Study of Z Boson Production in PbPb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

S. Chatrchyan et al.*
(CMS Collaboration)

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A search for Z bosons in the $\mu^{+}\mu^{-}$ decay channel has been performed in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the CMS detector at the LHC, in a 7.2 $\mu$b⁻¹ data sample. The number of opposite-sign muon pairs observed in the 60–120 GeV/$c^2$ invariant mass range is 39, corresponding to a yield per unit of rapidity ($y$) and per minimum bias event of $[33.8 \pm 5.5^{\text{(stat)}} \pm 4.4^{\text{(syst)}}] \times 10^{-8}$, in the $|y| < 2.0$ range. Rapidity, transverse momentum, and centrality dependencies are also measured. The results agree with next-to-leading order QCD calculations, scaled by the number of incoherent nucleon-nucleon collisions.

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The hot and dense matter produced in heavy-ion collisions, often referred to as the quark-gluon plasma (QGP), can be studied in various ways. One approach is to compare measurements made in heavy-ion (AA) collisions to those in proton-proton (pp) and proton- (or deuteron-)nucleus collisions. Another way is to compare in the same AA sample the yields of particles that are modified by the QGP to those of unmodified reference particles. At the Relativistic Heavy Ion Collider (RHIC), direct photons play the reference role [1], although their measurement is complicated by copious background from $\pi^0$ and other decays, and by the existence of a parton fragmentation component which is potentially modified by the medium [2]. At the Large Hadron Collider (LHC) energies, a new and cleaner reference becomes available: the Z boson, decaying into leptons [3,4].

Electroweak boson production is an important benchmark process at hadron colliders. At 7 TeV center-of-mass energy, measurements in pp collisions at the LHC [5,6] are well described by calculations based on higher-order perturbative quantum chromodynamics (pQCD), using recent parton distribution functions (PDFs). In AA collisions, Z boson production can be affected by various initial-state effects, though predictions indicate that these contributions are rather small [3,7–10]. First, the mix of protons and neutrons in AA collisions (the so-called isospin effect) is estimated to modify the Z yield by less than 3% compared to pp collisions [9]. Second, energy loss and multiple scattering of the initial partons can also alter the Z production, by about 3% [10]. The PDFs however are modified in nuclei and a depletion (shadowing) is expected for Z bosons at the LHC, modifying their yield by as much as 20% [9]. Precise measurements of Z production in heavy-ion collisions can therefore help to constrain nuclear PDFs.

Once produced, Z bosons decay within the medium, with a lifetime of 0.1 fm/c. Their leptonic decays are of particular interest since leptons lose negligible energy in the produced medium regardless of its nature (partonic or hadronic) and properties [4]. Dileptons from Z bosons can thus serve as a reference to the processes expected to be heavily modified in the QGP, such as quarkonia production, or the production of an opposite-side jet in Z + jet processes [3,11]. The Z bosons are therefore ideally suited to serve as a standard candle of the initial state in PbPb collisions at the LHC energies.

During the first PbPb LHC run at the end of 2010, at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV, Z bosons were observed by the Compact Muon Solenoid (CMS) experiment. The measurement reported in this Letter is performed with a $55 \times 10^6$ minimum bias (MB) event sample, corresponding to an integrated luminosity of 7.2 $\mu$b⁻¹.

A detailed description of the CMS detector can be found in [12]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass or scintillator hadron calorimeter. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition, CMS has extensive forward calorimetry, in particular, two steel or quartz-fiber Čerenkov, hadron forward (HF) calorimeters, which cover the pseudorapidity range 2.9 < $|\eta|$ < 5.2.

In this analysis, Z bosons are measured through their dimuon decays. The silicon pixel and strip tracker measures charged particle trajectories in the range $|\eta| < 2.5$. It consists of 66 M pixel and 10 M strip detector channels. It provides a distance-to-vertex resolution of $\sim 15 \mu$m in the transverse plane. Muons are detected in the $|\eta| < 2.4$ range, with detection planes based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A matching of the muons to the tracks measured...
in the silicon tracker results in a $p_T$ resolution between 1% and 2%, for $p_T$ values up to 100 GeV/c.

The centrality of AA collisions, i.e., the geometrical overlap of the incoming nuclei, is related to the energy released in the collisions. In CMS, centrality is defined as percentiles of the distribution of the energy deposited in the HF's [13,14]. The centrality classes used in this analysis are 30%–100%, 10%–30%, and 0%–10% (most central), ordered from the lowest to the highest HF energy deposit.

