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Constraining the nuclear gluon distribution in eA processes at RHIC

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ABSTRACT

A systematic determination of the gluon distribution is of fundamental interest in understanding the parton structure of nuclei and the QCD dynamics. Currently, the behavior of this distribution at small x (high energy) is completely undefined. In this Letter we analyze the possibility of constraining the nuclear effects present in xg_A using the inclusive observables which would be measured in the future electron-nucleus collider at RHIC. We demonstrate that the study of nuclear longitudinal and charm structure functions allows to estimate the magnitude of shadowing and antishadowing effects in the nuclear gluon distribution.

Since the early days of the parton model and of the first deep inelastic scattering (DIS) experiments, determining the precise form of the gluon distribution of the nucleon has been a major goal of high energy hadron physics. Over the last 30 years enormous progress has been achieved. In particular, data from HERA allowed for a good determination of the gluon density of the proton. A much harder task has been to determine the gluon distribution of nucleons bound in a nucleus, i.e., the nuclear gluon distribution $[xg_A(x,Q^2)]$. Several experiments were dedicated to high precision measurements of deep inelastic lepton scattering (DIS) off nuclei. In particular, 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 [1], taken over a wide kinematic range $10^{-5} \leqslant x \leqslant 0.1$ and $0.05\ \text{GeV}^2 \leqslant Q^2 \leqslant 100\ \text{GeV}^2$, show a systematic reduction of the nuclear structure function $F_2^A(x,Q^2)/A$ with respect to the free nucleon structure function $F_2^N(x,Q^2)$. This phenomenon is known as *nuclear shadowing effect* and is associated to 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 ep interactions (for a review see, e.g. [2,3]). 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 $0.1 < x < 0.3$. The experimental data for the nuclear structure function determine the behavior of the nuclear quark distributions, while the behavior of the nuclear gluon distribution is indirectly determined using the momentum sum rule as a constraint and/or studying the $\log Q^2$ slope of the ratio F_2^{Sn}/F_2^C [4]. Currently, the behavior of $xg_A(x,Q^2)$ at small x (high energy) is completely uncertain as shown in Fig. 1, where we present the ratio $R_g = xg_A/(A.xg_N)$, for $A = 208$, predicted by four different groups which realize a global analysis of the nuclear experimental data using the DGLAP evolution equations [5] in order to determine the parton densities in nuclei. In particular, the magnitude of shadowing and the presence or not of the antishadowing effect is completely undefined.

In the last years the analysis of the nuclear effects in deep inelastic scattering (DIS) has been extensively discussed [6–8] and motivated by the perspective that in a near future an experimental investigation of the nuclear shadowing at small x and $Q^2 \gg 1\ \text{GeV}^2$ using eA scattering could be performed at Brookhaven National Laboratory (eRHIC). It is expected that measurements over the extended x and Q^2 ranges ($10^{-4} \lesssim x \lesssim 1$ and $1.0\ \text{GeV}^2 \lesssim Q^2 \lesssim 10\,000\ \text{GeV}^2$), which would become possible at eRHIC, will give more information in order to discriminate between the distinct models of shadowing and the understanding of the QCD dynamics at small x. This collider is expected to have statistics high enough to allow for the determination of several inclusive and ex-

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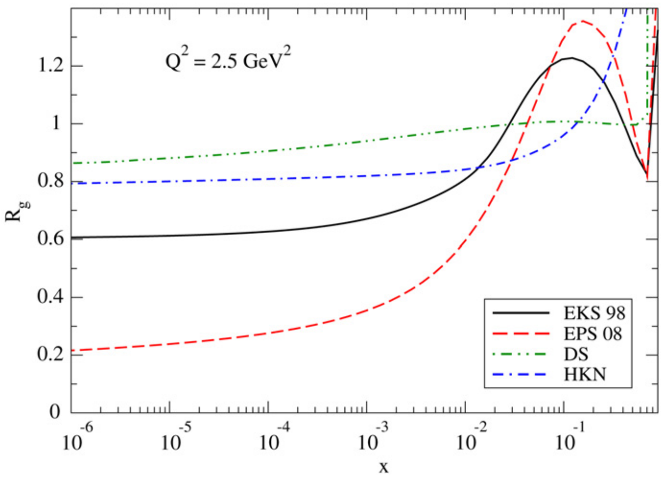

