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Saturation effects in $pA \to$ dilepton and photon production

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Abstract. I discuss the inclusive dilepton/photon cross section for proton (quark)–nucleus collisions at high energies in the very forward rapidity region, predicting leading twist shadowing together with anomalous scaling behavior.

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1 Introduction

This talk is based on the paper on saturation and shadowing in high-energy proton–nucleus dilepton production in collaboration with Mueller and Schiff [1], in which further details are given. Recent related work has been published by Jalilian-Marian [2], and by Betemps and Gay Ducati [3].

Hard probes are an excellent tool for analyzing the dense matter [4] produced in high-energy heavy ion collisions at RHIC [5] and at LHC [6].

Hard photons or dileptons coming from virtual photons are ideal probes[7–11]. A strong motivation for this study comes from recent dA data on high-$p_\perp$ hadron production at large rapidity (toward the deuteron side) from the BRAHMS Collaboration [12] showing a significant suppression of hadron production in dA collisions compared to the expectation from pp collisions, i.e. the disappearance of Cronin like enhancement due to the color glass condensate gluon distribution [13–15]. This gradual suppression of hard (charged) particle yield at forward rapidities has been predicted [16–24], although there is a surprise: "quantum evolution" [25–28] of the gluon distribution dominates in the nucleus at already rather small rapidities.

With hard photons one is less sensitive to fragmentation effects and final state effects are absent. This means that at transverse momenta around 2–3 GeV, one can expect leading twist factorization to be accurate, and hence x-values of the gluon distribution of the nucleus down to values somewhat smaller than 10^{-3} should be accessible.

The following discussion on production of dileptons in pA collisions is based on a picture, where the McLerran–Venugopalan model [13] is taken to represent the gluon distribution in a hard RHIC reaction at central values of rapidity, $y = 0$, and BFKL evolution [27–29] is used to evolve the distribution to higher values of y.

2 Dilepton production

The formula for lepton pair production, with lepton pair mass M, is given by

$$\frac{\mathrm{d}\sigma^{qA\to l^+l^-X}}{\mathrm{d}^2b\,\mathrm{d}^2k_\perp\,\mathrm{d}\ln z\,\mathrm{d}M^2} = \frac{\alpha_{\mathrm{em}}}{3\pi M^2}\frac{\mathrm{d}\sigma^{qA\to\gamma^*X}}{\mathrm{d}^2b\,\mathrm{d}^2k_\perp\,\mathrm{d}\ln z}\,, \tag{1}$$

where $\boldsymbol{k}_\perp$ is the transverse momentum of the γ^*, and z is the longitudinal momentum fraction of the γ^* with respect to the incident quark momentum, $z = k_+/p_+$, having the limit $p_+ \to \infty$ in mind. $\boldsymbol{b}$ denotes the impact parameter of the qA collision.

The $k_\perp$-factorized formula for high-$k_\perp$ (transversely polarized–virtual) photons produced in a quark–nucleus collision reads

$$\frac{\mathrm{d}\sigma^{qA\to\gamma^*X}}{\mathrm{d}^2b\,\mathrm{d}^2k_\perp\,\mathrm{d}z} = \frac{\alpha_{\mathrm{em}}}{[k_\perp^2+(1-z)M^2]} \times \int\frac{\mathrm{d}^2q_\perp}{q_\perp^2}H(k_\perp, zq_\perp, (1-z)M^2)\,\phi_G(\boldsymbol{b},\boldsymbol{q}_\perp,Y)\,, \tag{2}$$

which is illustrated in Fig. 1. H is the hard part in the $k_\perp$-factorized form.

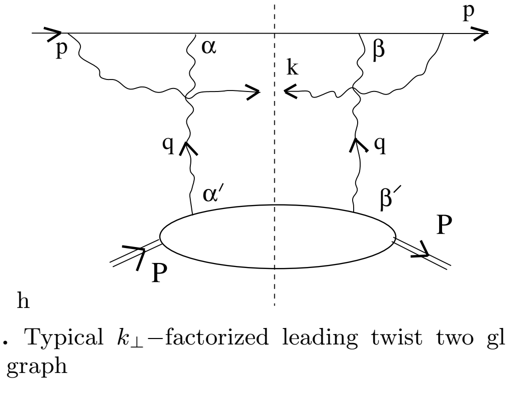

Fig. 1. Typical $k_\perp$–factorized leading twist two gluon exchange graph

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The unintegrated gluon distribution ϕ_G is expressed in terms of the forward scattering amplitude $N(\boldsymbol{b}, \boldsymbol{x}_\perp, Y) = N_{q\bar{q}}(\boldsymbol{b}, \boldsymbol{x}_\perp, Y)$ of a QCD $q\bar{q}$ dipole of transverse size $\boldsymbol{x}_\perp$ with rapidity $Y = \ln 1/x$, scattering off a nucleus A at impact parameter $\boldsymbol{b}$, by

