Jet Quenching from soft QCD Scattering in the Quark-Gluon Plasma

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Abstract

We show that partons traversing a quark-gluon plasma can lose substantial amounts of energy also by scatterings, and not only through medium-induced radiation as mainly considered previously. Results from Monte Carlo simulations of soft interactions of partons, emerging from a hard scattering, through multiple elastic scatterings on gluons in an expanding relativistic plasma show a sizeable jet quenching which can account for a substantial part of the effect observed in RHIC data.

Key words: jet quenching, quark-gluon plasma, QCD, scattering

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Partons emerging from hard scattering processes and traversing a quark-gluon plasma (QGP) are expected to lose a substantial amount of their energy through interactions with the plasma, resulting in a suppression of high-$p_\perp$ particles [1,2]. Such jet quenching has indeed been observed at RHIC [3,4,5,6] and is believed to be not only a signal for QGP formation, but also a tool for investigating the properties of the plasma. So far theoretical efforts have concentrated on medium-induced gluon bremsstrahlung as energy loss mechanism [7,8,9,10,11,12] based on arguments that the collisional energy loss is small [13,14,15]. In this letter, however, we demonstrate that energy loss caused by multiple elastic scatterings is not negligible, but can contribute significantly to the observed jet quenching effect. The importance was also realized in [16,17] and scattering was included at the same level as radiation in [18].

Such multiple scatterings can be related to recent developments to understand soft QCD interactions of a high energy parton with a colour background field. This has, in particular, been used as a novel way to understand diffractive hard...
scattering in $ep$ or $p\bar{p}$ collisions [19]. In the Soft Colour Interaction (SCI) model [20,21] a hard-scattered parton interacts with the proton remnant via soft gluon exchanges. Here, it is the exchange of colour charge which is important, since this changes the colour topology of the event such that hadronisation will produce a different final state, e.g. diffractive ones with a gap in the rapidity distribution of hadrons. The phenomenological success of the SCI model indicates that it captures the most essential QCD dynamics for soft gluon exchanges. A theoretical basis for this model has recently been found [22] in terms of QCD rescatterings of an energetic parton with the target colour field via one or more gluons as expressed through the Wilson line in the parton density definition.

In this letter, we develop the SCI model to apply for a parton that rescatters in a quark-gluon plasma. The essential quantity for the energy loss through such elastic scattering is then the energy-momentum transfer involved, rather than the colour exchange. Since the QGP is much denser and of larger volume than the colour background field of a single proton, the parton should experience many more interactions so that even a small momentum transfer per scattering could add up and result in a sizeable energy loss.

The SCI jet quenching model [23] is implemented as a Monte Carlo event generator based on PYTHIA (version 6.2) [24] which is used to simulate hard scattering processes based on perturbative QCD $2 \rightarrow 2$ matrix elements and initial and final state parton showers based on DGLAP evolution. These perturbative QCD (pQCD) processes are not altered, but are used as in standard high-$p_T$ $pp$ collisions. However, before the emerging partons hadronise, we introduce the possibility that they may interact with the plasma.

This interaction of the hard parton with the plasma is treated as elastic scattering on the partons in the QGP, with a squared momentum transfer $t$. Although this is treated as a $2 \rightarrow 2$ parton-parton scattering (in the cm frame), we cannot use pQCD matrix elements since that would only apply for the small cross-section processes with large $t$. Instead we want to examine energy loss through the dominant soft interactions where perturbation theory does not apply. Being unable to calculate a proper $t$-distribution from first principles, we assume that it can be approximated by a Gaussian distribution having a width $\sigma_t$ as a parameter of the model. Naturally, the mean momentum transfer should not exceed a few hundred MeV in order to be non-perturbative.