Fig. 1. Ratio $R_g = xg_A/(Axg_N)$ predicted by the EKS, DS, HKN and EPS parametrizations for $A = 208$ and $Q^2 = 2.5$ GeV^2.

clusive observables which are directly dependent on the behavior of the nuclear gluon distribution, as for example, the longitudinal and charm structure functions, the logarithmic slopes with respect to x and Q^2, as well as the diffractive leptoproduction of vector mesons. In particular, the longitudinal structure function is expected to be measured for the first time in the kinematical regime of small x, since the electron–ion collider will be able to vary the energies of both the electron and ion beams.

In this Letter we study the behavior of the nuclear longitudinal structure function F_L^A and the charm structure function $F_2^{c,A}$ and analyze the possibility to constrain the nuclear effects present in xg_A using these inclusive observables. We estimate the normalized ratios

$$R_L(x, Q^2) = \frac{F_L^A(x, Q^2)}{AF_L^p(x, Q^2)} \quad \text{and}$$
$$R_C(x, Q^2) = \frac{F_2^{c,A}(x, Q^2)}{AF_2^{c,p}(x, Q^2)}, \tag{1}$$

considering four different parametrizations for the nuclear gluon distributions and compare their behavior with those predicted for the ratio $R_g = xg_A/A.xg_N$. We analyze the similarity between these ratios and demonstrate that the experimental study of these observables allow to determine the magnitude of shadowing and antishadowing effects. We calculate these observables using the Altarelli–Martinelli equation [9,10] and the boson–gluon fusion cross section [11], respectively. In other words, we will restrict ourselves to the descriptions which use the DGLAP evolution equations [5] to describe the behavior of the nuclear parton distributions and will assume the validity of the collinear factorization. It is important to emphasize that the theoretical understanding of small-x and large A regime of the QCD dynamics has progressed in recent years (for recent reviews see, e.g. [12]), with the main prediction being a transition of the linear regime described by the DGLAP dynamics to a nonlinear regime where the physical process of parton recombination becomes important in the parton cascade and the evolution is given by a nonlinear evolution equation. One of the main motivations for the eRHIC experiment is the study of this new regime, denoted Color Glass Condensate (CGC) [12]. As in Ref. [13] the inclusive observables at eRHIC were studied using a generalized saturation model, based on the CGC physics, the current study can be considered as complementary to that reference.

Let us start presenting a brief review of the calculations of the longitudinal and charm structure functions. The longitudinal structure function in deep inelastic scattering is one of the observables from which the gluon distribution can be unfolded. Currently, there is a expectation for new experimental HERA data for F_L taken with reduced proton energies, which will provide more direct access to the proton gluon distribution and shed light on the QCD dynamics at small-x (see, e.g. Ref. [14]). Longitudinal photons have zero helicity and can exist only virtually. In the Quark–Parton Model (QPM), helicity conservation of the electromagnetic vertex yields the Callan–Gross relation, $F_L = 0$, for scattering on quarks with spin 1/2. This does not hold when the quarks acquire transverse momenta from QCD radiation. Instead, QCD yields at leading order (LO) the Altarelli–Martinelli equation [9,10]

$$F_L(x, Q^2) = \frac{\alpha_s(Q^2)}{2\pi} x^2 \int_x^1 \frac{dy}{y^3} \left[\frac{8}{3} F_2(y, Q^2) + 4 \sum_q e_q^2 \left(1 - \frac{x}{y}\right) yg(y, Q^2) \right], \tag{2}$$

expliciting the dependence of F_L on the strong coupling constant and the gluon density. At small x the second term with the gluon distribution is the dominant one. In this term the summation is over the number of flavors which we take to be three. In Ref. [15] the authors have suggested that expression (2) can be reasonably approximated by $F_L(x, Q^2) \approx 0.3 \frac{4\alpha_s}{3\pi} xg(2.5x, Q^2)$, which demonstrates the close relation between the longitudinal structure function and the gluon distribution. Therefore, we expect the longitudinal structure function to be sensitive to nuclear effects.

