High energy pA collisions in the Color Glass Condensate approach

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Abstract

We present a brief review of phenomenological applications of the gluon saturation approach to the proton-nucleus collisions at high energies.

Key words: pA collisions, gluon saturation, Color Glass Condensate

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1 Introduction: gluon saturation and structure functions

At very high energies corresponding to very small values of Bjorken $x$ variable the density of partons in the hadronic and nuclear wave functions is believed to become very large reaching the saturation limit (see [12] and references therein). In the saturation regime the growth of partonic structure functions with energy slows down sufficiently to unitarize the total hadronic cross sections. The gluonic fields in the saturated hadronic or nuclear wave function are very strong [12]. A transition to the saturation region can be characterized by the saturation scale $Q_s^2(s)$, which is related to the typical two dimensional density of the partons’ color charge in the infinite momentum frame of the hadronic or nuclear wave function. The saturation scale $Q_s^2(s)$ is an increasing function of energy $s$ and of the atomic number of the nucleus A. At high enough energies or for sufficiently large nuclei the saturation scale becomes much larger than $\Lambda_{QCD}^2$ allowing for perturbative description of the scattering process at hand. The presence of intrinsic large momentum scale $Q_s$ justifies the use of perturbative QCD expansion even for such a traditionally non-perturbative observables as total hadronic cross sections. There has been a lot of activity devoted to calculating hadronic and nuclear structure functions in the saturation regime. The original calculation of quark and gluon distribution functions including multiple rescatterings without QCD evolution in...
a large nucleus was performed in [3]. The resulting Glauber-Mueller formula provided us with expressions for the partonic structure functions which reach saturation at small $Q^2$. McLerran and Venugopalan has argued that the large density of gluons in the partonic wave functions at high energy allows one to approximate the gluon field of a large hadron or nucleus by a classical solution of the Yang-Mills equations. The resulting gluonic structure functions has been shown to be equivalent to the Glauber-Mueller approach [1][2].

To include quantum QCD evolution in this quasi-classical expression for the structure functions one has to resum the multiple BFKL pomeron exchanges. The evolution equation resumming leading logarithms of energy ($\alpha_s \ln s$) and the multiple pomeron exchanges was written in [1] using the dipole model of [5] and independently in [6] using the effective high energy lagrangian approach. The equation was written for forward scattering amplitude $N(r, b, Y)$ of a quark-antiquark dipole with transverse size $r$ at impact parameter $b$ with rapidity $Y$ scattering on a target hadron or nucleus, which, in turn can yield us the $F_2$ structure function of the target which is measured in DIS experiments.

The evolution equation for $N$ closes only in the large-$N_c$ limit of QCD and provides the basis for all phenomenological applications. It describes the onset of the gluon saturation for small $x$ and/or larger $A$. The most striking consequence of the gluon saturation is scaling of the total DIS cross section at small $x$ with variable $Q^2/Q_s(x, A)$, the so-called geometric scaling, observed in DIS on both proton [7] and nuclear targets[8].

Several other observables can be calculated in the framework of the saturation approach to hadronic and nuclear collisions. In this paper we review applications of the saturation approach for calculation of various inclusive observables in pA collisions.

2 Inclusive gluon production

Single inclusive gluon production in the quasi-classical approximation has been derived in [9]. The inclusive cross section for the scattering of a dipole of transverse $x_{01}$ on the target reads

$$\frac{d\hat{\sigma}_{q\bar{q}A}}{d^2k d y}(x_{01}) = \frac{\alpha_s C_F}{\pi^2} \int d^2b d^2z_1 d^2z_2 e^{-ik \cdot (z_1 - z_2)} \sum_{i,j=0} \frac{1}{(-1)^{i+j}} \frac{z_1 - x_i}{|z_1 - x_i|^2} \cdot \frac{z_2 - x_j}{|z_2 - x_j|^2}$$

$$\times \frac{1}{(2\pi)^2} \left( e^{-(z_1 - z_2)^2Q_0^2/4} - e^{-(z_1 - z_2)^2Q_0^2/4} - e^{-(z_2 - z_1)^2Q_0^2/4} + e^{-(z_1 - z_2)^2Q_0^2/4} \right)$$

(1)
This formula sums up the multiple rescatterings of the $q\bar{q}$ pair and the produced gluon on the nucleons in the target nucleus in the $A_+ = 0$ light cone gauge (+ is the direction of motion of the incident color dipole). Inclusion of quantum evolution amounts to resuming all possible real and virtual gluon emissions in addition to the emission of the measured gluon. In spite of the explicit breaking of factorization for individual diagrams in any known gauge the sum over all diagrams can be written in a simple $k_T$-factorized form \cite{10}

$$\frac{d\sigma_{pA}}{d^2kdy} = \frac{2\alpha_s}{C_F} \frac{1}{k^2} \int d^2q \Phi_p(q) \Phi_A(k - q),$$

where the unintegrated gluon distribution function is defined as

$$\phi(x, k^2) = \frac{C_F}{\alpha_s(2\pi)^3} \int d^2b d^2r e^{-\frac{i}{\pi} b \cdot r} \nabla^2 r N_G(r, b, y = \ln(1/x)),$$

with $N_G(r, b, y)$ the forward amplitude of a gluon dipole of transverse size $r$ at impact parameter $b$ and rapidity $y$ scattering on a nucleus. If the forward scattering amplitude of $q\bar{q}$ dipole is found from the evolution equation, then the gluon dipole scattering amplitude can be calculated from

$$N_G(r, b, y) = 2N(r, b, y) - N^2(r, b, y).$$

Let us emphasize that in this approach we consider gluon saturation effects only in nucleus, while treating proton as a dilute object. Analysis of the inclusive gluon production has been also performed in \cite{11,12,13}.

