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HIGH TRANSVERSE MOMENTUM PROCESSES

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The most common strong-interaction and even electromagnetic phenomena are characterized by low mean transverse momentum ($\langle p_{\perp} \rangle < 1 \text{ GeV}$) for the second-

dary hadrons. Yet most of the available phase-space is found elsewhere. Figure 1 shows two different maps of the phase-space appropriate to 30+30 GeV ISR

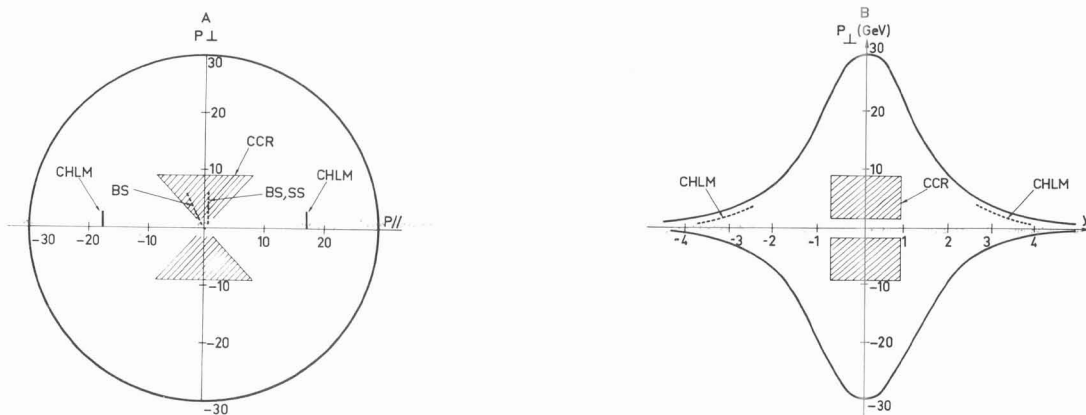


Fig.1 a) Peyrou plot for 30+30 GeV pp collisions at the ISR, with an indication of the territory thus far explored. b) The same, with p_{\perp} and rapidity $y \approx \log \tan \frac{\theta}{2}$ chosen as variables.

conditions, along with a rough sketch of the territory now explored. These explorations, along with others carried out at NAL, are quite new, and extremely interesting. This review will emphasize the theoretical perspectives, inasmuch as the summary of the parallel sessions covers well the experimental side [1,2]. This should not obscure the fact that the real news is experimental results not theoretical speculation. I will cover the following topics :

- 1.- Single-particle inclusive hadron spectra at high p_{\perp} .
- 2.- Structure of high- p_{\perp} hadronic events.
- 3.- Theoretical models and interpretations.
- 4.- Inclusive production of high- p_{\perp} leptons and lepton pairs, along with limits on production of W^{\pm} , Z^0 , and other massive objects.
- 5.- Multiple cores and high- p_{\perp} phenomena at still higher energies.

1.- INCLUSIVE HADRON SPECTRA.

1.1.- SCALING BEHAVIOR.- The observed spectrum of π^0 's at $\theta^* \sim 90^\circ$, as measured [1] by the CERN-Columbia-Rockefeller group at 53 GeV at the ISR, provides the highest-energy, highest- p_{\perp} hadron spectrum in existence. The observations show immediately :

- (1) The yield is much larger than an extrapolation based on the Hagedorn statistical model ;

$$Ed\sigma/d^3p \sim e^{-6p_{\perp}}$$

- (2) The yield is much larger (about 10^4) than what is expected from photon exchange (Figure 2)

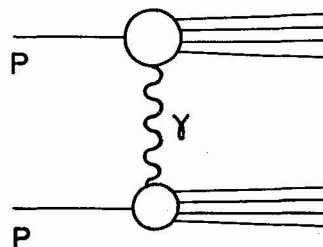


Fig.2 - Photon-exchange diagram leading to production of high p_{\perp} hadrons.

despite the fact that the photon-exchange contribution only falls as a power of p_{\perp} , roughly p_{\perp}^{-4} . This strongly suggests that the origin of the phenomenon is hadronic in nature.

The expected behaviour of the hadron inclusive distribution produced by the photon exchange mechanism is given [2] by dimensional analysis :

$$E \frac{d^3\sigma}{d^3p} = \frac{1}{p_{\perp}^4} F\left(\frac{p}{p_{\max}}, \theta_{\text{CM}}\right) \quad (1.1)$$

where F is of order α^2 . It was natural [3] to replace the photon exchange by a $J=1$ gluon exchange and speculate that the same form would work for the strong production [2,4,5]. But the evidence is now quite convincing that this idea is wrong. At $\theta_{\text{CM}} \approx 90^\circ$, the experiments show that the exponent 4 should be replaced approximately by 8, as suggested theoretically by Blankenbecler, Brodsky and Gunion [6]. This is shown by the CCR group in their contribution. The best tests of any scaling behaviour are at the highest energies and p_{\perp} , in order that any low p_{\perp} or low s backgrounds are not present, and therefore the CCR data provides the best test. Their estimated error on the power of p_{\perp} is small, $\lesssim 1$ and equation (1.1) appears untenable. Let us assume the exponent 8, and then plot the function $(p_{\perp}^8) E \frac{d^3\sigma}{d^3p}$ versus $2p_{\perp}/\sqrt{s} = \frac{p_{\perp}}{p_{\max}}$ for $\theta_{\text{CM}} \approx 90^\circ$ in order to better interpret the nature of this scaling (Figure 3).

We see that below $E_{\text{lab}} \sim 100$ GeV, the spectrum is in qualitative accord with an absolute Feynman scaling in p_{\perp} ; the only change is a horizontal compression of the distribution as a consequence of the choice of horizontal scale $2p_{\perp}/\sqrt{s}$. Above $E_{\text{lab}} \sim 100$ GeV, the approximate scaling behaviour sets in, in fact, quite abruptly. This observation was made by the NAL-NIU group detecting high- p_{\perp} γ -rays in the internal target area (although they use a quite different parametrization than here). By the time $\sqrt{s} = 53$ GeV, the scaling occurs for $p_{\perp} \gtrsim 3$ GeV.

It need scarcely be said that the evidence presented does not in itself prove the relevance of this parametrization. However, I shall here ignore all others. There are attractive theoretical properties for this form which should be familiar to anyone who has ever looked at cosmic-ray physics. Glennys Farrar and I call it the parent-child relation [7] :

Suppose we produce some parent (parton, isobar, etc.) of momentum p according to an inclusive

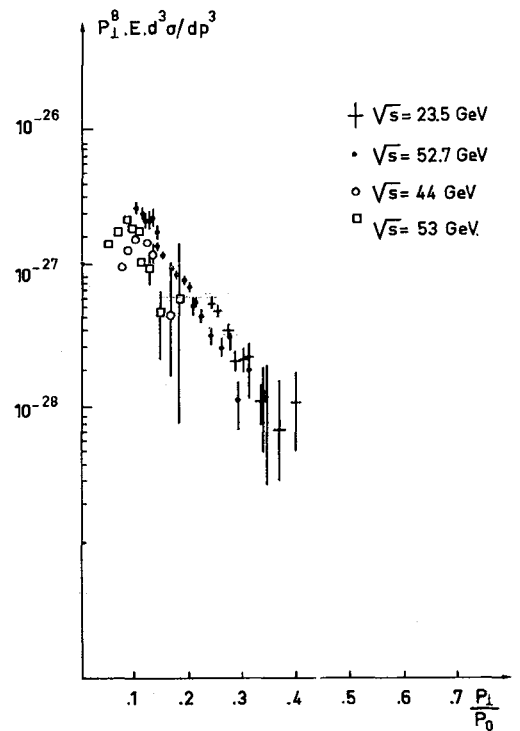
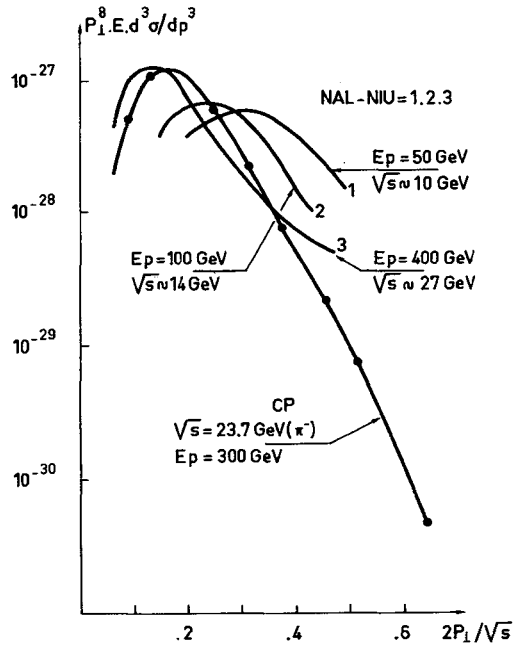


Fig.3 - Plot of $p_{\perp}^8 E \frac{d^3\sigma}{d^3p}$ versus the scale variable

$$\frac{2p_{\perp}}{\sqrt{s}} \approx \frac{p}{p_{\max}} \quad . \quad (a) \text{ NAL-NIU data at 50, 100, and 400 GeV ; CP data at 300 GeV, (b) CCR, BS, and SS ISR data.}$$

distribution

$$E \frac{d^3\sigma}{d^3p} \sim \frac{1}{p_{\perp}^n} f\left(\frac{p}{p_{\max}}, \theta^*\right) \quad (1.2)$$

Suppose the parent P decays into a hadron child c of momentum $p'_\mu = x p_\mu$ (with limited p_\perp relative to the direction of the parent) according to a Feynman scaling hypothesis

$$\frac{dN_c}{dx} \sim g_c^P(x) \quad (1.3)$$

(This is certainly true for isobar decays).

