Correlation between initial spatial anisotropy and final momentum anisotropies in relativistic heavy ion collisions

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The anisotropic flow (v_n) in relaitvistic heavy ion collisions arises due to the initial spatial anisotropy (ε_n) of the overlapping zone between the two colliding nuclei. The linear correlation between ε_n and v_n for small n is a quantitative measure of the efficiency of conversion of the initial spatial anisotropy to the final momentum anisotropy. We study the collision centrality, transverse momentum (p_T) and collision energy dependence of this correlation for charged particles using a hydrodynamical model framework. The p_T dependent correlation coefficient is found to be strongly dependent on the mass as well as p_T of the emitted particles. We also study p_T dependent relative fluctuation in anisotropic flow and show that it is sensitive to the value of η/s specially in low p_T region. In addition, we study the sensitivity of the correlation coefficient to the fluctuation size parameter.

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1. Introduction

The initial spatial asymmetry of the overlapping zone between two colliding nuclei gets converted into the final particles momentum anisotropy characterized by the flow coefficients which depend on particle mass, beam energy, collision centrality, transverse momentum etc. As the initial spatial anisotropy (ε_n) increases from central to peripheral collisions, the flow coefficient (v_n) also increases. The efficiency at which ε_n is converted to v_n depends on the initial state as well as on the evolution of the produced matter. Models based on relativistic hydrodynamics can be useful to estimate the initial states and the space time evolution of the matter which cannot be probed experimentally [1–11]. Several groups have studied the correlation between ε_n and v_n earlier [1, 10, 12–26]. It has been shown in different studies that the p_T, beam energy, collision centrality all play important role in the determination of the final momentum anisotropy [13, 27–31]. Thus, it is necessary to know the simultaneous effects of all these parameters on the correlation between ε_n and v_n better.

We study the p_T dependent correlation between ε_n and v_n (n=2&3) using a hydrodynamical model for Pb+Pb and Cu+Cu collisions in this work [32]. We also study how the correlation coefficients and the relative fluctuations in the anisotropic flow parameters vary with the shear viscosity (η/s) and fluctuation size parameter [33].

2. Framework

We use the (2+1)D longitudinally boost invariant hydrodynamical model framework MU-SIC [32] with fluctuating initial conditions. The initial formation time of the plasma is taken as 0.4 fm/c. A Monte Carlo Glauber initial condition is used and the value of η/s is chosen as 0.08 [33]. The fluctuation size parameter is taken as 0.4 fm. The freeze-out temperature is constant in our study and a lattice based equation of state is used for a cross-over transition between the QGP and hadronic matter phase [34]. The initial spatial eccentricity is calculated using the relation [13]:

$$\epsilon_n = -\frac{\int \mathrm{d}x\mathrm{d}y \, r^n \cos\left[n\left(\phi - \psi_n\right)\right] \varepsilon\left(x, y, \tau_0\right)}{\int \mathrm{d}x\mathrm{d}y \, r^n \varepsilon\left(x, y, \tau_0\right)} \,. \tag{1}$$

Where ψ_n is the nth order participant plane angle. The corresponding anisotropic flow parameters v_n can be obtained [13] from the invariant particle momentum distribution as :

$$\frac{dN}{d^2 p_T dY} = \frac{1}{2\pi} \frac{dN}{p_T dp_T dY}\left[1 + 2\sum_{n=1}^{\infty} v_n(p_T) \cos \mathrm{n}(\phi - \Psi_{\mathrm{n}})\right], \tag{2}$$

where Ψ_n is n^{th} order event plane angle.

The correlation coefficient C between the initial spatial eccentricity and final momentum anisotropies can be quantified using the relation [13]:

$$C(\epsilon_n, v_n) = \left\langle \frac{(\epsilon_n - \langle \epsilon_n \rangle_{\mathrm{av}})(v_n - \langle v_n \rangle_{\mathrm{av}})}{\sigma_{\epsilon_n} \sigma_{v_n}} \right\rangle_{\mathrm{av}} \,. \tag{3}$$

Where, σ_{ϵ_n} and σ_{v_n} are the standard deviations of ϵ_n and v_n respectively. The average is taken over events using hadron multiplicity as weight factor.

