Vector-meson production at large transverse momentum

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This paper considers possible extensions of the Landshoff-Polkinghorne quark-fusion model, for the production of large-p_T pseudoscalar mesons, to include the vector-meson nonet. The relative multiplicities of pseudoscalars, taking vector-meson decay into account, are calculated in two models. The leptonic decays of the ρ^0, ω, and ϕ give rise to a predicted e^+/π^+ ratio of about 5×10^{-5} in both models. Qualitative features of the models are discussed in the light of existing data on the structure of large-transverse-momentum events.

I. INTRODUCTION

At low transverse momentum ($p_T \lesssim 1$ GeV/c), it is well known that the dependence of particle yields on p_T can be described by exponential, s-independent falloffs. In the last few years, high-energy experiments with p-p and p-nucleus collisions have demonstrated the existence of a new regime at larger values of p_T.[1] There are three main qualitative differences in this new regime:

(1) less-rapid falloff in p_T (becoming an inverse power of p_T as $s \to \infty$?),
(2) strong s dependence, with the cross sections rising with increasing s,
(3) larger relative multiplicities for the heavier particles (K's, p's, $\bar{p}$'s, etc.).

In particular, the single-particle inclusive cross sections are roughly compatible with the form

$$E\frac{d\sigma}{d^3p} = s^{-N} f(x_T, \theta) \tag{1}$$

where $x_T = 2p_T/\sqrt{s}$, θ is center-of-mass scattering angle, and N lies between 4 and 6.

Parton mechanisms

These results have been widely received as further evidence for the existence of the partons (hadronic constituents with pointlike weak and electromagnetic interactions) "discovered" by Bjorken scaling. For the purposes of this paper we take these partons to be Gell-Mann–Zweig quarks.

All the various proposed parton mechanisms have the form of Fig. 1. The large transverse momentum is produced in a single hard scattering of a constituent (1) of A (or A itself) with a constituent (2) of B (or B itself) into two systems (3, 4), one of which (3) either is C or decays/fragments to give C; by a constituent we mean a system of one or more quarks arising from the parent hadron. The necessary inputs for a calculation of the process are the momentum distributions of 1 and 2 within their parent hadrons (these are related to the electromagnetic structure function $F_2(\omega)$ if 1, 2 are quarks), the momentum distribution of C in 3 (essentially the e^+e^- annihilation structure function $\bar{F}_2(\omega)$ if 3 is a quark), and a model for the hard-scattering amplitude. For the latter, dimensional counting is generally used as a guide[8]; then asymptotically ($s\to\infty$ at fixed x_T, θ) the form (1) is obtained with N given by $N = n-2$, where n is the total number of quark fields in the initial and final states of the hard scattering.

The following list gives the value of N corresponding to various hard scatterings. The secondary arrows denote some of the possible subsequent fragmentations, which do not change the value of N.

$N=2$: $q+q\to q+q$, $q \searrow q+M$, (2a)

$N=4$:
$q+\bar{q}\to M+M$, (2b)
$q+M\to q+M$, $q\searrow q+M$, (2c)
$q+q\to B+\bar{q}$, $\bar{q}\searrow \bar{q}+M$, (2d)
$q+q\to M+(qq)$, $(qq)\searrow \bar{q}+B$, (2e)

$N=6$:
$q+B\to q+B$, $q\searrow q+M$, (2f)
$q+(qq)\to B+\boldsymbol{M}$, (2g)
$M+M\to M+M$, (2h)

etc.

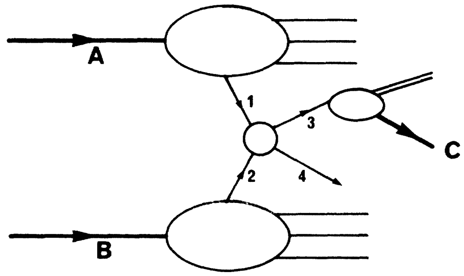

FIG. 1. General parton-model view of $A+B\to C+X$; C has large transverse momentum.

Now the data for meson production at large p_T are well described by the form (1) except that N has an apparent x_T dependence.[9] Since N is uniformly greater than 2, it appears that the mechanism (2a) is unimportant, perhaps because of a dynamical suppression or a selection rule[8] or some other mechanism.[10] The x_T dependence of N is plausibly explained by supposing that there are two (or two sets of) important mechanisms. One of these mechanisms has $N=4$ and the other has $N=6$, with the scaling function f in (1) of the latter falling off less rapidly as x_T approaches its kinematic limit $\sin\theta$. Then at any fixed energy the $N=6$ mechanism is dominant for sufficiently large x_T. Counting rules (see Ref. 11 and references therein) which are used to predict the different behaviors of the mechanisms in (2) as $x_T\to\sin\theta$ support this general picture.[11] These counting rules may also be used to indicate the relative importance of particular mechanisms, although at small values of x_T the extrapolation from the exclusive limit should be viewed with some caution. We here confine our attention to the CERN-ISR range $0.1\lesssim x_T\lesssim 0.4$, $23\lesssim\sqrt{s}\lesssim 62$ GeV, where the meson production data[2] are in good agreement with the form (1) with $N=4$.

Meson bremsstrahlung and quark fusion

We consider further the processes (2b) and (2c) for large-p_T meson production, noting that crossing symmetry implies that if one is present then so is the other. Blankenbecler, Brodsky, and Gunion[12] proposed the original model (Fig. 2) for a hard scattering of the form (2c)—"meson bremsstrahlung." Landshoff and Polkinghorne[13] have considered a model (Fig. 3) of type (2b)—"quark fusion." Both models assume the two-quark–two-meson amplitude to be dominated by quark exchange when the invariants become large together. More detailed descriptions of these two processes are given in Refs. 12 and 13; we note here that calculations in each model give a reasonable fit to the single-particle inclusive cross section at large p_T.

