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NUCLEAR MEDIUM EFFECTS IN J/Ψ PRODUCTION AT HERA-B

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In this paper we estimate the influence of the shadowing effect and initial state parton energy loss in the quarkonium production at HERA-B. We analyze the x_F behavior of the effective exponent $\alpha(x_F)$ and present a comparison with the preliminary HERA-B data for J/Ψ production. Moreover, we estimate the magnitude of these effects in the J/Ψ production at RHIC.

Keywords: Quarkonium production; shadowing effects; energy less.

The relativistic collider facilities RHIC and LHC provide the opportunity to systematically study the physics of hot and ultradense matter in hadron–nucleus (pA) and nucleus–nucleus (AB) collisions at high energies (for a review see, e.g. Refs. 1 and 2). The systematic study of pA collisions at the same energies is essential to gain insight into the structure of the dense medium effects. Such effects, as the energy loss and shadowing, are absent or small in pp collisions, but become increasingly prominent in pA collisions, and are of major importance in AA reactions. By comparing pA and AA reactions involving very heavy nuclei, one may be able to distinguish basic hadronic effects that dominate the dynamics in pA collisions, from a quark-gluon formation predicted to occur in heavy ion AA collisions. To gain insight into the underlying hadronic processes, one has to study collisions that are expected to not lead to a QGP formation. Once the physics of "QCD at high densities" is better understood, the mechanisms of quark-gluon plasma formation and related collective phenomena in heavy ion collisions could be disentangled from the basic hadronic effects.

In this paper we study the influence of the nuclear medium effects in the quarkonium production, particularly of the J/ψ, which is one of the proposed signatures of the QCD phase transition.[3] In particular, we will consider the shadowing effects in the parton distributions and the initial state parton energy loss, which have the strongest influence on the x_F ($\equiv x_1 - x_2$) behavior of the cross section (for a similar analyzes see, e.g. Ref. 4). Currently, the A dependence of J/Ψ production at $x_F > 0$ is known to rather high precision at several different energies (see e.g. Ref. 5). On the other hand, the behavior of the cross section and the magnitude of the nuclear medium effects at negative x_F region is still an open question. This situation should be improved by the experimental analyzes of quarkonium production in the fixed-target pA experiment HERA-B at DESY, which measures the quarkonium A dependence over $-0.5 < x_F < 0.3$. First results for the J/Ψ and Υ total cross sections have been recently published.[6] It motivates a detailed study of the A dependence for quarkonium production considering the current models for the nuclear medium effects. Here we focus our analyzes in the HERA-B kinematical range considering two estimates for the magnitude of the initial state parton energy loss and two distinct parametrizations for the shadowing effects. Moreover, we compare these predictions with the preliminary data recently obtained for the quarkonium production at negative values of x_F.[7] As we will show, these data could be used to discriminate between the different models for the nuclear medium effects. As an extra possibility of discriminate the different effects, we also present the corresponding predictions for RHIC energies.

Lets start presenting a brief review about the nuclear medium effects. One of the nuclear medium effects is the nuclear shadowing, which is the modification of the target parton distributions so that $xq^A(x,Q^2) < Axq^N(x,Q^2)$, as expected from a superposition of pp interactions (for a review see, e.g. Ref. 8). In the last years, several experiments have been dedicated to high precision measurements of deep inelastic lepton scattering (DIS) off nuclei. Experiments at CERN and Fermilab focus especially on the region of small values of the Bjorken variable $x = Q^2/2M\nu$, where $Q^2 = -q^2$ is the squared four-momentum transfer, ν the energy transfer and M the nucleon mass. The data,[9,10] taken over a wide kinematic range, have shown that the proton and neutron structure functions are modified by a nuclear environment. The modifications depend on the parton momentum fraction: for momentum fractions $x < 0.1$ (shadowing region) and $0.3 < x < 0.7$ (EMC region), a depletion is observed in the nuclear structure functions. These two regions are bridged by an enhancement known as antishadowing for $0.1 < x < 0.3$. We refer to the entire phenomena as *the nuclear shadowing effect.*

