CM-P00060518

Ref.TH.1930-CERN

HIGH ENERGY HADRON - HADRON COLLISIONS
AND INTERNAL HADRON STRUCTURE

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A B S T R A C T

As shown by many authors, central particle emission in pp collisions at centre-of-mass energies $\gtrsim 20$ GeV can be described in terms of independent cluster production. In Ref. 1) this process has been related to the quark-gluon picture of nucleon structure. The present paper carries this relation further and links the leading particle spectrum of non-diffractive hadron-hadron collisions to the x distribution of quarks in the hadron. Thus, the flat leading particle spectrum, as observed in non-diffractive pp collisions, is found to be naturally related to the steeply falling x distribution of quarks in the nucleon, as deduced from the structure functions measured in deep inelastic scattering of electrons and neutrinos on nucleons. Our analysis is extended to meson-nucleon collisions and leads to a prediction of the general shape of the quark x distribution in a meson.

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1. - INTRODUCTION

As discussed by many authors, and as recently reanalyzed by us ¹⁾, the dominant features of pp collisions at FNAL and ISR energies ($20 \lesssim s^{\frac{1}{2}} \lesssim 60$ GeV) can be qualitatively described in terms of independent cluster production (ICP). In this picture, non-diffractive collisions lead to final states which contain the two leading hadrons resulting from the incident protons (possibly excited) and a number of central clusters. The latter can be assumed to have zero total charge and to be produced independently as far as their number and (longitudinal) rapidity are concerned. As shown in 1), the density ρ of central clusters in rapidity has a value close to one. The leading hadron distribution in the centre-of-mass Feynman variable $x = |p_{\perp}| p_{\text{cm}}^{-1}$, which in ICP is given ²⁾ by

$$d\sigma/dx \propto (1-x)^{\rho-1} \quad (1)$$

is therefore predicted to be essentially flat, in agreement with the experimental facts [for $0.2 \lesssim x \lesssim 0.8$, see 1) for details].

In 1), we also argued that the ICP picture of pp collisions can be related to the quark-gluon picture of nucleon structure derived from deep inelastic electron-nucleon and neutrino-nucleon scattering. This question is discussed further in the present paper. We show in Sections 2 and 3 that the leading particle spectrum (1) of pp collisions can be linked with the x distribution of quarks in the nucleon, as derived from the measured structure functions of deep inelastic lepton-nucleon scattering. We find excellent compatibility between the flat spectrum (1) for $\rho \simeq 1$ and the steeply falling quark distribution given by the lepton-nucleon experiments. The extension of these considerations to mesons is considered in Sections 4 and 5. The last section is devoted to concluding remarks.

2. - RELATION BETWEEN ICP AND QUARK-GLUON PICTURE

As briefly discussed in 1), the ICP picture of particle production in pp collisions can be related to the quark-gluon picture of nucleon structure. In a non-diffractive pp collision, one can assume that the three valence quarks of each incident proton fly through and give rise to the leading hadrons, while glue is emitted in bremsstrahlung-like fashion and gives rise to the central clusters. Just as in lepton-proton scattering, one can disregard quark-antiquark pairs at least in first approximation.

To make these considerations more precise, we note what we believe to be a significant empirical fact. In lepton-proton scattering one finds that the total fraction x_q of the momentum of a high energy proton which is carried by the quarks has average value $\langle x_q \rangle \simeq 0.5$. On the other hand, with $\rho \simeq 1$ in Eq. (1), the Feynman variable of the leading hadrons in pp collisions also averages to $\langle x \rangle \simeq 0.5$.

It seems therefore natural to conjecture that the centre-of-mass momentum carried by a leading hadron in the final state of a non-diffractive pp collision is equal to the momentum originally carried by the quarks in the corresponding incident proton; i.e., $x \simeq x_q$, not only on the average, but in each non-diffractive collision. This is a rather compelling assumption as soon as we suppose that the quarks fly through with their original fraction of incident momentum. This indeed means that $x \gtrsim x_q$ (with $x - x_q$ the momentum fraction carried by whatever glue flies through), and the only way to achieve $\langle x \rangle \simeq \langle x_q \rangle$ is then to have $x \simeq x_q$ in individual collisions. In other words, the quarks and only the quarks fly through (obviously dressing up again with glue in the final state to form the leading hadrons, which can be excited or not).

