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

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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 $gg \to Z^{(*)}Z^{(*)} \to 4\ell$ 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 $4\ell$, $4\mu$, 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 $m_{\ell^+\ell^-} > 4$ 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 $|\eta| < 2.7$.

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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 $Z \to 4\ell$ 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 $m_{4\ell}: p_T > 5$ 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 $gg \to ZZ \to 4\ell$ 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 $Z^{(*)}Z^{(*)} \to 4\ell$ decays involving $\tau \to e/\mu + 2\nu$, 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 $Z \to 4\ell$ event selection closely follows the $H \to ZZ \to 4\ell$ analysis [26] with muon $p_T$ and dilepton invariant mass requirements loosened to increase the acceptance for the $Z \to 4\ell$ 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 pile-up contribution, is required to be less than 30% of the lepton $p_T$, reduced to 20% for electrons in the 8 TeV data.
set and 15% for stand-alone muons. 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 (\(\ell^+\ell^-\)) 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. One quadruplet is selected for each event, using the lepton four-momenta, requiring the fiducial region, defined at the MC generator level using the signal MC samples after the detector simulation. The third lepton must have \(\ell^+\ell^-\) region from 1.3% to 1.7% depending on the channel. 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 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) \quad \text{for all same(different)-flavor lepton pairs,} \quad m_{\ell\ell'} > 20 \text{ GeV for at least one lepton pair,} \quad m_{\ell\ell'} > 5 \text{ GeV for all same-flavor lepton pairs, and} \quad 80 < m_{4\ell} < 100 \text{ GeV. The four-momenta of all final-state photons within } \Delta R = 0.1 \text{ of a lepton are summed into the four-momentum of that lepton. The acceptance factor } A_{4\ell} \text{ is the fraction of } Z \to 4\ell \text{ events in the final phase space which falls into the fiducial region. The } C_{4\ell} \text{ uncertainty is mostly experimental and the } A_{4\ell} \text{ uncertainty is entirely theoretical. The } A_{4\ell} \text{ and } C_{4\ell} \text{ values are listed in Table I for each channel and data set. The } C_{4\ell} \text{ values for } 8 \text{ TeV are larger than for } 7 \text{ 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 ± 0.01 and 0.49 ± 0.04 events in the 7 and 8 TeV data sets.
Background events may contain two isolated leptons from \( p \) lepton flavor and \( (\ell\ell)^{jj} \) additional activity such as heavy-flavor jets or misidentified electromagnetic clusters matched to tracks in the ID that do not satisfy the identification criteria or isolation requirements. Electron-like jets, \( j_\text{e} \), are selected in place of two of the signal leptons. Electron-like jets, \( j_\text{e} \), in the \( \ell\ell j_\ell j_\ell \) 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 \( \ell\ell j_\ell j_\ell \) 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 \( tt \) events. The background from \( Z + \text{jets} \) 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 \( (\sigma_{Z\ell\ell}^{\text{fid}}) \), determined by \( (N_{Z\ell\ell}^{\text{obs}} - N_{Z\ell\ell}^{\text{bkg}}) / (L \times C_{Z\ell\ell}) \), are given in Table I. The cross section in the final phase space for each channel is calculated by \( \sigma_{Z\ell\ell}^{\text{fid}} / A_{Z\ell\ell} \). 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 \( Z \to 4\ell \) branching fraction, \( \Gamma_{Z\to4\ell} / \Gamma_Z \), is determined by subtracting the nonresonant contributions to the selected events and normalizing the resulting yield to the observed number of \( Z \to \mu^+\mu^- \) events in the same data set,

\[
\frac{\Gamma_{Z\to4\ell}}{\Gamma_Z} = \frac{(N_{Z\to4\ell}^{\text{obs}} - N_{Z\ell\ell}^{\text{bkg}})(1 - f_{\text{stat}})C_{2\mu} \cdot A_{2\mu}}{(N_{2\mu}^{\text{obs}} - N_{2\mu}^{\text{bkg}})C_{\ell\ell} \cdot A_{\ell\ell}},
\]

