



CERN-PH-EP-2014-047

Submitted to: Phys. Rev. Lett.

## Measurement of the $4\ell$ Cross Section at the $Z$ Resonance and Determination of the Branching Fraction of $Z \rightarrow 4\ell$ in $pp$ Collisions at $\sqrt{s} = 7$ and 8 TeV with ATLAS

The ATLAS Collaboration

### Abstract

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# Measurement of the $4\ell$ Cross Section at the $Z$ Resonance and Determination of the Branching Fraction of $Z \rightarrow 4\ell$ in $pp$ Collisions at $\sqrt{s} = 7$ and 8 TeV with ATLAS

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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 region  $m_{\ell^+\ell^-} > 5$  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 non-resonant  $4\ell$  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.

PACS numbers: 13.38.Dg

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 proton–proton collisions at  $\sqrt{s} = 7$  and 8 TeV using data recorded by the ATLAS detector [1] at the LHC [2] in 2011 and 2012. In the Standard Model (SM),  $4\ell$  production in the  $Z$  resonance region occurs dominantly via an  $s$ -channel diagram such as 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 also produced in a  $t$ -channel process such as shown in Fig. 1(b). The process  $gg \rightarrow Z^{(*)}Z^{(*)} \rightarrow 4\ell$  accounts for only about  $10^{-3}$  of the total  $4\ell$  event rate around the  $Z$  resonance [3]. A reso-

nity, inclusive  $4\ell$  production around the  $Z$  resonance, including the non-resonant 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  $m_{\ell\ell} > 4$  GeV for all pairs of leptons (regardless of lepton flavor or charge) [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.

The inclusive  $4\ell$  production cross section at the  $Z$  resonance is measured separately for the  $4e$ ,  $4\mu$  and  $2e2\mu$  final states for each of the  $\sqrt{s} = 7$  and 8 TeV datasets in a fiducial region (defined below) corresponding closely to the experimental acceptance. The measured fiducial cross sections are then extrapolated to 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 branching fraction  $\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z$  is determined by normalizing the resonant  $4\ell$  production rate to the  $Z \rightarrow \mu^+\mu^-$  production rate measured in the same dataset.

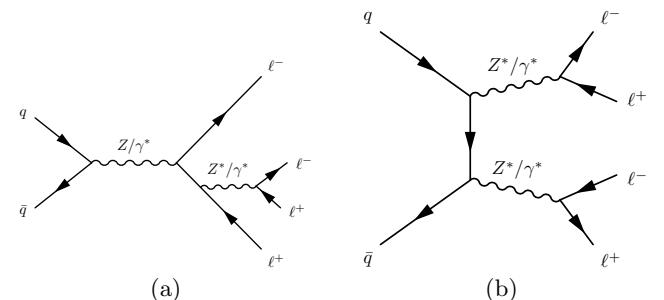


FIG. 1. Examples of (a)  $s$ -channel and (b)  $t$ -channel Feynman diagrams for  $4\ell$  production in  $pp$  collisions.

nant 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 non-resonant ( $t$ -channel and  $gg$ ) production mechanisms is expected to be very small around the  $Z$  resonance, the branching fraction of the rare decay  $Z \rightarrow 4\ell$  can be determined by subtracting the expected non-resonant  $4\ell$  contributions from the measured  $4\ell$  rate. For simplicity,

The ATLAS detector has a cylindrical geometry [7] and consists of an inner tracking detector surrounded by a 2 T superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field. The inner detector (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 muon spectrometer includes fast-

trigger chambers ( $|\eta| < 2.4$ ) and high-precision tracking chambers covering  $|\eta| < 2.7$ .

