THEORETICAL MODELS FOR LARGE TRANSVERSE MOMENTUM PHENOMENA

S D Ellis*

CERN

I Introduction

During the last two years one of the most active areas of high energy physics research has been the study of events containing hadrons with large transverse momentum. The experimental situation is reviewed elsewhere in these proceedings. In the following report a review(1) is given of the various models which have been proposed as explanations of the observed behaviour of such large $p_\perp$ events. The intent is to provide a fairly inclusive summary of the most recent work. As a result, the discussion is seldom very detailed. The interested reader is referred to the original papers or to more specific reviews for a more complete exposition of any single model. Only definite models which have been utilized phenomenologically will be discussed.(2) It should be emphasized that there does not yet exist a real theory of large $p_\perp$ phenomena and current efforts have concentrated on the phenomenological study of these various models.(3)

The first two sections of this report will comprise a discussion of the two major classes of specific models, fireball models and hard scattering (parton) models, largely within the context of the single particle inclusive spectrum near $\theta_{c.m} = 90^o$. This will be followed by a brief discussion of the possible ways in which more detailed information on correlations and particle composition may be understood and used to discriminate between various models. In particular some discussion will be given concerning what can be expected when the large $p_\perp$ particle is observed away from 90^o. Then there will be a short summary of some of the other possible explanations for large $p_\perp$ events and more novel forms of analysis which have been suggested but which do not fit into the two classes mentioned above. Finally there will be a brief concluding discussion. Althought the major emphasis will be on inclusive processes, and in particular $pp \to \pi X$, there will also be some discussion of the most recent applications of various models to large $p_\perp$ exclusive processes.(3) This is a field of study with a rich history and the present coverage is far from complete, including only some of the most recent work. This situation is to some extent justified by the fact that the bulk of the large angle exclusive data is at quite low energies compared to the inclusive data.

2. Fireball Models

The majority of the models which have been advanced as relevant to large $p_\perp$ physics can be classified into two categories: fireball models and "hard scattering" or parton models. The former class is characterized by the transformation of some or all of the incident energy of longitudinal motion into one or more very massive hadronic states. By assuming that these states decay essentially isotropically, such events can lead to hadrons with large transverse momentum in the final state. The initial fireballs are themselves generally assumed to have only small $p_\perp$ so that the observed single particle spectrum is given only by the physics of the decay. For example, if the hadronic matter in a fireball of mass M reaches thermodynamic equilibrium and then decays in a statistical fashion, the normalized single particle cross section, at $\theta_{c.m} = 90^o$ and with $p_\perp \simeq E >> M$, will be given essentially by a

*on leave from FNAL

Boltzman factor.[4]

$$\frac{E}{\sigma}\ \frac{d^3\sigma(M)}{d^3p} \sim p_\perp^{\ \beta} \exp\ (-cp_\perp/M^\alpha) \qquad (1)$$

Here M^α is the effective temperature of the hadronic matter, β and α ($\alpha \le 1$) are parameters related by $\beta = (1-3\alpha)\alpha$ and $\sigma(s,M)$ is the cross section to produce a fireball of mass M at energy s.

A specific example of Eq. 1 is the early nonrelativistic statistical model of Fermi[5] recently restudied by Meng-Ta-Chang.[6] In this case one has $M = \sqrt{s}$ and $\alpha = 1/4$, $\beta = 1$. For σ = constant Eq. 1 becomes

$$\frac{d^3\sigma}{d^3p} \sim \exp(-cp_\perp/s^{1/8}) \qquad (2)$$

which is compared to data in Fig. 1. Although the data may be consistent with a universal behaviour in $p_\perp/s^{1/8}$, the largest $p_\perp$ data would seem to argue against any simple exponential behaviour. Another, more sophisticated single fireball picture has been suggested by Heiko[7] who argues that the data indicate three distinct stages of evolution for the fireball. In particular there is to be an initial hot stage ($T\sim s^{1/4}$) which produces very large $p_\perp$ particles, a transition stage ($T\sim C+Ds^{1/4}$) producing intermediate $p_\perp$'s, and finally a cool stage ($T \sim T_o \sim M_\pi$) which yields the usual low $p_\perp$ spectrum.

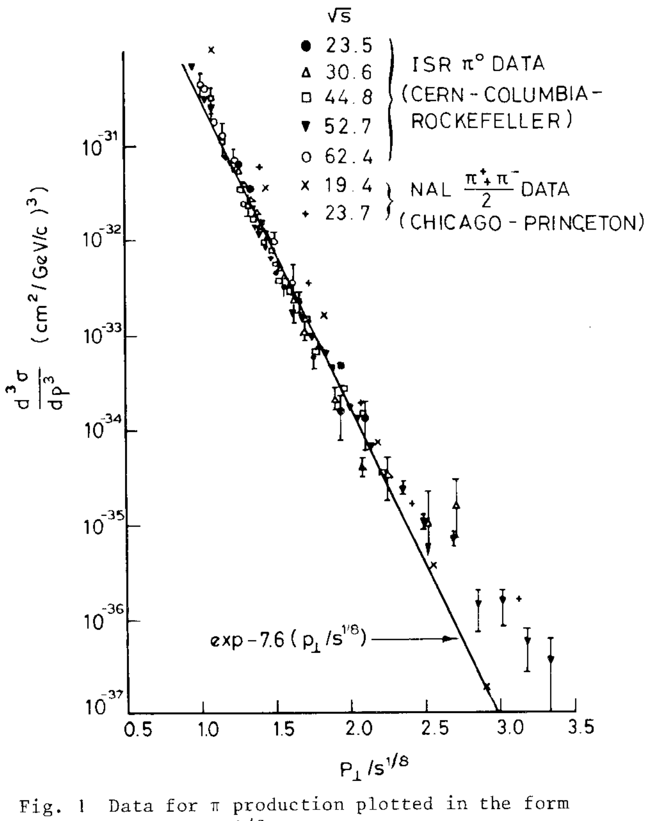


Fig. 1 Data for π production plotted in the form $d^3\sigma/dp^3$ versus $p_\perp/s^{1/8}$.

Another possibility is to utilize the freedom represented by the fireball production cross section $\sigma(s,M)$ in Eq. 1. In the case of a nontrivial distribution of fireball masses one must sum over the distribution to find (ignoring the longitudinal motion for simplicity).

$$E\ \frac{d^3\sigma}{d^3p} \sim \int_{2p_\perp}^{\sqrt{s}} dM\ \sigma\ (M,s)\ p_\perp^{\ \beta}\ \exp(-cp_\perp/m^\alpha) \qquad (3)$$

This formula illustrates that s dependence can arise both from that explicitly present in $\sigma(s,M)$ and from the fact that larger masses become accessible at higher s. Clearly a fairly complicated $p_\perp$ and s dependence can be achieved by a judicious choice of $\sigma(s,M)$. Such a procedure will be truly informative only if the required form of $\sigma(M,s)$ can be connected with other features of hadronic processes. Two possibilities for fireballs are to identify them with large mass diffractively produced states[8] or with the large mass tail of the mass distribution of the clusters[9] now being popularized as an explanation for short range correlations in the central region.[10]

At least two attempts to use a spectrum of fireball masses in order to explain the spectrum of particles at large $p_\perp$ have already been made. In the work of Sakai[11] a sequence of super resonances is postulated to start at $m_1 \sim 5$GeV with a spacing between resonances of $\Delta m \sim 5$-6 GeV. This author argues that evidence for such states already exists in cosmic ray data. Assuming a six pion decay throughout and a resonance production spectrum falling as $1/m_R^2$, Sakai achieves a reasonable discription of the data at one s . A study of the predicted s dependence is certainly called for.

Another example of a mass spectrum is the recent work of Bouquet, et al.[12] Here each fireball decays as prescribed by the statistical bootstrap model. The actual number of fireballs produced in any event is allowed to vary. In the calculation particular care is taken to include recoil effects for the case of two fireball production. This is sufficient to produce large $p_\perp$ particles (via a random walk process) even though, on average, each emission involves only small momentum in the relevant fireball rest frame. By assuming a specific mass and momentum spectrum for the fireballs and accounting for overall energy-momentum conservation, a reasonable description of data at $\sqrt{s}$ = 44.8 and 52.7 is obtained. Clearly such models are of interest. However, since the fireball mass spectrum plays an essential role, it is extremely important that attempts be made to connect it to physics in other regions of phase space as discussed above. Said more generally, it is important to more directly motivate these models. Further it is necessary to study what fireball models predict about the other features of large $p_\perp$ events, for example, correlations and particle ratios.

