PROCEEDINGS OF SCIENCE

Quark correlations in the Color Glass Condensate

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The explanation of the ridge observed in p-p and p-A collisions at the Large Hadron Collider constitutes one of the open questions in our understanding of high-energy hadronic collisions. Apart from final-state hydrodynamic models, correlations between gluons in the wave function of the incoming hadrons, computed in the framework of the Color Glass Condensate, offer an alternative rationale to explain such phenomenon. A natural question is then what happens to quarks. Here we consider, for the first time, correlations between produced quarks in p-A collisions in the light-cone wave function approach to the CGC. We find a quark-quark ridge that shows a dip at $\Delta\eta \sim 2$ relative to the gluon-gluon ridge. The origin of this dip is the short range (in rapidity) Pauli blocking experienced by quarks in the wave function of the incoming projectile. We observe that these correlations, present in the initial state, survive the scattering process. We discuss possibilities for observing experimentally such correlations and future developments.

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects
3-7 April 2017
University of Birmingham, UK

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PoS(DIS2017)065

1. Introduction

The ridge correlation observed at the Large Hadron Collider (LHC), first in high-multiplicity p-p collisions [1], then in p-Pb collisions [2] and, more recently [3], in p-p events with multiplicities close to those in minimum bias collisions, has been in the center of interest of the heavy-ion community for several years. Two main lines of explanations are discussed at present. One is based on a collective hydrodynamic behavior of the system produced in the collision in an analogous manner as in heavy-ion collisions. The other one is based on the Color Glass Condensate (CGC) framework to describe high-energy Quantum Chromodynamics in a weak coupling but nonperturbative regime, where a quantitative description of the data is achieved [4] in the "glasma graph" approach which ascribes the origin of the correlations entirely to the structure of the initial state. Though it is likely that both mechanisms, corresponding to final and initial state effects, are contributing to the correlations (probably in different transverse momentum ranges), the new p-p data mentioned above make the hydrodynamical description somewhat questionable and the possible initial state origin of the correlations more credible.

Within the "glasma graph" approach, we showed [5] that the physics underlying this contribution is the Bose enhancement of gluons in the projectile wave function. The effect is long range in rapidity since the CGC wave function is dominated by the rapidity integrated mode of the soft gluon field. A natural question that we have investigated in [6] is whether quarks (or antiquarks) in the CGC are also subject to correlations. One expects quarks to experience Pauli blocking, and thus the probability to find two identical quarks with the same quantum numbers in the CGC state should be suppressed. As we will show, the Pauli blocking effect is indeed present, but it is short range in rapidity. We also find that the suppression of Pauli blocking with respect to Bose enhancement is not $\mathscr{O}(\alpha_s^2)$ but rather $\mathscr{O}(\alpha_s^2 N_c)$, therefore quite moderate for $\alpha_s \sim 0.2$ and $N_c = 3$.

A candidate for the observation of such effects is open charm-open charm correlations that are expected to be less gluon-dominated than light hadrons. Data from the LHCb collaboration [7] exist on such process but at forward rapidities, whereas the approach discussed here is more suitable for central rapidities. Another interesting possibility would be the contribution of quark-quark correlations to the difference between the azimuthal correlations of equal and opposite sign charged particles, which have been measured to be of similar magnitude in p-Pb and Pb-Pb collisions at the LHC [8]. Naturally, one would expect Pauli blocking to contribute only to the equal sign charged particle correlations, and decrease them at $\Delta\phi = 0$, see [9]. Besides, it could also contribute to the difference between baryon-baryon and baryon-meson or baryon-antibaryon correlations [10].

The paper is organised as follows. In Section 2, we analyze the expression for the number of quark pairs in the CGC wave function to lowest order in α_s. In Section 3, we consider the double inclusive quark production in a scattering process. We show that the basic features of quark pair correlations in the wave function are indeed preserved by the production process. Finally, Section 4 contains a short summary of our results and an outlook. We rely on the light-cone wave function formalism, see e.g. [11]. The full calculation can be found in [6].