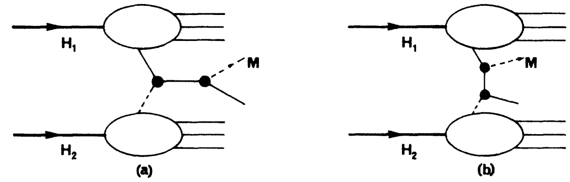

FIG. 2. Meson-bremsstrahlung processes for $H_1+H_2\to M+X$ at large p_T.

Since the over-all normalization of these contributions is a free parameter, the question of their relative normalization is important. There are reasons to believe that quark fusion is *at least* as important a mechanism as meson bremsstrahlung for large-p_T meson production at the CERN ISR: A calculation, to this effect, of the relative magnitudes of these two contributions to the inclusive cross section has been described elsewhere[14] (although this calculation was restricted to pseudoscalars, its extension to include vector mesons, following the methods of this paper, can only further tighten the upper bound on meson bremsstrahlung).

Some corroborative evidence is given by the experimental results of the British-Scandinavian collaboration[4] on the particle ratio π^-/π^+ in p-p collisions: At large p_T and $\theta\simeq 90°$, they find this ratio to be fairly constant at around 0.85. Unfortunately, although at some energies their p_T range extends as far as 4 or 5 GeV/c, the corresponding ranges in x_T do not exceed the rather small value of 0.2. (The results of the Chicago-Princeton collaboration[3] cover a much larger range of x_T; however, they use a nuclear target and it is an open question as to how much nuclear effects color the single-particle distributions arising from the individual p-nucleon collisions.) Despite this limited experimental x_T range, however, it is still interesting to note that the result $\pi^-/\pi^+\simeq 0.85$ is, as we shall see later, typical of quark-fusion models. On the other hand, with meson bremsstrahlung one expects a result closer to 0.5. The reason for this can be demonstrated by the follow-

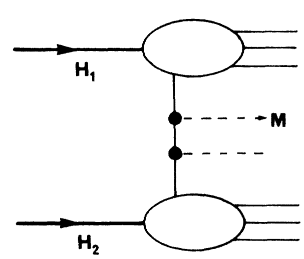

FIG. 3. Quark-fusion process for $H_1+H_2\to M+X$ at large p_T.

ing simple meson-bremsstrahlung model.

We restrict our attention to the process of Fig. 2(b), since this is numerically the dominant contribution because the central quark line in Fig. 2(a) has a greater momentum squared than its counterpart in Fig. 2(b). The quark constituent of the one proton is taken to be a valence quark, and twice as likely to be a $\mathcal{P}$ quark as an $\mathfrak{N}$ quark, while the meson constituent of the other proton is taken at least as likely to be $\pi^+, \bar{K}^0, \rho^+, \bar{K}^{*0}, \ldots$ as $\pi^-, K^-, \rho^-, K^{*-}, \ldots$, respectively (there is no need for restrictions on π^0, η, K^+, K^0, etc.)—not an unreasonable assumption in view of the quark content of these mesons and of their parent proton.[15] Consideration of the possible contributions quickly gives the result $\pi^-/\pi^+ \leq \frac{1}{2}$. Including the quark sea of the proton and the additional process of Fig. 2(a), together with the interference terms, can raise the predicted ratio a little; a more detailed calculation we have made gives $\pi^-/\pi^+ \simeq 0.6$.[16]

It is preferable to use the π^-/π^+ ratio to discriminate between models rather than the K^+/π^+, K^-/π^+ ratios because of the uncertainty of how to introduce SU(3) breaking; the π^-/π^+ ratio should be far less dependent on the nature and magnitude of this effect than the K/π ratios are [cf. the "U(3)" results of Table IV and the "broken-U(3)" results of Table II for ρ^-/ρ^+, K^*/ρ^+].

Other parton processes

Perhaps rather arbitrarily we rule out mechanisms other than quark fusion and meson bremsstrahlung as being the dominant process for large-p_T meson production at the CERN ISR, by supposing that amplitudes involving a diquark system are suppressed relative to corresponding amplitudes with a meson and that the falloff of cross sections with p_T gives a sufficient suppression to processes requiring secondary fragmentation since the primary must generally have a greater transverse momentum than the observed p_T. Accordingly, in Sec. II we consider quark fusion further and compare the data with other predictions of the model. We shall find that extension of the theory to include the vector mesons explains satisfactorily many aspects of the data. It should be noted, however, that the counting rules, referred to above, which are used to determine the $x_T \to \sin\theta$ behavior of the various mechanisms, do require that leading-particle processes dominate quark fusion as x_T approaches the exclusive limit.

Large-p_T baryons

Baryon production at large transverse momentum is not discussed here, although, as the British-Scandinavian results[4] (see Fig. 4) show, protons and antiprotons form a substantial fraction of the total of all charged particles found at large p_T. It is more difficult, however, to construct plausible simple models for the hard scattering in the baryon case, and we will restrict our attention to meson production, except for the following general comment:

Leading-particle processes such as (2f), in which one of the initial-state hadrons is a participant in the hard scattering, may be particularly important for large-p_T baryon production. Such processes should also leave a very noticeable signature in terms of event structure. Triggering on a baryon, of given p_T and rapidity, from a leading-particle process requires its partner in the hard scattering to emerge at a particular angle to the beams as well as with equal and opposite transverse momentum. Non-leading-particle processes, on the other hand, do not strongly constrain the direction of the balancing particle or jet of particles. It will be interesting to examine the opposite-side angular distributions in experiments with large-p_T proton triggers.

