

# Measurement of Prompt D-Meson Production in p-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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(ALICE Collaboration) Abelev, B.; ...; Antičić, Tome; ...; Gotovac, Sven; ...; Mudnić, Eugen; ...; Planinić, Mirko; ...; ...

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# Measurement of Prompt $D$ -Meson Production in $p$ -Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

B. Abelev *et al.*\*

(ALICE Collaboration)

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The  $p_T$ -differential production cross sections of the prompt charmed mesons  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  and their charge conjugate in the rapidity interval  $-0.96 < y_{\text{cms}} < 0.04$  were measured in  $p$ -Pb collisions at a center-of-mass energy  $\sqrt{s_{NN}} = 5.02$  TeV with the ALICE detector at the LHC. The nuclear modification factor  $R_{p\text{Pb}}$ , quantifying the  $D$ -meson yield in  $p$ -Pb collisions relative to the yield in  $pp$  collisions scaled by the number of binary nucleon-nucleon collisions, is compatible within the 15%–20% uncertainties with unity in the transverse momentum interval  $1 < p_T < 24$  GeV/ $c$ . No significant difference among the  $R_{p\text{Pb}}$  of the four  $D$ -meson species is observed. The results are described within uncertainties by theoretical calculations that include initial-state effects. The measurement adds experimental evidence that the modification of the momentum spectrum of  $D$  mesons observed in Pb-Pb collisions with respect to  $pp$  collisions is due to strong final-state effects induced by hot partonic matter.

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In hadronic collisions, heavy quarks are produced in scattering processes with large momentum transfer. Theoretical predictions based on perturbative quantum chromodynamics (QCD) describe the  $p_T$ -differential charm production cross sections in  $pp$  collisions at different energies [1–3].

The interpretation of heavy-ion collision experimental results is consistent with the formation of a high-density color-deconfined medium, the quark-gluon plasma (QGP) [4,5]. Heavy quarks are sensitive to the transport properties of the medium since they are produced on a short time scale and traverse the medium interacting with its constituents. In Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, the  $D$ -meson nuclear modification factor  $R_{AA}$ , defined as the ratio of the yield in nucleus-nucleus collisions to that observed in the  $pp$  ones scaled by the number of binary nucleon-nucleon collisions, indicates a strong suppression of the  $D$ -meson yield for  $p_T \gtrsim 2$  GeV/ $c$  [6]. The suppression is interpreted as due to in-medium energy loss [7–10]. A complete understanding of the Pb-Pb results requires an understanding of cold-nuclear-matter effects in the initial and final states, which can be accessed by studying  $p$ -Pb collisions assuming that the QGP is not formed in these collisions. In the initial state, the nuclear environment affects the quark and gluon distributions, which are modified in bound nucleons depending on the parton fractional momentum  $x$  and the atomic mass number  $A$  [11,12]. At LHC energies, the most relevant effect is gluon saturation at low  $x$ , which can modify the  $D$ -meson production significantly at

low  $p_T$ . This effect can be described either by means of calculations based on phenomenological modification of the parton distribution functions (PDFs) [13–15] or with the color glass condensate (CGC) effective theory [16–19]. Partons can also lose energy in the initial stages of the collision via initial-state radiation, thus modifying the center-of-mass energy of the partonic system [20], or experience transverse momentum broadening due to multiple soft collisions before the  $c\bar{c}$  pair is produced [21–23]. Recent calculations of parton energy loss in the nuclear medium suggest that the formed  $c\bar{c}$  pair is also affected by these processes in  $p$ -Pb collisions [24]. The presence of final-state effects in small collision systems is suggested by recent studies on long-range correlations of charged hadrons [25–28] in  $p$ -Pb collisions, by results on the species-dependent nuclear modification factors of pions, kaons, and protons [29] in  $d$ -Au collisions and on the larger suppression of the  $\psi'$  meson with respect to the  $J/\psi$  in both  $d$ -Au [30] and  $p$ -Pb [31] collisions.

Previous studies to address cold-nuclear-matter effects in heavy-flavor production were carried out at RHIC by measuring the production of leptons from heavy-flavor hadrons decays in  $d$ -Au collisions at  $\sqrt{s_{NN}} = 200$  GeV [32–34]. PHENIX measured an enhancement of about 40% of the heavy-flavor decay electrons in the 20% most central  $d$ -Au collisions with respect to  $pp$  collisions [32]. A description of this result in terms of hydrodynamic flow in small collision systems was recently proposed [35]. PHENIX also measured an enhancement (suppression) of heavy-flavor decay muons at backward (forward) rapidities in  $d$ -Au collisions [33]. The difference observed in the two rapidity regions exceeds predictions based on initial parton density modifications, suggesting the presence of other cold-nuclear-matter effects. The measurement of fully reconstructed charmed hadrons in  $p$ -Pb collisions at

\* Full author list given at the end of the article.

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the LHC can shed light on the different aspects of cold-nuclear-matter effects mentioned above and, in particular, can clarify whether the observed suppression of  $D$ -meson production in Pb-Pb collisions is a genuine hot QCD matter effect.

In this Letter, we present the measurement of the cross sections and of the nuclear modification factors,  $R_{p\text{Pb}}$ , of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV performed with the ALICE detector [36,37] at the LHC.  $D$  mesons were reconstructed in the rapidity interval  $|y_{\text{lab}}| < 0.5$  via their hadronic decay channels  $D^0 \rightarrow K^- \pi^+$  [with a branching ratio (BR) of  $3.88 \pm 0.05\%$ ],  $D^+ \rightarrow K^- \pi^+ \pi^+$  (BR of  $9.13 \pm 0.19\%$ ),  $D^{*+} \rightarrow D^0 \pi^+$  (BR of  $67.7 \pm 0.5\%$ ), and  $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$  (BR of  $2.28 \pm 0.12\%$ ) [38] and their charge conjugates. Because of the different energies per nucleon of the proton and the lead beams, the nucleon-nucleon center-of-mass frame was moving with a rapidity  $|\Delta y_{NN}| = 0.465$  in the proton beam direction (positive rapidities), leading to the rapidity coverage  $-0.96 < y_{\text{cms}} < 0.04$ .

Charged particles were reconstructed and identified with the central barrel detectors located within a 0.5 T solenoid magnet. Tracks were reconstructed with the inner tracking system (ITS) and the time projection chamber (TPC). Particle identification (PID) was based on the specific energy loss  $dE/dx$  in the TPC gas and on the time of flight from the interaction point to the time of flight (TOF) detector. The analysis was performed by using  $p$ -Pb data collected in 2013 with a minimum-bias trigger that required the arrival of bunches from both directions and coincident signals in both scintillator arrays of the V0 detector, covering the regions  $2.8 < \eta < 5.1$  and  $-3.7 < \eta < -1.7$ . Events were selected off-line by using the timing information from the V0 and the zero-degree calorimeters to remove background due to beam-gas interactions. Only events with a primary vertex reconstructed within  $\pm 10$  cm from the center of the detector along the beam line were considered. About  $10^8$  events, corresponding to an integrated luminosity of  $(48.6 \pm 1.6) \mu\text{b}^{-1}$ , passed the selection criteria.

$D$ -meson selection was based on the reconstruction of decay vertices displaced from the interaction vertex, exploiting the separation of a few hundred micrometers typical of the  $D$ -meson weak decays, as described in Refs. [6,39–41].  $D^0$ ,  $D^+$ , and  $D_s^+$  candidates were defined by using pairs or triplets of tracks with the proper charge sign combination. Tracks were required to have  $|\eta| < 0.8$ ,  $p_T > 0.4$  GeV/ $c$ , at least 70 out of 159 associated space points in the TPC, and at least two out of six hits in the ITS, out of which at least one in the two innermost layers.  $D^{*+}$  candidates were formed by combining  $D^0$  candidates with tracks with  $|\eta| < 0.8$ ,  $p_T > 0.1$  GeV/ $c$ , and at least three associated hits in the ITS. The selection strategy was based on the displacement of the tracks from the interaction vertex and the pointing of the reconstructed  $D$ -meson momentum

to the primary vertex. At low  $p_T$ , further background rejection was obtained by identifying charged kaons with the TPC and TOF by applying cuts in units of resolution ( $\pm 3\sigma$ ) around the expected mean values of  $dE/dx$  and time of flight. For  $D_s^+$  candidate selection, the invariant mass of at least one of the two opposite-charge track pairs was required to be compatible with the mass of the  $\phi$  meson ( $\pm 2\sigma$ ).