The partons emerging from the hard pQCD phase are traced through the plasma and scatter, with a probability $P_{\text{int}}$, on each plasma gluon along their way within a screening radius $R_{\text{scr}}$. We use $P_{\text{int}} \simeq 0.5$ since this was found as a universal parameter value for the SCI model to fit rapidity gap data from both $ep$ and $p\bar{p}$ collisions [20,21], as well as charmonium formation [25,26].
The QGP is represented by an ideal relativistic gluon gas, while quarks are neglected because the QGP is initially gluon rich and the gluons come much faster into thermal equilibrium than the quarks. This means that the number and energy densities of gluons are connected to the temperature via 

\[ n_g = g_g T^3 \frac{2}{\pi^2} \zeta(3) \]  
and 

\[ \epsilon_g = \frac{\pi^2 g_g T^4}{30} \]
so that \( n_g \propto \epsilon_g^{3/4} \).

The time evolution is governed by a Bjorken-like longitudinal expansion \([27]\), i.e. with the equation of state of an ultra-relativistic ideal gas the time dependence of the energy density and temperature is given by 

\[ \epsilon(\tau) \propto \tau^{-4/3} \]  
and 

\[ T(\tau) \propto \tau^{-1/3} \]
where \( \tau = \sqrt{t^2 - z^2} \) is the proper time. Therefore, the density of gluons drops very fast, namely as \( n_g(\tau) \propto \tau^{-1} \). It is assumed that the local initial energy density is proportional to the number of binary nucleon-nucleon collisions at impact parameter \( b \), i.e.

\[ \epsilon(x, y, b) \propto T_{Au}(x-b/2, y) \cdot T_{Au}(x+b/2, y) \]
where the nuclear thickness function \( T_{Au} \) is estimated with a simple Glauber model \([28]\).

The parameter that governs the energy density of the plasma is \( \epsilon_0 \), the energy density in most central collisions (i.e. \( b = 0 \)) at \( \tau_0 = 1 \text{ fm/c} \) averaged over the transverse area. This fixes the normalisation of the density profile for any centrality.

The centrality of a nucleus-nucleus collision is defined by the fraction of the total geometrical cross section it takes. A centrality class, i.e. a range in centrality can be translated into an impact parameter range using the Glauber model calculation. In the simulation an impact parameter is chosen for each event in a given range of centrality according to 

\[ d\sigma \propto bdb \]
(ignoring the fluctuations in the experimental quantity used to determine the centrality).

The hard scatterings are treated as in \( pp \) collisions and are distributed in the transverse plane according to the number of binary nucleon-nucleon collisions per unit transverse area, which is obtained from the Glauber model calculation. As discussed above, the emerging hard partons from the pQCD processes are then tracked through the plasma. It is assumed that no interactions occur before the formation of the QGP at \( \tau_i \), but thereafter the local gluon density is updated in each time step taking the changes due to expansion and the energy density profile into account. The procedure is stopped when either the parton under consideration leaves the QGP or the local temperature drops below \( T_c \), the critical temperature of the phase transition.

Hadronisation of partons emerging from the plasma presents new interesting problems. The conventional models developed for \( e^+e^- \) annihilation and applied for \( ep \) and \( pp \), need not be applicable but there is little guidance yet how the presence of a quark-gluon plasma affects the fragmentation of energetic partons. It is also desirable to disentangle the effects of direct energy loss and modified hadronisation. Therefore, in a first step, the standard fragmentation
procedure is used in this model. However, while the standard Lund string fragmentation model [29] is the best option to use for the pp reference, it is not easily applied to the case of partons emerging from a plasma after several soft colour exchanges which have changed the colour topology. It is quite unclear where the string from such a parton should be connected and if the concept of the normal string applies at all. The pragmatic way out that we have taken in this first study is to instead apply independent hadronisation [30,31] for our simulations of AuAu collisions, but keeping the same basic fragmentation function \( f(z) \) for the energy-momentum fraction \( z \) given to the produced hadron in each iteration.

Finally, one also has to account for the Cronin effect, i.e. the \( p_{\perp} \) broadening of the final state hadrons due to conventional initial state scatterings. We have included this according to the model suggested in [32,33], i.e. the variance of the intrinsic \( k_{\perp} \)-distribution is increased by a constant \( \alpha \) for each scattering prior to the hard interaction, i.e. 
\[
\sigma_{k_{\perp}}^2(x, y, b) = \sigma_{k_{\perp}}^2 + \alpha \cdot (N_{\text{scat}}(x, y, b) - 1).
\]
In our model \( \sigma_{k_{\perp}} \) does not depend on the hard scattering momentum transfer scale \( Q^2 \) because parton showers are treated explicitly. The parameter \( \alpha \) was fixed independently with the help of dAu data at the same energy.

