Is the average transverse momentum of partons greater than 1 GeV/*c*?

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Different experiments yielding estimates of the average transverse momentum $\langle q_t\rangle$ of a parton are reviewed. They all show that $\langle q_t\rangle > 1$ GeV/*c*. Analysis of the transformation of partons into hadrons shows that this high value of the transverse momentum of partons is not inconsistent with the low value (≈ 0.4 GeV/*c*) of the mean transverse momentum of pions created in hadron collisions. The high value of $\langle q_t\rangle$ can be used to justify the validity of the additive quark model at high energies, and to predict some of the properties of deep inelastic processes, which can be examined experimentally.

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1. INTRODUCTION

Strong interactions at high energies are frequently described in terms of the parton model in which it is assumed that a fast hadron consists of a set of point particles, i.e., partons, which have limited transverse momenta q_t and carry a definite fraction $x = q_\parallel/p_a$ of the hadron momentum p_a ($q_\parallel$ is the longitudinal momentum of the parton).[1/3] This model has become very popular because it provides a unified description of deep inelastic processes,[2] the creation of hadrons with high transverse momenta,[4,5] and the behavior of the total cross sections for hadron-hadron collisions.[1,3] However, recent years have seen the accumulation of a substantial amount of experimental data which directly or indirectly indicate that the mean transverse momentum of partons is very high, i.e., $\langle q_t\rangle \approx 1.5$ GeV/c.[5] At first sight, this is inconsistent with the mean transverse momentum of pions created in hadron-hadron collisions at high energies, i.e., $\langle p_{t\pi}\rangle \approx 0.4$ GeV/c,[6] and appears to be a serious argument against the parton model. This is not the case. It will be shown below that the apparent inconsistency is readily resolved if we recall that, most probably, each parton decays not into one but several ($l \approx 4$) pions. In that case, each pion will, on the average, take up the fraction $1/l$ of the transverse momentum of the parton, and $\langle p_{t\pi}\rangle \sim \langle q_t\rangle/l$.

In the Sec. 2 of this paper, we shall examine the evidence for the fact that $\langle q_t\rangle > 1$ GeV/c. In Sec. 3, we shall try to explain the fact that, despite the high value of $\langle q_t\rangle$, the mean transverse momentum of pions may, and probably should, turn out to be low, i.e., $\langle p_{t\pi}\rangle \approx 0.4$ GeV/c. We shall show that the transverse momentum of secondary pions is determined largely by the masses of hadron resonances and not by the quantity $\langle q_t\rangle$. In Sec. 4, we shall show that the relatively high transverse momentum of partons is also desirable from the theoretical standpoint because (a) it can be used to justify the validity of the additive quark model[7] and (b) it enables us to understand the low value of the three-pomeron vertex G_{3P},[8] and so on. Finally, in Sec. 5, we shall formulate some predictions, based on the high value of $\langle q_t\rangle$, which can be checked experimentally.

2. EXPERIMENTAL EVIDENCE FOR HIGH TRANSVERSE PARTON MOMENTA (>1 GeV/sec)

1. The most direct method of determining experimentally the mean transverse momentum of a parton is measurement of the azimuthal angular correlation in processes involving the creation of hadrons with high transverse momenta (p_t). In the parton model, these processes proceed in the following fashion. Two relatively fast point partons collide and are scattered through a finite angle, assuming transverse momenta $q_{t1'} > p_{tc}$. These partons then decay into hadrons which take up a fraction $\delta < 1$ of the parton momentum: $p_c = \delta_c q_{1'} + \langle p_\perp\rangle$; $p_{tc} = \delta_c q_{t1'} + \langle p_\perp\rangle$ (see Fig. 1), where $\langle p_\perp\rangle$ is the mean transverse momentum of hadrons relative to the momentum of the parton during the decay of the parton into hadrons. The result of this is the formation of two groups (streams) of hadrons (1′, 2′) with opposite transverse momenta. The distribution over the angle φ between the momenta p_{tc} of particles c from group 1′ and momenta p_{td} of particles d from group 2′ has a peak at $\varphi = 180°$. The width $\Delta\varphi$ of this peak is determined by the mean values $\langle q_t\rangle$ and $\langle p_\perp\rangle$. For large transverse momenta p_{tc}, p_{td} (suppose that $p_{tc} > p_{td}$)

$$\langle \mathrm{tg}^2\,\Delta\varphi\rangle \approx \langle q_t^2\rangle/q_{t1'}^2 + \langle p_{\perp c}^2\rangle/2p_{tc}^2 + \langle p_{\perp d}^2\rangle/2p_{td}^2. \tag{1}$$

The first term in this expression represents the distribution over the angle φ between the momenta of partons 1′ and 2′ (Fig. 1). The second and third terms describe the distribution over the angle between partons 1′ (2′) and hadrons p_{tc}, p_{td}. The figure 2 in the denominator appears because $\langle \Delta\varphi_{1'c}^2\rangle = (p_{\perp x})^2/p_{tc}^2$ (the z axis lies in the direction of the incident hadron p_a and the y axis in the direction of p_{tc}) and $p_\perp^2 = p_{\perp x}^2 + p_{\perp y}^2$. Unfortunately, experiments concerned with the distribution of hadrons over φ involve measurements of the momentum p_{tc} on only a single particle c and the value of p_{td} is left unknown.[9] Since the parton scattering cross section decreases rapidly with increasing q_{t1}, ($q_{t2'}$), we have $q_{t1'} \approx p_{tc}$ and, on the average, $p_{td} \sim p_{tc}/2$. Moreover, for the purposes of rough estimates, let us suppose that[1)] $\langle p_\perp\rangle = \langle q_t\rangle$. We then have $\langle \tan^2\Delta\varphi\rangle \approx 3.5\langle q_t^2\rangle/p_{tc}$. On the other hand, we have from experiment $\langle \tan^2\Delta\varphi\rangle \approx 1$ when $p_{tc} \gtrsim 3.5$ GeV/c[9] (see Fig. 2a). Hence, it follows that

$$\langle q_t\rangle = 1.8\ \mathrm{GeV/c} \tag{2}$$

However, this estimate is very dependent on the magnitude of the momentum p_{td}. When $p_{td} = p_{tc}/3$, we have $\langle p_t\rangle = 1.4$ GeV/c. Experiments in which the momenta of the two hadrons with high p_t (p_{tc} and p_{td}) are known will therefore be of considerable importance. In addition to measurements of $\langle q_t\rangle$, such experiments should enable us to investigate the behavior of the differential part of the cross section because in events in which $p_{td} \approx p_{tc}$, the momenta and the angles of emis-