The datasets 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  $Z \rightarrow 4\ell$  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  $4.5 \text{ fb}^{-1}$  at 7 TeV and  $20.3 \text{ fb}^{-1}$  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 datasets, 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  $m_{\ell^+\ell^-} > 5 \text{ GeV}$  and  $80 < m_{4\ell} < 100 \text{ GeV}$  phase space, the production cross sections calculated by POWHEG are  $53.4 \pm 1.2 \text{ fb}$  ( $45.8 \pm 1.1 \text{ fb}$ ) for the sum of the  $4e$  and  $4\mu$  final states, and  $51.5 \pm 1.2 \text{ fb}$  ( $44.2 \pm 1.1 \text{ fb}$ ) 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 expected fraction of  $4\ell$  events produced via the  $t$ -channel process,  $f_t$ , 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 [14], and the  $4\ell$  event fraction from this process is calculated to be around 0.1%. The overall non-resonant 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 [15] or PYTHIA8 [16] for showering and hadronization and to PHOTOS [17] for radiated photons from charged leptons.

The MC generators used to simulate the reducible background contributions are MC@NLO [18] (to model  $t\bar{t}$  and single-top production) and ALPGEN [19] (to model  $Z$  boson production in association with jets, referred to as  $Z+jets$ ). These generators are interfaced to HERWIG [20] and JIMMY [21] for parton showering and underlying-event simulations. The diboson background processes  $WZ$  and  $Z\gamma$ , and  $Z^{(*)}Z^{(*)} \rightarrow 4\ell$  decays involving  $\tau \rightarrow e/\mu + 2\nu$ , are modeled by POWHEG (interfaced to PYTHIA for parton showering) and SHERPA [22].

The detector response simulation [23] is based on the

GEANT4 program [24]. Additional inelastic  $pp$  interactions (referred to as pile-up) are included in the simulation, and events are re-weighted 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 [25] 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 (or track segments) reconstructed in the muon spectrometer and are matched to tracks reconstructed in the ID. The muon momentum is calculated by combining the information from the two subsystems, correcting for the energy lost in the calorimeters. Additionally, one muon in each event is allowed to be a stand-alone muon or a calorimeter-tagged muon, where the stand-alone muon is identified by only a muon spectrometer track in  $2.5 < |\eta| < 2.7$ , and the calorimeter-tagged muon is identified by an ID track with  $p_T > 15 \text{ GeV}$  associated with a compatible calorimeter energy deposit in  $|\eta| < 0.1$ . All muon candidates are required to have  $p_T > 4 \text{ GeV}$  and  $|\eta| < 2.7$ .

Electrons are reconstructed from energy deposits in the electromagnetic calorimeter matched to a track in the ID [26]. Tracks associated with electromagnetic clusters are fitted using a Gaussian Sum Filter [27], which allows bremsstrahlung energy losses to be taken into account. For  $\sqrt{s} = 8 \text{ TeV}$  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  $p_T > 7 \text{ GeV}$  and  $|\eta| < 2.47$ .

Collision events are selected by requiring at least one reconstructed vertex with at least three charged particle tracks with  $p_T > 0.4 \text{ GeV}$ . 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 pile-up contribution, is required to be less than 30% of the lepton  $p_T$ , reduced to 20% for electrons in the 8 TeV dataset and 15% for stand-alone muons. To further reject leptons from heavy-flavor jets, the impact parameter relative to the primary vertex is required to be less than 3.5 (6.0) standard deviations for all muons (electrons), where the looser electron requirement allows for tails in the electron impact parameter distribution

due to bremsstrahlung in the ID.