Then the inclusive distribution has the same form as equation (1.2), with a different function f' (which is a convolution of f with g).

There is also a corollary. If a local-exponent approximation is valid (i.e. for some range of p_\perp we may replace f by a constant and n by an effective exponent \tilde{n}) then (at the same p_\perp)

$$\frac{\left(E \frac{d\sigma}{d^3p} \right)_{\text{parent}}}{\left(E \frac{d\sigma}{d^3p} \right)_{\text{child}}} = \int_0^1 dx x^{\tilde{n}-2} g(x) \quad (1.4)$$

Thus there is a universality of the scaling law, (Eq.1.2), much like the universality of the central plateau-region in ordinary processes (we mean, e.g. if $dN/dy \sim \text{const.}$ (or $e^{\alpha y}$) for a parent (such as P, Δ) dN/dy also is constant (or $e^{\alpha y}$) for its children).

Notice also that in the cascade process, the cms. angle (and therefore the rapidity = $\log \tan \theta/2$) is approximately conserved. Therefore these considerations also suggest the usefulness of θ_{CM} or y as a variable of choice in high- p_\perp phenomena. Likewise p/p_{max} (at a given θ) is also a natural variable. Feynman's x -variable, $x = 2p_\parallel / \sqrt{s}$, is not a good choice. Also $2p_\perp / \sqrt{s}$ is only a good variable at $\theta_{CM} = 90^\circ$; it should be clear there can be no scaling of the invariant cross section in p_\perp / \sqrt{s} over a range of cms angles!

Before leaving these generalities, we note again that dimensional analysis would have predicted the exponent in Eq.(1.2) to be 4. To go from 4 to 8 implies that the basic matrix-element for the process be proportional to m^2 , with m a small (?) mass; $m \lesssim 1$ GeV. (?). The origin of this damping factor becomes a central theoretical question, to which we return in section 3.

1.2.- PARTICLE RATIOS.-

The most important feature of the data on particle ratios is that heavy particles (K^+, p, \bar{p}) comprise a larger fraction of the total yield. At the ISR, it is $\sim 35\%$ at $p_\perp \sim 3$ GeV as contrasted with $\sim 10\%$ at low p_\perp . And at NAL, the p/π^+ ratio hovers around 100% and K^+/π^+ around 50%.

The interpretation of these large ratios depends upon what one assumes as the ultimate parent of the hadrons we observe. It can be either a parton, which "fragments" as it is supposed to do in deep-inelastic lepton-induced processes [8], or an ordinary hadron or isobar (of limited mass), or perhaps a "fireball" [9].

If the parent is a low mass hadron, one does not have to go far to qualitatively understand the fact that the heavy particles are more dominant. While isobar and resonance decays tend to populate the central plateau with an excess of pions, this mechanism is greatly diminished in importance at high p_\perp because of the steeply falling spectrum. Glennys Farrar and I carried out a simple calculation to illustrate this effect [7]. We first assumed SU(3)-symmetric production of $\underline{35}$ and $\underline{56}$ mesons and baryons, in the ratio 2/1 and according to their statistical weight. The isobar decays provide considerable but not quite enough SU(3) violation. We get, for example,

$$\frac{K^-}{\pi^-} \sim 22\% \quad \frac{\bar{p}}{K^-} \sim 89\% \quad \frac{\eta}{\pi^0} \sim 4\% \quad (1.5)$$

However, if we make the corresponding assumption at high p_\perp , e.g. all members of the $\underline{35}$ and $\underline{56}$ are produced with a p_\perp^{-8} spectrum, again according to statistical weight, and again with $\underline{35}/\underline{56} = 2/1$, we get

$$\frac{K^-}{\pi^-} \sim 95\% \quad \frac{\bar{p}}{K^-} \sim 68\% \quad \frac{\eta}{\pi^0} \sim 57\% \quad (1.6)$$

Again, anyone who has familiarity with cosmic ray physics should understand this. For those who do not, it is a simple exercise utilizing Eq.(1.4): isobars have a nontrivial $g(x)$, while for the stable components $g(x) = \delta(1-x)$ and they are enhanced.

Those who use the hypothesis that the ultimate parents (or grandparents) of the hadron spectra that we observe are partons, in particular quarks, should also find the qualitative trends, with increasing p_\perp which are observed at the ISR reasonable. When $2p_\perp / \sqrt{s}$ is large, it is reasonable to suppose the partons are valence partons, predominantly u-quarks. These u-quarks (along with same d) preferentially fragment into p and K , not \bar{p} and \bar{K} . The u quark preferentially fragments into π^+ as well; thus a π^+/π^- ratio greater than unity is also reasonable (this latter phenomenon is observed in

deep-inelastic electroproduction). However if this is the right interpretation, we are also forced to conclude that the rather large p/π^+ ratio $\sim 30\%$ and K^+/π^+ ratio $\sim 35\%$ observed at the ISR for $p_{\perp} \gtrsim 3$ GeV implies similarly large ratios in e^+e^- colliding beams, which (according to the parton-model ideas) produce predominantly a mono-energetic beam of u and \bar{u} quarks. A cms energy ~ 8 GeV should suffice for a test.

The problem of interpretation becomes much more acute when the NAL data of the Chicago-Princeton group is taken into account. At such large values of p/p_{max} , it becomes ever more probable that the parton is a u-quark, and thus a large π^+/π^- ratio is expected. It is not observed ($1.0 \lesssim \pi^+/\pi^- \lesssim 1.2$ over the entire range of the data). And the p/π^+ ratio ~ 1 implies an extraordinary amount of baryon production in e^+e^- annihilation [10].

1.3.- ANGULAR DISTRIBUTION OF INCLUSIVE SPECTRA.-

From the phase-space plots in figure 1, we see that there is a great deal of territory from $\theta_{CM} \sim 100$ rad. to $\theta_{CM} \sim 45^\circ$ which, at the ISR, yield high p_{\perp} secondaries but which is not yet explored. For $1\text{GeV} < p_{\perp} < 3$ GeV, the data of the British-Scandinavian group show no discernible difference in the invariant cross-section, as function of p_{\perp} , for $\theta_{CM} = 60^\circ$ and $\theta_{CM} = 90^\circ$. Theoretical models are capable of describing the angular dependence, which is expected to be quite soft, once the factor p_{\perp}^{-8} has been extracted. I shall not review these, inasmuch as

existing theoretical ideas are sure to be refined, modified, or generalized considerably by the time any such data will appear.

2.- STRUCTURE IN PHASE-SPACE OF HIGH- p_{\perp} EVENTS.-

2.1.- THE GEOGRAPHY OF THE FINAL-STATE HADRON POPULATIONS.-

Of clear interest and importance is the determination of what is produced in association with a high- p_{\perp} secondary. We have already indicated that if the secondary is the decay product of a parent, both parent and secondary possess approximately the same laboratory angle [11]. (This is, by the way, a Lorentz covariant statement for all Lorentz boosts except those which make one of the secondaries wee). In other words a jet may be formed. Define a jet-axis by the direction of the momentum of the highest- p_{\perp} hadron emitted in a high- p_{\perp} event. Then a natural hypothesis is the following

(1) Particles of high p_{\perp} emitted in the same hemisphere as the highest p_{\perp} hadron emerge in the same direction, with angular fluctuation $\Delta\theta \lesssim 0.5/p_{\perp}$ in the collinear Lorentz frame in which the jet emerges at 90° to the beam direction.

This hypothesis is a necessary consequence of parton-model orthodoxy [10], but has a generality that extends beyond it. The region of phase space occupied by members of a jet is shown in figure 4. We see that the distribution in rapidity of associated hadrons should be peaked, with width less than 2 units of rapidity.

