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Jet lag effect and leading hadron production

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Abstract

We propose a solution for the long standing puzzle of a too steeply falling fragmentation function for a quark fragmenting into a pion, calculated by Berger [E.L. Berger, Phys. Lett. B 89 (1980) 241] in the Born approximation. Contrary to the simple anticipation that gluon resummation worsens the problem, we find good agreement with data. Higher quark Fock states slow down the quark, an effect which we call jet lag. It can be also expressed in terms of vacuum energy loss. As a result, the space–time development of the jet shrinks and the z-dependence becomes flatter than in the Born approximation. The space–time pattern is also of great importance for in-medium hadronization.

1. Leading hadrons in Born approximation

We are interested here in the production of leading pions which carry a major fraction of the momentum of a highly virtual quark originating from a hard reaction. The Born graph for the perturbative fragmentation $q \to \pi q$ is shown in Fig. 1(a), and the corresponding fragmentation function was calculated in [1],

$$\frac{\partial D_{\pi/q}^{(\text{Born})}(z)}{\partial k^2} \propto \frac{(1-z)^2}{k^4}, \tag{1}$$

where k and z are the transverse and fractional light-cone momenta of the pion. This expression is derived under the conditions $1-z \ll 1$ and $k^2 \ll Q^2$, where Q^2 is the scale of the hard reaction. We neglect higher twist terms [1,2], which are specific for deep-inelastic scattering (DIS).

The fragmentation function (FF) Eq. (1) is in an apparent contradiction to data, since it falls towards $z = 1$ much steeper than is known from phenomenological fits (e.g., see [3]), and even the inclusion of higher order correction does not seem to fix the problem. Moreover, at first glance gluon radiation should worsen the situation, producing even more suppression at $z \to 1$ because of energy sharing.

Nevertheless, we demonstrate below that the effect of jet lag (JL), i.e., the effect that comes from the fact that higher Fock states retard the quark, substantially changes the space–time pattern of jet development. The JL cuts off contributions with long coherence time in pion production and makes the z-dependence less steep.

One can rewrite (1) in terms of the coherence length of pion radiation,[1]

$$L_c^\pi = \frac{2E}{M_{\pi q}^2 - m_q^2} = \frac{2Ez(1-z)}{k^2 + z^2 m_q^2 + (1-z)m_\pi^2}, \tag{2}$$

where E is the jet energy; m_q is the quark mass which may be treated as an effective infrared cutoff; and

$$M_{\pi q}^2 = \frac{k^2}{z(1-z)} + \frac{m_\pi^2}{z} + \frac{m_q^2}{1-z} \tag{3}$$

is the final pion–quark invariant mass squared.

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[1] One should distinguish this from the coherence length of DIS which is $2E/Q^2$ and is very short at large Bjorken x we are interested in.

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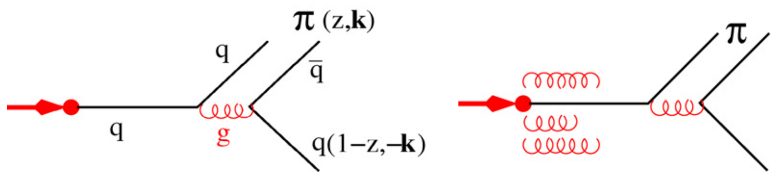

Fig. 1. (a) Berger mechanism [1] of leading pion production in Born approximation. (b) a high Fock component of the quark emerging from a hard reaction and producing a pion with a higher momentum fraction $\tilde{z} > z$ than measured experimentally.

Then, the Born approximation takes the form,

$$\frac{\partial D^{(\mathrm{Born})}_{\pi/q}(z)}{\partial L^\pi_c} \propto (1-z). \tag{4}$$

Thus, the production of the leading pion is homogeneously distributed over distance, from the point of jet origin up to the maximal distance $(L^\pi_c)_{\max} = 2E(1-z)/zm_q^2$.

