



Anisotropic Flow of Identified Hadrons by the Event Plane Method at FAIR Energies

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ABSTRACT

A comprehensive study of the elliptic flow of hadrons for non central $Au+Au$ collision with the impact parameter of $b = 5-9$ fm in the mid rapidity region of $(-1 \leq y_{cm} \leq 1)$ with the reaction plane angle Ψ in the mid-pseudorapidity of $|\eta| < 0.35$ is investigated in the FAIR energy regime of 25 A GeV by the AMPT model with both the default and the string melting scenarios. In both the versions of AMPT model, we have observed that at low P_T regions upto $P_T \approx 1.0$ GeV/c, elliptic flow shows an almost linear increase with the increase in the transverse momentum P_T . Also there is a clear mass ordering effect that is particles with higher mass shows a smaller v_2 at a given P_T than the particles with lower mass. In addition the constituent quark number scaling of elliptic flow has been investigated where we have observed a universal scaling in the string melting version of the AMPT model i.e with the partonic degrees of freedom due to quark coalescence model compared with the default version of the AMPT model. Further the scaling behavior has been observed for the transverse kinetic energy KE_T with both scenarios.

Keywords: Anisotropic flow, Elliptic flow, Scaling, Quark Coalescence, Transverse kinetic energy

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INTRODUCTION

The major goal of high energy heavy ion collision experiments is to create extremely hot and dense matter with partons as its fundamental components called the Quark Gluon Plasma (QGP). The various observables have been studied, both in experiments, and in model calculations, so as to unravel the properties of the dense hot matter created in the collisions. Of particular interest is the elliptic flow which is considered as one of the most important signatures of the formation of QGP as it is sensitive to the very early stage of the collision (Voloshin & Poskanzer; Ollitrault, 1992). It has its origin in the initial spatial asymmetry of the system, which is then transformed into the momentum anisotropy of the particles. It is well established experimental fact that in non-central heavy ion collisions there is an anisotropic flow phenomenon which refers to anisotropy in the azimuthal

distribution of the produced particles in the transverse plane with respect to the reaction plane (Poskanzer & Voloshin, 1998; Adams, 2005; Back, 2005). Therefore it is possible to determine an event plane with respect to which the angular distribution of particles momenta shows a strong $\cos(n(\phi - \Psi))$ dependence, called anisotropic flow. Anisotropic flow effects are present when the distribution of the azimuthal angles of the emitted particles relative to the reaction plane is not uniform. The term 'flow' generally refers to the magnitude of this anisotropy. The process which transforms the spatial anisotropy of the system into the final momentum anisotropy is related to the pressure gradients which develop anisotropically, the pressure and the energy density are maximal in the center of the reaction volume and decrease towards the outside, until they reach a value close to zero at the system boundary. The size of the system being the

shortest in the reaction plane, the pressure gradients must then be maximal. This is the reason why the outgoing particles will be emitted preferentially in the reaction plane. The elliptic flow as a powerful probe to study the properties of hot and dense matter in the relativistic heavy ion collision experiments is investigated at the CERN Super Proton Synchrotron (SPS), the BNL Relativistic Heavy Ion Collider (RHIC), and the CERN Large Hadron Collider (LHC) accelerators.

At these energies, the observed elliptic anisotropy is attributed to the presence of a collective motion (flow) of the particles produced in the collision. For non central collisions, the geometrical anisotropy of the almond shaped overlap region of the colliding nuclei causes a large pressure gradient in the reaction plane than in the direction orthogonal to it (Ollitrault, 1998; Sorge, 1997). Elliptic flow is also a very interesting observable for studying the phase transition from hadronic matter to the quark gluon plasma, in particular at FAIR energies where the onset of deconfinement is expected to take place (Alt, 2008; Alt, 2003). A collapse of elliptic flow of protons at mid-rapidity has been suggested as a signature of the first order phase transition (Stoecker, 2005). Moreover, the scaling of the elliptic flow parameter v_2 with the number of valence quarks as the constituent quark number scaling (Lacey, 2006) is an indication for flow generation in a partonic phase. The purpose of the present study is to explore the mass ordering effect of the transverse momentum P_T dependence of elliptic flow parameter v_2 at the intermediate lab energy range of 25 A GeV FAIR energies for different hadrons by using a multiphase transport model (AMPT) (Lin & Ko, 2002) with both the scenarios. Also the constituent quark number scaling behavior of elliptic flow has been investigated. The method applied in the analysis is the Event Plane method generalized in (Poskanzer & Voloshin, 1998). It has been successfully used in many heavy ion experiment, from AGS to SPS and RHIC, and in particular by the STAR collaboration. The Reaction Plane can be defined by the direction of the impact parameter b vector connecting the centers of the two nuclei, and the beam direction (z axis). The accuracy on the measurement of the anisotropic parameter v_2 strongly depends on the resolution of the reaction plane that one might expect in CBM.