Events are preselected if they contain a reconstructed primary vertex made of at least two tracks, and an offline coincidence of both of the HF's with a total deposited energy of at least 9 GeV. These criteria reduce contributions from single-beam interactions with the environment (e.g., beam-gas and beam halo collisions with the beam pipe), ultraperipheral electromagnetic collisions, and cosmic-ray muons. The acceptance of this selection is (97 ± 3)% of the hadronic inelastic cross section [13].

The events are also selected by the two-level trigger of CMS. At the first hardware level, two muon candidates in the muon detectors are required. At the software-based higher level, two reconstructed tracks in the muon detectors are required, each with a $p_T$ of at least 3 GeV/c. In order to study the dimuon trigger efficiency, events are also collected with a single-muon trigger, requiring $p_T$ > 20 GeV/c. For Z bosons, the trigger efficiency is estimated to be ≈ 94%.

Muon offline reconstruction is seeded with ≈ 99% efficiency by tracks in the muon detectors, called stand-alone muons. These tracks are then matched to tracks reconstructed in the silicon tracker by means of an algorithm optimized for the heavy-ion environment [14,15]. For a muon from Z decays the tracking efficiency is ≈ 85%, less than in the $pp$ case, as the track reconstruction requires more pixel hits to lower the number of combinations, due to the high multiplicity. Global fits of the muon and tracker tracks, called global muons, are used to obtain the results presented in this Letter.

Background muons from cosmic rays and heavy-quark semileptonic decays are rejected by requiring a transverse (longitudinal) impact parameter of less than 0.3 (1.5) mm from the measured vertex. Loose criteria applied on the reconstructed muons result in the dimuon mass spectrum shown in Fig. 1. No muon isolation criteria are applied, as they are expected to have reduced efficiency in the high particle density of the PbPb environment. The fraction of Z decays removed by the applied selection criteria is estimated to be ≈ 2.6%. A conservative upper limit of 4% for the residual background is estimated by extrapolations of various shapes from the low mass region, and no correction is applied. Thirty-nine Z candidates are observed in the mass interval 60–120 GeV/c². Their distribution is consistent with the one from $pp$ data at 7 TeV [6], scaled down to 39 counts and limited to the 60–120 GeV/c² mass range as displayed by the histogram in Fig. 1.

Muons trigger, reconstruction, and selection efficiencies, as well as acceptance, are estimated using the PYTHIA 6.424 simulation [16] with CTEQ6L PDFs [17] and full GEANT4 [18] detector simulation. To take into account the effect of the higher PbPb underlying-event activity, simulated Z decays are embedded in measured PbPb events at the level of detector hits and with generated vertices matched to the measured ones. These events were processed through the trigger emulation and event reconstruction chain. Track characteristics, such as the number of hits and the $x^2$ of the track fit, have similar distributions in data and simulation. The detector acceptance $\alpha$, defined as the fraction of Z bosons produced at rapidity $|y| < 2.0$ that decay into muons with $|\eta| < 2.4$ and $p_T > 10$ GeV/c, is estimated to be ≈ 87%. Within this acceptance, the overall trigger, reconstruction, and identification efficiency $e$ averages to 67%, and varies by less than 10% as a function of centrality.

The individual components of this efficiency are also estimated with a data-driven technique, called tag-and-probe, similar to the one used for the corresponding $pp$ measurement [6]. It consists in counting the Z candidates with and without applying the probed selection on one of the muons: (1) the stand-alone muon reconstruction efficiency is probed with tracker tracks; (2) the silicon tracker reconstruction efficiency is probed with stand-alone muons; (3) the trigger efficiency is probed by testing the trigger response to global muons from a sample triggered by a single-muon requirement. The last is also checked with high-quality reconstructed muons from MB events. In all cases, these data-driven efficiencies agree with those derived from simulation within the statistical uncertainties.

The total systematic uncertainty on the Z yield is estimated to be 1% by summing in quadrature the following contributions. The largest one is associated with the tracking efficiency and taken as the 9.8% precision of the above-mentioned data-driven efficiency determination. Similarly, the uncertainty associated with the dimuon
trigger is 4.5%. The 4% maximum contribution from un-subtracted background is taken as a systematic uncertainty. The uncertainty associated with the muon-pair selection is considered to be equal to the 2.6% loss of events. The MB trigger efficiency is known at the 3% level. The uncertainty coming from the acceptance correction is estimated to be less than 3%, by varying the underlying generated kinematics \((y, p_T)\) beyond reasonable modifications. Other systematic uncertainties are estimated to sum to less than 1.5%.

