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First Order Harmonic Flow of Heavy Quarks using a Hybrid Transport Model

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Abstract **Review Article**

We report the investigation of the first order flow of charmed quarks in gold-to-gold collision at the energy near to the speed of the light using A Multi-Phase Transport (AMPT) model. We have used the AMPT string melting version known as partonic interactions option. In this study, we investigated the directed flow v_1 of the charmed quark D^0 as a function of rapidity. The model predicts the correct sign for D^0v_1, but the size of the predicted directed flow signal is too small by about an order of magnitude comparing to the real data from the STAR collaboration analysis. The AMPT model shows that the charm quark v_1 magnitude is larger than that of the light quarks at large rapidity. This indicates that the charm quarks can retain more information from initial condition than the light quarks.
Keywords: A Multi-Phase Transport (AMPT), Hybrid Transport Model, Quantum Chromodynamics (QCD).
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1. INTRODUCTION

Quantum Chromodynamics (QCD) is a gauge theory which describes the strong interaction as an exchange of intermediate bosons (gluons) between particles with color charge [1]. QCD is the responsible interaction force between quarks and gluons. The theory of QCD was inspired by Quantum Electrodynamics, in which electromagnetic phenomena are described in terms of an exchange of photons. Gluons experience the strong force among themselves, by exchange of so-called color charge [2]. In the universe, there are four fundamental forces (interactions): gravitational, electromagnetic, strong nuclear, and weak nuclear. Each force has a corresponding carrier particle called a gauge boson. All of the fundamental particles along with their forces are presented in the Standard Model (SM) [3].

The SM of particle physics is the theory describing three of the four known fundamental forces (the electromagnetic, weak, and strong interactions, and not including the gravitational force) and two types of fundamental fermions: leptons and quarks. Both of which have spin 1/2 [4]. There are six different gauge bosons: The massive $W^{\pm}$ and Z^0 bosons, the massless photons (ϒ), as well as the gluons (g) and Higgs (H) boson.

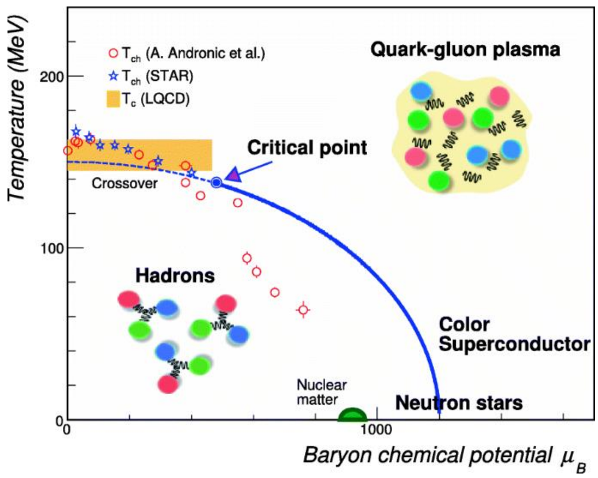

Fig. 1: Schematic picture of the QCD phase diagram

Figure 1 shows a cartoon-like phase diagram of QCD. It is shown in the plane of temperature versus net baryon density. A state of de-confined quarks and gluons is expected to be presented at very high T, while at low T and low baryon density, the quarks and gluons are known to be confined inside hadrons.

The QGP phase of nuclear matter can only be created in extreme conditions of temperature and density [5]. At the critical temperature Tc~175 MeV (at zero chemical potential μ_B) the hadron interactions are so intense that had ronic states do not present a favorable quantum basis to describe the properties of the medium any more. In this condition the matter transforms into QGP, where quarks and gluons are de-confined in a thermalized state where they are the fundamental degrees of freedom. The newly formed state of QGP can be observed in indirect ways to confirm its existence [6, 7].

2. THE AMPT MODEL

The AMPT model, which is a hybrid transport model, has four main stages: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and hadronic interactions [8]. It uses the same initial conditions as Heavy Ion Jet Interaction Generator HIJING [9]. Scattering among partons are modelled by Zhang's parton cascade [10], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. In the default AMPT model as shown in figure 2, partons are recombined with their parent strings and when they stop interacting, the resulting strings fragment into hadrons according to the Lund string fragmentation model [11]. However, in the string melting scenario (labeled as AMPT-SM) as shown in figure 3, these strings are converted into soft partons. The AMPT-SM uses a quark coalescence model to combine partons into hadrons. The evolution dynamics of the hadronic matter is described by A Relativistic Transport (ART) model [12].