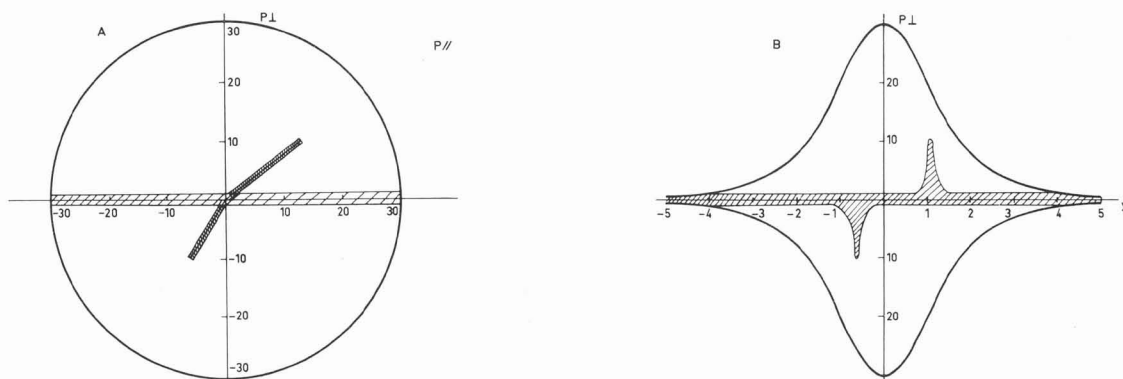


Fig.4 - Regions of phase space which may be populated according to the jet hypothesis ; i.e. the region outside the shaded region is expected to be not populated by high- p_{\perp} hadrons (a) Peyrou plot ; (b) p_{\perp} - y plot.

What about the opposite hemisphere ? Evidently the high p_{\perp} must be balanced. Unless the multiplicity of associated hadrons on the other side is linear in p_{\perp} , there will be at least one high- p_{\perp} hadron in this opposite hemisphere (at $p_{\perp} \gtrsim 10\text{GeV}$,

one would have to produce $\sim 20-30$ hadrons, each carrying $p_{\perp} \sim 0.3$ GeV to avoid this conclusion). Consider the hadron of largest p_{\perp} . Following the preceding argument, we would be led to expect a jet in

the opposite hemisphere as well. This has already been illustrated in Fig.4. The two jets need not emerge in opposite directions, i.e. with $\Delta\theta \sim 180^\circ$: Estimates of their correlation easily allow for fluctuations in their relative rapidity Δy of two units. This picture is summarized in the next two hypotheses.

(2) Event by event a plane may be defined by the beam momenta and the momentum of the hadron possessing the highest p_\perp . The distribution of secondary hadron momentum normal to this plane p_N is a steeply falling function as p_N increases.

(3) Event by event, the population of secondary hadrons is confined to the usual low- p_\perp region along the beam directions and to at most two approximately coplanar jet regions, as shown in figure 4, which are defined by the highest p_\perp particles in opposite hemispheres. It is very improbable to find hadrons large distances outside these jet regions or outside the usual low- p_\perp fragmentation regions and central plateau.

We do not mean to imply by these hypotheses that all shaded regions in figure 4 are well populated in a typical high- p_\perp event. Some jets may be almost empty sets. Different models say different things. But most models of which I am aware are not in conflict with the above hypotheses, and the hypotheses are therefore very important to test. In fact, the only models I know that are in conflict are statistical "nova" models [12,13] for which the multiplicity is assumed to grow less rapidly than linear with fireball mass. These violate the coplanarity hypothesis (2).

The coplanarity hypothesis has not yet been examined experimentally. The CCR data on 2-particle correlations are at least qualitatively in agreement with hypothesis (3). If a particle is observed in coincidence with the high p_\perp π^0 and in the same hemisphere, its rapidity is sharply correlated with the π^0 . In the opposite hemisphere the correlation is absent.

Before describing what in general the models say, it is useful to further dissect the region of particle production which we have described into fragmentation regions and "plateau" in order to organize our thinking about the quite complicated kinematics. I find it helpful to first consider the photon-exchange process. All the different regions already appear in that process and can be generalized over to the hadronic case without an overcommitment to specific models. Consider first electron-proton deep-

inelastic scattering in the electron-proton center of mass frame. An inelastic collision at large ω populates phase space as shown in figure 5. Deep-

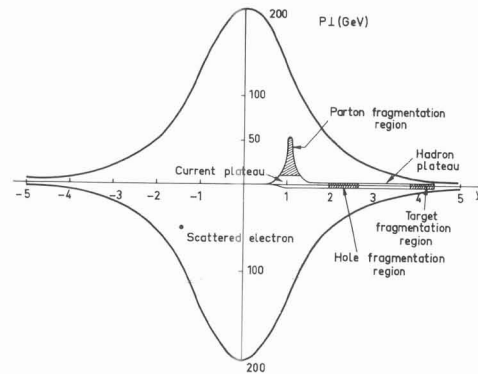


Fig.5 - Population in phase space for an electron-proton deep-inelastic collision at large ω . We are in the electron-proton cms. frame.

inelastic cognoscentes will recognize the parton-fragmentation region (containing the most energetic hadrons, for ordinary laboratory kinematics with initial proton at rest), target fragmentation region, hole-fragmentation region, and the two plateau regions, hadronic plateau and current plateau [14]. This picture uses ideas of short-range correlation in rapidity, which may be wrong-especially in the current-fragmentation region. Generally expected is that the multiplicity of hadrons in the current-plateau is related to the multiplicity of hadrons in the e^+e^- annihilation process, inasmuch as the hole and parton fragmentation regions along with the current plateau comprise the fragmentation region of the virtual photon. Now consider a proton-proton collision proceeding via photon exchange, as in Fig.2. Evidently we should invert the distribution of figure 5 about the origin to obtain the fragmentation of the left-mover. That would leave a gap between the two regions. However, there is good reason to believe the gap is filled by an ordinary hadron plateau. In addition to the photon exchange, pomeron exchange leading to particle production should be present and important inasmuch as the impact parameter in the collision is not large. That is, there is no reason to throw away diagrams such as figure 6.

The complete map of the possible populated regions of phase space is shown in figure 7a. There are 15 distinct regions. Impossible energies are required to see them all at the same time. Savit [15] has

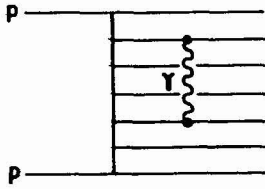


Fig.6 - Proton-proton scattering via photon exchange, with Pomeron-exchange correction.

worked this out in the actual practical case of p_{\perp} / \sqrt{s} not small. Then many of these regions merge, and we are left with only 9 mixed plateaux, as shown in Fig.7b. In realistic conditions ($p_{\perp} \ll 10\text{GeV}$) there is no current plateau or mixed plateaux and the regions reduce to 5. Let no one be deceived that the situation is not complex. All 15 regions can be generally identified in a variety of models: they are not specific to parton ideas. For example, just the three general hypotheses made earlier rather naturally account for all the regions except the hole-fragmentation regions. To see that they also are general, start with the configuration of Fig. 7a (where evidently $s \gg p_{\perp}^2$) and keep the hadron configurations in the jets constant while lowering the incident beam momenta. For sufficiently large s , variation of projectile energies is not supposed to affect what happens in the central region (at fixed p_{\perp}). Thus no change is forced as long as hadron plateaux (Pomeron couplings) exist adjacent to the projectile fragmentation regions - and as long as energy and momentum are conserved. We cannot decrease the beam energies to so low a value that the total four-momentum in the initial state is less than what exists in the hadron jets alone! Some easy examination of the kinematics shows that balance is attained when the projectile fragmentation regions overlap the hole fragmentation regions. This quite general argument indicates that the existence of the hole fragmentation regions is not specific to models, at least if it is assumed that the picture of short-range rapidity correlations in the projectile and hadronic plateau regions is not completely abandoned for this class of events.

