PROCEEDINGS OF SCIENCE

Multi gluon correlations in the Color Glass Condensate: quantum interference in proton-nucleus collisions

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We compute multi gluon production at mid rapidity in proton-nucleus collisions within the Color Glass Condensate framework. We show that, in the dilute-dense limit valid for such collisions, the terms responsible for the multi gluon correlation have two origins. On the one hand, the Hanbury-Brown-Twiss interference in the final state. On the other hand, the Bose enhancement of gluons in the projectile and target wave functions, with the latter being suppressed by the number of colors with respect to the former. We also demonstrate that such correlations come from the highest order relevant correlator of Wilson lines in the target wave function, i.e., the quadrupole and sextupole for two and three gluon correlations respectively. We develop a general method for the computation of such high order correlators that captures the bulk of their contribution to the multi gluon production cross section but does not employ the approximation of a large number of colours.

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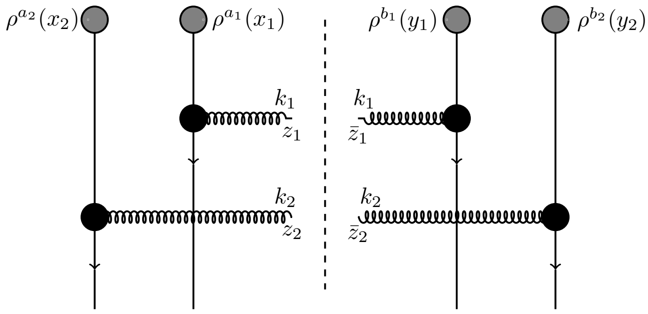

Figure 1: Graphical illustration of Eq. (2.1) with the vertical lines representing the rescatterings with the target through Wilson lines.

1. Introduction

The measurement of two particle correlations extended in pseudorapidity and peaked when the particles are parallel or antiparallel in azimuth - the ridge - in pp and pPb collisions at the LHC and dAu at RHIC, together with the finding of the striking similarities with nucleus-nucleus in this and many other observables usually considered as signatures of the existence of deconfined quark-gluon matter, has triggered a large theoretical and experimental activity on the subject, see [1]. While the standard explanation of such azimuthal correlations in nucleus-nucleus collisions are final state interactions leading to the applicability of relativistic hydrodynamics, it seems less justified in smaller systems and initial state approaches have also been essayed. Among them, those based on the Color Glass Condensate CGC seem to be the most promising for a first principle explanation of such phenomenon. CGC explanations have been successful [2] in describing the ridge in pp collisions under the 'Glasma graphs' approximation [3] valid for collisions between dilute systems.

We have shown in previous works [4] that the correlations in the Glasma graph approach have two origins: Bose enhancement (BE) of the gluons in the projectile and target wave function (WF), and Hanbury-Brown-Twiss (HBT) correlations of the final state gluons. In this contribution we summarise the findings in [5] where an extension of the CGC approach to dilute-dense collisions (see also [6]) has been obtained and applied to two and three gluon correlations. We focus here only in deriving the correlations giving rise to even harmonics, for the problem of odd harmonics and the comparison to experimental data see [1].

2. Two gluon correlations

In the CGC, the two gluon inclusive cross section (graphically shown in Fig. 1) is given by

$$\frac{d\sigma}{d^2k_1 d\eta_1 d^2k_2 d\eta_2} = \alpha_s^2 (4\pi)^2 \int_{z_1\bar{z}_1 z_2\bar{z}_2} e^{ik_1\cdot(z_1-\bar{z}_1)+ik_2\cdot(z_2-\bar{z}_2)} \tag{2.1}$$
$$\times \int_{x_1x_2y_1y_2} A^i(x_1-z_1)A^i(\bar{z}_1-y_1)A^j(x_2-z_2)A^j(\bar{z}_2-y_2)\left\langle \rho^{a_1}(x_1)\rho^{a_2}(x_2)\rho^{b_1}(y_1)\rho^{b_2}(y_2)\right\rangle_P$$
$$\times \left\langle \left[U(z_1)-U(x_1)\right]^{a_1c}\left[U^\dagger(\bar{z}_1)-U^\dagger(y_1)\right]^{cb_1}\left[U(z_2)-U(x_2)\right]^{a_2d}\left[U^\dagger(\bar{z}_2)-U^\dagger(y_2)\right]^{db_2}\right\rangle_T,$$