II. RELATIVE MULTIPLICITIES AND EVENT STRUCTURE

In Fig. 4 we have used the results obtained by the British-Scandinavian collaboration[4] at the CERN

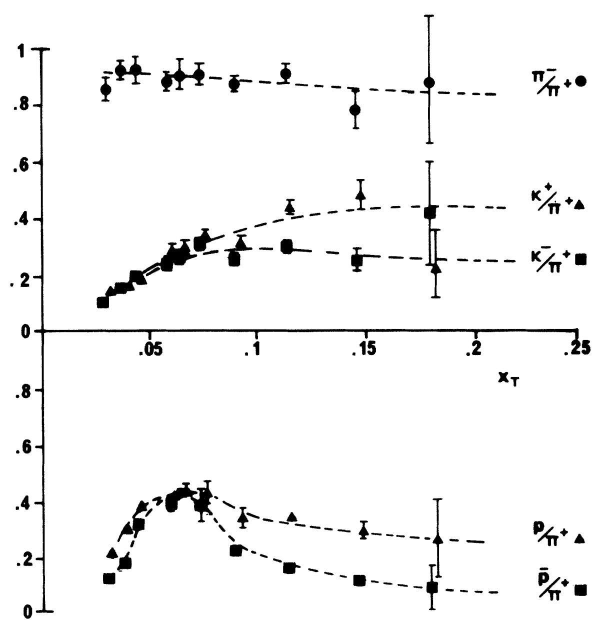

FIG. 4. Experimental results for charged-particle relative multiplicities at large p_T in p-p collisions at $\sqrt{s} = 52.8$ GeV, $\theta \simeq 90°$. Notional statistical errors are shown. The dashed curves are to guide the eye. The plot is based on data obtained by the British-Scandinavian collaboration (Ref. 4) at the CERN ISR.

ISR on charged-particle composition at large p_T in p-p collisions to plot the ratios π^-/π^+, K^+/π^+, K^-/π^+, p/π^+, and $\bar{p}/\pi^+$ versus x_T for $\sqrt{s}=52.8$ GeV and $\theta \simeq 90°$. The x_T range covered by this experiment is unfortunately rather limited; however, for our purposes, these are the most reliable data available, since particle ratios may be particularly sensitive to nuclear effects in the targets used in corresponding experiments[3] at Fermilab.

Table I gives the prediction of simple quark fusion (i.e., with pseudoscalars only) for meson relative multiplicities in p-p collisions with $x_T=0.2$, 0.4 and $\theta=90°$. Unlike Landshoff and Polkinghorne,[13] we have included the (supposed) SU(3) singlet, $X^0(958)$, by assuming U(3)-invariant vertices. This only changes slightly the predictions for the octet and is in line with the approach to vector-meson production described below. The π^-/π^+ ratio is in good agreement with experiment, and it is plausible that the experimentally smaller-than-predicted K/π ratios are due to a suitable breaking of the meson-vertex symmetry.

Although in general the various parton and other models agree equally well with the observed large-p_T single-particle inclusive cross section, they differ considerably in their predictions for the associated structure of these events. Accordingly there is increasing experimental investigation in this field to try to discriminate between models. Simple quark fusion, for example, predicts that, at large p_T, pseudoscalars are produced in pairs with nearly equal and opposite tranverse momenta, although their longitudinal rapidities can be quite different. There is little experimental encouragement for this view, however. Indeed, the picture which is now emerging, despite the difficulties in obtaining detailed studies of event structure at large multiplicity, is characterized by the results of the Pisa–Stony Brook collaboration,[17] who have observed that their data are compatible with the following: A large-p_T event is viewed as a normal hadronic reaction at a reduced energy, together with the triggering particle produced on one side and a "balancing" jet of particles produced on the other. The jet is approximately opposite to the trigger in azimuthal angle but not necessarily so in rapidity. Their calculation in this model gives the mean number of (charged) particles in the jet to be independent of s and approximately proportional to the trigger p_T for $0.8 \lesssim p_T \lesssim 3.8$ GeV/c. The slope of this p_T dependence is about 0.75 charged particles/(GeV/c). However, it must be emphasized that this is only a tentative description.

The most surprising feature of the data is that there are significantly large correlations between the trigger and particles emitted in the same (azimuthal) hemisphere.[17–19] Presumably these

TABLE I. Predicted pseudoscalar relative multiplicities at large p_T ($\theta=90°$) in a simple quark-fusion model for $pp \to M+X$.

x_T	π^+	π^0	π^-	K^+	K^0	$\bar{K}^0$	K^-	η	X^0
0.2	1.00	0.90	0.79	1.00	0.79	0.58	0.58	0.69	0.43
0.4	1.00	0.92	0.83	1.00	0.83	0.67	0.67	0.75	0.29

are the results of a dynamical mechanism, since they cannot be due to energy-momentum conservation. However, it should be noted that simple models can be constructed, with no dynamical correlations between the produced particles, which do show positive correlations of this type, though possibly not of the observed magnitude.[20]

π^0-π^0 correlations

Also, returning to the simple quark-fusion model, one can show that the predicted correlation between two neutral nonstrange mesons produced with large p_T at the same polar angle to one of the two proton beams, and on opposite sides, is zero, at least to leading order (this configuration corresponds to the mesons being produced at 90° in the center-of-mass frame for the hard-scattering subprocess). This zero also occurs for a small number of the other possible meson pairings. The zero is present for a more general γ-matrix structure of the meson vertices of Fig. 3 than that taken in Ref. 13 and is independent of whether the SU(3) meson-vertex symmetry, which the authors use, is broken or not. In Fig. 5 we have used the model of Ref. 13 [taking the value of N in (1) to be 4] to predict a π^0-π^0 correlation coefficient and show how this zero affects its general polar angular dependence. The dip due to the zero should be obvious experimentally even if the angular bins are fairly large. However, present data[19] indicate that π^0-π^0 rapidity correlations on opposite sides do not have such a marked structure.

It is conceivable that the data are compatible with the dominance of the meson-bremsstrahlung process (2c) where the scattered quark fragments, usually to give the balancing jet but occasionally to give the observed meson plus a small number of "same-side" particles. However, recent calculations by Schiff *et al.*[21] indicate that this process by itself is unable to explain the data.

