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Measurement of D-meson production in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

The ALICE Collaboration*

Abstract

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

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*See Appendix A for the list of collaboration members

In hadronic collisions heavy quarks are produced in scattering processes with large momentum transfer. Theoretical predictions based on perturbative Quantum Chromo-Dynamics (QCD) describe the $p_{\rm T}$-differential charm production cross sections in pp collisions at different energies [1–3].

The interpretation of heavy-ion collisions experimental results is consistent with the formation of a a high-density colour-deconfined medium, the Quark-Gluon Plasma (QGP) [4, 5]. Heavy quarks are sensitive to the transport properties of the medium since they are produced on a short time-scale and traverse the medium interacting with its constituents. In Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, the D-meson nuclear modification factor $R_{\rm AA}$, defined as ratio of the yield in nucleus-nucleus collisions to that observed in pp collisions scaled by the number of binary nucleon-nucleon collisions, indicates a strong suppression of the D-meson yield for $p_{\rm T} \gtrsim 2$ GeV/c [6]. The suppression is interpreted as due to in-medium energy loss [7–10]. A complete understanding of the Pb–Pb results requires an understanding of cold nuclear matter effects in the initial and final state, which can be accessed by studying p–Pb collisions assuming that the QGP is not formed in these collisions. In the initial state, the nuclear environment affects the quark and gluon distributions, which are modified in bound nucleons depending on the parton fractional momentum x and the atomic mass number A [11, 12]. At LHC energies, the most relevant effect is gluon saturation at low x, which can modify the D-meson production significantly at low $p_{\rm T}$. This effect can be described either by means of calculations based on phenomenological modification of the Parton Distribution Functions (PDF) [13–15] or with the Color Glass Condensate (GCG) effective theory [16–19]. Partons can also lose energy in the initial stages of the collision via initial state radiation, thus modifying the centre-of-mass energy of the partonic system [20], or experience transverse momentum broadening due to multiple soft collisions before the c$\bar{\rm c}$ pair is produced [21–23]. Recent calculations of parton energy loss in the nuclear medium suggest that the formed c$\bar{\rm c}$ pair is also affected by these processes in p–Pb collisions [24]. The presence of final-state effects in small collision systems is suggested by recent studies on long-range correlations of charged hadrons [25–28] in p–Pb collisions, by results on the species-dependent nuclear modification factors of pions, kaons and protons [29] and on the larger suppression of the ψ' meson with respect to the J/ψ [30] in d–Au collisions.

Previous studies to address cold nuclear matter effects in heavy-flavour production were carried out at RHIC by measuring the inclusive production of leptons from heavy-flavour hadrons decays in d–Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV [31–33]. PHENIX measured an enhancement of about 40% of the heavy-flavour decay electrons in the 20% most central d–Au collisions with respect to pp collisions [31]. A description of this result in terms of hydrodynamic flow in small collision systems was recently proposed [34]. PHENIX also measured an enhancement (suppression) of heavy-flavour decay muons at backward (forward) rapidities in d–Au collisions [32].

In this Letter, we present the measurement of the cross sections and of the nuclear modification factors, $R_{\rm pPb}$, of prompt $\rm D^0$, $\rm D^+$, $\rm D^{*+}$ and $\rm D_s^+$ mesons in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV performed with the ALICE detector [35, 36] at the LHC. D mesons were reconstructed in the rapidity interval $|y_{\rm lab}| < 0.5$ via their hadronic decay channels $\rm D^0 \to K^-\pi^+$ (with branching ratio, BR, of $3.88 \pm 0.05\%$), $\rm D^+ \to K^-\pi^+\pi^+$ (BR of $9.13 \pm 0.19\%$), $\rm D^{*+} \to D^0\pi^+$ (BR of $67.7 \pm 0.5\%$) and $\rm D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$ (BR of $2.28 \pm 0.12\%$) [37] and their charge conjugates. Due to the different energies per nucleon of the proton and the lead beams, the nucleon–nucleon centre-of-mass frame was moving with a rapidity $|\Delta y_{\rm NN}| = 0.465$ in the proton beam direction (positive rapidities), leading to the rapidity coverage $-0.96 < y_{\rm cms} < 0.04$.

Charged particles were reconstructed and identified with the central barrel detectors located within a 0.5 T solenoid magnet. Tracks were reconstructed with the Inner Tracking System (ITS)and the Time Projection Chamber (TPC). Particle IDentification (PID) was based on the specific energy loss $\mathrm{d}E/\mathrm{d}x$ in the TPC gas and on the time of flight from the interaction point to the Time Of Flight (TOF) detector. The analysis was performed using p–Pb data collected in 2013 with a minimum-bias trigger that required the arrival of bunches from both directions and coincident signals in both scintillator arrays of the V0 detector, covering the regions $2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$. Events were selected offline using the timing information from the V0 and the Zero Degree Calorimeters to remove background due to beam-gas interactions. Only events with a primary vertex reconstructed within ± 10 cm from the centre of the detector along the beam line were considered. About 1×10^8 events, corresponding to an integrated luminosity of (48.6 ± 1.6) $\mu\mathrm{b}^{-1}$, passed the selection criteria.

