# LEPTOQUARKS IN LEPTON–QUARK COLLISIONS

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Low-energy experiments permit the existence of leptoquarks with masses of order 100 GeV and couplings to quark–lepton pairs as large as gauge couplings. We study systematically the signatures of all possible scalar and vector leptoquarks in electron (positron)–proton collisions. Clear evidence for leptoquarks would be narrow peaks in the $x$-distributions of inclusive neutral and charged current processes. At HERA one will be able to explore the mass range up to 300 GeV through direct production, and even somewhat beyond the CM energy of 314 GeV through virtual effects. Conversely, leptoquarks with masses of 200 GeV can be discovered for couplings as small as $10^{-3}\,\alpha_{\rm em}$.

In the standard model of strong and electroweak interactions quarks and leptons enter as independent fields. However, as a quantum theory, the standard model is only consistent because of the remarkable cancellation between the quark and lepton contributions to triangle anomalies of gauged currents. This strongly suggests that in a more fundamental theory leptons and quarks should be interrelated. Correspondingly, in extensions of the standard model one expects new particles which mediate quark–lepton transitions. Such leptoquarks (LQ) occur naturally in all unified models such as SU(5) [1] or Pati–Salam SU(4) [2], but also in models of quark–lepton substructure (for reviews and references, see, e.g., ref. [3]).

Leptoquarks which have baryon or lepton number violating couplings must be very heavy in order to avoid rapid proton decay or large Majorana neutrino masses. However, in theories with conserved baryon and lepton number masses and couplings of leptoquarks have to satisfy only much weaker bounds. Especially in the case where one has one or more leptoquarks for each quark–lepton generation, it is possible to have flavour-diagonal couplings as large as gauge couplings for leptoquark masses of order 100 GeV [4].

Such low-mass leptoquarks could be produced at machines which are presently under construction. As leptoquarks couple to quark–lepton pairs, an ep collider such as HERA is an ideal machine to search for them. In this note we give a brief account of our complete calculation and illustrate possible leptoquark signals at HERA. A more detailed analysis will be presented elsewhere [5]. Leptoquarks with flavour-nondiagonal couplings have been discussed in ref. [6].

We start from an effective lagrangian with the most general dimensionless, SU(3)×SU(2)×U(1) invariant couplings of scalar and vector leptoquarks satisfying baryon and lepton number conservation:

$$\mathcal{L}=\mathcal{L}_{F=2}+\mathcal{L}_{F=0}, \tag{1a}$$

$$\begin{aligned}\mathcal{L}_{F=2}=&(g_{1L}\bar{\mathrm{q}}^{\mathrm{c}}_{\mathrm{L}}i\tau_2\ell_{\mathrm{L}}+g_{1R}\bar{\mathrm{u}}^{\mathrm{c}}_{\mathrm{R}}\mathrm{e}_{\mathrm{R}})\mathrm{S}_1\\&+\tilde{g}_{1R}\bar{\mathrm{d}}^{\mathrm{c}}_{\mathrm{R}}\mathrm{e}_{\mathrm{R}}\tilde{\mathrm{S}}_1+g_{3L}\bar{\mathrm{q}}^{\mathrm{c}}_{\mathrm{L}}i\tau_2\boldsymbol{\tau}\ell_{\mathrm{L}}\mathrm{S}_3\\&+(g_{2L}\bar{\mathrm{d}}^{\mathrm{c}}_{\mathrm{R}}\gamma^\mu\ell_{\mathrm{L}}+g_{2R}\bar{\mathrm{q}}^{\mathrm{c}}_{\mathrm{L}}\gamma^\mu\mathrm{e}_{\mathrm{R}})\mathrm{V}_{2\mu}\\&+\tilde{g}_{2L}\bar{\mathrm{u}}^{\mathrm{c}}_{\mathrm{R}}\gamma^\mu\ell_{\mathrm{L}}\tilde{\mathrm{V}}_{2\mu}+\text{c.c.},\end{aligned} \tag{1b}$$

