Where Is the Jet Quenching in Pb + Pb Collisions at 158*A* GeV?

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Because of the rapidly falling particle spectrum at large p_T from jet fragmentation at CERN SPS energy, the high-p_T hadron distribution should be highly sensitive to parton energy loss inside a dense medium as predicted by recent perturbative QCD (PQCD) studies. A careful analysis of recent data from CERN SPS experiments via PQCD calculation shows little evidence of energy loss. This implies that either the lifetime of the dense partonic matter is very short or one has to rethink parton energy loss in dense matter. The hadronic matter does not seem to cause jet quenching in Pb + Pb collisions at the CERN SPS. High-p_T two particle correlation in the azimuthal angle is proposed to further clarify this issue. [S0031-9007(98)07156-7]

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Hard processes have been considered good probes of the dense matter which is produced in high-energy heavy-ion collisions and is expected to be in the form of deconfined quarks and gluons or a quark-gluon plasma (QGP) at high-energy densities. These processes happen in the earliest stage of the collisions and therefore can probe the properties of the dense matter in its early form, whether a QGP or not. Furthermore, their production rates can be calculated with reasonable accuracy within the perturbative QCD (PQCD) parton model and has been tested extensively against vast experimental data in $p + p$ and $p + A$ collisions. These calculations [1] incorporating the minimum amount of normal nuclear effects (nuclear modification of parton distributions [2] and Cronin effect [3]) then provide a clean and reliable baseline against which one can extract signals of the dense matter. In this paper, we investigate what high-p_T particles from jet fragmentation tell us about the dense matter formed in Pb + Pb collisions at the CERN SPS.

Like other hard processes, large transverse momentum parton jets are produced in the early stage of high-energy heavy-ion collisions. They often have to travel through the dense matter produced in the collisions and finally hadronize into high-p_T particles in the central rapidity region. Recent theoretical studies [4–7] show that a fast parton will lose a significant amount of energy via induced PQCD radiation when it propagates through a dense partonic matter where the so-called Landau-Pomeranchuk-Migdal coherence effect becomes important. If this picture of parton energy loss can be applied to large transverse momentum parton jets in the central rapidity region of high-energy central $A + A$ collisions, one should expect a leading parton to lose energy when it propagates through a long-lived dense matter. Since the radiated gluons will eventually become incoherent from the leading parton which will fragment into large-p_T hadrons, one then should expect a reduction of the leading hadron's p_T or a suppression of the large-p_T particle spectrum [8–10]. At the CERN SPS energy, high-p_T jet or particle production ($p_T > 3$ GeV$/c$) is very rare and the power-law-like spectrum is very steep because of the limited phase space. It should be especially sensitive to any finite energy loss.

The single inclusive particle spectrum at large p_T in high-energy $p + p$ or $p + \bar{p}$ collisions can be calculated in a PQCD parton model with the information of parton distributions [11] and jet fragmentation functions [12] from deep-inelastic $e + p$ and e^+e^- experiments. This is one of the early successes of the QCD parton model [13–15]. It was already pointed out that the initial transverse momentum before the hard scattering is very important to take into account at lower energies and can significantly increase the single-inclusive differential cross section. The initial parton transverse momentum can be studied in detail via the Drell-Yan (DY) process [16–19], γ + jet, and $\gamma + \gamma$ production in $p + p$ collisions.

To the lowest order of PQCD, the single inclusive particle production cross section can be written as [15]

$$\frac{d\sigma_h^{pp}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b d^2k_{aT} d^2k_{bT} g_p(k_{aT},Q^2) \times g_p(k_{bT},Q^2) f_{a/p}(x_a,Q^2) f_{b/p}(x_b,Q^2) \times \frac{D^0_{h/c}(z_c,Q^2)}{\pi z_c}\frac{d\sigma}{d\hat{t}}(ab\to cd)\,, \tag{1}$$

where $x_{a,b}$ are the fractional energies and $k_{a,bT}$ the initial transverse momenta of the colliding partons. $d\sigma/d\hat{t}(ab \to cd)$ are the differential elementary parton-parton cross sections [15]. $K \approx 2$ is used to account for higher order corrections [20] and $Q = P_{cT} = p_T/z_c$. We will use MRSD$-'$ parametrization by Martin, Roberts, and Stirling [11] for the parton distributions $f_{a/p}(x,Q^2)$ and Binnewies-Kniehl-Kramer (BKK) parametrization for the jet fragmentation functions $D^0_{h/c}(z,Q^2)$. We will use a Gaussian form for the initial-k_T distribution $g_p(k_T,Q^2) = 1/(\pi\langle k_T^2\rangle_p)\exp(-k_T^2/\langle k_T^2\rangle_p)$ with a variance $\langle k_T^2\rangle_p = 1\ (\mathrm{GeV}^2/c^2) + 0.2Q^2\alpha_s(Q^2)$, where the