3. Hard Scattering Models

The second basic class of large $p_\perp$ models is characterized by the presence of a "hard scattering" process. The basic assumption is the existence of interactions involving hadrons or hadronic constituents (partons) which are damped only weakly(i.e as some small power) in the momentum transfer and which can be treated as a local interaction. In this case large $p_\perp$ hadrons can be efficiently produced by a single "hard" interaction. The motivation for such models is the observed behaviour of lepton-induced inclusive reactions in the limit where both the energy loss and momentum transfer to the lepton are large. In particular, for the process $ep \rightarrow eX$ one finds experimentally that the inclusive electron cross section behaves as[13]

$$E\frac{d^3\sigma}{d^3p} \simeq \frac{\alpha^2}{s^2}\, g(t/s,\, M_X^2/s) \qquad (4a)$$

or in a more familiar form for hadronic processes

$$E\frac{d^3\sigma}{d^3p} \simeq p_\perp^{-4}\, f\,(p_\perp/\sqrt{s},\, \theta^*) \qquad (4b)$$

when s is large and t/s and M_X^2/s are fixed. Here α is the fine structure constant, s is the total energy, t is the momentum transfer to the electron, and $p_\perp$ and θ^* are the transverse momentum and angle of the electron in the e-p c.m system. Note that the behaviour indicated in Eq. 4 is just what would follow from dimensional analysis under the assumption that the hadronic part of the interaction contains no scale factors (i.e no explicit parameters with dimension). This suggests that hadrons are able to absorb large momentum transfers in a scale invariant fashion when probed by local interactions and when no restrictions are placed on the final state hadrons. It is generally also assumed in such models that hadronic form factors have a power dependence on the momentum transfer in exclusive processes involving local interactions. The end result of the above framework of assumptions is that inclusive particle production at large $p_\perp$ is expected to have the form

$$E\frac{d^3\sigma}{d^3p} \sim p_\perp^{-N}\, f\,(p_\perp/\sqrt{s},\ \ \theta^*) \qquad (5)$$

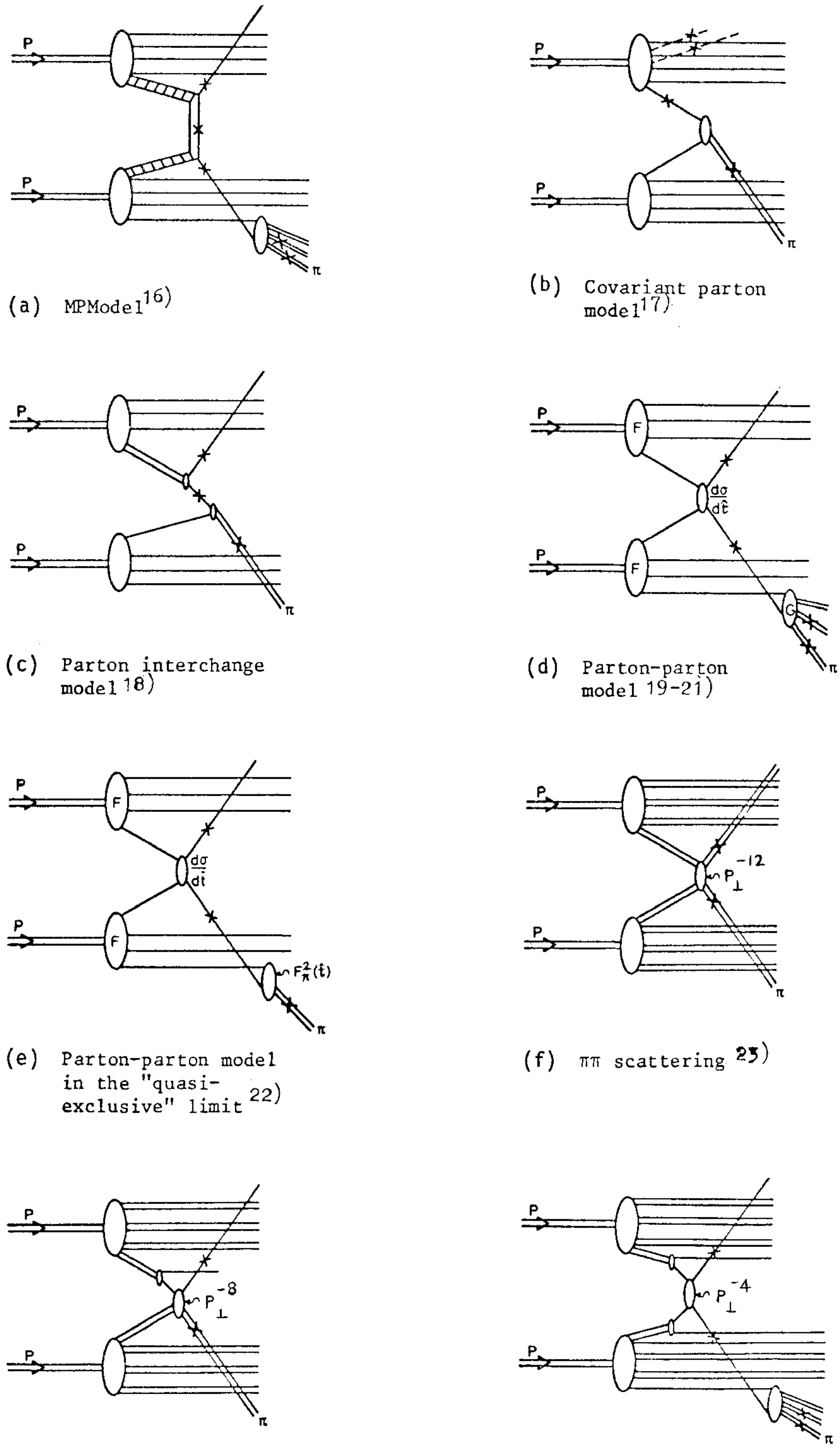
when s is large, $p_\perp/\sqrt{s}$ is fixed, and θ^* is not too near 0° or 180°.

This form of simple behaviour with a single power times a function of only scaling variables(e.g $p_\perp/\sqrt{s}$ and θ^*) is characteristic of hard scattering or parton models and is to be contrasted with the generally more complicated behaviour expected in fireball models. In parton models one explicitly assumes that dimensional quantities (e.g. masses) become unimportant in the limit of large momenta and hence such models exhibit simple behaviour in dimensional variables (momenta) and complicated behaviour only in scale free variables (ratios of momenta). Fireball models, on the other hand , exhibit dimensional constants even in the large momenta limit and so can have complicated behaviour (e.g. exponential) in the momenta. The data from the ISR, e.g. those of the CERN-Columbia-Rockefeller Group(14) ($x_\perp = \frac{2P_\perp}{\sqrt{s}} \leq 0.4$), are consistent with Eq. 5 for N = 8. However, the data of the Chicago-Princeton(15) group at FNAL suggest $N \approx 11$ for $x_\perp \gtrsim 0.4$. Thus the question of the existence at high energy of a single power law for the full $x_\perp$ range remains an open and extremely important question. In most of this report N is assumed to have the value 8. Emphasis will be placed on how the models are able to yield this value instead of the naive dimensional value N=4.

Hard scattering models are especially interesting in that the function f in Eq.(5) is generally related to the hadronic structure functions measured in lepton induced reactions (e.g. νW_2), and there exists the exciting possibility of connecting lepton-hadron reactions to purely hadronic ones. The models discussed below share this feature of seeking to relate leptonic and hadronic processes. Differences arise from the details of the specific hard scattering process assumed. However, all the models treat the scattering as basically a two body interaction. Hence they all predict a coplanar topology for the large $p_\perp$ event exhibiting little correlation between large $p_\perp$ particles and those produced perpendicular to the plane containing the incident beam and the large $p_\perp$ particle. Also the models suggest "jet structure" wherein the large $p_\perp$ particles tend to appear within two well defined cones in momentum space on either side of the beam direction. Included in some of the models is the case when the jet contains only a single particle or resonance. It should be emphasized that clear "jet" structure can be manifest in the data only in the limit where the average momentum of a particle in the jet is much larger than the expected width of the jet. This condition does not seem to be fulfilled in present data.

The various specific parton models are illustrated in Fig. 2. Note the general kinematic similarity of the models. In all cases a constituent of one hadron (either a parton or a virtual pion) interacts with a constituent of the other hadron to yield the observed large $p_\perp$ pion and generally other hadrons with large $p_\perp$. Here a parton may or may not be a quark but is definitely structureless so that the experimental absence of structureless hadrons requires that partons do not appear as free particles in the final state. One may take the attitude either that partons are truely the elementary hadronic constituents and are just difficult to produce directly or that partons are only an intuitively appealing and economical language with which to represent the internal degrees of freedom of a hadron.

