

<https://helda.helsinki.fi>

---

# $\bar{p}\bar{p} \rightarrow (c)(+)$ Production and Baryon-to-Meson Ratios in Collisions at $\sqrt{s\text{-NN}}=5.02$ TeV at the LHC

The ALICE collaboration

2021-11-09

---

The ALICE Collaboration , Acharya , S , Adamova , D , Kim , D J , Krizek , F , Novitzky , N ,  
Onnerstad , B S , Parkkila , J E , Rak , J , Rytönen , H M , Räsänen , S , Saarimäki , O A M  
 $\bar{p}\bar{p}$  , Slupecki , M & Trzaska , W H 2021 , '  $\bar{p}\bar{p} \rightarrow (c)(+)$  Production and Baryon-  
and p-Pb Collisions at  $\sqrt{s\text{-NN}}=5.02$  TeV at the LHC ' , Physical Review Letters , vol. 127 ,  
no. 20 , 202301 . <https://doi.org/10.1103/PhysRevLett.127.202301>

---

<http://hdl.handle.net/10138/337989>

<https://doi.org/10.1103/PhysRevLett.127.202301>

---

cc\_by

publishedVersion

---

*Downloaded from Helda, University of Helsinki institutional repository.*


*This is an electronic reprint of the original article.*

*This reprint may differ from the original in pagination and typographic detail.*

*Please cite the original version.*

## $\Lambda_c^+$ Production and Baryon-to-Meson Ratios in $pp$ and $p$ -Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the LHC

S. Acharya *et al.*\*  
(ALICE Collaboration)

 (Received 22 December 2020; revised 27 May 2021; accepted 10 August 2021; published 9 November 2021)

The prompt production of the charm baryon  $\Lambda_c^+$  and the  $\Lambda_c^+/D^0$  production ratios were measured at midrapidity with the ALICE detector in  $pp$  and  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. These new measurements show a clear decrease of the  $\Lambda_c^+/D^0$  ratio with increasing transverse momentum ( $p_T$ ) in both collision systems in the range  $2 < p_T < 12$  GeV/ $c$ , exhibiting similarities with the light-flavor baryon-to-meson ratios  $p/\pi$  and  $\Lambda/K_S^0$ . At low  $p_T$ , predictions that include additional color-reconnection mechanisms beyond the leading-color approximation, assume the existence of additional higher-mass charm-baryon states, or include hadronization via coalescence can describe the data, while predictions driven by charm-quark fragmentation processes measured in  $e^+e^-$  and  $e^-p$  collisions significantly underestimate the data. The results presented in this Letter provide significant evidence that the established assumption of universality (colliding-system independence) of parton-to-hadron fragmentation is not sufficient to describe charm-baryon production in hadronic collisions at LHC energies.

DOI: [10.1103/PhysRevLett.127.202301](https://doi.org/10.1103/PhysRevLett.127.202301)

Heavy-flavor hadron production in hadronic collisions occurs through the fragmentation of a charm or beauty quark, created in hard parton-parton scattering processes, into a given meson or baryon. Theoretical calculations of heavy-flavor production generally use the QCD factorization theorem [1], which describes the hadron cross section as the convolution of three terms: the parton distribution functions, the parton hard-scattering cross sections, and the fragmentation functions. It is generally assumed that the fragmentation functions are universal between collision systems and energies, and the measurement of the relative production of different heavy-flavor hadron species is sensitive to fragmentation functions used in perturbative QCD (pQCD)-based calculations. While perturbative calculations at next-to-leading order with next-to-leading-log resummation [2–5] generally describe the  $D$ - and  $B$ -meson cross-section measurements [6–10] and the ratios of strange and nonstrange  $D$  mesons [6,10] within uncertainties, heavy-flavor baryon production is less well understood.

The  $\Lambda_c^+$  production cross section in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV was reported by ALICE [11]. It was shown that in both collision systems the  $p_T$ -differential  $\Lambda_c^+$  production cross section is higher than predictions from pQCD calculations with

charm fragmentation tuned on previous  $e^+e^-$  and  $e^-p$  measurements [2,3]. The  $\Lambda_c^+/D^0$  ratio in  $pp$  and  $p$ -Pb collisions is consistent in both collision systems and also significantly underestimated by several Monte Carlo generators implementing different charm-quark fragmentation processes [12–15], suggesting that the fragmentation fractions of charm quarks into different hadronic states are nonuniversal with respect to collision system and center-of-mass energy. The production of charm baryons has recently been calculated within the  $k_T$ -factorization approach using unintegrated gluon distribution functions and the Peterson fragmentation functions [16], and with the general-mass variable-flavor-number scheme using updated fragmentation functions from OPAL and Belle [17]. These approaches are unable to simultaneously describe ALICE and LHCb data with the same set of parameters, suggesting that the independent parton fragmentation scheme is insufficient to fully describe the results. An alternative explanation has been offered by a statistical hadronization model, taking into account an augmented list of charm-baryon states based on guidance from the relativistic quark model (RQM) [18] and lattice QCD [19], which is able to reproduce the  $\Lambda_c^+/D^0$  ratio measured by ALICE. The magnitude of the relative yields of  $\Lambda_b^0$  baryons and beauty mesons in  $pp$  collisions measured by LHCb [20–22] and CMS [23] offers further evidence that the fragmentation fractions in the beauty sector also vary between collision systems.

The measurement of baryon production has also been important in heavy-ion collisions, where the high energy density and temperature create a color-deconfined state of matter [24]. A measured enhancement of the light-flavor

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

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

[25,26] and charm [27–29] baryon-to-meson ratio at the LHC and RHIC can be explained via an additional mechanism of hadronization known as coalescence (or recombination), where soft quarks from the medium recombine to form a meson or baryon [30], in addition to hydrodynamical radial flow. Measurements in  $p$ -Pb collisions are crucial to provide an “intermediate” collision system where the generated particle multiplicities and energy densities are between those generated in  $pp$  and  $A$ - $A$  collisions. ALICE and CMS reported an enhancement of the baryon-to-meson ratios in the light-flavor sector ( $p/\pi$  and  $\Lambda/K_S^0$ ) at intermediate  $p_T$  ( $2 < p_T < 10$  GeV/ $c$ ) in high-multiplicity  $pp$  and  $p$ -Pb collisions similar to that observed in heavy-ion collisions [31,32]. This adds to the evidence that small systems also exhibit collective behavior, which may have similar physical origins in  $pp$ ,  $p$ - $A$ , and  $A$ - $A$  collisions [33]. It has been suggested that hadronization of charm quarks via coalescence may also occur in  $pp$  and  $p$ -Pb collisions [34–36].

In this Letter, the measurements of the prompt production of the charm baryon  $\Lambda_c^+$  in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV in  $|y| < 0.5$  and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in  $-0.96 < y < 0.04$  are presented, with a focus on the  $\Lambda_c^+/D^0$  production ratios. The measurement is performed as an average of the  $\Lambda_c^+$  and its charge conjugate  $\Lambda_c^-$ , collectively referred to as  $\Lambda_c^\pm$  in the following. Two hadronic decay channels were measured:  $\Lambda_c^+ \rightarrow pK^-\pi^+$  (branching ratio BR =  $6.28 \pm 0.33\%$ ), and  $\Lambda_c^+ \rightarrow pK_S^0$  (BR =  $1.59 \pm 0.08\%$ ) [37], which were reconstructed exploiting the topology of the weakly decaying  $\Lambda_c^+$  ( $c\tau = 60.7$   $\mu\text{m}$ ) [37]. The results from both decay channels were averaged to obtain more precise production cross sections. With respect to the results presented in [11], this work studies a different center-of-mass energy for  $pp$  collisions, and the cross section is measured in finer  $p_T$  intervals and over a wider  $p_T$  range. The overall precision of the measurements is significantly improved by a factor of 1.5–2, depending on  $p_T$ , for both  $pp$  and  $p$ -Pb collisions. For a detailed description of the analysis techniques, corrections, systematic uncertainty determination, and supplementary measurements, the reader is referred to [38].

A description of the ALICE detector and its performance are reported in [39,40]. The  $pp$  data sample was collected in 2017, and the  $p$ -Pb data sample was collected in 2016 during the LHC Run 2. Both  $pp$  and  $p$ -Pb collisions were recorded using a minimum bias (MB) trigger, which required coincident signals in the two V0 scintillator detectors located on either side of the interaction vertex. Further offline selection was applied in order to remove background from beam-gas collisions and other machine-induced backgrounds. To reduce superposition of more than one interaction within the colliding bunches (pileup), events with multiple reconstructed primary vertices were rejected. Only events with a  $z$  coordinate of the reconstructed vertex position within 10 cm of the nominal interaction point were used. With these

requirements, approximately  $1 \times 10^9$  MB-triggered  $pp$  events were selected, corresponding to an integrated luminosity of  $\mathcal{L}_{\text{int}} = 19.5$   $\text{nb}^{-1}$  ( $\pm 2.1\%$  [41]). Approximately  $600 \times 10^6$  MB-triggered  $p$ -Pb events were selected, corresponding to  $\mathcal{L}_{\text{int}} = 287$   $\mu\text{b}^{-1}$  ( $\pm 3.7\%$  [42]).

The analysis techniques used for the results presented here are described in detail in [38]. Charged-particle tracks and particle decay vertices are reconstructed in the central barrel using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC), which are located inside a solenoid magnet of field strength 0.5 T. In order to reduce the large combinatorial background, selections on the  $\Lambda_c^+$  candidates were made based on the particle identification (PID) signals and the displacement of the decay tracks from the collision point. The PID was performed using information on the specific energy loss of charged particles as they pass through the gas of the TPC and, where available, with flight-time measurements given by the Time-Of-Flight detector (TOF).

For the  $\Lambda_c^+ \rightarrow pK^-\pi^+$  analysis, candidates were built by reconstructing triplets of tracks with the correct configuration of charges. For this analysis, the high-resolution tracking provided by the detectors meant that the decay vertex of the  $\Lambda_c^+$  candidates could be resolved from the interaction point. To identify each of the  $p$ ,  $K$ , and  $\pi$  daughter tracks, information from the TPC and TOF was combined using the “maximum-probability” Bayesian approach described in [43]. Kinematic selections were made on the  $p_T$  of the decay products of the  $\Lambda_c^+$ , and geometrical selections were made on topological properties related to the displaced vertex of the  $\Lambda_c^+$  decay.

The reconstruction of  $\Lambda_c^+ \rightarrow pK_S^0$  candidates relied on reconstructing the V-shaped decay of the  $K_S^0$  meson into two pions, which was then combined with a proton track (bachelor). In  $pp$  collisions, candidates were further selected using criteria related to PID and properties of the  $\Lambda_c^+ \rightarrow pK_S^0$  decay. The Bayesian probability of the combined TPC and TOF response for the bachelor track to be a proton was required to be above 80%. The selection criteria on kinematical and geometrical variables included the distance of closest approach between the decay daughters, the invariant mass, and the cosine of the pointing angle of the neutral decay vertex ( $K_S^0$ ) to the primary vertex.

For the  $\Lambda_c^+ \rightarrow pK_S^0$  decay channel in  $p$ -Pb collisions, the analysis was performed using a multivariate technique based on the boosted decision tree (BDT) algorithm provided by the Toolkit for Multivariate Data Analysis [44]. The BDT algorithm was trained using signal and background  $\Lambda_c^+ \rightarrow pK_S^0$  decay candidates simulated using PYTHIA 6.4.25 [45] with the Perugia 2011 tune [46], and the underlying  $p$ -Pb event simulated with HIJING 1.36 [47]. Candidates obtained with the same reconstruction strategy previously described were preselected using loose geometrical selections and PID selection on the bachelor proton track. The model was trained independently for each  $p_T$

interval analyzed, with input variables comprising the  $p_T$  and Bayesian PID probability of the proton track, the  $c\tau$  and invariant mass of the  $K_S^0$ , and the impact parameters of the  $\Lambda_c^+$  decay tracks to the primary vertex. This model was then applied on data, and a selection on the output response was chosen based on the expected maximum significance determined from simulations.

