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# $D$-meson production in $d + \mathrm{Au}$ process using a perturbative approach

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**Abstract**

The $D$-meson production at forward rapidities in $d + \mathrm{Au}$ processes is calculated using a pQCD based model, assuming that this treatment could be used as a baseline for distinct dynamical and medium effects. It is analysed how the nuclear effects in the nuclear partonic distributions may affect this process at RHIC and LHC energies. An enhancement in the moderate $q_T$ region for RHIC, due to antishadowing in the nuclear medium, is found. Our prediction for LHC suggests that shadowing will suppress the $D$-meson spectra for $q_T < 14$ GeV.


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*Keywords:* Shadowing; Nuclear collisions; Small-$x$ QCD

Relativistic heavy ion collisions provide an opportunity to study the QCD properties at energy densities several hundred times higher than the density of the atomic nuclei [1,2]. In these extreme conditions a deconfined state of quarks and gluons, the quark–gluon plasma (QGP), is expected to be formed in the early stage of the collision. These higher densities could induce a large amount of energy loss by gluon bremsstrahlung while hard partons propagate through the medium. The energy loss experienced by a fast parton may serve as a measure of the density of color charges of the medium it travels through [3,4]. In a dense medium, as the QGP, the energy loss may be huge. As large transverse momentum partons are produced very early in these processes, one expects that they can probe the early stage of the formed dense medium [5]. The mechanism of energy loss is thought to explain the observed suppression of the high transverse momenta ($q_T$) hadron spectra in central Au + Au collisions at RHIC [6]. However, this feature of data could be explained [7] as well by saturation effects in

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the initial nuclear wavefunctions using the color glass condensate (CGC) formalism [8].

In order to determine which mechanism is responsible for this suppression, $d + \mathrm{Au}$ collisions were studied at RHIC. At mid-rapidity the data [9–11] show an absence of jet quenching, which indicates that the observed high-$q_T$ suppression patterns in $\mathrm{Au} + \mathrm{Au}$ collisions are not initial state effects encoded in the wavefunction of the beam nucleus, but are caused by final state interaction of hard partons with the produced dense medium. In order to test the consistency of the interpretation of these quenching effects due to energy loss in a deconfined medium, a comparative study of the attenuation patterns for massless and heavy partons was proposed [12–14]. The large mass of heavy quarks modifies the gluon bremsstrahlung, since it is suppressed for small angles $\theta < m_Q/E$ [15], where $m_Q$ is the mass of heavy quark and $E$, its energy, implying different energy losses for heavy and light quarks propagating in a dense medium. As a consequence, one can observe a softening in the light hadron spectra accompanying heavy quark jets, and a hardening of the leading charmed hadrons [12,13,16]. The production of heavy mesons are also affected by initial state effects, and their magnitude has to be estimated for a realistic prediction of energy loss of heavy quarks.

In this work, the validity of the perturbative QCD and the collinear factorization is assumed for RHIC kinematical regime, and this treatment is considered as a baseline to explicitate the presence of new dynamical effects in charmed meson production in relativistic heavy ion collisions. Focus is given to hadron (deuteron)–nucleus processes, since studies at this kind of interactions can provide important benchmarks for further measurements in nucleus–nucleus processes. In particular, the forward rapidity region is studied, where the nuclear parton momentum fraction, $x_2$, reaches smaller values and saturation effects are expected to became important [17–19]. Since the $x$ values reached, at RHIC energies, are not very small, it is necessary to keep in mind what are the predictions of the conventional QCD models which assume nuclear shadowing. In what follows our analysis concerns to the rapidity dependence of the nuclear modification ratios, $R_{AB}$, defined by

$$R_{AB}(q_T) = \frac{d\sigma_{AB}/dy\, d^2q_T}{AB\, d\sigma_{pp}/dy\, d^2q_T}, \qquad (1)$$

