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Anisotropic flow v_2 in $Au + Au$ collisions at RHIC

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Abstract

Using the RQMD model, transverse momentum dependence of the anisotropic flow v_2 for π, K, *nucleon*, ϕ, and Λ, are studied for $Au + Au$ collisions at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV. Both hydrodynamic hadron-mass hiragracy (hhmh) at low p_T region and particle type dependence (baryon versus meson) at the intermediate p_T region are reproduced with the model calculations although the model under-predicted the overal values of v_2 by a factor of 2-3. As expected, when the rescatterings are turned off, all v_2 becomes zero. The failure of the hadronic model in predicting the absulte values of hadron v_2 clearly demonstrate the need of early dense partonic interaction in heavy-ion collisions at RHIC. At the intermediate p_T , the hadron type dependence cold also be explained by the vacume hadronic cross sections within the frame of the model.

The measurements of collective motion of hadrons from high-energy nuclear collisions can provide information on the dynamical equation of state information of the system [1, 2, 3]. Specifically, the strange and multi-strange hadron flow results have demonstrated the partonic collectivity [5] and the heavy-flavor flow will test the hypothesis of early thermalization in such collisions [4]. At RHIC, the measurements [6, 7] of elliptic flow v_2 and nuclear modification factor R_{AA} has lead to the conclusion that hadrons were formed via the coalescence/recombination of massive quarks [8, 9, 10]. This finding is directly related to the key issue in high-energy nuclear collisions such as deconfinement and chiral symmetry restoration. In addition, it also touched the important problem of hadronization process in high-energy collisions. Therefore a systematic study with different approaches becomes necessary. In this report, using a hadroic transport model UrQMD(v2.2)/RQMD(v2.4) [11, 12], we study the v_2 of π, K, p, ϕ, and Λ from $Au + Au$ collisions at 200 GeV. Properties of centrality denpendet and freeze-out time dependent will be discussed. We try to answer some specific questions like how much the observed features can be reproduced by the hadronic model and why. In this approach, the vacumme cross sections are used for strong interactions. Unlike the treatment in most hydrodynamic calculations, the transition from strong interaction and free-streming is determined by the local density and gradual. As we will discuss in the paper, the shortcomes of this method is lack of the partonic interactions which is important for the early dynamics in ultra-relativistic heavy ion collisions [13]. In order to take care of both partonic and hadronic interactions in high-energy nuclear collisions, a combination of hydrodynamic model for early stage (the perfect fliud stage) and hadronic transport model for later stage and freeze-out has been tried [14, 15].

The paper is organzed as follow: section 1: beirf introduction to the model; Section 2: model results and discussions. Summary and outlook will be presented in section 3.

Within the framework of the hadronic transport approach, a typical heavy ion collision may be schematically divided into three stages, *i.e.* pre-hadronic stage, hadronic pre-equilibrium stage and the stage from hadronic kinetic equilibrium to freeze-out. The pre-hadronic stage is determined by the initial excitation and fragmentation of color strings and ropes. This stage lasts about $1.5fm/c$ and the effective transverse pressure is rather soft. During the late hadronic stage, the hadronic system reaches local kinetic equilibrium followed by a break-down of equilibrium due to dilution of the hadronic gas and finite size of the system [11, 12, 16].

