Measurement of Z Boson Production in Pb-Pb Collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV with the ATLAS Detector

G. Aad et al.*
(ATLAS Collaboration)
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The ATLAS experiment has observed 1995 Z boson candidates in data corresponding to 0.15 nb$^{-1}$ of integrated luminosity obtained in the 2011 LHC Pb + Pb run at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. The Z bosons are reconstructed via dielectron and dimuon decay channels, with a background contamination of less than 3%. Results from the two channels are consistent and are combined. Within the statistical and systematic uncertainties, the per-event Z boson yield is proportional to the number of binary collisions estimated by the Glauber model. The elliptic anisotropy of the azimuthal distribution of the Z boson with respect to the event plane is found to be consistent with zero.

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Extensive studies of heavy ion (HI) collisions carried out by the experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL, and the Large Hadron Collider (LHC) at CERN, have established that the hot and dense matter produced in HI collisions causes a significant modification of the energetic color-charge carriers propagating through such a medium [1,2]. An understanding of this phenomenon requires measuring the unmodified production rates of the particles before they lose energy. The best candidates to perform such measurements are particles that do not interact via the strong force. The PHENIX experiment at RHIC measured the properties of photons [3]. At the LHC, the CMS experiment reported results on photons and W bosons [4,5]. The number of these bosons was found to scale with the number of incoherent nucleon-nucleon collisions. Both the ATLAS and CMS Collaborations have reported measurements of $Z \rightarrow \mu\mu$ production at $\sqrt{s_{\text{NN}}} = 2.76$ TeV [6,7], which show, within a limited statistical precision, the same scaling behavior. This Letter presents a precise measurement of Z boson production in Pb + Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, using the dielectron and dimuon decay channels. The Z boson production rate is measured as a function of centrality, rapidity ($y^Z$), transverse momentum ($p_T^Z$), and orientation with respect to the event plane [8].

The ATLAS detector [9] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three superconducting toroid magnet systems.

The inner detector system (ID) is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and is surrounded by the silicon microstrip tracker and the transition radiation tracker. The calorimeters cover the range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and end-cap high-granularity lead liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$. The electromagnetic calorimeter is backed by a hadronic calorimeter. Forward calorimeters (FCal) are located in the range $3.1 < |\eta| < 4.9$.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chambers cover the region $|\eta| < 2.7$ with three layers of monitored drift tubes (MDT), complemented by cathode strip chambers (CSC) in the innermost layer of the forward region. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the end-cap regions.

This analysis uses the 2011 LHC Pb + Pb collision data at $\sqrt{s_{\text{NN}}} = 2.76$ TeV, obtained by the ATLAS experiment with integrated luminosity of approximately 0.15 nb$^{-1}$. The data sample for this study was collected using a three-level trigger system [10], which selected events with electron or muon candidates.

Electron candidates were identified at the first trigger level (L1) as a cluster of cells in the electromagnetic calorimeter, formed into $(\Delta \phi \times \Delta \eta) = 0.1 \times 0.1$ trigger towers, within the range $|\eta| < 2.5$, excluding the transition region between calorimeter sections ($1.37 < |\eta| < 1.52$). The cluster transverse energy was required to exceed $E_T = 14$ GeV.

Muon candidates were selected using all three trigger levels. The L1 muon trigger searched for patterns of hits in the trigger chambers consistent with muons. If a muon
had $p_T$ exceeding 4 GeV, the event was accepted for further processing by the high-level trigger (HLT). The L1 muon algorithm also identified regions of interest (RoI) within the detector to be investigated by the HLT. In the HLT, the track parameters of each muon were recalculated by including the precision data from the MDT or CSC in the RoI defined by the previous trigger level. Muon candidates were reconstructed either solely from the MS or using combined data from the MS and ID. In addition to the events selected using the RoI-based muon trigger, the reconstruction was performed over the whole MS by the HLT to identify muons with $p_T > 10$ GeV. The full scan searched all events in which a neutral particle signal was detected in each of two zero degree calorimeters (ZDC) ($|\eta| > 8.3$), or which contained an energy deposition in the calorimeters of $E_T > 10$ GeV.

