Search For the Origin of the Away-side Double-humped Structure of jets in Heavy Ion Collisions

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A model is constructed for the origin of the double-humped structure found in the di-hadron azimuthal correlation on the away-side in heavy ion collisions. The parameters in the model are determined by fitting $\Delta \phi$ azimuthal distribution in central Au+Au collisions at RHIC given by STAR collaboration when the trigger momentum is in $3 - 4$ GeV/c and the associated particle momentum is in $1.3 - 1.8$ GeV/c. Then we apply our model to the semi-central and peripheral Au+Au collisions at RHIC and the responding $\Delta \phi$ azimuthal distribution are reproduced respectively. Our results show that the transverse flow effect plays an essential role in the experimentally observed di-hadron azimuthal distribution structure. The spread of the hard parton creation point and initial moving direction is also necessary for the double-humped structure.

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I. INTRODUCTION

The critical energy density predicted by Lattice Quantum Chromodynamics (LQCD) for the formation of Quark Gluon Plasma (QGP) [1] has been exceeded in central Au+Au collisions at Relativistic Heavy Ion Collider (RHIC) [2]. Some novel phenomena, such as jet-quenching and collective flows [3, 4], indicate the dense medium is produced in central Au+Au collisions at RHIC [5]. A natural subject is to study the properties of the produced medium through the interactions of jets and the medium.

In recent years, correlations among hadrons has been one of very active subjects, because it is a valuable tool for studying the interactions between jets and the medium produced in heavy ion collisions. Measurements of high transverse momentum particle spectra provide the first striking experimental evidence of jet-quenching. Further studies of the correlations among intermediate $p_T$ particles reveal a complex pattern of correlations as a function of $\Delta \eta$ and $\Delta \phi$ by STAR Collaboration [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19], where $\Delta \eta$ and $\Delta \phi$ are the pseudorapidity and azimuthal angle relative to the trigger particle, respectively. Similar $\Delta \eta$ and $\Delta \phi$ correlations have also been observed by the PHENIX [20, 21, 22] and the PHOBOS Collaboration [23]. For a brief summary of the experimental discoveries at RHIC, see [24]. There are several models for the medium response to jets, such as momentum kick model [25], Markovian parton scattering model [26], recombination model [27], Mach cone [28], Cerenkov gluon radiation [29], jet or shower broadening [30], etc, which can explain part of phenomena on the observed jet structure.

In heavy ion collisions, there are near-side and away-side associate-particles for a jet. For the near-side associate-particles, there are ridge and jet components. For the away-side ones, there exists complex structure of phenomena on the observed jet structure. The parameters in the model are determined by fitting $\Delta \phi$ azimuthal distribution in central Au+Au collisions at RHIC given by STAR collaboration when the trigger momentum is in $3 - 4$ GeV/c and the associated particle momentum is in $1.3 - 1.8$ GeV/c. Then we apply our model to the semi-central and peripheral Au+Au collisions at RHIC and the responding $\Delta \phi$ azimuthal distribution are reproduced respectively. Our results show that the transverse flow effect plays an essential role in the experimentally observed di-hadron azimuthal distribution structure. The spread of the hard parton creation point and initial moving direction is also necessary for the double-humped structure.

II. OUR MODEL

In principle, a pair of back-to-back jets can be produced at any points in the medium. The jets lose their energy during traversing the hot dense medium. Considering the trigger bias [31], the near-side jets are more likely produced near the surface of the medium. In our model, near-side jets are assumed to emerge on the surface of the medium for simplicity. We only focus on the physics origin of double-humped structure for the away-side associate-particles.

This paper is organized as follows: In section II, we give a brief introduction of our model. We show our results in section III. The last section is for a short conclusion.

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unit of $R$. Since only the azimuthal angle of final state particles plays a role, the absolute values of involved momenta have no importance so that we can set the initial hard parton momentum to be 1 and the measure momenta of all other particles in unit of the hard parton momentum. Then one can ask the initial momentum direction of the away-side hard partons at the point where the parton is created. If the pair of hard partons is created in the collision between partons with momentum fraction $x_1$ and $x_2$ of the nucleons, with zero transverse momentum, the jets will be back to back when $x_1 = x_2$. So generally the produced jets can deviate from back to back. In this paper, we assume that the near-side hard parton moves parallel to the impact parameter, and the angle $\theta$ between the initial moving direction of an away-side hard parton and the impact parameter is assumed to be given by a distribution

$$f(\theta) = \frac{1}{\sqrt{2\pi}\sigma^2} e^{-\frac{(\theta-\pi)^2}{2\sigma^2}}.$$ (1)

The standard deviation is chosen to be $\sigma = \sqrt{0.3}$. When this distribution is not used, one can study the case with exact back to back jets in the medium. More complexity comes from a fact that the creation point of the pair of hard partons may be anywhere on the medium surface. In this paper, we simplify our study by considering two cases with the hard parton’s creation point being at a fixed point or uniformly distributed on the medium surface.

