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Two-particle correlations in DIS and proton–nucleus collisions

J. Jalilian-Marian[a]

Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA

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Abstract. We give a brief introduction to small x QCD and the color glass condensate formalism. We discuss the signatures of the color glass condensate in structure functions, single particle and two particle production in DIS and proton–nucleus collisions.

1 Introduction

The high gluon density regime of QCD has been one of the most actively investigated fields of high energy and nuclear physics lately due to both new theoretical developments in small x physics and new experiments, such as RHIC, which can probe this dense regime. It is known in perturbative QCD that the gluon distribution function in a hadron grows very fast with $1/x$. This growth is confirmed experimentally at HERA. It is however believed that this fast growth cannot go on forever since it would violate unitarity of physical cross sections. The unitarization of cross sections (at fixed impact parameter) and taming of the growth of the gluon distribution function is expected to happen due to high gluon density effects which make it as likely for two small x gluons to recombine into a larger x gluon as it is for a large x gluon to emit a smaller x one. This recombination picture was first proposed by Gribov, Levin and Ryskin (GLR) [1] and was subsequently investigated formally by Mueller and Qiu who derived a non-linear evolution equation for gluons in pQCD [2].

There has been much progress made in our theoretical understanding of small x physics since the pioneering work of [1,2]. A significant step was taken by McLerran and Venugopalan [3] who recognized that at small x, one has a new scale, called the saturation scale Q_s, which can be much larger than $\Lambda_{\rm QCD}$ so that one can apply weak coupling methods to investigate the physics of small x QCD. An effective action for small x QCD was proposed in [3] and used to compute the DIS structure functions for large nuclei. A similar computation of the structure function at small x was carried out by Kovchegov [4] using the color dipole model developed by Mueller. A calculation of the gluon two point function using the MV effective action showed that indeed recombination of gluons lead to a softening of the infrared singularities present in pQCD [5]. Furthermore, it was shown that most gluons in the wave function of a hadron or nucleus reside in a coherent state characterized by the saturation scale. The resultant high gluon density state at small x in a hadron or nucleus is referred to as the color glass condensate.

In [6] the MV effective action was generalized and used in [7] to derive a non-linear equation, known as the JIMWLK equation, for small x observables, while the dipole model was used in [8] to derive a non-linear equation for the dipole cross section, known as the BK equation, which was shown to be the large N_c limit of the JIMWLK equations. These equations have been investigated by various authors recently, and approximate analytical solutions to the BK equation have been found. Numerical methods have also been used to study the JIMWLK and BK equations in [9]. Below, we discuss applications of color glass condensate and gluon saturation to structure functions and particle production in deep inelastic scattering (DIS), high energy heavy ion (AA) and proton– (deuteron)–nucleus (pA) collisions.

2 CGC in DIS

In deep inelastic scattering of electrons (positrons) on hadronic (nuclear) targets, one can probe the fundamental constituents of hadrons, the quarks and gluons. As long as the momentum transfer Q is much smaller than the Z mass, one can approximate the interaction via virtual photon exchange. In the rest frame of the target and at small x, the virtual photon fluctuates into a quark–antiquark pair which then propagates through the hadron (nucleus) undergoing multiple scatterings. During this propagation the transverse size of the virtual photon remains unchanged. The total cross section for virtual photon target scattering is usually written in terms of the structure functions F_1 and F_2 given by [3,4]

$$2xF_1 = \frac{N_c\,\sigma\,Q^2}{4\pi^3}\int_0^1 \mathrm{d}z \cdot \int \mathrm{d}r_t^2\,\gamma(x,r_t)\{a^2\,[z^2+(1-z)^2]\,K_1^2(ar_t)\},$$

[a] e-mail: jamal@phys.washington.edu

$$F_2 = \frac{N_c \sigma Q^2}{4\pi^3} \int_0^1 \mathrm{d}z \cdot \int \mathrm{d}r_t^2\, \gamma(x, r_t) \Big\{ 4z^2(1-z)^2 Q^2 K_0^2(ar_t) + a^2 \left[z^2 + (1-z)^2\right] K_1^2(ar_t) \Big\}, \quad (1)$$

with $a^2 \equiv z(1-z)Q^2$, and K_0 and K_1 are the modified Bessel functions. The energy (or x) dependence of the process can be included in (1) by using the solution of the JIMWLK (or BK) equations for the dipole cross section denoted by $\gamma(x, r_t)$. This expression has been used to compare the predictions of CGC with the HERA data on proton structure function F_2 in [10], where it was shown that CGC fits the data quite well for a wide range of Q^2 as long as $x \leq 0.01$. Other studies of the proton structure function at HERA show similar conclusions.

