This is an electronic reprint of the original article. This reprint *may differ* from the original in pagination and typographic detail.

**Author(s):** ALICE Collaboration

**Title:** D-Meson Azimuthal Anisotropy in Midcentral Pb-Pb Collisions at √sNN = 5.02 TeV

**Year:** 2018

**Version:**

**Please cite the original version:**

All material supplied via JYX is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.
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 [5,6] 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 $p\bar{p}$ 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 symmetry plane angle $\Psi_n$ (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 QCD 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 of coincident signals in the two scintillator arrays of the V0 detector, covering full azimuth in the pseudorapidity ($\eta$) 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.

---

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. Further distribution of this work must maintain attribution to the author(s) and the published article’s title, journal citation, and DOI.

DOI: 10.1103/PhysRevLett.120.1202301
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 × 10^8, corresponding to an integrated luminosity \( L_{\text{int}} \approx 13 \mu b^{-1} \) [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 \( D_i^+ \rightarrow \phi\pi^+ \rightarrow K^+K^0\pi^+ \). 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 \( \mu m \) of \( D^0 \), \( D^+ \), and \( D_i^+ \) 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 \( D_i^+ \) candidates are defined using pairs and triplets of tracks with \( |\eta| < 0.8 \), \( p_T > 0.4 \) GeV/c, 70–159 TPC space points, and 2–6 hits in the ITS (at least one in the two innermost layers). \( D_i^+ \) candidates are formed by combining \( D^0 \) candidates with tracks with \( |\eta| < 0.8 \), \( p_T > 0.1 \) 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 \( p_T = 1 \) GeV/c to \( |y| < 0.8 \) for \( p_T > 5 \) 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 \( D_i^+ \rightarrow \phi\pi^+ \rightarrow K^-K^+\pi^+ \) decays, one of the two pairs of opposite-sign tracks must have an invariant mass compatible with the \( \phi \)-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 \( \sigma \) is the resolution on the two variables. For \( D_i^+ \) candidates, tracks not matched to a hit in the TOF (mostly at low momentum) are required to have a 2\( \sigma \) 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 \( \Psi_2 \) is estimated, for each collision, by the event plane (EP) angle, denoted \( \psi_2 \), 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 \( \psi_2 \) was calculated by classifying \( D \) mesons in two groups, according to their azimuthal angle relative to the EP \( \Delta\phi = \phi_D - \psi_2 \): 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 \( dN/d\phi \) distribution in these two \( \Delta\phi \) intervals, \( \psi_2 \) can be expressed as [34]:

\[
\psi_2(EP) = \frac{1}{R_2} \frac{\pi N_{\text{in-plane}} - N_{\text{out-of-plane}}}{4 N_{\text{in-plane}} + N_{\text{out-of-plane}}},
\]

where \( N_{\text{in-plane}} \) and \( N_{\text{out-of-plane}} \) are the \( D \)-meson yields in the two \( \Delta\phi \) intervals. The factor \( (1/R_2) \) is the correction for the resolution in the estimation of the symmetry plane \( \Psi_2 \) via the EP angle \( \psi_2 \). It is calculated using three subevents of charged particles in the V0 and in the positive and negative \( \eta \) 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 \( \psi_2 \) calculation suppresses nonflow contributions to \( \psi_2 \) (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 \( \Delta\phi \) [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 \( D_i^+ \) candidate invariant-mass distributions and to the mass difference \( \Delta M = M(K\pi\pi) - M(K\pi) \) distributions for \( D_i^+ \) candidates. In the fit function, the signal was modeled with a Gaussian and the background with an exponential term for \( D^0 \), \( D^+ \), and \( D_i^+ \) candidates and with the function \( a\sqrt{\Delta M - m^2} e^{(\Delta M - m^2)/2\sigma^2} \) for \( D_i^+ \) 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 \( \Delta\phi \) intervals, where the signal has a higher statistical significance. In the \( D^0 \) invariant-mass fit, the contribution of signal candidates with the wrong \( K\pi \) 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 \( \psi_2 \), measured with Eq. (1), is a linear combination of the prompt and feed-down contributions:

