SIGNATURES OF A SCALAR LEPTOQUARK FROM SUPERSTRINGS AT LEP I

N.D. TRACAS and S.D.P. VLASSOPULOS
Department of Physics, National Technical University, Zografou, GR-15773 Athens, Greece

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We show that a scalar, colour triplet leptoquark with mass $\lesssim 80\ \mathrm{GeV}/c^2$, plausibly resulting from E_6 compactification in superstring-inspired models, when produced singly on-shell at LEP I gives rise to measurable monojets or dijets accompanied by sufficiently distant leptons, dominating over standard-model backgrounds.

Leptoquark are colour-triplet objects having a Yukawa-type coupling to a lepton–quark pair. They appear naturally in many models beyond the standard model (SM), namely in the strong-coupling version of the SM [1], in grand unifying models [2], in composite models [3] and in horizontal-symmetry schemes [4]. In particular, during the fast few years a lot of interest has been devoted to the charge $\pm 1/3$ colour-triplet, SU(2)-singlet, $D_{1/2}$ quarks and the D_0, D_0^c scalar quarks, which should plausibly appear in the matter generations of superstring-inspired E_6 models if the compactification of the extra dimensions is done on a Calabi–Yau manifold [5–7]. The allowed interactions of the D_0 and D_0^c to quarks and leptons are

$$\lambda_Q \epsilon^{\alpha\beta} D_0 (\overline{Q_R^{c\alpha}} Q_L^\beta) + \lambda_c D_0^c \bar{u}_R d_L^c + \lambda_L \epsilon^{\alpha\beta} D_0^c (\overline{Q_R^{c\alpha}} L_L^\beta)$$
$$+ \lambda_e D_0 \bar{u}_R e_L^c + \lambda_\nu D_0 \bar{d}_R \nu_L^c\,, \tag{1}$$

where Q, L are the quark and lepton SU(2) doublets, u, d, e and ν the corresponding singlets and $\epsilon^{\alpha\beta}$ the antisymmetric tensor (α, $\beta = 1, 2$). Colour (anti-)symmetrization should of course be applied to the above terms. In general, each Yukawa interaction in (1) enters with an independent different coupling constant. In order to avoid fast proton decay and to have naturally small Dirac neutrino masses, only one of the three lines of (1) should be present in the lagrangian. In this work we assume that the second line is the allowed one, i.e. the $D_0^{(c)}$ is treated as a leptoquark.

The non-observation of supersymmetry partners and the absence of additional neutral currents could, in principle, constrain the masses of these new quarks but model calculations [8] cannot give a definite lower bound, beyond the obvious one, $\simeq 26$ GeV, which comes from e^+e^- experiments; note, however, that on-shell pair production of such heavy particles is suppressed due to its kinematic threshold. Thus, phenomenological analysis has been called for and it has been found that pair production of these new heavy quarks at presently available hadron colliders leads to detectable signatures in almost all of their possible decay channels, provided their mass is less than 60–70 GeV [8].

Further, scalar-leptoquark production provides a characteristic signal of an unlike-sign dilepton pair, accompanied by distant jet activity, involving no missing energy, which is conveniently separable from the SM background in e^+e^- collisions. In this work we analyze in detail the processes

$$e^+e^- \to Z^0 \to \underset{\hookrightarrow\, \ell^+\bar{q}}{\bar{D}_0}\,\ell^- q\,,$$
$$\ell^+\bar{q}\underset{\hookrightarrow\, \ell^- q}{D} \qquad + (D_0 \leftrightarrow D_0^c)\,, \tag{2}$$

where one of the leptoquarks D_0, $\bar{D}_0$, D_0^c, $\bar{D}_0^c$ is produced on-shell and the more interesting mass region $m_{Z^0} > m_D > \frac{1}{2} m_{Z^0}$ is kinematically accessible at LEP I. The relevant graphs giving rise to (2) near the Z^0 pole are shown in fig. 1a. The prices paid for this deep access are the unknown Yukawa couplings λ_L, λ_e of the leptoquark to the lepton and the quark.