The yield of \(Z \rightarrow \mu^+ \mu^-\) decays per MB event is defined as \(dN/dy(\vert y \vert < 2.0) = N_Z/(\alpha e N_{MB} \Delta y)\), where \(N_Z = 39\) is the number of dimuons counted in the mass window of 60–120 GeV/\(c^2\), \(N_{MB} = 55 \times 10^6\) is the number of corresponding MB events, corrected for trigger efficiency, \(\alpha\) and \(e\) are the acceptance and overall efficiency, and \(\Delta y = 4.0\) is the rapidity bin width. We find \(dN/dy(\vert y \vert < 2.0) = (33.8 \pm 5.5 \pm 4.4) \times 10^{-8}\), where the first uncertainty is statistical and the second systematic. The analysis described above is repeated after subdividing the data into three bins for each of the following variables: event centrality and \(Z\) boson \(y\) and \(p_T\). The total systematic uncertainty does not vary significantly with these variables and is considered to be constant and dominantly uncorrelated.

In the absence of in-medium modifications, the yield of perturbative processes such as the \(Z\) boson production is supposed to scale with the number of incoherent nucleon-nucleon binary collisions [19]. In order to compare the PbPb measured yields to available \(pp\) cross-section calculations, a scaling factor \(T_{AB}\) is necessary. This nuclear overlap function is equal to the number of elementary nucleon-nucleon binary collisions divided by the elementary \(NN\) cross section, and can be interpreted as the \(NN\) equivalent integrated luminosity per \(AA\) collision, at a given centrality. In units of \(\text{mb}^{-1}\), the average \(T_{AB}\) amounts to 1.45 \(\pm\) 0.18, 11.6 \(\pm\) 0.7, and 23.2 \(\pm\) 1.0, for the centralities ranges 30%–100%, 10%–30%, and 0%–10%, respectively, and 5.66 \(\pm\) 0.35 for MB events. These numbers are computed with a Glauber model calculation [19], using the same parameters as in [13]. The quoted uncertainties are derived by varying within uncertainties the Glauber parameters and the MB trigger and selection efficiency.

The full circles in Fig. 2(a) show the centrality dependence of the \(Z\) yield divided by \(T_{AB}\), while the open square is for MB events. The variable used on the abscissa is the average number of participating nucleons \(N_{\text{part}}\) corresponding to the selected centrality intervals, computed in the same Glauber model. No centrality dependence of the binary-scaled \(Z\) yields is observed in data. A similar result was recently published by the ATLAS collaboration [20].

The normalized yields \((dN/dy)/T_{AB}\) are compared to various calculations: (1) using the nucleon CT10 and modified nuclear EPS09 PDFs [9,21], (2) using MSTW08 PDFs [22] and modeling incoming-parton energy loss [11], and (3) provided by the POWHEG [23].

FIG. 2 (color online). The yields of \(Z \rightarrow \mu^+ \mu^-\) per event: (a) \(dN/dy\) divided by the expected nuclear overlap function \(T_{AB}\) and as a function of event centrality parametrized as the number of participating nucleons \(N_{\text{part}}\), (b) \(dN/dy\) versus the \(Z\) boson \(y\), (c) \(d^2N/dyd\pT\) versus the \(Z\) boson \(p_T\). Data points are located horizontally at average values measured within a given bin. Vertical lines (bands) correspond to statistical (systematic) uncertainties. Theoretical predictions are computed within the same bins as the data, and are described in the text.
generator interfaced with the PYTHIA parton-shower generator and using CTEQ6.6 PDFs [17]. Only a marginal centrality dependence is predicted: the inhomogeneous (i.e., depending on the radial position in nuclei) shadowing is predicted to have negligible impact [7] and the energy-loss prediction drops by 3% from peripheral to central collisions [11].

Figures 2(b) and 2(c) show the differential yields, \( dN/dy \) and \( d^2N/dyd\pt \), as a function of the Z boson \( y \) and \( \pt \). They are compared to the same theoretical calculations as used for the centrality distribution (when available) multiplied by the minimum bias \( T_{AB} \) value. In all bins, no significant deviations from binary-collision scaling are observed.