For both decay channels, the yield of  $\Lambda_c^+$  baryons was extracted in each  $p_T$  interval via fits to the candidate invariant-mass distributions. The fitting function consisted of a Gaussian to estimate the signal and an exponential or polynomial function to estimate the background. The width of the Gaussian was fixed in each  $p_T$  interval to values obtained from Monte Carlo simulations, and the mean was treated as a free parameter. A statistical significance higher than 4 standard deviations was achieved in all  $p_T$  intervals.

Several corrections were applied to the measurement of the  $\Lambda_c^+$  cross section. The geometrical acceptance of the detector as well as the selection and reconstruction efficiencies for prompt  $\Lambda_c^+$  were taken into account. These correction factors were determined from  $pp$  collisions generated with PYTHIA 6 and PYTHIA 8.243 [48], with each event including either a  $c\bar{c}$  or a  $b\bar{b}$  pair. For  $p$ -Pb collisions, this was supplemented with an underlying event from the HIJING event generator. In  $p$ -Pb collisions, the efficiency was calculated after reweighting the events based on their charged particle multiplicity. This accounts for the fact that the event multiplicity in simulation does not reproduce the one in data, and the efficiency depends on the multiplicity of the event as a consequence of the improvement of the resolution of the primary vertex and thus of the performance of the topological selections at higher multiplicities. The fraction of the  $\Lambda_c^+$  yield originating from beauty decays (feed-down) was obtained using the beauty-quark production cross section from FONLL [4,5], the fraction of beauty quarks that fragment into beauty hadrons  $H_b$  from LHCb measurements [22], and  $H_b \rightarrow \Lambda_c^+ + X$  decay kinematics from PYTHIA 8, as well as the selection and reconstruction efficiency of  $\Lambda_c^+$  from beauty-hadron decays. The fraction of the  $\Lambda_c^+$  yield from beauty decays was found to be 2% at low  $p_T$  and up to 16% at high  $p_T$ , and was subtracted from the measured yield. As done in the  $D$ -meson analysis [49], the possible modification of beauty-hadron production in  $p$ -Pb collisions was included in the feed-down calculation by scaling the beauty-quark production by a nuclear modification factor  $R_{pPb}^{\text{feed-down}}$ , where it was assumed that  $R_{pPb}^{\text{feed-down}} = R_{pPb}^{\text{prompt}}$  with their ratio varied in the range  $0.9 < R_{pPb}^{\text{feed-down}}/R_{pPb}^{\text{prompt}} < 1.3$  to evaluate the systematic uncertainties.

Systematic uncertainties on the  $\Lambda_c^+$  cross sections were estimated considering the same sources as described in [11]. The contributions from the raw-yield extraction were evaluated by repeating the fits varying the fit interval and

the functional form of the background fit function. For each of these variations the four combinations of free and fixed Gaussian mean and width parameters of the fit were considered. Overall, the relative uncertainty ranged from 4% to 11% depending on the  $p_T$  and analysis. The uncertainties on the track reconstruction efficiency were estimated by adding in quadrature the uncertainty due to track quality selection and the uncertainty due to the TPC-ITS matching efficiency (from 3% to 7%). The former is estimated by varying the track-quality selection criteria, and the latter is estimated by comparing the probability to match the tracks from the TPC to the ITS hits in data and simulation. The uncertainty on the  $\Lambda_c^+$  selection efficiency was estimated by varying the selection on the kinematical and topological properties of the  $\Lambda_c^+$  decays or the selection on the BDT response (from 3% to 15%). The uncertainty on the PID efficiency was estimated by varying the selection on the Bayesian probability variables (from 2% to 5%). The systematic effect on the efficiencies due to the shape of the simulated  $\Lambda_c^+$   $p_T$  distribution was evaluated by reweighting the generated  $\Lambda_c^+$  from PYTHIA 6 to match the  $p_T$  distribution obtained from FONLL calculations for  $D$  mesons (maximum 1% uncertainty). The relative statistical uncertainty on the acceptance and efficiency correction was considered as an additional systematic uncertainty source (from 1%–2% at low  $p_T$  to 3%–5% at high  $p_T$ ). The uncertainties on  $f_{\text{prompt}}$  were estimated by varying the hypothesis on the production of  $\Lambda_c^+$  from  $B$ -hadron decays to account for the theoretical uncertainties of  $b$ -quark production within FONLL and experimental uncertainties on  $B$ -hadron fragmentation (around 2% at low  $p_T$  and from 4% to 7% at high  $p_T$ , depending on the analysis). Global uncertainties of the measurement include those from the luminosity and  $\Lambda_c^+$  branching ratios. The raw-yield extraction uncertainty source are considered to be uncorrelated across  $p_T$  bins, while all other sources are considered to be correlated.

The results in each collision system from the two  $\Lambda_c^+$  decay channels were averaged to obtain the final results. A weighted average of the results was calculated, with weights defined as the inverse of the quadratic sum of the relative statistical and uncorrelated systematic uncertainties. The sources of systematic uncertainty assumed to be uncorrelated between different decay channels were those due to the raw-yield extraction, the statistical uncertainties on the efficiency and acceptance, and those related to the  $\Lambda_c^+$  selection. The remaining uncertainties were assumed to be correlated, except the branching ratio uncertainties, which were treated as partially correlated among the hadronic-decay modes as defined in [37].

Figure 1 (left) shows a comparison of the  $\Lambda_c^+$   $p_T$ -differential cross sections in  $pp$  and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The  $D^0$   $p_T$ -differential cross sections measured in the same collision systems and at the same center-of-mass energy during the same data taking periods

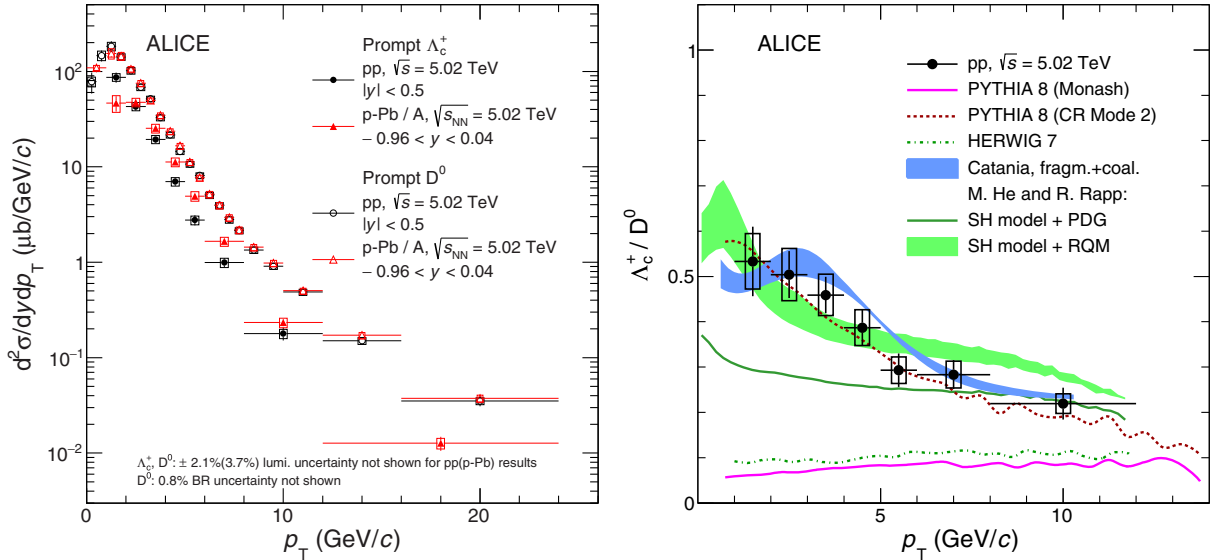


FIG. 1. Left: Prompt  $\Lambda_c^+$  and  $D^0$   $p_T$ -differential cross section in  $pp$  collisions and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. The results in  $p$ -Pb collisions are scaled with the atomic mass number  $A$  of the Pb nucleus. Right: The  $\Lambda_c^+/D^0$  ratio as a function of  $p_T$  measured in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV compared with theoretical predictions (see text for details). Statistical uncertainties are shown as vertical bars, while systematic uncertainties are shown as boxes, and the bin widths are shown as horizontal bars.

[10,50] are also shown. In order to compare the spectral shapes in the two different collision systems at the same energy, the results in  $p$ -Pb collisions are scaled by the atomic mass number of the lead nucleus. For  $\Lambda_c^+$  baryons the spectral shape in  $p$ -Pb collisions is slightly harder than in  $pp$  collisions, while for  $D^0$  mesons the spectral shapes are fully consistent within uncertainties.

Figure 1 (right) shows the baryon-to-meson ratio  $\Lambda_c^+/D^0$  measured in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV as a function of  $p_T$  compared to theoretical predictions. The uncertainty on the luminosity cancels in the ratio. The  $\Lambda_c^+/D^0$  ratio is measured to be 0.4–0.5 at low  $p_T$  and decreases to around 0.2 at high  $p_T$ . The previous results at  $\sqrt{s} = 7$  TeV hinted at a decrease of the  $\Lambda_c^+/D^0$  ratio with  $p_T$ , although the precision was not enough to confirm this [11]. The results in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV, with much higher precision than  $\sqrt{s} = 7$  TeV results, show a clear decrease with increasing  $p_T$ . The strong  $p_T$  dependence of the  $\Lambda_c^+/D^0$  ratio is in contrast to the ratios of strange and nonstrange  $D$  mesons in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV and  $\sqrt{s} = 7$  TeV [10,51] and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV [50], which do not show a significant  $p_T$  dependence within uncertainties and thus indicate that there are no large differences between fragmentation functions of charm quarks to charm mesons. The result presented here instead provides strong indications that the fragmentation functions of baryons and mesons differ significantly.

The measured  $\Lambda_c^+/D^0$  ratios in  $pp$  collisions are compared to predictions from several Monte Carlo generators and models in which different hadronization processes are implemented. The PYTHIA 8 predictions include

the Monash tune [12] and a tune that implements color reconnection beyond the leading-color approximation, corresponding to CR Mode 2 as defined in [13]. Hadronization in PYTHIA is built on the Lund string fragmentation model [52,53], where quarks and gluons connected by color strings fragment into hadrons, and color reconnection allows for partons created in the collision to interact via color strings. The latter tune introduces new color reconnection topologies beyond the leading-color approximation, including “junctions” that fragment into baryons, leading to increased baryon production. As a technical point, the PYTHIA 8 simulations are generated with all soft QCD processes switched on [48]. The PYTHIA 8 Monash tune and HERWIG 7.2 [15] predictions are driven by the fragmentation fraction  $f(c \rightarrow \Lambda_c^+)$  implemented in these generators, which all suggest a relatively constant  $\Lambda_c^+/D^0$  ratio versus  $p_T$  of about 0.1, significantly underestimating the data at low  $p_T$ . At high  $p_T$ , the data approach the predictions from these generators, although the measurement in  $8 < p_T < 12$  GeV/ $c$  is still underestimated by about a factor of 2. A significant enhancement of the  $\Lambda_c^+/D^0$  ratio is seen with color reconnection beyond the leading-color approximation (PYTHIA 8 CR Mode 2). This prediction is consistent with the measured  $\Lambda_c^+/D^0$  ratio in  $pp$  collisions, also reproducing the downward  $p_T$  trend. The statistical hadronization model (“SH model” in the legend) [19] uses either an underlying charm-baryon spectrum taken from the Particle Data Group, or includes additional excited charm baryons that have not yet been observed but are predicted by the RQM. These additional states decay strongly to  $\Lambda_c^+$  baryons, which contribute to the prompt  $\Lambda_c^+$  spectrum. The RQM predictions include a

