The Cronin Effect, Quantum Evolution and the Color Glass Condensate

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(Dated: March 30, 2022)

We show that the numerical solution of the classical SU(3) Yang-Mills equations of motion in the McLerran-Venugopalan model for gluon production in central heavy ion collisions leads to a suppression at low pt and an enhancement at the intermediate pt region as compared to peripheral heavy ion and pp collisions at the same energy. Our results are compared to previous, Color Glass Condensate inspired calculations of gluon production in heavy ion collisions. We revisit the predictions of the Color Glass Condensate model for pA (dA) collisions in Leading Order and show that quantum evolution—in particular the phenomenon of geometric scaling and change of anomalous dimensions—preserves the Cronin enhancement of pA cross section (when normalized to the leading twist term) in the Leading Order approximation even though the pt spectrum can change. We comment on the case when gluon radiation is included.

PACS numbers: xxx

I. INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) has opened a new frontier in high energy heavy ion collisions. The first data from RHIC which showed a large suppression in the ratio of produced hadrons in AA and pp collisions [1] has created much excitement in the heavy ion community. It has led to intense theoretical and experimental work in order to understand and characterize the outcome. More recently, hadron spectra in dA collisions at RHIC were measured [2] in order to clarify the role of and distinguish between initial state and final state (plasma) effects. Whether the observed suppression of hadronic spectra [3] and disappearance of back to back jets [4] in central Au+Au collisions, as well the large elliptic flow [5], in heavy ion collisions at RHIC is due to the Quark Gluon Plasma is still in need of further experimental investigation. Nevertheless, the recent results from the dA collisions at RHIC and the apparent lack of strong initial state effects in mid-rapidity and at high pt appear to necessitate the presence of final state interactions in the partonic matter created in heavy ion collisions at RHIC [6].

Even though the Cronin effect [7] (the observation, at fixed target experiments, that the ratio of pA and pp cross sections, scaled by the number of collisions, is above unity at some intermediate pt while below one at low pt) is likely small in high energy heavy ion collisions as compared to parton energy loss effects, it is one of the two main nuclear effects, along with shadowing, expected in high energy pA (dA) collisions. Since pA collisions were proposed in order to clarify the role of initial and final state (medium) effects in high energy heavy ion collisions, it is extremely important to have a firm understanding of the physics of shadowing and the Cronin effect in order to have a precise understanding of the role of parton energy loss effects in heavy ion collisions.

The Cronin effect in high energy pA and AA collisions has been the subject of renewed theoretical interest recently [8–10]. In this brief letter, we show that the numerical solution of the classical Yang-Mills equations of motion [11–14] in the McLerran-Venugopalan model [15] does indeed include the Cronin effect. We point out the differences between this numerical approach and other saturation inspired models [16, 17] which led to the absence of the Cronin effect in these models. We re-visit some of our earlier results for pA collisions and show that quantum evolution and the so called geometric scaling phenomenon [18–20] (plus change of anomalous dimension) preserves the Cronin enhancement even though its magnitude and peak may change.

II. THE CRONIN EFFECT IN AA COLLISIONS

In the McLerran-Venugopalan model, the classical Yang–Mills equations of motion are solved in the presence of external sources of color charge. These color charges can be thought of as the high x quarks and gluons in the wavefunction of a nucleus and are Gaussian distributed with a characteristic scale Λs. (In practice, Λs ≈ Qs, the saturation scale.) In principle, Λs can be determined from nuclear gluon distributions. It is an external parameter in the calculations described here. Physical quantities are computed by averaging over the Gaussian distributed color charges. The details of these computations for the real time gluodynamics of nuclear collisions can be found in Refs. [11–14].

Briefly, the numerical lattice calculations in Ref. [12] impose color neutrality condition at the nucleon level and realistic nuclear density profiles. In our computations, we first solve the classical Yang-Mills equations on the lattice for the two nuclei before the collision. In the radiation gauge (x+A− + x−A+ = 0), the initial conditions
of gauge fields $A^\mu$ for nucleus-nucleus collisions at $\tau = 0$ can be obtained by matching the solutions in the space-like and time-like regions. Requiring that the gauge fields be regular at $\tau = 0$, $D_\mu F^{\mu i} = 0$ and $D_\mu F^{\mu +} = J^+$ for $x^-, x^+ \to 0$ gives the boundary conditions at $\tau = 0$:

$$A^i(0, x^\tau) = A^i_1(0, x^\tau) + A^i_2(0, x^\tau), \quad (i = x, y),$$

$$A^\pm(0, x^\tau) = \pm x^\pm \frac{i}{2}[A^1_1(0, x^\tau), A^2_2(0, x^\tau)].$$

Here, $A^i_{1,2}$ are the pure gauge fields for two incoming nuclei. Using these initial conditions, classical Yang-Mills equations are solved, assuming boost invariance, on a 2-dimensional lattice. The definition of the number distribution in the non-perturbative region is discussed in detail in [11]. In the transverse Coulomb gauge $\nabla \cdot A = 0$, it is

$$N(k) = \sqrt{\langle |\phi(k)|^2 \rangle}\langle |\pi(k)|^2 \rangle,$$

where $\phi(k)$ and $\pi(k)$ correspond to the potential and kinetic terms in the Hamiltonian respectively.

