Why the observed jet quenching at RHIC is due to parton energy loss

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Significant jet quenching in central $Au + Au$ collisions has been discovered at RHIC. This paper provides theoretical arguments and lists experimental evidence that the observed jet quenching at RHIC is due to parton energy loss instead of hadron rescattering or absorption in a hadronic medium. These include: (1) hadron formation time based on the uncertainty principle, (2) $p_T$ dependence and (3) centrality dependence of the observed jet quenching, (4) jet-like leading hadron correlations (5) high-$p_T$ azimuthal anisotropy and (6) experimental data from $Pb + Pb$ collisions at SPS and $e + A$ collisions. Direct measurements of the parton energy loss in the direction of a triggered high-$p_T$ hadron and the medium modified fragmentation function on the back-side are proposed to further verify the partonic nature of the observed jet quenching. The importance of jet quenching studies at lower energies at RHIC is also discussed.

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I. INTRODUCTION

More than a decade after the original proposal [1,2] of jet quenching due to radiative parton energy loss, conclusive experimental evidence has been found in central $Au + Au$ collisions at the Relativistic Heavy-ion Collider (RHIC) not only from the suppression of high-$p_T$ single inclusive hadron spectra [3–5] but also the suppression of back-side jet-like correlations [6]. The latter provides direct evidence for medium modification of the parton fragmentation functions [7]. More recent results of $d + Au$ collisions [8–10] further prove that the observed jet quenching is due to final-state interactions with the produced medium. Initial-state scatterings in cold nuclei only broaden the initial transverse momentum, leading to the Cronin enhancement of intermediate high-$p_T$ hadron spectra as was first predicted for $p + A$ collisions at RHIC [11].

The original proposal of jet quenching in a dense (or normal) nuclear medium [1,2] was based on the idea that radiative energy loss during the propagation of an energetic parton must suppress the leading hadron distributions inside a jet. This leads to medium modification of the jet fragmentation functions [7] and suppression of the high-$p_T$ hadron spectra in high-energy heavy-ion collisions. Such medium-induced radiative parton energy loss has since been studied in detail and in many different approaches [12–18] in QCD that include the non-Abelian Landau-Pomeranchuk-Migdal (LPM) interference effect. The energy loss was found to be proportional to the gluon density of the medium. It was further predicted that jet quenching due to parton energy loss should also lead to the azimuthal anisotropy of high-$p_T$ hadron spectra in non-central heavy-ion collisions [19], which has been observed [20] at RHIC.

Phenomenological studies of hadron spectra based on parton energy loss have found that the observed suppression of high-$p_T$ single hadron spectra implies large parton energy loss or high initial gluon density [18,21–24]. The same parton energy loss is also found to reproduce the observed suppression of back-side correlation [25,26] and the high-$p_T$ azimuthal anisotropy [26,27]. Most importantly, the calculated centrality dependences of the suppression of both single hadron spectra and back-side correlation agree very well with the experimental measurements [26]. The deduced initial gluon density at an initial time $t_0 = 0.2$ fm/$c$ is found to be about 30 times of that in a normal nuclear matter [24,26]. If the transverse energy per particle is 0.5 GeV [28], the above gluon density will correspond to an initial energy density of $e = 15$ GeV/fm$^3$, which is about 100 times of the energy density in a cold nuclear matter. In addition, the measured large azimuthal anisotropy for soft hadrons is found to saturate the hydrodynamic limit [29,30]. These experimental results all point to an initial medium that is strongly interacting and has a large initial pressure gradient. Within our current understanding of QCD, such a strongly interacting medium with about 100 times normal nuclear energy density can no longer be a normal hadronic matter.

The aforementioned analyses of RHIC data on jet quenching are all based on a picture in which partons propagating through the dense medium lose energy first and then hadronize outside in the same way as in the vacuum. It is reasonable to ask whether leading hadrons from the jet fragmentation could have strong interaction with the medium and whether hadron absorption could be the main cause for the observed jet quenching. This paper will provide arguments against such a scenario in detail and list experimental evidence that the observed patterns of jet quenching in heavy-ion collisions at RHIC can only be the consequences of parton energy loss, not
hadronic absorption.