2. Quark correlations in the wave function

The dressed valence state in the light-cone wave function relevant to study quark-quark corre-

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lations reads as follows:

$$|v\rangle_4^D = \text{virtual} + \frac{g^4}{2}\int \frac{dk^+ d\alpha\, d^2p'\, d^2\bar{p}'}{(2\pi)^3}\frac{d\bar{k}^+ d\beta\, d^2q'\, d^2\bar{q}'}{(2\pi)^3} \tag{2.1}$$
$$\times \left[\zeta^{\varepsilon\iota}_{s_1's_2'}(k^+,p',\bar{p}';\alpha)\zeta^{\gamma\delta}_{r_1r_2}(\bar{k}^+,q',\bar{q}';\beta)\; d^{\dagger\varepsilon}_{s_1'}(\bar{\alpha}k^+,p')\,\bar{d}^{\dagger\iota}_{s_2'}(\alpha k^+,\bar{p}')\; d^{\dagger\gamma}_{r_1}(\bar{\beta}\bar{k}^+,q')\,\bar{d}^{\dagger\delta}_{r_2}(\beta\bar{k}^+,\bar{q}')\right]|v\rangle.$$

In this expression, $d^\dagger, \bar{d}^\dagger$ are creation operators of quarks and antiquarks, respectively. Greek indices denote color while Roman ones refer to spin. $\zeta^{\varepsilon\iota}_{s_1's_2'}(k^+,p',\bar{p}';\alpha)$ is the splitting amplitude of a gluon, with plus-momentum k^+ and transverse momentum k, coupled to a color source in the hadron, into a $q\bar{q}$ pair with transverse momenta $\bar{p}', p' = k-\bar{p}'$ and plus-momentum fraction $\bar{\alpha}, \alpha = 1-\bar{\alpha}$ respectively. We consider density enhanced corrections only i.e. the possibility of a single color source coupling to two gluons and then splitting into two $q\bar{q}$ pairs is neglected.

Using this wave function, then the pair quark density in the wave function is

$$\frac{dN}{dp^+d^2pdq^+d^2q} = \frac{1}{(2\pi)^6}\left\langle {}^D_4\langle v|d^\dagger_{\alpha,s_1}(p^+,p)d^\dagger_{\beta,s_2}(q^+,q)\,d_{\beta,s_2}(q^+,q)\,d_{\alpha,s_1}(p^+,p)\,|v\rangle_4^D\right\rangle_P, \tag{2.2}$$

where $\langle\rangle_P$ denotes the average over the color configurations of the projectile. This expression reads

$$\frac{dN}{d\eta_1 d^2pd\eta_2 d^2q} = \frac{1}{(2\pi)^4}g^8\int d^2kd^2\bar{k}d^2l\,d^2\bar{l}\,\langle\rho^a(k)\rho^c(\bar{k})\rho^b(l)\rho^d(\bar{l})\rangle_P \tag{2.3}$$
$$\times\left\{\mathrm{tr}(\tau^a\tau^b)\mathrm{tr}(\tau^c\tau^d)\Phi_2(k,l;p)\Phi_2(\bar{k},\bar{l};q)-\mathrm{tr}(\tau^a\tau^b\tau^c\tau^d)\Phi_4(k,l,\bar{k},\bar{l};p,q)\right\},$$

where g is the Yang-Mills coupling constant, $\rho^a(k)$ and $\rho^b(\bar{k})$ are the color charge densities in the amplitude and $\rho^c(l)$ and $\rho^d(\bar{l})$ are the color charge densities in the complex conjugate amplitude, and τ^a are color matrices in the fundamental representation of $SU(N)$. The rapidities are defined as $\eta_1 = \ln(p_0^+/p^+)$ and $\eta_2 = \ln(p_0^+/q^+)$, with p_0^+ some reference plus-momentum. The Φ_2^2 comes from the probability of two gluons splitting independently into two $q\bar{q}$ pairs, while the Φ_4 term is the corresponding interference term that contains a rapidity dependent coefficient, see [6], that will be the origin of the short range rapidity nature of the correlation. Performing Gaussian averages for the color charges of the projectile, $\left\langle\rho^a(k)\rho^b(p)\right\rangle_P = (2\pi)^2\mu^2(k)\;\delta^{ab}\;\delta^{(2)}(k+p)$, and taking only terms leading in the number of colors N_c, it turns out that only the Φ_4 terms contributes to the correlated quark pair production.

