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TRANSVERSE MOMENTUM FLUCTUATIONS AND CORRELATIONS* **

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We study fluctuations and correlations of the average transverse momentum of particles emitted in heavy-ion collisions. Fluctuations of the average transverse momentum are related to event-by-event fluctuations of the size and entropy of the initial source. Hydrodynamic calculations using a Glauber model with quark degrees of freedom reproduce the data. We study correlations of the average transverse momentum in different rapidity bins. We propose a definition of the observable that can be directly related to correlations of the collective flow variables.

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1. Introduction

Matter formed in relativistic heavy-ion collisions undergoes a collective expansion. The azimuthal asymmetry of the spectra is studied both experimentally and theoretically as a measure of the initial conditions in the collision, as well as a probe of the properties of the matter formed in the interaction region. The azimuthal asymmetry of the flow is caused by the asymmetric acceleration of the fluid. The pressure gradients in the fireball reflect the asymmetry and fluctuations of the density in the fireball.

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A very similar mechanism drives the fluctuations of the average transverse flow in the collision [2]. The transverse size of the fireball fluctuates event by event. In events with a small fireball size, the accumulated transverses flow is larger than for a fireball with a larger size (Fig. 1). Transverse momentum fluctuations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV have been calculated in hydrodynamic simulations with event-by-event fluctuating Glauber model initial conditions [3] and agree quantitatively with the experimental data [4,5]. This observable may be used as a constraint on the magnitude of fluctuations in the initial state.

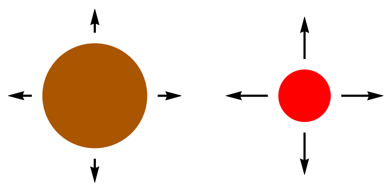

Fig. 1. Size fluctuations of the initial fireball bring $p_{\rm T}$ fluctuations in the spectra, from [1].

2. Transverse momentum fluctuations with wounded quarks

The Glauber Monte Carlo model is often used to obtain the initial state in heavy-ion collisions. It contains event-by-event fluctuations from random individual nucleon–nucleon collisions. Recently, a version of the model involving quark degrees of freedom [6] has been revived in the context of heavy-ion collisions at RHIC and the LHC [7,8]. The quark Glauber model uses parton degrees of freedom as objects that scatter inelastically in a heavy-ion collision. This model describes fairly well the scaling of the multiplicity at central rapidity with the number of quarks participating in the collision [9].

The variance of the average transverse flow is defined as [11]

$$C_{p_{\rm T}} = \left\langle \frac{1}{N(N-1)} \sum_{i \neq j} \left(p_{\rm T}^i - \langle [p_{\rm T}] \rangle\right) \left(p_{\rm T}^j - \langle [p_{\rm T}] \rangle\right) \right\rangle , \qquad (1)$$

where $[\ldots]$ denotes the average in a particular event and $\langle \ldots \rangle$ the average over the events. The above formula, excluding self-correlations, is a robust estimator of event-by-event fluctuations of the average transverse momentum. Typically, results are presented as the scaled variance $\frac{C_{p_{\rm T}}}{\langle [p_{\rm T}] \rangle^2}$.

In Fig. 2, there are presented results from two viscous hydrodynamic calculations, one using nucleon (squares) and one using quark Glauber model of initial conditions (circles). One notices that the calculation using quark degrees of freedom reproduces the ALICE Collaboration data fairly well. In particular, both the data and the simulation results show a similar multiplicity dependence. We note that this multiplicity dependence deviates from the simple scaling $\frac{C_{p_\mathrm{T}}^{1/2}}{\langle [p_\mathrm{T}] \rangle} \propto \left(\frac{\mathrm{d}N}{\mathrm{d}\eta}\right)^{-1/2}$. Hydrodynamic simulations show that fluctuations of the average transverse flow result from the event-by-event fluctuation of the initial size and entropy of the fireball [1, 12] on event-by-event basis.