In addition to the single-lepton trigger, each event had to pass the minimum-bias (MB) event selection, which required a timing signal coincidence of better than 3 ns between the MB trigger scintillators ($2.1 < |\eta| < 3.8$), as well as the reconstruction of a collision vertex in the ID. The total number of sampled events is $(1.03 \pm 0.02) \times 10^8$ [11].

Analyzed events are divided into centrality classes. Centrality reflects the overlap volume of the two colliding nuclei. Collisions with a small (large) impact parameter are referred to as central (peripheral). The overlap volume is closely related to the average number of participant nucleons which scatter inelastically in each nuclear collision $\langle N_{\text{part}} \rangle$, and to the average number of binary collisions between the nucleons of the colliding nuclei $\langle N_{\text{coll}} \rangle$. Equivalently, $\langle N_{\text{coll}} \rangle$ may be defined as the average nuclear thickness function ($T_{\text{AA}}$) multiplied by the total inelastic $p + p$ cross section of $64 \pm 5$ mb [12].

The Pb + Pb collision centrality is measured using the scalar sum of transverse energy ($\sum E_T$) deposited in the FCal, calibrated at the electromagnetic energy scale [13]. The fraction of events with more than one Pb + Pb collision is estimated not to exceed 0.05%, except for the most central 5% of events in which the fraction does not exceed 0.5%. A cut on the FCal energy of $\sum E_T < 3.8$ TeV is applied to prevent contamination by events with multiple Pb + Pb interactions. Glauber model calculations relate centrality to $\langle N_{\text{part}} \rangle$ and $\langle N_{\text{coll}} \rangle$, following the procedure documented in Ref. [14]. In the present sample, $\langle N_{\text{coll}} \rangle$ ($\langle N_{\text{part}} \rangle$) ranges from 1683 $\pm$ 130 (382 $\pm$ 2) for the most central class, 0%–5%, to 78 $\pm$ 7 (46 $\pm$ 3) for the most peripheral class, 40%–80%.

The efficiencies of the electron and muon triggers are evaluated from $5.5 \times 10^7$ events selected with the MB trigger during the 2011 run. The MB trigger required a transverse energy deposition of $E_T > 50$ GeV in the calorimeters or a coincidence of both ZDC signals and a track in the ID. The average trigger efficiency for muons with $p_T > 10$ GeV decreases from $(98.2 \pm 0.5\%)$ in peripheral events to $(90.9 \pm 0.5\%)$ in central events, where the ID occupancy is higher. The average trigger efficiency for electrons with $|\eta| < 2.5$ and $E_T > 20$ GeV is $(98.1 \pm 0.1\%)$ independent of centrality. The trigger efficiency for $Z \rightarrow \mu \mu$ decays ranges from $(99.0 \pm 0.6\%)$ in peripheral events to $(95.0 \pm 0.9\%)$ in central events. For $Z \rightarrow ee$ decays the efficiency is $(99.9 \pm 0.1\%)$ independent of centrality.

For the $Z \rightarrow ee$ analysis, electron candidates are formed using the standard ATLAS reconstruction algorithm [15], requiring the matching of a track to an energy cluster in the electromagnetic calorimeter. Electron selection is limited to $|\eta| < 2.5$ and both electrons are required to have $E_T > 20$ GeV. Following the reconstruction requirements, further electron identification cuts are made to reject background. The standard electron identification cuts [15] used in the $p + p$ environment are not suited to the Pb + Pb environment due to the large underlying event (UE) energy deposition in the calorimeter. To address this, a different set of cuts has been developed to accommodate the modification of the calorimeter variables by the presence of the UE. The cuts used are based on the energy balance between the track momentum and cluster energy ($E/p$), as well as calorimeter shower shape variables. Furthermore, the UE energy is estimated (following Ref. [16]) and subtracted on an electron-by-electron basis to recover the proper electron energy.

The electron combined reconstruction and identification efficiency is evaluated in a Monte Carlo simulation using electrons from $7 \times 10^5$ PYTHIA (version 6.425) [17] $p + p \rightarrow Z \rightarrow ee$ events with $66 < m_Z < 116$ GeV and $|y^{ee}| < 2.5$ embedded into Pb + Pb events generated by the HIJING event generator (version 1.38b) [18]. The response of the ATLAS detector to the generated particles is modeled using GEANT4 [19,20]. The combined reconstruction and identification efficiency for electrons of $E_T > 20$ GeV ranges from 72% to 76% from central to peripheral events, with a common absolute uncertainty of 5.4%.

