Azimuthal anisotropies of reconstructed jets in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in a multiphase transport model

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Azimuthal anisotropies of reconstructed jets (jet $v_n(n=2,3)$) have been investigated in Pb+Pb collisions at center of mass energy $\sqrt{s_{NN}} = 2.76$ TeV within the framework of a multiphase transport (AMPT) model. Jet $v_2$ is in good agreement with the recent ATLAS data. Jet $v_3$ has a smaller magnitude than jet $v_2$, and decreases quickly with the increasing of jet transverse momentum. The dynamical stage evolution of jet $v_n$ reveals that jet $v_n$ is generated by the strong interactions between jets and a dense partonic matter, and almost maintains until final freeze out through hadronization via coalescence and hadronic rescatterings. Furthermore, jet $v_n$ is sensitive to initial spatial eccentricity ($\varepsilon_n$) of parton distribution, which is consistent with a path-length dependence of jet energy loss in a strongly-interacting partonic matter.

PACS numbers: 25.75.-q

I. INTRODUCTION

A deconfined quark-gluon plasma (QGP) could be created in the early state of high-energy heavy-ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC) [1, 2]. Jet, produced by initial hard processes, is an important probe to understand the properties of the QGP, since it losses its energy when it pass through the hot partonic medium [3]. The phenomenon, so-called jet quenching, has been confirmed by many experimental observations. The nuclear modification factor $R_{AA}$ is strongly suppressed at high transverse momentum $p_T$ in central A+A collisions at the RHIC [4] and LHC [5] energies. The measured elliptic anisotropy (or elliptic flow $v_2$) of final hadrons remains positive beyond $\sim 10$ GeV/$c$ in A+A collisions at the RHIC [6] and LHC [7] energies, which discloses a path-length dependence of jet quenching [8]. Besides these above measurements based on high-$p_T$ leading particles, recent LHC measurements on reconstructed jets provide comprehensive characterizations of jet quenching. A larger $p_T$ asymmetry for dijet has been observed in the central Pb+Pb collisions than in p+p collisions at the LHC energy [9, 11], which is thought as another direct evidence of jet energy loss in the QGP as important as the disappearance of back-to-back jet in central Au+Au collisions at the top RHIC energy [11]. The data on the elliptic anisotropy of reconstructed jet are recently released by the ATLAS Collaboration, which show nonzero $v_2$ values for a jet $p_T$ range from 45 to 160 GeV/$c$ in all centrality bins of Pb+Pb collisions [12, 13]. The elliptic anisotropy of jet quenching have been theoretically reproduced by the JEWEL model within a perturbative framework for jet evolution in a dense medium [14]. In this work, not only elliptic anisotropy $v_2$ but also triangular anisotropy $v_3$ of reconstructed jets is investigated in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV within a multiphase transport (AMPT) model, which includes both dynamical evolutions of partonic and hadronic phases. It is found that jet $v_n$ (n=2 and 3) is generated by the strong interactions between jets and partonic matter. However, other final state interactions, including hadronization (via coalescence) and hadronic rescatterings, have little effect on the jet $v_n$. Jet $v_n$ is sensitive to initial spatial eccentricity ($\varepsilon_n$) of parton distribution, which is consistent with a path-length dependence of jet energy loss in the QGP.

II. THE AMPT MODEL

The AMPT model with string melting scenario is utilized in this work [15]. It consists of four main stages of high-energy heavy-ion collisions: the initial condition, parton cascade, hadronization, and hadronic rescatterings. In order to increase the simulation efficiency of jets with $p_T > 45$ GeV/$c$, a dijet of $p_T \sim 40$ GeV/$c$ is triggered in the initial condition based on the HIJING model [16, 17]. The high-$p_T$ primary partons pullulate into jet showers full of lower virtuality partons through initial- and final-state QCD radiations. The jet parton showers are converted into clusters of on-shell quarks and anti-quarks through the string melting mechanism of the AMPT model. After the melting process, both a quark and anti-quark plasma and jet quark showers are built up. Next, Zhang’s parton cascade (ZPC) model automatically simulates all possible elastic partonic interactions among medium partons and jet shower partons, but without including inelastic parton interactions or further radiations at present. When the partons freeze out, they are recombined into medium hadrons or jet shower hadrons via a simple coalescence mechanism which combines two nearest quarks into a meson and three nearest quarks into a baryon. The final-state hadronic interactions, including elastic and inelastic hadronic scatterings and resonance decays, can be described by a relativistic hadronic transport (ART) model [18]. Recently, the AMPT model with a partonic interaction cross section of 1.5 mb has successfully given many qualitative descriptions of the
experimental results about pseudorapidity and \( p_T \) distributions\(^ {21} \), harmonic flows\(^ {21, 22} \) and reconstructed jet observables, including \( \gamma \)-jet \( p_T \) imbalance\(^ {23} \), dijet \( p_T \) asymmetry\(^ {24} \), jet fragmentation function\(^ {25} \) and jet shape\(^ {20} \) in \( \text{Pb+Pb} \) collisions at the LHC energies. Consistently with the previous studies, a partonic interaction cross section, 1.5 mb, is kept to simulate \( \text{Pb+Pb} \) collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) in this work.

