

Monte-Carlo Simulations Displaying an Evolving and Fluctuating Heavy Ion Collision Yield

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Abstract

The relativistic heavy ion collisions undergo extremely hot and dense phases, which are postulated to resemble parts of the cosmological early stages. This suggests that the collisions could provide a QCD laboratory, in which phenomena of strong interactions are studied. The investigations of colour interactions in the collisions are made in a Monte-Carlo computational model which implements dynamical interactions. The dynamics are in present work modelled as a superposition of parametrized hydrodynamics and a media-modulated hard state. In the simulations, observations are differentiated in terms of density, position, and production modes; in combination with a higher order analysis. The heavy ion yield appears to have been reproduced to great detail in present model. The reproduction of both elliptic- and triangular flow speaks of a fluctuating-, and density-characterized first order geometric mode, in addition to higher order features. In the simulations, it seems that the particle fragmentation is density characterized, thus providing a channel for pressure differentiated observations. Therefore it is concluded that the present computational model is reproducing the heavy ion yield to higher orders, thus supporting observables which differentiates strong phenomena within the simulated evolving matter.

Introduction

There are analogues between the cosmological early stages and the conditions achieved in a modern day-, state-of-the-art high-energy experiment. This suggests that the dynamics of hadron genesis are possible to observe through the observation and simulation of ultra-relativistic heavy ion collisions [1, 2, 3, 4].

In the relativistic heavy ion collisions; the interacting matter is assumed to go through several phases when heating up and subsequently expanding and cooling to chemical- and thermal freeze out. The interacting matter is at present believed to be modulated by the evolving surroundings [5, 6, 7, 8]. In order to study these phenomena; a general framework needs to be defined.

The derivation of the heavy ion collision observables starts with the particle momentum distribution, which is split into a transverse momentum p_{\perp} spectra, a rapidity y dependence, and an azimuthal ϕ part [9, 10]

$$\begin{aligned} E \frac{d^3N}{d^3p} &= \frac{d^3N}{p_{\perp} dp_{\perp} dy d\phi} \\ &= \frac{1}{2\pi} \frac{d^2N}{p_{\perp} dp_{\perp} dy} \left(1 + \sum_{n=1}^{\infty} 2v_n(p_{\perp}, y) \cos[n(\phi - \Psi_n)] \right) \end{aligned} \quad (1)$$

From the expression 1: it is seen that the Fourier-coefficients v_n , are projected as

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle. \quad (2)$$

The observables from (1) and (2), provides information on interactions within the evolving matter, which are observed as features of the yield. To the best of the present author's knowledge, modulated interactions and harmonic-interplay have not been investigated to a great extent in computational flow-models.

It is here hypothesized that the correlations between the harmonic terms in (1), and (2) carries information on strong *in medio* modulated interactions; which are observed as correlations in the observed yield. Here, the relations between the main geometric mode v_2 , and the higher degree modes v_3 , and v_4 in (2), are observed in order to characterize the nature of the media-modulated vertexes.

The features of the harmonics are here believed to be possible to investigate with novel, relative compound-flow phase-space correlators.

Method

The ultra-relativistic heavy ion collisions are in this work investigated by generating event-data in the Monte-Carlo computational model HYDJET++ [11]. The model simulates an evolving state, which comprises of a hard-, and a thermal state. This superposition and projections of it, are thus made possible to investigate.

At present, multiple event-planes are implemented in the model, thus enabling simulations of harmonic interplay. This will provide for a rich investigation of correlators, such as compound flow of higher degree; thus supporting postulates of bulk phenomena and fluctuations.