The total cross section for hard processes  $\sigma_{p-A}^{\text{hard}}$  in proton-nucleus collisions scales as  $\sigma_{p-A}^{\text{hard}} = A\sigma_{NN}^{\text{hard}}$  [42], where  $\sigma_{NN}^{\text{hard}}$  is the equivalent cross section in  $pp$  collisions. Therefore, the  $R_{p\text{Pb}}$  for prompt  $D$  mesons is given by

$$R_{p\text{Pb}} = \frac{\left(\frac{d\sigma}{dp_T}\right)_{p\text{Pb}}}{A\left(\frac{d\sigma}{dp_T}\right)_{pp}}. \quad (1)$$

The production cross sections of prompt  $D$  mesons (not coming from beauty meson decays) were obtained as (e.g., for  $D^+$ )

$$\left.\frac{d\sigma^{D^+}}{dp_T}\right|_{|y_{\text{lab}}|<0.5} = \frac{f_{\text{prompt}} N_{\text{raw}}^{D^+}|_{|y_{\text{lab}}|<y_{\text{fid}}}}{2\alpha_y \Delta p_T (\text{Acc} \times \epsilon)_{\text{prompt}} \times \text{BR} \times L_{\text{int}}}. \quad (2)$$

$N_{\text{raw}}^{D^+}$  is the raw yield extracted in a given  $p_T$  interval (of width  $\Delta p_T$ ) by means of a fit to the invariant mass distribution of the  $D$ -meson candidates.  $f_{\text{prompt}}$  is the prompt fraction of the raw yield.  $(\text{Acc} \times \epsilon)_{\text{prompt}}$  is the geometrical acceptance multiplied by the reconstruction and selection efficiency of prompt  $D$  mesons. The factor  $\alpha_y = y_{\text{fid}}/0.5$  normalizes the yields, measured in  $|y_{\text{lab}}| < y_{\text{fid}}$ , to one unit of rapidity  $|y_{\text{lab}}| < 0.5$ .  $y_{\text{fid}}$  is the  $p_T$ -dependent fiducial acceptance cut ( $y_{\text{fid}}$  increases from 0.5 at  $p_T = 0$  to 0.8 at  $p_T = 5$  GeV/ $c$  and becomes constant at 0.8 for  $p_T > 5$  GeV/ $c$ ). The cross sections are given for particles; thus, a factor 1/2 was added to take into account that both particles and antiparticles are counted in the raw yield. The integrated luminosity  $L_{\text{int}}$  was computed as  $N_{p\text{Pb,MB}}/\sigma_{p\text{Pb,MB}}$ , where  $N_{p\text{Pb,MB}}$  is the number of  $p$ -Pb collisions passing the minimum-bias trigger condition and  $\sigma_{p\text{Pb,MB}}$  is the cross section of the V0 trigger, which was measured to be  $2.09\text{b} \pm 3.5\%$  (syst) with the  $p$ -Pb van der Meer scan [43]. The minimum-bias trigger is 100% efficient for  $D$  mesons with  $p_T > 1$  GeV/ $c$  and  $|y_{\text{lab}}| < 0.5$ .

The acceptance-times-efficiency ( $\text{Acc} \times \epsilon$ ) corrections were determined by using a Monte Carlo simulation. Proton-lead collisions were produced by using the HIJING v. 1.36 [44] event generator. A  $c\bar{c}$  or  $b\bar{b}$  pair was added in each event by using the PYTHIA v. 6.4.21 [45] generator with Perugia-0 tuning [46]. The generated particles were transported through the ALICE detector by using GEANT3 [47]. The efficiency for  $D$ -meson reconstruction and selection varies from 0.5%–1% for  $p_T < 2$  GeV/ $c$  to 20%–30% for  $p_T > 12$  GeV/ $c$  because of the larger displacement of the decay vertex of high- $p_T$

candidates due to the Lorentz boost. Hence the generated  $D$ -meson spectrum used to calculate the efficiencies was tuned to reproduce the shape given by fixed-order next-to-leading-log resummation (FONLL) [2] calculations at  $\sqrt{s} = 5.02$  TeV in each  $p_T$  interval. The efficiency depends also on the multiplicity of charged particles produced in the collision, since the primary vertex resolution, and consequently the resolution of the topological selection variables, improves with increasing multiplicity. This dependence is different for each meson species and  $p_T$  interval: e.g., the  $D^0$  efficiency in  $5 < p_T < 8$  GeV/ $c$  increases by a factor 1.5 for low multiplicity events until it becomes constant at about 20 reconstructed primary particles. Therefore, the efficiency was calculated by weighting the simulated events according to their charged particle multiplicity in order to reproduce the multiplicity distribution observed in data.

The fraction of prompt  $D$  mesons,  $f_{\text{prompt}}$ , was estimated as in Ref. [6] by using the beauty production cross section from FONLL calculations [2], the  $B \rightarrow D + X$  decay kinematics from the EVTGEN package [48] and the reconstruction and selection efficiency for  $D$  mesons from  $B$  hadron decays. The  $R_{p\text{Pb}}$  of prompt and feed-down  $D$  mesons were assumed to be equal and were varied in the range  $0.9 < R_{p\text{Pb}}^{\text{feed-down}}/R_{p\text{Pb}}^{\text{prompt}} < 1.3$  to evaluate the systematic uncertainties. This range was chosen by considering the predictions from calculations including initial-state effects based on the Eskola-Paukkunen-Salgado 2009 (EPS09) [13] parameterizations of the nuclear modification of the PDF and CGC [16].

The reference  $pp$  cross sections at  $\sqrt{s} = 5.02$  TeV were obtained by a perturbative-QCD-based energy scaling of the  $p_T$ -differential cross sections measured at  $\sqrt{s} = 7$  TeV [40]. The scaling factor for each  $D$ -meson species was determined as the ratio of the cross sections from the FONLL calculations at 5.02 and 7 TeV. The uncertainty on the scaling factor was evaluated by varying the calculation parameters as described in Ref. [49], and it ranges from  $+17.5\%$  at  $p_T = 1$  GeV/ $c$  to about  $\pm 3\%$  for  $p_T > 8$  GeV/ $c$ . In addition, the  $pp$  reference is affected by the uncertainty coming from the 7 TeV measurement ( $\sim 17\%$ ) [40]. Since the  $D^0$  cross section in  $pp$  collisions in the  $1 < p_T < 2$  GeV/ $c$  interval was measured at both 7 and 2.76 TeV, both results were scaled to 5.02 TeV and averaged by considering their relative statistical and systematic uncertainties as weights. Since the current measurement of the ALICE  $D^0$   $pp$  cross section at  $\sqrt{s} = 7$  TeV is limited to  $p_T = 16$  GeV/ $c$ , the cross section was extrapolated to higher  $p_T$  by using the spectrum predicted by FONLL [2] scaled to match  $pp$  data in  $5 < p_T < 16$  GeV/ $c$ . Then the  $D^0$  cross section at 7 TeV in  $16 < p_T < 24$  GeV/ $c$  was scaled to 5.02 TeV.

The systematic uncertainties on the  $D$ -meson cross sections include contributions from yield extraction (from 2% to 17% depending on  $p_T$  and  $D$ -meson species), an

imperfect description of the cut variables in the simulation (from 5% to 8% for  $D^0$ ,  $D^+$ , and  $D^{*+}$  and  $\sim 20\%$  for  $D_s^+$ ), tracking efficiency (3% for each track), simulated  $p_T$  shapes (from 2% to 3% depending on  $p_T$  and  $D$ -meson species), and the subtraction of feed-down  $D$  mesons from  $B$  decays (from 4% and 40% depending on  $p_T$  and  $D$ -meson species). For the  $D^0$  meson, the yield extraction systematic uncertainty also includes the contribution to the raw yield of signal candidates reconstructed by assigning the wrong mass to the final-state hadrons. This contribution, which is strongly reduced by the PID selection, was estimated to be 3% (4%) at low (high)  $p_T$  based on the invariant mass distribution of these candidates in the simulation. Details of the procedure for the systematic uncertainty estimation are reported in Refs. [6,39–41]. The measured cross sections have a global systematic uncertainty due to the determination of the integrated luminosity (3.7% [43]) and to the branching ratio [38]. For the  $R_{p\text{Pb}}$ , the  $pp$  and  $p$ -Pb uncertainties were added in quadrature except for the branching ratio uncertainty, which cancels out in the ratio, and the feed-down contribution, which partially cancels out.

The  $p_T$ -differential production cross sections of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons are shown in Fig. 1. The relative abundances of  $D$  mesons in  $p$ -Pb collisions are compatible within uncertainties with those measured in  $pp$ ,  $ep$ , and  $e^+e^-$  collisions at different energies [41]. The  $R_{p\text{Pb}}$  of the four  $D$ -meson species, shown in Fig. 2, are consistent, and they are compatible with unity within the

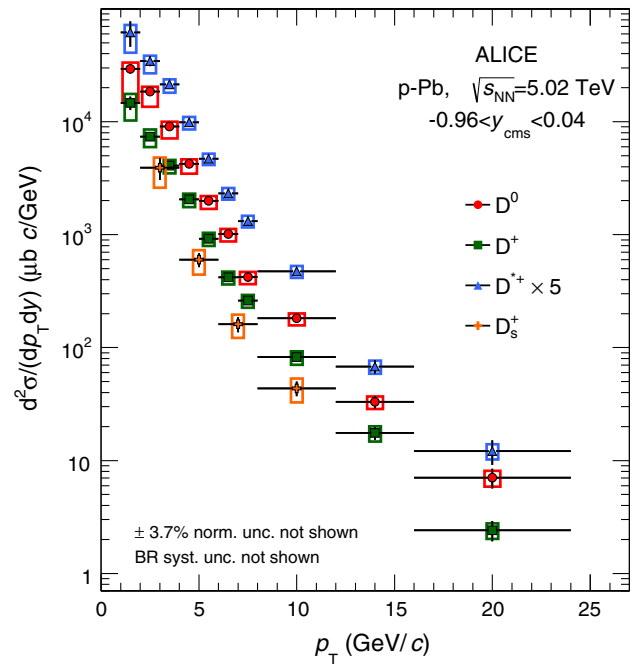


FIG. 1 (color online).  $p_T$ -differential inclusive production cross section of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. Statistical uncertainties (bars) and systematic uncertainties (boxes) are shown.