3. Results of Pb+Pb collision

It is well known that the mass ordering of differential anisotropic flow ($v_n(p_T)$) parameters is a signature of the collective behaviour of the medium formed in heavy ion collisions and models based on hydrodynamics can explain it well. Therefore, it is necessary to know whether there exists any mass dependence in the p_T dependent correlation coefficients for the different hadrons also. The correlation coefficient C(ϵ_n, $v_n(p_T)$) for π^+, K^+ and p at 0-20% and 40-60% centralities is shown in Fig 1 [33]. It can be seen that there is a clear mass ordering in the correlation coefficient between $\epsilon_2 - v_2$ for all the centrality bins.
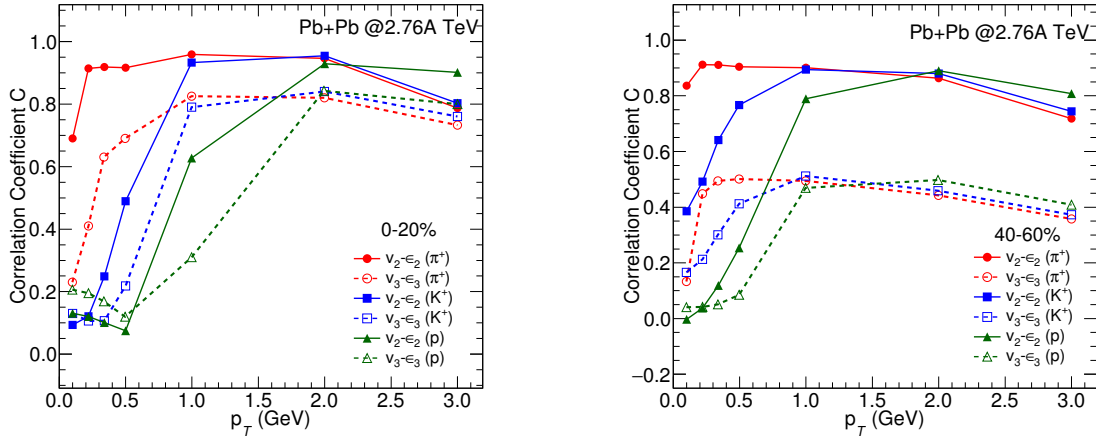

Figure 1: (Color online) C(ϵ_n,$v_n(p_T)$) for π^+, K^+ and p at $\sqrt{s_{NN}}$ = 2.76 TeV Pb+Pb collisions for $0-20\%$ and $40-60\%$ centrality bins respectively [33].

However, there is no mass dependence in the p_T integrated C($\epsilon_n - v_n$) of π^+, K^+ and p with centralities [33] although the (p_T integrated) v_n is different for them.

C(ϵ_3, $v_3(p_T)$) has considerably smaller magnitude and it drops faster at higher p_T values for peripheral collisions compared to central collision [33]. The results clearly show that the p_T dependent correlation coefficient strongly depends on the mass of the particle and p_T region that mainly contributes to the correlation strength is also different for different particles.

The relative fluctuation in the anisotropic flow parameters $\sigma_{v_n}/\langle v_n \rangle$, reflecting the ratio of the first two moments of the initial state eccentricity distribution (i.e, σ_{ϵ_n}) is considered to be a potential observable. Fig 2 shows the sensitivity of the correlation coefficient and $\sigma_{v_n}/\langle v_n \rangle$ to the the value of the η/s. It can be seen that the value of C for all the three particles varies only marginally, whereas, the p_T dependent $\sigma_{v_n}/\langle v_n \rangle$ is quite sensitive to η/s and the sensitivity is much stronger for protons than for pions and also in the low p_T (< 1 GeV) region for Pb+Pb collisions [33].