Q dependence accounts for initial k_T from initial-state radiation (or higher order $2 \rightarrow 2 + n$ processes) [19]. The parameters are chosen to best fit the experimental data of high-p_T particle spectra at all energies [21]. Because of the introduction of initial parton k_T, one of the Mandelstam variables for the elementary parton-parton scattering processes could vanish and cause the differential parton cross sections to diverge in certain phase space points. We use an effective parton mass $\mu = 0.8$ GeV to regulate the divergence as in the early studies [13]. The resultant spectrum is sensitive to the value of μ only at around $p_T \sim \mu$, where PQCD calculation is not reliable in any case.

Shown in Fig. 1 is an example of the calculated $\pi^{\pm}$ spectra in $p + p$ collisions at $E_{\rm lab} = 200$ GeV. The agreement with experimental data is very good not only for the overall inclusive cross section but also for the isospin dependence as shown by the p_T dependence of the π^-/π^+ ratio in the inserted figure. Similar analyses have been carried out at other energies up to Fermilab Tevatron [21]. The initial k_T is less important and becomes almost negligible for the single-inclusive parton spectra at these collider energies.

In $p + A$ collisions, there are two known nuclear effects: nuclear modification of the parton distributions [2] and nuclear enhancement of the large-p_T hadron spectra [3]. Both are caused by multiple initial scattering.

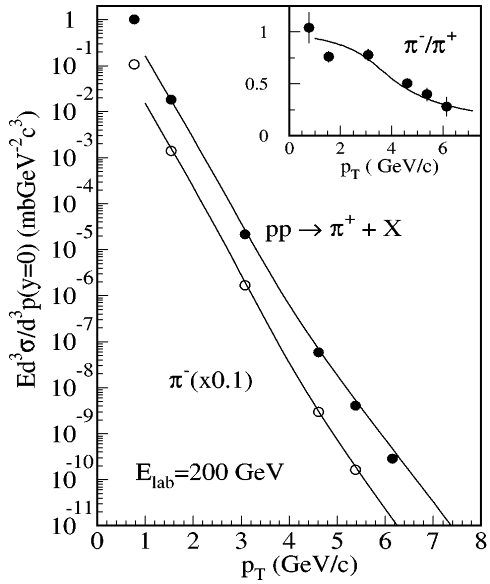

FIG. 1. Single-inclusive pion spectra in $p + p$ collisions at $E_{\rm lab} = 200$ GeV. The solid lines are from PQCD calculations and data from Ref. [3]. The inset shows the corresponding π^-/π^+ ratios.

We assume that the parton distributions per nucleon inside a nucleus at impact parameter b,

$$f_{a/A}(x, Q^2, b) = S_{a/A}(x, b)\left[\frac{Z}{A} f_{a/p}(x, Q^2) + \left(1 - \frac{Z}{A}\right) f_{a/n}(x, Q^2)\right], \tag{2}$$

is factorizable into the parton distributions inside a normal nucleon and the nuclear modification factor, $S_{a/A}(x, b)$, for which we use the HIJING parametrization in Ref. [22]. This should be adequate at the CERN SPS energy where the dominant process at large p_T is quark-quark scattering.

One can explain the Cronin effect within a multiple parton scattering model [23,24], in which the cancellation by the absorptive processes forces the nuclear enhancement to disappear at large p_T like $1/p_T^2$ and in the meantime causes a slight suppression of hadron spectra at small p_T so that the integrated spectra do not change much. This allows us to take into account the effect of multiple scattering via a broadening of the initial transverse momentum,

$$\langle k_T^2 \rangle_A(b) = \langle k_T^2 \rangle_p + [\nu(b) - 1]\Delta^2, \tag{3}$$

where $\nu(b) = \sigma_{pp} t_A(b)$ is the average number of scattering the parton's parent nucleon has suffered and $t_A(b)$ is the nuclear thickness function normalized to $\int d^2 b t_A(b) = A$. Since the Gaussian distribution is not a good approximation for the k_T kick during the initial multiple scattering, we found that we have to use a scale-dependent value, $\Delta^2 = 0.225 \ln^2(Q/\text{GeV})/[1 + \ln(Q/\text{GeV})]\ \text{GeV}^2/c^2$, to best describe the available data from $p + A$ collisions [21] which allow about (10–20)% uncertainty in the calculated spectra. For $Q = 2$–3 GeV, $\Delta^2 = 0.064$–$0.129\ \text{GeV}^2/c^2$, which is consistent with the analyses of p_T broadening for J/Ψ production in $p + A$ [25,26].

