LARGE-p_T PROTONS FROM CONSTITUENT DIQUARK SCATTERING

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Recent data from the CERN ISR on the fractional proton yield in pp collisions are explained within the Stockholm diquark model. Describing the proton as a $u(ud)_0$ system, the observed high magnitude and fall-off p_T, θ and $\sqrt{s}$ of the proton yield are natural consequences of constituent diquark elastic scattering. The p_T and θ dependence favour a value of around 10 GeV^2/c^2 for the size parameter in the diquark form factor, corresponding to a diquark rms radius of around 0.2 fm. This is consistent with earlier results of the model applied to deep inelastic lepton–nucleon scattering and e^+e^- annihilation.

1. Introduction. It is well known that the relatively high yield of protons in various high-energy processes is hard to understand within naive quark-parton models. This problem has been tackled mostly by introducing a finite probability for the initially struck quark to pick up a diquark during the fragmentation into hadrons. Such a creation of diquark–antidiquark pairs is conventionally assumed to result in production of baryon–antibaryon pairs on the level of 5–10% in comparison with pion production.

However, recent experimental results indicate that this mechanism is not sufficient for understanding the magnitude of proton production at high energies. The split field magnet group at the CERN ISR has found [1] that the fractional proton yield in 63 GeV pp collisions is not only high but also dependent on the transverse momentum, p_T, and CMS angle, θ, of the produced particle. Earlier, similar trends have been observed at Fermilab in pp and π^-p collisions in the 200–400 GeV/c range [2,3]. By comparing these data sets one can conclude that the fractional proton yield depends also on the collision energy, $\sqrt{s}$. Simultaneously, the fractional antiproton yield is an order of magnitude smaller and does not depend significantly on any of the variables p_T, θ and $\sqrt{s}$ in the quoted data sets. As pointed out by the CERN group [1], these findings cannot be understood within QCD-inspired quark fragmentation models, such as the Lund Monte Carlo or the Feynman–Field model, or within perturbative QCD, since the two processes that contribute to baryon production in these two classes of models, diquark–antidiquark pair production and gluon bremsstrahlung, respectively, would both lead to an equal number of protons and antiprotons. In addition, the Lund model obviously predicts a universal ratio, p/π^+, of proton to positive pion yields in all regions of phase space, reflecting only the fractional probability of creating a diquark–antidiquark pair instead of a quark–antiquark pair in the colour field from a struck quark. The ratio p/π^+ in fact exceeds unity at the lowest p_T values in ref. [1], and does not drop to its "natural" value of 5–10% until the squared momentum transfer from projectile to outgoing proton is well above a dozen GeV^2/c^2. This seems to exclude also explanations in terms of more exotic ("higher twist") quark processes like $q + q \to p + \bar{q}$ and $q + p \to p + q$. Both would be characterised by the proton form factor, which is strongly suppressive above a squared momentum transfer of 1 GeV^2/c^2. Neither can they explain why there are more protons than pions in some parts of phase space.

The aim of this letter is to show that all the features of the CERN ISR data on proton production can be reproduced within the Stockholm diquark model, developed by us and Jändel and Larsson earlier in a series of publications [4]. According to this mod-

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el, two quarks with unequal flavours can form a very small bound spin-0 system, a scalar diquark. No genuine spin-1 diquarks are assumed to exist. Therefore the proton is predominantly a $u(ud)_0$ system, with the $(ud)_0$ occupying only a few percent of the full proton volume, and with the gluon component being largely contained in the diquark. The high yield of protons from πp and pp collisions then comes about because of the possibility of diquark elastic scattering. The $(ud)_0$ diquark is elastically knocked out from a proton and thereafter fragments into a baryon. The observed fall-off in the fractional proton yield with p_T, θ and $\sqrt{s}$ is a natural consequence of the compositeness of the $(ud)_0$ diquark, which contributes a form factor in the scattering amplitude. This form factor represents the probability for the diquark to stay together during the scattering, and depends only on Q^2, the squared momentum transfer from the incoming to the scattered diquark. A slow fall-off with Q^2 means a small diquark, and our earlier analysis of lepton–nucleon scattering has led us to assume that the "break-point" Q^2 value in the $(ud)_0$ form factor is at least 10 GeV^2/c^2, which hints at a diquark radius smaller than 25% of that of the proton. If two-quark forces are strong and attractive enough to form such a small diquark, this non-perturbative QCD effect should appear in many other high-energy reactions. It has been speculated [5] that diquarks could be responsible for the bulk of QCD effects previously ascribed to perturbative gluonic reactions.

