

D-Meson Azimuthal Anisotropy in Midcentral Pb-Pb Collisions at $\sqrt{s_{NN}}=5.02$ TeV

(ALICE Collaboration) Acharya, S.; ...; Antičić, Tome; ...; Erhardt, Filip; ...; Gotovac, Sven; ...; Jerčić, Marko; ...; ...

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***D*-Meson Azimuthal Anisotropy in Midcentral Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV**S. Acharya *et al.**
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The azimuthal anisotropy coefficient v_2 of prompt D^0 , D^+ , D^{*+} , and D_s^+ mesons was measured in midcentral (30%–50% centrality class) Pb-Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV, with the ALICE detector at the LHC. The D mesons were reconstructed via their hadronic decays at midrapidity, $|y| < 0.8$, in the transverse momentum interval $1 < p_T < 24$ GeV/ c . The measured D -meson v_2 has similar values as that of charged pions. The D_s^+ v_2 , measured for the first time, is found to be compatible with that of nonstrange D mesons. The measurements are compared with theoretical calculations of charm-quark transport in a hydrodynamically expanding medium and have the potential to constrain medium parameters.

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Quantum chromodynamics predicts that strongly interacting matter under extreme conditions of a high temperature and energy density undergoes a transition from the hadronic phase to a color-deconfined medium, called quark-gluon plasma (QGP) [1–4]. Heavy-ion collisions at ultrarelativistic energies provide suitable conditions for the QGP formation and for characterizing its properties.

Heavy quarks (charm and beauty) are predominantly produced in hard scatterings before the QGP formation [5,6]. Therefore, they experience all stages of the medium evolution, interacting with its constituents via elastic [7] and inelastic (radiation of gluons) [8,9] processes (see [6,10] for recent reviews).

Evidence of in-medium interactions and energy loss of charm quarks is provided by the strong modification of the transverse momentum (p_T) distributions of heavy-flavor hadrons in heavy-ion collisions with respect to pp collisions. A large suppression of heavy-flavor hadron yields was observed for $p_T > 4$ –5 GeV/ c in central nucleus-nucleus collisions at the RHIC [11–14] and the LHC [15–19].

Measurements of anisotropies in the azimuthal distribution of heavy-flavor hadrons assess the transport properties of the medium. The collective dynamics of the expanding medium converts the initial-state spatial anisotropy [20] into final-state particle momentum anisotropy. This anisotropy is characterized by the Fourier coefficients v_n of the distribution of the particle azimuthal angle φ relative to

the initial-state symmetry plane angle Ψ_n (for the n th harmonic) [21,22]. In noncentral collisions, the largest contribution corresponds to $v_2 = \langle \cos[2(\varphi - \Psi_2)] \rangle$, called elliptic flow [22,23]. The D -meson v_2 at low p_T provides insight into the possible collective flow imparted by the medium to charm quarks [24], while at high p_T it is sensitive to the path-length dependence of parton energy loss [25,26]. At low and intermediate p_T , a fraction of charm quarks could hadronize via recombination with light quarks from the medium, leading to an increase of the D -meson v_2 with respect to that of charm quarks [27–29]; the comparison of the v_2 of D mesons without and with strange-quark content could be sensitive to these effects and to the charm coupling to the QGP and hadronic matter [30].

A positive heavy-flavor elliptic flow was observed in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [11,31,32] and in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [19,33–36]. Calculations based on heavy-quark transport in a hydrodynamically expanding medium describe the measurements [37–46]. Precise measurements of heavy-flavor v_2 constrain model parameters, e.g., the heavy-quark spatial diffusion coefficient D_s in the QGP, which is related to the relaxation (equilibration) time of heavy quarks $\tau_Q = (m_Q/T)D_s$, where m_Q is the quark mass and T is the medium temperature [47].

In this Letter, we report on the v_2 of D^0 , D^+ , D^{*+} , and, for the first time at the LHC, D_s^+ mesons, and their antiparticles, in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, for the 30%–50% centrality class. The analysis uses Pb-Pb collisions collected with the ALICE detector [48,49] in 2015. The interaction trigger consisted in coincident signals in the two scintillator arrays of the V0 detector, covering full azimuth in the pseudorapidity (η) regions $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$. Events from beam-gas interactions are removed using time information from the V0 and the neutron zero-degree calorimeters.

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Only the events with a primary vertex reconstructed within ± 10 cm from the detector center along the beam direction are analyzed. Events are selected in the centrality class 30%–50%, defined in terms of percentiles of the hadronic Pb-Pb cross section, using the amplitude of the V0 signals [50,51]. The number of selected events is 20.7×10^6 , corresponding to an integrated luminosity $L_{\text{int}} \approx 13 \mu\text{b}^{-1}$ [51].

The D mesons and their antiparticles are reconstructed using the decay channels $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$, $D^{*+} \rightarrow D^0 \pi^+$, and $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$. The analysis procedure [34,52] searches for decay vertices displaced from the interaction vertex, exploiting the mean proper decay lengths of about 123, 312, and $150 \mu\text{m}$ of D^0 , D^+ , and D_s^+ mesons, respectively [53]. Charged-particle tracks are reconstructed using the inner tracking system (ITS) and the time projection chamber (TPC), which are located within a solenoid magnet that provides a 0.5 T field, parallel to the beam direction. D^0 , D^+ , and D_s^+ candidates are defined using pairs and triplets of tracks with $|\eta| < 0.8$, $p_T > 0.4 \text{ GeV}/c$, 70–159 TPC space points, and 2–6 hits in the ITS (at least one in the two innermost layers). D^{*+} candidates are formed by combining D^0 candidates with tracks with $|\eta| < 0.8$, $p_T > 0.1 \text{ GeV}/c$, and at least three ITS hits. The selection of tracks with $|\eta| < 0.8$ limits the D -meson acceptance in rapidity, which varies from $|y| < 0.6$ for $p_T = 1 \text{ GeV}/c$ to $|y| < 0.8$ for $p_T > 5 \text{ GeV}/c$. The main variables used to select the D candidates are the separation between the primary and decay vertices, the displacement of the tracks from the primary vertex, and the pointing of the reconstructed D -meson momentum to the primary vertex. For the selection of $D_s^+ \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$ decays, one of the two pairs of opposite-sign tracks must have an invariant mass compatible with the ϕ -meson mass [53]. Further background reduction results from the particle identification. A $\pm 3\sigma$ window around the expected mean values of the specific ionization energy loss dE/dx in the TPC gas and time of flight from the interaction point to the time-of-flight (TOF) detector is used for each track, where σ is the resolution on the two variables. For D_s^+ candidates, tracks not matched to a hit in the TOF (mostly at low momentum) are required to have a 2σ compatibility with the expected dE/dx in the TPC. These selections result in signal-to-background ratios between 0.04 and 2.8 and a statistical significance between 3 and 20, depending on the D -meson species and p_T .

The second harmonic symmetry plane Ψ_2 is estimated, for each collision, by the event plane (EP) angle, denoted ψ_2 , using the signals produced by charged particles in the eight azimuthal sectors of each V0 array. Effects of nonuniform V0 acceptance are corrected for using the gain equalization method [54]. The v_2 was calculated by classifying D mesons in two groups, according to their azimuthal angle relative to the EP $\Delta\varphi = \varphi_D - \psi_2$: in plane

($[-(\pi/4), (\pi/4)]$ and $[(3\pi/4), (5\pi/4)]$) and out of plane ($[(\pi/4), (3\pi/4)]$ and $[(5\pi/4), (7\pi/4)]$). Integrating the $dN/d\varphi$ distribution in these two $\Delta\varphi$ intervals, v_2 can be expressed as [34]:

$$v_2\{\text{EP}\} = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}}, \quad (1)$$

where $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$ are the D -meson yields in the two $\Delta\varphi$ intervals. The factor $(1/R_2)$ is the correction for the resolution in the estimation of the symmetry plane Ψ_2 via the EP angle ψ_2 . It is calculated using three subevents of charged particles in the V0 and in the positive and negative η regions of the TPC [22]. The separation of at least 0.9 units of pseudorapidity ($|\Delta\eta| > 0.9$) between the D mesons and the particles used in the ψ_2 calculation suppresses nonflow contributions to v_2 (i.e., correlations not induced by the collective expansion but rather by decays and jet production).

Simulations showed that the D -meson reconstruction and selection efficiencies do not depend on $\Delta\varphi$ [34]; therefore, Eq. (1) can be applied using the D -meson raw yields, without an efficiency correction. The raw yields were obtained from fits to the D^0 , D^+ , and D_s^+ candidate invariant-mass distributions and to the mass difference $\Delta M = M(K\pi\pi) - M(K\pi)$ distributions for D^{*+} candidates. In the fit function, the signal was modeled with a Gaussian and the background with an exponential term for D^0 , D^+ , and D_s^+ candidates and with the function $a\sqrt{\Delta M - m_\pi} e^{b(\Delta M - m_\pi)}$ for D^{*+} candidates. The mean and the width of the Gaussian were fixed to those obtained from a fit to the sum of the invariant-mass distributions in the two $\Delta\varphi$ intervals, where the signal has a higher statistical significance. In the D^0 invariant-mass fit, the contribution of signal candidates with the wrong K - π mass assignment (about 2%–5% of the raw signal depending on p_T) was taken into account by including an additional term, parametrized from simulations with a double-Gaussian shape, in the fit function [34].