There has been much interest as to whether the production of this apparent jet structure is through a resonance-decay or a "continuum" mechanism. The former possibility has received a considerable boost recently from the measurement of single-lepton inclusive cross sections at large p_T.[7] These are significantly larger than expected from calculations of the Drell-Yan mechanism and are close to $10^{-4}\times$ (π^+ cross section) over a range of p_T and s. Now, certain vector mesons—ρ^0, ω, and particularly ϕ—have branching ratios to e^+e^-, $\mu^+\mu^-$ of the order of 10^{-4}, and this raises the interesting possibility that vector-meson production at large p_T, with similar cross sections to the pseudoscalars, can explain both this result and the apparent jet structure. This view is encouraged by the recent report of Gordon *et al.*[22] that, in $\pi^+ p$ interactions at 6 and 22 GeV/c, the particle ratio ρ^0/π^- has a linear rise with p_T^2, reaching 1 at $p_T \simeq 1$ GeV/c.

In the following section we discuss the extension of the simple quark fusion model to include vector-meson production. This is a logical step in that the hard-scattering subprocess should surely not differentiate *a priori* between the various spin configurations of the $(q\bar{q})$ state; however, for our purposes we shall suppose that production of the "excited" mesons ($L > 0$ and radial excitations) is numerically suppressed.

III. MODELS FOR LARGE-p_T VECTOR-MESON PRODUCTION

Simple quark fusion

In their quark-fusion model, Landshoff and Polkinghorne[13] take the (pseudoscalar octet) meson vertex to be $C\gamma_5(-k^2)^{-\gamma_0}$ when the momentum squared, k^2, in (just) one of the quark legs becomes large; the various vertex constants C are related by SU(3). This gives the inclusive cross section $Ed\sigma/d^3p$ as a sum of contributions of the form

$$\propto p_T^{-2N}\int d\alpha_1 d\alpha_2\,\delta(\alpha_1+\alpha_2-1)G(\alpha_1,\alpha_2)\times F_2^a\left(\frac{2\alpha_1}{x_T\tan\frac{1}{2}\theta}\right)F_2^b\left(\frac{2\alpha_2}{x_T\cot\frac{1}{2}\theta}\right), \qquad (3)$$

where $G(\alpha_1,\alpha_2)$ is one of $\alpha_1{}^N$, $\alpha_2{}^N$, and $-(\alpha_1\alpha_2)^{N/2}$, and $F_2^a(\omega)$ is the contribution from the quark a to the structure function of the proton (or other initial-state hadron),

$$F_2(\omega)=\sum_{\substack{a=\mathcal{P},\mathfrak{N},\lambda\\ \bar{\mathcal{P}},\bar{\mathfrak{N}},\bar{\lambda}}} Q_a{}^2F_2^a(\omega),$$

$Q_a e$ is the charge on the quark a, and $N = 2+4\gamma_0$. The expression (3) has the form of (1), as required. Some of the other possible γ-matrix structures for the meson vertex also give the result (3), though the relationship between N and the power falloff of the meson vertex may be different.

First quark-fusion model for vector mesons

In a similar spirit, for vector mesons we choose the "simplest" vertex $C_1\gamma^\mu(-k^2)^{-\gamma_1}$. Then a calculation similar to that described in Ref. 13 shows that the leading asymptotic contribution arises just from the longitudinal polarizations of the vector mesons and has the form (3) of the pseudoscalar case except for an additional factor $(1/m_1{}^2m_2{}^2)$ arising from the polarization vectors of the observed and balancing vector mesons (masses m_1, m_2). N is then related to γ_1 by $N = 4\gamma_1$. Production of the transverse polarizations is suppressed by a factor of s^{-1} relative to the longitudinal polarization.

Table II gives the results of a calculation, for p-p interactions, of the relative multiplicities of vector mesons at large p_T in this model, assuming U(3) couplings to the quarks. These values differ significantly from the corresponding entries in Table I because of the symmetry-breaking effect

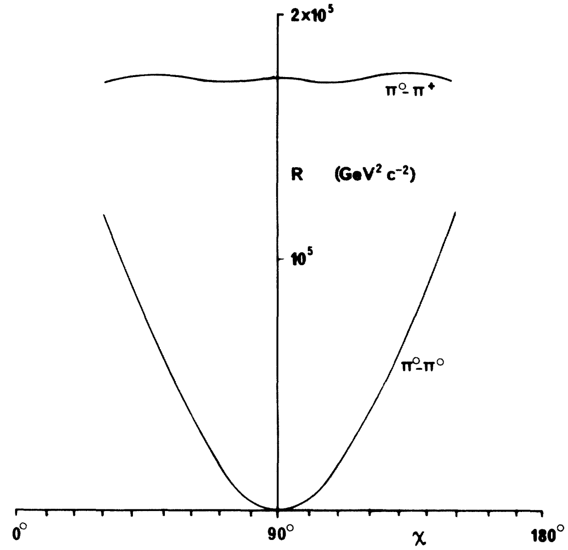

FIG. 5. Sample prediction of the simple quark-fusion model for a correlation function R in $pp\to\pi^0\pi^0+X$; the two π^0's are on opposite sides having large, balancing transverse momenta. The plot gives the variation of R with center-of-mass production angle χ of one π^0, given that the other has been detected at 90° with $x_T = 0.15$ on the opposite side. $\sqrt{s} = 52.7$ GeV. The plot shows the marked effect of the zero at $\chi = 90°$ described in the text. For a comparison the correlation function for a π^0 at 90° and a π^+ on the opposite side is also plotted. The correlation function R is defined by

$$R=\int d^2p_{2T}E_1E_2\frac{d\sigma}{d^3p_1d^3p_2}\,\sigma_{\text{inelastic}}\Big/E_1\frac{d\sigma}{d^3p_1}\,E_2\frac{d\sigma}{d^3p_2}\,,$$

where the subscripts refer to the two pions and the range of the $\vec{p}_{2T}$ integration is over a small region about $-\vec{p}_{1T}$, in which the balancing pion lies and which corresponds to the small transverse momentum distributions of the initial-state partons relative to their parent protons. Details of the calculation of the one- and two-particle distributions are given in the first paper of Ref. 13.

