Production of hadrons with large transverse momenta in the fragmentation region

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The inclusive cross section for the production of a hadron with large transverse momentum $p_\perp$ in the fragmentation region was obtained in the covariant parton model under the assumption that the hadron with large $p_\perp$ is the "decay product" of an isolated (in rapidity space) parton. Inclusive cross section characteristics that are typical of the given model and can be observed experimentally are noted.

Production of hadrons with large transverse momenta is being diligently studied of late. From among the recently obtained experimental results we note the following[1]: a) at large transverse momenta ($p_\perp \gtrsim 3$ GeV) the inclusive cross sections decrease with increasing p, in power-law fashion:

$$f = (2\pi)^3 2p_0 \frac{\partial^3 \sigma}{\partial p^3} \sim (p_\perp)^{-N},$$

where f is the inclusive cross section and $N \approx 8$; b) at fixed large $p_\perp$ the inclusive cross sections increase significantly with increasing energy of the colliding particles ($\sqrt{s}$).

A power-law decrease of the inclusive cross section was obtained in a large number of studies,[2–4] and $N = 8$ can be obtained both in the multiperipheral model with exchange and production of pointlike particles[2,3] and in the covariant parton model[4,5] with "ladder kinematics." In all the cited papers, hadrons with large $p_\perp$ were produced in the pionization region (angles ~90°).

It was of interest to consider the case of production of hadrons with large $p_\perp$ in the fragmentation region. We consider the production of a hadron with large $p_\perp$ in the fragmentation region within the framework of the covariant parton model[4,5] with "ladder kinematics." In this model, a process with large $p_\perp$ occurs when, upon formation of the parton "ladder" by the fast hadron, a large transverse momentum is imparted to the parton on one of the "rungs." The parton acquiring a large transverse momentum is isolated in rapidity space and its subsequent evolution is independent of the remaining partons.[6] This isolated parton decays into a "jet" of hadrons, one of which is detected.

We consider the case of production, with large $p_\perp$, of the fastest hadrons, with $p_\perp$ much smaller than the hadron 3-momentum p.

If we make the usual assumption that the partons in the "ladder" are ordered in terms of the longitudinal momenta, then in this case a large transverse momentum is transferred to the parton on the very first "rung of the ladder" and the detected hadron is the fastest from the "jet" of hadrons into which this parton has decayed. The main contribution to the inclusive cross section is made by diagrams containing the minimum possible number of virtual partons that carry the large transverse momentum. A diagram of this type (with allowance for the ordering of the parton in terms of the longitudinal momenta) is shown in Fig. 1.

In Fig. 1 the hadron lines are shown solid and the parton lines dashed. It is most convenient kinematically to "dump" the large transverse momentum on the next rung of the "ladder." The parton carrying away the large transverse momentum is shown singled out in Fig. 1. Only small transverse momenta are subsequently transferred along the "ladder," and the remaining part

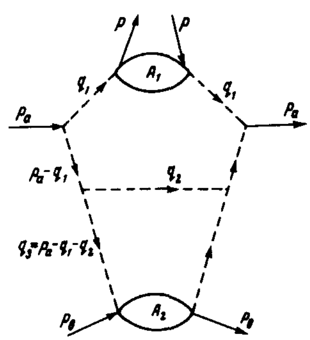

FIG. 1. Diagram making the predominant contribution, in the covariant parton model, to the inclusive cross section for the production of a hadron with large $p_\perp$ in the fragmentation region. Solid lines—hadrons, dashed—partons.

of the "ladder" is described by the absorption part of the amplitude for forward scattering of a parton by a hadron (block A_2). Block A_1 is in the kinematic region of the parton decay, and in accordance with the generalized optical theorem[7] we have $A_1(s', q_1^2) \sim \Gamma(s', q_1^2)$, where $\Gamma(s', q_1^2)$ is the width of the inclusive decay of the parton of "mass" $\sqrt{q_1^2}$ into a hadron with 4-momentum p and an arbitrary possible system of hadrons with mass $\sqrt{s}' = [(q_1 - p)^2]^{1/2}$, and $A_1(s', q_1^2)$ is the absorption part of the amplitude for the forward scattering of the parton by a hadron, continued analytically into the parton decay region. The inclusive cross section of the considered process is given by

