Anisotropic flow and the valence quark skeleton of hadrons

Meijian Li[1], Wenyang Qian[1], Bin Wu[1], and Hong Zhang[2]

1. Instituto Galego de Física de Altas Enerxías, Universidade de Santiago de Compostela, E-15782 Galicia, Spain
2. Institute of Frontier and Interdisciplinary Science, Key Laboratory of Particle, Physics and Particle Irradiation (MOE), Shandong University, Qingdao, Shandong 266237, China

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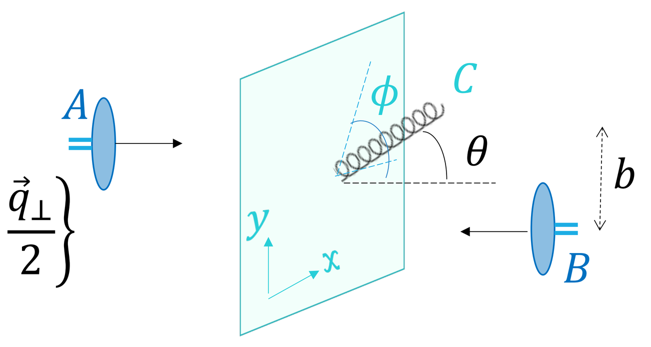
I. Introduction

In heavy-ion collisions, azimuthal anisotropies have long been viewed as a signature for the formation of strongly-coupled quark-gluon plasma fluid droplets. Could momentum anisotropies develop without final-state interactions or initial parton saturation in small systems, e.g., $\pi + \pi \to g + X$?



$$P_A^\mu = \left\{\frac{\sqrt{s}}{2}, 0, \frac{\vec{q}_\perp}{2}\right\} \quad (+,\ -,\ \perp) \qquad P_B^\mu = \left\{0, \frac{\sqrt{s}}{2}, -\frac{\vec{q}_\perp}{2}\right\}$$

We consider the process of two ultra-relativistic pions (A and B) colliding at the impact parameter b, producing one gluon (C). The cross section can be factorized into pion light-front wavefunction (LFWF) and dipole cross section,[1]

$$\frac{d\sigma}{d^2\mathbf{b}dO} = \prod_{i=A,B} \int d^2\mathbf{r}_i \sum_{s_q^i, s_{\bar{q}}^i} \frac{1}{4\pi} \int_0^1 d\xi_i \left|\psi_{s_q^i s_{\bar{q}}^i/\sigma}(\mathbf{r}_i, \xi_i)\right|^2 \frac{d\hat{\sigma}}{d^2\mathbf{b}dO}$$

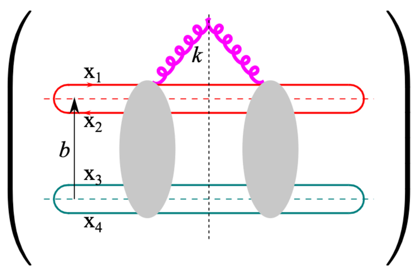
with observable O as the gluon $\vec{\mathrm{k}}_\perp = \{k_T, \phi\}$ to study anisotropies.

II. Methodology

❖ The dipole-dipole cross section

We derive the impact-parameter dependent dipole cross section for radiating one gluon

$$\frac{d\hat{\sigma}}{d^2\mathbf{b}d\eta d^2\mathbf{k}} = \frac{1}{2(2\pi)^3}\frac{1}{N_c^2}\left(\ \cdots\ \right)$$



$$= \frac{2\alpha_s^2 C_F}{N_c} \int \frac{d^2\mathbf{l}}{(2\pi)^2}\frac{1}{|\mathbf{l}|^2}\frac{d^2\mathbf{l}'}{(2\pi)^2}\frac{1}{|\mathbf{l}'|^2}\left(e^{-i\mathbf{l}\cdot\mathbf{x}_3} - e^{-i\mathbf{l}\cdot\mathbf{x}_4}\right)\left(e^{i\mathbf{l}'\cdot\mathbf{x}_3} - e^{i\mathbf{l}'\cdot\mathbf{x}_4}\right)$$
$$\times 4\alpha_s N_c \left(\frac{\mathbf{k}}{|\mathbf{k}|^2} - \frac{\mathbf{k}-\mathbf{l}}{|\mathbf{k}-\mathbf{l}|^2}\right)\cdot\left(\frac{\mathbf{k}}{|\mathbf{k}|^2} - \frac{\mathbf{k}-\mathbf{l}'}{|\mathbf{k}-\mathbf{l}'|^2}\right)$$
$$\times \left[e^{i(\mathbf{l}-\mathbf{k})\cdot\mathbf{x}_1} - e^{i(\mathbf{l}-\mathbf{k})\cdot\mathbf{x}_2}\right]\left[e^{-i(\mathbf{l}'-\mathbf{k})\cdot\mathbf{x}_1} - e^{-i(\mathbf{l}'-\mathbf{k})\cdot\mathbf{x}_2}\right],$$