The measured D -meson yield includes the contributions of prompt D mesons, from c -quark hadronization or strong decays of D^* states, and of feed-down D mesons from beauty-hadron decays. The observed v_2 , measured with Eq. (1), is a linear combination of the prompt and feed-down contributions: $v_2^{\text{obs}} = f_{\text{prompt}} v_2^{\text{prompt}} + (1 - f_{\text{prompt}}) v_2^{\text{feed-down}}$, where f_{prompt} is the fraction of prompt D mesons in the raw yields and $v_2^{\text{feed-down}}$ is the elliptic flow of D mesons from beauty-hadron decays. To calculate v_2^{prompt} , a hypothesis on $v_2^{\text{feed-down}}$ is used. The measured v_2 of nonprompt J/ψ [19] and the available model calculations [37,55,56] suggest that $0 < v_2^{\text{feed-down}} < v_2^{\text{prompt}}$. Assuming a uniform probability distribution of $v_2^{\text{feed-down}}$ in this interval, the central value for v_2^{prompt} is calculated considering $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$; thus, $v_2^{\text{prompt}} = 2v_2^{\text{obs}}/(1 + f_{\text{prompt}})$. The f_{prompt} fraction is estimated, as a function of p_T , as described in Ref. [57], using

the FONLL [58] calculation for the beauty-hadron cross section, the beauty-hadron decay kinematics from EvtGen [59], the reconstruction efficiencies for feed-down D mesons from the simulation, and a hypothesis for the nuclear modification factor of the feed-down D mesons, $R_{AA}^{\text{feed-down}}$. The nuclear modification factor is defined as the ratio of the p_T -differential yields in nucleus-nucleus and pp collisions scaled by the average number of nucleon-nucleon collisions in the considered centrality class [60]. By comparison of the R_{AA} of prompt D mesons [61] and J/ψ mesons from beauty-hadron decays [19] in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, the assumptions $R_{AA}^{\text{feed-down}} = 2R_{AA}^{\text{prompt}}$ for nonstrange D mesons and $R_{AA}^{\text{feed-down}} = R_{AA}^{\text{prompt}}$ for the D_s^+ meson are made to compute f_{prompt} .

The systematic uncertainty from feed-down on v_2^{prompt} was estimated by varying the central value of $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$ by $\pm v_2^{\text{prompt}}/\sqrt{12}$, corresponding to ± 1 rms of a uniform distribution in $(0, v_2^{\text{prompt}})$. The uncertainty on f_{prompt} was obtained from the variation of the FONLL calculation parameters and from the variation of the $R_{AA}^{\text{feed-down}}$ hypothesis in $1 < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 3$ for nonstrange D mesons [15] and $\frac{1}{3} < R_{AA}^{\text{feed-down}}/R_{AA}^{\text{prompt}} < 3$ for D_s^+ mesons [52]. The value of the absolute systematic uncertainty from feed-down ranges from 0.001 to 0.030.

The other sources of systematic uncertainty are related to the signal extraction from the invariant-mass distribution, nonflow effects, and centrality dependence in the EP resolution correction R_2 .

The signal extraction uncertainty was estimated by varying the background fit function and leaving the Gaussian width and mean as free parameters in the fit. Furthermore, an alternative method for the yield extraction based on counting the histogram entries in the signal invariant-mass region, after subtracting the background estimated from a fit to the sidebands, was considered. The absolute systematic uncertainties on v_2 due to the yield extraction range from 0.005 to 0.040 for D^0 , D^+ , and D^{*+} and from 0.015 to 0.070 for D_s^+ mesons. As a check of a possible efficiency dependence on $\Delta\phi$, the analysis was repeated with different selection criteria, and no systematic effect was observed.

The EP resolution correction R_2 depends on collision centrality [34]. The value used in Eq. (1) was computed assuming a uniform distribution of the D -meson yield within the centrality class. This value was compared with those obtained from the weighted averages of the R_2 values in narrow centrality intervals, using as weights either the D -meson yields or the number of nucleon-nucleon collisions. In addition, to account for the presence of possible nonflow effects in the estimation of R_2 , its value was recomputed using two different pseudorapidity gaps between the sub-events of the TPC tracks with positive or negative η . A systematic uncertainty of 2% on R_2 was estimated.

The v_2 of prompt D^0 , D^+ , D^{*+} , and D_s^+ mesons in the 30%–50% centrality class is shown in Fig. 1. The symbols

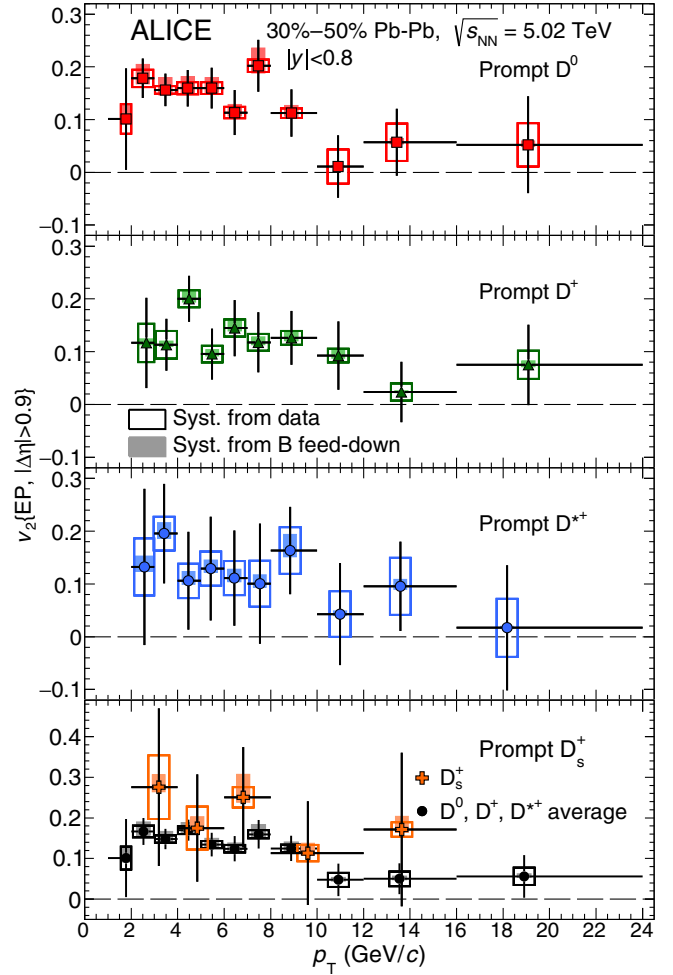


FIG. 1. Elliptic flow coefficient as a function of p_T for prompt D^0 , D^+ , D^{*+} , and D_s^+ mesons and their charge conjugates for Pb-Pb collisions in the centrality class 30%–50%. The bottom panel also shows the average v_2 of D^0 , D^+ , and D^{*+} . Vertical bars represent the statistical uncertainty, and empty boxes the systematic uncertainty associated with the D -meson anisotropy measurement and the event-plane resolution. Shaded boxes show the feed-down uncertainty.

are positioned at the average p_T of the reconstructed D mesons: this value was determined as the average of the p_T distribution of candidates in the signal invariant-mass region, after subtracting the contribution of the background candidates estimated from the sidebands. The v_2 of D^0 , D^+ , and D^{*+} are consistent, and they are larger than zero in $2 < p_T < 10$ GeV/c. The D^0 v_2 is compatible with the measurement by the CMS Collaboration [62]. The average of the v_2 measurements for D_s^+ mesons in the three p_T intervals within $2 < p_T < 8$ GeV/c is positive with a significance of 2.6σ , where σ is the uncertainty of the average v_2 , calculated using quadratic propagation for the statistical and uncorrelated systematic uncertainties (signal extraction) and linear propagation for the correlated systematic uncertainties (R_2 and feed-down correction). The average v_2 and p_T of D^0 , D^+ , and D^{*+} ,