In Fig. 1 we plot $R_{CP}$, the ratio of produced gluons in head-on ($b = 0$ fm) and in peripheral ($b = 11$ fm) Au-Au collisions normalized by the number of collisions $N_{\text{coll}}$, for an SU(3) gauge theory. $N_{\text{coll}}$ is computed self-consistently in our framework and agrees, for instance, with Ref. [17]. The ratio $R_{CP}$ is below unity at low $p_t$ and above unity at intermediate $p_t$. This shows that the original McLerran-Venugopalan model indeed has the Cronin enhancement. One can in principle show that this ratio goes to unity at high $p_t$, but this is numerically intensive and not shown here.

Instead, for simplicity, we show in Fig. 2 results from a computation of the real time evolution of an SU(2) gauge theory. There is no qualitative difference between the SU(2) and SU(3) cases. Our results for the SU(2) gauge theory are obtained for larger (512×512) lattices relative to the (256×256) lattices in the SU(3) case. Plotted in Fig. 2 is the ratio of the $p_t$ distribution of gluons from Au-Au collisions ($\Lambda_{s0} = 2$ GeV) divided by $p$-p collisions ($\Lambda_{s0} = 0.2$ GeV) and normalized by the ratio of their asymptotic values at large $p_t$. Here MV denotes the McLerran-Venugopalan model with color neutrality imposed globally; Color Neutral I & II impose color neutrality on each configuration at the nucleon level-see text for discussion.

![Fig. 1: $R_{CP}$ from the McLerran Venugopalan model for an SU(3) gauge theory. Here $\Lambda_{s0} = 2$ GeV, where $\Lambda_{s0}^2$ is the color charge squared per unit transverse area in the center of each nucleus. (The value of $\Lambda_s$ averaged over the entire nucleus is smaller $\sim 1.4$ GeV.) This result is obtained for a 256 × 256 lattice.](image1)

![Fig. 2: $R_{AA}$ for an SU(2) gauge theory. $R_{AA}$ is the ratio of the $p_t$ distribution of gluons for Au-Au collisions ($\Lambda_{s0} = 2$ GeV) to that in $p$-p collisions, normalized to the ratio of their asymptotic values ($N_{\text{coll}}$) at high $p_t$. The $p$-p results here are taken to be the lattice results for the very small value of $\Lambda_{s0} = 0.2$ GeV. The lattice result in the latter case is equivalent to the perturbative tree level result up to very small $p_t$'s. The reason $R_{AA}$ deviates from unity is due to the multiple scattering (“Cronin”) effect illustrated in Fig. 3 this point will be discussed further shortly. The three curves in Fig. 2 correspond to the following: MV denotes the McLerran-Venugopalan model with color neutrality imposed only globally over the entire nucleus in each configuration. Color Neutral I & II correspond to the more stringent condition where color neutrality is imposed on the scale of a nucleon. The former corresponds to the case where monopole component of the nucleon color charge is subtracted while in the latter case, both monopole and dipole components are subtracted. As has been noted previously in Ref. [12], the effect of these more stringent color neutrality conditions is to induce a power law dependence $p_t^n$ at low $p_t$ for the correlator of color charges in momentum space. This dependence, albeit non-perturbative in origin, is similar to that induced by perturbative color neutrality which arises from the color screening of saturated gluons generated in the quantum evolution [13]. The softening of the Cronin enhancement can therefore be understood as re-](image2)
sulting from color screening or “shadowing” of the initial gluon distributions.