D-meson reconstruction was based on the reconstruction of decay vertices displaced from the interaction vertex, exploiting the separation of a few hundred μm typical of the D-meson weak decays, as described in [6, 38–40]. D^0, D^+ and D_s^+ candidates were defined using pairs or triplets of tracks with the proper charge sign combination. Tracks were required to have $|\eta| < 0.8$, $p_\mathrm{T} > 0.4$ GeV/c, at least 70 out of 159 associated space points in the TPC and at least 2 out of 6 hits in the ITS, out of which at least one in the two innermost layers. D^{*+} candidates were formed combining D^0 candidates with tracks with $|\eta| < 0.8$, $p_\mathrm{T} > 0.1$ GeV/c and at least three associated hits in the ITS. The selection strategy was based on the displacement of the tracks from the interaction vertex and the pointing of the reconstructed D meson momentum to the primary vertex. At low-p_T, further background rejection was obtained by identifying charged kaons with the TPC and TOF by applying cuts in units of resolution ($\pm 3\sigma$) around the expected mean values of $\mathrm{d}E/\mathrm{d}x$ and time of flight. For D_s^+ candidate selection, the invariant mass of at least one of the two opposite-charge track pairs was required to be compatible with the mass of the ϕ meson.

The total cross section for hard processes $\sigma_\mathrm{pA}^\mathrm{hard}$ in proton–nucleus collisions scales as $\sigma_\mathrm{pA}^\mathrm{hard} = \mathrm{A}\ \sigma_\mathrm{NN}^\mathrm{hard}$ where A is the atomic mass number of the nucleus and $\sigma_\mathrm{NN}^\mathrm{hard}$ is the equivalent cross section in pp collisions. Therefore, the R_pPb for prompt D mesons is given by

$$R_\mathrm{pPb} = \frac{\left(\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}}\right)_\mathrm{pPb}}{\mathrm{A} \times \left(\frac{\mathrm{d}\sigma}{\mathrm{d}p_\mathrm{T}}\right)_\mathrm{pp}}. \tag{1}$$

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

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{D}^+}}{\mathrm{d}p_\mathrm{T}}\right|_{|y_\mathrm{lab}|<0.5} = \frac{f_\mathrm{prompt} \cdot N_\mathrm{raw}^{\mathrm{D}^\pm}|_{|y_\mathrm{lab}|<y_\mathrm{fid}}}{2\Delta y \Delta p_\mathrm{T} (\mathrm{Acc} \times \varepsilon)_\mathrm{prompt} \cdot \mathrm{BR} \cdot L_\mathrm{int}}. \tag{2}$$

$N_\mathrm{raw}^{\mathrm{D}^\pm}$ is the raw yield extracted in a given p_T interval (of width Δp_T) by means of a fit to the invariant mass distribution of the D-meson candidates. f_prompt is the prompt fraction of the raw yield. $(\mathrm{Acc} \times \varepsilon)_\mathrm{prompt}$ is the geometrical acceptance multiplied by the reconstruction and selection efficiency of prompt D mesons. $\Delta y = 2y_\mathrm{fid}$ is the width of the rapidity interval, where y_fid is the p_T dependent fiducial acceptance cut (y_fid increases from 0.5 at $p_\mathrm{T} = 0$ to 0.8 at $p_\mathrm{T} = 5$ GeV/c and becomes constant at 0.8 for $p_\mathrm{T} > 5$ GeV/c). The cross sections are given for particles, thus, a factor 1/2 was added to take into account that both particles and anti-particles are counted in the raw yield. The integrated luminosity, L_int, was computed as $N_\mathrm{pPb,MB}/\sigma_\mathrm{pPb,MB}$ where $N_\mathrm{pPb,MB}$ is the number of p–Pb collisions passing the minimum-bias trigger condition and $\sigma_\mathrm{pPb,MB}$ is the cross section of the V0 trigger, which was measured to be 2.09 b $\pm$ 3% (syst) with the p–Pb van der Meer scan [41]. The minimum-bias trigger is 100% efficient for D mesons with $p_\mathrm{T} > 1$ GeV/c and $|y_\mathrm{lab}| < 0.5$.

The acceptance-times-efficiency $(\mathrm{Acc} \times \varepsilon)$ corrections were determined using a Monte Carlo simulation. Proton–lead collisions were produced using the HIJING v1.36 [42] event generator. A $\mathrm{c\bar{c}}$ or $\mathrm{b\bar{b}}$ pair was added in each event using the PYTHIA v6.4.21 [43] generator with Perugia-0 tuning [44]. The generated particles were transported through the ALICE detector using GEANT3 [45]. The efficiency for D-meson reconstruction and selection varies from 0.5-1% for $p_\mathrm{T} < 2$ GeV/c to 20-30% for $p_\mathrm{T} > 12$ GeV/c because of the larger displacement of the decay vertex of high-p_T candidates due to the Lorentz boost.

Hence, in each $p_{\rm T}$ interval, the generated D-meson spectrum used to calculate the efficiencies was tuned to reproduce the shape given by Fixed-Order Next-To-Leading-Log resummation (FONLL) [2] calculations at $\sqrt{s} = 5.02$ TeV. The efficiency depends also on the multiplicity of charged particles produced in the collision since the primary vertex resolution, and consequently the resolution of the topological selection variables, improves with increasing multiplicity. This dependence is different for each meson species and $p_{\rm T}$ interval, being more pronounced for low multiplicities, where the efficiency increases with increasing multiplicity until it becomes constant at about 20 reconstructed primary particles. Therefore, the efficiency was calculated by weighting the simulated events according to their charged particle multiplicity in order to reproduce the multiplicity distribution observed in data.
The fraction of prompt D mesons, $f_{\rm prompt}$, was estimated as in [6] using the beauty production cross section from FONLL calculations [2], the $\rm B \to D + \mathit{X}$ decay kinematics from the EvtGen package [46] and the reconstruction and selection efficiency for D mesons from B hadron decays. The $R_{\rm pPb}$ of prompt and feed-down D mesons were assumed to be equal and were varied in the range $0.9 < R_{\rm pPb}^{\rm feed-down}/R_{\rm pPb}^{\rm prompt} < 1.3$ to evaluate the systematic uncertainties. This range was chosen considering the predictions from calculations including initial state effects based on EPS09 nuclear PDF parametrizations [13] and CGC [16].