Candidate quadruplets are formed by selecting two opposite-sign, same-flavor dilepton pairs in an event. The four leptons of the quadruplets are required to be well separated,  $\Delta R > 0.1$  for same-flavor lepton pairs and  $\Delta R > 0.2$  for  $e\mu$  pairs. The two leading leptons must have  $p_T > 20$  GeV and  $p_T > 15$  GeV. The third lepton must have  $p_T > 10$  (8) GeV if it is an electron (muon). The dilepton pair with greatest invariant mass (denoted  $m_{12}$ ) is called the leading lepton pair, while the sub-leading lepton pair is chosen to have the largest invariant mass (denoted  $m_{34}$ ) among the remaining possible pairs. The dilepton masses must satisfy  $m_{12} > 20$  GeV and  $m_{34} > 5$  GeV. In the  $4e$  and  $4\mu$  channels all same-flavor, opposite-sign lepton pairs are required to have  $m_{\ell^+\ell^-} > 5$  GeV. This helps to reject events containing  $J/\psi \rightarrow \ell^+\ell^-$  decays. The invariant mass of the lepton quadruplet 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 datasets, 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. The  $2e2\mu$  channel is divided into  $ee + \mu\mu$  and  $\mu\mu + ee$  channels indicating the lepton flavors of the leading and sub-leading 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 dataset. 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 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  $\mu\mu + \mu\mu$ ,  $ee + \mu\mu$ ,  $\mu\mu + ee$ , and  $ee + ee$ , respectively, where the labeling  $\ell\ell + \ell'\ell'$  indicates the leading and sub-leading lepton pairs. 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, range from 1.3% to 1.7% depending on channel. The theoretical uncertainties reflect 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  $A_{4\ell}$  for each PDF error set (52 CT10 eigenvectors varied by one standard deviation) and for an alternative PDF set, MSTW2008 [28], with respect to the nominal one.

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 datasets, respectively. Background contributions from  $Z + \text{jets}$  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 from data using a background-enriched control sample of  $\ell\ell j_e j_e$  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  $\ell\ell j_e j_e$  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. The reducible background in the signal sample is estimated by scaling each event in the  $\ell\ell j_e j_e$  control sample by  $f_1 \times f_2$ , where the factor  $f_i$  ( $i = 1, 2$ ) 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  $Z + \text{jets}$  or  $t\bar{t}$  events. The uncertainties on  $f$  are determined from the variations of  $f$  in data samples obtained with alternative lepton-like jet selections and different jet compositions. The estimated background from  $Z + \text{jets}$  and top processes ranges from 0.05 to 0.20 events for the different channels and datasets; for all  $4\ell$  channels combined it is

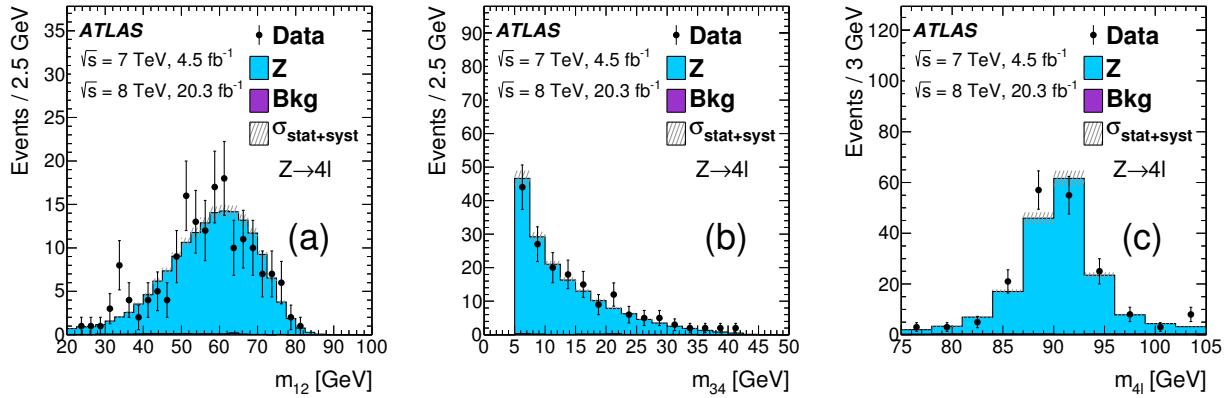


FIG. 2. Invariant mass distributions of (a) the leading lepton pair,  $m_{12}$ , (b) the subleading lepton pair,  $m_{34}$ , and (c) the four-lepton system,  $m_{4\ell}$ . The MC simulation expectation for a combination of all channels is compared to  $\sqrt{s} = 7$  and  $8$  TeV data. All selections are applied except in (c) there is no  $m_{4\ell}$  requirement. The background contributes  $< 1\%$  of the total expected signal (invisible in the plots).