II. HADRON FORMATION TIME

Fragmentation of a parton into hadrons involves mainly non-perturbative physics in QCD and thus is not calculable within perturbative QCD (pQCD). One can, nevertheless, use pQCD to calculate the evolution of the fragmentation process due to short distance interaction when the virtuality of the parton is larger than $Q_0 \sim 1$ GeV. Such perturbative processes can take place over a period of time,

$$\tau_{DGLAP} \sim 2 \sum_i E_z(1 - z_i) Q_i^2 \gtrsim 2 E_0(1 - z_0) Q_0^2,$$

(1)

where the sum is over gluon emission, and $Q_i$ and $z_i$ are the virtualities and fractional energies of the intermediate partons between each successive emission until $Q_0$ is reached. Afterwards, the non-perturbative processes of hadronization take place. One scenario of the non-perturbative process is that the produced partons (quarks and gluons) will recombine into the final hadrons. The hadron formation time can be considered as the time for partons to build up their color fields and develop the hadron wave function. According to the uncertainty principle, such a formation time in the rest frame of the hadron can be related to the hadron size $R_h$. In the laboratory frame, the hadron formation time is then [31]

$$\tau_f \sim R_h \frac{E_h}{m_h}.$$

(2)

For an $E_h = 10$ GeV pion, this amounts to $\tau_f \sim 35 - 70$ fm/c for $R_h = 0.5 - 1$ fm.

In some dipole models of hadronization [32], the quarks and anti-quarks from gluon splitting are assumed to combine into color singlet dipoles which will become the final hadrons. The hadron formation time is then assumed to be just the formation time for the gluon emission, ignoring the time of quark and anti-quark production and the time for dipoles to grow to the normal hadron size. Even if one considers this alternative hadronization process as successive emission of hadrons by the fragmenting jet, a hadron carrying a fraction $z$ of the parton energy will take

$$\tau_f \sim \frac{2E_h(1 - z)}{k_T^2 + m_h^2}$$

(3)

to be produced, where $k_T \sim A_{QCD}$ is the intrinsic transverse momentum of the hadron. As we will show later, a 10 GeV hadron comes from a parton with an average energy $E = 16.5$ GeV in $p+p$ collisions at RHIC, thus an average $\langle z \rangle = 0.6$. Using $A_{QCD} = 0.2$ GeV, the formation time for a 10 GeV pion is then $\tau_f \sim 40$ fm/c.

Though the above numbers can only serve as order-of-magnitude estimates, they are still much longer than the typical medium size or the lifetime of the dense medium in heavy-ion collisions at RHIC. Furthermore, the above estimates are for hadronization in vacuum only. Medium interaction with the fragmenting partons will only increase the hadron formation time. Certainly, in the extreme case, the hadron can never be formed inside a deconfined medium due to color screening and the formation time should never be shorter than the lifetime of a quark-gluon plasma.

III. MOMENTUM DEPENDENCE OF HADRON SUPPRESSION

The most striking feature of the observed jet quenching manifested in the suppression of high-$p_T$ hadrons is the almost flat $p_T$ dependence of the suppression at high $p_T$ [3,4]. The empirical total energy loss has to have a linear energy dependence in order to describe such a $p_T$ dependence [22,23]. This runs directly opposite to the trend of hadronic absorption or rescattering. Since the hadron formation time is proportional to the hadron or jet energy, the total effective energy loss due to hadron rescattering or absorption should decrease with energy, unless the energy dependence of the hadronic energy loss per unit distance is stronger than a quadratic dependence. Such a quadratic or stronger energy dependence of the energy loss can never be allowed in any physical scenario.

For elastic scatterings, the energy loss of a pion per scattering is $\Delta E_{el} \approx E_{\pi}(1 - \cos \theta_{cm})/2$, where $\theta_{cm}$ is the scattering angle in the center of mass frame. The averaged elastic energy loss can be estimated as

$$\frac{dE_{el}}{dx} = \langle \int dt \frac{d\sigma}{dt} E_{\pi} \frac{t}{s} \rho_h \rangle \approx \frac{\sigma_0}{B} \rho_h(\omega_h),$$

