Romanian Reports in Physics **71**, 302 (2019)

FLOW STUDIES IN NUCLEUS-NUCLEUS COLLISIONS AT FAIR-GSI AVAILABLE ENERGIES

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Received August 16, 2017

Abstract. In this work, the elliptic flow coefficients for charged pions, kaons and protons as a function of transverse momentum p_T, at midrapidity (-0.5< y <0.5), in Au-Au collisions at three colliding energies ($\sqrt{s_{NN}}$ = 3, 5 and 7.7 GeV) simulated with UrQMD and AMPT-SM (AMPT with string melting version) codes are presented. The scaling of v_2 with the number of valence quarks (n_q) has been studied as a function of transverse kinetic energy per quark, KE_T/n_q. A deviation from quark-number scaling is observed at larger values of KE_T/n_q in non-central Au-Au collisions for both simulation codes. The 7.7 GeV Au-Au simulated results were compared with STAR experimental data.

Key words: relativistic nuclear collisions; quark-gluon plasma; elliptic flow.

1. INTRODUCTION

In high energy nuclear collisions, hot and dense nuclear matter is produced and a phase transition to quark-gluon plasma (QGP) [1] could appear. In non-central collisions, the initial overlap of two nuclei has a spatial anisotropy like an almond shape and due to subsequent interactions among the fireball constituents, different pressure gradients produce more particles to be emitted on the direction of the short axis of the ellipse (in-plane direction) compared to out-of-plane direction. Therefore, the initial spatial anisotropy makes an anisotropy in momentum space.

The azimuthal distribution of produced particles (with respect to the reaction plane) in the momentum space can be expressed by a Fourier expansion,

$$\frac{dN}{d\phi} \sim 1 + 2\sum v_n cos(n(\phi - \Psi)) \qquad (1)$$

where ϕ is the azimuth angle of the particle, Ψ is the orientation of the reaction plane (defined as the plane spanned by the impact parameter and incoming beam directions) and v_2 is the second Fourier coefficient, referred as elliptic flow [2, 3]. The system expansion and decrease of the initial spatial anisotropy leads to a selfquenching process for v_2, therefore making it a probe to access the early stages of heavy ion collisions and of the QGP formation [4].

In this work, we will present a study of second Fourier coefficient, v_2, of the azimuthal distribution of charged pions, kaons and protons produced in semi-central Au-Au collisions at $\sqrt{s_{NN}}$ = 3, 5 and 7.7 GeV. We analyzed the simulated data obtained using the AMPT (string melting version) [5] and UrQMD [6, 7] simulation codes. In the present model calculations, the reaction plane angle is taken as zero, so v_2 is calculated directly as:

$$v_2 = \langle cos(2\phi) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle \tag{2}$$

where p_x, p_y are the momentum components in the OX and OY directions and p_T is the transverse momentum.

2. RESULTS

The elliptic flow has a centrality dependence which is driven by the changing initial spatial shape of the fireball (in a non-central heavy ion collision, the overlap region of the colliding nuclei is almond-shaped). Therefore, we performed this analysis for semi-central Au-Au collisions, b = 5-9 fm, where the elliptic flow is strongest. The simulated data analysis is done at midrapidity, which is the central region of the collision where hot and dense matter (possibly the QGP) is produced.

The results for elliptic flow coefficient of charged pions and protons produced in Au-Au collisions at $\sqrt{s_{NN}}$ = 3 GeV are presented in Figure 1. Particles are represented with closed symbols and anti-particles with open symbols. Because the elliptic flow is largest in semi-central collisions, we used an impact parameter cut of 5-9 fm and a rapidity window symmetric around midrapidity (-0.5< y <0.5). The v_2 values for charged pions are larger than the values for protons in the low p_T range ($p_T <$ 1 GeV/c) for both AMPT-SM and UrQMD Au-Au collisions. The $v_2(p_T)$ for charged kaons are not presented for this energy (3 GeV) due to limited statistics.

