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Multi-particle eccentricities in collisions dominated by fluctuations

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Abstract

We compute analytically the multi-particle eccentricities, $\epsilon_m\{2n\}$, for systems dominated by fluctuations, such as proton–nucleus collisions at the Large Hadron Collider. In particular, we derive a general relation for $\langle \epsilon_2^{2n} \rangle$. We further discuss the relations between various multi-particle eccentricities and demonstrate that $\epsilon_2\{2\} > \epsilon_2\{4\} \simeq \epsilon_2\{6\} \simeq \epsilon_2\{8\}$, in agreement with recent numerical calculations in a Glauber model.

Keywords: LHC; p + A; Quark–gluon plasma

1. Introduction

Recent measurements of high multiplicity proton–proton (p + p) and proton–nucleus (p + A) collisions at the Large Hadron Collider (LHC) revealed an unexpected enhancement of the two-particle correlation function at small azimuthal angles and large separation in rapidity [1–4]. This effect was also seen at the Relativistic Heavy Ion Collider (RHIC) in deuteron–gold (d + Au) and helium–gold (^{3}He + Au) collisions [5,6].

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The same correlation pattern was previously observed in nucleus–nucleus (A + A) collisions at RHIC [7]. In nucleus–nucleus collisions the azimuthal angle correlation function and its Fourier harmonics are well described by the relativistic *hydrodynamics*, an effective theory of long wave excitations in a strongly coupled system [8]. Using viscous hydrodynamics, the ratio of the shear viscosity over the entropy is found to be surprisingly small (see, e.g., Ref. [9]) and close to the conjectured lowest bound for a strongly interacting system [10].

Nucleus–nucleus collisions are immensely complicated, due to multi-particle rescattering, the possible formation of a thermal system, and subsequent collective evolution. They do not offer a direct possibility to study initial state effects. It was expected that elementary p + p and p + A collisions are dominated by the initial state effects and thus their behavior can be studied and described by quantum chromodynamics (QCD) at weak coupling. However, due to the high densities of partons, the effects of gluon saturation must be taken into account. This is done in the framework of the *Color Glass Condensate* (CGC) [11], an effective description of a hadron at asymptotically high energy in the regime of weakly coupled QCD. Although at present there is no compelling experimental evidence indicating that the CGC is an appropriate tool to interpret hadronic collisions at the LHC energies, there are attempts to describe the azimuthal angle correlation functions in p + p and p + A collisions at the LHC [12], see also Refs. [13–15], and very recent development in Ref. [16], which in particular showed that conventional CGC used in Ref. [12] is incompatible with the experimental data at high multiplicity. Recently, hydrodynamics was applied to p + A collisions [17–22] with a reasonably good fit to the data. This success however does not solve several conceptual theoretical problems, such as how quickly thermalization occurs, whether the initial conditions are boost invariant, and many other effects, which are implicitly assumed when hydrodynamics is applied. Very recently some of these problems were addressed in the AdS/CFT framework in Refs. [23,24]. Finally, a multi-phase transport model (AMPT) [25] was recently compared with the experimental data in p + p [26], p + A [27] and d + Au [28] interactions. Possible origin of the anisotropies within the AMPT model are discussed in Ref. [29].

In summary, at present we have two general approaches for the high multiplicity p + p and p + A collisions at the LHC energy: models of strongly interacting medium (hydrodynamics, AdS/CFT, cascade) and a rival effective theory of QCD at high energies in the weakly interacting regime, the CGC. Several observables and ideas were recently put forward to single out an appropriate language to describe phenomena in these collisions [30–33].

The motivation for this short note is the observation of Ref. [34], where the authors showed that the initial eccentricities of the interaction region in p + A and A + A interactions form a peculiar hierarchy, namely, the eccentricities computed with the two and higher number of particles satisfy the following relation:

$$\epsilon_2\{2\} > \epsilon_2\{4\} \simeq \epsilon_2\{6\} \simeq \epsilon_2\{8\} \simeq \dots \tag{1}$$

This relation was also verified in Ref. [35], where its origin was attributed to a power law distribution of ϵ_2.

Equation (1) has serious phenomenological implications. First, if the same hierarchy is observed for the Fourier coefficients of the azimuthal correlation function in p + A collisions, it would indicate that the azimuthal correlation of hadrons is determined by the geometry of the initial state. This favors approaches where the initial geometry is translated into momentum space from collective effects, such as in hydrodynamics. Current treatments of the CGC are independent of the geometry, so that equivalent hierarchy for the Fourier coefficients of the azimuthal correlation function is not apparent.