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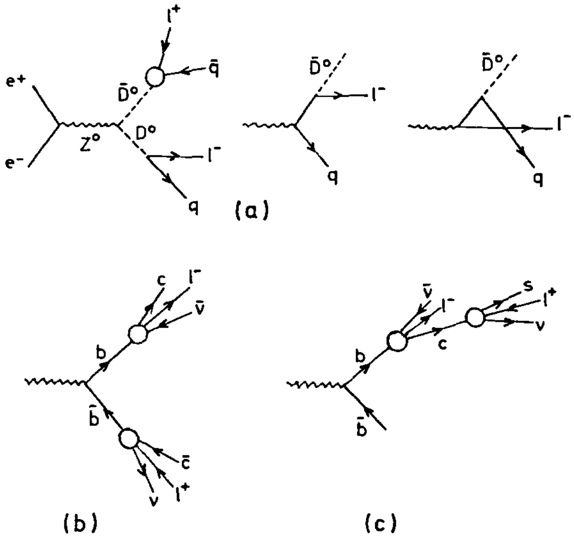

Fig. 1. (a) 2→3 graphs leading to an on-shell leptoquark at the Z^0 pole. (b) First-generation beauty decays, faking the signal of (a). (c) Same as (b), for second-generation beauty decays.

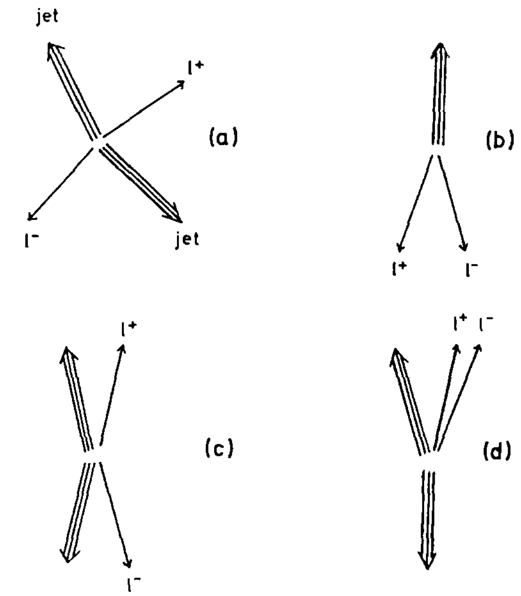

Fig. 2. (a), (b) Signal-event configurations. (c), (d) Background-event dominant configurations.

For a heavy leptoquark the process (2) 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 (fig. 2a). Several flat 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 (fig. 2b). A few three-jet events should also be there due to gluon bremsstrahlung.

Such event configurations receive SM contributions mainly from $b\bar{b}$ production (assuming $m_t > \frac{1}{2}m_{Z^0}$). First-generation beauty fragmentation into muons (fig. 1b) is known to be hard and leads to two opposite-side, unlike-sign muons, accompanied by close jet activity (fig. 2c). On the other hand, as far as the second-generation decays (fig. 1c) are concerned, excluding the trilepton and the like-sign dilepton events, which are clearly distinguishable experimentally from figs. 2a, 2b, we may have contamination from the opposite-side jet configurations with one of the jets being close to an unlike-sign dilepton pair (fig. 2d).

Note that, unlike the signal events, the SM background involves missing energ also, due to the produced neutrinos. That is, of the whole background, only the sub-sample for which the total neutrino energy $\sum E_\nu$ is less than the resolution ΔE of the detectors is competent to the signal. In this respect, this type of analysis is more sensitive to the scalar leptoquark D_0 than to its supersymmetry partner, the leptoquark $D_{1/2}$, since the latter involves a photino in its decay products and gives rise to missing energy also in its signal.