where $y$ is the rapidity and $A$ and $B$ are atomic mass numbers, considering the EKS parameterization [20] of nuclear effects. Predictions for rapidity distributions for $D$-mesons at RHIC ($\sqrt{s} = 200$ GeV) are also calculated and the analysis is extended for LHC ($\sqrt{s} = 5.5$ TeV). A comment related to the light hadron production is in order here. Currently, the description of the experimental results in the central rapidity region can be obtained using a perturbative approach which includes the nuclear shadowing effects in the partonic distributions and an intrinsic transverse momentum of the colliding partons in order to reproduce the Cronin peak [21–23]. However, it is important to emphasize that the existing conventional nuclear shadowing models cannot completely explain both Cronin effect and the suppression in the forward region, as well as the large value of that suppression. In contrast, in the framework of the color glass condensate [8] both effects are predicted [17] to follow from the nonlinear evolution equation. If a similar scenario will be present in charmed hadron production is a subject of intense study [24–26], since the bulk of the heavy quark cross section comes from larger-$x$ values than for light hadron production in all rapidity range [27].

Hadrons with heavy quarks are a very important tool to study the properties of the strong interactions. Their large quark masses provide a scale which allows the use of perturbative QCD for computing production processes, since the long distance dynamics is effectively decoupled from the short distance dynamics. The value of the charm quark mass is in the limit of applicability of perturbative QCD, being a matter of discussion. In this framework, one can use the collinear factorization to calculate the heavy quark production. In leading twist, the semi-inclusive cross section factorizes into the product of gluon distributions, heavy quark fragmentation function and the hard partonic cross section. The application of factorization, however, is not evident for the kinematic regime where the heavy quark mass $m_Q$ is much smaller than the center of mass energy, $\sqrt{s}$ [26]. For instance, it has been claimed that in RHIC energy range, the $x$ values reached by the nucleons are lower enough to justify the calculation with the nucleus assumed as a saturated dense partonic system (the CGC), with a characteristic saturation scale $Q_s$, breaking the factorization of the process [24]. In particular, the heavy quark production, and consequently the $D$-mesons production, was studied using this semi-classical approach in the Refs. [24,25], showing that the saturation phenomenon makes the spectra harder as compared to the PYTHIA prediction [24].

For jet production in a hadronic collision a pQCD-based model [22] is used in this work. In leading order pQCD, the $pp'$ inclusive cross section (where $p$ and $p'$ stand for a proton ($p$) or a nucleon ($N$)) for production of a parton of flavour $i = g, q, \bar{q}$ ($q = u, d, s, \ldots$) with transverse momentum $p_T$ and rapidity $y$ [28] is written as a sum of contributions of the cross sections coming from projectile ($p$) partons and from target ($p'$) partons:

$$\frac{d\sigma^{pp' \to iX}}{dp_T^2\, dy} = \langle x f_{i/p} \rangle_{y_i, p_T} \frac{d\sigma^{ip'}}{dy_i\, d^2 p_T}\bigg|_{y_i = y} + \langle x f_{i/p'} \rangle_{y_i, p_T} \frac{d\sigma^{ip}}{dy_i\, d^2 p_T}\bigg|_{y_i = -y}, \tag{2}$$

where

$$\langle x f_{i/p} \rangle_{y_i, p_T} = \frac{K}{\pi} \sum_j \frac{1}{1+\delta_{ij}} \int dy_2\, x_1 f_{i/p}\big(x_1, Q_p^2\big) \times \frac{d\hat{\sigma}^{ij}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u}) \frac{x_2 f_{j/p'}(x_2, Q_p^2)}{\frac{d\sigma^{ip'}}{d^2 p_T\, dy_i}}, \tag{3}$$

$$\frac{d\sigma^{ip'}}{d^2 p_T\, dy_i} = \frac{K}{\pi} \sum_j \frac{1}{1+\delta_{ij}} \int dy_2 \times \frac{d\hat{\sigma}^{ij}}{d\hat{t}}(\hat{s}, \hat{t}, \hat{u})\, x_2 f_{j/p'}\big(x_2, Q_p^2\big) \tag{4}$$

