PROCEEDINGS OF SCIENCE

Probling gluon saturation through dihadron correlations at an EIC

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It is the ultimate goal of nuclear physics to understand the emergence of nuclear structure and dynamics in terms of quarks and gluons. Although past experiments were successful in determining the quark behavior in the nucleon and light nuclei, the gluons that determine the essential features of the strong interactions, remain largely unexplored. Of great interest is especially the high parton density (small x) regime where gluon self-interaction is expected to dominate and lead to parton saturation. Two-particle azimuthal angle correlations have been reckoned to be one of the most direct and sensitive probes to access the underlying gluon dynamics. In this paper, we report on detailed studies of dihadron correlation measurements in $e+p$ and e+A collisions taking into account saturation effects as well as parton shower processes. The potential of using these measurements to study the saturation regime is also discussed.

XXII. International Workshop on Deep-Inelastic Scattering and Related Subjects,
28 April - 2 May 2014
Warsaw, Poland

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PoS(DIS2014)255

1. Introduction

Recent experimental data provided us some intriguing evidence that there exists a novel QCD regime at small-x in which non-linear gluon dynamics dominate, usually named as saturation regime [1]. The main physical ingredient of the saturation formalism is to incorporate the unitarity constraint for high-energy scattering amplitudes through the inclusion of non-linear recombination in the quantum evolution of hadronic wave functions. When the gluon density at low x becomes so large that different gluon clouds with fixed transverse size $\sim 1/Q^2$ start to overlap with each other, the QCD evolution dynamics essentially becomes non-linear [2, 3]. It is conceivable that gluons can recombine in a dense medium, thereby taming further rapid growth of the gluon density. This non-linear dynamical effect can be enhanced by a factor of $A^{1/3}$ in a nuclear target with mass number A.

At the theoretical level, complete calculations beyond leading order are quite important, since higher-order corrections are in general sizable. This work accounts for gluon radiation in the calculation of the e+A dihadron cross section through the inclusion of Sudakov factors. It is one of the most important corrections computed on the one-loop level and vital for the comparison between the theory calculations and the future Electron-Ion Collider (EIC) [4, 5] data on dihadron correlations.

It has been shown in the recent theoretical development of small-x physics, that there are two different fundamental unintegrated gluon distributions; namely the Weizsäcker-Williams (WW) gluon distribution and the dipole gluon distribution, which are involved in the calculation of various observables [6]. We want to emphasize that the WW gluon distribution only appears in few physical processes exclusively, and currently there is very little knowledge about its behavior. Fortunately, at an EIC, the DIS dijet process will provide us a unique and clean means to measure the WW gluon distribution [7]. Details about the calculation and simulations have been documented in Ref. [8].

2. Dihadron correlations in the saturation formalism

According to the effective small-x k_t factorization established in Ref. [7], which is briefly summarized above, the back-to-back correlation limit of the dihadron production cross section can be used to directly probe the WW gluon distribution $xG^{(1)}(x,q_\perp)$. As a comparison, the hadron production in semi-inclusive deep inelastic scattering (SIDIS), as shown in Ref. [9], is related to the so-called dipole gluon distributions $xG^{(2)}(x,q_\perp)$.

The coincidence probability $C(\Delta\phi) = \frac{N_{pair}(\Delta\phi)}{N_{trig}}$ is a commonly exploited observable in dihadron correlation studies, in which $N_{pair}(\Delta\phi)$ is the yield of the correlated trigger and associate particle pairs, while N_{trig} is the trigger particle yield. In terms of theoretical calculations, the correlation function is defined as

$$C(\Delta\phi) = \frac{1}{d\sigma_{SIDIS}^{\gamma^*+A\to h_1+X}/dz_{h1}} \frac{d\sigma_{tot}^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d\Delta\phi}. \tag{2.1}$$

At leading order (LO), the dihadron total cross section, which includes both the longitudinal and transverse contributions, can be written as follows [7]:

