Vol. 13 (2020) *Acta Physica Polonica B Proceedings Supplement* No 4

RECENT ADVANCES IN THE COLOR GLASS CONDENSATE*

Tolga Altinoluk

National Centre for Nuclear Research, 02-093 Warsaw, Poland

(Received May 13, 2020)

High-energy hadronic collisions have been one of the most appealing but also challenging problems in physics for many years. With the advancements in high-energy colliders over the last three decades, hadronic collisions are at the focus of both experimental and theoretical studies. The Color Glass Condensate (CGC) is the effective theory to study high-energy hadronic interactions such as proton–nucleus (pA) and proton–proton (pp) collisions. I will discuss the latest developments in the theoretical CGC framework and show that one can describe certain high-energy experimental data by employing these new techniques.

DOI:10.5506/APhysPolBSupp.13.695

1. Introduction

High-energy hadronic collisions, particularly between heavy nuclei, have been one of the most appealing but also challenging problems in physics for many years. They have been at the focus of the theoretical effort before the proposal of the Quantum Chromodynamics (QCD) as the quantum field theory to describe the strong interactions. On the other hand, the experimental studies to investigate QCD under extreme conditions via heavy-ion collisions have been going on for decades.

The energy (or equivalently rapidity) evolution of a hadronic wavefunction within the QCD framework has been considered in two different regimes: the Bjorken and the Regge–Gribov limits. Even though they both describe scattering at high energy, they probe completely different physics. In the Bjorken limit, the increase in energy is accompanied with an increase in virtuality and thus results in a more dilute partonic system. On the other hand, in the Regge–Gribov limit, the increase in energy is due to the decrease of the longitudinal momentum fraction carried by the interacting partons. This low-x evolution results in a rapid increase in the number of gluons in the colliding objects and it is governed by the linear BFKL equation.

---

* Invited talk presented at the 45$^{\text{th}}$ Congress of Polish Physicists, Kraków, September 13–18, 2019.

The BFKL equation was a milestone in the study of high-energy scattering and has given tremendous insight to both theoretical and experimental works. However, it was realised that this linear equation does not tame the rapid growth of the gluon densities and is only valid until gluon densities reach sufficiently high values where the nonlinear effects become important. These nonlinear effects slow down the growth of the gluon density, eventually causing the phenomenon known as *gluon saturation*. This phenomenon is characterised by a new perturbative scale $Q_{\rm s}$, known as the saturation momentum. Nowadays, the weak coupling but nonperturbative realization of saturation within QCD is called the Color Glass Condensate (CGC).

It was noted by McLerran and Venugopalan that a convenient approach to gluon saturation can be given by the nonlinearities of the classical Yang–Mills field theory [1]. With this new development, the nonlinear generalization of the BFKL equation, known as the Balitsky–Kovchegov/ Jalilian-Marian–Iancu–McLerran–Wiegert–Leonidov–Kovner (BK-JIMWLK) functional evolution equation was derived (for a review, see [2] and references therein).

In recent years, these developments have become the basis for phenomenological studies of saturation physics applied to high-energy collision data. This approach is valid as long as one of the colliding objects is dilute. Typical examples for dilute-dense scatterings are Deep Inelastic Scattering (DIS) on a nuclear target, DIS on a high-energy proton, *proton–nucleus (pA) collisions* and forward particle production in proton–proton collisions.

2. Forward particle production in pA collisions

2.1. Forward hadron production at NLO

With all the developments for over a decade, saturation physics (or equivalently CGC) has shown a great success in phenomenological studies of the high-energy collision data. One observable used frequently to test the compatibility of saturation physics with the pA data is particle production at forward rapidities. The state-of-the-art calculation of this observable is based on the "hybrid formalism" [3].

In this approach, the wave function of the dilute projectile is calculated perturbatively, without any kinematic approximation, in the spirit of the collinear factorization, while the scattering of the projectile partons on the target fields is treated in the eikonal approximation within the CGC framework. In recent years, there has been a lot of activity to calculate the single inclusive particle production at next to leading order (NLO) [4, 5], which has been extremely useful for the compatibility test of saturation physics with the high-energy collision data.