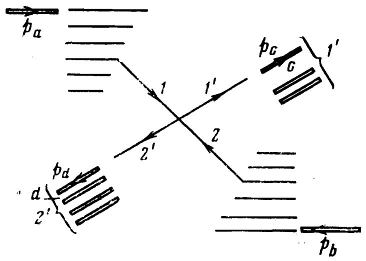

FIG. 1. Creation of particles with high transverse momenta in the parton model: solid lines—partons, double lines—hadrons.

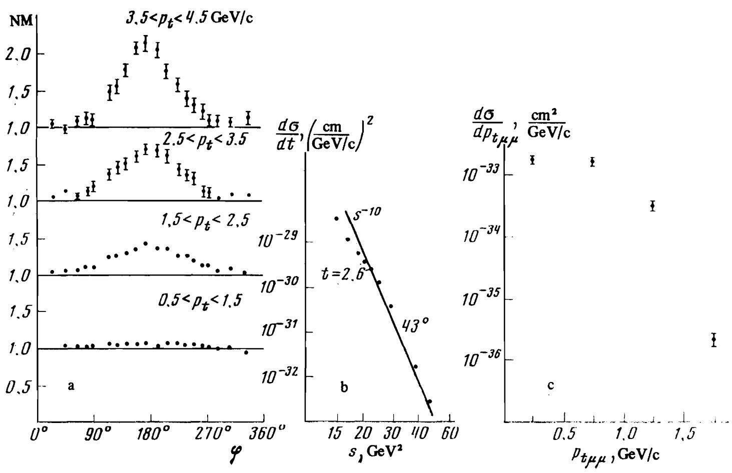

FIG. 2. Experimental data showing that the mean transverse parton momentum is high: (a) normalized multiplicity (NM) in the $pp \to \pi^0 + X$ reaction [ratio of multiplicity in events with $3.5 < p_{t\pi 0} < 4.5$ GeV/c to the multiplicity in events with $p_{t\pi 0} \approx 0.3$ GeV/c in the range $|y| < 0.7$ ($y_{\pi 0} = 0$) as a function of the azimuth φ [9]; (b) differential pp cross section at $\theta = 43°$ as a function of energy; [11] (c) distribution of $\mu^+\mu^-$ pairs from the $p + U \to \mu^+\mu^- + X$ reaction [13] over the transverse momentum.

sion of partons 1′, 2′ are equal to the momenta and angles of particles c and d with good accuracy ($\sim\langle q_t\rangle/p_{tc}$).

2. The elastic differential hadron cross section at large fixed angles θ = const is a power function of the initial energy $\sqrt{s}$ in the parton model:[10,11]

$$d\sigma/dt = s^{-n}F(\theta). \qquad (3)$$

A gradual reduction in the cross section (3) is expected only at sufficiently high energies when the transverse momentum of the hadrons after the collision exceeds the mean transverse momentum of the partons ($p_t > \langle q_t\rangle$). The expression given by (3) is in reasonable agreement with experiment beginning with $t \approx 2.6$ (GeV/c)^2 (for $\theta = 43°$)[11] (see Fig. 2b). Hence, we find that $\langle q_t\rangle = 1.6$ GeV/c. These values of $\langle q_t\rangle$ also correspond to the transition from the exponential to the power-law reduction in the inclusive cross section for the creation of pions with increasing $p_{t\pi}$.[6]

3. Another source of information about $\langle q_t\rangle$ is the distribution over the transverse momentum of the μ^+, μ^- pair created during a collision between nucleons. According to the parton model, the heavy μ^+, μ^- pair is produced as a result of the annihilation of a parton antiparton pair of mass equal to $m_{\mu^+\mu^-}$.[12] When the latter is much greater than $\langle q_t\rangle$, the mass of the parton-antiparton system is wholly determined by the longitudinal momenta of the partons, and the mean transverse momentum of the pair ($p_{t\mu\mu}$) is equal to the mean transverse momentum of the partons. Existing data[13] have been obtained at insufficiently high energies (E_{lab} = 29.5 GeV) and masses ($m_{\mu^+\mu^-} > 1$ GeV/c^2). However, even in this case, the distribution of $d\sigma/dp_{t\mu\mu}$ begins to fall only for $p_{t\mu\mu} \gtrsim 1$ GeV/c (Fig. 2c). Thus, this experiment also suggests that $\langle q_t\rangle > 1$ GeV/c.

4. According to the parton model, the virtual photon in the e^+, e^- annihilation at first creates a parton-antiparton pair which then transforms into hadrons (Fig. 3). It is natural to expect that the resulting hadron system is aligned in the direction of the z-momentum of the partons 1, 2 (or the momentum of the fastest hadrons) (Fig. 3b). Thus, in each event, there is a z direction relative to which the transverse momenta of the hadrons are much smaller than the longitudinal momenta. Experiment shows that, up to $\sqrt{s} \approx 4$ GeV, the hadrons are emitted with a spherically symmetric distribution.[14] This is possible (in the parton model) only when the mean transverse momentum of the hadron relative to the momentum of the parton $\langle p_\perp\rangle$ is comparable with the maximum momentum of the particles, $\frac{1}{2}\sqrt{s}(1 \text{ to } \frac{1}{3})$. This means that, to avoid conflict with data on hadron formation in e^+, e^- annihilation, we must have

$$\langle q_t\rangle \geqslant \langle p_\perp\rangle \gtrsim \tfrac{1}{2}\sqrt{s}(1-\tfrac{1}{3}) > (1-2)\,(\text{GeV}/c)^{-2}$$

where, as in Sec. 1, we are assuming that $\langle q_t\rangle = \langle p_\perp\rangle$.

