Hadronization in Nuclear Matter

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Abstract

Nuclei are unique analyzers of the space-time development of jets at early stage. We argue that the gluon bremsstrahlung, rather than the color string, is the main mechanism of hadronization of highly virtual quarks produced in a hard interaction. It results in an energy- and time-independent density of energy loss, like a color string, but steeply dependent on the quark virtuality. Effects of formation zone (FZ) and color transparency (CT) substantially affect the jet quenching in a nuclear matter. The latter also plays an important role in the broadening of transverse momentum distribution of a quark passing a nucleus. Parameter-free calculations provide a good description of available data on nuclear effects in the leading hadron production in deep-inelastic lepton scattering, back-to-back high-$p_T$ hadron pair production, broadening of the transverse momentum distribution in the Drell-Yan process of lepton pair production on nuclei.

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1 Introduction

Hadronization of highly virtual quarks is studied in $e^+e^-$ annihilation, deep-inelastic lepton scattering, high-$p_T$ jet production in hadronic interaction. Assuming factorization one can describe the hadronization stage phenomenologically by a fragmentation function $D(x, p_T)$ of a quark, which is a distribution of produced hadrons over share of the quark momentum, $x$, and transverse momentum, $p_T$.

1.1 Why nuclear target?

A quark knocked out of a parent hadron in a hard scattering, converts into colorless hadrons in a while due to the phenomenon of confinement. The Lorentz time delay considerably stretches the duration of this process, proportionally to the initial quark momentum. Hadrons created in the final state carry poor information about dynamics of hadronization. Most important details are hidden at its early stage. A nuclear target provides a unique opportunity to look inside the process at microscopic times after it starts. The quark-gluon system, originated from a quark knocked out in a hard collision, interacts while passing a nucleus. This can bring forth precious information about the structure of this system and its space-time development. On the other hand, the hadronization could be a sensitive probe of the state of the nuclear matter.

1.2 What energies?

The fundamental principle closely related to hadronization is the Landau-Pomeranchuk phenomenon [1]: multiple interaction of a projectile particle does not affect the emission of long-waved photons (gluons). In other words, a nucleus does not disturb a spectrum of gluons, which have time of emission much longer than the nuclear radius.

$$ t \approx \frac{\omega}{k_T^2} \gg R_A, \quad (1) $$

Here $\omega$ and $k_T$ are the energy and transverse momentum of a gluon. Note that it concerns only hard reactions, in soft interactions a nuclear target affects the particle production due to so called nonplanar diagrams [2].

It follows from (1) that in order to study the nuclear effects in hadronization one does not need superhigh energies, it is sufficient to have

$$ E \leq k_T^2 R_A, \quad (2) $$

what is 50 – 100 $GeV$ if $k_T^2 \approx 1 GeV^2$.

1.3 What reactions?

Probably the most direct way to study the nuclear effects in hadronization has a process of jet production in deep-inelastic lepton scattering on a nucleus. Measurement of lepton momenta provides information about virtuality and energy of a quark initiated the jet.

High-$p_T$ hadron production in hadron-nucleus and nuclei collisions provides additional information about the nuclear modification of structure function of an incoming hadron. Multiple interactions are essential in the inclusive hadron production with high $p_T$.

An effective way to suppress multiple rescattering effects is the study of production of symmetric hadron pairs with high $p_T$ on nuclei.

Multiple interaction of a quark propagating through nuclear matter leads to the increase of its transverse momentum. An undisturbed information about it brings forth the study of the nuclear broadening of transverse-momentum distribution of Drell-Yan lepton pairs.
Nuclear shadowing and the broadening of transverse momenta of heavy quarkonia also can provide a precious information about hadronization in a nuclear matted.

1.4 What are the observables of hadronization?

Usually experimental data are represented in the form of ratio of nucleus to nucleon cross sections,

\[ R_A = \frac{\sigma^A(x, \mathcal{p}_T)}{A \sigma^N(x, \mathcal{p}_T)}, \]

where \( x \) is the Feynman variable relative the initial quark momentum in the case of DIS, or incoming hadron. This simple quantity, \( R_A \), nevertheless contains rich information about dynamics of hadronization.

2 Gluon bremsstrahlung versus string model

2.1 Energy loss in a nuclear matter

Hard gluon bremsstrahlung. The hard reaction with a large square of momentum transfer \( Q^2 \) cannot resolve the quark structure at small impact parameters, \( b^2 < Q^2 \), and knocks out the quark together with a hard transverse components of its color field, \( k^2_T > Q^2 \). However the softer part of the quark color field, at impact parameters \( b^2 > Q^2 \) is "shaken off" in the form of gluon bremsstrahlung. This qualitative consideration demonstrates that there should be a steep \( Q^2 \)-dependence of the retarding force due to the hard gluon bremsstrahlung. It was demonstrated in \[3, 4, 5, 6\], that the bremsstrahlung like a string produces a constant density of energy loss

\[ \kappa_{br} = -\frac{dE}{dz} = \frac{2}{3\pi} \alpha_s(Q^2(t)) \frac{Q^2(t)}{z} \]  

Note that the time-independent energy loss (4) is the result of the high-energy approximation. Corrections important at moderate energies were introduced in \[5, 6\].