Nuclear modification factors, \( R_{AA} = dN/(T_{AB} \times d\sigma_{pp}) \), are computed from the AA measured yields \( dN \), the nuclear overlap function \( T_{AB} \), and the \( pp \rightarrow Z \) cross sections \( d\sigma_{pp} \) given by the POWHEG calculation (solid lines on Fig. 2, e.g., \( d\sigma_{pp}/dy = 59.6 \text{ pb} \) in \( |y| < 2.0 \)). The \( R_{AA} \) systematic uncertainty includes \( T_{AB} \) uncertainties, but no uncertainty is assigned to the theoretical \( pp \) cross section. All \( R_{AA} \) values are found compatible with unity. They are reported in Table I, together with the number of observed Z bosons and their yield per event.

In conclusion, the Z boson yield in PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) has been measured inclusively and as a function of rapidity, transverse momentum, and centrality. Within uncertainties, no modification is observed with respect to theoretical next-to-leading order perturbative quantum chromodynamics proton-proton cross sections scaled by the number of elementary nucleon-nucleon collisions. This measurement confirms the validity of the Glauber scaling for perturbative cross sections in nucleus-nucleus collisions at the LHC and establishes the feasibility of carrying out detailed Z physics studies in heavy-ion collisions with the CMS detector. With upcoming PbPb collisions at higher luminosity, the Z boson promises to be a powerful reference tool for final-state heavy-ion related signatures as well as providing a means to study the modifications of the parton distribution functions.

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### Table I

| \( |y| \)       | \( N_Z \)    | \( dN/dy (\times 10^{-8}) \) | \( R_{AA} \) |
|---------------|-------------|-------------------------------|-------------|
| [0, 2.0]      | 39          | 33.8 ± 5.5 ± 4.4              | 1.00 ± 0.16 ± 0.14 |
| [0, 0.5]      | 13          | 38.1 ± 10.7 ± 5.0             | 1.03 ± 0.29 ± 0.15 |
| [0.5, 1.0]    | 12          | 35.6 ± 10.4 ± 4.6             | 0.98 ± 0.29 ± 0.14 |
| [1.0, 2.0]    | 14          | 30.0 ± 8.1 ± 3.9              | 0.97 ± 0.26 ± 0.14 |
| \( \pt (\text{GeV/c}) \) | \( N_Z \)    | \( d^2N/dyd\pt (\times 10^{-8}) \) | \( R_{AA} \) |
| [0, 0.6]      | 11          | 1.65 ± 0.50 ± 0.22            | 0.84 ± 0.26 ± 0.12 |
| [0.6, 1.2]    | 15          | 2.05 ± 0.54 ± 0.27            | 1.32 ± 0.34 ± 0.19 |
| [12, 36]      | 12          | 0.44 ± 0.13 ± 0.06            | 1.06 ± 0.31 ± 0.15 |
| Centrality   | \( N_Z \)    | \( dN/dy (\times 10^{-8}) \) | \( R_{AA} \) |
| [30, 100]%    | 7           | 7.9 ± 3.0 ± 1.0               | 0.92 ± 0.35 ± 0.16 |
| [10, 30]%     | 14          | 59.5 ± 16.0 ± 7.7             | 0.86 ± 0.23 ± 0.12 |
| [0, 10]%      | 18          | 165 ± 40 ± 22                | 1.20 ± 0.29 ± 0.16 |
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1Yerevan Physics Institute, Yerevan, Armenia
2Institut für Hochenergiephysik der ÖAW, Wien, Austria
3National Centre for Particle and High Energy Physics, Minsk, Belarus
4Universiteit Antwerpen, Antwerpen, Belgium
5Vrije Universiteit Brussel, Brussel, Belgium
6Université Libre de Bruxelles, Bruxelles, Belgium
7Ghent University, Ghent, Belgium
8Université Catholique de Louvain, Louvain-la-Neuve, Belgium
9Université de Mons, Mons, Belgium
10Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
12Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
13Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
14University of Sofia, Sofia, Bulgaria
15Institute of High Energy Physics, Beijing, China
16State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
17Universidad de Los Andes, Bogota, Colombia
18Technical University of Split, Split, Croatia
19University of Split, Split, Croatia
20Institute Rudjer Boskovic, Zagreb, Croatia
21University of Cyprus, Nicosia, Cyprus
22Charles University, Prague, Czech Republic
23Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
24National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
25Department of Physics, University of Helsinki, Helsinki, Finland
26Helsinki Institute of Physics, Helsinki, Finland
27Lappeenranta University of Technology, Lappeenranta, Finland
28Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
29DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
30Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
31Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
32Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
33Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
34E. Andronikashvili Institute of Physics, Academy of Science, Tbilisi, Georgia
35Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
36RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
37RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
38RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
39Deutsches Elektronen-Synchrotron, Hamburg, Germany
40University of Hamburg, Hamburg, Germany
41Institut für Experimentelle Kernphysik, Karlsruhe, Germany
42Institute of Nuclear Physics “Demokritos,” Aghia Paraskevi, Greece
43University of Athens, Athens, Greece
44University of Ioannina, Ioannina, Greece
45KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
46Institute of Nuclear Research ATOMKI, Debrecen, Hungary
47University of Debrecen, Debrecen, Hungary
48Panjab University, Chandigarh, India
49University of Delhi, Delhi, India
50Bhabha Atomic Research Centre, Mumbai, India
51Tata Institute of Fundamental Research—EHEP, Mumbai, India
52Tata Institute of Fundamental Research—HECR, Mumbai, India
53Institute for Research and Fundamental Sciences (IPM), Tehran, Iran
54INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy
55INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
56INFN Sezione di Bari, Bari, Italy
57Università di Bari, Bari, Italy
58Politecnico di Bari, Bari, Italy
59INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
60INFN Sezione di Bologna, Bologna, Italy