### III. JET RECONSTRUCTION

To reconstruct jets, the kinematic cuts are chosen to be the same as in the ATLAS experiment\(^ {12, 13} \). An anti-\( k_t \) algorithm from the standard Fastjet package is used to reconstruct full jets\(^ {27} \), in which the jet cone size \( R \) is set to be 0.2. A pseudorapidity strip of width \( \Delta \eta = 1.0 \) centered on the jet position, with two highest-energy jets excluded, is used to estimate the background (“average energy per jet area”), which is subtracted from the reconstructed jet energy in \( \text{Pb+Pb} \) collisions. Only jets within a mid-rapidity range of \( |\eta| < 2 \) are considered in this analysis.

### IV. RESULTS AND DISCUSSIONS

The path-length dependence of jet energy loss can be reflected by jet \( v_2^{\text{jet}} \), i.e. \( v_2^{\text{jet}} = \langle \cos(2\phi^{\text{jet}} - \Psi_{RP}) \rangle \), where \( \phi^{\text{jet}} \) is the azimuthal angle of jet and \( \Psi_{RP} \) is the azimuthal angle of reaction plane formed by the impact parameter \( b \) and the beam direction which is fixed to \( \Psi_{RP} = 0 \) in our AMPT simulations. Fig. 1 (a)-(d) show the comparison of \( v_2^{\text{jet}} \) as functions of \( N_{\text{part}} \) between the AMPT results and the ATLAS experimental data for different jet \( p_T \) bins in \( \text{Pb+Pb} \) collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). The AMPT results give qualitative trends similar as the experimental data, but slightly overestimate the magnitudes.

It is well known that the odd orders of harmonic flows can arise from the initial geometry fluctuations through final state interactions\(^ {28} \). On the other hand, the even orders of harmonic flows is also affected if considering of initial geometry fluctuations\(^ {29} \). To calculate the n-th Fourier coefficient \( v_n \), the n-th event plane \( \Psi_n \) can be defined as

\[
\Psi_n = \frac{1}{n} \left[ \arctan \left( \frac{r^n \sin(n\varphi)}{r^n \cos(n\varphi)} \right) + \pi \right],
\]

where \( r \) and \( \varphi \) are the coordinate position and azimuthal angle of each parton in the AMPT initial state and the average \( \langle \cdots \rangle \) denotes density weighting. Then the n-th
harmonic coefficient of jets, \( v_n^{jet} \) can be obtained by the following equation

\[
v_n^{jet} = \langle \cos \left[n(\phi^{jet} - \Psi_n^r)\right] \rangle. \tag{2}
\]

Jet \( v_2 \) and \( v_3 \) as functions of \( N_{part} \) for two typical \( p_T \) bins of 45 < \( p_T < 60 \) GeV/c and 60 < \( p_T < 80 \) GeV/c are calculated by Eqs. (1) and (2), denoted as \( v_2^{jet} \{ \Psi_2^r \} \) and \( v_3^{jet} \{ \Psi_3^r \} \), which are shown in Figs. 2 (a) and (b). \( v_2^{jet} \{ \Psi_2^r \} \) (open triangles) is consistent with the previous jet \( v_2 \) calculations of \( v_2^{jet} \{ \Psi_{RP} = 0 \} \) (open circles), though it has a little higher magnitudes due to the initial fluctuation contribution \( [21] \). For jet \( v_3 \), it is smaller than jet \( v_2 \). By comparing jet \( v_3 \) between two different \( p_T \) bins, a significant decrease of jet \( v_3 \) is observed with the increasing of jet \( p_T \).

