SIGNATURE OF ACCIDENTAL SYMMETRY BREAKING IN TWO-PARTICLE CORRELATIONS WITHIN THE CGC*

Anderson Kendi Kohara

AGH University of Science and Technology
Faculty of Physics and Applied Computer Science
Mickiewicza 30, 30-059 Kraków, Poland

Cyrille Marquet

CPHT, CNRS, École Polytechnique, IP Paris, 91128 Palaiseau, France

Víctor Vila

Institute of Nuclear Physics Polish Academy of Sciences
Radzikowskiego 152, 31-342, Kraków, Poland
and
Instituto Galego de Física de Altas Enerxías (IGFAE)
Universidade de Santiago de Compostela, Galicia, Spain

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This work is devoted to the computation of the double inclusive gluon production cross section in a proton–nucleus collision within the framework of the Color Glass Condensate (CGC). Given the nature of the scattering, it is fitting to consider the dense-dilute particle production via going beyond the glasma graph approximation given its correspondence to the dilute–dilute limit of the CGC approach. More specifically, starting with the most general expression for the scattering amplitude of the process, not only we do re-obtain the piece encompassing the independent production of the two gluons from separate colour charge densities in the projectile wave function, but also we shed light on the picture encapsulating a correlation rooted in the incoming wave function. This procedure enables us to calculate the anisotropic second and third flow coefficients for both configurations, thereby revealing for the first time the odd azimuthal anisotropy harmonics at leading order in the eikonal expansion associated with the quantum correction embodying the original correlation, that is to say, a breaking of the accidental symmetry in the two-particle scenario.

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1. Introduction

The observation of two-particle long-range rapidity correlations in the collision of small systems is considered one of the major findings of the CMS Collaboration [1], confirming trends already spotted in relativistic heavy-ion data from RHIC. In this respect, elucidating the source of these so-called *ridge*-like correlations on account of its contour on the azimuthal angle-rapidity chart has been on a quest when it comes to small systems: from grounds of causality matter pointing to the very early stages of the collision to compelling evidence for collective behaviour of the final-state gluons cloud, the glasma graph approximation, grounded on the dilute-dilute limit of the CGC frame, appears to be the most accurate approach reproducing the observed anisotropic distribution of particles and, by extension, the two-particle Fourier harmonics coefficients v_n.

In this line, the emergence of even Fourier harmonics relies on two intrinsic quantum effects pertained to a system of identical bosons such as gluons: the Bose enhancement of gluons in the wave function of the incoming hadrons and the Hanbury-Brown-Twiss (HBT) interference effect in the emission of gluons in the final state. For its part, the odd ones seem not to surface at leading order within the eikonal expansion, a question still unresolved although a variety of positions have been proposed in the last few years. Some studies suggest exchanging the commonly used MV model for a more elaborated profile of both the projectile and the target sides, as well as accounting for the quantum correction taking notice of the two gluons being correlated in the incoming wave function. This work heads in the direction of the latter point, aiming at providing evidence that it is not necessary to incorporate those effects originating from a relaxation on the shockwave approximation to make odd harmonics appear.

2. The double inclusive gluon production cross-section

The partial amplitude for the two-gluon production with transverse momenta k and p in a dense-dilute scattering reads [2]

$$
\begin{aligned}
A^{ab}_{ij}(k,p) = & \int\limits_{u,z} \mathrm{e}^{ik\cdot z+ip\cdot u} \\
\times & \Bigg\{ \int\limits_{x_1,x_2} \Big\{ f_i(z-x_1)\,[S_z-S_{x_1}]^{ac}\,\rho^c_{x_1} \Big\} \Big\{ f_j(u-x_2)\,[S_u-S_{x_2}]^{bd}\,\rho^d_{x_2} \Big\} \\
- & \frac{1}{2}\int\limits_{x_1} f_i(z-x_1)f_j(u-x_1) \Big\{ [S_z-S_{x_1}]\,\bar{\rho}_{x_1}\left[S^\dagger_u+S^\dagger_{x_1}\right] \Big\}^{ab}
\end{aligned}
$$

$$+\int_{x_1} f_i(z-u) f_j(u-x_1)\Big\{\left[S_z - S_u\right]\bar{\rho}_{x_1} S_u^\dagger\Big\}^{ab}\Bigg\}\,, \tag{1}$$

where $\rho^a(x)$ accounts for the operator of the color charge density, $S^{ab}(x)$ denotes the eikonal scattering matrix determined by the target color fields, and $f_i(x-y)$ corresponds to the perturbative Weizsäcker–Williams gluon field. The previous amplitude is of special concern since it establishes a correspondence with the diagrams depicted in Fig. 1 when having a look at each of the three pieces that make up the probability amplitude.

