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Elliptic flow in small systems due to elliptic gluon distributions?

Yoshikazu Hagiwara [a], Yoshitaka Hatta [b,*], Bo-Wen Xiao [c], Feng Yuan [d]

[a] Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[b] Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan
[c] Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
[d] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

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ABSTRACT

We investigate the contributions from the so-called elliptic gluon Wigner distributions to the rapidity and azimuthal correlations of particles produced in high energy pp and pA collisions by applying the double parton scattering mechanism. We compute the 'elliptic flow' parameter v_2 as a function of the transverse momentum and rapidity, and find qualitative agreement with experimental observations. This shall encourage further developments with more rigorous studies of the elliptic gluon distributions and their applications in hard scattering processes in pp and pA collisions.

1. Introduction

One of the interesting experimental observations from the proton–proton and proton–nucleus collisions at the Large Hadron Collider (LHC) and Relativistic Heavy Ion Collider (RHIC) is the long range rapidity and azimuthal angle correlations between hadrons [1–9], see, e.g., a recent review in Ref. [10]. These intriguing observations have generated great theoretical investigations, and many models have been proposed to explain the experimental results, including (but not limited to) hydrodynamics [11–14], QCD motivated models [15–18], and in particular, the multi-gluon correlations calculated in the Color Glass Condensate (CGC) framework [19,20,22–33].

In this paper, we investigate the contribution from the double parton scattering (DPS) [34,35] coupled with the so-called elliptic gluon Wigner distribution [36–38]. In high energy collisions, we expect the DPS, or in general, the multi-parton scattering, is the dominant source for multi-particle productions. A unique feature of DPS is that its contribution is not strongly suppressed for near-side particle productions with large rapidity separation as compared to the single parton scattering (SPS) contribution. Therefore, DPS may well be the dominant source for long range correlations among produced hadrons.

It was first pointed out in Ref. [39] that the DPS plays an important role in two particle production in forward pA and dA collisions at RHIC. This idea was followed up in the saturation formalism in Ref. [40] to estimate the so-called pedestal contribution in the correlation measurements. Further study in Ref. [41] also confirmed the importance of these contributions in the two particle production in pA collisions. However, all these studies assumed that the two hard scatterings are essentially uncorrelated. In the following, we will extend the DPS mechanism to include the impact parameter dependence which naturally encodes the correlation between the two scatterings. If we average over the impact parameter space, this will reduce to the previous applications of the DPS mechanism in the CGC framework. However, the unintegrated gluon distribution involved in these scatterings depends on the impact parameter. In particular, there is a nonzero $\cos(2\phi)$ azimuthal correlation between the transverse momentum $k_\perp$ and the impact parameter $b_\perp$, which was referred to as the elliptic gluon Wigner distribution in Ref. [36]. Since the impact parameters for the two hard scatterings are correlated due to the DPS mechanism, we expect the transverse momenta from the two hard scatterings are correlated as well. This will naturally give rise to the $\cos(2\phi)$ two-particle correlation in the final state.

In Ref. [36], the elliptic gluon Wigner distribution has been shown to be measurable in diffractive dijet production in lepton-nucleon collisions at the future electron-ion collider (EIC). The present study suggests that the same distribution can affect various observables in different types of collisions.

The rest of this paper is organized as follows. In Sec. 2, we study the DPS contributions to the two particle production in the dilute-dense collisions and derive a formula for the 'elliptic flow' parameter v_2. The result is relevant to pp and pA experiments at RHIC and the LHC. In Sec. 3, we numerically evaluate v_2 in a model which incorporates the saturation effect in the target. We point out some generic features of the DPS contributions which

* Corresponding author.
E-mail address: hatta@yukawa.kyoto-u.ac.jp (Y. Hatta).

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can be compared to the experimental observations. We summarize our paper in Sec. 4.

2. Double parton scattering contributions in the dilute-dense collisions

In order to describe the near-side two particle correlations in pp and pA collisions, we introduce the impact parameter dependence in the DPS framework. Similarly to the derivation of DPS in Refs. [34,35], we write down the generic expression for the differential cross section of two parton production as

$$\left.\frac{d\sigma}{dy_1 d^2k_{1\perp} dy_2 d^2k_{2\perp}}\right|_{DPS} = \int d^2x_\perp d^2y_\perp d^2b_{1\perp} d^2b_{2\perp} e^{ik_{1\perp}\cdot x_\perp} e^{ik_{2\perp}\cdot y_\perp} F_A(x_p, x'_p; z_\perp) \times F_B(x_A, x'_A; \vec{b}_{1\perp}, \vec{b}_{2\perp}; \vec{x}_\perp, \vec{y}_\perp)\,, \tag{1}$$

