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Particle Correlations at High Partonic Density

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Abstract. We discuss manifestations of the particle correlations at high partonic density in the heavy-ion collisions at RHIC. In particular, we argue that the elliptic flow variable $v_2$ is dominated by particle correlations at high $p_T$.

Particle correlations at high partonic density (in Color Glass Condensate) are significantly different from those of the parton model. To illustrate this consider gluon production in Deep Inelastic Scattering on a heavy nucleus $A \sim 1/\alpha_s^6$ at high energies $x \sim e^{1/\alpha_s}$, Fig. 1. It was proved in [1] that the collinear factorization breaks down for this process. Instead $\gamma^* A$ cross section can be written in the $k_T$-factorized form [2]. This allows to introduce function $\phi(x, q_{\perp})$ which encodes quantum evolution and multiple gluon rescattering in nucleus. $\phi(x, q_{\perp})$ is simply related to the forward scattering amplitude which satisfies the QCD evolution equation for high partonic densities [3]. Solution to that equation implies that the scale inherent to function $\phi(x, q_{\perp})$ is $q_{\perp}^2 \sim Q_s^2 = \Lambda_{\text{QCD}}^2 A^{1/3} e^{4\alpha_s y}$. At high energies $Q_s^2 \gg \Lambda_{\text{QCD}}^2$, therefore one cannot neglect the virtuality of the $t$-channel gluons compared to the momentum of the produced hard particle $k_T \gg 1 \text{ GeV}$. As the result the transverse momentum conservation does not require anymore that the momentum of the hard jet be compensated by equally large momentum of another jet moving in the opposite direction in the transverse plane (in the center-of-mass frame).

The qualitative picture of the gluon production in heavy-ion collisions is pretty much the same as in DIS. Although the $k_T$ factorization has not been proved in this case, there are reasons to believe that it is at least a fairly good approximation. Feynman diagram for the inclusive gluon production in AA collisions is shown in Fig. 2a. To study the gluon correlations in heavy-ion collisions we define the two-particle multiplicity distribution.

FIGURE 1. Gluon production in DIS on a heavy nucleus.
FIGURE 2. Inclusive (a) and double-inclusive (b) gluon production in AA

\[ P(k_{1\perp}, y_1; k_{2\perp}, y_2) = \frac{dN}{d^2k_{1\perp}dy_1} \frac{dN}{d^2k_{2\perp}dy_2} + \frac{dN_{\text{corr}}}{d^2k_{1\perp}dy_1d^2k_{2\perp}dy_2}, \]  

where the first term in the right-hand-side is just the square of the diagram Fig. 2a which gives the uncorrelated piece, and the second term is the diagram Fig. 2b which gives the correlated piece. The transverse momentum conservation applied to the later diagram gives \( |k_{1\perp} - k_{2\perp}| \approx NQ_s \), where \( N \) is the number of gluons in the nuclei wave functions, cf. Fig. 1. Since \( N \) can be large, the collinear factorization can be violated at \( k_{\perp}^2 > Q_s^2 \). It was argued in [5] that the collinear factorization is recovered when \( k_{\perp}^2 \gtrsim \bar{Q}_s^2 = Q_s^2/A_{\text{QCD}}^{1/3} \). The preliminary dA data at \( \sqrt{s} = 200 \text{ GeV} \) suggest that \( \bar{Q}_s^2 \approx Q_s^2 \) at this energy. This means that at RHIC particles with momenta \( k_{\perp}^2 \gg Q_s^2 \) are correlated mostly back-to-back. It is important to emphasize, that bulk of particles is produced with \( k_{\perp} < Q_s \) and therefore, saturation plays crucial role in understanding of the total multiplicity at RHIC.

Analysis of particle correlations with respect to the reaction plane azimuthal angle defined as

\[ \tan 2\Psi_R = \frac{\sum_{i=1}^{N} \sin 2\phi_i}{\sum_{j=1}^{N} \cos 2\phi_i}, \]

shows that the angular momentum distribution of the large multiplicity event \( N \gg 1 \) is given by [6]

\[ \frac{dn}{d\phi_{pT}d\Psi_R} = \frac{1}{(2\pi)^2} [1 + 2v_2(p_T, B)\Delta \cos 2(\phi_{pT} - \Psi_R)], \]

where \( \Delta \) is the reaction plane resolution. The \( \cos 2(\phi_{pT} - \Psi_R) \) shape is the result of trivial autocorrelations of each particle with itself. However the coefficient \( v_2 \) carries information about the particle correlations. The elliptic flow variable \( v_2 \) is given by

\[ v_2(p_T) = \frac{\langle \cos 2(\phi_1(p_T) - \phi_2) \rangle}{\sqrt{\langle \cos 2(\phi_1 - \phi_2) \rangle}}, \]
model [7], i.e. treating the nuclear color field in the Weiszäcker-Williams approximation [8]. The diagram Fig. 2b requires the $\alpha_s$ quantum correction. For simplicity we assume that nuclei have cylindrical shape. We also neglect all finite state interactions. The result of calculation [8] is shown in Fig. 3. It is in a reasonable agreement with data.

We conclude that the particle correlations are essential to understand the behavior of the elliptic flow extracted from current flow analysis methods. It seems to account for most of the flow at large $p_T$. Elliptic flow appears to be sensitive to the saturation physics of the early stages of the collision.

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