The theoretical understanding of F_2^A in the full kinematic region has progressed in recent years, with several models which describe the experimental data with quite success.[8] Here we will restrict ourselves to the descriptions which use the DGLAP evolution equations[11] to describe the behavior of the nuclear parton distributions. In particular, Eskola, Kolhinen and Salgado (EKS)[12] have shown that the experimental results[9] presenting nuclear shadowing effects can be described using the DGLAP evolution equations with adjusted initial parton distributions. The basic idea of this framework is the same as in the global analyzes of parton distributions in the free proton: they determine the nuclear parton densities at a wide range of x and $Q^2 \geq Q_0^2 = 2.25$ GeV^2 through their perturbative DGLAP

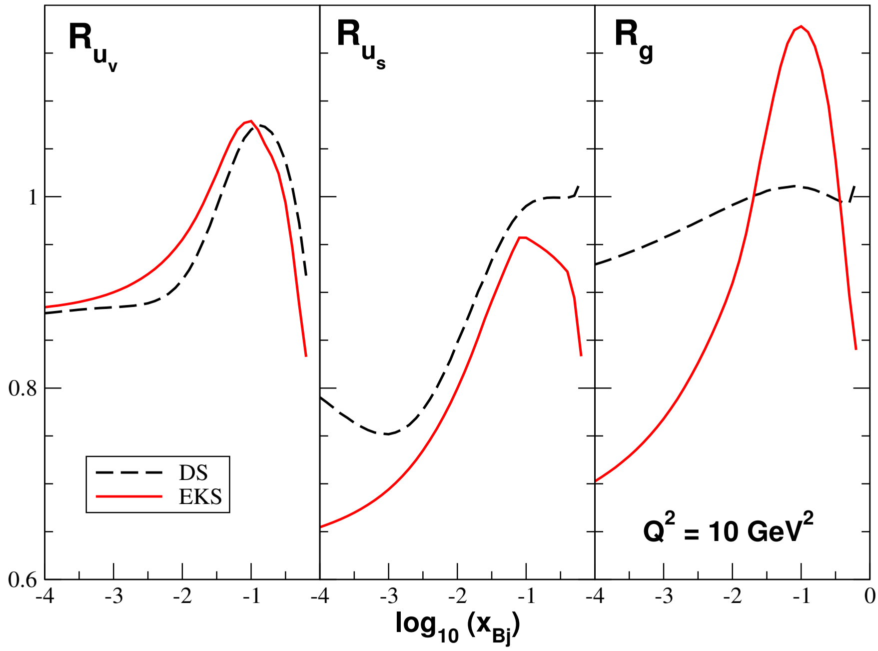


Fig. 1. Comparison between the EKS and DS parametrizations for the nuclear ratios $R^{184}_{u_V}(x, Q^2)$, $R^{184}_{u_S}(x, Q^2)$ and $R^{184}_g(x, Q^2)$.

evolution by using the available experimental data from lA DIS and Drell–Yan (DY) measurements in pA collisions as constraint. In this approach, the nuclear effects are taken into account in the initial parton distribution $xf^A(x, Q_0^2)$ of the DGLAP evolution. EKS have expressed the results in terms of the nuclear ratios $R_f^A(x, Q^2)$ for each parton flavor f in a nucleus with A nucleons ($A > 2$), at $10^{-6} \leq x \leq 1$ and $2.25\ \text{GeV}^2 \leq Q^2 \leq 10^4\ \text{GeV}^2$. Other groups have considered different set of data[13] and/or next-to-leading order corrections to the DGLAP equation and proposed a distinct approach[14] to describe the nuclear effects. In particular, De Florian and Sassot (DS)[14] proposed a framework where each nuclear parton distribution is described by a convolution of the corresponding free nucleon parton distribution with a simple flavor dependent weight function that takes into account the nuclear effects. As pointed out by the authors, the Mellin transform techniques allow a straightforward parametrization of the nuclear parton dynamical Q^2 evolution with a few parameters and an interpretation of the nuclear effects as a redistribution of longitudinal momentum among the partons in the nucleus.