$$\begin{aligned}\mathcal{L}_{F=0}=&(h_{2L}\bar{\mathrm{u}}_{\mathrm{R}}\ell_{\mathrm{L}}+h_{2R}\bar{\mathrm{q}}_{\mathrm{L}}i\tau_2\mathrm{e}_{\mathrm{R}})\mathrm{R}_2+\tilde{h}_{2L}\bar{\mathrm{d}}_{\mathrm{R}}\ell_{\mathrm{L}}\tilde{\mathrm{R}}_2\\&+(h_{1L}\bar{\mathrm{q}}_{\mathrm{L}}\gamma^\mu\ell_{\mathrm{L}}+h_{1R}\bar{\mathrm{d}}_{\mathrm{R}}\gamma^\mu\mathrm{e}_{\mathrm{R}})\mathrm{U}_{1\mu}\\&+\tilde{h}_{1R}\bar{\mathrm{u}}_{\mathrm{R}}\gamma^\mu\mathrm{e}_{\mathrm{R}}\tilde{\mathrm{U}}_{1\mu}+h_{3L}\bar{\mathrm{q}}_{\mathrm{L}}\boldsymbol{\tau}\gamma^\mu\ell_{\mathrm{L}}\mathrm{U}_{3\mu}+\text{c.c.}\end{aligned} \tag{1c}$$

Table 1
Quantum numbers of scalar and vector leptoquarks with $SU(3)\times SU(2)\times U(1)$ invariant couplings to quark–lepton pairs ($Y=Q_{em}-T_3$).

| | Spin | $F=3B+L$ | $SU(3)_c$ | $SU(2)_W$ | $U(1)_Y$ |
|---|---|---|---|---|---|
| $S_1$ | 0 | −2 | 3* | 1 | $\frac{1}{3}$ |
| $\tilde{S}_1$ | 0 | −2 | 3* | 1 | $\frac{4}{3}$ |
| $S_3$ | 0 | −2 | 3* | 3 | $\frac{1}{3}$ |
| $V_2$ | 1 | −2 | 3* | 2 | $\frac{5}{6}$ |
| $\tilde{V}_2$ | 1 | −2 | 3* | 2 | $-\frac{1}{6}$ |
| $R_2$ | 0 | 0 | 3 | 2 | $\frac{7}{6}$ |
| $\tilde{R}_2$ | 0 | 0 | 3 | 2 | $\frac{1}{6}$ |
| $U_1$ | 1 | 0 | 3 | 1 | $\frac{2}{3}$ |
| $\tilde{U}_1$ | 1 | 0 | 3 | 1 | $\frac{5}{3}$ |
| $U_3$ | 1 | 0 | 3 | 3 | $\frac{2}{3}$ |

Here $q_L$, $\ell_L$ are the left-handed quark and lepton doublets, and $e_R$, $d_R$, $u_R$ are the right-handed charged leptons, down- and up-quarks, respectively; $\psi^c = C\bar{\psi}^T$ is a charge-conjugated fermion field. The subscripts L, R of the coupling constants denote the lepton chirality. The indices of the LQ's give the dimension of their SU(2) representation. Colour, weak isospin and generation (flavour) indices have been suppressed. The leptoquarks S (i.e. $S_1$, $\tilde{S}_1$, $S_3$) and V (i.e. $V_2$, $\tilde{V}_2$) carry fermion number $F=3B+L=-2$, the leptoquarks R (i.e. $R_2$, $\tilde{R}_2$) and U (i.e. $U_1$, $\tilde{U}_1$, $U_3$) have $F=0$. The quantum numbers of the various leptoquarks are summarized in table 1.