In a nice paper, Kovchegov and Mueller have shown that the choice of gauge can determine whether interactions are “initial state” or “final state” effects \[21\]. In our numerical computations (carried out in $A^\tau = 0$ gauge) initial state as well as some final state interactions are included. We qualify the latter because due to the strong initial state as well as some final state interactions are of higher order in the classical approach, there is only a single scattering in the perturbative region where $k_t^2 \gg Q_s^2$. In the perturbative region where $k_t^2 \gg Q_s^2$

\[
\phi_A(x_1, k_t^2) \sim 1/k_t^2
\]

while in the saturation region where $k_t^2 \ll Q_s^2$

\[
\phi_A(x_1, k_t^2) \sim 1/\alpha_s.
\]

In \[16\] these two asymptotic forms of the unintegrated gluon distribution are then matched at $Q_s$. In this approach, there is only a single scattering in the $k_t > Q_s$ region and multiple scatterings at scales just above $Q_s$ are not included. Since the non-perturbative input in the form of the “gluon liberation factor” is included from the numerical lattice simulations \[11\], this approach likely includes phenomenologically the physics of the CGC for global observables such as the centrality and rapidity dependence of observables (further discussed in the next paragraph).

The same $k_t$-factorized formalism is considered in Ref. \[17\]. The authors however additionally consider the effects, at moderate $p_t$’s, due to the change in the unintegrated gluon distributions arising from quantum evolution. In particular, they take into account the change in the distributions due to the modification of the anomalous dimensions in the evolution. This change leads to a scaling with $N_{\text{part}}$ as opposed to $N_{\text{coll}}$ scaling. (Note that these modifications do not affect the prior results of Ref. \[16\] since the multiplicities, at the $p_t$’s at which they occur, are rather small.) However, the Cronin enhancement for $p_t$ distributions is missed in \[16\] \[17\]. On the other hand, in our numerical computations, all re-scatterings are included at the classical level leading to the Cronin enhancement. Note though that quantum evolution is absent in our lattice calculations-its effects
are only implicitly included through the magnitude of the saturation scale.

In addition to their importance for the Cronin effect, the non-factorized contributions illustrated in Fig. 3 likely play a significant role in determining the total gluon multiplicity as well. This can be understood by comparing the numerical results for the gluon liberation coefficient $f_N$ with the factorized contributions and is roughly 3 to 4 times larger.

A possible way of including this enhancement in the $k_t$ factorized form through quantum evolution is discussed in Ref. 21. A similar approximation of $\phi_A(x, k_t)$ in the context of $pA$ collisions also leads to a lack of Cronin enhancement in the cross section. It would be interesting to include quantum evolution effects in addition to the Cronin effect in our numerical work to quantify the importance of the energy loss contribution. This work is in progress and will be reported shortly.

Below, we consider $pA$ scattering and explicitly show that inclusion of higher order scatterings leads to the Cronin effect.

III. THE CRONIN EFFECT IN $pA$ COLLISIONS

Even though the Cronin effect in a high energy heavy ion collision is quite small at high $p_t$ as compared to the parton energy loss effects, it is quite important in a proton (deuteron) nucleus collision since energy loss effects in the hot medium produced in a heavy ion collision, are absent in a $pA$ collision. In this section, we revisit the Color Glass Condensate results for a quark or gluon scattering on a nucleus and show that the recent phenomenon of geometric scaling and changing of the anomalous dimension does not affect our conclusions as long as we divide our $pA$ cross section by its leading twist limit (rather than $pp$).

Scattering of a quark or gluon on a nucleus using the Color Glass Condensate formalism and its relation to DIS was discussed in Refs. 3 and 4. It was shown that the scattering cross section is given by

$$\frac{d\sigma^{A\rightarrow qX}}{d^2p_t dp^- d^2b_t} = \frac{1}{(2\pi)^2} \delta(q^- - p^-) \times \int d^2r_t e^{ip_r r_t} [2 - \sigma_{dipole}(x, r_t, b_t)]$$

(3)

with

$$\sigma_{dipole}(x, r_t, b_t) \equiv \frac{1}{N_c} Tr \left\{ 1 - V(b_t + \frac{r_t}{2}) V^\dagger(b_t - \frac{r_t}{2}) \right\}$$

(4)

where $q^-(p^-)$ is the longitudinal momentum of the incoming (outgoing) quark, with a similar equation for gluon scattering. This is the multiple scattering generalization of quark gluon scattering in pQCD and unlike the leading twist (single scattering) result, is finite as $p_t \rightarrow 0$ due to higher twist effects. In addition, defining

$$\gamma(x, p_t, b_t) \equiv \int d^2r_t e^{ip_r r_t} [2 - \sigma_{dipole}(x, r_t, b_t)]$$

(5)

and using the fact that $\sigma_{dipole}(x, r_t = 0, b_t) = 0$, we see that $\gamma$ satisfies the following sum rule

$$\int d^2p_t \gamma(x, p_t, b_t) = 2 (2\pi)^2,$$ 

(6)

for fixed $b_t$. It is clear from this sum rule that if the cross section in (3) is suppressed at low $p_t$, it must be enhanced at high $p_t$ in order to compensate for the low $p_t$ suppression so that the sum rule holds. The Cronin peak moves to higher $p_t$ as one goes to higher energy (or more forward rapidities as well as more central collisions).

