DIQUARKS

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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 \(SU(3) \times SU(2) \times U(1)\) is the following

\[
Q = \begin{pmatrix} u^c \\ d^c \\ e^c \end{pmatrix} \sim (3, 2, \frac{1}{6}), \quad u^c \sim (\bar{3}, 1, -\frac{2}{3}), \quad L = \begin{pmatrix} \nu^c \\ e \end{pmatrix} \sim (1, 2, -\frac{1}{2})
\]

\[
d^c \sim (\bar{3}, 1, \frac{1}{3}), \quad e^c \sim (1, 1, 1)
\]

\[
H = \begin{pmatrix} H^+ \\ \bar{H}^0 \end{pmatrix} \sim (1, 2, \frac{1}{2}), \quad \bar{H} = \begin{pmatrix} H^- \\ \bar{H} \end{pmatrix} \sim (1, 2, \frac{1}{2})
\]

\[
u^c \sim (1, 1, 0), \quad N \sim (1, 1, 0), \quad D \sim (3, 1, -\frac{1}{3}), \quad D^c \sim (\bar{3}, 1, \frac{1}{3})
\]

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 \(D_{2}\), while we are left with the scalar partners \(D_0\) and \(D^c_0\) (analogous to \(\bar{q}_L\) and \(\bar{q}_R\)). 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
\[
\mathcal{L} = \mathcal{L}_{\text{HAN}} + k \mathcal{L}_{\text{DD}^c N} \\
+ h_u Q_u e H + h_d Q_d e H \\
+ \tilde{\lambda}_L D d \tilde{\ell} e \\
+ \lambda_L D^c Q L + \lambda_e D e^c u \\
+ \lambda_e D^c Q L + \lambda_e D^c u^c e \\
\]

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 appearance of the three last rows in our superpotential. Therefore we can have the three choises: a) \( \lambda_L \neq 0 \), b) \( \lambda_L \lambda_e \neq 0 \), and c) \( \lambda_e \lambda_e \neq 0 \). 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 conventional quarks is possible. Single D production in hadron-hadron collisions can go through

\[
\bar{q}_i + \bar{q}_j \rightarrow D_s \rightarrow \bar{q}_i + \bar{q}_j , \quad q_i + q_j \rightarrow D_s \rightarrow q_i q_j 
\]

In Fig.1 we show the total cross sections for the above process as a function of the mass \( m_{D_s} \), assuming \( m_{D_s} = m_{D_s} \) and \( \lambda_e = \lambda_e = \lambda \) for simplicity. The common Yukawa coupling is parametrized by its ratio to the electromagnetic coupling

\[
F = \frac{\mathcal{A}^2/4\pi}{\alpha_{\text{em}}} 
\]

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 \( \sqrt{s}=630 \text{ GeV} \), FNAL \( \bar{p}p \) at \( \sqrt{s}=1600 \text{ GeV} \), LHC \( pp \) at \( \sqrt{s}=17 \text{ TeV} \) and SSC \( pp \) at \( \sqrt{s}=40 \text{ TeV} \).

In order to have an estimate of the background we have made a comparison of the signal-to-background ratio at \( \sqrt{s}=630 \text{ GeV} \) using data published by UA2. In Table 1 we compare their \( d\sigma/dM(\text{jet-jet}) \) spectrum multiplied by the widths \( \delta M \) of the bins they use, corresponding to their mass resolution, with the \( \tilde{D}_0^0 \) 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 \( \tilde{D}_0^0 \) 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

\[
\bar{p}p \to D_0^0 \bar{D}_0^0 + X \text{ or } pp \to D_0^0 \bar{D}_0^0 + X
\]

Possible signatures for the \( D \) and \( D_0^0 \) are

- \( D_0^0 \bar{D}_0^0 \) - (qq\( \bar{q} \))(qq\( \bar{q} \)) missing energy
- \( D_0^0 \bar{D}_0^0 \) - (qq)(\( \bar{q} \)) dijet mass bumps

where \( \tilde{X} \) is the lightest supersymmetric particle.

In Fig.2a, for \( \sqrt{s}=630 \text{ GeV} \), and for the process \( \bar{p}p \to D_0^0 \bar{D}_0^0 + X \), we show contours of constant cross sections \( \sigma=7 \text{ pb} \), \( 1.4 \text{ pb} \) and \( 0.28 \text{ pb} \) for monojets and multijets in the \( (m_{D_0^0}, m_{\tilde{X}}) \) plane. The three selected cross sections correspond to 5 events, 1 event (for \( 700 \text{ nb}^2 \)) and 5 events (\( \bar{p}p \) collider with ACOL). Thus a 5 multijet event limit would give a limit \( m_{D_0^0} < 60 \text{ GeV} \) for
m_f < 20 GeV, while for a 5 monojet event limit we get m_{b_{\nu_2}} \leq 60 GeV for \( m_f = 1/2 m_{b_{\nu_2}} \). Cross section curves are shown in Fig. 2b for \( \sqrt{s} = 1600 \text{ GeV} \) (FNAL \( \bar{p}p \)) and \( m_f = 1/2 m_{b_{\nu_2}} \).