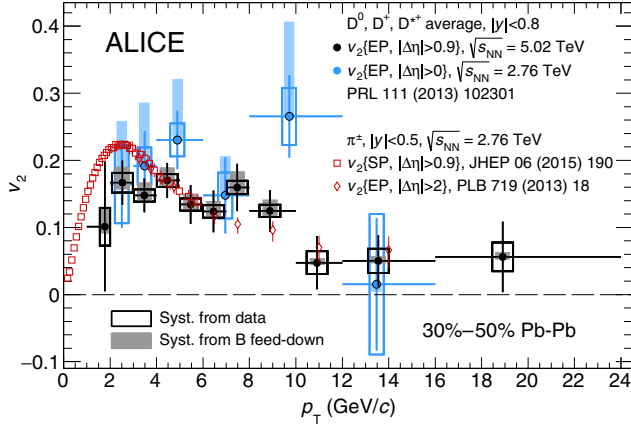


FIG. 2. Average of D^0 , D^+ , and D^{*+} v_2 as a function of p_T at $\sqrt{s_{NN}} = 5.02$ TeV, compared with the same measurement at $\sqrt{s_{NN}} = 2.76$ TeV [$L_{int} \approx 6 \mu\text{b}^{-1}$] [33], which has uncertainties larger by a factor of about 2 compared to the new result at 5.02 TeV. Note that the vertexing and tracking performance improved in 2015, and in Ref. [33] the correction for feed-down was made with the assumption $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$. The assumption used in the present analysis, $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$, would increase the values at $\sqrt{s_{NN}} = 2.76$ TeV by about 10%.

shown in the bottom panel in Fig. 1, was computed using the inverse of the squared statistical uncertainties as weights. The systematic uncertainties were propagated treating the R_2 and feed-down contributions as correlated among D -meson species.

Figure 2 shows that the average v_2 of D^0 , D^+ , and D^{*+} at $\sqrt{s_{NN}} = 5.02$ TeV is compatible with the same measurement at $\sqrt{s_{NN}} = 2.76$ TeV ($L_{int} \approx 6 \mu\text{b}^{-1}$) [33], which has uncertainties larger by a factor of about 2 compared to the new result at 5.02 TeV. Note that the vertexing and tracking performance improved in 2015, and in Ref. [33] the correction for feed-down was made with the assumption $v_2^{\text{feed-down}} = v_2^{\text{prompt}}$. The assumption used in the present analysis, $v_2^{\text{feed-down}} = v_2^{\text{prompt}}/2$, would increase the values at $\sqrt{s_{NN}} = 2.76$ TeV by about 10%.

The average D -meson v_2 is also compared with the π^\pm v_2 at $\sqrt{s_{NN}} = 2.76$ TeV measured with the EP method [63,64] considering a pseudorapidity separation of two units between π^\pm and the particles used to measure the EP angle, and the scalar-product method [65], also based on two-particle correlations. The comparison of the D -meson v_2 at $\sqrt{s_{NN}} = 5.02$ TeV and of the pion v_2 at $\sqrt{s_{NN}} = 2.76$ TeV is justified by the observation that the p_T differential v_2 of charged particles, which is dominated by the pion component, is compatible at these two energies [66]. The D -meson v_2 is similar to that of π^\pm in the common p_T interval (1–16 GeV/c), and it is lower in the interval below 4 GeV/c, the difference reaching about 2σ in 2–4 GeV/c, where a mass ordering of v_2 is observed for light-flavor hadrons and described by hydrodynamical calculations [65].

In Fig. 3, the average v_2 of the three nonstrange D -meson species is compared with theoretical calculations that include a hydrodynamical model for the QGP expansion (models that lack this expansion underestimated the D -meson v_2 measurements at $\sqrt{s_{NN}} = 2.76$ TeV in

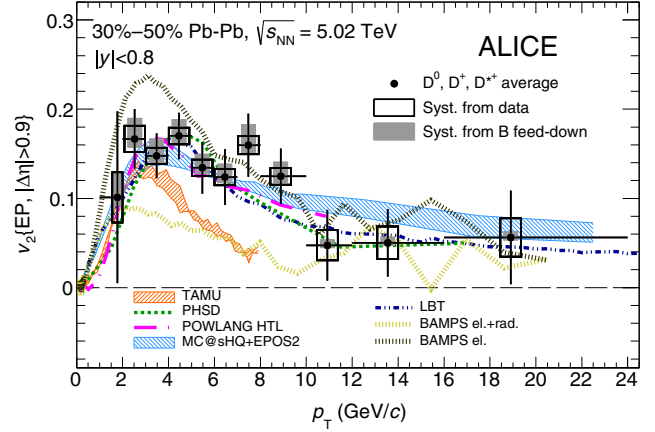


FIG. 3. Average of D^0 , D^+ , and D^{*+} v_2 as a function of p_T , compared with model calculations [38,42–46].

$2 < p_T < 6$ GeV/c [34]). The BAMPSE-el [44], POWLANG [45], and TAMU [38] calculations include only collisional (i.e., elastic) interaction processes, while the BAMPSE-el+rad [44], LBT [46], MC@sHQ [43], and PHSD [42] calculations also include energy loss via gluon radiation. All calculations, with the exception of BAMPSE, include hadronization via quark recombination, in addition to independent fragmentation. The MC@sHQ and TAMU results are displayed with their theoretical uncertainty band. All calculations provide a fair description of the nuclear modification factor of D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in $1 < p_T < 8$ GeV/c [15].

The v_2 measurement at $\sqrt{s_{NN}} = 5.02$ TeV is described by most of these calculations, in which the interactions with the hydrodynamically expanding medium impart a positive v_2 to charm quarks. The model-to-data consistency was quantified using the reduced χ^2 in the p_T interval where all calculations are available (2–8 GeV/c): The LBT, MC@sHQ, PHSD, and POWLANG models have $\chi^2/\text{ndf} < 1$, and the TAMU, BAMPSE-el+rad, and BAMPSE-el models have a χ^2/ndf of 4.1, 6.7, and 1.9, respectively. The χ^2 calculation includes the data uncertainties and the model uncertainties when available. For BAMPSE-el+rad, the low value of v_2 is caused by the absence of the recombination contribution [44]. For TAMU, the rapid decrease of v_2 with increasing p_T is due to the lack of radiative energy loss, which is also reflected in R_{AA} values larger than the measured ones at high p_T [15]. For most of these calculations, the medium effect on heavy quarks can be expressed using the dimensionless quantity $2\pi TD_s(T)$ [47]. In the interval from the critical temperature for QGP formation $T_c \approx 155$ MeV [2] to $2T_c$, the ranges of $2\pi TD_s(T)$ are 1–2 for BAMPSE-el, 6–10 for BAMPSE-el+rad, 2–6 for LBT [67], 1.5–4.5 for MC@sHQ [6], 4–9 for PHSD [42], 7–18 for POWLANG [10], and 4–10 for TAMU [6]. The calculations that describe the data with $\chi^2/\text{ndf} < 1$ use $2\pi TD_s(T)$ in the range of 1.5–7 at T_c . Remarkably, this range is consistent with that obtained by the comparison of the D^0 v_2 in Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV to

model calculations [32], and it includes the values obtained by lattice QCD calculations [68,69] which are independent of the collision energy, because they encode a property of the medium evaluated at a fixed temperature. The corresponding thermalization time [47] for charm quarks is $\tau_{\text{charm}} = (m_{\text{charm}}/T)D_s(T) \approx 3\text{--}14 \text{ fm}/c$ with $T = T_c$ and $m_{\text{charm}} = 1.5 \text{ GeV}/c^2$. These values are comparable to the estimated decoupling time of the high-density system [70]. It should also be pointed out that the models differ in several aspects, related to the medium expansion and the heavy quark-medium interactions both in the QGP and in the hadronic phase.

In summary, we have presented a measurement of the elliptic flow v_2 of prompt D^0 , D^+ , D^{*+} , and D_s^+ mesons in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. The average v_2 of nonstrange D mesons was measured with statistical and systematic uncertainties smaller by a factor about 2 with respect to our measurement at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$. The results at the two energies are compatible within statistical uncertainties. The D_s^+ v_2 was for the first time measured at the LHC, although with a limited precision, and found to be compatible with that of nonstrange D mesons. The comparison of the D -meson v_2 with that of pions and with model calculations indicates that low-momentum charm quarks take part in the collective motion of the QGP and that collisional interaction processes as well as the recombination of charm and light quarks both contribute to the observed elliptic flow. The calculations that describe the measurements use heavy-quark spatial diffusion coefficients in the range of $2\pi TD_s(T) \approx 1.5\text{--}7$ at the critical temperature T_c .