2.2. Forward jet production and gluon TMDs

Apart from the single inclusive particle production, hybrid formalism is also used to study forward dijet production in pA collisions. This process is particularly interesting since it can be studied both in the standard TMD factorization framework (by constructing hadronic matrix elements of bilocal products of field operators that contain gauge-links) and in the CGC framework. The results obtained from two different methods should coincide when one applies the appropriate limits on both sides. Recently, it has been shown that the high energy limit of the dijet production cross section calculated in the TMD factorization approach coincides with the correlation limit (when the two jets are produced back-to-back) of the cross section calculated in the CGC framework [6], and beyond the correlation limit by resumming the kinematic and genuine twists [7]. This result suggests an equivalence of the two frameworks at the appropriate limits at leading order and shows that one can get the whole set of different TMDs for this particular processes through CGC calculations. Recently, forward production of three final-state particles (dijet + photon in [8] and photoproduction three jets in [9]) have been studied. The result shows a similar behaviour as in the case of dijet production, namely in the correlation limit of the three final-state particles, one gets access to different sets of TMDs.

3. Two particle correlations in the CGC

Among most intriguing observables described in the saturation framework are the correlations between produced particles. These correlations have been observed by all experimental groups at the LHC for high multiplicity pp and pPb data. Earlier observations of these correlations at RHIC for HICs have an accepted explanation: the origin of these correlations is the collective flow in the final state due to strong final-state interactions that are described very well in the framework of relativistic viscous hydrodynamics. However, such an explanation in pp collisions looks tenuous since in a small size system like proton–proton, one does not naturally expect collectivity. These observations triggered the efforts to understand the correlations from the initial-state point of view. Several mechanisms have been suggested to explain these correlations in the CGC framework. One of the most successful ones is the "glasma graph" approach. The physics behind the glasma graphs has been understood in terms of the Bose enhancement of the gluons in the initial state [10]. The correlations between quarks have also been studied and it was shown that quarks in the initial state experience Pauli blocking due to their fermionic nature [11]. The extension of glasma graph approach has been recently studied by taking into account multiple scattering effects for double and triple inclusive particle production [12]. Although numerical studies showed that "glasma graph" calculations successfully describe the main aspects of the ridge data, it has been demonstrated that the accuracy of these calculations is insufficient to reproduce some qualitatively important features. In particular, these calculations cannot produce non-vanishing triangular flow harmonic v_3. Extensions of the glasma graph approach have been explored recently. In particular, it was found that taking into account saturation corrections to the initial CGC state allows for non-vanishing triangular flow v_3 [13].

4. Subeikonal corrections in the CGC

Another important direction beyond the current CGC-based calculations is to explore the effects of relaxing the standard "kinematic" approximations. One of the most frequently used approximations used in the CGC framework is the eikonal one. In this framework, the dense target is represented by a strong classical background field. In the high-energy limit, the dense target is highly boosted and the classical background field representing it is considered to be localized, due to Lorentz contraction, at some longitudinal position. This treatment amounts to the eikonal approximation. More realistically, one should consider a dense target with finite longitudinal extent. This step has been taken in [14] where a systematic method was developed to include corrections to the eikonal approximation that are associated with the finite width of the target. Its applications to single inclusive gluon production and to various spin asymmetries have been performed. This study has been further developed and the corrections to the Lipatov vertex due to the finite target thickness have been calculated [15]. The $k_{\rm t}$-factorization formula for single and double inclusive gluon production is now known at next-to-next-to-eikonal accuracy. Finally, in [16], it has been shown that subeikonal corrections also break the accidental symmetry of the CGC and produces non-zero odd harmonics. Subeikonal studies of the evolution equations have been also performed. Rapidity evolution of gluon TMDs from low to moderate values of Bjorken-x has been studied in [17], helicity evolution of quark and gluon distributions at small Bjorken-x have been studied in [18] and the rapidity evolution for flavour singlet and non-singlet polarized structure functions have been studied in [19].