\[
\psi_2^{\text{obs}} = f^{\text{prompt}} \psi_2^{\text{prompt}} + (1 - f^{\text{prompt}}) \psi_2^{\text{feed-down}},
\]

where \( f^{\text{prompt}} \) is the fraction of prompt \( D \) mesons in the raw yields and \( \psi_2^{\text{feed-down}} \) is the elliptic flow of \( D \) mesons from beauty-hadron decays. To calculate \( \psi_2^{\text{prompt}} \), a hypothesis on \( \psi_2^{\text{feed-down}} \) is used. The measured \( \psi_2 \) of nonprompt \( J/\psi \) [19] and the available model calculations [37,55,56] suggest that \( 0 < \psi_2^{\text{feed-down}} < \psi_2^{\text{prompt}} \). Assuming a uniform probability distribution of \( \psi_2^{\text{feed-down}} \) in this interval, the central value for \( \psi_2^{\text{prompt}} \) is calculated considering \( \psi_2^{\text{feed-down}} = \psi_2^{\text{prompt}}/2 \); thus, \( \psi_2^{\text{prompt}} = 2\psi_2^{\text{obs}}/(1 + f^{\text{prompt}}) \). The \( f^{\text{prompt}} \) 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 \( J/\psi \) mesons from beauty-hadron decays [19] in Pb-Pb collisions at \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \), 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 \( f_{\text{prompt}} \).

The systematic uncertainty from feed-down on \( v_2^{\text{prompt}} \) was estimated by varying the central value of \( v_2^{\text{feed-down}} = v_2^{\text{prompt}} / \sqrt{2} \) by \( \pm v_2^{\text{prompt}} / \sqrt{12} \), corresponding to \( \pm 1 \text{ rms} \) of a uniform distribution in \( (0, v_2^{\text{prompt}}) \). The uncertainty on \( f_{\text{prompt}} \) 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 \( 1 < R_{AA}^{\text{feed-down}} / R_{AA}^{\text{prompt}} < 3 \) 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 \( \eta \). 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 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 \( 2 < p_T < 10 \text{ GeV/c} \). 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 \( 2 < p_T < 8 \text{ GeV/c} \) is positive with a significance of \( 2.6 \sigma \), where \( \sigma \) 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 \( D^{++} \),...
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 $D^{++} v_2$ at $\sqrt{s_{NN}} = 5.02$ TeV is compatible with the same measurement at $\sqrt{s_{NN}} = 2.76$ TeV ($L_{int} \approx 6$ mb$^{-1}$) [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 $v_{\text{feed-down}} = v_{\text{prompt}}$. The assumption used in the present analysis, $v_{\text{feed-down}} = v_{\text{prompt}}/2$, 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 $\pi^\pm v_2$ at $\sqrt{s_{NN}} = 2.76$ TeV measured with the EP method [63,64] considering a pseudorapidity separation of two units between $\pi^\pm$ 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 $\pi^\pm$ 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

$2 < p_T < 6$ GeV/$c$ [34]). The BAMPS-el [44], POWLANG [45], and TAMU [38] calculations include only collisional (i.e., elastic) interaction processes, while the BAMPS-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 BAMPS, 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 $\chi^2$ 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, BAMPS-el+rad, and BAMPS-el models have a $\chi^2/\text{ndf}$ of 4.1, 6.7, and 1.9, respectively. The $\chi^2$ calculation includes the data uncertainties and the model uncertainties when available. For BAMPS-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 $2\pi T_D(s)(T)$ [47]. In the interval from the critical temperature for QGP formation $T_c \approx 155$ MeV [2] to $2T_c$, the ranges of $2\pi T_D(s)(T)$ are $\approx 1$–2 for BAMPS-el, 6–10 for BAMPS-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 $2\pi T_D(s)(T)$ 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 \[ \tau_{\text{charm}} = \left( \frac{m_{\text{charm}}}{T} \right) D_s(T) \approx 3-14 \text{ fm}/c \] 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 \( 2\pi T \bar{D}_s(T) \approx 1.5-7 \) at the critical temperature \( T_c \).