where $z_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$, and $\vec{b}_{1\perp}$ and $\vec{b}_{2\perp}$ denote the two hard scattering positions with respect to the center of the target. The 'dipole sizes' $x_\perp$ and $y_\perp$ are Fourier-conjugate variables to the partons' outgoing transverse momentum $k_{1\perp}$ and $k_{2\perp}$, respectively. The longitudinal momentum fractions x_p, x'_p, x_A, and x'_A are determined by the final state kinematics. The physics picture is that two partons from the incoming proton encounter multiple scattering off the target, and fragment into two final state particles. The multiple scattering is described in the CGC framework or in the color-dipole model. For a large nucleus, we can assume a factorized form

$$F_B \approx S_{x_A}\left(\vec{b}_{1\perp}, \vec{x}_\perp\right) S_{x'_A}\left(\vec{b}_{2\perp}, \vec{y}_\perp\right)\,, \tag{2}$$

where S is the dipole S-matrix which may be in the fundamental or adjoint representation depending on the partonic channels involved in the DPS. The terms neglected in (2) are of order $1/N_c^2$. It has been argued [33] that these color-suppressed, but 'connected' contributions can give rise to nonvanishing v_2 in pp and pA collisions. Moreover, if the target is small, as in pp collisions, factorization (2) is violated even in the large-N_c limit due to the small-x evolution in the target. (In the case of a dipole target, this can be shown analytically [42,43].) Such factorization breaking effects have been considered as another source of v_2 in small systems [19–21].

Here we show that, even if the factorization (2) holds strictly, there exist non-trivial angular correlations between the two outgoing particles due to the angular correlation between $\vec{b}_{1\perp}$ and $\vec{x}_\perp$ in the S-matrix. It should be mentioned that the idea that the correlation between impact parameter and dipole orientation generates anisotropy in the final state has been previously studied in the context of single [15,16] (see also, [45]) and double [31,32] parton scattering. Thus, the approach here is essentially the same as in [31,32]. Yet, our formulation is considerably more concise and clearly establishes the connection to the elliptic gluon Wigner distribution which is a fundamental object in the tomographic study of the nucleon/nucleus.

For this purpose, let us write (1) as

$$\left.\frac{d\sigma}{dy_1 d^2k_{1\perp} dy_2 d^2k_{2\perp}}\right|_{DPS} = \int d^2b_{1\perp} d^2b_{2\perp} F_A(x_p, x'_p; z_\perp) G_{x_A}(\vec{b}_{1\perp}, \vec{k}_{1\perp}) G_{x'_A}(\vec{b}_{2\perp}, \vec{k}_{2\perp}), \tag{3}$$

where $G(\vec{b}_\perp, \vec{k}_\perp)$ is the Fourier transform of $S(\vec{b}_\perp, \vec{x}_\perp)$ and we assumed (2). The angular correlation between $\vec{b}_\perp$ and $\vec{x}_\perp$ is transformed into the one between $\vec{b}_\perp$ and $\vec{k}_\perp$. At small-x, this correlation is dominantly *elliptic* [36,37], namely,

$$G(\vec{b}_\perp, \vec{k}_\perp) = G^0(b_\perp, k_\perp) + 2\cos 2(\phi_b - \phi_k)\widetilde{G}(b_\perp, k_\perp) + \cdots\,. \tag{4}$$

The angular integrals in (3) then lead to an elliptic angular correlation of the form $\cos 2(\phi_{k_1} - \phi_{k_2})$.

This can be seen most clearly and model-independently at large impact parameter where it is convenient to write $\vec{b}_{1,2\perp} = \vec{b}_\perp \pm \vec{z}_\perp/2$, so that $d^2b_{1\perp} d^2b_{2\perp} = d^2z_\perp d^2b_\perp$. Since the two partons are confined in the proton, the $z_\perp$ integral is limited within the confinement radius $z_\perp \lesssim 1/\Lambda$. When $b_\perp \gg 1/\Lambda \sim z_\perp$, we can approximately integrate over $z_\perp$ to obtain the collinear double parton distribution of the proton,

$$\int d^2z_\perp F_A(x_p, x'_p; z_\perp) = \mathcal{D}_p(x_p, x'_p)\,, \tag{5}$$

