Jet Quenching: the medium modification of the single and double fragmentation functions

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Abstract. The physics of the quenching of hard jets in dense matter is briefly reviewed. This is presented within the framework of the partonic medium modification of the fragmentation functions. Modifi cations in both deeply inelastic scattering (DIS) and heavy-ion collisions are presented.

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The quenching of jets and the medium modification of jet structure has emerged as a new diagnostic tool for the study of the partonic properties of dense matter [1]. The modification includes, not only a suppression of inclusive spectra of leading hadrons commonly referred to as jet quenching, but can be extended to include the medium modification of any particle observables. The simplest of these are the two-hadron correlations within the jet cone. Such one and two particle observables have been measured both in DIS [2] and high-energy heavy-ion collisions [3,4].

The single particle inclusive spectrum in DIS on a nucleus versus that in a nucleon (or deuterium) target demonstrates an increasing suppression as the momentum fraction z of the detected hadron with respect to the initial partonic energy is increased. This suppression at a given z has also been found to increase quadratically with the size of the nuclear target. For the two hadron correlation, a conditional ratio is measured: the distribution of associated hadrons given that there already exists a trigger hadron. This is measured in the case of a large nucleus and then divided by the same ratio in deuterium. The two-hadron correlation is, however, found to be very slightly suppressed, and almost independent of the nuclear size [4].

In high energy Au + Au collisions, the single inclusive spectra are suppressed compared to that in p + p collisions. What is presented is the differential cross section in Au + Au collisions divided by the binary scaled differential cross section in p + p collisions. This ratio is denoted as $R_{AA}$. Beyond a transverse momentum $p_T$ of 3 GeV for 0's and 6 GeV for charged hadrons, this suppression is almost a constant, independent of $p_T$ (at a $P_T = 200$ GeV). The suppression is seen to increase with centrality with $R_{AA}$ assuming a value of barely one for the most central events. In sharp contrast to this, the near side two particle correlation is moderately enhanced in central Au + Au collisions relative to that in p + p [5,4].

Theoretically, n-particle observables (where n > 1) in jet fragmentation and their medium modification can be studied through n-hadron fragmentation functions which can be deduced as the expectation values of partonic field operators on n-hadron states. These n-hadron fragmentation functions are non-perturbative and involve long distance processes. However, they may be factorized from the hard perturbative
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processes and their evolution with momentum scale may be systematically studied in perturbative Quantum Chromo-Dynamics (pQCD) \cite{3}. Such an evolution is very similar to the well-known case of $n = 1$ hadron fragmentation functions \cite{4}.

In these proceedings, the medium modification of fragmentation functions in DIS on nuclei will be sketched within the framework of generalized factorization and twist expansion \cite{13}. The results are then extended to the case of parton propagation in heavy-ion collisions. Alternative methods for calculating the single inclusive distributions in heavy-ion collisions, based on a screened potential scattering model, have been investigated by many authors \cite{5,6,7,8,9,10}. The advantage of the twist form alone \cite{10} lies not merely in the ease of its applicability to DIS and heavy-ion collisions, but also in the presence of a single unknown normalization constant. This is set by fitting one experimental data point at one set of kinematic variables. With this parameter determined, one may predict the variation of the medium single hadron fragmentation functions \cite{7,11}, as well as the medium modification of two-hadron correlations. Such behavior in both DIS on nuclei and heavy-ion collisions are presented in comparison with experimental data.

Applying factorization to hadron production in single jet events in DIS on a nucleus, $e(L_1) + A(p) \rightarrow e(L_2) + h_1(p_h) + \ldots + X$, one can obtain the $n$-hadron semi-inclusive cross section as,

$$E_{L_2} \frac{d^2P_1}{d^2L_2 dz_1 \ldots} = \frac{1}{2} \sum_{Q^2} \frac{dW}{dz_1 \ldots},$$

where the ellipsis indicates the possible presence of more than one detected hadron. The semi-inclusive tensor at leading twist has the simple form,

$$\frac{dW}{dz_1 \ldots} = X \sum_{Q^2} x_1 f_1^A(x_1 Q^2) H(x;p;q) D_{h_1;\ldots}(z_1;\ldots;Q^2):$$

In the above, $D_{h_1;\ldots}(z_1;\ldots)$ is the $n$-hadron fragmentation function, $L$ is the leptonically factor $H$ represents the hard part of quark scattering with a virtual photon which carries a four-momentum $q = (Q^2 = 2q \cdot p; 0_0)$ and $f_1^A(x;Q^2)$ is the quark distribution in the nucleus which has a total four-momentum $A(p;0_0)$. The hadron momentum fractions, $z_0 = p_{h_1} = q$ are defined with respect to the initial four-momentum $q$ of the fragmenting quark.