Couplings and masses of the leptoquarks introduced in the effective lagrangian eq. (1) are constrained by low-energy experiments. For flavour violating couplings one finds typically [7,4]

$$g, h < m_{LQ}/100\ \text{TeV}. \quad (2)$$

As to the flavour conserving processes, the limits depend strongly on the particular LQ-species. The strongest bounds are obtained for the couplings of the first generation to the scalars $S_1$ and $R_2$, which can mediate helicity unsuppressed leptonic two-body decays of pions. From the limit $BR(\pi^+\to e^+\nu_e) < 1.2\times 10^{-4}$ one finds [4]

$$(g_{1L}g_{1R})^{1/2},\ (h_{2L}h_{2R})^{1/2} < m_{LQ}/10\ \text{TeV}. \quad (3)$$

This bound implies that leptoquarks with masses of order 100 GeV can have sizeable couplings only to either left- or right-handed leptons. This requirement is naturally fulfilled in a class of supersymmetric theories where one has two leptoquarks $G_c$ and G of type $S_1$ with respective couplings $g_{1L}(G_c)\neq 0$, $g_{1R}(G_c)=0$ and $g_{1L}(G^*)=0$, $g_{1R}(G^*)\neq 0$ and, possibly, a very small $G_cG^*$ mixing (see, for example, ref. [4]).

Further constraints on the couplings $\lambda_L$ ($=g_L$, $h_L$) of left-handed leptons follow from quark–lepton universality, i.e. from a comparison of the Fermi constants in μ- and β-decay. One finds [4]

$$\lambda_L < m_{LQ}/1.7\ \text{TeV}, \quad (4)$$

which corresponds to $\lambda_L < 0.1$ for $m_{LQ}=200$ GeV. This bound assumes that leptoquark exchange is the only deviation from the standard model, and that therefore only $G_F^{(\beta)}$ is modified. There could be, however, also a modification of $G_F^{(\mu)}$, for instance through the exchange of additional Higgs scalars, in which case the bound eq. (4) would be weakened.

A more complete discussion of bounds on the couplings $g_{L,R}$ and $h_{L,R}$ will be given in ref. [5]. For estimates of possible leptoquark production cross sections at HERA we will consider the two sets of coupling constants

$$\lambda_L = 0.3, \qquad \lambda_R = 0; \quad (5a)$$

$$\lambda_L = 0.1, \qquad \lambda_R = 0. \quad (5b)$$

The results are qualitatively the same if one interchanges the couplings $\lambda_L$ and $\lambda_R$.

From the effective lagrangian eq. (1) one can easily calculate the various partial LQ decay widths. For the scalar ($J=0$) and vector ($J=1$) leptoquarks one obtains

$$\Gamma_{J=0} = (16\pi)^{-1}\lambda_{L,R}^2 m_{LQ}, \quad (6a)$$

$$\Gamma_{J=1} = (24\pi)^{-1}\lambda_{L,R}^2 m_{LQ}, \quad (6b)$$

where $\lambda_{L,R}$ denote the LQ couplings to a particular final state as given in table 2. The total widths are then obtained by summing over all possible final states. For instance, for the scalar $S_1$ one has

$$\Gamma_{S_1} = (16\pi)^{-1}(2g_{1L}^2 + g_{1R}^2)m_{S_1}, \quad (7a)$$

which yields

Table2
Couplings of scalar and vector leptoquarks to quark–lepton pairs. The subscripts L,R of the couplings refer to the lepton chirality.