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S. Acharya,¹³⁹ D. Adamová,⁹⁶ J. Adolfsson,³⁴ M. M. Aggarwal,¹⁰¹ G. Aglieri Rinella,³⁵ M. Agnello,³¹ N. Agrawal,⁴⁸ Z. Ahammed,¹³⁹ N. Ahmad,¹⁷ S. U. Ahn,⁸⁰ S. Aiola,¹⁴³ A. Akindinov,⁶⁵ S. N. Alam,¹³⁹ J. L. B. Alba,¹¹⁴ D. S. D. Albuquerque,¹²⁵ D. Aleksandrov,⁹² B. Alessandro,⁵⁹ R. Alfaro Molina,⁷⁵ A. Alici,^{54,27,12} A. Alkin,³ J. Alme,²² T. Alt,⁷¹ L. Altenkamper,²² I. Altsybeev,¹³⁸ C. Alves Garcia Prado,¹²⁴ C. Andrei,⁸⁹ D. Andreou,³⁵ H. A. Andrews,¹¹³ A. Andronic,¹⁰⁹ V. Anguelov,¹⁰⁶ C. Anson,⁹⁹ T. Antičić,¹¹⁰ F. Antinori,⁵⁷ P. Antonioli,⁵⁴ R. Anwar,¹²⁷ L. Aphecetche,¹¹⁷ H. Appelshäuser,⁷¹ S. Arcelli,²⁷ R. Arnaldi,⁵⁹ O. W. Arnold,^{107,36} I. C. Arsene,²¹ M. Arslanodok,¹⁰⁶ B. Audurier,¹¹⁷ A. Augustinus,³⁵ R. Averbeck,¹⁰⁹ M. D. Azmi,¹⁷ A. Badalà,⁵⁶ Y. W. Baek,^{61,79} S. Bagnasco,⁵⁹ R. Bailhache,⁷¹ R. Bala,¹⁰³ A. Baldisseri,⁷⁶ M. Ball,⁴⁵ R. C. Baral,⁶⁸ A. M. Barbaro,²⁶ R. Barbera,²⁸ F. Barile,^{33,53} L. Barioglio,²⁶ G. G. Barnaföldi,¹⁴² L. S. Barnby,⁹⁵ V. Barret,⁸² P. Bartalini,⁷ K. Barth,³⁵ E. Bartsch,⁷¹ M. Basile,²⁷ N. Bastid,⁸² S. Basu,¹⁴¹ G. Batigne,¹¹⁷ B. Batyunya,⁷⁸ P. C. Batzing,²¹ I. G. Bearden,⁹³ H. Beck,¹⁰⁶ C. Bedda,⁶⁴ N. K. Behera,⁶¹ I. Belikov,¹³⁵ F. Bellini,²⁷ H. Bello Martinez,² R. Bellwied,¹²⁷ L. G. E. Beltran,¹²³ V. Belyaev,⁸⁵ G. Bencedi,¹⁴² S. Beole,²⁶ A. Bercuci,⁸⁹ Y. Berdnikov,⁹⁸ D. Berenyi,¹⁴² R. A. Bertens,¹³⁰ D. Berzano,³⁵ L. Betev,³⁵ A. Bhasin,¹⁰³ I. R. Bhat,¹⁰³ A. K. Bhati,¹⁰¹ B. Bhattacharjee,⁴⁴ J. Bhom,¹²¹ L. Bianchi,¹²⁷ N. Bianchi,⁵¹ C. Bianchin,¹⁴¹ J. Bielčík,³⁹ J. Bielčíková,⁹⁶ A. Bilandzic,^{36,107} G. Biro,¹⁴² R. Biswas,⁴ S. Biswas,⁴ J. T. Blair,¹²² D. Blau,⁹² C. Blume,⁷¹ G. Boca,¹³⁶ F. Bock,^{106,84,35} A. Bogdanov,⁸⁵ L. Boldizsár,¹⁴² M. Bombara,⁴⁰ G. Bonomi,¹³⁷ M. Bonora,³⁵ J. Book,⁷¹ H. Borel,⁷⁶ A. Borissov,¹⁹ M. Borri,¹²⁹ E. Botta,²⁶ C. Bourjau,⁹³ L. Bratrud,⁷¹ P. Braun-Munzinger,¹⁰⁹ M. Bregant,¹²⁴ T. A. Broker,⁷¹ M. Broz,³⁹ E. J. Brucken,⁴⁶ E. Bruna,⁵⁹ G. E. Bruno,³³ D. Budnikov,¹¹¹ H. Buesching,⁷¹ S. Bufalino,³¹ P. Buhler,¹¹⁶ P. Buncic,³⁵ O. Busch,¹³³ Z. Buthelezi,⁷⁷ J. B. Butt,¹⁵ J. T. Buxton,¹⁸ J. Cabala,¹¹⁹ D. Caffarri,^{35,94} H. Caines,¹⁴³ A. Caliva,⁶⁴ E. Calvo Villar,¹¹⁴ P. Camerini,²⁵ A. A. Capon,¹¹⁶ F. Carena,³⁵ W. Carena,³⁵ F. Carnesecchi,^{27,12} J. Castillo Castellanos,⁷⁶ A. J. Castro,¹³⁰ E. A. R. Casula,⁵⁵ C. Ceballos Sanchez,⁹ P. Cerello,⁵⁹ S. Chandra,¹³⁹ B. Chang,¹²⁸ S. Chapeland,³⁵ M. Chartier,¹²⁹ J. L. Charvet,⁷⁶ S. Chattopadhyay,¹³⁹ S. Chattopadhyay,¹¹² A. Chauvin,^{36,107} M. Cherney,⁹⁹ C. Cheshkov,¹³⁴ B. Cheynis,¹³⁴ V. Chibante Barroso,³⁵ D. D. Chinellato,¹²⁵ S. Cho,⁶¹ P. Chochula,³⁵ K. Choi,¹⁹ M. Chojnacki,⁹³ S. Choudhury,¹³⁹ T. Chowdhury,⁸² P. Christakoglou,⁹⁴ C. H. Christensen,⁹³ P. Christiansen,³⁴ T. Chujo,¹³³ S. U. Chung,¹⁹ C. Cicalo,⁵⁵ L. Cifarelli,^{12,27} F. Cindolo,⁵⁴ J. Cleymans,¹⁰² F. Colamaria,³³ D. Colella,^{35,66} A. Collu,⁸⁴ M. Colocci,²⁷ M. Concas,^{59,‡} G. Conesa Balbastre,⁸³ Z. Conesa del Valle,⁶² M. E. Connors,^{143,§} J. G. Contreras,³⁹ T. M. Cormier,⁹⁷ Y. Corrales Morales,⁵⁹ I. Cortés Maldonado,² P. Cortese,³² M. R. Cosentino,¹²⁶ F. Costa,³⁵ S. Costanza,¹³⁶ J. Crkovská,⁶² P. Crochet,⁸² E. Cuautele,⁷³ L. Cunqueiro,⁷² T. Dahms,^{36,107} A. Dainese,⁵⁷ M. C. Danisch,¹⁰⁶ A. Danu,⁶⁹ D. Das,¹¹² I. Das,¹¹² S. Das,⁴ A. Dash,⁹⁰ S. Dash,⁴⁸ S. De,^{124,49} A. De Caro,³⁰ G. de Cataldo,⁵³ C. de Conti,¹²⁴ J. de Cuveland,⁴² A. De Falco,²⁴ D. De Gruttola,^{30,12} N. De Marco,⁵⁹ S. De Pasquale,³⁰ R. D. De Souza,¹²⁵ H. F. Degenhardt,¹²⁴ A. Deisting,^{109,106} A. Deloff,⁸⁸ C. Deplano,⁹⁴ P. Dhankher,⁴⁸ D. Di Bari,³³ A. Di Mauro,³⁵ P. Di Nezza,⁵¹ B. Di Ruzza,⁵⁷ M. A. Diaz Corchero,¹⁰ T. Dietel,¹⁰² P. Dillenseger,⁷¹ R. Divià,³⁵ Ø. Djuvsland,²² A. Dobrin,³⁵ D. Domenicis Gimenez,¹²⁴ B. Dönigus,⁷¹ O. Dordic,²¹ L. V. V. Doremalen,⁶⁴ A. K. Dubey,¹³⁹ A. Dubla,¹⁰⁹ L. Ducroux,¹³⁴ A. K. Duggal,¹⁰¹ P. Dupieux,⁸² R. J. Ehlers,¹⁴³ D. Elia,⁵³ E. Endress,¹¹⁴ H. Engel,⁷⁰ E. Epple,¹⁴³ B. Erazmus,¹¹⁷ F. Erhardt,¹⁰⁰ B. Espagnon,⁶² S. Esumi,¹³³ G. Eulisse,³⁵ J. Eum,¹⁹ D. Evans,¹¹³ S. Evdokimov,¹¹⁵ L. Fabbietti,^{107,36} J. Faivre,⁸³ A. Fantoni,⁵¹ M. Fasel,^{97,84} L. Feldkamp,⁷² A. Feliciello,⁵⁹ G. Feofilov,¹³⁸ J. Ferencei,⁹⁶ A. Fernández Téllez,² E. G. Ferreira,¹⁶ A. Ferretti,²⁶ A. Festanti,^{29,35} V. J. G. Feuillard,^{76,82} J. Figiel,¹²¹ M. A. S. Figueredo,¹²⁴ S. Filchagin,¹¹¹ D. Finogeev,⁶³ F. M. Fionda,^{22,24} E. M. Fiore,³³ M. Floris,³⁵ S. Foertsch,⁷⁷ P. Foka,¹⁰⁹ S. Fokin,⁹² E. Fragiaco,⁶⁰ A. Francescon,³⁵ A. Francisco,¹¹⁷ U. Frankenfeld,¹⁰⁹ G. G. Fronze,²⁶ U. Fuchs,³⁵ C. Furget,⁸³ A. Furs,⁶³ M. Fusco Girard,³⁰ J. J. Gaardhøje,⁹³ M. Gagliardi,²⁶ A. M. Gago,¹¹⁴ K. Gajdosova,⁹³ M. Gallio,²⁶ C. D. Galvan,¹²³ P. Ganoti,⁸⁷ C. Gao,⁷ C. Garabatos,¹⁰⁹ E. Garcia-Solis,¹³ K. Garg,²⁸ C. Gargiulo,³⁵ P. Gasik,^{36,107} E. F. Gauger,¹²² M. B. Gay Ducati,⁷⁴ M. Germain,¹¹⁷ J. Ghosh,¹¹² P. Ghosh,¹³⁹ S. K. Ghosh,⁴ P. Gianotti,⁵¹ P. Giubellino,^{109,59,35} P. Giubilato,²⁹ E. Gladysz-Dziadus,¹²¹ P. Glässel,¹⁰⁶ D. M. Gómez Coral,⁷⁵ A. Gomez Ramirez,⁷⁰