The Stockholm diquark model was used by Larsson [6] to explain the p/π^+ ratio in the Fermilab data from π^-p collisions quoted above. Here we must, however, make more specific assumptions, both inside and outside the domains of the original model, because the CERN ISR data are taken in kinematic regions where our previous fits of model parameters to lepton–proton scattering data do not help. A model very similar in spirit to ours has also been used by the CERN ISR group in a recent preprint [7] and shown to be in line with the data. Some basic assumptions about diquarks differ from our approach though, but this only strengthens our belief that the data give evidence for the existence of very small spin-0 diquarks inside nucleons, irrespective of the particular assumptions about the momentum distributions of the initial diquark, the fragmentation function of the outgoing diquark and the exact expression for the constituent scattering amplitude.

Some early attempts by other groups to analyse proton yields in terms of diquark scattering were quoted in ref. [6]. These models do not bear much resemblance to ours, and the old data were not detailed enough to pinpoint such important model parameters as the relative admixture, quantum numbers and radius of diquarks in nucleons.

2. The diquark in action. In order to derive proton yields from our model we need to specify quite a few quantities, some of which are already given in the model, while others have to be derived from independent data or fitted to the present CERN ISR data. The most relevant quantities are the following: (i) The diquark form factor; (ii) The momentum distributions of quarks and diquarks in the proton; (iii) The nature of the constituent subprocesses that give rise to pions and protons; (iv) The expressions for the constituent cross sections as functions of the kinematic variables; (v) The fragmentation functions for quarks and diquarks into pions and protons.

For the purpose of this work we assume that the strong form factor of the $(ud)_0$ diquark is identical to the electromagnetic form factor

$$F(Q^2) = M^2/(Q^2 + M^2)\,, \qquad (1)$$

used by us earlier [4]. Here we have found that $M^2 = 10\ \mathrm{GeV}^2/c^2$ (and, in fact, even values up to 20 GeV^2/c^2) fits well the data from deep-inelastic lepton–nucleon scattering. Such high M^2 values point to a diquark radius of 0.2 fm or smaller.

In ref. [4] we also found that the momentum distribution of the $(ud)_0$ is fairly similar in shape to that of a u quark at Bjorken x values of $0.25 < x < 0.75$. We therefore assume here that $x\mathrm{D}(x) = x\mathrm{u_v}(x)$ for all x, D being the $(ud)_0$ and $\mathrm{u_v}$ the single u quark. In a more recent analysis [8] we, in turn, argued that the single u quark momentum distribution can be derived by taking the difference between proton and neutron deep inelastic structure functions $F_2^{\mu\mathrm{p}}$ and $F_2^{\mu\mathrm{n}}$. The data of ref. [9] fit well to the parametrisation

$$\begin{aligned} x\mathrm{D}(x) &= x\mathrm{u_v}(x) \\ &= 0.3(0.87 - x) \quad \text{at } 0.25 < x < 0.87\,, \\ &= 0 \qquad\qquad\quad\ \ \text{at } 0.87 \leqslant x\,. \end{aligned} \qquad (2)$$

The region $x < 0.25$ is not relevant for the present analysis. It is also necessary to specify the momentum distributions $xu_D(x)$ and $xd_D(x)$ of the u and d quarks inside the $(ud)_0$, because the diquark is gradually dissolved into its two constituents as Q^2 increases. The vanishing of the diquark contribution as $F^2(Q^2)D(x)$ is therefore accompanied by a corresponding enhancement of the contribution from its quarks as $(1-F^2)q_D$. We assume isospin symmetry, $u_D = d_D$, and adopt the well-known parametrisation

$$xd(x) = xd_D(x) = xu_D(x) = 1.23\sqrt{x}(1-x)^4 , \quad (3)$$

of the d quark momentum distribution. Finally, we neglect contributions from sea quarks and gluons.