3.- MODELS. - Given this geography of phase-space for high- p_{\perp} processes we can compare the predictions of the various theoretical models as to how the various regions are populated. Also, as we proceed, we

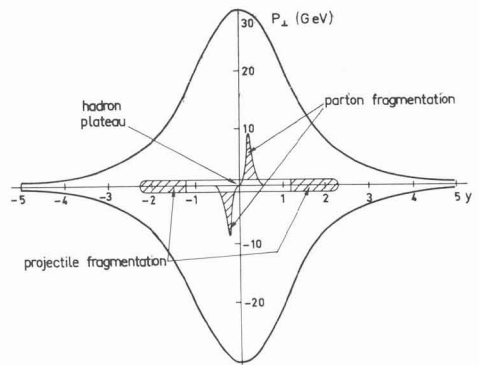
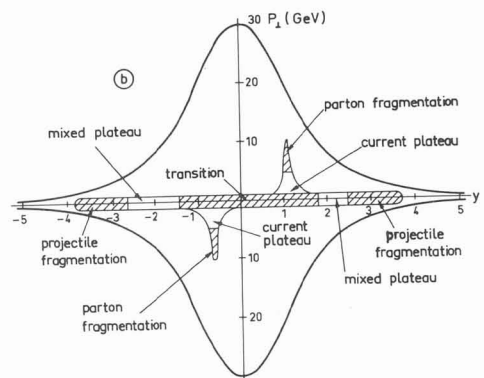
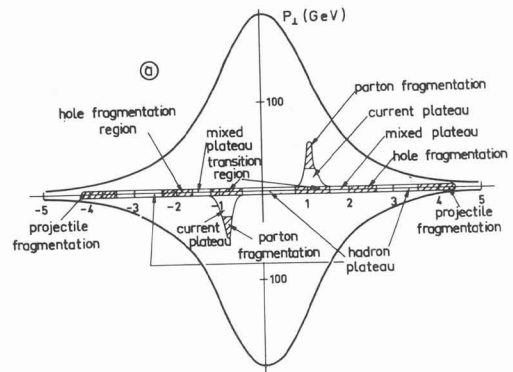


Fig.7 - Fragmentation regions and plateaux for a high- p_{\perp} pp interaction.
 (a) General case.
 (b) Minimum-energy configuration; a finite fraction of initial-state energy has emerged in the high- p_{\perp} jets.
 (c) Real life; there is no current plateau until $p_{\perp} \gg 10\text{-}20\text{ GeV}$.

must remember that a central dynamical problem is to discover the origin of the factor $\sim m^2$ in the matrix element (or $\sim m^4$ in the cross-section) which characterizes the violation of dimensional scaling.

The phase-space populations for 6 different models are shown schematically in figure 8.

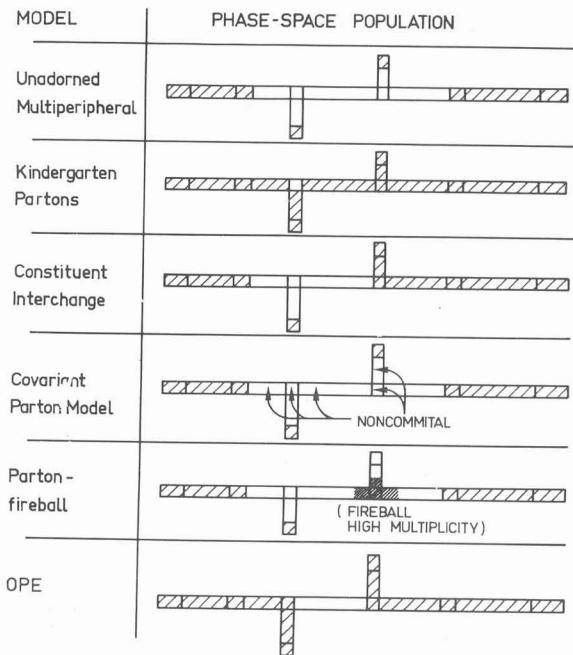


Fig.8 - Phase-space-populations (shown shaded) for 6 different models of high - p_{\perp} processes
 a) Multiperipheral model
 b) Kindergarten parton model
 c) Constituent interchange model
 d) Covariant parton model
 e) Parton-fireball
 f) One-pion exchange

3.1. - THE MULTIPERIPHERAL MODEL UNADORNED[16].-

In such models a multiperipheral ladder fills the hadron plateau regions in figure 8a until the hole-fragmentation regions are reached. Beyond, in the transition, mixed plateau, and current plateau regions, all is left empty until the parton-fragmentation regions are reached. In each such region one particle is found. Or if isobars are included, a finite number of particles may be found there. The power of m^2 needed in the amplitude can in this model be provided by taking the members of the ladder to be spinless, and the vertices without form-factor. Then the amplitude essentially contains a $J=0$ parton-parton scattering proportional to the square of a trilinear coupling constant $g^2 \sim [m^2]$.

3.2. - THE KINDERGARTEN PARTON MODEL [2,4,5].- In this model all fragmentation regions are assumed to be full, with roughly the same density as expected

in deep inelastic processes. In particular the multiplicity in the current-fragmentation region should be the same as observed for the corresponding region in deep inelastic electroproduction. If a high- p_{\perp} hadron is observed, as in an inclusive experiment, it carries about 70% of the energy of its parent parton [5,7] because of the steep fall of the primary spectrum with increasing p_{\perp} . This is true for any reasonably smooth inclusive parton fragmentation function $g(x)$, as follows from Eq.(1.4). Thus there should be a gap of $\sim 1-2$ units of rapidity between the observed hadron and the rest of the population in the current fragmentation region. If the trigger is on the total hadron energy in a jet, as would be the case were the hadron detector a calorimeter, then this bias is removed. In such a case the distribution should be similar to what is found in the current-fragmentation region in electroproduction. There the evidence favors (thanks to the recent Cornell experiment [17] on multiplicities in the deep inelastic region: $\omega \sim 2.5$ GeV, $1 < Q^2 < 10$ GeV²) a distribution quite similar to what is found in ordinary processes. In an experiment in which one triggers on a high- p_{\perp} particle in one hemisphere and then observes the hadrons emerging in the opposite hemisphere they should (in this model) again comprise an "unbiased jet". Thus a higher associated multiplicity is expected in the hemisphere opposite to the high- p_{\perp} trigger hadron than on the same side. The difference in multiplicities on the two sides should be roughly independent of p_{\perp} at sufficiently high (i.e. impossibly high) p_{\perp} . Ellis and Kisslinger [5] have carried out more detailed studies of many of these questions.

The main difficulty with the kindergarten parton model is its expectation of dimensional scaling for the inclusive distribution (an exponent 4 instead of the observed 8-10 in Eq.(1.4)). To obtain the power m^2 in the matrix-element appears to require again $J=0$ partons scattering via $J=0$ exchange, while the data (in particular the very large p/π ratio (~ 1) reported in the NAL experiment suggests that what is scattered contains the quantum numbers of the projectiles, in particular baryon number. Without major adjustments, this model of hadron-hadron collisions (or at least the quark-parton-plus-gluon version of it) appears to be simply wrong.

3.3. - THE CONSTITUENT INTERCHANGE MODEL [6,41].- Blankenbecler, Brodsky, and Gunion [6] argued that whether or not high- p_{\perp} hadrons may be produced via

hard parton-parton collisions, as assumed in the preceding model, they can be produced by a constituent-interchange mechanism. To me this line of argument has led by far to the most comprehensive and consistent description of high- p_{\perp} inclusive and exclusive processes in existence. Brodsky and Farrar [41] have developed a very related (but not identical) line of argument which very easily summarizes the physics involved. First of all (as discussed by Brodsky and Farrar [41] and by Matveev, Muradian, and Tavkhelidze [19]), for exclusive processes at fixed angle and high energy, the elastic scattering of a parton from another parton is assumed to proceed according to dimensional analysis. If a parton scatters elastically from a meson the amplitude is damped by a power of m^2/s where m^2 is a small mass. That is the price that has to be paid to keep the mass of the final $q\bar{q}$ bound system small. (Brodsky and Farrar have examined classes of diagrams in scale-invariant theories to support this contention). For each additional bound constituent, one includes another power of m^2/s . Thus we get the table below