are interpreted, respectively, as the average flux of incoming partons of flavour $i$ from the hadron $p$, and the cross section for the parton–hadron scattering. The rapidities of the $i$ and $j$ partons in the final state are labelled by $y_i$ and $y_2$. In this model infrared regularization is performed by adding a small mass to the gluon propagator and defining $m_T = \sqrt{p_T^2 + p_0^2}$. The fractional momenta of the colliding partons $i$ and $j$ are $x_{1,2} = \frac{m_T}{\sqrt{s}}(\mathrm{e}^{\pm y_i} + \mathrm{e}^{\pm y_2})$, with the integration region for $y_2$ given by $-\log(\sqrt{s}/m_T - \mathrm{e}^{-y_i}) \leqslant y_2 \leqslant \log(\sqrt{s}/m_T - \mathrm{e}^{y_i})$. More details are given in Refs. [22,28].

For the charmed meson production at high energies the dominant subprocess is $gg \to c\bar{c}$. This cross section $d\hat{\sigma}^{ij}/d\hat{t}$ can be found, e.g., in [29] and is proportional to $\alpha_s(\mu^2)$, with $\mu = Q_p = \sqrt{m_T^2 + m_Q^2}$. The factor $K$ in (2) is introduced in order to account for next-to-leading order (NLO) corrections and is, in general, energy and scale dependent [28]. For the parton distributions the CTEQ5 parameterization at leading order [30], evaluated at $Q_p$, will be used and when the nuclear shadowing effects are considered in the calculation, the EKS parameterization [20] will be employed.

Inclusive hadron production through independent fragmentation of the parton $i$ into a hadron $h$, is computed as a convolution of the partonic cross section (2) with a fragmentation function $D_{i\to h}(z, Q_h^2)$:

$$\frac{d\sigma^{pp' \to hX}}{dq_T^2\, dy_h} = \frac{d\sigma^{pp' \to iX}}{dp_T^2\, dy_i} \otimes D_{i\to h}\big(z, Q_h^2\big), \tag{5}$$

where $q_T$ is the transverse momentum of the hadron $h$, $y_h$ its rapidity, and $z$ the light-cone fractional momentum of the hadron and of its parent parton $i$. For details, see Eqs. (8)–(11) of [28]. This pQCD-based model has been successful in describing the data for charged hadrons and neutral pions, at mid-rapidity [22]. In the low-$q_T$ region, it was considered an intrinsic $k_T$ for the colliding partons, in order to correct the curvature of the hadron spectrum. However, since the interest here is the modifications due to nuclear shadowing, the intrinsic $k_T$ is not considered in this calculation. For the fragmentation function, the Peterson function [31] will be used with $\epsilon = 0.043$, as in Ref. [24] in the CGC framework.

Since in heavy quark production at high energies the dominant process is the gluon fusion, the cross section is strongly dependent of the behavior of the nuclear gluon distribution. Currently, there are several parameterizations in the literature which predict distinct behaviors and magnitude of the nuclear effects in the gluon distribution and a recent comparison is given in Ref. [27]. For example, the EKS parameterization [20] has a strong antishadowing ($R_g^A \equiv xG_A/AxG_N > 1$) at intermediate $x$ ($x \sim 0.1$–$0.2$), due to momentum conservation constraint, and the EMC effect ($R_g^A < 1$) at $x \sim 0.2$–$0.8$. For lower values of $x$, it presents shadowing ($R_g^A < 1$). On the other hand, the HKM one [32], presents less shadowing at small-$x$ values and the EMC effect is not present at intermediate $x$. Furthermore, the momentum sum rule is underestimated by the HIJING parameterization [33], due to a strong gluon shadowing and a lack of antishadowing effect (for a recent NLO analysis see Ref. [34]). Due to these differences between the parameterizations, only bounds can be estimated for nuclear effects and the EKS one is used in order to provide a conservative estimate. The distinct effects in different $x$ regions present in this parameterization create an asymmetry in the rapidity distribution: at large negative rapidities, the nuclear momentum fraction, $x_2$, is large, while $x_1$ is small; conversely, the positive rapidities access small $x_2$ and large $x_1$. Since our goal is to study the nuclear modifications, our analysis deals with positive rapidities. A similar study for light hadrons is presented in Ref. [23,35] (for an interesting discussion about this subject see Ref. [36]).