Taking into account these nuclear effects which already exist in $p + A$ collisions, the single inclusive particle spectra in $A + A$ collisions can be estimated as

$$\begin{aligned}\frac{d\sigma_h^{AA}}{dy d^2 p_T} = {} & K \sum_{abcd} \int d^2 b \int d^2 r t_A(r) t_A(|\mathbf{b} - \mathbf{r}|) \int dx_a dx_b d^2 k_{aT} d^2 k_{bT} g_A(k_{aT}, Q^2, r) g_A(k_{bT}, Q^2, |\mathbf{b} - \mathbf{r}|) \\ & \times f_{a/A}(x_a, Q^2, r) f_{b/A}(x_b, Q^2, |\mathbf{b} - \mathbf{r}|) \frac{D^0_{h/c}(z_c, Q^2)}{\pi z_c} \frac{d\sigma}{d\hat{t}}(ab \rightarrow cd)\,.\end{aligned} \tag{4}$$

The initial-k_T distribution $g_A(k_T, Q^2, b)$ is similar to that of a proton in Eq. (1) with a broadened width given by Eq. (3) which now depends on the impact parameter b.

For central $A + A$ collisions, we limit the integration over the impact parameter to $b_{\max}$. Using the geometrical cross section of a hard-sphere nucleus, we determine $b_{\max}$ by matching $b_{\max}^2/4\pi R_A^2$ ($R_A \approx 1.12 A^{1/3}$ fm) to the fractional cross section of the triggered central events in experiments. In Eq. (4), we actually use the Wood-Saxon distribution to calculate the thickness function $t_A(b)$.

Shown in Fig. 2 are the calculated single-inclusive spectra for π^0 in central S + S ($E_{\rm lab} = 200$ GeV) and Pb + Pb ($E_{\rm lab} = 158$ GeV) collisions with (solid) and without (dashed) nuclear k_T broadening as compared to WA80 [27] and WA98 [28] data. Besides small effects of the nuclear modification of the parton distributions on the spectra at these energies, the dashed lines are simply the spectra in $p + p$ collisions multiplied by the nuclear geometrical factor. It is clear that one has to include the k_T broadening due to the initial multiple scattering in order to describe the data. This is also consistent with the analysis by WA80 [27].

One can conclude from this analysis that the factorized PQCD parton model seems to work well for large-p_T hadron production in $A + A$ collisions. But one can also immediately realize that there is no evidence of parton energy loss as predicted by previous theoretical studies [4–7]. If there is parton energy loss and the radiated gluons become incoherent from the leading parton, the effective fragmentation functions should be modified such that the leading high-p_T particles should be suppressed as compared to $p + p$ and $p + A$ collisions [8–10]. At

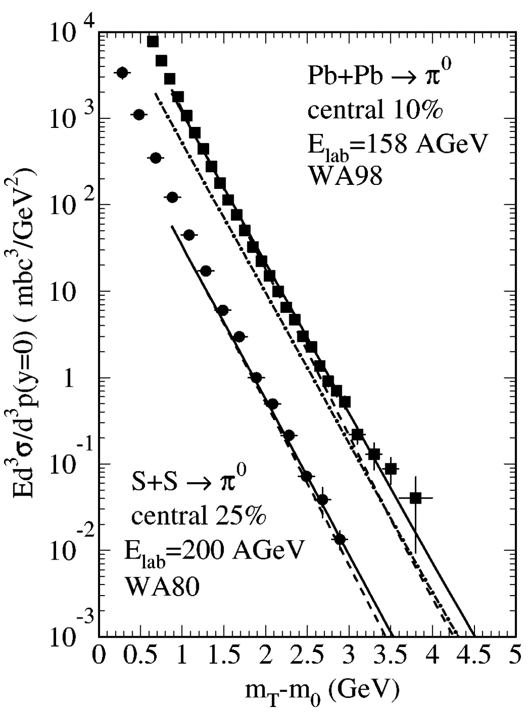

FIG. 2. Single-inclusive π^0 spectra in central S + S at $E_{\rm lab} = 200$ GeV and Pb + Pb collisions at $E_{\rm lab} = 158$ GeV. The solid lines are PQCD calculations with initial-k_T broadening, and dashed lines are without. The S + S data are from WA80 [27], and Pb + Pb data are from WA98 [28]. The dot-dashed line is obtained from the solid line for Pb + Pb by shifting p_T by 0.2 GeV/c.

