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A Detailed Study and Synthesis of Flow Observables in the IP-Glasma+MUSIC+UrQMD Framework

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Abstract

In this work we use the IP-Glasma+MUSIC+UrQMD framework to systematically study a wide range of hadronic flow observables at 2.76 TeV. In addition to the single particle spectra and anisotropic flow coefficients v_n previously studied in [1], we consider event-plane correlations, non-linear response coefficients χ_{npq}, and event shape engineering. Taken together, these observables provide a wealth of insight into the collective behavior of the QGP and initial state fluctuations. They shed light on flow fluctuations, flow at fixed system size but different initial geometries, as well as the non-linear hydrodynamic response to the initial state spatial eccentricities. By synthesizing this information we can gain further insight into the transport properties of the QGP as well as the fluctuation spectrum of the initial state.

Keywords: IP-Glasma, event-by-event hydrodynamics, QGP, collective behavior, event-shape-engineering

Introduction

A number of models have been developed to study the formation and subsequent evolution of Quark Gluon Plasma (QGP), a deconfined state of quarks and gluons formed under extreme temperatures and pressures in heavy ion collisions at RHIC and the LHC. Many phenomenological studies of QGP investigate the sensitivity of one or more observables to a parameter or set of parameters within a model, with the goal of extracting information about QGP. The current study aims to take a more comprehensive look at flow observables within a single theoretical framework. Having used the hybrid IP-Glasma+MUSIC+UrQMD model to reproduce flow observables, the current work expands the study done in [1] to consider more differential flow observables with the goal of further constraining the physics of the QGP.

Model and Parameters

The IP-Glasma model, originally developed in [2], includes realistic event-by-event geometric and sub-nucleonic quantum fluctuations. A new implementation [1] is used to initialize MUSIC [3], a second-order relativistic viscous hydrodynamics code. A constant shear viscosity to entropy density ratio is used $\eta/s = 0.095$ along with a temperature dependent bulk viscosity $\zeta/s(T)$ based on [4, 5]. After hydrodynamic

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evolution, the fluid hadronizes at an isothermal hypersurface of $T_{sw} = 145$ MeV, from which UrQMD is initialized. Hadrons then undergo resonance decays and hadronic re-scatterings in UrQMD [6] before freezing out. A more in-depth discussion of the model, parameters, and centrality selection can be found [1].

Results

It has been known for some time that IP-Glasma's initial state fluctuations are able to describe event-by-event distributions of v_n's [7] when coupled to viscous hydrodynamics. Such event-by-event flow fluctuations give rise to non-trivial flow correlations. By fixing the system size, and isolating fluctuations in the momentum space geometry in a given centrality bin, event shape engineering (ESE) gives a measure of the spread of values of v_n while simultaneously illuminating correlations between different harmonics. In practice, ESE is done by re-binning centrality using the reduced flow vector [8],

$$q_n = \frac{Q_n}{\sqrt{N}}, \qquad Q_n = \sum_{i=1}^{N} e^{in\phi_i}, \tag{1}$$

where N is the number of particles in the event. Fig. 1 shows Pb-Pb collisions at 2.76 TeV in q_2 bins. Within

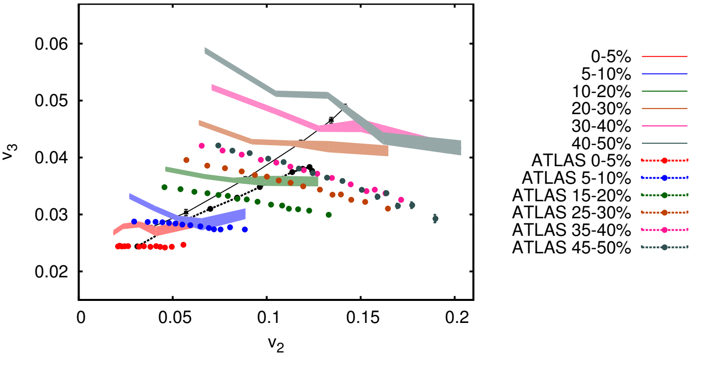

Fig. 1. v_3 vs v_2 for 0.5 GeV $\leq p_T \leq$ 2.0 GeV in q_2 bins at 2.76 TeV, compared to ATLAS data [9]. The dashed black line represents the centrality bin averaged values from ATLAS for 0-50%, and the solid black line corresponds to the same quantities from the IP-Glasma+MUSIC+UrQMD simulations.

each centrality bin, one can see a wide spread of values for v_2, and an anti-correlation between v_2 and v_3 for peripheral collisions. Such an anti-correlation has received much attention recently with the non-symmetric cumulant [10], but is unmistakably present in ESE in both experiment and theory. It is worth noting that the overestimation of the data in Fig .1 is largely due to the fact that our transport coefficients, η/s and $\zeta/s(T)$, were extracted in [11] from particle spectra and integrated v_n at the expense of not describing the differential $v_n(p_T)$ for all p_T. This was done with ALICE data for which 0.2 GeV $\leq p_T \leq$ 5.0 GeV. Considering the p_T-dependence of $v_n(p_T)$ in [1], where we slightly underestimate the data below about 0.7 GeV and overestimate above this point, it is clear that the ATLAS p_T-cut will lead to overestimates of the integrated flow harmonics. Nonetheless, the spread of values and the correlation between v_2 and v_3 that are present in the experimental data are qualitatively reproduced in the simulations.

The ESE provides many data points by which to constrain model parameters, and the relationship between different centrality averaged v_n's, sometimes referred to as the "boomerang," has been shown to be quite sensitive to the shear viscosity [12]. These features make ESE an excellent candidate to constrain the shear and bulk viscosities of the QGP through direct comparison between theory and experiment.