When it comes to keeping track of all the subprocesses that can give rise to protons and pions we will make a few simplifying assumptions. First, we split up only one of the initial protons in quarks and diquarks, while treating the other as an effective target with the mean constituent momentum distribution

$$xq_{eff}(x) \propto \sqrt{x}(1-x)^3 . \quad (4)$$

This ignorance of the detailed structure of the target is motivated by the fact that we will study only the fractional proton yields from scattered quarks and diquarks in the projectile, and they turn out not to depend much on target properties. In addition, we will choose a phenomenological constituent cross section that is known to reproduce pion yields successfully when the target is described by eq. (4). Secondly, we assume that only leading hadrons from the fragmenting quarks and diquarks contribute to the ratio of protons to positive pions at large p_T values. Then we need to consider only three processes: (i) a scattered $(ud)_0$ fragmenting to a proton; (ii) a scattered u quark giving a leading π^+; (iii) a u quark giving a leading proton. The latter case happens when the u quark picks up a diquark from a created $D\bar{D}$ pair. We assume that this occurs for 5% of the scattered u quarks. As the CERN ISR data are presented as the ratio of protons to all positive hadrons, we also have to consider K^+ production and therefore assume that $K^+/\pi^+ \equiv 0.5$ in all the phase space of relevance for this analysis. This conjecture has support from the 90° Fermilab data [2] as well as from the 45° CERN ISR data [1], while the influence of kaons in the 13° and 20° CERN ISR data is unknown.

All constituent elastic cross sections are assumed to be of the empirical form suggested by Field and Feynman [10] for quark–quark elastic scattering:

$$d\hat{\sigma}/d\hat{t} \propto -1/\hat{s}\hat{t}^3 , \quad (5)$$

where $\hat{s}$ and $\hat{t}$ are the Mandelstam variables for the constituent process. This choice makes certain that we reproduce the measured pion spectrum with the simplified eq. (4) for the target substructure. Other, more QCD inspired, choices [11] give practically the same proton-to-pion ratios. The rapid fall-off with $\hat{t}$ guarantees that we can neglect the quarks and diquarks from the "target" proton that are backscattered to $180° - \theta$, since $\theta = 13°$, 20° and 45° in the data of ref. [1].

Also the function describing the fragmentation, $D \to p$, of a diquark to a proton is a priori unknown, i.e. cannot be taken from some independent data (backward protons from $\bar{\nu}p \to pX$, for instance, could come also from the non-diquark ud combination). Therefore, we adopt for the diquark fragmentation function the formula used by Peterson et al. [12] for describing the fragmentation of heavy quarks:

$$D^{p}_{(ud)_0}(z) = Nz^{-1}[1 - 1/z - \epsilon/(1-z)]^{-2} , \quad (6)$$

where ϵ is a parameter that was supposed in ref. [12] to be inversely proportional to the squared quark mass, and where N is a constant which can, in principle, be used to normalise the fragmentation function. We prefer, however, to keep both ϵ and N as free parameters to be fitted to the data, since z is restricted to $z \gtrsim 0.3$ in the data of ref. [1], and we do not want to commit ourselves to formula (6) also for smaller z values. For quarks fragmenting to pions we again follow ref. [12] and use

$$D^{\pi^+}_{u}(z) = 0.95(1-z)^2/z , \quad (7)$$

and consequently

$$D^{p}_{u}(z) = 0.05(1-z)^2/z , \quad (8)$$

in line with our assumption of a 5% probability of $D\bar{D}$ production in the fragmentation chain. As we study only fractional yields and keep N in eq. (6) free, we need not care about the absolute normalisation of (7) and (8).

The inclusive yield of hadron C from the subprocess $ab \to cX$ is

$$E\frac{d\sigma}{d^3p} = \int_{x_a^{min}}^{1} dx_a \int_{x_b^{min}}^{1} dx_b G_{A\to a}(x_a) G_{B\to b}(x_b) \times D^{C}_{c}(z)(\pi z)^{-1} d\hat{\sigma}/d\hat{t} . \quad (9)$$

