Collectivity in small systems: Initial correlations or final state flow?

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Abstract. I review recent progress in understanding correlation measurements in small collision systems, such as proton+lead and proton+proton collisions at the Large Hadron Collider (LHC) and proton+gold, deuteron+gold, and ^{3}He+gold collisions at the Relativistic Heavy Ion Collider (RHIC). I discuss two distinct theoretical approaches to describing the experimental data on multi-particle correlations. The first attributes the origin of the measured correlations to strong final state interactions, often described by hydrodynamics, the second employs the color glass condensate effective theory and is able to reproduce many features of the data from initial state effects only. I discuss how to distinguish which of the two sources of correlations dominates the experimental observables, and give an outlook on how to make progress on the theory side.

1. Introduction
Collective effects such as long range correlations in rapidity with distinct azimuthal structures have been observed in nuclear collision systems ranging from p+p to A+A collisions, at least for high enough multiplicity events [1]. Our experience with heavy ion collisions, where such correlations are understood as being generated via the response of the evolving hot and dense matter to the initial fluctuating geometry [2], led many to believe that small systems, such as p+A collisions, behave in a similar way, at least when large numbers of particles are produced. This is conceivable, at least for particles with low enough transverse momentum, which are numerous. Nevertheless, the applicability of viscous hydrodynamics may be questioned as the system becomes smaller, since quantities like the Knudsen number or the inverse Reynolds number become large [3]. This does not immediately exclude significant final state effects but questions the tool of hydrodynamics, which assumes small deviations from local thermal equilibrium and isotropy, for describing these effects. In the following I will briefly discuss the hydrodynamic description of small collision systems followed by the initial state picture. I will then address how to distinguish the two scenarios using experimental observables.

2. Hydrodynamics
Hydrodynamics, supplemented with an appropriate initial state, has been applied to compute particle production in small collision systems. Agreement with certain experimental data on spectra and correlations can be very good [4, 5, 6, 7, 8, 9, 10, 11]. In fact, one could say that hydrodynamics, a gradient expansion, does an "unreasonably good" job in describing the experimental data, because pressure anisotropies in the small systems can be very large. This

was most recently summarized in [12], where it is argued that hydrodynamics working does not necessarily imply near-equilibrium behavior of the matter.

Assuming that at least for low momenta ($p_T \lesssim 2\,\text{GeV}$) hydrodynamics provides a good description of the final state interactions, and thus can provide reliable calculations of the integrated azimuthal anisotropy coefficients v_n, the disagreement of hydrodynamic calculations using the very successful IP-Glasma initial state model with experimentally obtained v_n was surprising [13]. While the smaller system size in this framework [14] is more compatible with experimental Hanbury-Brown-Twiss (HBT) data [15] than calculations in the MC-Glauber model [16], the v_n from the latter agree much better with the data.

Detailed HBT calculations using IP-Glasma initial conditions are still outstanding, however, it is likely that a consistent description of all low p_T data is only possible with the IP-Glasma initial state when including one important modification: The inclusion of a more refined geometric substructure of the proton.

3. The fluctuating shape of the proton
The original IP-Glasma model, which has been successfully applied to heavy ion collisions, assumes individual nucleons to be round (up to small variations from color charge fluctuations). This feature led to extremely small anisotropy coefficients in p+A collisions. Because in the IP-Glasma model the interaction region is dominated by the shape of the smaller projectile, i.e., the proton, a round proton shape led to an approximately round distribution of deposited energy, which in turn led to almost isotropic expansion and small anisotropic flow coefficients. This was a strong first hint at the fact that p+A collisions provide data sensitive to the geometric shape of the proton.

In fact, it was recently found that HERA data on diffractive exclusive vector meson production in e+p collisions [17, 18, 19, 20] also requires the model description to include strong geometric fluctuations of the gluon distribution in a proton at high energies [21, 22]. In particular, the transverse momentum transfer $|t|$ dependent incoherent cross section is sensitive to fluctuations at various length scales. In the dipole picture employed in [21, 22] not including geometric fluctuations leads to an under-estimation of the incoherent cross section at the largest measured $|t|$ by almost an order of magnitude. Qualititively, the observed effect of fluctuations is in line with early discussions of incoherent diffraction [23].