Let us now discuss charm production and its contribution to the structure function. In the last years, both the H1 and ZEUS Collaborations have measured the charm component F_2^c of the structure function at small x and have found it to be a large (approximately 25%) fraction of the total [16]. This is in sharp contrast to what is found at large x, where typically $F_2^c/F_2 \approx \mathcal{O}(10^{-2})$. This behavior is directly related to the growth of the gluon distribution at small-x. In order to estimate the charm contribution to the structure function we consider the formalism advocated in [17] where the charm quark is treated as a heavy quark and its contribution is given by fixed-order perturbation theory. This involves the computation of the boson–gluon fusion process. A $c\bar{c}$ pair can be created by boson–gluon fusion when the squared invariant mass of the hadronic final state is $W^2 \geqslant 4m_c^2$. Since $W^2 = \frac{Q^2(1-x)}{x} + M_N^2$, where M_N is the nucleon mass, the charm production can occur well below the Q^2 threshold, $Q^2 \approx 4m_c^2$, at small x. The charm contribution to the proton/nucleus structure function, in leading order (LO), is given by [11]

$$\frac{1}{x} F_2^c(x, Q^2, m_c^2) = 2e_c^2 \frac{\alpha_s(\mu'^2)}{2\pi} \int_{ax}^1 \frac{dy}{y} C_{g,2}^c\left(\frac{x}{y}, \frac{m_c^2}{Q^2}\right) g(y, \mu'^2), \tag{3}$$

where $a = 1 + \frac{4m_c^2}{Q^2}$ and the factorization scale μ' is assumed $\mu'^2 = 4m_c^2$. $C_{g,2}^c$ is the coefficient function given by

$$C_{g,2}^c\left(z, \frac{m_c^2}{Q^2}\right) = \frac{1}{2}\left\{\left[z^2 + (1-z)^2 + z(1-3z)\frac{4m_c^2}{Q^2} - z^2\frac{8m_c^4}{Q^4}\right] \ln\frac{1+\beta}{1-\beta} + \beta\left[-1 + 8z(1-z) - z(1-z)\frac{4m_c^2}{Q^2}\right]\right\}, \tag{4}$$

where $\beta = 1 - \frac{4m_c^2 z}{Q^2(1-z)}$ is the velocity of one of the charm quarks in the boson–gluon center-of-mass frame. Therefore, in leading order, $\mathcal{O}(\alpha_s)$, F_2^c is directly sensitive only to the gluon density via the