The ALICE Collaboration thanks 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 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), Universidade Federal do Rio Grande do Sul (UFRGS), Financiadora de Estudos e Projetos (Finep), and Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Brazil; Ministry of Science and Technology of China (MSTC), National Natural Science Foundation of China (NSFC) and Ministry of Education of China (MOEC), China; Ministry of Science, Education and Sport and Croatian Science Foundation, Croatia; Ministry of Education, Youth and Sports of the Czech Republic, Czech Republic; The Danish Council for Independent Research–Natural Sciences, the Carlsberg Foundation, 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, Wissenschaft, Forschung und Technologie (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) and Council of Scientific and Industrial Research (CSIR), New Delhi, India; Indonesian Institute of Science, Indonesia; Centro Fermi—Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi and Istituto Nazionale di Fisica Nucleare (INFN), Italy; Institute for Innovative Science and Technology, Nagasaki Institute of Applied Science (IIST), Japan Society for the Promotion of Science (JSPS) KAKENHI, and Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT), 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 and National Science Centre, 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 Romanian National Agency for Science, Technology and Innovation, Romania; Joint Institute for Nuclear Research (JINR), Ministry of Education and Science of the Russian Federation, and National Research Centre Kurchatov Institute, Russia; Ministry of Education, Science, Research and Sport of the Slovak Republic, Slovakia; National Research Foundation of South Africa, South Africa; Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEC), Cubaenerga, Cuba, Ministerio de Ciencia e Innovacion and Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Spain; Swedish Research Council (VR) and Knut and Alice Wallenberg Foundation (VK) and Knut and Alice Wallenberg Foundation (VK).


J. Adam et al. (ALICE Collaboration), Transverse momentum dependence of D-meson production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, J. High Energy Phys. 03 (2016) 081.

B. Abelev et al. (ALICE Collaboration), Production of Muons from Heavy Flavor Decays at Forward Rapidity in pp and Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. Lett. 109, 112301 (2012).


J. Adam et al. (ALICE Collaboration), Measurement of electrons from beauty-hadron decays in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, J. High Energy Phys. 07 (2017) 052.


L. Adamczyk et al. (STAR Collaboration), Elliptic flow of electrons from heavy-flavor hadron decays in Au + Au


[34] B. Abelev et al. (ALICE Collaboration), Azimuthal anisotropy of D-meson production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C 90, 034904 (2014).


