Momentum Kick Model Analysis of PHENIX Near-Side Ridge Data and Photon Jet

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We analyze PHENIX near-side ridge data for central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV. We find that the data can be described well by the momentum kick model. The systematics of the extracted parameters provide useful information on the magnitude of the momentum kick per jet-medium-parton collision, the number of jet-medium-parton collisions, and the momentum distribution of medium partons at the early stage of the nucleus-nucleus collision. We explore further the use of a photon jet to test models for the ridge phenomenon.

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I. INTRODUCTION

Recently, the STAR Collaboration observed a \( \Delta \phi \) correlation of particles associated with a high-\( p_t \) near-side hadron trigger particle in central Au+Au collisions at \( \sqrt{s_{NN}} = 200 \) GeV, where \( \Delta \phi \) and \( \Delta \eta \) are the azimuthal angle and pseudorapidity differences measured relative to the trigger particle, respectively. Particles associated with the near-side jet can be decomposed into a "jet component" at \( \Delta \phi \sim 0 \) with a ridge structure in \( \Delta \eta \). A similar correlation with a high-\( p_t \) trigger has also been observed by the PHENIX Collaboration and the PHOBOS Collaboration. Recent reviews of the ridge phenomenon and hard probes have also been presented.

In this manuscript, we shall limit our attention to the ridge phenomenon involving a high \( p_t \) jet on the near-side. We shall not consider ridge-type \( \Delta \phi \)-\( \Delta \eta \) correlations that have also been observed between two low-\( p_t \) hadrons without a high-\( p_t \) trigger.

Many theoretical models have been proposed to discuss the ridge phenomenon. The model of Ref. assumes that the ridge particles arise from the extra particles deposited by the forward and backward beam jets at the source point associated with the two transverse jets. The correlation of the jet source transverse position and the transverse medium flow then leads to an azimuthal distribution with a width \( \Delta \phi \) obtained from such a model is wide in comparison with experimental data. The Correlated Emission Model assumes that ridge particles arise from soft thermal gluons radiated along the jet direction, with an enhancement due to the radial flow. The model deals with the azimuthal correlations in the central rapidity region, and the pseudorapidity correlation has not yet been considered. The back splash model assumes that the ridge on the near-side arises from the hydrodynamical back-splash of the away-side jet flow; hydrodynamical calculations for such a model has not yet been made. The Glasma model examines \( \Delta \phi \)-\( \Delta \eta \) correlation between two low-\( p_t \) hadrons without a high-\( p_t \) trigger and assumes that the ridge in soft low-\( p_t \) pairs arises from the initially boost-invariant distribution that persists in the bulk matter for low-\( p_t \) particles. The Jet Broadening models consider the ridge particles as arising from radiated gluons of the incident jet; they have not been compared quantitatively with the ridge data. Taking the features of jet broadening as free parameters in a hydrodynamical calculation leads to a theoretical jet peak to ridge ratio large in comparison with experiment. The possibility of the intermediate \( p_t \) trigger arising from medium-medium recombination adds further complications to the analysis of the ridge phenomenon. Recent PHOBOS observation that the ridge extends to pseudorapidity separations as large as \( |\Delta \eta| \sim 4 \) provides an important test for many of these models.

Successful quantitative analyses of experimental near-side data have been obtained in the momentum kick model, over large phase space of the associated particles in \( p_t, \Delta \phi, \) and \( \Delta \eta \). In this model, a near-side jet emerges near the surface, kicks medium partons, loses energy, and fragments into the trigger particle and fragmentation products. By assumption of parton-hadron duality, the kicked medium partons subsequently materialize as the observed ridge particles, which can be used to extract valuable information on the jet-medium interaction and the properties of the early parton medium.

In the description of the interaction between the medium and a jet in the momentum kick model, we have chosen to represent the medium as particles instead of fields, because of (i) the short-range nature of the color screening interaction between partons in a dense color medium and (ii) the
observed azimuthal kinematic correlation between the ridge particles and the jet.

Our task can be made easier here as we can divide the theoretical analysis in three steps. The first step is to set up the basic theory of the momentum kick model in which physical quantities enter as important parameters. The second step consists of the construction of theoretical models that can explain these physical quantities. The third step consists of relating the physical quantities to other observed phenomena.

Following such a strategy, we describe the production process of associated particles as consisting of the jet component and the ridge component. The ridge component magnitude depends on the number of jet-medium-parton collisions, and the ridge component shape depends on the early medium parton momentum distribution shape and the magnitude of the momentum kick. The jet component in a nucleus-nucleus collision per trigger can be depicted as an attenuated jet component in $pp$ collisions. Thus, the physical parameters can be divided into three categories: those pertaining to (i) associated particles in a $pp$ collision, (ii) intrinsic shape of the medium parton momentum distribution, and (iii) the jet-medium-parton interaction characteristics.

Our successful description of the experimental data allows us to extract physical quantities from experimental data for the near-side jet in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV [25]. In the process, we infer that the early parton momentum distribution possesses a thermal-like transverse distribution and a rapidity plateau structure. We find that the magnitude of the momentum kick is about 1 GeV per jet-medium-parton collision. We infer also that for a central Au+Au collision the number of jet-medium-parton collision multiplied by the attenuation factor is about 4. As not much is known about these physical quantities, the extracted quantities provide useful insight into the early properties of the partons and their interaction with the jet in nucleus-nucleus collisions.

In our second step to construct models to explain the features of the physical quantities extracted from the momentum kick model, we note that the presence of the rapidity plateau in the early history of a central nucleus-nucleus collision as inferred is not a surprising result, as the elementary process involves the fragmentation of flux tubes in many particle production models (such as the Lund Model, the Dual Parton Model, the Multiple Collision Model, the ART model, the Lexus Model, the Venus Model, and the Glasma Model, etc). To investigate the origin of the rapidity plateau in a quantum mechanical framework, we can go a step further to use the physical argument of transverse confinement to establish a connection between QCD and QED2 (Quantum Electrodynamics in 2-dimensions) [23]. One finds that a rapidity plateau of produced particles is a natural occurrence when color charges pull away from each other at high energies as in QED2 [51, 52, 53, 54]. Experimental evidence for a plateau in rapidity distributions along the sphericity axis or the thrust axis has been observed earlier in $\pi^\pm$ production in high-energy $e^+e^-$ annihilation [55, 56, 57, 58].

