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 $\pi^0$ 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 $\pi^0$ 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

$$\frac{d\sigma_{AB}}{dydp_T^2} = K \sum_{abcd} \int d^2b d^2r dx_a dx_b d^2k_a d^2k_b d^2k_T \left[ t_A(b-r) t_B(\mathbf{b-r}) g_A(k_a T, r) g_A(k_b T, b-r) \right. \\
left. f_{a/A}(x_a, Q^2, r) f_{b/B}(x_b, Q^2, b-r) D_{h/c}(z_c, Q^2, \Delta E_c) \frac{d\sigma}{dt}(ab \rightarrow cd) \right],$$

where $z_c = p_T/\langle p_T \rangle$, $y = y_c$, $\sigma(ab \rightarrow cd)$ are parton scattering cross sections and $t_A(b)$ is the nuclear thickness function normalized to $\int d^2b t_A(b) = A$. 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]

$$D_{h/c}(z_c, Q^2, \Delta E_c) = \left(1 - \frac{z_c}{\langle z_c \rangle} \right) \left[ \frac{z_c'}{\langle z_c' \rangle} D_{h/c}^0(z_c', Q^2) \right] + \frac{\Delta L}{\lambda} \frac{z_c'}{\langle z_c' \rangle} D_{h/c}^0(z_c', Q^2),$$

provided that the actual energy loss is about 1.6 times of the input value. Here $z_c' = p_T/(\langle p_T \rangle - \Delta E_c)$, $z_c' = (\Delta L/\lambda)p_T/\Delta E_c$ are the rescaled momentum fractions and $\Delta E_c$ is the total parton energy loss during $\langle \Delta L/\lambda \rangle$ number of scatterings. The FF’s in free space $D_{h/c}^0(z_c, Q^2)$ 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

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

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 $\phi$ relative to the reaction plane in a collision with impact-parameter $b$.

The corresponding energy loss in a static medium with an initial uniform gluon density will use an effective quark energy loss for a parton with finite initial energy. In this paper we further increase the energy dependence [20]. Detailed balance between induced gluon emission and absorption will further increase the energy dependence [20]. 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 $R_{AB}(p_T) = \frac{d\sigma_{AB}^h}{d\sigma_{pp}^h}$ for hadron spectra ($|y| < 0.5$) in $Au+Au$ collisions at $\sqrt{s} = 200$ GeV, as compared to experimental data. Here, $\langle N_{\text{bin}}^{AB} \rangle$ = $\int d^2 b d^{2}\tau_A(r) t_B(|\vec{b} - \vec{r}|)$. To fit the observed $\pi^0$ suppression in the most central collisions, we have used (solid lines) $\mu_0 = 1.5$ GeV, $\epsilon_0 = 1.07$ GeV/fm and $\lambda_0 = 1/(\sigma_{pt0}) = 0.3$ 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.

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,

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

where $\rho_0$ is the averaged initial gluon density at $\tau_0$ 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 uniform initial gluon density $\rho_0$. The corresponding energy loss in a static medium with a uniform gluon density $\rho_0$ 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

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

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The flat $p_T$ dependence of the $\pi^0$ 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 $\tilde{c} = 1 + \exp(2p_{Tc} - 15)$. The functional form and parameters are adjusted so that $(K + p)/\pi$ $= 2$ 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 $h^\pi$ and $\pi^0$ suppression via the $(K + p)/\pi$ ratio: $R_{AA}^{h^\pi} = R_{AA}^{\pi^0}[1/(1 + (K + p)/\pi)]_{AA}/[1/(1 + (K + p)/\pi)]_{pp}$. 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 $R_{AA}^{h^\pi}$ 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 $\langle N_{\text{binary}} \rangle$ 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.

$$\int dz_a dz_d t_A (r) t_B (|b-r|) g_A (k_T r) g_A (k_T |b-r|) f_{a/A} (x_a, Q^2, r) f_{b/B} (x_b, Q^2, |b-r|) D_{h/A} (z_a, Q^2, \Delta E_c) D_{h/B} (z_d, Q^2, \Delta E_d) \frac{\hat{s}}{2 \pi z_a^2 z_d^2} \frac{d\sigma}{dt} (ab \to cd) \delta^4 (p_a + p_b - p_c - p_d),$$

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

$$D^{h_1 h_2} (z_T, \phi, p_T^{\text{trig}}) = p_T^{\text{trig}} \frac{d\sigma^{h_1 h_2}_{AA}}{d^3 p_T^{\text{trig}}} \frac{d\sigma^{p_T}}{d^3 p_T^{\text{trig}}} d\phi,$$

similarly to the direct-photon triggered FF [10] in $\gamma$-jet events. Here, $z_T = p_T/p_T^{\text{trig}}$ 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 $\langle k_T \rangle = 0.8 \text{ GeV/c}$.

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 $B(p_T)[1 + 2v_2(p_T) \cos(2\Delta \phi)]$ 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 $0.75 < |\phi| < 2.24 \text{ rad}$ [4].

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 suppress-
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 $\phi$, one obtains a hadron-triggered FF, $D_{h}^{T_{h}}(z_{T},p_{T}^{\text{trig}}(z_{T},\phi,p_{T}^{\text{trig}}))$. Shown in Fig. 4 are the suppression factors of the hadron-triggered FF's for different values of $p_{T}^{\text{trig}}$ 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 $p_{T}^{\text{trig}}$ 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.

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 as compared to RHIC data can be quantitatively described by hadron spectra and back-to-back correlations, 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.

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