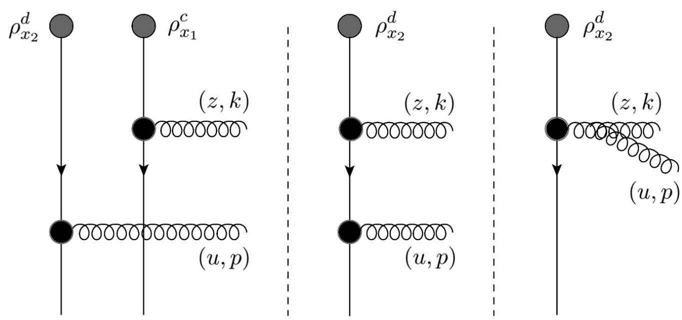

Fig. 1. The three diagrams playing a part in the double gluon production process. Rescatterings off the target color field come in the form of vertical lines.

The next step involves the squaring of the previous probability amplitude, which leads to three contributions in the cross section, namely

$$\frac{\mathrm{d}N}{\mathrm{d}^2p\,\mathrm{d}^2k\,\mathrm{d}\eta\,\mathrm{d}\xi} = \left\langle \sigma^4 + \sigma^3 + \sigma^2 \right\rangle_{\mathrm{P,T}}\,, \tag{2}$$

where[1]

$$\begin{aligned}\sigma^4 = &\int_{u,z,\bar{u},\bar{z}} \mathrm{e}^{ik\cdot(z-\bar{z})+ip\cdot(u-\bar{u})}\\ &\times \int_{x_1,x_2,\bar{x}_1,\bar{x}_2} f(\bar{z}-\bar{x}_1)\cdot f(z-x_1)\ f(\bar{u}-\bar{x}_2)\cdot f(u-x_2)\\ &\times\Big\{\rho_{x_1}\left[S_z^\dagger - S_{x_1}^\dagger\right]\left[S_{\bar{z}} - S_{\bar{x}_1}\right]\rho_{\bar{x}_1}\Big\}\Big\{\rho_{x_2}\left[S_u^\dagger - S_{x_2}^\dagger\right]\left[S_{\bar{u}} - S_{\bar{x}_2}\right]\rho_{\bar{x}_2}\Big\}\,, \end{aligned}\tag{3}$$

[1] Given the lengthy and cumbersome appearance of both σ^3 and σ^2, in this manuscript, we restrict ourselves to elaborate the way of proceeding until reaching the cross section by means of the expressions for σ^4, since aside from this reason, the development of the remaining terms is analogous.

according to the power in the density of the projectile. In this connection, an insightful interpretation passes through a rendering within the BFKL picture, as σ^4 matches with a piece of a diagram composed of two independent ladders, while σ^3 and σ^2 are in line with the double gluon emission within the same ladder.

Moving on with the averaging over the projectile wave function via using the McLerran–Venugopalan (MV) model[2] [3], then adopting the widely known *area enhancement model* for breaking the correlation functions of multiple Wilson lines on the target side — this way easing the computation of high-point correlators such as the quadrupole function under the large-N_c limit, that is to say,

$$\begin{aligned}
\tilde{Q}(\bar{u},u,z,\bar{z}) &\approx D^2(\bar{u},u)D^2(z,\bar{z}) + D^2(\bar{u},\bar{z})D^2(u,z)\,,\\
\tilde{D}(\bar{u},u) &= \left\langle \frac{1}{N^2-1}\mathrm{Tr}\left[S^\dagger(\bar{u})S(u)\right]\right\rangle_\mathrm{T},\\
\tilde{Q}(\bar{u},u,z,\bar{z}) &= \left\langle \frac{1}{N^2-1}\mathrm{Tr}\left[S^\dagger(\bar{u})S(u)S^\dagger(z)S(\bar{z})\right]\right\rangle_\mathrm{T},
\end{aligned}\tag{4}$$

where the Wilson lines are written in the adjoint representation; and finally, using the dipole model in its form suggested by Golec-Biernat–Wüsthoff (GBW)

$$D(r) = \int \frac{\mathrm{d}^2q}{\pi}\mathrm{e}^{-iq\cdot r}\frac{1}{Q_\mathrm{s}^2}\mathrm{e}^{-\frac{q^2}{Q_\mathrm{s}^2}}\,, \tag{5}$$

we find for the σ^4 and σ^2 pieces that generate a great deal of interest,

$$\begin{aligned}
\sigma^{4([i+iii].\mathrm{I})} \approx\ & \alpha_\mathrm{s}^2(4\pi)^2\left(N^2-1\right)\mu^4 S_\perp \frac{2\pi}{Q_\mathrm{s}^2}\mathrm{e}^{-\frac{(k+p)^2}{4Q_\mathrm{s}^2}}\\
&\times\left[\frac{2\left(k^4+p^4+2\,(k\cdot p)^2\right)}{k^2p^2\,(k-p)^4} + \frac{8Q_\mathrm{s}^2\,(k+p)^4}{k^2p^2\,(k-p)^6}\right.\\
&\left.+\frac{64Q_\mathrm{s}^4\left(k^4+4(k\cdot p)^2+p^4+8(k\cdot p)(k^2+p^2)+14k^2p^2\right)}{k^2p^2\,(k-p)^8}\right]\\
&+\{(p\to -p)\}\,,
\end{aligned}\tag{6}$$

[2] It is noticeable that as the MV model weight functional is gaussian, all odd point functions such as σ^3 vanish.