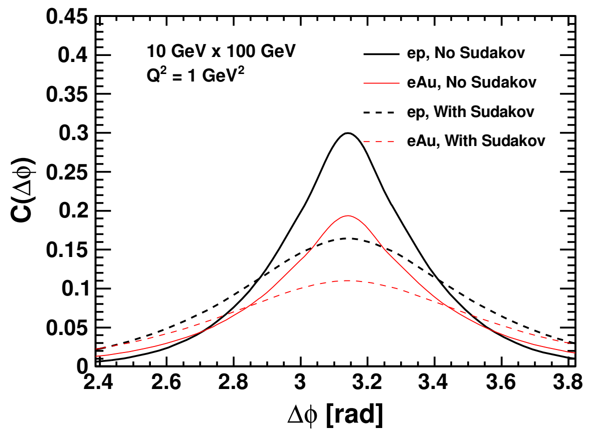

Figure 1: π^0-correlation curves calculated in the saturation formalism at 10 GeV$\times$100 GeV for $e+p$ (thick line) and e+Au (thin line) with (dashed curve) and without (solid curve) the Sudakov factor. The kinematics chosen are: $y = 0.7$, $Q^2 = 1\,\mathrm{GeV}^2$, $z_{h1} = z_{h2} = 0.3$, $p_{h1\perp} > 2\,\mathrm{GeV}/c, 1\,\mathrm{GeV}/c < p_{h2\perp} < p_{h1\perp}$.

$$\frac{d\sigma_{tot}^{\gamma^*+A\to h_1+h_2+X}}{dz_{h1}dz_{h2}d^2p_{h1\perp}d^2p_{h2\perp}} = C\int_{z_{h1}}^{1-z_{h2}} dz_q \frac{z_q(1-z_q)}{z_{h2}^2 z_{h1}^2} d^2p_{1\perp}d^2p_{2\perp}\mathscr{F}(x_g,q_\perp)\mathscr{H}_{tot}(z_q,k_{1\perp},k_{2\perp}) \times \sum_q e_q^2 D_q(\tfrac{z_{h1}}{z_q},p_{1\perp})D_{\bar{q}}(\tfrac{z_{h2}}{1-z_q},p_{2\perp}), \quad (2.2)$$

where $C = \frac{S_\perp N_c \alpha_{em}}{2\pi^2}$ gives the normalization factor. $\mathscr{F}(x_g,q_\perp)$ comes from the relevant WW gluon distribution $xG^{(1)}(x_g,q_\perp)$ evaluated with the gauge links for a large nucleus at small x by using the McLerran-Venugopalan model [10],

$$\mathscr{F}(x_g,q_\perp) = \frac{1}{2\pi^2}\int d^2r_\perp e^{-iq_\perp r_\perp}\frac{1}{r_\perp^2}[1-\exp(-\frac{1}{4}r_\perp^2 Q_s^2)], \quad (2.3)$$

in which $x_g = \frac{z_q p_{h1\perp}^2}{z_{h1}^2 s} + \frac{(1-z_q)p_{h2\perp}^2}{z_{h2}^2 s} + \frac{Q^2}{s}$ is the longitudinal momentum fraction of the small-x gluon with respect to the target hadron and Q_s is the gluon saturation scale. $D_q(\frac{z_h}{z_q},p_\perp)$ represents the transverse momentum dependent fragmentation functions, where $p_\perp$ shows the additional transverse momentum introduced by fragmentation processes.

As to the single-inclusive-hadron production cross section, which enters the denominator of the definition of the correlation function $C(\Delta\phi)$, it has been calculated and well demonstrated in [9], we will not repeat the calculations here. However, all the above results are estimated based on the LO Born level contribution. At the EIC energy scale the one-loop contribution [11], which is also known as the Sudakov factor, can be important as well. To include the Sudakov factor contribution at leading double logarithm level, one can rewrite the relevant WW distribution as follows [12]:

$$\mathscr{F}(x_g,q_\perp) = \frac{1}{2\pi^2}\int d^2r_\perp e^{-iq_\perp r_\perp}\frac{1}{r_\perp^2}[1-\exp(-\frac{1}{4}r_\perp^2 Q_s^2)]\exp[-\frac{\alpha_s N_c}{4\pi}\ln^2\frac{K^2 r_\perp^2}{c_0^2}], \quad (2.4)$$

