PHYSICAL REVIEW D VOLUME 10, NUMBER 11 1 DECEMBER 1974

Production of large-transverse-momentum mesons from a meson beam

B. L. Combridge
Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England
(Received 8 April 1974)

The Landshoff-Polkinghorne quark-fusion model for the production of large-transverse-momentum mesons from high-energy hadronic processes is applied to meson-nucleon collisions. A second, leading-particle, contribution from large-angle scattering of the incident meson is included in the calculation and has the same power dependence on p_T at fixed $p_T/\sqrt{s}$ and fixed center-of-mass scattering angle. Numerical calculations are presented for $\pi^+p \rightarrow M + X$ assuming SU(3) couplings of quarks to the pseudoscalar mesons M. Mainly because of the leading-particle effect, some of the cross sections are substantially higher than in proton-proton collisions. Although the over-all normalization is obtained by fitting just the quark-fusion model to the experimental data on $pp \rightarrow \pi + X$ at large p_T, it is estimated that the choice of normalization is not substantially changed by the inclusion in this fit of the hadronic bremsstrahlung process proposed by Blankenbecler, Brodsky, and Gunion.

I. INTRODUCTION

In the past year or so, a number of experiments[1-3] have been reported giving inclusive cross sections at large transverse momentum ($p_T \gtrsim 1$ GeV/c) in proton-proton collisions rising with increasing energy, and showing a falloff with p_T (at fixed $p_T/\sqrt{s}$) better described by an inverse power than the exponential decrease found at small p_T.

Although the available data is not good enough to put strong constraints on the form of the single-particle inclusive cross section, it is at least compatible with

$$E\frac{d\sigma}{d^3p} \sim p_T^{-N} f(p_T/\sqrt{s}, \theta) \tag{1}$$

as $s \rightarrow \infty$ at fixed $p_T/\sqrt{s}$. θ is the center-of-mass scattering angle.

Almost all the mechanisms invoked to describe the large-p_T behavior give rise to the above form, although they may differ in the value of N and the form of the function f. Fits to the data suggest $N \simeq 8$ (Ref. 1) or even 11 (Ref. 3) and seem definitely to rule out the naive scaling result $N=4$ (although it may be that the true asymptotic behavior has yet to be seen[4]).

The scaling observed in electron- and neutrino-initiated reactions in the deep-inelastic region encourages the belief that hadrons are composite systems of pointlike partons, which may be tentatively identified as quarks. The best possibility for seeing similar structure in hadron-hadron interactions is generally supposed to occur in large-transverse-momentum production processes where the dominant mechanism(s) may be expected to be relatively simple. Figure 1 illustrates two popular classes of models which attempt to describe these purely hadronic phenomena in such terms, although the basic assumptions are not as well defined or as well motivated as those in the electromagnetic- or weak-current processes. In Fig. 1(a), a parton of low transverse momentum fuses with one of high transverse momentum to produce the observed large-p_T meson.[5] In Fig. 1(b), two partons of low transverse momentum scatter at large angle; one of the partons subsequently evolves into the observed large-p_T meson.[6]

Both processes can give rise to the form (1) by relating the various parton-hadron amplitudes to the structure functions occurring in electroproduction and e^+e^- annihilation, although in the case of Fig. 1(a) a further assumption must be made as to the dominant production mechanism of the large-transverse-momentum parton from its parent hadron. Figure 1(b) gives the unwanted scale-free result if large-angle high-energy parton-parton scattering has the same behavior as the minimum connected diagram (single-gluon exchange); the process of Fig. 1(a) must be counted more successful in this respect, as an inherent scale can be naturally introduced by a suitable softening of the parton-parton-meson vertex.

Landshoff and Polkinghorne[8] have considered a particular contribution to Fig. 1(a) in which the large transverse momentum of one of the partons is produced in the bremsstrahlung of a large-transverse-momentum meson (Fig. 2). They suppose that the parton-parton-meson vertex has the form $C\gamma_5(-k^2)^{-\gamma}$ when the momentum squared (k^2) in (just) one of the parton legs is large, with C dependent only on the choice of partons and meson. Assuming then that the mesons of the pseudoscalar octet have the most nearly pointlike coupling to the partons and hence the least value of γ, these dominate and $N=4+8\gamma$.

