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)

(Received 22 March 2014; published 13 June 2014)

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 $Z \to \mu^+\mu^-$ 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.

DOI: 10.1103/PhysRevLett.112.231806

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 $pp$ 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 $gg \to Z^{(*)}Z^{(*)} \to 4\ell$ 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 $H \to 4\ell$ [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 $Z \to 4\ell$ 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 $Z \to 4\ell$ from here on, except that the branching fraction $\Gamma_{Z \to 4\ell}/\Gamma_Z$ refers to the $s$-channel contribution alone. The CMS Collaboration has observed the $Z \to 4\ell$ resonance in $\sqrt{s} = 7$ TeV data and determined a branching fraction, summed over the $4e$, $4\mu$, and $2e2\mu$ final states, of $\Gamma_{Z \to 4\ell}/\Gamma_Z = (4.2^{+0.9}_{-0.8}$(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 $\Gamma_{Z \to 4\ell}/\Gamma_Z$ 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 ± 1.2 fb (45.8 ± 1.1 fb) for the sum of the $4e$ and $4\mu$ final states, and 51.5 ± 1.2 fb (44.2 ± 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 $Z\tau$, 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 [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 $\Delta R = (\Delta \eta)^2 + (\Delta \phi)^2 = 0.2$ 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.
One quadruplet is selected for each event, the fiducial region, defined at the MC generator level. The third lepton must have masses satisfying $m_4 > (6.0)$ standard deviations for all muons (electrons), where the loosen 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 ($\ell^+\ell^-$) pairs in an event. The four leptons of a quadruplet are required to be well separated: $\Delta R > 0.1$ for same-flavor lepton pairs and $\Delta R > 0.2$ for $e\mu$ pairs. At most one muon is allowed to be a stand-alone muon or a calorimeter-tagged muon. The two leading leptons must have $p_T > 20$ and 15 GeV. The third lepton must have $p_T > 10(8)$ GeV if it is an electron (muon). One quadruplet is selected for each event, formed from the $\ell^+\ell^-$ pair with greatest invariant mass (the leading lepton pair, with mass $m_{12}$) and the $\ell^+\ell^-$ pair with the largest invariant mass among the remaining possible pairs (the subleading lepton pair, with mass $m_{34}$). The dilepton masses must satisfy $m_{12} > 20$ GeV and $m_{34} > 5$ GeV. In the 4e and 4$\mu$ channels all the $\ell^+\ell^-$ pairs are required to have $m_{\ell^+\ell^-} > 5$ GeV, to reject events containing $J/\psi \to \ell^+\ell^-$ decays. The 4$\ell$ invariant mass is restricted to $80 < m_{4\ell} < 100$ GeV. A total of 21 and 151 $Z \to 4\ell$ 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 $Z \to 4\ell$ 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 $Z \to 4\ell$ 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 $Z \to \ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ decays. The uncertainties on the $Z \to 4\ell$ 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. 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 $l^+l^−j_j$ 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 $l^+l^-j_j$ 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 $l^+l^-j_j$ control sample by $f_i \times f_2$, 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 $Z + jets$ or $t\bar{t}$ 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 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 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, $\Gamma_{Z\rightarrow4\ell}/\Gamma_Z$, 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.

$$\Gamma_{Z\rightarrow4\ell}/\Gamma_Z = \frac{\Gamma_{Z\rightarrow\mu\mu}}{\Gamma_Z} \frac{(N_{4\ell}^{\text{obs}} - N_{4\ell}^{\text{bkg}})(1 - f_{4\ell})C_{4\ell} \cdot A_{4\ell}}{(N_{2\mu} - N_{2\mu}^{\text{bkg}})C_{2\mu} \cdot A_{2\mu}},$$

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 data sets, respectively, and $(C \times A)_{2\mu}$ is $(41.4 \pm 0.6)\%$ and $(41.8 \pm 0.6)\%$, respectively. The background ($N_{4\ell}^{\text{bkg}}$) 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

$$\Gamma_{Z\rightarrow4\ell}/\Gamma_Z = (3.20 \pm 0.25(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-6}$$

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 $m_{4\ell} > 4$ GeV and $80 < m_{4\ell} < 100$ GeV, similar to that used by CMS, the acceptance factors $A_{4\ell}$ and the nonresonant fractions $f_{4\ell}$, and their uncertainties, are also evaluated (leaving the fiducial region unchanged), and the measured branching fraction becomes $\Gamma_{Z \rightarrow 4\ell} / \Gamma_Z = (4.31 \pm 0.34(stat) \pm 0.17(syst)) \times 10^{-6}$, 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 $Z \rightarrow 4\ell$ production cross sections in the phase-space region $m_{4\ell} > 5$ GeV and $80 < m_{4\ell} < 100$ GeV are measured to be $\sigma_{4\ell} = 76 \pm 18(stat) \pm 4(syst) \pm 1.4(lumi)$ fb at 7 TeV and $107 \pm 9(stat) \pm 4(syst) \pm 3.0(lumi)$ 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 $Z \rightarrow 4\ell$ branching fraction is determined to be $(3.20 \pm 0.25(stat) \pm 0.13(syst)) \times 10^{-6}$, 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; CPNP 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; DLR and DFKI, Germany; INFN, Italy; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MICINN, 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, USA. 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.

