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ScienceDirect

Nuclear Physics A 967 (2017) 105–112

NUCLEAR PHYSICS A

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Origins of collectivity in small systems

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Abstract

We review recent developments in the theoretical description and understanding of multi-particle correlation measurements in collisions of small projectiles (p/d/^{3}He) with heavy nuclei (Au, Pb) as well as proton+proton collisions. We focus on whether the physical processes responsible for the observed long range rapidity correlations and their azimuthal structure are the same in small systems as in heavy ion collisions. In the latter they are interpreted as generated by the initial spatial geometry being transformed into momentum correlations by strong final state interactions. However, explicit calculations show that also initial state momentum correlations are present and could contribute to observables in small systems. If strong final state interactions are present in small systems, recent developments show that results are sensitive to the shape of the proton and its fluctuations.

Keywords: correlations and fluctuations, heavy ion collisions, anisotropic flow, color glass condensate

1. Introduction

Multi-particle correlation measurements in collisions of small projectiles (e.g. p/d/^{3}He) with other small projectiles or heavy ions (e.g. Au, Pb) show characteristic structures that are long range in rapidity and have azimuthal anisotropies very similar to what was measured in heavy ion collisions [1]. In heavy ion collisions these structures have for a long time been interpreted as emerging from the system's response (via strong final state interactions) to the initial shape of the interaction region [2, 3, 4, 5]. In this case the long range nature of the correlation is due to the transverse geometry being almost rapidity independent. To model the final state either relativistic hydrodynamics or transport simulations have been employed. When combined with sophisticated event-by-event initial state models, very good agreement with a wide range of experimental data, including the correlations under consideration, has been achieved with these calculations [3].

The natural question to ask is whether multi-particle correlation measurements in small collision systems are described within the same framework and thus can be interpreted to have the same physical origin. The reason why the answer to that question is not a simple yes is two-fold. First, the applicability of some of the most successful final state simulations, namely relativistic viscous hydrodynamics, becomes more questionable as the system size decreases and gradients become larger. Second, a wide range of calculations, mostly within the color glass condensate (CGC) framework, which is an effective theory of quantum chromo

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http://dx.doi.org/10.1016/j.nuclphysa.2017.05.017

dynamics (QCD) at high energy, show that initial state momentum correlations of produced gluons are present and have similar structures as the experimentally observed correlations [1, 6].

In the following we discuss the question of applicability of hydrodynamics, the role of subnucleonic fluctuations, and the contribution from initial state momentum correlations. We then follow with a discussion of what observables could give further insight into what source of correlation dominates in a given system for a given multiplicity range.

2. Applicability of hydrodynamics and the role of non-equilibrium evolution

Even in the case of heavy ion collisions applying hydrodynamics to describe the system at relatively early times has been under debate. This is because to this date it has not been understood from first principles how the system can evolve from very far from equilibrium (two colliding nuclei moving in opposite directions) to close to locally equilibrated, or at least close to locally isotropic [7] quickly enough. In fact, in a rapidly expanding system like heavy ion collisions, no theory, neither in the strong nor weak coupling limit, has ever found pressure anisotropies (between longitudinal and transverse pressures) that are smaller than 50% [8].

Yet, for reasons unknown, hydrodynamics describes the system even for large pressure anisotropies extremely well [9, 10, 11, 12, 13]. A recent attempt [14, 8] at an explanation for this behavior is based on studies of the hydrodynamic and non-hydrodynamic modes of various theories (e.g. in AdS/CFT or kinetic theory) [15, 16, 17, 18, 19]. It is argued that the system behaves hydrodynamically as long as the hydrodynamic modes (for which $\omega(k) \to 0$ as $k \to 0$) dominate, independent of the system's isotropy. Within this interpretation a lower limit of $\sim 0.15\,\mathrm{fm}$ for the size of a droplet of fluid nuclear matter was extracted [8].

Even if hydrodynamics is applied at times $\gtrsim 0.5\,\mathrm{fm}$ the details of the non-equilibrium evolution before that time will be more important in small systems, whose total evolution time is often only $\lesssim 3\,\mathrm{fm}$. This increased importance of the non-equilibrium stage has been demonstrated for photon production in [20]. Thus, better theoretical understanding is needed of this hard to describe part of the evolution. Recent progress in this direction has been made in both the weak and strong coupling limits. See [21] and [22] for recent reviews.

Final state interactions can also be simulated microscopically without relying on the applicability of hydrodynamics. Calculations performed in the AMPT framework, which uses a parton cascade to describe the final state interactions, can also reproduce the anisotropic momentum distributions of produced particles in small systems [23, 24, 25, 26, 27]. Interestingly the data is well described when using a rather small parton-parton cross section. This leads to an interpretation dubbed "parton escape mechanism", which is fundamentally different from the collective motion produced in hydrodynamics. In the AMPT simulations only a few collisions are required to produce the momentum anisotropy, which emerges because partons are more likely not to scatter, and thus escape, if the medium is shorter in the direction they are moving. It is not clear at this point how to distinguish the two scenarios experimentally.

3. Subnucleonic fluctuations and their effect on anisotropic flow in p+Pb collisions

Assuming that hydrodynamics is in fact applicable to describe the final state dynamics of small collision systems, many different calculations have produced results for anisotropic flow coefficients comparable to the experimental data from the LHC (see the review [1] and more recent work [28, 29]). The available calculations differ mainly in the choice of initial state, which in proton+proton and proton+heavy ion collisions is not well constrained. Calculations that employ variations of the Monte-Carlo Glauber model produced results compatible with most of the data, even when subnucleonic fluctuations of the proton were ignored. However, the IP-Glasma model [30, 31] for example, which is one of the few initial state models not excluded by data from heavy ion collisions, such as the event-by-event distributions of anisotropic flow coefficients, could not reproduce the momentum anisotropy in p+Pb collisions at the LHC [32]. The reason for the disagreement was the assumption of an approximately (modulo small color charge fluctuations)