$y = 0$, parton energy loss can be directly translated into p_T reduction for the leading hadrons. To estimate the experimental constraints on parton energy loss, one can simply shift the p_T values of the solid line for Pb + Pb in Fig. 2 by 0.2 GeV/c (dot-dashed line). Assuming 20% uncertainty of the calculated spectrum, one can quickly exclude a total energy loss $\Delta E < 0.1$ GeV. With the transverse size of a Pb nucleus, this corresponds to an energy loss $dE/dx < 0.02$ GeV/fm. Detailed model calculations will give a more stringent limit [21]. This is in direct contradiction with the current theoretical studies of parton energy loss in dense matter and calls into question current models of energy loss. It also implies that there is not a dense partonic matter which exists long enough to cause parton energy loss.

Most of the recent theoretical studies [4–7] of energy loss are based on PQCD calculation for a single fast parton propagating through a large dense medium. If we assume that it is valid for a parton propagating through a deconfined medium, the absence of parton energy loss in the experimental data on high-p_T particle spectra implies that either there is no such deconfined partonic matter being formed or it only lived for a very short period of time. Using the measured $dE_T/d\eta \approx 405$ GeV [29] in the central rapidity region of most central Pb + Pb collisions (2% of the total inelastic cross section) one can estimate the initial energy density at $\tau_0 = 1$ fm/c to be about $\epsilon_0 = (dE_T/d\eta)/(\pi\tau_0 R_A^2) \approx 2.9$ GeV/fm^3. This is an optimistic estimate assuming that the formation time of the dense matter is about 1 fm/c. Because of longitudinal expansion, the energy density will decrease like $\epsilon/\epsilon_0 = (\tau_0/\tau)^\alpha$. The value of α could range from 1 for free-streaming to 4/3 for hydroexpansion of an ideal gas of massless particles. Assuming a critical energy density of $\epsilon_c \approx 1$ GeV/fm^3, the system can only live above this critical density for about 2.2–2.9 fm/c. Equilibrating processes and transverse expansion certainly will reduce this lifetime even further. During such a short time, a highly virtual parton has small interaction cross section before it virtually decreases through PQCD evolution. Therefore, a produced large p_T parton will not have much time to lose its energy before the dense matter drops below the critical density. The recent theoretical studies [4–7] are not applicable to such a short-lived system. Nevertheless, this analysis at least tells us that the lifetime of the dense partonic matter must be short if it is ever formed in Pb + Pb collisions at 158A GeV. Otherwise, it is difficult to reconcile the absence of parton energy loss with the strong parton interaction which drives the equilibration and maintains a long lifetime of the initial parton system.

One definite conclusion one can draw from this analysis is that the hadronic matter in the later stage of heavy-ion collisions does not seem to cause parton energy loss or jet quenching at the CERN SPS. This will make jet quenching an even better probe of long-lived initial partonic matter since it will not be affected by the hadronic phase of the matter. Because of its long formation time ($\tau_f \sim 20$ fm$/c$ for a pion with $p_T \sim 3$ GeV$/c$), a high-p_T pion is formed only either after freeze-out or in a very dilute hadronic matter. Otherwise, inelastic scattering with other soft pions can also cause the suppression of high-p_T particle spectra or apparent jet quenching. What is traveling through the hadronic matter is thus a fragmenting parton whose interaction with a hadronic matter might be nonperturbative in nature. The PQCD estimate of parton energy loss is then not applicable here even though it might be adequate for a parton propagating in a hot QGP. The fact that a fragmenting parton does not lose much energy in hadronic matter might be related to the absence of parton energy loss to the quarks and antiquarks prior to DY hard processes in $p + A$ and $A + A$ collisions.

The initial energy density at BNL Relativistic Heavy-ion Collider (RHIC) is expected to be higher than at SPS. If one observes significant suppression of large-p_T hadrons at RHIC as was predicted [8–10], it clearly reveals an initial condition dramatically different from the CERN SPS.

The observed high-p_T pion spectra in central Pb + Pb collisions cannot be due to collective hydrodynamic flow, since there will always be high-p_T partons produced in the coronal region of the two overlapped nuclei where jet propagation and fragmentation will not be influenced by the dense matter. To verify that these spectra are from jet production and fragmentation rather than from hydrodynamic flow, one can measure the azimuthal particle correlation (selecting particles above a certain p_T) relative to a triggered high-p_T particle as was proposed in Ref. [30]. One should see a double-peak structure characteristic of a jet profile. One can use this method at even moderate p_T (where there are still not many particles per event) to determine the contribution from semihard processes and the p_T range for which use of a thermal fireball model is justified. Otherwise, the extracted temperature and radial flow velocity can be misleading.

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