Figure 2 shows the p_T-dependence of the elliptic flow of identified hadrons (charged pions, positive kaons and protons) in simulated Au-Au collisions using AMPT-SM (left panel) and UrQMD (right panel) at $\sqrt{s_{NN}}$ = 5 GeV. The elliptic flow increases linearly up to $v_2 \sim$ 0.1 for AMPT-SM and 0.05 for UrQMD at low p_T and saturates at $p_T >$ 1 GeV/c. As can be seen also in Figure 3, for both codes and for all three studied energies, a mass-ordering of v_2 is observed, for a given value of p_T, v_2 decreases with increase of hadron mass. This mass ordering was predicted by hydrodynamic models [8] and was observed experimentally in heavy ion collisions at RHIC [9].

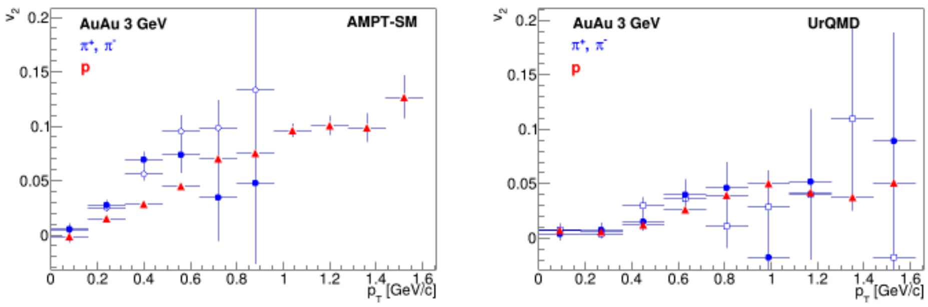

Fig. 1 – (Color online) Elliptic flow coefficient as a function of transverse momentum for charged pions (blue symbols) and protons (red triangles) produced in semi-central (b = 5-9 fm) Au-Au collisions simulated with AMPT-SM (left) and UrQMD (right) codes. Positive pions are represented with closed symbols and negative pions with open symbols.

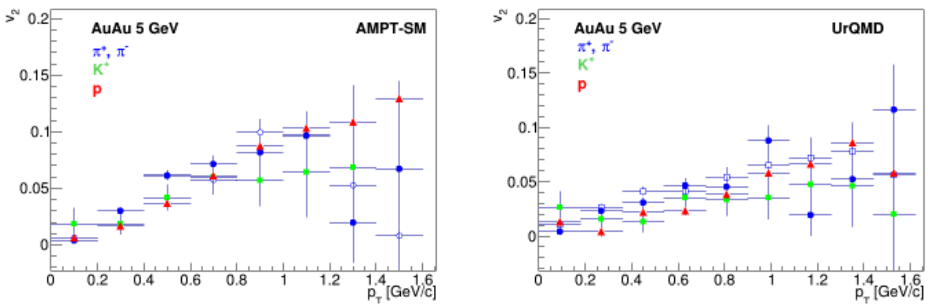

Fig. 2 – (Color online)The v_2 as a function of p_T for charged pions (blue), positive kaons (green squares) and protons (red triangles) produced in semi-central Au-Au collisions simulated with AMPT-SM (left) and UrQMD (right).

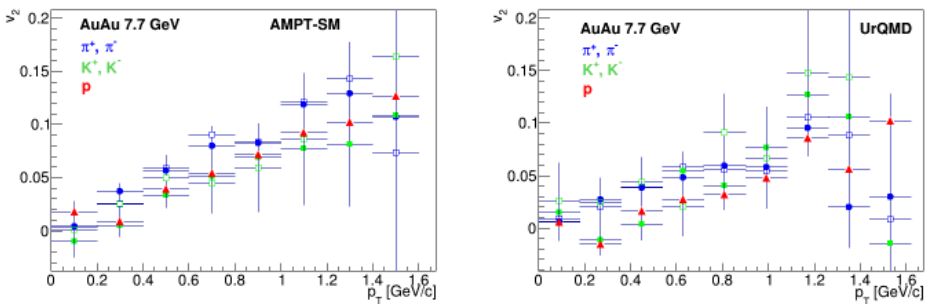

Fig. 3 – (Color online)The p_T dependence of elliptic flow in semi-central Au-Au collisions at 7.7 GeV. The notations are the same as in Figure 2.