TABLE II. Predicted relative multiplicities of vector mesons at large p_T ($\theta = 90°$) in the first quark-fusion model described in the text for $pp \rightarrow M + X$.

x_T	ρ^+	ρ^0	ρ^-	K^{*+}	K^{*0}	$\bar{K}^{*0}$	K^{*-}	ϕ	ω
0.2	1.00	0.90	0.80	0.66	0.55	0.35	0.35	0.25	0.52
0.4	1.00	0.92	0.84	0.68	0.60	0.38	0.38	0.29	0.36

of the appearance of the vector-meson masses in the expression for the cross section. Table III gives the pseudoscalar relative multiplicities arising from the decay of the longitudinal vector mesons in this model; details of how the decay distributions were calculated are contained in the Appendix. The decays introduce further symmetry breaking. It is interesting to note the fine agreement between Fig. 4 and Table III before turning to consider the addition of directly produced pseudoscalars. Indeed, the relative normalization of the pseudoscalar- and vector-meson vertices raises a possible difficulty. If, for example, the qqM vertex is regarded as a collinear process, even though in the calculation one of the quarks is highly virtual, and if an $SU(2)_W$ symmetry is imposed, then the pseudoscalars are also suppressed since they are in the same W multiplet as the transverse polarizations. Thus, in this (extreme) version of the model, the asymptotically dominant process for pseudoscalar-meson production at large p_T is longitudinal vector-meson decay alone.

We comment no further on how to "add in" directly produced pseudoscalars, but turn to consider a second model.

Second vector-meson model

The different scaling behaviors assigned to the different vector-meson polarizations by the previous model violate the dimensional counting of Brodsky and Farrar[8]: In the framework of the simple connected Born diagrams, which form a basis of their argument, all spin configurations of $(q\bar{q})$ can be shown to be produced with the same scaling behavior. The difference here arises because the form of their diagrams implies a more complicated γ-matrix structure for the vector-meson vertex than just γ^μ. A related view is to consider a Bethe-Salpeter-equation (Fig. 6) approach to the vertex, and then it can be seen that there is no compelling reason why the γ-matrix structure should be particularly simple, even in the limit of large momentum squared in one of the quark legs. With the notation of Fig. 6, a complete list of linearly independent γ-matrix structures is ($\not{a} \equiv \gamma^\mu a_\mu$)

$$(a-b)^\mu,\quad (a-b)^\mu \not{a},\quad (a-b)^\mu \not{b},\quad \gamma^\mu,$$

$$\gamma^\mu \not{a},\quad \gamma^\mu \not{b},\quad (a-b)^\mu \not{a}\not{b},\quad \epsilon^{\mu\nu\rho\sigma} a_\nu b_\rho \gamma_\sigma \gamma_5 .$$

Some of these, either singly or in linear combination, can suppress the longitudinal polarization with respect to the transverse ones.

Faced with this abundance of possibilities we take refuge in a "statistical" approach. We suppose that *each* vector-meson polarization is produced with the same cross section as the corresponding pseudoscalar meson in simple quark fusion.[23] For this purpose we consider a pseudoscalar nonet in which the $I = 0$ mesons are $\lambda\bar{\lambda}$, $(1/\sqrt{2})(p\bar{p} + n\bar{n})$ so as to get cross sections for ϕ and ω production. As can be seen by comparing Table IV, which gives the resulting relative multiplicities, with Table I, switching from $8 \oplus 1$ to ideal mixing does not affect the entries for the other mesons.

Table V gives the pseudoscalar relative multiplicities arising from direct production plus vector-meson decay in this model; details of how the decay distributions were calculated are given in the Appendix. Table V shows the symmetry breaking effect of the vector-meson decays; for example, the SU(3) and U(3) result $K^+/\pi^+ = 1$ is lost. Unfortunately there is no significant gain in agreement with the data for the K/π ratios, although the π^-/π^+ prediction is still good, so again symmetry breaking at the vertices has to be invoked. In our calculation 26% of the total π^+ cross section at $x_T = 0.2$ comes from ρ decay (other decays are unimportant for pion production); at $x_T = 0.4$ the figure is 20%. These relatively large proportions are a consequence of relativistic kinematics which allows, with $\rho \rightarrow \pi\pi$ as an example, one of the pions to have more than 96% of the momentum of the ρ, and this effect partially offsets the numerical suppression due to the vector meson requiring a greater transverse momentum than the correspon-

TABLE III. Predicted pseudoscalar and electron relative multiplicities arising from vector-meson decay in the first model described in the text. $\theta = 90°$.

x_T	π^+	π^0	π^-	K^+	K^0	$\bar{K}^0$	K^-	η	X^0	e^+
0.2	1.00	0.95	0.90	0.39	0.42	0.23	0.23	···	···	5.3×10^{-5}
0.4	1.00	0.96	0.92	0.43	0.45	0.27	0.27	···	···	5.5×10^{-5}

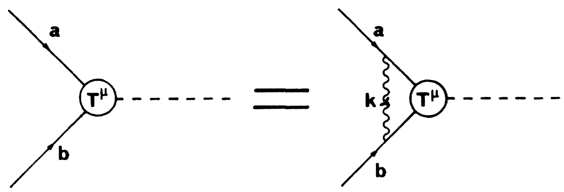

FIG. 6. Bethe-Salpeter equation for the vector-meson vertex. The ladder approximation has been taken for simplicity. Inspection of the right-hand side shows there is no particular reason to suppose that the γ-matrix structure is "simple".

ding directly produced pseudoscalar. Of course, it is also useful in this respect that we have assumed vector mesons to be produced three times more copiously than pseudoscalars.