The above conjecture implies that the distribution $F(x_q)$ of x_q in a proton is the same as Eq. (1) with $\rho \simeq 1$, i.e., is approximately constant. Since we limit ourselves to the valence quarks, we have

$$x_q = x_1 + x_2 + x_3 \quad (2)$$

where x_i is the fraction of proton momentum carried by the i^{th} quark. On the other hand, deep inelastic lepton-proton experiments measure the distribution $f(x)$ for single quarks in the proton (x being x_1, x_2 or x_3 and each type of quark being weighted by the square of the relevant charge).

The distribution $f(x)$ is very large at small x (perhaps infinite for $x \rightarrow 0$) and drops rapidly to zero for $x \rightarrow 1$ [a decrease $\propto (1-x)^3$ is compatible with the data]. In familiar notation and except for normalization, the shape of $xf(x)$ is directly given by the structure function νW_2 expressed in the scaling variable $x = \omega^{-1} = q^2/2m_p \nu$.

The question is then whether such a steeply decreasing f is, under Eq. (2), compatible with a flat distribution F . The next section shows on very simple grounds that it is.

3. - QUARK DISTRIBUTION AND LEADING PARTICLE SPECTRUM

We consider the joint distribution $g(x_1, x_2, x_3)$ for the three valence quarks inside a proton. Assuming for convenience g to be symmetric in all three quarks, we have

$$F(x) = \int g(x - x_2 - x_3, x_2, x_3) dx_2 dx_3 \quad (3)$$

$$f(x) = \int g(x, x_2, x_3) dx_2 dx_3 \quad (4)$$

The function g is defined in the tetrahedron OABC of Fig. 1, where the plane ABC has equation $x_1 + x_2 + x_3 = 1$. The integration in Eq. (3) covers the triangle A'B'C' where $x_1 + x_2 + x_3 = x$, the one in (4) the triangle A'B''C'' where $x_1 = x$. If the integral of g over the complete tetrahedron OABC is normalized to one, we have

$$\int_0^1 F(x) dx = \int_0^1 f(x) dx = 1$$

The geometrical situation in Fig. 1 makes it immediately clear that a constant $F(x)$ will in general correspond to a rapidly decreasing $f(x)$. Indeed, since the area of A'B'C' grows like x^2 , constant F means that the mean value of g over A'B'C' must decrease like x^{-2} . But the area of A'B''C'' decreases like $(1-x)^2$. Hence, barring an increase of g near the points A, B, C, one expects f to decrease at least as fast as $(1-x)^2$ for $x \rightarrow 1$.

We illustrate this trend by considering two simple examples, both corresponding to the idealized case of F strictly constant over $0 < x < 1$. They are given by

$$g(x_1, x_2, x_3) \propto (x_1 + x_2 + x_3)^{-2} \quad (\text{I})$$

$$g(x_1, x_2, x_3) \propto (x_1^2 + x_2^2 + x_3^2)^{-1} \quad (\text{II})$$

The curves I and II of Fig. 2 represent in each case the resulting function $xf(x)$ approximately normalized to the same maximum as the data for νW_2 (the trend of the data is indicated by the shaded band, see the figure caption).

Case I corresponds to g constant over each triangle $A'B'C'$ and gives $f \propto x - 1 - \ln x$. It is seen in Fig. 2, curve I, that the resulting decrease of f for $x \rightarrow 1$ is too slow compared to the data. Hence g , considered over $A'B'C'$, should decrease toward the points $A'B'C'$. A rather weak decrease of this type is embodied in case II, and the agreement is already much better. Note also that F itself, as deduced from pp collisions, may well decrease for $x \rightarrow 1$; this would entail a stronger decrease of $g(x_1, x_2, x_3)$ as the point x_1, x_2, x_3 approaches the plane ABC and therefore favour a more rapid decrease of $f(x)$ for $x \rightarrow 1$.

In both cases I and II, $f(x)$ vanishes as $(1-x)^2$ for $x \rightarrow 1$. Through the Drell-Yan relation ⁵⁾ this corresponds to an asymptotic behaviour $F_p(q^2) \propto q^{-3}$ for the proton form factor, a behaviour proposed on other grounds by Bjorken and Kogut ⁶⁾. Experiment favours $F_p(q^2) \propto q^{-4}$ corresponding to $f(x) \propto (1-x)^3$. We obtain this in our scheme if the function $g(x_1, x_2, x_3)$ vanishes linearly when the point (x_1, x_2, x_3) approaches the points A, B or C of Fig. 1.