Near the Z^0 pole we can neglect γ, Z'^0 [new gauge boson, corresponding to the extra U(1)] and q exchanges and the expression of the product $MM^\dagger$ of matrix elements for the 2→3 process (2), averaged over initial spins and summed over final spins and colours, can be written as

$$\tfrac{1}{4}\sum MM^\dagger = \tfrac{1}{4}\sum\,(M_1M_1^\dagger + M_2M_2^\dagger + M_3M_3^\dagger + 2\ \mathrm{Re}\,M_1M_2^\dagger + 2\,\mathrm{Re}\,M_2M_3^\dagger + 2\,\mathrm{Re}\,M_1M_3^\dagger) \times 3\lambda_D^2\,(g_A^2+g_B^2)\frac{16\pi^2\alpha^2}{s_w^4}[(s-m_{Z^0}^2)^2+m_{Z^0}^2\Gamma_{Z^0}^2]^{-1}\,, \tag{3}$$

where m_{Z^0}, Γ_{Z^0} are the mass and width of Z^0. We find

$$\sum MM_1^\dagger = 4g_D^2(m_D^2+t_1+t_2-t_3)(t_i\leftrightarrow u_i) - s(s_{12}-s_{13}-s_{23}+3m_D^2)s_{12}(s_{12}-m_D^2)^{-2}\,, \tag{4a}$$

$$\sum M_2M_2^\dagger = 2(g_{A_u}^2+g_{B_u}^2)\,[s_{13}u_2t_3+m_D^4u_2 - m_D^2(s_{13}t_2+u_2t_1+u_2t_3)+u_i\leftrightarrow t_i]s_{13}^{-2}\,, \tag{4b}$$

$$\sum M_3M_3^\dagger = (g_{A_u}\to g_A,\, g_{B_u}\to g_B,\, 1\leftrightarrow 2)\,, \tag{4c}$$

$$\begin{aligned}\sum 2\,\mathrm{Re}\, M_2M_3^\dagger =& 2(g_{A^c}g_{B_u}+g_{B^c}g_{A_u})\\ &\times [m_D^4(t_1+t_2)-m_D^2t_1(u_2-u_3+s_{23})\\ &- m_D^2t_2(s_{13}-u_3)+t_i\leftrightarrow u_i+m_D^2ss_{12}\\ &- 2s_{12}(m_D^2-t_3)(m_D^2-u_3)]s_{13}^{-1}s_{23}^{-1}\,,\end{aligned} \tag{4d}$$

$$\begin{aligned}\sum 2\,\mathrm{Re}\, M_1M_2^\dagger =& \tfrac{1}{2}g_D(g_{A_u}+g_{B_u})\\ &\times [(m_D^2+u_1+u_2-u_3)(t_2s_{13}-t_3s_{12}-t_1s_{23})\\ &- m_D^2(t_1+t_2+s_{12})+t_i\leftrightarrow u_i-2ss_{12}(s_{13}-2m_D^2)]\\ &\times s_{13}^{-1}(s_{12}-m_D^2)^{-1}\,,\end{aligned} \tag{4e}$$

$$\sum 2\,\mathrm{Re}\, M_1M_3^\dagger = (g_{A_u}\to g_A,\, g_{B_u}\to g_B,\, 1\leftrightarrow 2)\,, \tag{4f}$$

where ($s_w=\sin\theta_w$, $c_w=\cos\theta_w$)

$$g_A=(-\tfrac{1}{2}+s_w^2)c_w^{-1}=-g_{B^c}\,,\quad g_B=s_w^2c_w^{-1}=-g_{A^c}\,, \tag{5a}$$

$$g_{A_u}=(\tfrac{1}{2}-\tfrac{2}{3}s_w^2)c_w^{-1}\,,\quad g_{B_u}=-\tfrac{2}{3}s_w^2c_w^{-1}\,, \tag{5b}$$

$$g_D=\tfrac{1}{3}s_w^2c_w^{-1}\,, \tag{5c}$$

and the kinematic variables are defined by

$$s=(p_++p_-)^2\,,\quad s_{ij}=(p_i+p_j)^2\,, \tag{6a}$$

$$t_i=(p_+-p_i)^2\,,\quad u_i=(p_--p_i)^2\,, \tag{6b}$$

for $i,j=1\equiv \mathrm{q}$, $2\equiv \ell$, $3\equiv \mathrm{D}$.