$$\begin{aligned} &\phi_G(\boldsymbol{b}, \boldsymbol{q}_\perp, Y) \\ &= \frac{N_c}{(2\pi)^3 \alpha_s} \int \mathrm{d}^2 x_\perp \mathrm{e}^{\mathrm{i}\boldsymbol{q}_\perp \cdot \boldsymbol{x}_\perp} \boldsymbol{\nabla}^2_{x_\perp} N(\boldsymbol{b}, \boldsymbol{x}_\perp, Y) \\ &= \frac{N_c}{(2\pi)^3 \alpha_\mathrm{s}} \, q_\perp^2 \boldsymbol{\nabla}^2_{q_\perp} \int \frac{\mathrm{d}^2 x_\perp}{x_\perp^2} \mathrm{e}^{\mathrm{i}\boldsymbol{q}_\perp \cdot \boldsymbol{x}_\perp} N(\boldsymbol{b}, \boldsymbol{x}_\perp, Y) \,. \end{aligned} \quad (3)$$

The quasi-classical model by McLerran–Venugopalan [13] (at fixed $\boldsymbol{b}$ and at $Y = 0$) is a reasonable starting point of the Y evolution of ϕ_G,

$$N^{\mathrm{MV}}(\boldsymbol{b}, \boldsymbol{x}_\perp, Y = 0) = 1 - \exp[-x_\perp^2 {Q_\mathrm{s}}^2(\boldsymbol{b})/4], \quad (4)$$

with the saturation scale ${Q_\mathrm{s}}^2(\boldsymbol{b})$ [25,30].

3 BFKL evolution in the presence of saturation

Increasing the photon rapidity into the forward region, $y > 0$, the values of x of the gluon in the nucleus become rapidly small, namely $x \simeq (M_\perp/\sqrt{s})\mathrm{e}^{-y}$, such that $Y = \ln 1/x \simeq y$ increases with y. Typical values are estimated from the kinematics for parton$_1$ + parton$_2$ $\longrightarrow$ photon* production, e.g. for transverse mass $M_\perp = 5.0\,\mathrm{GeV}$ ($M \sim 2.0$, $k_\perp \sim 4.5\,\mathrm{GeV}$) $y = 0\,(3.5)$, at RHIC energy $\sqrt{s} = 200\,\mathrm{GeV}$, $x = 2.5\ 10^{-2}$ $(9.1\ 10^{-4})$; at LHC energy $\sqrt{s} = 5500\,\mathrm{GeV}$, $x = 7.5\ 10^{-4}$ $(2.7\ 10^{-5})$, i.e. indeed a fast quark producing forward dileptons probes the small x gluon distribution in the nucleus.

In the following for positive large rapidities $Y = y$ the fixed coupling leading order approximation of the Y evolution is considered, which effectively depends on the product of $\alpha_\mathrm{s} Y$.

Following the same steps as described in the paper [28], the solution of ϕ_G for large values of $\alpha_\mathrm{s} Y$ is extended into the geometric scaling region [31,32]. This is achieved by demanding that $\phi_G(\boldsymbol{b}, \boldsymbol{q}_\perp, Y)$ vanishes close to the saturation boundary, i.e. for $q_\perp^2 < Q_\mathrm{s}^2(\boldsymbol{b}, Y)$, to be defined below. This pragmatic procedure includes non-linear effects which are present in the Balitsky–Kovchegov equation for $N(\boldsymbol{b}, \boldsymbol{x}_\perp, Y)$ [33]. This characteristic behavior is also discussed in [34] from a more mathematical point of view. It is achieved by a linear superposition of two BFKL type solutions by shifting the positions of their maxima by a finite amount. The final scaling solution, expressed in terms of the Y dependent saturation momentum

$$Q_\mathrm{s}^2(\boldsymbol{b}, Y) = c_s {Q_\mathrm{s}}^2(\boldsymbol{b}) \, \frac{\exp\left[2\bar{\alpha}\, \frac{\chi(\lambda_0)}{1-\lambda_0} Y\right]}{(\alpha_\mathrm{s} Y)^{\frac{3}{2(1-\lambda_0)}}} \,, \quad (5)$$

is (for the case of constant α_s)

$$\begin{aligned} &\phi_G(\boldsymbol{b}, \boldsymbol{q}_\perp, Y) \\ &= \phi_G^{\max}\,(1-\lambda_0) \exp\left[-(1-\lambda_0) \ln \frac{q_\perp^2}{Q_\mathrm{s}^2(\boldsymbol{b}, Y)}\right] \\ &\qquad \times \left[\ln\left(\frac{q_\perp^2}{Q_\mathrm{s}^2(\boldsymbol{b}, Y)}\right) + \frac{1}{1-\lambda_0}\right], \end{aligned} \quad (6)$$

where c_s and $\phi_G^{\max} = O(1/\alpha_\mathrm{s})$ are constants; $\chi(\lambda)$ is the BFKL eigenvalue function.