A. S. Gonzalez,³⁵ V. Gonzalez,¹⁰ P. González-Zamora,¹⁰ S. Gorbunov,⁴² L. Görlich,¹²¹ S. Gotovac,¹²⁰ V. Grabski,⁷⁵ L. K. Graczykowski,¹⁴⁰ K. L. Graham,¹¹³ L. Greiner,⁸⁴ A. Grelli,⁶⁴ C. Grigoras,³⁵ V. Grigoriev,⁸⁵ A. Grigoryan,¹ S. Grigoryan,⁷⁸ N. Grion,⁶⁰ J. M. Gronefeld,¹⁰⁹ F. Grosa,³¹ J. F. Grosse-Oetringhaus,³⁵ R. Grosso,¹⁰⁹ L. Gruber,¹¹⁶ F. Guber,⁶³ R. Guernane,⁸³ B. Guerzoni,²⁷ K. Gulbrandsen,⁹³ T. Gunji,¹³² A. Gupta,¹⁰³ R. Gupta,¹⁰³ I. B. Guzman,² R. Haake,³⁵ C. Hadjidakis,⁶² H. Hamagaki,^{86,132} G. Hamar,¹⁴² J. C. Hamon,¹³⁵ M. R. Haque,⁶⁴ J. W. Harris,¹⁴³ A. Harton,¹³ H. Hassan,⁸³ D. Hatzifotiadou,^{12,54} S. Hayashi,¹³² S. T. Heckel,⁷¹ E. Hellbär,⁷¹ H. Helstrup,³⁷ A. Herghelegiu,⁸⁹ G. Herrera Corral,¹¹ F. Herrmann,⁷² B. A. Hess,¹⁰⁵ K. F. Hetland,³⁷ H. Hillemanns,³⁵ C. Hills,¹²⁹ B. Hippolyte,¹³⁵ J. Hladky,⁶⁷ B. Hohlweger,¹⁰⁷ D. Horak,³⁹ S. Hornung,¹⁰⁹ R. Hosokawa,^{83,133} P. Hristov,³⁵ C. Hughes,¹³⁰ T. J. Humanic,¹⁸ N. Hussain,⁴⁴ T. Hussain,¹⁷ D. Hutter,⁴² D. S. Hwang,²⁰ S. A. Iga Buitron,⁷³ R. Ilkaev,¹¹¹ M. Inaba,¹³³ M. Ippolitov,^{85,92} M. Irfan,¹⁷ V. Isakov,⁶³ M. Ivanov,¹⁰⁹ V. Ivanov,⁹⁸ V. Izucheev,¹¹⁵ B. Jacak,⁸⁴ N. Jacazio,²⁷ P. M. Jacobs,⁸⁴ M. B. Jadhav,⁴⁸ J. Jadlovsky,¹¹⁹ S. Jaelani,⁶⁴ C. Jahnke,³⁶ M. J. Jakubowska,¹⁴⁰ M. A. Janik,¹⁴⁰ P. H. S. Y. Jayarathna,¹²⁷ C. Jena,⁹⁰ S. Jena,¹²⁷ M. Jercic,¹⁰⁰ R. T. Jimenez Bustamante,¹⁰⁹ P. G. Jones,¹¹³ A. Jusko,¹¹³ P. Kalinak,⁶⁶ A. Kalweit,³⁵ J. H. Kang,¹⁴⁴ V. Kaplin,⁸⁵ S. Kar,¹³⁹ A. Karasu Uysal,⁸¹ O. Karavichev,⁶³ T. Karavicheva,⁶³ L. Karayan,^{109,106} P. Karczmarczyk,³⁵ E. Karpechev,⁶³ U. Kebschull,⁷⁰ R. Keidel,¹⁴⁵ D. L. D. Keijdener,⁶⁴ M. Keil,³⁵ B. Ketzer,⁴⁵ Z. Khabanova,⁹⁴ P. Khan,¹¹² S. A. Khan,¹³⁹ A. Khanzadeev,⁹⁸ Y. Kharlov,¹¹⁵ A. Khatun,¹⁷ A. Khuntia,⁴⁹ M. M. Kielbowicz,¹²¹ B. Kileng,³⁷ B. Kim,¹³³ D. Kim,¹⁴⁴ D. J. Kim,¹²⁸ H. Kim,¹⁴⁴ J. S. Kim,⁴³ J. Kim,¹⁰⁶ M. Kim,⁶¹ M. Kim,¹⁴⁴ S. Kim,²⁰ T. Kim,¹⁴⁴ S. Kirsch,⁴² I. Kisel,⁴² S. Kiselev,⁶⁵ A. Kisiel,¹⁴⁰ G. Kiss,¹⁴² J. L. Klay,⁶ C. Klein,⁷¹ J. Klein,³⁵ C. Klein-Bösing,⁷² S. Klewin,¹⁰⁶ A. Kluge,³⁵ M. L. Knichel,¹⁰⁶ A. G. Knospe,¹²⁷ C. Kobdaj,¹¹⁸ M. Kofarago,¹⁴² T. Kollegger,¹⁰⁹ A. Kolojvari,¹³⁸ V. Kondratiev,¹³⁸ N. Kondratyeva,⁸⁵ E. Kondratyuk,¹¹⁵ A. Konevskikh,⁶³ M. Konyushikhin,¹⁴¹ M. Kopicik,¹¹⁹ M. Kour,¹⁰³ C. Kouzinopoulos,³⁵ O. Kovalenko,⁸⁸ V. Kovalenko,¹³⁸ M. Kowalski,¹²¹ G. Koyithatta Meethalevedu,⁴⁸ I. Králik,⁶⁶ A. Kravčáková,⁴⁰ M. Krivda,^{66,113} F. Krizek,⁹⁶ E. Kryshen,⁹⁸ M. Krzewicki,⁴² A. M. Kubera,¹⁸ V. Kučera,⁹⁶ C. Kuhn,¹³⁵ P. G. Kuijjer,⁹⁴ A. Kumar,¹⁰³ J. Kumar,⁴⁸ L. Kumar,¹⁰¹ S. Kumar,⁴⁸ S. Kundu,⁹⁰ P. Kurashvili,⁸⁸ A. Kurepin,⁶³ A. B. Kurepin,⁶³ A. Kuryakin,¹¹¹ S. Kushpil,⁹⁶ M. J. Kweon,⁶¹ Y. Kwon,¹⁴⁴ S. L. La Pointe,⁴² P. La Rocca,²⁸ C. Lagana Fernandes,¹²⁴ Y. S. Lai,⁸⁴ I. Lakomov,³⁵ R. Langoy,⁴¹ K. Lapidus,¹⁴³ C. Lara,⁷⁰ A. Lardeux,^{21,76} A. Lattuca,²⁶ E. Laudi,³⁵ R. Lavicka,³⁹ L. Lazaridis,³⁵ R. Lea,²⁵ L. Leardini,¹⁰⁶ S. Lee,¹⁴⁴ F. Lehas,⁹⁴ S. Lehner,¹¹⁶ J. Lehrbach,⁴² R. C. Lemmon,⁹⁵ V. Lenti,⁵³ E. Leogrande,⁶⁴ I. León Monzón,¹²³ P. Lévai,¹⁴² S. Li,⁷ X. Li,¹⁴ J. Lien,⁴¹ R. Lietava,¹¹³ B. Lim,¹⁹ S. Lindal,²¹ V. Lindenstruth,⁴² S. W. Lindsay,¹²⁹ C. Lippmann,¹⁰⁹ M. A. Lisa,¹⁸ V. Litichevskyi,⁴⁶ H. M. Ljunggren,³⁴ W. J. Llope,¹⁴¹ D. F. Lodato,⁶⁴ P. I. Loenne,²² V. Loginov,⁸⁵ C. Loizides,⁸⁴ P. Loncar,¹²⁰ X. Lopez,⁸² E. López Torres,⁹ A. Lowe,¹⁴² P. Luetig,⁷¹ J. R. Luhder,⁷² M. Lunardon,²⁹ G. Luparello,^{60,25} M. Lupi,³⁵ T. H. Lutz,¹⁴³ A. Maevskaya,⁶³ M. Mager,³⁵ S. Mahajan,¹⁰³ S. M. Mahmood,²¹ A. Maire,¹³⁵ R. D. Majka,¹⁴³ M. Malaev,⁹⁸ L. Malinina,^{78,11} D. Mal'Kevich,⁶⁵ P. Malzacher,¹⁰⁹ A. Mamonov,¹¹¹ V. Manko,⁹² F. Manso,⁸² V. Manzari,⁵³ Y. Mao,⁷ M. Marchisone,^{77,131} J. Mareš,⁶⁷ G. V. Margagliotti,²⁵ A. Margotti,⁵⁴ J. Margutti,⁶⁴ A. Marín,¹⁰⁹ C. Markert,¹²² M. Marquard,⁷¹ N. A. Martin,¹⁰⁹ P. Martinengo,³⁵ J. A. L. Martinez,⁷⁰ M. I. Martínez,² G. Martínez García,¹¹⁷ M. Martinez Pedreira,³⁵ A. Mas,¹²⁴ S. Masciocchi,¹⁰⁹ M. Maserà,²⁶ A. Masoni,⁵⁵ E. Masson,¹¹⁷ A. Mastroserio,⁵³ A. M. Mathis,^{107,36} A. Matyja,^{121,130} C. Mayer,¹²¹ J. Mazer,¹³⁰ M. Mazzilli,³³ M. A. Mazzoni,⁵⁸ F. Meddi,²³ Y. Melikyan,⁸⁵ A. Menchaca-Rocha,⁷⁵ E. Meninno,³⁰ J. Mercado Pérez,¹⁰⁶ M. Meres,³⁸ S. Mhlanga,¹⁰² Y. Miake,¹³³ M. M. Mieskolainen,⁴⁶ D. Mihaylov,¹⁰⁷ D. L. Mihaylov,¹⁰⁷ K. Mikhaylov,^{65,78} L. Milano,⁸⁴ J. Milosevic,²¹ A. Mischke,⁶⁴ A. N. Mishra,⁴⁹ D. Miśkowiec,¹⁰⁹ J. Mitra,¹³⁹ C. M. Mitu,⁶⁹ N. Mohammadi,⁶⁴ B. Mohanty,⁹⁰ M. Mohisin Khan,^{17,11} E. Montes,¹⁰ D. A. Moreira De Godoy,⁷² L. A. P. Moreno,² S. Moretto,²⁹ A. Morreale,¹¹⁷ A. Morsch,³⁵ V. Muccifora,⁵¹ E. Mudnic,¹²⁰ D. Mühlheim,⁷² S. Muhuri,¹³⁹ M. Mukherjee,⁴ J. D. Mulligan,¹⁴³ M. G. Munhoz,¹²⁴ K. Munning,⁴⁵ R. H. Munzer,⁷¹ H. Murakami,¹³² S. Murray,⁷⁷ L. Musa,³⁵ J. Musinsky,⁶⁶ C. J. Myers,¹²⁷ J. W. Myrcha,¹⁴⁰ B. Naik,⁴⁸ R. Nair,⁸⁸ B. K. Nandi,⁴⁸ R. Nania,^{12,54} E. Nappi,⁵³ A. Narayan,⁴⁸ M. U. Naru,¹⁵ H. Natal da Luz,¹²⁴ C. Nattress,¹³⁰ S. R. Navarro,² K. Nayak,⁹⁰ R. Nayak,⁴⁸ T. K. Nayak,¹³⁹ S. Nazarenko,¹¹¹ A. Nedosekin,⁶⁵ R. A. Negrao De Oliveira,³⁵ L. Nellen,⁷³ S. V. Nesbo,³⁷ F. Ng,¹²⁷ M. Nicassio,¹⁰⁹ M. Niculescu,⁶⁹ J. Niedziela,^{35,140} B. S. Nielsen,⁹³ S. Nikolaev,⁹² S. Nikulin,⁹² V. Nikulin,⁹⁸ A. Nobuhiro,⁴⁷ F. Noferini,^{54,12} P. Nomokonov,⁷⁸ G. Nooren,⁶⁴ J. C. C. Noris,² J. Norman,¹²⁹ A. Nyanin,⁹² J. Nystrand,²² H. Oeschler,^{106,†} S. Oh,¹⁴³ A. Ohlson,^{35,106} T. Okubo,⁴⁷ L. Olah,¹⁴² J. Oleniacz,¹⁴⁰ A. C. Oliveira Da Silva,¹²⁴ M. H. Oliver,¹⁴³ J. Onderwaater,¹⁰⁹ C. Oppedisano,⁵⁹ R. Orava,⁴⁶ M. Oravec,¹¹⁹ A. Ortiz Velasquez,⁷³ A. Oskarsson,³⁴ J. Otwinowski,¹²¹ K. Oyama,⁸⁶ Y. Pachmayer,¹⁰⁶ V. Pacik,⁹³ D. Pagano,¹³⁷ P. Pagano,³⁰ G. Paic̃,⁷³ P. Palni,⁷ J. Pan,¹⁴¹ A. K. Pandey,⁴⁸ S. Panebianco,⁷⁶ V. Papikyan,¹