(4)

which has a very weak energy dependence. Here $t \approx -s(1 - \cos \theta_{cm})/2$, $s \approx 2E_{\pi}\omega_h$ and $\langle \cdot \cdot \cdot \rangle$ is the thermal average over hadron energy $\omega_h$ with density $\rho_h(\omega_h)$. We have considered only the dominant t-channel when $\sqrt{s}$ is much larger than the $\pi-h$ resonance mass and $\sigma_0/B$ can be described by its geometrical form $\sigma_0/B = \sigma_0(B) \exp(tB)$, with $B/\sigma_0 \approx 0.3$ according to the observed geometrical scaling property of high energy hadron collisions for $\sqrt{s} < 100$ GeV [33]. Here, $\sigma_0$ is assumed to be the total cross section. Normally, elastic cross section is about 17% of the total cross section. This elastic energy loss is also related to the transverse momentum broadening,

$$\left( \frac{q_T^2}{\lambda} \right) \approx \frac{\sigma_0}{B} \langle \rho_h \rangle.$$

(5)

For a pion gas at $T \sim 150$ MeV, the elastic energy loss is very small, about 0.036 GeV/fm, independent of the pion’s energy. The corresponding transverse momentum broadening will be also very small. The energy loss due to inelastic $\pi-h$ scattering is difficult to estimate. However,
it should not have a linear energy dependence, according to the estimate based on the uncertainty principle [34], taking into account the LPM interference effect. Therefore, the energy loss due to hadronic interaction should have an energy dependence weaker than a linear dependence. Hadronic rescattering or absorption, with the energy dependence of the formation time, cannot give rise to the observed flat $p_T$ dependence of the hadron suppression.

\[ \Delta E \approx \left( \frac{dE}{dL} \right)_{1d} \int_{\tau_0}^{\tau_0 + \Delta L} d\tau \frac{\tau - \tau_0}{\tau_0 \rho_0} \rho_g(\tau, b, \vec{r} + \vec{u}_\tau), \quad (6) \]

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-dimensional expanding medium with an initial uniform 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 $dE_0/dL = (R_A/2\tau_0)\langle dE/dL \rangle_{1d}$ [18]. The gluon density $\rho_g(\tau, b, \vec{r})$ is assumed to be proportional to the transverse profile of participant nucleons, which is consistent up to 30% with the measured charged hadron multiplicity [40,41].

The calculated centrality dependence of the single hadron suppression in $Au + Au$ collisions agrees very well with the experimental measurements, as shown in Fig. 2. The centrality dependence of the back-side suppression is also in excellent agreement with the data [26]. These are the consequences of the centrality dependence of the averaged total energy loss in Eq. (6) and the surface emission of the surviving jets. Jets produced around the core of the overlapped region are strongly suppressed, since they lose the largest amount of energy.

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**IV. CENTRALITY DEPENDENCE OF HADRON SUPPRESSION**

This paper will not describe the details of the calculation of single hadron and dihadron spectra in heavy-ion collisions, but refer readers to Ref. [26]. It is, however, important to point out that the effective total parton energy loss in a dynamic system is proportional to a path integral of the gluon density along the propagation trajectory. According to recent theoretical studies [18,27,39],

\[ \Delta E \approx \left( \frac{dE}{dL} \right)_{1d} \int_{\tau_0}^{\tau_0 + \Delta L} d\tau \frac{\tau - \tau_0}{\tau_0 \rho_0} \rho_g(\tau, b, \vec{r} + \vec{u}_\tau), \quad (6) \]
On the other hand, if the finite hadron formation time were shorter than the medium size in the most central collisions and jet quenching were only caused by the subsequent rescattering or absorption of the leading hadrons, one should expect a more rapid disappearance or reduction of jet quenching when the medium size becomes smaller than the hadron formation time in non-central $Au + Au$ collisions. This is clearly absent in the observed centrality dependence.

![Graph showing the centrality dependence of the measured single inclusive hadron suppression](image)

**FIG. 2.** The centrality dependence of the measured single inclusive hadron suppression [3,4] at high $p_T$ as compared to theoretical calculation with parton energy loss

The large suppression of single hadron spectra, about a factor of 5, in the most central $Au + Au$ collisions can actually lead to a strong constraint on the hadron formation time if no parton energy loss is allowed. One can take the most extreme scenario: There is no jet attenuation before a finite hadron formation time $\tau_f$ and every hadron is absorbed if it is still inside the medium at the formation time. The suppression factor is then determined by the ratio of the volume of the outer layer with a width $\tau_f$ and the total overlapping volume. Here one neglects the finite transverse flow velocity in the early time. With a hard-sphere nuclear geometry, one finds that a factor of 5 suppression would require a formation time shorter than $2 \text{ fm}/c$, which is hard to reconcile with the theoretical estimate for a 10 GeV pion.