The mass ordering of identified particle elliptic flow is caused by the presence of radial transverse flow [10]. The momentum gain due to radial collective flow is larger for heavier particles (due to higher rest mass) resulting in a flattening of p_T spectra of heavy particles at low p_T values. This radial flow effect for heavier particles cause smaller v_2 values compared to lighter particles at a fixed value of p_T, in the low p_T region (as can be seen for protons as compared to pions) and a shift towards higher values at higher p_T.

For all studied center-of-mass energies (3 GeV, 5 GeV and 7.7 GeV), AMPT with string melting (AMPT-SM) yields larger v_2 values compared to UrQMD code. One can see that the magnitude of v_2 increases as a function of available colliding energy ($\sqrt{s_{NN}}$) for all the particle species studied.

In the intermediate p_T region, v_2 can be related to the hadron production mechanisms. Results from RHIC showed that $v_2(p_T)$ of identified particles, in the intermediate p_T region, tend to group based on their hadron types, baryons or mesons [9, 11, 12] and were interpreted as a signature of quark recombination or coalescence processes. Experimental results showed that when both v_2 and p_T of identified hadrons are divided by number of constituent quarks, n_q (n_q = 2 for mesons and 3 for baryons), all the hadrons follow a common curve [13, 14]. This is known as the number of constituent quark (NCQ) scaling and was interpreted as an evidence for dominance of quark degrees of freedom in the early stages of heavy-ion collision, suggesting existence of a partonic medium where v_2 is built. After hadronization, when the hadrons are created by recombination or coalescence of partons, the flow of the quarks is carried by the produced particles.

Another way of representing NCQ scaling is to plot v_2/n_q as a function of KE_T/n_q, where KE_T is the transverse kinetic energy defined as:

$$KE_T = (m_T - m_0) = \left(\sqrt{p_T^2 + m_0^2} - m_0\right) \tag{3}$$

where m_T is the transverse mass and m_0 is the rest mass of hadron.

Since NCQ scaling is considered as a signal of the partonic mater, at lower collision energies, where hadronic degrees of freedom dominate the evolution, one does not expect such scaling in v_2. To test the scaling properties of v_2, v_2/n_q is plotted as a function of kinetic energy per quark, KE_T/n_q, for charged pions, kaons and protons produced in semi-central Au-Au collisions at 3, 5 and 7.7 GeV in Figures 4, 5 and 6. While UrQMD code considers only hadronic interactions where hadrons are formed *via* string fragmentations, AMPT string-melting code allows for testing the coalescence process.

Both models, AMPT-SM (left) and UrQMD (right), exhibit an approximate scaling for lower KE_T/n_q values, while at higher KE_T/n_q values we observe deviations from n_q scaling. These results at higher KE_T/n_q indicate either

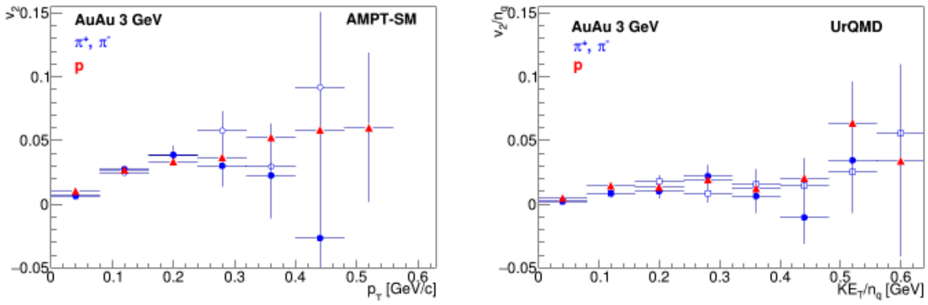

Fig. 4 – (Color online) The n_q scaled v_2 as a function of KE_T/n_q in Au-Au collisions at 3 GeV simulated with AMPT-SM (left) and UrQMD (right). Blue points are charged pions (full symbols-particles, open symbols-antiparticles) and red triangles are protons.