Here a is a diquark or quark from the "projectile" proton and $G_{A\to a}(x_a)$ the functions $D(x_a)$, $u_v(x_a)$ or $u_D(x_a)$ given by eqs. (2), (3), $D(x_a)$ accompanied by the squared form factor $F^2(Q^2)$ and $u_D(x_a)$ by the complementary $1 - F^2$. Similarly, b is the mean constituent of the "target" proton, and $G_{B\to b}(x_b)$ is hence given by $q_{\text{eff}}(x_b)$ in eq. (4). $D_c^C(z)$ is taken from any of eqs. (6) to (8) and $d\hat{\sigma}/d\hat{t}$ from eq. (5). Finally, eq. (9) is summed over $a = (ud)_0$, u_v and u_D for proton production and over $a = u_v$ and u_D for pion production. The kinematic variables obey the following relations:

$$x_a^{\min} = x_T \cot \tfrac{1}{2}\theta / (2 - x_T \tan \tfrac{1}{2}\theta) , \qquad (10)$$

$$x_b^{\min} = x_a x_T \tan \tfrac{1}{2}\theta / (2x_a - x_T \cot \tfrac{1}{2}\theta) . \qquad (11)$$

$$z = \tfrac{1}{2} x_T (x_a^{-1} \cot \tfrac{1}{2}\theta + x_b^{-1} \tan \tfrac{1}{2}\theta) , \qquad (12)$$

$$-\hat{t} = Q^2 = (s x_a x_T / 2z) \tan \tfrac{1}{2}\theta , \qquad (13)$$

where $x_T = 2p_T/\sqrt{s}$.

3. Results and discussion. When confronting eq. (9) with the data on the fractional proton yields we have manipulated only the fragmentation function for diquarks in eq. (6) by testing various values of the parameters ϵ and N. In all calculations they are, however, combined as to fit the fractional proton yield at $\theta = 13°$ and $p_T = 2$ GeV/c. With this restriction we test the set of fragmentation functions within the shaded area in fig. 1. The resulting fits to data are shown in fig. 2 for three different values of the crucial parameter M^2 in the diquark form factor of eq. (1). It can be seen that $M^2 = 10$ GeV$^2/c^2$ gives a good fit to the data, while 5 and 20 GeV$^2/c^2$ cannot reproduce the θ dependence from 13° to 20°. At 45° the form factor suppresses the diquark scattering so that the protons come mostly from quark fragmentation, which explains why the fit is less sensitive to M^2 here than at 20°.

Before concluding that the Stockholm diquark model is successful also in reproducing these large-p_T data, it is important to analyse the sensitivity of the fits to the various extra assumptions made necessary by our lack of knowledge of the important diquark fragmentation function and elastic cross section. First, it should be noted that these two quantities appear together in eq. (9), which means that even if $d\hat{\sigma}/d\hat{t}$ would differ drastically from subprocess to subprocess, we would only find another best-fit fragmentation function for the diquark, while the quality of the fit would be about the same. Secondly, we have found that the particular choice of diquark fragmentation function is important only for the absolute normalisation of the fractional proton yield, i.e. for the fit to one single data point ($\theta = 13°$, $p_T = 2$ GeV/c, say). In addition, it seems that the most crucial feature of the diquark fragmentation function is its value in the region $z \approx 0.7$ in comparison with that of the quark fragmentation function.

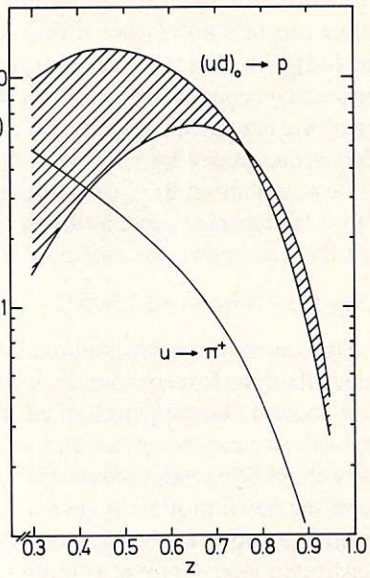

Fig. 1. The quark and diquark fragmentation functions used in the analysis, as given in eqs. (6) and (7). The normalisation is arbitrary, since it is unimportant for the fractional hadron yields. The shaded area shows the range of diquark fragmentation functions used for the parameter value $M^2 = 10$ GeV$^2/c^2$ in the diquark form factor, eq. (1). The extreme values of the parameters N and ϵ in eq. (6) are (17.5, 1.35) and (1.1, 0.28). For all diquark fragmentation functions they are combined as to fit the data point at $p_T \approx 2$ GeV/c, $\theta = 13°$. The same procedure for $M^2 = 5$ and 20 GeV$^2/c^2$ gives sets of fragmentation functions that are similar in shape but different in magnitude from the one shown for 10 GeV$^2/c^2$. The variable z is the fraction of the constituent momentum carried by the detected hadron.

