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Measurement of Prompt D-Meson Production in p-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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The p_T-differential production cross sections of the prompt charmed mesons D^0, D^+, D^{*+}, and D_s^+ and their charge conjugate in the rapidity interval $-0.96 < y_{\rm cms} < 0.04$ were measured in p-Pb collisions at a center-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector at the LHC. The nuclear modification factor $R_{p\mathrm{Pb}}$, 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 $1 < p_T < 24$ GeV/c. No significant difference among the $R_{p\mathrm{Pb}}$ 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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In hadronic collisions, heavy quarks are produced in scattering processes with large momentum transfer. Theoretical predictions based on perturbative quantum chromodynamics (QCD) describe the p_T-differential charm production cross sections in pp collisions at different energies [1–3].

The interpretation of heavy-ion collision experimental results is consistent with the formation of a high-density color-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 $\sqrt{s_{NN}} = 2.76$ TeV, the D-meson nuclear modification factor R_{AA}, defined as the ratio of the yield in nucleus-nucleus collisions to that observed in the pp ones scaled by the number of binary nucleon-nucleon collisions, indicates a strong suppression of the D-meson yield for $p_T \gtrsim 2$ 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 states, 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_T. This effect can be described either by means of calculations based on phenomenological modification of the parton distribution functions (PDFs) [13–15] or with the color glass condensate (CGC) effective theory [16–19]. Partons can also lose energy in the initial stages of the collision via initial-state radiation, thus modifying the center-of-mass energy of the partonic system [20], or experience transverse momentum broadening due to multiple soft collisions before the $c\bar{c}$ pair is produced [21–23]. Recent calculations of parton energy loss in the nuclear medium suggest that the formed $c\bar{c}$ 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] in d-Au collisions and on the larger suppression of the ψ' meson with respect to the J/ψ in both d-Au [30] and p-Pb [31] collisions.

Previous studies to address cold-nuclear-matter effects in heavy-flavor production were carried out at RHIC by measuring the production of leptons from heavy-flavor hadrons decays in d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV [32–34]. PHENIX measured an enhancement of about 40% of the heavy-flavor decay electrons in the 20% most central d-Au collisions with respect to pp collisions [32]. A description of this result in terms of hydrodynamic flow in small collision systems was recently proposed [35]. PHENIX also measured an enhancement (suppression) of heavy-flavor decay muons at backward (forward) rapidities in d-Au collisions [33]. The difference observed in the two rapidity regions exceeds predictions based on initial parton density modifications, suggesting the presence of other cold-nuclear-matter effects. The measurement of fully reconstructed charmed hadrons in p-Pb collisions at

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the LHC can shed light on the different aspects of cold-nuclear-matter effects mentioned above and, in particular, can clarify whether the observed suppression of D-meson production in Pb-Pb collisions is a genuine hot QCD matter effect.

In this Letter, we present the measurement of the cross sections and of the nuclear modification factors, $R_{p\mathrm{Pb}}$, of prompt D^0, D^+, D^{*+}, and D_s^+ mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV performed with the ALICE detector [36,37] at the LHC. D mesons were reconstructed in the rapidity interval $|y_{\mathrm{lab}}| < 0.5$ via their hadronic decay channels $D^0 \to K^-\pi^+$ [with a branching ratio (BR) of $3.88 \pm 0.05\%$], $D^+ \to K^-\pi^+\pi^+$ (BR of $9.13 \pm 0.19\%$), $D^{*+} \to D^0\pi^+$ (BR of $67.7 \pm 0.5\%$), and $D_s^+ \to \phi\pi^+ \to K^-K^+\pi^+$ (BR of $2.28 \pm 0.12\%$) [38] and their charge conjugates. Because of the different energies per nucleon of the proton and the lead beams, the nucleon-nucleon center-of-mass frame was moving with a rapidity $|\Delta y_{NN}| = 0.465$ in the proton beam direction (positive rapidities), leading to the rapidity coverage $-0.96 < y_{\mathrm{cms}} < 0.04$.

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 dE/dx 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 by 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 off-line by 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 center of the detector along the beam line were considered. About 10^8 events, corresponding to an integrated luminosity of $(48.6 \pm 1.6)\ \mu\mathrm{b}^{-1}$, passed the selection criteria.

