Are "Gluon Effects" Caused by Diquarks?

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The possible importance of diquarks in high-energy physics is discussed and it is suggested that this nonperturbative phenomenon can explain the trends in high-energy data that are usually attributed to gluon processes as described by perturbative QCD. Several experimental tests are suggested for discriminating between gluon and diquark phenomena.

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In this Letter we discuss the role of diquarks in high-energy physics. Our interest in such tightly bound quark pairs has been raised by the fact that their predicted effects happen to be similar to the ones normally attributed to gluons, as described by perturbative quantum chromodynamics (PQCD). This has been implicitly demonstrated by many groups in recent years through fits to various experimental data.[1]

The new approach here is to take the diquark concept to its limits, and suggest several new applications, all of which "simulate" gluon effects and agree with existing data. In order to to discriminate between gluon and diquark phenomena in the future, we point out many reactions where they would reveal themselves in completely different ways. The details are given in a series of existing and upcoming publications.

Should it turn out that the present agreement between data and the expected diquark effects persists also in more accurate future experiments, or that the new tests suggested here turn out in favor of diquarks in contrast to perturbative gluons, one has to ask whether the conventional approach within PQCD is correct. Obviously, any QCD effect that has to do with bound two-quark systems is nonperturbative. Therefore, the more data that can be understood as diquark signatures, the less "need" there is for perturbative gluon effects, which in turn would imply that the crucial QCD parameter Λ is much smaller than commonly believed. Since the present data can be understood both within PQCD alone and within our diquark model alone, it is of utmost importance to probe the diquarks further in experiment, along, for instance, the lines sketched here.

Before we go into details, it could be instructive to review a similar situation in quantum *electrodynamics,* namely that of superconductivity. That phenomenon cannot be described with perturbative QED as there is a nonperturbative substructure in the form of Cooper pairs. Trying to fit the data with perturbative methods would, at best, lead to an unrealistically strong QED coupling, and it is only after the *ad hoc* introduction of (e^-e^-) bosons that a further perturbative expansion is meaningful. The analogy with diquarks is obvious, although Cooper pairs are formed by the coupling to the lattice, while diquarks might be kept together by their own internal forces. The strongest such phenomenon in QCD is naturally confinement, but as long as there is no complete understanding of nonperturbative effects, there is also the possibility of an intermediate substructure of bound diquarks, whose importance can, at present, only be investigated phenomenologically.

Let us start with discussing *deep-inelastic electron, muon, and neutrino scattering on nucleons,* and the picture of the nucleon as a bound quark-diquark system that, according to us,[2,3] emerges from the data. It turns out that the proton is nearly always in a $u(ud)_0$ state. The $(ud)_0$ diquark has $J^P=0^+$, a momentum distribution similar to that of the u quark, and a form factor $\sim(1+Q^2/M_0^2)^{-1}$, with $M_0^2\approx 10\ \mathrm{GeV}^2$, which is surprisingly "pointlike." The nucleon also contains a small fraction of spin-1 diquarks, which are more energetic on the average than the $(ud)_0$, and also bigger. We consider them *accidental* in the nucleon.[3] They do not exist as bound two-quark states, but appear only because the single quark sometimes comes so close to one of the quarks in the $(ud)_0$ that an incoming probe cannot resolve the charge distribution and therefore sees a "false" $(ud)_1$ or $(uu)_1$ diquark. This idea explains the best-fit values of their absolute number and form factor, but is in sharp contrast to diquark models with SU(6) symmetry.[4] In νN reactions, the spin-flip process $(ud)_0\to(uu)_1$ is important compared to, for instance, $(ud)_1\to(uu)_1$ in spite of a weak W-$(ud)_0$ coupling, because the $(ud)_0$ is so abundant. This transition to an unbound spin-

1 system is the only process of relevance where a $(ud)_0$ behaves collectively but still breaks up. With muon and electron beams the rare $(ud)_0 \to (ud)_1$ is drowned by the elastic channel.

Our model has the following advantages ("A") in common with gluon effects in PQCD:

(A1) It fits the data on the structure functions $F_2^{lN}(x, Q^2)$ with $l=e, \mu, \nu$ beams.[2] The Q^2 dependence reflects the diquark form factors.