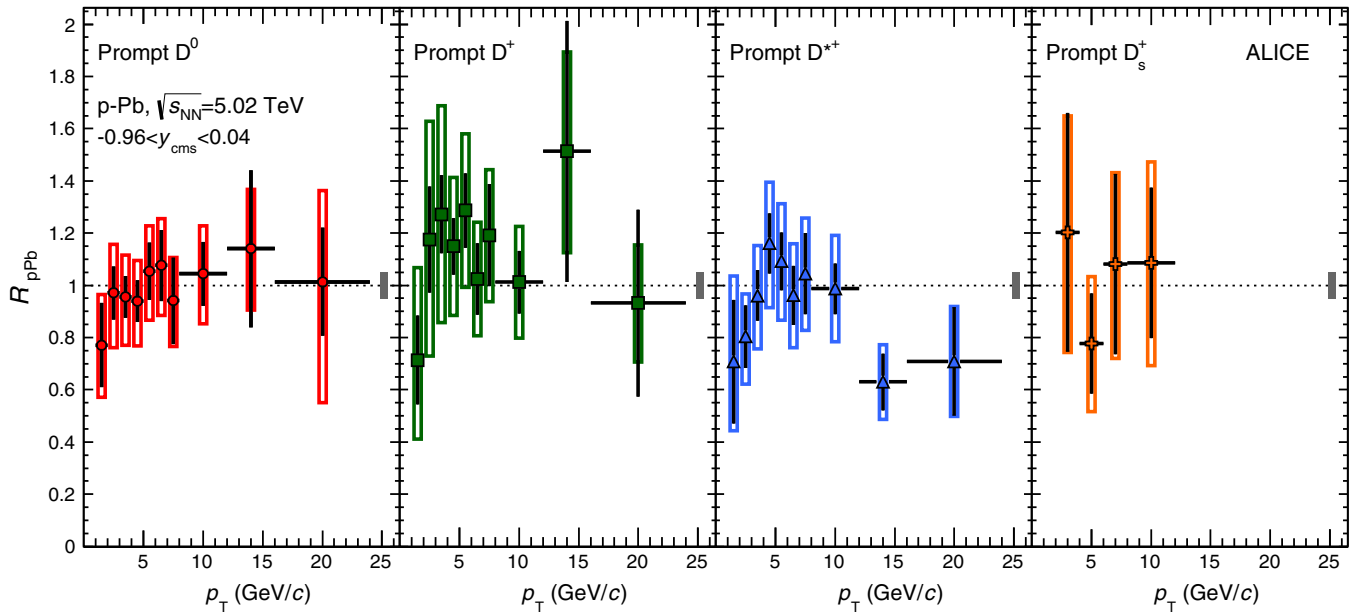


FIG. 2 (color online).  $R_{pPb}$  as a function of  $p_T$  for prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_s^+$  mesons in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. Statistical (bars), systematic (empty boxes), and normalization (full box) uncertainties are shown.

uncertainties in the measured  $p_T$  range.  $D$ -meson production in  $p$ -Pb collisions is consistent within statistical and systematic uncertainties with the binary collision scaling of the production in  $pp$  collisions. Moreover, within the uncertainties, the  $D_s^+$  nuclear modification factor is compatible with that of nonstrange  $D$  mesons. The average of the  $R_{pPb}$  of  $D^0$ ,  $D^+$ , and  $D^{*+}$  in the  $p_T$  range  $1 < p_T < 24$  GeV/ $c$  was calculated by using the relative statistical uncertainties as weights. The systematic error on the average was calculated by propagating the uncertainties through the weighted average, where the contributions from tracking efficiency,  $B$  feed-down correction, and scaling of the  $pp$  reference were taken as fully correlated among the three species. Figure 3 shows the average  $R_{pPb}$  compared to theoretical calculations. Predictions based either on next-to-leading order (NLO) pQCD calculations (Mangano, Nason, and Ridolfi (MNR) [50]) of  $D$ -meson production, including the EPS09 [13] nuclear modification of the CTEQ6M PDF [51], or on calculations based on the color glass condensate [16] can describe the measurement by considering only initial-state effects. Data are also well described by calculations which include cold-nuclear-matter energy loss, nuclear shadowing, and  $k_T$  broadening [9]. The possible effects due to the formation of a hydrodynamically expanding medium as calculated in Ref. [35] are expected to be small in minimum-bias collisions at LHC energies. The present uncertainties of the measurement do not allow any sensitivity to this effect. In Fig. 4, the average  $R_{AA}$  of prompt  $D$  mesons in central (0–20%) and in semiperipheral (40%–80%) Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV [6] is reported along with the average  $R_{pPb}$  of prompt  $D$  mesons in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, showing that

cold-nuclear-matter effects are smaller than the uncertainties for  $p_T \gtrsim 3$  GeV/ $c$ . In addition, as reported in Ref. [6], the same EPS09 nuclear PDF parametrization that describes the  $D$ -meson  $R_{pPb}$  results predicts small initial-state effects (less than 10% for  $p_T > 5$  GeV/ $c$ ) for Pb-Pb collisions. As a consequence, the suppression observed in central Pb-Pb collisions for  $p_T \gtrsim 2$  GeV/ $c$  is predominantly induced by final-state effects, e.g., the charm energy loss in the medium [7–10].

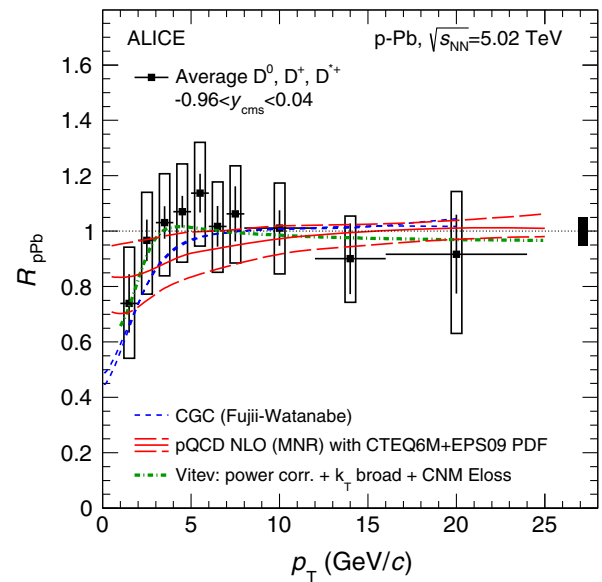


FIG. 3 (color online). Average  $R_{pPb}$  of prompt  $D^0$ ,  $D^+$ , and  $D^{*+}$  mesons as a function of  $p_T$  compared to model calculations. Statistical (bars), systematic (empty boxes), and normalization (full box) uncertainties are shown.

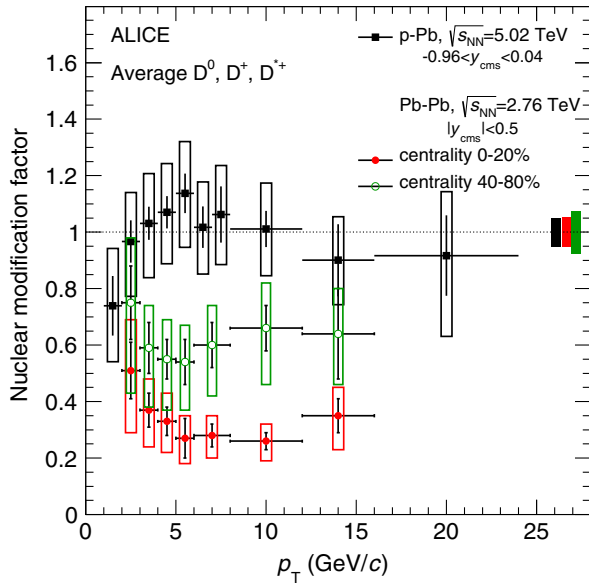


FIG. 4 (color online). Average  $R_{pPb}$  of prompt  $D^0$ ,  $D^+$ , and  $D^{*+}$  mesons as a function of  $p_T$  compared to  $D$ -meson  $R_{AA}$  in the 20% most central and in the 40%–80% Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  TeV from Ref. [6]. Statistical (bars), systematic (empty boxes), and normalization (full boxes) uncertainties are shown.

In summary, we reported the measurement of the  $D$ -meson cross section and nuclear modification factor in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The latter is consistent within uncertainties of about 15%–20% with unity and is compatible with theoretical calculations including gluon saturation. Thus, the suppression of  $D$  mesons with  $p_T \gtrsim 2$  GeV/ $c$  observed in Pb-Pb collisions cannot be explained in terms of initial-state effects but is due to strong final-state effects induced by hot partonic matter.

