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Systematics of elliptic flow in heavy-ion collisions

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Abstract. We analyze elliptic flow from SIS to RHIC energies systematically in a realistic dynamical cascade model. We compare our results with the recent data from STAR and PHOBOS collaborations on elliptic flow of charged particles at midrapidity in Au + Au collisions at RHIC. In the analysis of elliptic flow at RHIC energy, we find a good fitting with data at 1.5 times a scaling factor to our model, which characterizes that the model is required to have extra pressure generated from the subsequent parton scattering after the initial minijet production. In energy dependence of elliptic flow, we notice re-hardening nature at RHIC energies. Both these two observations would probably imply the possible formation of quark–gluon plasma.

Keywords. Heavy-ion collisions; elliptic flow.

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1. Introduction

The main goal of ultra-relativistic heavy-ion collisions is to understand the behavior of QCD under extreme conditions of density and temperature. Under such extreme conditions, nuclear matter is expected to undergo a phase transition to quark–gluon plasma. In order to elucidate the nature of this phase transition, various high energy collisions are taking place at LBL, SIS, AGS, SPS and RHIC energies and will start at LHC around 2007. This field at present has generated lots of interest and excitement, since the new qualitative data are forthcoming at RHIC energy experiments at BNL. In these energies, soon after the collisions of heavy nuclei, particles are produced and move collectively. This collective motion of particles are called as flow and are identified as radial, sideward and elliptic flow. Recently, data on these various flows have been reported up to AGS, SPS and RHIC energies. At AGS these are well-described by a dynamical microscopic simulation model [1]. Also, the elliptic and radial flow are observed at SPS, specially, the strong radial flow is measured in central Pb + Pb collisions. In non-central collisions, the initial nucleus–nucleus overlap has an elliptic shape and the initial pressure gradient is large and anisotropic and hence give more precise information of the equation of state (EOS). At RHIC, it has been seen that since the elliptic flow is built up from pressure gradients at the earliest stage of evolution, it may be less sensitive to EOS than the initial large parton re-scattering in a deconfined phase. The elliptic flow dependence on beam energy and centrality are expected to be sensitive to the EOS over the phase transition between confined and deconfined matter.

2. Model

In our recent calculation, we have analyzed elliptic flow systematically from SIS to RHIC energies using a dynamical jet-implemented hadron-string cascade model, (JAM) [2]. The JAM is a simulation model, where the initial primary collisions produce minijet partons in a similar way to the HIJING model. These partons later enter into string configurations, then strings are made to fragment to hadrons using the LUND fragmentation model constructed in the PYTHIA routine [3]. In this model, we have not included subsequent re-scattering among minijet partons, which would be necessary to understand the re-hardening behavior at RHIC. There is a strong evidence that the hadron mass spectra at RHIC get much stiffer than those at SPS energy [4]. This stiffness can be explained as follows: According to the large level density of hadrons, the hadronic matter is expected to be softer. However, this phenomena cannot exist at such high energies, since they are dissolved into quark and gluons in vacuum. Therefore in that level, pressure grows rapidly and becomes stiffer as a function of energy density. In other words, we say re-hardening of spectra at RHIC energies [5] is due the probable formation of quark–gluon plasma. We believe that this point is quite premature but will be more clear if one includes interactions among minijets as well as parton–hadron-string interaction dynamically. However, at present very few models (no dynamical models) exist in the literature which hold such a complicated treatment at RHIC energy.

3. Results and discussions

In this calculation, we concentrate on the systematics of elliptic flow by using the same dynamical JAM model for two reasons: (i) we have lots of data from RHIC experiments and (ii) it is more fundamental to understand the physics at extreme conditions which has direct reflection from the scattering among the produced particles. Therefore, we make an analysis from SIS to RHIC energies and more detailed diagnosis at RHIC energy with functions of centrality, pseudorapidity and transverse momentum. For non-central collisions, the overlap geometry between the two nuclei is almond-shaped. As the initial almond shape expands it becomes more spherical, quenching the driving force that produces the elliptic flow. The elliptic flow is the anisotropic emission of particles in- and out- of reaction plane defined by the beam direction and the impact parameter direction. This spatial anisotropy can be translated into a momentum anisotropy in the presence of strong rescattering. One can measure this through the second Fourier coefficient in the azimuthal distribution of particles with respect to reaction plane and is usually characterized by the particle momentum distribution, $v_2 = \langle (p_x^2 - p_y^2)/(p_x^2 + p_y^2) \rangle$. Also, the elliptic flow is influenced by the formation of QGP transition at the non-central collisions with function of beam energies since it depends on the early stages of the system evolution. Then the question arises: If the QGP is formed, does it live long at SPS or at RHIC? Recently, it has been estimated experimentally [6] that the hard QGP phase is expected to live longer at RHIC than at the SPS. If this is true, then the elliptic flow of the produced particles should reflect this difference at the end. Therefore, it is urgently required to estimate the elliptic flow from SIS to RHIC energies more systematically as well as to derive the new physics. Experimentally, it has been found that at higher energies, e.g., at AGS and above, the coefficient $v_2 > 0$, the 'in-plane' flow. This fact has been verified and well-described by a dynamical transport