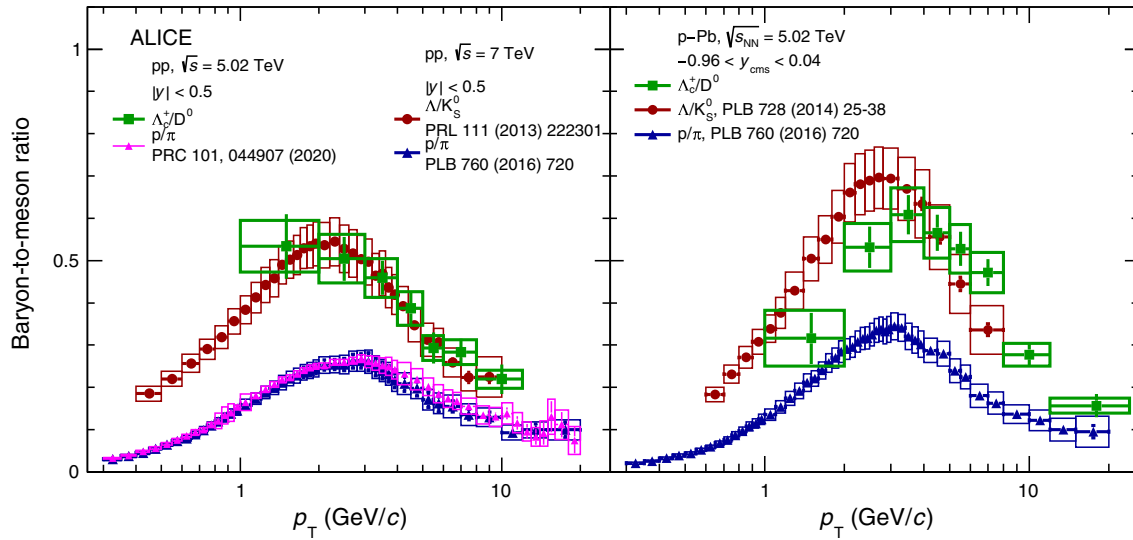


FIG. 2. The charm baryon-to-meson ratio  $\Lambda_c^+/D^0$  in  $pp$  collisions (left) and  $p$ -Pb collisions (right) at  $\sqrt{s_{NN}} = 5.02$  TeV compared to the light-flavor baryon-to-meson ratios  $\Lambda/K_S^0$  and  $p/\pi$ . Statistical uncertainties are shown as vertical bars, while systematic uncertainties are shown as boxes, and the bin widths are shown as horizontal bars.

source of uncertainty related to the branching ratios of the excited baryon states into  $\Lambda_c^+$  final states, which is estimated by varying the branching ratios between 50% and 100%. With the Particle Data Group charm-baryon spectrum, the model underpredicts the data. With the additional baryon states, the model instead gives a good description of the  $pp$  data, both in the magnitude of the ratio and the decreasing trend with  $p_T$ . The Catania model [36] assumes that a color-deconfined state of matter is formed and hadronization can occur via coalescence in addition to fragmentation. Coalescence is implemented through the Wigner formalism, where a blast wave model is used to determine the  $p_T$  spectrum of light quarks and FONLL pQCD calculations are used for heavy quarks. Hadronization via coalescence is predicted to dominate at low  $p_T$ , while fragmentation dominates at high  $p_T$ . This model provides a good description of both the magnitude and shape of the data over the full  $p_T$  range.

Figure 2 shows the  $\Lambda_c^+/D^0$  baryon-to-meson ratio measured in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV (left) and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV (right) as a function of  $p_T$  compared to baryon-to-meson ratios in the light-flavor sector,  $\Lambda/K_S^0$  [25,54] and  $p/\pi$  [31,55] [calculated as the sum of both charged particles and antiparticles,  $(p + \bar{p})/(\pi^+ + \pi^-)$ ]. The  $p/\pi$  ratio in  $pp$  collisions is shown at both  $\sqrt{s} = 5.02$  TeV and  $\sqrt{s} = 7$  TeV, displaying consistent results at both center-of-mass energies, while the  $\Lambda/K_S^0$  ratio in  $pp$  collisions is shown only at  $\sqrt{s} = 7$  TeV. Unlike heavy-flavor hadron production, which occurs primarily through the fragmentation of a charm quark produced in the initial hard scattering, light-flavor hadrons have a significant contribution from gluon fragmentation. Low- $p_T$  light-flavor hadrons also primarily originate from soft scattering

processes involving small momentum transfers. All particle yields in these ratios were corrected for feed-down from weak decays, although the pion spectrum is expected to have significant feed-down contributions also from the strong decays of other particle species, primarily  $\rho$  and  $\omega$  mesons. Despite these differences, the three ratios— $\Lambda_c^+/D^0$ ,  $\Lambda/K_S^0$ , and  $p/\pi$ —demonstrate some remarkably similar characteristics in both collision systems. All ratios exhibit a decreasing trend after  $p_T \gtrsim 2-3$  GeV/c. The  $\Lambda_c^+/D^0$  and  $\Lambda/K_S^0$  ratios are consistent, in terms of both shape and magnitude, within uncertainties. The light-flavor ratios both peak at  $\sim 2-3$  GeV/c in both  $pp$  and  $p$ -Pb collisions, and there is an indication of a peak at  $2 < p_T < 4$  GeV/c in the  $\Lambda_c^+/D^0$  ratio in  $p$ -Pb collisions. These similarities between heavy-flavor and light-flavor measurements hint at a potential common mechanism for light- and charm-baryon formation in  $pp$  and  $p$ -Pb collisions at LHC energies. It is interesting to note that all baryon-to-meson ratios also indicate a shift toward higher momenta in  $p$ -Pb collisions, which for light-flavor particle production is often attributed to radial flow [54]. However, while flow effects in the charm sector ( $D^0$  and heavy-flavor decay leptons) have been observed in high-multiplicity  $p$ -Pb collisions [56,57], these effects are expected to be smaller at lower multiplicities as well as smaller for charm than for light-flavor hadrons.

In summary,  $\Lambda_c^+$ -baryon production was measured in  $pp$  collisions at midrapidity ( $|y| < 0.5$ ) and in  $p$ -Pb collisions in the rapidity interval  $-0.96 < y < 0.04$  at  $\sqrt{s_{NN}} = 5.02$  TeV. A clear  $p_T$  dependence of the  $\Lambda_c^+/D^0$  ratio is reported, with the ratio decreasing as the  $p_T$  increases. This trend is similar to that of baryon-to-meson ratios measured in the light-flavor sector in  $pp$  and  $p$ -Pb collisions, suggesting common mechanisms for light- and

charm-baryon formation. While models incorporating fragmentation parameters from  $e^+e^-$  and  $e^-p$  collisions significantly underestimate the  $\Lambda_c^+/D^0$  ratio, three models can reproduce the measurements. The first is a tune of PYTHIA 8 that considers that, in  $pp$  collisions at high energy, multiparton interactions produce a rich hadronic environment that requires an extension of color reconnection in hadronization processes beyond the leading-color approximation. The second method is the statistical hadronization + RQM model, which relies on the presence of a large set of yet-unobserved higher-mass charm-baryon states with relative yields following the statistical hadronization model. The third relies on hadronization via coalescence and fragmentation after the formation of a color-deconfined state of matter. All three models imply a substantially different description of the charm-baryon production in  $pp$  collisions with respect to  $e^+e^-$  and  $e^-p$  collisions, indicating that the assumption of universal parton-to-hadron fragmentation between collision systems is not sufficient to describe charm-baryon production.

The ALICE Collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex. The ALICE Collaboration gratefully acknowledges the resources and support provided by all Grid centers and the Worldwide LHC Computing Grid (WLCG) collaboration. The ALICE Collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector: A. I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation (ANSL), State Committee of Science and World Federation of Scientists (WFS), Armenia; Austrian Academy of Sciences, Austrian Science Fund (FWF): [M 2467-N36] and Nationalstiftung für Forschung, Technologie und Entwicklung, Austria; Ministry of Communications and High Technologies, National Nuclear Research Center, Azerbaijan; Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (Finep), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Federal do Rio Grande do Sul (UFRGS), Brazil; Ministry of Education of China (MOEC), Ministry of Science and Technology of China (MSTC) and National Natural Science Foundation of China (NSFC), China; Ministry of Science and Education and Croatian Science Foundation, Croatia; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Cubaenergía, Cuba; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research—Natural Sciences, the VILLUM FONDEN and Danish National Research Foundation (DNRF), Denmark; Helsinki Institute of Physics (HIP), Finland; Commissariat à l’Energie Atomique (CEA) and Institut National de Physique Nucléaire et de Physique des

Particules (IN2P3) and Centre National de la Recherche Scientifique (CNRS), France; Bundesministerium für Bildung und Forschung (BMBF) and GSI Helmholtzzentrum für Schwerionenforschung GmbH, Germany; General Secretariat for Research and Technology, Ministry of Education, Research and Religions, Greece; National Research, Development and Innovation Office, Hungary; Department of Atomic Energy Government of India (DAE), Department of Science and Technology, Government of India (DST), University Grants Commission, Government of India (UGC) and Council of Scientific and Industrial Research (CSIR), India; Indonesian Institute of Science, Indonesia; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology, Nagasaki Institute of Applied Science (IIST), Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) and Japan Society for the Promotion of Science (JSPS) KAKENHI, Japan; Consejo Nacional de Ciencia (CONACYT) y Tecnología, through Fondo de Cooperación Internacional en Ciencia y Tecnología (FONCICYT) and Dirección General de Asuntos del Personal Académico (DGAPA), Mexico; Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands; The Research Council of Norway, Norway; Commission on Science and Technology for Sustainable Development in the South (COMSATS), Pakistan; Pontificia Universidad Católica del Perú, Peru; Ministry of Science and Higher Education, National Science Centre and WUT ID-UB, Poland; Korea Institute of Science and Technology Information and National Research Foundation of Korea (NRF), Republic of Korea; Ministry of Education and Scientific Research, Institute of Atomic Physics and Ministry of Research and Innovation and Institute of Atomic Physics, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, National Research Centre Kurchatov Institute, Russian Science Foundation and Russian Foundation for Basic Research, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW), Sweden; European Organization for Nuclear Research, Switzerland; Suranaree University of Technology (SUT), National Science and Technology Development Agency (NSDTA) and Office of the Higher Education Commission under NRU project of Thailand, Thailand; Turkish Atomic Energy Agency (TAEK), Turkey; National Academy of Sciences of Ukraine, Ukraine; Science and Technology Facilities Council (STFC), United Kingdom; National Science Foundation of the United States of America (NSF) and United States Department of Energy, Office of Nuclear Physics (DOE NP), United States of America.