In both cases I and II, one obtains that $f(x)$ grows like $\ln x^{-1}$ for $x \rightarrow 0$. It is in the small x region, however, that the quark-antiquark pairs present in the nucleon but neglected in our treatment will make their contribution. Although their momentum share is very low, their number may be large or infinite. They are often believed to give to $f(x)$ an additional contribution growing as x^{-1} for $x \rightarrow 0$. They are of no importance for our considerations because they should contribute little to the leading particle spectrum.

Knowledge of $F(x)$ and $f(x)$ is, of course, insufficient to determine g completely, and we did not attempt to fit more general choices of g to the experimental F and f distributions. We believe it to be significant, however, that a flat distribution F and a steeply falling f are obviously compatible with simple forms of the three-quark distribution g . As to the latter, it would be interesting to have direct experimental access to its properties as a function of three variables, but this seems unfortunately to be difficult.

4. - THE MESON CASE

It is natural to extend the preceding considerations to the case of mesons. We assume that the ICP model also applies to non-diffractive Mp collisions ($M=\pi$ or K), so that the spectrum (1) holds not only for the leading hadron p^* resulting from the incident proton, but also for the one M^* resulting from the incident meson ^{*}). It seems then rather compelling to assume that $\rho \simeq 1$ also in meson-proton collisions. Indeed, the density of central clusters in rapidity should be universal if we are to account for the remarkable degree of universality of mean multiplicity and integrated correlation f_2 in pp , π^+p and K^+p collisions; this universality is particularly striking when one uses as incident energy variable the so-called Q value, which is the centre-of-mass energy available for particle production and reduces to $s^{\frac{1}{2}}$ at high energy ⁷⁾. Of course, direct tests of ICP with $\rho \simeq 1$ will become possible for Mp collisions when leading particle spectra and central region correlations will be measured in the relevant energy range $s^{\frac{1}{2}} \gtrsim 20$ GeV.

Accepting ICP with $\rho \simeq 1$ for Mp collisions, we can proceed as in Sections 2 and 3 to determine the valence quark distribution in a meson. The only difference is that we now deal with quark contents $q\bar{q}$ rather than qqq . The function g has therefore two variables only and, using its symmetry, we have

^{*}) For the ICP model of meson-nucleon collisions, Eq. (4.2) of Ref. 1) holds unchanged. Equation (4.3), on the other hand, only holds if $(m^2 + p_T^2)^{\frac{1}{2}}$ for the leading hadron can be set equal to the mass m_0 of the corresponding leading particle, which is approximately valid for nucleons. The general case is taken care of by introduction of a factor $(m^2 + p_T^2)^{\frac{1}{2}}/m_0$ in front of each exponential in (4.3).

$$F_M(x) = \int_0^x g_M(x-x_2, x_2) dx_2$$

$$f_M(x) = \int_0^{1-x} g_M(x, x_2) dx_2$$

The index M refers to the mesonic case. Constancy of F_M requires that the average of g_M over the line $x_1 = x - x_2$ ($0 \leq x_2 \leq x$) decreases as x^{-1} . The pion form factor has then the asymptotic behaviour $F_\pi(q^2) \propto q^{-2}$, as conjectured by various authors on other grounds. We note with Barger [Ref. 8), esp. Fig. 32] that the available data ⁹⁾ are well represented by an expression $(1+aq^2)^{-1}$, $a = 2(\text{GeV}/c)^2$. In our framework, of course, we may have $g_M(1,0) = g_M(0,1) = 0$, and $f(x)$ would then vanish faster than $1-x$. As to the behaviour for $x \rightarrow 0$, we have $f \propto -\ln x$ as in the nucleon case.

We now consider the examples

$$g_M(x_1, x_2) \propto (x_1 + x_2)^{-1} \quad (\text{MI})$$

$$g_M(x_1, x_2) \propto (x_1^2 + x_2^2)^{-1/2} \quad (\text{MII})$$

which are analogous to the nucleonic cases I, II of Section 3. Figure 3 shows the resulting curves for $xf_M(x)$ together with curve II of the nucleon case, all curves being normalized to the same maximum as before. There is greater similarity between curves MI and MII than between curves I and II of Fig. 2. Since this may be due to the fact that g_M of case MII varies less than g of case II on the manifold $\Sigma x_1 = x$, we calculate a third example

$$g_M(x_1, x_2) \propto [8x_1x_2 + (x_1 + x_2)^2] / (x_1 + x_2)^3 \quad (\text{MIII})$$

which gives the same range of variation over $\Sigma x_1 = x$ as in the nucleonic case II. The result is shown in Fig. 3 as curve MIII, and is found to be rather close to MI and MII.