The second, third, and fourth order model-fireball deformations are here implemented, in order to reproduce the observed event-plane characteristics. The modulation of the fireball geometry and dynamics in concord with the generation of the event-planes, is providing the means for the simulation of higher harmonics. The multiple scattering Glauber model [12], models the interacting bulk matter in this model. An implementation of a Bjorken-scaling evolution (Fig.1a) with decays, and pressure-dependent *in medio* modulated processes [5, 6, 7, 8] (Fig.1c), provides a realistic simulation of an evolving fireball. The expanding matter, is here modelled to freeze out thermally and chemically; thus forming the observable particles (Fig.1b).

The simulated flow is here forming sixth order correlators. These correlations provides information on harmonic interplay; thus investigating the interaction modes of the heavy ion collision yield.

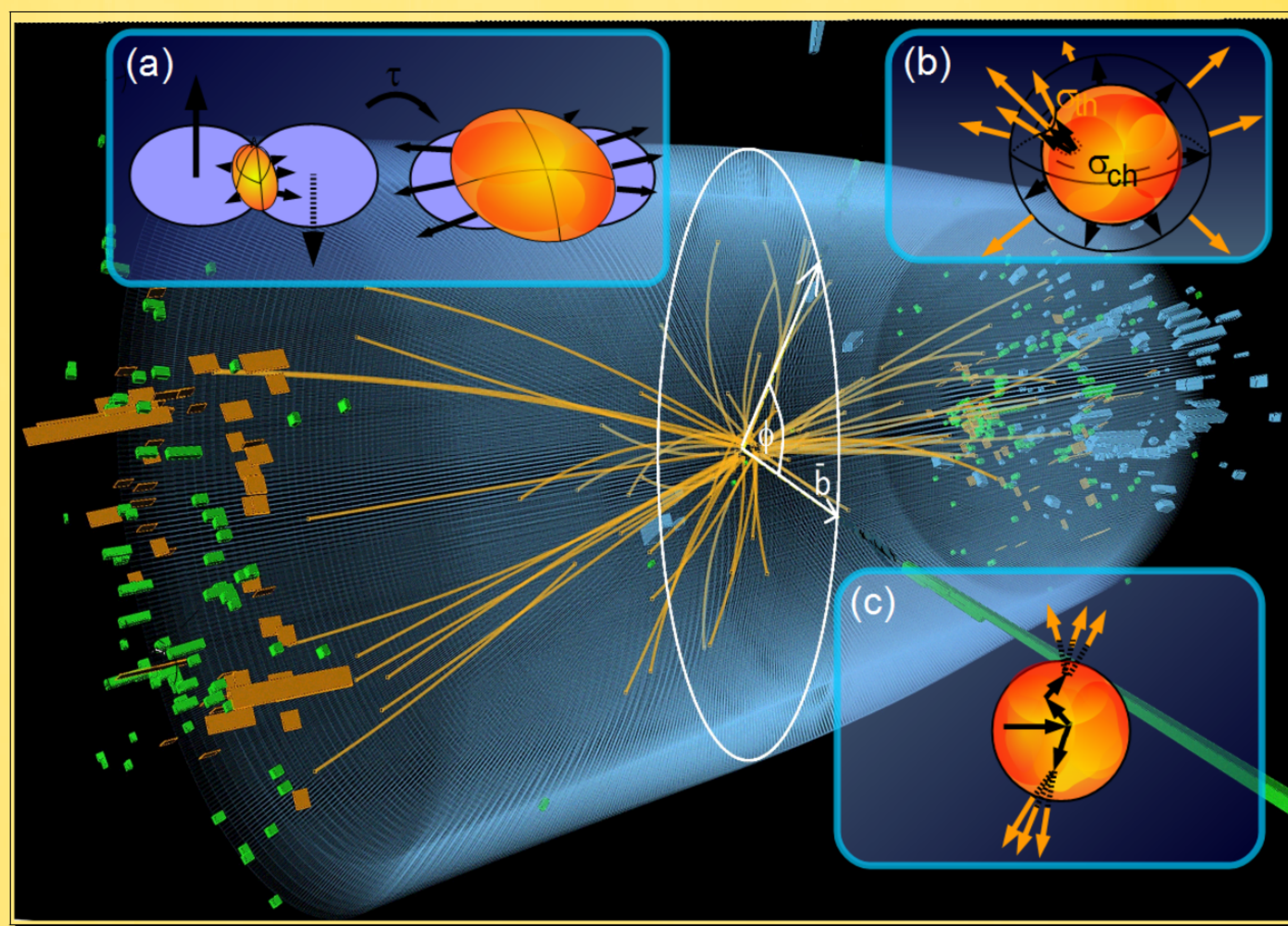


Figure 1: Initial participant matter in a non-central heavy ion collision possesses large pressure gradients, which evolves into an observed matter momentum space anisotropy (a). Freeze out of chemical composition and subsequent thermal freeze out of the particle distribution (b). An *in medio* modulated event (c).

Results and Discussion

The interplay of the model event-planes are here investigated by observing compound-flow observables.

In line with the development of the HYDJET++ model, the hexagonal flow v_6 is investigated in terms of the fluctuating Ψ_3 plane, and the main, geometric Ψ_2 plane. In addition, a fourth order flow is simulated and measured in the Ψ_2 plane of the computational model. The implementation of the second and third order plane thus provides for the simulation of sixth order compound flow-terms. In specific, the flow terms: v_3v_3 , v_2v_4 , and $v_2v_2v_2$, are related in transverse-momentum space, and also investigated in centrality projections [2].