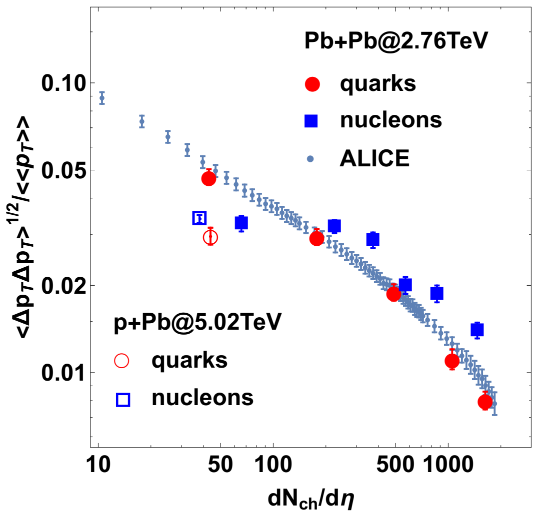

Fig. 2. The scaled transverse momentum fluctuations plotted *vs.* charged hadron multiplicity. Results of the hydrodynamic simulations are presented for the nucleon Glauber model (squares) and quark Glauber model (circles) initial conditions. The filled symbols correspond to the case of Pb+Pb collisions, whereas the empty symbols indicate our predictions for p+Pb collisions at centrality 0–3%. The experimental data for Pb+Pb case come from the ALICE Collaboration (small points) [10]. From [1].

3. p_T–p_T correlations

Flow generated at two different rapidities is expected to be strongly correlated. This correlation results from the early stage of the collision and reflects correlations in the fluctuations of the initial fireball. One can define correlations between any pair of observables related to collective flow or initial entropy: multiplicity, transverse flow, azimuthal flow coefficients, azimuthal flow angles.

The correlation of transverse flow in two pseudorapidity regions F and B can be defined using the standard Pearson coefficient of the average transverse flow

$$b\left([p_{\rm T}]_F,[p_{\rm T}]_B\right)=\frac{\langle([p_{\rm T}]_F-\langle[p_{\rm T}]_F\rangle)\left([p_{\rm T}]_B-\langle[p_{\rm T}]_B\rangle\right)\rangle}{\sqrt{\left\langle\left([p_{\rm T}]_F-\langle[p_{\rm T}]_F\rangle\right)^2\right\rangle\left\langle\left([p_{\rm T}]_B-\langle[p_{\rm T}]_B\rangle\right)^2\right\rangle}}\,. \tag{2}$$

The preliminary data for the ALICE Collaboration [13] are qualitatively reproduced by the model (Fig. 3). However, the main contribution to the denominator in Eq. (2) comes from statistical fluctuations in finite multiplicity events and not from fluctuations of the average collective flow. Thus, this observable cannot be directly interpreted as a measure of the correlation of the collective flow in different pseudorapidity bins.

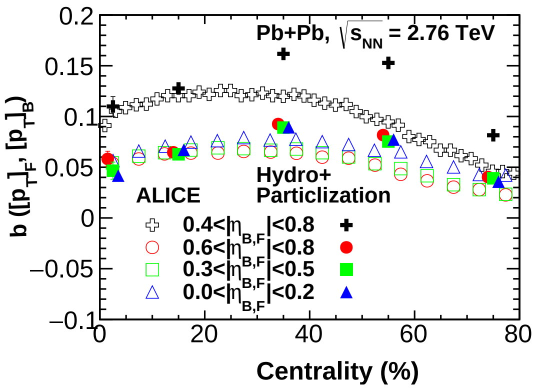

Fig. 3. Preliminary data from the ALICE Collaboration [13] on $b\left([p_{\rm T}]_F,[p_{\rm T}]_B\right)$ are compared to hydrodynamic model predictions, from [14].

The transverse flow–transverse flow correlation coefficient can be defined by excluding self-correlations in the definition of the variance [14]

$$\rho\left([p_{\rm T}]_F,[p_{\rm T}]_B\right)=\frac{\langle([p_{\rm T}]_F-\langle[p_{\rm T}]_F\rangle)\left([p_{\rm T}]_B-\langle[p_{\rm T}]_B\rangle\right)\rangle}{\sqrt{C_{p_{\rm T}}(F)C_{p_{\rm T}}(B)}}\,. \tag{3}$$

The results of the calculation using quark Glauber initial conditions are shown in Fig. 4. We predict that the $p_{\rm T}$–$p_{\rm T}$ correlation coefficient is close to one ($\rho>0.8$), significantly larger than the Pearson correlation coefficient $b\left([p_{\rm T}]_F,[p_{\rm T}]_B\right)$. The results show noticeable non-flow contributions.