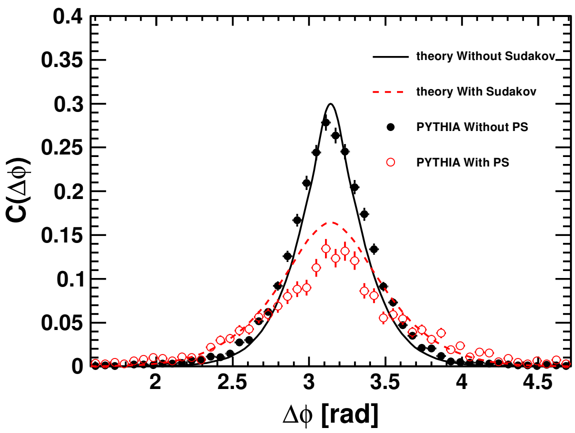

Figure 2: π^0 $\Delta\phi$ correlation comparing PYTHIA and theoretical saturation calculations for $e+p$ 10 GeV $\times$ 100 GeV for events from PGF and resolved gluon channel subprocesses at $1.0\,\mathrm{GeV}^2 < Q^2 < 2.0\,\mathrm{GeV}^2$, $0.65 < y < 0.75$, $p_T^{trig} > 2\,\mathrm{GeV}/c, 1\,\mathrm{GeV}/c < p_T^{assoc} < p_T^{trig}$, $0.25 < z_h^{trig}, z_h^{assoc} < 0.35$. The solid and dashed curves show theoretical predictions including saturation effects for $e+p$ without and with Sudakov factor, respectively. The filled and empty circles illustrate PYTHIA simulations for $e+p$ without and with parton showers (PS).

where K^2 represents the hard momentum scale in two-particle production processes. It can be chosen as $K^2 = P_\perp^2$ or $K^2 = Q^2$, depending on which one is larger, and $c_0 = 2e^{-\gamma_E}$ with the Euler constant γ_E. It is known that the single logarithmic terms as well as the next-to-leading order (NLO) contribution of the Sudakov factor also have sizable contributions compared to the above leading double logarithmic contribution. Therefore, the numerical value of α_s in the Sudakov factor used in this calculation may be different from what one normally expects according to a QCD running coupling constant calculation.

An illustration of this Sudakov effect with $\alpha_s = 0.35$ can be found in Fig. 1 labeled by the dashed lines. It is worthwhile to point out that the Sudakov effect in a nuclear environment is still not very well known. In the current small-x scenario as shown in Eq. (2.4), it is convoluted with the gluon distribution function. The theoretical calculation indicates that the Sudakov factor has no nuclear A dependence at LO. As shown in Fig. 1, the away-side suppression of the dihadron correlation is due to the combination of the Sudakov suppression and saturation effects. It is conceivable that the suppression due to saturation effects shall become more and more dominant when the ion beam species are changed from proton to gold, while the Sudakov effect remains more or less the same.

3. Experimental measurements of dihadron correlations at an EIC

The simulation part of this study is based on the PYTHIA-6.4 Monte Carlo program, with the PDF input from the LHAPDF library and JETSET used for fragmentation processes. To simulate $e+p$ events the CTEQ6M PDF in the $\overline{\mathrm{MS}}$ scheme is used. For the e+A event sample, the NLO

EPS09 parton distribution functions [13] and hard parton energy loss [14] based on the medium geometry have been applied to account for nuclear effects in the simulation.

In the saturation formalism, the parton shower contribution is effectively cast into the Sudakov factor for the DIS dijet process at small x. To illustrate this point, Fig. 2 shows the correlation function simulated with and without parton showers, compared to the corresponding theoretical predictions with and without Sudakov effects. The simulated PYTHIA $e+p$ data agree with the $e+p$ theoretical predictions with and without Sudakov effect when parton shower is switched on and off considering the model uncertainties. The agreement in $e+p$ collisions enables one to estimate the nuclear medium effects on parton showers in the theoretical predictions for saturation including Sudakov effects.

