Probing the profile of bulk matter in $p + \text{Pb}$ collisions via directed flow of heavy quarks

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The asymmetric initial geometry in $p + \text{Pb}$ collisions provide an opportunity to probe the initial matter distribution in these collisions. Using a multiphase transport (AMPT) model, we have studied the production of light and heavy quark particles in $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The pseudorapidity density ($dN/d\eta$) and elliptic flow (v_2) of light quark particles from AMPT reasonably agrees with the measurements by ALICE. We predicted the directed flow of light and heavy quarks in $p + \text{Pb}$ collisions. The v_1 of both light and heavy quark mesons show a nontrivial p_T dependence in p - and Pb-going directions. When integrated over the transverse momentum range $0 < p_T < 5$ GeV/c, the magnitude of heavy quark directed flow (v_1) is found to be 15 times larger than the light quark species in the Pb-going direction while the same in the p -going direction are comparable. The light and heavy quarks v_1 may offer the possibility to probe the initial matter density as well as the collective dynamics in $p + \text{Pb}$ collisions.

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I. INTRODUCTION

Relativistic heavy-ion collision ($A + A$) experiments are performed to understand the formation and evolution of a strongly interacting matter, called quark gluon plasma (QGP) [1]. Experiments at the Brookhaven Relativistic Heavy Ion Collider (RHIC) and at the CERN Large Hadron Collider (LHC) facilities have established the existence of such strongly interacting matter [2]. Collective motion of the particles (flow) emitted from $A + A$ collisions is of special interest because of its sensitivity to the equation of state of the system. Initially it was assumed that the small system collisions, such as $p + A$, do not create a QGP medium. However, the recent measurement of high multiplicity events in $p + A$ collisions at both LHC and RHIC energies reveal a strikingly similar collective behavior as those observed in $A + A$ collisions at comparable multiplicities [3–6]. It is still under debate what is the origin of collective behavior in small system collisions. Several hydrodynamics and transport model calculations have shown that such collective behavior in $p + A$ collisions may be attributed to final-state interactions similar to $A + A$ collisions [7–10]. The directed flow (called v_1) quantifies the first-order azimuthal anisotropy of particles of interest in the momentum space. The magnitude of v_1 is a response of the initial spatial anisotropy, the expansion dynamics, and

the equation of state of the medium [11–13]. The v_1 is defined as [14,15]

$$v_1 = \langle \cos(\phi_s - \Psi_{RP}) \rangle, \quad (1)$$

where ϕ_s denotes the particle azimuthal angle, $\langle \dots \rangle$ represents the average at a given rapidity, and Ψ_{RP} is the reaction plane angle.

The heavy quark play a crucial role in probing the QGP. The heavy quarks are produced in hard partonic scatterings following a binary collision profile during the early stages of collisions. Hence, the distribution of their production profile is expected to be symmetric with respect to the beam axis. The probability of their thermal production is expected to be small. Due to large mass, they decouple in the early stages of the collision. The total number of charm quarks is frozen quite early in the history of collision. This allows us to use heavy quarks to obtain information on early time dynamics. It is pointed out in Refs. [16,17] that the heavy quark directed flow (v_1) can be used as a probe for the longitudinal profile of the bulk matter distribution. Recently, the STAR experiment at RHIC observed about 25 times larger magnitude of v_1 slope for the D^0 mesons compared to the charged kaons [18]. These measurements provide vital information about the geometry of the matter distribution in the longitudinal direction in heavy-ion collisions, i.e., the tilting of bulk medium with respect to the colliding beam direction (z direction). In a hydrodynamic calculation, the rapidity dependence of v_1 is reproduced by a tilted source [19]. In $p + \text{Pb}$ collisions, there is an inherent asymmetry in matter distribution along the longitudinal direction. Moreover, the transverse size of the matter distribution is expected to be larger in the Pb-going than in the p -going direction. It can result in a stronger collective flow in the Pb-going direction. The ALICE Collaboration measured

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the elliptic flow of muons in $p + \text{Pb}$ collisions at 5.02 TeV. It is observed that the flow of muons in the Pb-going direction is about 16% stronger than in the p -going direction [5]. Such an enhancement of flow on the Pb-going side were predicted by hydrodynamic and transport model calculations [20].