Since heavy-ion collisions are dynamical evolutions which involve many important evolution stages, it is important to investigate the formation mechanisms of jet \( v_n \). Figs. 3 (a) and (b) display jet \( v_2 \) and \( v_3 \) for the \( p_T \) bin of 45 < \( p_T < 60 \) GeV/c at different evolution stages in Pb+Pb collisions from the AMPT simulations, respectively. The jet \( v_n \) is nearly zero in the initial state. However, jet \( v_n \) arises from the process of parton cascade, which indicates jet \( v_n \) is generated owing to the strong interactions between jet and the paronic medium. On the other hand, the processes of hadronization via coalescence and final hadronic rescatterings have little impact on jet \( v_n \).

Figs. 4 (a) and (b) show the AMPT results on the averaged jet energy loss fraction \( \Delta p_T/p_T \), as functions of \( \Delta \phi = \phi^{jet} - \Psi_n^r \) [\( n=2 \) (solid circles) and \( n=3 \) (open circles)] for the jet \( p_T \) bins of 45 < \( p_T < 60 \) GeV/c (a) and 60 < \( p_T < 80 \) GeV/c (b) in the centrality bin of 20-30% in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. Some points are slightly shifted along the x axis for better representation.
event plane or $\Delta \phi \sim \pi/3$ with respect to the third order of event plane. It is reasonable because jets transverse a longer path length through the medium in the direction of $\Delta \phi \sim \pi/2$ or $\Delta \phi \sim \pi/3$ for an elliptic or triangle shape profile, which are consistent with the path-length effect of jet energy loss [8].

The conversion efficiency ($v_n/\varepsilon_n$) is an important observable to understand the collective flow phenomena in high-energy heavy-ion collisions [28, 29]. However, $v_n^{v_{et}}/\varepsilon_n$ discloses how path-length dependence of jet quenching depends on the initial geometry shape. To calculate the n-th order eccentricity $\varepsilon_n$, we use the definition as follow,

$$\varepsilon_n = \sqrt{\left(\langle r^n \sin(n\phi) \rangle^2 + \langle r^n \cos(n\phi) \rangle^2\right) / \langle r^n \rangle^2},$$  \hspace{1cm} (3)$$

generating to the information about the coordinate space of initial partons. Fig. 5 shows the AMPT results on $v_n^{v_{et}}/\varepsilon_n$ as functions of $N_{part}$ for the jet $p_T$ bin of $45 < p_T < 60$ GeV/c in Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV. The $v_n^{v_{et}}/\varepsilon_n$ increases with $N_{part}$ except the most central centrality bin where jet $v_n$ is close zero, which reveals that azimuthal anisotropies of jets is more easily formed in more central collisions owing to a larger jet energy loss in a denser partonic matter. Fig. 6 presents jet $v_n$ as functions of the eccentricity $\varepsilon_n$ for the jet $p_T$ bin of $45 < p_T < 60$ GeV/c in a selected centrality bin of 20-30% in Pb+Pb collisions. It is shown that the final jet $v_n$ increases with the initial spatial eccentricity or triangularity, which indicates that jet azimuthal anisotropies are indeed produced by path-length dependences of jet energy loss.

V. CONCLUSION

In conclusion, azimuthal anisotropies of reconstructed jets have been investigated in Pb+Pb collisions at $\sqrt{s_{NN}}=2.76$ TeV within a framework of a multiphase transport (AMPT) model. The AMPT results can qualitatively describe the measured jet $v_2$ data. It is also observed that jet $v_3$ is smaller than jet $v_2$, and decreases more quickly than jet $v_2$ with the increasing of $p_T$. The azimuthal anisotropies of jets are found to be generated by the strong interactions between jets and partonic matter in the process of parton cascade. Both the hadronization of coalescence and final hadronic rescatterings have little impact on jet $v_n$. Jet energy loss fraction is dependent of the azimuthal angles with respect to the different orders of event plane. The ratio $v_n^{v_{et}}/\varepsilon_n$ basically increases with $N_{part}$ in non-central Pb+Pb collisions. Jet $v_n$ is sensitive to initial spatial asymmetry ($\varepsilon_n$) of partonic density for a given centrality bin. All of these features are consistent with a path-length dependence of jet energy loss in the QGP.

ACKNOWLEDGMENTS

This work was supported by the Major State Basic Research Development Program in China under Contract No. 2014CB845404, the NSFC of China under Projects No. 11175232, No. 11035009, and No. 11375251, the Knowledge Innovation Program of CAS under Grant No. KJCX2-EW-N01, the Youth Innovation Promotion Association of CAS, the project sponsored by SRF for ROCS, SEM, CCNU-QLPL Innovation Fund under Grant No. QLPL2011P01 and the "Shanghai Pujiang Program" under Grant No. 13PJ1410600.
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