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INDIRECT SEARCHES FOR LEPTOQUARKS AT PRESENT AND FUTURE COLLIDERS

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A B S T R A C T

We explore the sensitivities of e^+e^- colliders (LEP, CLIC) and hadron-hadron colliders (CERN $\bar{p}p$, FNAL $\bar{p}p$, LHC pp and SSC pp) to the indirect effects of virtual scalar particles with superstring-inspired leptoquark and diquark couplings. We find that e^+e^- colliders have better sensitivities via total cross-section measurements of $e^+e^- \rightarrow qq$ than via asymmetry measurements, and that LEP 2 is much more sensitive than LEP 1. Hadron-hadron colliders are sensitive via lepton-pair production cross-sections ($q\bar{q} \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$).

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A perennial theme in particle physics beyond the Standard Model is the possible existence of leptoquarks, i.e., bosons of spin 0 or 1 with couplings to lepton-quark combinations. These have been searched for in e^+e^- collisions - where a lower mass limit of 23 GeV has been established [1] - and more recently in $\bar{p}p$ collisions - where a lower mass limit of 33 GeV for a spin-0 leptoquark decaying into $q(\mu \text{ or } \nu)$ has been established [2]. A new variation on the leptoquark theme has been provided by the ten-dimensional heterotic string [3] compactified on some Calabi-Yau manifold [4]. Such models generally contain colour-triplet, $SU(2)$ -singlet, charge-(-1/3) scalar particles, called here D_0 , and their spin-1/2 supersymmetric partners $D_{1/2}$. In addition, there are charge-(+1/3), colour-anti-triplet conjugate particles D_0^c and $D_{1/2}^c$ [5]. These particles may have leptoquark couplings arising from superpotential terms

$$\lambda_l D_l q + \lambda_l^c D_l^c l^c u^c \quad (1)$$

and/or diquark couplings arising from superpotential terms

$$\lambda_q D_q q q + \lambda_q^c D_q^c d^c u^c \quad (2)$$

It is very dangerous to have both the sets of couplings (1,2), since in combination they can give proton decay via D_0/D_0^c exchange, which could be very rapid if the D_0/D_0^c masses ~ 1 TeV. Accordingly, it is usually assumed that light D particles can have only couplings of type (1) or of type (2), but not both. (See, however, Ref. [6].) If they only have couplings of type (1), the D_0/D_0^c may be regarded as conventional leptoquarks whereas in case (2) they would resemble diquarks. In most of this paper we will concentrate on the leptoquark possibility, discussing searches for indirect effects of the D_0/D_0^c through their virtual exchanges in $e^+e^- \rightarrow \bar{q}q$ and $q\bar{q} \rightarrow l^+l^-$ processes [7].

We first discuss the search for indirect leptoquark exchange effects in $e^+e^- \rightarrow \bar{q}q$ at SLC or LEP 1 ($\sqrt{s} = 100$ GeV), LEP 2 ($\sqrt{s} = 200$ GeV) and CLIC ($\sqrt{s} = 2$ TeV) [8], expressing our results as regions of the $(\lambda, m_{D_0/D_0^c})$ plane which could be excluded by measurements of total cross-sections σ and forward-backward asymmetries A at different levels of precision. We find that LEP 1 is very insensitive because of the nearby Z^0 pole, whereas LEP 2 is sensitive to $m_{D_0/D_0^c} > \sqrt{s}$, particularly through measurements of $\sigma(e^+e^- \rightarrow \bar{q}q)$. In the case of hadron-hadron colliders (CERN $\bar{p}p$ at $\sqrt{s} = 630$ GeV, FNAL $\bar{p}p$ at $\sqrt{s} = 1800$ GeV, LHC pp at $\sqrt{s} = 17$ TeV [9] and SSC pp at $\sqrt{s} = 40$ TeV [10]) we concentrate on changes in the different Drell-Yan cross-sections ($\bar{q}q \rightarrow e^+e^-, \mu^+\mu^-, \tau^+\tau^-$) at the largest values of $M_{l^+l^-}$ for which observable rates are given by the conventional γ^* and Z^{0*} exchanges. We again

find that there is sensitivity to values of m_{D^0}/D_0^c which are inaccessible to direct searches.

The D_0/D_0^c contributions to $e^+e^- \rightarrow \bar{q}q$ come from exchanges of these particles in the crossed channel. The inclusion of these diagrams, in addition to the usual γ and Z exchanges, gives rise to the following additional term in the differential cross-section

$$\Delta\left(\frac{d\sigma}{d\cos\theta}\right) = \frac{N_c}{128\pi} (\lambda_{LQ})^2 e^2 \frac{s}{(t-m_D^2)} \left[-\frac{q_u}{s} + \frac{q_{u_L}^2 q_{e_L}^2 + q_{u_R}^2 q_{e_R}^2}{\sin^2\theta_W \cos^2\theta_W (s-m_Z^2)} \right] (1+\cos\theta)^2 + \frac{N_c}{256\pi} (\lambda_{LQ})^4 \frac{1}{(t-m_D^2)^2} (1-\cos\theta)^2 \quad (3)$$

where

$$N_c = 3, \quad t = -\frac{s}{2}(1-\cos\theta), \quad q_u = \frac{2}{3};$$

$$q_{u_L}^2 = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W, \quad q_{u_R}^2 = -\frac{2}{3}\sin^2\theta_W, \quad q_{e_L}^2 = -\frac{1}{2} + \sin^2\theta_W, \quad q_{e_R}^2 = \sin^2\theta_W \quad (4)$$

and we have assumed one D_0/D_0^c pair with degenerate masses, and that the couplings $\lambda_1 = \lambda_1^c \equiv \lambda_{LQ}$.