In this paper, we would like to probe the initial distribution of the bulk medium in $p + \text{Pb}$ collisions via the directed flow of light and heavy quark particles. We have used a string melting version (v2.26t9b) of a multiphase transport (AMPT) model [21] (which includes parton coalescence). Approximately 5 million minimum-bias $p + \text{Pb}$ collision events at $\sqrt{s_{NN}} = 5.02$ TeV has been used for the results presented here. Experimental sign conventions of the p -going side being the forward (positive) rapidity and the Pb-going side is the backward (negative) rapidity has been followed. While the rapidity-odd component of v_1 [$v_1^{\text{odd}}(y) = -v_1^{\text{odd}}(-y)$] is related to the reaction plane, the even component v_1 (v_1^{even}) is expected to originate from the fluctuations within the initial-state colliding nuclei and not related to the reaction plane [22]. Typically one utilizes multi-particle correlation method [23] to evaluate v_1^{even} . In our calculations, the reaction plane angle is fixed at $\Psi_{RP} = 0$ (described later). We consider only the rapidity-odd component of directed flow and v_1 implies v_1^{odd} . We studied both the transverse momentum (p_T) and rapidity (y) dependence of v_1 for both heavy and light quarks.

This paper is organized as follows. In Sec. II, we discuss briefly the AMPT model. Section III describes the pseudorapidity distribution ($dN/d\eta$), v_1 , and elliptic flow (v_2) results from 5.02-TeV $p + \text{Pb}$ collisions using AMPT. Section IV presents a summary of the results.

II. THE AMPT MODEL

The AMPT is a hybrid transport model [21]. It consists of four main components: the initial conditions, partonic interactions, the conversion from the partonic to the hadronic matter, and hadronic interactions. It uses the initial conditions from Heavy Ion Jet Interaction Generator (HIJING) [24]. In the string melting scenario (labeled as AMPT-SM), the excited strings from HIJING are converted to soft partons. The scattering among partons is modeled by Zhang's parton cascade [25], which calculates two-body parton scatterings using cross sections from pQCD with screening masses. Once partons stop interacting (called parton freezeout later in the text), a quark coalescence model is employed to combine parton into hadrons. The subsequent hadronic interactions are described by a hadronic cascade, which is based on the ART model [26]. The parton-parton interaction cross section (σ_{pp}) in the string-melting version of the AMPT is given by

$$\sigma_{pp} = \frac{9\pi\alpha_s^2}{2\mu^2}. \quad (2)$$

For this study, we set the strong coupling constant $\alpha_s = 0.33$ and the parton screening mass $\mu = 2.265 \text{ fm}^{-1}$. This leads to $\sigma_{pp} = 3 \text{ mb}$. A partonic cross section of 1.5–3 mb is sufficient to reproduce the $p + \text{Pb}$ observations at the LHC energies [27].

FIG. 1. Pseudorapidity distribution ($dN/d\eta$ vs η) of charged particles in $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The blue open squares are results from AMT-SM model and red solid circles are experimental measurements from the ALICE Collaboration [28]. The vertical lines on the experimental measurements are the uncertainties.

III. RESULTS AND DISCUSSION

The AMPT model with choice of parameter settings as discussed above fairly well reproduce the measured pseudorapidity and elliptic flow in $p + \text{Pb}$ collisions at 5.02 TeV. Figure 1 shows the $dN/d\eta$ distribution of charged particles in 5.02 TeV $p + \text{Pb}$ collisions from the AMPT-SM model. Model results are compared to measurement by the ALICE Collaboration [28]. We observe that AMPT-SM moderately captures the feature in the data. The pseudorapidity distribution in asymmetric collisions (such as $p + \text{Pb}$) is explained by the fact that each participant source preferably showers particles along its direction of motion [29]. Figure 2 presents the elliptic flow ($v_2\{2\}$) of charged particles from AMPT-SM