In Fig. 2a is illustrated the multiperipheral parton model of Amati, Caneschi and Testa(16) which is distinguished by its assumption of an underlying $\lambda\phi^3$ theory of scalar partons. Explicit scales enter the model via the dimensional coupling constants (λ has units of mass) and lead to N = 8 ($E\, d^3\sigma/dp^3 \propto \lambda^4$) with no constraints on the final



(a) MPModel[16)]

(b) Covariant parton model[17)]

(c) Parton interchange model[18)]

(d) Parton-parton model[19-21)]

(e) Parton-parton model in the "quasi-exclusive" limit[22)]

(f) ππ scattering[23)]

(g) π-parton scattering[23)]

(h) Parton-parton scattering[23)]

Fig. 2 Pictorial representation of various parton hard scattering models for the process $p + p \to \pi + X$, where the π has large $p_\perp$. The notation is double lines for hadrons, single lines for partons and crosses for particles with large $p_\perp$.

state structure except that the partons must evolve into the observed hadrons in a scale invariant fashion. The "co-variant" parton model of Landshoff and Polkinghorne[17] appears in Fig. 2b. Although the basic model as illustrated is quite general the specific example used for calculations by these authors corresponds to a single pion balancing the large $p_\perp$ of the parton emerging from the upper vertex in the figure. Thus the basic "hard" process is parton + antiparton → 2 mesons and again yields N = 8. The required extra dimensional factors (N=4 is the purely dimensional result) can be traced to the vertices where two partons "fuse" to form a pion and a scale, the size of the pion, naturally appears. These vertices are related to the pion form factor $F_\pi(t)$ and N = 8 arises if $F_\pi(t) \sim {}^1/t$ for large t. A related picture is the "constituent interchange model" of Brodsky, Blankenbecle and Gunion[18] (BBG) which, like the previous picture, explicitly avoids the notion of parton-parton scattering and instead utilizes the concept of a wave function which represents hadrons in terms of constituents. These constituents have a finite probability to carry large $p_\perp$ and be highly virtual and it is the interchange of such a highly virtual large $p_\perp$ parton which drives the basic "pion" + parton → pion + parton process as illustrated in Fig. 2c. Again the basic process yields only a single pion (or resonance) at large $p_\perp$ (not a full jet) and scales appear in the wave function (vertex) describing this particle. By relating this wave function to the pion form factor with the usual ${}^1/t$ asymptotic behaviour one again finds N = 8. This concept of the production of a single pion (or meson resonance) carrying all of the large $p_\perp$ is illustrated in Fig. 3 and is hereafter labelled as a quasi-exclusive process. In contrast to the naive two-jet picture of the totally inclusive events, other large $p_\perp$ particles appear in the same direction as the trigger particle only when a well defined resonance is produced and subequently decays to yield the observed particle plus a few others.

The original parton-parton scattering picture, first studied by Berman, Bjorken and Kogut[19] (BBK) and later by others[20,21], is illustrated in Fig. 2d. As in the first model discussed, the scattered parton is required to evolve into the observed hadrons at the lower vertex (G). If this process introduces no scale and there is no scale in the basic parton-parton interaction, one finds N = 4 in contradiction with the data. In order to generalize this simple picture, it has been suggested, that one consider the "quasi-exclusive" limit of the parton-parton scattering model[22] as indicated in Fig. 2c. The scattered, large $p_\perp$, parton, presumably in cooperation with an antiparton, evolves into a single pion which carries all of the $p_\perp$. Again this "fusion" vertex is assumed to be related to the pion form factor (explicitly it is taken to behave as $F_\pi^{\,2}(t) \sim {}^1/t^2$ for $|t| \to \infty$). In parton language, the function G(y) ($y = P_\pi/p$-parton), which describes the process parton → π+X, is taken to have contributions from specific exclusive channels which appear near threshold (y → 1) as shown in Fig. 4 in analogy to the threshold behaviour of the usual structure functions (e.g. νW_2).

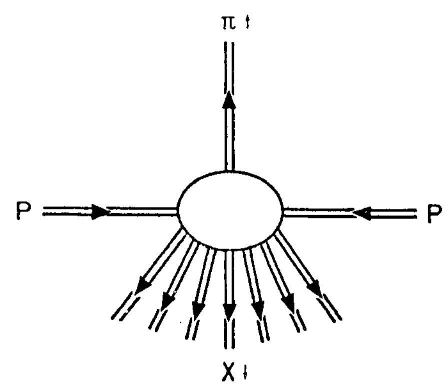


Fig. 3 Pictorial representation of a "quasi-exclusive" process as defined in the text.

These threshold contributions contain scale factors appropriate to the specific exclusive channels and decrease with momentum transfer in a fashion given by the appropriate form factor. Unlike the previous models, the present picture definitely predicts the dominance of a $p_\perp^{-4}$ behaviour at very large s or with different triggering technique. The N = 8 form is thought to dominate at the ISR because at these energies the suppression factor introduced by producing a 5 GeV/c pion directly from a 5 GeV/c parton, namely a factor $p_\perp^{-4}$, has less effect than the suppression introduced by requiring a much larger momentum parton which can yield a "full jet" containing the 5 GeV/c pion plus other hadrons. This explaination is borne out in explicit calculations[22] as long as the scale characterizing the exclusive channel effects is of order 4 GeV.

Similar conclusions are reached by Bardu, Barnett and Silverman [23] (BBS) in a model with three levels of "quasi-exclusiveness). These levels include virtual $\pi\pi \rightarrow \pi\pi$ (Fig. 2f with N = 12), virtual π + partons $\rightarrow \pi$ + parton (Fig. 2g with N = 8), and finally parton-parton scattering where the partons are from virtual pions (Fig. 2h, N = 4).

A recent entry to the list of large $p_\perp$ models which shares some features with both parton and fireball models, is the application of "massive quark model" to large $p_\perp$ inclusive processes by Preparata[24]. The distinguishing feature of this model is that the problem of free quarks is explicitly removed by putting the quark pole at infinite mass and simultaneously cutting off the quark propagator so that quarks can never be on-shell. The model has no explicit quark-quark interactions nor can the interchange of highly virtual quarks give a sizeable contribution. Only objects with hadronic quantum numbers can have large masses and, as illustrated in Fig. 5, the dominant terms of interest here involve quark-antiquark annihilation into massive fireballs. When the initial fireball decays into two smaller fireballs with large $p_\perp$ (Fig.5a), Preparata finds N = 4 and for the "quasi-exclusive" case with one massive fireball and a single hadron as decay products (Fig. 5b), he finds N = 8. Kinematic constraints at present energies suppress the first term and allow the model to explain the observed N = 8 behaviour at the ISR.

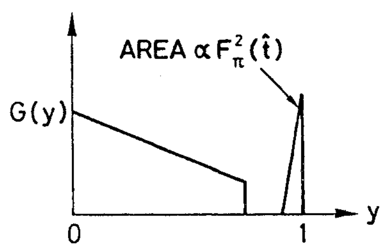


Fig. 4 Pictorial representation of the idealized structure function [22] discussed in the text.

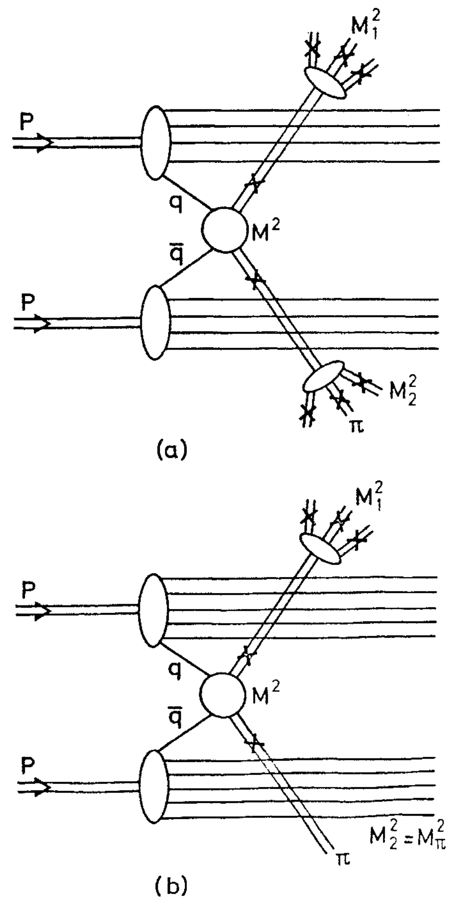


Fig. 5 Pictorial representation of the "massive quark model"[24] for pp $\rightarrow \pi$ + x. The notation is the same as Fig. 2. a) $p_\perp^{-4}$ contribution. b) $p_\perp^{-8}$ contribution.

