THE RIDGE EFFECT

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Two particle correlation measurements in small systems like proton-proton or proton-lead collisions show strikingly similar features to those in heavy ion collisions. In particular one observes a long-range correlation in pseudo-rapidity with an azimuthal $\cos(2\Delta\phi)$ modulation, dubbed the (double-)ridge. I review the current theoretical status on interpreting this effect in small systems. Its origin could be dominated by final state effects like in heavy ion collisions or initial state effects, whose importance should increase with decreasing system size.

1 Introduction

Two-particle correlations of charged hadrons visualized in two dimensions as a function of $\Delta\eta$ and $\Delta\phi$, the difference in the two particles' pseudo-rapidity and azimuthal angle, respectively, show a characteristic (double-)ridge like structure (see Fig. 1). This long range correlation in pseudo-rapidity with a typically dominant $\cos(2\Delta\phi)$ modulation in azimuth is well understood in heavy ion collisions.[1,2] It emerges from fluctuating initial transverse collision geometries that vary weakly with rapidity and are transformed into anisotropic final particle distributions via the almost perfect fluid evolution of the medium.[3] As shown in Fig. 1, the same ridge structure is seen in (high-multiplicity) p+p and p+Pb collisions. In the following we discuss the current status of the interpretation of the ridge in small systems. A recent review gives more detail on this topic.[4]

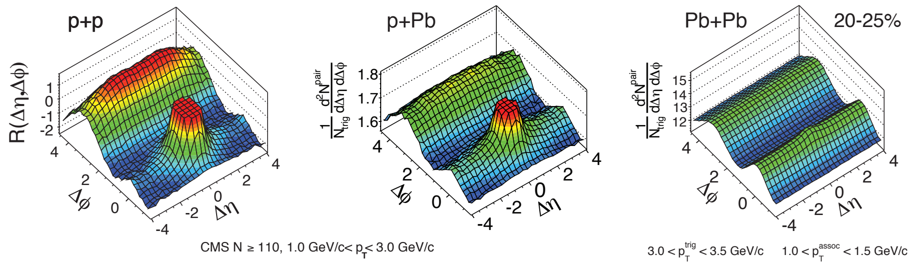

Figure 1 – Ridge structure in the two-particle correlator as observed by CMS in proton+proton [5] (left), proton+lead [6] (center), and lead+lead [7,8] (right) collisions.

2 Hydrodynamics

In heavy ion collisions viscous fluid dynamic calculations with a fluctuating initial state can describe the coefficients $V_{n\Delta}$ of the Fourier expansion of the azimuthal structure at large $|\Delta\eta|$ quantitatively.[3] This includes both the average values and the event-by-event distributions.[9,10]

Because the ridge structure looks very similar in small collision systems (that reach similar multiplicities as peripheral heavy ion collisions), it is a logical first assumption that it is produced by the same physical mechanism. In fact, predictions for two-particle correlations within a hydrodynamic framework were made early on.[11,12,13,14]

Different calculations within the hydrodynamic framework produce rather different results for the Fourier coefficients in p+Pb collisions when different prescriptions for the initial state are used. In a Glauber Monte Carlo model [15] that has all participating nucleons contribute equally to the initial geometry, much better agreement with the data is achieved compared to the IP-Glasma model [16,17], where the initial geometry is closer to the actual overlap region of the proton and the heavy nucleus. Agreement of the latter model with the data can be much improved if a more fluctuating substructure of the proton is taken into account.[18]

Both this strong sensitivity to the initial state and the fact that the applicability of hydrodynamics in small systems itself is questionable makes the quantitative theoretical results very uncertain. The applicability of hydrodynamics can be quantified by the Knudsen number, which measures the ratio of a microscopic to a macroscopic scale (like the mean free path to the system size). It was shown to be significantly larger over a larger fraction of the system evolution than in heavy ion collisions for a given shear viscosity.[19] The values of the Knudsen number reached indicate that one approaches the limits of where the hydrodynamic description of a system should be trusted.

However, even if viscous hydrodynamics is not the appropriate framework to describe them, final state effects that generate the observed collective behavior can still be important.