**V. JET-LIKE HADRON CORRELATION**

Perhaps the most discriminating experimental evidence against jet quenching via hadron rescattering or absorption comes from two-particle correlations. Jet structure of azimuthal correlations of leading hadrons is clearly seen in RHIC experiments and it is the same in $p + p$, $d + Au$ and peripheral $Au + Au$ collisions [6,9]. It consists of one peak in the near-side of the triggered hadron and another in the back-side. As one increases the centrality in $Au + Au$ collisions, the back-side correlation is significantly suppressed just as the single hadron spectra. The near-side correlation, on the other hand, remains the same as in $p + p$ and $d + Au$ collisions. This is clear evidence that jet hadronization takes place outside the dense medium with a reduced parton energy.

It should be stressed that the above argument is only true when the transverse momenta of the leading and subleading hadrons are close to each other. This is to ensure that both of them come from hadronization of the leading parton. If the subleading hadron is very soft, then contribution from emitted gluons induced by bremsstrahlung can become important. These soft hadrons will then have different correlation and azimuthal profile from that in $pp$ collisions.

Because of the trigger bias, the triggered high-$p_T$ hadrons mainly come from jets that are produced near the surface of the overlapped region. However, on the average the original jet should lose a finite amount of energy. In the pQCD parton model, one can calculate the average energy of the initial jet that, after rescattering and induced bremsstrahlung, eventually produces a leading hadron with transverse momentum $p_T^{\text{trig}}$. Shown in Fig. 3 are the averaged jet energies minus $p_T^{\text{trig}}$ as functions of $(N_{\text{part}})$ for different values of $p_T^{\text{trig}}$. Note that the averaged $(z) = p_T^{\text{trig}}/(E_T)^{\text{ref}}$ in $p + p$ collisions is about 0.6-0.7, with the triggered hadron carrying most of the jet energy. In heavy-ion collisions, the jet loses some amount of energy before it hadronizes. Therefore, it has to have higher initial energy than in $p + p$ collisions in order to produce a leading hadron with the same $p_T^{\text{trig}}$. The extra amount of energy increases with centrality as shown by the solid lines.
In the most central collisions, jets that produce a leading particle with gluon bremsstrahlung and produces a leading particle energy loss for a jet that survived multiple scattering and finite parton energy loss that describes the inclusive hadron suppression and dashed lines for calculation without parton energy loss (but with initial multiple scatterings).

Note that \( \langle E_T \rangle_{\text{jet}} \) evaluated here is the transverse energy in the center of mass frame of the two colliding partons. Initial multiple scattering will increase the initial parton transverse momentum leading to the observed Cronin enhancement of high-\( p_T \) single hadron spectra in \( d + Au \) collisions [11,9,8,10]. The trigger bias then leads to smaller values of \( \langle E_T \rangle_{\text{jet}} \) in \( Au + Au \) collisions without energy loss than in \( p + p \) for a fixed \( p_T^{\text{trig}} \) as shown by the dashed lines in Fig. 3. The difference between solid and dashed lines should then be the averaged energy loss for a jet that survived multiple scattering and gluon bremsstrahlung and produces a leading particle with \( p_T^{\text{trig}} \). This is shown in Fig. 4 as a function of \( \langle N_{\text{part}} \rangle \). In the most central collisions, jets that produce a leading hadron at \( p_T^{\text{trig}} = 5 - 15 \text{ GeV/c} \) lose about \( 1.4 - 2.2 \text{ GeV} \) energy on the average.

In experimental determination of the initial jet energy, one has to count all hadrons in the jet cone, including those coming from the emitted gluons. Some of these hadrons are very soft. One has to use a momentum cut-off as small as possible in order to make sure the measured total energy is as close to the true value of the initial jet energy as possible. Since soft hadrons from medium induced gluons could have a broader angular distribution, one should have a large jet cone with \( |\Delta \phi| < \pi/2 \).