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55b Università di Bologna, Bologna, Italy
56 INFN Sezione di Catania, Università di Catania, Catania, Italy
56 INFN Sezione di Catania, Catania, Italy
56b Università di Catania, Catania, Italy
57 INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
57a INFN Sezione di Firenze, Firenze, Italy
57b Università di Firenze, Firenze, Italy
58 INFN Laboratori Nazionali di Frascati, Frascati, Italy
59 INFN Sezione di Genova, Genova, Italy
60 INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
60a INFN Sezione di Milano-Bicocca, Milano, Italy
60b Università di Milano-Bicocca, Milano, Italy
61 INFN Sezione di Napoli, Università di Napoli “Federico II,” Napoli, Italy
61a INFN Sezione di Napoli, Napoli, Italy
61b Università di Napoli “Federico II,” Napoli, Italy
62 INFN Sezione di Padova, Università di Padova, Università di Trento (Trento), Padova, Italy
62a INFN Sezione di Padova, Padova, Italy
62b Università di Padova, Padova, Italy
62c Università di Trento (Trento), Padova, Italy
63 INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
63a INFN Sezione di Pavia, Pavia, Italy
63b Università di Pavia, Pavia, Italy
64 INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
64a INFN Sezione di Perugia, Perugia, Italy
64b Università di Perugia, Perugia, Italy
65 INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy
65a INFN Sezione di Pisa, Pisa, Italy
65b Università di Pisa, Pisa, Italy
65c Scuola Normale Superiore di Pisa, Pisa, Italy
66 INFN Sezione di Roma, Università di Roma “La Sapienza,” Roma, Italy
66a INFN Sezione di Roma, Roma, Italy
66b Università di Roma “La Sapienza,” Roma, Italy
67 INFN Sezione di Torino, Università di Torino, Università del Piemonte Orientale (Novara), Torino, Italy
67a INFN Sezione di Torino, Torino, Italy
67b Università di Torino, Torino, Italy
67c Università del Piemonte Orientale (Novara), Torino, Italy
68 INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
68a INFN Sezione di Trieste, Trieste, Italy
68b Università di Trieste, Trieste, Italy
69 Kyungpook National University, Daegu, Korea
70 Kyungpook National University, Daegu, Korea
71 Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
72 Korea University, Seoul, Korea
73 University of Seoul, Seoul, Korea
74 Sungkyunkwan University, Suwon, Korea
75 Vilnius University, Vilnius, Lithuania
76 Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
77 Universidad Iberoamericana, Mexico City, Mexico
78 Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
79 Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
80 University of Auckland, Auckland, New Zealand
81 University of Canterbury, Christchurch, New Zealand
82 National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
83 Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
84 Soltan Institute for Nuclear Studies, Warsaw, Poland
85 Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
86 Joint Institute for Nuclear Research, Dubna, Russia
87 Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
88 Institute for Nuclear Research, Moscow, Russia
89 Institute for Theoretical and Experimental Physics, Moscow, Russia
90 Moscow State University, Moscow, Russia

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91. P.N. Lebedev Physical Institute, Moscow, Russia
92. State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
93. University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
94. Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
95. Universidad Autónoma de Madrid, Madrid, Spain
96. Universidad de Oviedo, Oviedo, Spain
97. Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
98. CERN, European Organization for Nuclear Research, Geneva, Switzerland
99. Paul Scherrer Institut, Villigen, Switzerland
100. Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
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