Table 1
Parameters of the model for the quark-gluon plasma (using input from hydrodynamics and lattice calculations) and the SCI jet quenching mechanism.

| Parameter                          | value    | obtained from                  |
|-----------------------------------|----------|--------------------------------|
| QGP formation time \( \tau_i \)  | 0.2 fm/c | based on saturation scale [35] |
| energy density at \( \tau_0 = 1 \text{ fm/c} \) \( \epsilon_0 \) | 5.5 GeV fm\(^{-3}\) | fixed from hydro [36]          |
| critical temperature \( T_c \)   | 0.175 GeV| fixed from lattice [34]        |
| gluon mass \( m_g \)             | 0.2 GeV  | chosen here                    |
| interaction probability \( P_{\text{int}} \) | 0.5 | fixed from SCI [20,21]          |
| screening radius \( R_{\text{scr}} \) | 0.3 fm  | cf. [37]                       |
| width of Gaussian \( t \) distr. | \( \sigma_t \) | 0.5 GeV\(^2\) | chosen here |
| increase of \( \sigma_{k_{\perp}}^2 \) per scattering \( \alpha \) | 1 GeV\(^2\) | fitted from dAu data          |

The parameters of the model are listed in Table 1. Not all of them are free, the critical temperature \( T_c \) is taken from lattice calculations [34]. The energy density has been determined with hydrodynamic calculations [36] and can vary only in a small range when considered at a fixed time \( \tau_0 = 1 \text{ fm/c} \). The formation time is chosen in accordance with saturation scale considerations [35]. Using the known time evolution the energy density at any time can be calculated, in particular at the time \( \tau_i \) when the QGP is formed. The soft interaction probability \( P_{\text{int}} \) is fixed from the SCI model. The gluons in the plasma have an effective mass, which is a free parameter. This mass has
important dynamical consequences for the energy loss, since a larger mass results in smaller energy loss. In fact, it was the assumption of static scattering centres, i.e. infinitely massive plasma partons, that gave vanishing energy loss through scattering so that only losses through the medium-induced radiation was treated in [2]. The width of the momentum transfer distribution $\sigma_t$ is free and may be regarded as the most important parameter because it regulates how much energy can be lost per collision.

The results are discussed in terms of the nuclear modification factor and the two-particle azimuthal correlation. The nuclear modification factor defined as

$$R_{AB}(p_\perp, \eta) = \left( \frac{1}{N_{\text{evt}}} \frac{d^2N_{\text{AB}}}{dp_\perp \, d\eta} \right) \cdot \left( \frac{\langle N_{\text{coll}} \rangle}{\sigma_{pp}^{\text{inel}}} \frac{d^2\sigma_{pp}}{dp_\perp \, d\eta} \right)^{-1}$$  \hspace{1cm} (1)

is a measure of deviations of the $p_\perp$-spectra obtained in nucleus-nucleus collisions from the $pp$ result scaled with the average number of binary collisions $\langle N_{\text{coll}} \rangle$. The two-particle azimuthal correlation

$$D(\Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{dN}{d(\Delta \phi)}$$

is the azimuthal separation from a trigger particle, normalised to the number of trigger particles in the data set. Here, both the trigger particle and the other particles are required to be in certain ranges of $p_\perp$.

The model results for the nuclear modification factor (above 3 GeV) are shown in Fig. 1 together with the PHENIX data [38] for different centrality classes. Also shown are the results for d+Au collisions that were used to determine the Cronin parameter $\alpha$. The resulting Cronin effect of a broadened intrinsic $k_\perp$-distribution is shown separately for the most central and the most peripheral AuAu collisions, demonstrating that it is bigger in central events where the number of collisions of a nucleon is larger for geometrical reasons.