- [1] J. C. Collins, D. E. Soper, and G. F. Sterman, Factorization of hard processes in QCD, *Adv. Ser. Dir. High Energy Phys.* **5**, 1 (1989).
- [2] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, Collinear subtractions in hadroproduction of heavy quarks, *Eur. Phys. J. C* **41**, 199 (2005).
- [3] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, Inclusive charmed-meson production at the CERN LHC, *Eur. Phys. J. C* **72**, 2082 (2012).
- [4] M. Cacciari, M. Greco, and P. Nason, The  $p_T$  spectrum in heavy-flavour hadroproduction, *J. High Energy Phys.* **05** (1998) 007.
- [5] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, Theoretical predictions for charm and bottom production at the LHC, *J. High Energy Phys.* **10** (2012) 137.
- [6] A. Andronic *et al.*, Heavy-flavour and quarkonium production in the LHC era: From proton-proton to heavy-ion collisions, *Eur. Phys. J. C* **76**, 107 (2016).
- [7] R. Aaij *et al.* (LHCb Collaboration), Measurements of prompt charm production cross-sections in  $pp$  collisions at  $\sqrt{s} = 13$  TeV, *J. High Energy Phys.* **03** (2016) 159; Erratum, *J. High Energy Phys.* **09** (2016) 013; Erratum, *J. High Energy Phys.* **05** (2017) 074.
- [8] V. Khachatryan *et al.* (CMS Collaboration), Measurement of the total and differential inclusive  $B^+$  hadron cross sections in  $pp$  collisions at  $\sqrt{s} = 13$  TeV, *Phys. Lett. B* **771**, 435 (2017).
- [9] R. Aaij *et al.* (LHCb Collaboration), Measurement of the  $B^\pm$  production cross-section in  $pp$  collisions at  $\sqrt{s} = 7$  and 13 TeV, *J. High Energy Phys.* **12** (2017) 026.
- [10] S. Acharya *et al.* (ALICE Collaboration), Measurement of  $D^0$ ,  $D^+$ ,  $D^{*+}$  and  $D_s^+$  production in  $pp$  collisions at  $\sqrt{s} = 5.02$  TeV with ALICE, *Eur. Phys. J. C* **79**, 388 (2019).
- [11] S. Acharya *et al.* (ALICE Collaboration),  $\Lambda_c^+$  production in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *J. High Energy Phys.* **04** (2018) 108.
- [12] P. Skands, S. Carrazza, and J. Rojo, Tuning PYTHIA 8.1: The Monash 2013 tune, *Eur. Phys. J. C* **74**, 3024 (2014).
- [13] J. R. Christiansen and P. Z. Skands, String formation beyond leading colour, *J. High Energy Phys.* **08** (2015) 003.
- [14] C. Bierlich and J. R. Christiansen, Effects of color reconnection on hadron flavor observables, *Phys. Rev. D* **92**, 094010 (2015).
- [15] J. Bellm *et al.*, Herwig 7.0/Herwig<sup>++</sup> 3.0 release note, *Eur. Phys. J. C* **76**, 196 (2016).
- [16] R. Maciuła and A. Szczurek, Production of  $\Lambda_c$  baryons at the LHC within the  $k_T$ -factorization approach and independent parton fragmentation picture, *Phys. Rev. D* **98**, 014016 (2018).
- [17] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger,  $\Lambda_c^\pm$  production in  $pp$  collisions with a new fragmentation function, *Phys. Rev. D* **101**, 114021 (2020).
- [18] D. Ebert, R. N. Faustov, and V. O. Galkin, Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture, *Phys. Rev. D* **84**, 014025 (2011).
- [19] M. He and R. Rapp, Charm-Baryon production in proton-proton collisions, *Phys. Lett. B* **795**, 117 (2019).
- [20] R. Aaij *et al.* (LHCb Collaboration), Measurement of  $b$ -hadron production fractions in 7 TeV  $pp$  collisions, *Phys. Rev. D* **85**, 032008 (2012).
- [21] R. Aaij *et al.* (LHCb Collaboration), Study of the production of  $\Lambda_b^0$  and  $\bar{B}^0$  hadrons in  $pp$  collisions and first measurement of the  $\Lambda_b^0 \rightarrow J/\psi p K^-$  branching fraction, *Chin. Phys. C* **40**, 011001 (2016).
- [22] R. Aaij *et al.* (LHCb Collaboration), Measurement of  $b$  hadron fractions in 13 TeV  $pp$  collisions, *Phys. Rev. D* **100**, 031102 (2019).
- [23] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the  $\Lambda_b$  cross section and the  $\bar{\Lambda}_b$  to  $\Lambda_b$  ratio with  $J/\psi\Lambda$  decays in  $pp$  collisions at  $\sqrt{s} = 7$  TeV, *Phys. Lett. B* **714**, 136 (2012).
- [24] W. Busza, K. Rajagopal, and W. van der Schee, Heavy ion collisions: The big picture, and the big questions, *Annu. Rev. Nucl. Part. Sci.* **68**, 339 (2018).
- [25] B. Abelev *et al.* (ALICE Collaboration),  $K_S^0$  and  $\Lambda$  Production in Pb-Pb Collisions at  $\sqrt{s_{NN}} = 2.76$  TeV, *Phys. Rev. Lett.* **111**, 222301 (2013).
- [26] J. Adams *et al.* (STAR Collaboration), Measurements of identified particles at intermediate transverse momentum in the STAR experiment from Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, [arXiv:nucl-ex/0601042](https://arxiv.org/abs/nucl-ex/0601042).
- [27] S. Acharya *et al.* (ALICE Collaboration),  $\Lambda_c^+$  production in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Lett. B* **793**, 212 (2019).
- [28] J. Adam *et al.* (STAR Collaboration), First measurement of  $\Lambda_c$  baryon production in Au + Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, *Phys. Rev. Lett.* **124**, 172301 (2020).
- [29] A. M. Sirunyan *et al.* (CMS Collaboration), Production of  $\Lambda_c^+$  baryons in proton-proton and lead-lead collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Lett. B* **803**, 135328 (2020).
- [30] R. J. Fries, V. Greco, and P. Sorensen, Coalescence models for hadron formation from quark gluon plasma, *Annu. Rev. Nucl. Part. Sci.* **58**, 177 (2008).
- [31] J. Adam *et al.* (ALICE Collaboration), Multiplicity dependence of charged pion, kaon, and (anti)proton production at large transverse momentum in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Lett. B* **760**, 720 (2016).
- [32] V. Khachatryan *et al.* (CMS Collaboration), Multiplicity and rapidity dependence of strange hadron production in  $pp$ ,  $p$ Pb, and PbPb collisions at the LHC, *Phys. Lett. B* **768**, 103 (2017).
- [33] J. L. Nagle and W. A. Zajc, Small system collectivity in relativistic hadronic and nuclear collisions, *Annu. Rev. Nucl. Part. Sci.* **68**, 211 (2018).
- [34] J. Song, H.-h. Li, and F.-l. Shao, New feature of low  $p_T$  charm quark hadronization in  $pp$  collisions at  $\sqrt{s} = 7$  TeV, *Eur. Phys. J. C* **78**, 344 (2018).
- [35] H.-H. Li, F.-L. Shao, J. Song, and R.-Q. Wang, Production of single-charm hadrons by quark combination mechanism in  $p$ -Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Rev. C* **97**, 064915 (2018).
- [36] V. Minissale, S. Plumari, and V. Greco, Charm hadrons in  $pp$  collisions at LHC energy within a coalescence plus fragmentation approach, [arXiv:2012.12001](https://arxiv.org/abs/2012.12001).
- [37] P. A. Zyla *et al.* (Particle Data Group), Review of particle physics, *Prog. Theor. Exp. Phys.* **2020**, 083C01 (2020).



- [38] S. Acharya *et al.* (ALICE Collaboration), companion paper,  $\Lambda_c^+$  production in pp and in p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Rev. C*, **104**, 054905 (2021).
- [39] K. Aamodt *et al.* (ALICE Collaboration), The ALICE experiment at the CERN LHC, *J. Instrum.* **3**, S08002 (2008).
- [40] B. Abelev *et al.* (ALICE Collaboration), Performance of the ALICE Experiment at the CERN LHC, *Int. J. Mod. Phys. A* **29**, 1430044 (2014).
- [41] ALICE Collaboration, ALICE 2017 luminosity determination for pp collisions at  $\sqrt{s} = 5$  TeV, ALICE-PUBLIC-2018-014, <http://cds.cern.ch/record/2648933>.
- [42] B. Abelev *et al.* (ALICE Collaboration), Measurement of visible cross sections in proton-lead collisions at  $\sqrt{s_{NN}} = 5.02$  TeV in van der Meer scans with the ALICE detector, *J. Instrum.* **9**, P11003 (2014).
- [43] J. Adam *et al.* (ALICE Collaboration), Particle identification in ALICE: A Bayesian approach, *Eur. Phys. J. Plus* **131**, 168 (2016).
- [44] A. Höcker *et al.*, TMVA: Toolkit for Multivariate Data Analysis, *Proc. Sci. ACAT* (2007) 040 [arXiv:physics/0703039].
- [45] T. Sjöstrand, S. Mrenna, and P.Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [46] P.Z. Skands and The Perugia tunes, in *Proceedings of the 1st International Workshop on Multiple Partonic Interactions at the LHC (MPI08)*, Perugia, Italy, 2008 (2009), pp. 284–297, <https://dx.doi.org/10.3204/PUBDB-2017-128830>.
- [47] X.-N. Wang and M. Gyulassy, HIJING: A Monte Carlo model for multiple jet production in pp, pA and AA collisions, *Phys. Rev. D* **44**, 3501 (1991).
- [48] T. Sjöstrand, S. Mrenna, and P.Z. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
- [49] J. Adam *et al.* (ALICE Collaboration), D-meson production in p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV and in pp collisions at  $\sqrt{s} = 7$  TeV, *Phys. Rev. C* **94**, 054908 (2016).
- [50] S. Acharya *et al.* (ALICE Collaboration), Measurement of prompt  $D^0$ ,  $D^+$ ,  $D^{*+}$ , and  $D_S^+$  production in p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *J. High Energy Phys.* **12** (2019) 092.
- [51] S. Acharya *et al.* (ALICE Collaboration), Measurement of D-meson production at mid-rapidity in pp collisions at  $\sqrt{s} = 7$  TeV, *Eur. Phys. J. C* **77**, 550 (2017).
- [52] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjöstrand, Parton fragmentation and string dynamics, *Phys. Rep.* **97**, 31 (1983).
- [53] B. Andersson, *The Lund Model* (Cambridge University Press, Cambridge, England, 2005), Vol. 7.
- [54] B. Abelev *et al.* (ALICE Collaboration), Multiplicity dependence of pion, kaon, proton and lambda production in p-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Lett. B* **728**, 25 (2014).
- [55] S. Acharya *et al.* (ALICE Collaboration), Production of charged pions, kaons and (anti-)protons in Pb-Pb and inelastic pp collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Rev. C* **101**, 044907 (2020).
- [56] A. M. Sirunyan *et al.* (CMS Collaboration), Elliptic Flow of Charm and Strange Hadrons in High-Multiplicity p + Pb Collisions at  $\sqrt{s_{NN}} = 8.16$  TeV, *Phys. Rev. Lett.* **121**, 082301 (2018).
- [57] S. Acharya *et al.* (ALICE Collaboration), Azimuthal Anisotropy of Heavy-Flavor Decay Electrons in p-Pb Collisions at  $\sqrt{s_{NN}} = 5.02$  TeV, *Phys. Rev. Lett.* **122**, 072301 (2019).