5. An indication that $\langle q_t\rangle$ has a large value is provided by the slow variation of the parameter b of the diffraction cone ($d\sigma/dt = Ae^{bt}$) with increasing energy s.

In pp scattering, we have[15]

$$b = b_0 + 2\alpha' \ln s, \quad \alpha' \leqslant 0.28\ (\text{GeV}/c)^{-2}. \qquad (4)$$

The parameter b characterizes the effective transverse size of colliding particles. In the parton model in which the target (at rest in the laboratory system) interacts with slow (longitudinal momentum $q_\parallel \sim \langle q_t\rangle$) partons of the incident hadron,[1,3,16] the quantity b is determined by the size of the region in which the slow partons are distributed.[2)] We shall assume that the slow parton is formed as a result of successive and independent decays of fast particles (the initial hadron or faster partons; Fig. 4a) (c.f. the diffusion picture described

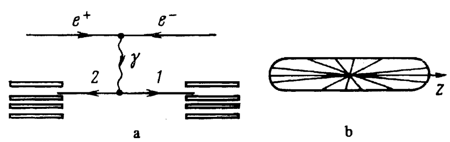

FIG. 3. (a) e$^+$e$^-$ annihilation into hadrons in the parton model; (b) angular distribution of hadron momenta about the z axis (the directions of the momenta of partons 1, 2 are clear from Fig. 3a).

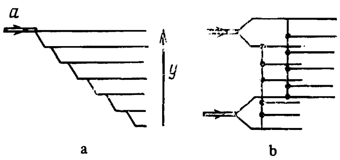

FIG. 4. Creation of slow partons in the diffusion picture.

in[16]). In each decay, the parton impact parameter ρ then changes by an amount of the order of $1/\langle q_t \rangle$ and after n decays the slow parton turns out to be distributed within the region $\langle \Delta\rho^2 \rangle \sim n/\langle q_t^2 \rangle$. As the energy increases, the number of decays necessary for the formation of a slow parton $(q_\parallel \approx q_t)$ is found to increase by a finite amount Δn, and the transverse size of the region within which the slow partons are distributed increases by $\Delta n/\langle q_t^2 \rangle$. Thus, $\partial b/\partial \ln s = 2\alpha' = (\partial n/\partial \ln s)/\langle q_t^2 \rangle$,

$$\alpha' = \frac{\partial n/\partial \ln s}{2\langle q_t^2 \rangle} \tag{5}$$

The number of decays necessary to slow down the parton by a factor of e in this model (Fig. 4a) is equal to the parton density in rapidity space (by definition, rapidity $y = \frac{1}{2}\ln[(E + p_\parallel)/(E - p_\parallel)]$). Assuming, as usual,[1,2] that quarks play the role of partons, we can estimate the quark density (a) from the structure function νW_2 of deep inelastic ep scattering for $x \to 0$[3)] and (b) from the multiplicity of particles generated in hadron-hadron collisions. Let us begin with method (a). The quantity $\nu W_2(x)$ is determined by the probability $(f(x))$ of finding a parton with a given fraction of longitudinal momentum x, multiplied by its mean square charge $\langle e_i^2 \rangle$:[2]

$$\nu W_2(x) = \langle e_i^2 \rangle x f(x) = \langle e_i^2 \rangle (\partial n/\partial \ln s). \tag{6}$$

For quarks $\langle e_i^2 \rangle = 2/9$ and $\nu W_2\ (x \to 0) = 0.32 - 0.16$,[18] so that

$$\partial n/\partial \ln s = 1.45 - 0.7. \tag{7}$$

In method (b), we use data on the multiplicity of pions created in p, p collisions at high energies (pions provide roughly 80% of the secondary particles),[6] and have

$$d\sigma/\sigma_{in} dy_{\pi^-} = 0.75, \tag{8}$$

and if we suppose that each quark-antiquark pair produces one meson, then

$$\frac{\partial n}{\partial \ln s} = \frac{d\sigma}{\sigma_{in}\, dy_{\pi^-}} \cdot 2 \frac{3}{0.8} \approx 5.5, \tag{9}$$

which is very different from (7). (We note that the coefficient 2 in (9) corresponds to the presence of the quark and antiquark in the meson, and the coefficient 3/0.8 represents the presence, in addition to the negative pion, of a positive pion, a neutral pion, and other hadrons.) The difference between (7) and (9) is due to a number of factors.

Firstly, we must remember that hadron collisions may result in the emission of several parton combs (Fig. 4b), whereas we are interested in the density of partons in a single comb, which is lower by a factor of C, where:

$$C = \frac{d\sigma}{\sigma_{in}\, dy} \Big/ \frac{d\sigma_1}{\sigma_1\, dy},$$

and $d\sigma_1/\sigma_1 dy$ is the density of particles in a single comb. The increase in the particle density (the coefficient C) due to the emission of several combs can be determined with the aid of the results reported in[19]. If we neglect the contribution of enhanced diagrams, assuming that the three-pomeron vertex G_{3P} is small,[8] then in the limit as $G_{3P} \to 0$, we have $C = \sigma_{in}(s)/\sigma_{tot}$ $(s \to \infty)$. Estimates based on[17,20] yield $1/C = 1.6-2.2$ for $s = 400-4000$ GeV^2. Therefore, $d\sigma_1/\sigma_1 dy \approx 0.4$, which agrees with the predictions of realistic multiperipheral models with constant cross section (see[21]).

Secondly, the quark-antiquark pair may not undergo a transition to a single meson. The quark-antiquark pair may, for example, result in a ρ meson (this is the main mode in the models discussed in[21]), which then decays into 2π. If we take these two factors into account, we obtain

$$\frac{\partial n}{\partial \ln s} = \frac{d\sigma}{\sigma_{in}\, dy_{\pi^-}} \cdot 2 \cdot \frac{3}{0.8} \frac{1}{C} \frac{1}{2} \approx 1.4 \tag{10}$$

where the coefficient $\frac{1}{2}$ is due to the $\rho \to 2\pi$ decay.