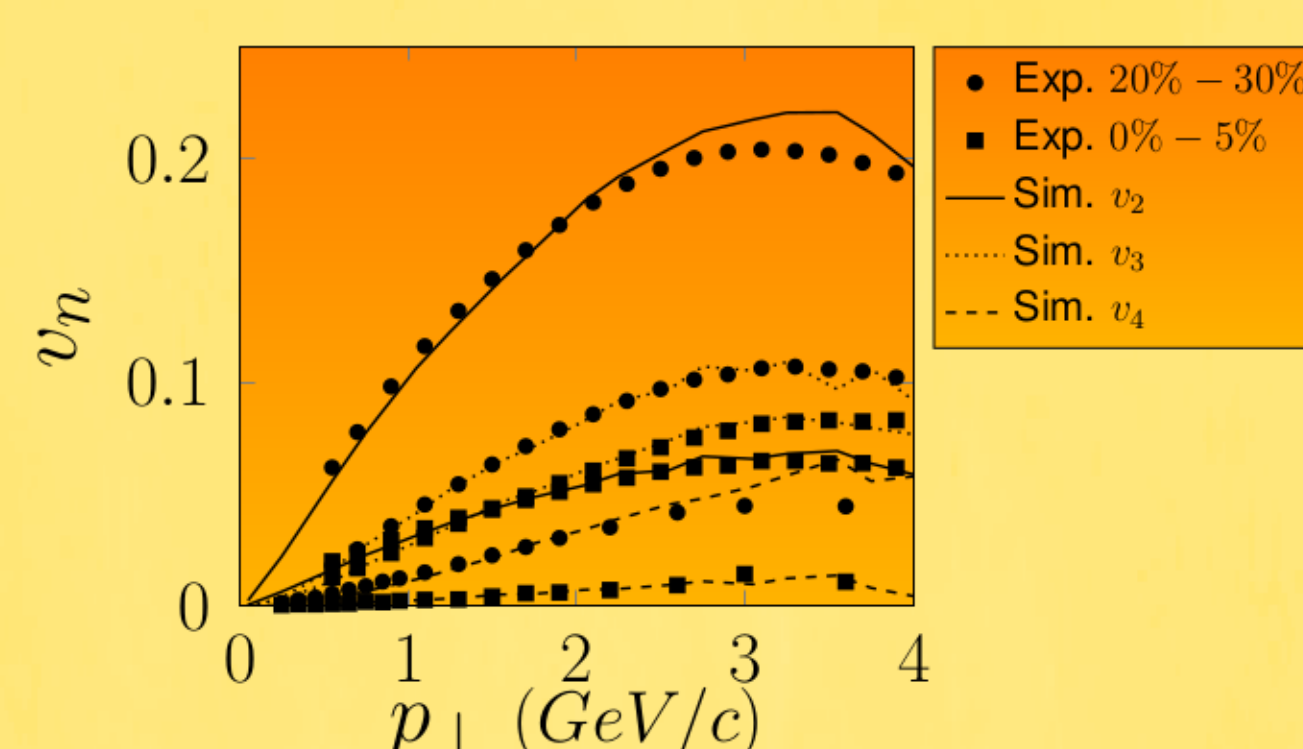


Fig.1 Azimuthal anisotropy. The simulated azimuthal anisotropy is displayed for the centralities $\frac{\sigma_{\text{ch}}}{\sigma_{\text{Geom}}} \in \{0\% - 5\%, 20\% - 30\%\}$ [14, 15]. Collider-data are included for comparison.

In Fig.1, the simulated azimuthal anisotropy is compared with experimental collider-data.

In the $0 < p_{\perp} < 3.5$ GeV/c transverse-momentum regime, the elliptic flow is seen to be reproduced for the central collisions (0% to 5%), and also for the more peripheral collisions (20% to 30%) [14]. The simulated triangular flow also appears to agree with collider-data for both of the displayed centralities. In this work, the fourth order flow is measured in the model Ψ_2 plane and also compared with corresponding collider-data [15]. The quadrangular flow is seen to be reproduced in the Ψ_2 plane to a high degree, although the absence of an implemented Ψ_4 plane puts a firm constraint on the simulations. It is here seen that the observed level of flow-reproduction will provide for a more refined investigation of flow correlators.

In Fig.2, the $v_3^{1/3}/v_2^{1/2}$ ratio is seen to display a differentiated behaviour in transverse-momentum space.