FIG. 2. Two-particle cumulant method based elliptic flow (v_2) of charged particles as a function of transverse momentum (p_T) in $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The open squares are the results from the AMPT-SM model and the red solid circles are the corresponding measurements by the ALICE Collaboration [4].

and the same is compared to the measurements from ALICE [4]. The $v_2\{2\}$ is obtained from a two-particle cumulant (2PC) method, which gives the rms value of the quantity measured [30]. So the $v_2\{2\}$ measurement is in fact $\sqrt{v_2^2}$. Although we set $\Psi_{RP} = 0$ in the AMPT-SM calculation, the direction of participant plane is ambiguous and hence the 2PC method is suitable for v_2 estimation, especially for p + Pb collisions. We observed that the AMPT model fairly describes the p_T dependence of elliptic flow v_2 of charged particles measured by ALICE [4]. The AMPT calculation slightly overpredicts the magnitude of v_2 because the 2PC method is susceptible to nonflow, which is the dominant process in p + Pb collisions. It is also possible that AMPT may have more contribution from the nonflow compared to data. The directed flow refers to the collective motion of particles within the reaction plane, which consists of the impact parameter (x axis) and beam direction (z direction). To understand the initial geometry in p + Pb collisions in the AMPT model, we study the density profile of quarks in yx and xz Cartesian frame before and after the Zhang's Parton Cascade (ZPC) phase of AMPT-SM model. Since p + Pb is an asymmetric system, we recenter x, y coordinates of each partons as $x' = x - \langle x \rangle$ and $y' = y - \langle y \rangle$, where $\langle x \rangle$ and $\langle y \rangle$ corresponds to event-by-event average of x and y positions of the partons. For illustration purposes, we show the density profile for u and c quarks in p + Pb collisions at a fixed impact parameter (b) of 4 fm/c. From Fig. 3, we observe that the density profile of both u and c quarks are asymmetric along the x direction (i.e., along b). There is a relative shift in c quarks (more asymmetric along the x axis) with respect to that of light u quarks. To quantify this difference in asymmetry for u and c quarks, we calculate the initial rapidity-odd eccentricity (ϵ_1) as a function of center-of-mass pseudorapidity (η_s) using the equation [31,32]

$$\epsilon_1 = \langle \cos(\phi_s - \Psi_{RP}) \rangle. \quad (3)$$

Figure 4 presents ϵ_1 as function of spatial pseudorapidity (η_s) for u and c quarks, before and after the ZPC, for p + Pb collisions at impact parameter $b = 4$ fm. We observe a nonzero magnitude of ϵ_1 for both u and c quarks before the ZPC in both p - and Pb-going directions. After the end of partonic interactions, the magnitude of ϵ_1 is reduced for both the u and c quarks. However, we observe that the ϵ_1 is an order of magnitude (≈ 3.92 times at $\eta_s \approx -2.0$) higher for c quark compared to u quark in the Pb-going direction. In the p -going side, the ϵ_1 of the c quark is slightly larger (32% at $\eta_s \approx 2.0$) than the u quark. Since the v_1 is a response to initial spatial anisotropy, the observed difference in ϵ_1 can cause the difference in v_1 for u and c quarks. We also observed that the slope of the p_T spectra is harder for c quarks compared to u quarks and the p_T slope does not change appreciably before and after the ZPC.

Next we calculate the v_1 in minimum-bias p + Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the AMPT-SM. For v_1 we measure the shift of the medium, and hence we use a particle average as described in Eq. (1). Recently, in a completely different approach using a hydrodynamic model [16,17] for a symmetric Au+Au collisions, it was pointed out that the shift between the bulk medium and binary collision profile

FIG. 3. The longitudinal and transverse density profile in xz and xy Cartesian frame for light (u) and heavy (c) quarks in p + Pb collisions at 5.02 TeV from AMPT-SM model. η_s corresponds to spatial pseudorapidity of the quarks. $\eta_s > 0$ and $\eta_s < 0$ corresponds to p -going direction and Pb-going direction, respectively. The x, y position of the partons have been recentered event by event (see text for details).

of heavy quarks can induce a huge directed flow for the heavy quarks. Similar features were also observed in AMPT-SM calculations [33] done for symmetric Au+Au collisions at RHIC energies. The measurement of large magnitude of D^0 directed flow compared to the light mesons in Au+Au collisions by the STAR Collaboration [18] confirms such a scenario.

