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D-meson azimuthal anisotropy in mid-central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

ALICE Collaboration*

Abstract

The azimuthal anisotropy coefficient v_2 of prompt D^0, D^+, D^{*+} and D_s^+ mesons was measured in mid-central (30–50% centrality class) Pb–Pb collisions at a centre-of-mass energy per nucleon pair $\sqrt{s_{\rm NN}} = 5.02$ TeV, with the ALICE detector at the LHC. The D mesons were reconstructed via their hadronic decays at mid-rapidity, $|y| < 0.8$, in the transverse momentum interval $1 < p_{\rm T} < 24$ 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 non-strange 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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*See Appendix A for the list of collaboration members

Quantum Chromodynamics calculations predict that strongly-interacting matter under extreme conditions of high temperature and energy density undergoes a transition from the hadronic phase to a colour-deconfined medium, called Quark–Gluon Plasma (QGP) [1–5]. Heavy-ion collisions at ultra-relativistic energies provide suitable conditions for the QGP formation and for characterizing its properties.

Heavy quarks (charm and beauty) are predominantly produced via hard scattering processes on a time scale shorter than the QGP formation time [6, 7] and, therefore, they experience all stages of the system evolution, interacting with the medium constituents via both elastic [8] and inelastic (radiation of gluons) [9, 10] processes (see Refs. [7, 11] for recent reviews).

Evidence of substantial interactions of charm quarks with the medium is provided by the observation of a strong modification of the transverse momentum ($p_{\rm T}$) distributions of heavy-flavour hadrons in heavy-ion collisions with respect to pp collisions. In particular, a large suppression of heavy-flavour hadron yields up to a factor 5–6 was observed for $p_{\rm T} > 4$–5 GeV$/c$ in central nucleus–nucleus collisions at RHIC [12–15] and LHC [16–20]. This is understood in terms of parton energy loss in the medium [21–23].

Measurements of anisotropies in the azimuthal distribution of heavy-flavour hadron momenta provide information on the transport properties of the medium. The collective dynamics of the expanding medium converts the initial-state spatial anisotropy (originating from collision geometry and fluctuations in the distributions of nucleons within the nuclei [24]) into final-state particle momentum anisotropy. This momentum anisotropy can be 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 $n^{\rm th}$ harmonic) [25,26]. In non-central collisions, the largest contribution is given by the second coefficient $v_2 = \langle\cos[2(\varphi - \Psi_2)]\rangle$, called elliptic flow [26, 27]. The measurement of D-meson v_2 at low $p_{\rm T}$ (< 5 GeV$/c$) provides insight into the possible collective flow imparted by the medium to charm quarks [28], while at high $p_{\rm T}$ it can constrain the path-length dependence of parton energy loss [29, 30]. At low and intermediate $p_{\rm T}$, a significant 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 [31–33]. In this scenario it was suggested that the comparison of the v_2 of D mesons without and with strange-quark content (i.e. $\rm D^0$, $\rm D^+$ or $\rm D^{*+}$ compared to $\rm D_s^+$) is sensitive to recombination effects in the hadronization process, as well as to the charm coupling to the QGP and hadronic matter [34].

A positive elliptic flow in the heavy-flavour sector was observed at RHIC and LHC. The PHENIX and STAR Collaborations reported measurements of v_2 of electrons from heavy-flavour hadron decays [12, 35] and $\rm D^0$ mesons [36] in Au–Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The ALICE Collaboration measured the v_2 of $\rm D^0$, $\rm D^+$ and $\rm D^{*+}$ mesons [37, 38] and electrons from heavy-flavour decays [39] at mid-rapidity, and of muons from heavy-flavour decays at forward rapidity [40] in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV. The azimuthal anisotropy of beauty quarks was studied by the CMS Collaboration via the elliptic flow of non-prompt $\rm J/\psi$ [20]. Several calculations based on heavy-quark transport in a hydrodynamically-expanding strongly-interacting medium describe the measured azimuthal anisotropy [41–50]. Precise measurements of v_2 of heavy-flavour hadrons help to constrain model parameters, e.g. the heavy-quark spatial diffusion coefficient D_s in the QGP, which is directly related to the relaxation (equilibration) time of heavy quarks $\tau_{\rm Q} = \frac{m_{\rm Q}}{T} D_s$, where $m_{\rm Q}$ is the quark mass and T is the medium temperature [51].