We can therefore conclude that, in our picture, the quark momentum distribution $xf_M(x)$ for mesons is predicted to have the general trend of curves MI, II, III of Fig. 3, except of course in the small x range where, as in the nucleonic case, additional quark-antiquark pairs are expected to contribute. It is unfortunate that deep inelastic scattering of leptons on mesons is difficult to measure experimentally.

5. - FURTHER DISCUSSION OF HADRON HADRON-COLLISIONS

It is useful to summarize at this stage the quark-gluon picture of non-diffractive hadron-hadron collisions which emerges from our considerations. The basic assumption, mentioned in Section 2, says that in each non-diffractive collision, the centre-of-mass momentum carried off by each leading hadron is equal to the share of incident momentum originally carried by the quarks in the corresponding incident hadron (the quarks here concerned are the valence ones and additional quark-antiquark pairs are neglected). The gluon parts of the incident hadrons give rise to the central clusters occurring in the final state, and, in particular, transfer to them their complete fraction of incident centre-of-mass energy. This suggests that the glue field has a strong self-interaction, which makes it the active agent for central particle production.

In contrast, the quarks fly through and behave essentially as passive spectators, with one important exception. In the final state the group of quarks (qqq or $q\bar{q}$) originating from either incident hadron must dress up again with glue to give the corresponding leading hadron. This dressing up process is a sort of final state interaction involving a redistribution of momentum from the quarks to the new gluon cloud. Contrary to what happens in the deep inelastic lepton-nucleon case, the quarks of each leading hadron have small relative momenta. Consequently, the dressing up process is expected to produce the leading hadron either in its ground state or in relatively low excited states.

It should be stressed that the picture just described applies only to non-diffractive collisions. It does not hold for hadron-hadron collisions of diffractive type, be it elastic scattering, diffraction

dissociation or multiperipheral exchange of two or more Pomerons. The existence of the latter process is not established experimentally ; if it exists its cross-section must be very small (a recent search for double Pomeron exchange at 205 GeV/c ¹⁰⁾ gives estimates of $30 \pm 11 \mu\text{b}$ for $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$ and $68 \pm 16 \mu\text{b}$ for $pp \rightarrow pp \pi^+ \pi^-$). As to elastic scattering and diffraction dissociation, there is no difficulty in interpreting them as shadow effects of the non-diffractive collisions [see Ref. 11) for a study of this problem in the framework of an ICP model].

We now mention some further consequences of our picture of non-diffractive collisions. The flat x distributions of the two leading hadrons should be uncorrelated, since they are determined by the quark configuration (value of $x_1 + x_2$ or $x_1 + x_2 + x_3$) in the incident hadrons. A related consequence concerns the centre-of-mass properties of centrally produced particles in meson-proton collisions ^{*)}. Since the gluon part of each incident hadron carries on the average half of its centre-of-mass momentum, the two gluon parts have on the average the same centre-of-mass system as the whole collision. This will then also be the average centre-of-mass system of the central secondaries, although the secondaries need not have in this system a distribution with forward-backward symmetry (the reason is that a meson and a nucleon are not expected to carry the same amount of glue). The situation in our model is thereby different from particle production mechanisms where quark-quark collisions are the primary agents, as originally proposed by Satz ¹²⁾ and recently again by Goldhaber ¹³⁾. In mechanisms of the latter type, the average centre-of-mass system of central secondaries is expected to be the average quark-quark centre-of-mass system (i.e., a system where the momenta of the incident meson and proton are in the ratio 2 to 3), and the centrally produced particles may be expected to have a forward-backward symmetric distribution in this system.

The above subject has an interesting experimental history. It was first found by Elbert et al. ¹⁴⁾ that symmetry is achieved in the average quark-quark centre-of-mass system for $\pi^- p$ collisions at 25 GeV/c. It was realized, however, that this property strongly depends on multiplicity, the higher multiplicity collisions tending to show symmetry in the over-all centre-of-mass system. A good review of this question as of 1971 was given by Deutschmann ¹⁵⁾. It will be very interesting to resume its investigation at FNAL energies.

^{*)} We are grateful to E. Berger for drawing our attention to this point.