In order to address these aspects in p + Pb collisions, we study the v_1 of u and c quarks in p + Pb collisions. Figure 5 presents p_T differential v_1 for u and c quark in the forward ($y > 0$, p -going) and backward rapidity ($y < 0$, Pb-going) regions. We observe a nontrivial p_T dependence of v_1 for both u and c quarks in forward and backward rapidity regions. The qualitative features of p_T dependence of v_1 for u quarks are similar at both forward and backward rapidity regions, while the c quark's v_1 has a different trend at forward and backward rapidities. This is an interesting observation. We also observe that the p_T spectra of pions (and u quark) are much softer compared to that of D^0 meson (and c quark). The $\langle p_T \rangle$ for D^0 is 2.19 GeV/c while the same for pions is 0.636 GeV/c.

FIG. 4. Rapidity-odd eccentricity ϵ_1 of u and c quarks as function of spatial pseudorapidity η_s in 5.02 TeV $p + \text{Pb}$ collisions for $0 < p_T < 5$ GeV/c before and after the ZPC in the AMPT-SM model.

The observed nontrivial p_T dependence of v_1 for u and c quarks may indicate a convoluted effect of initial geometry and different slope of p_T spectra.

Figure 6 presents the v_1 as a function of center-of-mass rapidity ($y_{\text{c.m.}}$) for $0 < p_T < 5$ GeV/c for u and c quarks after ZPC (i.e., after partonic interactions). We observe that the v_1 of c quarks is orders of magnitude larger than that of the u quarks in the Pb-going direction. Since the $\langle p_T \rangle$ of c quarks is large than u quarks, the rapidity dependence of v_1 of u quarks predominantly comes from the low- p_T part of the spectra. The different $v_1(y)$ trends of u and c quarks may possibly be due to the shift in their transverse density profile (shown in Fig. 3) combined with their p_T spectra.

As described in Sec. II, to form mesons from the quarks after the partonic interactions, a dynamic coalescence mechanism is used in AMPT-SM [34]. In this mechanism, the probability of formation of a meson is calculated based on the overlap of the position-space distributions of the quark-antiquark pair with the phase space distribution of the meson (in its rest frame) [34]. Following this method, the u and $\bar{d}$ quarks coalesce to form pions, while c and $\bar{u}$ quarks coalesce to form the D^0 mesons. After the hadronization, these mesons participate in subsequent late-stage hadronic interactions described by the ART model [26]. The lifetime of hadronic

FIG. 5. Comparison of $v_1(p_T)$ for c and u quarks in forward (top) and backward (bottom) rapidity. Results are from $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV using AMPT-SM model.

phase in our study corresponds to 30 fm/c which is a default value in AMPT-SM.

Figure 7 presents p_T differential v_1 for D^0 and π 's in the forward ($y > 0$) and backward ($y < 0$) rapidity region. At

FIG. 6. Comparison of $v_1(y_{\text{c.m.}})$ for c and u quarks in p_T range 0–5 GeV/c. Results are from $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the AMPT-SM model.