For the $Z \rightarrow ee$ analysis, all electrons found in triggered events are paired with each other, requiring that at least one electron in the pair matches a trigger object. The opposite-sign charged pairs with an invariant mass satisfying $66 < m_{ee} < 102$ GeV are accepted as signal $Z$ boson candidates. The same-sign pairs in this window are taken as an estimate of the combinatorial background. In total, 772 opposite-sign pairs and 42 same-sign pairs are reconstructed.

In the $Z \rightarrow \mu \mu$ analysis, single muons are reconstructed with several levels of quality [21]. High quality muons are reconstructed in both the MS and ID with consistent angular measurements, as well as with a good match to the event vertex. At least one muon in each pair, matched to the trigger, is required to be of such quality. If the second muon in the pair has hit patterns in the MS and ID satisfying criteria of high reconstruction quality, the minimum $p_T$ threshold is set to 10 GeV for both muons. If the second muon fails this condition, both muons are required to satisfy $p_T > 20$ GeV.
The muon combined reconstruction and identification efficiency is evaluated using muons from 5.3 × 10^7 PYTHIA p + p → Z → μμ events with 66 < m_Z < 116 GeV and |y^2| < 2.5 embedded into HIJING events. For muons with p_T > 20 GeV, |η| < 2.5 and associated to the event vertex, the reconstruction efficiency of the MS varies from (97 ± 1)% to (98 ± 1)% from central to peripheral events. Requiring a match between the MS and ID reduces the uncertainty. The number of pairs with momentum, rapidity, and centrality. Bars represent the statistical normalized in the region (marked by the vertical dashed lines) is listed. The simulation region efficiencies in data and simulation agree to 1% (2% for measurement channels are associated with the precision to uncertainty related to the background.

As in the Z → ee analysis, an invariant mass window of 66 < m_μμ < 102 GeV is used to define oppositely charged muon pairs as Z boson candidates and same-sign charged pairs as a background estimate. In total, 1223 opposite-sign candidates and 14 same-sign pairs are reconstructed in the Z → μμ channel.

The invariant mass distributions of the selected pairs together with estimated combinatorial backgrounds for all p_T^Z and |y^2| < 2.5 are shown in Fig. 1, compared with the simulation normalized to the number of pairs in the region 66 < m_μμ < 102 GeV (ℓ = e, μ). In order to calculate the yield, the combinatorial background estimated with the same-sign pairs must be subtracted. Backgrounds from electroweak processes and top pair decays [22] are small compared to the combinatorial backgrounds, and their contribution is accounted for in the systematic uncertainty related to the background.

The main sources of systematic uncertainty in both measurement channels are associated with the precision to which the corrections applied to the data can be calculated. In the p + p environment, the muon reconstruction efficiencies in data and simulation agree to 1% (2% for p_T < 15 GeV) [23]. The MS maintains low occupancy in the Pb + Pb environment. The difference in the fraction of muons reconstructed only in the MS, between data and simulation is used to estimate the systematic uncertainty on the reconstruction efficiency. To evaluate the uncertainty on the efficiency of the electron identification cuts stemming from the simulation, the efficiency is computed from the HI data using a tag-and-probe technique [15] and compared to the efficiency computed from simulation. The systematic uncertainty due to momentum resolution is estimated by introducing additional momentum smearing to the simulation. The efficiency (resolution) uncertainties are ≈ 5.5% (2.5%) for Z → μμ, and 8% (2.5%) in Z → ee; these estimates vary with p_T^Z and y^2.

The trigger efficiency uncertainties are estimated by using alternative methods and comparing their results with those obtained from the MB data set. For this comparison the simulation trigger efficiency is used, as well as the conditional trigger efficiency of a second lepton in a triggered pair reconstructed as a Z boson.