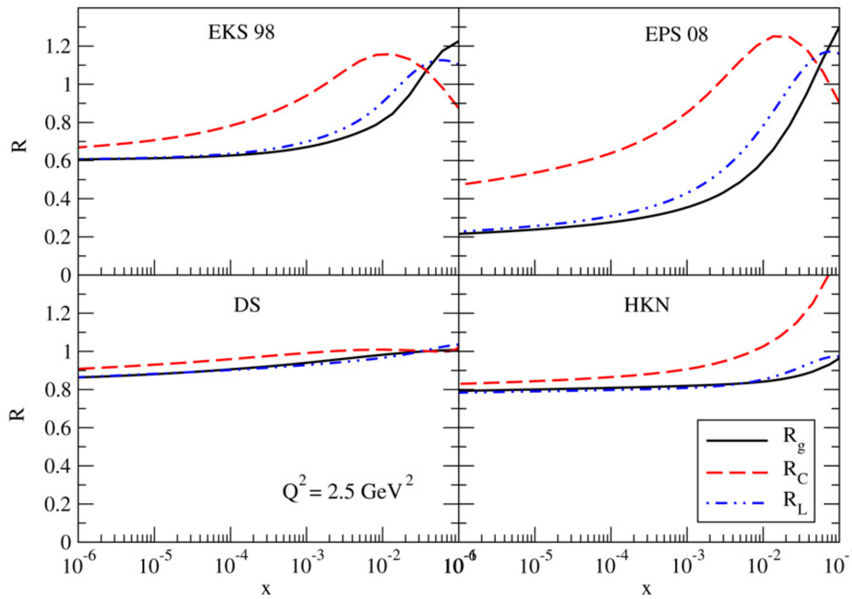

Fig. 2. Ratios R_g, R_C and R_L for the four considered nuclear parametrizations and $Q^2 = 2.5\ \text{GeV}^2$.

well-known Bethe–Heitler process $\gamma^* g \to c\bar{c}$. The dominant uncertainty in the QCD calculations arises from the uncertainty in the charm quark mass. In this Letter we assume $m_c = 1.5$ GeV.

Finally, let us briefly discuss the different parametrizations for the nuclear parton distributions (for details see the recent review [3]). We will make use of the existing nuclear parton distribution functions based on a global fit of the nuclear data using the DGLAP evolution equations. Currently there are four parametrizations, proposed by Eskola et al. [20], by de Florian and Sassot [21], by Hirai et al. [22] and the very recent one proposed by Eskola et al. [23]. In what follows they will be called EKS, DS, HKN and EPS, respectively. The basic idea of these approaches is that the experimental results [1] presenting nuclear shadowing effects can be described using the DGLAP evolution equations with adjusted initial parton distributions. Similarly to 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 through their perturbative DGLAP evolution by using the available experimental data from lA DIS and pA collisions as a constraint. As pointed out in Ref. [3], different approaches differ in the form of the parametrizations at the initial scale, in the use of different sets of experimental data, in the order of the DGLAP evolution, in the different nucleon parton densities used in the analysis, in the treatment of isospin effects and in the use of sum rules as additional constraints for the evolution. For instance, the DS and HKN groups provide leading (LO) and next-to-leading order (NLO) parametrizations, while EKS and EPS perform only a LO QCD global analysis. There are noticeable differences between the HKN analysis results and the ones in Ref. [21] especially in the strange-quark and gluon modifications. These differences come from various sources. First, the analyzed experimental data sets are slightly different. Second, the strange-quark distributions are created by the DGLAP evolution by assuming $s(x) = 0$ at the initial Q^2 scale, and the charm distributions are neglected in Ref. [21]. These differences lead to discrepancies among the gluon modifications. It is important to emphasize that in Ref. [21] the authors have estimated the difference between the NLO and LO R_g predictions at low x and in heavy nuclei as being almost 10% (4%) at $Q^2 = 1.0$ (10) GeV^2. In contrast to the EKS, DS and HKN parametrizations, the EPS one has included the RHIC data from [19] in the global fitting procedure. The main assumption is that these data can be understood with linear evolution. The inclusion of the high-p_T hadron data from RHIC at forward rapidities provided important further constraints for the gluon shadowing region. By construction, these parametrizations describe the current experimental data. However, the resulting parton distribution sets are very distinct. In particular, the predictions of the different groups for R_g differ largely about the magnitude of the shadowing and the presence or not of the antishadowing. This is associated to the fact that the data included in the global analyses probe the quark distribution, while the gluon is constrained only by the evolution and the momentum sum rule. In what follows we consider only the leading order versions of the DS and HKN sets, in order to compare with other nPDFs and since we will calculate the nuclear structure functions at leading order. As shown in Fig. 1, while the HKN and DS parametrizations predict a small value of shadowing, the EKS and EPS one predict a large amount, with the distinct predictions differing by a factor 4 at $x = 10^{-5}$. Furthermore, while the DS parametrization does not predict antishadowing and EMC effects in the nuclear gluon distribution, these effects are present in the EKS and EPS parametrizations. In the particular case of HKN, it predicts a steep growth of the ratio R_g in the region $x \geqslant 10^{-1}$. It is important to emphasize that the magnitude of shadowing and antishadowing effects in EKS and EPS are directly related by the momentum sum rule. The large discrepancies between the predictions of the four parametrization for xg_A in all kinematical x range imply a large uncertainty in the predictions for the observables which would be measured in pA/AA collisions at LHC, for instance.