Alternatively, the covariance of the average transverse in two pseudorapidity bins flow can be measured. In Fig. 5, there is shown the prediction for the covariance scaled by the average transverse momentum. Multiplying by

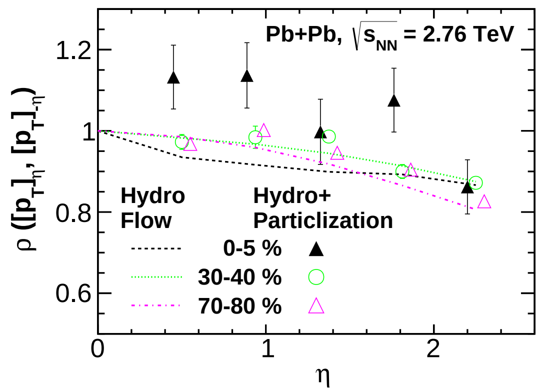

Fig. 4. Transverse flow–transverse flow correlation coefficient $\rho([p_{\rm T}]_\eta,[p_{\rm T}]_{-\eta})$ as a function of η. Symbols are for results from realistic finite multiplicity events and lines are obtained from spectra integration, from [14].

$(\mathrm{d}N/\mathrm{d}\eta)^{1/2}$ compensates for the trivial multiplicity scaling of fluctuations. The quantity weakly depends on the bin separation, but has an interesting centrality dependence, with a maximum for semi-central collisions.

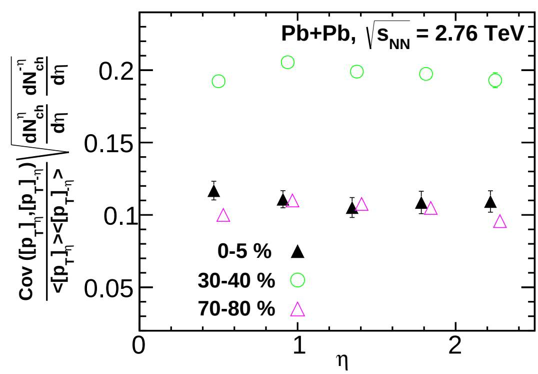

Fig. 5. Covariance $\mathrm{Cov}([p_{\rm T}]_\eta,[p_{\rm T}]_{-\eta})$ of the average transverse momentum in two pseudorapidity bins scaled by the product of the square roots of the charged particle densities and by the inverse of the average transverse momenta in the two pseudorapidity bins. Results are shown as a function of the bin position η, for three different centralities.

The decorrelation as a function of pseudorapidity separation can be studied using a three-bin observable, as proposed by the CMS Collaboration to measure azimuthal flow decorrelations [15]

$$r_{p_{\rm T}}(\eta)=\frac{\langle\left([p_{\rm T}]_{\eta_{\rm ref}}-\langle[p_{\rm T}]_{\eta_{\rm ref}}\rangle\right)\left([p_{\rm T}]_{-\eta}-\langle[p_{\rm T}]_{-\eta}\rangle\right)\rangle}{\langle\left([p_{\rm T}]_{\eta_{\rm ref}}-\langle[p_{\rm T}]_{\eta_{\rm ref}}\rangle\right)\left([p_{\rm T}]_{\eta}-\langle[p_{\rm T}]_{\eta}\rangle\right)\rangle}\,. \tag{4}$$

The covariance is measured for two bins (at η and $-\eta$) with respect to a forward bin at η_{ref}. In some range of η, one can impose a minimal pseudotrapidity separation, reducing non-flow contributions. The decorrelation (or factorization breaking) of the transverse flow is small and increases with the pseudorapidity separation (Fig. 6).

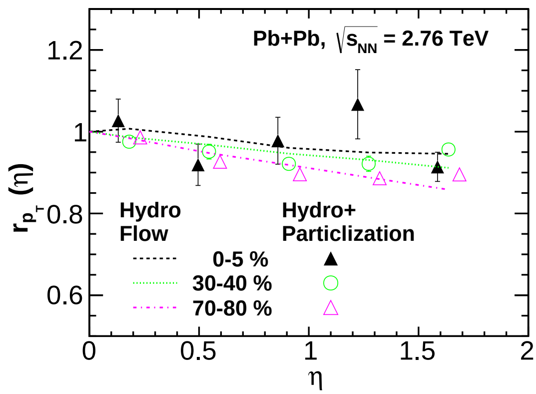

Fig. 6. Factorization breaking coefficient $r_{p_{\mathrm{T}}}(\eta)$ of the average transverse momentum at different pseudorapidities. Symbols are for results from realistic finite multiplicity events and lines are obtained from spectra integration.

4. Summary

We present a study of the average transverse flow of particles emitted in heavy-ion collisions. Our main observations are:

— transverse flow fluctuations result from fluctuations of the size and entropy of the fireball,

— the hydrodynamic model with the quark Glauber initial conditions describes fairly well the variance of the average transverse flow,

— the decorrelation of the transverse flow in two pseudorapidity bins can be studied using the correlation coefficient.

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