The same expression as in (1) can be applied to scattering of a virtual photon off a nuclear target. In this case, one would need to solve the JIMWLK equation with a boundary condition appropriate to a nuclear target. This has been done for example in [11], where a reasonable agreement with the data on nuclear structure functions is seen. One should however keep in mind that the data on nuclear targets are mostly at not so small x for Q^2 which are not too small. We should also mention the application of CGC to diffractive structure functions, for example, in [12].

One can also apply CGC to particle production in DIS off hadronic and nuclear targets. In [13] the cross section for single gluon production was derived, including the non-linear evolution in the target wavefunction. It was shown that the cross section could be written in a form which looks like the usual one based on k_t factorization with the appropriate definition of the intrinsic gluon distribution function of the target. The expressions derived here can be used, with the use of a gluon/hadron fragmentation function, to make numerical predictions for hadron production in forward rapidity region of HERA.

In [14], the two particle production cross section in DIS was derived, including the non-linear evolution in the target. This would enable one to investigate azimuthal correlations between the produced particles. Studying azimuthal correlations is perhaps the best way to map out the different "phases" predicted by the color glass condensate. Unlike the collinear factorization based pQCD processes which are $2 \to 2$ processes, the leading order processes in CGC are $2 \to 1$ processes so that one does not expect azimuthal correlations. This picture changes due to higher order (in α_s) corrections, where a second parton may be produced. Therefore, in general, one expects smaller azimuthal correlations in CGC as compared to pQCD. To probe this, one can measure two hadrons (or one hadron and one photon), keep the transverse momentum and rapidity of one of the produced hadrons fixed while changing the transverse momentum or rapidity of the second hadron. As the rapidity of the second hadron is changed (at fixed transverse momentum) to higher values, one will move from the DGLAP regime (leading twist with no anomalous dimension) to the BFKL regime (leading twist with anomalous dimensions) to the saturation (all twist) regimes of QCD.

3 CGC in high energy heavy ion collisions

To apply CGC to high energy heavy ion collisions, one needs to solve the classical equations of motion in the presence of two nuclei in the forward light cone region, subject to the boundary condition on the light cone given by single nucleus solutions which are known. This is highly non-trivial and, up to now, has not been done rigorously, even though approximate analytical solutions can be derived [15]. The solution in the forward light cone then could be used to construct expressions for the particle production in high energy heavy ion collisions. To include quantum (small x) evolution is even more difficult and there has not been any serious effort to compute them. Even though the exact solutions to the classical equations of motion in the presence of two nuclei are not known, one can use the known properties of CGC in various regimes to build models which include the essential properties of gluon saturation. This approach was advocated in [16].

The earliest experimental evidence that the color glass condensate was indeed the correct theory of high energy QCD came from measurements of particle multiplicities in high energy heavy ion collisions at RHIC. The predicted rapidity, centrality and energy dependence of charged hadron multiplicities were in agreement with the RHIC data. In contrast to pQCD, where particle multiplicities cannot be reliably computed due to infrared divergences (which require a infrared cutoff and thus introduce a power dependence on the cutoff), the high gluon density effects and the saturation scale introduce a infrared cutoff which makes reliable computation of particle multiplicities possible. The introduction of the saturation scale also explains the slow rise of the multiplicities with center of mass energy and their centrality dependence. In the very forward region, the color glass condensate naturally explains the observed phenomenon of limiting fragmentation. This can be understood as the unitarization of the cross section for scattering of projectile partons on a very dense target described as a color glass condensate [17].

To calculate particle production in high energy heavy ion collisions using the color glass condensate formalism rigorously is very difficult. A promising approach is to solve the classical equations of motion on a lattice [18] and construct numerical solutions for the produced gluon field, which can then be used (along with some hadron fragmentation functions) to predict spectra of produced particles. The constructed gluon field in the forward light cone can also be used to compute quark pair production. Nevertheless, the issue of inclusion of quantum effects remains an open problem. This is crucial, for example, at LHC kinematics, where one expects small x evolution to be crucial even at mid rapidity unlike RHIC, where evolution effects seem to be crucial only in the forward rapidity region.