As mentioned above it is well known that the inclusive observables F_L and F_2^c are strongly dependent on the gluon distribution. Our goal is to quantify and determine the kinematical region where these observables directly determine the behavior of R_g. In order to obtain model independent conclusions we calculate R_L and R_C using the four parametrizations described above and compare with the corresponding predictions for R_g. As the small-x region at eRHIC will be probed at small-Q^2 we concentrate our analysis on two characteristic values of Q^2: $Q^2 = 2.5\ \text{GeV}^2$ and $10\ \text{GeV}^2$.

In Figs. 2 and 3 we present our results. Firstly, let us discuss the small-x region, $x \leqslant 10^{-3}$, determined by shadowing effects. We observe that R_L practically coincides with R_g for all parametrizations and for the two values of Q^2 considered. This suggests that shad-

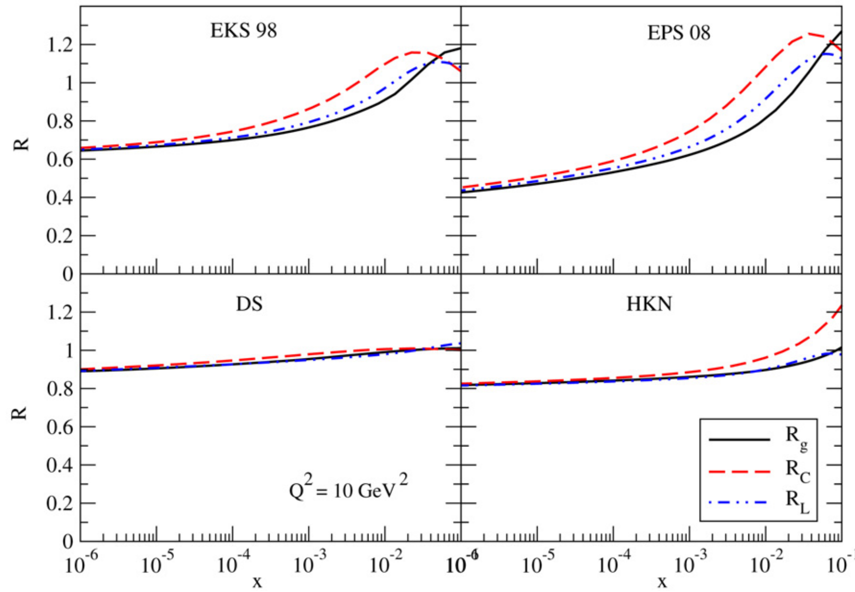

Fig. 3. The same as Fig. 2 for $Q^2 = 10$ GeV^2.