| Channel | $F=-2$, scalars | | | $F=-2$, vectors | |
|---|---|---|---|---|---|
| | $S_1$ | $\tilde{S}_1$ | $S_3$ | $V_2$ | $\tilde{V}_2$ |
| $e^-_{L,R}u$ | $g_{1L,R}$ | – | $-g_{3L}$ | $g_{2R}$ | $\tilde{g}_{2L}$ |
| $\nu_L d$ | $-g_{1L}$ | – | $-g_{3L}$ | $g_{2L}$ | – |
| $e^-_{L,R}d$ | – | $\tilde{g}_{1R}$ | $-\sqrt{2}\,g_{3L}$ | $g_{2L,R}$ | – |
| $\nu_L u$ | – | – | $\sqrt{2}g_{3L}$ | – | $\tilde{g}_{2L}$ |
| Channel | $F=0$, vectors | | | $F=0$, scalars | |
| | $U_1$ | $\tilde{U}_1$ | $U_3$ | $R_2$ | $\tilde{R}_2$ |
| $e^-_{L,R}\bar{d}$ | $h_{1L,R}$ | – | $-h_{3L}$ | $-h_{2R}$ | $\tilde{h}_{2L}$ |
| $\nu_L\bar{u}$ | $h_{1L}$ | – | $h_{3L}$ | $h_{2L}$ | – |
| $e^-_{L,R}\bar{u}$ | – | $\tilde{h}_{1R}$ | $\sqrt{2}h_{3L}$ | $h_{2L,R}$ | – |
| $\nu_L\bar{d}$ | – | – | $\sqrt{2}h_{3L}$ | – | $\tilde{h}_{2L}$ |

$$\Gamma_{S_1} \simeq 0.7\ \mathrm{GeV}\,\frac{2g_{1L}^2+g_{1R}^2}{0.18}\,\frac{m_{S_1}}{200\mathrm{GeV}}, \qquad (7b)$$

where eq. (5a) has been used. Because of the few possible final states and the smallness of the couplings $g$ and $h$, leptoquarks accessible in ep collisions in the TeV range will be very narrow!

The production cross sections for leptoquarks are also easily calculated. Whereas S and V are mainly produced in $e^-p$ collisions, R and U are primarily created in the $e^+p$ channel as indicated in fig. 1. The cross sections for the production of scalar ($J=0$) and vector ($J=1$) leptoquarks $e^{(}\bar{q}^{)}$-fusion read, in the narrow-width approximation,

$$\sigma(\mathrm{ep}\to\mathrm{LQ}) = \frac{\pi}{4s}\lambda_{L,R}^2\,{}^{(}\bar{q}^{)}\left(\frac{m_{LQ}^2}{s}\right)\times 1, \quad J=0,$$
$$\times 2, \quad J=1, \qquad (8)$$

where $\lambda_{L,R}$ can be read off from table 2, and ${}^{(}\bar{q}^{)}(x)$ is the probability of finding a quark (antiquark) with momentum fraction $x$ inside a proton. $\sqrt{s}$ is the total ep CM energy, at HERA $\sqrt{s}=314$ GeV. Fig. 2 shows the production cross sections for leptoquarks of type $S_1$ as a function of the mass $m_{S_1}$ for the two choices of coupling constants (5a) and (5b). We have used set (I) of the structure functions of Duke and Owens [8]. Our results agree with those previously obtained by Wudka [9]. The main message of fig. 2 is that the present bounds allow copious production of leptoquarks at HERA. For $g_{1L}=0.3$, $g_{1R}=0$ and $m_{S_1}=200$ GeV one expects 20000 events per 100 $\mathrm{pb}^{-1}$! Conversely, leptoquarks with $m_{S_1}\simeq 200$ GeV can still be discovered even if their coupling is 30 times smaller, that is, for $g_{1L}\simeq 0.01$!

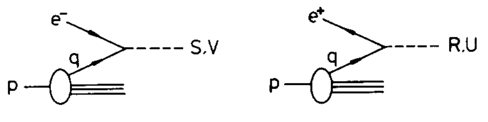


Fig. 1. Leptoquark resonance production in $e^{\mp}p$ collisions.