The ridge data also give information on the magnitude of the momentum kick acquired by a medium parton per jet-medium-parton collision and the number of kicked partons. These physical quantities are clearly related to the energy loss of a jet in the dense medium. A consistent picture of both the ridge yield and jet quenching emerges from the momentum kick model analyses [23] and complements other studies of the jet quenching phenomenon [60].

The momentum kick model has been applied successfully to explain the STAR near-side ridge data. It is of interest to see whether the momentum kick model is consistent with other experimental measurements. Our first test of the momentum kick model gives a good prediction of the PHOBOS data at forward rapidities [18, 24, 25], indicating the approximate validity of the momentum kick model and the presence of the rapidity plateau.

In the present manuscript, we wish to focus our attention on the near-side ridge data obtained by the PHENIX Collaboration. In contrast to the STAR and PHOBOS data, which covers a large range of pseudorapidities, the PHENIX data cover a smaller region of pseudorapidities ($|\eta| < 0.35$) but a large number of combinations of trigger and associated particle transverse momenta. In the small $\Delta p_t$ region on the near-side of the jet, both the jet and ridge components contribute. We would like to examine here whether the momentum kick model can describe the PHENIX near-side ridge data and what one can learn from the systematics of quantities extracted therefrom.

The analysis of the PHENIX near-side ridge data also provides an opportunity to examine an additional test of the momentum kick model using a high-$p_t$ photon jet, in contrast to photon triggers arising from the decay of $\pi^0$. Nucleon-nucleon collisions can lead to the occurrence of a high-$p_t$ parton jet in coincidence with a high-$p_t$ photon jet. In a central nucleus-nucleon collision with the away-side parton (quark or gluon) jet, we can use a photon near-side jet to test different ridge models [61]. We can separate out effects owing to the collision of the near-side jet or to other types of response of the away-side jet or longitudinal jet. If the ridge arises from the medium as a result of the collision of the near-side parton jet, as in the momentum kick model, the substitution of a near-side photon jet will lead to a greatly-reduced yield of ridge particles. If the ridge particles arise from “several extra particles deposited by forward-backward beam jets into the fireball”, as in the position-flow model of Ref. [26] and [27], then the near-side ridge will remain for a near-side photon jet. If the ridge arises from the back splash of the propagation of away-side parton jet, then the large ridge structure will remain for a near-side photon jet. It is therefore of interest to make theoretical estimates of the ridge yield in association with a near-side, high $p_t$ photon jet in the momentum kick model so as to assist experiments in such an analysis.

This paper is organized as follows. In Section II, we review and summarize the main results of the momentum kick
model. In Section III, we compare theoretical results with PHENIX experimental near-side ridge data using hadron triggers in different \( p_t^{\text{trig}} \) intervals. In Section IV, we review and study the centrality dependence of the ridge yield when a near-side photon jet emerges in a nucleus-nucleus collision. We calculate the ridge yield when a high-\( p_t \) photon jet occurs. The results can be used to guide our search for ways to discriminate different models. In Section V, we present our discussions and conclusions.

II. REVIEW OF THE MOMENTUM KICK MODEL

We can briefly summarize the main contents of the momentum kick model as described in detail in \[23\]–\[25\]. We follow a jet as it collides with medium partons in a dense medium and study the yield of associated particles for a given \( p_t^{\text{trig}} \). The evaluation of the ridge yield and the quenching of the jet will be greatly simplified by using average values of various physical quantities, whose “average” attribute will be made implicit. We label the normalized initial momentum distribution of medium partons at the moment of jet-medium-parton collisions by \( E dF / dp_i \). As a result of the jet-medium-parton collision, the jet imparts a momentum \( \mathbf{q} \) onto a kicked medium parton, which changes its momentum from \( \mathbf{p}_i \) to \( \mathbf{p} = (p_t, \eta, \phi) = \mathbf{p}_f = \mathbf{p}_i + \mathbf{q} \). By assumption of parton-hadron duality, the kicked medium partons subsequently materialize as observed ridge particles. The momentum \( \mathbf{p} \) of the kicked medium partons can also be used interchangeably to label the momentum \( \mathbf{p}^{\text{assoc}} \) of associated ridge particles. The normalized final parton momentum distribution \( E dF / d\mathbf{p}_i \) at \( \mathbf{p}_i \), at a shifted momentum, \( \mathbf{p}_f = \mathbf{p} - \mathbf{q} \), and we have \[22\]

\[
\frac{dF}{p_t dp_t d\eta d\phi} = \left[ \frac{dF}{p_t dp_t d\eta d\phi} \frac{E}{E_i} \right]_{p_t = \mathbf{p} - \mathbf{q}} \sqrt{1 - \frac{m^2}{(m^2 + p_t^2) \cosh^2 y}},
\]

(1)

where the factor \( E/E_i \) ensures conservation of particle numbers and the last factor changes the rapidity distribution of the kicked partons to the pseudorapidity distribution \[48\].

We characterize the number of the partons kicked by the jet by \( \langle N_k \rangle \), which depends on the centrality and the jet-medium-parton cross section. The (charged) ridge particle momentum distribution in a central A+A collision per trigger is then

\[
\left[ \frac{dN_{\text{ch}}}{N_{\text{trig}} p_t dp_t d\Delta \eta d\Delta \phi} \right]_{\text{ridge}}^{\text{AA}} = \left[ f_R \frac{2}{3} \langle N_k \rangle \frac{dF}{p_t dp_t d\Delta \eta d\Delta \phi} \right]_{\text{ridge}}^{\text{AA}}
\]

\[
= f_R \frac{2}{3} \langle N_k \rangle \left[ \frac{dF}{p_t dp_t d\eta d\phi} \frac{E}{E_i} \right]_{p_t = \mathbf{p} - \mathbf{q}} \sqrt{1 - \frac{m^2}{(m^2 + p_t^2) \cosh^2 y}},
\]

(2)

where \( f_R \) is the average attenuation factor for produced ridge particles to reach the detector and the factor \( 2/3 \) is to indicate that \( 2/3 \) of the produced associated particles (presumably pions) are charged.\(^1\) Present measurements furnish information only on the product \( f_R N_k \). The momentum kick \( \mathbf{q} \) will be distributed in the form of a cone around the trigger jet direction with an average \( \mathbf{q} = \mathbf{e}^{\text{trig}} \) directed along the trigger direction \( \mathbf{e}^{\text{trig}} \), characterized by the momentum kick magnitude \( q \).