The model reproduces the approximately flat shape of the $R_{\text{AuAu}}$ data. Although the model is in agreement with the data in peripheral collisions, it reaches only ~ 50% of the suppression for the most central collisions. The comparison of the SCI jet quenching model with the data in Figure 2 illustrates again that the model is in agreement with the data for peripheral and semiperipheral collisions but shows a weaker dependence on centrality when going to more central collisions. Nevertheless, even in the most central collisions, the model shows a strong jet quenching effect which should be taken relative to the increase in $R_{\text{AuAu}}$ due to the Cronin effect. It should be noted in this context that interactions with the hadronic final state can also result in a significant suppression of high-$p_\perp$ hadrons [39] and this effect would have to be added to any QGP suppression.
Fig. 1. Nuclear modification factor, eq. (1), for different centrality classes (0–10% represents the most central and 80–92% the most peripheral collisions) of gold-gold (and minimum bias deuterium-gold in lower right panel). PHENIX data [38] compared to the SCI jet quenching model (starting at $p_\perp = 3$ GeV due to the cut-off used on PYTHIA’s hard scattering matrix elements). The result from initial state scattering, but no interactions with the plasma, is shown by the curves 'Cronin effect only'.

In order to reproduce the data in central collisions with the SCI jet quenching model alone one would have to roughly double the overall energy loss. There are several ways how this can be achieved: One could for instance increase the number of scatterings by increasing the screening radius from 0.3 fm to 0.5 fm, or one could double the momentum transfer by increasing $\sigma_t$ from 0.5 GeV$^2$ to 2 GeV$^2$. While with the latter we think we are leaving the reasonable scale for soft interactions one could consider the former, which effectively increases the in-medium parton-parton cross section from 3 to 8 mb$^1$. It is not sufficient to increase the number of scatterings by a factor 2 because the energy loss

$^1$ In a recent study the parton-parton cross section had to be increased to 45 mb to describe elliptic flow data in a parton-cascade [40]
in a single scattering decreases with decreasing parton energy so that the parton loses less energy in the additional scatterings when its energy is already reduced. With either of these two parameter variations the SCI jet quenching model agrees with the data for the most central collisions, but the centrality dependence is not linear so that the calculation falls below the data in semi-central and, to a lesser degree, peripheral events (Fig. 2).

The centrality dependence is sensitive to the energy and path length dependence of the energy loss mechanisms and can be used to discriminate between different types of model as investigated in [41]. In particular, models in which the energy loss is based on coherent processes and grows with the path length squared, seem to describe the linear centrality dependence better. However, also the energy dependence is relevant for the dependence of $R_{AuAu}$ on centrality. In the SCI jet quenching model, using our default parameters, the energy loss in a single scattering is negligible for small parton energies ($\lesssim 1$ GeV depending on the plasma temperature), then it rises steeply and flattens at high energies reaching roughly 400 MeV at 20 GeV in the case of light quarks.

![Graph showing the nuclear modification factor $R_{AuAu}$ versus centrality for AuAu data [38] and for the SCI jet quenching model, with default parameters and with the screening radius $R_{scr}$ increased from 0.3 to 0.5 fm. The quenching effect should not be considered relative to $R_{AuAu} = 1$ (dotted line) corresponding to no nuclear effects, but relative to the upper curve including the Cronin effect.](image)

The resulting azimuthal correlation, Fig. 3, show that in peripheral collisions there is a clear jet-like peak at $\Delta \phi = 0$ and a somewhat lower and broader one at $\Delta \phi = \pi$, much like in $pp$ interactions. In central collisions, however, there is a clearly suppressed away side jet, although the peak does not disappear as in the data [42,43]. To understand the quenching of the away side jet is a general problem and we are not aware of any successful model. Therefore, we discuss it here in more general terms.

The amount of energy that a parton loses through the interactions with the QGP is determined by the number of interactions and the energy loss in a single scattering. The latter is dominated by the width of the $t$-distribution, but depends also on the gluon mass and the temperature. A higher gluon
mass or a higher temperature lead to a smaller energy loss (the energy of the
 gluons in the QGP is proportional to $T$ and, due to kinematics, the energy
 loss is largest when the gluon has a small energy). While the QGP expands
 the temperature drops according to $T \propto \tau^{-1/3}$ and the energy loss mechanism
 becomes more efficient at later stages, but the density of gluons in the plasma
 drops much faster, namely $n \propto \tau^{-1}$ so that the dilution exceeds the effect of
 cooling. Furthermore the amount of energy lost by a parton depends much
 stronger on the gluon density than on the temperature. Consequently, the
 energy loss at early times dominates the total energy loss.