In Fig. 1 we present a comparison between the different parametrizations for the nuclear ratios $R^A_{u_V}(x, Q^2)$, $R^A_{u_S}(x, Q^2)$ and $R^A_g(x, Q^2)$ at $A = 184$. We can see that these parametrizations predict very distinct behavior for the nuclear parton distributions. In particular, the magnitude of the antishadowing in the nuclear gluon distribution is still an open question. This scenario should be improved by the experimental analyzes of the quarkonium production at HERA-B, since it probes the parton distributions in this x range.

Another important effect in nuclear collisions is the initial state energy loss. In the last years the understanding of partonic energy loss has been extensively developed (for a review see e.g. Refs. 1 and 2), because of the expectation that the order of magnitude of the effect in hot matter is much larger than in cold nuclear matter, which implies that the resulting jet quenching can be considered a probe of the QGP formation. Our analyzes are focused in the parton energy loss in cold nuclear matter. It has been studied by Gavin and Milana[15] and subsequently developed by Brodsky and Hoyer[16] and Baier *et al.*,[17] considering a multiple scattering approach that essentially depletes the projectile parton momentum fraction, x_1, as the parton moves through the nucleus. The basic idea is that both the quarks and gluons can scatter elastically and loose energy before the hard scattering. Consequently, the original projectile parton momentum fraction x_1 when the parton first entered the target is modified to $x_1' = x_1 - \Delta x_1$, where Δx_1 represents the loss in x_1 due to multiple scatterings, being x_1' the projectile parton momentum fraction involved in the hard scattering. One has that the shifted value x_1' enters the partonic cross sections but the parton distributions must be evaluated at the initial x_1. Considering the relation between the averaged radiative energy loss $-dE/dz$ and the characteristic squared transverse momentum of the parton $\langle p_{\perp W}^2 \rangle$, derived in Ref. 17 and given by

$$-\frac{dE}{dz} = \frac{3\alpha_s}{4}\langle p_{\perp W}^2 \rangle\,, \tag{1}$$

one obtains that Δx_1 is then

$$\Delta x_1 = \frac{3\alpha_s}{2}\frac{m_p}{x_1 s}L_A\langle\,, p_{\perp W}^2 \rangle\,, \tag{2}$$

where L_A is the nuclear medium length. As the average transverse momentum $\langle p_{\perp W}^2 \rangle$ is proportional to $A^{1/3}$ [17] (and $L_A \propto A^{1/3}$ as well), one has that $\Delta x_1 \propto A^{2/3}$ rather than $A^{1/3}$. In what follows we consider two estimates for $\langle p_{\perp W}^2 \rangle$.[17] The larger value, which comes from single nuclear rescattering of photoproduced dijets estimated in Ref. 18, is given by

$$\langle p_{\perp W}^2 \rangle \simeq 0.658\alpha_s A^{1/3}\ \mathrm{GeV}^2\,. \tag{3}$$

Considering that the initial states could not be explicitly identified, one assumes that $\langle p_{\perp W}^2 \rangle$ is identical for quarks and gluons. In this case one has that when $\alpha_s \sim 0.3$ and $A = 184$, $-dE/dz \simeq 1.28$ GeV/fm. We refer to this as "LQS" in the remainder of the discussion. The second estimate takes into account the difference between quarks and gluon interactions and has been derived in Ref. 17 considering the relation between the characteristic squared transverse momentum of the parton and the nucleon gluon distribution given by

$$\begin{aligned} \langle p_{\perp W}^2 \rangle_q &= \frac{2\pi^2 \alpha_s}{3} \rho_A x G(x, Q^2) L_A \simeq 0.07 \alpha_s A^{1/3} \text{ GeV}^2 \,, \\ \langle p_{\perp W}^2 \rangle_g &= \frac{9}{4} \langle p_{\perp W}^2 \rangle_q \simeq 0.15\, \alpha_s\, A^{1/3}\, \text{GeV}^2 \,, \end{aligned} \tag{4}$$

where $xG(x) \sim 1-2$ for the x_1 range of HERA-B. This lower estimate is referred to subsequently as "BDMPS". In this case one has that when $\alpha_s \sim 0.3$ and $A = 184$, $-dE_q/dz \simeq 0.12$ GeV/fm and $-dE_g/dz \simeq 0.28$ GeV/fm. It is important to emphasize that a similar energy loss effect is expected for Drell–Yan production.[4,19] In Ref. 19 the quark mean energy loss per unit length has been constrained to be $-dE_q/dz \simeq 0.2 \pm 0.15$ GeV/fm considering a leading order analyzes of E866/NuSea and NA3 Drell–Yan data, which reasonably agrees with the BDMPS estimate. A comment is in order here. As pointed out in Ref. 4, the application of the BDMPS model at $x_F < 0$ may becomes problematic since Δx_1 grows larger than x_1, suggesting that the calculation may not be applicable for $\Delta x_1 > x_1$. As it still is an open question, in a first approximation we will apply the model in the whole x_F range.