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B. Abelev,<sup>1</sup> J. Adam,<sup>2</sup> D. Adamová,<sup>3</sup> M. M. Aggarwal,<sup>4</sup> G. Aglieri Rinella,<sup>5</sup> M. Agnello,<sup>6,7</sup> A. Agostinelli,<sup>8</sup> N. Agrawal,<sup>9</sup> Z. Ahammed,<sup>10</sup> N. Ahmad,<sup>11</sup> I. Ahmed,<sup>12</sup> S. U. Ahn,<sup>13</sup> S. A. Ahn,<sup>13</sup> I. Aimo,<sup>6,7</sup> S. Aiola,<sup>14</sup> M. Ajaz,<sup>12</sup> A. Akindinoy,<sup>15</sup> S. N. Alam,<sup>10</sup> D. Aleksandrov,<sup>16</sup> B. Alessandro,<sup>6</sup> D. Alexandre,<sup>17</sup> A. Alici,<sup>18,19</sup> A. Alkin,<sup>20</sup> J. Alme,<sup>21</sup> T. Alt,<sup>22</sup> S. Altinpinar,<sup>23</sup> I. Altsybeev,<sup>24</sup> C. Alves Garcia Prado,<sup>25</sup> C. Andrei,<sup>26</sup> A. Andronic,<sup>27</sup> V. Anguelov,<sup>28</sup> J. Anielski,<sup>29</sup> T. Antičić,<sup>30</sup> F. Antinori,<sup>31</sup> P. Antonioli,<sup>19</sup> L. Aphecetche,<sup>32</sup> H. Appelshäuser,<sup>33</sup> S. Arcelli,<sup>8</sup> N. Armesto,<sup>34</sup> R. Arnaldi,<sup>6</sup> T. Aronsson,<sup>14</sup> I. C. Arsene,<sup>27,35</sup> M. Arslandok,<sup>33</sup> A. Augustinus,<sup>5</sup> R. Averbeck,<sup>27</sup> T. C. Awes,<sup>36</sup> M. D. Azmi,<sup>11,37</sup> M. Bach,<sup>22</sup> A. Badalà,<sup>38</sup> Y. W. Baek,<sup>39,40</sup> S. Bagnasco,<sup>6</sup> R. Bailhache,<sup>33</sup> R. Bala,<sup>41</sup> A. Baldisseri,<sup>42</sup> F. Baltasar Dos Santos Pedrosa,<sup>5</sup> R. C. Baral,<sup>43</sup> R. Barbera,<sup>44</sup> F. Barile,<sup>45</sup> G. G. Barnaföldi,<sup>46</sup> L. S. Barnby,<sup>17</sup> V. Barret,<sup>40</sup> J. Bartke,<sup>47</sup> M. Basile,<sup>8</sup> N. Bastid,<sup>40</sup>

S. Basu,<sup>10</sup> B. Bathen,<sup>29</sup> G. Batigne,<sup>32</sup> B. Batyunya,<sup>48</sup> P. C. Batzing,<sup>35</sup> C. Baumann,<sup>33</sup> I. G. Bearden,<sup>49</sup> H. Beck,<sup>33</sup> C. Bedda,<sup>7</sup> N. K. Behera,<sup>9</sup> I. Belikov,<sup>50</sup> F. Bellini,<sup>8</sup> R. Bellwied,<sup>51</sup> E. Belmont-Moreno,<sup>52</sup> R. Belmont III,<sup>53</sup> V. Belyaev,<sup>54</sup> G. Bencedi,<sup>46</sup> S. Beole,<sup>55</sup> I. Berceanu,<sup>26</sup> A. Bercuci,<sup>26</sup> Y. Berdnikov,<sup>56,57</sup> D. Berenyi,<sup>46</sup> M. E. Berger,<sup>58</sup> R. A. Bertens,<sup>59</sup> D. Berzano,<sup>55</sup> L. Betev,<sup>5</sup> A. Bhasin,<sup>41</sup> I. R. Bhat,<sup>41</sup> A. K. Bhati,<sup>4</sup> B. Bhattacharjee,<sup>60</sup> J. Bhom,<sup>61</sup> L. Bianchi,<sup>55</sup> N. Bianchi,<sup>62</sup> C. Bianchin,<sup>59</sup> J. Bielčík,<sup>2</sup> J. Bielčíková,<sup>3</sup> A. Bilandzic,<sup>49</sup> S. Bjelogrić,<sup>59</sup> F. Blanco,<sup>63</sup> D. Blau,<sup>16</sup> C. Blume,<sup>33</sup> F. Bock,<sup>64,28</sup> A. Bogdanov,<sup>54</sup> H. Bøggild,<sup>49</sup> M. Bogolyubsky,<sup>65</sup> F. V. Böhmer,<sup>58</sup> L. Boldizsár,<sup>46</sup> M. Bombara,<sup>66</sup> J. Book,<sup>33</sup> H. Borel,<sup>42</sup> A. Borissov,<sup>53,67</sup> F. Bossú,<sup>68</sup> M. Botje,<sup>69</sup> E. Botta,<sup>55</sup> S. Böttger,<sup>70</sup> P. Braun-Munzinger,<sup>27</sup> M. Bregant,<sup>25</sup> T. Breitner,<sup>70</sup> T. A. Broker,<sup>33</sup> T. A. Browning,<sup>71</sup> M. Broz,<sup>2</sup> E. Bruna,<sup>6</sup> G. E. Bruno,<sup>45</sup> D. Budnikov,<sup>72</sup> H. Buesching,<sup>33</sup> S. Bufalino,<sup>6</sup> P. Buncic,<sup>5</sup> O. Busch,<sup>28</sup> Z. Buthelezi,<sup>68</sup> D. Caffarri,<sup>5,73</sup> X. Cai,<sup>74</sup> H. Caines,<sup>14</sup> L. Calero Diaz,<sup>62</sup> A. Caliva,<sup>59</sup> E. Calvo Villar,<sup>75</sup> P. Camerini,<sup>76</sup> F. Carena,<sup>5</sup> W. Carena,<sup>5</sup> J. Castillo Castellanos,<sup>42</sup> E. A. R. Casula,<sup>77</sup> V. Catanescu,<sup>26</sup> C. Cavicchioli,<sup>5</sup> C. Ceballos Sanchez,<sup>78</sup> J. Cepila,<sup>2</sup> P. Cerello,<sup>6</sup> B. Chang,<sup>79</sup> S. Chapeland,<sup>5</sup> J. L. Charvet,<sup>42</sup> S. Chattopadhyay,<sup>10</sup> S. Chattopadhyay,<sup>80</sup> V. Chelnokov,<sup>20</sup> M. Cherney,<sup>81</sup> C. Cheshkov,<sup>82</sup> B. Cheynis,<sup>82</sup> V. Chibante Barroso,<sup>5</sup> D. D. Chinellato,<sup>83,51</sup> P. Chochula,<sup>5</sup> M. Chojnacki,<sup>49</sup> S. Choudhury,<sup>10</sup> P. Christakoglou,<sup>69</sup> C. H. Christensen,<sup>49</sup> P. Christiansen,<sup>84</sup> T. Chujo,<sup>61</sup> S. U. Chung,<sup>67</sup> C. Cicalo,<sup>85</sup> L. Cifarelli,<sup>8,18</sup> F. Cindolo,<sup>19</sup> J. Cleymans,<sup>37</sup> F. Colamaria,<sup>45</sup> D. Colella,<sup>45</sup> A. Collu,<sup>77</sup> M. Colocci,<sup>8</sup> G. Conesa Balbastre,<sup>86</sup> Z. Conesa del Valle,<sup>87</sup> M. E. Connors,<sup>14</sup> J. G. Contreras,<sup>88,2</sup> T. M. Cormier,<sup>36,53</sup> Y. Corrales Morales,<sup>55</sup> P. Cortese,<sup>89</sup> I. Cortés Maldonado,<sup>90</sup> M. R. Cosentino,<sup>25</sup> F. Costa,<sup>5</sup> P. Crochet,<sup>40</sup> R. Cruz Albino,<sup>88</sup> E. Cuautle,<sup>91</sup> L. Cunqueiro,<sup>62,5</sup> A. Dainese,<sup>31</sup> R. Dang,<sup>74</sup> A. Danu,<sup>92</sup> D. Das,<sup>80</sup> I. Das,<sup>87</sup> K. Das,<sup>80</sup> S. Das,<sup>93</sup> A. Dash,<sup>83</sup> S. Dash,<sup>9</sup> S. De,<sup>10</sup> H. Delagrangé,<sup>32,†</sup> A. Deloff,<sup>94</sup> E. Dénes,<sup>46</sup> G. D'Erasmus,<sup>45</sup> A. De Caro,<sup>95,18</sup> G. de Cataldo,<sup>96</sup> J. de Cuveland,<sup>22</sup> A. De Falco,<sup>77</sup> D. De Gruttola,<sup>95,18</sup> N. De Marco,<sup>6</sup> S. De Pasquale,<sup>95</sup> R. de Rooij,<sup>59</sup> M. A. Diaz Corchero,<sup>63</sup> T. Dietel,<sup>29,37</sup> P. Dillenseger,<sup>33</sup> R. Divià,<sup>5</sup> D. Di Bari,<sup>45</sup> S. Di Liberto,<sup>97</sup> A. Di Mauro,<sup>5</sup> P. Di Nezza,<sup>62</sup> Ø. Djuvsland,<sup>23</sup> A. Dobrin,<sup>59</sup> T. Dobrowolski,<sup>94</sup> D. Domenicis Gimenez,<sup>25</sup> B. Dönigus,<sup>33</sup> O. Dordic,<sup>35</sup> S. Dørheim,<sup>58</sup> A. K. Dubey,<sup>10</sup> A. Dubla,<sup>59</sup> L. Ducroux,<sup>82</sup> P. Dupieux,<sup>40</sup> A. K. Dutta Majumdar,<sup>80</sup> T. E. Hilden,<sup>98</sup> R. J. Ehlers,<sup>14</sup> D. Elia,<sup>96</sup> H. Engel,<sup>70</sup> B. Erasmus,<sup>5,32</sup> H. A. Erdal,<sup>21</sup> D. Eschweiler,<sup>22</sup> B. Espagnon,<sup>87</sup> M. Esposito,<sup>5</sup> M. Estienne,<sup>32</sup> S. Esumi,<sup>61</sup> D. Evans,<sup>17</sup> S. Evdokimov,<sup>65</sup> D. Fabris,<sup>31</sup> J. Faivre,<sup>86</sup> D. Falchieri,<sup>8</sup> A. Fantoni,<sup>62</sup> M. Fasel,<sup>28</sup> D. Fehlker,<sup>23</sup> L. Feldkamp,<sup>29</sup> D. Felea,<sup>92</sup> A. Feliciello,<sup>6</sup> G. Feofilov,<sup>24</sup> J. Ferencei,<sup>3</sup> A. Fernández Téllez,<sup>90</sup> E. G. Ferreira,<sup>34</sup> A. Ferretti,<sup>55</sup> A. Festanti,<sup>73</sup> J. Figiel,<sup>47</sup> M. A. S. Figueredo,<sup>99</sup> S. Filchagin,<sup>72</sup> D. Finogeev,<sup>100</sup> F. M. Fionda,<sup>45</sup> E. M. Fiore,<sup>45</sup> E. Floratos,<sup>101</sup> M. Floris,<sup>5</sup> S. Foertsch,<sup>68</sup> P. Foka,<sup>27</sup> S. Fokin,<sup>16</sup> E. Fragiaco,<sup>102</sup> A. Francescon,<sup>5,73</sup> U. Frankenfeld,<sup>27</sup> U. Fuchs,<sup>5</sup> C. Furget,<sup>86</sup> M. Fusco Girard,<sup>95</sup> J. J. Gaardhøje,<sup>49</sup> M. Gagliardi,<sup>55</sup> A. M. Gago,<sup>75</sup> M. Gallio,<sup>55</sup> D. R. Gangadharan,<sup>103,64</sup> P. Ganoti,<sup>36,101</sup> C. Garabatos,<sup>27</sup> E. Garcia-Solis,<sup>104</sup> C. Gargiulo,<sup>5</sup> I. Garishvili,<sup>1</sup> J. Gerhard,<sup>22</sup> M. Germain,<sup>32</sup> A. Gheata,<sup>5</sup> M. Gheata,<sup>5,92</sup> B. Ghidini,<sup>45</sup> P. Ghosh,<sup>10</sup> S. K. Ghosh,<sup>93</sup> P. Gianotti,<sup>62</sup> P. Giubellino,<sup>5</sup> E. Gladysz-Dziadus,<sup>47</sup> P. Glässel,<sup>28</sup> A. Gomez Ramirez,<sup>70</sup> P. González-Zamora,<sup>63</sup> S. Gorbunov,<sup>22</sup> L. Görlich,<sup>47</sup> S. Gotovac,<sup>105</sup> L. K. Graczykowski,<sup>106</sup> A. Grelli,<sup>59</sup> A. Grigoras,<sup>5</sup> C. Grigoras,<sup>5</sup> V. Grigoriev,<sup>54</sup> A. Grigoryan,<sup>107</sup> S. Grigoryan,<sup>48</sup> B. Grinyov,<sup>20</sup> N. Grion,<sup>102</sup> J. F. Grosse-Oetringhaus,<sup>5</sup> J.-Y. Grossiord,<sup>82</sup> R. Grosso,<sup>5</sup> F. Guber,<sup>100</sup> R. Guernane,<sup>86</sup> B. Guerzoni,<sup>8</sup> M. Guilbaud,<sup>82</sup> K. Gulbrandsen,<sup>49</sup> H. Gulkanyan,<sup>107</sup> M. Gumbo,<sup>37</sup> T. Gunji,<sup>108</sup> A. Gupta,<sup>41</sup> R. Gupta,<sup>41</sup> K. H. Khan,<sup>12</sup> R. 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Jacobs,<sup>64</sup> C. Jahnke,<sup>25</sup> H. J. Jang,<sup>13</sup> M. A. Janik,<sup>106</sup> P. H. S. Y. Jayarathna,<sup>51</sup> C. Jena,<sup>73</sup> S. Jena,<sup>51</sup> R. T. Jimenez Bustamante,<sup>91</sup> P. G. Jones,<sup>17</sup> H. Jung,<sup>39</sup> A. Jusko,<sup>17</sup> V. Kadyshchikov,<sup>48</sup> S. Kalcher,<sup>22</sup> P. Kalinak,<sup>112</sup> A. Kalweit,<sup>5</sup> J. Kamin,<sup>33</sup> J. H. Kang,<sup>113</sup> V. Kaplin,<sup>54</sup> S. Kar,<sup>10</sup> A. Karasu Uysal,<sup>114</sup> O. Karavichev,<sup>100</sup> T. Karavicheva,<sup>100</sup> E. Karpechev,<sup>100</sup> U. Keschull,<sup>70</sup> R. Keidel,<sup>115</sup> D. L. D. Keijdener,<sup>59</sup> M. M. Khan,<sup>116,11</sup> P. Khan,<sup>80</sup> S. A. Khan,<sup>10</sup> A. Khanzadeev,<sup>57</sup> Y. Kharlov,<sup>65</sup> B. Kileng,<sup>21</sup> B. Kim,<sup>113</sup> D. W. Kim,<sup>13,39</sup> D. J. Kim,<sup>79</sup> J. S. Kim,<sup>39</sup> M. Kim,<sup>39</sup> M. Kim,<sup>113</sup> S. 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Kuijter,<sup>69</sup> I. Kulakov,<sup>33</sup> J. Kumar,<sup>9</sup> P. Kurashvili,<sup>94</sup> A. Kurepin,<sup>100</sup> A. B. Kurepin,<sup>100</sup> A. Kuryakin,<sup>72</sup> S. Kushpil,<sup>3</sup> M. J. Kweon,<sup>120,28</sup> Y. Kwon,<sup>113</sup>