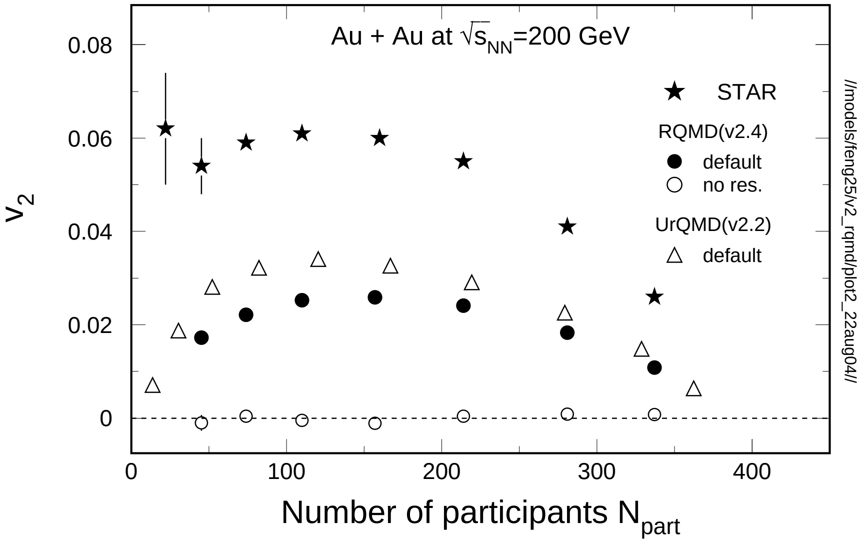

Figure 1: Charged hadron v_2 versus collision cnetrality, represented as a function of number of participants. Experimental data [17, 18] and RQMD results are shown as stars, filled circles (with rescatterings) and open-cirles (without rescatterings), respectively. The results from UrQMD(v2.2) calculations are shown as open-triangles.

In Figure 1, the integrated values of v_2 versus collision centrality are shown. Symbol stars represent the experimental data. The circles and triangles are from RQMD(v2.4) [11] and UrQMD(v2.2) [12], respectively. Without rescatterings, shown as open-circles, all values of v_2 are zero. There are about 20-25% difference in the model calculations and we treat this difference as a systematic error in such hadronic transport model calculations. However, both results are consistently lower than the experimental data by a factor of 2 to 3 although the shape of the centrality dependent are similar as data. Since both RQMD and UrQMD are hadronic transport and no partinic interactions are included in the calculation. The descranpancy clearly demonstrats the necessaricity of early partinic interactions in order to achieve the experimental values of v_2 .

Now let us discuss the p_T dependence of the event anisotropy parameters. The model results of hadron v_2 versus transverse momenta p_T are shown in Figure 2(a). As one can see that at the lower transverse momentum region, $p_T \leq 1.5$ GeV/c, heavier hadrons have smaller values of v_2. Such mass dependence is exactly what observed in the experimental data [6] and hydrodynamic calculations