4 CGC in high energy proton–(deuteron)–nucleus collisions

Proton– (deuteron)–nucleus collisions (pA) at high energy are a simpler system than a high energy heavy ion collision to understand theoretically. Nevertheless, they are also very important for two reasons. First, they provide a benchmark against which one can compare heavy ion collisions in order to determine whether the observed phenomena are final state (quark gluon plasma) or initial state (CGC) effects. A second and more interesting reason is that pA collisions do not lead to the creation of a quark gluon plasma so therefore one can study the initial state (CGC) effects without having to worry about final state effects. Furthermore, pA collisions studied in the forward region provide a unique opportunity in a hadron/heavy ion collider environment to study gluon saturation in a relatively clean environment.

The earliest studies of particle production in pA collisions in the context of the color glass condensate formalism were done in [19], where gluon production in mid rapidity was considered. A similar study of gluon production was performed using the solutions of the classical equations of motion in [20] and was re-derived later in [21]. In all these studies, the projectile is assumed to be a dilute collection of gluons while the target is a dense system of gluons. These results have been used to predict particle production spectra at RHIC and give generally good agreement with the data. As one goes to the forward rapidity region (proton fragmentation region), one probes the large x region in the projectile proton and the small x region in the target nucleus. In this kinematics, the dominant contribution to the particle production cross section comes from scattering of valence quarks of the projectile on the dense system of gluons in the target. Therefore, it is more appropriate to treat the projectile proton as a dilute system of quarks and gluons using the standard collinear factorization (rather than the k_{t} factorization) while describing the target nucleus as a color glass condensate. This approach was advocated in [22], where the cross section for scattering of a quark or gluon on a color glass condensate was derived and later applied successfully to the forward rapidity data at RHIC [23].

One can go one step further and study two particle production in pA collisions. Again, one can use the azimuthal correlations to probe the different "phases" of the color glass condensate by varying the transverse momentum and/or rapidity of one of the produced hadrons while keeping the other one fixed. The two particle production cross section was derived in [14]. The resulting expressions are quite complicated and require knowledge of higher point functions of Wilson lines, while in the single particle production case knowledge of the two point function is sufficient. This requires solving the JIMWLK equations for the higher point functions in order to make detailed predictions for two particle azimuthal correlations. Alternatively, one can make a phenomenological model which captures the essentials of saturation physics to make numerical predictions which can then be compared to experimental results. This was done in [24].

Another way to test the predictions of the color glass condensate formalism is to measure non-strongly interacting particles, such as dileptons and photons. These processes have the advantage that they do not suffer from multiple re-scatterings after they are produced and are therefore a cleaner signal. Furthermore, one does not have to worry about non-perturbative effects such as hadronization. However, they suffer from low rates and, in the case of photons, may require some isolation cuts which makes the experimental measurements non-trivial. Nevertheless, these will eventually be measured at RHIC and LHC and will serve as further probes of the color glass condensate predictions.

In [25], the cross sections for the production of photons and dileptons were derived and used in [27] to make detailed numerical predictions for RHIC and LHC. Furthermore, the relation between DIS and virtual photon production in pA was investigated in [26], where it was shown that one can relate the two processes using the crossing symmetry present in QCD amplitudes. Another reason why measuring photons and dileptons is important is that there are new models based on recombination of partons [28] which, albeit with a few parameters, can fit the forward rapidity hadron production data at RHIC. Since hadron recombination is irrelevant for electromagnetic observables, measuring photons and dileptons can verify/rule out these models.

5 Summary

The color glass condensate is a firm prediction of high energy QCD. It has very distinct predictions for particle production in high energy heavy ion, proton–nucleus and DIS processes. The HERA results on structure functions of a proton lend support to existence of CGC at small x even though the evidence is not conclusive. The high energy heavy ion collisions at RHIC also seem to indicate the presence of CGC in nuclei, while the observed suppression of the forward rapidity hadron spectra at RHIC strongly supports the CGC view.