P. Ladron de Guevara,<sup>91</sup> C. Lagana Fernandes,<sup>25</sup> I. Lakomov,<sup>87</sup> R. Langoy,<sup>121</sup> C. Lara,<sup>70</sup> A. Lardeux,<sup>32</sup> A. Lattuca,<sup>55</sup> S. L. La Pointe,<sup>59,6</sup> P. La Rocca,<sup>44</sup> R. Lea,<sup>76</sup> L. Leardini,<sup>28</sup> G. R. Lee,<sup>17</sup> I. Legrand,<sup>5</sup> J. Lehnert,<sup>33</sup> R. C. Lemmon,<sup>122</sup> V. Lenti,<sup>96</sup> E. Leogrande,<sup>59</sup> M. Leoncino,<sup>55</sup> I. León Monzón,<sup>123</sup> P. Lévai,<sup>46</sup> S. Li,<sup>74,40</sup> J. Lien,<sup>121</sup> R. Lietava,<sup>17</sup> S. Lindal,<sup>35</sup> V. Lindenstruth,<sup>22</sup> C. Lippmann,<sup>27</sup> M. A. Lisa,<sup>103</sup> H. M. Ljunggren,<sup>84</sup> D. F. Lodato,<sup>59</sup> P. I. Loenne,<sup>23</sup> V. R. Loggins,<sup>53</sup> V. Loginov,<sup>54</sup> D. Lohner,<sup>28</sup> C. Loizides,<sup>64</sup> X. Lopez,<sup>40</sup> E. López Torres,<sup>78</sup> X.-G. Lu,<sup>28</sup> P. Luetig,<sup>33</sup> M. Lunardon,<sup>73</sup> G. Luparello,<sup>59,76</sup> C. Luzzi,<sup>5</sup> R. Ma,<sup>14</sup> A. Maevskaya,<sup>100</sup> M. Mager,<sup>5</sup> D. P. Mahapatra,<sup>43</sup> S. M. Mahmood,<sup>35</sup> A. Maire,<sup>28,50</sup> R. D. Majka,<sup>14</sup> M. Malaev,<sup>57</sup> I. Maldonado Cervantes,<sup>91</sup> L. Malinina,<sup>124,48</sup> D. Mal'Kevich,<sup>15</sup> P. Malzacher,<sup>27</sup> A. Mamonov,<sup>72</sup> L. Manceau,<sup>6</sup> V. Manko,<sup>16</sup> F. Manso,<sup>40</sup> V. Manzari,<sup>96</sup> M. Marchisone,<sup>40,55</sup> J. Mareš,<sup>110</sup> G. V. Margagliotti,<sup>76</sup> A. Margotti,<sup>19</sup> A. Marín,<sup>27</sup> C. Markert,<sup>118</sup> M. Marquard,<sup>33</sup> I. Martashvili,<sup>125</sup> N. A. Martin,<sup>27</sup> P. Martinengo,<sup>5</sup> M. I. Martínez,<sup>90</sup> G. Martínez García,<sup>32</sup> J. Martin Blanco,<sup>32</sup> Y. Martynov,<sup>20</sup> A. Mas,<sup>32</sup> S. Masciocchi,<sup>27</sup> M. Maserà,<sup>55</sup> A. Masoni,<sup>85</sup> L. Massacrier,<sup>32</sup> A. Mastroserio,<sup>45</sup> A. Matyja,<sup>47</sup> C. Mayer,<sup>47</sup> J. Mazer,<sup>125</sup> M. A. Mazzoni,<sup>97</sup> F. Meddi,<sup>126</sup> A. Menchaca-Rocha,<sup>52</sup> E. Meninno,<sup>95</sup> J. Mercado Pérez,<sup>28</sup> M. Meres,<sup>127</sup> Y. Miake,<sup>61</sup> K. Mikhaylov,<sup>48,15</sup> L. Milano,<sup>5</sup> J. Milosevic,<sup>128,35</sup> A. Mischke,<sup>59</sup> A. N. Mishra,<sup>129</sup> D. Miśkowiec,<sup>27</sup> J. Mitra,<sup>10</sup> C. M. Mitu,<sup>92</sup> J. Mlynarz,<sup>53</sup> N. Mohammadi,<sup>59</sup> B. Mohanty,<sup>130,10</sup> L. Molnar,<sup>50</sup> L. Montaña Zetina,<sup>88</sup> E. Montes,<sup>63</sup> M. Morando,<sup>73</sup> D. A. Moreira De Godoy,<sup>25</sup> S. Moretto,<sup>73</sup> A. Morreale,<sup>32</sup> A. Morsch,<sup>5</sup> V. Muccifora,<sup>62</sup> E. Mudnic,<sup>105</sup> D. Mühlheim,<sup>29</sup> S. Muhuri,<sup>10</sup> M. Mukherjee,<sup>10</sup> H. Müller,<sup>5</sup> M. G. Munhoz,<sup>25</sup> S. Murray,<sup>37</sup> L. Musa,<sup>5</sup> J. Musinsky,<sup>112</sup> B. K. Nandi,<sup>9</sup> R. Nania,<sup>19</sup> E. Nappi,<sup>96</sup> C. Nattrass,<sup>125</sup> K. Nayak,<sup>130</sup> T. K. Nayak,<sup>10</sup> S. Nazarenko,<sup>72</sup> A. Nedosekin,<sup>15</sup> M. Nicassio,<sup>27</sup> M. Niculescu,<sup>5,92</sup> B. S. Nielsen,<sup>49</sup> S. Nikolaev,<sup>16</sup> S. Nikulin,<sup>16</sup> V. Nikulin,<sup>57</sup> B. S. Nilsen,<sup>81</sup> F. Noferini,<sup>18,19</sup> P. Nomokonov,<sup>48</sup> G. Nooren,<sup>59</sup> J. Norman,<sup>99</sup> A. Nyanin,<sup>16</sup> J. Nystrand,<sup>23</sup> H. Oeschler,<sup>28</sup> S. Oh,<sup>14</sup> S. K. Oh,<sup>131,39</sup> A. Okatan,<sup>114</sup> L. Olah,<sup>46</sup> J. Oleniacz,<sup>106</sup> A. C. Oliveira Da Silva,<sup>25</sup> J. Onderwaater,<sup>27</sup> C. Oppedisano,<sup>6</sup> A. Ortiz Velasquez,<sup>91,84</sup> A. Oskarsson,<sup>84</sup> J. Otwinowski,<sup>47,27</sup> K. Oyama,<sup>28</sup> M. Ozdemir,<sup>33</sup> P. Sahoo,<sup>129</sup> Y. Pachmayer,<sup>28</sup> M. Pachr,<sup>2</sup> P. Pagano,<sup>95</sup> G. Paic,<sup>91</sup> F. Painke,<sup>22</sup> C. Pajares,<sup>34</sup> S. K. Pal,<sup>10</sup> A. Palmeri,<sup>38</sup> D. Pant,<sup>9</sup> V. Papikyan,<sup>107</sup> G. S. Pappalardo,<sup>38</sup> P. Pareek,<sup>129</sup> W. J. Park,<sup>27</sup> S. Parmar,<sup>4</sup> A. Passfeld,<sup>29</sup> D. I. Patalakha,<sup>65</sup> V. Paticchio,<sup>96</sup> B. Paul,<sup>80</sup> T. Pawlak,<sup>106</sup> T. Peitzmann,<sup>59</sup> H. Pereira Da Costa,<sup>42</sup> E. Pereira De Oliveira Filho,<sup>25</sup> D. Peresunko,<sup>16</sup> C. E. Pérez