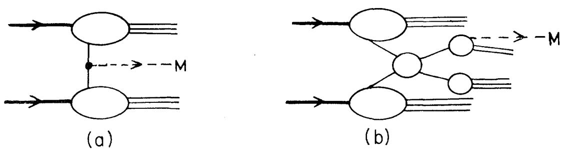

FIG. 1. (a) A fusion process. (b) A scattering process.

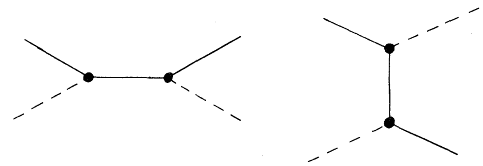

FIG. 3. Born-like approximations for high-energy large-angle parton-meson scattering.

A value for γ of $\frac{1}{2}$ is compatible with CERN Intersecting Storage Rings (ISR) data[1] and agrees with the dimensional counting of Brodsky and Farrar and Matveev *et al.*[9] for exclusive processes if large-angle parton-meson scattering at high energy can be assumed to have the same behavior as the Born-like terms of Fig. 3.

Further, by identifying the partons with quarks and using a two-component fit to the electron and neutrino data and relating the various vertex constants C by SU(3), Landshoff and Polkinghorne[6,7] obtain the function $f(p_T/\sqrt{s}, \theta)$ of (1) up to a multiplicative constant arising from the vertex functions.

In the following we consider, in this model, the general process

$$M'N \to M + X$$

for nucleon N, mesons M, M'; M with large transverse momentum. As well as the contribution of Fig. 2, we include a term from the large-angle scattering of M' with a low-transverse-momentum quark from N using the Born-like terms of Fig. 3 for the quark-meson amplitude (Fig. 4); note that this allows $M \neq M'$. These diagrams have previously been discussed by Gunion, Brodsky, and Blankenbecler.[14] The contribution from this leading-particle effect can be calculated under the above assumptions and has the form of (1), with again $N=4+8\gamma$ ($=8$ if $\gamma=\frac{1}{2}$ as we will assume), and is the dominant contribution near the kinematic boundary for those mesons M for which it is present. Numerical calculations have been made for $\pi^+p \to M+X$ and we find that this leading-particle process is also the major mechanism at more moderate $p_T/\sqrt{s}$. Furthermore, some cross sections are orders of magnitude higher than the corresponding $pp \to M+X$ processes.

Our choice of over-all normalization depends on the quark-fusion model fit to data[1,3] on $pp \to \pi + X$ at large p_T. This choice is partially justified by showing that the inclusion in the fit of a hadronic bremsstrahlung process of the type proposed by Blankenbecler, Brodsky, and Gunion[15] does not substantially affect our predictions.

II. CALCULATION

The process of Fig. 2 is calculated by taking the relevant discontinuities in the forward amplitudes of Figs 5(a)–5(d). The result is a sum of contributions to $E d\sigma/d^3p$ having the form[8]

$$p_T^{-4-8\gamma} \int d\alpha_1 d\alpha_2 \delta(\alpha_1+\alpha_2-1) G(\alpha_1, \alpha_2) \times F_2^{N,a}\left(\frac{\alpha_1}{x\tan\frac{1}{2}\theta}\right) F_2^{M',b}\left(\frac{\alpha_2}{x\cot\frac{1}{2}\theta}\right) ,$$
$$x = p_T/\sqrt{s}$$

where G is a known function arising from the couplings of the mesons to the quarks and $F_2^{y,z}(\omega)$ is the contribution of quark z to the structure function $F_2(\omega)$ of the hadron y. For $F_2^{N,z}(\omega)$ we use the two-component fit of Landshoff and Polkinghorne[10] to the electron and neutrino data:

$$F_2^{N,z}(\omega) = v_{N,z} R_N(\omega) + D_N(\omega) ,$$

where

$$R_N(\omega) = \tfrac{15}{16}\left(1-\frac{1}{\omega}\right)^2 \omega^{-1/2}\theta(\omega-1) ,$$

$$D_N(\omega) = \tfrac{1}{10}\left(1-\frac{2}{\omega}\right)\theta(\omega-2) ,$$

and $v_{N,z}$ is the number of valence z quarks in the nucleon N. For $F_2^{M'z}(\omega)$ we use a similar two-component model used by Fidler[11]:

$$F_2^{M',z}(\omega) = v_{M',z} R_{M'}(\omega) + D_{M'}(\omega) ,$$

where

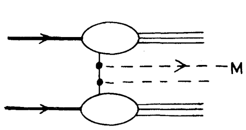

FIG. 2. A particular contribution to Fig. 1(a).