4. Results of Cu+Cu collision

The system produced in Cu+Cu collisions at 200A GeV at RHIC is expected to have smaller temperature and energy density as well as smaller transverse dimension compared to Pb+Pb collisions at LHC. Also, the Cu+Cu collision is expected to have a higher initial state density fluctuations.
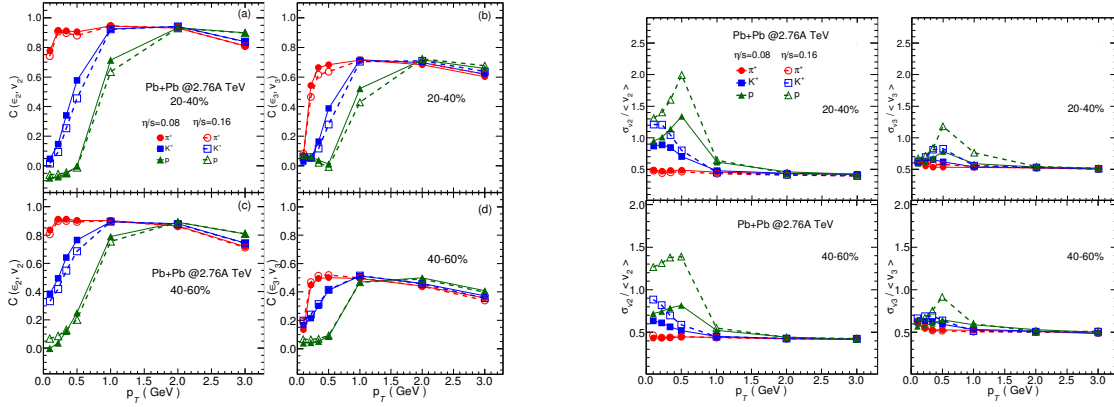
Figure 2: (Color online) [Left:] p_T dependent correlation coefficients at the LHC considering two different η/s values. [Right:] Relative fluctuations in the anisotropic flow parameters at the LHC considering two different η/s values [33].
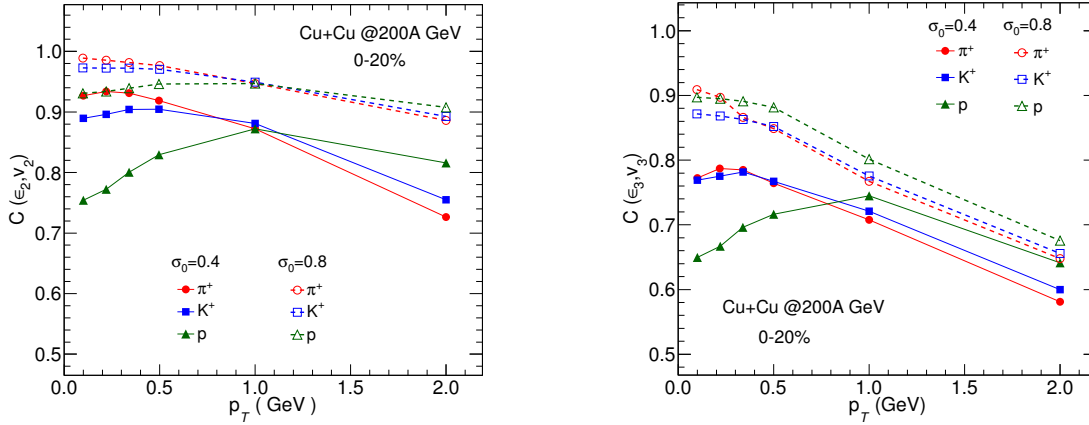

Figure 3: (Color online) p_T dependent correlation coefficients for Cu+Cu collision at 0-20% centrality for two fluctuation parameters.

A clear mass dependence of the correlation coefficient is seen in a relatively narrower p_T range for Cu+Cu collisions compared to Pb+Pb collisions [33]. We also change the fluctuation size parameter (σ) to see the sensitivity of correlation coefficient with σ and the values of C for all the particles increase considerably with relatively smoother initial energy density distribution (for σ=0.8 fm) [33] as shown in Fig. 3.

5. Acknowledgment

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