Lara,<sup>69</sup> A. Pesci,<sup>19</sup> V. Peskov,<sup>33</sup> Y. Pestov,<sup>132</sup> V. Petráček,<sup>2</sup> M. Petran,<sup>2</sup> M. Petris,<sup>26</sup> M. Petrovici,<sup>26</sup> C. Petta,<sup>44</sup> S. Piano,<sup>102</sup> M. Pikna,<sup>127</sup> P. Pillot,<sup>32</sup> O. Pinazza,<sup>19,5</sup> L. Pinsky,<sup>51</sup> D. B. Piyarathna,<sup>51</sup> M. Płoskoń,<sup>64</sup> M. Planinic,<sup>133,30</sup> J. Pluta,<sup>106</sup> S. Pochybova,<sup>46</sup> P. L. M. Podesta-Lerma,<sup>123</sup> M. G. Poghosyan,<sup>81,5</sup> E. H. O. Pohjoisaho,<sup>98</sup> B. Polichtchouk,<sup>65</sup> N. Poljak,<sup>30,133</sup> A. Pop,<sup>26</sup> S. Porteboeuf-Houssais,<sup>40</sup> J. Porter,<sup>64</sup> B. Potukuchi,<sup>41</sup> S. K. Prasad,<sup>53,93</sup> R. Preghenella,<sup>19,18</sup> F. Prino,<sup>6</sup> C. A. Pruneau,<sup>53</sup> I. Pshenichnov,<sup>100</sup> G. Puddu,<sup>77</sup> P. Pujahari,<sup>53</sup> V. Punin,<sup>72</sup> J. Putschke,<sup>53</sup> H. Qvigstad,<sup>35</sup> A. Rachevski,<sup>102</sup> S. Raha,<sup>93</sup> J. Rak,<sup>79</sup> A. Rakotozafindrabe,<sup>42</sup> L. Ramello,<sup>89</sup> R. Raniwala,<sup>134</sup> S. Raniwala,<sup>134</sup> S. S. Räsänen,<sup>98</sup> B. T. Rascanu,<sup>33</sup> D. Rathee,<sup>4</sup> A. W. Rauf,<sup>12</sup> V. Razazi,<sup>77</sup> K. F. Read,<sup>125</sup> J. S. Real,<sup>86</sup> K. Redlich,<sup>135,94</sup> R. J. Reed,<sup>53,14</sup> A. Rehman,<sup>23</sup> P. Reichelt,<sup>33</sup> M. Reicher,<sup>59</sup> F. Reidt,<sup>5</sup> R. Renfordt,<sup>33</sup> A. R. Reolon,<sup>62</sup> A. Reshetin,<sup>100</sup> F. Rettig,<sup>22</sup> J.-P. Revol,<sup>5</sup> K. Reygers,<sup>28</sup> V. Riabov,<sup>57</sup> R. A. Ricci,<sup>136</sup> T. Richert,<sup>84</sup> M. Richter,<sup>35</sup> P. Riedler,<sup>5</sup> W. Riegler,<sup>5</sup> F. Riggi,<sup>44</sup> A. Rivetti,<sup>6</sup> E. Rocco,<sup>59</sup> M. Rodríguez Cahuantzi,<sup>90</sup> A. Rodríguez Manso,<sup>69</sup> K. Røed,<sup>35</sup> E. Rogochaya,<sup>48</sup> S. Rohni,<sup>41</sup> D. Rohr,<sup>22</sup> D. Röhrich,<sup>23</sup> R. Romita,<sup>122,99</sup> F. Ronchetti,<sup>62</sup> L. Ronflette,<sup>32</sup> P. Rosnet,<sup>40</sup> A. Rossi,<sup>5</sup> F. Roukoutakis,<sup>101</sup> A. Roy,<sup>129</sup> C. Roy,<sup>50</sup> P. Roy,<sup>80</sup> A. J. Rubio Montero,<sup>63</sup> R. Rui,<sup>76</sup> R. Russo,<sup>55</sup> E. Ryabinkin,<sup>16</sup> Y. Ryabov,<sup>57</sup> A. Rybicki,<sup>47</sup> S. Sadovsky,<sup>65</sup> K. Šafařík,<sup>5</sup> B. Sahlmuller,<sup>33</sup> R. Sahoo,<sup>129</sup> P. K. Sahu,<sup>43</sup> J. Saini,<sup>10</sup> S. Sakai,<sup>62,64</sup> C. A. Salgado,<sup>34</sup> J. Salzwedel,<sup>103</sup> S. Sambyal,<sup>41</sup> V. Samsonov,<sup>57</sup> X. Sanchez Castro,<sup>50</sup> F. J. Sánchez Rodríguez,<sup>123</sup> L. Šándor,<sup>112</sup> A. Sandoval,<sup>52</sup> M. Sano,<sup>61</sup> G. Santagati,<sup>44</sup> D. Sarkar,<sup>10</sup> E. Scapparone,<sup>19</sup> F. Scarlassara,<sup>73</sup> R. P. Scharenberg,<sup>71</sup> C. Schiaua,<sup>26</sup> R. Schicker,<sup>28</sup> C. Schmidt,<sup>27</sup> H. R. Schmidt,<sup>109</sup> S. Schuchmann,<sup>33</sup> J. Schukraft,<sup>5</sup> M. Schulc,<sup>2</sup> T. Schuster,<sup>14</sup> Y. Schutz,<sup>32,5</sup> K. Schwarz,<sup>27</sup> K. Schweda,<sup>27</sup> G. Scioli,<sup>8</sup> E. Scomparin,<sup>6</sup> R. Scott,<sup>125</sup> G. Segato,<sup>73</sup> J. E. Seger,<sup>81</sup> Y. Sekiguchi,<sup>108</sup> I. Selyuzhenkov,<sup>27</sup> J. Seo,<sup>67</sup> E. Serradilla,<sup>63,52</sup> A. Sevcenco,<sup>92</sup> A. Shabetai,<sup>32</sup> G. Shabratova,<sup>48</sup> R. Shahoyan,<sup>5</sup> A. Shangaraev,<sup>65</sup> N. Sharma,<sup>125</sup> S. Sharma,<sup>41</sup> K. Shigaki,<sup>137</sup> K. Shtejer,<sup>55</sup> Y. Sibiriak,<sup>16</sup> S. Siddhanta,<sup>85</sup> T. Siemiarz, <sup>94</sup> D. Silvermyr,<sup>36</sup> C. Silvestre,<sup>86</sup> G. Simatovic,<sup>133</sup> R. Singaraju,<sup>10</sup> R. Singh,<sup>41</sup> S. Singha,<sup>10,130</sup> V. Singhal,<sup>10</sup> B. C. Sinha,<sup>10</sup> T. Sinha,<sup>80</sup> B. Sitar,<sup>127</sup> M. Sitta,<sup>89</sup> T. B. Skaali,<sup>35</sup> K. Skjerdal,<sup>23</sup> M. Slupecki,<sup>79</sup> N. Smirnov,<sup>14</sup> R. J. M. Snellings,<sup>59</sup> C. Sjøgaard,<sup>84</sup> R. Soltz,<sup>1</sup> J. Song,<sup>67</sup> M. Song,<sup>113</sup> F. Soramel,<sup>73</sup> S. Sorensen,<sup>125</sup> M. Spacek,<sup>2</sup> E. Spiriti,<sup>62</sup> I. Sputowska,<sup>47</sup> M. Spyropoulou-Stassinaki,<sup>101</sup> B. K. Srivastava,<sup>71</sup> J. Stachel,<sup>28</sup> I. Stan,<sup>92</sup> G. Stefanek,<sup>94</sup> M. Steinpreis,<sup>103</sup> E. Stenlund,<sup>84</sup> G. Steyn,<sup>68</sup> J. H. Stiller,<sup>28</sup> D. Stocco,<sup>32</sup> M. Stolpovskiy,<sup>65</sup> P. Strmen,<sup>127</sup> A. A. P. Suaide,<sup>25</sup> T. Sugitate,<sup>137</sup> C. Suire,<sup>87</sup> M. Suleymanov,<sup>12</sup> R. Sultanov,<sup>15</sup> M. Šumbera,<sup>3</sup> T. Susa,<sup>30</sup> T. J. M. Symons,<sup>64</sup> A. Szabo,<sup>127</sup> A. Szanto de Toledo,<sup>25</sup> I. Szarka,<sup>127</sup> A. Szczepankiewicz,<sup>5</sup> M. Szymanski,<sup>106</sup> J. Takahashi,<sup>83</sup> M. A. Tangaro,<sup>45</sup> J. D. Tapia Takaki,<sup>138,87</sup> A. Tarantola Peloni,<sup>33</sup> A. Tarazona Martinez,<sup>5</sup>