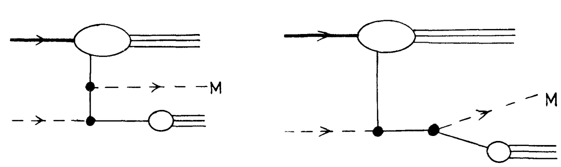

FIG. 4. Leading-particle contribution to $M'N \to M+X$.

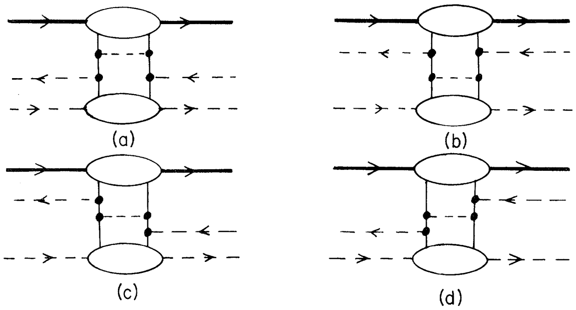

FIG. 5. Contributions to the inclusive cross section from the fusion process of Fig. 2.

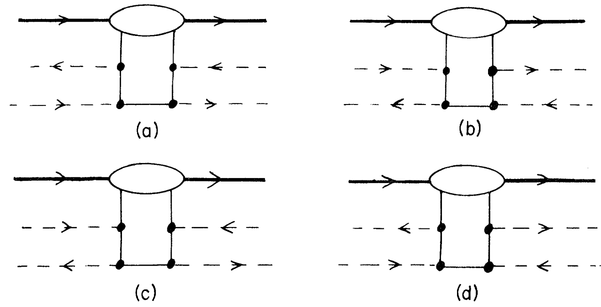

FIG. 6. Contributions to the inclusive cross section from the leading-particle process of Fig. 4.

$$R_{M'}(\omega)=k\left(1-\frac{1}{\omega}\right)^{\lambda}\omega^{-1/2}\theta(\omega-1)\,,$$

$$k \text{ such that } \int_1^{\infty}\frac{d\omega}{\omega}R_{M'}(\omega)=1$$

$$D_{M'}(\omega)=\tfrac{1}{15}\left(1-\frac{2}{\omega}\right)\theta(\omega-2)\,.$$

We take $\lambda=1$ (hence $k=\frac{3}{4}$) to give the linear threshold behavior expected in some models.[12]

The process of Fig. 4 is calculated by taking the relevant discontinuities in the forward amplitudes of Figs. 6(a)–6(d). These give a sum of contributions to $Ed\sigma/d^3p$ of the form[13]

$$\left(\frac{p_T\cot\frac{1}{2}\theta}{\omega^{1/2}}\right)^{-4-8\gamma}H(x\cot\tfrac{1}{2}\theta)F_2^{N,a}(\omega)\,,$$

$$\omega=\frac{1-x\cot\frac{1}{2}\theta}{x\tan\frac{1}{2}\theta}$$

where H is a known function arising from the couplings of the mesons to the quarks. γ is taken equal to $\frac{1}{2}$.

The ratio of the contributions of the two processes is then determined and their absolute values require only the magnitude of the meson-quark-quark vertex. This has effectively been found by comparing data[1,3] on $pp\to\pi+X$ at large transverse momentum with the corresponding calculations of Fig. 2. Of course, other mechanisms must also contribute to $pp\to\pi+X$, and so to check this procedure, we have calculated a contribution to $pp\to\pi^++X$ at large p_T from the hadronic bremsstrahlung process of Blankenbecler, Brodsky, and Gunion[15] in which a quark from one of the protons scatters at large angle with a pion from the other proton. The quark-pion scattering was calculated as described above and we assumed that 10% of the momentum of a proton was carried by its pion cloud.[16] We find that the hadronic bremsstrahlung and quark-fusion processes are nearly equal for $pp\to\pi^++X$ in the range $x=0.1$ to 0.2 (the range in which most of the data fall). Thus it seems likely that the effect of neglecting the hadronic bremsstrahlung process on our choice of normalization will not greatly exceed the uncertainty introduced by the normalization discrepancies in the present data.