AMPT MODEL

We use A Multi-Phase Transport (AMPT) model to investigate the effect of parton dynamics related to the elliptic flow dynamics. The AMPT model which is a hybrid transport model is based on partonic level transport dynamics. This model mainly consists of four main components initial conditions, partonic interactions, conversion from partonic matter into hadronic matter and hadronic interactions in collision evolution. The AMPT model uses the same initial conditions as in Heavy Ion Jet Interaction Generator (HIJING) (Wang & Gyulassy, 1991). Scattering among partons are modelled by Zhangs parton cascade (ZPC), which calculates two-body parton scatterings using cross sections from lattice QCD with screening masses. There are two versions of AMPT model, one is the default AMPT, and the other is AMPT with string melting. In the default AMPT

model (Lin, Pal, Ko, 2001) partons are recombined with their parent strings when they stop interacting, and the resulting strings fragment into hadrons according to the Lund string fragmentation model (Andersson & Gustafson, 1983). In the AMPT model with string melting scenario (Lin & Ko, 2002; Lin, Ko & Pal, 2002), a quark coalescence model is used to combine parton into hadrons. The evolution dynamics of the hadronic matter is described by A Relativistic Transport (ART) model (Li & Ko, 1995). The string melting version of the AMPT model is based on the idea that for energy densities beyond a critical value of about $1 \text{ GeV}/f m^3$, it is difficult to visualize the coexistence of strings (or hadrons) and partons. Hence the need to melt the strings to partons. This is done by converting the mesons to a quark and anti-quark pair, baryons to three quarks (through intermediate diquark process) etc. The scattering of the quarks are based on parton cascade ZPC (Lin & Ko, 2002). Once the interactions stops, the partons then hadronizes through the mechanism of parton coalescence. The interactions between the mini-jet partons in AMPT model and those between partons in the AMPT string melting model could give rise to a substantial v_2 .

The results from AMPT string melting would indicate the contribution of partonic interactions to the observed v_2 . In this article, we present a detailed study of the elliptic flow v_2 at the FAIR energies based on the AMPT model with the default and the string melting scenario. The string melting scenario is believed to be much more appropriate than the default AMPT scenario because of the quark coalescence model present in the string version of AMPT. The AMPT model with string melting scenario has successfully described the elliptic flow of stable baryons and mesons (Lin & Ko, 2002; Lin, Ko & Pal, 2002). It can also describe higher-order anisotropic flow parameters v_n including the odd- n ones (Lin & Ko, 2002). In this work, we focus on the elliptic flow v_2 .

MASS ORDERING OF ELLIPTIC FLOW v_2 AT P_T

Experimentally, the most direct evidence of flow comes from the observation of anisotropic flow, which is the anisotropy in particle momentum distributions correlated to the reaction plane. The azimuthal anisotropy in particle production is the clearest experimental signature of collective flow in heavy-ion collisions (Heiselberg & Levy, 1999; Brachmann et al., 2002). Rescattering within the interaction regions almond shaped spatial anisotropy will give rise to a momentum anisotropy that may be observed. The momentum anisotropy is examined by performing a Fourier decomposition of the momentum space particle distribution in the x - y plane (Bleicher & Stocker, 2002; Appelshauser et al., 1998). This gives us the following equation