Experimental measurements of associated particles include contributions from both the jet component and the ridge component. By comparing the associated ridge yield per trigger in central Au+Au collisions and the pp associated particle yield at \( \Delta \eta \sim 0 \) and high \( p_t \), one finds that in the region of \( p_t < 4 \text{ GeV} \), the jet component in central Au+Au collisions can be described as the associated particle yield in a pp collision attenuated by a semi-empirical factor of \( f_j = 0.632 \) \[25\] (see also modifications of \( f_j \) for high \( p_t^{\text{assoc}} \) in Eq. \[16\]). The total observed yield of associated particles per trigger in A+A collisions is therefore

\[
\left[ \frac{1}{N_{\text{trig}} p_t dp_t d\Delta \eta d\Delta \phi} \right]_{\text{total}}^{\text{AA}} = f_R \frac{2}{3} \langle N_k \rangle \left[ \frac{dF}{p_t dp_t d\Delta \eta d\Delta \phi} \right]_{\text{ridge}}^{\text{AA}} + f_j \frac{dN_{pp}^{\text{assoc}}}{p_t dp_t d\Delta \eta d\Delta \phi}^{\text{jet}}.
\]

(3)

To obtain the near-side associated particle yield in the second term of the righthand side, we need the yield of associated particles in pp collision. The experimental associated particle distribution in pp collisions can be described

\(^1\) The charge fraction \( 2/3 \) assumed for a pion system can be modified for a medium with a more general composition.
well by \[ \frac{dN_{pp}^{pp}}{p_{i}dp_{i}d\Delta \eta d\Delta \phi} = N_{\text{jet}} \exp\left\{ \left( m - \sqrt{m^{2} + p_{i}^{2}}/T_{\text{jet}} \right) \right\} \frac{1}{2\pi \sigma_{\phi}^{2}} e^{-|\phi - \phi'|/2\sigma_{\phi}^{2}}. \]

where \( N_{\text{jet}} \) is the number of near-side (charged) associated “jet component” particles in a \( pp \) collision, and \( T_{\text{jet}} \) is the jet inverse slope (“temperature”) parameter of the “\( pp \) jet component”, and \( m \) is taken as the pion mass \( m_{\pi} \). In our search for parameter values we find that the width parameter \( \sigma_{\phi} \) depends slightly on \( p_{t} \) which we parametrize as

\[ \sigma_{\phi} = \sigma_{\phi 0} \frac{m_{a}}{\sqrt{m_{d}^{2} + p_{t}^{2}}} \]

To obtain the associated ridge yield in the first term on the righthand side of Eq. (3) for \( A+A \) collisions, we need information on the medium parton distribution. We describe the normalized initial medium parton momentum distribution, which implicitly includes all possible physical effects, as represented by \[ \frac{dF}{p_{t}dp_{t}dy_{t}d\phi_{t}} = A_{\text{ridge}}(1 - x)^{a} e^{-\sqrt{m^{2} + p_{t}^{2}}/T_{\text{jet}}} \]

where \( A_{\text{ridge}} \) is a normalization constant defined (and determined numerically) by

\[ \int dy_{t}d\phi_{t}p_{t}dp_{t}A_{\text{ridge}}(1 - x)^{a} \exp\left\{ -\sqrt{m^{2} + p_{t}^{2}}/T_{\text{jet}} \right\} = 1, \]

\( x \) is the light-cone variable

\[ x = \frac{\sqrt{m^{2} + p_{t}^{2}}e^{y_{b} - y_{b}}}{m_{b}} \]

\( a \) is the fall-off parameter that specifies the rate of decrease of the distribution as \( x \) approaches unity, \( y_{b} \) is the beam parton rapidity, and \( m_{b} \) is the mass of the beam parton. A small value of \( a \) indicates a relatively flat rapidity distribution. In particular, a boost-invariant rapidity distribution will be characterized by \( a = 0 \). A large value of \( a \gg 1 \) indicates a relatively sharp fall-off rapidity distribution. As \( x \leq 1 \), there is a kinematic boundary that is a function of \( y_{t} \) and \( p_{t} \) at \( x = 1 \) or,

\[ \sqrt{m^{2} + p_{t}^{2}} = m_{b}e^{y_{b} - |y_{b}|}. \]

We set \( m_{b} \) equal to \( m_{\pi} \) and \( y_{b} \) equal to \( y_{N} \), the rapidity of the beam nucleons in the CM system.

From the above discussion, we note that the momentum kick model physical parameters can be divided into three categories as given in Table I where the meaning of each parameter is listed. There are parameters \( N_{\text{jet}}, T_{\text{jet}}, \sigma_{\phi 0}, \) and \( m_{a} \) which pertain to the properties of particles associated with a high \( p_{t} \) trigger in \( pp \) collisions, as given in Eq. (4).

They also provide information on the ‘jet component’ of associated particles in A+A collisions. There are parameters \( q, f_{R}(N_{k}), \) and \( f_{L} \) which pertain to the jet-medium interaction. They provide information on the momentum kick per collision \( q \), the number of jet-medium-parton collisions \( (N_{k}) \) multiplied by \( f_{R} \), and the ratio \( f_{L} \) of the jet component in A+A collisions per trigger relative to the jet component in \( pp \) collisions. Finally, there are parameters \( a, T \), and \( m_{d} \) which pertain to the properties of the medium at the moments of jet-medium-parton collisions. They provide information on the shape of the early medium parton momentum distribution. A computer program to carry out the momentum kick model analysis outlined above can be obtained from the author upon request.