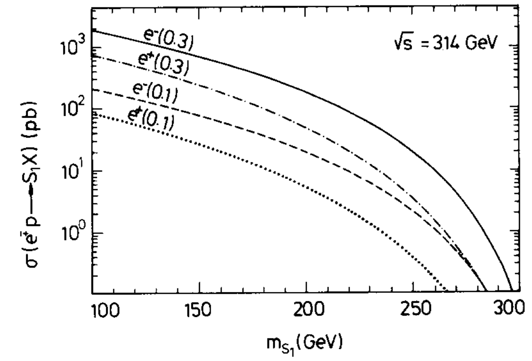


Fig. 2. Production cross sections of the $S_1$ leptoquark at HERA. Shown are $e^-u$ fusion yields for $g_{1L}=0.3$, $g_{1R}=0$ (full curve) and $g_{1L}=0.1$, $g_{1R}=0$ (dashed curve) and $e^+\bar{u}$ fusion yields for $g_{1L}=0.3$, $g_{1R}=0$ (dashed-dotted curve) and $g_{1L}=0.1$, $g_{1R}=0$ (dotted curve).

The simplest processes to search for leptoquarks are the inclusive reactions $e^{\mp}p\to e^{\mp}X$ and $e^{\mp}p\to {}^{(}\bar{\nu}^{)}{}_{e}X$. In general, the leptoquark amplitudes can interfere with the standard model amplitudes due to photon, Z-boson and W-boson exchange. The relevant subprocesses are

$$e^-q\to e^-q, \tag{9a}$$

$$e^-q\to \nu_e q', \tag{9b}$$

$$e^+q\to e^+q, \tag{10a}$$

$$e^+q\to \bar{\nu}_e q', \tag{10b}$$

and the charge-conjugate ones. It is convenient to use the Mandelstam variables

$$\hat{s}=(p_e+p_q)^2=xs, \qquad t=(p_e'-p_e)^2=-Q^2,$$

$$u=(p_q'-p_e)^2=-\hat{s}+Q^2, \tag{11}$$

where $p_e$ ($p_e'$) and $p_q$ ($p_q'$) are the initial (final) lepton and quark momenta. From table 1 we see that S and V contribute to the processes (9) in the $s$-channel and to the processes (10) in the $u$-channel, whereas R and U enter in the opposite way.

The total squared amplitude for the process $e^-_{L,R}q\to e^-_{L,R}q$ ($e^+_{R,L}\bar{q}\to e^+_{R,L}\bar{q}$), averaged over the quark spin, takes the form

$$|A|^2_{L,R}=|A_\gamma+A_Z|^2_{L,R}+2\,\mathrm{Re}[(A_\gamma+A_Z)A^*_{LQ}]_{L,R}$$
$$+|A_{LQ}|^2_{L,R}, \tag{12}$$

where $A_\gamma$, $A_Z$ and $A_{LQ}$ denote the photon, Z-boson and leptoquark amplitudes, respectively, depicted in fig. 3a. The standard model contribution is given by

$$|A_\gamma+A_Z|^2_{L,R}=\frac{2e^4Q_e^2Q_q^2}{t^2}(\hat{s}^2+u^2)$$
$$+\frac{4Q_eQ_qe^2g^2}{t(t-m_Z^2)}(v_e\pm a_e)\,[v_q(\hat{s}^2+u^2)\pm a_q(\hat{s}^2-u^2)]$$
$$+\frac{2g^4}{(t-m_Z^2)^2}(v_e\pm a_e)^2$$
$$\times[(v_q^2+a_q^2)(\hat{s}^2+u^2)\pm 2v_qa_q(\hat{s}^2-u^2)]. \tag{13}$$

Here, $e$ and $g=e/(\sin\theta_w\cos\theta_w)$ are the gauge couplings of photon and Z-boson, $Q_e$ and $Q_q$ are the

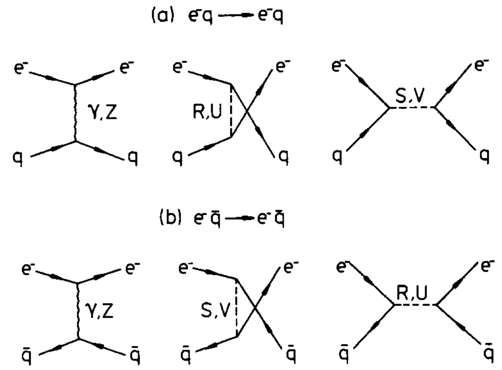


Fig. 3. Diagrams contributing to the inclusive neutral current process $e^-p\to e^-X$.