In summary, parton models lead to $p_\perp^{-8}$ behaviour either because the basic parton-parton scattering has this behaviour, as in the first model discussed, or because in the present experiments the observed large $p_\perp$ is produced essentially by itself (quasi-exclusive process). This second feature is common to all of the other models with N = 8 and seems to be in reasonable qualitative agreement with the bulk of the data. The quality of the fit to the single particle data to be achieved in such "quasi-exclusive" models is illustrated in Fig. 6, taken from Ref. 22. The present data[25,26] on associated charged multiplicities indicate little variation with $p_\perp$ of the multiplicity in the same direction as the trigger particle but strong variation in the opposite direction as illustrated in Fig. 7. This would seem to be in good qualitative agreement with those "quasi-exclusive" models where the trigger particle is produced essentially by itself but its momentum is usually balanced by several particles (the remnants of parton decay ?). However, it should be noted that energy momentum conservation may already be sufficient to explain much of this effect[21]. There are also recent data with more complete momentum analysis[26] which indicate the existence of events where two large $p_\perp$ particles appear in the same hemisphere. In the "quasi-exclusive" context these events would arise from resonance production at large $p_\perp$ but as yet there is little evidence for resonance structure in the data. A more optimistic view for partonists is perhaps that these few events correspond to the true parton-parton → two-jet process with p^{-4} behaviour. These questions anxiously await further experimental and theoretical study.

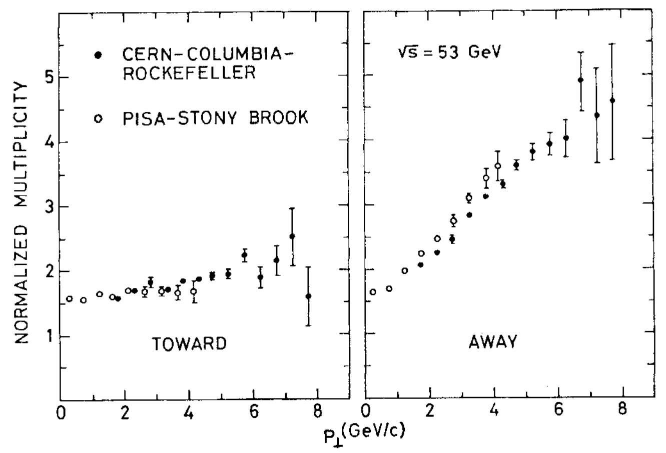


Fig. 7 Partial multiplicities around $\theta_{cm} \approx 90^o$ directly towards ($\phi \sim 0^o$) and away ($\phi \sim 180^o$) from the detected photons (π^o's) as a function of $p_\perp$. These data[25,26] are normalized to average inelastic multiplicities and not to multiplicities at low $p_\perp$.

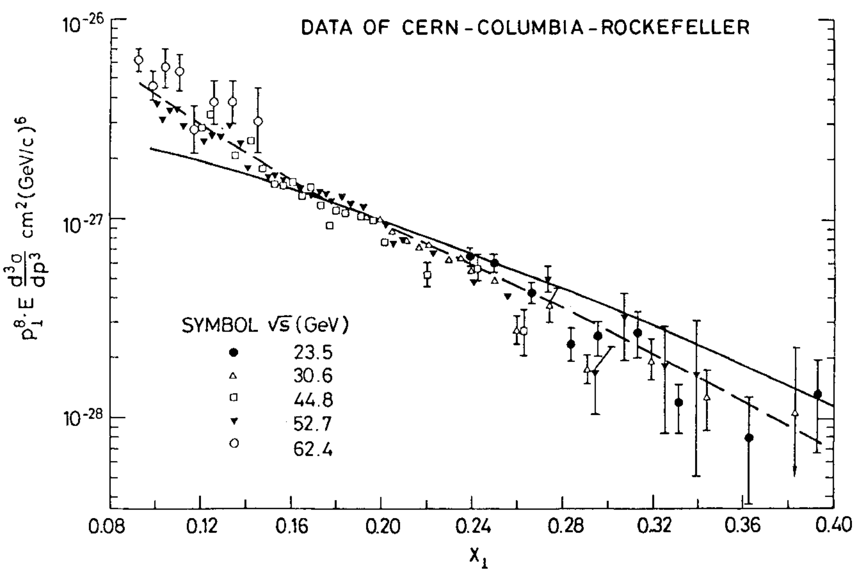


Fig. 6 Fit to the π^o data with the "quasi-exclusive" parton model (22). The solid curve is for F(x) given by the experimental structure function νW_2 and the dashed curve is for $F(x) \sim (1 - x)^3$.

With respect to the Chicago-Princeton[15] data on nuclear targets at FNAL where N = 11 is suggested for $X_\perp >_0 4$, a description has been attempted within the context of the constituent interchange model.[27] Both a $(p_\perp^2 + m^2)^{-6}$ term with baryon production and the usual $(p_\perp^2 + m^2)^{-4}$ term are included and a reasonable description of the pion production data at both FNAL and the ISR is obtained. Another explanation has been given by Amati and Caneschi[28] utilizing the strong angular dependence in their multiperipheral parton model. Since these data are taken at fixed θ_{LAB},θ_{cm} varies with s. However, θ_{cm} has already passed through 90^o at the highest energy (400 GeV/c) and the general consistency of the latest data with the lower energy data argues against such an explaination. Although it is perhaps premature to be comparing directly nuclear target and hydrogen target data, this sort of effort is certainly interesting, particularly if the observed particle ratios can also be understood.

Parton ideas have also proved useful in the study of exclusive processes in the limit of fixed angle as $s \to \infty$. With similar assumptions to those discussed above the usual parton model prediction is that in this limit the exclusive cross section should behave as

$$\frac{d\sigma}{dt} \sim s^{-n} f(\theta) \qquad (6)$$

Of course specific models make predictions for the value of the exponent n. An easy way to remember the results of many of the models is the so called "counting rule" suggested by Brodsky and Farrar[29] and Matveev, Musadyan and Tavkhelidze[30]. The rule states that n is given by the sum of the number of elementary constituents (quarks) present in the participating hadrons minus two. This yields, for example, $n_{NN} = 10$, $n_{N\pi} = 8$ and $n_{\pi\pi} = 6$. This rule was motivated by a study of certain limited sets of Feynman graphs and raised the hope that the asymptotic fixed angle behaviour of hadronic amplitudes might be determined by singularities arising from the short distance behaviour of some underlying field theory. Doubt has been cast in this conjecture, however, by the papers of Landshoff[31] and Ezawa[32] which point out the presence of other singularities in these amplitudes which are not related to the short distance behaviour of the fields and give behaviour violating the counting rule. Although the theoretical situation is therefore unclear, the basic form,Eq. 6, and the counting rule both seem to be satisfactory phenomenologically. Recent papers which discuss exclusive reactions and give specific forms also for $f(\theta)$ in Eq. 6 include those by Matveev, Musadyan and Tavkhelidze[33], Freund and Naudi,[34] Gunion,[35] and Preparata[36]. The constituent interchange model has also been used to study the transition from fixed angle behaviour to fixed t, Regge, behaviour.[37] Various other parton-motivated models have also been proposed[38,39] to describe both inclusive and exclusive data over the full kinematic region, including both large and small $p_\perp$. These last models tend to give different large $p_\perp$ results from those discussed earlier and high energy, fixed angle exclusive data should prove most informative.

Other aspects of various parton models have also been studied. For example Combridge[40] emphasises the interest of doing inclusive reactions with meson beams since the differences from the proton case, especially the anticipated asymmetry in θ, should yield important information. In another study, Scott[41] points out the important role of "leading particle" effects in the transition region between inclusive and exclusive processes at the edge of phase space.

A specific model field theory with fermion quarks and scalar gluons has been studied by Efremov[42] using the assumption of short distance scale invariance and also utilizing certain rúles for treating on-shell amplitudes which have been suggested from studies of Feynman diagrams. The results are of a specific nature and, hence, quite interesting. For example, it is predicted that $\pi\pi$, πN and NN will all exhibit the same s^{-10} behaviour for $s \to \infty$, θ fixed which is different from the results of the other models discussed above and seems also to be inconsistant with present data.