Table I and Figs. 7–9 give the result of numerical calculations in the case of $\pi^+p\to M+X$. Table I shows the relative multiplicities for large-p_T mesons for various angles and values of x. The dominance of π^+ production is due to the magnitude of the leading-particle effect for this process: Figure 7 shows the variation with x at fixed s of the π^+ inclusive cross section and the quark-fusion contribution to it. The leading-particle term is less important for the other mesons M for which it is present, viz. π^0, K^+, $\bar{K}^0$, η. Figures 8 and 9 show the angular distribution of π^+ at $x=0.1$ and 0.2, respectively; the two contributions are also displayed. The values shown for the cross sections in Figs. 7–9 are for $s=500$ GeV^2, but the shape of the distributions is s-independent. Finally, we note that the results are fairly insensitive to the assumptions on the structure functions, particularly for small x; also, the π^- and K^0 inclusive cross sections are identical under the assumptions of the calculation.

TABLE I. Relative multiplicities in $\pi^+p\to M+X$ ($x=p_T/\sqrt{s}$; θ is angle with π^+ beam in the center-of-mass frame).

θ	x	π^+	π^0	π^-	K^+	K^0	$\bar{K}^0$	K^-	η
37°	0.1	1	0.45	0.03	0.19	0.03	0.38	0.02	0.12
	0.2	1	0.52	0.0007	0.15	0.0007	0.26	0.0002	0.06
90°	0.1	1	0.45	0.12	0.28	0.12	0.26	0.06	0.17
	0.2	1	0.36	0.03	0.13	0.03	0.12	0.009	0.10
	0.3	1	0.33	0.007	0.05	0.007	0.05	0.0002	0.07
143°	0.1	1	0.54	0.26	0.51	0.26	0.11	0.05	0.20
	0.2	1	0.33	0.07	0.15	0.07	0.0009	0.0001	0.10

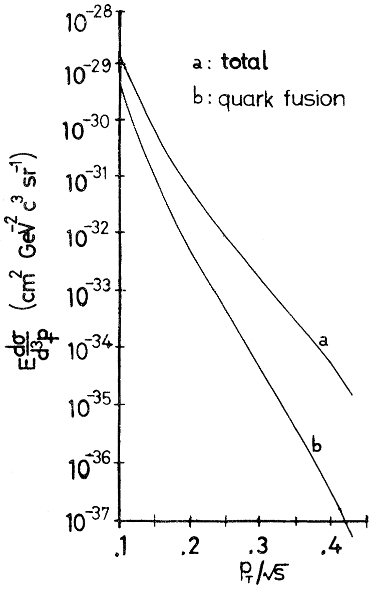

FIG. 7. Prediction for $\pi^+ p \to \pi^+ + X$ at 90° and $s = 500$ GeV^2. The contribution from quark fusion is also displayed.

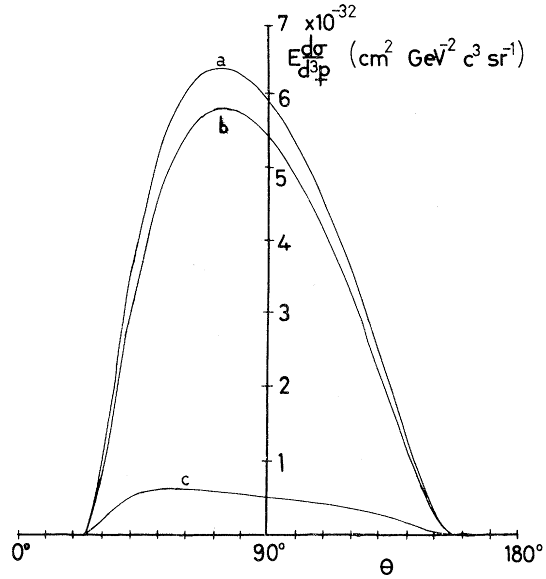

FIG. 9. Prediction for the angular distribution in $\pi^+ p \to \pi^+ + X$ at $s = 500$ GeV^2 with $p_T/\sqrt{s} = 0.2$. See caption to Fig. 8.

III. DISCUSSION

The major feature of the numerical calculation is that $\pi^+ p \to \pi^+ + X$ is already an order of magnitude larger than $pp \to \pi^+ + X$ at $x = 0.1$ and falls much slower with increasing x. This is mainly due to the leading-particle effect, although the quark-fusion contribution is itself enhanced by the valence antiquark in the incident meson. Moreover, the calculation is still an underestimate in that the fragmentation of the quark which scatters with the incident meson has been neglected.