In calculating theoretical differential distribution \( dN_{ch}/N_{\text{trig}}d\Delta \eta \) as a function of \( \Delta \eta \), we impose the experimental constraints of \( \eta_{\text{min}}^{\text{trig}} \leq \eta^{\text{trig}} \leq \eta_{\text{max}}^{\text{trig}} \) and \( \eta_{\text{min}}^{\text{assoc}} \leq \eta^{\text{assoc}} \leq \eta_{\text{max}}^{\text{assoc}} \) which generate various pseudorapidity differences \( \Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}} \). We add up all yields \( dN_{ch}/N_{\text{trig}}d\Delta \eta \) of the same \( \Delta \eta = \eta^{\text{assoc}} - \eta^{\text{trig}} \), to get the uncorrected yield as a function of \( \Delta \eta \). Theoretical acceptance-corrected yield is then equal to the product of the uncorrected yield and the acceptance correction factor \( f_{\text{acc}}(\Delta \eta) \). We assume that the acceptance is uniform in regions of both \( \eta^{\text{assoc}} \) and \( \eta^{\text{trig}} \). The acceptance correction factor \( f_{\text{acc}}(\Delta \eta) \) can be obtained from geometrical considerations by plotting the acceptance region in the plane of \( \eta^{\text{assoc}} \) and \( \eta^{\text{trig}} \) and changing the axes to \( \eta^{\text{assoc}} - \eta^{\text{trig}} \) and \( \eta^{\text{assoc}} + \eta^{\text{trig}} \). From the geometrical areas after the change of axes, the \( \Delta \eta \) acceptance correction factor is given by

\[ f_{\text{acc}}(\Delta \eta) = \begin{cases} 0 & \text{for } \eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} < \Delta \eta \leq \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{min}}^{\text{trig}} \ \text{or} \ \eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} < \Delta \eta \leq \eta_{\text{max}}^{\text{assoc}} - \eta_{\text{max}}^{\text{trig}}, \\ \frac{\eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} - \Delta \eta}{\eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{max}}^{\text{trig}}} & \text{for } \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{min}}^{\text{trig}} \leq \Delta \eta \leq \eta_{\text{max}}^{\text{assoc}} - \eta_{\text{max}}^{\text{trig}} \\ \frac{\eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} - \Delta \eta}{\eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{min}}^{\text{trig}}} & \text{for } \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{min}}^{\text{trig}} \leq \Delta \eta \leq \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{max}}^{\text{trig}} \\ \frac{\eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} - \Delta \eta}{\eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{assoc}} - \eta_{\text{max}}^{\text{trig}}} & \text{for } \eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{trig}} \leq \Delta \eta \leq \eta_{\text{max}}^{\text{assoc}} - \eta_{\text{min}}^{\text{trig}}. \end{cases} \]
TABLE I: Physical parameters in Eqs. (4), (6), and (2) in the momentum kick model, and the meaning each parameter

| Category | Physical Parameter | Meaning |
|----------|-------------------|---------|
| Properties of jet particles associated with a trigger in a pp collision | \( N_{\text{jet}} \) | total number of associated particles per trigger |
| | \( T_{\text{jet}} \) | “temperature” in \( p_t \) distribution |
| | \( \sigma_{\phi 0} \) | jet cone width parameter |
| | \( m_a \) | mass parameter to modify the variation of jet cone width \( \sigma_{\phi} \) with \( p_t \) |
| Properties of jet-medium interaction | \( q \) | magnitude of momentum kick per jet-medium-parton collision |
| | \( f_R(N_k) \) | number of kicked partons per trigger multiplied by the attenuation factor \( f_R \) |
| | \( f_J \) | ratio of (jet component yield per trigger in \( AA \) collisions) to (associated jet component in \( pp \) collisions) |
| Properties of medium parton momentum distribution in central \( AA \) Collisions | \( a \) | fall-off parameter of medium parton rapidity distribution in the form \( (1-x)^a \) |
| | \( T \) | “temperature” of the medium parton \( p_t \) distribution |
| | \( m_d \) | mass parameter to modify the \( p_t \) distribution for low \( p_t \) |

III. ANALYSIS OF PHENIX HADRON TRIGGER DATA

Our previous momentum kick model analysis of the STAR near-side ridge data covered a large phase space for central (0-5%) \( AA \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV, with hadron triggers at \( 4 < p_{t,\text{trig}} < 6 \) GeV. We find in Ref. [25] that the associated particles in \( pp \) collisions can be described by Eq. (4) with parameters

\[
N_{\text{jet}} = 0.67, \quad T_{\text{jet}} = 0.55 \text{ GeV}, \quad \sigma_{\phi 0} = 0.50, \text{ GeV}, \quad \text{and} \quad m_a = 1.1 \text{ GeV},
\]

as shown in Column 3 of Table II. The totality of the STAR associated particle data [1, 3, 5], with associated particle transverse momentum \( p_t^{\text{assoc}} \) from 0.15 GeV to 4 GeV and \( \mid \eta \mid \) from zero up to 3.9 can be described by the set of parameters

\[
q = 1.0 \text{ GeV}, \quad f_R(N_k) = 3.8, \quad \text{and} \quad f_J = 0.632,
\]

in conjunction with the initial parton momentum distribution Eq. (6) with parameters

\[
a = 0.5, \quad T = 0.50 \text{ GeV}, \quad \text{and} \quad m_d = 1 \text{ GeV},
\]

as tabulated in Column 3 of Table III. The initial momentum distribution of the medium partons in Eq. (6), \( (1-x)^a \exp[-\sqrt{m^2 + p_t^2}/T]/\sqrt{m^2 + p_t^2} \), gives an initial parton momentum distribution which has three prominent features. First, it has a thermal-like transverse distribution whose characteristic slope parameter \( T \) is between those of the jet and the bulk inclusive matter. Second, the rapidity distribution is relatively flat around \( y \sim 0 \). Third, the rapidity distribution is quite extended, reaching out to large rapidities. Thus, the momentum distribution is in the form of a rapidity plateau with a thermal-like transverse distribution.

