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High-p_T Hadron Spectra, Azimuthal Anisotropy and Back-to-Back Correlations in High-energy Heavy-ion Collisions

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The observed suppression of high-p_T hadron spectra, finite azimuthal anisotropy, disappearance of jet-like back-to-back correlations, and their centrality dependence in $Au+Au$ collisions at RHIC are shown to be quantitatively described by jet quenching within a pQCD parton model. The difference between $h^\pm$ and π^0 suppression in intermediate p_T is consistent with the observed $(K+p)/\pi$ enhancement which should disappear at $p_T > 6$ GeV/c. The suppression of back-to-back correlations is shown to be directly related to the medium modification of jet fragmentation functions (FF) similar to direct-photon triggered FF's.
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The degradation of high-p_T partons during their propagation in the dense medium can provide critical information necessary for detection and characterization of the strongly interacting matter produced in high-energy heavy-ion collisions. Because of radiative parton energy loss induced by multiple scattering, the final high-p_T hadron spectra from jet fragmentation are expected to be significantly suppressed [1]. Such a phenomenon, known as jet quenching, was observed for the first time in $Au+Au$ collisions at the Relativistic Heavy-ion Collider (RHIC) [2,3]. One also observes the disappearance of back-to-back jet-like hadron correlations [4] and finite azimuthal anisotropy [5] of high-p_T hadron spectra. These three seemingly unrelated high-p_T phenomena are all predicted as consequences of jet quenching [1,6–8]. Together, they can provide unprecedented information on the properties of dense matter produced at RHIC.

In this Letter, we will study these three high-p_T phenomena simultaneously within a lowest order (LO) pQCD parton model that includes initial nuclear k_T broadening, parton shadowing and medium induced parton energy loss. We point out that an enhanced $(K+p)/\pi$ ratio leads naturally to different suppression of $h^\pm$ and π^0 spectra at intermediate p_T range. We will also show that the suppression of back-to-back correlations is directly related to the medium modification of hadron-triggered FF's similar to a direct-photon triggered FF [10].

In a LO pQCD model [9], the inclusive high-p_T hadron cross section in $A+A$ collisions is given by

$$\frac{d\sigma^h_{AB}}{dyd^2p_T} = K\sum_{abcd}\int d^2bd^2rdx_adx_bd^2k_{aT}d^2k_{bT} \\ t_A(r)t_B(|\mathbf{b}-\mathbf{r}|)g_A(k_{aT},r)g_A(k_{bT},|\mathbf{b}-\mathbf{r}|) \\ f_{a/A}(x_a,Q^2,r)f_{b/B}(x_b,Q^2,|\mathbf{b}-\mathbf{r}|) \\ \frac{D_{h/c}(z_c,Q^2,\Delta E_c)}{\pi z_c}\frac{d\sigma}{d\hat{t}}(ab\to cd), \quad (1)$$

where $z_c = p_T/p_{Tc}$, $y = y_c$, $\sigma(ab\to cd)$ are parton scattering cross sections and $t_A(b)$ is the nuclear thickness function normalized to $\int d^2bt_A(b) = A$. We will use a hard-sphere model of nuclear distribution in this paper. The $K \approx 1.3-2$ factor is used to account for higher order pQCD corrections. The parton distributions per nucleon $f_{a/A}(x_a,Q^2,r)$ inside the nucleus are assumed to be factorizable into the parton distributions in a free nucleon given by the MRS D$-'$ parameterization [11] and the impact-parameter dependent nuclear modification factor [12,13]. The initial transverse momentum distribution $g_A(k_T,Q^2,b)$ is assumed to have a Gaussian form with a width that includes both an intrinsic part in a nucleon and nuclear broadening. Details of this model and systematic data comparisons can be found in Ref. [9].

As demonstrated in recent studies, a direct consequence of parton energy loss is the medium modification of FF's [14,15] which can be well approximated by [16]

$$D_{h/c}(z_c,Q^2,\Delta E_c) = (1-e^{-\langle\frac{\Delta L}{\lambda}\rangle})\left[\frac{z'_c}{z_c}D^0_{h/c}(z'_c,Q^2) \right. \\ \left. +\langle\frac{\Delta L}{\lambda}\rangle\frac{z'_g}{z_c}D^0_{h/g}(z'_g,Q^2)\right] + e^{-\langle\frac{\Delta L}{\lambda}\rangle}D^0_{h/c}(z_c,Q^2), \quad (2)$$

provided that the actual energy loss is about 1.6 times of the input value. Here $z'_c = p_T/(p_{Tc}-\Delta E_c)$, $z'_g = \langle\Delta L/\lambda\rangle p_T/\Delta E_c$ are the rescaled momentum fractions and ΔE_c is the total parton energy loss during $\langle\Delta L/\lambda\rangle$ number of scatterings. The FF's in free space $D^0_{h/c}(z_c,Q^2)$ are given by the BBK parameterization [17].