In this Letter, we report on the v_2 of $\rm D^0$, $\rm D^+$, $\rm D^{*+}$ and, for the first time at the LHC, of $\rm D_s^+$ mesons, and their antiparticles, in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, for the 30–50% centrality class in which the elliptic flow reaches its maximum value [52]. The analysis uses a sample of Pb–Pb collisions collected with the ALICE detector [53, 54] in 2015. The interaction trigger was defined by requiring coincident signals in the two scintillator arrays of the V0 detector, which cover the 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 offline using the time information provided by the V0 and the neutron Zero-Degree Calorimeters (ZDC). Only events with a primary vertex reconstructed within ± 10 cm from the centre of the detector along the beam direction are analysed. Events are selected in the centrality class 30–50%, defined in terms of percentiles of the hadronic Pb–Pb cross section, using the total amplitude of the signals in the V0 arrays [55,56]. The number of events in the 30–50% centrality class analysed is 20.7×10^6, corresponding to an integrated luminosity, $L_{\rm int}$, of about 13 μb^{-1} [56].

The D mesons and their antiparticles are reconstructed using the decay channels $D^0 \to K^-\pi^+$ (with branching ratio, BR, of $3.93 \pm 0.04\%$), $D^+ \to K^-\pi^+\pi^+$ (BR of $9.46 \pm 0.24\%$), $D^{*+} \to D^0\pi^+$ (BR of $67.7 \pm 0.5\%$) and $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$ (BR of $2.27 \pm 0.08\%$) [57]. The analysis is based on the reconstruction of decay vertices displaced from the interaction vertex, exploiting the mean proper decay lengths of about 123, 312 and 150 μm of D^0, D^+ and D_s^+ mesons [57]. The analysis procedure is the same as used for previous publications [38, 58]. Charged particles were reconstructed using the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). Both detectors are located within a solenoid magnet that provides a 0.5 T field, parallel to the beam direction. The D^0, D^+ and D_s^+ candidates are defined using pairs and triplets of tracks with proper charge-sign combination within $|\eta| < 0.8$, $p_{\rm T} > 0.4$ GeV/c, at least 70 (out of 159) space points in the TPC and at least two hits (out of six) in the ITS, with at least one in the two innermost layers. The D^{*+} candidates are formed by combining D^0 candidates with tracks with $|\eta| < 0.8$, $p_{\rm T} > 0.1$ 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 $p_{\rm T} = 1$ GeV/c to $|y| < 0.8$ for $p_{\rm T} > 5$ 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 $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$ decays, one of the two pairs of opposite-sign tracks is required to have an invariant mass compatible with the ϕ-meson mass [57]. Further background reduction results from the identification of charged pions and kaons. A $\pm 3\sigma$ window around the expected mean values of the specific ionisation 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 particle identification, where σ is the resolution of the two variables. For D_s^+ candidates, tracks not matched to a hit in the TOF (mostly at low momentum) are identified using only the TPC information and requiring a 2σ compatibility with the expected dE/dx. These selections result in a signal-to-background ratio that ranges between 0.04 and 2.8 and a statistical significance between 3 and 20, depending on the D-meson species and $p_{\rm T}$.

The second harmonic symmetry plane Ψ_2 is estimated, for each Pb–Pb collision, by the so-called Event Plane (EP) angle, denoted ψ_2, on the basis of the signals produced by charged particles in the eight azimuthal sectors of each V0 array. Effects of non-uniform acceptance in the determination of the flow vectors are corrected using the gain equalisation method described in [59]. The v_2 was calculated by classifying the D mesons in two groups, according to their azimuthal angle relative to the EP angle $\Delta\varphi = \varphi_{\rm D} - \psi_2$, namely in-plane ($]-\frac{\pi}{4}, \frac{\pi}{4}]$ and $]\frac{3\pi}{4}, \frac{5\pi}{4}]$) and out-of-plane ($]\frac{\pi}{4}, \frac{3\pi}{4}]$ and $]\frac{5\pi}{4}, \frac{7\pi}{4}]$). By integrating the d$N$/d$\varphi$ distribution in the two $\Delta\varphi$ intervals, v_2 can be expressed as [38]:

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

where $N_{\text{in-plane}}$ and $N_{\text{out-of-plane}}$ are the D-meson yields in the two $\Delta\varphi$ intervals. The factor $\frac{1}{R_2}$ is the correction for the finite resolution in the estimation of the symmetry plane Ψ_2 via the EP angle ψ_2. The resolution of the V0 EP angle was calculated using three sub-events of charged particles in the V0 itself and in the positive and negative η regions of the TPC [26]. 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 non-flow contributions (i.e. correlations not induced by the collective expansion but rather by decays and jet production) in the v_2 measurement.