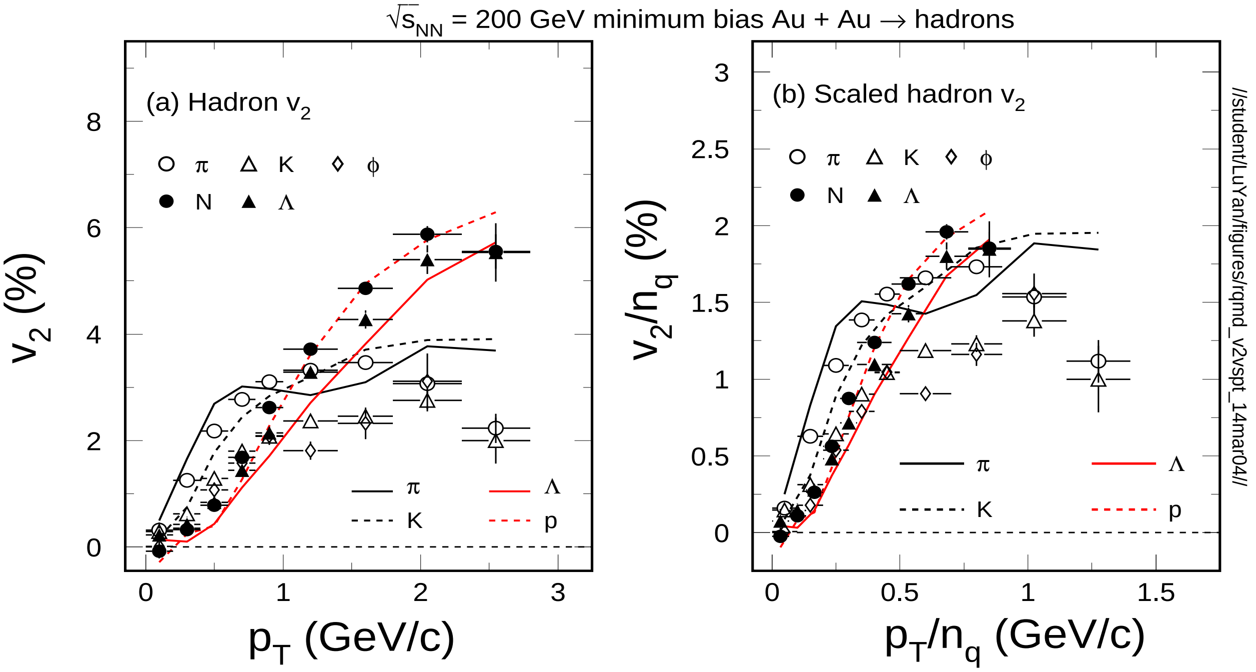

Figure 2: (a) Hadron v_2, from minimum bias $Au + Au$ collisions at $\sqrt{s_{\rm NN}}$= 200 GeV; (b) The scaled hadron v_2 are shown. The n_q referes to the number of constituent quakes. Symbols represent results from RQMD (v2.4) model and lines represent the results fromUrQMD(v2.2). At low $p_T/N_q \leq 0.5$ GeV/c, π does not follow the scaling perhaps caused by the resonance decay [4]. In higher p_T region, both K- and ϕ-mesons seem fall off the scaling curve due to the samll hadronic cross sections in the model.

[19]. Hadronic interactions, though take palce at later satge of the collisions, also contribute to the observed collective motion. In the higher p_T region, the mass ordering seems disappearing and the $v_2(p_T\ )$ depends on either meson or baryon. The particle type rather than the particle mass dependence has also been observed in data [6]. Note that ϕ-meson has a mass that is close to baryons p and Λ. Recent result on ϕ v_2 show a perfect meson behavior [20]. However, the amplitudes of the v_2 from both model calculations are lower by a factor 2-3 compared to the experimental data.

Figure 2(b) shows the scaled hadron v_2. The scaling factor, according to the coalescence approach [8, 9, 10], is the number of constituent quarks (NCQ). For mesons and baryons, n_q = 2 and n_q=3, respectively. Except pions, the NCQ-scaling is observed in the RQMD and UrQMD model calculations. However, but seems does not work for Kaons and $\phi-$meson in 0.5 $<p_T/n_q<$ 1.

The coalesence or recombination mechanism for hadronization is rather general, even for elementary collisions. For example, in $e + e^+$ collisions, in string picture, hadrons are formed via $'coalescence'$ of quarks from the same string. In high-energy nuclear collisions the parton density is much higher than that in elementary collisions. Hadrons can be formed, in principle, via $'coalescence'$ of quarks from difference strings. The patonic collectivity, therefore, will be manefested in the observed hadron momentum distributions [21].

As one can see in Fig.3 that the value of v_2 is the largest at earlytime of the collisions. In addition, at the given time, the higher the transverse momentum p_T the larger the value of v_2 - the collision time the transverse momentum are correlated. This of course is consistent with the cooling processes

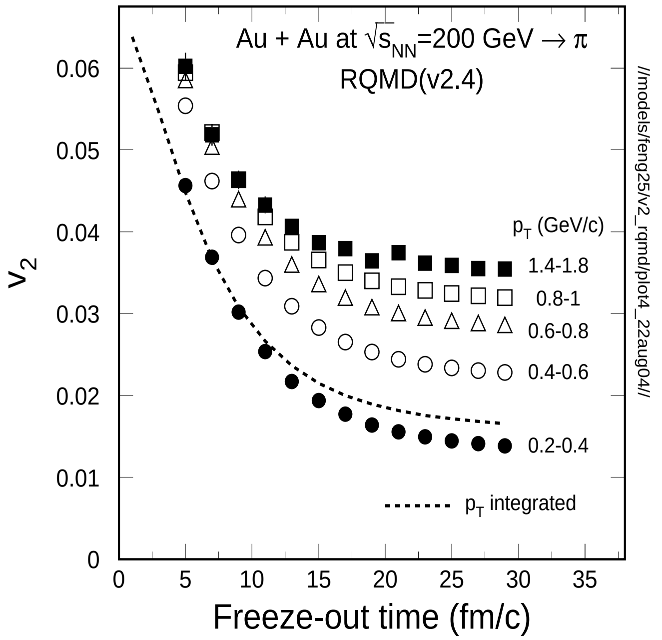

Figure 3: RQMD π v_2 versus freeze-out time for several p_T windows. All data are from minimum bias $Au + Au$ collisions at $\sqrt{s_{\rm NN}}$= 200 GeV. Dashed-line represents the p_T integrated distribution. The higher the p_T , the higher the values of v_2 and the sooner it reaches the saturation.

taking place in high-energy nuclear collisions. Fig.4 shows the collision centrality dependence of the v_2 for π, K, p, and Λ. Both the hydrodynamic behavior at the low p_T region and hadron type dependent at the intermediate p_T region are observed in all centrality bins. The importance of the obervation is that the explanation of the number of constituent quark is not unique because hadronic interactions alone also predict the hadron type dependence.