In Fig. 1 we present the rapidity distributions of the $D$-meson spectra at four distinct values of $q_T$ for $d + \mathrm{Au}$ collisions at $\sqrt{s} = 200$ GeV. The dot-dashed curve, labelled CTEQ5, shows the prediction without nuclear shadowing and the solid curve, labelled EKS98, shows the predictions when the nuclear shadowing is considered. An asymmetry is observed at low-$q_T$, but disappears for higher-$q_T$. At $q_T = 2$ GeV, a strong antishadowing enhances the spectra at negative rapidities, and shadowing suppresses it for positive ones. For increasing $q_T$, this asymmetry is weakened, with the $x_2$ values at positive rapidities increasing, entering in the antishadowing region. At $q_T = 5$ GeV, the rapidity symmetry is recovered. Higher

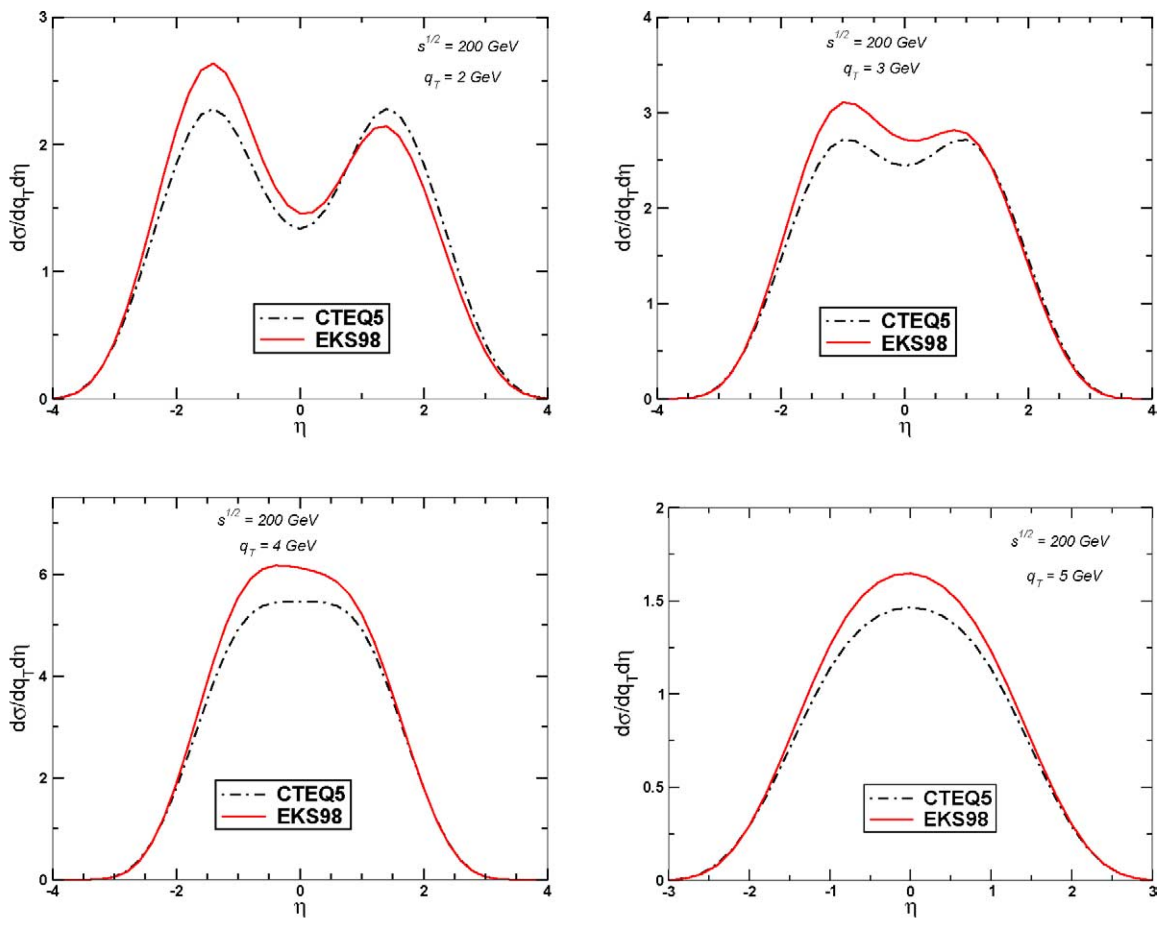


Fig. 1. Rapidity distributions for RHIC ($\sqrt{s} = 200$ GeV) for distinct values of the transverse momentum.

values of $q_T$ presents the reversion in the rapidity asymmetry, with enhancement of spectra at positive rapidities.

At LHC energy ($\sqrt{s} = 5.5$ TeV) and $p + \text{Pb}$ collisions, the cross section for the charm production probes the gluon distribution in the region of $x \geqslant 3 \times 10^{-5}$ for $y \leqslant 3$ [27]. In this region, the EKS parameterization, which is based on the DGLAP evolution equation and global fits of the DIS and Drell–Yan data above $Q^2 = 1\ \text{GeV}^2$ and $x \geqslant 10^{-3}$, assumes that the nuclear gluon distribution behaves similarly to the nucleon one, which implies that the ratio $R_g^A$ keeps constant. Consequently, it does not consider any new dynamical effect associated to the high density of the medium in this kinematic regime, which could modify $xg_A$ in comparison to $xg_N$. This is a conservative assumption, since recent results for forward rapidity indicate that the inclusion of the saturation effects is necessary. However, as our goal is to provide a baseline for future comparison, we use the EKS parameterization as input in our calculation. In Fig. 2 we present our predictions for the rapidity distributions for the $D$-meson production at LHC energy. We have that at forward rapidities, the suppression in the spectra decreases with increasing $q_T$, while the antishadowing dominates at large negative values. The crossover between the curves signalizes the rapidity value where the nuclear shadowing begins to dominate and, with increasing $q_T$, this point gets closer the central rapidity.

Our analysis regards to forward rapidities, since in this region the values reached for $x_2$ becomes small enough to consider the saturation in the nuclear wave function. The BRAHMS Collaboration has investi-