Process	Fixed-angle cross-section
$qq \rightarrow qq$	$\frac{d\sigma}{dt} \sim s^{-2}$
$q\pi \rightarrow q\pi$	$\frac{d\sigma}{dt} \sim [m^2]^2 s^{-4}$
$qp \rightarrow qp$	$\frac{d\sigma}{dt} \sim [m^2]^4 s^{-6}$
$\gamma p \rightarrow \gamma p$	$\frac{d\sigma}{dt} \sim [m^2]^4 s^{-6}$
$\gamma p \rightarrow \pi p$	$\frac{d\sigma}{dt} \sim [m^2]^5 s^{-7}$
$\pi\pi \rightarrow \pi\pi$	$\frac{d\sigma}{dt} \sim [m^2]^4 s^{-6}$
$\pi p \rightarrow \pi p$	$\frac{d\sigma}{dt} \sim [m^2]^6 s^{-8}$
$pp \rightarrow pp$	$\frac{d\sigma}{dt} \sim [m^2]^8 s^{-10}$

which in fact is in good accord with the data. Given the rule, the systematic behavior of inclusive processes made on the basis of the interchange model can be reduced to dimensional analysis (or automodelity [19]). Given that for some reason the qq scattering term (which controls the kindergarten-parton description) is absent, the next most important contribution is the scattering of a meson M from a quark, either $qq \rightarrow MM$ or $qM \rightarrow qM$. By a "meson" M is meant a correlated $q\bar{q}$ pair in the proton's wave function, which possesses a low invariant mass. Because of the factor $[m^2]^2$ in this cross-section, we get, again using dimensional ana-

lysis, $n = 8$ in Eq.(1.4). In an Mq collision, the q and M in the initial beams reside in the hole-fragmentation regions. The collision transports them to the parton-fragmentation regions. The "meson" M does not fragment (unless it is an isobar), while the parton fragments preferentially into a high-mass system, leading to an inclusive spectrum which fills its current-fragmentation region. Hence the filled regions of phase-space are as shown in figure 8c. For a $q\bar{q} \rightarrow MM$ collision the current-fragmentation regions remain empty, as in the multiperipheral model. Another piece of evidence favors these ideas. The NAL data at $\sqrt{s} = 20$ and 25 GeV show a large p/π^+ ratio ≈ 1 . This indicates that at those (relatively low) energies parton-baryon scattering should not be ignored. The inclusive distribution associated with that component has an exponent n , in Eq.(1.4), of 12, not 8. Thus the experimental exponent of ~ 10 observed in that range can be at least qualitatively understood as an average of 8 and 12. As the energy increases, one would then expect, at fixed p/p_{\max} , the p/π^+ ratio to decrease as p_{\perp}^4 , which would make it quite small at $\sqrt{s} \sim 44$ at the ISR, in contradiction with observation. However the process

$$q + q \rightarrow B + \bar{q},$$

apparently omitted by Brodsky and Farrar, has the same scaling behaviour (an exponent 8) as

$$\begin{aligned} q + q &\rightarrow M + M \\ q + M &\rightarrow q + M, \end{aligned}$$

and consequently at fixed x the p/π^+ ratio would eventually be expected to tend to a non vanishing constant. With the variety of mechanisms available, it should be possible to account for the data [20].

Another possibly relevant piece of evidence comes from BNL data at 28 GeV. The BNL-VPI-Wisconsin-Purdue collaboration using the ARGO spectrometer [21] observes the reaction $pp \rightarrow p + \text{hadrons}$, where the observed p has high p_{\perp} . There appear to be no pions associated with fragmentation of the observed high- p_{\perp} proton. The associated multiplicity at fixed missing mass increases sharply as the p_{\perp} of the trigger proton increases beyond 1 GeV/c. The first observation is in accord with the interchange picture. The rise in \bar{n} is not; at fixed missing mass the behaviour is supposed to be qualitatively the same as in electro-production, where the evidence favors no increase in \bar{n} at fixed missing mass.

3.4.- THE COVARIANT PARTON MODEL [18].- Inasmuch as Professor Polkinghorne [22] has described this viewpoint in some detail, I shall only very briefly paraphrase his remarks using this language.

The diagram of figure 9a which is described aptly

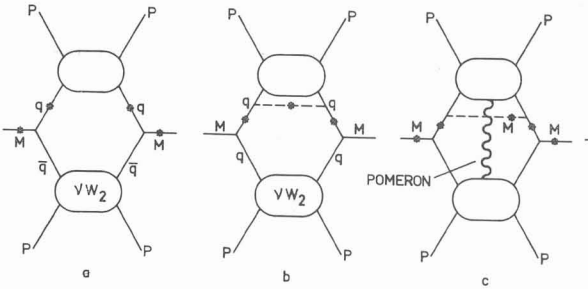


Fig.9 - a) Mueller diagram in covariant-parton-model description of high- p_{\perp} inclusive distribution; the starred lines possess high p_{\perp} . b) A simple, possible dissection of diagram (a). c) Pomeron-cut correction.

as "parton-parton fusion", exhibits explicitly only the one high- p_{\perp} particle observed in an inclusive experiment. The parton-proton amplitude labeled VW_2 accounts for one hadron-plateau and one target fragmentation region. However high- p_{\perp} is carried into the black box at the top by two off-shell partons, and considerable flexibility exists in how to choose the structure of that amplitude. The choice described by Fig.9b corresponds, in the interchange terminology, to a $qq \rightarrow MM$ scattering which would produce a configuration in phase space similar to the unadorned multiperipheral model if the masses of the mesons M were to be limited. However, using spectra of masses for the two "mesons" M can result in a filling in of the current fragmentation regions and addition of Pomeron exchange can further populate the vacant areas of phase space in the low- p_{\perp} central regions (Fig.9c). Hence the model is capable of a variety of responses depending upon the trend of the data.

3.5.- PARTON-FIREBALL MODEL [9].- Berger and Branson [9] envisage a two step process in which two fireballs of high- p_{\perp} are produced by a mechanism essentially amounting to a direct parton-parton interaction. From considerations similar to what I described as the parent-child relation, the fireball produced in association with an inclusive trigger hadron of high p_{\perp} has low mass (in order that the inelasticity in the parton \rightarrow hadron transition be low). The fireball on the other side has a large mass. This picture is therefore in line with what data

exists on associated multiplicity. Also, the predominance of heavy particles in the spectrum also might be understood inasmuch as the fireball components all have roughly the same γ and hence p and K have the highest momentum. The authors guessed a p/π^+ ratio of 5 for NAL conditions of $p/p_{\text{max}} \sim 1/2$, instead of the observed 1. They furthermore expected the ratio to be a sharply rising function of $2p_{\perp} / \sqrt{s}$.

3.6.- ONE-PION EXCHANGE.- Dremin [40] considers a diagram similar to figure 2, with a highly virtual pion exchanged instead of γ . The virtual pion is treated similarly to a virtual photon, but because it has $J=0$ the exponent 8 is found instead of 4. Development of many of the parton-fragmentation ideas can be found in this paper. The properties of the final states will be most similar to the kindergarten parton model.

3.7.- MUELLER-REGGE DIAGRAMS AND THE COLEMAN PREPARATA MODEL [23,24].- In 1969, Coleman Preparata (and in quite a similar way, L.P. Yu) invented a parton model for deep-inelastic scattering which accounts for scaling, and also is capable of providing a Mueller-Regge framework for discussing inclusive spectra, including the difficult current-fragmentation regions. The diagrams are shown in figure 10.

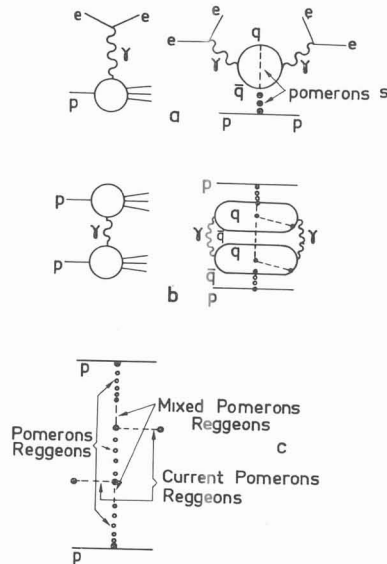


Fig.10 - Mueller-Regge diagrams in the Coleman-Preparata model. (a) Deep-inelastic electroproduction. (b) pp scattering via photon and Pomeron exchange, as in Fig.2. (c) General Mueller-Regge tree appropriate to the description of hadron final states in high- p_{\perp} processes for any case in which all allowed phase space regions (Fig.7) are filled and short-range correlation assumed.

Rapidity is measured in the vertical direction and the fragmentation regions now become vertices. The rules for calculation sound crazy :

- (i) The quarks in propagator lines have very large mass.
- (ii) The quark mass is set to zero in the vertices.
- (iii) The Regge trajectory for the current region is flat and its intercept set to unity, in order to obtain scaling.

The inclusive distribution functions are generated from these structures in the same way as described by Mueller. This may be generalized to hadron collisions as we did before by first considering photon exchange in the pp collision. After doing the obvious doubling and then adding the pomeron exchange between current fragmentation regions, we get Fig. 10b. The horizontal Reggeons describe the high- p_{\perp} current plateau. This is the basic structure for a Mueller-diagram approach to the kindergarten model B.

Other models can be similarly described in terms of a basic Reggeon "tree" as shown in Fig.10c. I think, it should be possible to develop a Mueller-Regge phenomenology along these lines. In fact, I will make the only theoretical prediction that is likely to be correct : Preparata will work all this out in the coming year.