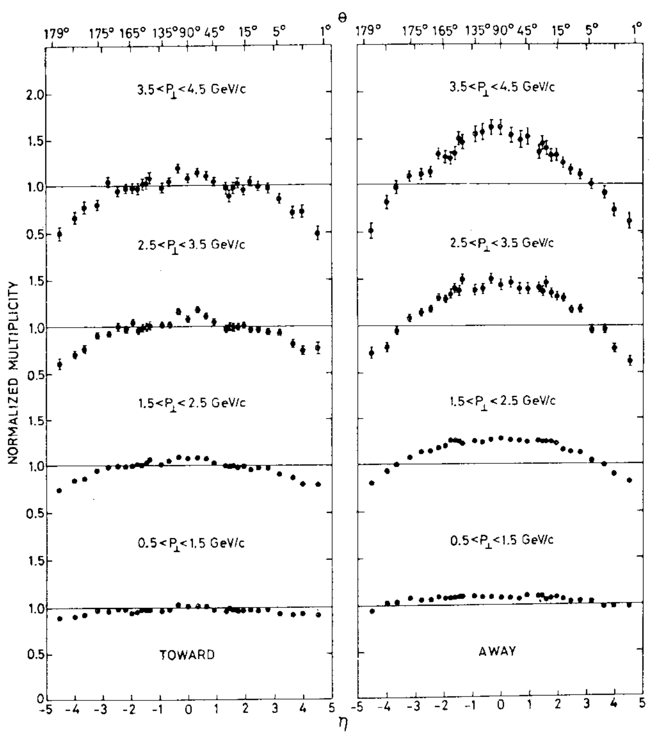
Overall, the application of simple parton concepts to large $p_\perp$ phenomena has been quite successful. However, the models have tended to become quite complex compared to the original naive picture and the development of more well defined theoretical guide lines, arising perhaps from the study of field theory, bag models, etc) is of extreme importance. Likewise the study of the complete event structure in such models will be very informative as is illustrated in the next section.

4. Particle Composition and Correlations

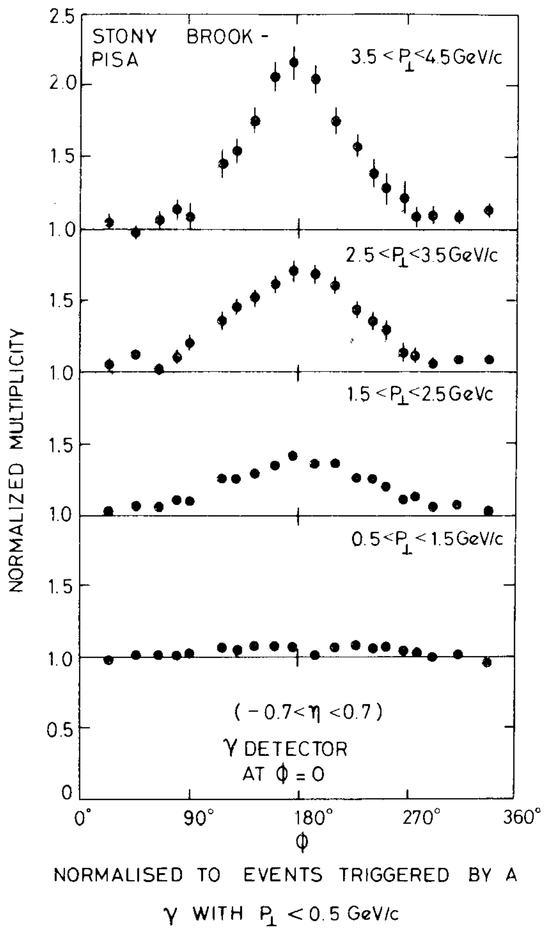
In the following brief discussion of particle composition and correlations the emphasis is on those features of the data which may serve to differentiate between the fireball and hard scattering pictures. Some characteristics of specific parton models are also described.

The question of particle composition has not yet been systematically studied in fireball models. However, on quite general grounds one may expect that for transverse momentum much larger there the particle masses, so that kinematic mass effects are no longer important,[43] fireball models will predict little variation with $p_\perp$ of the particle ratios. In particular one would expect particle/antiparticle ratios to be relatively $p_\perp$ independent at large $p_\perp$. This behaviour is to be contrasted to that in parton-quark models where the valance quarks play an increasingly dominant role as $x_\perp = 2p_\perp/\sqrt{s}$ increases and the particle ratios vary accordingly. In particular for proton-proton reactions one expects an increasing dominance of positive charge, nonnegative strangeness mesons for increasing $x_\perp$. The structure observed in both the British-Scandinavian[44] and the Chicago-Princeton[15] data seems to argue for the quark picture. However, the absence of scaling in the variable $x_\perp$, observed by the second group, is a serious problem. Further study is definitely needed. Finally, it is interesting to note that quark-parton models predict[21] that in events where a large $p_\perp$ π^+ is observed in one direction the most likely large $p_\perp$ particle in the other direction, for proton-proton reactions, is again a π^+. This is quite different from the $\pi^+ - \pi^-$ correlation observed at low $p_\perp$.

From the standpoint of correlations, the basic difference between fireball and hard scattering models arises from the expected event "shape". Fireballs which yield large $p_\perp$ particles are naively expected to give an isotropic secondary distribution in the fireball rest frame, except for the constraints of momentum conservation. Hard scattering models are expected to instead yield a definitely coplanar structure with only weak $p_\perp$ correlations for particles out of the plane defined by the beam and the large $p_\perp$ particle. Therefore one might expect that measurements of the average momentum and average multiplicity of other secondaries normal to the scattering plane in large $p_\perp$ events would be particularly informative. The observation of an appreciable increase in either quantity with increasing $p_\perp$ at fixed s or with s at fixed $p_\perp$ would suggest the presence of massive fireballs, whereas no observed variation would indicate a scattering picture. Unfortunately it is also necessary to consider the following caveats. First, except in the case of single fireballs with $M = \sqrt{s}$, the process responsible for the large $p_\perp$ particle is not the only physics present. The hadronic matter not participating directly in the large $p_\perp$ process presumably also interacts to produce particles and is coupled to the primary process at least by energy momentum conservation. This will tend to produce more complicated correlations than in the naive expectations. Also in the limit of small fireball masses energy-momentum conservation will strongly influence the decay structure and distort the naive expectation. Clearly then, only a large increase in the multiplicity or average momentum normal to the large $p_\perp$ scattering plane will give an unambiguous answer, i.e. massive fireballs are present. Less dramatic effects require more careful studies in order to be correctly interpreted. The structure of the present multiplicity data from the Pisa-Stony Brook experiment[25] is shown in Fig. 8. The absence of strong variation near $\phi = 90^o$ in Fig. 86 would seem to argue against very massive fireballs. It will be interesting to see what else can be learned from such data by more detailed analyses. The measurement of the correlation between $p_\perp$ and the charged multiplicity toward and away from the large $p_\perp$ particle is shown in Fig. 7 and was discussed above as evidence for the quasi-exclusive" explaination of $p_\perp^{-8}$ behaviour in



a) Multiplicities in the two 180^o azimuthal intervals towards and away from the detected photons as a function of $\eta = -\ln |\tan \theta/2|$.



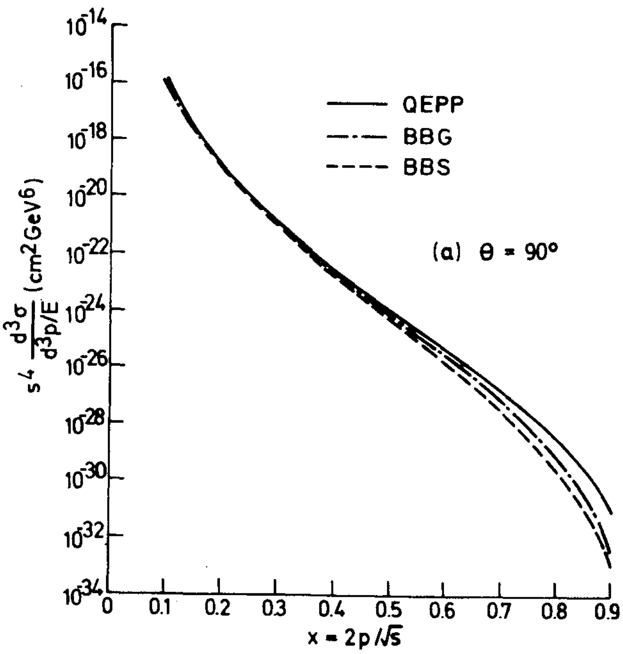
b) Multiplicities in the interval $-0.7 < \eta < 0.7$ as a function of the azimuthal angle measured from the photon detector.

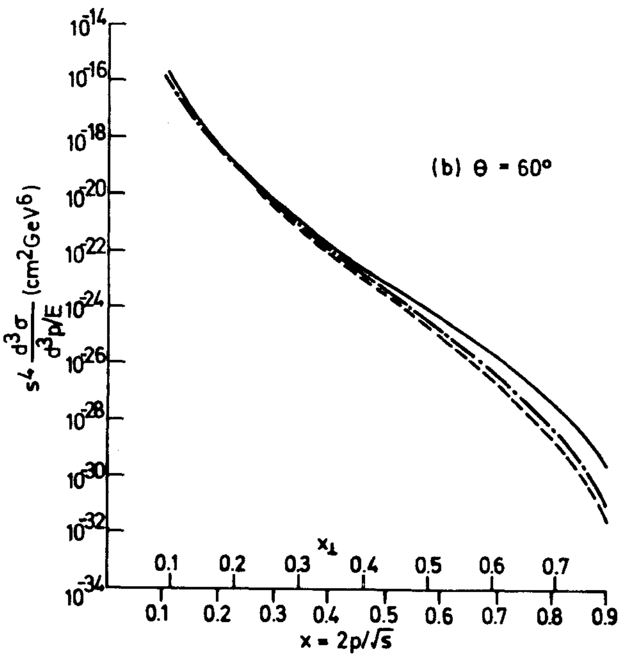
Fig. 8 Data on partial charged multiplicities from the Pisa-Stony-Brook group at the ISR[25] for various $p_\perp$'s of the photon always normalized to the low $p_\perp$ bin.