We examined next the PHOBOS near-side ridge yield as a function of \( \Delta \eta \) for \( -4 > \Delta \eta > 2 \), \( |\Delta \phi| < 1 \), and \( p_t^{\text{assoc}} > 0.02 \) GeV, in central (0-10%) \( AA \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV with trigger particles at \( p_{t,\text{trig}} > 2.5 \) GeV [18].

TABLE II: Jet component distribution parameters in Eq. (4) for particles associated with a hadron trigger of different \( p_{t,\text{trig}} \) in \( pp \) collisions at \( \sqrt{s_{NN}}=200 \) GeV

| STAR \( p_{t,\text{trig}} \) | PHOBOS | PHENIX |
|-----------------|--------|--------|
| Hadron trigger | \( p_{t,\text{trig}} \) | 4-6GeV | 2.5GeV |
| Properties of particles associated with a trigger in \( pp \) collisions | \( N_{\text{jet}} \) | 0.67 | 0.4 | 0.5 |
| | \( T_{\text{jet}} \) | 0.55 | 0.34 | 0.40 |
| | \( \sigma_{\phi 0} \) | 0.50 | | |
| | \( m_a \) | | | 1.1 GeV |

We examined next the PHOBOS near-side ridge yield as a function of \( \Delta \eta \) for \( -4 > \Delta \eta > 2 \), \( |\Delta \phi| < 1 \), and \( p_t^{\text{assoc}} > 0.02 \) GeV, in central (0-10%) \( AA \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV with trigger particles at \( p_{t,\text{trig}} > 2.5 \) GeV [18].
TABLE III: (Color online) Jet-medium interaction and medium parton distribution parameters in Eqs. (6) and (2) in the momentum kick model for particles associated with a hadron trigger with different $p_t^{trig}$ in central Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV.

| Centrality          | STAR | PHOBOS | PHENIX |
|---------------------|------|--------|--------|
|                      | 0-5% | 0-10%  | 0-20%  |
| Hadron trigger      | $p_t^{trig}$ | 4-6 GeV | >2.5 GeV | 2-3 GeV | 3-4 GeV | 4-5 GeV | 5-10 GeV |
| Momentum kick       | $q$  | 1.0 GeV | 0.80 GeV |        |        |        |        |
| Number kicked partons | $f_K(N_k)$ | 3.8 | 3.0 |        |        |        |        |
| Jet component       | $f_J$| 0.632 |        | 0.632 for $p_t^{assoc}$ < 2 GeV | 0.82 for 2 < $p_t^{assoc}$ < 3 GeV | 1.00 for 3 GeV < $p_t^{assoc}$ |
| survival factor     |      |        |        |        |        |        |        |
| Medium parton       | $a$  | 0.5    |        |        |        |        |        |
| distribution parameters in central Au+Au Collisions | $T$ | 0.5 GeV |        |        |        |        |        |
|                     | $m_d$ | 1.0 GeV |        |        |        |        |        |

FIG. 1: (Color online) PHENIX azimuthal angular distribution of associated particles per trigger in different ($p_t^{trig} \otimes p_t^{assoc}$) regions for a hadron trigger at $2 < p_t^{trig} < 3$ GeV. The solid and open circles are the total associated particle yield per trigger, $dN_{ch}/N_{trig}d\Delta \phi$, in central Au+Au and pp collisions, respectively. The solid, dashed, and dashed-dot curves are the theoretical total Au+Au associated particle yields per trigger, the Au+Au ridge particle yields per trigger, and the pp associated particle yields, respectively.

Theoretical predictions were carried out using the same set of parameters as those in our previous investigation with the STAR data (Column 3 of Tables II and III). Theoretical predictions agree well with the measurement from the PHOBOS Collaboration, indicating the approximate validity of the momentum kick model and the picture of a rapidity plateau extending to large rapidities [18, 24, 25].

In this Section, we investigate the PHENIX near-side ridge data associated with a hadron trigger. The PHENIX experimental measurements for pp and central (0-20%) Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV with hadron triggers cover the regions $|\eta^{trig}| < 0.35$ and $|\eta^{assoc}| < 0.35$, for a large number of $p_t^{trig}$ and $p_t^{assoc}$ combinations [15].

We carry out theoretical calculations for the associated particle yield per trigger as a function of $\Delta \phi$ within the acceptance constraints of $|\eta^{trig}| < 0.35$ and $|\eta^{assoc}| < 0.35$. Our first task is to represent the pp associated particle data for a hadron trigger with the distribution of Eq. (13). In this search, we find that the properties of particles associated with a pp collision as represented by $N_{jet}$ and $T_{jet}$ varies substantially as a function of $p_t^{trig}$. In particular, they increase linearly with $p_t^{trig}$ in pp collisions as

$$N_{jet} = N_{jet0} + d_N p_t^{trig},$$

$$T_{jet} = T_{jet0} + d_T p_t^{trig},$$

where the parameters in Table II gives $N_{jet0} = 0.15$, $d_N = 0.1$/GeV, $T_{jet0} = 0.19$ GeV, and $d_T = 0.06$, for $2 \leq p_t^{trig} \leq 5$ GeV. In Figs. 1–4, the experimental pp associated particle yields $dN_{ch}/d\Delta \phi$ are shown as open circles and the corresponding theoretical yields are represented by the dashed-dot curves. The comparison in Figs. 1–4 indicates that...
the form of Eq. (11) with the parameters in Table II give a good description of the experimental pp associated particle data.