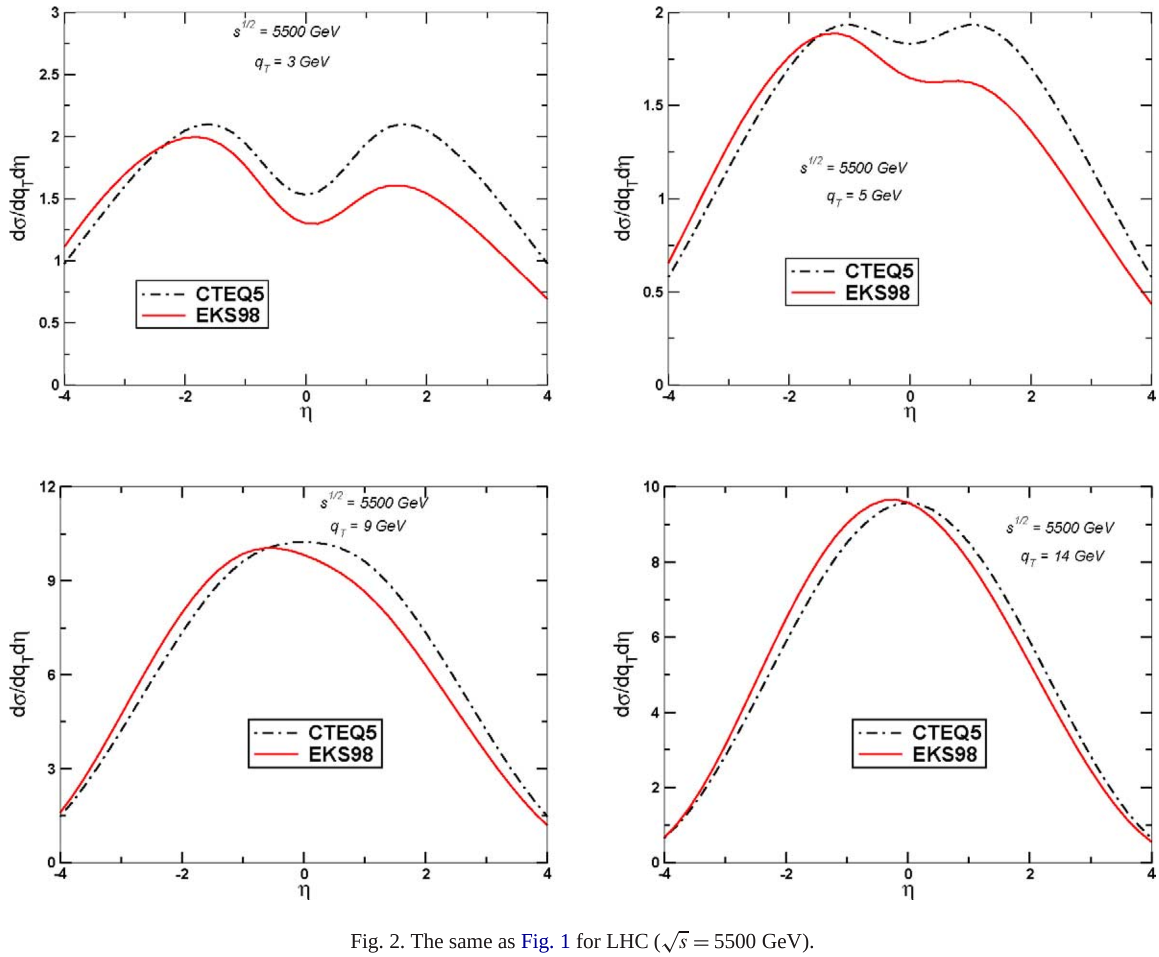


Fig. 2. The same as Fig. 1 for LHC ($\sqrt{s} = 5500$ GeV).

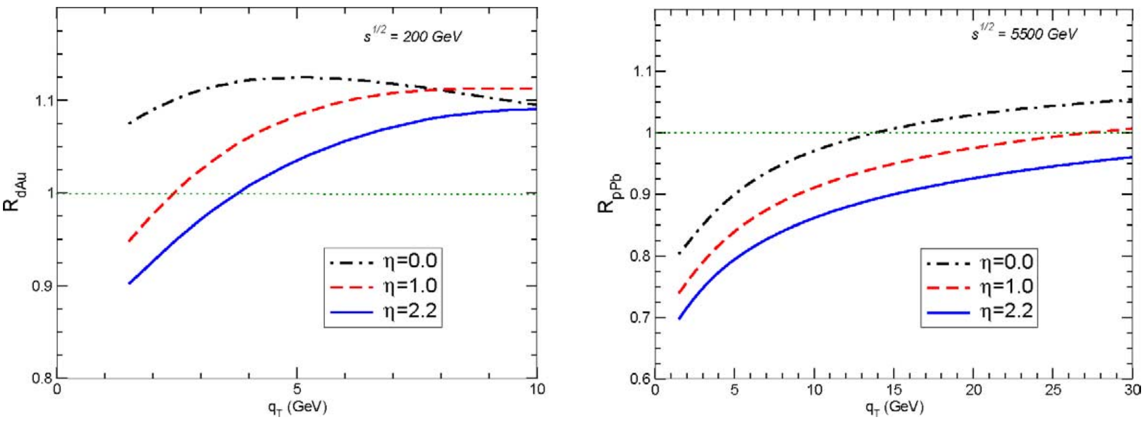


Fig. 3. Nuclear modification ratio for $D$ mesons in $d + \mathrm{Au}$ ($\sqrt{s} = 200$ GeV) and $p + \mathrm{Pb}$ ($\sqrt{s} = 5.5$ TeV) processes.

