The Ridge Associated with the Near-side Jet in High Energy-Heavy-Ion Collisions†

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The ridge particles associated with a near-side jet are identified as medium partons kicked by the jet near the surface. They carry direct information on the parton momentum distribution at the moment of jet-parton collisions and the magnitude of the longitudinal momentum kick. The extracted early parton momentum distribution has a rapidity plateau structure with a thermal-like transverse momentum distribution. Such a rapidity plateau structure may arise from particle production in flux tubes, as color charges and anti-color charges separate at high energies.

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I. INTRODUCTION

In central high-energy heavy-ion collisions, jets are produced in nucleon-nucleon collisions and they interact with the dense matter produced in the interacting region. Depending on the degree of jet attenuation and energy loss, jets of high $p_t$ particles can be classified as near-side jets or away-side jets in the opposite direction. A near-side jet is characterized by the presence of associated particles within a narrow cone along the trigger direction which correspond to jet remnants of the high $p_t$ jet. They retain the jet remnant characteristics as those in $pp$ and peripheral heavy-ion collisions. The near-side jet occurs when the high $p_t$ trigger emerges near the surface of the produced parton medium. In these experiments, one measures the azimuthal angle $\phi$ and the pseudorapidity angle $\eta$ of the jet and its associated particles, from which one obtains the corresponding relative differences $\Delta \phi = \phi_{\text{ass}} - \phi_{\text{jet}}$ and $\Delta \eta = \eta_{\text{ass}} - \eta_{\text{jet}}$. The probability distribution in $(\Delta \phi, \Delta \eta)$ was found to be in the form of a ridge at $\Delta \phi \sim 0$ running along the $\Delta \eta$ direction, in addition to the narrow cone of the jet component at $\Delta \phi \sim 0$ and $\Delta \eta \sim 0$.

Since the observation of the ridge associated with the near-side jet by the STAR Collaboration [1, 2, 3], similar ridge phenomena were observed by the PHOBOS [5] and PHENIX Collaborations [6]. Although many theoretical models have been put forth to explain the ridge phenomenon [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21], few provide direct comparisons with the extensive set of experimental data. Comparisons with experimental data over an extended region of the associated particle phase space of $p_t$, $\Delta \phi$, and $\Delta \eta$ have been carried out in the momentum kick model [7, 8, 9, 10, 11, 12]. By successfully explaining the experimental data, the momentum kick model has extracted a wealth of valuable information on the state of the dense matter formed at the early stage of the collision process.

II. THE MOMENTUM KICK MODEL

In the momentum kick model, particles in the ridge component are described as medium partons scattered (kicked) by the jet passing through the medium. Such a conclusion comes from the following considerations. It is observed that (i) the ridge yield increases with the number of participants, (ii) the ridge yield is nearly independent of the trigger jet properties, (iii) the baryon to meson ratio of the ridge particles is more similar to those of the bulk matter of the medium than those of the jet, and (iv) the slope parameter of the transverse momentum distribution of ridge particles is intermediate between those of the jet and the bulk matter [1, 4]. These features suggest that the ridge particles are medium partons, at an earlier stage of
the medium evolution during the passage of the jet. The azimuthal correlation of the ridge particle with the jet suggests that the associated ridge particle and the trigger jet are related by a collision.

As a result of the jet-parton collision, a medium parton received a momentum kick $q$ from the jet. The momentum distribution of a ridge parton at momentum $p$ is then the momentum distribution of the parton before the jet-parton collision at the shifted initial momentum $p_i = p - q$. The addition of the momentum kick along the jet direction to the collided medium parton gives rise to the peak in $\Delta \phi \sim 0$, and the extended pseudorapidity distribution of the associated particles on the ridge arises from the initial parton pseudorapidity distribution before the jet-parton collision.

The momentum distribution of associated particles in the 'jet component' at $\Delta \phi = 0$ and $\Delta \eta \sim 0$ in a nucleus-nucleus collision can be assumed to be an attenuated distribution of associated particles in a $pp$ collision, as expected for production in an interacting medium near the surface. Therefore, the total observed yield of associated particles per trigger in $A+A$ collisions consists of the sum of the jet and ridge components,

$$\left[ \frac{1}{N_{\text{trig}} p_i dp_i d\Delta \eta d\Delta \phi} \right]_{\text{total}}^{\text{AA}} = \left[ f_J \frac{dN_{pp}^{jet}}{p_i dp_i d\Delta \eta d\Delta \phi} \right]_{\text{jet}}^{\text{AA}} + \left[ f_R \frac{2}{3} (N_k) \frac{dF}{p_i dp_i d\Delta \eta d\Delta \phi} \right]_{\text{ridge}}^{\text{AA}}, \quad (1)$$

where $dN_{pp}^{jet}/p_i dp_i d\Delta \eta d\Delta \phi$ is the distribution of associated particles in a $pp$ collision, $\langle N_k \rangle$ is the average number of kicked partons per jet, and $dF/p_i dp_i d\eta d\phi$ is the normalized initial parton momentum distribution before the jet-parton collisions, evaluated at the shifted initial momentum $p_i = p - q$. Here $f_J$ and $f_R$ are the survival factors for the associated particles, as they continue to pass through the medium after production.