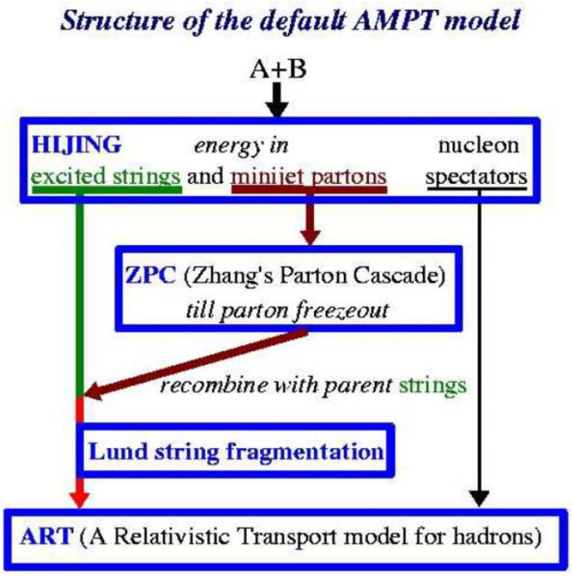

Fig. 2: (Color online) Illustration of the structure of the default AMPT model

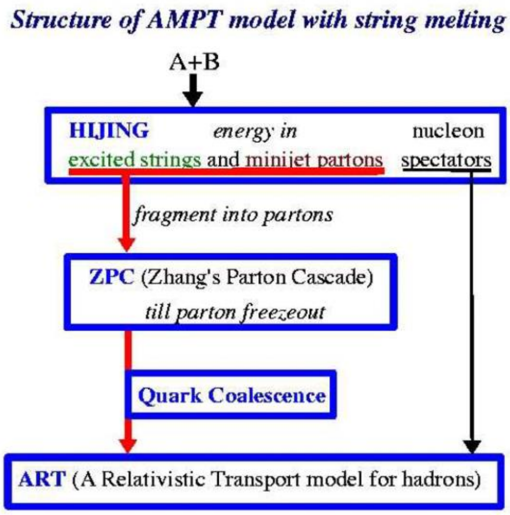

Fig 3: (Color online) Illustration of the structure of the AMPT model with string melting

3. COLLECTIVE FLOW

One of the most important heavy-ion collision observables is the collective flow of the produced matter when a collision occurs at non-zero impact parameter. The collective behavior is illustrated in figure 4. This spatial anisotropy produces pressure gradients in the expanding medium, boosting particles in the direction of the pressure gradients and transforming into anisotropies in the particle momenta.

The azimuthal anisotropy of produced particles with respect to the reaction plane is conventionally expanded in a Fourier series as can be seen below [13]:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos n\,(\phi - \Psi_r)\right]$$

where ϕ is the azimuthal angle of a particle, Ψ_r is the azimuth of the reaction plane, and the coefficients v_n are called the flow harmonics [14, 15].

Directed flow, v_1, is the first harmonic coefficients of the Fourier expansion. Directed flow is a promising observable for investigating a possible phase transition. The shape of v_1 as a function of rapidity, y, in the midrapidity ($|y| < 1.8$) region is of interest because its magnitude is a response of the initial anisotropy, the expansion dynamics and the equation of state of the medium. It has also been argued that it offers sensitivity to crucial details of the expansion of the participant matter during the early stages of the collision [16].

Rapidity, y, is a Lorentz additive quantity and the shape of a rapidity distribution of a physics quantity stays the same in all reference systems. The value of rapidity is zero for a particle emitted normal to the beam axis ($P_Z = 0$) and achieves its maximum value for beam particles. Rapidity can be described as a relativistic quantity usually used in particle physics acceleration. It is defined as:

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

Where E= √ $(p^2+m^2_0)$ is the particle's energy and P_Z = p cos(θ) the momentum projection on the beam axis (θ is the polar angle). In the limit where the particle is traveling near the speed of light where p >> m_0 or for massless particles such as photons.

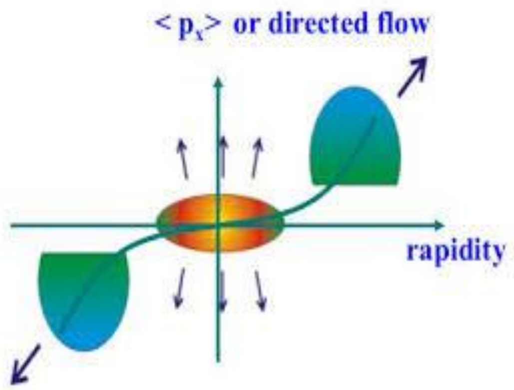

Fig. 4: A non-central collision viewed in the plane perpendicular to the beam direction

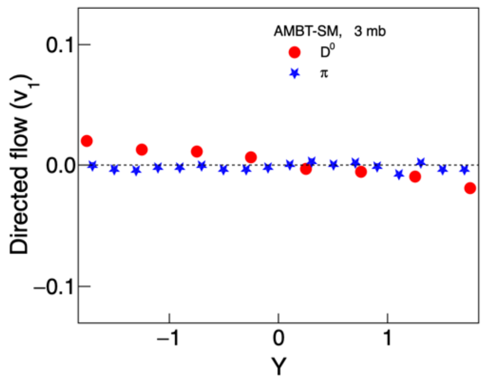

Fig. 5: Comparison of v_1(y) for D^0 and Л$^+$ in 200 GeV Au+Au collisions using AMPT-SM model.