We assume a 1-dimensional expanding medium with a gluon density $\rho_g(\tau,r)$ that is proportional to the transverse profile of participant nucleons. The average number of scatterings along the parton propagating path is then

$$\langle\Delta L/\lambda\rangle = \int_{\tau_0}^{\tau_0+\Delta L} d\tau\sigma\rho_g(\tau,b,\vec{r}+\vec{n}\tau), \quad (3)$$

where $\Delta L(b,\vec{r},\phi)$ is the distance a jet, produced at $\vec{r}$, has

to travel along $\vec{n}$ at an azimuthal angle ϕ relative to the reaction plane in a collision with impact-parameter b.

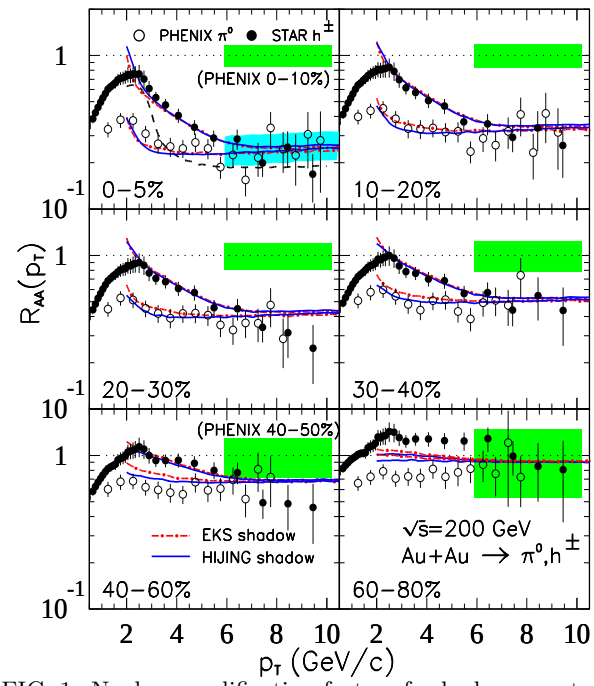

FIG. 1. Nuclear modification factors for hadron spectra in $Au + Au$ collisions as compared to data from STAR [3] and PHENIX [2]. See text for a detailed explanation.

According to recent theoretical studies [8,15,16] the total parton energy loss in a finite and expanding medium can be written as a path integral,

$$\Delta E \approx \langle \frac{dE}{dL} \rangle_{1d} \int_{\tau_0}^{\tau_0+\Delta L} d\tau \frac{\tau - \tau_0}{\tau_0 \rho_0} \rho_g(\tau, b, \vec{r} + \vec{n}\tau), \quad (4)$$

where ρ_0 is the averaged initial gluon density at τ_0 in a central collision and $\langle dE/dL \rangle_{1d}$ is the average parton energy loss over a distance R_A in a 1-d expanding medium with an initial uniform gluon density ρ_0. The corresponding energy loss in a static medium with a uniform gluon density ρ_0 over a distance R_A is [16] $dE_0/dL = (R_A/2\tau_0)\langle dE/dL \rangle_{1d}$. In the high-energy limit, the parton energy loss has a logarithmic energy dependence [18]. However, for a parton with finite initial energy the energy loss has a stronger energy dependence because of restricted phase space for bremsstrahlung [19]. Detailed balance between induced gluon emission and absorption will further increase the energy dependence [20] for a parton with finite initial energy. In this paper we will use an effective quark energy loss

$$\langle \frac{dE}{dL} \rangle_{1d} = \epsilon_0 (E/\mu_0 - 1.6)^{1.2}/(7.5 + E/\mu_0), \quad (5)$$

from the numerical results in Ref. [20]. The detailed balance reduces the effective parton energy loss and at the same time increases the energy dependence. The threshold is a consequence of gluon absorption that competes with bremsstrahlung and effectively shuts off energy loss for lower energy partons.