$$f = (2\pi)^3 2p_0 \frac{\partial^3\sigma}{\partial p^3} = \frac{\lambda_1^2\lambda_2^2}{2s} \int d^4q_1 d^4q_2 \frac{A_1(s', q_1^2)}{(q_1^2-\mu^2)^2} \frac{\delta(q_2^2-\mu^2)}{[(p_a-q_1)^2-\mu^2]^2} \times \frac{A_2(s'', q_3^2)}{(q_3^2-\mu^2)^2} \quad (1)$$

λ_1 is the constant of the parton "decay" into a system of two hadrons and λ_2 is the constant of the three-parton interaction. Since the partons are assumed to be pointlike, there are no form factors in the vertices. μ and m are the masses of the parton and the hadron. The partons are assumed to be scalar;

$$s = (p_a + p_b)^2; \quad s' = (q_1 - p)^2; \quad s'' = (p_a + p_b - q_1 - q_2)^2; \quad q_3 = (p_a - q_1 - q_2). \quad (2)$$

We consider the asymptotic limit, when

$$s \to \infty, \quad p_\perp^2 \to \infty; \quad m^2/p_\perp^2 << z_\perp^2 = \frac{4p_\perp^2}{s} << 1. \quad (3)$$

To calculate the inclusive cross section we make the following assumptions: 1) Amplitudes with virtual external partons decrease sufficiently rapidly (in power-law fashion) when the "masses" of the virtual partons are large. According to this assumption, the main contribution to the integral[1] comes from the integration region in which q_1^2 and q_3^2 are bounded ($\sim m^2$). 2) The hadrons produced upon decay of a fast parton that is isolated in rapidity space are emitted in a narrow cone about the parton three-momentum. The probability of observing a hadron outside a cone with apex angle $\sim m/p$ decreases exponentially. 3) The behavior of $A_2(s'', q_3^2)$ at $s'' \gg |q_3^2|$ is determined by the contribution of the pomeron ($\alpha_P(0) = 1$). We introduce the variables $x = p_0/q_{10}$ and $z = 2p_0/s$, where p_0 and q_{10} are the zeroth components of the 4-vectors p and q_1. In terms of these variables, we have

$$A_2(s'', q_3^2) \sim (s''/|q_3^2|)^{\alpha_P(0)} \sim (x - z) z^s / p_\perp^2. \quad (4)$$

4) $A_1(s', q_1^2)$ with $0 \leqslant s' \leqslant (\sqrt{q_1^2} - m)^2$ can be represented in the form

$$A_1(s', q_1^2) = A_1^{(0)}(q_1^2)\delta(s' - m^2) + \bar{A}_1(s', q_1^2)\theta(s' - 4m^2). \quad (5)$$

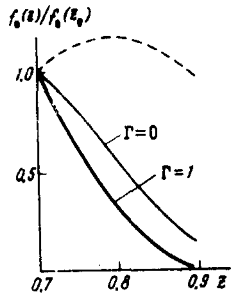

FIG. 2. Solid lines—dependence of the ratio $f_0(z)/f_0(z_0)$ on z in the covariant parton model at different values of the parameter Γ and $z_0 = 0.7$; dashed line—analogous dependence in the multiperipheral model.

Expression (5) is equivalent to stating that the parton decay amplitude, as an analytic function of s', has a pole corresponding to two-hadron decay and branch points corresponding to n-hadron decays ($n \geqslant 3$). In accordance with assumption (1) we obtain for $A_1^{(0)}$ and $\bar{A}_1$ the following expressions:

$$A_1^{(0)}(q_1^2) \sim (q_1^2)^{-2\Gamma}; \quad \bar{A}_1(s', q_1^2) \sim (q_1^2)^{-2\Gamma}(s'/q_1^2)^\gamma \sim (q_1^2)^{-2\Gamma}(1-x)^\gamma, \quad (6)$$

where Γ and γ are positive.