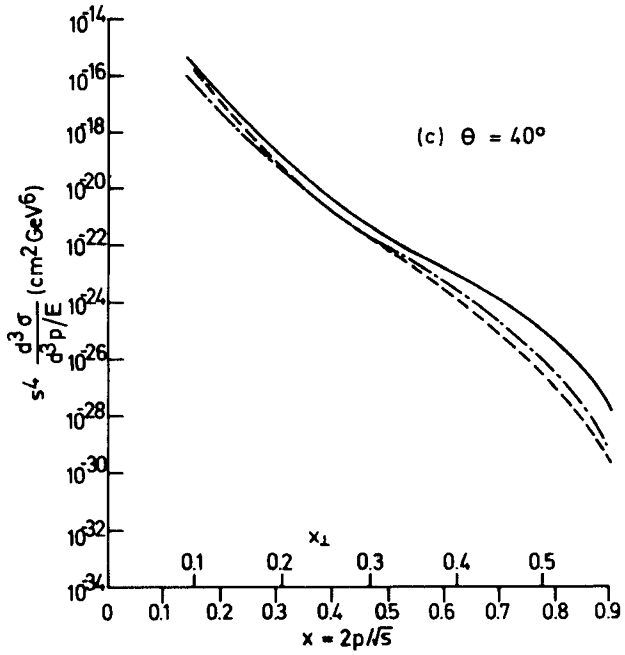
parton models.

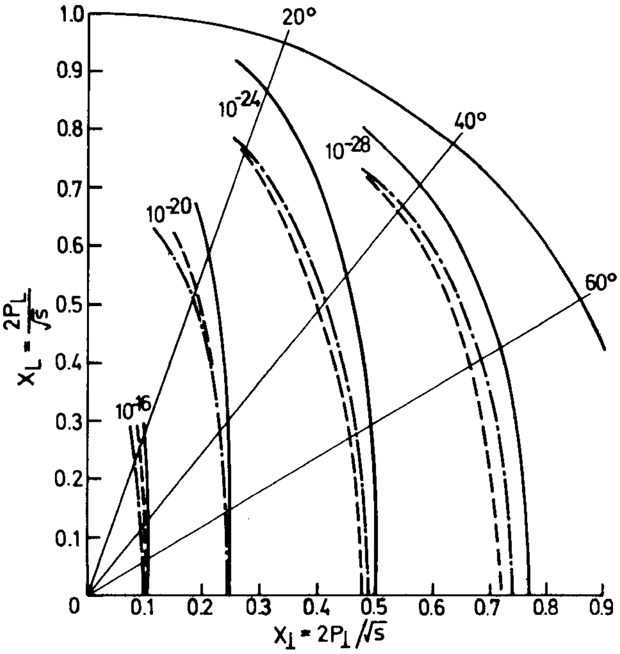
Another interesting question is how correlations vary as a function of the c.m. angle of the large $p_\perp$ particle. For example, in hard scattering models one naively expects a back-to-back configuration, whereas for relatively low mass fireballs one might expect $p_\perp$ to be balanced locally in rapidity (that is at the same $\theta_{c.m.}$ but 180° away in ϕ). To actually utilize the data on these questions now becoming available[45,46] detailed calculations are, of course, required. As an example of what may be learned from such studies, Figs. 9-10 illustrate the results of calculations[47] in a few simple parton models (all with $p_\perp^{-8}$ behaviour). The models include a quasi-exclusive parton-parton scattering model[22] (QEPP), a simple BBG model[18] with $\left.\frac{d\sigma}{d\hat{t}}\right|_{\pi q} \propto (1/\hat{s}^4 + 1/\hat{s}^2\,\hat{u}^2)$[48] ($\hat{s}$, $\hat{t}$, and $\hat{u}$ refer to the variables in the quark scattering process), and a model of the BBS type[23] with $\left.\frac{d\sigma}{d\hat{t}}\right|_{\pi q} \propto 1/\hat{t}^4$. Hence the first and last models have essentially the same behaviour ($1/\hat{t}^4$) in the basic scattering process but differ in the constituents involved and their distributions (see Fig. 2 d and g). The QEPP model involves only parton distributions ($F_q \propto (1-x)^3$ was used) whereas the BBS model involves also a virtual pion distribution ($F_\pi \propto (1-x)^5$ was taken). The second and third models have the same constituent distributions but a different scattering structure. The models are all normalized at $\theta = 90^\circ$ and $x_\perp = 0.2$. The single particle distribution as a function of θ and $x_\perp$ is shown in Fig. 9 and indicates that the QEPP model so somewhat less θ dependent at fixed $x_\perp$. This difference arises from the more rapidly cut off constituent (virtual pion) distributions present in the other models.

Calculations of the one pion - one parton (jet) cross-section are shown in Fig. 10. The cross-section









e) Topological plot of fixed values of the cross-sections in the $x_\perp$ - x_L plane.

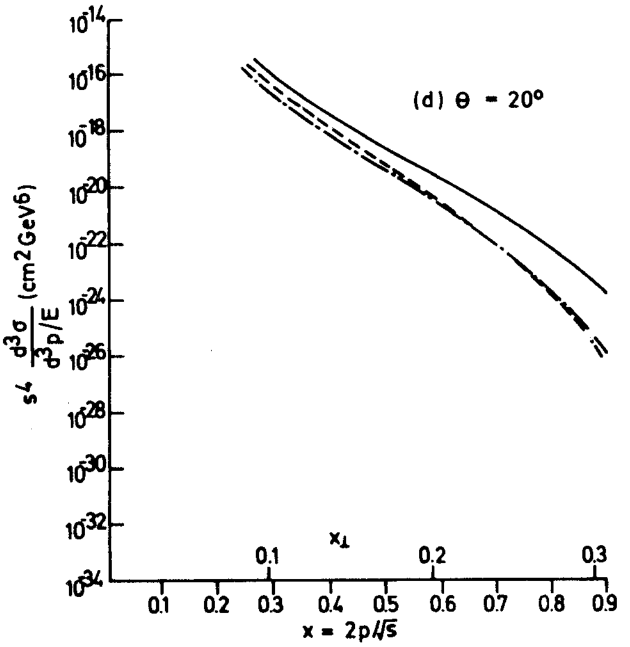
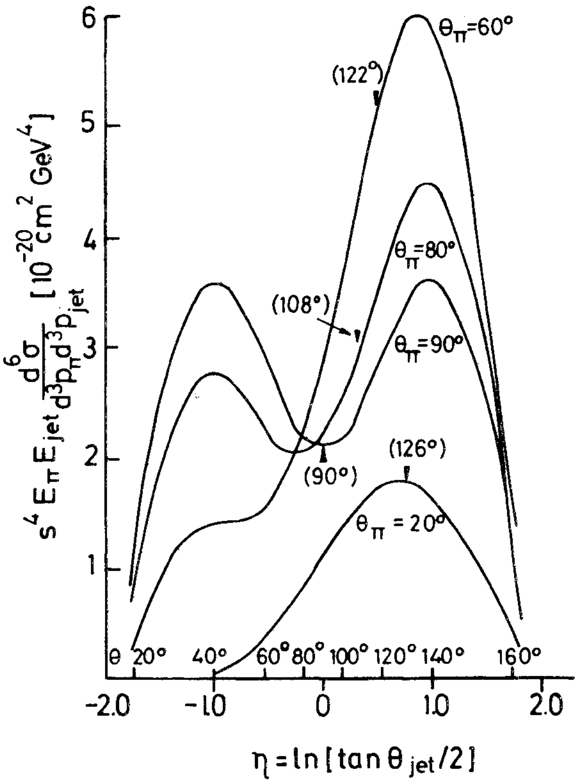
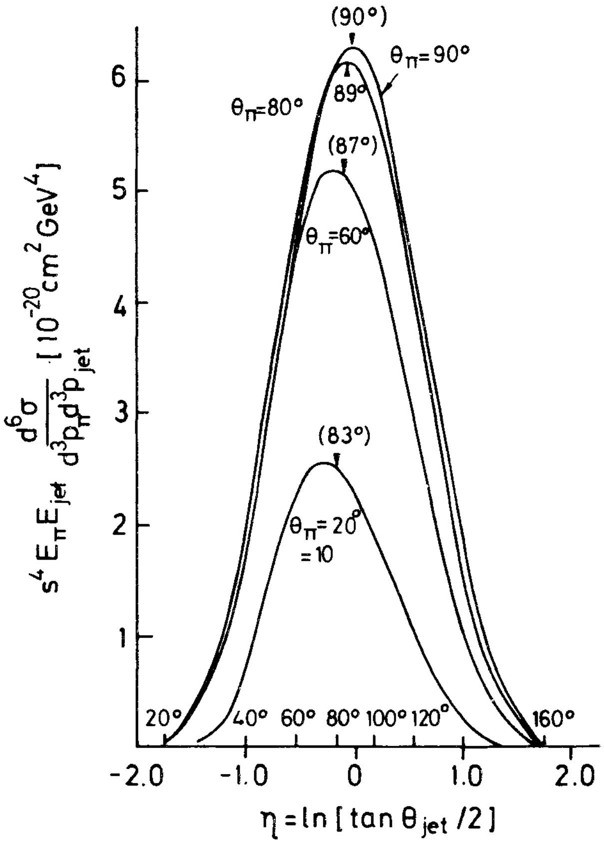