Integrating (4) over L^π_c up to $(L^\pi_c)_{\max}$ we recover the $(1-z)^2$ dependence of Eq. (1). Now we understand where the extra power of $(1-z)$ comes from: it is generated by the shrinkage of the coherence pathlength for $z \to 1$. This is the source of the too steep fall off of the Born term Eq. (1) in the FF.

2. Jet lag effect and the fragmentation function

The color field of a quark originated from a hard reaction (high-p_T, DIS, e^+e^-, etc.) is stripped off, and gluon radiation from the initial state generates the scale dependence of the quark structure function of the incoming hadron (if any). Therefore the quark originated from such a hard process is bare, lacking a color field up to transverse frequencies $q \lesssim Q$. Then the quark starts regenerating its field by radiating gluons, i.e., forming a jet. This can be described by means of an expansion of the initial "bare" quark over Fock states containing a physical quark and different number of physical gluons with different momenta, as is illustrated in Fig. 1(b). Originally this is a coherent wave packet equivalent to a single bare quark $|q\rangle$. However, different components have different invariant masses and start gaining relative phase shifts as function of time. As a result, the wave packet is losing coherence and gluons are radiated in accordance with their coherence times.

Notice that the Born expression (1) corresponds to the lowest Fock components relevant to this process, just a bare quark, $|q\rangle$, and a quark accompanied by a pion, $|q\pi\rangle$. In this case the initial quark momentum and the pion fractional momentum z in (1) are the observables (at least in e^+e^- or SIDIS).

An important observation is that the quark in higher Fock states carries only a fraction of the full momentum of the wave packet. At the same time, the pion momentum is an observable and is fixed. Therefore, one should redefine the fractional momentum of the pion convoluting the fragmentation function Eq. (1) with the quark momentum distribution within different Fock states,

$$\frac{\partial D_{q/\pi}(z)}{\partial L^\pi_c} = \left\langle \frac{\partial D_{q/\pi}(z)}{\partial L^\pi_c} \right\rangle_x = \frac{\sum_i C^q_i \int_z^1 dx \frac{\partial D^{(\mathrm{Born})}_{q/\pi}(z/x)}{\partial L^\pi_c} F^i_q(x)\Theta(L^\pi_c - l^i_c)}{\sum_i C^q_i \int_z^1 dx\, F^i_q(x)\Theta(L^\pi_c - l^i_c)}. \tag{5}$$

Here $F^i_q(x)$ is the fractional momentum distribution function of a physical quark in the ith Fock component of the initial bare quark. Such a component contributes to (5) only if it lost coherence with the rest of the wave packet. This is taken into account in (5) by means of the step function, where l^i_c is the coherence length for this Fock state. We sum in (5) over different Fock states with proper weight factors C^q_i.

Thus, the inclusion of higher Fock states results in a retarding of the quark, an effect which we call jet lag (JL). This effect plays a key role in shaping the quark fragmentation function for leading hadrons. Due to JL the variable of the Born FF in (5) increases, $z \Rightarrow z/x$, causing a suppression. Then the convolution Eq. (5) leads to the following modification of the Born fragmentation function Eq. (4),

$$\frac{\partial D_{q/\pi}(z)}{\partial L^\pi_c} \propto 1 - \tilde{z}, \tag{6}$$

where

$$\tilde{z} = \left\langle \frac{z}{x} \right\rangle = z\left(1 + \frac{\Delta E}{E}\right) + O\left[z(1-z)^2\right]. \tag{7}$$

Here we made use of the limiting behavior at $1 - z \ll 1$ we are interested in. The fractional energy loss of the quark is related to the energy carried by other partons within those Fock components which have lost coherence on the pathlength L^π_c,

$$\frac{\Delta E(L^\pi_c)}{E} = \left\langle 1 - x\left(L^\pi_c\right)\right\rangle = \frac{\sum_i C^q_i \int_z^1 dx\,(1-x)\,F^i_q(x)\Theta(L^\pi_c - l^i_c)}{\sum_i C^q_i \int_z^1 dx\, F^i_q(x)\Theta(L^\pi_c - l^i_c)}. \tag{8}$$

Notice that in the above expressions we implicitly assume also integration on the other kinematic variables related to the participating partons.