The work of T.A. is supported by grant No. 2018/31/D/ST2/00666 (SONATA 14 — the National Science Centre, Poland (NCN)) and MSCA RISE 823947 "Heavy ion collisions: collectivity and precision in saturation physics" (HIEIC).

REFERENCES

[1] L.D. McLerran, R. Venugopalan, *Phys. Rev. D* **49**, 3352 (1994); *ibid.* **49**, 2233 (1994).

[2] F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, *Annu. Rev. Nucl. Part. Sci.* **60**, 463 (2010).

[3] A. Dumitru, A. Hayashigaki, J. Jalilian-Marian, *Nucl. Phys. A* **765**, 464 (2006).

[4] T. Altinoluk, A. Kovner, *Phys. Rev. D* **83**, 105004 (2011); T. Altinoluk *et al.*, *Phys. Rev. D* **91**, 094016 (2015); **93**, 054049 (2016).

[5] G.A. Chirilli, B.W. Xiao, F. Yuan, *Phys. Rev. Lett.* **108**, 122301 (2012); *Phys. Rev. D* **86**, 054005 (2012); E. Iancu, A.H. Mueller, D.N. Triantafyllopoulos, *J. High Energy Phys.* **1612**, 041 (2016); B. Ducloué, T. Lappi, Y. Zhu, *Phys. Rev. D* **95**, 114007 (2017).

[6] A. van Hameren *et al.*, *Phys. Rev. D* **89**, 094014 (2014); P. Kotko *et al.*, *J. High Energy Phys.* **1509**, 106 (2015); C. Marquet, E. Petreska, C. Roiesnel, *J. High Energy Phys.* **1610**, 065 (2016).

[7] T. Altinoluk, R. Boussarie, P. Kotko, *J. High Energy Phys.* **1905**, 156 (2019); T. Altinoluk, R. Boussarie, *J. High Energy Phys.* **1910**, 208 (2019).

[8] T. Altinoluk *et al.*, *J. High Energy Phys.* **1804**, 063 (2018); T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, *J. High Energy Phys.* **1907**, 079 (2019).

[9] T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, `arXiv:2001.00765 [hep-ph]`.

[10] T. Altinoluk *et al.*, *Phys. Lett. B* **751**, 448 (2015); *ibid.* **752**, 113 (2016).

[11] T. Altinoluk *et al.*, *Phys. Rev. D* **95**, 034025 (2017).

[12] T. Altinoluk, N. Armesto, D.E. Wertepny, *J. High Energy Phys.* **1805**, 207 (2018); T. Altinoluk, N. Armesto, A. Kovner, M. Lublinsky, *Eur. Phys. J. C* **78**, 702 (2018).

[13] A. Kovner, M. Lublinsky, V. Skokov, *Phys. Rev. D* **96**, 016010 (2017); Y.V. Kovchegov, V.V. Skokov, *Phys. Rev. D* **97**, 094021 (2018).

[14] T. Altinoluk *et al.*, *J. High Energy Phys.* **1407**, 068 (2014); T. Altinoluk, N. Armesto, G. Beuf, A. Moscoso, *J. High Energy Phys.* **1601**, 114 (2016).

[15] T. Altinoluk, A. Dumitru, *Phys. Rev. D* **94**, 074032 (2016).

[16] P. Agostini, T. Altinoluk, N. Armesto, *Eur. Phys. J. C* **79**, 600 (2019); *ibid.* **79**, 790 (2019).

[17] I. Balitsky, A. Tarasov, *J. High Energy Phys.* **1510**, 017 (2015); *ibid.* **1606**, 164 (2016); *ibid.* **1805**, 150 (2018).

[18] Y.V. Kovchegov, D. Pitonyak, M.D. Sievert, *J. High Energy Phys.* **1601**, 072 (2016); *Phys. Rev. D* **95**, 014033 (2017); *Phys. Rev. Lett.* **118**, 052001 (2017); *Phys. Lett. B* **772**, 136 (2017); *J. High Energy Phys.* **1710**, 198 (2017).

[19] G.A. Chirilli, *J. High Energy Phys.* **1901**, 118 (2019).