To get eq. (4), in order to avoid unnecessarily lengthy formulas, we assume that D_0 and D_0^c are degenerate in mass, $m_{D_0}=m_{D_0^c}\equiv m_D$, and also that the Yukawa couplings are equal, $\lambda_L=\lambda_e\equiv\lambda_D$, with λ_D treated as a parameter. In our calculations we assume that the strength of this coupling is equal to the electromagnetic one, i.e. $\alpha_\lambda=\lambda_D^2/4\pi=\alpha$. Since the cross section is proportional to α_λ, it is easy to read the results for any desired value of α_λ. With the above simplifications, eq. (4) gives the matrix elements for the production of a real D_0, $\bar{D}_0$, D_0^c and $\bar{D}_0^c$ plus a quark and a lepton of any charge, within a family. We note, that if the $D_0^{(c)}$ of different families have similar masses, our results should be multiplied by a factor of 3.

In treating the two-body on-shell leptoquark decay, $D_0\to\ell q$, we meet a branching fraction $\mathrm{BR}(D_0^{(c)}\to\ell q)=2/3$, since we are working within the class of superstring=inspired models where D_0 is a pure leptoquark with possible decays $D_0\to e_Ru_R$, e_Lu_L, $d_L\nu_L$ for each generation.

To estimate the SM background, which arises from beauty-quark production and its subsequent decays, resulting in event configurations of the types 2c, 2d as explained above, we employ the heavy-quark production differential cross section for the process $e^+e^-\to Q\bar{Q}$ at the Z^0 pole and the matrix element for each b, c on-shell decay $Q\to q\ell\nu$.

To take very roughly into account heavy-quark hadronization we allow for an energy loss of $\sim 15\%$ (35%) for each b (c) decay. This is equivalent to introducing a fragmentation function $D_{HQ/Q}(z)=\delta(z-\langle z_Q\rangle)$, where $\langle z_b\rangle\simeq 0.85$ and $\langle z_c\rangle\simeq 0.65$. With the cut $\sum E_\nu<\Delta E$ imposed below we find that second-generation beauty decays give generally negligible contributions. Our results depend on the value of $\langle z_b\rangle$ chosen. Note, however, that with the cut $\sum E_\nu<\Delta E$ the SM background is practically controlled solely by the geometrical condition imposed below that the angle between any pair of jet and lepton be larger than $\theta_{\ell-j}^{\min}$.

To calculate cross sections with specified cuts, we apply a standard Monte Carlo procedure, where the appropriate kinematic variables for each on-shell decay are randomly generated at the respective rest frames and then boosted to the common e^+e^- CM frame. In order to define our theoretical jet cross sections we check for the angle $\theta_{qq'}$ between the two final-state parton momenta. When $\theta_{qq'}>\theta_{\rm jet}$ we encounter a genuine two-jet event, while, otherwise, the configuration is assumed to be recorded as an effective one-jet event by the detectors. We neglect all further parton-hadronization effects.

The cross sections obtained in this way are presented in fig. 3 for the characteristic jet-algorithm choices $\theta_{\rm jet}=30°, 20°, 15°$. As already noted, the SM events due to b decays (figs. 1b, 1c) with total neutrino energy $\sum E_\nu>\Delta E$ are to be clearly distinguished experimentally from the signal events, involving no missing energy. Hence, only the part of the b-decay cross sections with $\sum E_\nu<\Delta E$ could be a "background" to the scalar-leptoquark signals. As far as the monojet$+\ell^+\ell^-$ configuration is concerned, with the jet definition given above, a SM background is practically non-existent for $\theta_{\rm jet}$ up to $\sim 40°$ (with a fixed $\Delta E=10$ GeV) and ΔE up to ~ 15–20 GeV (with a fixed $\theta_{\rm jet}=30°$) and, with the expected luminosities at LEP I, the cross section is measurable for $m_D\lesssim 85$ GeV$/c^2$.