Simulations showed that the D-meson reconstruction and selection efficiencies do not depend on $\Delta\varphi$ [38], 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 $\Delta M = M(\mathrm{K}\pi\pi) - M(\mathrm{K}\pi)$ distributions for D^{*+} candidates. In the fit function, the signal was modelled with a Gaussian and the background was described by an exponential term for D^0, D^+ and D_s^+ candidates and by the function $a\sqrt{\Delta M - m_\pi} \cdot \mathrm{e}^{b(\Delta M - m_\pi)}$ for D^{*+} candidates. The mean and the width of the Gaussian were fixed to those obtained from a fit to the invariant-mass distribution integrated over $\Delta\varphi$, where the signal has higher statistical significance. In the determination of the D^0-meson yield, the contribution of signal candidates present in the invariant-mass distribution with the wrong K–π mass assignment (about 2–5% of the raw signal depending on $p_{\rm T}$) was taken into account by including an additional term, parametrised from simulations with a double-Gaussian shape, in the fit function [38].

The measured D-meson yield includes the contributions of prompt D mesons, from c-quark hadronisation or strong decays of D^* states, and of feed-down D mesons from beauty-hadron decays. The observed v_2, measured with Eq. (1), can be expressed as a linear combination of the prompt and feed-down contributions: $v_2^{\rm obs} = f_{\rm prompt} \cdot v_2^{\rm prompt} + (1 - f_{\rm prompt}) v_2^{\text{feed-down}}$, where $f_{\rm prompt}$ 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 $v_2^{\rm prompt}$, a hypothesis on $v_2^{\text{feed-down}}$ is used. The measured v_2 of non-prompt J/ψ [20] and the available model calculations [41, 60, 61] suggest that $0 < v_2^{\text{feed-down}} < v_2^{\rm prompt}$. Assuming a uniform probability distribution of $v_2^{\text{feed-down}}$ in this interval, the central value for $v_2^{\rm prompt}$ is calculated considering $v_2^{\text{feed-down}} = v_2^{\rm prompt}/2$, thus $v_2^{\rm prompt} = 2\,v_2^{\rm obs}/(1 + f_{\rm prompt})$. The $f_{\rm prompt}$ fraction is estimated, as a function of $p_{\rm T}$, as described in [62], using (i) the FONLL [63] calculation for the beauty-hadron cross section, (ii) the beauty-hadron decay kinematics from the EvtGen package [64], (iii) the reconstruction and selection efficiencies for feed-down D mesons from simulation, (iv) a hypothesis for the nuclear modification factor of the feed-down D mesons, $R_{\rm AA}^{\text{feed-down}}$. The nuclear modification factor is defined as $R_{\rm AA} = (\mathrm{d}N_{\rm AA}/\mathrm{d}p_{\rm T})/(\langle T_{\rm AA}\rangle \mathrm{d}\sigma_{\rm pp}/\mathrm{d}p_{\rm T})$, where $\mathrm{d}N_{\rm AA}/\mathrm{d}p_{\rm T}$ and $\mathrm{d}\sigma_{\rm pp}/\mathrm{d}p_{\rm T}$ are the $p_{\rm T}$-differential yield and production cross section in nucleus–nucleus (AA) and pp collisions, respectively, and $\langle T_{\rm AA}\rangle$ is the average nuclear overlap function in the considered centrality class [65]. On the basis of the comparison of the $R_{\rm AA}$ of prompt D mesons [66] and J/ψ mesons from beauty-hadron decays [20] in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, the assumptions $R_{\rm AA}^{\text{feed-down}} = 2R_{\rm AA}^{\rm prompt}$ for non-strange D mesons and $R_{\rm AA}^{\text{feed-down}} = R_{\rm AA}^{\rm prompt}$ for the D_s^+ meson are made to compute $f_{\rm prompt}$.