In the next step, we need to find out how the jet component in Au+Au collisions is related to the jet component in pp collisions. Previously, we find that the jet component per trigger in Au+Au collisions can be considered as an attenuated jet component in pp collisions with an attenuation factor \( f_J \sim 0.632 \) [25]. Upon comparing PHENIX experimental data for the total associated particle yield per trigger in Au+Au collisions and pp collisions, we find however that these two yields are approximately equal for high \( p_{\text{assoc}}^t \), where the ridge component yield for the region of interest, \(|\eta|<0.35\), is expected to be relatively small. This indicates that \( f_J \) increases to unity as \( p_{\text{assoc}}^t \) increases to 3-4 GeV. We can understand this behavior because the high-\( p_{\text{assoc}}^t \) associated particles are likely to come from the fragmentation of the jet outside the interacting region. As \( f_J \) is equal 0.632 and 1.0 for \( p_{\text{assoc}}^t < 2 \) GeV and \( p_{\text{assoc}}^t > 3 \) GeV respectively, we can interpolate \( f_J = 0.82 \) in the intermediate region. We are therefore advised to use a semi-empirical attenuation factor \( f_J \) that depends on \( p_{\text{assoc}}^t \),

\[
 f_J(p_{\text{assoc}}^t) = \begin{cases} 
 0.632 & \text{for } p_{\text{assoc}}^t < 2 \text{ GeV}, \\
 0.82 & \text{for } 2 < p_{\text{assoc}}^t < 3 \text{ GeV}, \\
 1.0 & \text{for } 3 \text{ GeV} < p_{\text{assoc}}^t,
\end{cases} 
\]

where \( f_J = 0.632 \) used in [25] may be sufficient only for associated particles with low \( p_{\text{assoc}}^t \).

With the jet component in A+A collisions considered as an attenuated jet component in pp collisions, the knowledge of the pp associated particle data allows us to determine the characteristics of the jet-medium interaction and the properties of the medium. The comparison of the PHENIX near-side jet data [15] for collisions at \( \sqrt{s_{NN}} = 200 \) GeV with the momentum kick model results are shown in Figs. 1-4. In these figures, the solid data point are the total associated particle yield per trigger, \( dN_{\text{ch}}/N_{\text{trig}}d\Delta\phi \), in central Au+Au collisions, and the open circles are the associated particle yields per trigger, \( dN_{\text{ch}}/N_{\text{trig}}d\Delta\phi \), in pp collisions [15]. Theoretical results are given as various
curves. The solid, dashed, and dashed-dot curves are the theoretical total Au+Au associated particle yields per trigger, the pp associated particle yields, respectively. In each figure, the different subfigures are the yields for associated particles with different $p_{\text{assoc}}^t$, spanning $p_{\text{assoc}}^t$ from 0.4 GeV up to $p_{\text{trig}}^t$.

Comparison of the PHENIX near-side data with the results of the momentum kick model in Figs. 1-4, for $2<p_{\text{trig}}^t<10$ GeV and $0.4$ GeV<$p_{\text{assoc}}^t<p_{\text{trig}}^t$ indicates that the set of PHENIX data for central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV [15] can be well described by the momentum kick model. Our present investigation reveals that different $p_{\text{trig}}^t$ jet triggers have very different associated jet component properties, as $N_{\text{jet}}$ and $T_{\text{jet}}$ vary linearly with $p_{\text{trig}}^t$ (Table II and Eqs. (14) and (15)). In spite of these variations, the ridge data reveals properties of the jet-medium interaction and the shape of the medium parton momentum distribution that are rather robust and do not change with the properties of the probing jet and the associated particle $p_{\text{assoc}}^t$. Specifically, we find that for all different $(p_{\text{trig}}^t \otimes p_{\text{assoc}}^t)$ combinations in Figs. 1-4, the momentum kick $q=0.8$ GeV and the number of (attenuated) kicked partons $f_R\langle N_k \rangle = 3.0$ describe the properties of the jet-medium interaction in these central Au+Au collisions, whereas the parameters $a=0.5$, $T=0.5$ GeV and $m_{d}=1.0$ GeV describes the intrinsic properties of the initial parton momentum distribution. The robust nature of these physical quantities enhances their quality as basic properties of the produced medium.

We can compare the extracted values of physical parameters of the jet-medium interaction and medium parton characteristics with those extracted previously from STAR data. The centrality region covered by the present PHENIX measurement [13] extends from 0 to 20%, where the STAR data [1] extends from 0 to 5%. The method of subtracting the $v_2$ background are also different [42]. Whereas the STAR detector covers $|\eta|<1$ and $0<\phi<2\pi$, the PHENIX detector covers $|\eta|<0.35$ and only about half of the full range of azimuthal angles. The medium parton parameters $a$, $T$, and $m_{d}$ are the same, whereas $(q, f_R\langle N_k \rangle)$ is (1GeV,3.8) for STAR data and (0.8GeV,3.0) for PHENIX data. The difference in $q$ and $f_R\langle N_k \rangle$ may arise from differences in centrality selections and methods of processing the data.

From the present study of the PHENIX ridge data in the region of $|\eta|<0.35$, we can briefly compare the relative importance of the associated ridge component and the jet component in Au+Au collisions, as a function of $p_{\text{assoc}}^t$. We

FIG. 3: (Color online) PHENIX azimuthal angular distribution of associated particles per trigger in different ($p_{\text{trig}}^t \otimes p_{\text{assoc}}^t$) regions for a hadron trigger at $4<p_{\text{trig}}^t<5$ GeV. The solid and open circles are the total associated particle yield per trigger, $dN_{\text{ch}}/N_{\text{trig}}d\Delta\phi$, in central Au+Au and pp collisions, respectively [15]. The solid, dashed, and dashed-dot curves are the theoretical total Au+Au associated particle yields per trigger, the Au+Au ridge particle yields per trigger, and the pp associated particle yields, respectively.
find from Figs. 1-4 that the ridge associated particle yield per trigger is comparable to the jet associated particle yield for \( p_{\text{assoc}} \lesssim 2 \) GeV. However, for \( p_{\text{assoc}} > 2-3 \) GeV, the jet associated particle yield dominates over the ridge particle yield per trigger. This variation of the relative strengths of the jet and ridge components is reproduced well by the momentum kick model. The physical reason for the large contribution of the ridge component around \( p_t \sim 1 \) GeV arises from the fact that the ridge momentum distribution is in fact the initial transverse momentum distribution shifted by a momentum of about 1 GeV.

The jet component decreases rapidly away from the peak at \((\Delta \phi, \Delta \eta) \sim 0\), while the ridge component extends to regions of large \(|\Delta \eta|\), as observed by the STAR \[5\] and PHOBOS \[18\]. Therefore, in the region of large \(|\Delta \eta|\), the ridge associated particle yield can dominate over the jet associated particle yield. This feature is also found in the momentum kick model.