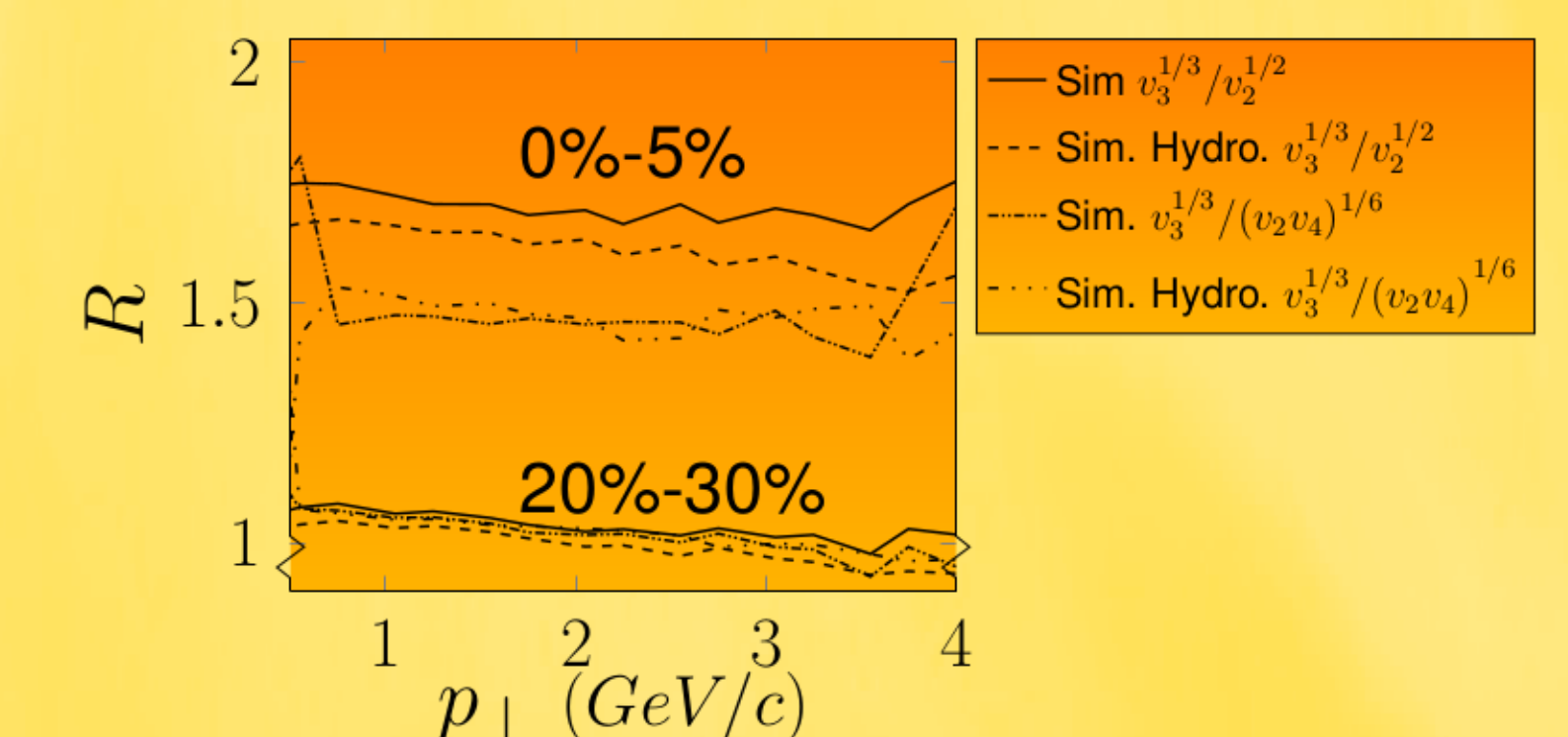


Fig.2 Flow correlators of sixth order. The ratios are displayed for the centralities: $\frac{\sigma_{\text{ch}}}{\sigma_{\text{Geom}}} \in \{0\% - 5\%, 20\% - 30\%\}$, for a hydrodynamical projection, and an inclusive projection.

For both of the displayed centralities, it appears that the hydrodynamic projection has a monotonic dependence on ellipticity, while the inclusive production mode displays features of fluctuations, jet-, and mini-jet production.

Also, the scaled sixth-order ratio $v_3^{1/3}/(v_2v_4)^{1/6}$ is displayed in Fig.2. Its hydrodynamic projection displays a behaviour that seems to be congruent with the corresponding $v_3^{1/3}/v_2^{1/2}$ ratio, which is in line with present theory [1, 2]. Also, the inclusive projection displays a weaker correspondence to the $v_3^{1/3}/v_2^{1/2}$ ratio. In fact, the v_4 -ratio displays an almost perfect scaling for the central hits. This is here interpreted as a support of the view of fluctuation dependent higher-order harmonics.

Conclusion

In the present model: the elliptic-, triangular-, and quadrangular Ψ_2 -flow are seen to be reproduced in the transverse momentum regime of $0 < p_{\perp} < 3.5$ GeV/c, and in the centrality regime of (0% to 50%) [3].

The harmonic interplay is here investigated in the correlator-ratios: $v_3^{1/3}/v_2^{1/2}$, and $v_3^{1/3}/(v_2v_4)^{1/6}$, which displays higher order features when related in the model.

It is concluded that the correlators display behaviour that are related to fluctuations. The observed characteristics are under a complex conclusion providing rich information on fluctuations and bulk matter evolution. In specific, the fourth order flow is displaying a differentiated behaviour for central hits, where fluctuations, jets, and mini-jets are seen to produce an almost perfect scaling.

This differentiation can be further elaborated upon in an implementation of a finer model of the evolving particle production vertexes.

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