The reference pp cross sections at $\sqrt{s} = 5.02$ TeV were obtained by a pQCD-based energy scaling of the $p_{\rm T}$-differential cross sections measured at $\sqrt{s} = 7$ TeV [39]. The scaling factor for each D-meson species was determined as the ratio of the cross sections from the FONLL calculations at 5.02 and 7 TeV. The uncertainty on the scaling factor was evaluated by varying the calculation parameters as described in [47] and it ranges from $^{+17.5\%}_{-4\%}$ at $p_{\rm T} = 1$ GeV$/c$ to about $\pm3\%$ for $p_{\rm T} > 8$ GeV$/c$. In addition, the pp reference is affected by the uncertainty coming from the 7 TeV measurement ($\sim$17%) [39]. Since the $\rm D^0$ cross section in pp collisions in the $1 < p_{\rm T} < 2$ GeV$/c$ interval was measured at both 7 and 2.76 TeV, both results were scaled to 5.02 TeV, and averaged considering their relative statistical and systematic uncertainties as weights. Since the current measurement of the ALICE $\rm D^0$ pp cross section at $\sqrt{s} = 7$ TeV is limited to $p_{\rm T} = 16$ GeV$/c$, the cross section was extrapolated to higher $p_{\rm T}$ using the spectrum predicted by FONLL [2] scaled to match pp data in $5 < p_{\rm T} < 16$ GeV$/c$. Then the $\rm D^0$ cross section at 7 TeV in $16 < p_{\rm T} < 24$ GeV$/c$ was scaled to 5.02 TeV.

The systematic uncertainties on the D-meson cross sections include contributions from yield extraction (from 2% to 17% depending on $p_{\rm T}$ and D-meson species), imperfect description of the cut variables in the simulation (from 5% to 8% for $\rm D^0$, $\rm D^+$ and $\rm D^{*+}$, $\sim$20% for $\rm D_s^+$), tracking efficiency (3% for each track), simulated $p_{\rm T}$ shapes (from 2% to 3% depending on $p_{\rm T}$ and D-meson species) and the subtraction of feed-down D mesons from B decays. For the $\rm D^0$ meson the yield extraction systematic uncertainty also includes the contribution to the raw yield of signal candidates reconstructed with wrong mass assignment to the final state hadrons. This contribution, which is strongly reduced by the PID selection, was estimated to be 3%(4%) at low(high) $p_{\rm T}$ based on the invariant mass distribution of these candidates in the simulation. Details of the procedure for the systematic uncertainty estimation are reported in [6, 38–40]. The measured cross sections have a global systematic uncertainty due to the branching ratio [37] and to the determination of the integrated luminosity, 3.2% [41]. For the $R_{\rm pPb}$, the pp and p–Pb uncertainties were added in quadrature except for the feed-down contribution, which partially cancels out in the ratio.

The $p_{\rm T}$-differential production cross sections of prompt $\rm D^0$, $\rm D^+$, $\rm D^{*+}$ and $\rm D_s^+$ mesons are shown in Fig. 1. The relative abundances of D mesons in p–Pb collisions are compatible within uncertainties with those measured in pp collisions [40]. This confirms the independence of the D-meson relative abundances on the collision system and colliding energy. The $R_{\rm pPb}$ of the four D-meson species, shown in Fig. 2, are consistent, and they are compatible with unity within the uncertainties in the measured $p_{\rm T}$-range. D-meson production in p–Pb collisions is consistent within statistical and systematic uncertainties with the binary collision scaling of the production in pp collisions. Moreover, within the uncertainties, the $\rm D_s^+$ nuclear modification factor is compatible with that of non-strange D mesons. The average of

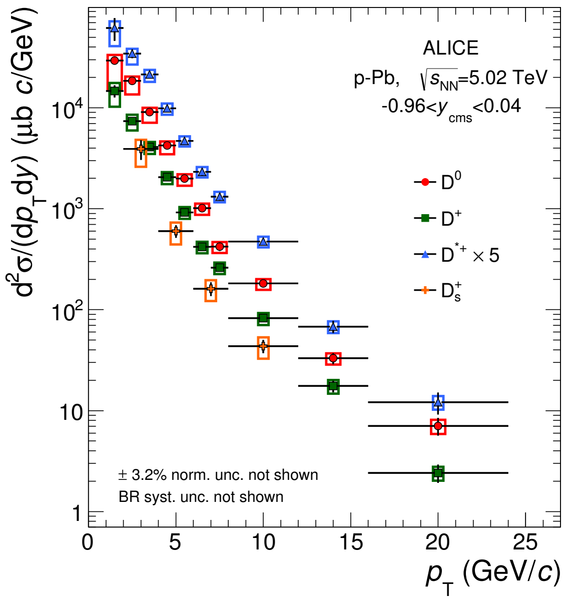

Figure 1: p_T-differential inclusive production cross section of prompt D^0, D^+, D^{*+} and D_s^+ mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical uncertainties (bars) and systematic uncertainties (boxes) are shown.