IV. THE CENTRALITY DEPENDENCE OF PHENIX RIDGE YIELDS

The momentum kick model separates the ridge yield into a geometrical factor part that depends on the average number of kicked partons \( \langle N_k \rangle / 3 \) and another factor of differential distribution \( E dF / d\rho \) in Eq. (2). The quantity \( \langle N_k \rangle \) depends on the centrality. We review here the description of the centrality dependence in the momentum kick model.

We consider a jet source point at \( b_0 \), from which a mid-rapidity jet parton originates. The number of jet-medium-parton collisions along the jet trajectory, which makes an angle \( \phi_s \) with respect to the reaction plane, is

\[
N_k(b_0, \phi_s) = \int_0^\infty \sigma dl \frac{dN_{\text{parton}}}{dV}(b'(b_0, \phi_s)), \tag{17}
\]

where \( 0 < l < \infty \) parametrizes the jet trajectory, \( \sigma \) is the jet-medium-parton scattering cross section, and \( dN_{\text{parton}}(b')/dV \) is the parton density of the medium at \( b' \) along the trajectory \( l \).
Jet-medium-parton collisions take place along different parts of the trajectory at different $l$ and involve the medium at different stages of the expansion. They depend on the space-time dynamics of the jet and the medium. Assuming hydrodynamical expansion of the fluid in both the longitudinal and transverse directions and focusing our attention on mid-rapidity, we can determine the distribution of the number of jet-medium-parton collisions $P(N)$ as a function of the transverse jet source point coordinate $b_0$ and the azimuthal angle $\phi_s$ [25]. We need to weight the number of kicked medium particles by the local binary collision number element $dN_{\text{bin}}/db_0$. The normalized probability distribution $P(N, \phi_s)$ with respect to the number of ridge particles (or jet-medium-parton collisions) is

$$P(N, \phi_s) = \frac{1}{N_{\text{bin}}} \int dN_{\text{bin}} \frac{dN_{\text{bin}}}{db_0}(b_0) \delta(N - N_k(b_0, \phi_s)).$$  \hspace{1cm} (18)

Thus, the number of ridge particle yield per trigger particle (or the number of jet-medium-parton collisions per trigger) at an azimuthal angle $\phi_s$, averaged over all source points of binary collisions at all $b_0$ points, is [25]

$$\bar{N}_k(\phi_s) = \int NP(N, \phi_s) e^{-\zeta N} dN \int P(N, \phi_s) e^{-\zeta N} dN,$$  \hspace{1cm} (19)

where $\zeta$ is the exponential index in the ratio of the fragmentation function after $N$ jet-medium-parton collisions relative to the fragmentation function before any collision,

$$e^{-\zeta N} = \frac{D(p_{\text{trig}}, p_j) - \sum^n_q q_n - \Delta_r}{D(p_{\text{trig}}, p_j)}.$$  \hspace{1cm} (20)

We get the jet quenching measure [25]

$$R_{AA}(\phi_s) = \frac{N_{\text{trig}}}{N_{\text{bin}}} = \int P(N, \phi_s) e^{-\zeta N} dN = \sum_{N=0}^{N_{\text{max}}} P(N, \phi_s) e^{-\zeta N},$$  \hspace{1cm} (22)

which can also be obtained as

$$R_{AA}(\phi_s) = \frac{1}{N_{\text{bin}}} \int dN_{\text{bin}} \exp\{-\zeta N_k(b_0, \phi_s)\} \frac{dN_{\text{bin}}}{db_0}.$$  \hspace{1cm} (23)

After $\bar{N}_k(\phi_s)$ and $R_{AA}(\phi_s)$ have been evaluated, we can average over all azimuthal angles $\phi_s$ and obtain the ridge particles (or jet-medium-parton collisions) per trigger

$$\langle N_k \rangle = \int_0^{\pi/2} d\phi_s \bar{N}_k(\phi_s) / (\pi/2),$$  \hspace{1cm} (24)

and

$$\langle R_{AA} \rangle = \int_0^{\pi/2} d\phi_s R_{AA}(\phi_s) / (\pi/2),$$  \hspace{1cm} (25)

which is usually expressed just as $R_{AA}$.

In our previous analysis of the STAR ridge yield and jet quenching, we find that the experimental data of the centrality dependence of $R_{AA}$ and the centrality dependence of the ridge yield using hadron trigger can be explained well when we use [25]

$$\zeta = 0.20, \; \text{and} \; \sigma = 1.4 \; \text{mb}.$$  \hspace{1cm} (26)

For the acceptance of the STAR Collaboration in [3], the data of ridge yield per hadron trigger as a function of the number of participants are shown in Fig. 5(a) and compared with the momentum kick model results obtained in [25]. They are included here for comparison with predictions of the associated particle yield for a photon jet calculated below in Fig. 5(b).
One can consider experiments with two transverse jets in which one of the two jets is a photon jet on the near side while the other jet is a strongly interacting parton of a quark or gluon on the away side. The use of a near-side photon jet allows one to probe the origin of the ridge particles as we discussed in the Introduction [61]. If the ridge arises from the medium as a result of the collision of the near-side jet, as in the momentum kick model, the substitution of a photon jet for a hadron jet will lead to a greatly-reduced yield of the ridge particles. On the other hand, if the ridge particles arise from “several extra particles deposited by forward-backward beam jets into the fireball” [26] or from the back splash model [32], then the ridge particles yield will not be significantly reduced.