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

Where N is the number of particles, v_1 is the first coefficient of the Fourier expansion of the azimuthal distribution of the emitted particles describing directed-in-plane flow, v_2 is the second Fourier coefficient of anisotropy known as elliptic flow, and ϕ is the angle between flow of particles and the reaction plane. Ψ is the reaction plane angle

which can be estimated by using the azimuthal angle distribution of particles as

$$\Psi_n = \tan^{-1} \left(\frac{\sum_i \sin(n\phi_i)}{\sum_i \cos(n\phi_i)} \right) / n \quad (2)$$

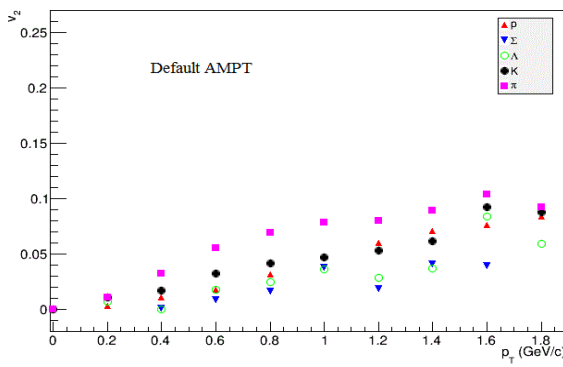
Where sum goes over all i particles used in the event plane determination and are chosen in such a way to make the reaction plane resolution the best that is possible. This event plane angle Ψ_n is in the range $0 \leq \Psi_n \leq \frac{2\pi}{n}$. For $n=2$ it is $0 \leq \Psi_n \leq \pi$ is equivalent to the event plane determined from the transverse sphericity matrix (Ollitrault, 1992; Ollitrault, 1993). The directed flow measures the total amount of transverse flow; and has a definite direction, along the impact parameter. It is most pronounced in semi-central interactions around target and projectile rapidities where the spectators are deflected away from the beam axis due to a bounce-off from the compressed and heated matter in the overlap region. v_1 is defined by

$$v_1 = \left\langle \frac{p_x}{\sqrt{p_x^2 + p_y^2}} \right\rangle = \langle \cos(\phi - \Psi) \rangle \quad (3)$$

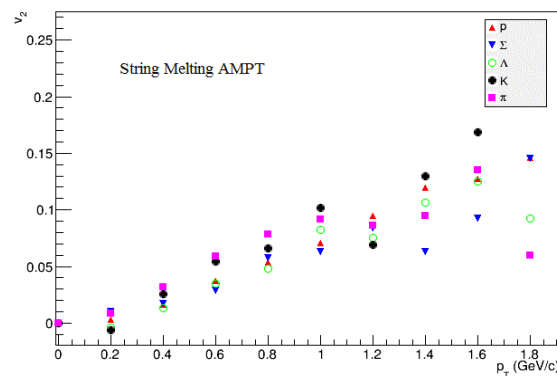
The second coefficient of the Fourier expansion of the azimuthal distribution of the emitted particles v_2 is the elliptic flow (Lacey et al., 2007). This type of flow is strongest around central rapidities in non-central collisions. v_2 (Appelshauser, 1998) is defined by

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2(\phi - \Psi) \rangle \quad (4)$$

In the present article we have calculated the elliptic flow of hadrons for non central Au + Au collision with the impact parameter of $b = 5 - 9$ fm in the mid rapidity region of $(-1 \leq y_{cm} \leq 1)$ and mid-pseudorapidity of $|\eta| < 0.35$ with the reaction plane angle Ψ investigated in the FAIR energy regime of 25 A GeV by using the AMPT model with both the default and the string melting scenarios as shown in Fig. 1.



(a) Default version of the AMPT model



(b) String Melting version of the AMPT model

Fig1. Elliptic flow v_2 as a function of P_T at 25 A GeV FAIR energies from the (a) default version of the AMPT model i.e without partonic degrees of freedom and (b) with the the string melting version i.e with partonic degrees of freedom for non central Au + Au collisions with the impact parameter $b = 5 - 9$ fm.