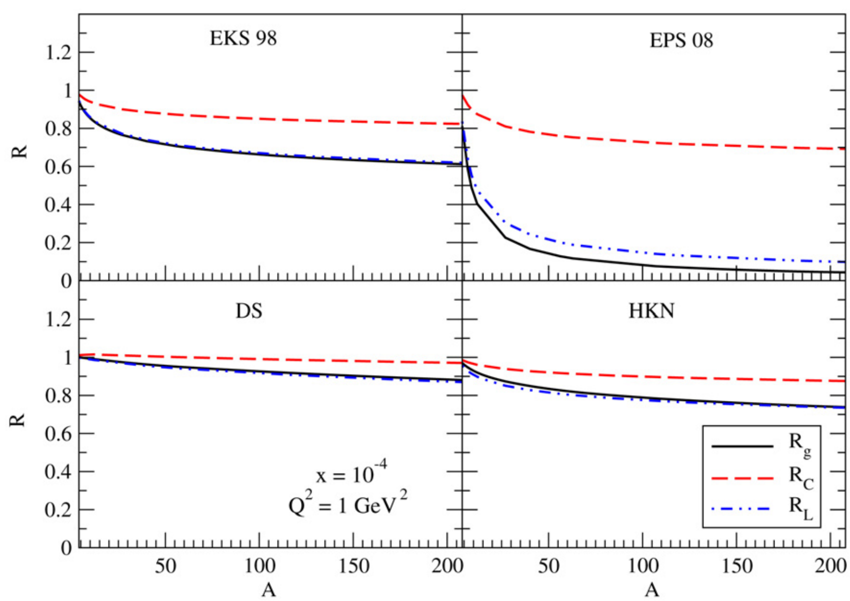

Fig. 4. Ratios R_g, R_C and R_L as a function of the atomic number A for the four nuclear parametrizations with $x = 10^{-4}$ and $Q^2 = 1$ GeV^2.

owing effects can be easily constrained at eRHIC by measuring F_L. This conclusion is, to a good extent, model independent. On the other hand, the ratio R_C gives us an upper bound for the magnitude of the shadowing effects. For example, if it is found that R_C is equal to ≈ 0.6 at $x = 10^{-4}$ and $Q^2 = 2.5$ GeV^2 the nuclear gluon distributions from DS and HKN parametrizations are very large and should be modified. At $Q^2 = 10$ GeV^2 the behavior of R_C is almost identical to R_g, which implies that by measuring F_2^c at this virtuality we can also constrain the shadowing effects. Considering now the kinematical range of $x > 10^{-3}$ we can analyze the correlation between the behavior of R_L and R_C and the antishadowing present or not in the nuclear gluon distribution. As in the case of small values of x, the behavior of R_L is very close to the R_g one in the large-x range. In particular, the presence of antishadowing in xg_A directly implies an enhancement in F_L^A. Inversely, if we assume the nonexistence of the antishadowing in the nuclear gluon distribution at $x < 10^{-1}$, as in the DS and HKN parametrizations, no enhancement will be present in F_L^A in this kinematical region. This suggests that also the antishadowing effects can be easily constrained at eRHIC measuring F_L. On the other hand, in this kinematical range the behavior of R_C is different from R_g at a same x. However, we observe that the behavior of R_C at $x = 10^{-2}$ is directly associated to R_g at $x = 10^{-1}$. In other words, the antishadowing is shifted in R_C by approximately one order of magnitude in x. For example, the large growth of R_g predicted by the HKN parametrization at $x \geqslant 10^{-1}$ shown in Fig. 1 implies the steep behavior of R_C at $x \geqslant 10^{-2}$ observed in Fig. 2. A similar conclusion can be drawn from Fig. 3. Consequently, by measuring F_2^c it is also possible to constrain the existence and magnitude of the antishadowing effects.

So far we have considered only $A = 208$. Now we discuss the A dependence of our results. In Figs. 4 and 5 we show the ratios R_g, R_C and R_L obtained with the EKS, EPS, DS and HKN parametrizations for two typical combinations of x and Q^2: $x = 10^{-4}$ and