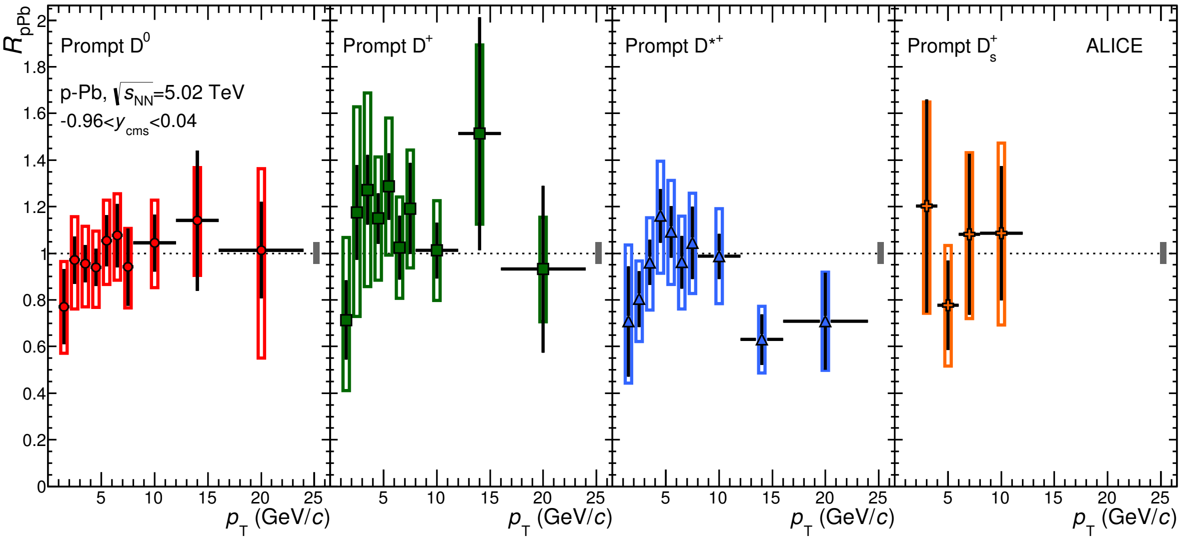

Figure 2: R_{pPb} as a function of p_T for prompt D^0, D^+, D^{*+} and D_s^+ mesons in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical uncertainties (bars), systematic (empty boxes) and normalization (full box) uncertainties are shown.

the R_{pPb} of D^0, D^+ and D^{*+} in the p_T range $1 < p_T < 24$ GeV/c was calculated using the relative statistical uncertainties as weights. The systematic error on the average was calculated by propagating the uncertainties through the weighted average, where the contributions from tracking efficiency, B feed-down correction and scaling of the pp reference were taken as fully correlated among the three species. Figure 3 shows the average R_{pPb} compared to theoretical calculations. Predictions based on NLO pQCD calculations (MNR [48]) of D-meson production, including the EPS09 [13] nuclear modification of the CTEQ6M PDF [49] and calculations based on the Color Glass Condensate [16] can describe the measurement considering only initial state effects. Data are also well described by calculations which

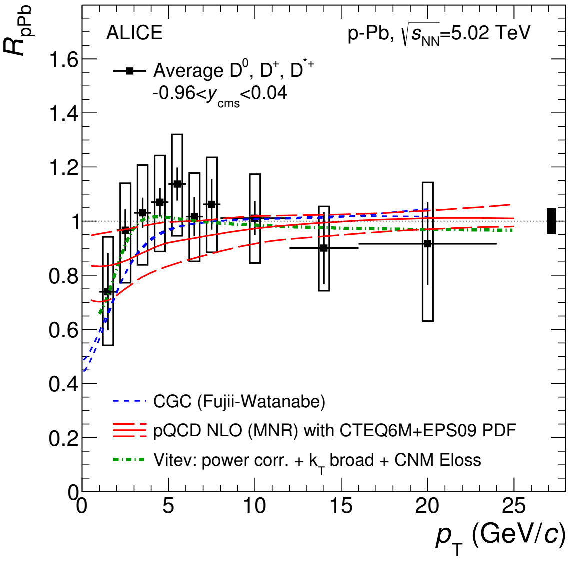

Figure 3: Average $R_{\rm pPb}$ of prompt $\rm D^0$, $\rm D^+$ and $\rm D^{*+}$ mesons as a function of $p_{\rm T}$ compared to model calculations. Statistical (bars), systematic (empty boxes) and normalization (full box) uncertainties are shown.