Fig. 9 Model calculations of the single-particle cross-section times s^4 versus $x_\perp$ at various values of θ. The three curves correspond to simple models of the "quasi-exclusive" parton-parton type[22] (solid curve), the BBG type[18] with $d\sigma/d\hat{t}|_{\pi q} \propto 1/\hat{s}^2\hat{u}^2 + 1/\hat{s}^4$ (dot-dash), and the BBS type [23] with $d\sigma/d\hat{t}|_{\pi q} \propto 1/\hat{t}^4$ (dashed). The calculations are all normalized to give the same value at $x = 0.2$, $\theta = 90^\circ$.

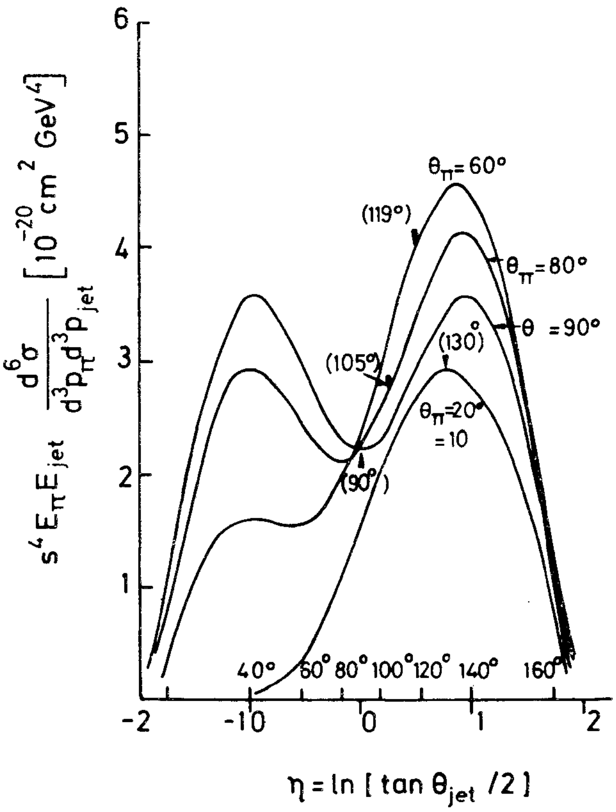
is plotted versus $\eta_{jet} = \ln(\tan\theta_{jet}/2)$, where θ_{jet} is measured from the same axis as θ_π but is 180° away in ϕ, for various values of θ_π with $x_{\perp\pi} = 0.2$. The intent is to study where in η the large $p_\perp$ of the pion is balanced, i.e. what is the η of the scattered parton. For questions of particle multiplicity alone one must smear the jet distribution by the average jet width ($\Delta\eta\sim1$) so that the two hump structure of the QEPP and BBS models is presumably washed out. Hence one expects a flat, broad multiplicity distribution in these models in contrast to the more peaked distribution of the BBG model studied here. Such a broad distribution is, in fact, in quite good agreement with the data of Fig. 8a. The real question is



a) Simple quasi-exclusive parton-parton model[22].



b) Simple BBG model[18] with $d\sigma/d\hat{t}|_{\pi q} \propto 1/\hat{s}^2\hat{u}^2 + 1/\hat{s}^4$.



c) Simple BBS model[23] with $d\sigma/d\hat{t}|_{\pi q} \propto 1/\hat{t}^4$.

Fig. 10 Model calculations of the one particle-one jet double cross-section $s^4 E_\pi E_{jet}(d^6\sigma/d^3p_\pi d^3p_{jet})$ for various values of $\theta\pi$ as a function of $\eta = \ln \tan\theta_{jet}/2$ (θ_{jet} and θ_π measured from the same direction but 180° away in ϕ) with $x_\perp = 0.2$. The centre of gravity of each distribution is marked with a tick. The normalization is the same as in Fig. 9.

where the centre of gravity of the distributions (marked with a tick) move as θ_π is varied. In the first and third models the jet moves into the hemisphere opposite the π (approximate back-to-back behaviour) as naively expected. The relatively small magnitude of the effect is also not inconsistent with data[45,46]. Surprisingly the BBG correlation peak stays near 90° with a slight tendancy to move to smaller θ (anti-back-to-back behaviour). The explanation for this is presumably the combination of the weak angular dependence of the assumed scattering process and the fact that the parton-pion c.m. system tends to be moving in the direction of the initial parton which carries higher momentum on average. If both particles appear near 90° in their c.m. system then the motion of that system puts them in the same hemisphere of the overall c.m. system. A stronger angular dependence such as $\frac{1}{\hat{u}^4}$ [49] for the π-g process leads to results very similar to the other models. In any case such measurements are clearly useful for testing specific models.

5. Other Models

Besides the models discussed above, several other, generally novel, explanations of large $p_\perp$ phenomena have also been suggested. One formalism which seeks to explain the enhanced multiplicities observed in large $p_\perp$ events is the Bremsstrahlung of neutral vector mesons which is discussed by several authors.[50] The general picture is that for low momentum transfers some sort of multiperipheral mechanism is operative whereas at large $p_\perp$ Bremsstrahlung effects become important and lead to both power behaviour in $p_\perp$ and rising multiplicities. This picture also offers an explanation of the observed increase in multiplicity for increasing momentum transfer at fixed missing mass in the process $pp \to pX$.[51] A somewhat different Bremsstrahlung picture has also been studied by Choudhury[52] to explain this same data.

An extremely novel idea is the suggestion of Sen[53] that the observed properties of using σ_{TOT}, scaling in deep inelastic ep, and activity at large $p_\perp$ are all manifestations of a large transition in the hadronic matter. He suggests that this situation may then be studied in terms of an effective field theory wherein the use of perturbation theory is justified. Such a formalism might then allow, for example, the derivation of the counting rule discussed above. Another interesting idea is proposed by Teper[54] who attempts to set a lower bound on large $p_\perp$ inclusive amplitudes by using elastic unitarity to relate these amplitudes to the elastic amplitude at large t. The resulting analysis has strong model dependences but it is an interesting approach. This same author[55] has also suggested a model for large $p_\perp$ phenomena which kinematically looks almost identical to the BBS model[23] of Fig. 2f-h. However, in this case the central π-π dynamics is not to be taken from a parton model but rather from actual experiment which is here assumed to exhibit simple power behaviour. In this way Teper attempts to describe large $p_\perp$ events without introducing partons. In particular he finds a simple qualitative explanation of the observed particle ratios.

Finally D C Carey, et al[56] suggest that the empirical form

$$E \frac{d^3\sigma^i}{d^3p} \sim g(p_\perp)\ f^i(x_R) \qquad (7)$$

where $x_R = \frac{2|\vec{P}|}{\sqrt{s}}$, offers a good description of a large portion of the present large $p_\perp$ data over a wide range in s, $p_\perp$ and θ. The function $g(p_\perp)$ has the universal form $(p_\perp^2 + .86)^{-4.5}$ and $f^i(x_R)$ behaves as $(1-x_R)^{n_i}$ where n_i depends on the produced particle. Although this formula does not fit well, the data of the CCR experiment[14], its simplicity and the apparent factorization are certainly interesting empirical features.