G. S. Pappalardo,⁵⁶ P. Pareek,⁴⁹ J. Park,⁶¹ S. Parmar,¹⁰¹ A. Passfeld,⁷² S. P. Pathak,¹²⁷ V. Paticchio,⁵³ R. N. Patra,¹³⁹ B. Paul,⁵⁹ H. Pei,⁷ T. Peitzmann,⁶⁴ X. Peng,⁷ L. G. Pereira,⁷⁴ H. Pereira Da Costa,⁷⁶ D. Peresunko,^{92,85} E. Perez Lezama,⁷¹ V. Peskov,⁷¹ Y. Pestov,⁵ V. Petráček,³⁹ V. Petrov,¹¹⁵ M. Petrovici,⁸⁹ C. Petta,²⁸ R. P. Pezzi,⁷⁴ S. Piano,⁶⁰ M. Pikna,³⁸ P. Pillot,¹¹⁷ L. O. D. L. Pimentel,⁹³ O. Pinazza,^{54,35} L. Pinsky,¹²⁷ D. B. Piyarathna,¹²⁷ M. Płoskoń,⁸⁴ M. Planinic,¹⁰⁰ F. Pliquett,⁷¹ J. Pluta,¹⁴⁰ S. Pochybova,¹⁴² P. L. M. Podesta-Lerma,¹²³ M. G. Poghosyan,⁹⁷ B. Polichtchouk,¹¹⁵ N. Poljak,¹⁰⁰ W. Poonsawat,¹¹⁸ A. Pop,⁸⁹ H. Poppenborg,⁷² S. Porteboeuf-Houssais,⁸² J. Porter,⁸⁴ V. Pozdniakov,⁷⁸ S. K. Prasad,⁴ R. Preghenella,⁵⁴ F. Prino,⁵⁹ C. A. Pruneau,¹⁴¹ I. Pshenichnov,⁶³ M. Puccio,²⁶ G. Puddu,²⁴ P. Pujahari,¹⁴¹ V. Punin,¹¹¹ J. Putschke,¹⁴¹ A. Rachevski,⁶⁰ S. Raha,⁴ S. Rajput,¹⁰³ J. Rak,¹²⁸ A. Rakotozafindrabe,⁷⁶ L. Ramello,³² F. Rami,¹³⁵ D. B. Rana,¹²⁷ R. Raniwala,¹⁰⁴ S. Raniwala,¹⁰⁴ S. S. Räsänen,⁴⁶ B. T. Rascanu,⁷¹ D. Rathee,¹⁰¹ V. Ratza,⁴⁵ I. Ravasenga,³¹ K. F. Read,^{97,130} K. Redlich,^{88,**} A. Rehman,²² P. Reichelt,⁷¹ F. Reidt,³⁵ X. Ren,⁷ R. Renfordt,⁷¹ A. R. Reolon,⁵¹ A. Reshetin,⁶³ K. Reygers,¹⁰⁶ V. Riabov,⁹⁸ R. A. Ricci,⁵² T. Richert,⁶⁴ M. Richter,²¹ P. Riedler,³⁵ W. Riegler,³⁵ F. Riggi,²⁸ C. Ristea,⁶⁹ M. Rodríguez Cahuantzi,² K. Røed,²¹ E. Rogochaya,⁷⁸ D. Rohr,^{35,42} D. Röhrich,²² P. S. Rokita,¹⁴⁰ F. Ronchetti,⁵¹ E. D. Rosas,⁷³ P. Rosnet,⁸² A. Rossi,^{57,29} A. Rotondi,¹³⁶ F. Roukoutakis,⁸⁷ A. Roy,⁴⁹ C. Roy,¹³⁵ P. Roy,¹¹² A. J. Rubio Montero,¹⁰ O. V. Rueda,⁷³ R. Rui,²⁵ B. Rumyantsev,⁷⁸ A. Rustamov,⁹¹ E. Ryabinkin,⁹² Y. Ryabov,⁹⁸ A. Rybicki,¹²¹ S. Saarinen,⁴⁶ S. Sadhu,¹³⁹ S. Sadovsky,¹¹⁵ K. Šafařík,³⁵ S. K. Saha,¹³⁹ B. Sahlmuller,⁷¹ B. Sahoo,⁴⁸ P. Sahoo,⁴⁹ R. Sahoo,⁴⁹ S. Sahoo,⁶⁸ P. K. Sahu,⁶⁸ J. Saini,¹³⁹ S. Sakai,^{133,51} M. A. Saleh,¹⁴¹ J. Salzwedel,¹⁸ S. Sambyal,¹⁰³ V. Samsonov,^{85,98} A. Sandoval,⁷⁵ D. Sarkar,¹³⁹ N. Sarkar,¹³⁹ P. Sarma,⁴⁴ M. H. P. Sas,⁶⁴ E. Scapparone,⁵⁴ F. Scarlassara,²⁹ R. P. Scharenberg,¹⁰⁸ H. S. Scheid,⁷¹ C. Schiaua,⁸⁹ R. Schicker,¹⁰⁶ C. Schmidt,¹⁰⁹ H. R. Schmidt,¹⁰⁵ M. O. Schmidt,¹⁰⁶ M. Schmidt,¹⁰⁵ N. V. Schmidt,^{71,97} S. Schuchmann,¹⁰⁶ J. Schukraft,³⁵ Y. Schutz,^{135,117,35} K. Schwarz,¹⁰⁹ K. Schweda,¹⁰⁹ G. Scioli,²⁷ E. Scomparin,⁵⁹ R. Scott,¹³⁰ M. Šeščík,⁴⁰ J. E. Seger,⁹⁹ Y. Sekiguchi,¹³² D. Sekihata,⁴⁷ I. Selyuzhenkov,^{85,109} K. Senosi,⁷⁷ S. Senyukov,^{3,135,35} E. Serradilla,^{75,10} P. Sett,⁴⁸ A. Sevcenco,⁶⁹ A. Shabanov,⁶³ A. Shabetai,¹¹⁷ R. Shahoyan,³⁵ W. Shaikh,¹¹² A. Shangaraev,¹¹⁵ A. Sharma,¹⁰¹ A. Sharma,¹⁰³ M. Sharma,¹⁰³ M. Sharma,¹⁰³ N. Sharma,^{130,101} A. I. Sheikh,¹³⁹ K. Shigaki,⁴⁷ Q. Shou,⁷ K. Shtejer,^{26,9} Y. Sibiriak,⁹² S. Siddhanta,⁵⁵ K. M. Sielewicz,³⁵ T. Siemiarczuk,⁸⁸ D. Silvermyr,³⁴ C. Silvestre,⁸³ G. Simatovic,¹⁰⁰ G. Simonetti,³⁵ R. Singaraju,¹³⁹ R. Singh,⁹⁰ V. Singhal,¹³⁹ T. Sinha,¹¹² B. Sitar,³⁸ M. Sitta,³² T. B. Skaali,²¹ M. Slupecki,¹²⁸ N. Smirnov,¹⁴³ R. J. M. Snellings,⁶⁴ T. W. Snellman,¹²⁸ J. Song,¹⁹ M. Song,¹⁴⁴ F. Soramel,²⁹ S. Sorensen,¹³⁰ F. Sozzi,¹⁰⁹ E. Spiriti,⁵¹ I. Sputowska,¹²¹ B. K. Srivastava,¹⁰⁸ J. Stachel,¹⁰⁶ I. Stan,⁶⁹ P. Stankus,⁹⁷ E. Stenlund,³⁴ D. Stocco,¹¹⁷ M. M. Storetvedt,³⁷ P. Strmen,³⁸ A. A. P. Suaide,¹²⁴ T. Sugitate,⁴⁷ C. Suire,⁶² M. Suleymanov,¹⁵ M. Suljic,²⁵ R. Sultanov,⁶⁵ M. Šumbera,⁹⁶ S. Sumowidagdo,⁵⁰ K. Suzuki,¹¹⁶ S. Swain,⁶⁸ A. Szabo,³⁸ I. Szarka,³⁸ U. Tabassam,¹⁵ J. Takahashi,¹²⁵ G. J. Tambave,²² N. Tanaka,¹³³ M. Tarhini,⁶² M. Tariq,¹⁷ M. G. Tarzila,⁸⁹ A. Tauro,³⁵ G. Tejeda Muñoz,² A. Telesca,³⁵ K. Terasaki,¹³² C. Terrevoli,²⁹ B. Teyssier,¹³⁴ D. Thakur,⁴⁹ S. Thakur,¹³⁹ D. Thomas,¹²² F. Thoresen,⁹³ R. Tieulent,¹³⁴ A. Tikhonov,⁶³ A. R. Timmins,¹²⁷ A. Toia,⁷¹ S. Tripathy,⁴⁹ S. Trogolo,²⁶ G. Trombetta,³³ L. Tropp,⁴⁰ V. Trubnikov,³ W. H. Trzaska,¹²⁸ B. A. Trzeciak,⁶⁴ T. Tsuji,¹³² A. Tumkin,¹¹¹ R. Turrisi,⁵⁷ T. S. Tveter,²¹ K. Ullaland,²² E. N. Umaka,¹²⁷ A. Uras,¹³⁴ G. L. Usai,²⁴ A. Utrobicic,¹⁰⁰ M. Vala,^{119,66} J. Van Der Maarel,⁶⁴ J. W. Van Hoorne,³⁵ M. van Leeuwen,⁶⁴ T. Vanat,⁹⁶ P. Vande Vyvre,³⁵ D. Varga,¹⁴² A. Vargas,² M. Vargyas,¹²⁸ R. Varma,⁴⁸ M. Vasileiou,⁸⁷ A. Vasiliev,⁹² A. Vauthier,⁸³ O. Vázquez Doce,^{107,36} V. Vechemin,¹³⁸ A. M. Veen,⁶⁴ A. Velure,²² E. Vercellin,²⁶ S. Vergara Limón,² R. Vernet,⁸ R. Vértesi,¹⁴² L. Vickovic,¹²⁰ S. Vigolo,⁶⁴ J. Viinikainen,¹²⁸ Z. Vilakazi,¹³¹ O. Villalobos Baillie,¹¹³ A. Villatoro Tello,² A. Vinogradov,⁹² L. Vinogradov,¹³⁸ T. Virgili,³⁰ V. Vislavicius,³⁴ A. Vodopyanov,⁷⁸ M. A. Völkl,^{106,105} K. Voloshin,⁶⁵ S. A. Voloshin,¹⁴¹ G. Volpe,³³ B. von Haller,³⁵ I. Vorobyev,^{107,36} D. Voscek,¹¹⁹ D. Vranic,^{35,109} J. Vrláková,⁴⁰ B. Wagner,²² H. Wang,⁶⁴ M. Wang,⁷ D. Watanabe,¹³³ Y. Watanabe,^{132,133} M. Weber,¹¹⁶ S. G. Weber,¹⁰⁹ D. F. Weiser,¹⁰⁶ S. C. Wenzel,³⁵ J. P. Wessels,⁷² U. Westerhoff,⁷² A. M. Whitehead,¹⁰² J. Wiechula,⁷¹ J. Wikne,²¹ G. Wilk,⁸⁸ J. Wilkinson,^{106,54} G. A. Willems,⁷² M. C. S. Williams,⁵⁴ E. Willsher,¹¹³ B. Windelband,¹⁰⁶ W. E. Witt,¹³⁰ S. Yalcin,⁸¹ K. Yamakawa,⁴⁷ P. Yang,⁷ S. Yano,⁴⁷ Z. Yin,⁷ H. Yokoyama,^{133,83} I. -K. Yoo,^{35,19} J. H. Yoon,⁶¹ V. Yurchenko,³ V. Zaccolo,^{59,93} A. Zaman,¹⁵ C. Zampolli,³⁵ H. J. C. Zanoli,¹²⁴ N. Zardoshti,¹¹³ A. Zarochentsev,¹³⁸ P. Závada,⁶⁷ N. Zaviyalov,¹¹¹ H. Zbroszczyk,¹⁴⁰ M. Zhalov,⁹⁸ H. Zhang,^{22,7} X. Zhang,⁷ Y. Zhang,⁷ C. Zhang,⁶⁴ Z. Zhang,^{7,82} C. Zhao,²¹ N. Zhigareva,⁶⁵ D. Zhou,⁷ Y. Zhou,⁹³ Z. Zhou,²² H. Zhu,²² J. Zhu,⁷ X. Zhu,⁷ A. Zichichi,^{12,27} A. Zimmermann,¹⁰⁶ M. B. Zimmermann,^{35,72} G. Zinovjev,³ J. Zmeskal,¹¹⁶ and S. Zou⁷