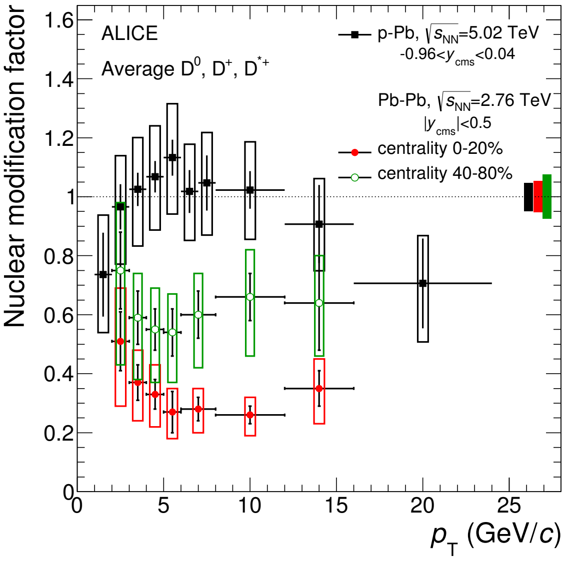

Figure 4: Average $R_{\rm pPb}$ of prompt $\rm D^0$, $\rm D^+$ and $\rm D^{*+}$ mesons as a function of $p_{\rm T}$ compared to D-meson $R_{\rm AA}$ in the 20% most central and in the 40-80% Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV from [6]. Statistical (bars), systematic (empty boxes) and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

include cold nuclear matter energy loss, nuclear shadowing and $k_{\rm T}$-broadening [9]. The possible effects due to the formation of a hydrodynamically expanding medium as calculated in [34] are expected to be small in minimum-bias collisions at LHC energies. The present uncertainties of the measurement do not allow any sensitivity on this effect. In Fig. 4 the average $R_{\rm AA}$ of prompt D mesons in central (0-20%) and in semi-peripheral (40-80%) Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [6] is reported along with the average $R_{\rm pPb}$ of prompt D mesons in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, showing that cold nuclear matter effects are smaller than the uncertainties for $p_{\rm T} \gtrsim 3$ GeV$/c$. In addition, as reported in [6], the same EPS09 nuclear PDF parametrization that describes the D-meson $R_{\rm pPb}$ results predicts small initial state effects (less than 10% for $p_{\mathrm{T}} > 5$ GeV$/c$) for Pb–Pb collisions. As a consequence, the suppression observed in central Pb–Pb collisions for $p_{\mathrm{T}} \gtrsim 2$ GeV$/c$ is predominantly induced by final-state effects, e.g. the charm energy loss in the medium [7–10].