FIG. 7. Comparison of $v_1(p_T)$ in forward rapidity (top) and backward rapidity (bottom) for D^0 and π in 5.02 TeV p +Pb collisions using AMPT-SM model.

both forward and backward rapidity, the pions have a strong (p_T) dependence v_1 . For D^0 mesons, the v_1 is consistent with zero in the forward rapidity and comparable with π at the backward rapidity. This feature is qualitatively similar to the behavior of constituent quarks, which is shown in Fig. 5. We observe that the magnitude of pion and D^0 v_1 is larger than that of u and c quarks' v_1 . It possibly comes from the hadronization by coalescence and a subsequent late-stage interaction in AMPT. We also observe that the magnitude of v_1 is different in Pb- and p -going directions. To quantify the difference, we present the ratio of v_1 in Pb-going to the p -going direction as a function of p_T in Fig. 8. Since v_1 of D^0 in the p -going direction is ≈ 0 , we fit the points with a constant. The fit results into $v_1(y > 0) = 0.00049 \pm 0.00098$ for the D^0 . We then make the ratio of v_1 for D^0 in the Pb-going direction with this fit value. For pions, the ratio has a nontrivial p_T dependence, while for D^0 mesons ratio is 15 times larger than for pions for $p_T > 1.5$ GeV/c. We also observe an enhancement of D^0 v_2 (about 20%, not shown here) in AMPT-SM in the Pb-going side which is of similar order to that observed for muons by the ALICE [18] experiment.

Figure 9 shows the rapidity dependence of v_1 for D^0 and π for $0 < p_T < 5$ GeV/c. The values of D^0 v_1 is about two orders of magnitude larger than pions in the backward

FIG. 8. Ratio of v_1 in Pb-going to p -going directions as function of p_T for D^0 (solid line) and π (dotted line) in 5.02 TeV p +Pb collisions using the AMPT-SM model.

rapidity (Pb-going direction). In the forward rapidity (p -going direction), the v_1 for both D^0 and π is consistent with zero. The enhanced magnitude of D^0 meson heavy v_1 may possibly comes from the shifted profile of the light and heavy quarks (as shown in Fig. 3) in conjunction with different p_T spectra, coalescence mechanism, and late-stage hadronic interactions. This is an interesting observation that suggests that the simultaneous measurement of pions and D^0 v_1 can be a useful probe to understand the initial bulk matter distribution in small system (p +Pb) collisions. The ALICE Collaboration observed that the v_2 of muons in the Pb-going direction is about 16% larger than that in the p -going direction and can be qualitatively captured by the AMPT model calculation [5,20]. We have shown that the directed flow heavy quark particles in the Pb-going direction are about 15 times larger than those in the p -going direction. Therefore, the measurement of heavy quark particle's v_1 has better sensitivity to the early stage medium than the light quark particles. It has been studied for

FIG. 9. Comparison of $v_1(y_{c.m.})$ for D^0 and π in the p_T interval 0–5 GeV/c in 5.02 TeV p +Pb collisions using the AMPT-SM model.

Au+Au collisions in Ref. [31] that the hadronization mechanisms and late-stage hadronic interactions can modify the v_1 . In the future, it will be interesting to study the sensitivity of v_1 with different coalescence hadronization mechanisms (such as coordinate space versus momentum space coalescence) and with different lifetimes of hadronic interactions in $p + \text{Pb}$ collisions.

IV. SUMMARY AND CONCLUSION

In summary, we have presented the directed flow (v_1) of light and heavy hadrons, and their constituent quarks in $p + \text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV using a string melting version of the AMPT model. We observe a nontrivial p_T dependence of v_1 for light and heavy quarks. When integrated over $0 < p_T < 5$ GeV/c, the magnitude of D^0 meson v_1 in the Pb-going direction is orders of magnitude larger than that of the pions. The ordering of magnitude of v_1 for pions and D^0 mesons in Pb- and p -going direction is consistent with that of the ϵ_1 for light and heavy quarks in the initial stage. The difference in v_1 for light and heavy hadrons possibly reflects the effect of the shifted transverse profile in the initial stages weighted with their p_T spectra. This unique feature of v_1 in

forward and backward rapidities for light and heavy quarks may be used to probe the distribution of the bulk matter along the longitudinal direction. The v_1 results may also help us understand the nature of collective dynamics in small system collisions. A recent paper [35] predicted that the initial magnetic field can induce a charge-dependent v_1 in $p + \text{Pb}$ collisions. The effect of charge-dependent splitting for heavy quarks is expected to be larger than for light quarks [36]. In the future, one can study these effects using the same AMPT model as discussed in this work.

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