In order to control the SM background to the di-

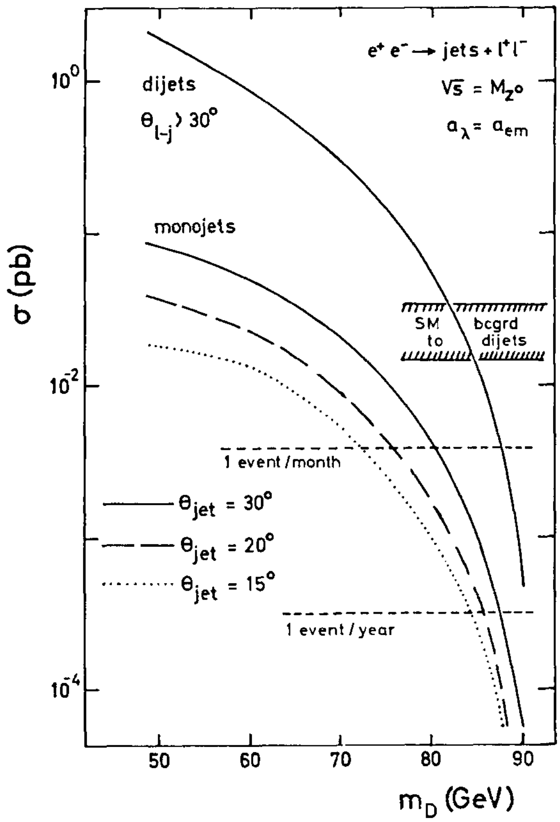

Fig. 3. Jet cross sections arising from the graphs of fig. 1a. The dijet cross section is practically independent of the jet algorithm. The SM background to the dijet+$\ell^+\ell^-$ signal is obtained with $\Sigma E_\nu < \Delta E = 10$ GeV, $m_b = 5.0 \pm 0.2$ GeV, $\langle z_b \rangle = 0.85 \pm 0.03$.

jet+$\ell^+\ell^-$ events, we impose the extra cut that neither lepton should be closer than $\theta_{\ell-j}^{min}$ to any jet axis, given by the final-state quark momenta 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 above. From fig. 3 it is clear that, for $\theta_{\ell-j}^{min} = 30^\circ$ and $\Delta E = 10$ GeV, the signal dijet+$\ell^+\ell^-$ cross section is more than two times its SM background for $m_D \lesssim 80$ GeV/c^2 and is conveniently measurable with the expected LEP I luminosities. The SM background to the dijet+$\ell^+\ell^-$ signal can be further drastically reduced, with a moderate decrease of the signal cross section, by increasing $\theta_{\ell-j}^{min}$: specifically, for $\Delta E = 10 \pm 5$ GeV we find that the cut values $\theta_{\ell-j}^{min} \simeq (45 \pm 10)^\circ$ practically diminish the SM background, while suppressing the signal to about 60% of the values shown in fig. 3. Our SM estimates are consistent with results obtained with a standard LUND Monte Carlo.

We note that non-standard Higgs production, $e^+e^- \to H^0(\to q\bar{q})H^0(\to \ell^+\ell^-)$ could give a jets+$\ell^+\ell^-$ signal competitive only to the third-generation D signals, since the leptonic decay modes of the Higgs boson involve almost exclusively τ leptons.

Given the projected luminosity $d\mathscr{L}/dt \simeq 10^{32}$ cm^2 s^{-1} of LEP I, since the SM background to the proposed signals (i) monojet+$\ell^+\ell^-$ and (ii) dijet+a sufficiently distant $\ell^+\ell^-$ pair is under control, we conclude that the scalar leptoquark of superstring-inspired models (producing no missing energy) should be detectable for a mass of up to ~ 80 GeV/c^2, unless its Yukawa coupling to the lepton–quark pair is unexpectedly small. A similar conclusion should plausibly be expected for a more general scalar leptoquark with couplings to both left- and right-handed leptons.

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