---

S. Acharya,<sup>142</sup> D. Adamová,<sup>97</sup> A. Adler,<sup>75</sup> J. Adolfsson,<sup>82</sup> G. Aglieri Rinella,<sup>35</sup> M. Agnello,<sup>31</sup> N. Agrawal,<sup>55</sup> Z. Ahammed,<sup>142</sup> S. Ahmad,<sup>16</sup> S. U. Ahn,<sup>77</sup> Z. Akbar,<sup>52</sup> A. Akindinov,<sup>94</sup> M. Al-Turany,<sup>109</sup> D. S. D. Albuquerque,<sup>124</sup> D. Aleksandrov,<sup>90</sup> B. Alessandro,<sup>60</sup> H. M. Alfanda,<sup>7</sup> R. Alfaro Molina,<sup>72</sup> B. Ali,<sup>16</sup> Y. Ali,<sup>14</sup> A. Alici,<sup>26</sup> N. Alizadehvandchali,<sup>127</sup> A. Alkin,<sup>35</sup> J. Alme,<sup>21</sup> T. Alt,<sup>69</sup> L. Altenkamper,<sup>21</sup> I. Altsybeev,<sup>115</sup> M. N. Anaam,<sup>7</sup> C. Andrei,<sup>49</sup> D. Andreou,<sup>92</sup> A. Andronic,<sup>145</sup> M. Angeletti,<sup>35</sup> V. Anguelov,<sup>106</sup> T. Antičić,<sup>110</sup> F. Antinori,<sup>58</sup> P. Antonioli,<sup>55</sup> N. Apadula,<sup>81</sup> L. Aphecetche,<sup>117</sup> H. Appelshäuser,<sup>69</sup> S. Arcelli,<sup>26</sup> R. Arnaldi,<sup>60</sup> M. Arratia,<sup>81</sup> I. C. Arsene,<sup>20</sup> M. Arslanodk,<sup>147,106</sup> A. Augustinus,<sup>35</sup> R. Averbeck,<sup>109</sup> S. Aziz,<sup>79</sup> M. D. Azmi,<sup>16</sup> A. Badalà,<sup>57</sup> Y. W. Baek,<sup>42</sup> X. Bai,<sup>109</sup> R. Bailhache,<sup>69</sup> R. Bala,<sup>103</sup> A. Balbino,<sup>31</sup> A. Baldisseri,<sup>139</sup> M. Ball,<sup>44</sup> D. Banerjee,<sup>4</sup> R. Barbera,<sup>27</sup> L. Barioglio,<sup>25</sup> M. Barlou,<sup>86</sup> G. G. Barnaföldi,<sup>146</sup> L. S. Barnby,<sup>96</sup> V. Barret,<sup>136</sup> C. Bartels,<sup>129</sup> K. Barth,<sup>35</sup> E. Bartsch,<sup>69</sup> F. Baruffaldi,<sup>28</sup> N. Bastid,<sup>136</sup> S. Basu,<sup>82,144</sup> G. Batigne,<sup>117</sup> B. Batyunya,<sup>76</sup> D. Bauri,<sup>50</sup> J. L. Bazo Alba,<sup>114</sup> I. G. Bearden,<sup>91</sup> C. Beattie,<sup>147</sup> I. Belikov,<sup>138</sup> A. D. C. Bell Hechavarría,<sup>145</sup> F. Bellini,<sup>35</sup> R. Bellwied,<sup>127</sup> S. Belokurova,<sup>115</sup> V. Belyaev,<sup>95</sup> G. Bencedi,<sup>70,146</sup> S. Beole,<sup>25</sup> A. Bercuci,<sup>49</sup> Y. Berdnikov,<sup>100</sup> A. Berdnikova,<sup>106</sup> D. Berenyi,<sup>146</sup> L. Bergmann,<sup>106</sup> M. G. Besoiu,<sup>68</sup> L. Betev,<sup>35</sup> P. P. Bhaduri,<sup>142</sup> A. Bhasin,<sup>103</sup> I. R. Bhat,<sup>103</sup> M. A. Bhat,<sup>4</sup> B. Bhattacharjee,<sup>43</sup> P. Bhattacharya,<sup>23</sup> A. Bianchi,<sup>25</sup> L. Bianchi,<sup>25</sup> N. Bianchi,<sup>53</sup> J. Bielčák,<sup>38</sup> J. Bielčiková,<sup>97</sup> A. Bilandzic,<sup>107</sup> G. Biro,<sup>146</sup> S. Biswas,<sup>4</sup> J. T. Blair,<sup>121</sup> D. Blau,<sup>90</sup> M. B. Blidaru,<sup>109</sup> C. Blume,<sup>69</sup> G. Boca,<sup>29</sup> F. Bock,<sup>98</sup> A. Bogdanov,<sup>95</sup> S. Boi,<sup>23</sup> J. Bok,<sup>62</sup> L. Boldizsár,<sup>146</sup> A. Bolozdynya,<sup>95</sup> M. Bombara,<sup>39</sup> G. Bonomi,<sup>141</sup> H. Borel,<sup>139</sup> A. Borissov,<sup>83,95</sup> H. Bossi,<sup>147</sup> E. Botta,<sup>25</sup> L. Bratrud,<sup>69</sup> P. Braun-Munzinger,<sup>109</sup> M. Bregant,<sup>123</sup> M. Broz,<sup>38</sup> G. E. Bruno,<sup>108,34</sup> M. D. Buckland,<sup>129</sup> D. Budnikov,<sup>111</sup> H. Buesching,<sup>69</sup> S. Bufalino,<sup>31</sup> O. Bugnon,<sup>117</sup> P. Buhler,<sup>116</sup> P. Buncic,<sup>35</sup> Z. Buthelezi,<sup>73,133</sup> J. B. Butt,<sup>14</sup> S. A. Bysiak,<sup>120</sup> D. Caffarri,<sup>92</sup> A. Caliva,<sup>109</sup> E. Calvo Villar,<sup>114</sup> J. M. M. Camacho,<sup>122</sup> R. S. Camacho,<sup>46</sup> P. Camerini,<sup>24</sup> F. D. M. Canedo,<sup>123</sup> A. A. Capon,<sup>116</sup> F. Carnesecchi,<sup>26</sup> R. Caron,<sup>139</sup>

J. Castillo Castellanos,<sup>139</sup> E. A. R. Casula,<sup>56</sup> F. Catalano,<sup>31</sup> C. Ceballos Sanchez,<sup>76</sup> P. Chakraborty,<sup>50</sup> S. Chandra,<sup>142</sup> W. Chang,<sup>7</sup> S. Chapeland,<sup>35</sup> M. Chartier,<sup>129</sup> S. Chattopadhyay,<sup>142</sup> S. Chattopadhyay,<sup>112</sup> A. Chauvin,<sup>23</sup> C. Cheshkov,<sup>137</sup> B. Cheynis,<sup>137</sup> V. Chibante Barroso,<sup>35</sup> D. D. Chinellato,<sup>124</sup> S. Cho,<sup>62</sup> P. Chochula,<sup>35</sup> P. Christakoglou,<sup>92</sup> C. H. Christensen,<sup>91</sup> P. Christiansen,<sup>82</sup> T. Chujo,<sup>135</sup> C. Cicalo,<sup>56</sup> L. Cifarelli,<sup>26</sup> F. Cindolo,<sup>55</sup> M. R. Ciupek,<sup>109</sup> G. Clai,<sup>55,a</sup> J. Cleymans,<sup>126</sup> F. Colamaria,<sup>54</sup> J. S. Colburn,<sup>113</sup> D. Colella,<sup>54</sup> A. Collu,<sup>81</sup> M. Colocci,<sup>35,26</sup> M. Concas,<sup>60,b</sup> G. Conesa Balbastre,<sup>80</sup> Z. Conesa del Valle,<sup>79</sup> G. Contin,<sup>24</sup> J. G. Contreras,<sup>38</sup> T. M. Cormier,<sup>98</sup> P. Cortese,<sup>32</sup> M. R. Cosentino,<sup>125</sup> F. Costa,<sup>35</sup> S. Costanza,<sup>29</sup> P. Crochet,<sup>136</sup> E. Cuautle,<sup>70</sup> P. Cui,<sup>7</sup> L. Cunqueiro,<sup>98</sup> T. Dahms,<sup>107</sup> A. Dainese,<sup>58</sup> F. P. A. Damas,<sup>117,139</sup> M. C. Danisch,<sup>106</sup> A. Danu,<sup>68</sup> D. Das,<sup>112</sup> I. Das,<sup>112</sup> P. Das,<sup>88</sup> P. Das,<sup>4</sup> S. Das,<sup>4</sup> S. Dash,<sup>50</sup> S. De,<sup>88</sup> A. De Caro,<sup>30</sup> G. de Cataldo,<sup>54</sup> L. De Cilladi,<sup>25</sup> J. de Cuveland,<sup>40</sup> A. De Falco,<sup>23</sup> D. De Gruttola,<sup>30</sup> N. De Marco,<sup>60</sup> C. De Martin,<sup>24</sup> S. De Pasquale,<sup>30</sup> S. Deb,<sup>51</sup> H. F. Degenhardt,<sup>123</sup> K. R. Deja,<sup>143</sup> S. Delsanto,<sup>25</sup> W. Deng,<sup>7</sup> P. Dhankher,<sup>19,50</sup> D. Di Bari,<sup>34</sup> A. Di Mauro,<sup>35</sup> R. A. Diaz,<sup>8</sup> T. Dietel,<sup>126</sup> P. Dillenseger,<sup>69</sup> Y. Ding,<sup>7</sup> R. Divià,<sup>35</sup> D. U. Dixit,<sup>19</sup> Ø. Djuvsland,<sup>21</sup> U. Dmitrieva,<sup>64</sup> J. Do,<sup>62</sup> A. Dobrin,<sup>68</sup> B. Dönigus,<sup>69</sup> O. Dordic,<sup>20</sup> A. K. Dubey,<sup>142</sup> A. Dubla,<sup>109,92</sup> S. Dudi,<sup>102</sup> M. Dukhishyam,<sup>88</sup> P. Dupieux,<sup>136</sup> T. M. Eder,<sup>145</sup> R. J. Ehlers,<sup>98</sup> V. N. Eikeland,<sup>21</sup> D. Elia,<sup>54</sup> B. Erasmus,<sup>117</sup> F. Erhardt,<sup>101</sup> A. Erokhin,<sup>115</sup> M. R. Ersdal,<sup>21</sup> B. Espagnon,<sup>79</sup> G. Eulisse,<sup>35</sup> D. Evans,<sup>113</sup> S. Evdokimov,<sup>93</sup> L. Fabbietti,<sup>107</sup> M. Faggin,<sup>28</sup> J. Faivre,<sup>80</sup> F. Fan,<sup>7</sup> A. Fantoni,<sup>53</sup> M. Fasel,<sup>98</sup> P. Fecchio,<sup>31</sup> A. Feliciello,<sup>60</sup> G. Feofilov,<sup>115</sup> A. Fernández Téllez,<sup>46</sup> A. Ferrero,<sup>139</sup> A. Ferretti,<sup>25</sup> A. Festanti,<sup>35</sup> V. J. G. Feuillard,<sup>106</sup> J. Figiel,<sup>120</sup> S. Filchagin,<sup>111</sup> D. Finogeev,<sup>64</sup> F. M. Fionda,<sup>21</sup> G. Fiorenza,<sup>54</sup> F. Flor,<sup>127</sup> A. N. Flores,<sup>121</sup> S. Foertsch,<sup>73</sup> P. Foka,<sup>109</sup> S. Fokin,<sup>90</sup> E. Fragiaco,<sup>61</sup> U. Fuchs,<sup>35</sup> C. Furget,<sup>80</sup> A. Furs,<sup>64</sup> M. Fusco Girard,<sup>30</sup> J. J. Gaardhøje,<sup>91</sup> M. Gagliardi,<sup>25</sup> A. M. Gago,<sup>114</sup> A. Gal,<sup>138</sup> C. D. Galvan,<sup>122</sup> P. Ganoti,<sup>86</sup> C. Garabatos,<sup>109</sup> J. R. A. Garcia,<sup>46</sup> E. Garcia-Solis,<sup>10</sup> K. Garg,<sup>117</sup> C. Gargiulo,<sup>35</sup> A. Garibli,<sup>89</sup> K. Garner,<sup>145</sup> P. Gasik,<sup>107</sup> E. F. Gauger,<sup>121</sup> M. B. Gay Ducati,<sup>71</sup> M. Germain,<sup>117</sup> J. Ghosh,<sup>112</sup> P. Ghosh,<sup>142</sup> S. K. Ghosh,<sup>4</sup> M. Giacalone,<sup>26</sup> P. Gianotti,<sup>53</sup> P. Giubellino,<sup>109,60</sup> P. Giubilato,<sup>28</sup> A. M. C. Glaenger,<sup>139</sup> P. Glässel,<sup>106</sup> V. Gonzalez,<sup>144</sup> L. H. González-Trueba,<sup>72</sup> S. Gorbunov,<sup>40</sup> L. Görlich,<sup>120</sup> S. Gotovac,<sup>36</sup> V. Grabski,<sup>72</sup> L. K. Graczykowski,<sup>143</sup> K. L. Graham,<sup>113</sup> L. Greiner,<sup>81</sup> A. Grelli,<sup>63</sup> C. Grigoras,<sup>35</sup> V. Grigoriev,<sup>95</sup> A. Grigoryan,<sup>1</sup> S. Grigoryan,<sup>76</sup> O. S. Groettvik,<sup>21</sup> F. Grosa,<sup>60</sup> J. F. Grosse-Oetringhaus,<sup>35</sup> R. Grosso,<sup>109</sup> R. Guernane,<sup>80</sup> M. Guilbaud,<sup>117</sup> M. Guittiere,<sup>117</sup> K. Gulbrandsen,<sup>91</sup> T. Gunji,<sup>134</sup> A. Gupta,<sup>103</sup> R. Gupta,<sup>103</sup> I. B. Guzman,<sup>46</sup> R. Haake,<sup>147</sup> M. K. Habib,<sup>109</sup> C. Hadjidakis,<sup>79</sup> H. Hamagaki,<sup>84</sup> G. Hamar,<sup>146</sup> M. Hamid,<sup>7</sup> R. Hannigan,<sup>121</sup> M. R. Haque,<sup>143,88</sup> A. Harlenderova,<sup>109</sup> J. W. Harris,<sup>147</sup> A. Harton,<sup>10</sup> J. A. Hasenbichler,<sup>35</sup> H. Hassan,<sup>98</sup> D. Hatzifotiadou,<sup>55</sup> P. Hauer,<sup>44</sup> L. B. Havener,<sup>147</sup> S. Hayashi,<sup>134</sup> S. T. Heckel,<sup>107</sup> E. Hellbär,<sup>69</sup> H. Helstrup,<sup>37</sup> T. Herman,<sup>38</sup> E. G. Hernandez,<sup>46</sup> G. Herrera Corral,<sup>9</sup> F. Herrmann,<sup>145</sup> K. F. Hetland,<sup>37</sup> H. Hillemanns,<sup>35</sup> C. Hills,<sup>129</sup> B. Hippolyte,<sup>138</sup> B. Hohlweger,<sup>107</sup> J. Honermann,<sup>145</sup> G. H. Hong,<sup>148</sup> D. Horak,<sup>38</sup> S. Hornung,<sup>109</sup> R. Hosokawa,<sup>15</sup> P. Hristov,<sup>35</sup> C. Huang,<sup>79</sup> C. Hughes,<sup>132</sup> P. Huhn,<sup>69</sup> T. J. Humanic,<sup>99</sup> H. Hushnud,<sup>112</sup> L. A. Husova,<sup>145</sup> N. Hussain,<sup>43</sup> D. Hutter,<sup>40</sup> J. P. Iddon,<sup>35,129</sup> R. Ilkaev,<sup>111</sup> H. Ilyas,<sup>14</sup> M. Inaba,<sup>135</sup> G. M. Innocenti,<sup>35</sup> M. Ippolitov,<sup>90</sup> A. Isakov,<sup>38,97</sup> M. S. Islam,<sup>112</sup> M. Ivanov,<sup>109</sup> V. Ivanov,<sup>100</sup> V. Izucheev,<sup>93</sup> B. Jacak,<sup>81</sup> N. Jacazio,<sup>35,55</sup> P. M. Jacobs,<sup>81</sup> S. Jadlovská,<sup>119</sup> J. Jadlovsky,<sup>119</sup> S. Jaelani,<sup>63</sup> C. Jahnke,<sup>123</sup> M. J. Jakubowska,<sup>143</sup> M. A. Janik,<sup>143</sup> T. Janson,<sup>75</sup> M. Jercic,<sup>101</sup> O. Jevons,<sup>113</sup> M. Jin,<sup>127</sup> F. Jonas,<sup>98,145</sup> P. G. Jones,<sup>113</sup> J. Jung,<sup>69</sup> M. Jung,<sup>69</sup> A. Jusko,<sup>113</sup> P. Kalinak,<sup>65</sup> A. Kalweit,<sup>35</sup> V. Kaplin,<sup>95</sup> S. Kar,<sup>7</sup> A. Karasu Uysal,<sup>78</sup> D. Karatovic,<sup>101</sup> O. Karavichev,<sup>64</sup> T. Karavicheva,<sup>64</sup> P. Karczmarczyk,<sup>143</sup> E. Karpechev,<sup>64</sup> A. Kazantsev,<sup>90</sup> U. Keschull,<sup>75</sup> R. Keidel,<sup>48</sup> M. Keil,<sup>35</sup> B. Ketzer,<sup>44</sup> Z. Khabanova,<sup>92</sup> A. M. Khan,<sup>7</sup> S. Khan,<sup>16</sup> A. Khanzadeev,<sup>100</sup> Y. Kharlov,<sup>93</sup> A. Khatun,<sup>16</sup> A. Khuntia,<sup>120</sup> B. Kileng,<sup>37</sup> B. Kim,<sup>62</sup> D. Kim,<sup>148</sup> D. J. Kim,<sup>128</sup> E. J. Kim,<sup>74</sup> H. Kim,<sup>17</sup> J. Kim,<sup>148</sup> J. S. Kim,<sup>42</sup> J. Kim,<sup>106</sup> J. Kim,<sup>148</sup> J. Kim,<sup>74</sup> M. Kim,<sup>106</sup> S. Kim,<sup>18</sup> T. Kim,<sup>148</sup> T. Kim,<sup>148</sup> S. Kirsch,<sup>69</sup> I. Kisel,<sup>40</sup> S. Kiselev,<sup>94</sup> A. Kisiel,<sup>143</sup> J. L. Klay,<sup>6</sup> J. Klein,<sup>35,60</sup> S. Klein,<sup>81</sup> C. Klein-Bösing,<sup>145</sup> M. Kleiner,<sup>69</sup> T. Klemenz,<sup>107</sup> A. Kluge,<sup>35</sup> A. G. Knospe,<sup>127</sup> C. Kobdaj,<sup>118</sup> M. K. Köhler,<sup>106</sup> T. Kollegger,<sup>109</sup> A. Kondratyev,<sup>76</sup> N. Kondratyeva,<sup>95</sup> E. Kondratyuk,<sup>93</sup> J. König,<sup>69</sup> S. A. Königstorfer,<sup>107</sup> P. J. Konopka,<sup>2,35</sup> G. Kornakov,<sup>143</sup> S. D. Koryciak,<sup>2</sup> L. Koska,<sup>119</sup> O. Kovalenko,<sup>87</sup> V. Kovalenko,<sup>115</sup> M. Kowalski,<sup>120</sup> I. Králik,<sup>65</sup> A. Kravčáková,<sup>39</sup> L. Kreis,<sup>109</sup> M. Krivda,<sup>113,65</sup> F. Krizek,<sup>97</sup> K. Krizkova Gajdosova,<sup>38</sup> M. Kroesen,<sup>106</sup> M. Krüger,<sup>69</sup> E. Kryshen,<sup>100</sup> M. Krzewicki,<sup>40</sup> V. Kučera,<sup>35</sup> C. Kuhn,<sup>138</sup> P. G. Kuijer,<sup>92</sup> T. Kumaoka,<sup>135</sup> L. Kumar,<sup>102</sup> S. Kundu,<sup>88</sup> P. Kurashvili,<sup>87</sup> A. Kurepin,<sup>64</sup> A. B. Kurepin,<sup>64</sup> A. Kuryakin,<sup>111</sup> S. Kushpil,<sup>97</sup> J. Kvapil,<sup>113</sup> M. J. Kweon,<sup>62</sup> J. Y. Kwon,<sup>62</sup> Y. Kwon,<sup>148</sup> S. L. La Pointe,<sup>40</sup> P. La Rocca,<sup>27</sup> Y. S. Lai,<sup>81</sup> A. Lakrathok,<sup>118</sup> M. Lamanna,<sup>35</sup> R. Langoy,<sup>131</sup> K. Lapidus,<sup>35</sup> P. Larionov,<sup>53</sup> E. Laudi,<sup>35</sup> L. Lautner,<sup>35</sup> R. Lavicka,<sup>38</sup> T. Lazareva,<sup>115</sup> R. Lea,<sup>24</sup> J. Lee,<sup>135</sup> S. Lee,<sup>148</sup> J. Lehrbach,<sup>40</sup> R. C. Lemmon,<sup>96</sup> I. León Monzón,<sup>122</sup> E. D. Lesser,<sup>19</sup> M. Lettrich,<sup>35</sup> P. Lévai,<sup>146</sup> X. Li,<sup>11</sup> X. L. Li,<sup>7</sup> J. Lien,<sup>131</sup> R. Lietava,<sup>113</sup> B. Lim,<sup>17</sup> S. H. Lim,<sup>17</sup> V. Lindenstruth,<sup>40</sup> A. Lindner,<sup>49</sup> C. Lippmann,<sup>109</sup> A. Liu,<sup>19</sup> J. Liu,<sup>129</sup> I. M. Lofnes,<sup>21</sup> V. Loginov,<sup>95</sup> C. Loizides,<sup>98</sup> P. Loncar,<sup>36</sup> J. A. Lopez,<sup>106</sup> X. Lopez,<sup>136</sup> E. López Torres,<sup>8</sup> J. R. Luhder,<sup>145</sup> M. Lunardon,<sup>28</sup>

