Elliptic flow of transported and non-transported proton in Au+Au collisions within the UrQMD model

Biao Tu, Shusu Shi,* and Feng Liu†

Key Laboratory of Quarks and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan, 430079, China

With the framework of UrQMD model, by tracing the number of initial quarks in protons, we study the elliptic flow of transported protons, produced protons and anti-protons in Au+Au collisions at √sNN = 7.7, 11.5, 39, 200 GeV. The difference of elliptic flow between transported protons and anti-protons is observed. The results of UrQMD model show a good agreement with the STAR results at low energies, but are deviate at high energies. It partly explains the v2 difference between proton and anti-proton observed in the Beam Energy Scan program in Relativistic Heavy Ion Collider (RHIC).

I. INTRODUCTION

A strongly interacting hot and dense QCD matter called Quark-Gluon plasma (QGP) is created in the experiments of high energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and Large hadron Collider (LHC) [1–6]. To understand the properties and phase structure of nuclear matter, the Beam Energy Scan (BES) program involving Au+Au collisions has been carried out at RHIC. Various observables have been measured such as particle ratios, moments of the conserved gradient, degree of freedom, equation of state (EoS) and created matter [7–9], since it is sensitive to the pressure of the medium.

Some interesting phenomena have been observed in heavy ion collisions of BES program. The smaller v2 of p, K− and π+ than those of p, K+ and π−, are observed respectively. The difference of v2 decreases with increasing collision energies [10–14]. These interesting results were attributed to the different v2 of transported and produced quarks during the initial stage of heavy ion collisions in ref. [15]. It is argued that the effect results from quark transporttion from forward to middle rapidity. The authors assume that the v2 of transported quarks is larger than that of produced quarks. Thus, the different numbers of constituent quarks and anti-quarks in the particles and corresponding anti-particles lead to a systematically larger v2 of the baryons compared to the anti-baryons. The energy dependence is explained by the increase of nuclear stopping in heavy-ion collisions with decreasing collision energy. In ref. [16], it was suggested that the chiral magnetic effect induced by the strong magnetic field in noncentral collisions could be responsible for the observed difference between the v2 of π+ and π−.

A calculation [17, 18] based on the Nambu-Jona-Lasin(NJL) model can also qualitatively explain the difference between p−p, Λ−Λ and K+−K− by incorporating repulsive potential for quarks and attractive potential for antiquarks, which results in different flow patterns. The other study [19] based on AMPT model including mean-field potential can also qualitatively explain the difference between the elliptic flow of particles and their corresponding antiparticles. Because of the more attractive potentials of Λ compared to p, smaller v2 is obtained for Λ. Within the attractive K− and repulsive K+ potentials, slightly attractive π+ and repulsive π− potentials, smaller v2 is obtained for K− and π+ than that of K+ and π−.

In this paper, we study the elliptic flows of transported, produced protons and anti-protons at BES energies with a ultra relativistic quantum molecular dynamics (UrQMD) model [20, 21]. The paper is organized as followsings: in section II, the observable is introduced. A brief description of the UrQMD model is given in section III. The results and discussions are presented in section IV. Finally, a summary is given in section V.

II. OBSERVABLE

The azimuthal anisotropy is one of the most important observables in heavy ion collisions. In the non-central heavy ion collisions, the overlap region is an almond shape with the major axis perpendicular to the reaction plane which is defined by the impact parameter and the beam direction. As the system evolves, the pressure gradient from the overlapping region of two nuclei in the collisions is the origin of the collective motion component in mid-rapidity. The anisotropy in the coordinate space is transferred to the anisotropy in the momentum space. The anisotropic parameters are defined by the Fourier coefficients of the expansion of the azimuthal distribution [22, 23] of the produced particles with respect to the reaction plane which can be written as

\[ E \frac{d^3N}{dp^2} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} (1 + 2 \sum v_n \cos[n(\phi - \Psi_{RP})]) \]
where $\phi$ is the azimuthal angle of the particles. $\Psi_{RP}$ is the reaction plane. The anisotropic parameter is defined as the $n$th Fourier coefficient $v_n$:

$$v_n = \langle \cos[n(\phi - \Psi_{RP})] \rangle,$$  \hspace{1cm} (2)

here $\langle \cdots \rangle$ is taking the average over all the particles in the sample. The second harmonic coefficient is denoted as elliptic flow $v_2$. In the UrQMD model, $\Psi_{RP}$ is fixed at zero degree.

### III. URQMD MODEL

The ultrarelativistic quantum molecular dynamics (UrQMD) model is a microscopic transport model which could simulate the $p + p$, $p + A$, and $A + A$ collisions at relativistic energies and describes the time-evolution of a many-body system by using covariant equations of motion. It includes the string excitation and fragmentation, the formation and decay of hadronic resonances, and rescattering of hadrons. At low and intermediate energies, this microscopic transport model describes the interactions via the interaction between known baryon and meson species and their resonances. The excitation and fragmentation of color strings play important roles in the particle production at high energies in the UrQMD model. The version of the UrQMD model we used in this article is 2.3, and no modification was made to the model itself except for some additional outputs for tracing the particles origin as explained in ref [24]. We marked particles as produced or transported particles by tracing the number of initial quarks in a particle. In this article, protons with three(zero) initial quarks are treated as transported(produced) protons. Produced and transported protons are both made of three produced quarks, thus they should be similar in many aspects.