with η the (pseudo)rapidity of the gluon.

❖ The pion LFWF

Obtained from the Basis Light-Front Quantization (BLFQ) approach, with an effective light-front Hamiltonian[2]:

$$H_{\rm eff} = \overbrace{\underbrace{\frac{\vec{k}_\perp^2 + m_q^2}{x} + \frac{\vec{k}_\perp^2 + m_{\bar{q}}^2}{1-x}}_{\text{LF kinetic energy}} + \underbrace{\kappa^4 x(1-x)\vec{r}_\perp^2 - \frac{\kappa^4}{(m_q+m_{\bar{q}})^2}\frac{\partial}{\partial x}\left(x(1-x)\frac{\partial}{\partial x}\right)}_{\text{confinement}}}^{H_0} + \underbrace{V_g}_{\text{one-gluon exchange}} + H_{\gamma 5}$$

III. The azimuthal distribution

❖ The flow coefficients

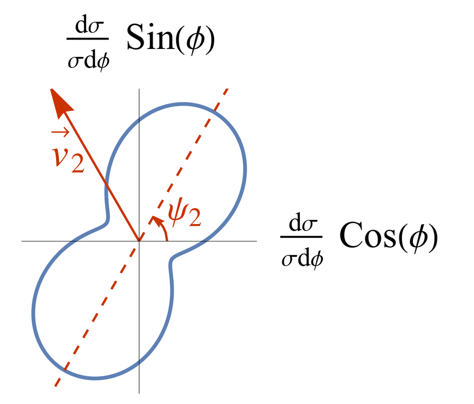
The azimuthal flow coefficients v_n and the reaction plane angle ψ_n are defined as

$$\frac{d\sigma}{d\phi} = \frac{\sigma}{2\pi}\left[1 + 2\sum_n\left(v_n^x\cos(n\phi) + v_n^y\sin(n\phi)\right)\right]$$

With $\boldsymbol{v}_n = \{v_n^x, v_n^y\}$, we have $v_n = |\boldsymbol{v}_n|$ and $\psi_n = \phi_{\boldsymbol{v}_n}/n$.

