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TWO-PARTICLE CORRELATIONS FROM HIGH ENERGY QCD*

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Angular correlations in two-gluon inclusive production are argued to be a generic feature of high energy/high density QCD. I, first, briefly review the wavefunction approach to high energy collisions and then, consider single and double inclusive gluon production within the formalism.

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1. Introduction

The CMS observation of angular and long range rapidity correlations in the hadron spectrum, the so-called "ridge" in proton–proton collisions [1] (Fig. 1), has triggered a lot of discussions in recent literature. A similar, if more pronounced correlated structure was observed in gold–gold collisions at RHIC. There is a variety of candidate explanations for the RHIC observation but most of them are utilizing strong radial flow as a collimating mechanism. Although flow measurements have not been reported for the LHC data, it is difficult to imagine that flow will have a significant effect in p–p collisions. Thus, the viable explanation should probably not appeal to any collective behavior of produced particles.

What is the origin of angular collimation and what is the origin of long range rapidity correlations? There could be many answers to these questions. From causality considerations we know that correlations exist in early stage of the collision. We hopefully see signs of universality between pp and HI collisions, which is implied by high energy QCD: In both experiments the effect emerges only when high densities are involved.

The purpose of this note is to point out that at high energy, rapidity and angular correlations between produced particles are to be expected on

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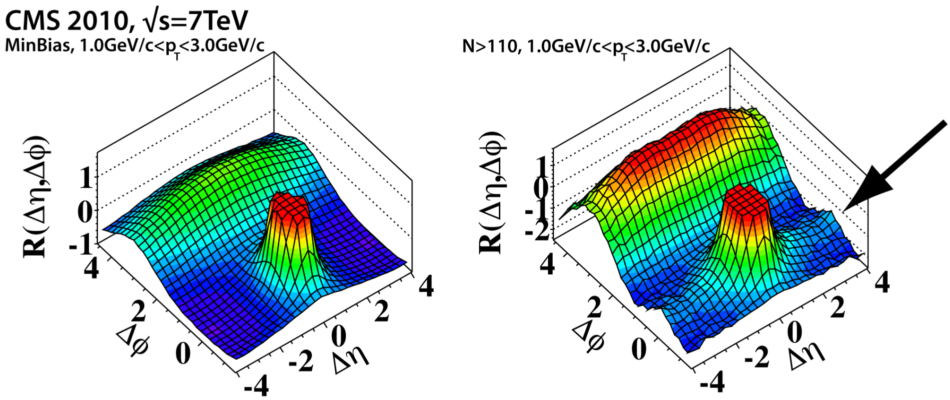

Fig. 1. The structure of the CMS ridge: Left: minimal bias data; no ridge. Right: high multiplicity data with ridge.

very general grounds. The framework of our discussion here is similar to that of [2], but the argumentation will be quite general without referring to specific models of high energy evolution and/or hadronic wave function.

The quantity related to the ridge is a correlated part of two-point inclusive gluon production rate of two gluons with transverse momenta and rapidity (p,η) and (k,ξ)

$$\left[\frac{d^2N}{d^2p\,d\eta\,d^2k\,d\xi} - \frac{dN}{d^2k\,d\xi}\,\frac{dN}{d^2p\,d\eta}\right] \Bigg/ \frac{dN}{d^2k\,d\xi}\,\frac{dN}{d^2p\,d\eta}\,. \tag{1}$$

While we do not yet know how to reliably compute inclusive production in the collision of two dense objects, we have a lot of experience with the DIS processes, when one of the colliding particles can be treated as dilute. Here, I discuss one source for the observed phenomena, the initial conditions, as follows from quite general QCD-based considerations. There will be no quantitative results presented.

Due to near-boost invariance of the (projectile) hadron light-cone wavefunction, the long range rapidity correlations emerge naturally. Namely, if, in the wavefunction we find with certain probability a gluon with rapidity Y_1, with the same probability we find another one with rapidity Y_2. Moreover, these rapidities are not necessary close to each other. At high densities, we can find two gluons widely separated in rapidity, but correlated in their color charge. For this to happen, they have to be within a correlation length in the transverse plane. It is given by the inverse of the projectile's saturation momentum.

