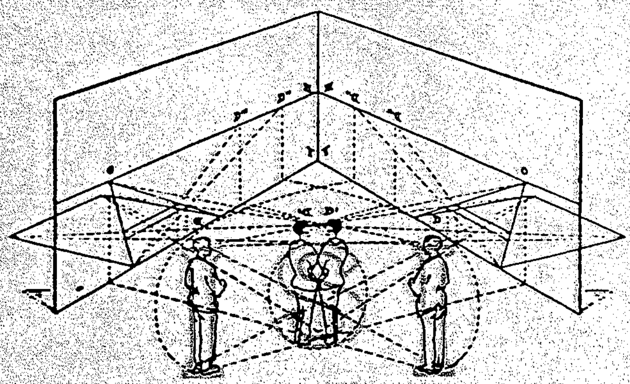
Workshop on

DIQUARKS

Villa Gualino, Torino
October 24-26, 1988

Edited by
I.S.I.—Mauro Anselmino
Enrico Predazzi
University of Torino



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Signatures of New Quarks Suggested by the Superstrings

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Abstract

We examine the sensitivity of e^+e^- hadron colliders and CP violating processes to the signals coming from the new D quarks suggested by the phenomenology of superstrings at low energies.

Superstrings have launched a plethora of phenomenological models ~~inspired by them~~[1]. The exceptional group E(6) plays an important role in the scenario where the extra dimensions are compactified on a manifold with SU(3) holonomy[2]. In that case the observable particles appear in the fundamental representation of E(6) which is the 27[3]. The decomposition of the 27 under the standard model group SU(3)xSU(2)xU(1) is the following

$$Q \equiv \begin{pmatrix} u \\ d \end{pmatrix} \sim (3, 2, 1/6)\,,\quad u^c \sim (\bar{3}, 1, -2/3)\,,\quad L \equiv \begin{pmatrix} \nu \\ e \end{pmatrix} \sim (1, 2, -1/2)$$

$$d^c \sim (\bar{3}, 1, 1/3)\,,\quad e^c \sim (1, 1, 1)$$

$$H \equiv \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} \sim (1, 2, 1/2)\,,\quad \bar{H} \equiv \begin{pmatrix} \bar{H}^0 \\ \bar{H}^- \end{pmatrix} \sim (1, 2, 1/2)$$

$$\nu^c \sim (1, 1, 0)\,,\quad N \sim (1, 1, 0)\,,\quad D \sim (3, 1, -1/3)\,,\quad D^c \sim (\bar{3}, 1, 1/3)$$

where all multiplets are left-handed. H and $\bar{H}$ give masses, through the Higgs mechanism, to the known quarks, while N gives masses to the D and D^c. In the same way as the normal quarks, the spinor members of D and D^c multiplets will combine to give the fermion $D_{1/2}$ while we are left with the scalar partners D_0 and D_0^c (analogous to $\tilde{q}_L$ and $\tilde{q}_R$). The above states have Yukawa interactions, besides the gauge couplings. The most general form, of the superpotential, allowed by the Hosotani symmetry-breaking mechanism[4], is

$$
\begin{aligned}
f = {} & \lambda H\bar{H}N + k\, DD^cN \\
& + h_U Q u^c H + h_E L e^c \bar{H} + h_\nu H L \nu^c + h_D Q d^c \bar{H} \\
& + \lambda_\nu D d^c \nu^c \\
& + \lambda_L D^c Q L + \lambda_e D e^c u^c \\
& + \lambda_Q D Q Q + \lambda_c D^c u^c d^c
\end{aligned}
$$

The last three rows show that the D's could couple to two quarks (diquarks) or to a lepton and a quark (leptoquark). In order to avoid rapid proton decay and to have naturally small Dirac neutrino masses we cannot allow the simultaneous appearence of the three last rows in our superpotential. Therefore we can have the three choises: a) $\lambda_\nu \neq 0$, b) $\lambda_L, \lambda_e \neq 0$, and c) $\lambda_Q, \lambda_c \neq 0$. All other couplings are zero in each case. Let us start with the last one by treating the D's as diquarks.

COUPLING TO TWO QUARKS. We assume that no mixing of D's with conventioanal quarks is possible. Single D production in hadron-hadron collisions can go through[5]

$$\bar{q} + \bar{q} \longrightarrow D_0 \longrightarrow \bar{q} + \bar{q} \quad , \quad q + q \longrightarrow D_0^c \longrightarrow q + q$$

In Fig.1 we show the total cross sections for the above process as a function of the mass m_{D_0}, assuming $m_{D_0} = m_{D_0^c}$ and $\lambda_Q = \lambda_c = \lambda$ for simplicity. The common Yukawa coupling is parametrized by its ratio to the electromagnetic coupling

$$F = \frac{\lambda^2/4\pi}{\alpha_{em}}$$

In the case where the three generations of D particles have the same masses, the estimated cross sections should be increased by a factor of three. We draw curves for CERN $\bar{p}p$ at $\sqrt{s}$=630 GeV, FNAL $\bar{p}p$ at $\sqrt{s}$=1600 GeV, LHC pp at $\sqrt{s}$=17 TeV and SSC pp at $\sqrt{s}$=40 TeV.