For each Z → ll analysis, correction factors to account for the efficiency (relative to Z bosons produced with 66 < m_Z < 116 GeV) and detector resolution within the selected acceptance based on the simulation are calculated differentially in event centrality, p_T^ll, and y^2. In each decay channel, the correction factor is applied and the background, estimated by the same-sign pairs, is subtracted. The two measurements are averaged with weights set by their respective uncertainties.

The fully corrected y^2 distribution is shown in Fig. 2. No centrality dependence of this shape is observed. The data are compared to a model composed of PYTHIA events normalized to the Z → ll cross section in p + p collisions at √s_{NN} = 2.76 TeV taken from next-to-next-to-leading-order (NNLO) calculations used in Ref. [24] and scaled by (T_AA). Using the same computational approach as in

FIG. 1 (color online). The invariant mass distributions of Z → ee (left) and Z → μμ (right) candidates, integrated over momentum, rapidity, and centrality. Bars represent the statistical uncertainty. The number of pairs with 66 < m_μμ < 102 GeV (marked by the vertical dashed lines) is listed. The simulation is weighted to match the centrality distribution in data and normalized in the region 66 < m_μμ < 102 GeV.

FIG. 2 (color online). The corrected per-event rapidity distribution of measured Z bosons. Bars and boxes represent statistical and systematic uncertainties, respectively. The data are compared to the model distribution shown as a band whose width is the normalization uncertainty.
The fully corrected $p_T$ distributions in five centrality classes are shown in the left panel of Fig. 3 along with the model prediction. The shape as a function of $p_T$ is well reproduced by PYTHIA. The right panel of Fig. 3 shows the ratios of the data to the PYTHIA prediction scaled by $<T_{AA}>$. The ratios are constant within uncertainties for all centrality classes over the range of measured $p_T$.

To further examine the binary collision scaling of the data, the $Z$ boson per-event yields, divided by $<N_{coll}>$, are shown in Fig. 4 as a function of $<N_{part}>$, in several $p_T$ bins. The figure demonstrates that the $Z \rightarrow ee$ and $Z \rightarrow \mu \mu$ results are consistent within their uncertainties for all $p_T$ and centrality regions. Within the statistical significance of the data sample, the $Z$ boson per-event yield obeys binary collision scaling.

The elliptic anisotropy $v_2$ of the $Z$ boson is defined as $v_2 = \langle \cos 2(\phi - \Psi_2) \rangle / \sigma_2$, where $\phi$ is the azimuthal angle of the $Z$ boson momentum vector and $\Psi_2$ is the azimuthal angle of the event plane, the plane containing the momentum vectors of both lead nuclei and measured with resolution $\sigma_2$ [25]. The $v_2$ values measured in the two decay channels are consistent and are combined. The main uncertainty on the $v_2$ measurement arises from the event plane (EP) resolution, which is measured from the difference of $\Psi_2$ determined using the two sides of the FCal at positive and negative rapidities [25]. To ensure that the jets associated with $Z$ boson production do not affect the determination of $\Psi_2$, the EP resolution is also measured comparing the FCal signal on the side which may be affected by a recoiling jet to the one of the unaffected side. A systematic uncertainty of 12 mrad is assigned for possible EP distortion.

The $v_2$ of the $Z$ boson is shown in Fig. 5 as a function of $|y^Z|$, $p_T^Z$, and $<N_{part}>$. The averaged $v_2$ of the $Z$ boson has been measured to be $v_2 = -0.015 \pm 0.018(\text{stat}) \pm 0.014(\text{sys})$, which indicates an isotropic distribution. This observation is an independent measurement consistent with $Z \rightarrow ll$ yields being unaffected by the medium in HI collisions.
Using the ATLAS detector, Z boson production has been measured in \( \text{Pb} + \text{Pb} \) collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \) using 0.15 nb\(^{-1}\) of integrated luminosity collected in the 2011 LHC physics run. Within \( |y| < 2.5 \), and 66 < \( m_{\ell\ell} \) < 102 GeV, a total of 772 and 1223 Z boson candidates are reconstructed in the \( Z \rightarrow ee \) and \( Z \rightarrow \mu\mu \) channels, respectively. The combinatorial background is at the level of 5% in the dielectron channel and 1% for the dimuon channel. The \( Z \) boson production yield integrated over \( |y| < 2.5 \) is consistent between the two channels in all measured \( p_T \) and centrality regions. The momentum and rapidity distributions of the \( Z \) bosons are consistent with PYTHIA simulations of \( Z \) boson production in \( p + p \) collisions scaled to the NNLO cross section and multiplied by \( \langle T_{\text{AA}} \rangle \). Within the uncertainties the \( Z \) boson yield is found to be proportional to \( \langle N_{\text{coll}} \rangle \). The elliptic anisotropy of the \( Z \) boson measured as a function of rapidity, \( p_T^2 \) and \( \langle N_{\text{part}} \rangle \) is consistent with zero within the uncertainties of the measurements.