In the expression for $\bar{A}_1$ we have taken into account the threshold behavior as $x \to 1$. We calculate the inclusive cross section in the kinematic region:

$$z_\perp^2 << 1 - z << 1. \quad (7)$$

Under the assumptions made above, we can calculate the zeroth term of the expansion of the inclusive cross section (f_0) and the small parameter z^2, inasmuch as in the calculation of f_0 it is possible to factor out the variables of the upper and lower blocks of Fig. 1, and we obtain for f_0 the expression

$$f_0 \sim \frac{1}{p_\perp^8} z^4 \int_{m^2/z(1-z)}^{\infty} dq_1^2 (q_1^2)^{-2\Gamma-2} \int_z^{\frac{1}{2}(1+\sqrt{1-4m^2/q_1^2})} dx (x-z) \delta \times \left[q_1^2(1-x) - \frac{m^2}{x}\right] + \bar{f}_0. \quad (8)$$

The limits with respect to x in (8) are obtained from the condition $s' = (q_1^2 - m^2/x)(1-x) \geqslant m^2$, and $\bar{f}_0$ is the contribution from the second term in (5). Integrating (8) we obtain

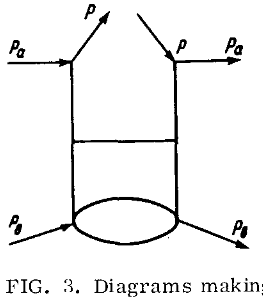

FIG. 3. Diagrams making the dominant contribution to the inclusive cross section of the production of hadrons with large $p_\perp$ in the fragmentation region in the multiperipheral model.

$$f_0(z, p_\perp^2) \quad \frac{z^4}{p_\perp^8} (1-z)^{3+2\Gamma}$$

$$\times \left(1 + \sum_{n=1}^{\infty} \frac{(-1)^n (2\Gamma+2)(2\Gamma+1)\ldots(2\Gamma+2-n+1)}{n!\,(2\Gamma+2+n)(2\Gamma+3+n)} (1-z)^n\right) + \bar{f}_0. \tag{9}$$

At $1 - z \ll 1$ the sum over n in (9) is actually determined by the first several terms. If 2Γ is an integer, then this sum has a finite number of terms. An estimate of $\bar{f}_0$ shows that at $1 - z \ll 1$ and at reasonable values of Γ and γ this term is much smaller than the first term in (9). This is due to the presence of the threshold factor $(1-z)^\gamma$ and of the higher threshold in q_1^2, namely at $q_{1\,\min}^2(s' = 4m^2) = m^2(1+3z)/z(1-z)$. The ratio of $\bar{f}_0$ to the first term in (9) is $\sim(1-z)^\gamma(1+3z)^{-2\Gamma-1}$ Thus, the inclusive cross section is described with good accuracy by the first term of (9).

Let us examine in greater detail the characteristic properties of the inclusive cross sections: 1) The dependence of the inclusive cross section on $p_\perp$ is the same as in the pionization region, namely $f \sim (p_\perp)^{-8}$. 2) The inclusive cross section depends strongly on z and decreases rapidly with increasing z. The rate of decrease depends on the parameter Γ. Figure 2 shows the dependence of the ratio $f_0(z)/f_0(z_0)$ on z at different values of Γ and $z \geq z_0 = 0.7$. If p_0 is kept constant and s is increased, then the inclusive cross section increases. It seems to us that this growth is analogous to the growth of the inclusive cross section at 90° at fixed $p_\perp$ and increasing s. 3) In the multiperipheral model, in which (pointlike) hadrons with large $p_\perp$ are emitted directly from the "stepladder" (Fig. 3), the dependence of the inclusive cross section on $p_\perp^2$ and z takes the form $f \sim p_\perp^{-8} z^4(1-z)$, i.e., the dependence on z differs significantly from the corresponding dependence in the parton model (dashed curve in Fig. 2). Thus, the parton and the multiperipheral pictures of the production of hadrons with large $p_\perp$, which in principle give the same dependence of the inclusive cross section on $p_\perp$, lead to essentially different dependences of the inclusive cross section on z, and an experimental study of the dependence of the inclusive cross section on z can help determine which of these pictures is more realistic.

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