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Anisotropy of flow and the order of phase transition in relativistic heavy ion collisions

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Abstract

Using a hydrodynamical model we study how the order of phase transition in the equation of state of strongly interacting matter affects single particle spectra, elliptic flow and higher order anisotropies in Au + Au collisions at RHIC ($\sqrt{s_{\mathrm{NN}}} = 200$ GeV energy). We find that the single particle spectra are independent of the order of phase transition and that the fourth harmonic $v_4(p_T)$ shows only a weak dependence in the p_T region where hydrodynamics is expected to work. The differential elliptic flow, $v_2(p_T)$, of baryons shows the strongest dependence on equation of state. Surprisingly the closest fit to data was obtained when the equation of state had a strong first order phase transition and a lattice inspired equation of state fits the data as badly as a purely hadronic equation of state.

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Keywords: Relativistic heavy ion collisions; Elliptic flow; Order of phase transition; Hydrodynamic model

1. Introduction

In non-central heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) of BNL the particle distributions exhibit quite large anisotropies [1–3]. The second Fourier coefficient of the azimuthal distribution of particles, so-called elliptic flow, has been exten-

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sively studied [4] since it is sensitive to the early dense stage of the evolution [5]. Recently also higher harmonics have been measured [3,6]. It has been claimed that they should be even more sensitive to the initial configuration of the system [7].

Ideal fluid hydrodynamics has been particularly successful in describing the observed anisotropy of particles at low p_T in minimum bias collisions [8,9]. This success has been interpreted as a sign of formation of thermalized matter rapidly after the primary collision [10]. Studies of both single particle spectra and anisotropies have also shown that a reasonable reproduction of data favours an Equation of State (EoS) of strongly interacting matter with a phase transition [11,12].

The lattice QCD calculations of the EoS of strongly interacting matter support such a scenario by predicting a phase transition at $T_c \approx 170$ MeV temperature. For a physical scenario of two light and one heavier quark, the phase transition is predicted to be a smooth crossover at small values of baryochemical potential. Contrary to naive expectations, lattice QCD predicts that pressure and energy density do not reach their ideal Stefan–Boltzmann values immediately above the critical temperature, but approach them slowly [13].

At mid-rapidity at collisions at RHIC, the net baryon density is small and the relevant EoS should exhibit a crossover transition. However, so far all hydrodynamical calculations of elliptic flow [10–12,14–19] have used an EoS with a strong first order phase transition and ideal parton gas to describe the plasma phase. The usual point of view has been that it is unlikely that the details of phase transition would lead to significant dynamical effects [9]. This standpoint has been supported by the early calculations [20,21], where it was found that the width of the phase transition region, ΔT, had only little effect on the final flow pattern in one-dimensional flow. Thus it was considered safe to claim that the final particle distributions would not be sensitive to ΔT either.

However, full three-dimensional expansion is more complicated than one-dimensional. It is known that in three-dimensional expansion the differential elliptic anisotropy, $v_2(p_T)$, of (anti)protons is sensitive to the existence of phase transition and its latent heat [11,12,15]. The anisotropy of flow might thus be sensitive to other details of phase transition as well. In this paper we address this possible sensitivity. We use a hydrodynamical model to calculate single particle spectra, elliptic flow and higher order anisotropies in $\sqrt{s_{\mathrm{NN}}} = 200$ GeV Au + Au collisions using four different EoSs with different phase transitions and plasma properties. As a representative of lattice QCD results, we use an EoS based on the thermal quasiparticle model of Schneider and Weise [22] (EoS qp). This model is tuned to reproduce the lattice QCD EoS and provides a method to extrapolate the results to physical quark masses. To facilitate comparison with earlier calculations we use as reference points the EoSs Q and H used in Refs. [10,12,14–16]. EoS Q has a first order phase transition between hadron gas and an ideal parton gas whereas EoS H is a hadron gas EoS without any phase transition. To study the effects of the order of phase transition and slow approach to the Stefan–Boltzmann limits separately we also use a simple parametrisation for an EoS (EoS T) where the hadron gas and ideal parton gas phases are connected using a hyperbolic tangent function. Such an EoS has a smooth crossover transition but the plasma properties approach their ideal values much faster than in EoS qp.

We find that the main sensitivity to the details of an EoS lies in the differential elliptic flow of heavy particles ($m \gtrsim 1$ GeV) where EoS Q with a first order phase transition leads to an anisotropy closest to the data. Surprisingly, the lattice inspired EoS qp re-