gated the charged hadron production in $d + \mathrm{Au}$ collisions at forward rapidities, with the values $\eta = 1$, $\eta = 2.2$ and $\eta = 3.2$ [11]. Two of these values are considered to compute the evolution of the nuclear modification ratio $R_{AB}$, defined in Eq. (1), in the transverse momentum. The prediction for mid-rapidity is also shown for comparison. Even thought the NLO corrections may affect the shape of the $q_T$ distributions, the higher-order corrections should largely cancel out in this ratio. Our results are presented in Fig. 3 for $\sqrt{s} = 200$ GeV and for $\sqrt{s} = 5.5$ TeV, where to compute the denominator $d + \mathrm{Au}$ processes were used in the first case and $p + \mathrm{Pb}$ processes in the later one.

At RHIC, as shown in the left panel of Fig. 3, the spectra are enhanced in high-$q_T$ region, and the value of $q_T$ where the enhancement begins depends on the rapidity. If no effects are present, we expect the ratio as unity. At mid-rapidity, all the spectra is enhanced, weakening with increasing $q_T$. With increasing rapidity, the spectra is suppressed at low-$q_T$, but becomes enhanced for higher values of $q_T$, which is characteristic of the parameterization used. At fixed rapidity, $x \propto m_T/\sqrt{s} \approx q_T/\sqrt{s}$ and the values of $x$ increases with $q_T$, entering the antishadowing region of the EKS parameterization. At very high $q_T$, we expect that the ratio could fall below 1, due to EMC effect in the EKS. At RHIC, this result suggests that in the region where the validity of the perturbative treatment is expected, $q_T > 3$ GeV, the $D$-meson spectra will be enhanced due to nuclear antishadowing. This behavior is also present in charged pion production in same energies [23]. The preliminary open charm data from STAR Collaboration [37] at mid-rapidity show this feature in the region 1 GeV $< q_T <$ 4 GeV. In order to check our calculations, we have calculated the $D$-meson spectrum and verified that our results describe reasonably the experimental data [37] in the region of interest for this study ($q_T \geqslant 2$ GeV), underestimating the data in the region of lower $q_T$, as expected, since we are not including an intrinsic transverse momentum. This result is not shown since our main focus is the nuclear modification factor $R_{d\mathrm{Au}}$, which can be described using a leading order calculation. On the other hand, in the calculation of the charmed hadron $q_T$ spectra, the NLO corrections should be included, since it modifies the shape of the $q_T$ spectra as well as the normalization of the cross section. Both effects largely cancel in the calculation of the ratio $R_{d\mathrm{Au}}$. It is important to emphasize that in the last quark matter conference, the STAR Collaboration has presented its preliminary results for the open charm spectrum in a broad transverse momentum region ($0 < q_T < 11$ GeV) [38], with the measured open charm spectrum being much harder than the PYTHIA prediction, which is in line with the predictions from Ref. [24]. Such result indicate that the saturation phenomenon may be important for the heavy quark production at RHIC. However, more detailed studies related to the hadronization process are necessary before a definitive conclusion (see discussion in Ref. [38]).

For LHC, as shown in the right panel of Fig. 3, the behavior of $R_{p\mathrm{Pb}}$ is similar for the three rapidities analyzed. At low-$q_T$ the spectra is suppressed, and the exact value where the enhancement takes place depends on the rapidity. At mid-rapidity, this point is $q_T \approx 14$ GeV; for $\eta = 1$, it happens at $q_T \approx 27$ GeV, and this value increases for $\eta = 2.2$. Since the region to be studied at LHC is $q_T < 14$ GeV, this result suggests that a substantial suppression at positive rapidities is due to nuclear shadowing effects. Both panels in Fig 3 show a suppression in hadron spectra for $q_T < 3$ GeV due to nuclear shadowing. However, the pQCD formulation might not be valid anymore for a quantitative calculation in this small $q_T$ region.