Shown in Fig. 1 are the calculated nuclear modification factors $R_{AB}(p_T) = d\sigma^h_{AB}/\langle N^{AB}_{\rm bin} \rangle d\sigma^h_{pp}$ for hadron spectra ($|y| < 0.5$) in $Au + Au$ collisions at $\sqrt{s} = 200$ GeV, as compared to experimental data. Here, $\langle N^{AB}_{\rm bin} \rangle = \int d^2b d^2r t_A(r) t_B(|\vec{b} - \vec{r}|)$. To fit the observed π^0 suppression in the most central collisions, we have used (solid lines) $\mu_0 = 1.5$ GeV, $\epsilon_0 = 1.07$ GeV/fm and $\lambda_0 = 1/(\sigma\rho_0) = 0.3$ fm with the new HIJING parameterization [13] of parton shadowing. The hatched area (also in other figures in this paper) indicates a variation of $\epsilon_0 = \pm 0.3$ GeV/fm. The hatched boxes around $R_{AB} = 1$ represent experimental errors in overall normalization. Alternatively, one has to set $\mu_0 = 1.3$ GeV and $\epsilon_0 = 1.09$ when EKS parameterization [12] of parton shadowing is used (dot-dashed lines). Without parton energy loss, the spectra is slightly enhanced at $p_T = 2 - 5$ GeV/c due to nuclear k_T broadening even with parton shadowing.

The flat p_T dependence of the π^0 suppression is a consequence of the strong energy dependence of the parton energy loss, which is also observed by other recent studies [21]. The slight rise of R_{AB} at $p_T < 4$ GeV/c in the calculation is due to the detailed balance effect in the effective parton energy loss. In this region, one expects the fragmentation picture to gradually lose its validity and other non-perturbative effects [22] become important that will give an enhanced $(K + p)/\pi$ ratio in central $Au + Au$ collisions. To include this effect, we add a soft component to kaon and baryon FF's that is proportional to the pion FF with a weight $\sim \langle N_{\rm bin}(b, r) \rangle / [1 + \exp(2p_{Tc} - 15)]$. The functional form and parameters are adjusted so that $(K + p)/\pi \approx 2$ at $p_T \sim 3$ GeV/c in the most central $Au + Au$ collisions and approaches its $p + p$ value at $p_T > 5$ GeV/c. The resultant suppression for total charged hadrons and the centrality dependence agree well with the STAR data. One can relate $h^\pm$ and π^0 suppression via the $(K + p)/\pi$ ratio: $R^{h^\pm}_{AA} = R^{\pi^0}_{AA}[1 + (K + p)/\pi]_{AA}/[1 + (K + p)/\pi]_{pp}$. It is clear from the data that $(K + p)/\pi$ becomes the same for $Au + Au$ and $p + p$ collisions at $p_T > 5$ GeV/c. To demonstrate the sensitivity to the parameterized parton energy loss in the intermediate p_T region, we also show $R^{h^\pm}_{AA}$ in 0-5% centrality (dashed line) for $\mu_0 = 2.0$ GeV and $\epsilon_0 = 2.04$ GeV/fm without the soft component.

Since jets produced in the central core of the dense medium are suppressed due to parton energy loss, only those jets that are produced near the surface emerge from the medium. The observed high-p_T hadron multiplicity should be proportional to the number of surviving jets in the outer layer of the overlapped volume which in turn is approximately proportional to the total number of participant nucleons. The nuclear modification factor normalized by $\langle N_{\rm binary} \rangle$ should decrease with centrality. This agrees well with the observed centrality dependence. This surface emission picture also gives a natural geometrical limit of the azimuthal anisotropy [23].

In non-central collisions, the average path length of parton propagation will vary with the azimuthal angle relative to the reaction plane. This leads to an azimuthal dependence of the total parton energy loss and therefore azimuthal asymmetry of high-p_T hadron spectra [7,8]. Such asymmetry is another consequence of parton energy loss and yet it is not sensitive to the nuclear k_T broadening and parton shadowing. Shown in Fig. 2 is $v_2(p_T)$ (second Fourier coefficient of the azimuthal angle distribution) of charged hadrons generated from parton energy loss (dot-dashed) as compared to preliminary STAR data [24] using the 4-particle cumulant moments method [25] which is supposed to reduce non-geometrical effects such as inherent two-particle correlations from di-jet production [26]. The energy loss extracted from high-p_T hadron spectra suppression can also account for the observed azimuthal anisotropy at large p_T. If the remaining v_2 at intermediate p_T is made up by kaons and baryons from the soft component, one find that they must have $v_2 \approx 0.23$ (0.11) for 20-50% (0-10%) collisions. The total $v_2(p_T)$ is shown by the solid lines.