The experimental data calls for an early parton momentum distribution that has a thermal-like transverse momentum distribution, modified for the low-$p_t$ region, and a rapidity distribution that retains the flatness at mid-rapidity but also respects the kinematic boundaries at large rapidities and large $p_t$. Accordingly, we parametrize the normalized initial parton momentum distribution as

$$\frac{dF}{p_i dp_i dy_i d\phi_i} = A_{\text{ridge}} (1 - x)^a e^{-\sqrt{m_i^2 + p_i^2} / T}, \quad (2)$$

where $A_{\text{ridge}}$ is a normalization constant, $x$ is the light-cone variable

$$x = \frac{\sqrt{m_i^2 + p_i^2}}{m_b} e^{|y_i - y_0|}, \quad (3)$$

$a$ is the fall-off parameter that specifies the rate of decrease of the rapidity distribution, $y_0$ is the beam parton rapidity, and $m_b$ is the mass of the beam parton. We expect $y_0$ to have a distribution centered around the nucleon rapidity, $y_N = \cosh^{-1}(\sqrt{s_{NN}/2m_N})$. For lack of a definitive determination, we shall set $y_0$ equal to $y_N$ and $m_b$ equal to $m_\pi$.

**FIG. 1:** The symbols represent STAR experimental data [1, 2] and the curves theoretical results of $dN_{ch}/N_{\text{trig}} p_i dp_i$, for $pp$ and central $Au+Au$ collisions.

**III. ANALYSIS OF EXPERIMENTAL ASSOCIATED PARTICLE DATA**

We analyze associated particles data for central $Au+Au$ collisions and $pp$ collisions at
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\[ \sqrt{s_{NN}} = 200 \text{ GeV}. \]

The experimental data of the near-side associated particles in \( pp \) collisions, \( dN_{ch}/p_t dp_t d\Delta \phi \) in Eq. (1), can be easily parametrized as a cone distribution with a cone width as given in [10, 11]. The near-side associated particle data [1, 2, 5, 6] for the experimental range of \( p_t, \Delta \phi \), and \( \Delta \eta \) can be described by

\[ a = 0.5, T = 0.5 \text{ GeV}, m_d = 1.0 \text{ GeV}, f_J = 0.632. \tag{4} \]

The jet-medium interaction parameters depends on the centrality. They are

\[ q_L = 1 \text{ GeV}, f_R \langle N_K \rangle = 3.8, \tag{5} \]

for STAR and PHOBOS data with 0-5% and 0-10% centrality, respectively, and

\[ q_L = 0.8 \text{ GeV}, f_R \langle N_K \rangle = 3.0. \tag{6} \]

for the PHENIX data with 0-20% centrality. In Figs. 1-4, we compare the experimental solid data points [1, 2, 5, 6] for the associated particle momentum distribution with theoretical momentum kick model results shown as the solid curves. There is a general agreement between the theoretical results and experimental data over an extended region of \( p_t, \Delta \phi \), and \( \Delta \eta \), indicating the approximate validity of the momentum kick model. In these figures, we also show the contributions from the ridge component as dashed curves. The open circles and the dash-dot curves give the experimental associated particle data with the corresponding parametrized theoretical fit for \( pp \) collisions.