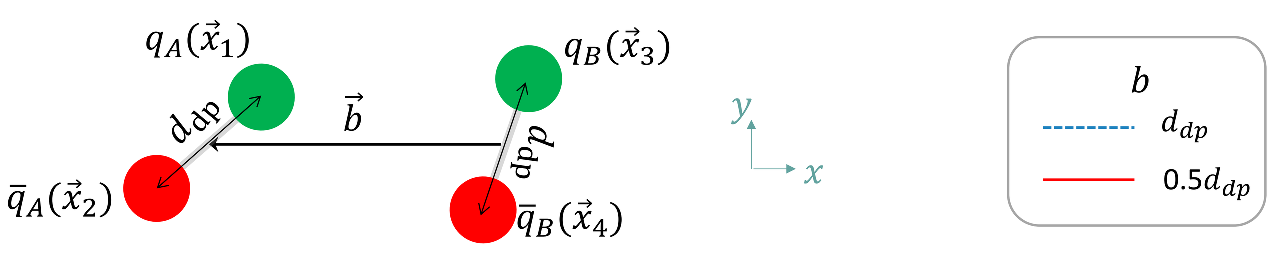
The elliptic flow v_2

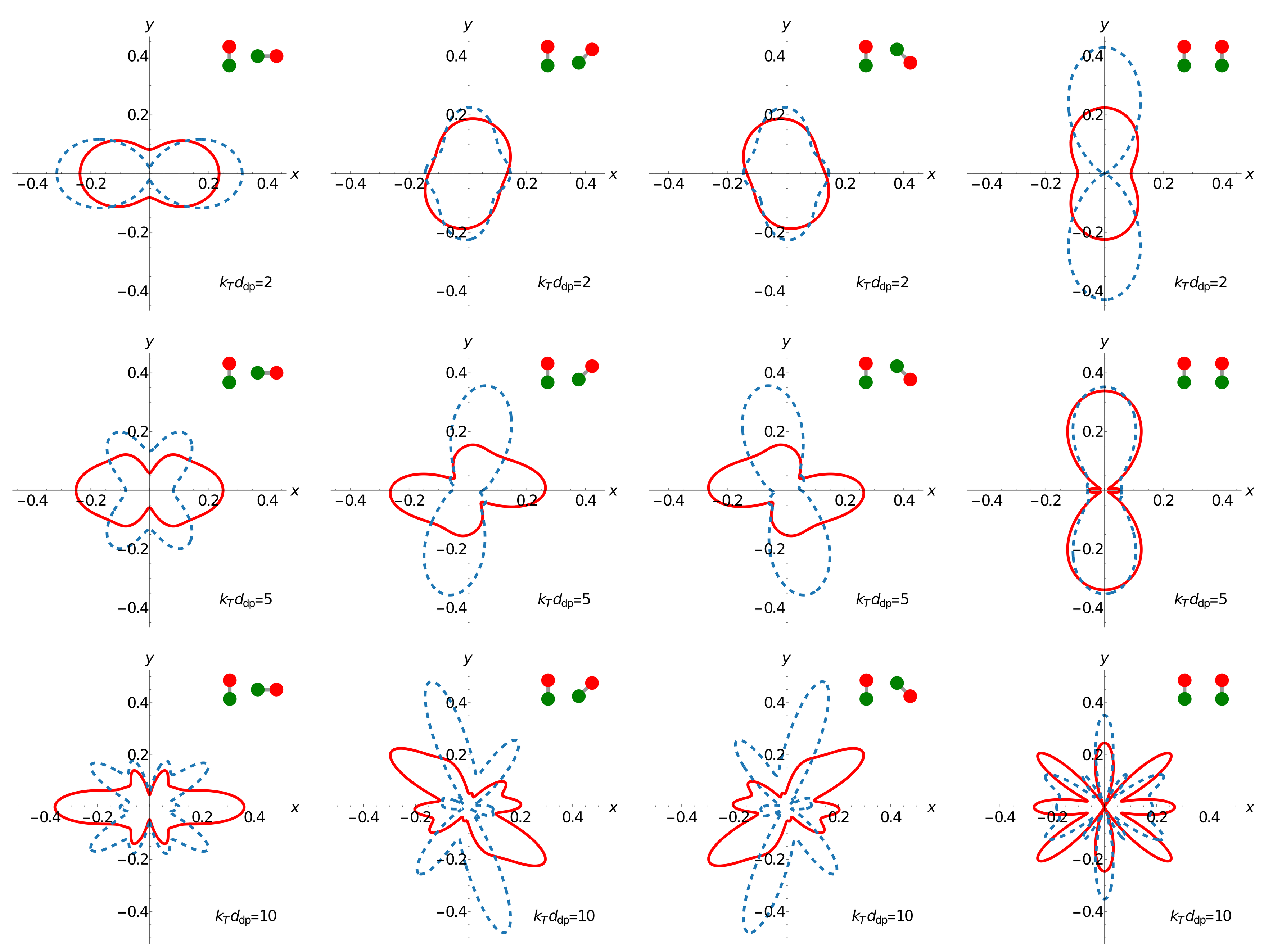
$$\frac{d\sigma}{d\phi} = \frac{\sigma}{2\pi}\left[1 + 2v_2\mathrm{Cos}(2(\phi-\psi_2))\right]$$



❖ At different dipole configurations and k_T regimes

The azimuthal distribution $\frac{1}{\hat{\sigma}}\frac{d\hat{\sigma}}{d\phi}(\cos\phi, \sin\phi)$ at $k_T d_{dp} = 2, 5, 10$.