Large-p_T leptons

Charged-lepton production at large p_T is of great current interest. We can calculate the contribution to this process from ρ^0, ω, and ϕ decay in the above models, and the results for the ratio e^+/π^+ are included in Tables III and V (recall that the entries in Table III are for *no* directly produced π^+). These predictions are not far from the observed values, being in both models about 5×10^{-5} at each of $x_T = 0.2, 0.4$. (These are the asymptotic results; at finite p_T and s the ratio e^+/π^+ is kinematically enhanced, although this effect must then be set against the approach to scaling of the vector-meson distributions.) In the calculations ϕ decay accounts for between $\frac{1}{2}$ and $\frac{3}{4}$ of the electron cross section.

In the following we summarize some useful features of both vector-meson models.

1. Jet structure on side opposite to trigger?

The decay products of a balancing vector meson will possess a jetlike structure, since they will be close in azimuthal and polar angles although having a large spread in their momentum distributions; this is a purely kinematical effect, as can be seen by considering the vector-meson rest frame and then transforming back along the line of flight to the center-of-mass frame. An apparent rise in multiplicity of the balancing jet[17] with trigger p_T

TABLE IV. Predicted relative multiplicities of vector mesons at large p_T ($\theta = 90°$) in the second quark-fusion model described in the text for $pp \to M + X$.

x_T	ρ^+	ρ^0	ρ^-	K^{*+}	K^{*0}	$\bar{K}^{*0}$	K^{*-}	ϕ	ω
0.2	1.00	0.90	0.79	1.00	0.79	0.58	0.58	0.56	0.55
0.4	1.00	0.92	0.83	1.00	0.83	0.67	0.67	0.66	0.38

may be partly due to the spread in momentum distributions, since as p_T increases so does the probability that all the products are found on the same side. Another factor to note in this respect is that, in *any* parton-model view of the Pisa–Stony Brook experiment,[17] the trigger favors events in which the partons participating in the hard scattering have their initial small transverse momenta, relative to the parent protons, in the direction of the trigger because in these events the transverse momentum which has to be created by the hard scattering is less than the trigger p_T. Thus the residual hadronic reaction (i.e., minus trigger and jet) has on the average a net transverse momentum away from the trigger and will not be symmetric as the Pisa–Stony Brook workers assume in their analysis.

2. Significant correlations on the same side?

If the triggering particle is a product of a vector-meson decay, there will usually be another particle on the same side (although not always for $p_T < 2$ GeV/c because of the large spread in momentum distribution described above). Generally, however, this second particle will only have a *small* fraction of the trigger p_T since the trigger will generally select events in which almost all the transverse momentum of the primary is carried off by the triggering particle. Again direct comparison with experiment may be misleading because of the "recoil" of the residual "normal" hadronic reaction and its products as described above and the difficulty of experimentally disentangling the latter from the products of the hard-scattering subprocess plus subsequent decays. However, results from the Pisa–Stony Brook collaboration[17] are qualitatively encouraging.

TABLE V. Predicted pseudoscalar relative multiplicities, from direct production plus vector-meson decay, in the second model described in the text. The predicted e^+/π^+ ratios are also shown. $\theta = 90°$.

x_T	π^+	π^0	π^-	K^+	K^0	$\bar{K}^0$	K^-	η	X^0	e^+
0.2	1.00	0.91	0.82	0.91	0.77	0.55	0.55	0.51	0.30	5.0×10^{-5}
0.4	1.00	0.93	0.86	0.93	0.81	0.65	0.65	0.61	0.23	4.7×10^{-5}

3. Absence of structure in π^0-π^0 rapidity correlations on opposite sides?

As described previously, simple quark fusion gives a zero in the π^0-π^0 inclusive distribution at large p_T when the π^0's are at the same angle with respect to one of the beams and on opposite sides. However, $\rho^{\pm} \to \pi^{\pm}\pi^0$ are the important vector-meson processes for large-p_T π^0 production and there are no corresponding zeros in charged ρ-charged ρ and π^0-$\rho^{\pm}$ correlations. The zero does occur for ρ^0-ρ^0 and π^0-ρ^0 (changing the meson vertex structure from γ_5 to γ^{μ} does not affect its occurrence), but the consequent zeros in charged π-charged π and π^0-$\pi^{\pm}$ rapidity correlations are again obscured by other contributory processes. However, η-$\pi^{+,-,0}$ and η-$\rho^{+,-,0}$ distributions all have the zero and this should therefore be observable in η-π rapidity correlations on opposite sides.[24]

4. The predicted pseudoscalar inclusive cross sections

These have a very similar x_T dependence to those from the simple quark-fusion model; the falloff is just slightly steeper. The fit to the data is preserved.

Meson-beam experiments

Vector-meson models can also have important predictive consequences for the process $M'B \to M + X$ at large p_T. In a recent calculation[14] of $\pi^+ p \to M + X$, we included a contribution from the leading-particle processes of Fig. 7, which have the same asymptotic behavior as the quark-fusion terms. The calculation was based on simple quark fusion and thus was restricted to the pseudoscalars; it was shown that the leading-particle mechanism gave the numerically larger contributions. However, introducing the second vector-meson model discussed above effectively quadruples the quark-fusion contribution relative to the leading-particle process. This is balanced by a reduction in the over-all normalization of the meson vertices as determined by the new fit to the $pp \to \pi + X$ data at large p_T. The net effect is to leave the quark-fusion contribution nearly unchanged and to reduce the leading-particle contribution by a factor of about 4. Thus the predicted cross sections of Ref. 14 are significantly reduced in magnitude. Alternatively, if the extreme version of the first model is adopted, then quark fusion alone gives the leading asymptotic behavior in $M' B \to M + X$ and the leading-particle process can be disregarded; again the quark-fusion contribution is left nearly unchanged, and the predicted cross sections are even smaller. There are preliminary indications that such modifications may provide a better description of large-p_T experiments with a meson beam.