Comparing a model that assumes gluons to be centered around three valence quarks, whose positions fluctuate randomly, to experimental data, allowed to constrain the shape and degree of fluctuations of the gluon distribution. Other models such as a stringy proton can also lead to good agreement with the data, yet all models have one thing in common - the requirement of strong geometric fluctuations.

The next step is now to use such constrained fluctuating protons as input for IP-Glasma + hydrodynamics calculations in p+A collisions, and to see if experimental observables can be systematically reproduced, including v_n coefficients and HBT measurements.

4. Initial state gluon correlations
Long range correlations are present in the initial gluon production from colliding color glass condensates (CGC) [1, 24]. They show a similar azimuthal structure as the experimental data and calculations in the CGC framework have been able to quantitatively reproduce a variety of data from small systems [25]. These calculations were done in the dilute-dense limit, where one projectile is assumed to be dilute, and one can constrain the calculation to two-gluon exchange. For very high multiplicity events that assumption may no longer hold and calculations have to take into account multiple gluon exchanges. This can be achieved in the classical Yang-Mills framework and calculations of azimuthal anisotropies of gluons in p+A collisions yield magnitudes of v_2 and v_3 comparable to the experimental data [26].

Of course one cannot directly compare gluons with final state hadrons that are measured in the experiments. First attempts to implement fragmentation using Lund strings [27] were presented in [28]. It was shown that 1) the azimuthal correlations survive the hadronization and 2) characteristic differences in the mean transverse momentum and v_2 as a function of hadron mass are comparable to those observed in the experimental data. This "mass-splitting" effect clearly comes from particle production from a common boosted source, which in this case is the moving string, in hydrodynamics a fluid cell on the freeze-out surface. Thus it is natural that both pictures yield similar features.

The initial state correlations are uncorrelated with the global geometry of the collision system and their strength decreases with the number of uncorrelated color field domains [26]. Thus, their importance decreases as the system becomes bigger, and azimuthal anisotropies in heavy ion collisions cannot be explained without final state interactions of the produced matter.

5. Distinguishing the two scenarios

At this point it is still unresolved what mechanism dominates the generation of the observed structures in the experimental data for different small systems, multiplicities and collision energies. Hydrodynamics has a good chance of providing a reasonable description for very high multiplicities and small transverse momentum particles, which also dominate in the integrated v_n. Above a p_T of approximately $1.5\,\mathrm{GeV}$ viscous effects are too large to get reliable results from hydrodynamics, which means that the tool starts to fail, but not that final state effects become irrelevant.

More generally though, the strong final state interaction interpretation faces various challenges, in particular with respect to jet quenching: There is a surprising lack of quenching of the pronounced back-to-back correlation of di-hadrons in small systems [29], which is present in larger systems [30]. Thus, a more detailed study of such effects could shed more light on whether strong final state effects are actually present.

A promising experiment driven venue for distinguishing the two scenarios is the systematic study of small systems with expected differences in the initial geometry: At RHIC different systems such as p+Au, d+Au and ^{3}He+Au have been analyzed [31]. Due to the nucleon content of the smaller projectile on average one expects a somewhat larger elliptic shape in d+Au and a larger triangular shape in ^{3}He+Au compared to p+Au collisions. The hydrodynamic framework thus predicts [32] a larger elliptic flow in d+Au collision, and triangular flow v_3 in ^{3}He+Au, consistent with the experimental data. Initial state frameworks have yet to perform such a systematic comparison across various collision systems.

On the theory side it is desirable to develop a combined framework that includes both initial correlations and final state interactions, potentially via a parton cascade simulation. This is work in progress and it will allow to vary the system size/multiplicity to systematically study which contribution dominates under which circumstances.

It should be mentioned that there is a third scenario which could be described as weak final state interactions that produce an anisotropic parton escape. This situation was observed within AMPT simulations [33, 34] and the effect could be dominant at multiplicities/system sizes between those where the other scenarios dominate.

6. Summary

The study of correlations in small collision systems provides a unique opportunity to learn about the many-body features of quantum chromo dynamics (QCD) at high energy. There is likely a window in multiplicity and transverse momentum that will allow us to study the geometric structure of gluons in the proton via p+A collisions. Furthermore, we can potentially access intrinsic correlations within the incoming nuclear wave functions which can lead to a deeper understanding of how QCD acts within high energy nuclei.

Acknowledgments

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