Concluding the case where the D is treated as diquark we find that single production of scalar \( D_{\nu_2}^{(*)} \) at h-h colliders through \( q\bar{q} \) annihilation is likely to be overwhelmed by a large QCD jet-jet background. Pair production of \( D_{\nu_2} \bar{D}_{\nu_2} \) and \( D_{\nu_2} \bar{D}_{\nu_2} \) offers a promising way to search for these particles, since they give characteristic experimental signatures if \( m_f < 1/2 m_{b_{\nu_2}} \). The CERN \( \bar{p}p \) Collider has probably sensitivity to these particles for masses \( \leq 60 \) to 70 GeV. ACDL would increase this limit to 100 GeV. Fermilab Tevatron collider should give a limit of \( \sim 150 \) GeV, while in the long term LHC or SSC would push it up to 2 TeV.

The D as a diquark also could contribute to low energy (weak hadronic decays) and to CP-violating processes \(^{62}\). In Fig. 3 we show relevant diagrams to the two cases. In general the Ds 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 Ds. In the case of the famous \( \Delta I = 1/2 \) rule in hyperon decays, the contribution of the Ds, even in the most favorable case (coupling = 0.3 and mixing between \( D_{\nu_2} \) and \( D_{\nu_2}^{(*)} \)) does not enhance the (first order) \(^{98}\) result from the weak effective Hamiltonian by more than 20%, if \( M_{b_{\nu_2}} \geq 200 \) Gev. The interesting thing comes in relation with the box and the penguin diagrams (Fig. 3) and the \( |\epsilon| \) and \( |\epsilon'/\epsilon| \) CP violating parameters. Here, in contrast to the
usual results, we can have an enhancement in the Δl=1/2 rule, through the penguin diagram, without exceeding the experimental values of Δm, |e| and |e'/e|.

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 1-channel. We have calculated the cross sections at LEP2 (J/ς=200 GeV) and CLIC (J/ς=2 TeV) and we express our results as a function of m_D and m_ς. In Fig.4 we plot contours of constant Δς/ς, in the plane (ς,m_D), where Δς=Σ₅(ς-ς₅) including D-exchange, and Δς is the additional contribution due to D-exchange. If we assume a Δς/ς<1, we find the discovery limits shown in Table II.

Next we calculate the contribution of D-exchange to p̅p→e⁺e⁻ due to parton process q̅q→D⁺(ς→e⁺e⁻) which is the inverse of the previous process. The main contribution comes from the interferences with χ and 2. We present our results in the following way: for each accelerator (CERN p̅p J/ς=630 GeV, FNAL p̅p J/ς=1.8 TeV, LHC pp J/ς=17 TeV and SSC pp J/ς=40 TeV with the corresponding integrated luminosity (10¹⁰ cm⁻², 10²⁰ cm⁻², 10³⁰ cm⁻²) we first choose the invariant mass Mₑₑ of the pair which corresponds to a minimum observable dς/dMₑₑ (1 event/year) for the usual Drell-Yan process. These are Mₑₑ = (0.175, 0.200, 1.0, 1.2) TeV respectively. Then working with this value of Mₑₑ, we obtain the contours of Δς/ς in the (m_D, ς) 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 accessible to direct production.

In LEP I ($\sqrt{s} = m_\gamma$) 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 $D_\gamma(D^\ast_\gamma)$ associated with a jet and a lepton. Further the $D_\gamma(D^\ast_\gamma)$ 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 $D_\gamma$ 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 $m_\psi < m_\gamma$). 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 bigger than $30^\circ$ 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-\$E_T$ events, we impose the extra cut that neither lepton should be closer than $30^\circ$ 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 luminosity $d\mathcal{L}/dt \sim 10^{32}$ cm$^{-2}$ s$^{-1}$ of LEP I, since there is practically no SM background to the proposed signals (i) monojet-$E_T$ and (ii) dijet-\$E_T$ pair, we conclude that a scalar leptoquark producing no missing energy with a mass up to $\sim 80$ GeV should be easily detectable.
unless its Yukawa coupling to the lepton-quark pair is unexpectedly small.
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