Consequently, the interesting fall-off in the fractional proton yield with p_T and θ is sensitive practically only to the diquark form factor, and therefore gives a good measure of the size parameter M^2. The form factor naturally also influences the absolute yield of protons, but that effect alone cannot be distinguished from that of the fragmentation function.

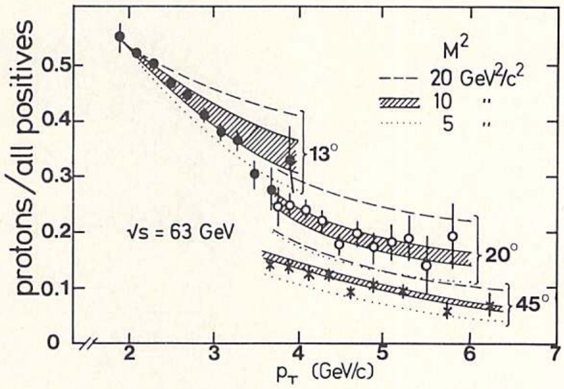

Fig. 2. The inclusive yield of protons relative to that of all positively charged hadrons as a function of p_T, the hadron transverse momentum, for three different CMS production angles, and at a CMS collision energy of 63 GeV. The experimental data are from the CERN ISR [1], and the lines are the results of the Stockholm diquark model. The shaded area for the parameter value $M^2 = 10\ \mathrm{GeV}^2/c^2$ in the diquark form factor of eq. (1) corresponds to the set of diquark fragmentation functions given by the shaded area in fragmentation functions given by the shaded area in fig. 1. For $M^2 = 5$ and $20\ \mathrm{GeV}^2/c^2$ these areas have been indicated only by their centre lines [when using all fragmentation functions with $0.28 \leqslant \epsilon \leqslant 1.35$ in eq. (6) and taking N as to fit the leftmost data point].

An independent test of our choice of form factor is provided by the $\sqrt{s}$ dependence from Fermilab to CERN ISR data. The 200–400 GeV/c data on the ratio p/π^+ [2,3] are well fitted by the present formalism for $p_T \geqslant 4$ GeV/c and $\theta = 90$–$113°$. At $p_T \leqslant 3$ GeV/c we overestimate the data by 20–40%, which could be due to an incorrect choice of K^+/π^+, or to the fact that the Fermilab data probe other z values in the fragmentation function, where eq. (6) perhaps does not work so well. The nice fits in ref. [6] with equal fragmentation functions for quarks and diquarks support this guess.

By ignoring the substructure of one of the protons, we might bias the results. The diquark–diquark scattering should, for instance, be isotropic instead of following the $1/\hat{t}^3$ fall-off. However, that would be almost compensated by the extra form factor $\sim 1/\hat{t}^2$ from the "target" diquark, and the best-fit proton yields would stay almost the same as before.

Our claim that the data provide a good measure of the size of the $(ud)_0$ diquark in the proton is further supported by the fact that the CERN ISR group [7] finds practically the same best-fit values of M^2 (10–20 GeV^2/c^2) in an analysis that is completely different from ours in details, but shares the view that there exists a $(ud)_0$ diquark with a form factor given by (1). It is encouraging to find that this parameter is, in turn, consistent with the one we have already found to fit other data, such as the scale-breaking in deep-inelastic lepton–nucleon scattering [4]. Unlike the situation for those data, there seems, however, not to be any realistic alternative explanation in terms of conventional perturbative quantum chromodynamics and its gluonic processes, for the high yield of protons at high p_T. We consider this fact to be a strong support for our view [4,5] that the non-perturbative phenomenon of diquark formation might be responsible for many of the data trends hitherto attributed to perturbative gluon reactions.

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