[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.
34Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35Nevis Laboratory, Columbia University, Irvington, New York, USA
36Niels Bohr Institute, University of Copenhagen, København, Denmark
37a INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Rende, Italy
37b Dipartimento di Fisica, Università della Calabria, Rende, Italy
38a AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
38b Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40Physics Department, Southern Methodist University, Dallas, Texas, USA
41DESY, Hamburg and Zeuthen, Germany
42Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
44Department of Physics, Duke University, Durham, North Carolina, USA
45SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
46INFN Laboratori Nazionali di Frascati, Frascati, Italy
47Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
48Section de Physique, Université de Genève, Geneva, Switzerland
49INFN Sezione di Genova, Genova, Italy
50b Dipartimento di Fisica, Università di Genova, Genova, Italy
51a E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
51b High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
55Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56Department of Physics, Hampton University, Hampton, Virginia, USA
57Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
58Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59c ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
59d Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
59e Department of Physics, Indiana University, Bloomington, Indiana, USA
59f Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
59g University of Iowa, Iowa City, Iowa, USA
59h Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
60Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
61KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
62Graduate School of Science, Kobe University, Kobe, Japan
62Faculty of Science, Kyoto University, Kyoto, Japan
63Kyoto University of Education, Kyoto, Japan
64Department of Physics, Kyushu University, Fukuoka, Japan
65Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
66Physics Department, Lancaster University, Lancaster, United Kingdom
67INFN Sezione di Lecce, Lecce, Italy
68Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
69Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
70School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
71Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
72Department of Physics and Astronomy, University College London, London, United Kingdom
73Louisiana Tech University, Ruston, Los Angeles, USA
74Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
75Fysiska institutionen, Lunds universitet, Lund, Sweden
76Departamento de Física Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
77Institut für Physik, Universität Mainz, Mainz, Germany
78School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
79CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
80Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
INFN Sezione di Roma Tor Vergata, Roma, Italy  
Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy  
INFN Sezione di Roma Tre, Roma, Italy  
Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy  
Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco  
Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco  
Facultés des Sciences Semlalia, Université Cadi Ayyad, LPTHE-Marrakech, Morocco  
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco  
Facultés des sciences, Université Mohammed V-Agdal, Rabat, Morocco  
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), GIF-sur-Yvette, France  
Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA  
Department of Physics, University of Washington, Seattle, Washington, USA  
Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom  
Department of Physics, Shinshu University, Nagano, Japan  
Fachbereich Physik, Universität Siegen, Siegen, Germany  
Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada  
SLAC National Accelerator Laboratory, Stanford, California, USA  
Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic  
Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Košice, Slovak Republic  
Department of Physics, University of Cape Town, Cape Town, South Africa  
Department of Physics, University of Johannesburg, Johannesburg, South Africa  
School of Physics, University of the Witwatersrand, Johannesburg, South Africa  
Department of Physics, Stockholm University, Sweden  
The Oskar Klein Centre, Stockholm, Sweden  
Physics Department, Royal Institute of Technology, Stockholm, Sweden  
Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook, New York, USA  
Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom  
School of Physics, University of Sydney, Sydney, Australia  
Institute of Physics, Academia Sinica, Taipeh, Taiwan  
Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel  
Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel  
Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece  
International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan  
Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan  
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan  
Department of Physics, University of Toronto, Toronto, Ontario, Canada  
TRIUMF, Vancouver, British Columbia, Canada  
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada  
Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan  
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA  
Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia  
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA  
INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy  
ICTP, Trieste, Italy  
Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy  
Department of Physics, University of Illinois, Urbana, Illinois, USA  
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden  
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-CNRM), University of Valencia and CSIC, Valencia, Spain  
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada  
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada  
Department of Physics, University of Warwick, Coventry, United Kingdom  
Waseda University, Tokyo, Japan  
Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel  
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA  
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany  
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
Also at TRIUMF, Vancouver BC, Canada.
Also at Department of Physics, California State University, Fresno CA, USA.
Also at Novosibirsk State University, Novosibirsk, Russia.
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
Also at Université di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Louisiana Tech University, Ruston LA, USA.
Also at Institut Catala de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at CERN, Geneva, Switzerland.
Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
Also at Manhattan College, New York NY, USA.
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.
Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.
Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at Section de Physique, Université de Genève, Geneva, Switzerland.
Also at Department of Physics, The University of Texas at Austin, Austin TX, USA.
Also at International School for Advanced Studies (SISSA), Trieste, Italy.
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, USA.
Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
Also at Physics Department, Brookhaven National Laboratory, Upton NY, USA.
Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
Also at Department of Physics, Oxford University, Oxford, United Kingdom.
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
Also at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.