On the back-side of the triggered hadrons, one can define a hadron-triggered effective fragmentation function [26],

\[
D^{h_2}(z_T, p_T^{\text{trig}}) = p_T^{\text{trig}} \frac{d\sigma_{h_1+h_2}^{AA}/dp_T}{d\sigma_{h_1}^{AA}/dp_T^{\text{trig}}}, \tag{7}
\]

for associated hadron \( h_2 \) with \( p_T \) in the back-side direction of \( h_1 \) with \( p_T^{\text{trig}} \), where \( z_T = p_T/p_T^{\text{trig}} \). The back-side direction is defined by \( |\Delta \phi - \pi| < \pi/2 \). This way, one can ensure that the jet cone includes most of the soft hadrons. This is equivalent to finding remnants of lost jets in heavy-ion collisions [44]. Shown in Fig. 5 are the hadron-triggered fragmentation functions in \( pp \) collisions. The differences between different values of \( p_T^{\text{trig}} \) are caused by scale dependence of the parton fragmentation functions and the different parton flavor composition, in particular the ratio of quark and gluon jets. The parton fragmentation functions used in the calculation are given by parameterization. With finite values of initial jet energy, mass and other higher-twist corrections become important. The actual fragmentation functions will saturate and decrease for small values of \( z_T \). The larger the \( E_T \), the smaller the \( z_T \) of the saturation point.
lead to a large azimuthal anisotropy of high-dependence of the path length of propagation. This will have finite azimuthal anisotropy due to the azimuthal profile could change due to transverse momentum broadening. Thus if one chooses large energy loss and the enhancement of soft hadrons from emitted gluons. Soft hadrons from emitted gluons become significant only at small $z_T$. At large $z_T$ hadrons mainly come from fragmentation of the jet with reduced energy. Thus if one chooses large $z_T$, the near-side jet profile should not change. On the other hand, the back-side profile could change due to transverse momentum broadening.

Since azimuthal anisotropy in hadron spectra is generated by the geometrical eccentricity of the dense medium, it is only sensitive to the evolution of the dense matter at very early time [42]. As the system expands, the geometry becomes more symmetric and thus loses its ability to generate spectra anisotropy. This is particularly true in late hadronic stage [43]. If there were no parton energy loss and no jet attenuation before a finite hadron formation time, then any anisotropy in spectra will be caused by the geometrical eccentricity at the time when hadron absorption starts. At this late time, a few fm/c for example, the geometry is already quite symmetric and can no longer generate large anisotropy in the final hadron spectra. Therefore, the observed large azimuthal anisotropy at high $p_T$ cannot be generated by hadronic absorption of jets in the late stage of the evolution.

VI. HIGH $p_T$ AZIMUTHAL ANISOTROPY

In non-central heavy-ion collisions, the parton energy loss has finite azimuthal anisotropy due to the azimuthal dependence of the path length of propagation. This will lead to a large azimuthal anisotropy of high-$p_T$ hadron spectra [19] which has been observed by RHIC experiments [20]. After correction for two-particle correlations, the observed azimuthal anisotropy is consistent with that observed at parton energy loss [26]. The same energy loss also explains quantitatively the single hadron suppression and suppression of back-side jet correlations.

Since azimuthal anisotropy in hadron spectra is generated by the geometrical eccentricity of the dense medium, it is only sensitive to the evolution of the dense matter at very early time [42]. As the system expands, the geometry becomes more symmetric and thus loses its ability to generate spectra anisotropy. This is particularly true in late hadronic stage [43]. If there were no parton energy loss and no jet attenuation before a finite hadron formation time, then any anisotropy in spectra will be caused by the geometrical eccentricity at the time when hadron absorption starts. At this late time, a few fm/c for example, the geometry is already quite symmetric and can no longer generate large anisotropy in the final hadron spectra. Therefore, the observed large azimuthal anisotropy at high $p_T$ cannot be generated by hadronic absorption of jets in the late stage of the evolution.