6. Summary

There is, as yet, no truly compelling single theoretical interpretation of large p_t phenomena. Models which itilize the notion of partons have been the most carefully studied and are generally consistent with the present data. However, other models, in particular fireball models, have also succeeded in explaining some of the features of the data. Clarification of the situation will require progress on at least two fronts. First, the specific models must be interrogated more fully in order to utilize the more detailed data now becoming available. For example, are the latest correlation measurements a problem for parton models? Are the particle ratios a serious threat to fireballs? At the same time, as the models mature and become more complex, it is imperative that one attempt to develop a foundation in more fundamental ideas in order to better motivate and simultaneously control the development of the models. There are also experimental questions of singular importance. For example, is a single power law behaviour adequate also at larger $p_\perp$'s at the energies of the ISR? Can the canonical two-jet $p_\perp^{-4}$ behaviour be found at larger energies or by means of more novel detection techniques? Clearly this field will remain interesting for some time to come.

Acknowledgements

The author gratefully acknowledges many helpful discussions with his colleagues at CERN. Special recognition goes to the session organiser, L Lederman, and the scientific secretaries, L Carroll and M B Green, for their assistance.

References

1. For other recent reviews of this topic see:
S D Ellis, R Thun, IX^e Rencontre de Moriond, 1974, CERN preprint TH 1874 (1974);
S D Ellis, Vth International Symposium on Many Particle Hadrodynamics, Eisenach-Leipzig, 1974,
R Savit, preprint SLAC-PUB-1324 (1973);
S V Brodsky, preprint SLAC-PUB-1329 (1973).

2. As an example of an alternate picture which has not been studied in detail in the present context but is in qualitative agreement with the data, see J Benecke, T T Chou, C N Yang, E Yen., Phys. Rev. 188, 2159 (1969).

3. For further discussions of this and related topics see also the reports of P V Landshoff and J F Gunion in these proceedings.

4. See for example: J Engels, K Schilling, H Satz, Nuovo Cim. 17A, 535 (1973).

5. E Fermi, Progr. Theor. Phys. 5, 570 (1950); Phys. Rev. 81, 683 (1951).

6. Meng Ta-Cheng, Freie Universitat,Berlin preprint FUB HEP 74/2 (1974).

7. L Heiko, Universite Catholique de Louvain preprint (1974), paper 158.

8. S Pokorski, L Van Hove, Nucl. Phys. B60, 379 (1973).

9. S Pokorski, L Van Hove, CERN preprint TH 1772 (1973) [to be published in Acta Phys. Polon B].

10. G Ranft, J Ranft, CERN preprint TH 1838 (1974); E L Berger, CERN preprint TH 1816 (1974).

11. S Sakai, Tokyo University preprint TUETP-73-6 (1973).

12. A Bouquet, University of Paris, Thesis, (1974); A Bouquet, V Letessia, A Tounsi, preprint PAR-LPTHE 74/1, IPNO 74-20 (1974).

13. For the present experimental situation see the report of F J Gilman in these proceedings.

14. F W Büsser, et al., Phys. Lett. 46B, 471 (1973).

15. J W Cronin, et al., Phys. Rev. Lett 31, 1426 (1973); see also EFI preprint, University of Chicago (1974), Production of Hadrons at Large Transverse Momentum at 200 , 300 and 400 GeV, paper 357.

16. D Amati, L Caneschi, M Testa., Phys. Lett. 43B, 186 (1973); and CERN preprint TH 1644 (1973).

17. P V Landshoff, J C Polkinghorne., Phys. Rev. D8, 4159 (1973); Phys. Lett. 45B, 361 (1973); and preprint DAMTP 73/31; Phys. Rev. D8, 927 (1973)

18. R Blankenbecler, S V Brodsky, J F Gunion., Phys. Rev. D6, 2652 (1972); Phys. Lett. 42B, 461 (1973); Phys. Lett. 39B, 649 (1972); Phys. Rev. D8, 287 (1973).

19. S M Berman, J D Bjorken, J Kogut, Phys. Rev. D4, 3388 (1971); J D Bjorken., Phys. Rev. D8,4098 (1973).

20. D Cline, F Halzen, H Waldrop., Nucl Phys. B55, 157 (1973).

21. S D Ellis, M B Kislinger., Phys. Rev. D9, 2027 (1974).

22. S D Ellis., Phys. Lett. 49B, 189 (1974).

23. M Bander, R M Barnett, D Silverman., Phys. Lett. 48B, 243 (1974).

24. G Preparata, CERN preprint TH 1859 (1974).

25. F Finocchiaro, et al., CERN preprint (1974), Measurement of Charged particle multiplicities associated with large transverse momentum photons in proton-proton collisions, paper 988; R Kephart, et al, CERN preprint (1974), s-dependence of charged particle multiplicities associated with large transverse momentum photons at the ISR, paper 989.

26. F W Büsser et al., CERN preprint (1974), Correlations between Large Transverse Momentum π^0 mesons and Charge Particles or π^0 mesons at the CERN ISR, paper 728.

27. R Blankenbecler, preprint SLAC-PUB-1438 (1974); talk presented at the IXth Balaton Symposium on Particle Physic, Hungary (1974).

28. D Amati, L Canuschi, CERN preprint TH 1854 (1974).

29. S Brodsky, G Farrar., Phys. Rev. Lett. 31, 1153 (1973).

30. V Matveev, R Muradyan, A Tavkhildze., Lett Nuovo Cim. 7, 719 (1973).

31. P V Landshoff, preprint DAMTP 73/36 (1973), (to be published in Phys. Rev.).

32. Z F Ezawa, preprint DAMTP 74/5 (1974), paper 120, (to be published in Nuovo Cim.).

33. V Matveev, R Muradyan, A Tavkhelidze, Joint Institute for Nuclear Research Report No. EZ-8048 (1974), paper 1101.

34. P G O Freund, S Nandi, University of Chicago preprint EFI 74/33 (1974), paper 833.

35. J F Gunion, University of Pittsburgh preprint PITT-126 (1974), paper 717.

36. G Preparata , CERN preprint TH-1836 (1974).

37. R Blankenbecler, S J Brodsky, J F Gunion, R Savit, SLAC-PUB-1294 (1973).

38. Y Igarashi, T Nishitani, Nagoya preprint (1974), paper 69; Y Igarashi, T Matsuoka, S Sawada, Nagoya preprint (1974), Paper 70; K. Awaya, S. Sawada, Nagoya preprint (1974), paper 71; Y Igarashi, T Matsuoka, S Sawada, Nagoya preprint (1974), paper 72.

39. K Kinoshita, Y Myozyo, Kyushu University preprint (1974), paper 113; K Kinoshita, H Noda, Kyushu University preprint KYUSHU-74-HE-7 (1974), paper 126; K Kinoshita, Y Kinoshita, Y Myozo, H Noda, Kyushu University preprint KYUSHU-74-HE-11 (1974), paper 125.

40. B L Combridge, University of Cambridge preprint (1974), paper 508.

41. D M Scott, preprint DAMTP 73/37 (1973), paper 250.

42. A V Efremov, Joint Institute for Nuclear Research preprint (1974), paper 674.

43. On quite general grounds one expects the relative proportion of heavy particles to increase with $p_\perp$ at small $p_\perp$ simply because kinematic mass effects are becoming less important.

44. B Alper, et al., CERN preprint (1974), High Transverse Momentum Charged Particle Production in Proton-Proton Collisions at the CERN-ISR,paper 834.

45. G Finocchiaro et al., CERN preprint (1974), Charged particle multiplicities associated with large transverse momentum photons at the ISR, paper 990.

46. B Betev, et al., CERN preprint (1974), Observation of proton-proton interactions with π^0 of large transverse momentum at the ISR, paper 590.

47. S D Ellis, in the proceedings of the V^{th} International Symposium on Many Particle Hadrodynamics, Eisenach-Leipzig, 1974. See also the report of J F Gunion in these proceedings.

48. For a discussion of this form of $\left.\frac{d\sigma}{dt}\right|_{\pi q}$ see the last paper in Ref. 1. It is straighforward to get this result from the picture in Fig. 2c if the spin of the parton is ignored.

49. This form for $\left.\frac{d\sigma}{dt}\right|_{\pi q}$ is suggested by R Blankenbecler, IX^e Rencontre de Moriond, 1974. Still another form is discussed by J F Gunion elsewhere in these proceedings where calculations similar to those given here are presented.

50. H M Fried, Brown University preprint (1974), paper 35; A P Contogouris, J P Holden, E N Argyres, McGill University preprint (1974), paper 570.

51. A Ramanauskos, et al., Phys. Rev. Lett. 31, 1371 (1973).

52. S Rai Choudhury, preprint (1974), paper 482.

53. S Sen, Trinity College preprint (1974), paper 248.

54. M Teper, Westfield College preprint (1974), paper 298.

55. M Teper, Westfield College preprint (1974), paper 299.

56. D C Carey, et al., preprint NAL-PUB-74/49-THY/EXP (1974), paper 746.