1. A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
2. Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
3. Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
4. Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
5. Budker Institute for Nuclear Physics, Novosibirsk, Russia
6. California Polytechnic State University, San Luis Obispo, California, United States
7. Central China Normal University, Wuhan, China
8. Centre de Calcul de l’IN2P3, Villeurbanne, Lyon, France
9. Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
10. Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
11. Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
12. Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche ‘Enrico Fermi’, Rome, Italy
13. Chicago State University, Chicago, Illinois, United States
14. COMSATS Institute of Atomic Energy, Islamabad, Pakistan
15. Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
16. Department of Physics, Aligarh Muslim University, Aligarh, India
17. Department of Physics, Ohio State University, Columbus, Ohio, United States
18. Department of Physics, Pusan National University, Pusan, Republic of Korea
19. Department of Physics, Sejong University, Seoul, Republic of Korea
20. Department of Physics, University of Oslo, Oslo, Norway
21. Department of Physics and Technology, University of Bergen, Bergen, Norway
22. Dipartimento di Fisica dell’Università ‘La Sapienza’ and Sezione INFN, Rome, Italy
23. Dipartimento di Fisica dell’Università and Sezione INFN, Cagliari, Italy
24. Dipartimento di Fisica dell’Università and Sezione INFN, Trieste, Italy
25. Dipartimento di Fisica dell’Università and Sezione INFN, Turin, Italy
26. Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Bologna, Italy
27. Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Catania, Italy
28. Dipartimento di Fisica e Astronomia dell’Università and Sezione INFN, Padova, Italy
29. Dipartimento di Fisica ‘E.R. Caianiello’ dell’Università and Gruppo Collegato INFN, Salerno, Italy
30. Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
31. Dipartimento di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
32. Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
33. Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
34. European Organization for Nuclear Research (CERN), Geneva, Switzerland
35. Excellence Cluster Universe, Technische Universität München, Munich, Germany
36. Faculty of Engineering, Bergen University College, Bergen, Norway
37. Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
38. Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
39. Faculty of Science, P.J. Šafárik University, Košice, Slovakia
40. Faculty of Technology, Buskerud and Vestfold University College, Tonsberg, Norway
41. Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
42. Gangneung-Wonju National University, Gangneung, Republic of Korea
43. Gauhati University, Department of Physics, Guwahati, India
44. Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
45. Helsinki Institute of Physics (HIP), Helsinki, Finland
46. Hiroshima University, Hiroshima, Japan
47. Indian Institute of Technology Bombay (IIT), Mumbai, India
48. Indian Institute of Technology Indore, Indore, India
49. Indonesian Institute of Sciences, Jakarta, Indonesia
50. INFN, Laboratori Nazionali di Frascati, Frascati, Italy
51. INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
52. INFN, Sezione di Bari, Bari, Italy
53. INFN, Sezione di Bologna, Bologna, Italy
54. INFN, Sezione di Cagliari, Cagliari, Italy
55. INFN, Sezione di Catania, Catania, Italy
56. INFN, Sezione di Padova, Padova, Italy
57. INFN, Sezione di Roma, Rome, Italy
INFIN, Sezione di Torino, Turin, Italy
69 INFIN, Sezione di Trieste, Trieste, Italy
61 Inha University, Incheon, Republic of Korea
62 Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
63 Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
64 Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
65 Institute for Theoretical and Experimental Physics, Moscow, Russia
66 Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
67 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
68 Institute of Physics, Bhubaneswar, India
69 Institute of Space Science (ISS), Bucharest, Romania
70 Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
71 Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
72 Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
73 Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
74 Instituto de Física, Universidad Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
75 Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
76 IRFU, CEA, Université Paris-Saclay, Saclay, France
77 iThemba LABS, National Research Foundation, Somerset West, South Africa
78 Joint Institute for Nuclear Research (JINR), Dubna, Russia
79 Konkuk University, Seoul, Republic of Korea
80 Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
81 KTO Karatay University, Konya, Turkey
82 Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France
83 Laboratoire de Physique Subatomicque et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
84 Lawrence Berkeley National Laboratory, Berkeley, California, United States
85 Moscow Engineering Physics Institute, Moscow, Russia
86 Nagasaki Institute of Applied Science, Nagasaki, Japan
87 National and Kapodistrian University of Athens, Physics Department, Athens, Greece
88 National Centre for Nuclear Studies, Warsaw, Poland
89 National Institute for Physics and Nuclear Engineering, Bucharest, Romania
90 National Institute of Science Education and Research, HBNI, Jatni, India
91 National Nuclear Research Center, Baku, Azerbaijan
92 National Research Centre Kurchatov Institute, Moscow, Russia
93 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
94 Nikhef, Nationaal instituut voor subatomaire fysica, Amsterdam, Netherlands
95 Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Rež u Prahy, Czech Republic
96 Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
97 Petersburg Nuclear Physics Institute, Gatchina, Russia
98 Physics Department, Creighton University, Omaha, Nebraska, United States
99 Physics Department, Faculty of Science, University of Zagreb, Zagreb, Croatia
100 Physics Department, Panjab University, Chandigarh, India
101 Physics Department, University of Cape Town, Cape Town, South Africa
102 Physics Department, University of Jammu, Jammu, India
103 Physics Department, University of Rajasthan, Jaipur, India
104 Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
105 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
106 Physik Department, Technische Universität München, Munich, Germany
107 Purdue University, West Lafayette, Indiana, United States
108 Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
109 Rudjer Bošković Institute, Zagreb, Croatia
110 Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
111 Saha Institute of Nuclear Physics, Kolkata, India
112 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
113 Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
114 SSC IHEP of NRC Kurchatov institute, Protvino, Russia
115 Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria

102301-12