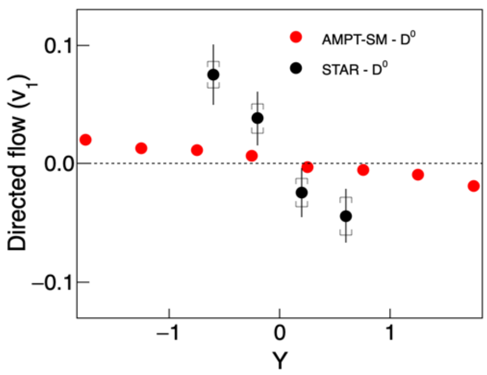

Fig. 6: Directed ow v_1(y) of D^0 mesons of AMPT-SM in 200 GeV Au+Au collisions compared to real data

4. CALCULATIONS AND DISCUSSION

The calculation and the systematic errors in this study were performed by a ROOT software which was written based on C++. ROOT is an object-oriented program and library developed by CERN [21]. There are several sources of systematic errors study in a measurement. A typical way to estimate their magnitude is by varying the measurement of the signal and extracting its uncertainty. In this study, we evaluate the signal of each element at specific depth several times. The mean values of the resulting signals are the typical final values that we obtained.

We perform the directed flow v_1 of charm mesons D^0 in Au+Au collisions at 200 GeV within the framework of AMPT model. The study of D^0v_1 can offer insight into the initial dynamics of the system because it is generated in early times of the collision and also the charm production limited to the primordial stage of the collisions. We have used string melting version (ver. 2.26) of AMPT model [17] (which includes parton coalescence) for the estimation of directed flow. For this analysis, we have generated 0.5 Million events to investigate the $v_1(y)$ of both heavy and light quarks. In order to form hadrons from quarks, we have employed the dynamic coalescence mechanism. Finally, we set the cross-section to be 3 mb with turning the hadronic interactions on.

In this study, we investigated the rapidity dependence of D^0v_1 and Л$^+v_1$ in 10-80% central Au+Au collisions at 200 GeV using AMPT-SM model. Figure 5 shows the AMPT-SM D^0v_1 calculation (presented as solid red circle) and AMPT-SM Л$^+v_1$ calculation (presented as solid blue stars). The results indicate that the D^0v_1 has larger magnitude than that of pions Л$^+v_1$ for full pT and within the range (|y| < 1.8). Our observation from AMPT-SM model calculation suggests that D^0v_1 can be used as a useful probe of the early stage of the collision.

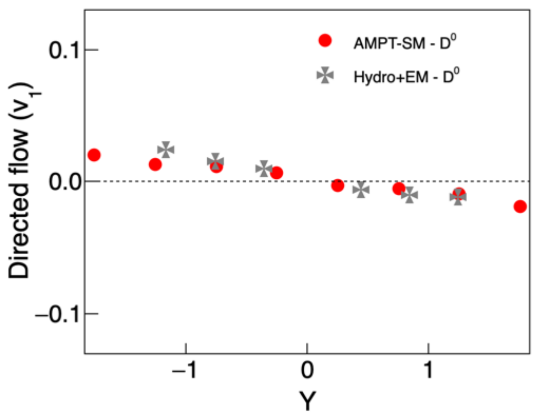

Fig. 7: D^0 v_1(y) from AMPT-SM compared to D^0 v_1(y) from Hydro model

The results of AMPT-SM D^0v_1 calculation (presented as solid red circle) as shown in figure 6 is compared to the heavy flavor results from STAR collaboration at Brookhaven National Laboratory (presented as solid black circle). The model predicts the correct sign for D^0v_1 mesons in 10-80% central Au+Au collisions at 200 GeV, but the magnitude of AMPT-SM D^0v_1 is under estimated. The large directed flow of D^0 mesons from the real data could be driven by the tilted initial bulk medium a friction of second after the collision.

Figure 7 presents the AMPT-SM analysis (presented as solid red circle) for the directed ow $v_1(y)$ of D^0 in 10- 80% central Au+Au collisions at 200 GeV compared to the heavy favor results from hydro+EM model calculation [19, 20], where Langevin dynamics for heavy quarks are combined with a hydrodynamic medium and a tilted initial source. The AMPT-SM result of D^0v_1 shows strong agreements with the prediction of Hydro+EM model calculation.

5. SUMMARY AND CONCLUSION

In conclusion, we have studied the directed flow of heavy and light flavor hadrons in Au+Au collisions at 200 GeV for 10-80\% using the string melting version of AMPT model. The $v_1(y)$ magnitude for AMPT-SM heavy flavor hadrons is larger than that of the light hadrons at large rapidity. This observation indicates that the charm hadrons could retain more information of the initial dynamics than the light quarks. The results of D^0v_1 AMPT-SM model predicts anti-flow for D^0v_1 but the size of the predicted directed flow signal is underestimated compared to the real data results of the heavy flavor quarks.

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