String model. It is assumed that even a highly virtual quark, knocked out in a hard process forms a stationary color tube \[7, 8, 10, 11, 12\]. Properties of a string stretched between a \( q \) and \( \bar{q} \) (diquark), flying apart, are the same as for the static system. This assumption fixes the density of energy loss, \( dE_q/dz = -\kappa \approx 1 GeV/fm \). It is assumed to be independent on the quark virtuality, \( Q^2 \).

It is difficult to justify these assumptions and the ignorance of the gluon bremsstrahlung, especially at high \( Q^2 \).

2.2 Formation zone of leading hadron production

During hadronization a quark loses energy for hadron production, until its color is neutralized. The produced colorless wave packet develops a hadron wave function after a while. We call hereafter the time of color screening, the formation zone (FZ). It plays an important role in nuclear attenuation of leading hadron. Indeed, an inelastic interaction of the produced colorless wave packet induces new energy loss and a strong attenuation, rather than reinteraction of the quark before the color neutralization \[13\].

The crucial point is the behavior of the FZ, \( l_f \), at \( x \to 1 \). Energy conservation imposes the restriction,

\[ l_f \leq \frac{\nu}{\kappa} (1 - x) \]  

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Indeed, the quark radiates hadrons and loses the energy during FZ, hence at $x_F \to 1$ it has to convert into a colorless state shortly. This restriction was found in [14, 8] and confirmed in [15] using Monte-Carlo simulation of the string decay.

Expression (5) has general character. The models under discussion, differ only in a value of energy loss density, $\kappa$. Since the energy loss of a highly virtual quark may be much higher than $1 \text{GeV/fm}$, due to the gluon bremsstrahlung, FZ is substantially shorter than is expected in the string model.

2.3 Attenuation of a quark in nuclear matter

A high-energy quark cannot be absorbed, because soft color-exchange rescatterings provide no longitudinal momentum transfer. However each color-exchange scattering of the quark initiates an additional production of low-energy particles, what leads to an increase of the energy loss, i.e. attenuation. It was found in [13] that due to this effect a nuclear matter only slightly modifies the quark fragmentation function at high energy and long FZ, $l_f \gg R_A$, but produces a dramatic effect at intermediate energies.

2.4 Nuclear attenuation of a colorless wave packet

At this point two models under consideration differ crucially. The colorless wave packet attenuates with an inelastic cross sections, which depends on its transverse size due to color transparency (CT) [16]. At $x \to 1$, a quark of virtuality $Q^2$, produces according to (5), a colorless wave packet instantaneously. So it has a small transverse size, about $1/Q^2$, and does not attenuate. In the case of a finite FZ the quark gradually looses its virtuality, and produces a wave packet of virtuality 

$$Q^2(l_f) = \frac{Q^2 \kappa}{\kappa + Q^2(1-x)}$$

It follows from (4) and (6) that the initial size of the colorless wave packet depends mainly on $x_F$.

To the contrary, in the naive version of string model considered here, the CT effects are neglected, and it is assumed that the produced colorless wave packet attenuates with the hadronic cross section, independently on $Q^2$ [11, 12]. Note that in more realistic version of string model the transverse size of the produced state is also small at $x \to 1$, similar to (6), because the distance between the leading quark and the kink, produced in the color field of the target vanishes proportionally to $(1-x)$ (X.Artru, private communication)

3 Deep-inelastic scattering

In this case the ratio $R_A$, (3), is simply the ratio of the quark fragmentation function in nucleus to the one in vacuum. Some corrections come from the modification of the structure function of bound nucleon (EMC-effect). We compare in fig. 1a the parameter-free calculations [5, 6] of energy-dependence of $R_{Cu}$ with the data [17, 18] averaged over interval $x > 0.2$. $x$-dependence is presented in fig. 1b, as compared with high energy data [17]. Note that the naive version of string model [11, 12], predicts a strong decrease of $R_A$ towards $x = 1$, in the region which is not covered by the available data. The $Q^2$-dependence of $R_A$ is compared with data [17] in fig. 1c. Curves calculated with zero FZ, or neglecting CT, demonstrate the relative role of these phenomena. One can see that CT is more important for the observed suppression of nuclear shadowing. Actually, the $Q^2$-dependence is flat, just due to CT. The decrease of $R_A$ at $Q^2 > 40 \text{GeV}^2$ comes from the EMC effect in the nuclear structure function.
4 High-$p_T$ hadron production

High-$p_T$ probe of quark-gluon plasma. I was argued in [19] that energy loss of a quark propagating through a nuclear matter is sensitive to the temperature of the medium. At high temperature a quark-gluon plasma may be formed and integration over $k_T$ of gluon bremsstrahlung is cut by the reversed Debye screening radius, $\mu$. In this additional energy loss induced by the medium, $\Delta \kappa \propto \mu^2$ is sensitive to the temperature. However in inclusive production of particles with high $p_T$ the quark multiple rescattering corrections are out of a control. They are just the reason of the “Cronin effect”, nuclear antishadowing at high $p_T$. So the large momentum transfer, $p_T \gg \mu$, is shared between all rescattering and the sensitivity to the value of $\mu$ vanishes.