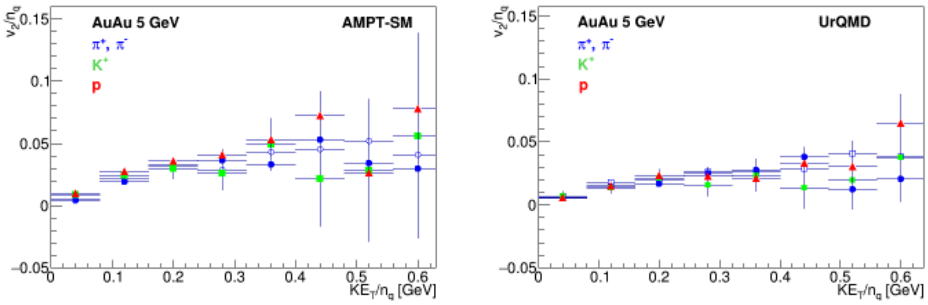

Fig. 5 – (Color online) The n_q scaled v_2 as a function of KE_T/n_q in Au-Au collisions at 5 GeV simulated with AMPT-SM (left) and UrQMD (right).

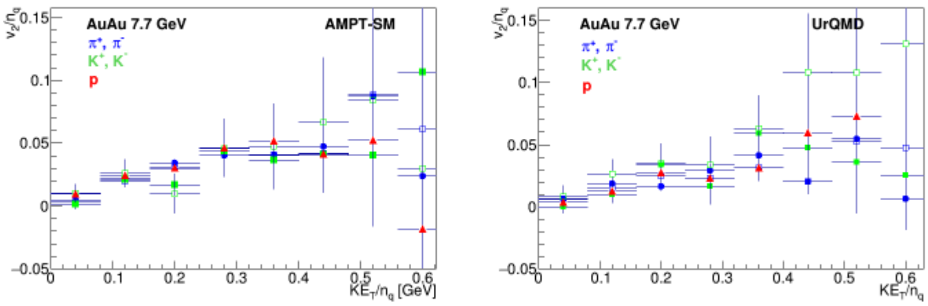

Fig. 6 – (Color online) The n_q scaled v_2 as a function of KE_T/n_q in Au-Au collisions at 7.7 GeV simulated with AMPT-SM (left) and UrQMD (right). The legend is the same as in Fig. 5.

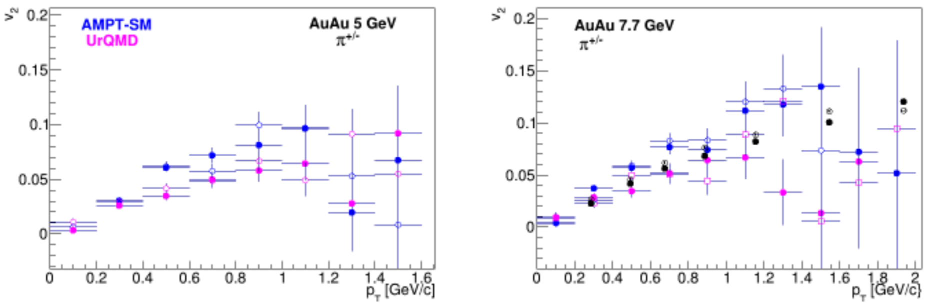

Fig. 7 – (Color online) The positive and negative pion v_2 as a function of p_T in semi-central Au-Au collisions at 5 GeV (left) and 7.7 GeV (right). At 7.7 GeV, the black points are STAR experimental data (statistical errors on experimental data are smaller than the marker size) [14].

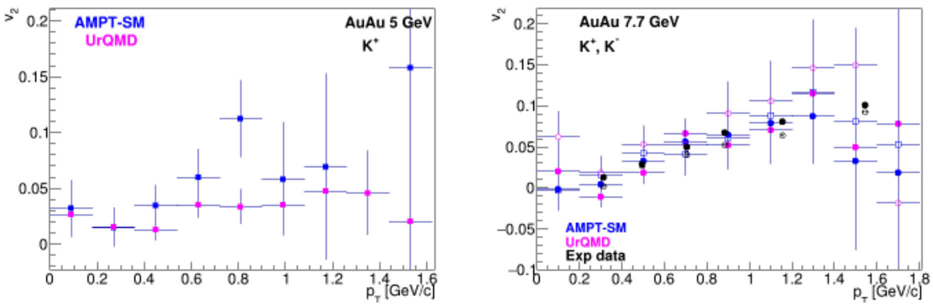

Fig. 8 – (Color online) The positive kaon v_2 as a function of p_T in semi-central Au-Au collisions at 5 GeV (left) and positive and negative kaon $v_2(p_T)$ at 7.7 GeV (right). The notations are the same as in Fig.7.