Finally, one expects that, because of their large mass, radiative energy loss for heavy quarks would be lower than for light quarks. It occurs due to combined mass effects [12,13]: the formation time of gluon radiation is reduced and their mass also suppresses gluon radiation amplitude at angles smaller than the ratio of the quark mass to its energy by destructive quantum interference [15]—the dead-cone effect. Due to these different energy losses, the ratio between hadrons with heavy quarks and with light quarks can provide a tool to investigate the medium formed in heavy ion collisions. The predicted consequence of this distinct energy losses is an enhancement of this ratio at moderately large transverse momentum, relative to that observed in the absence of energy loss (a recent analysis for LHC energies is given in Ref. [14]).

In Fig. 4, results for the ratio between $D$ mesons and $\pi$, defined by

$$\mathcal{R}_{D\pi}\left(\sqrt{s}, q_T\right) = \frac{R^D_{hA}}{R^\pi_{hA}}, \qquad (6)$$

are presented considering hadron–nucleus collisions, where the final state effects, as energy loss, are minimal. The behavior of the ratio considering only the shadowing in the nuclear wavefunctions is presented. The ratio $R^\pi_{hA}$, defined as in Eq. (1), is calculated following Ref. [22] without the intrinsic transverse momentum. At mid-rapidity, for RHIC, the $D$-meson production is more enhanced comparative to pions. This behavior also happens at large-$q_T$, for $\eta = 2.2$. For LHC energies, the $D$-meson production is smaller that the pions, even at mid-rapidity. It suggests that the shadowing predicted in Fig. 3 at LHC for $D$ mesons in $p + \text{Pb}$ processes is stronger that the shadowing for pion production, due to the quadratic dependence on the gluon distribution present in the charm production.

As a summary, the charmed meson production is studied using a perturbative approach. The rapidity distributions for $d + \text{Au}$ processes at RHIC and for $p + \text{Pb}$ processes at LHC are computed, and the disappearance of the asymmetry observed at low values of transverse momentum was found for increasing $q_T$, since the $x_2$ values increases with it. So, at high-$q_T$ and RHIC energies, the $D$-meson spectra is enhanced at forward rapidities. For LHC, the analysis predicts a suppression for positive rapidities due to nuclear shadowing, in the region $q_T < 14$ GeV, even at mid-rapidity. We also studied the different behavior of charmed mesons and light hadrons in $hA$ processes, where a minimal energy loss are expected. Stronger nuclear effects for heavy quarks were found, which cause an enhancement for $D$ mesons at mid-rapidity in RHIC, and their suppression for LHC, relative to pion production. This feature is based in a conservative perturbative approach, which assumes the validity of the collinear factorization and that the EKS parameterization is reasonable model for the nuclear effects. Although several points deserve more detailed studies, we believe that it can be used as a baseline for the CGC dynamics, expected to be present in this kinematical regime, as well as for future studies of jet quenching effects in $AA$ collisions.

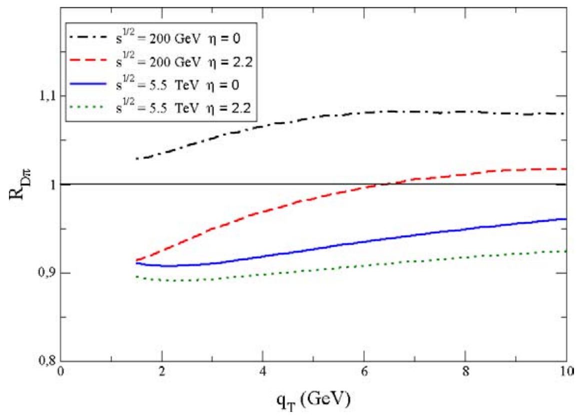


Fig. 4. Ratio between $D$ meson and pions, for RHIC and LHC energies and different rapidities.

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