4.- INCLUSIVE PRODUCTION OF LEPTONS.- Electromagnetic production of charged lepton-antilepton pairs in pp collisions is of prime importance in normalizing the production of even more interesting pairs, such as $\mu^+\nu_{\mu}$ or $e^+\nu_e$ emerging from decay of a W^+ . However the phenomenon is of interest independent of that. Among the relevant experiments are

- (1) The original BNL-Columbia experiment [25] : $pU \rightarrow \mu^+ \mu^- + \text{anything at } 28 \text{ GeV/c.}$
- (2) The CCR experiment [26] at the ISR : $pp \rightarrow e^+e^- + \text{anything.}$
- (3) A lepton search at IHEP [27] : $pAe \rightarrow \ell + \text{anything.}$

The standard of reference for theoretical cross-section estimates is the Drell-Yan [28] parton model calculation. In this model, the protons are replaced by beams of partons (quarks and antiquarks) whose momentum distribution are determined from the phenomenology of deep-inelastic electron and neutrino scattering. There are six such distributions [29] to determine $(u, d, s, \bar{u}, \bar{d}, \bar{s})$. The useful experimental inputs are the two high-accuracy experiments on ep and en scattering plus the evidence from neutrino

experiments that the antiparton contribution at low and moderate ω is small ($0.3 < \sigma_{\nu N} / \sigma_{\nu N} < 0.4$).

There is a need for updated theoretical studies of this problem using the best information on parton momentum distributions. I know that Farrar and Jaffe are presently working on it. And there is recent work by Fidler [30], of the Cambridge group. I will follow a course quite parallel to Fidler's. The distributions are defined as

$$x \frac{dN_u}{dx} = u(x) \text{ etc...}$$

and satisfy the sum rules

$$\int_0^1 \frac{dx}{x} [u(x) - \bar{u}(x)] = 2$$

$$\int_0^1 \frac{dx}{x} [d(x) - \bar{d}(x)] = 1$$

$$\int_0^1 \frac{dx}{x} [s(x) - \bar{s}(x)] = 0.$$

To proceed further, we use the following assumptions.

- 1) For $x < 0.3$ ignore (to first order) $\bar{u}, \bar{d}, \bar{s}, s$, and determine u and d from data.
- 2) For $x < 0.1$; take the duality choice [31,32]

$$\bar{u} = \bar{d} = \bar{s} = s$$

$$u - \bar{u} = 2(d - \bar{d}).$$
- 3) For $x < 0.05$ extrapolate, assuming $(u-d) \sim \omega^{-1/2}$ and $\nu W_2 \rightarrow 0.35$ as $\omega \rightarrow \infty$.

These assumptions give the parton fluxes shown in figure 11.

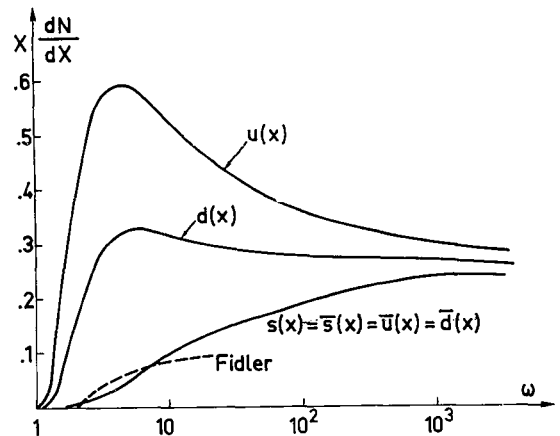


Fig.11 - Rough estimate of flux of partons in a proton as a function of their inverse longitudinal fraction $\omega = X^{-1}$. Notice that the area between $p(n\lambda)$ and $\bar{p}(n\lambda)$ distributions is normalized to $2(1,0)$ by the sum rules.

The point of elaborating on all this is to emphasize the smallness and the uncertainty of the \bar{u} flux at moderate x . This is crucial for the estimate of the μ -pair cross-section.

Furthermore, the \bar{q} fluxes cannot be increased without encountering trouble with $\bar{\nu}$ data [33]. The curves in figure 11 already imply $\sigma(\bar{\nu}N)/\sigma(\nu N) = 0.44$.

An estimate of Fidler is shown in figure 12 using

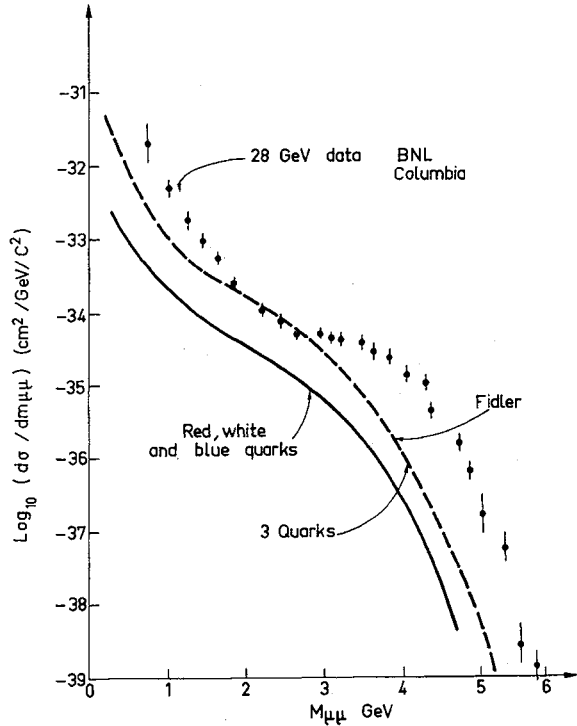


Fig.12 - Muon-pair spectra for the 28 GeV experiment on $pp \rightarrow \mu^+\mu^- + \text{hadrons}$. The dashed curve is the estimate of Fidler using 3 quarks; the solid curve is the prediction of the red, white, and blue quark model.

the standard quark model. For the red, white, and blue quark model one should divide by an additional factor three, as shown. In either case the agreement is scarcely impressive.

At the ISR, an upper limit on lepton-pair production has been quoted by the CCR group [26]. The expected Drell-Yan yield can again be computed from the parton spectra of figure 11. It is shown in figure 13. Considering the difficulty of adequately accounting for the shape and perhaps size of the BNL data using the Drell-Yan model or its elaborations, I think a direct calculation is more reliable than the use of the Drell-Yan dimensional scaling, and extrapolation in m^2/s of the BNL data to ISR energies [34].

We see that:

- (1) there is no conflict of the model predictions

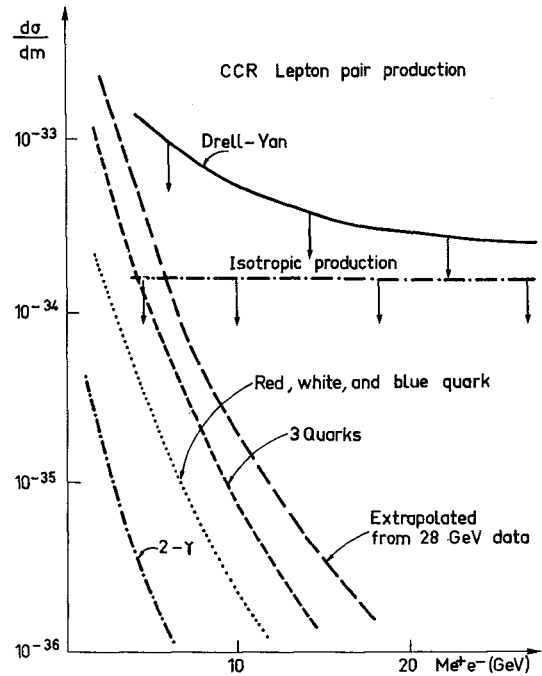


Fig.13 - Limits on lepton-pair production as reported by CCR, along with theoretical estimates.

with the ISR data, and

- (2) care must be taken with regard to the detection efficiency. According to the model, at small m^2/s the lepton pairs are produced with a flat rapidity spectrum, and most decay in the beam directions, while the detectors cover only large cms angles. Anyone making better and more detailed calculations than I present here (they are needed!) should provide the full differential spectrum for the pair production. Also, from the experimental side, it would be more useful to present the limits as a bound on $\frac{d\sigma}{dm^2 dy}$ (at $\theta_{cm} = 90^\circ$). This is a better meeting-point between theory and experiment.

Limits on the mass of W^+ have been quoted by the CCR group, based on their measurement of an upper limit for the inclusive electron spectrum in $pp \rightarrow e^\pm + \text{anything}$. It is based on the extrapolation of the 28 GeV data using the Drell-Yan scaling behaviour, and is shown in their contribution. Inasmuch as the Drell-Yan model is uncertain to at least a factor 2 (perhaps 6) the conclusions to be drawn must be handled with extreme care. Jaffe and Primack [36] have also considered limits on the neutral Z^0 mass in various gauge theories as a consequence of the CCR bounds on lepton pair production. They

also conclude that no limit can yet be set on m_W , even within the Drell-Yan picture.