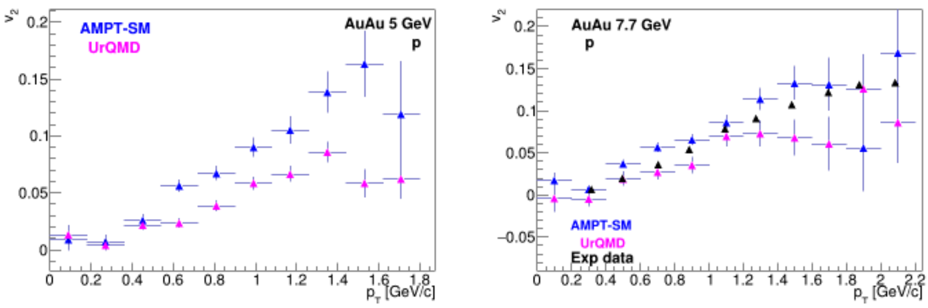

Fig. 9 – (Color online) The proton v_2 as a function of p_T in semi-central Au-Au collisions at 5 GeV and 7.7 GeV.

that the parton fragmentation processes may play a role in generating the azimuthal anisotropy of particle emission or, at the studied colliding energies, there are contributions from hadronic interactions over the partonic interactions in the system evolution.

The similarity of AMPT-SM and UrQMD results are questioning the NCQ scaling interpretation as a signature for the partonic phase formation in heavy ion collisions.

UrQMD code is a hadronic model, which does not consider the partonic degrees of freedom and the magnitude of the elliptic flow is smaller in this model. The contribution of partonic degrees of freedom, which becomes more and more important as the beam energy increases, is expected to enhance the strength of the collective flow.

In the AMPT with string melting model, the hadrons are "melted" into their valence quarks (partons) and these produced partons have partonic interactions in the hot and dense medium. The hadronization of partons is described by a coalescence model. The AMPT calculations were made considering a parton-parton interaction cross sections of 3 mb. The AMPT-SM results could indicate additional contributions to the elliptic flow from the partonic interactions. Therefore, the AMPT-SM values are higher than the UrQMD results for all the particles.

We also compared the two code results for the elliptic flow coefficients of charged pions, kaons and protons in Figures 7, 8 and 9. For 7.7 GeV Au-Au collisions, the simulated results are compared with similar experimental data from STAR experiment [14]. The experimental data are shown in the Figures 7, 8 and 9 with black symbols.

For lower p_T values, charged pion and proton STAR data are closer to the UrQMD model indicating that the hadronic interactions become more dominant at the lower beam energies, while at higher p_T values the experimental data are closer to the AMPT-SM results.

The study of elliptic flow of identified particles is one of the scientific objectives of CBM collaboration and will contribute to our understanding of the hot and dense nuclear matter properties and behavior and to the phase transition from hadronic to partonic matter [15].

3. CONCLUSIONS

In this work, we have investigated the energy and particle dependence of the elliptic flow in Au-Au collisions at moderate energies using AMPT-SM and UrQMD simulation codes. We found that the elliptic flow increases with energy for all studied particles and the AMPT-SM results are larger than UrQMD results for the same energy. Mass ordering of $v_2(p_T)$ for lower p_T values is observed, such ordering being explained by considering a hydrodynamic evolution, as well as coalescence processes in relativistic heavy-ion collisions. Also, the NCQ scaling of elliptic flow at the FAIR energies was studied. We observed a breaking of the NCQ scaling at higher KE_T/n_q values and this could indicate increased contributions from hadronic interactions in the system evolution with decreasing beam energy.

Acknowledgements. This work was supported by IFA, RO-FAIR program, project number 09-FAIR/16.09.2016. CR was partially supported by Program-NUCLEU, INFLPR PN 16 47.

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