M. G. Tarzila,<sup>26</sup> A. Tauro,<sup>5</sup> G. Tejada Muñoz,<sup>90</sup> A. Telesca,<sup>5</sup> C. Terrevoli,<sup>77</sup> J. Thäder,<sup>27</sup> D. Thomas,<sup>59</sup> R. Tieulent,<sup>82</sup> A. R. Timmins,<sup>51</sup> A. Toia,<sup>33,31</sup> V. Trubnikov,<sup>20</sup> W. H. Trzaska,<sup>79</sup> T. Tsuji,<sup>108</sup> A. Tumkin,<sup>72</sup> R. Turrisi,<sup>31</sup> T. S. Tveter,<sup>35</sup> K. Ullaland,<sup>23</sup> A. Uras,<sup>82</sup> G. L. Usai,<sup>77</sup> M. Vajzer,<sup>3</sup> M. Vala,<sup>112,48</sup> L. Valencia Palomo,<sup>40</sup> S. Vallero,<sup>55,28</sup> P. Vande Vyvre,<sup>5</sup> J. Van Der Maarel,<sup>59</sup> J. W. Van Hoorne,<sup>5</sup> M. van Leeuwen,<sup>59</sup> A. Vargas,<sup>90</sup> M. Vargyas,<sup>79</sup> R. Varma,<sup>9</sup> M. Vasileiou,<sup>101</sup> A. Vasiliev,<sup>16</sup> V. Vechernin,<sup>24</sup> M. Veldhoen,<sup>59</sup> A. Velure,<sup>23</sup> M. Venaruzzo,<sup>76,136</sup> E. Vercellin,<sup>55</sup> S. Vergara Limón,<sup>90</sup> R. Vernet,<sup>139</sup> M. Verweij,<sup>53</sup> L. Vickovic,<sup>105</sup> G. Viesti,<sup>73</sup> J. Viinikainen,<sup>79</sup> Z. Vilakazi,<sup>68</sup> O. Villalobos Baillie,<sup>17</sup> A. Vinogradov,<sup>16</sup> L. Vinogradov,<sup>24</sup> Y. Vinogradov,<sup>72</sup> T. Virgili,<sup>95</sup> Y. P. Viyogi,<sup>10</sup> A. Vodopyanov,<sup>48</sup> M. A. Völkl,<sup>28</sup> K. Voloshin,<sup>15</sup> S. A. Voloshin,<sup>53</sup> G. Volpe,<sup>5</sup> B. von Haller,<sup>5</sup> I. Vorobyev,<sup>24</sup> D. Vranic,<sup>27,5</sup> J. Vrláková,<sup>66</sup> B. Vulpescu,<sup>40</sup> A. Vyushin,<sup>72</sup> B. Wagner,<sup>23</sup> J. Wagner,<sup>27</sup> V. Wagner,<sup>2</sup> M. Wang,<sup>74,32</sup> Y. Wang,<sup>28</sup> D. Watanabe,<sup>61</sup> M. Weber,<sup>5,51</sup> J. P. Wessels,<sup>29</sup> U. Westerhoff,<sup>29</sup> J. Wiechula,<sup>109</sup> J. Wikne,<sup>35</sup> M. Wilde,<sup>29</sup> G. Wilk,<sup>94</sup> J. Wilkinson,<sup>28</sup> M. C. S. Williams,<sup>19</sup> B. Windelband,<sup>28</sup> M. Winn,<sup>28</sup> C. G. Yaldo,<sup>53</sup> Y. Yamaguchi,<sup>108</sup> H. Yang,<sup>59</sup> P. Yang,<sup>74</sup> S. Yang,<sup>23</sup> S. Yano,<sup>137</sup> S. Yasnopolskiy,<sup>16</sup> J. Yi,<sup>67</sup> Z. Yin,<sup>74</sup> I.-K. Yoo,<sup>67</sup> I. Yushmanov,<sup>16</sup> V. Zaccolo,<sup>49</sup> C. Zach,<sup>2</sup> A. Zaman,<sup>12</sup> C. Zampolli,<sup>19</sup> S. Zaporozhets,<sup>48</sup> A. Zarochentsev,<sup>24</sup> P. Závada,<sup>110</sup> N. Zaviyalov,<sup>72</sup> H. Zbroszczyk,<sup>106</sup> I. S. Zgura,<sup>92</sup> M. Zhalov,<sup>57</sup> H. Zhang,<sup>74</sup> X. Zhang,<sup>74,64</sup> Y. Zhang,<sup>74</sup> C. Zhao,<sup>35</sup> N. Zhigareva,<sup>15</sup> D. Zhou,<sup>74</sup> F. Zhou,<sup>74</sup> Y. Zhou,<sup>59</sup> Z. Zhou,<sup>23</sup> H. Zhu,<sup>74</sup> J. Zhu,<sup>74</sup> X. Zhu,<sup>74</sup> A. Zichichi,<sup>18,8</sup> A. Zimmermann,<sup>28</sup> M. B. Zimmermann,<sup>29,5</sup> G. Zinovjev,<sup>20</sup> Y. Zoccarato,<sup>82</sup> and M. Zyzak<sup>33</sup>