We can make a quantitative estimate of the ridge yield in the momentum kick model for a photon jet that arises from hard-scattering. The number of ridge particles depends on the jet-medium-parton cross section and the attenuation coefficient $\zeta$. For the high-$p_t$ photon jet, the photon jet-medium-parton cross section is

$$\sigma(\text{photon jet} - \text{medium} - \text{parton}) = \left(\frac{\alpha_e}{\alpha_s}\right)^2 \sigma(\text{parton jet} - \text{medium} - \text{parton}),$$  \hspace{1cm} (27)

where $\alpha_e = 1/137$ is the fine-structure constant. We can take $\alpha_s = 0.2$ as the strong-interaction coupling constant. With $\sigma(\text{parton jet} - \text{medium} - \text{parton}) \sim 1.4 \text{ mb}$ as given by Eq. (26), we can estimate

$$\sigma(\text{photon jet} - \text{medium} - \text{parton}) = 1.86 \mu\text{b}.$$  \hspace{1cm} (28)

As the average number of collisions is much less than 1, we can take $\zeta = 0$ in Eq. (21) without much error. One finds
that the ridge yield per photon trigger is then

$$\langle N_k \rangle = \frac{1}{N_{\text{bin}}} \int d\phi_s \frac{dN_{\text{bin}}}{db_0} N_k(b_0, \phi_s) \frac{dN_{\text{bin}}}{db_0}. \quad (29)$$

We can evaluate $N_k(b_0, \phi_s)$ by using Eq. 17 and the photon-medium-parton cross section of Eq. 28 and obtain the total number of ridge particle yield per photon jet as a function of the participant number shown in Fig. 7(b), for the acceptance region as in 3. The yield for the photon jet is about 0.002 per photon jet for the most central Au+Au collision, which is small indeed. For all practical purposes, a high-$p_t$ photon jet does not lead to significant production of ridge particles in the momentum kick model.

V. CONCLUSION AND DISCUSSIONS

Using the momentum kick model, we examine the PHENIX near-side ridge particle yields for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The PHENIX data covers the range of pseudorapidity, $|\eta| < 0.35$, and a large combinations of $p_t^{\text{trig}}$ and $p_t^{\text{assoc}}$. We find that the PHENIX near-side ridge data can be described by the momentum kick model.

The extracted parameters contain physical quantities that give useful information on the medium, the jet, and the interaction between the jet and the medium. Specifically, we learn that particles associated with the jet component in $pp$ and Au+Au collisions changes its properties significantly as $p_t^{\text{trig}}$ changes. The temperature $T_{\text{jet}}$ and the number of these associated particles $N_{\text{jet}}$ increases linearly with $p_t^{\text{trig}}$. The jet-attenuation parameter $f_J$ increases to unity as $p_t^{\text{assoc}}$ increases, which can be understood as the high-$p_t^{\text{assoc}}$ associated particles are likely to come from the fragmentation of the jet outside the interacting region.

In contrast to the large variation of the properties of the jet component as a function of $p_t^{\text{trig}}$, physical parameters associated with the medium partons appears to be relatively robust, independent of $p_t^{\text{trig}}$. The same set of medium property parameters of $a$, $T$, and $m_d$ apply to the medium parton momentum distribution, for all $p_t^{\text{trig}}$ and $p_t^{\text{assoc}}$ combinations. They coincide also with those from STAR and PHOBOS measurements 23. The robust nature of these physical quantities enhances their quality as basic properties of the produced medium. The fall-off parameter $a = 0.5$ for the distribution $(1 - x)^a$ of Eq. 6 reveals that the early medium parton rapidity distribution is relatively flat but not boost-invariant, which would correspond to $a = 0$. The $(1 - x)^a$ distribution with the kinematic limit of $x = 1$ indicates that the distribution is in the shape of a rapidity plateau, as shown in Fig. 6(b) of 23. The temperature parameter $T = 0.5$ GeV shows that it is a thermal-like distribution with a temperature between those of a high-$p_t$ jet and the bulk matter. The quantity $m_d = 1$ GeV indicates a small modification of the thermal distribution at lower $p_t$.

Similarly, the set of physical parameters that describe the jet-medium interaction, $q$ and $f_R(N_K)$, appear also to be robust as the same set can describe the ridge component for all different $p_t^{\text{trig}}$ and $p_t^{\text{assoc}}$ combinations. The extracted magnitude of the momentum kick is $q = 0.8$ GeV per jet-medium-parton collision, and the number of jet-medium parton collision for the most central collisions multiplied by the attenuation factor is 3.

There is however a difference of about 20% in the values of $q$ and $f_R(N_K)$ extracted from the PHENIX near-side ridge data, compared to those extracted from the STAR near-side ridge data. This difference may reflect the difference in centrality selection and the degree of uncertainty in processing the experimental data.

In the region of $|\eta| < 0.35$ for the near-side jet investigated by the PHENIX Collaboration, we learn that the ridge component contribution is the same order as the jet component contribution, for $p_t^{\text{assoc}} < 2$ GeV, but the jet component dominates for $p_t^{\text{assoc}} > 2$ GeV. Thus, ridge particles show up as an excess to the jet component in the small $\Delta \eta$ and $\Delta \phi \sim 0$ region for $p_t^{\text{assoc}} \lesssim 2$ GeV. However, in the region of large $\Delta \eta$ when the jet component diminishes its strength, the ridge yield dominates over the jet component yield, as in the large $\Delta \eta$ regions in STAR 18 and PHOBOS measurements.

While the momentum kick model appears to give theoretical results consistent with the main features of experimental data from PHENIX, STAR, and PHOBOS Collaborations, it is of interest to propose the use of high-$p_t$ photon jets to examine the associated particles. In the momentum kick model, the collision of a high-$p_t$ hadron jet with the medium partons leads to the recoil of the medium partons which subsequently materialize as ridge particles. However, for a high-$p_t$ photon jet the photon-medium-parton cross section is greatly reduced, leading to a much smaller number of produced ridge particles. Thus, a photon jet on the near-side will lead to a very small yield of ridge particles. Such a feature may be used to discriminate among different models.

In summary, we have analyzed PHENIX near-side ridge data for central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We found that the data can be described well by the momentum kick model and the systematics of the extracted parameters provide useful information on the nucleus-nucleus collision process. This however is only the first step
in the theoretical analysis. The second step consists of the construction of theoretical models that can explain these physical quantities. Another further step is to connect the observed physical quantities to other observables such as the momentum distribution of the bulk matter at subsequent stages of the nucleus-nucleus collision. The momentum kick model can be further improved with additional inclusion of other effects such as the collective flow, a better description of the elementary jet-medium-parton collision processes, and perhaps a better Monte Carlo tracking of the jet trajectory and kicked partons.

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