A USSR group [27] at IHEP has reported limits on quasi-stable heavy lepton production. They search for heavy penetrating particles which live long enough to traverse the muon channel emerging from an internal target at the Serpukhov machine. The muon channel contains five gas Cerenkov counters to separate any heavy leptons from muons. The production model again uses the BNL data scaled up à la Drell-Yan. However, for most of their limits they have factors $10^2 - 10^4$ to spare and the estimates therefore appear safe. Their limits are shown in figure 14.

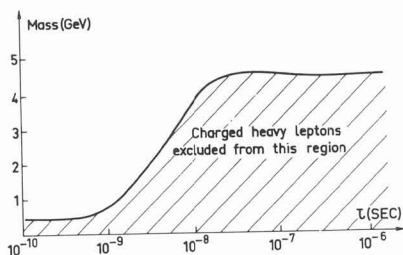


Fig.14 - Region of mass-lifetime space for charged heavy leptons excluded by the IHEP experiment.

5.- MULTIPLE CORES : PHENOMENA AT HIGHER ENERGIES.-

If the parent of the high- p_{\perp} hadrons is a parton (and perhaps even if it is not) we may expect the high- p_{\perp} fragmentation region to be filled up with a system of relatively high mass ($M^2 \lesssim p_{\perp}$) and multiplicity i.e. a jet [2]. The inclusive cross-section for production of jets can be estimated [3,5,35] from the parent-child relation, equation (1.4), provided the cascade of parent to child obeys Feynman scaling, equation (1.3). Guessing [2,37] $g(x) \sim 2(1-x)$ to be the distribution-function for finding any hadron with longitudinal fraction x , and taking $n \sim 8$, gives a ratio jet/hadron $\sim 50 - 100$ (at the same p_{\perp}). It is therefore attractive to search for inclusive production of jets using a large-solid-angle hadron calorimeter.

To do this requires some care and understanding in what a jet really is [35]. Suppose the jet is composed of "parton fragments", whose momentum distribution follows the orthodoxy of Feynman scaling with a dx/x spectrum for small x . (This is in fact almost as optimistic as one can be). Then, while more than half the energy goes, on the average, into a small angular cone surrounding the jet axis, a significant part of the remaining missing energy

(a GeV or two) goes, on the average, into large angles. For $p_{\perp} \sim 5$ GeV at $\theta_{CM} = 90^\circ$, a full steradian of cms solid angle is required to catch, on the average, 80% of the jet energy. And inside that cone (on the average) reside only 2 or 3 charged particles. Nevertheless observation of such jets and their structure would get us much closer to the heart of the dynamics responsible for these high- p_{\perp} spectra. A very attractive possibility lies in the simultaneous observation of both jets, in which case it is possible, in principle, to reconstruct the kinematics (s and t) of the two-body parton-parton (or parton - "meson" in the case of the interchange models) collisions.

While the detecting of cores has these serious difficulties of experimental resolution at present energies, when one indulges in futurism (ISABELLE, etc. energies) and considers much larger p_{\perp} , the 20% accuracy of jet kinematics at 5 GeV becomes 2% accuracy. Cline, Halzen and Luthe [38] have collected the scraps of evidence in favor of high p_{\perp} ($\gtrsim 5$ GeV) cores in cosmic ray collisions at $E \gtrsim 10$ TeV, with $\sigma_{\text{cores}}/\sigma_{\text{tot}} \sim 10^{-3}$. This yield could be accounted for by an extrapolation of present data using an exponent of 4 in the scaling law, Eq.(1.1). While the credibility of such an extrapolation now seems low, extrapolation using an exponent of 8 may still give a sizeable yield. In any case it is still fun to estimate the hadron yield at, say, $E_{CM} \sim 2000$ GeV. It, along with Hagedorn's exponential, and the BBK electromagnetic and weak contributions, are shown in figure 15. The weak and electromagnetic yields should be good to an order of magnitude or so from $E_{CM} \sim 200$ GeV on upward. Only the weak contribution is a sharp function of energy; it grows roughly linearly with \sqrt{s} at small p_{\perp} .

6.- CONCLUSIONS.- There has been observed a large yield of high- p_{\perp} hadrons ($3 \text{ GeV} < p_{\perp} < 9 \text{ GeV}$) in pp collisions ($3000 \text{ GeV}^2 > s > 200 \text{ GeV}^2$), relatively rich in strange particles and baryons. Although normalizations between different experiments may still be not determined to better than a factor 2, it is clear that the inclusive distribution does not obey dimensional scaling, as in Eq.(1.2), and that if a scaling law of the form given in Eq.(1.4) is an appropriate description of the phenomenon then the exponent n is ~ 8 . The onset of such a conjectured scaling then occurs at $s \gtrsim 200 \text{ GeV}^2$.

The next big step in understanding will come when the structure of these events is observed in detail.

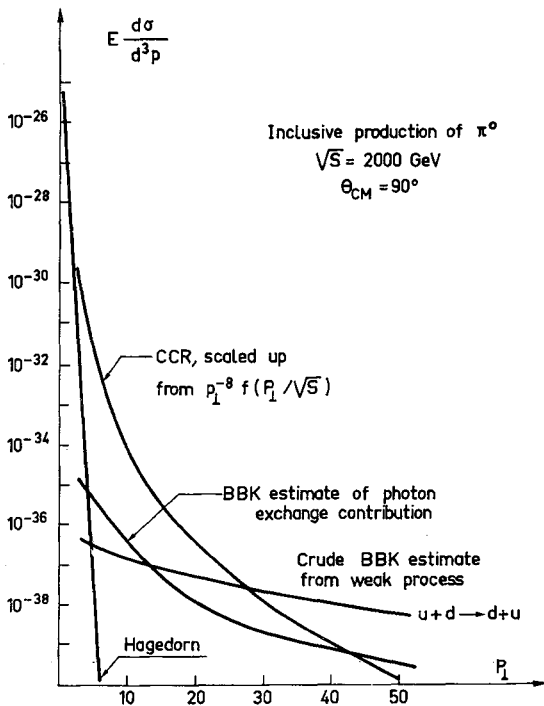


Fig.15 - Estimated inclusive production of hadrons at $\sqrt{s} = 2000$ GeV.

Especially important to test are the three hypotheses described in section 2, dealing with the coplanarity and jet-structure of the events. If these hypotheses are not satisfied, statistical pictures of the production process may be the most successful interpretation of the phenomenon. If the hypotheses are satisfied, the parent-child relation, Eq.(1.4), becomes of special relevance.

Then the natural question to ask would be. "What is the ultimate parent or grandparent of the high- p_{\perp} hadrons we observe?"

Among the choices are :

a) Quark-partons : This suffers from two difficulties. The first is that dimensional scaling ($n = 4$, not 8) is expected but not observed. The second is that many baryons are observed but not expected. The large p/π^+ ratio implies a similarly large ratio in $e^+e^- \rightarrow$ hadrons. This may in fact occur, but is more than a factor 10 out of line with (admittedly poor quality) a priori theoretical estimates [37].

b) Other partons : According to the parton-model lore about 50% of the hadron momentum is found in

neutral partons, usually assumed to be $J = 0$ or $J = 1$ gluons. $J = 0$ gluons interacting via $J = 0$ exchange can provide the exponent 8. And there are advantages in having the strong interactions reside in very strong trilinear couplings of the gluons with each other, with the quarks bound relatively weakly into the gluon fabric. Such a picture, as emphasized by T.D. Lee, can account better for the scaling behaviour observed in deep-inelastic electro-production. But unless the gluons carry baryon-number (why not ?), it will be difficult to understand the large p/π^+ ratio observed at NAL.

c) Ordinary hadrons : This is the view of the interchange-model which in fact predicted the exponent $n = 8$. However the large baryon yield may be a difficulty, and in particular its dependence on x and p_{\perp} . Inasmuch, as the mechanisms for production of B and M are so different in this picture it may be difficult to account for the stability of the p/π^+ ratio with p_{\perp} and s . The ratio of baryons to mesons in the initial state is a strong function of p_{\perp}^2/s . At large p_{\perp}^2/s , most of the initial energy (where the baryon-number and not pion cloud is found) is converted to high- p_{\perp} hadrons. In this circumstance the ratio B/M in the initial beams of "hadrons" is a sharply increasing function of p_{\perp}^2/s . The cross-section $q+B \rightarrow q+B$ falls with increasing p_{\perp}^2 much faster than that for $q+M \rightarrow q+M$, leading to a sharp decrease of the ratio B/M with increasing p_{\perp} . These two competing effects might lead to a p/π^+ ratio \sim constant function of p_{\perp} . Also the process $q+q \rightarrow B+\bar{q}$ can provide an exponent of 8 for baryons as well as mesons. But specific calculations will certainly be needed to better understand the problem.