We assume that the medium partons produced in heavy ion collisions have been thermalized, whose momentum satisfies the two-dimensional Boltzmann distribution,

$$f(P) = \omega^2 P e^{-\omega P},$$ (2)

where $P$ is the medium parton momentum and $\omega$ is a model parameter. The mean magnitude of momentum of the medium parton is $\langle P \rangle = \frac{1}{2} P$. One can sample the thermal momentum $P_{thermal}$ of the medium parton by Eq. 2 with random direction. The transverse flow effect can be considered in our model. So the medium parton may also have a flow momentum. We assume the flow momentum is proportional to the position vector, similar to the Hubble law

$$\vec{P}_{flow} = f_a \vec{r},$$ (3)

where $f_a$ is another model parameter. Then the momentum of a medium parton is the sum of thermal and flow components

$$\vec{P}_{parton} = \vec{P}_{thermal} + \vec{P}_{flow}.$$ (4)

With a mean free path $\lambda$, we assume that the stepsizes $l$ between a hard parton’s two successive collisions with medium partons fulfills the distribution

$$f(l) = \frac{1}{\lambda} e^{-l/\lambda}.$$ (5)

After traversing $l$ the hard parton collides with a medium parton and loses momentum, and the momentum transfer in the collision is assumed as a simple form

$$\Delta \vec{P} = \alpha (\vec{P}_{jet} - \vec{P}_{parton}).$$ (6)

After each collision, both the hard and medium partons change their moving directions. If the hard parton momentum is smaller than the mean thermal momentum, the hard parton is also assumed to materialize into the observed final state particles, otherwise the hard parton keeps on colliding with the medium partons until it runs out the system.

III. RESULTS

In order to search for the origin of double-humped structure in $\Delta \phi$ on the away-side, we use Monte Carlo to simulate the process for an away-side jet going through the medium produced in Au+Au collisions. There are three physics effects considered here: (1) with/without the flow effect; (2) with/without the variation of initial position for hard parton pair creation; (3) with/without the initial momentum direction distribution of hard parton. For simplicity, we classify our investigations into two major categories: (1) without flow effect; (2) with flow effect. For each category, there are four different cases corresponding to different combinations of with/without hard parton variation of creation point and initial moving angle distribution.

First, let’s consider four different cases with no flow effect. In our model, we set $f_a = 0$ to exclude the flow

![Fig. 1: (Color online) Double-humped structure for the away-side associate-particle distribution. The data points (solid dots) are from STAR collaboration [32] measured in Au+Au collisions at 0-12% centrality.](image)

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The dip is around $\Delta \phi$ multiplied to adjust the magnitude of the distribution. Is always directed at the surface of the medium system and its initial momentum is assumed to be generated at a fixed point on the structure. The collective flow effect is essential for the double-humped effect. For all the four choices on the distributions of initial hard parton creation position and the moving direction, we find that the away-side di-hadron azimuthal angle distribution is a single peak on the away-side for different parameter combinations. So we can conclude that collective flow effect is essential for the double-humped structure.

Second, the flow effect is included. When the hard parton is assumed to be generated at a fixed point on the surface of the medium system and its initial momentum is always directed at $\theta = \pi$, no double-humped structure can be found on the away-side di-hadron azimuthal distribution. The double-humped structure does appear on the away-side when (1) the hard parton is generated at one point with distributed initial moving direction; or (2) the hard parton is generated on the semi-circle surface of the collision system on the near-side without diverse initial moving direction. But the simulated $\Delta \phi$ correlation can’t fit the experimental data well. When the hard parton is generated on the semi-circle surface of the medium with $\theta$ distribution for the initial moving direction, we can fit the experimental data well with suitably chosen parameters. In Fig. 11 shows the di-hadron correlation distribution from our model for the away-side together with the experimental data [32]. The best fit corresponds to $\omega = 40, f_a = 0.1, \lambda = 0.05, \alpha = 0.1$. A factor has been multiplied to adjust the magnitude of the distribution. The dip is around $\Delta \phi = \pi$ and double humps are at $\Delta \phi \sim \pi \pm 1.1$.

The value of $\omega = 40$ means that the mean magnitude of momentum for the medium parton is $\frac{2}{\omega} = \frac{1}{20}$ that for a hard parton. Considering the fact that the mean transverse momentum of medium parton is about $\sqrt{2T_c}$, the value of $\omega$ obtained in the fit corresponds to hard parton momentum $k = 20 \times \sqrt{2T_c} \simeq 5 \text{GeV}$ for $T_c = 0.17 \text{GeV}$. This result seems reasonable for $P_{\text{trig}} \simeq 3 - 4 \text{GeV}$.

In order to further check the model, we consider the dependence of di-hadron azimuthal distribution on the centrality. We apply our model with exactly the same parameters to the semi-central and peripheral Au+Au collisions with the three physical effects mentioned above. One can see from Fig. 2 that the corresponding experimental $\Delta \phi$ distributions can also be reproduced very well. Also one can observe a transition from a double-humped to single peak structure for the away-side azimuthal distributions for Au+Au collisions from semi-central to peripheral. This means that our model can describe the away-side $\Delta \phi$ distributions for different collisions.

IV. CONCLUSION

We have considered a model for the origin of the double-humped structure on the away-side in heavy ion collisions. We simulated the jet-medium interactions and obtained the di-hadron azimuthal angle correlation. All of the parameters are fixed by fitting the experimental data for central collisions. Then, we applied our model to the semi-central and peripheral Au+Au collisions. The corresponding azimuthal distribution on the away-side can also be reproduced very well. From the results, we can conclude that the transverse flow effect is the main origin of the double-humped structure on the away-side in heavy ion collisions. Another necessary effect for the double-humped structure is due to distributions for the hard parton creation point and/or its initial moving direction. Probably more realistic jet-medium interactions need to be introduced to quantitatively explain the experimental data.

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