In order to analyze the quarkonium production we will consider the color evaporation model (CEM).[20] In this model, the color charges of the $c\bar{c}$ produced are randomized by the exchange of soft gluons, such that no information remains of the color configuration given by the preceding hard interactions. SU(3) algebra gives the probability 1/9 for the $c\bar{c}$ to be in a color singlet state and 8/9 to be in a color octet state. It is then assumed that all color singlet pairs with invariant mass below the threshold for open charm will form a charmonium state. The cross section for for the charmonium state i is then

$$\frac{d\sigma_i}{dx_F} = \frac{\rho_i}{9} \int_{2m_c}^{2m_D} dm_{c\bar{c}} \, \frac{d\sigma^{c\bar{c}}}{dx_F dm_{c\bar{c}}} \,, \tag{5}$$

where $m_{c\bar{c}}$ is the invariant mass of the $c\bar{c}$ pair, m_c is the charm quark mass and $2m_D = 3.74$ GeV is the $D\overline{D}$ threshold. $\frac{d\sigma^{c\bar{c}}}{dx_F dm_{c\bar{c}}}$ is the usual convolution of the perturbative QCD cross section with the parton density functions for the proton/nucleus. ρ_i are nonperturbative universal factors which give the relative rates of producing the different charmonium states. Once ρ_i has been determined for each state, e.g. ψ, ψ' or χ_{cJ}, the model successfully predicts the energy and momentum dependencies. We note that ρ_ψ includes both direct ψ production and indirect production through radiative decays of the χ_{cJ} states and hadronic ψ' decays. The pQCD cross section is taken in LO for simplicity, since we are just interested in ratios of cross sections. Also, the dependency on the overall factors $\rho_i/9$ cancels out in the ratios. It is important to emphasize that although we will use the CEM to describe the quarkonium production, similar results are expected if the nonrelativistic QCD model (NRQCD)[21] is considered.

In order to investigate the medium dependence of the quarkonium production cross section, we will follow the usual procedure used to describe the experimental data on nuclear effects in the hadronic quarkonium production,[22] where the atomic mass number A dependence is parameterized by $\sigma_{pA} = \sigma_{pN} \times A^{\alpha}$. Here σ_{pA} and σ_{pN} are the particle production cross sections in proton-nucleus and proton-nucleon interactions, respectively. If the particle production is not modified by the presence of nuclear matter, then $\alpha = 1$. A number of experiments have measured a less than linear A dependence for various processes of production, which indicates that the medium effects cannot be disregarded (see e.g. Ref. 5). To estimate the modification of quarkonium production cross section due to the medium effects, we calculate the effective exponent $\alpha(x_F)$, which is given by

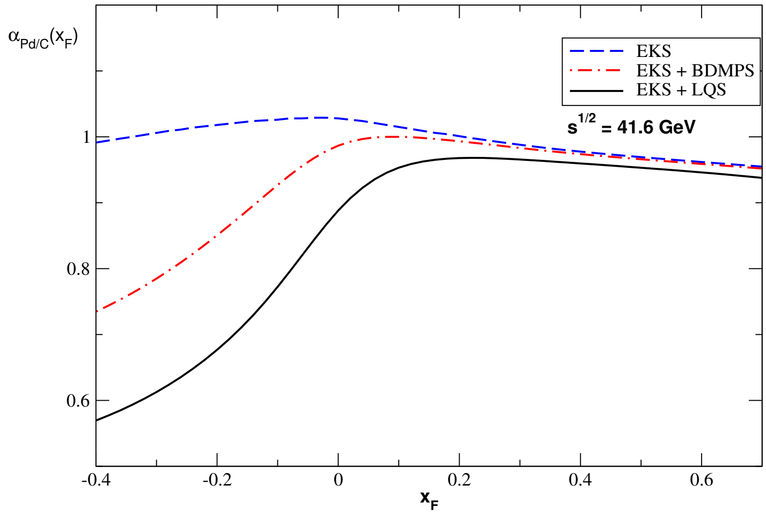
$$\alpha(x_F) = \left\{ \ln \left(\frac{d\sigma_{pA}}{dx_F} \Big/ \frac{d\sigma_{pN}}{dx_F} \right) \Big/ \ln A \right\} . \tag{6}$$