D-meson selection was based on the reconstruction of decay vertices displaced from the interaction vertex, exploiting the separation of a few hundred micrometers typical of the D-meson weak decays, as described in Refs. [6,39–41]. D^0, D^+, and D_s^+ candidates were defined by using pairs or triplets of tracks with the proper charge sign combination. Tracks were required to have $|\eta| < 0.8$, $p_T > 0.4$ GeV/c, at least 70 out of 159 associated space points in the TPC, and at least two out of six hits in the ITS, out of which at least one in the two innermost layers. D^{*+} candidates were formed by combining D^0 candidates with tracks with $|\eta| < 0.8$, $p_T > 0.1$ 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 dE/dx 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 ($\pm 2\sigma$).

The total cross section for hard processes $\sigma_{p-A}^{\mathrm{hard}}$ in proton-nucleus collisions scales as $\sigma_{p-A}^{\mathrm{hard}} = A\sigma_{NN}^{\mathrm{hard}}$ [42], where $\sigma_{NN}^{\mathrm{hard}}$ is the equivalent cross section in pp collisions. Therefore, the $R_{p\mathrm{Pb}}$ for prompt D mesons is given by

$$R_{p\mathrm{Pb}} = \frac{\left(\frac{d\sigma}{dp_T}\right)_{p\mathrm{Pb}}}{A\left(\frac{d\sigma}{dp_T}\right)_{pp}}. \qquad (1)$$

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

$$\left.\frac{d\sigma^{D^+}}{dp_T}\right|_{|y_{\mathrm{lab}}|<0.5} = \frac{f_{\mathrm{prompt}} N_{\mathrm{raw}}^{D^\pm}|_{|y_{\mathrm{lab}}|<y_{\mathrm{fid}}}}{2\alpha_y \Delta p_T (\mathrm{Acc}\times\epsilon)_{\mathrm{prompt}} \times \mathrm{BR} \times L_{\mathrm{int}}}. \qquad (2)$$

$N_{\mathrm{raw}}^{D^\pm}$ 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. $(\mathrm{Acc}\times\epsilon)_{\mathrm{prompt}}$ is the geometrical acceptance multiplied by the reconstruction and selection efficiency of prompt D mesons. The factor $\alpha_y = y_{\mathrm{fid}}/0.5$ normalizes the yields, measured in $|y_{\mathrm{lab}}| < y_{\mathrm{fid}}$, to one unit of rapidity $|y_{\mathrm{lab}}| < 0.5$. y_{fid} is the p_T-dependent fiducial acceptance cut (y_{fid} increases from 0.5 at $p_T = 0$ to 0.8 at $p_T = 5$ GeV/c and becomes constant at 0.8 for $p_T > 5$ GeV/c). The cross sections are given for particles; thus, a factor 1/2 was added to take into account that both particles and antiparticles are counted in the raw yield. The integrated luminosity L_{int} was computed as $N_{p\mathrm{Pb,MB}}/\sigma_{p\mathrm{Pb,MB}}$, where $N_{p\mathrm{Pb,MB}}$ is the number of p-Pb collisions passing the minimum-bias trigger condition and $\sigma_{p\mathrm{Pb,MB}}$ is the cross section of the V0 trigger, which was measured to be $2.09\mathrm{b} \pm 3.5\%$ (syst) with the p-Pb van der Meer scan [43]. The minimum-bias trigger is 100% efficient for D mesons with $p_T > 1$ GeV/c and $|y_{\mathrm{lab}}| < 0.5$.

The acceptance-times-efficiency $(\mathrm{Acc}\times\epsilon)$ corrections were determined by using a Monte Carlo simulation. Proton-lead collisions were produced by using the HIJING v. 1.36 [44] event generator. A $c\bar{c}$ or $b\bar{b}$ pair was added in each event by using the PYTHIA v. 6.4.21 [45] generator with Perugia-0 tuning [46]. The generated particles were transported through the ALICE detector by using GEANT3 [47]. The efficiency for D-meson reconstruction and selection varies from 0.5%–1% for $p_T < 2$ GeV/c to 20%–30% for $p_T > 12$ GeV/c because of the larger displacement of the decay vertex of high-p_T