It is observed in Fig 1 as in both the versions of AMPT model i.e with the default Fig 1(a) and the string melting versions Fig 1(b), we have observed that at low P_T regions upto $P_T \approx 1.0$ GeV/c, elliptic flow shows an almost linear increase with the increase in the transverse momentum P_T . Also we have observed that there is a clear mass ordering effect that is particles with higher mass shows a smaller v_2 at a given P_T than the particles with lower mass. This mass ordering effect has been predicted by hydrodynamic model calculations (Huovinen, Kolb, Heinz, 2001) which describe these observations in this P_T region attributing the mass ordering to an underlying common transverse velocity field. However the production of high P_T hadrons is small compared to that of RHIC (Adams et al.,).

This mass ordering is caused by the presence of radial flow which boosts particles to higher momenta (Abelev et al., 2008). The momentum gain is larger for heavier particles resulting in a flattening of the transverse momentum spectra of heavy particles. This, in its turn, results in a decrease of v_2 at low P_T and a shift towards higher P_T of the linear rise of v_2 (P_T).

The effect of the phase transition is more pronounced in the heavier protons because they are more influenced by the

collective velocity which is sensitive to the equation of state. At intermediate P_T particle production by coalescence or recombination (Adams et al., 2005) predicts that v_2 depends on the quark content of the particle (Adcox et al., 2005). We cannot go beyond $P_T \approx 2$ GeV/c as the simulated data suffer from large fluctuations. It is important to note that hydrodynamic models fail to describe the mass and momentum dependence of elliptic flow as long as they don't invoke a phase transition from partonic to hadronic degrees of freedom.

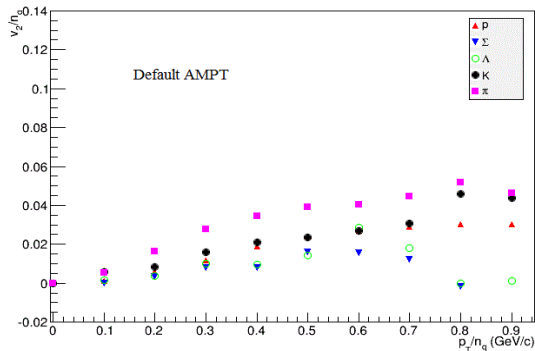
This sensitivity to the equation of state justifies the importance of elliptic flow for the understanding of hot and dense nuclear matter, including the possible creation of Quark Gluon Plasma (QGP). Also the Fig 1(b) shows that the string melting version of the AMPT model generates larger elliptic (v_2) values compared to the Fig 1(a) default AMPT model because of the partonic degrees of freedom present in the string melting AMPT.

The results of elliptic flow v_2 has been compared with the results of elliptic flow published in (Bhaduri & Chattopadhyay 2010) calculated at FAIR energy where elliptic flow is obtained directly from its definition and the reaction plane angle is taken as zero.

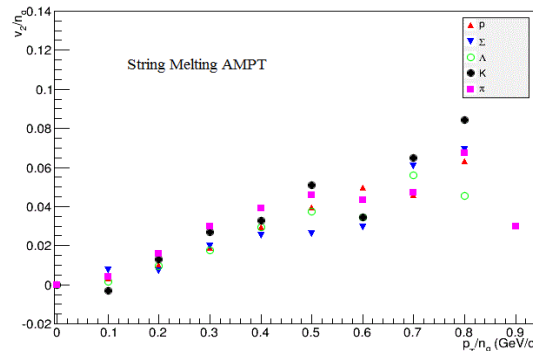
SCALING BEHAVIOR OF ELLIPTIC FLOW

The scaling behaviour has been considered as an indication at the early stage when v_2 has been built, is partonic in nature and the effective constituent quark degrees of freedom plays an important role in the hadronization process. It has thus been speculated that this scaling is directly related to the formation of the color-deconfined phase, where all the hadrons are created at hadronization of the quark gluon matter by recombination or coalescence of partons. This scaling factor, according to the quark coalescence approach, is the number of constituent quarks which will be $n_q = 2$ for mesons and $n_q = 3$ for baryons. Here we have calculated the constituent quark number scaling behavior of elliptic flow v_2 as a function of P_T for different hadrons. Fig.2 shows the variations of v_2/n_q as a function of P_T/n_q for non central Au + Au collisions at an impact parameter of $b = 5-9$ fm. Where n_q is the number of quarks which may be 2 or 3 depends upon whether it came from baryons or mesons. Also it is observed that in Fig. 2 (a) the default version of the AMPT model i.e without partonic degrees of freedom there is not a