Moreover, to obtain the available observable measured in the experiments, we also replace the nucleon by a light nucleus target (Carbon), calculating the ratio

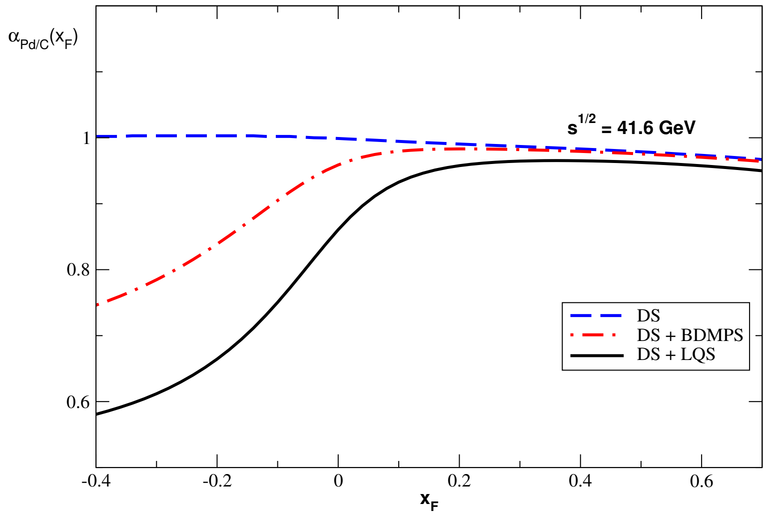
$$\alpha_{A_2/A_1}(x_F) = \left\{ \ln \left(\frac{d\sigma_{pA_2}}{dx_F} \Big/ \frac{d\sigma_{pA_1}}{dx_F} \right) \Big/ \ln(A_2/A_1) \right\} , \tag{7}$$

where $A_1 = C$ and $A_2 = Pd, W$. Our results for the effective exponent $\alpha_{A_2/A_1}(x_F)$ in J/Ψ production at HERA-B energy of $\sqrt{s} = 41.6$ GeV, with paladium and carbon targets are shown in Fig. 2 considering the EKS [Fig. 2(a)] and DS [Fig. 2(b)] parametrizations for the nuclear shadowing effects. In the dashed curves only the nuclear shadowing effects are taken into account. Energy loss effects are also included in the dot-dashed (BDMPS estimate) and full (LQS estimate) curves. The x_F behavior of the effective exponent when considering the EKS and DS parametrization is similar. Whereas the shadowing alone produces a small enhancement for negative x_F (antishadowing indeed) and a small suppression for higher positive values of x_F, the inclusion of energy loss leads to a large suppression for the heavy nuclear target, for negative values of x_F. This suppression can be understood in terms of the basic properties of the energy loss models. For a fixed value of negative x_F, the corresponding value of x_1' is smaller than the value of x_1 that enters in the parton distribution evaluation, since the projectil parton looses its momentum when traversing the nuclear target. This effect corresponds to a shift in the parton momentum to higher values of x in the nuclear case, which reduces the amount of partons in the initial state of partonic subprocesses as compared to the free nucleon scattering, since the parton distributions grow as x goes to zero due to the dynamical QCD evolution.