candidates due to the Lorentz boost. Hence 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 in each p_T interval. 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_T interval: e.g., the D^0 efficiency in $5 < p_T < 8$ GeV/c increases by a factor 1.5 for low multiplicity events 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_{prompt}, was estimated as in Ref. [6] by using the beauty production cross section from FONLL calculations [2], the $B \to D + X$ decay kinematics from the EVTGEN package [48] and the reconstruction and selection efficiency for D mesons from B hadron decays. The $R_{p\mathrm{Pb}}$ of prompt and feed-down D mesons were assumed to be equal and were varied in the range $0.9 < R_{p\mathrm{Pb}}^{\text{feed-down}}/R_{p\mathrm{Pb}}^{\text{prompt}} < 1.3$ to evaluate the systematic uncertainties. This range was chosen by considering the predictions from calculations including initial-state effects based on the Eskola-Paukkunen-Salgado 2009 (EPS09) [13] parameterizations of the nuclear modification of the PDF and CGC [16].

The reference pp cross sections at $\sqrt{s} = 5.02$ TeV were obtained by a perturbative-QCD-based energy scaling of the p_T-differential cross sections measured at $\sqrt{s} = 7$ TeV [40]. 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 Ref. [49], and it ranges from $^{+17.5\%}_{-4\%}$ at $p_T = 1$ GeV/c to about $\pm 3\%$ for $p_T > 8$ GeV/c. In addition, the pp reference is affected by the uncertainty coming from the 7 TeV measurement ($\sim 17\%$) [40]. Since the D^0 cross section in pp collisions in the $1 < p_T < 2$ GeV/c interval was measured at both 7 and 2.76 TeV, both results were scaled to 5.02 TeV and averaged by considering their relative statistical and systematic uncertainties as weights. Since the current measurement of the ALICE D^0 pp cross section at $\sqrt{s} = 7$ TeV is limited to $p_T = 16$ GeV/c, the cross section was extrapolated to higher p_T by using the spectrum predicted by FONLL [2] scaled to match pp data in $5 < p_T < 16$ GeV/c. Then the D^0 cross section at 7 TeV in $16 < p_T < 24$ 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_T and D-meson species), an imperfect description of the cut variables in the simulation (from 5% to 8% for D^0, D^+, and D^{*+} and $\sim 20\%$ for D_s^+), tracking efficiency (3% for each track), simulated p_T shapes (from 2% to 3% depending on p_T and D-meson species), and the subtraction of feed-down D mesons from B decays (from 4% and 40% depending on p_T and D-meson species). For the D^0 meson, the yield extraction systematic uncertainty also includes the contribution to the raw yield of signal candidates reconstructed by assigning the wrong mass 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_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 Refs. [6,39–41]. The measured cross sections have a global systematic uncertainty due to the determination of the integrated luminosity (3.7% [43]) and to the branching ratio [38]. For the $R_{p\mathrm{Pb}}$, the pp and p-Pb uncertainties were added in quadrature except for the branching ratio uncertainty, which cancels out in the ratio, and the feed-down contribution, which partially cancels out.

The p_T-differential production cross sections of prompt D^0, D^+, D^{*+}, and 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, ep, and e^+e^- collisions at different energies [41]. The $R_{p\mathrm{Pb}}$ of the four D-meson species, shown in Fig. 2, are consistent, and they are compatible with unity within the