which can be further simplified as $\mathcal{D}_p(x_p, x'_p) = \mathcal{C}(x_p, x'_p) f(x_p) \times f(x'_p)$ with $\mathcal{C} \approx 1$. With this approximation, we can write down the differential cross section as

$$\left.\frac{d\sigma}{dy_1 d^2k_{1\perp} dy_2 d^2k_{2\perp}}\right|_{DPS} \sim \int_{1/\Lambda} d^2b_\perp f(x_p) f(x'_p) G_{x_A}(\vec{b}_\perp, \vec{k}_{1\perp}) G_{x'_A}(\vec{b}_\perp, \vec{k}_{2\perp}) \tag{6}$$
$$\propto \pi \int_{1/\Lambda} db_\perp^2 \Big[G^0_{x_A}(b_\perp, k_{1\perp}) G^0_{x'_A}(b_\perp, k_{2\perp}) + 2\cos 2(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}) \widetilde{G}_{x_A}(b_\perp, k_{1\perp}) \widetilde{G}_{x'_A}(b_\perp, k_{2\perp}) \Big].$$

As expected, we recognize the $\cos 2(\phi_{k_1} - \phi_{k_2})$ correlation proportional to the elliptic part $\widetilde{G}$ squared.

We now turn to the small impact parameter region $b_\perp \sim z_\perp \sim 1/\Lambda$. To proceed, we introduce a Gaussian model $F_A(z_\perp) \propto e^{-z_\perp^2 \Lambda^2}$. The angular integrals can then be performed as

$$\int^{1/\Lambda} d^2b_{1\perp} d^2b_{2\perp} e^{-\Lambda^2 |\vec{b}_{1\perp} - \vec{b}_{2\perp}|^2} G_{x_A}(b_{1\perp}, k_{1\perp}) G_{x'_A}(b_{2\perp}, k_{2\perp})$$
$$= 4\pi^2 \int_0^{1/\Lambda} b_{1\perp} db_{1\perp} b_{2\perp} db_{2\perp} e^{-\Lambda^2 (b_{1\perp}^2 + b_{2\perp}^2)} \times \Big[I_0(2\Lambda^2 b_{1\perp} b_{2\perp}) G^0_{x_A}(b_{1\perp}, k_{1\perp}) G^0_{x'_A}(b_{2\perp}, k_{2\perp}) + 2\cos 2(\phi_{k_{1\perp}} - \phi_{k_{2\perp}}) I_2(2\Lambda^2 b_{1\perp} b_{2\perp}) \times \widetilde{G}_{x_A}(b_{1\perp}, k_{1\perp}) \widetilde{G}_{x'_A}(b_{2\perp}, k_{2\perp}) \Big]. \tag{7}$$

We again find the elliptic correlation $\cos 2(\phi_{k_1} - \phi_{k_2})$. Other models of F_A will also give rise to this correlation, as long as F_A depends on the angle between $\vec{b}_{1\perp}$ and $\vec{b}_{2\perp}$ via $z_\perp = |\vec{b}_{1\perp} - \vec{b}_{2\perp}|$.

Noting that the upper limit of the $b_{1,2\perp}$-integrations in (7) can actually be extended to some value $R_{cut} > 1/\Lambda$, we define

$$V_2(k_{1\perp}, k_{2\perp}) \equiv \frac{\int_0^{R_{cut}} b_{1\perp} db_{1\perp} b_{2\perp} db_{2\perp} e^{-\Lambda^2(b_{1\perp}^2 + b_{2\perp}^2)} I_2(2\Lambda^2 b_{1\perp} b_{2\perp}) \widetilde{G}_{x_A}(b_{1\perp}, k_{1\perp}) \widetilde{G}_{x'_A}(b_{2\perp}, k_{2\perp})}{\int_0^{R_{cut}} b_{1\perp} db_{1\perp} b_{2\perp} db_{2\perp} e^{-\Lambda^2(b_{1\perp}^2 + b_{2\perp}^2)} I_0(2\Lambda^2 b_{1\perp} b_{2\perp}) G^0_{x_A}(b_{1\perp}, k_{1\perp}) G^0_{x'_A}(b_{2\perp}, k_{2\perp})}, \tag{8}$$

This is related to the experimentally measured v_2 via

$$v_2(k_\perp, k_\perp^{ref}) \equiv \frac{V_2(k_\perp, k_\perp^{ref})}{\sqrt{V_2(k_\perp^{ref}, k_\perp^{ref})}}\,, \tag{9}$$