We also recall that, to avoid contradiction between the values $\langle q_t \rangle \approx 1.5$ GeV/c and $\langle p_{t\pi} \rangle \approx 0.4$ GeV/c, we must assume that, on average, one parton results in four pions (see the Introduction and Sec. 3), from which it follows that

$$\frac{\partial n}{\partial \ln s} = \frac{d\sigma}{\sigma_{in}\, dy_{\pi^-}} \frac{3}{0.8} \frac{1}{4} \approx 0.7. \tag{11}$$

The numerical values given y (7), (10), and (11) are now in reasonable agreement and, if we suppose that $\partial n/\partial \ln s = 1$, we have from (4) and (5)

$$\langle q_t \rangle \gtrsim 1.4 \text{ GeV/c} \tag{12}$$

where the sign of approximate equality is due to the fact that, in addition to quarks, $\partial n/\partial \ln s$ may contain gluons, and this increases the resultant density of partons and hence $\langle q_t \rangle$.

6. There is one further method of determining $\langle q_t \rangle$, namely, comparison of proton formfactors at high transferred momenta $G(q^2)$ and νW_2 as $x \to 1$. In the parton model, the formfactor is proportional to the probability of finding the parton configuration in the hadron for which one parton carries practically the entire hadron momentum and the distribution of the remaining partons (in the coordinate frame in which the gamma-ray energy is zero and the hadron momentum is $\sqrt{-q^2}/2$) is spherically symmetric,[1,22] i.e.,

$$\langle q_z \rangle = \langle q_x \rangle = \langle q_y \rangle = \langle q_t \rangle / \sqrt{2}.$$

The parton distribution is specified by the structure function νW_2 so that

$$G(q^2) \leqslant \int_{x_0}^{1} \nu W_2(x) \frac{\langle e_i \rangle}{\langle e_i^2 \rangle} dx, \quad x_0 = 1 - \frac{\langle q_t \rangle}{\sqrt{2}} \Big/ \frac{\sqrt{-q^2}}{2}$$

where the lower limit of integration is determined by the fact that the momentum of the fastest of the slow partons should not exceed $\langle q_t \rangle / \sqrt{2}$.

Experiments on e, p scattering in the region 1 < x

< 0.6[18] show that $\nu W_2 \approx d(1 - x)^3$ ($d = 1.2$). Since for large x the main contribution is due to valence quarks, the mean charge is $\langle e_i \rangle = \langle e_i^2 \rangle = 1/3$. Hence,[4)]

$$G(q^2) \leqslant \frac{d}{4} \frac{2\langle q_t \rangle^4}{q^4} = \frac{0.6\langle q_t \rangle^4}{q^4}. \qquad (13)$$

On the other hand, for large q^2,[23]

$$G(q^2) = \frac{1}{(1-q^2/0.71)^2} \approx \frac{(0.71)^2 (\mathrm{GeV/c})^4}{q^4}. \qquad (14)$$

Comparison of (13) with (14) yields $\langle q_t \rangle > 1$ GeV/c.

We thus see that numerous estimates obtained by different methods based on different experimental data are in good agreement with one another and show that the mean transverse momentum of the parton is $\langle q_t \rangle \approx 1.5$ GeV/c.

3. TRANSVERSE MOMENTA OF PIONS CREATED IN HADRON COLLISIONS

The only well-known fact which favors small values of $\langle q_t \rangle$ is the distribution of secondary pions over the transverse momentum, $\langle p_{t\pi} \rangle \approx 0.4$ GeV. Let us consider how new hadrons are formed after the collision of the initial particles. Unfortunately, no adequately developed theory of this process exists at the moment and our analysis will therefore be essentially qualitative in character.

When the fast hadron has collided with the target and the slow parton has interacted with it, the coherence of the parton system forming the fast hadron is violated. The result is that the partons begin to interact with one another or decay into hadrons. Since the transverse momenta of the partons are large ($\langle q_t \rangle \approx 1.5$ GeV/c), each parton occupies a relatively small region of space ($\Delta\rho \sim 1/\langle q_t \rangle$), and a substantial proportion of the partons turn out to be isolated from one another. All that they can then do is to decay into hadrons. Suppose that quarks play the role of partons. The decay process can then be described as follows. An isolated quark 1 creates (as if by bremsstrahlung) a quark-antiquark pair $(q, \tilde{q})$ which is already coherent with the initial quark. [By combining with the antiquark in this pair, quark 1 can form a meson which, on the average, takes up half the momentum (both longitudinal and transverse) of quark 1. The second half of the momentum is taken up by quark 2; see Fig. 5a.]

The quark-antiquark pairs are produced side by side (at distances of $\sim 1/\langle q_t \rangle$) and can, in principle, immediately form a meson. However, the probability of this is low because, in the meson, the quark and antiquark are distributed over a substantially greater region of space ($\sim 1/m_0$). It follows that these quarks, too, will in a substantial proportion of all cases begin to emit $(q, \tilde{q})$ pairs. This emission of new quark-antiquark pairs (Fig. 5a) will continue until the transverse momenta of the partons (quarks) will fall to values of the order of the meson masses m_ρ (for example, when the quark and antiquark wave functions begin to overlap in a sufficiently large region of space and will be able to unite into a meson[5)]). When $\langle q_t \rangle \approx 1.5$ GeV, one or two decays (emissions of quark-antiquark pairs) are sufficient for this to occur.

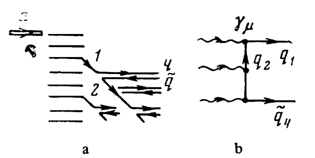

FIG. 5. Transformation of partons into hadrons.

During the first stage of the parton-hadron transition, relatively heavy resonances are predominantly created. In fact, since the transverse parton momenta are high, the high mass of the resonance does not reduce the probability of its formation. On the contrary, since the resonance widths increase with increasing mass, the mass of the system of partons is more likely to enter the region of the resonance peak for heavy hadrons. Moreover, heavy resonances have high spins and, consequently, high statistical weight.