### IV. RESULTS AND DISCUSSIONS

The upper panel of Figure 1 shows the elliptic flow of transported $p$, produced $p$ and $\bar{p}$ within $0.2 < p_T < 2.0$ GeV/$c$ as a function of collision centrality in Au+Au collisions at various collision energies. One can find that $v_2$ shows strong centrality dependence since it mainly driven by the initial spatial eccentricity. The lower panel shows the difference of $v_2$ between transported $p$ versus $\bar{p}$ and produced $p$ versus $\bar{p}$. The difference of $v_2$ between produced $p$ versus $\bar{p}$ does not show clear centrality dependence, and is approximately consistent with 0. It is understandable, as the produced $p$ should be similar to $\bar{p}$ in many respects. They are all made up by produced quarks. Produced $p$ and $\bar{p}$ both only could be produced at the early stage of the system which energy density is relatively large in low collision energies. Produced $p$ and $\bar{p}$ all experience the full evolution of the system which leads to similar $v_2$. Larger elliptic flow of transported $p$ than that of produced $p$ and $\bar{p}$ is observed. It means the $v_2$ of $p$ transported from forward rapidity to mid-rapidity due to nuclear stopping effect is different with the $v_2$ of produced $p$ and $\bar{p}$. The results show that the elliptic flow of transported quarks is larger than that of produced quarks. The transported quarks which have been transported over a large rapidity suffer more scatterings than the produced quarks. It develops a larger $v_2$ of transported quarks than that of produced quarks, thus can leads to a larger $v_2$ of transported protons than that of produced protons. The difference of $v_2$ between transported $p$ and $\bar{p}$ shows a strong centrality dependence. Larger difference is observed in mid-central collisions than that in most central and peripheral collisions at 7.7 and 11.5 GeV. The transported proton experienced the whole process that the initial geometry eccentricity is transformed into anisotropy in the momentum space, at the same time the produced proton may only partly experienced this process. The baryon stopping effect is stronger in mid-central than central collisions and scattering is stronger in mid-central than peripheral collisions. The competition between these two effects makes the difference of $v_2$ is largest in mid-central collisions. This may lead to such a centrality dependence of the $v_2$ difference between the produced protons and anti-protons. But no significance centrality dependence was observed at 200 GeV due to the small difference of $v_2$ between produced $p$ and $\bar{p}$.

The upper panel of Figure 2 shows the elliptic flow of transported $p$, produced $p$ and $\bar{p}$ as a function of transverse momentum $p_T$ in 0-80% Au+Au collisions at $\sqrt{s_{NN}} = 7.7, 11.5, 39, 200$ GeV. The lower panel shows the difference of $v_2$ between transported $p$ versus $\bar{p}$ and produced $p$ versus $\bar{p}$. The difference of $v_2$ between produced $p$ and $\bar{p}$ does not show a clearly $p_T$ dependence and are consistent with 0. But the difference of $v_2$ between transported $p$ and $\bar{p}$ shows a weak $p_T$ dependence. The splitting of $v_2$ between transported protons and produced protons may be due to the a stronger flow of transported quarks which experience more interactions than produced quarks. This phenomenon is consistent the study in ref [15], by assuming the $v_2$ transported quarks are stronger than that of produced quark, it results a splitting of $v_2$ between proton and anti-proton.

When compared with the STAR results, we present the $p_T$ integrated $v_2$ of transported proton, produced proton and anti-proton within $0.2 < p_T < 2.0$ GeV/$c$ as a function with collision energy. In Figure 3, panel (a) shows the integrated elliptic flow $v_2$ of transported $p$, produced $p$, $\bar{p}$ as a function of collision energy in Au+Au collisions. Panel (b) shows the difference in $v_2$ from STAR measurements and UrQMD model as function of collision energy in Au+Au collisions. The $v_2$ of transported proton is systematically larger than that of the produced proton and anti-proton. So the $v_2$ difference between transported proton and anti-proton is larger than 0. The $v_2$ difference between produced proton and anti-proton is slightly smaller than 0 or consistent with 0 depending
FIG. 1: (Color online) Upper panel: The elliptic flow of transported $p$, produced $p$ and $\bar{p}$ are plotted as a function of collision centrality in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 39, 200 GeV. Lower panel: The difference of $v_2$ between transported $p$ versus $\bar{p}$ and produced $p$ versus $\bar{p}$ as a function of collision centrality in Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 39, 200 GeV.