In high-energy nuclear collisions the density is high at the center of the created fireball - there is matter density grediant. The interactions among the constituents will therefore push matter moving out-wards. In this way the collective flow is developed in nucleus-nucleus collisions [3]. We would like to stress that $flow$ means matter and energy flow. It is independent of the type of particles, either partons or hadrons, or different kinds of hadrons. Hence by studying the collective motion of the produced hadrons one should be able to, in principle, extract the information of early collision dynamics [1, 2, 21].

$$v_2(p_T) \propto \int_t \int_\Sigma \sigma(\rho, p_T) \otimes \rho_\Sigma(t, x, y, p_T) d\vec{A}_\Sigma(x, y) dt \tag{1}$$

where Σ denotes the hyperspace where hadrons are emitted the σ is the interaction cross-section which, in principle, depends on the particle density and relative momenta. The ρ_Σ is the particle density that is a function of collision time t, location, and momentum. The transverse flow is intimately related to the pressure density which is in turn depends on the density and temperature of the matter understudy [22]. At low p_T region the frequent re-scatterings, in this case among the hadrons, lead to hydrodynamic like mass dependence.

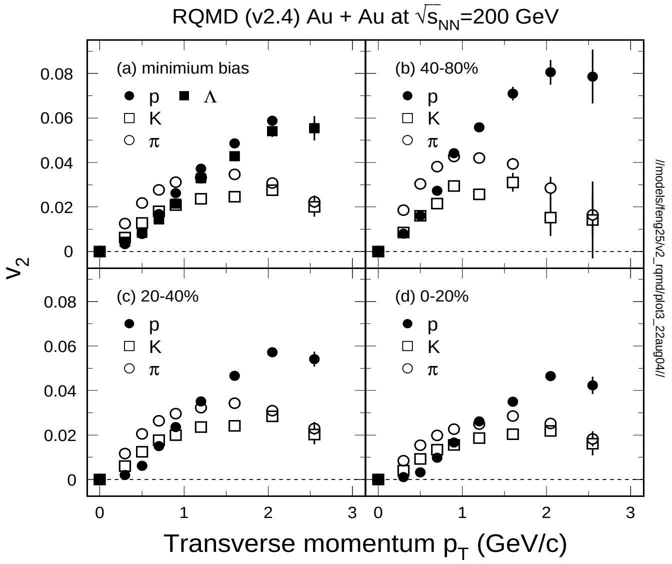

Figure 4: RQMD results of π, K, p, and Λ v_2 from $Au + Au$ collisions at $\sqrt{s_{\mathrm{NN}}}$= 200 GeV. (a) Minimum bias collisions: At about $p_T \sim 1.2$ geV/c, baryon and meson v_2 are crossing each other; (b) 40-80%; (c) 20-40%; (d) 0-20%.

At the higher region, $p_T > 1.5$ GeV/c, the low density hidrens the developement of the hydrodynamics and the details of the interactions become important. Since the cross-section depends on the particle type, meson or baryon, it a la constituent quark model [8] **speciles, marcus thesis**

In addition, with Eq.1, it is easy to understand why the hadronic model underpredicted the strength of v_2 at RHIC. Since the early partonic interaction is not included in the model, the early stage high density effect is therefore missing. The failure of the hadronic model clearly demonstrate the need of early dense partonic interaction in heavy-ion collisions at RHIC.

In summary, using the hadronic transport model UrQMD(v2.2)/RQMD(v2.4), we studied the elliptic flow from $Au + Au$ collisions at RHIC. We analyzed the v_2 as a function of collision centrlaity, collision time for π, K, p, ϕ, and Λ. We find: The model failed to reproduce the absulute value of v_2 due to lack of initial hot and dense partonic stage. However, because of the hadronic interactions, the hadron-mass hiragracy is well reproduced in the low p_T region. Rescattering is the key that leads to the hydrodynamic behavior in $v_2(p_T)$. At the intemediate p_T region, the hadron type dependent is also predicted by the model. This dependence is induced by the vacume hadronic cross sections used in the model. This finding challenging uniqueness of the coalescence approach for hadron formation in high-energy nuclear collisions. To further test this hypothesis, high precision measurements of resonance hadrons like K^*, ρ, Δ, Λ^*, and Ξ^* are necessary.

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