At next-to-leading twist, the dihadron semi-inclusive tensor receives contributions from multiple scattering of the struck quark or soft gluons inside the nucleus with induced gluon radiation. One can recognize the total contribution (leading and next-to-leading twist) into a product of the effective quark distribution in a nucleus, the hard part of photon-quark scattering $H$ and a modified $n$-hadron fragmentation function $D_{h_1;\ldots}(z_1;\ldots)$. The calculation of the modified dihadron fragmentation function at next-to-leading twist in a nucleus \cite{12} proceeds in similar fashion to that for the medium modification of single hadron fragmentation functions \cite{13}. The results of the medium modification of the single hadron fragmentation functions are shown in the left plot of Fig. 1 in comparison with experimental data. The experimental points at the lowest $z$ in nitrogen is used to test the overall normalization constant. The variation with $z$ and with nuclear size is a prediction of the calculation and shows excellent agreement with the experimental results.

With no additional parameters, one can predict the nuclear modification of dihadron fragmentation functions within the same kinematics. This is shown in the right hand plot of Fig. 1, where results are presented for DIS on nitrogen.
In high-energy heavy-ion (or p+p and p+A) collisions, jets are always produced in back-to-back pairs. Correlations of two high-p_T hadrons in azimuth angle generally have two Gaussian peaks [3,4]. Relative to the triggered hadron, away-side hadrons come from the fragmentation of the away-side jet and are related to single hadron fragmentation functions. On the other hand, near-side hadrons come from the fragmentation of the same jet as the triggered hadron and therefore the integral of the near side Gaussian peaks are related to dihadron fragmentation functions.

To extend the study of the medium modification of the fragmentation functions to heavy-ion collisions, one also has to include the effect of the medium jet energy dependence of the energy loss will be different from the DIS case. Such a procedure, applied to the study of the medium modification of the single hadron fragmentation functions successfully describes the quenching of single inclusive hadron spectra, their azimuthal anisotropy and the suppression of the away-side high p_T hadron correlations [4]. The result for the suppression of the single inclusive spectra as a function of the centrality of the collision is shown in the left side plot in Fig. 1. The ratio $R_{AA}$ for $^0$Au (PHENIX [3]) and charged hadrons (STAR [4]) is plotted. The overall normalization constant is fixed at a given value of $p_T$ for the most central event. The variation of the suppression with $p_T$ and centrality is a prediction and shows very good agreement with the data. The overall gluon density is assumed to vary with centrality as the number of participants. Due to space constraints, we will skip the discussion of the suppression of the away-side spectra and baryon meson differences. We refer the reader instead to Ref. [4] for this and further details regarding the glue.

The change of the near-side correlation due to the medium modification of dihadron fragmentation functions in heavy-ion collisions can be similarly calculated. For a given value of $p_T^{\text{trig}}$ of the triggered hadron, one can calculate the average total jet energy $H_T$ in a jet. Because of trigger bias and parton energy loss, $H_T$ in heavy-ion collisions is generally larger than that in p+p collisions for a fixed $p_T^{\text{trig}}$ [4].

Using the overall parameter, determine in the single inclusive measurement, one
calculates the modified dihadron distributions. The ratio of such associated hadron distributions in Au + Au versus p + p collisions, referred to as $I_A$, is plotted as the solid line in the right hand plot of Fig. 2 together with the STAR data as a function of the number of participant nucleons. We also present data from PHENIX which accounts for correlations at a lower $p_T$. In central Au + Au collisions, triggering on a high $p_T$ hadron biases toward a larger initial jet energy and therefore smaller $z_1$ and $z_2$. This leads to an enhancement in $I_A$ due to the shape of dihadron fragmentation functions. The enhancement increases with $N_{part}$ because of increased total energy loss. In the most peripheral collisions, the effect of smaller energy loss is counteracted by the Cronin effect due to initial-state multiple scattering that biases toward a smaller $p_T$ relative to p + p collisions. As a result, the associated hadron distribution is slightly suppressed. For higher $p_T$, the suppression will diminish because of the disappearance of the Cronin effect. (See Refs. [2] for further discussions.}

![Figure 2. Calculated medium modification of single (left plot, from Ref. [3]) and associated (right plot, from Ref. [3]) hadron distribution from jet fragmentation in Au + Au collisions at $\sqrt{s} = 200$ GeV. The left plot shows a variation of $R_{AA}$ vs. $p_T$ for different centralities. The right plot shows a variation of $I_A$ vs. centrality for dijet trigger and associated $p_T$ as compared to experimental data [3,4].]

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