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Event-by-Event Observables and Fluctuations

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Abstract

In this talk the status and open questions of the phenomenological description of all the stages of a heavy ion reaction are highlighted. Special emphasis is put on event-by-event fluctuations and associated observables. The first part is concentrated on high RHIC and LHC energies and the second part reviews the challenges for modeling heavy ion reactions at lower beam energies in a more realistic fashion. Overall, the main conclusion is that sophisticated theoretical dynamical approaches that describe many observables in the same framework are essential for the quantitative understanding of the properties of hot and dense nuclear matter.

1. Introduction

The consideration of event-by-event fluctuations in heavy ion collisions has recently received new attention of theorists and experimentalists. In summer 2010 it has been realized that higher flow harmonics in addition to elliptic flow exist and are sensitive to fluctuations in the initial state profile and to the transport coefficients of the quark gluon plasma. Within the last 2 years, the following new paradigm has been developed: Higher order eccentricities are used to characterize initial state distributions, the hydrodynamic response to these fluctuating initial conditions is studied to extract the shear viscosity over entropy coefficient by a final state momentum space analysis of anisotropic flow coefficients of order $n = 2 - 6$.

The basic question underlying this new way of thinking is why single collisions of in principle indistinguishable ground state nuclei have different properties. Even if all the controllable differences like the beam energy, centrality and system size are chosen perfectly well-defined, quantum fluctuations are unavoidable. The resulting challenge is that the corresponding fluctuations affect the probes of the quark gluon plasma. On the other hand, there is the opportunity that initial state fluctuations provide new constraints on the transport coefficients. In addition heavy ion event-by-event measurements will contribute towards determining these highly energetic nuclear initial states, that cannot be observed in any other way.

There are different types of observables associated with event-by-event fluctuations. There are the 'traditional' event-by-event observables, such as mean transverse momentum, particle ratio and conserved charge fluctuations enhanced more recently by measurements of the higher moments of e.g. the net proton distribution (skewness, curtosis, 6th order cumulant,..). The measurements of dynamic fluctuations of elliptic flow are similar to those in the sense, that they require large statistics and sophisticated analysis methods to be determined. Odd-numbered flow harmonics where the event plane is uncorrelated to the reaction plane, most prominently triangular flow, are observables of a different quality, since they are sensitive to fluctuations on the average over events as shown in Fig. 1.

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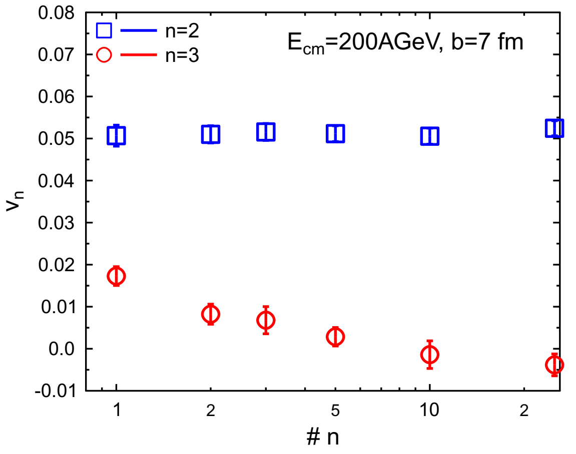

Figure 1: Triangular has the advantage to be sensitive to fluctuations as an averaged quantity (taken from [1]).

At the moment there is a wealth of experimental data on all these event-by-event measurements, but theoretical calculations of many different observables in one approach are rare. A realistic dynamical approach needs to incorporate the following stages of the reactions: initial conditions, pre-equilibrium evolution, relativistic hydrodynamics, hadronization, hadronic rescattering and freeze-out. The ultimate goal is to calculate the collision of two nuclei at almost the speed of light as a dynamical many-body problem starting from the QCD Lagrangian. As long as this is still 'wishful thinking' one needs to rely on realistic event-by-event simulations to understand the bulk properties in full detail and the fluctuation observables in heavy ion reactions. These calculations are also important to serve as a medium background for hard probes, like jets and charm quarks, especially when considering more advanced correlation observables.

2. Initial Conditions and Pre-Equilibrium Evolution

The observation of higher flow harmonics like triangular flow has demonstrated the need to consider initial state fluctuations on the scale of individual nucleons of size ~ 1 fm. It is important to realize that there is not anymore a binary choice between Glauber and CGC type initial state models, but that a reasonable parametrization for the initial distribution of matter right after the collision of the two nuclei needs to be found on more general grounds.

Considering nucleon degrees of freedom the sources of fluctuations that have been identified so far are the fluctuations in the nucleon positions and in the positions of the binary collisions, the finite size of the nucleons and the nucleon-nucleon correlations [2] and the fluctuations in the energy deposition per collision. An important constraint on these types of fluctuations is provided by the multiplicity distributions in elementary proton-proton collisions that follow a negative binomial distributions as it is shown in Fig. 2 (left).

A different way to consider initial state structures on smaller scales of $1/Q_s$, where Q_s is the saturation scale, is to calculate the fluctuations associated with the underlying gluon distributions within the nuclei [5, 6]. In Fig. 2 (right) the correlation length of the energy density has been calculated in a Gaussian Color Glass Condensate approach and indicates that the associated