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

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A The ALICE Collaboration

B. Abelev[69] , J. Adam[37] , D. Adamová[77] , M.M. Aggarwal[81] , M. Agnello[105,88] , A. Agostinelli[26] , N. Agrawal[44] , Z. Ahammed[124] , N. Ahmad[18] , I. Ahmed[15] , S.U. Ahn[62] , S.A. Ahn[62] , I. Aimo[105,88] , S. Aiola[129] , M. Ajaz[15] , A. Akindinov[53] , S.N. Alam[124] , D. Aleksandrov[94] , B. Alessandro[105] , D. Alexandre[96] , A. Alici[12,99] , A. Alkin[3] , J. Alme[35] , T. Alt[39] , S. Altinpinar[17] , I. Altsybeev[123] , C. Alves Garcia Prado[113] , C. Andrei[72,72] , A. Andronic[91] , V. Anguelov[87] , J. Anielski[49] , T. Antičić[92] , F. Antinori[102] , P. Antonioli[99] , L. Aphecetche[107] , H. Appelshäuser[48] , S. Arcelli[26] , N. Armesto[16] , R. Arnaldi[105] , T. Aronsson[129] , I.C. Arsene[91] , M. Arslandok[48] , A. Augustinus[34] , R. Averbeck[91] , T.C. Awes[78] , M.D. Azmi[83] , M. Bach[39] , A. Badalà[101] , Y.W. Baek[64,40] , S. Bagnasco[105] , R. Bailhache[48] , R. Bala[84] , A. Baldisseri[14] , F. Baltasar Dos Santos Pedrosa[34] , R.C. Baral[56] , R. Barbera[27] , F. Barile[31] , G.G. Barnaföldi[128] , L.S. Barnby[96] , V. Barret[64] , J. Bartke[110] , M. Basile[26] , N. Bastid[64] , S. Basu[124] , B. Bathen[49] , G. Batigne[107] , B. Batyunya[61] , P.C. Batzing[21] , C. Baumann[48] , I.G. Bearden[74] , H. Beck[48] , C. Bedda[88] , N.K. Behera[44] , I. Belikov[50] , F. Bellini[26] , R. Bellwied[115] , E. Belmont-Moreno[59] , R. Belmont III[127] , V. Belyaev[70] , G. Bencedi[128] , S. Beole[25] , I. Berceanu[72] , A. Bercuci[72] , Y. Berdnikov[ii,79] , D. Berenyi[128] , M.E. Berger[86] , R.A. Bertens[52] , D. Berzano[25] , L. Betev[34] , A. Bhasin[84] , I.R. Bhat[84] , A.K. Bhati[81] , B. Bhattacharjee[41] , J. Bhom[120] , L. Bianchi[25] , N. Bianchi[66] , C. Bianchin[52] , J. Bielčík[37] , J. Bielčíková[77] , A. Bilandzic[74] , S. Bjelogrlic[52] , F. Blanco[10] , D. Blau[94] , C. Blume[48] , F. Bock[87,68] , A. Bogdanov[70] , H. Bøggild[74] , M. Bogolyubsky[106] , F.V. Böhmer[86] , L. Boldizsár[128] , M. 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Di Mauro[34] , P. Di Nezza[66] , Ø. Djuvsland[17] , A. Dobrin[52] , T. Dobrowolski[71] , D. Domenicis Gimenez[113] , B. Dönigus[48] , O. Dordic[21] , S. Dørheim[86] , A.K. Dubey[124] , A. Dubla[52] , L. Ducroux[122] , P. Dupieux[64] , A.K. Dutta Majumdar[95] , T. E. Hilden[42] , R.J. Ehlers[129] , D. Elia[98] , H. Engel[47] , B. Erazmus[34,107] , H.A. Erdal[35] , D. Eschweiler[39] , B. Espagnon[46] , M. Esposito[34] , M. Estienne[107] , S. Esumi[120] , D. Evans[96] , S. Evdokimov[106] , D. Fabris[102] , J. Faivre[65] , D. Falchieri[26] , A. Fantoni[66] , M. Fasel[87] , D. Fehlker[17] , L. Feldkamp[49] , D. Felea[57] , A. Feliciello[105] , G. Feofilov[123] , J. Ferencei[77] , A. Fernández Téllez[2] , E.G. Ferreiro[16] , A. Ferretti[25] , A. Festanti[28] , J. Figiel[110] , M.A.S. Figueredo[117] , S. Filchagin[93] , D. Finogeev[51] , F.M. Fionda[31] , E.M. Fiore[31] , E. Floratos[82] , M. Floris[34] , S. Foertsch[60] , P. Foka[91] , S. Fokin[94] , E. Fragiacomo[104] , A. 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Olah[128] , J. Oleniacz[126] , A.C. Oliveira Da Silva[113] , J. Onderwaater[91] , C. Oppedisano[105] , A. Ortiz Velasquez[32] , A. Oskarsson[32] , J. Otwinowski[91] , K. Oyama[87] , P. Sahoo[45] , Y. Pachmayer[87] , M. Pachr[37] , P. Pagano[29] , G. Paić[58] , F. Painke[39] , C. Pajares[16] , S.K. Pal[124] , A. Palmeri[101] , D. Pant[44] , V. Papikyan[1] , G.S. Pappalardo[101] , P. Pareek[45] , W.J. Park[91] , S. Parmar[81] , A. Passfeld[49] , D.I. Patalakha[106] , V. Paticchio[98] , B. Paul[95] , T. Pawlak[126] , T. Peitzmann[52] , H. Pereira Da Costa[14] , E. Pereira De Oliveira Filho[113] , D. Peresunko[94] , C.E. Pérez Lara[75] , A. Pesci[99] , V. Peskov[48] , Y. Pestov[5] , V. Petráček[37] , M. Petran[37] , M. Petris[72] , M. Petrovici[72] , C. Petta[27] , S. Piano[104] , M. Pikna[36] , P. Pillot[107] , O. Pinazza[99 ,34] , L. Pinsky[115] , D.B. Piyarathna[115] , M. Płoskoń[68] , M. Planinic[121 ,92] , J. Pluta[126] , S. Pochybova[128] , P.L.M. Podesta-Lerma[112] , M.G. Poghosyan[34] , E.H.O. Pohjoisaho[42] , B. Polichtchouk[106] , N. Poljak[92] , A. Pop[72] , S. Porteboeuf-Houssais[64] , J. Porter[68] , B. Potukuchi[84] , S.K. Prasad[127] , R. Preghenella[99 ,12] , F. Prino[105] , C.A. Pruneau[127] , I. Pshenichnov[51] , G. Puddu[23] , P. Pujahari[127] , V. Punin[93] , J. Putschke[127] , H. Qvigstad[21] , A. Rachevski[104] , S. Raha[4] , J. Rak[116] , A. Rakotozafindrabe[14] , L. Ramello[30] , R. Raniwala[85] , S. Raniwala[85] , S.S. Räsänen[42] , B.T. Rascanu[48] , D. Rathee[81] , A.W. Rauf[15] , V. Razazi[23] , K.F. Read[118] , J.S. Real[65] , K. Redlich[,vii,71] , R.J. Reed[129] , A. Rehman[17] , P. Reichelt[48] , M. Reicher[52] , F. Reidt[34] , R. Renfordt[48] , A.R. Reolon[66] , A. Reshetin[51] , F. Rettig[39] , J.-P. Revol[34] , K. Reygers[87] , V. Riabov[79] , R.A. Ricci[67] , T. Richert[32] , M. Richter[21] , P. Riedler[34] , W. Riegler[34] , F. Riggi[27] , A. Rivetti[105] , E. Rocco[52] , M. Rodríguez Cahuantzi[2] , A. Rodriguez Manso[75] , K. Røed[21] , E. Rogochaya[61] , S. Rohni[84] , D. Rohr[39] , D. Röhrich[17] , R. Romita[76] , F. Ronchetti[66] , L. Ronflette[107] , P. Rosnet[64] , A. Rossi[34] , F. Roukoutakis[82] , A. Roy[45] , C. Roy[50] , P. Roy[95] , A.J. Rubio Montero[10] , R. Rui[24] , R. Russo[25] , E. Ryabinkin[94] , Y. Ryabov[79] , A. Rybicki[110] , S. Sadovsky[106] , K. Šafařík[34] , B. Sahlmuller[48] , R. Sahoo[45] , P.K. Sahu[56] , J. Saini[124] , S. Sakai[68] , C.A. Salgado[16] , J. Salzwedel[19] , S. Sambyal[84] , V. Samsonov[79] , X. Sanchez Castro[50] , F.J. Sánchez Rodríguez[112] , L. Šándor[54] , A. Sandoval[59] , M. Sano[120] , G. Santagati[27] , D. Sarkar[124] , E. Scapparone[99] , F. Scarlassara[28] , R.P. Scharenberg[89] , C. Schiaua[72] , R. Schicker[87] , C. Schmidt[91] , H.R. Schmidt[33] , S. Schuchmann[48] , J. Schukraft[34] , M. Schulc[37] , T. Schuster[129] ,