In Figs. 1a,b we plot contours of $\Delta\sigma/\sigma$ in the (m_D, λ_{LQ}) plane, where $\sigma = \sum_{\text{all } q} \sigma(e^+e^- \rightarrow \bar{q}q)$ including D-exchange, and $\Delta\sigma$ is obtained from (3) by integrating over θ . Since we are interested only in indirect signatures of the D's, we only plot contours for $m_D > \sqrt{s}$. We have chosen two values of $\sqrt{s}$: 200 GeV (LEP 2) shown in Fig. 1a and $\sqrt{s} = 2,000$ GeV (CLIC) shown in Fig. 1b. The indirect effects of D-exchange at LEP 1 are not so interesting because the cross-section is dominated by the Z peak. One must go off-peak to gain sensitivity to D-exchange, whose main contribution comes from the interference terms in (3). From Figs. 1a,b we see that a sensitivity to $\Delta\sigma/\sigma = 0.02$ would lead to the discovery limits for m_D which are shown in Table 1 for different values of λ_{LQ} . We show in Figs. 1c,d the corresponding changes in the forward-backward asymmetry, which seems to be less sensitive to D-exchanges: $\delta A = 0.02$ corresponds to $m_D = 0.3$ TeV (3 TeV) at $\sqrt{s} = 200$ GeV (2 TeV) for $\lambda_{LQ} = 1$.

Next we calculate the contribution of D-exchange to $\sigma(\text{hadron}+\text{hadron} \rightarrow l^+l^-+X)$ due to the parton process $\bar{u}u \rightarrow l^+l^-$ [7], which is the inverse of the previous

process. As before, the main contribution comes from the interferences with γ and Z exchange. 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 value of the invariant mass M_{l+l-} of the $l+l-$ pair which corresponds a minimum observable $d\sigma/dM_{l+l-}^2$ (~ 1 event/year) for the usual Drell-Yan process. These are $M_{l+l-} = 0.175, 0.200, 1.0, 1.2$ TeV respectively. Then, working with the value of M_{l+l-} so chosen, we obtain the contours of $\Delta\sigma/\sigma$ in the (m_D, λ_{LQ}) plane shown in Fig. 3. From these graphs we can obtain (for example) lower bounds on m_D if we assume $\lambda_{LQ} = 1$ and demand that $\Delta\sigma/\sigma \leq 1$. These limits are shown in Table 2 together with the corresponding upper bounds on the λ_{LQ} obtained if one assumes $m_D \leq 1$ TeV. Comparing Tables 1 and 2, we infer that LEP 2 has comparable sensitivity to the highest energy hadron-hadron colliders, whilst the present CERN and FNAL colliders are much less sensitive, and CLIC would be much more sensitive.

The results of this paper indicate that e^+e^- and hadron-hadron colliders have considerable sensitivity to leptoquark particles with masses larger than those accessible to direct production. We have presented cross-section calculations in a superstring-inspired model, although the results have more general validity. Since some superstring-inspired models [4] expect leptoquark masses $m_{D_0/D_0^c} \sim 1$ TeV [5], and future colliders have sensitivities beyond this mass, such indirect searches for leptoquarks are very topical and relevant.

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$\sqrt{s}$	200 GeV	2 TeV
λ_{LQ}	m_{D_0} (TeV)	m_{D_0} (TeV)
0.3	< 0.5	< 6.0
0.5	< 0.9	< 9.0
1.0	< 1.8	< 20

TABLE 1

Sensitivity in e^+e^- collisions

$\sqrt{s}$ [M_{1+1-}]	range of m_{D_0} (TeV) for $\lambda_{LQ} = 1$	range of λ_{LQ} for $m_{D_0} = 1$ TeV
630 GeV (CERN) [175 GeV]	< 0.25	< 3.3
1.8 TeV (FNAL) [200 GeV]	< 0.30	< 2.9
17 TeV (LHC) [1 TeV]	< 1.35	< 0.8
40 TeV (SSC) [2 TeV]	< 1.60	< 0.75

TABLE 2

Sensitivity in hadron-hadron collisions
assuming $\Delta\sigma/\sigma > 1$ at chosen value of M_{1+1-}

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FIGURE CAPTION

Figure 1: Indirect effects of leptoquarks in e^+e^- collisions, expressed as contours in the (m_{D_0}, λ_{LQ}) plane, of (a) $\Delta\sigma/\sigma$ at $\sqrt{s} = 200$ GeV (LEP 2), (b) $\Delta\sigma/\sigma$ at $\sqrt{s} = 2$ TeV (CLIC), (c) ΔA at $\sqrt{s} = 200$ GeV (LEP 2), and (d) ΔA at $\sqrt{s} = 2$ TeV (CLIC).

Figure 2: Indirect effects of leptoquarks in hadron+hadron collisions, expressed as contours in the (m_{D_0}, λ_{LQ}) plane, of $\Delta\sigma/\sigma$ at (a) $\sqrt{s} = 630$ GeV (CERN $\bar{p}p$), (b) $\sqrt{s} = 1.8$ TeV (FNAL $\bar{p}p$), (c) $\sqrt{s} = 17$ TeV (LHC pp), and (d) $\sqrt{s} = 40$ TeV (SSC pp).

Fig. 1a

Fig. 1b

Fig. 1c

Fig. 1d

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d