If, for example, a quark-antiquark pair is emitted by one or more gluons (Fig. 5b), and the interaction of the gluon with a quark conserves helicity [takes the form $\bar{u}(q_1)\gamma_\mu u(q_2)$], then for high longitudinal momenta the spin wave function of the quark-antiquark system corresponds to spin 1 (the helicity of the system is ± 1) and this pair can transform only into ρ, ω, and A_2 mesons but not into a pion. We emphasize that these resonances are formed only when the parton wave functions begin to overlap in a relatively large region of space ($\sim 1/m_\rho$), so that the transverse momenta of the resonances will be of the same scale of magnitude as their masses. Of course, the new hadrons are formed not only through the emission of additional partons ($q\tilde{q}$ pairs) but also from the old, initial, partons. Out of the large number of noncoherent old partons, we can select a coherent set which will form a hadron. However, since it consists of a large number of coherent partons,[6)] this hadron will have transverse momentum much smaller than $\langle q_t \rangle$ ($\sim m_{res}$, since its size in the transverse plane is of the order of $1/m_{res}$).

Thus, during the initial stage of the transition of partons into hadrons, we see the formation of resonances with masses $\sim \langle q_t \rangle/2$ and transverse momenta $\sim \langle q_t \rangle/2 \approx 0.75$ GeV/c $\approx m_\rho$.

Subsequently (during the second stage), these resonances (ρ, f, ω, A_2, f$'$, ...) decay into several (l) pions (kaons). During the decay process, the transverse pion momenta decrease by a further factor (l) (we note that large values of $\langle p_{t\,res} \rangle$ will have heavier resonances which then decay into a large number of pions), so that $\langle p_{t\pi} \rangle \approx m_\rho/2 \approx 0.4$ GeV/c. This stage (decay of relatively heavy resonances) was investigated in[24] where it was shown that the distribution of pions produced as a result of the decay of resonances with mean transverse momenta $\langle p_{t\,res} \rangle \sim m_\rho$ (according to the multiperipheral model[21]) is in good agreement with experiment.

We thus see that, in the above scheme of pion (kaon) generation, the mean transverse momentum $\langle p_{t\pi} \rangle$ is largely determined by the masses of the resonances ($\langle p_{t\pi} \rangle \approx m_\rho/2$) and is almost independent of the transverse parton momentum $\langle q_t \rangle$. As $\langle q_t \rangle$ increases, there is an increase only in the mean number of hadrons into which each parton is transformed. In view of Sec. 2, if we assume that $\langle q_t \rangle \approx 1.5$ GeV/c, each parton will, on the average, decay into two resonances, for example, 2ρ with $\langle p_{t\rho} \rangle \approx \langle q_t \rangle/2 \approx m_0$, and these resonances subsequently decay into pions ($\rho \to 2\pi$) so that $\langle p_{t\pi} \rangle \approx m_\rho/2 \approx 0.4$ GeV/c.

4. WHY ARE LARGE VALUES OF $\langle q_t \rangle$ THEORETICALLY DESIRABLE?

We shall now briefly consider a few cases for which high values of transverse parton momenta are desirable from the theoretical point of view. Two such cases, namely, e^+, e^- annihilation and the slow contraction of the diffraction cone $[\alpha' < 0.3\ (\text{GeV/sec})^2]$ have already been discussed in Sec. 2.4 and 2.5, and we shall not consider them again here.

1. Large $\langle q_t \rangle$ will justify the use of the additive quark model[7] in which each baryon consists of trivalent quarks and a meson consists of a quark-antiquark pair. In processes with small transferred momenta, these valence quarks interact with one another like free independent isolated particles. The additive quark model is in good agreement with numerous experimental data[7,25] and, in particular, predicts that $\sigma_{tot}(\pi p)/\times\sigma_{tot}(pp) = 2/3$.

However, we know that, at high energies, fast particles interact with the target through their slow partons which, in the transverse plane, are distributed over the region

$$R_k^2 = \ln s\,\frac{\partial n/\partial \ln s}{\langle q_t^2 \rangle} \approx \frac{\ln s}{\langle q_t^2 \rangle}$$

(see Sec. 5.2). If the transverse parton momentum were small ($\langle q_t \rangle \approx 2m_\pi$), the size R_k^2 of the occupied region would be much greater than the size of the proton $R_p^2 \approx 1/4m_\pi^2$. In that case, slow partons of different valence quarks would strongly overlap, interact with one another, and shield one another, so that the additive model would have no justification.

On the other hand, when $\langle q_t \rangle \approx 1.5$ GeV/c, R_k^2 and R_p^2 become comparable only for $s > 10^{11}$ GeV^2 and, at contemporary energies, the parton clouds belonging to different valence quarks do not overlap (Fig. 6a), so that, in fact, the quarks interact additively as if they were independent individual particles.

2. High transverse parton momenta taken together with the additive quark model enable us to understand the small value of the three-pomeron vertex G_{3P} obtained from experiments on the inclusive creation of protons ($p_1 p_2 \to p_3 X$; $p\pi \to pX$) in the region $x = p_3/p_{max} \to 1$[8] (see Fig. 6b). The vertex G_{3P} is proportional to the probability that two partons from different combs (Fig. 4b and Fig. 6b) but with similar longitudinal momenta will interact with one another.

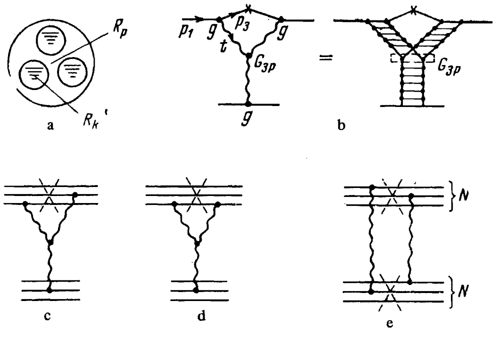

FIG. 6. (a) Baryon in additive quark model with high $\langle q_t \rangle$ ($R_k \sim 1/\langle q_t \rangle \ll R_p \sim m_\pi/2$); (b)–(d) diagrams describing the inclusive process $pp \to p + X$ in the three-pomeron region; (e) diagram corresponding to the elastic pp scattering through small angles in the additive quark model.