Y. Schutz[107,34], K. Schwarz[91], K. Schweda[91], G. Scioli[26], E. Scomparin[105], R. Scott[118], G. Segato[28], J.E. Seger[80], Y. Sekiguchi[119], I. Selyuzhenkov[91], J. Seo[90], E. Serradilla[10,59], A. Sevcenco[57], A. Shabetai[107], G. Shabratova[61], R. Shahoyan[34], A. Shangaraev[106], N. Sharma[118], S. Sharma[84], K. Shigaki[43], K. Shtejer[25], Y. Sibiriak[94], S. Siddhanta[100], T. Siemiarczuk[71], D. Silvermyr[78], C. Silvestre[65], G. Simatovic[121], R. Singaraju[124], R. Singh[84], S. Singha[124,73], V. Singhal[124], B.C. Sinha[124], T. Sinha[95], B. Sitar[36], M. Sitta[30], T.B. Skaali[21], K. Skjerdal[17], M. Slupecki[116], N. Smirnov[129], R.J.M. Snellings[52], C. Søgaard[32], R. Soltz[69], J. Song[90], M. Song[130], F. Soramel[28], S. Sorensen[118], M. Spacek[37], E. Spiriti[66], I. Sputowska[110], M. Spyropoulou-Stassinaki[82], B.K. Srivastava[89], J. Stachel[87], I. Stan[57], G. Stefanek[71], M. Steinpreis[19], E. Stenlund[32], G. Steyn[60], J.H. Stiller[87], D. Stocco[107], M. Stolpovskiy[106], P. Strmen[36], A.A.P. Suaide[113], T. Sugitate[43], C. Suire[46], M. Suleymanov[15], R. Sultanov[53], M. Šumbera[77], T. Susa[92], T.J.M. Symons[68], A. Szabo[36], A. Szanto de Toledo[113], I. Szarka[36], A. Szczepankiewicz[34], M. Szymanski[126], J. Takahashi[114], M.A. Tangaro[31], J.D. Tapia Takaki[viii,46], A. Tarantola Peloni[48], A. Tarazona Martinez[34], M.G. Tarzila[72], A. Tauro[34], G. Tejeda Muñoz[2], A. Telesca[34], C. Terrevoli[23], J. Thäder[91], D. Thomas[52], R. Tieulent[122], A.R. Timmins[115], A. Toia[102], V. Trubnikov[3], W.H. Trzaska[116], T. Tsuji[119], A. Tumkin[93], R. Turrisi[102], T.S. Tveter[21], K. Ullaland[17], A. Uras[122], G.L. Usai[23], M. Vajzer[77], M. Vala[54,61], L. Valencia Palomo[64], S. Vallero[87], P. Vande Vyvre[34], J. Van Der Maarel[52], J.W. Van Hoorne[34], M. van Leeuwen[52], A. Vargas[2], M. Vargyas[116], R. Varma[44], M. Vasileiou[82], A. Vasiliev[94], V. Vechernin[123], M. Veldhoen[52], A. Velure[17], M. Venaruzzo[24,67], E. Vercellin[25], S. Vergara Limón[2], R. Vernet[8], M. Verweij[127,127], L. Vickovic[109], G. Viesti[28], J. Viinikainen[116], Z. Vilakazi[60], O. Villalobos Baillie[96], A. Vinogradov[94], L. Vinogradov[123], Y. Vinogradov[93], T. Virgili[29], Y.P. Viyogi[124], A. Vodopyanov[61], M.A. Völkl[87], K. Voloshin[53], S.A. Voloshin[127], G. Volpe[34], B. von Haller[34], I. Vorobyev[123], D. Vranic[91,34], J. Vrláková[38], B. Vulpescu[64], A. Vyushin[93], B. Wagner[17], J. Wagner[91], V. Wagner[37], M. Wang[7,107], Y. Wang[87], D. Watanabe[120], M. Weber[115], J.P. Wessels[49], U. Westerhoff[49], J. Wiechula[33], J. Wikne[21], M. Wilde[49], G. Wilk[71], J. Wilkinson[87], M.C.S. Williams[99], B. Windelband[87], M. Winn[87], C.G. Yaldo[127], Y. Yamaguchi[119], H. Yang[52], P. Yang[7], S. Yang[17], S. Yano[43], S. Yasnopolskiy[94], J. Yi[90], Z. Yin[7], I.-K. Yoo[90], I. Yushmanov[94], V. Zaccolo[74], C. Zach[37], A. Zaman[15], C. Zampolli[99], S. Zaporozhets[61], A. Zarochentsev[123], P. Závada[55], N. Zaviyalov[93], H. Zbroszczyk[126], I.S. Zgura[57], M. Zhalov[79], H. Zhang[7], X. Zhang[68,7], Y. Zhang[7], C. Zhao[21], N. Zhigareva[53], D. Zhou[7], F. Zhou[7], Y. Zhou[52], Zhou, Zhuo[17], H. Zhu[7], J. Zhu[7], X. Zhu[7], A. Zichichi[12,26], A. Zimmermann[87], M.B. Zimmermann[34,49], G. Zinovjev[3], Y. Zoccarato[122], M. Zyzak[48]