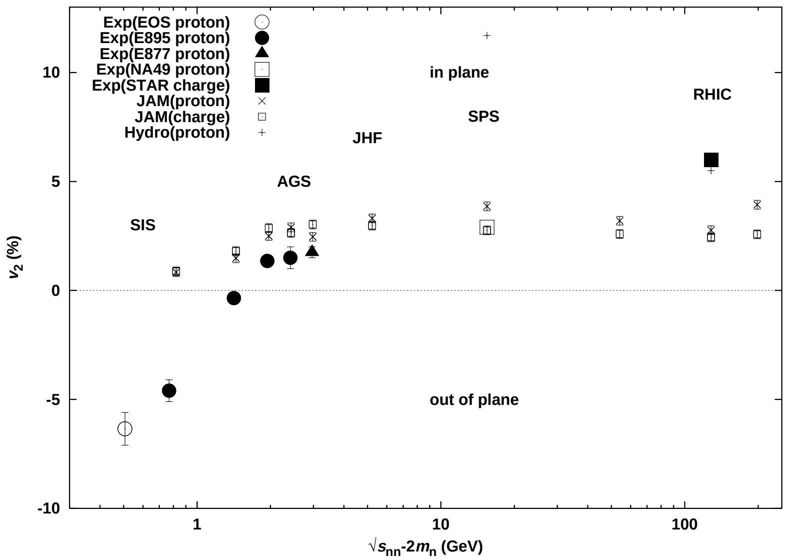

Figure 1. Elliptic flow as a function of energy for non-central collisions.

model with mean field up to AGS energies [1]. In any case, whether the transport model has mean field or not, the elliptic flow v_2 is positive at higher energies. Recently, the elliptic flow has been predicted to be positive and to increase with beam energies by RQMD [7] as well as by hydrodynamic models [8].

In figure 1, we display the results of v_2 as a function of beam energies in JAM. For completeness, we show the results of hydrodynamic model in the figure. It is very clear from the figure that the hydrodynamic model for protons is very well on top of the STAR data at RHIC energy, where JAM underpredicts by a factor of 1/2 of data. However, the situation is reverse at the SPS, where JAM gives reasonable description of data and hydrodynamic model fails to describe the data; it overestimates the data by a factor of more than 2. We can understand this well, because hydrodynamic model has assumed first-order phase transition to quark matter at the initial condition. Since the initial condition is in quark–gluon plasma region, the data at RHIC is well-reproduced in this model, e.g., the quark–gluon plasma is already formed at RHIC. In our JAM model, we are very good at SPS energy, whereas we fail to explain STAR data at RHIC. Thus we understand that our model lacks the interaction between minijets, which is at present very difficult to implement in our model. However, the overall trend from low energy at SIS to high energy at RHIC seems to be very exciting. This systematic analysis shown in figure 1 indicates that we still have re-hardening at RHIC energy in non-central collisions. Similar feature was claimed by us from the analysis of radial flow in the central collisions [5]. From these observations, we derive that some interesting phenomena is occurring at RHIC energy, may be possible formation of quark–gluon plasma.

In figure 2, we display JAM results on elliptic flow of charged particles as functions of pseudorapidity, centrality and transverse momentum for minimum bias events at RHIC energy. In all these figures, we notice that our model is reasonably good for pions and protons, see figure 2c. However, in figures 2a, 2b, our model is 1.5 times off from the data. If

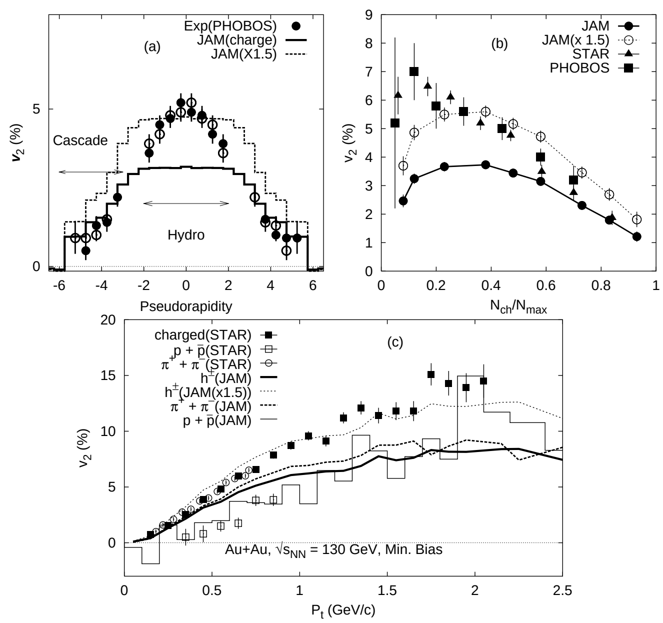

Figure 2. Elliptic flow as functions of pseudorapidity, centrality and transverse momentum for minimum bias events for charged particles.

we include the subsequent partonic interactions, we hope to describe the data better in future. In contrast, hydrodynamic models show excellent agreements (a) at mid-rapidity [9], (b) at central and semi-central collisions, and (c) at low p_t ($<$ 1.5 GeV/c) [8]. However, due to incomplete thermalization, they fail (a) at non-mid-rapidities, (b) at peripheral collisions, and (c) at higher p_t due to saturation and predominance of direct emission from hard processes. We would like to mention here that in figures 2b and 2c, the data may come further down due to elimination of non-flow effects, measurements of elliptic flow using four-particle correlation method [10]. So, we conclude here that the dynamic microscopic model is urgently needed at RHIC energy and we are working on that.

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