6. - CONCLUDING REMARKS

The picture here discussed proposes a simple relation between internal hadron structure and high energy hadron-hadron collisions. In brief, it says that, in common hadron-hadron collisions of non-diffractive type, the glue is the active element producing the central secondaries, and the quarks fly through as passive spectators dressing up in the final state to give rise to the leading hadrons. As we have shown, under this simple picture, the steeply falling momentum distribution $f(x)$ of a quark in a high momentum nucleon (as measured in deep inelastic lepton-nucleon scattering) is naturally linked to the flat leading hadron spectrum $d\sigma/dx$ observed in non-diffractive pp collisions at high energy. Crucial for this relation is that the nucleon contains three valence quarks, as seen by comparison with the meson case when treated by the same method (Fig. 3).

It is in the rôle attributed to the glue that the present picture differs from both the early additive quark model ¹⁶⁾ and the later parton model ¹⁷⁾ of hadron-hadron collisions at high energy. The former considers the valence quarks only, the latter has in addition a "sea" of partons frequently assumed to be quarks and antiquarks. As shown by the deep inelastic lepton-nucleon experiments, some form of sea must be there, but the leptons interact very little with it ; hence the assumption that it is mainly composed of neutral glue, not of quark-antiquark pairs. Our point is that this glue, taken as a strongly self-interacting meson field, can be regarded as the main agent for central particle production in high energy hadron-hadron collisions. In our picture, the glue is quite distinct from the quarks and the glue-quark interaction plays only a secondary rôle in non-diffractive hadron-hadron processes.

This does not mean, of course, that quarks are altogether unimportant in strong interaction collisions. Since they are the charge carriers in the hadron, they must play an important rôle in collisions of exchange type (ρ exchange, A_2 exchange, etc.), but such collisions get very rare at the energies here considered ($s^{\frac{1}{2}} \gtrsim 20$ GeV). They may also be important in large p_T phenomena, but these again have very small cross-section. One can raise the objection that by attributing the dominant collisions to the glue, we lose the well-known quark additivity prediction of a value $\frac{3}{2}$ for the ratio R of pp to πp total cross-sections. This objection is rather weak, however, because R is now known to decrease very slowly and to have still the value 1.68 at the highest measured momentum of $p_{lab} = 200$ GeV/c ⁸⁾.

In our interpretation, the ratio R has to do with the spatial extent of the glue in nucleons and mesons, and this could well have a complicated relation to the number of quarks.

As to the real nature of quarks and glue, it remains as mysterious as before. The quarks are introduced as carriers of electric and weak charges inside the hadron. From the interpretation of available experimental evidence in terms of quarks, one is led to give them the following attributes : spin $\frac{1}{2}$, small effective mass inside the nucleon, size at least an order of magnitude smaller than the nucleon, additive sharing of nucleon momentum by quarks and glue. But quarks have not been seen as individual particles. Their rôle in e^+e^- annihilation into hadrons is not understood, and we are also lacking a description in terms of $q\bar{q}$ creation of how excited hadronic systems decay into mesons, baryons and antibaryons. We have on the one hand these two difficulties, strong confinement of quarks in hadrons and lack of understanding of $q\bar{q}$ pair creation, and on the other hand the impressive list of successes of the quark-gluon picture in hadron spectroscopy and in high energy processes. The challenge confronting hadron physics stands out in clear outline and it is hard to believe that the steady flow of new experimental data currently produced will not contain some clues to the solution of the riddle.

The first author (L.V.H.) is indebted to many CERN colleagues for remarks and information. The second (S.P.) thanks Professor W. Krolikowski for discussions on the parton model.

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FIGURE CAPTIONS

- Figure 1 The domain of definition of $g(x_1, x_2, x_3)$.
- Figure 2 The function $xf(x)$ for the choices I and II of g (see text), but approximately normalized to the same maximum as the data for νW_2 . The shaded band indicates the trend of the data [it is based on Fig. 4 of Ref. 3) itself constructed from Ref. 4) for $R = \sigma_L/\sigma_T = 0.18$ with the cuts $W = \sqrt{s} > 2 \text{ GeV}$, $q^2 > 1.5 \text{ GeV}^2$].
- Figure 3 The function $xf(x)$ for the meson case, choices MI, MII, MIII (see text), normalized as in Fig. 2. Curve II refers to the nucleon case and is the same as curve II of Fig. 2.

FIG 1

FIG. 2

FIG. 3