In order to provide some estimates, we make the following approximations: $\eta_1-\eta_2 \gg 1$, $|p|\sim|q|\sim|p-q|\gg Q_s$, with $Q_s = g^2\mu$ any saturation scale, we assume translational invariance of the color charges in the hadron, color neutrality on length scales larger than $1/Q_s$ and we keep only leading logarithms. The result reads

$$\left[\frac{dN^P(p,q;\eta_1,\eta_2)}{d^2pd^2qd\eta_1 d\eta_2}\right]_{\text{correlated}} \simeq \tag{2.4}$$
$$-\frac{S}{(2\pi)^2}e^{\eta_2-\eta_1}(\eta_1-\eta_2)^2\frac{\mu^4}{p^4q^4}g^8\frac{N_c^3}{4}\left\{\frac{25\pi^2}{2}q^4\left[\eta_1-\eta_2+\ln\frac{p^2}{Q_s^2}\right]^2\delta^{(2)}(q-p)\right.$$
$$\left.+\pi\left[\frac{3(p^2+q^2)}{(p-q)^4}\left\{5\left[p^2q^2-(p\cdot q)^2\right]-(p-q)^2p\cdot q\right\}\ln\frac{(p-q)^2}{Q_s^2}+(\eta_1-\eta_2)p\cdot q\right]\right\},$$

where $S \equiv (2\pi)^2\delta^{(2)}(0)$ is proportional to the transverse area of the hadron. Eqn. (2.4) shows the minus sign corresponding to Pauli blocking, and the result is short range in rapidity and $\mathscr{O}(\alpha_s^2 N_c)$ with respect to the gluon pair correlated production.

3. Correlations for produced quarks

For the production process, the pair quark density reads

$$\frac{d\sigma}{dp^+d^2p dq^+d^2q} = \frac{1}{(2\pi)^6}\langle v|\Omega\hat{S}^\dagger\,\Omega^\dagger\;[d^\dagger_{\alpha,s_1}(p^+,p)\,d^\dagger_{\beta,s_2}(q^+,q)d_{\beta,s_2}(q^+,q)\,d_{\alpha,s_1}(p^+,p)]\,\Omega\hat{S}\Omega^\dagger|v\rangle\,. \tag{3.1}$$

Here $\hat{S}$ is the eikonal S-matrix operator and Ω is the unitary operator which (perturbatively) diagonalizes the QCD Hamiltonian, in the CGC approximation, to the order in α_s in which the ground state contains two quarks as in Eqn. (2.1). Note that in Eqn. (3.1), the averagings over the projectile color charge densities and over the target fields are implicit. This expression gives

$$\begin{aligned}\frac{d\sigma}{d\eta_1\, d^2p\, d\eta_2\, d^2q} &= \frac{g^8}{(2\pi)^4}\int_{x,y,\bar{x},\bar{y}}\int_{z_1,z_2,\bar{z}_1,\bar{z}_2,\bar{z},\bar{w}}\frac{1}{2}\,\langle\rho^a(x)\rho^b(\bar{x})\rho^c(y)\rho^d(\bar{y})\rangle_P\\
&\times\Big\langle\Phi_2(x,y;z_1,z_2,\bar{z};p)\Phi_2(\bar{x},\bar{y};\bar{z}_1,\bar{z}_2,\bar{w};q)\\
&\times\mathrm{tr}\Big\{[\tau^a - S_A^{a\bar{a}}(x)S_F(z_1)\tau^{\bar{a}}S_F^\dagger(\bar{z})][\tau^c - S_A^{c\bar{c}}(y)S_F(\bar{z})\tau^{\bar{c}}S_F^\dagger(z_2)]\Big\}\\
&\times\mathrm{tr}\Big\{[\tau^b - S_A^{b\bar{b}}(\bar{x})S_F(\bar{z}_1)\tau^{\bar{b}}S_F^\dagger(\bar{w})][\tau^d - S_A^{d\bar{d}}(\bar{y})S_F(\bar{w})\tau^{\bar{d}}S_F^\dagger(\bar{z}_2)]\Big\}\\
&-\Phi_4(x,y,\bar{x},\bar{y};z_1,z_2,\bar{z}_1,\bar{z}_2;\bar{z},\bar{w};p,q)\\
&\times\mathrm{tr}\Big\{[\tau^a - S_A^{a\bar{a}}(x)S_F(z_1)\tau^{\bar{a}}S_F^\dagger(\bar{z})][\tau^c - S_A^{c\bar{c}}(y)S_F(\bar{w})\tau^{\bar{c}}S_F^\dagger(z_2)]\\
&\times\;[\tau^b - S_A^{b\bar{b}}(\bar{x})S_F(\bar{z}_1)\tau^{\bar{b}}S_F^\dagger(\bar{w})][\tau^d - S_A^{d\bar{d}}(\bar{y})S_F(\bar{z})\tau^{\bar{d}}S_F^\dagger(\bar{z}_2)]\Big\}\Big\rangle_T,\end{aligned} \tag{3.2}$$