FIG. 2: The symbols represent STAR experimental data [1] and the curves theoretical results, for \( pp \) and central AuAu collisions. (a) and (b) give the \( dN_{ch}/N_{trig} d\Delta \phi \) distributions. (c) and (d) give the \( dN_{ch}/N_{trig} d\Delta \eta \) distributions.

\[ \text{Fig. 3: The symbols represent PHOBOS experimental data [2] and the curves theoretical results of } dN_{ch}/N_{trig} d\Delta \eta, \text{ for central AuAu collisions. The dash-dot curve give the theoretical } pp \text{ jet yield.} \]

\[ \text{Fig. 4: The symbols represent PHENIX experimental data [6] and the curves theoretical results of } dN_{ch}/N_{trig} d\Delta \phi, \text{ for } pp \text{ and central AuAu collisions.} \]
IV. INFORMATION EXTRACTED FROM THE MOMENTUM KICK MODEL

With the help of the momentum kick model, the comparison with experimental data furnished the following pieces of valuable information:

1. The extracted early parton momentum distribution has a thermal-like transverse momentum distribution and a rapidity plateau structure, as represented by the parameters $a$, $T$, and $m_d$ and shown in Fig. 5. The rapidity plateau extends to large rapidities and gives rise to the flat distribution of the associated particles as observed by the PHOBOS Collaboration. It is narrower than the pp rapidity plateau but wider than the Au-Au Gaussian structure [11, 27], and places the early partons to be at an intermediate stage of the parton rapidity evolution.

2. The inverse slope $T$ of the early parton transverse momentum distribution is intermediate between those for the pp jet $T_{jet}$ and $T_{bulk}$ for central Au-Au collisions [2]. This again indicates the intermediate nature of the early partons in the evolution of the parton momentum distribution.

3. The longitudinal momentum transfer by the jet onto the medium parton in a collision is $q_L=0.8-1.0$ GeV. Such a longitudinal momentum transfer corresponds to a $|t|$ value of about 0.26 GeV$^2$, which places the jet-parton collision within the realm of non-perturbative parton-parton scattering, as in the non-perturbative scattering with the exchange of a Pomeron. The transverse correlation length $a$ extracted from the momentum kick model is compatible with those from other non-perturbative treatment of parton-parton scattering as an exchange of a Pomeron [11].

4. For the most central Au-Au collision, the average number $\langle N_k \rangle$ of medium partons kicked by the jet on the near-side, multiplied by the survival factor $f_R$ is $f_R \langle N_k \rangle = 3.0 - 3.8$. The trend of the decrease of the number of kicked medium partons and the degree of jet quenching as a function of centrality are consistent with this simple picture of the momentum kick model [10].

V. CONCLUSIONS AND DISCUSSIONS

The characteristics of the associated particle experimental data reveal that particles associated with a near-side jet arise from two different components. The ridge component can be interpreted as arising from the medium partons which suffer an elastic scattering from the jet passing through the dense matter. The jet component can be described as an attenuated distribution from a pp collision. Such a picture provides a good description of the experimental associated particle data from the STAR, PHOBOS, and PHENIX Collaborations.

The momentum kick model analysis allows us to extract a wealth of valuable information on the states of the matter formed at the early stage of the collision process. We find that the momentum distribution of the early partons at the moments of jet-parton collisions has a rapidity plateau structure and a thermal-like transverse momentum distribution.

Rapidity plateau structures appear in many multi-particle production processes. Theoretically, a rapidity plateau is expected in QED$^2$ fragmentation in a flux tube, which mimics particle production in QCD as a $q$ and a $\bar{q}$ pull away from each other at high energies [22, 23, 24, 25]. Experimentally, a rapidity plateau has been ob-
served in high energy $e^+e^-$ annihilations, and pp collisions [26, 27]. Thus, the possibility of a rapidity plateau for the ridge particles should not come as a surprise. However, the fact that a parton of large absolute rapidity can occur together with a jet of central rapidities, as revealed by the PHOBOS data and the momentum kick model analysis, poses an interesting conceptual question. For those medium partons with large magnitude of the longitudinal momentum to collide with the jet so as to become an associated ridge particle in the PHOBOS experiment, the partons must be present in the longitudinal neighborhood of the jet at the moment of the jet-medium collision, at an early stage of the nucleus-nucleus collision.

In many classical descriptions of particle production processes such as the Lund model, a particle with a large absolute rapidity is associated with a large separation from the longitudinal origin at a later time. Jet parton and medium parton collisions take place at an early stage. Par-tons with large rapidities may not be produced for the jet to collide.

It is important to point out that there are important quantum effects [12, 22] that are beyond the realm of such classical considerations. The space-time dynamics of produced particles in string fragmentation can be obtained by evaluating the Wigner function of the produced particles when a strongly-coupled fermion separates from an antifermion at high energies in QED2. We find that produced particles with different momenta in different regions of the rapidity plateau are present at the moment when the overlapping fermion-antifermion pair begin to separate [12], in contrast to the classical description of particle production. Thus, the momentum kick model is consistent with other knowledge of the interaction processes and supports the picture of color flux tube production of the medium partons at an early stages, as in Schwinger’s non-perturbative QED2 string fragmentation.

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