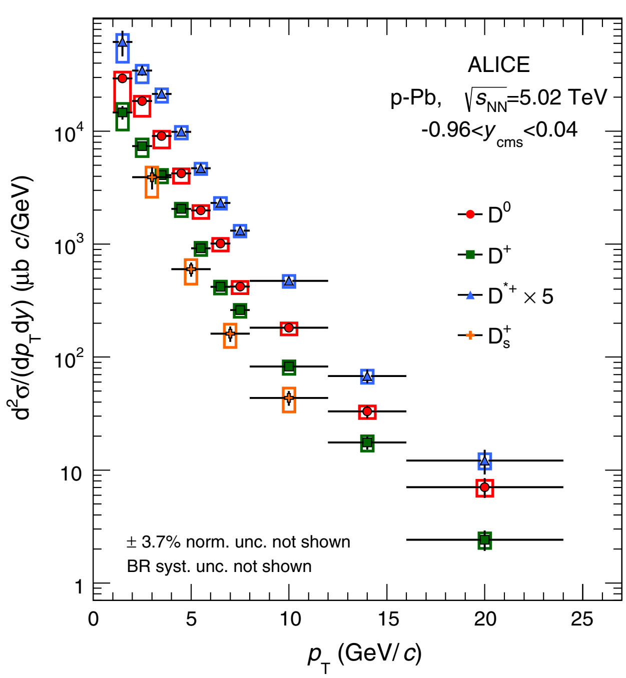

FIG. 1 (color online). p_T-differential inclusive production cross section of prompt D^0, D^+, D^{*+}, and D_s^+ mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical uncertainties (bars) and systematic uncertainties (boxes) are shown.

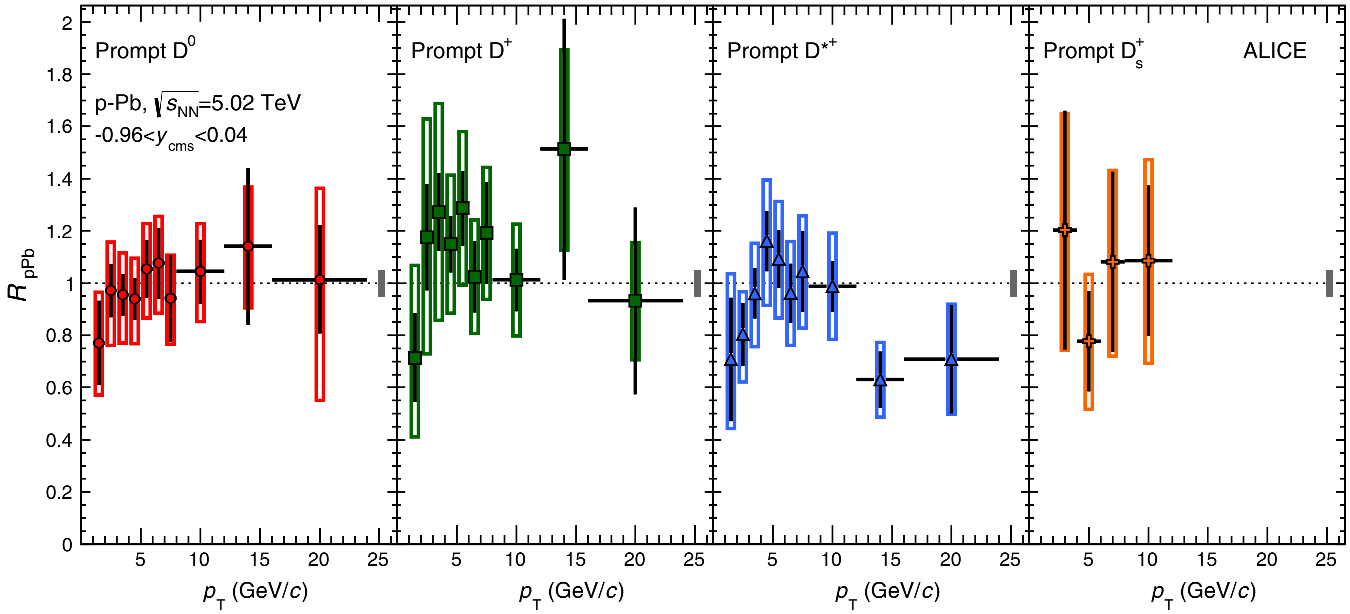

FIG. 2 (color online). R_{pPb} as a function of p_T for prompt D^0, D^+, D^{*+}, and D_s^+ mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical (bars), systematic (empty boxes), and normalization (full box) uncertainties are shown.