(ALICE Collaboration)

- ¹A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
- ²Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
- ³Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
- ⁴Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
- ⁵Budker Institute for Nuclear Physics, Novosibirsk, Russia
- ⁶California Polytechnic State University, San Luis Obispo, California, United States
- ⁷Central China Normal University, Wuhan, China
- ⁸Centre de Calcul de l'IN2P3, Villeurbanne, Lyon, France
- ⁹Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- ¹⁰Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ¹¹Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- ¹²Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Rome, Italy
- ¹³Chicago State University, Chicago, Illinois, United States
- ¹⁴China Institute of Atomic Energy, Beijing, China
- ¹⁵COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
- ¹⁶Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
- ¹⁷Department of Physics, Aligarh Muslim University, Aligarh, India
- ¹⁸Department of Physics, Ohio State University, Columbus, Ohio, United States
- ¹⁹Department of Physics, Pusan National University, Pusan, Republic of Korea
- ²⁰Department of Physics, Sejong University, Seoul, Republic of Korea
- ²¹Department of Physics, University of Oslo, Oslo, Norway
- ²²Department of Physics and Technology, University of Bergen, Bergen, Norway
- ²³Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
- ²⁴Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- ²⁵Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
- ²⁶Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
- ²⁷Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
- ²⁸Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
- ²⁹Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
- ³⁰Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
- ³¹Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
- ³²Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
- ³³Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
- ³⁴Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
- ³⁵European Organization for Nuclear Research (CERN), Geneva, Switzerland
- ³⁶Excellence Cluster Universe, Technische Universität München, Munich, Germany
- ³⁷Faculty of Engineering, Bergen University College, Bergen, Norway
- ³⁸Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
- ³⁹Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
- ⁴⁰Faculty of Science, P.J. Šafárik University, Košice, Slovakia
- ⁴¹Faculty of Technology, Buskerud and Vestfold University College, Tonsberg, Norway
- ⁴²Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- ⁴³Gangneung-Wonju National University, Gangneung, Republic of Korea
- ⁴⁴Gauhati University, Department of Physics, Guwahati, India
- ⁴⁵Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
- ⁴⁶Helsinki Institute of Physics (HIP), Helsinki, Finland
- ⁴⁷Hiroshima University, Hiroshima, Japan
- ⁴⁸Indian Institute of Technology Bombay (IIT), Mumbai, India
- ⁴⁹Indian Institute of Technology Indore, Indore, India
- ⁵⁰Indonesian Institute of Sciences, Jakarta, Indonesia
- ⁵¹INFN, Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵²INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
- ⁵³INFN, Sezione di Bari, Bari, Italy
- ⁵⁴INFN, Sezione di Bologna, Bologna, Italy
- ⁵⁵INFN, Sezione di Cagliari, Cagliari, Italy
- ⁵⁶INFN, Sezione di Catania, Catania, Italy
- ⁵⁷INFN, Sezione di Padova, Padova, Italy
- ⁵⁸INFN, Sezione di Roma, Rome, Italy

- ⁵⁹INFN, Sezione di Torino, Turin, Italy
⁶⁰INFN, Sezione di Trieste, Trieste, Italy
⁶¹Inha University, Incheon, Republic of Korea
⁶²Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
⁶³Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
⁶⁴Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
⁶⁵Institute for Theoretical and Experimental Physics, Moscow, Russia
⁶⁶Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
⁶⁷Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
⁶⁸Institute of Physics, Bhubaneswar, India
⁶⁹Institute of Space Science (ISS), Bucharest, Romania
⁷⁰Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
⁷¹Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
⁷²Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
⁷³Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
⁷⁴Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
⁷⁵Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
⁷⁶IRFU, CEA, Université Paris-Saclay, Saclay, France
⁷⁷iThemba LABS, National Research Foundation, Somerset West, South Africa
⁷⁸Joint Institute for Nuclear Research (JINR), Dubna, Russia
⁷⁹Konkuk University, Seoul, Republic of Korea
⁸⁰Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
⁸¹KTO Karatay University, Konya, Turkey
⁸²Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
⁸³Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
⁸⁴Lawrence Berkeley National Laboratory, Berkeley, California, United States
⁸⁵Moscow Engineering Physics Institute, Moscow, Russia
⁸⁶Nagasaki Institute of Applied Science, Nagasaki, Japan
⁸⁷National and Kapodistrian University of Athens, Physics Department, Athens, Greece
⁸⁸National Centre for Nuclear Studies, Warsaw, Poland
⁸⁹National Institute for Physics and Nuclear Engineering, Bucharest, Romania
⁹⁰National Institute of Science Education and Research, HBNI, Jatni, India
⁹¹National Nuclear Research Center, Baku, Azerbaijan
⁹²National Research Centre Kurchatov Institute, Moscow, Russia
⁹³Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
⁹⁴Nikhef, Nationaal instituut voor subatomaire fysica, Amsterdam, Netherlands
⁹⁵Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
⁹⁶Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
⁹⁷Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
⁹⁸Petersburg Nuclear Physics Institute, Gatchina, Russia
⁹⁹Physics Department, Creighton University, Omaha, Nebraska, United States
¹⁰⁰Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
¹⁰¹Physics Department, Panjab University, Chandigarh, India
¹⁰²Physics Department, University of Cape Town, Cape Town, South Africa
¹⁰³Physics Department, University of Jammu, Jammu, India
¹⁰⁴Physics Department, University of Rajasthan, Jaipur, India
¹⁰⁵Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
¹⁰⁶Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
¹⁰⁷Physik Department, Technische Universität München, Munich, Germany
¹⁰⁸Purdue University, West Lafayette, Indiana, United States
¹⁰⁹Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
¹¹⁰Rudjer Bošković Institute, Zagreb, Croatia
¹¹¹Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
¹¹²Saha Institute of Nuclear Physics, Kolkata, India
¹¹³School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
¹¹⁴Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
¹¹⁵SSC IHEP of NRC Kurchatov institute, Protvino, Russia
¹¹⁶Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria

- ¹¹⁷*SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France*
¹¹⁸*Suranaree University of Technology, Nakhon Ratchasima, Thailand*
¹¹⁹*Technical University of Košice, Košice, Slovakia*
¹²⁰*Technical University of Split FESB, Split, Croatia*
¹²¹*The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*
¹²²*The University of Texas at Austin, Physics Department, Austin, Texas, United States*
¹²³*Universidad Autónoma de Sinaloa, Culiacán, Mexico*
¹²⁴*Universidade de São Paulo (USP), São Paulo, Brazil*
¹²⁵*Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*
¹²⁶*Universidade Federal do ABC, Santo André, Brazil*
¹²⁷*University of Houston, Houston, Texas, United States*
¹²⁸*University of Jyväskylä, Jyväskylä, Finland*
¹²⁹*University of Liverpool, Liverpool, United Kingdom*
¹³⁰*University of Tennessee, Knoxville, Tennessee, United States*
¹³¹*University of the Witwatersrand, Johannesburg, South Africa*
¹³²*University of Tokyo, Tokyo, Japan*
¹³³*University of Tsukuba, Tsukuba, Japan*
¹³⁴*Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, Lyon, France*
¹³⁵*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France*
¹³⁶*Università degli Studi di Pavia, Pavia, Italy*
¹³⁷*Università di Brescia, Brescia, Italy*
¹³⁸*V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia*
¹³⁹*Variable Energy Cyclotron Centre, Kolkata, India*
¹⁴⁰*Warsaw University of Technology, Warsaw, Poland*
¹⁴¹*Wayne State University, Detroit, Michigan, United States*
¹⁴²*Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary*
¹⁴³*Yale University, New Haven, Connecticut, United States*
¹⁴⁴*Yonsei University, Seoul, Republic of Korea*
¹⁴⁵*Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany*

[†]Deceased

[‡]Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy

[§]Also at: Georgia State University, Atlanta, Georgia, United States

^{||}Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia

[¶]Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India

^{**}Also at: Institute of Theoretical Physics, University of Wrocław, Poland