(ALICE Collaboration)

<sup>1</sup>Lawrence Livermore National Laboratory, Livermore, California, USA

<sup>2</sup>Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic

<sup>3</sup>Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic

<sup>4</sup>Physics Department, Panjab University, Chandigarh, India

<sup>5</sup>European Organization for Nuclear Research (CERN), Geneva, Switzerland

<sup>6</sup>Sezione INFN, Turin, Italy

<sup>7</sup>Politecnico di Torino, Turin, Italy

<sup>8</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy

<sup>9</sup>Indian Institute of Technology Bombay (IIT), Mumbai, India

<sup>10</sup>Variable Energy Cyclotron Centre, Kolkata, India

<sup>11</sup>Department of Physics, Aligarh Muslim University, Aligarh, India

<sup>12</sup>COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan

<sup>13</sup>Korea Institute of Science and Technology Information, Daejeon, South Korea

<sup>14</sup>Yale University, New Haven, Connecticut, USA

<sup>15</sup>Institute for Theoretical and Experimental Physics, Moscow, Russia

<sup>16</sup>Russian Research Centre, Kurchatov Institute, Moscow, Russia

<sup>17</sup>School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

<sup>18</sup>Centro Fermi—Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” Rome, Italy

<sup>19</sup>Sezione INFN, Bologna, Italy

<sup>20</sup>Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine

<sup>21</sup>Faculty of Engineering, Bergen University College, Bergen, Norway

<sup>22</sup>Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

<sup>23</sup>Department of Physics and Technology, University of Bergen, Bergen, Norway

<sup>24</sup>V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia

<sup>25</sup>Universidade de São Paulo (USP), São Paulo, Brazil

<sup>26</sup>National Institute for Physics and Nuclear Engineering, Bucharest, Romania

<sup>27</sup>Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

<sup>28</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

<sup>29</sup>Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany

<sup>30</sup>Rudjer Bošković Institute, Zagreb, Croatia

<sup>31</sup>Sezione INFN, Padova, Italy

<sup>32</sup>SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France

<sup>33</sup>Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany

<sup>34</sup>Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain

<sup>35</sup>Department of Physics, University of Oslo, Oslo, Norway

<sup>36</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

<sup>37</sup>Physics Department, University of Cape Town, Cape Town, South Africa

<sup>38</sup>Sezione INFN, Catania, Italy

- <sup>39</sup>Gangneung-Wonju National University, Gangneung, South Korea
- <sup>40</sup>Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
- <sup>41</sup>Physics Department, University of Jammu, Jammu, India
- <sup>42</sup>Commissariat à l'Energie Atomique, IRFU, Saclay, France
- <sup>43</sup>Institute of Physics, Bhubaneswar, India
- <sup>44</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
- <sup>45</sup>Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
- <sup>46</sup>Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
- <sup>47</sup>The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
- <sup>48</sup>Joint Institute for Nuclear Research (JINR), Dubna, Russia
- <sup>49</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>50</sup>Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
- <sup>51</sup>University of Houston, Houston, Texas, USA
- <sup>52</sup>Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- <sup>53</sup>Wayne State University, Detroit, Michigan, USA
- <sup>54</sup>Moscow Engineering Physics Institute, Moscow, Russia
- <sup>55</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
- <sup>56</sup>St. Petersburg State Polytechnical University, St. Petersburg, Russia
- <sup>57</sup>Petersburg Nuclear Physics Institute, Gatchina, Russia
- <sup>58</sup>Physik Department, Technische Universität München, Munich, Germany
- <sup>59</sup>Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
- <sup>60</sup>Gauhati University, Department of Physics, Guwahati, India
- <sup>61</sup>University of Tsukuba, Tsukuba, Japan
- <sup>62</sup>Laboratori Nazionali di Frascati, INFN, Frascati, Italy
- <sup>63</sup>Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- <sup>64</sup>Lawrence Berkeley National Laboratory, Berkeley, California, USA
- <sup>65</sup>SSC IHEP of NRC Kurchatov institute, Protvino, Russia
- <sup>66</sup>Faculty of Science, P. J. Šafárik University, Košice, Slovakia
- <sup>67</sup>Pusan National University, Pusan, South Korea
- <sup>68</sup>iThemba LABS, National Research Foundation, Somerset West, South Africa
- <sup>69</sup>Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
- <sup>70</sup>Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- <sup>71</sup>Purdue University, West Lafayette, Indiana, USA
- <sup>72</sup>Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
- <sup>73</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
- <sup>74</sup>Central China Normal University, Wuhan, China
- <sup>75</sup>Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- <sup>76</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
- <sup>77</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- <sup>78</sup>Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- <sup>79</sup>University of Jyväskylä, Jyväskylä, Finland
- <sup>80</sup>Saha Institute of Nuclear Physics, Kolkata, India
- <sup>81</sup>Physics Department, Creighton University, Omaha, Nebraska, USA
- <sup>82</sup>Université de Lyon, Université Lyon 1, CNRS-IN2P3, IPN-Lyon, Villeurbanne, France
- <sup>83</sup>Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
- <sup>84</sup>Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
- <sup>85</sup>Sezione INFN, Cagliari, Italy
- <sup>86</sup>Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
- <sup>87</sup>Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
- <sup>88</sup>Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- <sup>89</sup>Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
- <sup>90</sup>Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
- <sup>91</sup>Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- <sup>92</sup>Institute of Space Science (ISS), Bucharest, Romania
- <sup>93</sup>Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
- <sup>94</sup>National Centre for Nuclear Studies, Warsaw, Poland
- <sup>95</sup>Dipartimento di Fisica "E. R. Caianiello" dell'Università and Gruppo Collegato INFN, Salerno, Italy
- <sup>96</sup>Sezione INFN, Bari, Italy

- <sup>97</sup>*Sezione INFN, Rome, Italy*
- <sup>98</sup>*Helsinki Institute of Physics (HIP), Helsinki, Finland*
- <sup>99</sup>*University of Liverpool, Liverpool, United Kingdom*
- <sup>100</sup>*Institute for Nuclear Research, Academy of Sciences, Moscow, Russia*
- <sup>101</sup>*Physics Department, University of Athens, Athens, Greece*
- <sup>102</sup>*Sezione INFN, Trieste, Italy*
- <sup>103</sup>*Department of Physics, Ohio State University, Columbus, Ohio, USA*
- <sup>104</sup>*Chicago State University, Chicago, Illinois, USA*
- <sup>105</sup>*Technical University of Split FESB, Split, Croatia*
- <sup>106</sup>*Warsaw University of Technology, Warsaw, Poland*
- <sup>107</sup>*A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia*
- <sup>108</sup>*University of Tokyo, Tokyo, Japan*
- <sup>109</sup>*Eberhard Karls Universität Tübingen, Tübingen, Germany*
- <sup>110</sup>*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
- <sup>111</sup>*Department of Physics, Sejong University, Seoul, South Korea*
- <sup>112</sup>*Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia*
- <sup>113</sup>*Yonsei University, Seoul, South Korea*
- <sup>114</sup>*KTO Karatay University, Konya, Turkey*
- <sup>115</sup>*Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany*
- <sup>116</sup>*Department of Applied Physics, Aligarh Muslim University, Aligarh, India*
- <sup>117</sup>*California Polytechnic State University, San Luis Obispo, California, USA*
- <sup>118</sup>*The University of Texas at Austin, Physics Department, Austin, Texas, USA*
- <sup>119</sup>*Suranaree University of Technology, Nakhon Ratchasima, Thailand*
- <sup>120</sup>*Inha University, Incheon, South Korea*
- <sup>121</sup>*Vestfold University College, Tonsberg, Norway*
- <sup>122</sup>*Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom*
- <sup>123</sup>*Universidad Autónoma de Sinaloa, Culiacán, Mexico*
- <sup>124</sup>*M. V. Lomonosov Moscow State University, D. V. Skobel'syn Institute of Nuclear Physics, Moscow, Russia*
- <sup>125</sup>*University of Tennessee, Knoxville, Tennessee, USA*
- <sup>126</sup>*Dipartimento di Fisica dell'Università "La Sapienza" and Sezione INFN Rome, Italy*
- <sup>127</sup>*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia*
- <sup>128</sup>*University of Belgrade, Faculty of Physics and "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia*
- <sup>129</sup>*Indian Institute of Technology Indore, Indore (IITI), India*
- <sup>130</sup>*National Institute of Science Education and Research, Bhubaneswar, India*
- <sup>131</sup>*Konkuk University, Seoul, South Korea*
- <sup>132</sup>*Budker Institute for Nuclear Physics, Novosibirsk, Russia*
- <sup>133</sup>*University of Zagreb, Zagreb, Croatia*
- <sup>134</sup>*Physics Department, University of Rajasthan, Jaipur, India*
- <sup>135</sup>*Institute of Theoretical Physics, University of Wrocław, Wrocław, Poland*
- <sup>136</sup>*Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy*
- <sup>137</sup>*Hiroshima University, Hiroshima, Japan*
- <sup>138</sup>*University of Kansas, Lawrence, Kansas, USA*
- <sup>139</sup>*Centre de Calcul de l'IN2P3, Villeurbanne, France*

<sup>†</sup>Deceased.