FIG. 2: (Color online) Upper panel: The elliptic flow of transported protons, produced proton and antiprotons as a function of the transverse momentum $p_T$ for 0-80% central Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 39, 200 GeV. The lower panels show the difference of $v_2(p_T)$ between transported $p$ versus $\bar{p}$, and produced $p$ versus $\bar{p}$.

on the collision energy. The UrQMD model can not predict the right magnitude of the $v_2$ difference in relatively high collisions energy (39 and 200 GeV) because there are no partonic interactions in this model. The difference of $v_2$ between the transported $p$ and $\bar{p}$ show a similar energy dependence compared with the STAR results. Our results show a good agreement with the STAR results below 11.5 GeV. At 39 and 200 GeV, the $v_2$ difference of transported $p$ and anti-$p$ are not consistent with the STAR results quantitatively. This study indicates that the $v_2$ difference may be partly due to the $v_2$ difference between transported protons and anti-protons. At low energies, the source of $v_2$ difference may dominate by the hadronic interactions. But at high energies, both the partonic and hadronic interaction play an important role as a source of the $v_2$ difference. The magnitude of $v_2$ difference is consistent well between STAR data and UrQMD model in Au+Au collisions at 7.7 and 11.5 GeV indicated the hadronic interactions are dominant in these collision energies.
FIG. 3: (Color online) Panel (a): The integrated $v_2$ of transported proton, produced proton and anti-proton as a function of collision energy for 0-80% central Au+Au collisions. Panel (b): The difference in $v_2$ between transported $p$ versus $\bar{p}$ and produced $p$ versus $\bar{p}$ as a function of collision energy for 0-80% central Au + Au collisions.

V. SUMMARY

In summary, by tracing the number of initial quarks in the UrQMD model, the transported and produced protons can be distinguished. It provides us a way to study the elliptic flow of transported protons, produced protons and anti-protons. We found that the elliptic flow of produced protons show similar dependence of collision centrality, transverse momentum and collision energy with anti-proton. The possible explanation is produced protons and anti-protons are both made up of produced quarks. At the same time, the produced protons and anti-protons can be only produced at the early stage in the hadronic evolution of the system. Both of them experience the same magnitude of interactions in the system which lead to similar $v_2$. For the transported protons, The elliptic flow are systematically larger than anti-proton when we present as a function of collision centrality, transverse momentum and collision energy. Because the transported quarks which are transported from the forward rapidity to middle rapidity due to the baryon stopping effect gain larger $v_2$ than the produced quarks. Our results show a good quantitative agreement with the STAR results at low energies (7.7 and 11.5 GeV), but large deviation in high energies (> 39 GeV) with the STAR data. It indicates the hadronic interactions are dominant in collisions at 7.7 and 11.5 GeV. By studying with UrQMD model, our results indicate that the splitting of $v_2$ for protons may be partly leaded by the difference of $v_2$ between transported quarks and produced quarks. The source of $v_2$ difference may dominate by hadronic interactions in low energies at RHIC. On the other hand, both hadronic and partonic interactions play important roles in the source of $v_2$ difference at high energies.

ACKNOWLEDGMENTS

This work is supported in part by the MoST of China 973-Project No. 2015CB856901, Natural Science Foundation of China under Grants No. 11475070 and self-determined research funds of CCNU from the colleges base research and operation of MoE under Grant No. CCNU18TS031.

[1] I. Arsene et al. [BRAHMS Collaboration], Nucl. Phys. A 757 (2005) 1
[2] B. B. Back et al. [PHOBOS Collaboration], Nucl. Phys. A 757, 28 (2005)
[3] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757, 102 (2005)
[4] K. Adcox et al. [PHENIX Collaboration], Nucl. Phys. A 757, 184 (2005)
[5] K. Aamodt et al. [ALICE Collaboration], Phys. Rev. Lett. 105, 252302 (2010)
[6] K. Aamodt et al. [ALICE Collaboration], Phys. Rev. Lett. 106, 032301 (2011)
[7] J. Y. Ollitrault, Phys. Rev. D 46, 229 (1992).
[8] H. Sorge, Phys. Rev. Lett. 78, 2309 (1997)
[9] H. Sorge, Phys. Rev. Lett. 82, 2048 (1999)
[10] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. Lett. 110, no. 14, 142301 (2013)
[11] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 88, 014902 (2013)
[12] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 86, 054908 (2012)
[13] L. Adamczyk et al. [STAR Collaboration], Phys. Rev. C 93, 014907 (2016)
[14] Shusu Shi, Adv. High Energy Phys. 2016, 1987432 (2016)
[15] J. C. Dunlop, M. A. Lisa and P. Sorensen, Phys. Rev. C 84, 044914 (2011)
[16] Y. Burnier, D. E. Kharzeev, J. Liao and H. U. Yee, Phys. Rev. Lett. 107, 052303 (2011)
[17] J. Xu, T. Song, C. M. Ko and F. Li, Phys. Rev. Lett. 112, 012301 (2014)
[18] C. M. Ko, T. Song, F. Li, V. Greco and S. Plumari, Nucl. Phys. A 928, 234 (2014)
[19] J. Xu, L. W. Chen, C. M. Ko and Z. W. Lin, Phys. Rev. C 85, 041901 (2012)
[20] M. Bleicher et al., J. Phys. G 25, 1859 (1999)
[21] S. A. Bass et al., Prog. Part. Nucl. Phys. 41, 255 (1998)
[22] S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996)
[23] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C 58, 1671 (1998)
[24] Y. Guo, F. Liu and A. Tang, Phys. Rev. C 86, 044901 (2012)