Heavy quark jet quenching with collisional plus radiative energy loss and path length fluctuations

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Abstract

With the QGP opacity computed perturbatively and with the global entropy constraints imposed by the observed $dN_{\text{ch}}/dy \approx 1000$, radiative energy loss alone cannot account for the observed suppression of single non-photonic electrons. We show that collisional energy loss, which previously has been neglected, is comparable to radiative loss for both light and heavy jets and may in fact be the dominant mechanism for bottom quarks. Predictions taking into account both radiative and collisional losses significantly reduce the discrepancy with data. In addition to elastic energy loss, it is critical to include jet path length fluctuations to account for the observed pion suppression.

Key words: 

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Heavy Ion Collider (RHIC) has been remarkably consistent thus far with predictions. However, recent non-photonic single electron data [2,3], which present an indirect probe of heavy quark energy loss, have significantly challenged the underlying assumptions of the jet tomography theory. A much larger suppression of electrons than predicted was observed in the $p_T \sim 4 - 8$ GeV region (see Fig. 2). These data falsify the assumption that heavy quark quenching is dominated by radiative energy loss when the bulk QCD matter parton density is constrained by the observed $dN_{ch}/dy \approx 1000$ of produced hadrons.

This discrepancy between radiative energy loss predictions and current data and recent papers motivated us to revisit the assumption that pQCD elastic energy loss is negligible compared to radiative energy loss. In some earlier studies, the elastic energy loss was found to be $dE_{el}/dx \sim 0.3 - 0.5$ GeV/fm, which was erroneously considered to be small compared to the several GeV/fm expected from radiative energy loss. In Fig. 1 we see that above $E > 10$ GeV the light and charm quarks have elastic energy losses smaller but of the same order of magnitude as the inelastic losses. Due to the large mass effect, both radiative and elastic energy losses remain significantly smaller for bottom quarks than for light quark and charm jets, but the elastic loss can now be greater than inelastic up to $\sim 15$ GeV. The uncertainties from the Coulomb log, as illustrated by the difference between the TG and BT lines [4,5], are largest for the heaviest b quark: as they are not ultrarelativistic, the leading log approximation breaks down in the jet energy range accessible at RHIC.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{Average $\Delta E/E$ for $u, c, b$ quarks as a function of $E$ in a Bjorken expanding QGP. Radiative DGLV first order energy loss is compared to elastic parton energy loss in TG or BT approximations.}
\end{figure}

2 RHIC predictions and uncertainties

We present a calculation of jet suppression using the model explained in [6]. We assume initial $dN_g/dy = 1000$ and a fixed coupling, $\alpha_s = 0.3$. The main difference from the previous calculation [7] is the inclusion of two new physics
components in the energy loss probability $P(E_i \rightarrow E_f)$. First, $P(E_i \rightarrow E_f)$ is generalized to include both elastic and inelastic energy loss and their fluctuations. The second major change is that we now take into account geometric path length fluctuations. The geometric path averaging used here is similar to that used elsewhere, but the inclusion of elastic energy loss together with path fluctuations in more realistic geometries was not considered.

The results for the suppression of non-photonic single electrons are shown in the upper plot in Fig. 2. As emphasized in [7], any proposed energy loss mechanisms must also be checked for consistency with the extensive pion quenching data [1], for which preliminary data now extend out to $p_T \sim 20$ GeV. This is also shown in Fig. 2.

![Graph showing suppression factor $R_{AA}(p_T)$ for non-photonic electrons and pions.](image)

**Fig. 2.** The suppression factor, $R_{AA}(p_T)$, of non-photonic electrons (left) and pions (right) in central Au+Au reactions at 200 AGeV are compared to data. For electrons, the upper yellow band [7] takes into account radiative energy loss only, using a fixed $L = 6$ fm; the lower yellow band is the new prediction. The dashed curves illustrate the lower extreme of the uncertainty from production, by showing the radiative plus elastic prediction with bottom quark jets neglected.

It is important to examine the theoretical uncertainties involved in these predictions. Uncertainty in the leading log approximation has already been shown and two other sources are illustrated in Fig. 3. The radiative and elastic energy losses are strongly dependent on the coupling. To estimate the uncertainty involved from this approximation, the results of varying $\alpha_s$ are shown. While increasing fixed $\alpha_s$ to 0.4 improves the fit to the electron data, this then over-predicts the pion quenching.

![Graph showing variation in $R_{AA}(p_T)$ with $\alpha_s$.](image)

The ratio $R_{AA}$ is not sensitive to the scaling of all cross-sections by a constant. However, the electron $R_{AA}$ is sensitive to any uncertainty in the relative contribution of charm and bottom jets [8]. The result of changing the charm to bottom production ratio by a constant is shown, as well as the lower bound extreme of electrons from charm jet only.
Fig. 3. The variation in $R_{AA}(p_T)$ predictions is shown for change in the fixed coupling $\alpha_s$ and for variation in the charm to bottom ratio in the production spectra.

3 Conclusion

The elastic component of the energy loss cannot be neglected when considering pQCD jet quenching. While the results are encouraging, further improvements will be required before stronger conclusions can be drawn. It will be important to deconvolute the charm and bottom contribution to the electrons, so direct measurement of $D$ spectra will be essential. On the theoretical side, further work on the deconvolution of coherence and finite time effects as well as implementing a running coupling will significantly reduce the theoretical uncertainties in the predictions.

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