In Fig. 3, we present our results for J/Ψ production at same energy, in a tungsten and carbon targets, compared with preliminary HERA-B data for J/Ψ production.[7] Concerning the EKS parametrization [Fig. 3(a)], neither the enhancement due to the shadowing effects alone, nor the strong suppression for $x_F < 0$ due to energy loss are seen in the data, which indicate a small and x_F-independent suppression. These results may indicate that the magnitude of the antishadowing is overestimated in the EKS parametrization or that the energy loss is smaller that predicted by the



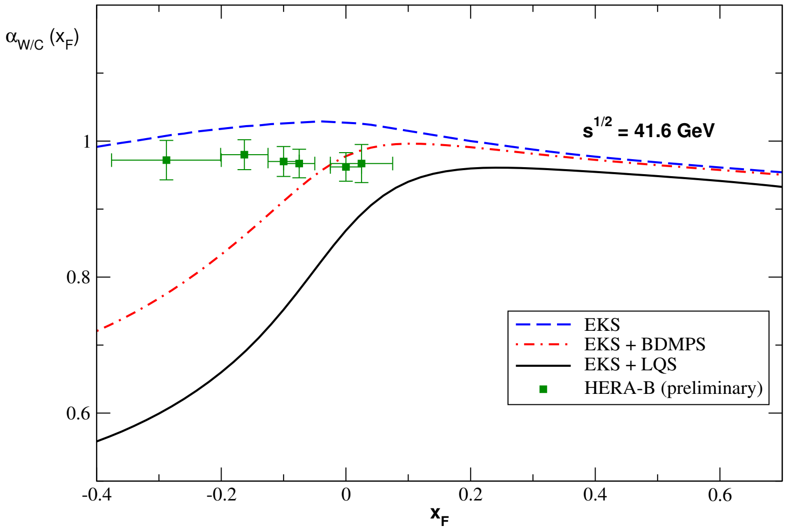
(a)



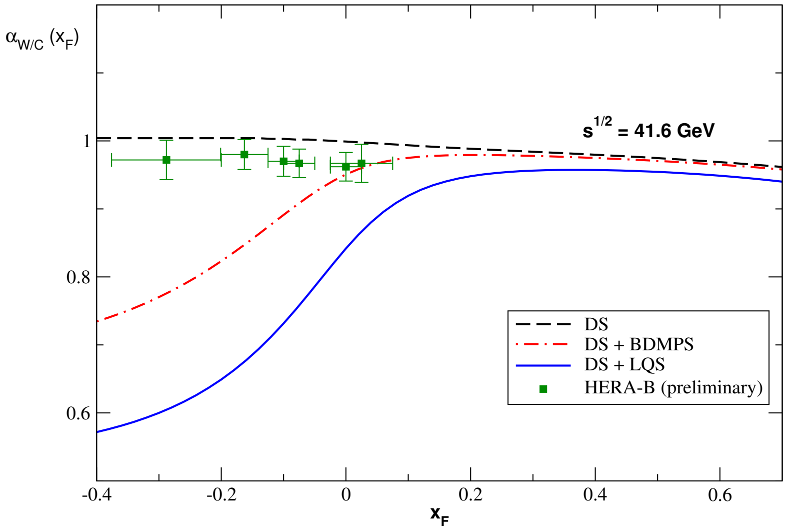
(b)

Fig. 2. Effective exponent as a function of x_F for charmonium production at HERA-B considering paladium and carbon targets.

LQS and BDMPS models. When the shadowing effects are taken into account via DS parametrization, the prediction get closer to the HERA-B data. This is due to the fact that the DS parametrization does not predict anti-shadowing behavior of the sea quark and gluon nuclear distributions, as we can see in Fig. 1. Again, when compared to the HERA-B data, the models BDMPS and LQS for the energy loss overestimate the suppression of the nuclear cross section for negative x_F.



(a)



(b)

Fig. 3. Effective exponent as a function of x_F for charmonium production at HERA-B considering tungsten and carbon targets.