d) Other, new hadrons : May be this option is unlikely, but it should not be overlooked. Suppose we produce some kind of charmed or colored hadrons by an associated production mechanism :

$$p+p \rightarrow p+A+B+\text{mesons} \quad (6.1)$$

where, say,

$$\begin{aligned} A &\text{ is an SU(3) } \underline{3} \text{ with } B = 0 \\ B &\text{ is an SU(3) } \underline{\bar{3}} \text{ with } B = 1 \end{aligned} \quad (6.2)$$

and $m_B > m_A$, so that

$$B \rightarrow \bar{A}+p+\text{mesons} \quad (\tau \ll 10^{-10} \text{ sec} ?) \quad (6.3)$$

followed by

$$\bar{A} \rightarrow \text{hadrons}, A \rightarrow \text{hadrons} \quad (\tau \ll 10^{-10} \text{ sec} ?). \quad (6.4)$$

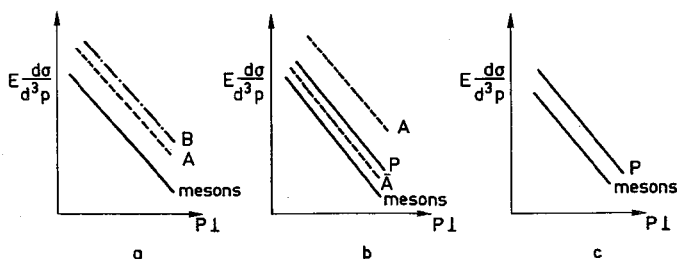


Fig.16 - Inclusive spectra of conjectured new hadrons A and B. a) At production. b) After the decay $B \rightarrow \bar{A} + p+$ hadrons. c) After the decay of A and \bar{A} .

At the production stage the inclusive distribution could be as in figure 16a. After B decays we have figure 16b and after A and \bar{A} decay, figure 16c. Thus the size and stability of the p/π^+ ratio and perhaps the threshold at $s \sim 200 \text{ GeV}^2$ are interpreted easily from this point of view. But the main message is that if one observes the inclusive distribution of the entire group (or jet) of hadrons, triggering on its total p_{\perp} , the composition of the spectrum would be dominated by the A and B. Therefore it will be important to examine in detail the structure of these jets or particle clusters (mass distributions, composition, etc).

An enthusiast of this interpretation may find inspiration in the Niu event ($E \sim 10 \text{ TeV}$), observed in a cosmic-rays emulsion chamber experiment [39] and which has created a prolific literature in Progress of Theoretical Physics on associated production mechanisms and models of hadron substructure.

Of all these pictures, something along the lines of the interchange model appears most credible. Perhaps its most distinguishing feature is that at a given p_{\perp} , the ratio of the inclusive spectrum of high-multiplicity jets to the single-hadron inclusive spectrum is ~ 1 and not ~ 100 as in a parton jet picture.

It is a pleasure to thank Ludwik Dobrzynski and André Rougé for their tireless and very able assistance in preparing this manuscript

REFERENCES

- [1] C.C.R., Report by POPE (B.G.) in parallel session and paper, 204. For an excellent review of the experimental results see the lectures of JACOB (M.), CERN TH 1683
- [2] BERMAN (S.M.), BJORKEN (J.D.) and KOGUT (J.B.) Phys. Rev. **D4**, 3388 (1971)
- [3] BERMAN (S.M.) and JACOB (M.), Phys. Rev. Letters **25**, 1683 (1970)
- [4] CLINE (D.), HALZEN (F.) and WALDROP (M.), Nuclear Physics **B55**, 157 (1973)
- [5] ELLIS (S.D.) and KISSLINGER (M.B.), N.A.L. PUB 73/40 THY June 1973, paper 124 in this Conference
- [6] BLANKENBECLER (R.), BRODSKY (S.J.), GUNION (J.F.) Phys. Letters **39B** (1972) 649
Phys. Rev. **D6** (1972) 2652
SLAC - PUB 1140 (1972)
- [7] BJORKEN (J.D.) and FARRAR (G.R.), SLAC preprint (1973)
- [8] FEYNMAN (R.P.), Photon-Hadron interactions Benjamin (W.A.), Inc. Reading Massachusetts (1972)
- [9] BERGER (E.L.) and BRANSON (D.), paper 142 - CERN/TH 1664, Phys. Letters **45B** (1973) 57
- [10] This is discussed in more detail in my report to the Bonn Conference Proceedings of the 8th International Conf. on Electron and Photon Interactions at high Energy (to be published).
- [11] This is true provided that the mass of both parent and secondary may be neglected, i.e. y and $\log \tan \theta/2$ can be equated. I thank I. MONTVAY for emphasizing this to me.
- [12] POKORSKI (S.) and VAN HOVE (L.), preprint CERN TH 1656
- [13] ENGELS (J.), SCHILLING (K.) and SATZ (H.), CERN preprint TH 1674 (1973)
- [14] See for example BJORKEN (J.D.) (Cornell Conference)
- [15] SAVIT (R.), SLAC-PUB 1185 (1973)
- [16] AMATI (D.), CANESCHI (L.) and TESTA (M.), Phys. Letters **43B** (1973) 186, CERN TH 1644, paper 27 to this Conference.
LEVIN (E.), RYSKIN (M.), Leningrad Nucl. Phys. Institute preprint (1973)
- [17] BERKELMAN (K.) et al., Contribution to the 8th International Conf. on Electron and Photon Interactions at high energy (to be published)
- [18] LANDSHOFF (P.V.), POLKINGHORNE (J.C.), DAMTP 73/22, paper 71 to this Conference
- [19] MATVEEV (V.A.), MURADYAN (R.M.), TAVKHELIDZE (A.N.), Lett. al N.C. **5** (1972) 907, Dubna preprint D2 - 7110 (1973)

- [20] One is reminded here of Feynman's admonition to theorists in his talk to the 1st Aix Conference : Proceeding of the 1st Aix-en-Provence Conf. on high energy physics (1961)
- [21] SCHÜBELIN (P.), Report in parallel session and paper 454 to this Conference
- [22] POLKINGHORNE (J.C.), Report in parallel session
- [23] COLEMAN (S.) and PREPARATA (G.), 1969 Erice Summer School, edited by A. Zichichi (Academic Press (1970))
PREPARATA (G.), Phys. Rev. D7 (1973) 2973
- [24] YU (L.P.), Phys. Rev. D4 (1971) 2775 ibid. D6 (1972) 215
- [25] CHRISTENSON (J.H.), HICKS (G.S.), LEDERMAN (L.M.), LIMON (P.J.), POPE (B.G.) and ZAVATTINI (E.), Phys. Rev. Letters 25 (1971) 1523
- [26] Report by POPE (B.G.) in parallel session and paper 203 to this Conference
- [27] BRESHNIN (Yu., B.), DUNAYTREV (A.F.), GODOVKIN (S.V.), KUBAROVSKY (V.P.), LANDSBERG (L.G.), LEONTYEV (V.M.), PETRUNINA (T.I.) SENKO (V.A.), ZAYTZEV (A.M.), paper 355 to this Conference
- [28] DRELL (S.D.) and YAN (T.M.), Ann. Phys. 66, (1971) 578
- [29] See Feynman's book, ref.8 for a discussion of this
- [30] FIDLER (R.W.), DAMTP preprint 73/25
- [31] KUTI (J.) and WEISSKOPF (V.), Phys. Rev. D4 (1971) 3418
- [32] LANDSHOFF (P.V.), POLKINGHORNE (J.C.) and SHORT (R.), N.P. E20 (1970) 225.
- [33] MUSSET (P.), Report to this Conference
- [34] JAFFE (R.), (MIT preprint CTP 344) has given a nice discussion of this whole question
- [35] BJORKEN (J.D.), SLAC-PUB 1280 (1973)
- [36] JAFFE (R.) and PRIMACK (J.), MIT preprint CTP 379 (1973)
- [37] BJORKEN (J.D.) and KOGUT (J.B.), Phys. Rev. D8 (1973) 1341
- [38] CLINE (D.), HALZEN (F.) and LUTHE (J.), Phys. Rev. Letters 31 (1973) 491
- [39] NIU (K.), MIKUMO (E.) and MAEDA (U.), Prog. Theor. Phys. 46 (1971) 1644
- [40] DREMIN (I.M.), paper 21 to this Conference.
- [41] BRODSKY (S.J.) and FARRAR (G.R.), SLAC preprint (1973), paper 344 to this Conference.