where \( \Gamma_{Z\to\mu\mu} / \Gamma_Z = (3.366 \pm 0.007)\% \) [29], \( N_{Z\ell\ell}^{\text{obs}} \) 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 \((41.4 \pm 0.6)\% \) \((41.8 \pm 0.6)\% \), respectively. The background \( N_{Z\ell\ell}^{\text{bkg}} \) is estimated to be around 0.3% of the selected \( Z \to \mu^+\mu^- \) events. The branching fraction for \( Z \to 4\ell \), 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

\[
\frac{\Gamma_{Z\to4\ell}}{\Gamma_Z} = (3.20 \pm 0.25(\text{stat}) \pm 0.13(\text{syst})) \times 10^{-6}
\]

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 \(m_{\ell^+\ell^-} > 4\) GeV and \(80 < m_{4\ell} < 100\) GeV, similar to that used by CMS, the acceptance factors \(A_{4\ell}\) and the nonresonant fractions \(f_{nr}\), and their uncertainties, are also evaluated (leaving the fiducial region unchanged), and the measured branching fraction becomes \(\Gamma_{Z \rightarrow 4\ell}/\Gamma_Z = (4.31 \pm 0.34(stat) \pm 0.17(syst)) \times 10^{-6}\), 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 \(m_{\ell^+\ell^-} > 5\) GeV and \(80 < m_{4\ell} < 100\) GeV are measured to be \(\sigma_{Z \rightarrow 4\ell} = 76 \pm 18(stat) \pm 4(syst) \pm 1.4(lumi)\) 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 \((3.33 \pm 0.01) \times 10^{-6}\).

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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.
R. Zimmermann,1 S. Zimmermann,2 S. Zimmermann,4 Z. Zinonos,5 M. Ziolkowski,14 G. Zobernig,17 A. Zoccoli,20a,20b M. zur Nedden,16 G. Zurzolo,103a,103b V. Zutshi107 and L. Zwalinski30

(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
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4dTurkish Atomic Energy Authority, Ankara, Turkey
5LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, The University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13aInstitute of Physics, University of Belgrade, Belgrade, Serbia
13bVinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14Department for Physics and Technology, University of Bergen, Bergen, Norway
15Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16Department of Physics, Humboldt University, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19aDepartment of Physics, Bogazici University, Istanbul, Turkey
19bDepartment of Physics, Dogus University, Istanbul, Turkey
19cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
19dINFN Sezione di Bologna, Bologna, Italy
20aDipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
20bPhysikalisches Institut, University of Bonn, Bonn, Germany
21Department of Physics, Boston University, Boston, Massachusetts, USA
22Department of Physics, Brandeis University, Waltham, Massachusetts, USA
23Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
24aFederal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
24bFederal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
24cInstituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25Physics Department, Brookhaven National Laboratory, Upton, New York, USA
26aNational Institute of Physics and Nuclear Engineering, Bucharest, Romania
26bNational Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
26cUniversity Politehnica Bucharest, Bucharest, Romania
26dWest University in Timisoara, Timisoara, Romania
27Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29Department of Physics, Carleton University, Ottawa, Ontario, Canada
30CERN, Geneva, Switzerland
31Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
32aDepartment of Física, Pontificia Universidad Católica de Chile, Santiago, Chile
32bDepartment of Física, Universidad Técnica Federico Santa Maria, Valparaiso, Chile
33aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
33bDepartment of Modern Physics, University of Science and Technology of China, Anhui, China
33cDepartment of Physics, Nanjing University, Jiangsu, China
33dSchool of Physics, Shandong University, Shandong, China
33ePhysics Department, Shanghai Jiao Tong University, Shanghai, China
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 Università 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 Institucio Catalana 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.

Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.