When these combs are emitted by different quarks (Fig. 3c), the probability that two partons will meet in the band $\Delta y = 1$ is proportional to

$$1/(R_p^2 \langle q_t^2 \rangle) < 1/20 \tag{15}$$

$[R_p^2 = 1/4m_\pi^2, \langle q_t^2 \rangle \approx 2\ (\text{GeV/c})^2]$. If, on the other hand, the combs are emitted by a single quark (Fig. 6d), the probability that the partons will meet is of the order of unity, but the emission and absorption of two combs by the same quark (out of the three in the proton) exceeds by a factor of only

$$1/3^2 = 1/9 \tag{16}$$

the fraction of cases as compared with the elastic process (compare with Figs. 6d and 6e). Experiment shows that[8] G_{3P} is smaller by a factor of 30–50 as compared with g (the vertex representing the coupling between the pomeron and the proton, Fig. 6d), and this is in reasonable agreement with (15) and (16) if we recall that not every encounter of partons will result in the coalescence of two combs into one, and the "transparency" of point partons with $\Delta y \approx 1$ is of the order of $\langle q_t^2 \rangle/\tilde{s} \approx 1/5$ [$\tilde{s} = 2\langle q_t^2 \rangle (1 + \text{ch}\langle \Delta y \rangle) \approx 5\langle q_t^2 \rangle$ is the mean square of the mass of the two neighboring partons]. Moreover, the high value $\langle q_t \rangle \approx 1.5$ GeV/c and the fact that the main contribution to G_{3P} is due to processes involving the emission of two combs by the same quark explain the weak dependence of the vertex G_{3P} on the transferred momentum $t = (p_1 - p_3)^2 [G_{3P}(t) \propto \exp(R_{3P}^2 t), R_{3P}^2 < 1\ (\text{GeV/c})^{-2}]$.[8] For the processes in Fig. 6d, $G_{3P}(t)$ will vary appreciably only for $|t| > \langle q_t^2 \rangle$, i.e., one would expect that $R_{3P}^2 \approx 1/\langle q_t^2 \rangle < 0.5\ (\text{GeV/c})^{-2}$.

3. As already noted in Sec. 2.2, the inclusive cross section for the creation of hadron c with large transverse momentum p_{tc}

$$f_c = E_c d\sigma/d^3p_c \sim p_{tc}^{-n} \Phi(x_\perp) \qquad (n = \text{const},\quad x_\perp = 2p_{tc}/\sqrt{s}) \tag{17}$$

decreases as a power function with increasing p_{tc}.[4,5] However, measurements on the reaction $p + W \to \pi + X$ with $\sqrt{s} = 20$–28 GeV have shown that the exponent n is very dependent on $x_\perp$ (and, possibly, on p_{tc}):[26] $n \approx 6$ for $x_\perp \approx 0.1$ and $n \approx 11$ when $x_\perp \approx 0.5$. This variation of n is explained by the competition between the number of different mechanisms resulting in the formation of a hadron with high p_t,[27,28] each of which has its own exponent n_i and its own function $\Phi_i(x_\perp)$, and dominates in its own region of $x_\perp$. These mechanisms can be the following:

(a) Formation of a hadron in the decay of a parton with large q_t[4,5] (Fig. 1; this mechanism has the smallest exponent n_i).

(b) Formation of a hadron from one fast ($q_t \approx p_{tc}$) and several slow ($q_\parallel \approx \langle q_t \rangle/2$) partons[27,28] [this mechanism is measured by a quantity proportional to the formfactor $G(4q_t^2)$; see Sec. 6.2].

(c) Formation of a parton with high q_t during the collision between, say, four partons (two diquarks)[28] (this process is measured by a quantity proportional to the diquark formfactor). Subsequently, this process proceeds either along (a) or along (b).

Since the different reaction mechanisms contain different powers of the ratio $\langle q_t \rangle/p_{tc}$,[7] the competition between them is possible only when the ratio $\langle q_t \rangle/p_{tc}$ is not too small, i.e., provided $\langle q_t \rangle > 1$–1.5 GeV/c, since the change in the exponent n was observed in[26] up to $p_{tc} \sim 4$ GeV/c.

5. OBSERVED CONSEQUENCES OF HIGH TRANSVERSE PARTON MOMENTA

1. The clearest manifestation of high $\langle q_t \rangle$ can be seen in the distribution over the transverse momentum of hadrons created in deep inelastic $ep(\nu N)$ scattering in the photon fragmentation region. It is well known that, in deep inelastic collisions, the virtual gamma ray (γ^* in Fig. 7) ejects one parton (1′) from the hadron, which then goes over into new hadrons.[1,2] In the rest system of the proton, this parton (1′) carries off practically the entire momentum of the gamma ray ($q_{\parallel 1'} \approx q_{\gamma^*}$) and has transverse momentum (relative to q_{γ^*}) of $q_{t1'} \approx \langle q_t \rangle$ (i.e., it retains the value q_{t1} which it had in the proton).

In the usual transition into hadrons (l pions, as described in Sec. 3), parton 1′ emits several quark-antiquark pairs and the result of this is that the transverse momentum of the created pions is small: $\langle p_{t\pi} \rangle \approx \langle q_t \rangle / l \approx 0.4$ GeV/c. However, the longitudinal pion momentum is also reduced by a factor of l as compared with q_{γ^*}. Let us select those events in which one of hadrons d carries off practically the entire momentum q_{γ^*} (for example, $x_d = p_{d\parallel}/q_{\gamma^*} > 0.9$), and let us measure the transverse momentum $\langle p_{td} \rangle$. The fraction of such events will, of course, be small. Since hadron d takes on practically the entire momentum of parton 1′, it will take up, in addition to the longitudinal part ($p_{d\parallel} \approx x q_{\parallel 1'}$), a comparable transverse part of the momentum $q_{1'}$ ($p_{td} \approx x q_{t1'} \approx x\langle q_t \rangle$), and the distribution over the transverse momentum of particles in the photon fragmentation region ($x_d > 0.9$) should turn out to be unusually broad: $\langle p_{td} \rangle \approx \langle q_t \rangle \approx 1.5$ GeV/c. We note that an increase in $\langle p_{td} \rangle$ is expected only for sufficiently large $q_{\gamma^*}^2$, when $q_{\gamma^*}/2 \gg \langle q_t \rangle$ (i.e., $Q^2 = -q_{\gamma^*}^2 \gg 4\langle q_t^2 \rangle$). We are aware of only the data on electrocreation for $Q^2 \leq 3$ (GeV/c)^2.[29] Even in this region, $\langle p_{td} \rangle$ increases with increasing x_d and increasing Q^2 roughly from 0.4 to 0.5 GeV/c.