This approach to the high energy pA collisions leads to a rather successful phenomenological applications which allow the direct comparison with the experimental data, see Fig. 1. While the multiple rescatterings in the nucleus without quantum evolution lead to mere redistribution of the gluon’s transverse momentum towards higher values (Cronin effect), the effect of quantum evolution is to tame the growth of the scattering amplitude at higher energies/rapidities and/or for heavy nuclei. As the result the saturation approach predicted the onset of suppression of the nuclear modification factor in dAu collisions at forward rapidities \cite{14,15,16,13,17}, see Fig. 1.

It was suggested already in the pioneering papers on the gluon saturation that the particle correlations in the saturation regime must be significantly suppressed as compared to the low density regime (see \cite{2}). Indeed, unlike in hard processes where two jets are produced back-to-back, in saturation regime most gluons are produced with a semi-hard momentum of the order of $Q_s$ ("monojets"). From the McLerran-Venugopalan model point of view, the emitted gluons correspond to the commuting classical non-Abelian fields.
The double inclusive gluon production in the quasi-classical approximation has been addressed in [21,22] where it was argued that the monojet correlations are responsible for generation of the azimuthal asymmetry in heavy ion collisions at large $p_T$. Quantum evolution effects where discussed in [23] where it was predicted that suppression of correlations at forward rapidities is larger than at central ones and that this suppression grows with the rapidity interval between the produced hadrons, see Fig. 2. Other possible signatures of the gluon saturation in the hadron correlation function were discussed in [24].

Fig. 2. (a) Azimuthal correlations between forward and backward hadrons, (b) scaled elliptic flow variable $v_2 \cdot M$ as a function of $p_T$ [25]. $M$ is multiplicity.
Exact theoretical result for the double-gluon production case has been obtained in [26]. It turns out that the $k_T$-factorization fails. Instead a more complicated factorization picture emerges.

3 Heavy quark production

Heavy quark production in hadronic collisions in high energy QCD is one of the most interesting and difficult problems. It is characterized by two hard scales: heavy quark mass $m$ and the saturation scale $Q_s$. The threshold for the invariant mass of the quark $q$ and antiquark $\bar{q}$ production is $2m$. Therefore, if $m$ is much larger than the confinement scale $\Lambda_{QCD}$, it guarantees that a non-perturbative long distance physics has little impact on the quark production making perturbative calculations possible (for a review see [27]). For all processes involving heavy quarks with momentum transfer of the order of $Q_s^2 \sim m^2$ large saturation scale implies breakdown of the collinear factorization approach. The factorization approach may be extended by allowing the incoming partons to be off-mass-shell. This results in conjectured $k_T$-factorization. Although the phenomenological applications of the $k_T$-factorization approach seem to be numerically reasonable at not very high energies [28] its theoretical status is not completely justified. Like collinear factorization it is based on the leading twist approximation. However, at sufficiently high energies, higher twist contributions proportional to $(Q_s/m)^{2n}$ become important in the kinematic region of small quark’s transverse momentum, indicating a breakdown of factorization approaches.

The fact that the saturation scale at high enough energies and for large nuclei is large, $Q_s \gg \Lambda_{QCD}$, combined with the observation that the typical transverse momentum of particles produced in $pA$ scattering is of the order of that saturation scale, leads to the conclusion that $Q_s$ sets the scale for the coupling constant, making it small. This allows one to perform calculations for, say, gluon production cross section in $pA$ collisions using the small coupling approach [10]. The same line of reasoning can be applied to heavy quark production considered here: the saturation scale $Q_s$ is the important hard scale making the coupling weak even if the quark mass $m$ was small. Having the quark mass $m$ as another large momentum scale in the problem only strengthens the case for applicability of perturbative approach.

Production of quark-antiquark pairs in high energy proton-nucleus collisions and in DIS has been calculated in [29,30,31,32,33]. The results of the calculations in a model based on the $k_T$-factorization approach are displayed in Fig. 3(a). The heavy quark mass delays the onset of the gluon saturation effects to higher rapidities $\eta \sim 2$ (for charm). The recent experimental results for the nuclear modification factor for muons associated with $D$-meson decays
are consistent with this prediction, see Fig. 3(b).

Fig. 3. (a) Charmed meson yield as a function of $N_{\text{coll}}$ [34], (b) Nuclear modification factor for muons associated with $D$-meson decays [35].

4 Future perspectives

In this admittedly brief review article we discussed how the effect of gluon saturation can be taken into account in the framework of the perturbation theory in the case of gluon and quark spectra, multiplicities and correlations. These observables are in agreement with the recent experimental data. In addition to the aforementioned calculations of the gluon and quark spectra and multiplicities an extensive work has been done on computing the production of $J/\psi$ [36], valence quarks [41,42], prompt photons [37] and di-leptons [38,39,40]. These observables still require detailed experimental investigation. Although we observed the onset of the gluon saturation at RHIC, this effect will be far more dramatic at LHC. In fact, production of bulk of particles in AA and pA collisions at midrapidity at LHC is predicted to be governed by the saturation regime. Measurement of the energy dependence of the various physical quantities is an important test for the gluon saturation approach.

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