(A2) It fits also the data on $F_1^{eN}(x, Q^2)$, and hence explains why the polarization ratio $R \equiv \sigma_L/\sigma_T$ does not vanish.[3]

In addition to those, there is the following important advantage:

(A3) Quarks and diquarks seem to carry the *full* nucleon nomentum.[3] No explicit gluon component is needed in the nucleon, since there is no "missing" energy fraction! Then, it is naturally a matter of taste whether one looks upon a diquark as a two-quark system kept together by an extra dense gluon cloud.

The predictions ("P") for structure functions are as follow:

(P1) The vanishing of the diquark form factors gives $F_{1,2}^{lN}(x, Q^2) \to f(x) > 0$ as $Q^2 \to \infty$. In PQCD, $F_{1,2} \to 0$ as $Q^2 \to \infty$.[5]

(P2) Because of the accidental spin-1 diquarks, $F_{1,2}(x, Q^2)$ are expected to have *maxima* at $Q^2 \lesssim 2$ GeV^2 as long as $0.2 \lesssim x \lesssim 0.5$.[3]

Leptoproduction and hadroproduction of baryons is of special value for probing diquarks, since a produced baryon is supposed to be formed by a diquark that was either directly knocked out from the target by the projectile, or left over in the target region after a quark was knocked out, or created together with an antidiquark in the color field of a fragmenting quark. When relating the diquark content of the target to the baryon yield one must know the probability for a diquark to break up instead of directly forming a baryon. As shown by two of us,[6] recent neutrino data[7] favor the view that the true diquark, $(ud)_0$, always stays together after the lone quark has been knocked away, while spin-1 diquarks tend to break up in similar situations. In spite of the admixture of many diquark processes one can pinpoint a few signatures of the most interesting ones, namely those where a diquark is directly knocked out from the target:

(A4) Recoiling constituent diquarks give rise to energetic baryons, and hence explain[8] the following experimental findings of "too many" baryons (compared to expectations from quark reactions): (a) The baryon-to-meson ratio in the current fragmentation region of μN reactions grows with increasing hadron momentum.[9] (b) The proton-to-meson ratio at high p_T in pp collisions at the CERN intersecting storage rings[10] is "too high" and falls with p_T like the $(ud)_0$ form factor.
(c) The Λ yield per event in the forward region is twice as high in νn as in νp reactions.[11] This excess is caused by the reaction $\nu + (dd)_1 \to \mu^- + (ud)_0$, which cannot take place in the proton.

The *production of high-mass dileptons* in hadron collisions is harder to analyze in the diquark model, as well as in PQCD, because two complicated systems take part in the interaction. A few qualitative trends can, however, be discussed.

(A5) Diquark processes add to $q\bar{q}$ annihilation in creating dileptons, which may explain part or all of the fact that the naive Drell-Yan model underestimates the yield by a factor $K \approx 2$.[12] With a *pion* projectile, one gets a "contribution" to K by *not* assuming that pions contain gluons.

(P3) $D\bar{D}$ annihilation contributes substantially to *double* dilepton production, since the rate of two simultaneous $q\bar{q}$ annihilations grows like $1/R^2$, where R is the mean distance within the qq and $\overline{qq}$ pairs before the reaction.[13] The excess of double dileptons compared to predictions from diquark-free models should be particularly clear in $p\bar{p}$ collisions.

(P4) If diquarks are responsible for the fact that $K > 1$, then K must *decrease* towards unity at $M_{ll}^2 \gg 10$ GeV^2 because of the falloff of the diquark form factors.

Since the quarks in the $(ud)_0$ are confined to a much smaller volume than that of the proton, they have high internal momenta, k_T, which enhances the p_T of the lepton pairs at high M_{ll}^2, where all diquarks are "resolved." Hence, there is another advantage:

(A6) The dilepton mean transverse momentum increases with M_{ll}^2 towards a constant value at $M_{ll}^2 \gg 10$ GeV^2, in accordance with data.[14] The approach to this plateau is proportional to the $(ud)_0$ timelike form factor.

