} - N_{2\mu}^{bkg})C_{4\ell} \cdot A_{4\ell}},
$$

where $\Gamma_{Z \rightarrow \mu\mu}/\Gamma_Z = (3.366 \pm 0.007)\%$ [29], $N_{Z4\ell}^{obs}$ is around 1.7 million and 8.9 million in the 7 and 8 TeV data sets, respectively, and $(C \times A)_{2\mu}$ is $(41.4 \pm 0.6)\%$ and $(41.8 \pm 0.6)\%$, respectively. The background ($N_{Z4\ell}^{bkg}$) is estimated to be around 0.3% of the selected $Z \rightarrow \mu^+\mu^-$ events. The branching fraction for $Z \rightarrow 4\ell$, summed over all $\ell = e, \mu$ final states, is determined with both the 7 and 8 TeV data sets. The measured branching fractions for each data set are consistent within uncertainties and are combined, giving

$$
\frac{\Gamma_{Z \rightarrow 4\ell}}{\Gamma_Z} = (3.20 \pm 0.25(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-6}
$$

in the final phase-space region, where the systematic uncertainty includes a contribution (about 0.2%) due to

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>4$\ell$ state</th>
<th>$N_{Z4\ell}^{obs}$</th>
<th>$N_{Z4\ell}^{exp}$</th>
<th>$N_{Z4\ell}^{bkg}$</th>
<th>$C_{4\ell}$</th>
<th>$\sigma_{Z4\ell}^{fid}$ [fb]</th>
<th>$A_{4\ell}$</th>
<th>$\sigma_{Z4\ell}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>$ee + ee$</td>
<td>1</td>
<td>1.8 ± 0.3</td>
<td>0.12 ± 0.04</td>
<td>21.5%</td>
<td>0.9$^{+1.4}_{-0.7}$ ± 0.14 ± 0.02</td>
<td>7.5%</td>
<td>$4e, 4\mu$</td>
</tr>
<tr>
<td>7 TeV</td>
<td>$\mu\mu + \mu\mu$</td>
<td>8</td>
<td>11.3 ± 0.5</td>
<td>0.08 ± 0.04</td>
<td>59.2%</td>
<td>3.0$^{+2.2}_{-0.9}$ ± 0.07 ± 0.05</td>
<td>18.3%</td>
<td>$2e2\mu$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$ee + ee$</td>
<td>7</td>
<td>7.9 ± 0.4</td>
<td>0.18 ± 0.09</td>
<td>49%</td>
<td>3.1$^{+1.4}_{-1.1}$ ± 0.16 ± 0.05</td>
<td>15.8%</td>
<td>$2e2\mu$</td>
</tr>
<tr>
<td>8 TeV</td>
<td>$ee + ee$</td>
<td>21</td>
<td>24.2 ± 1.2</td>
<td>0.44 ± 0.14</td>
<td>36.3%</td>
<td>3.0$^{+1.6}_{-1.2}$ ± 0.30 ± 0.06</td>
<td>8.8%</td>
<td>$2e2\mu$</td>
</tr>
<tr>
<td>combined</td>
<td>$ee + ee$</td>
<td>16</td>
<td>14.4 ± 0.3</td>
<td>0.14 ± 0.03</td>
<td>36.1%</td>
<td>2.2$^{+0.7}_{-0.6}$ ± 0.20 ± 0.06</td>
<td>7.3%</td>
<td>$2e2\mu$</td>
</tr>
</tbody>
</table>
the interference between the s-channel and t-channel processes, calculated using \textsc{CalcHep} [30]. The measured branching fraction is consistent with the SM prediction of \((3.33 \pm 0.01) \times 10^{-6}\), calculated using \textsc{powheg}. For a larger final phase-space region defined by \(m_{\ell^+\ell^-} > 4\) GeV and \(80 < m_{4\ell} < 100\) GeV, similar to that used by CMS, the acceptance factors \(A_{4\ell}\) and the nonresonant fractions \(f_{\text{nr}}\), and their uncertainties, are also evaluated (leaving the fiducial region unchanged), and the measured branching fraction becomes \(\Gamma_{Z\to 4\ell}/\Gamma_Z = (4.31 \pm 0.34(\text{stat}) \pm 0.17(\text{syst})) \times 10^{-6}\), compared with an SM prediction of \((4.50 \pm 0.01) \times 10^{-6}\). This result is consistent with the CMS result measured with data collected from \(pp\) collisions at 7 TeV.