Symmetric pair production. As was mentioned, symmetric production of particles with high $p_T$ on nuclei allows to suppress the influence of multiple rescatterings. However no sensitivity to the Debye screening appears in this case. The integration over $k_T$ is restricted in this case by an acceptance of a spectrometer, which defines the nuclear quenching of the symmetric jets.

It is argued in [8, 9] that at moderate values of $p_T < 1 - 2$ GeV the main contribution to back-to-back particle production comes from an uncorrelated production of two particles, in symmetric configuration. This follows from $p_T$-dependences of the correlation function and the slope. Using data on $A$-dependence of inclusive production of hadron with high $p_T$, one can calculate this uncorrelated contribution to the cross section of pair production without free parameters. The results are presented in fig. 2 for the exponent of $A^{a_2}$-dependence of the cross section (a-c) and the ratio $R_{W/Be}$. This contribution is responsible for the bumps observed at moderate values of $p_T$. The data [21, 22, 23, 24, 25, 26] confirm the existence of this contribution at all available energies. The contribution of the hard, back-to-back scattering is shown in fig.2a by the dashed curve [20]. It is a parameter-free calculation, analogous to the previous case of DIS. The main difference is a smearing of the initial quark momenta, weighted with the hadron structure functions. Another distinction is energy loss of the projectile quark participating in the hard scattering in the initial state. It is reduced to the nuclear modification of the projectile hadron structure function, and also induces an attenuation.

5 Nuclear broadening of the transverse-momentum distribution

A quark propagating through a nuclear matter increases its transverse momentum due to the multiple rescattering on bound nucleons. An important phenomenon affecting this process is CT. Due to confinement the color of a quark is always compensated by the colors of other accompanying partons. While this fact is unimportant at high momentum transfers, it is crucial for soft processes. It cuts off all soft gluons whose wavelength is longer than the color screening-radius [27]. The remarkable conclusion of [27] is the universality of the broadening of $< p_T^2 >$ which is independent on the radius of color screening, $r$. It is the direct consequence of the color screening: the smaller is $r$ the rarer are the quark rescatterings, but the larger is $\Delta < p_T^2 >$ in each interaction.

Drell-Yan process. The momentum distribution of a quark after the multiple interaction with the target nucleons can be measured in a Drell-Yan process of lepton-antilepton pair production. Since the lepton pair does not interact on its way out of the nucleus, it carries the undistorted information about the interactions of the quark. The experiment NA10 [28] has measured a value $\Delta < p_T^2 >_{DY}^{\pi^0} = 0.15 \pm 0.03$stat $\pm 0.03$syst (GeV/c)$^2$ for incoming pions at 140 and 286 GeV, while the experiment E772 with 800 GeV protons [29] reports a value $\Delta < p_T^2 >_{DY}^{\pi^0} = 0.113 \pm 0.016$ (GeV/c)$^2$. The two values coincide within the error bars which implies that indeed no dependence on the type of incident hadron and its energy is visible. The parameter-free calculation gives, $\Delta < p_T^2 >_{DY}^{\pi^0} = 0.17$(GeV/c)$^2$ in fair agreement with the data.
The results of calculations \[27\] of the normalized ratio of differential cross sections of the Drell-Yan process on nucleus to nucleon targets, \(R(A/N)\), are compared with experimental data \[28, 30\] on fig. 3. One can see that this parameter-free calculation also provides a good description of the experimental data.

**Deep-inelastic scattering.** The broadening of the transverse momenta of produced hadrons, \(\Delta <p_T^2>\), is smaller by factor of \(x^2\) than that of the quark. The latter is expected to be the same at high FZ as in the Drell-Yan process. No broadening was observed in \[31\] at high energies. It obviously is connected with a small value of \(<x^2>\approx 0.075\) in this data. So we expect the usual ”sea-gull” behavior of \(x\)-dependence of \(\Delta <p_T^2(x)>_h\) at high energies, with the same \(\Delta <p_T^2>_q\) as in Drell-Yan process. According to results of \[27\] no \(Q^2\)-dependence of \(\Delta <p_T^2(x)>_h\) is expected, except \(x \rightarrow 1\), where FZ is small, and decreasing \(Q^2\)-dependence is predicted \[6\].

6 Conclusions

Existing theoretical approaches to the hadronization dynamics and its modification in a nuclear matter, though being quite rough, provide a good description of available experimental data with a small number of parameters, or parameter-free. Even the naïve version of string model, facing severe problems at a theoretical level, does not contradict the data. It is a consequence of the lack of detailed and high-statistics measurements. New experimental study of of high-\(p_T\) hadron production with large \(x_T\) and different flavors, electroproduction of hadrons with measurement of \(\nu-, Q^2-, x-\) and \(p_T\) distributions, on nuclear targets are highly desirable.

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