Another possibility to constrain the magnitude of the medium effects is the study of the quarkonium production in proton(deuteron)-nucleus collisions at RHIC (see e.g. Refs. 23 and 24). In this case, due to the larger center of mass energy, the nuclear effects should be amplified. In Fig. 4 we present our estimates for the effective exponent for J/Ψ production at $\sqrt{s} = 200$ GeV RHIC energy, with proton

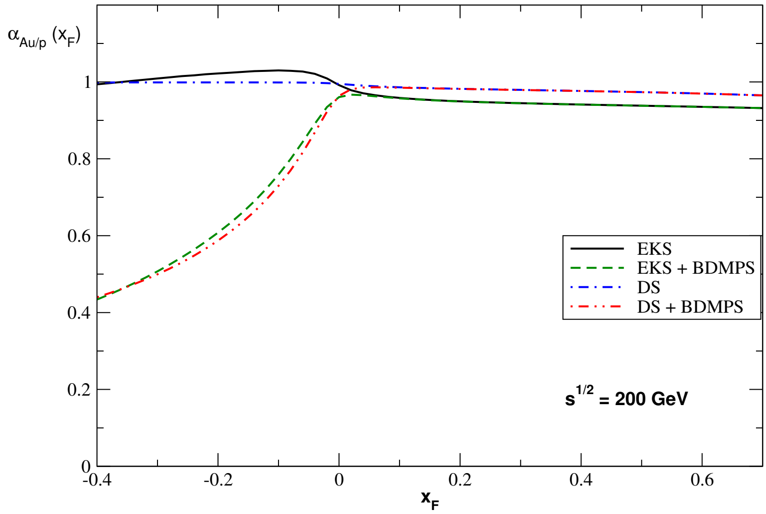


Fig. 4. Effective exponent as a function of x_F for charmonium production at RHIC considering gold and proton targets.

and gold targets. As we can see, the effective exponent is almost x_F independent in the positive x_F range, with the EKS prediction being smaller due to the larger shadowing present in this parametrization. On the other hand, the energy loss leads to a very strong suppression for negative x_F, larger than that predicted at HERA-B. It implies that the experimental analyzes of the quarkonium production is ideal to constrain the initial state energy loss effects in cold nuclear matter.

One effect which we have disregarded in our analyzes was the nuclear absorption associated with the fact that the $c\bar{c}$ pair may interact with nucleons and be dissociated or absorbed before it can escape the target. This effect has been estimated in Ref. 25 considering different models for the quarkonium production and color singlet and color octet absorption. At HERA-B energy, the CEM and color singlet absorption in J/Ψ production implies that $\alpha(x_F = -0.5) \approx 0.97$ and $\alpha(x_F > 0) \approx 1$. On the other hand, if color octet absorption is considered one has $\alpha(x_F = -0.5) \approx 0.96$ and $\alpha(x_F > 0) \approx 0.95$. Consequently, if only the absorption effect is included in the calculations a reasonable description of the preliminary data is possible. However, the inclusion of this effect in combination with shadowing and energy loss effects will implicate a larger suppression at negative x_F, which is disfavoured by the data. Thus, the estimate of the nuclear effects in quarkonium production is still an open question.

As a summary, in this paper we have studied the quarkonium production at HERA-B and RHIC. In particular, we have considered two distinct parametrizations for the shadowing and two estimates for the magnitude of initial energy loss effects and analyzed the x_F behavior of the effective exponent. Our main emphasis was in the negative x_F range which have been probed at HERA-B. We have verified that the inclusion of the energy loss strongly modifies the behavior of $\alpha(x_F)$ in this kinematical range. The comparison of our predictions with the preliminary data indicates that the combination of shadowing and energy loss effects, as described by the EKS or DS parametrizations and LQS or BDMPS models, is not able to describe the data. This may be related to the applicability of the BDMPS approach in cold matter and/or the overestimation of the antishadowing effect in the EKS parametrization. Another possibility is that the correct model for the initial state parton energy loss is one similar to the Gavin–Milana model,[15] where $\Delta x_1 = \epsilon_i x_1 A^{\frac{1}{3}}$ ($\epsilon_q = 0.00412$ and $\epsilon_g = \frac{9}{4}\epsilon_q$), which implies $\alpha(x_F) \approx 1$ at negative x_F. Another uncertainty present is the validity of the collinear factorization in nuclear collisions. Some authors advocate that the coherence phenomena cannot be disregarded.[26] Since the suppression predicted in RHIC is larger, it would be desirable to have measurements in that region to constrain the different models and disentangle the different effects. To conclude, nuclear collisions remain a fascinating place to study different effects including the interplay of perturbative and non-perturbative QCD, and nuclear effects.

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