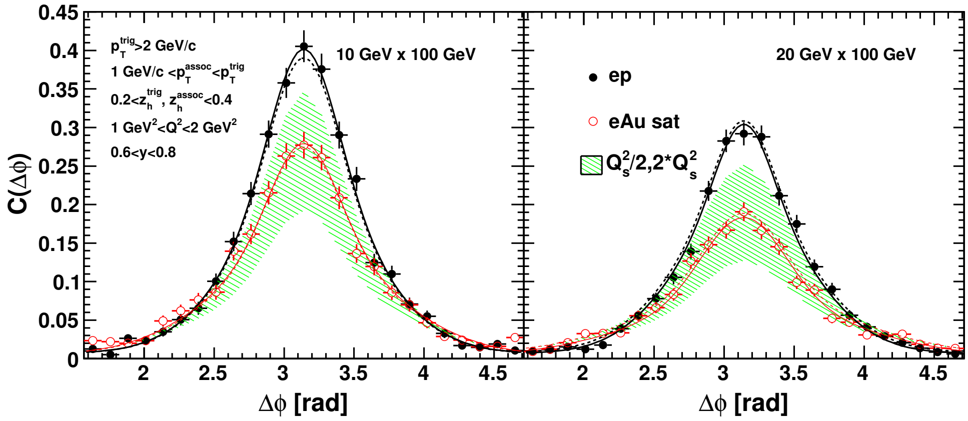

Figure 3: The correlation function at $1\,\mathrm{GeV}^2 < Q^2 < 2\,\mathrm{GeV}^2$, $0.6 < y < 0.8$ for an integrated luminosity of $1\,fb^{-1}$. The $e+p$ result comes from PYTHIA simulations. The e+Au results are a combination of simulations from a saturation-based model plus modified PYTHIA simulations. The suppression factor uncertainty was estimated by varying Q_s^2 by a factor of 0.5 and 2. Sudakov resummation has also been incorporated for e+Au. The solid lines represent a fit for the simulated pseudo-data including detector effects; the dashed line excludes detector effects.

On the basis of agreement in $e+p$ simulation and theoretical prediction, we can extract the ratio of $C(\Delta\phi)_{eAu}/C(\Delta\phi)_{ep}$ from the theoretical prediction and put that on top of our $e+p$ simulations to get reasonable projections for the saturation based e+Au correlation function. In Fig. 3 we compare the strength of the coincidence probability based on a theoretical saturation model prediction for the away-side $\Delta\phi$ correlations for $e+p$ and e+Au. Accepted charged hadrons in $-4 < \eta < 4$ have been correlated to make the analysis. The filled circles in Fig. 3 are simulated with PYTHIA for $e+p$ collisions, including detector smearing and acceptance effects. The uncertainties represent the statistical precision from an integrated luminosity of $1\,fb^{-1}$. The solid (dashed) lines in Fig. 3 represent fits to the simulated data points with (without) detector effects included in the simulation.

Since to date there is no exact knowledge of the saturation scale, the uncertainty in the suppression factor is estimated by varying the saturation scale by a factor of 0.5 and 2. The resulting uncertainty bands are depicted in Fig. 3. The suppression of the away-side peak remains significant even with this additional uncertainty compared to the result with a leading twist suppression. In summary, the suppression effects on dihadron correlations due to saturation can be clearly discriminated with a well-designed EIC machine.

4. Summary

Dihadron correlation measurements at an EIC are very vital and intriguing in that they will probe the saturation physics and directly measure for the first time the behavior of the Weizsäcker-Williams gluon distribution, about which we still know very little, and which we can hardly extract from other measurements. In the current framework, Sudakov resummation has been performed in the saturation formalism. It is very important to bridge the theory calculation and the future EIC data. The nuclear modification of Sudakov effect in DIS dijet process is found to be very small in this framework. Nevertheless, there might be some nuclear dependence in the Sudakov factor at higher orders or in the non-perturbative part, while an EIC will permit unique measurements that give a definite answer to this question.

In conclusion, the proposed high-luminosity, high-energy Electron-Ion Collider, together with the designed detector, can provide an ideal apparatus to study gluon saturation with high precision through the measurement of the dihadron correlation function.

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