remarkable universal scaling as compared to that of Fig 2 (b) AMPT model with string melting i.e with the partonic degrees of freedom as the default version of AMPT model does not show the behavior that would be expected if quark coalescence were dominant. This observed behavior of scaling has been well explained by the quark coalescence models. These models assume that in this P_T range particle production is dominant by coalescing quarks. Two quarks moving with the same momentum make up a meson with twice the momentum of the original quarks, three quarks coalescing into a baryon with three times the quark momentum (Molnar & Voloshin 2003). Therefore by scaling the observed v_2 signal and the transverse momentum by the number of constituent quarks one obtains the underlying quark flow. The success of these quark coalescence models in describing the measured v_2 is a strong hint that the observed large anisotropic flow builds up at the partonic stage of the system's evolution already. On one hand this suggests that the system evolves through a state of partonic degrees of freedom, which on the other hand suffer a lot of re-scattering and therefore should be close to local thermal equilibrium.



(a) Default version of the AMPT model



(b) String Melting Version of the AMPT mode

Fig 2. Elliptic flow as a function of P_T scaled according to the number of constituent quarks (n_q) of the hadrons at 25 A GeV FAIR energies with the default and the string melting versions of AMPT model for non central Au + Au collisions with the impact parameter $b = 5 - 9$ fm.

Such scaling behavior is thus considered as an indication that the early stage, when v_2 has been built up, is partonic in nature and the effective constituent quark degrees of freedom play an important role in the hadronization process. It has thus been speculated that this scaling is directly related to the formation of the color-deconfined phase, where all the

hadrons are created at hadronization of the quark-gluon matter, by recombination or coalescence of partons.

We compare the scaling behavior of elliptic flow v_2 again with the FAIR energies which provide another detailed set of scaling tests published in (Bhaduri & Chattopadhyay 2010) as shown in Fig 3 and the results seems to be inconsistent.

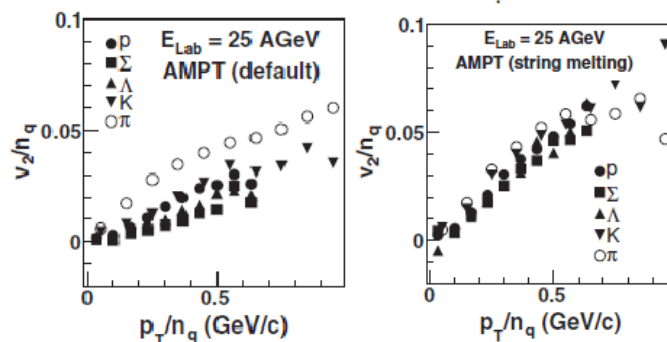
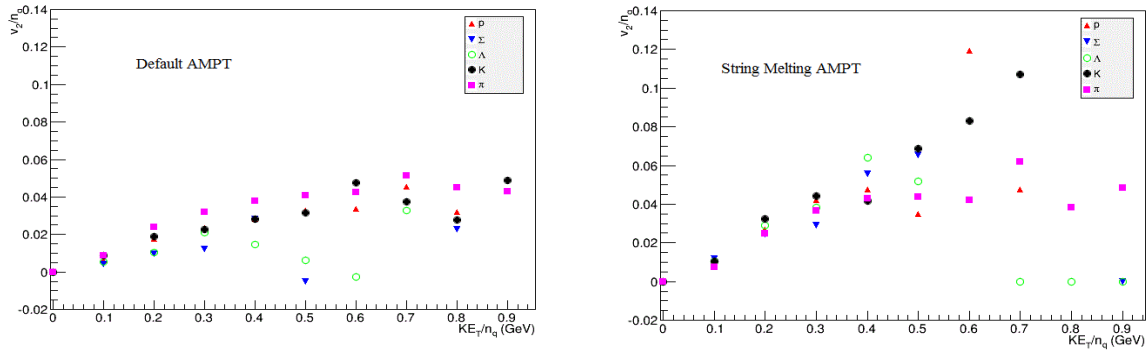