In summary, using data collected by the ATLAS detector corresponding to an integrated luminosity of 4.5 fb\(^{-1}\) and 20.3 fb\(^{-1}\) at \(\sqrt{s} = 7\) and 8 TeV, respectively, the total \(Z \to 4\ell\) production cross sections in the phase-space region \(m_{\ell^+\ell^-} > 5\) GeV and \(80 < m_{4\ell} < 100\) GeV are measured to be \(\sigma_{Z\to 4\ell} = 76 \pm 18(\text{stat}) \pm 4(\text{syst}) \pm 1.4(\text{lumi})\) fb at 7 TeV and \(107 \pm 9(\text{stat}) \pm 4(\text{syst}) \pm 3.0(\text{lumi})\) fb at 8 TeV, consistent with the SM predictions of 90.0 \pm 2.1 fb and 104.8 \pm 2.5 fb, respectively. The \(Z \to 4\ell\) branching fraction is determined to be \((3.20 \pm 0.25(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-6}\), consistent with the SM prediction of \((3.33 \pm 0.01) \times 10^{-6}\).

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[7] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector, and the z axis along the beam line. The x axis points from the IP to the center of the LHC ring, and the y axis points upwards. Cylindrical coordinates (\(r, \phi\)) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam line. The pseudorapidity is defined in terms of the polar angle \(\theta\) as \(\eta = -\ln(\tan(\theta/2))\). Observables labeled “transverse” are projected into the \(x-y\) plane.
[9] The 2012 luminosity measurement follows the same methodology as that detailed in Ref. [8]. It is based on a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4Department of Physics, Ankara University, Ankara, Turkey
4aDepartment of Physics, Gazi University, Ankara, Turkey
4bDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4cTurkish Atomic Energy Authority, Ankara, Turkey
5LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
6aDepartment of Physics, University of Arizona, Tucson, Arizona, USA
6bUniversity of Athens, Athens, Greece
6cPhysics Department, National Technical University of Athens, Zografou, Greece
7Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
8Institut de Física d’Altes Energies, University of Belgrade, Belgrade, Serbia
8aInstitute of Physics, University of Belgrade, Belgrade, Serbia
8bDepartment for Physics and Technology, University of Bergen, Bergen, Norway
9Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
9aDepartment of Physics, Humboldt University, Berlin, Germany
9bAlbert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
10School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
10aDepartment of Physics, Bogazici University, Istanbul, Turkey
10bDepartment of Physics, Dogus University, Istanbul, Turkey
10cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
10dINFN Sezione di Bologna, Bologna, Italy
11Physikalisches Institut, University of Bonn, Bonn, Germany
12Department of Physics, Boston University, Boston, Massachusetts, USA
12aDepartment of Physics, Brandeis University, Waltham, Massachusetts, USA
13Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
13aUniversidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
13bInstituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
14Physics Department, Brookhaven National Laboratory, Upton, New York, USA
14aNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
14bNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
14cUniversity Politehnica Bucharest, Bucharest, Romania
14dWest University in Timisoara, Timisoara, Romania
15Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
16Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
16aDepartment of Physics, Carleton University, Ottawa, Ontario, Canada
17CERN, Geneva, Switzerland
18Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
19Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
19aDepartment of Physics, Universidad Técnica Federico Santa Maria, Valparaíso, Chile
20Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
20aDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
20bDepartment of Physics, Nanjing University, Jiangsu, China
20cSchool of Physics, Shandong University, Shandong, China
20dPhysics Department, Shanghai Jiao Tong University, Shanghai, China
Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
Nevis Laboratory, Columbia University, Irvington, New York, USA
Niels Bohr Institute, University of Copenhagen, København, Denmark
INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Rende, Italy
Dipartimento di Fisica, Università della Calabria, Rende, Italy
AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
Physics Department, University of Texas at Dallas, Richardson, Texas, USA
DESY, Hamburg and Zeuthen, Germany
Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
Department of Physics, Duke University, Durham, North Carolina, USA
SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
Section de Physique, Université de Genève, Geneva, Switzerland
INFN Sezione di Genova, Genova, Italy
Dipartimento di Fisica, Università di Genova, Genova, Italy
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
Department of Physics, Hampton University, Hampton, Virginia, 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, Indiana, USA
Institut für Astro-und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, Iowa, USA
Department of Physics and Astronomy, Iowa State University, Ames, Iowa, 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, 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
School of Physics and Astronomy, University College London, London, United Kingdom
Louisiana Tech University, Ruston, Los Angeles, USA
Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Fysiska institutionen, Lund 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, Massachusetts, USA