VII. SPS DATA

The final piece of the evidence comes from experiments at SPS. Hadron spectra at this energy are very steep at high $p_T$ and are very sensitive to initial transverse momentum broadening and parton energy loss [11]. However, the measured $\pi$ spectra in central $Pb+Pb$ collisions only show the expected Cronin enhancement [45,46] with no sign of significant suppression. More recent analyses of the $Pb + Pb$ data at the SPS energy also show [47] that both same-side and back-side jet-like correlations are not suppressed, though the back-side distribution is broadened. Shown in Fig. 7 as a solid line is the energy dependence of the calculated single pion suppression factor at $p_T = 4$ GeV/$c$ as compared to data at RHIC and SPS. The initial gluon density $\rho_0$ at $\tau_0 = 0.2$ fm/$c$ in the calculation of the parton energy loss in Eq. (6) is assumed to be proportional to the measured $dN_{ch}/d\eta$ [48]. The measured multiplicity at SPS is only about 2.0 smaller than the highest energy of RHIC. The calculated suppression increases more rapidly and reaches at 1 at the SPS energy. This is partly because of the Cronin effect which is much stronger at SPS and compensates some of the energy loss effect. However, the calculation is still about a factor of 3 smaller than the data. Similar results are reported in Ref. [24] when the same gluon density is used.

There could be several reasons for such a big discrepancy between data and our calculation at SPS [11]. The initial formation time $\tau_0$ could be much larger than at RHIC or the lifetime of the dense matter at SPS could be much shorter. A critical behavior of the screening mass, which influence parton energy loss, could also lead to a sudden decrease of energy loss [49] at lower energies. Since a hadronic gas should have at least existed in $Pb + Pb$ collisions at SPS and the particle density and duration of such a hadronic state should not be much different from that in $Au + Au$ collisions at RHIC, hadronic rescattering or absorption should have significantly sup-
pressed the pion spectra, were it responsible for most of the jet quenching at RHIC. Therefore, in any circumstances, the SPS data are not consistent with a hadronic absorption picture at RHIC.

Nevertheless, jet quenching at SPS energies still remains a less explored territory. As shown in Fig. 7, it will be important to have a few measurements between SPS and RHIC energy to explore the colliding energy dependence of jet quenching and find out whether there is any threshold behavior of jet quenching. By changing the colliding energy, one essentially changes the initial parton density without changing the initial medium size. This will allow one to observe the initial density dependence of jet quenching, obtain more information about formation time or lifetime of the medium, and search for critical behaviors that might be caused by phase transitions in the evolution of the dense medium.

**FIG. 7.** The colliding energy dependence of the nuclear modification factor for single inclusive hadron spectra at fixed $p_T$ in the most central Au+Au (or Pb+Pb) collisions as compared to the parton model calculation. The parton energy loss is assumed to be proportional to the measured charge multiplicity $dN_c h/d\eta$ while the medium formation time and lifetime of the medium are assumed to be the same. The data are from PHENIX [3], STAR [4] and WA98 [45].

This paper has provided arguments and listed experimental evidence that the observed jet quenching in Au + Au collisions at RHIC is caused mainly by parton energy loss, not hadron absorption in a hadronic medium. The estimated hadron formation time in jet hadronization is much longer than the typical lifetime of the dense matter and thus cannot be responsible for the observed jet quenching. The observed $p_T$ and centrality dependence of jet quenching are not consistent with a hadronic absorption picture with a finite formation time that is smaller than the size of the medium. The measured high-$p_T$ azimuthal anisotropy can only be caused by the geometrical anisotropy of the medium in a very early stage and thus cannot be due to hadronic rescattering. The most direct evidence for partonic energy loss and jet hadronization outside the medium is the universal same-side leading hadron correlations inside a jet in $p+p$, $d+Au$ and $Au+Au$ collisions. Hadronic rescattering or absorption inside the medium would have destroyed the jet-like same-side correlation. Finally, the absence of jet quenching in $Pb + Pb$ collisions at SPS also indirectly proves that hadronic rescattering cannot be responsible for the observed jet quenching at RHIC.

A direct measurement of parton energy loss is proposed which requires the reconstruction of the total energy of a jet that has a triggered hadron with a fixed value of $p_T^{\text{trig}}$. The difference between Au+Au and $p+p$ measurements (plus $p_T$ broadening due to initial multiple parton scattering) should be related to the averaged total energy loss for the jet whose leading parton produces the triggered hadron after energy loss. The measurement of softening of the effective hadron-triggered fragmentation function will further detail the pattern of energy loss and induced gluon emission. The importance of jet quenching at lower RHIC energies is also discussed.

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