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References

1. L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys. Rept. **100**, 1 (1983)
2. A.H. Mueller, J. w. Qiu, Nucl. Phys. B **268**, 427 (1986)
3. L. McLerran, R. Venugopalan, Phys. Rev. D **49**, 2233 (1994); D **49**, 3352 (1994); D **59**, 094002 (1999)
4. Y.V. Kovchegov, Phys. Rev. D **60**, 034008 (1999)
5. J. Jalilian-Marian, A. Kovner, L.D. McLerran, H. Weigert, Phys. Rev. D **55**, 5414 (1997)
6. J. Jalilian-Marian, A. Kovner, A. Leonidov, H. Weigert, Nucl. Phys. B **504**, 415 (1997)

7. J. Jalilian-Marian, A. Kovner, A. Leonidov, H. Weigert, Phys. Rev. D **59**, 014014 (1999); D **59**, 034007 (1999) [Erratum D **59**, 099903 (1999)]; J. Jalilian-Marian, A. Kovner, H. Weigert, Phys. Rev. D **59**, 014015 (1999); A. Kovner, J.G. Milhano, Phys. Rev. D **61**, 014012 (2000); H. Weigert, Nucl. Phys. A **703**, 823 (2002); E. Iancu, A. Leonidov, L.D. McLerran, Nucl. Phys. A **692**, 583 (2001); E. Ferreiro, E. Iancu, A. Leonidov, L. McLerran, Nucl. Phys. A **703**, 489 (2002); I. Balitsky, Nucl. Phys. B **463**, 99 (1996)
8. Y.V. Kovchegov, Phys. Rev. D **61**, 074018 (2000)
9. K. Rummukainen, H. Weigert, Nucl. Phys. A **739**, 183 (2004)
10. E. Iancu, K. Itakura, S. Munier, Phys. Lett. B **590**, 199 (2004); E. Gotsman, E. Levin, M. Lublinsky, U. Maor, Eur. Phys. J. C **27**, 411 (2003)
11. A. Freund, K. Rummukainen, H. Weigert, A. Schafer, Phys. Rev. Lett. **90**, 222002 (2003); N. Armesto, C.A. Salgado, U.A. Wiedemann, hep-ph/0407018
12. Y.V. Kovchegov, E. Levin, Nucl. Phys. B **577**, 221 (2000)
13. Y.V. Kovchegov, K. Tuchin, Phys. Rev. D **65**, 074026 (2002)
14. J. Jalilian-Marian, Y.V. Kovchegov, hep-ph/0405266
15. A. Kovner, L.D. McLerran, H. Weigert, Phys. Rev. D **52**, 6231 (1995); D **52**, 3809 (1995); Y.V. Kovchegov, Nucl. Phys. A **692**, 557 (2001)
16. D. Kharzeev, M. Nardi, Phys. Lett. B **507**, 121 (2001)
17. J. Jalilian-Marian, Phys. Rev. C **70**, 027902 (2004)
18. A. Krasnitz, Y. Nara, R. Venugopalan, Nucl. Phys. A **727**, 427 (2003); J. Jalilian-Marian, Y. Nara, R. Venugopalan, Phys. Lett. B **577**, 54 (2003)
19. Y.V. Kovchegov, A.H. Mueller, Nucl. Phys. B **529**, 451 (1998)
20. A. Dumitru, L.D. McLerran, Nucl. Phys. A **700**, 492 (2002)
21. J.P. Blaizot, F. Gelis, R. Venugopalan, Nucl. Phys. A **743**, 13 (2004)
22. A. Dumitru, J. Jalilian-Marian, Phys. Lett. B **547**, 15 (2002), Phys. Rev. Lett. **89**, 022301 (2002)
23. J. Jalilian-Marian, nucl-th/0402080
24. D. Kharzeev, E. Levin, L. McLerran, hep-ph/0403271
25. F. Gelis, J. Jalilian-Marian, Phys. Rev. D **66**, 014021 (2002); D **66**, 094014 (2002)
26. F. Gelis, J. Jalilian-Marian, Phys. Rev. D **67**, 074019 (2003)
27. J. Jalilian-Marian, Nucl. Phys. A **739**, 319 (2004); R. Baier, A.H. Mueller, D. Schiff, Nucl. Phys. A **741**, 358 (2004)
28. R.C. Hwa, C.B. Yang, R.J. Fries, nucl-th/0410111