In order to have an estimate of the background we have made a comparison of the signal-to-background ratio at $\sqrt{s}$=630 GeV using data published dy UA2. In Table I we compare their $d\sigma/dM$(jet-jet) spectrum multiplied by the widths δM of the bins they use, corresponding to their mass resolution, with the $D_0^{(c)}$ cross section we would expect for F=1. We see that the QCD jet-jet background is between one and two orders of magnitude larger than our expected $D_0^{(c)}$ cross sections. We expect this state of affairs to be repeated at future colliders.

We turn now to D pair production in hadron-hadron colliders

$$\overset{(-)}{p}p \to D_0 \bar{D}_0 + X \quad \text{or} \quad pp \to D_{1/2} \bar{D}_{1/2} + X$$

Possible signatures for the D and D are

$$D_{1/2}\bar{D}_{1/2} \to (qq\tilde{\chi})(qq\tilde{\chi}) \qquad \text{missing energy}$$

$$D_0\bar{D}_0 \to (qq)(qq) \qquad \text{dijet mass bumps}$$

where $\tilde{\chi}$ is the lightest supersymmetric particle.

In Fig.2a, for $\sqrt{s}$=630 GeV, and for the process $\bar{p}p \to D_{1/2}\bar{D}_{1/2}+X$, we show contours of constant cross sections σ=7 pb, 1.4 pb and 0.28 pb for monojets and multijets in the $(m_{D_{1/2}}, m_{\tilde{\chi}})$ plane. The three selected cross sections correspond to 5 events, 1 event (for a 700nb^{-1}) and 5 events ($\bar{p}p$ collider with ACOL). Thus a 5 multijet event limit would give a limit $m_{D_{1/2}} \lesssim 80$ GeV for

$m_{\tilde{g}} < 20$GeV, while for a 5 monojet event limit we get $m_{D_{1/2}} < 60$ GeV for $m_{\tilde{g}} \simeq 1/2 m_{D_{1/2}}$. Cross section curves are shown in Fig.2b for $\sqrt{s}=1600$ GeV (FNAL $\bar{p}p$) and $m_{\tilde{g}}=1/2 m_{D_{1/2}}$

Concluding the case where the D is treated as diquark we find that single production of scalar $D_0^{(c)}$ at h-h colliders through $\overset{(-)}{q}\overset{(-)}{q}$ annihilation is likely to be overwhelmed by a large QCD jet-jet background. Pair production of $D_0 \bar{D}_0$ and $D_{1/2} \bar{D}_{1/2}$ offers a promising way to search for these particles, since they give characteristic experimental signatures if $m_{\tilde{g}} \leq 1/2 m_{D_{1/2}}$. The CERN $\bar{p}p$ Collider has probably sensitivity to these particles for masses ≤ 60 to 70 GeV. ACOL would increase this limit to 100 GeV. Fermilab Tevatron collider should give a limit of ~150 GeV, while in the long term LHC or SSC would push it up to 2TeV.

The D as a diquark also could contribute to low energy (weak hadronic decays) and to CP-violating processes [6]. In Fig.3 we show relevant diagrams to the two cases. In general the D's take the place of W, but it is not the same case as the scalar standard Higgs, since the coupling of Higgs with quarks is proportional to the quark mass while this is not the case for the D's. In the case of the famous $\Delta I=1/2$ rule in hyperon decays, the contribution of the D's, even in the most favorable case (coupling=0.3 and mixing between D_0 and D_0^c) does not enhance the (first order) [7] result from the weak effective Hamiltonian by more than 20%, if $M_{D_0}=200$ Gev. The interesting thing comes in relation with the box and the penguin diagrams (Fig.3) and the $|\varepsilon|$ and $|\varepsilon'/\varepsilon|$ CP violating parameters. Here, in contrast to the usual results, we can have an enhancement in the $\Delta I=1/2$ rule, through the penguin diagram, without exceeding the experimental values of Δm , $|\varepsilon|$ and $|\varepsilon'/\varepsilon|$.