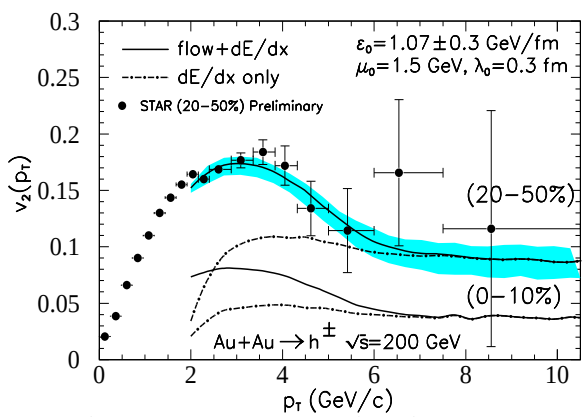

FIG. 2. Azimuthal anisotropy in $Au+Au$ collisions as compared to the STAR [24] 4-particle cumulant result.

In the same LO pQCD parton model, one can also calculate di-hadron spectra,

$$E_1E_2\frac{d\sigma_{AB}^{h_1h_2}}{d^3p_1d^3p_2} = \frac{K}{2}\sum_{abcd}\int d^2bd^2rdx_adx_bd^2k_{aT}d^2k_{bT}$$
$$\int dz_cdz_d\, t_A(r)t_B(|\mathbf{b}-\mathbf{r}|)g_A(k_{aT},r)g_A(k_{bT},|\mathbf{b}-\mathbf{r}|)$$
$$f_{a/A}(x_a,Q^2,r)f_{b/B}(x_b,Q^2,|\mathbf{b}-\mathbf{r}|)$$
$$D_{h/c}(z_c,Q^2,\Delta E_c)D_{h/d}(z_d,Q^2,\Delta E_d)$$
$$\frac{\hat{s}}{2\pi z_c^2z_d^2}\frac{d\sigma}{d\hat{t}}(ab\to cd)\delta^4(p_a+p_b-p_c-p_d), \qquad (6)$$

for two back-to-back hadrons from independent fragmentation of the back-to-back jets. Set $p_{T1} = p_T^{\rm trig}$, we define a hadron-triggered FF as the back-to-back correlation with respect to the triggered hadron:

$$D^{h_1h_2}(z_T,\phi,p_T^{\rm trig}) = p_T^{\rm trig}\frac{d\sigma_{AA}^{h_1h_2}/d^2p_T^{\rm trig}dp_Td\phi}{d\sigma_{AA}^{h_1}/d^2p_T^{\rm trig}}, \qquad (7)$$

similarly to the direct-photon triggered FF [10] in γ-jet events. Here, $z_T = p_T/p_T^{\rm trig}$ and integration over $|y_{1,2}| < \Delta y$ is implied. In a simple parton model, the two jets should be exactly back-to-back. The initial k_T distribution in our model will give rise to a Gaussian-like angular distribution. In addition, we also take into account the intra-jet distribution using a Gaussian form with a width of $\langle k_T\rangle = 0.8$ GeV/c.

Shown in Fig. 3 are the calculated back-to-back correlations for charged hadrons in $Au+Au$ collisions as compared to the STAR data [4]. The same energy loss that is used to calculate single hadron suppression and azimuthal anisotropy can also describe well the observed away-side hadron suppression and its centrality dependence. In the data, a background $B(p_T)[1+2v_2^2(p_T)\cos(2\Delta\phi)]$ from uncorrelated hadrons and azimuthal anisotropy has been subtracted. The value of $v_2(p_T)$ is measured independently while $B(p_T)$ is determined by fitting the observed correlation in the region $0.75 < |\phi| < 2.24$ rad [4].