TABLE I. Summary of the observed ( $N_{4\ell}^{\text{obs}}$ ) and expected ( $N_{4\ell}^{\text{exp}}$ ) number of selected  $Z \rightarrow 4\ell$  candidate events, and the estimated number of background events ( $N_{4\ell}^{\text{bkg}}$ ) in each  $4\ell$  channel for  $\sqrt{s} = 7$  and  $8$  TeV. The associated uncertainties are statistical and systematic combined. The central values of the acceptance and efficiency factors ( $A_{4\ell}$ ) and ( $C_{4\ell}$ ), the measured fiducial cross sections ( $\sigma_{Z4\ell}^{\text{fid}}$ ), and the total cross sections for  $m_{\ell^+\ell^-} > 5$  GeV,  $80 < m_{4\ell} < 100$  GeV ( $\sigma_{Z4\ell}$ ) are also presented. The fiducial regions are defined in the text and are different for each channel. The  $\sigma_{Z4\ell}$  are given for same-flavor ( $4e$  and  $4\mu$ ), different-flavor ( $2e2\mu$ ), and all channels combined. The uncertainties on  $\sigma_{Z4\ell}^{\text{fid}}$  and  $\sigma_{Z4\ell}$  are the statistical and systematic uncertainties, and the uncertainty due to the luminosity measurement.

$\sqrt{s}$	$4\ell$ state	$N_{4\ell}^{\text{obs}}$	$N_{4\ell}^{\text{exp}}$	$N_{4\ell}^{\text{bkg}}$	$C_{4\ell}$	$\sigma_{Z4\ell}^{\text{fid}} [\text{fb}]$	$A_{4\ell}$	$\sigma_{Z4\ell} [\text{fb}]$
7 TeV	$ee + ee$	1	$1.8 \pm 0.3$	$0.12 \pm 0.04$	21.5%	$0.9^{+1.4}_{-0.7} \pm 0.14 \pm 0.02$	7.5%	$\left. \begin{array}{l} 4e, 4\mu \\ 2e2\mu \end{array} \right\}$
	$\mu\mu + \mu\mu$	8	$11.3 \pm 0.5$	$0.08 \pm 0.04$	59.2%	$3.0^{+1.2}_{-0.9} \pm 0.07 \pm 0.05$	18.3%	
	$ee + \mu\mu$	7	$7.9 \pm 0.4$	$0.18 \pm 0.09$	49.0%	$3.1^{+1.4}_{-1.1} \pm 0.16 \pm 0.05$	15.8%	
	$\mu\mu + ee$	5	$3.3 \pm 0.3$	$0.07 \pm 0.04$	36.3%	$3.0^{+1.6}_{-1.2} \pm 0.30 \pm 0.06$	8.8%	$\left. \begin{array}{l} 2e2\mu \\ \text{combined} \end{array} \right\}$
	combined	21	$24.2 \pm 1.2$	$0.44 \pm 0.14$				76 $\pm 18 \pm 4 \pm 1.4$
8 TeV	$ee + ee$	16	$14.4 \pm 1.4$	$0.14 \pm 0.03$	36.1%	$2.2^{+0.6}_{-0.5} \pm 0.20 \pm 0.06$	7.3%	$\left. \begin{array}{l} 4e, 4\mu \\ 2e2\mu \end{array} \right\}$
	$\mu\mu + \mu\mu$	71	$68.8 \pm 2.7$	$0.34 \pm 0.05$	71.1%	$4.9^{+0.7}_{-0.6} \pm 0.13 \pm 0.14$	17.8%	
	$ee + \mu\mu$	48	$43.2 \pm 2.1$	$0.32 \pm 0.05$	55.5%	$4.2^{+0.7}_{-0.6} \pm 0.16 \pm 0.12$	14.8%	
	$\mu\mu + ee$	16	$19.3 \pm 1.3$	$0.18 \pm 0.04$	46.2%	$1.7^{+0.5}_{-0.4} \pm 0.10 \pm 0.04$	7.9%	$\left. \begin{array}{l} 2e2\mu \\ \text{combined} \end{array} \right\}$
	combined	151	$146 \pm 7$	$1.0 \pm 0.11$				107 $\pm 9 \pm 4 \pm 3.0$

estimated to be  $0.38 \pm 0.14$  and  $0.49 \pm 0.10$  events for the 7 and 8 TeV data, respectively.