where S_A denotes the eikonal S-matrix (i.e. a Wilson line) in the adjoint representation, we use coordinate space expressions for Φ_2 and Φ_4, and we have neglected the contribution from two rescattered gluons that should not contribute to correlated pair production. After expanding the S-matrices in the color field of the target and performing Gaussian averages for projectile and target (for the latter, we use λ instead of μ and Q_T instead of Q_s), only the Φ_4 term contributes to correlated production in the large N_c limit and it does with a minus sign, as it was the case in Eqn. (2.3) for quark pair production in the initial wave function.

Finally, under the same approximations leading to Eqn. (2.4) and assuming that $Q_T < Q_s$ so that the interaction with the target does not destroy affect sizeably the correlations, we get the estimate

$$\begin{aligned}\left[\frac{d\sigma}{d^2pd^2qd\eta_1 d\eta_2}\right]_{\text{correlated}} &= -S(2\pi)^2N_c^5\frac{Q_s^2Q_T^2}{4g^4}e^{\eta_2-\eta_1}(\eta_1-\eta_2)^2\ln\left(\frac{Q_T^2}{\Lambda^2}\right)\frac{\pi^3}{p^4}\left\{\frac{50\pi}{16}\ln\left(\frac{Q_s^4}{Q_T^2\Lambda^2}\right)\right.\\
&\left.\times\delta^{(2)}(q-p)+\frac{9Q_s^2}{q^4}\left[\frac{2(p^2+q^2)^2+p^2q^2}{(p-q)^4}\right]\ln\left[\frac{(p-q)^2}{Q_s^2}\right]+\frac{9Q_s^2}{2q^4}\left[\ln\left(\frac{q^2}{Q_s^2}\right)+\ln\left(\frac{p^2}{Q_s^2}\right)\right]\right\}.\end{aligned} \tag{3.3}$$

This result looks similar to the one for quark correlation in the wave function. Noticeably, the $\delta^{(2)}(q-p)$ survives the scattering process and, additionally, a non perturbative regulator Λ appears due to poles in internal transverse momenta not regulated by the saturation momenta.

4. Summary and outlook

We have performed a CGC calculation, in the light-cone wave function approach, for quark-quark correlations, under the Glasma graph approximations used to describe the gluon ridge. We have shown that quarks experience Pauli blocking, that their correlations are short-range in rapidity and that they are parametrically suppressed, $\mathcal{O}(\alpha_s^2 N_c)$, with respect to the gluon pair correlated production.

In principle, these effects could be observed in D-D correlations but the mass effects should be taken into account in the calculation. They could contribute to odd harmonics and, as commented in the Introduction, to other experimentally observed effects like charge separation with respect to the reaction plane and baryon-baryon correlations. The calculation could also be extended to the forward region in the hybrid formalism. Work along these lines is planned for the future.

Acknowledgements: The research was supported by the EU FP7 IRSES network "High-Energy QCD for Heavy Ions" under REA grant agreement #318921; the NSF grant 1614640 (AK); the ISRAELI SCIENCE FOUNDATION grants # 1635/16 and # 147/12 (ML) and the BSF grants #2012124 and #2014707 (AK, ML); the European Research Council grant HotLHC ERC-2011-StG-279579, Ministerio de Ciencia e Innovación of Spain under project FPA2014-58293-C2-1-P and Unidad de Excelencia María de Maetzu under project MDM-2016-0692, Xunta de Galicia (Consellería de Educación) within the Strategic Unit AGRUP2015/11, and FEDER (NA); and Fundação para a Ciência e a Tecnologia (Portugal) under projects CERN/FIS-NUC/0049/2015 and SFRH/BPD/112655/2015 (TA).

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