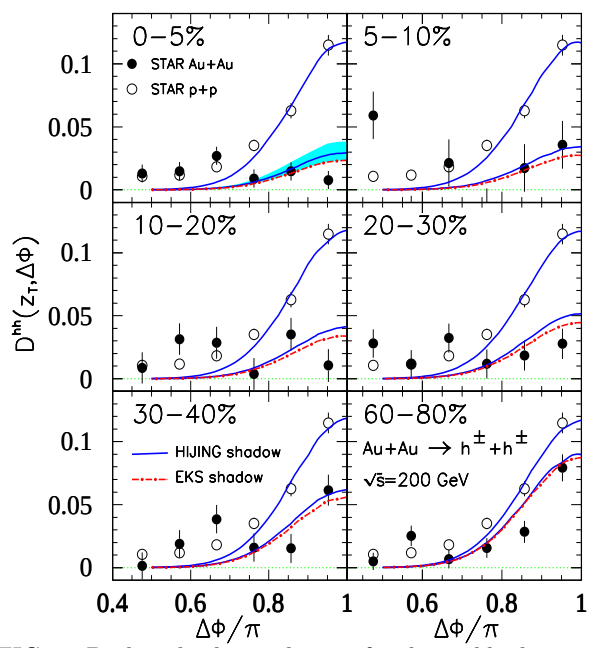

FIG. 3. Back-to-back correlations for charged hadrons with $p_T^{\rm trig} > p_T > 2$ GeV/c, $p_T^{\rm trig} = 4-6$ GeV/c and $|y| < 0.7$ in $Au+Au$ (lower curves) and $p+p$ (upper curves) collisions as compared to the STAR [4] data.

Since most of jets produced in the central core of the colliding volume are suppressed, the triggered high-p_T hadrons mainly come from jets produced near the surface traveling away from the dense core. These jets are not quenched, as observed in STAR data [4]. Most away-side jets, however, will be suppressed as they go through the dense core, except those that are propagating in directions tangent to the surface. This leads to a much smaller azimuthal anisotropy of the away-side suppres-

sion. On the average, both the magnitude of the away-side suppression and the centrality dependence should be similar to the single hadron suppression, as seen in the data. Contrary to another study [27], we find that the p_T broadening associated with energy loss has no significant effect on the observed back-to-back correlations, since those jets that have large final-state broadening also have large energy loss and thus are suppressed.

Integrating over ϕ, one obtains a hadron-triggered FF, $D^{h_1h_2}(z_T, p_T^{\rm trig}) = \int_{\pi/2}^{\pi} d\phi D^{h_1h_2}(z_T, \phi, p_T^{\rm trig})$. Shown in Fig. 4 are the suppression factors of the hadron-triggered FF's for different values of $p_T^{\rm trig}$ in central $Au + Au$ collisions as compared to a STAR data point that is obtained by integrating the observed correlation over $\pi/2 < |\Delta\phi| < \pi$. The dashed lines illustrate the small suppression of back-to-back correlations due to the initial nuclear k_T broadening in $d+A$ collisions. The strong QCD scale dependence on $p_T^{\rm trig}$ of FF's is mostly canceled in the suppression factor. The approximately universal shape reflects the weak p_T dependence of the hadron spectra suppression factor in Fig. 1, due to a unique energy dependence of parton energy loss.

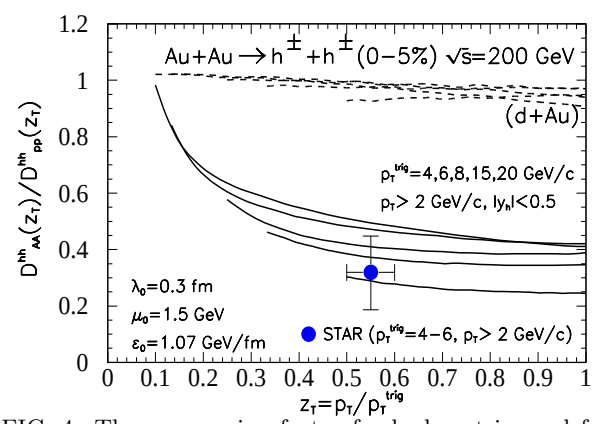

FIG. 4. The suppression factor for hadron-triggered fragmentation functions in central (0-5%) $Au + Au$ (d+Au) collisions as compared to the STAR data [4].

In summary, we have studied simultaneously the suppression of hadron spectra and back-to-back correlations, and high-p_T azimuthal anisotropy in high-energy heavy-ion collisions within a single LO pQCD parton model incorporating current theoretical understanding of parton energy loss. Experimental data of $Au + Au$ collisions from RHIC can be quantitatively described by jet quenching in an expanding medium. With HIJING (EKS) parton shadowing, the extracted average energy loss for a 10 GeV quark in the expanding medium is $\langle dE/dL\rangle_{1d} \approx 0.85(0.99) \pm 0.24$ GeV/fm, which is equivalent to $dE_0/dL \approx 13.8(16.1) \pm 3.9$ GeV/fm in a static and uniform medium over a distance $R_A = 6.5$ fm. This value is about a factor of 2 larger than a previous estimate [16] because of the variation of gluon density along the propagation path and the more precise RHIC data considered here .

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