D's AS LEPTOQUARKS. The D's having couplings with a quark and a lepton, can participate in the process where it is exchanged in the t-channel [8]. We have caluclated the cross sections at LEP2 ($\sqrt{s}$=200GeV) and CLIC ($\sqrt{s}$=2 TeV) and we express our results as a function of λ and m_{D_0}. In Fig.4 we plot contours of constant $\delta\sigma/\sigma$, in the plane (λ, m_{D_0}), where $\sigma=\sum_{\text{all } q}\sigma(e^+e^-\to\bar{q}q)$ including D-exchange, and $\delta\sigma$ is the additional contribution due to D-exchange. If we assume a $\delta\sigma/\sigma<1$, we find the discovery limits shown in Table II.

Next we calculate the contribution of D-exchange to $\overset{(-)}{p}p\to e^+e^-$ due to parton process $\overset{(-)}{q}\overset{(-)}{q}\to D_0(D_0^c)\to e^+e^-$ which is the inverse of the previous process. The main contribution comes from the interferences with γ and Z. We present our results in the following way: for each accelerator (CERN $\bar{p}p$ $\sqrt{s}$=630 GeV, FNAL $\bar{p}p$ $\sqrt{s}$=1.8 TeV, LHC pp $\sqrt{s}$=17 TeV and SSC pp $\sqrt{s}$=40 TeV with the corresponding integrated luminosity (10^{37} cm^{-2}, 10^{37} cm^{-2}, 10^{40} cm^{-2}, 10^{40} cm^{-2}) we first choose the invariant mass $M_{\ell^+\ell^-}$ of the $\ell^+\ell^-$ pair which corresponds to a minimum observable $d\sigma/dM_{\ell^+\ell^-}$ (1 event/year) for the usual Drell-Yan process. These are $M_{\ell^+\ell}$ =(0.175, 0.200, 1.0, 1.2)TeV respectively. Then working with this value of $M_{\ell^+\ell}$, we obtain the contours of $\delta\sigma/\sigma$ in the (m_{D_0}, λ) plane shown in Fig.5. Limits from these graphs are shown in Table III. These results show that the e^+e^- and hadron-hadron colliders have considerable sensitivity to leptoquarks particles with masses larger than those accesible to direct production.

In LEP I ($\sqrt{s}=m_{Z_o}$) indirect D effects are not interesting since we are at the Z-peak. But the leptoquark nature of D can give clear signatures through the diagrams shown in Fig.6. We consider production of an on-shell $D_o(D_o^c)$ associated with a jet and a lepton. Further the $D_o(D_o^c)$ decays to a $\bar{u}(u)$ and an $e^+(e^-)$. The signal is one (or two) jet(s) accompanied by two leptons. The scalar nature of $D_o^{(c)}$ can give jet(s)-leptons distributions which is easily distinguished from the Standard Model background with appropriate cuts.

The decay of the heavy leptoquark gives rise to an approximately isotropic distribution of quarks and leptons. That is, unlike-sign dileptons should be produced with comparable rates at any angle with respect to each other, being accompanied most probably by two jets, again at any angle with respect to the lepton. Several fat monojets should also be present, balanced by same side dileptons, due to the approximate flatness of the two-jet rate with respect to their relative angle. A few three-jet events should also be there due to gluon bremsstrahlung.

In Fig.7 we show the cross sections for one- and two- jet events assuming the strength of the Yukawa coupling to be equal to the electromagnetic.

The background event configurations receive SM contributions mainly from $\bar{b}b$ production (assuming $m_t < 1/2\ m_{Z_o}$). First generation beauty fragmentation into muons is known to be hard and leads to two opposite-side, unlike sign muons, accompanied by close jet activity. On the other hand, as far as the second generation decays are concerned, excluding the trilepton and the like-sign dilepton events which are clearly distinguishable experimentally, we may have contamination from the two opposite-side jet configurations one of which is close to an unlike-sign dilepton pair. Note also that ,unlike to signal events, the SM background involves missing energy due to the produced neutrinos.

Our cuts are the following. If the angle between the two final state quarks is biger than 30° we encounter a genuine two-jet event, while, otherwise, the configuration is assumed to be recorded as an effective one jet event. We neglect all further parton-hadronization effects. In order to practically eliminate the SM background of the dijet+$\ell^+\ell^-$ events, we impose the extra cut that neither lepton should be closer than 30° to any jet axis, given by the parent-quark momentum in our model. Despite this cut the signal cross section remains significant, since it is approximately isotropic with respect to the momenta of the produced particles, as explained before (Fig. 8).

Given the projected luminocity $d\mathcal{L}/dt \sim 10^{32}\ cm^{-2}\, s^{-1}$ of LEP I, since there is practically no SM background to the proposed signals (i) monojet+$\ell^+\ell^-$ and (ii) dijet+a sufficiently distant $\ell^+\ell^-$ pair, we conclude that a scalar leptoquark producing no missing energy with a mass up to ~ 80 GeV should be easily detectable.

unless its Yukawa coupling to the lepton-quark pair is unexpectedly small.

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