with $\int_z \equiv \int d^2z$, $U(x)$ the adjoint Wilson line at transverse position x and

$$A^i(x-y) = -\frac{1}{2\pi}\frac{(x-y)_i}{(x-y)^2} = \int \frac{d^2k}{(2\pi)^2} e^{-ik\cdot(x-y)} \frac{k^i}{k^2}\,. \tag{2.2}$$

$\langle\cdots\rangle_{P,T}$ denote the averages on the projectile and target wave function of the projectile sources and Wilson lines describing the rescattering with the target, respectively.

For the dilute projectile average, we consider pairwise contractions

$$\begin{aligned} \left\langle \rho^{a_1}(x_1)\rho^{a_2}(x_2)\rho^{b_1}(y_1)\rho^{b_2}(y_2)\right\rangle_P &= \left\langle \rho^{a_1}(x_1)\rho^{a_2}(x_2)\right\rangle_P \left\langle \rho^{b_1}(y_1)\rho^{b_2}(y_2)\right\rangle_P \\ + \left\langle \rho^{a_1}(x_1)\rho^{b_1}(y_1)\right\rangle_P \left\langle \rho^{a_2}(x_2)\rho^{b_2}(y_2)\right\rangle_P &+ \left\langle \rho^{a_1}(x_1)\rho^{b_2}(y_2)\right\rangle_P \left\langle \rho^{a_2}(x_2)\rho^{b_1}(y_1)\right\rangle_P, \end{aligned} \tag{2.3}$$

using a generalisation of the McLerran-Venugopalan model [7]

$$\left\langle \rho^a(x)\rho^b(y)\right\rangle_P = \delta^{ab}\mu^2(x,y) \tag{2.4}$$

that results in dipole-dipole and quadrupole target averages, where $\mu^2(x,y)$ is a distribution that falls rapidly for $|x+y| > R_P$ with R_P the radius of the projectile describing the valence colour charges in the projectile. For performing the target averages, we note that the cross section (2.1) involves integration over all transverse coordinates, so the largest contribution comes from maximising the distances. In the Glasma graphs approximation, the Wilson lines are expanded to the lowest order in the target fields and then pairwise contractions are performed. We follow here a different strategy (see also [8, 9]), taking into account that the target ensemble must be colour neutral and that in the CGC colour neutralisation takes place at distances $1/Q_s$ with Q_s the saturation scale of the target, so the S-matrix becomes non zero for colour singlets of size $> 1/Q_s$. Therefore, the leading contribution (in powers of $R_P Q_s$) comes from the $2n$ points in $\langle\cdots\rangle_T$ combined into n singlets at distances as large as possible. We realise this idea defining

$$\left\langle U^{ab}(x)U^{cd}(y)\right\rangle_T = \delta^{ac}\delta^{bd}\frac{1}{(N_c^2-1)^2}\left\langle \mathrm{tr}\left[U(x)U^\dagger(y)\right]\right\rangle_T = \delta^{ac}\delta^{bd}\frac{1}{N_c^2-1}d(x,y), \tag{2.5}$$

where

$$d(x,y) \equiv \langle D(x,y)\rangle_T, \tag{2.6}$$

so

$$\langle Q(x,y,z,v)\rangle_T \longrightarrow d(x,y)d(z,v) + d(x,v)d(z,y) + \frac{1}{N_c^2-1}d(x,z)d(y,v), \tag{2.7}$$

$$\langle D(x,y)D(z,v)\rangle_T \longrightarrow d(x,y)d(z,v) + \frac{1}{(N_c^2-1)^2}\left[d(x,v)d(y,z) + d(x,z)d(v,y)\right]. \tag{2.8}$$