Affiliation notes

[i] Deceased
[ii] Also at: St. Petersburg State Polytechnical University
[iii] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[iv] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia
[v] Also at: University of Belgrade, Faculty of Physics and ”Vinča” Institute of Nuclear Sciences, Belgrade, Serbia
[vi] Permanent Address: Permanent Address: Konkuk University, Seoul, Korea
[vii] Also at: Institute of Theoretical Physics, University of Wroclaw, Wroclaw, Poland
[viii] Also at: University of Kansas, Lawrence, KS, United States

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, CA, United States
[7] Central China Normal University, Wuhan, China
[8] Centre de Calcul de l’IN2P3, Villeurbanne, 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, USA
[14] Commissariat à l’Energie Atomique, IRFU, Saclay, France
[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 and Technology, University of Bergen, Bergen, Norway
[18] Department of Physics, Aligarh Muslim University, Aligarh, India
[19] Department of Physics, Ohio State University, Columbus, OH, United States
[20] Department of Physics, Sejong University, Seoul, South Korea
[21] Department of Physics, University of Oslo, Oslo, 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 di Scienze e Innovazione Tecnologica dell’Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy
[31] Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy
[32] Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
[33] Eberhard Karls Universität Tübingen, Tübingen, Germany
[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[35] Faculty of Engineering, Bergen University College, Bergen, Norway
[36] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
[37] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[38] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[39] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[40] Gangneung-Wonju National University, Gangneung, South Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helsinki Institute of Physics (HIP), Helsinki, Finland
[43] Hiroshima University, Hiroshima, Japan
[44] Indian Institute of Technology Bombay (IIT), Mumbai, India
[45] Indian Institute of Technology Indore, Indore (IITI), India
[46] Institut de Physique Nucléaire d’Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France
[47] Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[48] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[49] Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany
[50] Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
[51] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[52] Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands
[53] Institute for Theoretical and Experimental Physics, Moscow, Russia
[54] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[55] Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
[56] Institute of Physics, Bhubaneswar, India
[57] Institute of Space Science (ISS), Bucharest, Romania
[58] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[59] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[60] iThemba LABS, National Research Foundation, Somerset West, South Africa
[61] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[62] Korea Institute of Science and Technology Information, Daejeon, South Korea

[63] KTO Karatay University, Konya, Turkey
[64] Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France
[65] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[66] Laboratori Nazionali di Frascati, INFN, Frascati, Italy
[67] Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
[68] Lawrence Berkeley National Laboratory, Berkeley, CA, United States
[69] Lawrence Livermore National Laboratory, Livermore, CA, United States
[70] Moscow Engineering Physics Institute, Moscow, Russia
[71] National Centre for Nuclear Studies, Warsaw, Poland
[72] National Institute for Physics and Nuclear Engineering, Bucharest, Romania
[73] National Institute of Science Education and Research, Bhubaneswar, India
[74] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[75] Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands
[76] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[77] Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic
[78] Oak Ridge National Laboratory, Oak Ridge, TN, United States
[79] Petersburg Nuclear Physics Institute, Gatchina, Russia
[80] Physics Department, Creighton University, Omaha, NE, United States
[81] Physics Department, Panjab University, Chandigarh, India
[82] Physics Department, University of Athens, Athens, Greece
[83] Physics Department, University of Cape Town, Cape Town, South Africa
[84] Physics Department, University of Jammu, Jammu, India
[85] Physics Department, University of Rajasthan, Jaipur, India
[86] Physik Department, Technische Universität München, Munich, Germany
[87] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[88] Politecnico di Torino, Turin, Italy
[89] Purdue University, West Lafayette, IN, United States
[90] Pusan National University, Pusan, South Korea
[91] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
[92] Rudjer Bošković Institute, Zagreb, Croatia
[93] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[94] Russian Research Centre Kurchatov Institute, Moscow, Russia
[95] Saha Institute of Nuclear Physics, Kolkata, India
[96] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[97] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[98] Sezione INFN, Bari, Italy
[99] Sezione INFN, Bologna, Italy
[100] Sezione INFN, Cagliari, Italy
[101] Sezione INFN, Catania, Italy
[102] Sezione INFN, Padova, Italy
[103] Sezione INFN, Rome, Italy
[104] Sezione INFN, Trieste, Italy
[105] Sezione INFN, Turin, Italy
[106] SSC IHEP of NRC Kurchatov institute, Protvino, Russia
[107] SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France
[108] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[109] Technical University of Split FESB, Split, Croatia
[110] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[111] The University of Texas at Austin, Physics Department, Austin, TX, USA
[112] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[113] Universidade de São Paulo (USP), São Paulo, Brazil
[114] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[115] University of Houston, Houston, TX, United States

[116] University of Jyväskylä, Jyväskylä, Finland
[117] University of Liverpool, Liverpool, United Kingdom
[118] University of Tennessee, Knoxville, TN, United States
[119] University of Tokyo, Tokyo, Japan
[120] University of Tsukuba, Tsukuba, Japan
[121] University of Zagreb, Zagreb, Croatia
[122] Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France
[123] V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia
[124] Variable Energy Cyclotron Centre, Kolkata, India
[125] Vestfold University College, Tonsberg, Norway
[126] Warsaw University of Technology, Warsaw, Poland
[127] Wayne State University, Detroit, MI, United States
[128] Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary
[129] Yale University, New Haven, CT, United States
[130] Yonsei University, Seoul, South Korea
[131] Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany