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EXPERIMENTAL INDICATIONS FOR DIQUARKS IN
LARGE p_T PHYSICS

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Abstract

Various phenomena in particle physics suggest that two quarks in the proton can form diquarks – bound two quark objects inside the nucleons. The crucial tests of the diquark models are given by the processes with high momentum transfers. This short review tries to summarize the present status of the diquark hypothesis in large transverse momentum (p_T) collisions at high energies. The data, mainly from the Split Field Magnet detector at the Intersecting Storage Rings at CERN, show abundant proton production at medium values of p_T with properties which cannot be explained by the standard parton models.

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Experimental Indications for Diquarks in Large p_T Physics

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Abstract. Various phenomena in particle physics suggest that two quarks in the proton can form diquarks – bound two quark objects inside the nucleons. The crucial tests of the diquark models are given by the processes with high momentum transfers. This short review tries to summarize the present status of the diquark hypothesis in large transverse momentum (p_T) proton-proton collisions at high energies. The data, mainly from the Split Field Magnet detector at the Intersecting Storage Rings at CERN, show abundant proton production at medium values of p_T with properties which cannot be explained by the standard parton models.

1 Introduction

An interesting question concerning the proton structure is whether two quarks in the proton behave collectively, forming bound two-quark objects inside the nucleons. Such diquark concept was introduced in 1966 [1] and from then it was applied in various models of elementary particles phenomena [2]. Although some properties of the diquarks can be tested in "soft", small momentum transfer phenomena, the crucial test of the diquark model is given by the "hard" processes with high momentum transfers. If a diquark is really a tightly bound system of two quarks, it can participate in deep inelastic reactions of leptons and hadrons as a quasi elementary particle. The scattering of diquarks should lead to the substantial production of baryons in certain regions of phase space in lepton-nucleon and in nucleon-nucleon reactions.

This short review tries to summarize the present status of the diquark hypothesis in large transverse momentum (p_T) proton-proton collisions at high energies. The data come mainly from the Split Field Magnet (SFM) detector at the Intersecting Storage Rings (ISR) at CERN. In sec. 2 the properties of inclusive proton production at large p_T in high energy pp collisions are described. Sec. 3 provides more quantitative description of the data with the simple diquark model. In sec. 4 the independent evidence for the diquark scattering is shown in the data on the correlations of particles in events with high p_T proton production. Conclusions are given in sec. 5.

2 Inclusive proton production

Scatterings of protons with large four momentum transfers (Q^2) allow the study of the parton structure of protons [3]. Initial protons can be considered as two beams of quarks and gluons. In a hard collision, two partons interact elastically by the exchange of a gluon. The scattered partons fragment into hadrons and give rise to two jets of particles with high transverse momenta – trigger and away jets. The remaining spectator partons do not interact and they fragment into two other jets with low p_T particles. Such proton-proton collisions show the characteristic four jet structure [4]. The fragmentation of partons into particles can be treated to a fairly good approximation as an independent process described by universal fragmentation functions.

If events with hard collisions of protons are selected in a detector by a requirement of one high p_T particle, the sample of events will be biased. From all the configurations of fragmenting high p_T partons, the trigger will preferentially choose those with one particle much faster than the others in the trigger jet. Such a particle will be called a leading particle. At ISR energies, a leading particle takes on average about 70 % of the parent parton momentum [5]. For events with high p_T particle trigger the distribution of particles in the trigger jet is no longer described by the universal fragmentation function. For such jets however, strong correlations between the quantum numbers of the parent parton and the type of the leading particle have been observed [6]. The identification of the leading particle allows very often the identification of the parent parton.

The reflection of such correlations is the ratio of the inclusive cross-sections for high p_T production of positive and negative pions shown in Fig. 1 [7]. Since there are two u valence quarks and one d valence quark in a proton, we observe $\sigma(\pi^+)/\sigma(\pi^-) \approx 2$ for higher values of p_T , where the scattering of valence quarks is a dominant process. The decrease of $\sigma(\pi^+)/\sigma(\pi^-)$ for smaller values of p_T is explained by the contribution from gluons scattering and their fragmentation with equal probabilities into π^+ and π^- .

Since the fragmentation of a parton is independent of the elementary parton-parton scattering, the production of various leading particles should show a very similar dependence on kinematical variables if the particles come from the same type of parent parton. Considering only the dominant valence quark scattering shown in Fig. 2, we can expect that the cross-sections ratios for high p_T π^+ , K^+ and p production will depend only weakly on transverse momenta and scattering angles. Their magnitudes should reflect the relative probabilities for creations of $d\bar{d}$, $s\bar{s}$ and $(u\bar{d})(\bar{u}d)$ pairs during fragmentation of the u quark.

Fig. 1: Ratio of inclusive cross-sections for π^+ and π^- production versus $x_T = 2p_T/\sqrt{s}$ at $\sqrt{s} = 45$ and 62 GeV.

Fig. 2: Dominant fragmentation schemes for π^+ , K^+ , p , π^- , K^- and $\bar{p}$. P_{ii} is a probability to create an $\bar{u}u$ pair of partons in the colour field.

The negative leading particles come from two kinds of partons. Leading π^- mesons are dominantly produced by valence d quarks but leading K^- and $\bar{p}$ arise mainly from gluon fragmentation since the initial protons do not contain valence s , $\bar{u}$ and $\bar{d}$ quarks. Since gluons carry, on the average, a smaller fraction of the proton momentum than do valence quarks, we expect that $\sigma(K^-)/\sigma(\pi^-)$ and $\sigma(\bar{p})/\sigma(\pi^-)$ will decrease with increasing p_T . On the other hand, for gluon scattering the ratio $\sigma(K^-)/\sigma(\bar{p})$ should be fairly independent of θ and p_T and its magnitude should reflect the relative probabilities for the production of $s\bar{s}$ and $(ud)(\bar{u}\bar{d})$ pairs during the gluon fragmentation (Fig. 2). The ratio $\sigma(K^-)/\sigma(\bar{p})$ should be equal to the ratio $\sigma(K^+)/\sigma(p)$.

In Figs. 3, 4 and 5, the p_T dependence of the ratios of inclusive cross-sections are shown. The data come from the Split Field Magnet detector [7, 8]. The results for the ratios of pions and kaons agree well with the quark-parton model

predictions. The relative cross-section for the production of $\bar{p}$, at the level of a few percent, depends slightly on p_T but shows no dependence on a polar angle θ (Fig. 6). The only exception are the results for the proton production. The relative cross-section for protons is an order of magnitude larger than the corresponding one for antiproton. It depends strongly on θ . For fixed θ , the fraction of protons decreases with increasing p_T .

Fig. 3: Production ratios for K^+/π^+ and K^-/π^- in pp collisions at 45 and 62 GeV for $\theta = 50^\circ$, plotted as a function of x_T .

Fig. 4: Particle ratios in pp collisions at $\sqrt{s} = 62$ GeV and $\theta \approx 45^\circ$ plotted as a function of p_T .

Fig. 5: Particle ratios in pp collisions at $\sqrt{s} = 62$ GeV and three c.m.s. scattering angles $\theta \approx 10^\circ, 20^\circ$ and 45° , plotted as a function of p_T .

Fig. 6: Angular dependence of $R(p) = \sigma(p)/\sigma(pos.)$ and $R(\bar{p}) = \sigma(\bar{p})/\sigma(neg.)$ in pp collisions at 62 GeV and fixed values of p_T .

The stronger dependence of inclusive cross-section for p on p_T , which leads to $\sigma(p)/\sigma(\pi^+) \sim 1/p_T^4$ [9] could suggest that protons are produced in the fragmentation of gluons. In this case, however, we should observe a similar magnitude of production cross-sections and properties for antiprotons.

If diquark objects can be scattered at large angles, they will provide the additional mechanism for high p_T proton production. With increasing four momentum transfer Q^2 , it will be more difficult to scatter diquarks without breaking them. For the description of the extended diquarks, a form factor $F(Q^2)$ should be introduced with $F(Q^2) \sim 1/Q^2$. This additional dependence on Q^2 leads to the decreasing of $R(p) = \sigma(p)/\sigma(\text{positives})$ with increasing θ and p_T .

3 Diquark model

The above qualitative arguments for the presence of diquark scattering at high p_T can be complemented by more quantitative predictions of a simple parton model [10]. The invariant cross-section for inclusive production of a particle in pp scattering can be expressed as the weighted sum of the differential cross-sections $d\sigma/d\hat{t}$ of all possible parton scatterings ($ij \rightarrow kl$) with a four momentum transfer $\hat{t}$ which can contribute

$$E_h \frac{d^3\sigma}{dp_h^3} = \sum_{ijkl} \int_0^1 dx_i \int_0^1 dx_j f_p^i(x_i) f_p^j(x_j) \frac{d\sigma}{d\hat{t}}(ij \rightarrow kl) \frac{1}{\pi z_k} D_k^h(z_k)$$

where x_i is the fraction of the proton momentum carried by a parton i and z_k is the fraction of the momentum of a parton k carried by hadron h . The cross-section can be calculated if in addition to $d\sigma/d\hat{t}$, the proton structure functions $f_p^i(x_i)$ and the fragmentation functions of a parton k into hadron h — $D_k^h(z_k)$, are known. For diquarks all the required ingredients are unknown. The models make different assumptions about diquark structure functions, diquark scattering amplitudes and form factors and diquark fragmentation functions [10, 11, 12, 13, 14]. To reduce the number of parameters in a model a dominance of scalar ud diquarks is usually assumed.

In the ABCDHW Collaboration model [10, 15] the fragmentation functions for quarks, gluons and diquarks into various hadrons were generated according to the Lund fragmentation scheme. For $0.2 < z < 1.0$ they can be parametrized in the following form

$$z D_k^h(z) = (c_1 + c_2 z + c_3/z)(1-z)^{c_4}$$

where c_1, c_2, c_3, c_4 are adjustable parameters. For all $z > 0.2$, the fragmentation function of a ud system into a proton is the dominating process.

Since diquarks are not truly elementary objects, the description of the diquark scattering cannot be treated in QCD in a strict way. An approximation can be made by assuming that the nonperturbative part of the diquark scattering amplitude is described simply by the diquark form factor and the perturbative

part is dominated by the elementary scattering amplitudes for scalar particles as given by QCD [15].

The proton wave function with a diquark component can be written in the form

$$|p\rangle = (1 - \lambda)^{1/2} |u, u, d, g, sea\rangle + \lambda^{1/2} |\tilde{u}, (\tilde{u}\tilde{d}), \tilde{g}, \tilde{sea}\rangle$$

where λ describes the probability for a diquark state in a proton. This parametrization simplifies a more physical picture of a proton always in a quark-diquark state but with different dynamical configurations of two quarks in the diquark. The description of the first part (qqq) in the formula can be taken from νp deep inelastic scattering data [16]. The second term (q -diquark) is unknown. Varying the fraction of the gluon component contained in the diquark, different parametrizations of the diquark structure functions are obtained. For two extreme cases, the distributions are the following:

- Model 1: $\tilde{u}(x) = 0.5u(x)$ $\tilde{d}(x) = 0$
 $\tilde{u}\tilde{d}(x) = 0.5u(x) + d(x)$ $\tilde{g}(x) = g(x)$
- Model 2: $\tilde{u}(x) = 0.5u(x)$ $\tilde{d}(x) = 0$
 $\tilde{u}\tilde{d}(x) = 0.5u(x) + d(x) + g(x)$ $\tilde{g}(x) = 0$

For both models $\tilde{sea}(x) = sea(x)$ is assumed. In Model 1, the diquark does not contain any gluons from the proton. In Model 2, all the gluons from the proton are contained in the diquark. Both models are unphysical but they test the sensitivity of the data to the assumptions about the gluon component.

There are theoretical and experimental arguments that diquarks should appear dominantly at higher Bjorken x values. This can be taken into account if λ increases with x . In Model 3, the structure functions of Model 2 are complemented by a simple parametrization $\lambda = x$.

In all the models, the form factor is parametrized as $F(Q^2) = 1/(1+Q^2/M^2)$. The scale factor M^2 and the probability λ are adjusted to fit the measured ratio $\sigma(p)/\sigma(\pi^+)$ at $\sqrt{s} = 62$ GeV, $\theta = 45^\circ$ and $p_T = 4$ GeV/c :

- Model 1: $\lambda = 0.30$ and $M^2 = 20$ GeV²
- Model 2: $\lambda = 0.17$ and $M^2 = 10$ GeV²
- Model 3: $\lambda = x$ and $M^2 = 9$ GeV²

The obtained values for λ and M^2 are large in all models pointing to a substantial fraction of tightly bound diquarks in a proton.

With fixed λ and M^2 the measured p_T , θ and energy dependence of the proton fractions can be predicted. The comparison of the model predictions with the SFM data are shown in Figs.7, 8 and 9. They describe roughly the data. The θ dependence of $R(p)$ suggests that a more realistic model with only part of proton gluons contained in the diquark can fit the data. Some λ dependence should also be introduced but the simple parametrization in Model 3 gives too strong a dependence on θ and the energy.

The predictions of the standard parton model without diquarks are also shown in the figures for comparison. As expected, both models correctly describe the behaviour of antiprotons ratios since there is no contribution of the diquark scattering in these processes. A dramatic difference is however observed for the proton ratios. The standard parton model predicts a similar behaviour of high p_T p and $\bar{p}$ production and fails to describe the proton data.

We can conclude that the unusual features of the inclusive high p_T proton production cannot be explained by the standard quark-parton model. The diquark scattering is at present the only proposed mechanism consistent with the experimental data.

Fig. 7: Particle ratios $\sigma(p)/\sigma(K^+)$, $\sigma(\bar{p})/\sigma(K^-)$ (a), and $\sigma(p)/\sigma(\pi^+)$, $\sigma(\bar{p})/\sigma(\pi^-)$ (b) versus p_T for $\theta \approx 45^\circ$ and $\sqrt{s} = 62$ GeV. The lines represent the predictions of the models described in the text.

Fig. 8: Angular dependence of the proton $R(p)$ and antiproton $R(\bar{p})$ fractions at fixed p_T . The lines represent the predictions of the models described in the text.

Fig. 9: Energy dependence of $\sigma(p)/\sigma(\pi^+)$ at $x_T = 0.15$ and $\theta \approx 45^\circ$. The Fermilab data at $\theta \approx 90^\circ$ are also shown. The lines represent the predictions of the models described in the text.

4 Correlations of particles in events with large p_T proton production

If the dominant mechanism of high p_T proton production is the diquark scattering, well-defined correlations between particles produced in the trigger jet and the corresponding spectator jet should be observed. Also the study of correlations of particles from the proton trigger jet can reveal the properties of the scattered diquarks. On the other hand, particles from the remaining away and second spectator jets are only weakly correlated with high p_T proton production and their properties are similar to the properties of the particles from the corresponding jets in events triggered by high p_T pions and kaons.

4.1 Correlations between trigger and spectator jets

The correlations between the trigger particle and the quantum numbers of fast particles coming from the fragmentation of noninteracting partons are symbolically shown in Fig.10. For u or d quark scattering which leads to high p_T π^+ , π^- or K^+ meson production, there are remaining valence quarks ud or uu which give rise to the spectator jet. These two quark systems easily produce fast protons when they are joined by the third quark during the fragmentation process. Strong correlations between high p_T π^+ , π^- or K^+ production and the presence of fast protons in the spectator jet should be observed. The production of high p_T K^- mesons by gluons leads to similar correlations. The same effect

is also observed if the high p_T protons are produced in quark scattering with creation of two-quark system in the quark fragmentation. The baryon number is compensated locally in the trigger jet in this case.

Fig. 10: Expected flavour composition of spectator jets for pion and proton triggers.

For the high p_T protons coming from the fragmentation of hard-scattered diquarks only one valence quark remains in the spectator jet. The production of fast baryons at small angles is then suppressed for high p_T proton triggers.

A fast baryon studied usually in the experiments is a proton. For soft proton-proton collisions final state protons dominate the positive particle distributions for $x_F > 0.5$. In the experiments where the identification of the fast particle is not possible, the assumption is therefore usually made that the majority of fast positive particles with $x_F > 0.5$ are protons.

The densities of positive (ρ^+) and negative (ρ^-) particles associated with proton and pion triggers were measured in The Split Field Magnet experiment [17, 18]. It is convenient to study the ratios of particle densities $R^+(p/\pi) = \rho^+(p)/\rho^+(\pi)$ and $R^-(p/\pi) = \rho^-(p)/\rho^-(\pi)$ where acceptance corrections are cancelled.

The experimental results for R^+ are shown in Fig. 11. The ratios $R^+(p/\pi^+)$ and $R^+(p/\pi^-)$ decrease substantially with increasing x_F from the values of around 1 for small x_F . It means that the number of fast positive particles (mainly protons) is suppressed for proton triggers.

These negative proton correlations are confirmed in the experiment where both the high p_T trigger particle at $\theta = 90^\circ$ and fast spectator protons could be identified [19]. The depletion of fast protons from the fragmentation of spectator partons for events with a high p_T proton trigger is observed in the data shown in Fig.12.

All the above observations agree qualitatively with the expectations of the hard diquark scattering mechanism for high p_T proton production.

Fig. 11: Ratios of positive spectator secondaries associated with proton and pion triggers at $\theta \approx 10^\circ$, (a) π^+ trigger, (b) π^- trigger.

Fig. 12: The ratio of forward protons per proton trigger to forward protons per π^+ trigger as a function of x_F . Both triggers are at $\theta \approx 90^\circ$.

To show more quantitatively the difference between the charged particles densities ρ^+ and ρ^- for fragmentations of various spectator quark combinations the SFM and deep inelastic νp and $\bar{\nu} p$ scattering data can be compared. The neutrino reactions lead to the well-defined two-quark jets in the backward hemi-

sphere of the produced hadrons c.m.s.: uu jets for νp scattering and ud jets for $\bar{\nu} p$ collisions. To compare the results from the two types of experiments, the relation between the fragmentation function variable z used in ν data analysis and x_F measured for spectator jet particles in the SFM detector is needed. For spectator jets in high p_T collisions, it can be obtained using the quark-parton model. Since the relation between x_F and z is mainly kinematical it is not very sensitive to the dynamical assumptions of the model.

The difference between the fragmentation of ud and uu systems is enhanced if the ratio $R_\rho = \rho^-/\rho^+$ is formed. The results for the spectator jets in events with high p_T proton, π^+ and π^- are shown in Fig.13 and compared with νp and $\bar{\nu} p$ scattering data [20].

Fig. 13: Charge density ratio $R_\rho = \rho^-/\rho^+$ as a function of x_F for spectator jets in events with high p_T pion and proton triggers in proton-proton collisions. The shaded strips are predictions from deep inelastic neutrino and antineutrino scattering experiments for ud and uu target jet systems.

For the π^- trigger, the properties of the uu spectator system agree very well with R_ρ of about 1 % measured for uu jets in the νp scattering. For the π^+ trigger R_ρ of about 10 % is measured for fast particles from ud systems both in pp and $\bar{\nu} p$ hard scattering. In contrast, the events with the proton trigger have $R_\rho \approx 40$ %, much higher than the events with meson triggers. For high p_T diquark scattering the properties of the spectator quark fragmentation can be compared to the corresponding features of the quark fragmentation in νp and $\bar{\nu} p$ scattering. The comparison of the ratios R_ρ is shown in Fig.14. For the pp data the results depend on the quantum numbers of diquarks in protons. For ud diquarks the spectator quark is always the u quark and R_ρ should correspond

to the ratio measured for the u quark fragmentation in νp scattering. The pp data are slightly above the νp data. This result points to a contribution from uu diquarks. If both two quark combinations are equally probable in a proton the mixture of $2/3$ of ud diquarks and of $1/3$ of uu diquarks should be observed. The ratio R_ρ can be calculated for the correspondingly weighted νp and $\bar{\nu} p$ data. The results shown in Fig.14 lie far above the pp data.

Fig. 14: Charge density ratio $R_\rho = \rho^-/\rho^+$ for spectator jets in events with high p_T proton triggers in pp collisions compared to predictions from deep inelastic ν and $\bar{\nu}$ scattering for pure u quark fragmentation and for a mixture of 33% d quarks and 67% u quarks.

4.2 Correlations of particles in the proton trigger jet

The particles coming from the fragmentation of the same parton as the trigger particle form a trigger jet. For high p_T pion and kaon triggers, an enhanced density of charged particles in the phase space region close to the trigger particle is observed. The production of particles in the trigger jet is usually analyzed using the variable z_F

$$z_F = \vec{p}_T \cdot \vec{p}_T^r / |\vec{p}_T^r|^2$$

where $\vec{p}_T^r$ is the transverse momentum of a particle associated with the trigger particle with transverse momentum $\vec{p}_T$.

Since the properties of particles from the trigger jets are well-measured for meson triggers, it is convenient to compare the observed features of proton trigger jets to those for the meson jets.

If the high p_T protons are produced in the fragmentation of ud diquarks, the second rank π^- mesons in the trigger jet (Fig. 15) should occur as frequently as the second rank π^- mesons in the π^+ trigger jet. In contrast, for uu diquark scattering π^+ mesons are the second rank particles in the high p_T proton production. The ratios of negatively and positively charged particles associated

with proton and meson triggers are shown in Fig. 16 as functions of z_F . The errors are large but both ratios are close to 1. This means that for the events with a high p_T proton the same features as in a high p_T meson production are observed — the formation of the trigger jet. The data are consistent with similar $\langle z_{TR} \rangle$ for both kinds of trigger jets.

Fig. 15: Schemes for u , ud and uu fragmentations into leading and the second rank hadrons.

Fig. 16: Ratio of negative (a) and positive (b) particle densities in the trigger jet for proton and π^+ meson triggers at $\theta \approx 45^\circ$ and $p_T > 3.5$ GeV/c as a function of z_F .

The similar properties of second rank particles in the π^+ and p trigger jets point again to the dominance of ud diquark scattering. The small enhancement of positive particles observed for the proton jets for the positive particles could suggest the small admixture of uu diquarks scattering. This conclusion is supported by the observation of high p_T Δ^{++} production in the events with high p_T proton triggers [17].

5 Conclusions

This short review of the experimental results in high p_T proton-proton scattering at ISR energies show that there are strong indications of two quark clustering in protons. The evidence is growing for the dominance of the tightly bound scalar ud diquarks in nucleons. The observation of production of the Δ^{++} resonance at large p_T and the charge density structure in the spectator jets in events with a high p_T proton provides the evidence for a small admixture of uu vector diquarks.

The diquark effects are visible both in low and high momentum transfer processes. In the latter, the diquarks can be observed more directly. The hard processes however can bias the measurements of diquark properties choosing only the special and rare configurations of the wavefunction of quark-diquark baryons. This is suggested by the apparent contradiction between the rather extended, loosely bound two-quark systems obtained in the potential models for static properties of baryons and the tightly bound diquarks required to describe the data presented in this review for the deep inelastic proton-proton collisions.

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