The systematic uncertainty from feed-down on $v_2^{\rm prompt}$ is estimated by varying the central value of $v_2^{\text{feed-down}} = v_2^{\rm prompt}/2$ by $\pm v_2^{\rm prompt}/\sqrt{12}$, corresponding to ± 1 RMS of a uniform distribution in $(0,\, v_2^{\rm prompt})$. The uncertainty on $f_{\rm prompt}$ is obtained from the variation of the renormalisation and factorisation scales and of the charm mass in the FONLL calculation, and from the variation of the $R_{\rm AA}^{\text{feed-down}}$ hypothesis in $1 < R_{\rm AA}^{\text{feed-down}}/R_{\rm AA}^{\rm prompt} < 3$ for non-strange D mesons [16] and $\frac{1}{3} < R_{\rm AA}^{\text{feed-down}}/R_{\rm AA}^{\rm prompt} < 3$ for D_s^+ mesons [58]. 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, non-flow effects, and centrality dependence in the EP resolution correction R_2.

The signal extraction uncertainty is estimated by testing the stability of the yield in each $p_{\rm T}$ and $\Delta\varphi$ interval when varying the fit configurations. Different fit functions were used for the background; the Gaussian width and mean were left as free parameters in the fit. Furthermore, the yield was defined by counting the histogram entries in the invariant-mass region of the signal, after subtracting the background contribution estimated from a fit to the side bands. 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, depending on the $p_{\rm T}$ interval. As a further check of a possible efficiency dependence on $\Delta\varphi$, the analysis was repeated with different selection criteria and no systematic effect was observed.

The EP resolution correction R_2 depends on the collision centrality [38]. 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 two alternative approaches based on weighted averages of the

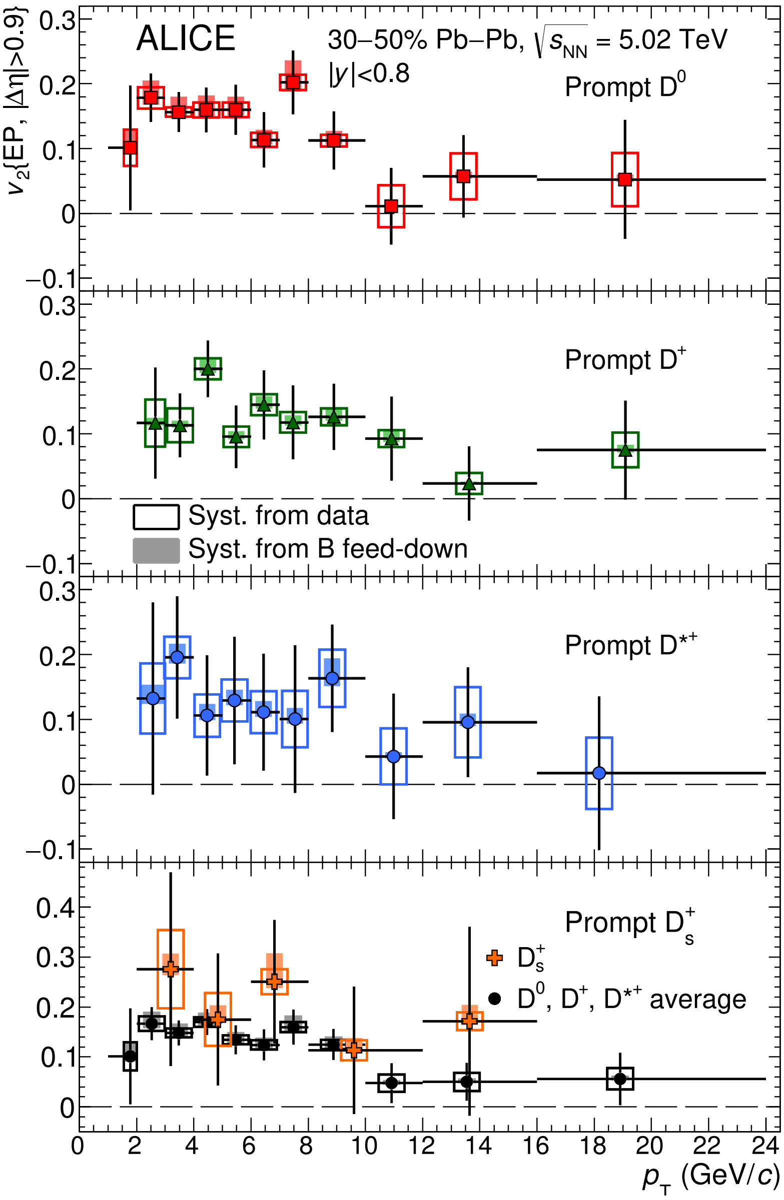

Figure 1: Elliptic flow coefficient as a function of p_T for prompt D^0, D^+, D^{*+} and D_s^+ mesons and their charge conjugates for Pb–Pb collisions in the centrality class 30–50%. The bottom panel also shows the average v_2 of D^0, D^+ and D^{*+}. The symbols are positioned horizontally at the average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

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 non-flow effects in the estimation of R_2, its value was re-computed after introducing two different pseudorapidity gaps between the sub-events of the TPC tracks with positive/negative η. A systematic uncertainty of 2% on R_2 was estimated from these studies.

The v_2 of prompt D^0, D^+, D^{*+} and D_s^+ mesons in the 30–50% centrality class is shown as a function of p_T 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 side bands. The v_2

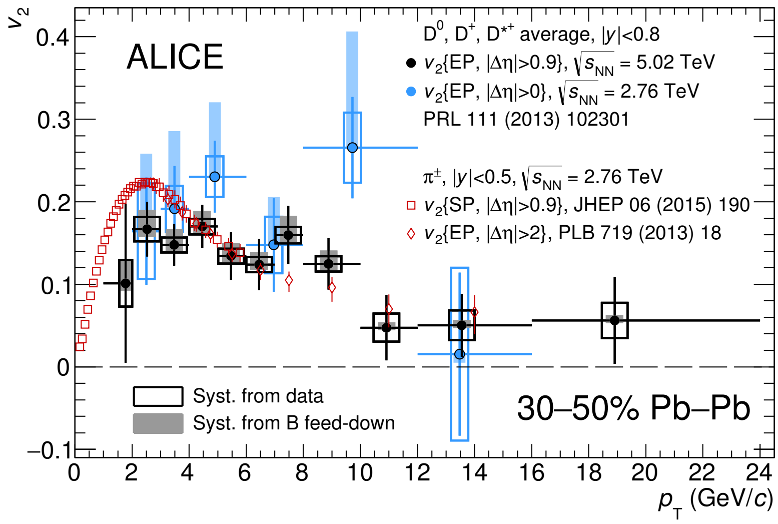

Figure 2: Average of D^0, D^+ and D^{*+} v_2 as a function of $p_{\rm T}$ at $\sqrt{s_{\rm NN}} = 5.02$ TeV, compared with the same measurement at $\sqrt{s_{\rm NN}} = 2.76$ TeV [37] and to the $\pi^{\pm}$ v_2 measured with the EP method [67, 68] and with the scalar production (SP) method [69].

of D^0, D^+ and D^{*+} are consistent with each other and they are larger than zero in $2 < p_{\rm T} < 10$ GeV/c. The average of the v_2 measurements for D_s^+ mesons in the three $p_{\rm T}$ intervals within $2 < p_{\rm T} < 8$ GeV/c is positive with a significance of $2.6\,\sigma$, where σ is the uncertainty of the average v_2, calculated using quadratic error 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 $p_{\rm T}$ of D^0, D^+ and D^{*+}, shown in the bottom panel of Fig. 1, was computed using the inverse of the squared statistical uncertainties as weights. The systematic uncertainties were propagated by treating the contributions from R_2 and the feed-down correction as correlated among the D-meson species.

Figure 2 shows that the average v_2 of D^0, D^+ and D^{*+} at $\sqrt{s_{\rm NN}} = 5.02$ TeV is compatible with the same measurement at $\sqrt{s_{\rm NN}} = 2.76$ TeV ($L_{\rm int} \approx 6\ \mu\mathrm{b}^{-1}$) [37], which has uncertainties larger by a factor of about two compared to the new result at 5.02 TeV. Note that the vertexing and tracking performance improved in 2015 and in [37] 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 $\sqrt{s_{\rm NN}} = 2.76$ TeV by about 10%.