2. High values of $\langle q_t \rangle$, taken together with the additive quark model, force us to reconsider highly inelastic processes at energies currently available. In the interval

$$1/R_p^2 = 4m_\pi^2 \ll Q^2/4 \ll \langle q_t^2 \rangle \qquad (18)$$

the virtual photon receives a valence quark surrounded by its cloud of partons (Fig. 6a) as if it were a point particle. The result is that, in the region defined by (18) [$Q^2 < 8$ (GeV/c)^2], we have the scaling relation $\nu W_2(\nu, Q^2) = F_2(\omega)$ ($\omega = 2m_p\nu/Q^2$, where ν is the photon energy in the system in which the nucleon is at rest), but the structure function will correspond to the fact that the nucleon consists of only three valence quarks and the sea of quark-antiquark pairs is absent (this is precisely the situation observed at the present time in various experimental situations (see, for example,[30]).

As Q^2 increases, the gamma ray begins to "feel" the structure of the parton clouds surrounding the valence quarks and a violation of the scaling relation may be observed in the intermediate region where $Q^2/4 \sim \langle q_t^2 \rangle$. The structure function will contain a contribution due to the quark-antiquark pair, and the value of νW_2 should increase for large ω (and the ratio of cross sections for deep inelastic reactions produced by the neutrino and the antineutrino should tend to unity). Next, the scaling relation is reestablished when $Q^2/4 \gg \langle q_t^2 \rangle$, but with new structure functions (the gamma ray is absorbed by the individual partons and not by the system consisting of the valence quark and its cloud of partons).

In the case of e^+, e^- annihilation, the asymptotic behavior corresponding to the picture discussed above begins only for values of $s = (p_{e^+} + p_{e^-})^2$ for which the energy $\sqrt{s}/2$ of quark 1 initially created by the photon (Fig. 3a) will, at the very least, be greater than $2\langle q_t \rangle$. This is connected with the fact that the hadrons consist of valence quarks (even in the case of annihilation into mesons, there are four such quarks) surrounded by a parton cloud (Fig. 6a). The energy necessary to produce each cloud is at least of the order of the mean transverse parton momentum ($\gtrsim \langle q_t \rangle$). Hence, it follows that $\sqrt{s}/2 > 2\langle q_t \rangle$ ($s > 16\langle q_t^2 \rangle > 32$ GeV^2).

We have thus obtained a quantitative estimate for the difference between deep inelastic scattering where ready "fully clad" valence quarks exist, and the e^+, e^- annihilation where they do not.

The above examples show that studies of deep inelastic processes for $Q^2 > 10$ (GeV/c)^2 are of fundamental importance. More detailed experiments involving the high value of $\langle q_t \rangle$, and other experiments which can be used to verify and improve the predictions of the parton model, are described in[31].

We are indebted to V. N. Gribov and J. D. Bjorken for interesting discussions of our results.

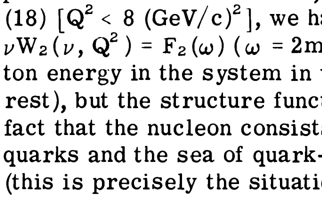

FIG. 7. Deep inelastic scattering in the parton model.

[1)]It is natural to suppose (this will be clear from Sec. 3) that $\langle p_\perp \rangle < \langle q_t \rangle$. Therefore, by substituting $\langle p_\perp \rangle = \langle q_t \rangle$, we obtain the lower limit for $\langle q_t \rangle$.

[2)]We are interested, in this section, in the distribution of the slow parton in one "comb" (Fig. 4a). The emission of several combs ("branching" in the terminology of the theory of complex angular momenta) leads to an increase in the size of the region occupied by the slow partons and an increase in the measured values of $b_{0\,\mathrm{eff}}$ and α'_{eff}, [17] as compared with the b_0 and α' for a single comb. This is why we have the inequality sign in (4) [$\alpha' \leqslant 0.28$ (GeV/c)$^{-2}$].

[3)]We are indebted to M. I. Strikman for suggesting this method of estimating the density of quark distribution (in rapadity space) over νW_2.

[4)]If the gamma ray interacts only with the u-quark as $x \to 1$, then $\langle e_i^2 \rangle = 4/9$, $\langle e_i \rangle = 2/3$ and this reduces $\langle q_t \rangle$ by 10% as compared with the estimate given by (13).

[5)]Nonemission of quarks means, in our language, that the quark and antiquark with $q_t \lesssim m_\rho$ (i.e., occupying a region $\gtrsim 1/m_\rho$) must necessarily unite into hadrons.

[6)]The formation of a hadron from a small number of partons is highly suppressed because, in the ground state, a fast hadron with momentum p_c contains $\ln p_c$ partons.

[7)]The mean transverse momentum of partons, $\langle q_t \rangle$, is a measure of the transverse hadron momentum p_{tc} in (17).

[1] R. P. Feynmann, Photon-Hadron Interactions (Russ. Transl., Mir, 1975, Chap. 16, pp. 310–366). R. P. Feynmann, Phys. Rev. Lett. 23, 1415 (1969).

[2] J. D. Bjorken and E. Paschos, Phys. Rev. 186, 1975 (1969).

[3] V. N. Gribov, Materialy 8-ĭ zimneĭ shkoly LIYaF po fizike yadra i élementarynykh chastits, Leningrad, 1973 (Proceedings of the Eighth Winter School of the

Leningrad Institute of Nuclear Physics on the Physics of the Nucleus and Elementary Particles, Leningrad, 1973), Part. 2, p. 5; Élementarnye chastitsy, 1 shkola fiziki ITÉF (Elementary Particles, First School of Physics of ITEF), No. 1, Atomizdat, 1973, p. 65.