IV. SUMMARY

We have discussed how resonance production at large transverse momentum can qualitatively explain many aspects of recent data on the structure of large-p_T events. In constructing a particular model for the production of large-p_T mesons, we described various reasons for supposing a quark-fusion mechanism to be an important process, at least in the $\{x_T, s\}$ range experimentally available at the CERN ISR. Accordingly, two quark-fusion models incorporating vector-meson production were proposed. In the first (γ^{μ}-coupling) model, only the longitudinal polarizations were produced with the leading asymptotic behavior. In the second (statistical) model, each vector-meson polarization was produced with the same cross section as the corresponding pseudoscalar meson. Both models give a pseudoscalar-meson inclusive cross section similar in shape to the fit to the data achieved by the simple quark-fusion model, which considers the direct production of pseudoscalar mesons only. The quantitative consequences of each model for pseudoscalar-meson relative multiplicities at large transverse momentum were calculated, and in both cases the results were in good agreement with the general features of the particle-ratio data; indeed, an extreme version of the first model in which *all* the pseudoscalars arose from the decay of longitudinally polarized vector mesons (no pseudoscalars produced directly) agreed very closely with the data on charged-particle relative multiplicities. The predicted e^+/π^+ ratios, with the electrons coming from the decays of ρ^0, ω, and ϕ, were in both models encouragingly close to the experimental results.

We noted that simple quark fusion predicts strong (and experimentally unobserved) rapidity correlations for two π^0's produced at large p_T in opposite azimuthal hemispheres, and described

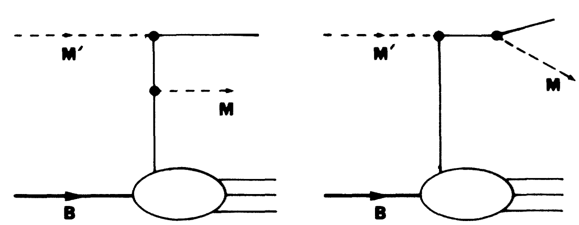

FIG. 7. Leading-particle contributions to $M' + B \to M + X$ at large p_T.

how the incorporation of meson resonances in a quark-fusion model will mask these correlations. Finally, the important consequences of the models for a theoretical calculation of meson beam experments at large p_T were indicated.

To conclude: Using extensions of a particular parton model, we have tried to account, mainly qualitatively, for the features of the more detailed data on large-p_T events now becoming available. Whether or not future results support our particular approach, experimental searches for vector-meson (and other resonance) production at large transverse momentum are of general importance in view of the links with event structure and large-p_T lepton production.

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APPENDIX

The basic computational formulas for the relative multiplicities given in Tables III and V are,[25] respectively,

$$\frac{A_C}{A_{\pi^+}}, \quad \frac{3A_C+B_C}{3A_{\pi^+}+B_{\pi^+}}$$

where

$$A_C = \sum_{\text{vector mesons } V} B_V \times (\text{branching ratio to } C+X) \times (\text{decay factor})$$

and B_Y is the relative multiplicity for directly produced Y as given by one of Tables I, II, IV. The branching ratios are either taken from the latest Particle Data Group tables[26] or derived from isospin invariance; for example,

$$\frac{K^{*+}\to K^0\pi^+}{K^{*+}\to K^+\pi^0}=2.$$

The calculation of the decay factors is described below. For pseudoscalar production, only the important two-body strong decays have been considered; vector mesons, decaying to three particles, generally require much greater transverse momentum to give one of their products the observed p_T. Furthermore, kaon production from ϕ decay and pion production from K^* decay are suppressed by the kinematics, the former because the small relative motion of the kaon pair requires the parent to have much greater transverse momentum than that necessary in the competing process of K^* decay and the latter because the kaon, accompanying the pion, always takes up a substantial fraction of the transverse momentum of the K^*. This leaves ρ decay to give pions and K^* decay to give kaons. Subtleties such as the effect of resonance widths and ρ-ω mixing have been consistently ignored. Longitudinal ρ's, ω's, and ϕ's are assumed to decay isotropically into lepton pairs, in the rest frames of the former.

For two-body decays, the decay factor for a given primary and product can be shown to be

$$f^{-1}(x_T)\int_{(Mx_T/m^2)(E-p)}^{(Mx_T/m^2)(E+p)} \frac{x_T dx_T'}{2x_T'} f(x_T')g(x_T,x_T')$$

asymptotically, where E is the energy, and p is the magnitude of the 3-momentum, of the product (mass m) in the rest frame of the primary (mass M). $g(x_T,x_T')$ is related to the probability distribution for a vector meson (x_T') to give a product (x_T). From general considerations it can be shown that $g(x_T,x_T')=M/x_T'p$ for isotropic decays and $g(x_T,x_T')=[3M/(x_T'p)^3]\,(Mx_T-Ex_T')^2$ for longitudinal vector-meson decay into two pseudoscalars. $f(x_T)$ is the quark-fusion prediction for the inclusive distribution $Ed\sigma/d^3p$ at $\theta=90°$, with s dependence removed. For ease of calculation, we took the following approximate fit to the simple quark-fusion prediction for π^+ production (all the inclusive distributions are similar in shape):

$$f(x_T)\propto x_T^{-8}e^{-12x_T}, \quad 0.2\le x_T\le 0.44$$
$$\propto(0.62-x_T)^5, \quad 0.44\le x_T\le 0.54$$

with continuity at $x_T=0.44$. (Only the range $0.2\le x_T\le 0.54$ was required in practice). The resulting decay factors are given in Table VI.

TABLE VI. Decay factors (see text). The first figure in each entry is for a longitudinally polarized vector-meson primary; the second corresponds to the unpolarized case.

x_T	$\rho\to\pi(+\pi)$	$K^*\to K(+\pi)$	ρ^0, ω, or $\phi\to e(+e)$
0.2	0.134, 0.062	0.170, 0.090	0.086, 0.086
0.4	0.105, 0.044	0.137, 0.064	0.069, 0.069

[1]A selection of the data is contained in Refs. 2–5; Refs. 6 and 7 are useful experimental and theoretical reviews of the subject.