The average D-meson v_2 is also compared with the $\pi^{\pm}$ v_2 at $\sqrt{s_{\rm NN}} = 2.76$ TeV measured with the EP method [67, 68] and with the scalar product (SP) method [69]. The comparison of the D-meson v_2 at $\sqrt{s_{\rm NN}} = 5.02$ TeV and of the pion v_2 at $\sqrt{s_{\rm NN}} = 2.76$ TeV is justified by the observation that the $p_{\rm T}$-differential v_2 of charged particles, which is dominated by the pion component, is compatible at these two energies [52]. The D-meson v_2 is similar to that of $\pi^{\pm}$ in the common $p_{\rm T}$ interval (1–16 GeV/c) and it is lower by about $2\,\sigma$ in the interval below 4 GeV/c, where a mass ordering of v_2 is observed and described by hydrodynamical calculations for light-flavour hadrons [69].

In Fig. 3, the average v_2 of the three non-strange D-meson species is compared with theoretical calculations that include a hydrodynamical model for the QGP expansion (models that lack such an expansion underestimated the D-meson v_2 measurements at $\sqrt{s_{\rm NN}} = 2.76$ TeV in $2 < p_{\rm T} < 6$ GeV/c [38]). The BAMPS-el [48], POWLANG [49] and TAMU [42] calculations include only collisional (i.e. elastic) interaction processes, while the BAMPS-el+rad [48], LBT [50], MC@sHQ [47] and PHSD [46] calculations also include energy loss via gluon radiation. All calculations, with the exception of BAMPS, include hadronisation via quark recombination, in addition to independent fragmentation. The MC@sHQ

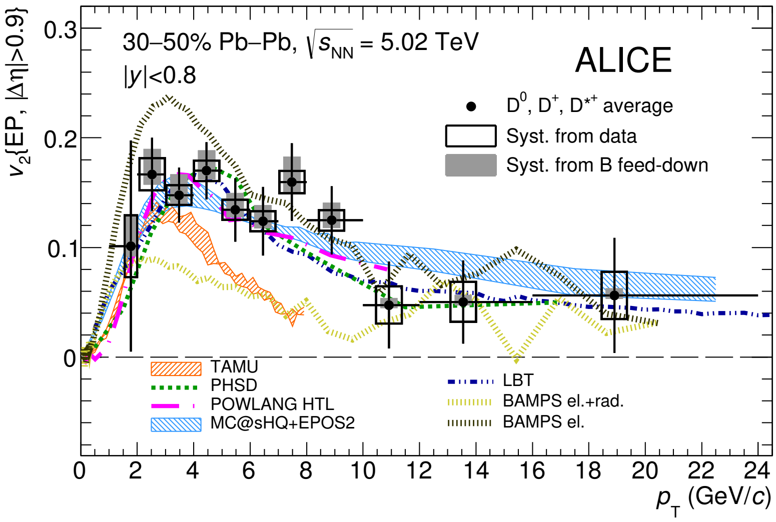

Figure 3: Average of D^0, D^+ and D^{*+} v_2 as a function of $p_{\rm T}$, compared with model calculations [42, 46–50]. For MC@sHQ+EPOS2 and TAMU the band represents the uncertainty of the calculation.

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 $\sqrt{s_{\rm NN}} = 2.76$ TeV in $1 < p_{\rm T} < 8$ GeV/c [16].

The v_2 measurement at $\sqrt{s_{\rm NN}} = 5.02$ 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 level of model-to-data consistency was quantified in terms of the reduced χ^2 in the $p_{\rm T}$ interval where all calculations are available (2–8 GeV/c): the LBT, MC@sHQ, PHSD and POWLANG models have $\chi^2/\text{ndf} < 1$, the TAMU, BAMPS-el+rad and BAMPS-el models have a χ^2/ndf of about 4.1, 6.7 and 1.9, respectively. The χ^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 [48]. For TAMU, the rapid decrease of v_2 with increasing $p_{\rm T}$ is due to the lack of radiative energy loss, which is also reflected in $R_{\rm AA}$ values larger than the measured ones at high $p_{\rm T}$ [16]. For most of these calculations, the medium effect on heavy quarks can be expressed in terms of the dimensionless quantity $2\pi T D_s(T)$ [51]. In particular, in the interval from the critical temperature for QGP formation $T_{\rm c} \approx 155$ MeV [2] to $2\,T_{\rm c}$, the ranges of $2\pi T D_s(T)$ are: 1–2 for BAMPS-el, 6–10 for BAMPS-el+rad, 2–6 for LBT [70], 1.5–4.5 for MC@sHQ [7], 4–9 for PHSD [46], 7–18 for POWLANG [11] and 4–10 for TAMU [7]. The calculations that describe the data with $\chi^2/\text{ndf} < 1$ use values of $2\pi T D_s(T)$ in the range 1.5–7 at $T_{\rm c}$. The corresponding thermalisation time [51] for charm quarks is $\tau_{\rm charm} = \frac{m_{\rm charm}}{T} D_s(T) \approx$ 3–14 fm/c with $T = T_{\rm c}$ and $m_{\rm charm} = 1.5$ GeV/c^2. These values are comparable to the estimated decoupling time of the high-density system [71]. 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 $\sqrt{s_{\rm NN}} = 5.02$ TeV. The average v_2 of non-strange D mesons was measured with statistical and systematic uncertainties smaller by a factor about two with respect to our measurement at $\sqrt{s_{\rm NN}} = 2.76$ 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 non-strange 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 recombination of charm and light quarks both contribute to the observed elliptic flow. The model calculations that provide a fair description of the measurements use values of the heavy-quark spatial diffusion coefficient in the range of $2\pi T D_s(T) \approx 1.5$–7 at the critical temperature $T_{\rm c}$.