These two gluons scatter of the target via eikonal scattering, which is rapidity independent. If, on top of being correlated in color, these two gluons are sufficiently close in the impact parameter space, they would scatter on the very same target field configuration and this way would scatter approximately to the very same direction. This is the origin of angular correlations. The relevant correlation length associated with the target field fluctuations is given by the inverse of the target saturation scale.

2. High Energy Scattering: CGC-type approach

The hadronic wave function at high energy can be computed in QCD using light-cone Hamiltonian perturbation theory [3, 4]

$$|P\rangle = \Omega|v\rangle = \exp\left\{i\int d^2x b_i^a(x)\int d\eta\left(a_i^{\dagger a}(x,\eta)+a_i^a(x,\eta)\right)\right\} B\left(a,a^\dagger\right)|v\rangle\,. \tag{2}$$

Here, $|v\rangle$ is the wave function of valence charges, that determines the distribution of fast partons responsible for the color charge density ρ; B is a Bogolyubov-type operator of the soft gluon fields a, and the Weizsacker–Williams (WW) field b is given in terms of ρ via classical Yang–Mills equations of motion. For small (dilute) projectile

$$b_i^a(x) = \frac{g}{\pi}\int_y f_i(x-y)\,\rho^a(y)\,, \qquad f_i(x-y) = \frac{(x-y)_i}{(x-y)^2}\,, \qquad B=1\,. \tag{3}$$

The rapidity evolution of the wave function is generated via boost encoded in the evolution operator Ω as shown in Fig. (2). Given the evolution of the hadronic wave function one can calculate the evolution of an arbitrary observable $\hat{\mathcal{O}}(\rho)$ which depends on the color charge density

$$\langle v|\,\hat{\mathcal{O}}[\rho]\,|v\rangle = \int D\rho\, W[\rho]\;\mathcal{O}[\rho]\,. \tag{4}$$

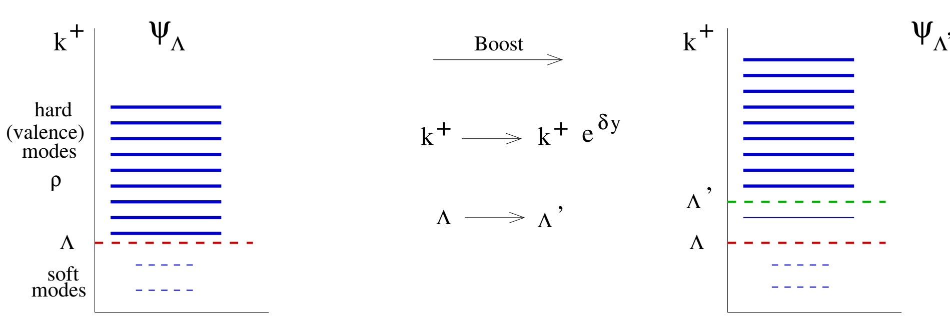

Fig. 2. Light-cone wavefunction before and after boost.

The evolution of the expectation value

$$\begin{aligned}\frac{d\,\langle v|\hat{\mathcal{O}}|v\rangle}{d\,Y} &= \lim_{Y\to Y_0}\frac{\langle v|\Omega_Y^\dagger\,\hat{\mathcal{O}}[\rho+\delta\rho]\,\Omega_Y|v\rangle\;-\;\langle v|\hat{\mathcal{O}}[\rho]|v\rangle}{Y\;-\;Y_0}\\ &= -\int D\rho\,W[\rho]\,H^{\rm RFT}\;\mathcal{O}[\rho]\,. \end{aligned} \tag{5}$$

In other words, the weight functionals W is a subject to high energy evolution which determines the dependence on rapidity

$$\frac{dW}{dY} = H^{\rm RFT}\,W\,. \tag{6}$$

Here $H^{\rm RFT}$ is the effective Hamiltonian of QCD at high energies. $H^{\rm RFT}$ has to be derived directly from QCD, practically from the evolution operator Ω. The derivation of $H^{\rm RFT}$ at the moment is incomplete. For processes when one of the scattering hadrons is dilute and another dense, a valid approximation to $H^{\rm RFT}$ is the JIMWLK [5]. It includes a tripple-Pomeron vertex and effectively resums the fan diagrams of the Pomeron Calculus.