Fig 3. Variations of v_2/n_q with P_T/n_q at 25 A GeV FAIR energies with the zero reaction plane angle from both the string melting scenario and default hadronic version of AMPT model

CONSTITUENT QUARK NUMBER SCALING OF ELLIPTIC FLOW v_2 WITH THE TRANSVERSE KINETIC ENERGY KE_T

The transverse kinetic energy $KE_T = m_T - m$, where $m_T = \sqrt{m^2 + P_T^2}$ is the transverse mass of the particle is also take as a scaling variable to explore the scaling behavior of elliptic

flow v_2 because KE_T is a robust scaling variable as it takes into account relativistic effects, which are especially important for the lightest particles. If this aspect of v_2 is driven by a hydrodynamic pressure gradient, the prediction is that the differential v_2 values observed for each particle species should scale with KE_T .



(a) Default version of the AMPT model

(b) String melting version of the AMPT model

Fig 4. Elliptic flow as a function of transverse kinetic energy (KE_T) for different particle species scaled according to the number of constituent quarks (n_q) of the hadrons at 25 A GeV FAIR energies with both the default and string melting version of AMPT model for non-central Au + Au collisions with impact parameter $b = 5 - 9$ fm.

The pressure gradient that drives elliptic flow is directly linked to the collective kinetic energy of the emitted particles. Here we have calculated the transverse kinetic energy KE_T for different particle species scaled according to the number of constituent quarks (n_q) of the hadrons at 25 A GeV FAIR energies with both the versions of AMPT model as shown in Fig 4.

It is observed that all particle species scale to a common set of elliptic flow values for $KE_T \leq 1$ GeV, confirming the strong influence of hydrodynamic pressure gradients. The results are again compared with the scaling behaviour of elliptic flow v_2 with the already published results in (Bhaduri & Chattopadhyay 2010) as shown in fig 5 and the results seems to be inconsistent.

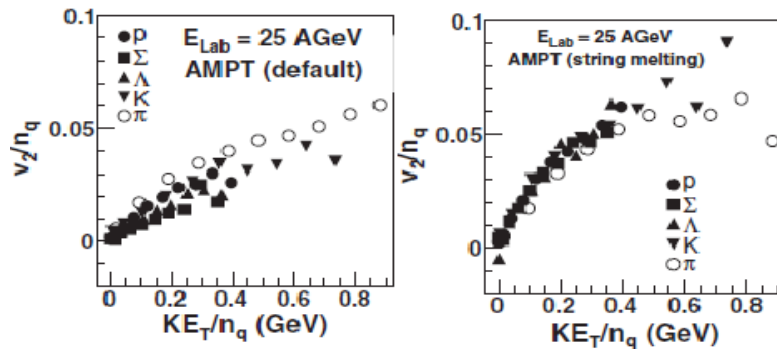


Fig 5. Variations of v_2/n_q with KE_T/n_q at 25 A GeV FAIR energies with the zero reaction plane angle from both the string melting scenario and default hadronic version of AMPT model

SUMMARY

In summary we have presented the detailed study of the elliptic flow of hadrons at 25 A GeV FAIR energies for non central collisions of $b = 5 - 9$ fm in the mid rapidity region by using the default and the string melting versions of AMPT model with the event plane method. We have observed that there is a mass ordering effect in both the versions of AMPT model and is a linear scaling of elliptic flow with the transverse momentum. Also we have observed the scaling behavior of elliptic flow which is more in the string melting versions of AMPT model compared with the default version.

Then the results are compared with the elliptic flow results at FAIR energies but with the zero reaction plane angle and our results seems to be in consistent with the result but with the more accuracy. Anisotropic flow at FAIR energies has produced very important and exciting results. Also it can be concluded that the measurements calculated in Au + Au collisions at FAIR energies will create the deconfined and mostly thermalized matter. Also the hadronization scenario via constituent quark coalescence has yet another importance in our understanding of the dynamic of multi-particle production.

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