3 Initial state correlations

It has been shown that the particle production mechanism in high-multiplicity p+p or p+Pb collisions itself leads to correlations at least qualitatively compatible with the experimentally observed ridge structure.[4] In particular, in the color glass condensate framework, long range correlations in rapidity and $\cos(2\Delta\phi)$ azimuthal structures appear naturally. Various existing calculations use different approximations, which have been recently compared.[20]

Here, we focus on the situation where both the target and the projectile are considered dense, which should be a good limit for very high multiplicity events. This limit is described by the classical Yang-Mills framework, thus calculations can be done in the IP-Glasma picture, which is also used to produce initial conditions for hydrodynamic calculations as discussed above.

In the IP-Glasma framework one computes the gluon fields produced in the collision from the gluon fields of the two incoming nuclei by means of solving the Yang-Mills equations. From these gluon fields one can compute the gluon transverse momentum spectra. Using these to determine two-gluon correlations one extracts the Fourier coefficients of their azimuthal distribution (the rapidity correlations are long because the solutions are boost-invariant). Even at the initial time, immediately after the collision, $V_{2\Delta}$ is non-zero. The third harmonic $V_{3\Delta}$ is built up during the time evolution of the gluon fields via the source-free Yang-Mills equations.[21]

The magnitude of these coefficients for the gluon distribution is close to that of charged hadrons in the experimental data. A direct comparison requires the inclusion of a hadronization mechanism, which has been done in other color glass condensate calculations of the ridge [22], but is still work in progress in the dense-dense limit.

It is important to point out that the calculation finds the magnitude of the Fourier coefficients for gluons in the initial state to be much smaller in heavy ion collisions. This can be understood when considering that the physical interpretation of these initial correlations involves production of gluons from the same "flux-tube" or correlated region in the transverse plane. Gluons produced from different flux tubes are uncorrelated. Thus, the correlation strength is suppressed by the number of flux tubes. In central heavy ion collisions, which have a large overlap area, this number is large and the effect from initial correlations negligible. This also emphasizes the necessity for final state effects to generate the observed correlations in heavy ion collisions.

4 Status of distinguishing the two pictures

Various observables have been suggested to prove that final state effects described by viscous hydrodynamics have an important effect. Here we list several of them and review what various models predict for them:

- Mass splitting of the mean transverse momentum and Fourier coefficients of the azimuthal anisotropy: This effect is natural in any picture where particles are produced from a common moving source, like a fluid cell in hydrodynamics.[23] So the initial state framework together with a certain hadronization mechanism where particles are produced from a fragmenting string, which has an effective transverse momentum, produces a similar effect.[24]

- The observed four-particle cumulant $c_2\{4\}$ changes sign at a certain multiplicity in p+Pb collisions.[25] This can be seen as the final state collectivity setting in at this multiplicity. However, there are alternative explanations in the initial state framework that predict such behavior.[26]

- 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.[27] 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. This is because some of the events will have configurations where the two or three nucleons of the projectile, respectively, are arranged in a certain way in the transverse plane of the collision. The hydrodynamic framework thus predicts [28] a larger elliptic flow in d+Au collision, and triangular flow v_3 in ^{3}He+Au consistent with the experimental data. The same analyses have not yet been conducted in the purely initial state frameworks.

- Equality of higher order cumulants $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \ldots$ was observed in p+Pb collisions at the LHC.[29] Because in hydrodynamics all particles are correlated with a common geometry, this is a result expected in this framework. This is however not necessarily a unique feature of the hydrodynamic framework and still needs to be investigated within the initial state models.

There is further observables one should consider, like Hanbury-Brown-Twiss radii in various collision systems,[30] to draw conclusions about the origin of the ridge effect in small systems. While every observable seems consistent with the hydrodynamic framework, contributions from initial state correlations, clearly present in the theoretical analysis, thus far could not be excluded by any piece of data.

5 Conclusions

Initial state correlations with a double-ridge like azimuthal structure are clearly present. The question is whether and if so in which system and at what multiplicity they contribute a noticeable or even dominant effect compared to final state effects, which we know dominate in heavy ion collisions. Currently no observable presents clear evidence of either scenario. A way to clarify the situation will be to develop a computational framework that includes both initial and final state effects. Varying the system size and multiplicity should then lead to a clear answer.

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