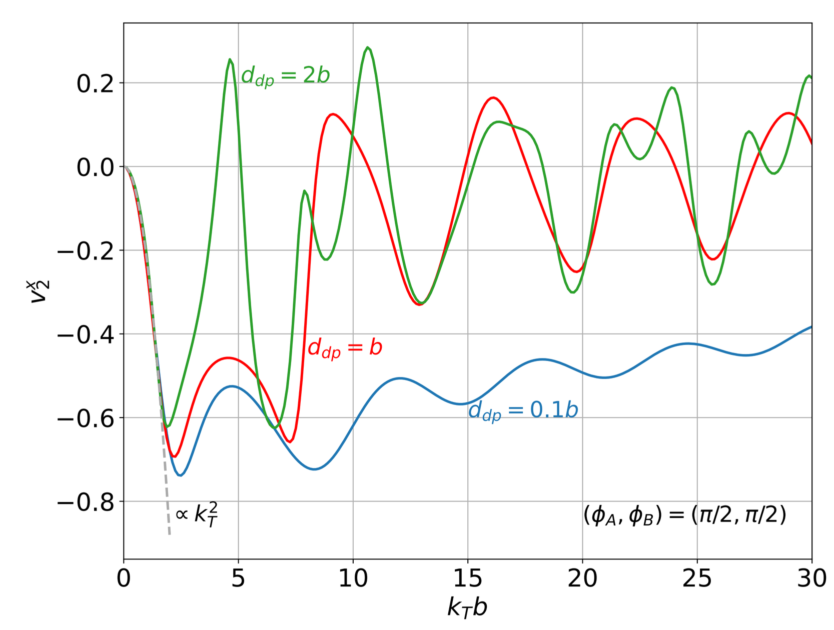


small k_T
Elliptical pattern, (ϕ_A, ϕ_B) – integrated v_2 is sizable

large k_T
Highly oscillatory, (ϕ_A, ϕ_B) – integrated v_2 is vanishing

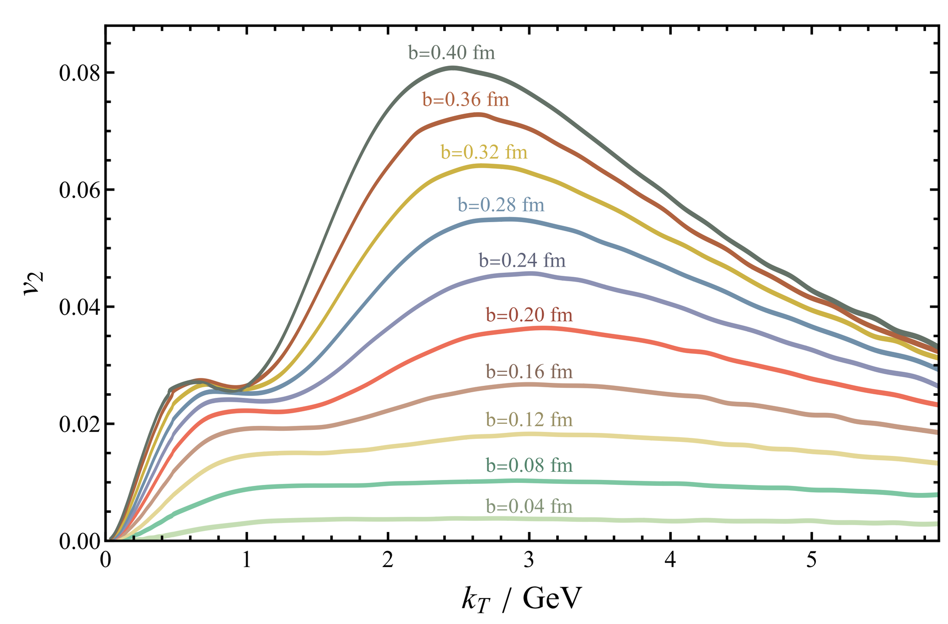
IV. v_2

❖ $q\bar{q} + q\bar{q} \to g + X$



Observations:
1) $v_2 \propto k_T^2$ at small k_T
2) v_2 oscillates and decreases at larger k_T
3) v_2 is larger at smaller d_{dp} or equivalently larger b

❖ $\pi + \pi \to g + X$



Observations:
1) $v_2 \propto k_T^2$ at small k_T
2) v_2 at larger k_T depends on the centrality of the collisions

References

[1] B. Wu, JHEP 07 (2021) 002, arXiv: 2102.12916.
[2] W. Qian, S. Jia, Y. Li, and J.P. Vary, Phys. Rev. C102 (2020) 5, 055207.