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[8] The ATLAS reference system is a Cartesian right-handed coordinate system, with the nominal collision point at the origin. The anticlockwise beam direction defines the positive \( z \) axis, while the positive \( x \) axis is defined as pointing from the collision point to the center of the LHC ring and the positive \( y \) axis points upwards. Transverse quantities, such as \( p_T \) and \( E_T \), are defined in the \((y, p_T)\) plane. The azimuthal angle \( \phi \) is measured around the beam axis, and the polar angle \( \theta \) is measured with respect to the \( z \)-axis. The rapidity is given by \( y = \frac{1}{2} \ln \frac{E + P_z}{E - P_z} \) and pseudorapidity is defined as \( \eta = -\ln \tan \frac{\theta}{2} \).

N. I. Zimin,64 R. Zimmermann,21 S. Zimmermann,21 S. Zimmermann,48 M. Ziolkowski,141 R. Zitoun,5
L. Živković,35 V. V. Zmouchko,128,a G. Zobernig,173 A. Zoccoli,20a,20b M. zur Nedden,16
V. Zutshi,106 and L. Zwalinski30

(ATLAS Collaboration)

1School of Chemistry and Physics, University of Adelaide, Adelaide, Australia
2Physics Department, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bDepartment of Physics, Dumlupinar University, Kütahya, Turkey
4cDepartment of Physics, Gazi University, Ankara, Turkey
4dDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
4eTurkish 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
13aInstitute of Physics, University of Belgrade, Belgrade, Serbia
13bYinca 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,
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19aDepartment of Physics, Bogazici University, Istanbul, Turkey
19bDivision of Physics, Dógus University, Istanbul, Turkey
19cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
19dDepartment of Physics, Istanbul Technical University, Istanbul, Turkey
19eINFN Sezione di Bologna, Bologna, Italy
20aDipartimento di Fisica, Università di Bologna, Bologna, Italy
21Physikalisches Institut, University of Bonn, Bonn, Germany
22Department of Physics, Boston University, Boston, Massachusetts, USA
23Department of Physics, Brandeis University, Waltham, Massachusetts, USA
24Universidade 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 do 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
26bUniversity Politehnica Bucharest, Bucharest, Romania
26cWest 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
32aDepartamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
32bDepartamento de Física, Universidad Técnica Federico Santa María, Valparaíso, 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
Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco
Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), 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, Shinsha 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, Kosice, Slovak Republic
School of Physics, University of the Witwatersrand, Johannesburg, South Africa
Department of Physics, Stockholm University, Sweden
The Oskar Klein Centre, Stockholm, Sweden
Departments of Physics & Astronomy, 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, Taipei, 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, 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-CNM), 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
Department of Physics, Yale University, New Haven, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
Also at TRIUMF, Vancouver, British Columbia, Canada.

Also at Department of Physics, California State University, Fresno, CA, USA.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Fermilab, Batavia, IL, USA.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at Department of Physics, UASLP, San Luis Potosi, Mexico.

Also at Università di Napoli Parthenope, Napoli, Italy.

Also at Institute of Particle Physics (IPP), Canada.

Also at Department of Physics, Middle East Technical University, Ankara, Turkey.

Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal.

Also at Department of Physics and Astronomy, University College London, London, United Kingdom.

Also at Department of Physics, University of Cape Town, Cape Town, South Africa.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Department of Physics, University of Coimbra, Coimbra, Portugal.

Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at School of Physics, Shandong University, Shandong, China.

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

Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at California Institute of Technology, Pasadena, CA, USA.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

Also at Nevis Laboratory, Columbia University, Irvington, NY, USA.

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

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.