Related to this is our finding that the largest energy loss is obtained when
the hard scattering takes place in the centre of the overlap region. This is
illustrated in Figure 4 which shows the energy loss of light quarks in a central
collision for different emission points. When moving the hard emission point
from the centre towards the surface the energy loss gets smaller because even
those quarks that move towards the centre ($\phi = \pi$) cannot have a longer
effective path length (i.e. gluon density integrated along the path) in the plasma
than those coming from the centre due to the expansion of the plasma. By
the time a quark coming from a distance ($r$) reaches the centre, the density
has already dropped and, moreover, for part of the quark’s path-length there
will even be no plasma to interact with due to the plasma’s limited life time
of only $5.2 \text{ fm}/c$ compared to the $\sim 14 \text{ fm}$ diameter of the gold nucleus.

Another point is that the locations of the hard interactions are, in fact,
concentrated towards the centre of the QGP where the number of binary nucleon-
nucleon collisions per unit transverse area is highest. The path lengths of the
two hard-scattered partons are thus typically similar which makes it unlikely
that one of them loses much more energy than the other (which is needed for
the disappearance of one jet). Again, the limited plasma life time (in rela-
tion to the gold nucleus size) prevents large asymmetries in the path lengths through the plasma (the path length difference cannot become larger than the plasma lifetime).

These three points prevent large asymmetries and may explain why it is so difficult to get a substantial suppression (or disappearance) of the away-side jet. On the other hand, the inhomogeneous energy density distribution can help to amplify small asymmetries. Furthermore the hard interaction is at RHIC energies dominated by $q + g \rightarrow q + g$ scatterings, which should also help because the gluon interacts more strongly than the quark and should thus lose more energy. These effects are included in our simulations, but are not strong enough to create a large enough asymmetry with associated strong quenching of the away side jet.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{energy_loss.png}
\caption{Energy loss $\Delta E$ of light quarks emerging from a hard scattering with 5 GeV energy at different distances $r$ from the centre in central AuAu collisions ($b = 0$) with azimuthal angle $\phi$ (as illustrated to the right). Quarks emitted at large $r$ with $\phi \rightarrow \pi$ have a long path through the collision region, but by the time they reach the centre (where the QGP is densest) the density has already dropped to very low values due to the expansion or the QGP has even already hadronised.}
\end{figure}

It should be noted that this discussion is not only valid for this particular model, but is of a more general nature since the arguments are independent of the details of the interaction mechanism. It should thus apply to all scenarios in which the energy loss depends strongly on the density of scattering centres, which is also the case for medium-induced gluon radiation.

In fact, it seems that the two-particle azimuthal correlation is sensitive to details of the fragmentation procedure and is therefore afflicted with an additional uncertainty. Already Lund string fragmentation and independent fragmentation with the same fragmentation function lead to quite different associated multiplicities. A softer fragmentation function produces more hadrons but with lower momentum and since the parton $p_\perp$ spectrum is steeply falling already small changes in the fragmentation function might cause that the hadrons fall below the $p_\perp$ threshold of 2 GeV used for the azimuthal correlations.
In conclusion, energy loss due to soft scattering of energetic partons in the QGP can contribute significantly to the jet quenching observed at RHIC. The SCI jet quenching model gives a nuclear modification factor having the correct $p_{\perp}$ dependence and a magnitude which can account for most of the effect observed in peripheral collisions and about half the effect in central collisions. There is also a suppression of the away-side jet, although not as strong as in data. This depends on the distribution of hard scattering events and initial energy density as well as the plasma evolution, which are not specific to our particular model. This may give handles for further investigations of the quark-gluon plasma. The centrality dependence of the observed jet quenching may indicate the need for taking into account the coherence between individual scatterings in the plasma. For an improved understanding of the jet quenching phenomenon, one needs to take into account both energy loss through medium-induced radiation and through scattering.

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