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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. Šefčík[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. Vechernin[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], S. Zou[7]

Affiliation notes

[i] Deceased
[ii] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy
[iii] Also at: Georgia State University, Atlanta, Georgia, United States
[iv] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia
[v] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[vi] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] Benemérita Universidad Autónoma 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]China Institute of Atomic Energy, Beijing, China
[15]COMSATS Institute of Information Technology (CIIT), Islamabad, Pakistan
[16]Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[17]Department of Physics, Aligarh Muslim University, Aligarh, India
[18]Department of Physics, Ohio State University, Columbus, Ohio, United States
[19]Department of Physics, Pusan National University, Pusan, Republic of Korea
[20]Department of Physics, Sejong University, Seoul, Republic of Korea
[21]Department of Physics, University of Oslo, Oslo, Norway
[22]Department of Physics and Technology, University of Bergen, Bergen, Norway
[23]Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy
[24]Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[25]Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[26]Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[27]Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[28]Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[29]Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[30]Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[31]Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[32]Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
[33]Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[34]Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
[35]European Organization for Nuclear Research (CERN), Geneva, Switzerland
[36]Excellence Cluster Universe, Technische Universität München, Munich, Germany
[37]Faculty of Engineering, Bergen University College, Bergen, Norway
[38]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
[39]Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[40]Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[41]Faculty of Technology, Buskerud and Vestfold University College, Tonsberg, Norway
[42]Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[43]Gangneung-Wonju National University, Gangneung, Republic of Korea
[44]Gauhati University, Department of Physics, Guwahati, India
[45]Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[46]Helsinki Institute of Physics (HIP), Helsinki, Finland
[47]Hiroshima University, Hiroshima, Japan
[48]Indian Institute of Technology Bombay (IIT), Mumbai, India
[49]Indian Institute of Technology Indore, Indore, India
[50]Indonesian Institute of Sciences, Jakarta, Indonesia
[51]INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[52]INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
[53]INFN, Sezione di Bari, Bari, Italy
[54]INFN, Sezione di Bologna, Bologna, Italy

[55]INFN, Sezione di Cagliari, Cagliari, Italy
[56]INFN, Sezione di Catania, Catania, Italy
[57]INFN, Sezione di Padova, Padova, Italy
[58]INFN, Sezione di Roma, Rome, Italy
[59]INFN, Sezione di Torino, Turin, Italy
[60]INFN, 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, Universidade 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 Subatomique 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 Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[96]Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
[97]Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[98]Petersburg Nuclear Physics Institute, Gatchina, Russia
[99]Physics Department, Creighton University, Omaha, Nebraska, United States
[100]Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[101]Physics Department, Panjab University, Chandigarh, India
[102]Physics Department, University of Cape Town, Cape Town, South Africa
[103]Physics Department, University of Jammu, Jammu, India
[104]Physics Department, University of Rajasthan, Jaipur, India
[105]Physikalisches Institut, Eberhard Karls Universität Tübingen, Tübingen, Germany
[106]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[107]Physik Department, Technische Universität München, Munich, Germany
[108]Purdue University, West Lafayette, Indiana, United States

[109]Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[110]Rudjer Bošković Institute, Zagreb, Croatia
[111]Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[112]Saha Institute of Nuclear Physics, Kolkata, India
[113]School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[114]Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[115]SSC IHEP of NRC Kurchatov institute, Protvino, Russia
[116]Stefan 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 Andre, 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