G. Luparello,<sup>61</sup> Y. G. Ma,<sup>41</sup> A. Maevskaya,<sup>64</sup> M. Mager,<sup>35</sup> S. M. Mahmood,<sup>20</sup> T. Mahmoud,<sup>44</sup> A. Maire,<sup>138</sup> R. D. Majka,<sup>147,†</sup>  
M. Malaev,<sup>100</sup> Q. W. Malik,<sup>20</sup> L. Malinina,<sup>76,c</sup> D. Mal'Kevich,<sup>94</sup> N. Mallick,<sup>51</sup> P. Malzacher,<sup>109</sup> G. Mandaglio,<sup>33,57</sup>  
V. Manko,<sup>90</sup> F. Manso,<sup>136</sup> V. Manzari,<sup>54</sup> Y. Mao,<sup>7</sup> M. Marchisone,<sup>137</sup> J. Mareš,<sup>67</sup> G. V. Margagliotti,<sup>24</sup> A. Margotti,<sup>55</sup>  
A. Marín,<sup>109</sup> C. Markert,<sup>121</sup> M. Marquard,<sup>69</sup> N. A. Martin,<sup>106</sup> P. Martinengo,<sup>35</sup> J. L. Martinez,<sup>127</sup> M. I. Martínez,<sup>46</sup>  
G. Martínez García,<sup>117</sup> S. Masciocchi,<sup>109</sup> M. Masera,<sup>25</sup> A. Masoni,<sup>56</sup> L. Massacrier,<sup>79</sup> A. Mastroserio,<sup>140,54</sup> A. M. Mathis,<sup>107</sup>  
O. Matonoha,<sup>82</sup> P. F. T. Matuoka,<sup>123</sup> A. Matyja,<sup>120</sup> C. Mayer,<sup>120</sup> F. Mazzaschi,<sup>25</sup> M. Mazzilli,<sup>54</sup> M. A. Mazzoni,<sup>59</sup>  
A. F. Mechler,<sup>69</sup> F. Meddi,<sup>22</sup> Y. Melikyan,<sup>64</sup> A. Menchaca-Rocha,<sup>72</sup> C. Mengke,<sup>7</sup> E. Meninno,<sup>116,30</sup> A. S. Menon,<sup>127</sup>  
M. Meres,<sup>13</sup> S. Mhlanga,<sup>126</sup> Y. Mlake,<sup>135</sup> L. Micheletti,<sup>25</sup> L. C. Migliorin,<sup>137</sup> D. L. Mihaylov,<sup>107</sup> K. Mikhaylov,<sup>76,94</sup>  
A. N. Mishra,<sup>146,70</sup> D. Miśkowiec,<sup>109</sup> A. Modak,<sup>4</sup> N. Mohammadi,<sup>35</sup> A. P. Mohanty,<sup>63</sup> B. Mohanty,<sup>88</sup> M. Mohisin Khan,<sup>16</sup>  
Z. Moravcova,<sup>91</sup> C. Mordasini,<sup>107</sup> D. A. Moreira De Godoy,<sup>145</sup> L. A. P. Moreno,<sup>46</sup> I. Morozov,<sup>64</sup> A. Morsch,<sup>35</sup> T. Mrnjavac,<sup>35</sup>  
V. Muccifora,<sup>53</sup> E. Mudnic,<sup>36</sup> D. Mühlheim,<sup>145</sup> S. Muhuri,<sup>142</sup> J. D. Mulligan,<sup>81</sup> A. Mulliri,<sup>23,56</sup> M. G. Munhoz,<sup>123</sup>  
R. H. Munzer,<sup>69</sup> H. Murakami,<sup>134</sup> S. Murray,<sup>126</sup> L. Musa,<sup>35</sup> J. Musinsky,<sup>65</sup> C. J. Myers,<sup>127</sup> J. W. Myrcha,<sup>143</sup> B. Naik,<sup>50</sup>  
R. Nair,<sup>87</sup> B. K. Nandi,<sup>50</sup> R. Nania,<sup>55</sup> E. Nappi,<sup>54</sup> M. U. Naru,<sup>14</sup> A. F. Nassirpour,<sup>82</sup> C. Natrass,<sup>132</sup> R. Nayak,<sup>50</sup>  
S. Nazarenko,<sup>111</sup> A. Neagu,<sup>20</sup> L. Nellen,<sup>70</sup> S. V. Nesbo,<sup>37</sup> G. Neskovic,<sup>40</sup> D. Nesterov,<sup>115</sup> B. S. Nielsen,<sup>91</sup> S. Nikolaev,<sup>90</sup>  
S. Nikulin,<sup>90</sup> V. Nikulin,<sup>100</sup> F. Noferini,<sup>55</sup> S. Noh,<sup>12</sup> P. Nomokonov,<sup>76</sup> J. Norman,<sup>129</sup> N. Novitzky,<sup>135</sup> P. Nowakowski,<sup>143</sup>  
A. Nyanin,<sup>90</sup> J. Nystrand,<sup>21</sup> M. Ogino,<sup>84</sup> A. Ohlson,<sup>82</sup> J. Oleniacz,<sup>143</sup> A. C. Oliveira Da Silva,<sup>132</sup> M. H. Oliver,<sup>147</sup>  
B. S. Onnerstad,<sup>128</sup> C. Oppedisano,<sup>60</sup> A. Ortiz Velasquez,<sup>70</sup> T. Osako,<sup>47</sup> A. Oskarsson,<sup>82</sup> J. Otwinowski,<sup>120</sup> K. Oyama,<sup>84</sup>  
Y. Pachmayer,<sup>106</sup> S. Padhan,<sup>50</sup> D. Pagano,<sup>141</sup> G. Paić,<sup>70</sup> J. Pan,<sup>144</sup> S. Panebianco,<sup>139</sup> P. Pareek,<sup>142</sup> J. Park,<sup>62</sup> J. E. Parkkila,<sup>128</sup>  
S. Parmar,<sup>102</sup> S. P. Pathak,<sup>127</sup> B. Paul,<sup>23</sup> J. Pazzini,<sup>141</sup> H. Pei,<sup>7</sup> T. Peitzmann,<sup>63</sup> X. Peng,<sup>7</sup> L. G. Pereira,<sup>71</sup>  
H. Pereira Da Costa,<sup>139</sup> D. Peresunko,<sup>90</sup> G. M. Perez,<sup>8</sup> S. Perrin,<sup>139</sup> Y. Pestov,<sup>5</sup> V. Petráček,<sup>38</sup> M. Petrovici,<sup>49</sup> R. P. Pezzi,<sup>71</sup>  
S. Piano,<sup>61</sup> M. Pikna,<sup>13</sup> P. Pillot,<sup>117</sup> O. Pinazza,<sup>55,35</sup> L. Pinsky,<sup>127</sup> C. Pinto,<sup>27</sup> S. Pisano,<sup>53</sup> M. Płoskoń,<sup>81</sup> M. Planinic,<sup>101</sup>  
F. Pliquett,<sup>69</sup> M. G. Poghosyan,<sup>98</sup> B. Polichtchouk,<sup>93</sup> N. Poljak,<sup>101</sup> A. Pop,<sup>49</sup> S. Porteboeuf-Houssais,<sup>136</sup> J. Porter,<sup>81</sup>  
V. Pozdniakov,<sup>76</sup> S. K. Prasad,<sup>4</sup> R. Preghenella,<sup>55</sup> F. Prino,<sup>60</sup> C. A. Pruneau,<sup>144</sup> I. Pshenichnov,<sup>64</sup> M. Puccio,<sup>35</sup> S. Qiu,<sup>92</sup>  
L. Quaglia,<sup>25</sup> R. E. Quishpe,<sup>127</sup> S. Ragoni,<sup>113</sup> J. Rak,<sup>128</sup> A. Rakotozafindrabe,<sup>139</sup> L. Ramello,<sup>32</sup> F. Rami,<sup>138</sup>  
S. A. R. Ramirez,<sup>46</sup> A. G. T. Ramos,<sup>34</sup> R. Raniwala,<sup>104</sup> S. Raniwala,<sup>104</sup> S. S. Räsänen,<sup>45</sup> R. Rath,<sup>51</sup> I. Ravasenga,<sup>92</sup>  
K. F. Read,<sup>98,132</sup> A. R. Redelbach,<sup>40</sup> K. Redlich,<sup>87,d</sup> A. Rehman,<sup>21</sup> P. Reichelt,<sup>69</sup> F. Reidt,<sup>35</sup> R. Renfordt,<sup>69</sup> Z. Rescakova,<sup>39</sup>  
K. Reygers,<sup>106</sup> A. Riabov,<sup>100</sup> V. Riabov,<sup>100</sup> T. Richert,<sup>82,91</sup> M. Richter,<sup>20</sup> P. Riedler,<sup>35</sup> W. Riegler,<sup>35</sup> F. Riggi,<sup>27</sup> C. Ristea,<sup>68</sup>  
S. P. Rode,<sup>51</sup> M. Rodríguez Cahuantzi,<sup>46</sup> K. Røed,<sup>20</sup> R. Rogalev,<sup>93</sup> E. Rogochaya,<sup>76</sup> T. S. Rogoschinski,<sup>69</sup> D. Rohr,<sup>35</sup>  
D. Röhrich,<sup>21</sup> P. F. Rojas,<sup>46</sup> P. S. Rokita,<sup>143</sup> F. Ronchetti,<sup>53</sup> A. Rosano,<sup>33,57</sup> E. D. Rosas,<sup>70</sup> A. Rossi,<sup>58</sup> A. Rotondi,<sup>29</sup> A. Roy,<sup>51</sup>  
P. Roy,<sup>112</sup> O. V. Rueda,<sup>82</sup> R. Rui,<sup>24</sup> B. Rumyantsev,<sup>76</sup> A. Rustamov,<sup>89</sup> E. Ryabinkin,<sup>90</sup> Y. Ryabov,<sup>100</sup> A. Rybicki,<sup>120</sup>  
H. Rytkonen,<sup>128</sup> O. A. M. Saarimaki,<sup>45</sup> R. Sadek,<sup>117</sup> S. Sadvovskiy,<sup>93</sup> J. Saetre,<sup>21</sup> K. Šafařík,<sup>38</sup> S. K. Saha,<sup>142</sup> S. Saha,<sup>88</sup>  
B. Sahoo,<sup>50</sup> P. Sahoo,<sup>50</sup> R. Sahoo,<sup>51</sup> S. Sahoo,<sup>66</sup> D. Sahu,<sup>51</sup> P. K. Sahu,<sup>66</sup> J. Saini,<sup>142</sup> S. Sakai,<sup>135</sup> S. Sambyal,<sup>103</sup>  
V. Samsonov,<sup>100,95</sup> D. Sarkar,<sup>144</sup> N. Sarkar,<sup>142</sup> P. Sarma,<sup>43</sup> V. M. Sarti,<sup>107</sup> M. H. P. Sas,<sup>147,63</sup> J. Schambach,<sup>98,121</sup>  
H. S. Scheid,<sup>69</sup> C. Schiaua,<sup>49</sup> R. Schicker,<sup>106</sup> A. Schmah,<sup>106</sup> C. Schmidt,<sup>109</sup> H. R. Schmidt,<sup>105</sup> M. O. Schmidt,<sup>106</sup>  
M. Schmidt,<sup>105</sup> N. V. Schmidt,<sup>98,69</sup> A. R. Schmier,<sup>132</sup> R. Schotter,<sup>138</sup> J. Schukraft,<sup>35</sup> Y. Schutz,<sup>138</sup> K. Schwarz,<sup>109</sup>  
K. Schweda,<sup>109</sup> G. Scioli,<sup>26</sup> E. Scomparin,<sup>60</sup> J. E. Seger,<sup>15</sup> Y. Sekiguchi,<sup>134</sup> D. Sekihata,<sup>134</sup> I. Selyuzhenkov,<sup>109,95</sup>  
S. Senyukov,<sup>138</sup> J. J. Seo,<sup>62</sup> D. Serebryakov,<sup>64</sup> L. Šerkšnytė,<sup>107</sup> A. Sevcenco,<sup>68</sup> A. Shabanov,<sup>64</sup> A. Shabetai,<sup>117</sup>  
R. Shahoyan,<sup>35</sup> W. Shaikh,<sup>112</sup> A. Shangaraev,<sup>93</sup> A. Sharma,<sup>102</sup> H. Sharma,<sup>120</sup> M. Sharma,<sup>103</sup> N. Sharma,<sup>102</sup> S. Sharma,<sup>103</sup>  
O. Sheibani,<sup>127</sup> A. I. Sheikh,<sup>142</sup> K. Shigaki,<sup>47</sup> M. Shimomura,<sup>85</sup> S. Shirinkin,<sup>94</sup> Q. Shou,<sup>41</sup> Y. Sibiriak,<sup>90</sup> S. Siddhanta,<sup>56</sup>  
T. Siemiarczuk,<sup>87</sup> D. Silvermyr,<sup>82</sup> G. Simatovic,<sup>92</sup> G. Simonetti,<sup>35</sup> B. Singh,<sup>107</sup> R. Singh,<sup>88</sup> R. Singh,<sup>103</sup> R. Singh,<sup>51</sup>  
V. K. Singh,<sup>142</sup> V. Singhal,<sup>142</sup> T. Sinha,<sup>112</sup> B. Sitar,<sup>13</sup> M. Sitta,<sup>32</sup> T. B. Skaali,<sup>20</sup> M. Slupecki,<sup>45</sup> N. Smirnov,<sup>147</sup>  
R. J. M. Snellings,<sup>63</sup> C. Soncco,<sup>114</sup> J. Song,<sup>127</sup> A. Songmoolnak,<sup>118</sup> F. Soramel,<sup>28</sup> S. Sorensen,<sup>132</sup> I. Sputowska,<sup>120</sup>  
J. Stachel,<sup>106</sup> I. Stan,<sup>68</sup> P. J. Steffanic,<sup>132</sup> S. F. Stiefelmaier,<sup>106</sup> D. Stocco,<sup>117</sup> M. M. Storetvedt,<sup>37</sup> L. D. Stritto,<sup>30</sup>  
C. P. Stylianidis,<sup>92</sup> A. A. P. Suaide,<sup>123</sup> T. Sugitate,<sup>47</sup> C. Suire,<sup>79</sup> M. Suljic,<sup>35</sup> R. Sultanov,<sup>94</sup> M. Šumbera,<sup>97</sup> V. Sumberia,<sup>103</sup>  
S. Sumowidagdo,<sup>52</sup> S. Swain,<sup>66</sup> A. Szabo,<sup>13</sup> I. Szarka,<sup>13</sup> U. Tabassam,<sup>14</sup> S. F. Taghavi,<sup>107</sup> G. Taillepied,<sup>136</sup> J. Takahashi,<sup>124</sup>  
G. J. Tambave,<sup>21</sup> S. Tang,<sup>136,7</sup> Z. Tang,<sup>130</sup> M. Tarhini,<sup>117</sup> M. G. Tazila,<sup>49</sup> A. Tauro,<sup>35</sup> G. Tejada Muñoz,<sup>46</sup> A. Telesca,<sup>35</sup>  
L. Terlizzi,<sup>25</sup> C. Terrevoli,<sup>127</sup> G. Tersimonov,<sup>3</sup> S. Thakur,<sup>142</sup> D. Thomas,<sup>121</sup> F. Thoresen,<sup>91</sup> R. Tieulent,<sup>137</sup> A. Tikhonov,<sup>64</sup>  
A. R. Timmins,<sup>127</sup> M. Tkacik,<sup>119</sup> A. Toia,<sup>69</sup> N. Topilskaya,<sup>64</sup> M. Toppi,<sup>53</sup> F. Torales-Acosta,<sup>19</sup> S. R. Torres,<sup>38,9</sup> A. Trifiró,<sup>33,57</sup>  
S. Tripathy,<sup>70</sup> T. Tripathy,<sup>50</sup> S. Trogolo,<sup>28</sup> G. Trombetta,<sup>34</sup> L. Tropp,<sup>39</sup> V. Trubnikov,<sup>3</sup> W. H. Trzaska,<sup>128</sup> T. P. Trzcinski,<sup>143</sup>