The effects of quantum evolution on our classical results can be investigated using the Renormalization Group equations and in particular the Balitsky-Kovchegov (BK) equation for the dipole cross section in the large $N_c$ limit. It is straightforward to apply the BK equation to the $qA$ (or $gA$) scattering cross section in order to prove that quantum evolution preserves the sum rule in (3). For our purposes, it suffices to notice that $\sigma_{dipole}(x, r_t = 0, b_t) = 0$ at any $x$ (energy) so that the sum rule is preserved by quantum evolution and therefore, the Cronin enhancement is still present. Nevertheless, the $p_t$ spectra will look different at different energies since the location of the Cronin peak as well as its magnitude changes as one goes to higher energies (see for example, Figure 4 in the last paper of Ref. 9.). In addition, the change of the anomalous dimension $\gamma$ could modify the magnitude of the Cronin effect. Nevertheless, since the BK equation preserves the sum rule in (3) at the partonic level, this modification in the high $p_t$ region will be compensated by an analogous modification in the low $p_t$ region so that the sum rule is not violated.

One should keep in mind that at RHIC and for mid rapidity and high $p_t$ processes (such as the suppression of hadron yields) the effective $x$ of the partons is quite large. For example, for $p_t \sim 5 - 10$ GeV in mid rapidity, the $x$ range is $\sim 0.05 - 0.1$. The only potential evidence for gluon saturation and geometrical scaling in hadrons is from HERA where saturation models work very well only for $x < 0.01$ and fail at higher $x$. In the case of nuclei, this effective $x$ may be slightly higher but can not be too much higher since otherwise, strong gluon shadowing would manifest itself in the $F_2$ structure function which shows no strong shadowing effects at the $x$ range $0.05 - 0.1$ and as a matter of fact, shows anti shadowing! The Color Glass Condensate model is an effective theory of QCD at small $x$ only and likely breaks down at the high $x$'s relevant for high $p_t$ processes in mid rapidity at RHIC. (This situation will improve as one goes to higher collision energies or stays in the low $p_t$ region.)

Moving to more forward rapidities (in the projectile fragmentation region) will make applications of the Color Glass Condensate model more reliable since smaller values of $x$ in the target are probed. The saturation scale
is larger, rendering weak coupling methods more reliable. In addition, the contribution of high $x$ region to the cross section will be less important than that in the mid rapidity region. Whether the most forward rapidities accessible at RHIC are large enough for the physics of gluon saturation to be the dominant physics remains to be seen.

IV. SUMMARY

We considered in this note gluon production in heavy ion collisions using the numerical simulations of the Color Glass Condensate. We showed that the ratio of central to peripheral cross sections (or equivalently, the ratio of central to pp cross sections), normalized by the number of collisions, shows the Cronin enhancement at high $p_t$ as well the suppression at low $p_t$. We discussed other gluon saturation and Color Glass Condensate inspired models and commented on the absence of the Cronin effect in these models. We also considered $pA$ collisions and showed that, at the partonic level and in leading order in $\alpha_s$, quantum evolution with energy and the change of anomalous dimension preserves the Cronin enhancement (when normalized to its leading twist term rather than $pp$) due to a sum rule satisfied by the dipole cross section even though the magnitude and location of Cronin peak is energy dependent. When divided by the $pp$ cross section as done experimentally, our ratio will have suppression at high $p_t$ in agreement with the results of Ref. [28].

After this work was completed, we were made aware of similar work by Kharzeev, Kovchegov and Tuchin [29]. Although there is some overlap in our discussion of the $pA$ case (their focus here being on gluon production), they do not explicitly consider the Cronin effect for $AA$ collisions as we have.

Acknowledgments

J.-J.-M. and Y.N. would like to thank the Institute for Nuclear Theory at the University of Washington for hospitality and the Department of Energy for partial support while this work was being completed. J.-J.-M. & R.V. are supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 and J.-J.-M. is supported in part by a Program Development Fund Grant from Brookhaven Science Associates. R.V. thanks the RIKEN-BNL Research Center at BNL for continued support. R.V. and Y.N. thank Alex Krasnitz for discussions. Y.N.’s research is supported by the DOE under Contract No. DE-FG03-93ER40792.

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[30] In the first paper of [8], a careless wording of the paragraph after eq. 24 gives the impression that there is no Cronin enhancement. This is not the case and the qA scattering cross section, first derived there, does have the Cronin enhancement.