[2]CERN-Columbia-Rockefeller Collaboration (F. W. Büsser *et al.*), Phys. Lett. 46B, 471 (1973); 51B, 306 (1974); 51B, 311 (1974).

[3]Chicago-Princeton Collaboration (J. W. Cronin *et al.*), Phys. Rev. Lett. 31, 1426 (1973); papers submitted to the XVII International Conference on High Energy Physics, London, 1974 (unpublished).

[4]British-Scandinavian Collaboration (B. Alper *et al.*), Nucl. Phys. B87, 19 (1975).

[5]CERN-Columbia-Rockefeller-Saclay Collaboration (F. W. Büsser *et al.*), Phys. Lett. 55B, 232 (1975).

[6]S. D. Ellis and R. Thun, invited talk presented at the IXth Rencontre de Moriond, 1974 [CERN Report No. Th 1874, 1974 (unpublished)].

[7]Review by P. V. Landshoff, in *Proceedings of the XVII International Conference on High Energy Physics, London, 1974*, edited by J. R. Smith (Rutherford Laboratory, Chilton, Didcot, Berkshire, England, 1974), p. V-57.

[8]S. J. Brodsky and G. R. Farrar, Phys. Rev. Lett. 31, 1153 (1973). Dimensional counting has also been proposed by V. A. Matveev. R. M. Muradyan, and A. N. Tavkhelidze, Lett. Nuovo Cimento 7, 719 (1973).

[9]A plot of $N(x_T)$ by the Chicago-Princeton Collaboration is given by Landshoff, Ref. 7.

[10]See, for example, J. C. Polkinghorne, Phys. Lett. 49B, 277 (1974); Z. F. Ezawa and J. C. Polkinghorne, Phys. Rev. D 11, 1993 (1975). A model in which parton-parton scattering, process (2a), *is* the dominant mechanism and the "$N=4$" behavior seen at present energies is due to a threshold effect in the secondary fragmentation of the scattered parton has been proposed by S. D. Ellis, Phys. Lett. 49B, 189 (1974). Another mechanism on similar lines has been suggested by M. Bander, R. M. Barnett and D. Silverman, Phys. Lett. 48B, 243 (1974).

[11]A detailed discussion of the various mechanisms is given by R. Blankenbecler and S. J. Brodsky, Phys. Rev. D 10, 2973 (1974).

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

[13]P. V. Landshoff and J. C. Polkinghorne, Phys. Rev. D 8, 4157 (1973); 10, 891 (1974).

[14]B. L. Combridge, Phys. Rev. D 10, 3849 (1974).

[15]We have neglected the variation of the relative probability distributions of the possible proton constituents with the fraction of the proton's momentum that they carry. In particular, the well-known phenomenon of $\mathcal{P}$-quark dominance as this variable tends to unity implies that for smaller values of the variable there must be less than twice as many $\mathcal{P}$ quarks as $\mathfrak{N}$ quarks. However, we expect the effect on our result to be small.

[16]We have considered only directly produced pseudoscalars. Incorporating vector-meson production will increase the π^-/π^+ ratio a little. ρ decay is the important vector-meson process for large-p_T pions (see Appendix), and so, if we set ρ^-/ρ^+ $(\sim\pi^-/\pi^+)\simeq 0.6$ and use $2d\sigma(\rho^0)=d\sigma(\rho^+)+d\sigma(\rho^-)$, then we have $\pi^-/\pi^+ \simeq(0.8+0.6)/(1+0.8)\simeq 0.8$, and this result is on the lower limits of the experimental data. However, this value of 0.8 is for pions from vector-meson decays alone, and any substantial component of directly produced pions will pull the ratio down again.

[17]Pisa-Stony Brook Collaboration (R. Kephart *et al.*), paper submitted to the XVII International Conference on High Energy Physics, London, 1974 (unpublished).

[18]Second paper in Ref. 2.

[19]Third paper in Ref. 2.

[20]I am grateful to Dr. S. D. Ellis for this remark.

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[22]H. A. Gordon *et al.*, Phys. Rev. Lett. 34, 284 (1975).

[23]Two similar "statistical" approaches to vector-meson production, with calculations of the resulting pseudoscalar distributions, are given in (1) V. V. Anisovich and V. M. Shekhter, Nucl. Phys. B55, 455 (1973); V. V. Anisovich *et al.*, *ibid.* B55, 474 (1973) and (2) J. D. Bjorken and G. R. Farrar, Phys. Rev. D 9, 1449 (1974). These discussions are mainly concerned with low-p_T phenomena.

[24]A significant cross section for η production, with $3<p_T<6$ GeV/c and $\sqrt{s}=52.7$ GeV, has recently been reported from the CERN ISR (Ref. 5). The η/π^0 ratio is about 0.5, although the error bars are rather large at the upper values of p_T. Now, although η production by vector mesons is fairly negligible, this result does not immediately rule out the extreme version (asymptotically, no directly produced pseudoscalar mesons) of the first vector-meson model proposed in this paper because the vector-meson decay factors (see Appendix) cancel a significant fraction of the suppression of the directly produced pseudoscalars at these values of p_T. However, a *rough* calculation, taking this into account, does give a predicted η/π^0 ratio of only about 0.15 at $p_T=3$ GeV/c decreasing to about 0.07 at $p_T=6$ GeV/c, thus indicating, in our picture, the presence of a substantial component of directly produced pseudoscalar mesons at large p_T.

[25]A similar calculation, for $\rho\to\mu(+\mu)$, has been made, in the context of a model for large-p_T ρ production, by R. M. Barnett and D. Silverman, report, 1975 (unpublished). They obtain a decay factor of about $\frac{1}{13}$, which agrees with our values. The same authors have also given [Phys. Rev. D 8, 4151 (1973)] a general treatment applicable to single-particle distributions arising from isotropic two-body decays.

[26]Particle Data Group, Phys. Lett. 50B, 1 (1974).