B. A. Trzeciak,<sup>38</sup> A. Tumkin,<sup>111</sup> R. Turrisi,<sup>58</sup> T. S. Tveter,<sup>20</sup> K. Ullaland,<sup>21</sup> E. N. Umaka,<sup>127</sup> A. Uras,<sup>137</sup> G. L. Usai,<sup>23</sup> M. Vala,<sup>39</sup> N. Valle,<sup>29</sup> S. Vallerio,<sup>60</sup> N. van der Kolk,<sup>63</sup> L. V. R. van Doremalen,<sup>63</sup> M. van Leeuwen,<sup>92</sup> P. Vande Vyvre,<sup>35</sup> D. Varga,<sup>146</sup> Z. Varga,<sup>146</sup> M. Varga-Kofarago,<sup>146</sup> A. Vargas,<sup>46</sup> M. Vasileiou,<sup>86</sup> A. Vasiliev,<sup>90</sup> O. Vázquez Doce,<sup>107</sup> V. Vechernin,<sup>115</sup> E. Vercellin,<sup>25</sup> S. Vergara Limón,<sup>46</sup> L. Vermunt,<sup>63</sup> R. Vértesi,<sup>146</sup> M. Verweij,<sup>63</sup> L. Vickovic,<sup>36</sup> Z. Vilakazi,<sup>133</sup> O. Villalobos Baillie,<sup>113</sup> G. Vino,<sup>54</sup> A. Vinogradov,<sup>90</sup> T. Virgili,<sup>30</sup> V. Vislavicius,<sup>91</sup> A. Vodopyanov,<sup>76</sup> B. Volkel,<sup>35</sup> M. A. Völkl,<sup>105</sup> K. Voloshin,<sup>94</sup> S. A. Voloshin,<sup>144</sup> G. Volpe,<sup>34</sup> B. von Haller,<sup>35</sup> I. Vorobyev,<sup>107</sup> D. Voscek,<sup>119</sup> J. Vrláková,<sup>39</sup> B. Wagner,<sup>21</sup> M. Weber,<sup>116</sup> A. Wegrzynek,<sup>35</sup> S. C. Wenzel,<sup>35</sup> J. P. Wessels,<sup>145</sup> J. Wiechula,<sup>69</sup> J. Wikne,<sup>20</sup> G. Wilk,<sup>87</sup> J. Wilkinson,<sup>109</sup> G. A. Willems,<sup>145</sup> E. Willsher,<sup>113</sup> B. Windelband,<sup>106</sup> M. Winn,<sup>139</sup> W. E. Witt,<sup>132</sup> J. R. Wright,<sup>121</sup> Y. Wu,<sup>130</sup> R. Xu,<sup>7</sup> S. Yalcin,<sup>78</sup> Y. Yamaguchi,<sup>47</sup> K. Yamakawa,<sup>47</sup> S. Yang,<sup>21</sup> S. Yano,<sup>47,139</sup> Z. Yin,<sup>7</sup> H. Yokoyama,<sup>63</sup> I.-K. Yoo,<sup>17</sup> J. H. Yoon,<sup>62</sup> S. Yuan,<sup>21</sup> A. Yuncu,<sup>106</sup> V. Yurchenko,<sup>3</sup> V. Zaccolo,<sup>24</sup> A. Zaman,<sup>14</sup> C. Zampolli,<sup>35</sup> H. J. C. Zanoli,<sup>63</sup> N. Zardoshti,<sup>35</sup> A. Zarochentsev,<sup>115</sup> P. Závada,<sup>67</sup> N. Zaviyalov,<sup>111</sup> H. Zbroszczyk,<sup>143</sup> M. Zhalov,<sup>100</sup> S. Zhang,<sup>41</sup> X. Zhang,<sup>7</sup> Y. Zhang,<sup>130</sup> V. Zhrebchevskii,<sup>115</sup> Y. Zhi,<sup>11</sup> D. Zhou,<sup>7</sup> Y. Zhou,<sup>91</sup> J. Zhu,<sup>7,109</sup> Y. Zhu,<sup>7</sup> A. Zichichi,<sup>26</sup> G. Zinovjev,<sup>3</sup> and N. Zurlo<sup>141</sup>