The numbers 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 ( $\sigma_{Z4\ell}^{\text{fid}}$ ), determined by  $(N_{4\ell}^{\text{obs}} - N_{4\ell}^{\text{bkg}})/(L \times C_{4\ell})$ , are given in Table I.

The cross section in the final phase space for each channel is calculated by  $\sigma_{Z4\ell}^{\text{fid}}/A_{4\ell}$ . 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 inclusive  $4\ell$  cross section is a sum of the two com-

bined cross sections, and the uncertainty includes correlations between the four channels. The cross sections listed in Table I are consistent with the SM predictions given earlier.

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

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

where  $\Gamma_{Z \rightarrow \mu\mu}/\Gamma_Z = (3.366 \pm 0.007)\%$  [29],  $N_{2\mu}^{\text{obs}}$  is around 1.7 million and 8.9 million in the 7 and 8 TeV

datasets, respectively, and  $(C \times A)_{2\mu}$  is  $(41.4 \pm 0.6)\%$  and  $(41.8 \pm 0.6)\%$ , respectively. The background ( $N_{2\mu}^{\text{bkg}}$ ) is estimated to be around 0.3% of the selected  $Z \rightarrow \mu^+ \mu^-$  events, where the multijet and  $W + \text{jets}$  contributions are obtained using a data-driven method similar to that used for the  $Z \rightarrow 4\ell$  background estimation, and other background contributions are estimated with simulated MC samples. 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 datasets. The measured branching fractions for each dataset are consistent within uncertainties and are combined, giving

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

in the final phase-space region, where the systematic uncertainty includes a contribution (about 0.2%) due to the interference between the  $s$ -channel and  $t$ -channel processes, calculated using CALCHEP [30]. The measured branching fraction is consistent with the SM prediction of  $(3.33 \pm 0.01) \times 10^{-6}$ , calculated using POWHEG. For a larger final phase-space region defined by  $m_{\ell^+\ell^-} > 4 \text{ GeV}$  and  $80 < m_{4\ell} < 100 \text{ GeV}$ , similar to that used by CMS, the acceptance factors  $A_{4\ell}$  and the non-resonant fractions  $f_{\text{nr}}$ , and their uncertainties, are also evaluated (leaving the fiducial region unchanged), and the measured branching fraction becomes  $\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z = (4.31 \pm 0.34 \text{ (stat)} \pm 0.17 \text{ (syst)}) \times 10^{-6}$ , 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, measurements of the cross sections of  $4\ell$  production at the  $Z$  resonance in  $pp$  collision data collected by the ATLAS detector at the LHC have been presented. The datasets analyzed correspond to an integrated luminosity of  $4.5 \text{ fb}^{-1}$  and  $20.3 \text{ fb}^{-1}$  at  $\sqrt{s} = 7$  and 8 TeV, respectively. The total  $Z \rightarrow 4\ell$  production cross sections in the phase-space region  $m_{\ell^+\ell^-} > 5 \text{ GeV}$  and  $80 < m_{4\ell} < 100 \text{ GeV}$  are measured to be  $\sigma_{Z4\ell} = 76 \pm 18 \text{ (stat)} \pm 4 \text{ (syst)} \pm 1.4 \text{ (lumi)} \text{ fb}$  at 7 TeV and  $107 \pm 9 \text{ (stat)} \pm 4 \text{ (syst)} \pm 3.0 \text{ (lumi)} \text{ fb}$  at 8 TeV, consistent with the SM predictions of  $90.0 \pm 2.1 \text{ fb}$  and  $104.8 \pm 2.5 \text{ fb}$ , respectively. Normalizing to the measured  $Z \rightarrow \mu^+ \mu^-$  production, the  $Z \rightarrow 4\ell$  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  $(3.33 \pm 0.01) \times 10^{-6}$ .

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, DNSRC

and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, 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.

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