$$\begin{aligned}\sigma^{2[(iii)+(iv)]} &= \alpha_{\mathrm{s}}^2(4\pi)^2N^3\mu^2S_\perp\Bigg\{\frac{1}{(2\pi)^2Q_{\mathrm{s}}^4}\mathrm{e}^{-\frac{k^2+p^2}{2Q_{\mathrm{s}}^2}}\\ &\quad\times\int\limits_{s_1,s_2}\left[\left(\frac{s_1^i}{s_1^2}+\frac{k^i}{k^2}\right)^2\left(\frac{s_2^j}{s_2^2}+\frac{p^j}{p^2}\right)-\frac{1}{k^2}\frac{p^j}{p^2}\right]\frac{(s_1-s_2)^j}{(s_1-s_2)^2}\\ &\quad\times\mathrm{e}^{-\frac{s_1^2+2k\cdot s_1}{2Q_{\mathrm{s}}^2}}\mathrm{e}^{-\frac{s_2^2-2p\cdot s_2}{2Q_{\mathrm{s}}^2}}+\frac{1}{k^2}\frac{p\cdot(k+p)}{p^2(k+p)^2}\left(\mathrm{e}^{-\frac{(k+p)^2}{4Q_{\mathrm{s}}^2}}-1\right)\Bigg\}.\end{aligned}\tag{7}$$

These contributions to σ^4 and σ^2 are of significant interest since, on the one hand, $\sigma^{4([i+iii].\mathrm{I})}$ corresponds to one of the quadrupole components encapsulating the earlier introduced quantum interference effects and, more specifically, is equivalent to the Bose enhancement piece. $\sigma^{2[(iii)+(iv)]}$, on the other hand, represents the centerpiece that generates a great deal of interest for the purposes of this study since it contains the physics underlying the emergence of odd harmonics at leading order in two-particle correlations. In particular, this component arises from the interference between the second and third diagrams schematized in Fig. 1.

3. A numerical evaluation of the correlators

This final section is devoted to numerically evaluate the momentum-dependent second and third flow coefficients, namely v_2 and v_3, for the previously outlined piece of σ^2. To this end, we will use the following definition for the Fourier n-coefficients [4],

$$v_n^2(k,p)=\frac{\int \mathrm{d}\phi_k\,\mathrm{d}\phi_p\mathrm{e}^{\mathrm{i}n(\phi_k-\phi_p)}\frac{\mathrm{d}^2N^{(2)}}{\mathrm{d}^2k\,\mathrm{d}^2p}}{\int \mathrm{d}\phi_k\,\mathrm{d}\phi_p\frac{\mathrm{d}^2N^{(2)}}{\mathrm{d}^2\,k\mathrm{d}^2p}}\,,\tag{8}$$

where ϕ_k and ϕ_p refer to the azimuthal angles of the corresponding transverse momenta. Here, the numerator is filled with only the correlated contributions such as the Bose enhancement component, as the uncorrelated one is cancelled out on account of the angular integration, while the only input to the denominator comes from the square of the single inclusive gluon production spectrum.

With this in mind, Fig. 2 displays a numerical evaluation of v_2 and v_3 for the very last piece of Eq. (7) over the momenta in units of the saturation scale Q_{s}. It is interesting to note that the second Fourier coefficient barely showcases any dependence on the transverse momentum, this way suggesting a scaling with the same power of momentum as the uncorrelated component, that is, the square of the single inclusive gluon production cross section (Fig. 2, left panel). Finally, the right panel of Fig. 2 gives evidence of the emergence of odd azimuthal anisotropic harmonics. Although the other part of this contribution has not been incorporated in this analysis yet, this suffices given the prime purpose of this work, which is none other than proving the surfacing of odd harmonics in two-particle correlations by staying at leading order within the eikonal approximation.

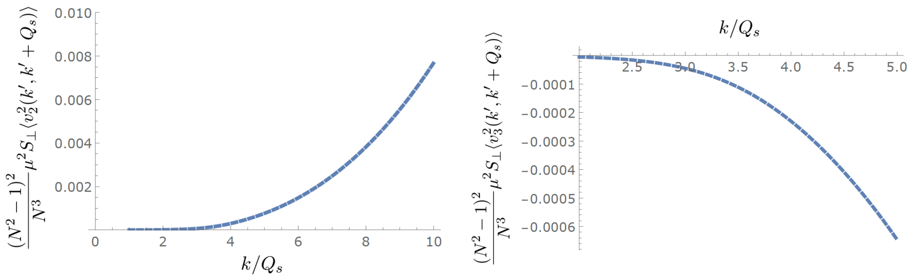

Fig. 2. The second (left) and third (right) flow harmonic coefficients for the very final component of Eq. (7) plotted over the momenta in units of Q_s.

4. Conclusions

In this work, we calculate the double inclusive gluon production cross section within the approach of the dense-dilute CGC via going beyond the glasma graph approach.

As a novelty, we provide the quantum correction accounting for the two gluons being correlated with each other in the incoming wave function, ultimately leading to the surfacing of odd azimuthal anisotropic harmonics at leading order in the eikonal expansion, the signature of a breaking of the accidental symmetry in two-particle correlations within the CGC framework.

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