(ALICE Collaboration)

<sup>1</sup>A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia

<sup>2</sup>AGH University of Science and Technology, Cracow, Poland

<sup>3</sup>Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine

<sup>4</sup>Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India

<sup>5</sup>Budker Institute for Nuclear Physics, Novosibirsk, Russia

<sup>6</sup>California Polytechnic State University, San Luis Obispo, California, USA

<sup>7</sup>Central China Normal University, Wuhan, China

<sup>8</sup>Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba

<sup>9</sup>Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico

<sup>10</sup>Chicago State University, Chicago, Illinois, USA

<sup>11</sup>China Institute of Atomic Energy, Beijing, China

<sup>12</sup>Chungbuk National University, Cheongju, Republic of Korea

<sup>13</sup>Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia

<sup>14</sup>COMSATS University Islamabad, Islamabad, Pakistan

<sup>15</sup>Creighton University, Omaha, Nebraska, USA

<sup>16</sup>Department of Physics, Aligarh Muslim University, Aligarh, India

<sup>17</sup>Department of Physics, Pusan National University, Pusan, Republic of Korea

<sup>18</sup>Department of Physics, Sejong University, Seoul, Republic of Korea

<sup>19</sup>Department of Physics, University of California, Berkeley, California, USA

<sup>20</sup>Department of Physics, University of Oslo, Oslo, Norway

<sup>21</sup>Department of Physics and Technology, University of Bergen, Bergen, Norway

<sup>22</sup>Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy

<sup>23</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy

<sup>24</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy

<sup>25</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy

<sup>26</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy

<sup>27</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy

<sup>28</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy

<sup>29</sup>Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia and Sezione INFN, Pavia, Italy

<sup>30</sup>Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy

<sup>31</sup>Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy

<sup>32</sup>Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy

<sup>33</sup>Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy

<sup>34</sup>Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy

<sup>35</sup>European Organization for Nuclear Research (CERN), Geneva, Switzerland

<sup>36</sup>Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia

<sup>37</sup>Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway

<sup>38</sup>Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic

<sup>39</sup>Faculty of Science, P.J. Šafárik University, Košice, Slovakia

- <sup>40</sup>Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- <sup>41</sup>Fudan University, Shanghai, China
- <sup>42</sup>Gangneung-Wonju National University, Gangneung, Republic of Korea
- <sup>43</sup>Gauhati University, Department of Physics, Guwahati, India
- <sup>44</sup>Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
- <sup>45</sup>Helsinki Institute of Physics (HIP), Helsinki, Finland
- <sup>46</sup>High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
- <sup>47</sup>Hiroshima University, Hiroshima, Japan
- <sup>48</sup>Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
- <sup>49</sup>Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- <sup>50</sup>Indian Institute of Technology Bombay (IIT), Mumbai, India
- <sup>51</sup>Indian Institute of Technology Indore, Indore, India
- <sup>52</sup>Indonesian Institute of Sciences, Jakarta, Indonesia
- <sup>53</sup>INFN, Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>54</sup>INFN, Sezione di Bari, Bari, Italy
- <sup>55</sup>INFN, Sezione di Bologna, Bologna, Italy
- <sup>56</sup>INFN, Sezione di Cagliari, Cagliari, Italy
- <sup>57</sup>INFN, Sezione di Catania, Catania, Italy
- <sup>58</sup>INFN, Sezione di Padova, Padova, Italy
- <sup>59</sup>INFN, Sezione di Roma, Rome, Italy
- <sup>60</sup>INFN, Sezione di Torino, Turin, Italy
- <sup>61</sup>INFN, Sezione di Trieste, Trieste, Italy
- <sup>62</sup>Inha University, Incheon, Republic of Korea
- <sup>63</sup>Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
- <sup>64</sup>Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
- <sup>65</sup>Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
- <sup>66</sup>Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
- <sup>67</sup>Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
- <sup>68</sup>Institute of Space Science (ISS), Bucharest, Romania
- <sup>69</sup>Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- <sup>70</sup>Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- <sup>71</sup>Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
- <sup>72</sup>Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- <sup>73</sup>iThemba LABS, National Research Foundation, Somerset West, South Africa
- <sup>74</sup>Jeonbuk National University, Jeonju, Republic of Korea
- <sup>75</sup>Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
- <sup>76</sup>Joint Institute for Nuclear Research (JINR), Dubna, Russia
- <sup>77</sup>Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
- <sup>78</sup>KTO Karatay University, Konya, Turkey
- <sup>79</sup>Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
- <sup>80</sup>Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
- <sup>81</sup>Lawrence Berkeley National Laboratory, Berkeley, California, USA
- <sup>82</sup>Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
- <sup>83</sup>Moscow Institute for Physics and Technology, Moscow, Russia
- <sup>84</sup>Nagasaki Institute of Applied Science, Nagasaki, Japan
- <sup>85</sup>Nara Women's University (NWU), Nara, Japan
- <sup>86</sup>National and Kapodistrian University of Athens, School of Science, Department of Physics, Athens, Greece
- <sup>87</sup>National Centre for Nuclear Research, Warsaw, Poland
- <sup>88</sup>National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
- <sup>89</sup>National Nuclear Research Center, Baku, Azerbaijan
- <sup>90</sup>National Research Centre Kurchatov Institute, Moscow, Russia
- <sup>91</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>92</sup>Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
- <sup>93</sup>NRC Kurchatov Institute IHEP, Protvino, Russia
- <sup>94</sup>NRC «Kurchatov» Institute - ITEP, Moscow, Russia
- <sup>95</sup>NRNU Moscow Engineering Physics Institute, Moscow, Russia
- <sup>96</sup>Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
- <sup>97</sup>Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
- <sup>98</sup>Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
- <sup>99</sup>Ohio State University, Columbus, Ohio, USA

- <sup>100</sup>*Petersburg Nuclear Physics Institute, Gatchina, Russia*
- <sup>101</sup>*Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia*
- <sup>102</sup>*Physics Department, Panjab University, Chandigarh, India*
- <sup>103</sup>*Physics Department, University of Jammu, Jammu, India*
- <sup>104</sup>*Physics Department, University of Rajasthan, Jaipur, India*
- <sup>105</sup>*Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany*
- <sup>106</sup>*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- <sup>107</sup>*Physik Department, Technische Universität München, Munich, Germany*
- <sup>108</sup>*Politecnico di Bari and Sezione INFN, Bari, Italy*
- <sup>109</sup>*Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany*
- <sup>110</sup>*Rudjer Bošković Institute, Zagreb, Croatia*
- <sup>111</sup>*Russian Federal Nuclear Center (VNIIEF), Sarov, Russia*
- <sup>112</sup>*Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India*
- <sup>113</sup>*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- <sup>114</sup>*Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru*
- <sup>115</sup>*St. Petersburg State University, St. Petersburg, Russia*
- <sup>116</sup>*Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria*
- <sup>117</sup>*SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France*
- <sup>118</sup>*Suranaree University of Technology, Nakhon Ratchasima, Thailand*
- <sup>119</sup>*Technical University of Košice, Košice, Slovakia*
- <sup>120</sup>*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*
- <sup>121</sup>*The University of Texas at Austin, Austin, Texas, USA*
- <sup>122</sup>*Universidad Autónoma de Sinaloa, Culiacán, Mexico*
- <sup>123</sup>*Universidade de São Paulo (USP), São Paulo, Brazil*
- <sup>124</sup>*Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*
- <sup>125</sup>*Universidade Federal do ABC, Santo Andre, Brazil*
- <sup>126</sup>*University of Cape Town, Cape Town, South Africa*
- <sup>127</sup>*University of Houston, Houston, Texas, USA*
- <sup>128</sup>*University of Jyväskylä, Jyväskylä, Finland*
- <sup>129</sup>*University of Liverpool, Liverpool, United Kingdom*
- <sup>130</sup>*University of Science and Technology of China, Hefei, China*
- <sup>131</sup>*University of South-Eastern Norway, Tonsberg, Norway*
- <sup>132</sup>*University of Tennessee, Knoxville, Tennessee, USA*
- <sup>133</sup>*University of the Witwatersrand, Johannesburg, South Africa*
- <sup>134</sup>*University of Tokyo, Tokyo, Japan*
- <sup>135</sup>*University of Tsukuba, Tsukuba, Japan*
- <sup>136</sup>*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
- <sup>137</sup>*Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France*
- <sup>138</sup>*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France*
- <sup>139</sup>*Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Département de Physique Nucléaire (DPhN), Saclay, France*
- <sup>140</sup>*Università degli Studi di Foggia, Foggia, Italy*
- <sup>141</sup>*Università di Brescia and Sezione INFN, Brescia, Italy*
- <sup>142</sup>*Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India*
- <sup>143</sup>*Warsaw University of Technology, Warsaw, Poland*
- <sup>144</sup>*Wayne State University, Detroit, Michigan, USA*
- <sup>145</sup>*Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany*
- <sup>146</sup>*Wigner Research Centre for Physics, Budapest, Hungary*
- <sup>147</sup>*Yale University, New Haven, Connecticut, USA*
- <sup>148</sup>*Yonsei University, Seoul, Republic of Korea*

<sup>†</sup>Deceased.

<sup>a</sup>Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy.

<sup>b</sup>Also at Dipartimento DET del Politecnico di Torino, Turin, Italy.

<sup>c</sup>Also at M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia.

<sup>d</sup>Also at Institute of Theoretical Physics, University of Wrocław, Poland.