uncertainties in the measured p_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 D_s^+ nuclear modification factor is compatible with that of nonstrange D mesons. The average of the R_{pPb} of D^0, D^+, and D^{*+} in the p_T range $1 < p_T < 24$ GeV/c was calculated by 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 either on next-to-leading order (NLO) pQCD calculations (Mangano, Nason, and Ridolfi (MNR) [50]) of D-meson production, including the EPS09 [13] nuclear modification of the CTEQ6M PDF [51], or on calculations based on the color glass condensate [16] can describe the measurement by considering only initial-state effects. Data are also well described by calculations which include cold-nuclear-matter energy loss, nuclear shadowing, and k_T broadening [9]. The possible effects due to the formation of a hydrodynamically expanding medium as calculated in Ref. [35] are expected to be small in minimum-bias collisions at LHC energies. The present uncertainties of the measurement do not allow any sensitivity to this effect. In Fig. 4, the average R_{AA} of prompt D mesons in central (0–20%) and in semiperipheral (40%–80%) Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [6] is reported along with the average R_{pPb} of prompt D mesons in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, showing that cold-nuclear-matter effects are smaller than the uncertainties for $p_T \gtrsim 3$ GeV/c. In addition, as reported in Ref. [6], the same EPS09 nuclear PDF parametrization that describes the D-meson R_{pPb} results predicts small initial-state effects (less than 10% for $p_T > 5$ GeV/c) for Pb-Pb collisions. As a consequence, the suppression observed in central Pb-Pb collisions for $p_T \gtrsim 2$ GeV/c is predominantly induced by final-state effects, e.g., the charm energy loss in the medium [7–10].

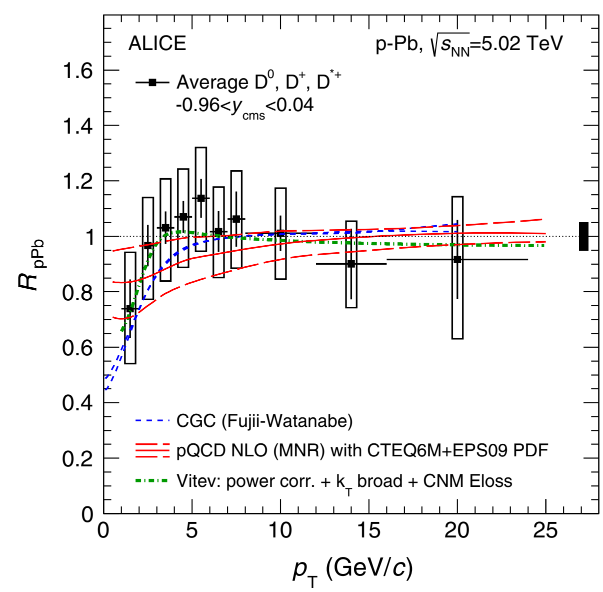

FIG. 3 (color online). Average R_{pPb} of prompt D^0, D^+, and D^{*+} mesons as a function of p_T compared to model calculations. Statistical (bars), systematic (empty boxes), and normalization (full box) uncertainties are shown.

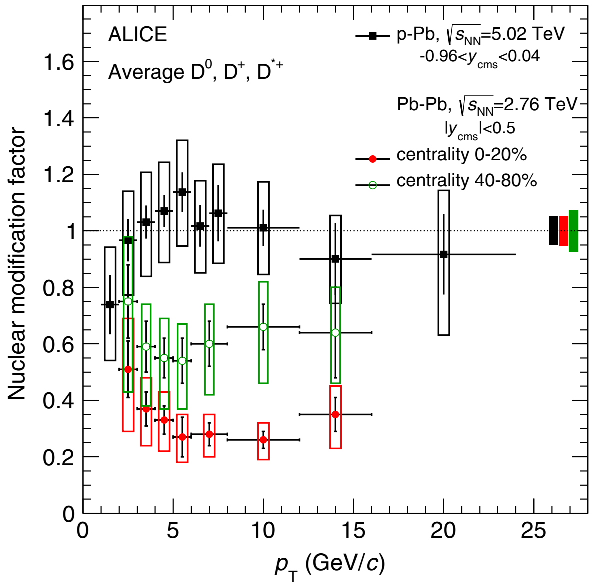

FIG. 4 (color online). Average $R_{p\mathrm{Pb}}$ of prompt D^0, D^+, and D^{*+} mesons as a function of p_T compared to D-meson R_{AA} in the 20% most central and in the 40%–80% Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from Ref. [6]. Statistical (bars), systematic (empty boxes), and normalization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

In summary, we reported the measurement of the D-meson cross section and nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ 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 D mesons with $p_T \gtrsim 2$ GeV/c 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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