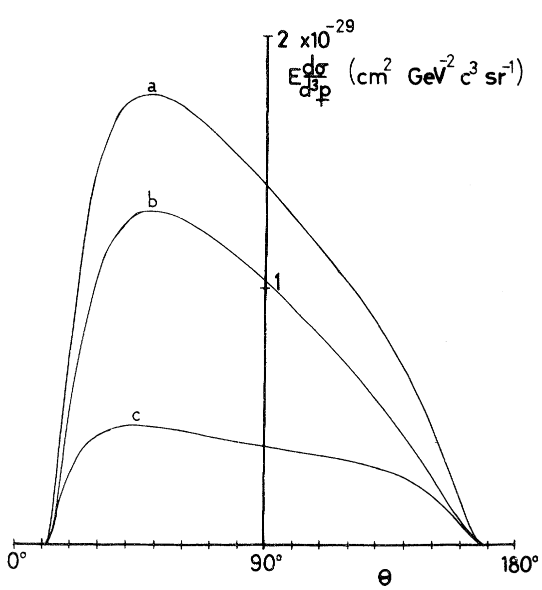

FIG. 8. Prediction for the angular distribution in $\pi^+ p \to \pi^+ + X$ at $s = 500$ GeV^2 with $p_T/\sqrt{s} = 0.1$. θ is the angle with the pion beam in the center-of-mass frame. Besides the total (a), both the leading-particle contribution (b) and the quark-fusion contribution (c) are also displayed.

However, although the ratio of the two contributions is determined by the model, their normalization depends on the assumption that quark fusion (perhaps together with a similar contribution from meson bremsstrahlung) is the important mechanism in $pp \to M + X$ at large p_T. Thus meson beam experiments determining the size of these inclusive cross sections or showing the distinctive relative multiplicities associated with the leading-particle effect could also throw interesting light on proton-proton collisions.

Finally, our results may have important consequences for the production of large-transverse-momentum mesons from a proton beam on a nuclear target. Since, in the model, the replacement of a proton beam by a pion beam very greatly increases the number of large-p_T events, it may be that the generation of secondary mesons within the nucleus and their subsequent interaction with other nucleons is a significant mechanism, even though rather few of the secondary mesons have high enough energy to produce large p_T. This possibility is under investigation in the light of recent Fermi National Accelerator Laboratory data.[3]

ACKNOWLEDGMENTS

I am very grateful to Dr. P. V. Landshoff for his advice and encouragement. I would also like to thank K. J. Evans, R. W. Fidler, R. P. Hughes, and D. M. Scott for useful discussions. I am grateful to the Science Research Council and Churchill College for financial support.

---

[1]CERN-Columbia-Rockefeller Collaboration (F.W. Büsser *et al.*), Phys. Lett. 46B, 471 (1973).

[2]Saclay-Strasbourg Collaboration (M. Banner *et al.*), Phys. Lett. 44B, 537 (1973).

[3]Chicago-Princeton Collaboration (J. W. Cronin *et al.*), Phys. Rev. Lett. 31, 1426 (1973).

[4]S. D. Ellis, Phys. Lett. 49B, 189 (1974).

[5]P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. D 8, 927 (1973). A similar process is the interchange model of R. Blankenbecler, S. J. Brodsky, and J. F. Gunion, Refs. 14 and 15.

[6]S. M. Berman, J. D. Bjorken, and J. B. Kogut, Phys. Rev. D 4, 3388 (1971). See also Ref. 7.

[7]P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. D 10, 891 (1974).

[8]P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. D 8, 4157 (1973).

[9]S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973); V. A. Matveev, R. M. Muradyan, and A. N. Tavkhelidze, Nuovo Cimento Lett. 7, 719 (1973).

[10]P. V. Landshoff and J. C. Polkinghorne, Phys. Lett. 34B, 621 (1971), and references therein.

[11]R. W. Fidler, Phys. Lett. 46B, 455 (1973).

[12]For example, see R. P. Hughes, Nucl. Phys. B79, 153 (1974).

[13]D. M. Scott, Nucl. Phys. B74, 524 (1974).

[14]J. F. Gunion, S. J. Brodsky, and R. Blankenbecler, Phys. Rev. D 6, 2652 (1972).

[15]R. Blankenbecler, S. J. Brodsky, and J. F. Gunion, Phys. Lett. 42B, 461 (1972).

[16]For the pion momentum distribution we used Eq. (9) of R. Blankenbecler and S. J. Brodsky, Phys. Rev. D 10, 2973 (1974).