The value of the anomalous dimension λ_0 is determined by

$$\frac{\chi'(\lambda_0)}{\chi(\lambda_0)} = -\frac{1}{1-\lambda_0}, \quad \lambda_0 = 0.372 \,. \quad (7)$$

It is well known that this leading order calculation with fixed coupling yields a large exponent in (5), namely $2\bar{\alpha}\, \frac{\chi(\lambda_0)}{1-\lambda_0} = 4.66...\alpha_\mathrm{s}$, which is too large to agree with phenomenology [35,36]. However, this discrepancy is resolved in [37], using the next-to-leading BFKL formalism, which as a result reduces the exponent to a value in agreement with the Golec-Biernat and Wüsthoff model [36].

It is important to note that this analytical function (6) successfully compares with the numerical studies [19,29] of the Kovchegov equation. Indeed in [19] a good fit by (6) is obtained for a fixed value of the anomalous dimension, $\lambda_0 = 0.37$, and for $5 < q_\perp/Q_\mathrm{s}(Y) < 1000$, mainly because of the logarithmic factor, $\ln\left(\frac{q_\perp^2}{Q_\mathrm{s}^2(\boldsymbol{b}, Y)}\right)$, which is present in (6). This comparison also indicates that the scaling behavior is rather rapidly approached.

4 Anomalous scaling and shadowing in dilepton production

4.1 Qualitative results

I first investigate its scaling properties. In order to exhibit the anomalous A dependence we deduce a parametric estimate of the ratio with respect to the proton target,

$$R_{pA} = \frac{\mathrm{d}\sigma^{qA \to \gamma^* X}/\mathrm{d}^2 b}{\rho T(b) \sigma^{qp \to \gamma^* X}} \,. \quad (8)$$

For central collisions, $\boldsymbol{b} = 0$, and assuming that the extended geometric scaling regions for protons p and nuclei A indeed overlap, this ratio becomes

$$R_{pA} \approx A^{-\lambda_0/3} \,. \quad (9)$$

A similar suppression in terms of anomalous scaling, as given e.g. by (9), is also predicted for the nuclear modification factor R_{pA}^G in case of gluon production [17–21,23,24].

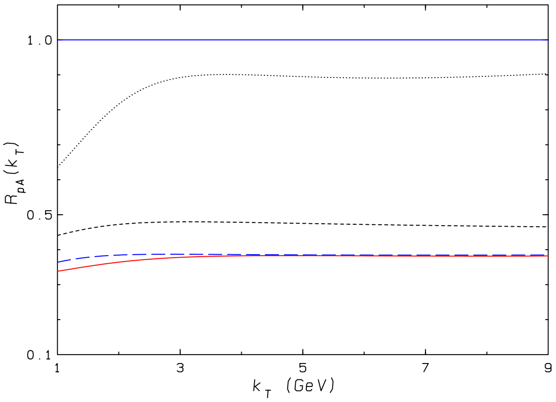

Fig. 2. BFKL-saturation model: R_{pA} as a function of $k_\perp$ for different values of y and for $M = 2\,\mathrm{GeV}$: dotted ($y = 0.5$), short-dashed ($y = 1.5$), long-dashed ($y = 3.0$). Solid curve for $M = 4\,\mathrm{GeV}$ and $y = 3$

4.2 Quantitative results

In order to illustrate results at large photon rapidities based on the BFKL evolution in the presence of saturation, the Y dependence of the scale is chosen to be compatible with phenomenology, following [31,36],

$$Q_s^2(\boldsymbol{b} = 0, Y) = (Q_s^{\mathrm{MV}})^2 \exp(\lambda_{\mathrm{GBW}}\, Y),\ \ \lambda_{\mathrm{GBW}} = 0.3\ . \tag{10}$$

Significant shadowing is obtained, as shown in Fig. 2 as a function of $k_\perp$, especially when the dileptons are produced rather forward, e.g. with $y = 3$. Similar results for $k_\perp$-integrated dilepton rates are presented in [2].

5 Summary

(1) I hope that the predictions are encouraging enough for experimenters to measure in $p(d)A$ collisions at RHIC and LHC the (energy dependence of the) suppression at large rapidities;
(2) for photons, dileptons and hadrons at moderate transverse momenta;
(3) in order to obtain finally support of the saturation picture of gluon dynamics at high energies and small values of x.
(4) The detailed knowledge of the initial state is crucial to develop the theory, which describes finally the dynamics of the transition from the dense gluon state (CGC) to the (thermalized) QGP in AA collisions at highest energies.
(5) It is also necessary to extend the presented analysis to running α_s and even beyond leading order BFKL.

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