The final result for a translationally invariant target can be organised in powers of the number of colours N_c:

$$\frac{d\sigma}{d^2k_1 d\eta_1 d^2k_2 d\eta_2} = \alpha_s^2 (4\pi)^2 (N_c^2-1)^2 \int \frac{d^2q_1}{(2\pi)^2}\frac{d^2q_2}{(2\pi)^2} d(q_1)d(q_2)\left\{I_0 + \frac{1}{N_c^2-1}I_1 + \frac{1}{(N_c^2-1)^2}I_2\right\}, \tag{2.9}$$

with I_0 giving the uncorrelated emission of two gluons coming from the dipole-dipole terms, I_1 giving Bose enhancement of the projectile wave function and HBT coming from the quadrupole terms, and I_2 Bose enhancement in the target wave function coming from the dipole-dipole terms and N_c corrections to projectile Bose and HBT coming from the quadrupole terms.

3. Three gluon correlations

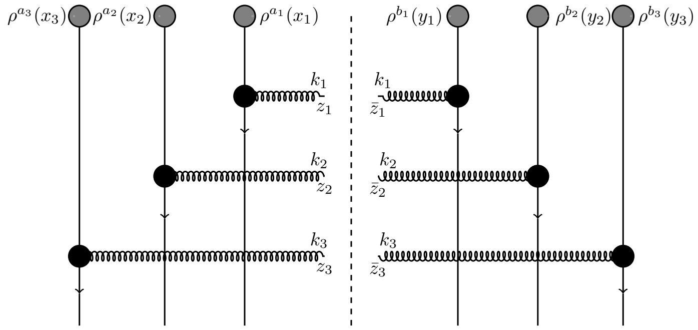

Figure 2: Graphical illustration of Eq. (3.1) with the vertical lines representing the rescatterings with the target through Wilson lines.

The three gluon inclusive cross section (graphically shown in Fig. 2) is given by

$$\frac{d\sigma}{d^2k_1 d\eta_1\, d^2k_2 d\eta_2\, d^2k_3 d\eta_3} = \alpha_s^3\,(4\pi)^3 \int_{z_1\bar{z}_1 z_2\bar{z}_2 z_3\bar{z}_3} e^{ik_1\cdot(z_1-\bar{z}_1)+ik_2\cdot(z_2-\bar{z}_2)+ik_3\cdot(z_3-\bar{z}_3)}$$
$$\times \int_{x_1y_1x_2y_2x_3y_3} A^i(x_1-z_1)A^i(\bar{z}_1-y_1)A^j(x_2-z_2)A^j(\bar{z}_2-y_2)A^k(x_3-z_3)A^k(\bar{z}_3-y_3) \tag{3.1}$$
$$\times \left\langle \rho^{a_1}(x_1)\rho^{a_2}(x_2)\rho^{a_3}(x_3)\rho^{b_1}(y_1)\rho^{b_2}(y_2)\rho^{b_3}(y_3)\right\rangle_P$$
$$\times \left\langle \left(U_{z_1}-U_{x_1}\right)^{a_1c_1}\left(U^\dagger_{\bar{z}_1}-U^\dagger_{y_1}\right)^{c_1b_1}\left(U_{z_2}-U_{x_2}\right)^{a_2c_2}\left(U^\dagger_{\bar{z}_2}-U^\dagger_{y_2}\right)^{c_2b_2}\left(U_{z_3}-U_{x_3}\right)^{a_3c_3}\left(U^\dagger_{\bar{z}_3}-U^\dagger_{y_3}\right)^{c_3b_3}\right\rangle_T .$$