[4] S. M. Berman, J. D. Bjorken, and J. B. Kogut, Phys. Rev. D 4, 3388 (1971); P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. D 8, 927, 4157 (1973); J. Kogut, C. Frae, and L. Susskind, Phys. Lett. B 40, 469 (1972); A. Casker, S. Nussinov, and L. Susskind, Phys. Lett. B 44, 511 (1973); S. D. Ellis and M. B. Kinslinger, Phys. Rev. D 9, 2027 (1974); E. M. Levin and M. G. Ryskin, Yad. Fiz. 18, 1108 (1973) [Sov. J. Nucl. Phys. 18, 570 (1974)], Preprint No. 97, LIYaF, 1974; Yad. Fiz. 21, 1072 (1975) [Sov. J. Nucl. Phys. 21, 553 (1975)].

[5] E. M. Levin and M. G. Ryskin, Materialy 10-ĭ zimneĭ shkoly LIYaF po fizike yadra i élementarnykh chastits (Proc. Tenth Winter School of the Leningrad Institute of Nuclear Physics on the Physics of the Nucleus and Elementary Particles), Part. 1, Leningrad, 1975, p. 46.

[6] M. Banner, J. L. Hamel, J. P. Pansart et al., Phys. Lett. B 41, 547 (1972); 44, 537 (1973). B. Alper, H. Bøggild, G. Jarlskog, et al., Nucl. Phys. B 87, 19 (1975).

[7] E. M. Levin and L. L. Frankfurt, ZhETF Pis'ma Red. 3, 125 (1966) [JETP Lett. 3, 79 (1966)]; Usp. Fiz. Nauk 94, 243 (1968) [Sov. Phys.-Usp. 11, 106 (1968)] Materialy 9-ĭ zimneĭ shkoly LIYaF po fizike yadra i élementarnykh chastits (Proc. Ninth Winter School of the Leningrad Institute of Nuclear Physics on the Physics of the Nucleus and Elementary Particles), Vol. 3, Leningrad, 1974, p. 28.

[8] A. B. Kaĭdalov, Yu. F. Pirogov, N. L. Ter-Isaakyan, and V. A. Khoze, ZhETF Pis'ma Red. 17, 626 (1973) [JETP Lett. 17, 440 (1973)].

[9] F. Finocchiaro, R. Grannis, D. Green, et al., Phys. Lett. B 50, 396 (1974).

[10] D. Horn and M. Moske, Nucl. Phys. B 48, 557 (1972); J. Gunion, S. J. Brodsky, and R. Blenkenbecler, Phys. Lett. B 39, 649 (1972).

[11] P. V. Landshoff and J. C. Polkinghorne, Phys. Lett. B 44, 293 (1973).

[12] S. Drell and T. M. Yan, Phys. Rev. Lett. 25, 316 (1970).

[13] J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, B. G. Pope, and E. Zavattini, Phys. Rev. D 8, 2016 (1973).

[14] B. Richter, Report on Seventeenth Intern. Conf. on High Energy Physics, London, 1974, IV-37.

[15] V. Bartenev, A. Kuznetsov, B. Morozov, et al., Phys. Rev. Lett. 31, 1088 (1973).

[16] V. N. Gribov, Yad. Fiz. 9, 640 (1969) [Sov. J. Nucl. Phys. 9, 369 (1969)].

[17] Yu. I. Azimov, V. A. Khoze, E. M. Levin, and M. G. Ryskin, Nucl. Phys. B 89, 508 (1975).

[18] G. M. Miller, E. D. Bloom, G. Buschhorn, et al., Phys. Rev. D 5, 528 (1972).

[19] V. A. Abramovskiĭ, V. N. Gribov, and O. V. Kancheli, Yad. Fiz. 18, 595 (1973) [Sov. J. Nucl. Phys. 18, 308 (1974)].

[20] K. G. Boreskov, A. N. Lapidus, S. T. Sukhorukov, and K. A. Ter-Martirosyan, Yad. Fiz. 14, 814 (1971) [Sov. J. Nucl. Phys. 14, 457 (1972)]. K. A. Ter-Martirosyan, Phys. Lett. B 44, 377 (1973).

[21] E. M. Levin and M. G. Ryskin, Yad. Fiz. 17, 388 (1973) [Sov. J. Nucl. Phys. 17, 199 (1973)]; Phys. Lett. B 41, 626 (1972).

[22] S. Drell and T. M. Yan, Phys. Rev. Lett. 24, 181 (1970).

[23] D. M. Coward, H. Destaebler, R. A. Early, et al., Phys. Rev. Lett. 20, 292 (1968).

[24] E. M. Levin and M. G. Ryskin, ZhETF Pis'ma Red. 16, 495 (1972) [JETP Lett. 16, 353 (1972)]; Yad. Fiz. 19, 904 (1974) [Sov. J. Nucl. Phys. 19, 461 (1974)].

[25] J. J. Kokkede and L. Van Hove, Nuovo Cimento 42, 711 (1966); A. Bialas and A. Zalewsky, Nucl. Phys. B 6, 465, 449, 478 (1968).

[26] J. M. Cronin, Proc. Summer Institute on Particle Physics, July 29-August 10, 1974, Vol. 2, SLAC-Rep No. 179, November 1974.

[27] M. Bander, R. M. Barnett, and D. Silverman, Phys. Lett. B 48, 243 (1974); S. D. Ellis, Phys. Lett. B 49, 189 (1974); V. F. Gunion, S. J. Brodsky, and R. Blankenbecler, Univ. of Pittsburgh Preprint PITT-124, 1974.

[28] R. Blankenbecler and S. J. Brodsky, Phys. Rev. D 10, 2973 (1974); E. M. Levin and M. G. Ryskin, Yad. Fiz. 22, 428 (1975) [Sov. J. Nucl. Phys. 22, 219 (1975)].

[29] J. T. Dakin, G. J. Feldman, F. Martin, M. L. Perl, and W. T. Toner, Phys. Rev. D 10, 1401 (1974).

[30] F. Gilman, Report on Seventeenth Intern. Conf. on High Energy Phys., London, 1974, SLAC-PUB-1455 (T) (E), July, 1974.

[31] E. M. Levin and M. G. Ryskin, Preprint No. 165, LIYaF, 1975.

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