3. Correlations in DIS

The observable from which single inclusive gluon production is computed is (see Fig. (3))

$$\hat{\mathcal{O}}_g\;\sim\;a_i^{\dagger\,a}(k)\,a_i^a(k)\,. \tag{7}$$

For fixed configuration of projectile charges ρ and fixed target fields the result is [6]

$$\begin{aligned}\frac{dN}{d^2k\,dy} &= \langle\,\sigma(k)\,\rangle_{\rm P,T}\,,\\ \sigma(k) &= \int_{z,\bar z,x_1,\bar x_1} e^{ik(z-\bar z)}\vec f(\bar z-\bar x_1)\cdot\vec f(x_1-z)\\ &\quad\times\left\{\rho(x_1)\left[S^\dagger(x_1)-S^\dagger(z)\right][S(\bar x_1)-S(\bar z)]\rho(\bar x_1)\right\}\,. \end{aligned} \tag{8}$$

Here, S stands for the Wilson line, which is an S-matrix of a projectile gluon scattering on a fixed target field configuration. This probability then has to be averaged over the projectile and target wave functions — the projectile ensemble determining the distribution of $\rho(x)$ and the (independent) target ensemble which determines the distribution of $S(x)$.

For the double inclusive gluon production in DIS, without rapidity evolution between produced gluons, we have

$$\mathcal{O} = a^\dagger(k)\,a(k)\;a^\dagger(p)\,a(p) \tag{9}$$

which leads to the following expression for the amplitude

$$\frac{dN}{d^2pd^2kd\eta d\xi} = \langle\ \sigma(k)\ \sigma(p)\ \rangle_{\rm P,T} + \text{terms subleading in } \rho\,. \tag{10}$$

If $\sigma(k)$ as a function of k has a maximum at some value $k = q_0$. Clearly then the two gluon production probability, configuration by configuration, has a maximum at $k = p = q_0$. This is the near side correlation. The correlations emerge due to averages $\langle\cdots\rangle_{\rm P,T}$ over the projectile and target wavefunctions. The value of q_0 depends on configuration, but the fact that $k \simeq p$ does not. We expect q_0 to be of the order of Q_s.

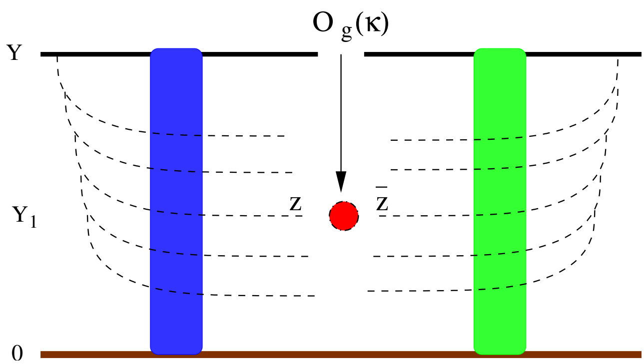

Fig. 3. Single gluon inclusive production.

So far, I have argued that gluon production at high energy leads naturally to rapidity correlations and angular correlations. There just have to be many gluons so that more than one is produced at fixed impact parameter (within $\Delta b \sim 1/Q_s$). None of these qualitative features presented above depends on what averaging procedure is used to average over the projectile and target fields, but quantitative of course it will.

In [7] we argued that angular correlations is a leading large N_c effect, and hence it is worth to study them within this approximation. Within this approximation, $\mathcal{O}^T_Y$ is related to the evolution of double trace operator, or, in other words, of two-dipole operators

$$\mathcal{O}^T_Y = \frac{1}{N_c^2}\int DS\,\mathrm{tr}\left[S\,S^\dagger\right]\ \mathrm{tr}\left[S\,S^\dagger\right]\ W^T_Y[S]\,, \tag{11}$$

while the evolution is now the dipole evolution given by the Balitsky–Kovchegov equation [8]. We have initiated a study of this question in [9]. The results reveal very fast anisotropisation with correlations washed away after one-two units of rapidity evolution. The correlation radius shrinks much faster than decrease of the saturation radius. The BK-JIMWLK evolution destroys correlations when introduced in the initial conditions. Pomeron loops have to be included in the evolution in order to have dynamical correlations with the correlation radius of the order of the saturation radius. Those are accounted for in the full RFT Hamiltonian [10].

4. Conclusions

I have argued that angular correlations in two-gluon inclusive production are a generic feature of high energy/high density QCD, as encoded in the theory of Color Glass Condensate. In order to properly study rapidity dependence of the correlations, we need to include Pomeron loops in high energy evolution equations.

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