Projectile averages done through pairwise contractions give rise to 15 terms which correspond to triple dipole (ddd), dipole-quadrupole (dQ) and sextupole (X) target averages. For these we follow the strategy explained in the previous Section which for the sextupole results in

$$\left\langle X(x_1,x_1',x_2,x_2',x_3,x_3')\right\rangle_T \longrightarrow d(x_1,x_1')d(x_2,x_2')d(x_3,x_3') + d(x_1,x_3')d(x_2,x_1')d(x_3,x_2')$$
$$+ d(x_1,x_1')d(x_2,x_3')d(x_3,x_2') + d(x_2,x_2')d(x_3,x_1')d(x_1,x_3') + d(x_3,x_3')d(x_1,x_2')d(x_2,x_1')$$
$$+\frac{1}{N_c^2-1}\Big\{ d(x_1,x_1')d(x_2,x_3)d(x_2',x_3') + d(x_2,x_2')d(x_3,x_1)d(x_3',x_1') + d(x_3,x_3')d(x_1,x_2)d(x_1',x_2')$$
$$+ d(x_2,x_3)d(x_1,x_3')d(x_1',x_2') + d(x_3,x_1)d(x_2,x_1')d(x_2',x_3') + d(x_1,x_2)d(x_3,x_2')d(x_3',x_1')\Big\}$$
$$+\frac{1}{(N_c^2-1)^2}\Big\{ d(x_1,x_2)d(x_3,x_1')d(x_2',x_3') + d(x_2,x_3)d(x_1,x_2')d(x_3',x_1') + d(x_3,x_1)d(x_2,x_3')d(x_1',x_2')$$
$$+d(x_1,x_2')d(x_3,x_1')d(x_2,x_3')\Big\}. \tag{3.2}$$

Again, the final result for a translationally invariant target can be organised in powers of N_c:

$$\frac{d\sigma}{d^2k_1 d\eta_1\, d^2k_2 d\eta_2\, d^2k_3 d\eta_3} = \alpha_s^3\,(4\pi)^3\,(N_c^2-1)^3 \int \frac{d^2q_1}{(2\pi)^2}\frac{d^2q_2}{(2\pi)^2}\frac{d^2q_3}{(2\pi)^2}\, d(q_1)d(q_2)d(q_3)$$
$$\times \Big\{ I_{\rm ddd,0} + \frac{1}{N_c^2-1}\left[I_{\rm dQ,1}+I_{\rm dQ,2}+I_{\rm dQ,3}\right] + \frac{1}{(N_c^2-1)^2}\Big(\left[I_{\rm ddd,1}+I_{\rm ddd,2}+I_{\rm ddd,3}\right] \tag{3.3}$$
$$+\left[I'_{\rm dQ,1}+I'_{\rm dQ,2}+I'_{\rm dQ,3}\right] + \left[I_{\rm X,1}+I_{\rm X,2}+I_{\rm X,3}+I_{\rm X,4}+I_{\rm X,5}\right]\Big) + \mathscr{O}\left[(N_c^2-1)^{-3}\right] + \mathscr{O}\left[(N_c^2-1)^{-4}\right]\Big\} .$$

This final result contains independent emission of 3 gluons ($I_{\mathrm{ddd},0}$), independent emission of one gluon and projectile BE and HBT of the other two ($I_{\mathrm{dQ,i}}$), independent emission of one gluon and target BE of the other two ($I_{\mathrm{ddd,i}}$), N_c-suppressed independent emission of one gluon and projectile BE of the other two ($I'_{\mathrm{dQ,i}}$), HBT of two gluons and projectile BE of other two ($I_{\mathrm{X},1,2,3}$), and projectile BE ($I_{\mathrm{X},4}$) and HBT ($I_{\mathrm{X},5}$) of the three gluons.

Summarising, by explicitly computing two and three gluon inclusive cross sections under the mentioned target averaging procedure, we find that the two main effects contributing to correlations, BE of the gluons in the projectile and target WFs, and HBT correlations of the final state gluons, survive density corrections in the target, that correlations between all particles come from the highest order Wilson line correlator, and that target BE correlations are suppressed by the number of colours with respect to projectile ones (at variance with what happens in the symmetric Glasma graphs approach where both are of the same order in N_c).

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