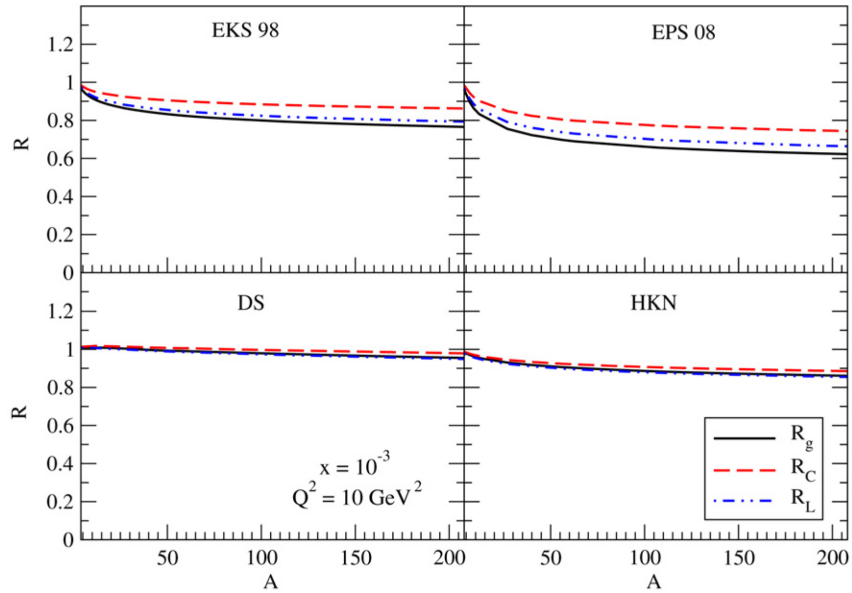

Fig. 5. The same as Fig. 4 for $x = 10^{-3}$ and $Q^2 = 10$ GeV^2.

$Q^2 = 1$ GeV^2 in Fig. 4 and $x = 10^{-3}$ and $Q^2 = 10$ GeV^2 in Fig. 5. We observe a stronger A dependence of the ratios for the lower values of x and Q^2 (Fig. 4), which is directly associated to the magnitude and behavior of the shadowing effects, expected to be larger in this kinematical range. The EPS parametrization predicts a rapid fall of R_g in the region $A < 50$, in contrast to the other parametrizations, which predict a softer behavior. On the other hand, moving to higher x and Q^2 (Fig. 5), the A dependence of the ratios practically disappears. A prominent feature of these figures is that they corroborate our previous conclusion, namely that in all kinematical domains and for different targets R_g nearly coincides with R_L, which is a measurable quantity. This is the most important result of this work.

Some comments are in order here. Firstly, it is important to emphasize that we have calculated F_L and F_2^c at leading order. For the sake of consistency, our calculations were performed with LO parton densities. Higher order corrections would enter in the formulas for F_L and F_2^c as well as in the pdf's. In the former we expect them to give origin to a constant K factor, as it happens in the formulas for particle production. This type of correction would cancel out, since we are taking ratios. On the other hand, higher order corrections would also modify the nuclear parton distribution functions. However, as shown in [21], these modifications are of the order of 10%. Therefore we expect that our LO results remain approximately true at NLO. Nevertheless, it might be interesting to calculate R_L and R_C at NLO and use as input the DS and HKN nuclear parton distributions at this order. We postpone this analysis for a future publication. Secondly, in our study we only have considered two examples of inclusive observables which would be measured at eRHIC. As demonstrated in Ref. [18] the study of the logarithmic Q^2 slope of the nuclear structure function is another important quantity to directly probe the nuclear effects and the QCD dynamics at small-x. The basic relation between these two quantities is $\frac{dF_2(x,Q^2)}{d\log Q^2} = \frac{10\alpha_s}{27\pi} xg(2x, Q^2)$ [24], which is valid at small values of x. Furthermore, the exclusive production of vector mesons is an important complementary observable to determine the nuclear gluon distribution, since in this case the total cross section is proportional to the square of xg^A (see e.g. Refs. [25,26]). Finally, we have disregarded the presence of non-linear effects in the QCD dynamics and used the current parametrizations based on the DGLAP dynamics, extrapolating them to lower values of x. Consequently, our results can be regarded as conservative and serve as a baseline. Deviations from this baseline may indicate the emergence of the saturation regime of QCD. A recent comparison between the collinear and saturation predictions for F_L and F_2^c was presented in Ref. [27]. In that work it was shown that collinear and saturation models predict a similar depletion in the ratios R_g, R_C and R_L.

Summarizing, our results indicate that the study of the inclusive observables F_L and F_2^c in eA process at eRHIC is ideal to constrain the nuclear effects present in the nuclear gluon distribution, which, in turn, is a crucial ingredient to estimate the cross sections of the processes which will be studied in the future accelerators. Basically, we see that by measuring these observables we will have a direct access to the nuclear gluon distribution and allow to discriminate between the different parametrizations. We hope that this Letter can motivate a more accurate determination of F_L and F_2^c in the next years.

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