The most exciting process for exploring diquarks is e^+e^- *annihilation into hadrons*. If diquarks in nucleons are altogether accidental, or perhaps caused by the presence of a third quark, they should not play a role in e^+e^- processes. If diquarks, on the other hand, are "real," they appear on two levels—*directly* produced in $e^+e^- \to D\bar{D}$, and *indirectly* produced in $e^+e^- \to q\bar{q}$ followed by a fragmentation like $q \to q(D\bar{D})$ prior to the hadronization. So far, only the indirect ones have been treated in the literature,[15] and found to be of importance for baryon production. However, the smallness of our diquarks implies that also the direct ones are important. Since the spin-0 $(ud)_0$ dominates in nucleons, we assume that there are no spin-1 diquarks involved in e^+e^- reactions. There must, however, appear spin-0 diquarks with heavier quarks and these are even smaller than the $(ud)_0$ because of their high masses. In line with our finding in Ref. 6 we assume that all spin-0 diquarks end up in baryons without breaking (neglecting possible $D\bar{D}$ bosons). Among the most straightforward results are the following:

(A7) Indirect diquarks influence the production of slow (identified) baryons. The data here can be understood with the help of light $(ud)_0$, $(us)_0$, and $(ds)_0$ diquarks,[16] the best-fit $(ud)_0$ mass being only 225 MeV.

(A8) Direct diquarks contribute to the hadronic R factor, the inclusive hadron spectrum, and the two-jet angle distribution,[17] so that the data can be fitted without gluonic processes. The most visible diquark is the $(uc)_0$ because of its high charge $(+4e/3)$. Together with the $(dc)_0$ and $(sc)_0$, it is responsible for the broad structure in R at $5 \lesssim W \lesssim 8$ GeV,[18] as well as for the significant deviation from the form $1+\cos^2\theta$ in the hadronic two-jet angle dependence found at $9 \lesssim W \lesssim 10$ GeV.[19]

All crucial predictions from our model have to do with the fact that the diquarks are scalar and end up in baryons[16,17]:

(P5) Spin-$\frac{3}{2}$ baryons, e.g., the Δ and the $\Sigma(1385)$, are much rarer than the spin-$\frac{1}{2}$ ones, since they cannot be directly produced from diquarks.

(P6) The very fastest baryons are predicted to come from direct diquarks, and should hence have some striking features, which could best be explored at $5 \lesssim W \lesssim 10$ GeV where charmed diquarks dominate: (a) The angle dependence is $1-\cos^2\theta$. (b) The absolute number is proportional to the difference between the measured R and the contribution from quarks only (excluding resonances). (c) A fast baryon has its antibaryon back to back in the c.m. system (contrary to the slow ones from indirect diquarks).

So far we have discussed direct diquarks from the process $e^+e^- \to D\bar{D}$. There should, however, also be diquarks from reactions like $e^+e^- \to (qq)\bar{D}$ with the two-quark system in an unbound configuration. But such events give rise to *three* hadronic jets, and it would therefore be interesting to find out whether they form the bulk of three-jet events, or if they, as one would believe are effectively suppressed by the form factor at high energies. Unfortunately, one cannot compute, without several extra assumptions, the coupling of a photon to a $(qq)\bar{D}$ system, and the absolute rate of such events can therefore not be estimated in a convincing way. The three-jet events are nevertheless of great principle importance for the consistency of the model, since a failure of the model to explain the features of such events would leave perturbative gluon processes as the only plausible explanation. That would support the conventional, rather high best-fit value for the strong coupling constant, which in turn would make our diquark effects "unnecessary" also for understanding other processes. Fortunately, the admixture of $(qq)\bar{D}$ events among the three-jet events can be reasonably well *measured*, since the diquark is expected to give some unmistakable signatures in the data:

(P7) The fastest jet in a $qq\bar{D}$ or $\bar{q}\bar{q}D$ three-jet event comes from a diquark and therefore always contains a fast baryon.

(P8) The slowest ("gluon") jet comes from a quark, and should fragment accordingly, except for the fact that it most likely contains the baryon needed to conserve the baryon number.

(P9) The mean baryon number in three-jet events is more than doubled compared to unbiased events because of the obligatory baryon-antibaryon pair caused by the diquark.

To conclude, we have on purpose kept the discussion of existing and predicted data trends on a qualitative level. More detailed results are, or will be, presented elsewhere.[2,3,6,8,16,17] Instead of too much data fitting it seems, however, more rewarding to first explore experimentally the very phenomenon of diquark formation. Many of the predicted trends would, if confirmed, make necessary a completely new view of the nature of quark-gluon reactions in high-energy physics.

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