electric charges of the electron and quark, and $v_{e,q}$ and $a_{e,q}$ denote the usual vector and axial-vector couplings with the convention $a_e=-\frac{1}{4}$. The upper (lower) signs in eq. (13) correspond to left-handed (right-handed) electrons in the process $e^-_{L,R}q\to e^-_{L,R}q$ and right-handed (left-handed) positrons in the reaction $e^+_{R,L}\bar{q}\to e^+_{R,L}\bar{q}$. For the interference terms of $A_{LQ}$ and $A_\gamma+A_Z$ we find

$$2\mathrm{Re}[(A_\gamma+A_Z)A^*_{LQ}]_{L,R}=-2a(LQ)_{L,R}$$
$$\times\frac{e^2Q_eQ_q}{t}+\frac{g^2(v_e\pm a_e)(v_q\pm a_q)}{t-m_Z^2}, \quad LQ=S,U,$$
$$\times\frac{e^2Q_eQ_q}{t}+\frac{g^2(v_e\pm a_e)(v_q\mp a_q)}{t-m_Z^2}, \quad LQ=V,R, \tag{14a}$$

with

$$a(S)_{L,R}=\lambda^2_{L,R}\hat{s}(\hat{s}-m_S^2/[(\hat{s}-m_S^2)^2+m_S^2\Gamma_S^2], \tag{14b}$$

$$a(V)_{L,R}=2\lambda^2_{L,R}u^2(\hat{s}-m_V^2)/[(\hat{s}-m_V^2)^2+m_V^2\Gamma_V^2], \tag{14c}$$

$$a(R)_{L,R}=\lambda^2_{L,R}u^2/(u-m_R^2), \tag{14d}$$

$$a(U)_{L,R}=2\lambda^2_{L,R}\hat{s}^2/(u-m_U^2). \tag{14e}$$

Here, $\lambda_{L,R}$ are again the LQ couplings to the particular electron–quark pairs as given in table 2. The convention with respect to the upper (lower) signs in eq. (14a) is the same as in eq. (13). For the quadratic leptoquark terms in eq. (12) we obtain

$$|A_S|^2_{L,R} = \frac{1}{2} \frac{\lambda^2_{L,R}}{(\hat{s}-m_S^2)^2 + m_S^2\Gamma_S^2} (\lambda_L^2 + \lambda_R^2)\hat{s}^2, \quad (15a)$$

$$|A_V|^2_{L,R} = 2 \frac{\lambda^2_{L,R}}{(\hat{s}-m_V^2)^2 + m_V^2\Gamma_V^2} (\lambda^2_{L,R}u^2 + \lambda^2_{R,L}t^2), \quad (15b)$$

$$|A_R|^2_{L,R} = \frac{1}{2} \frac{\lambda^2_{L,R}}{(u-m_R^2)^2} (\lambda_L^2 + \lambda_R^2)u^2, \quad (15c)$$

$$|A_U|^2_{L,R} = 2 \frac{\lambda^2_{L,R}}{(u-m_U^2)^2} (\lambda^2_{L,R}\hat{s}^2 + \lambda^2_{R,L}t^2). \quad (15d)$$

We note the interchange of $u$ and $t$ in eq. (15b), and $\hat{s}$ and $t$ in eq. (15d) under the change of polarization.

A similar set of formulas follows for the process $e^-_{L,R}\bar{q} \to e^-_{L,R}\bar{q}$ ($e^+_{R,L}q \to e^+_{R,L}q$) from the diagrams of fig. 3b. In this case the standard model contribution reads

$$|A_\gamma + A_Z|^2_{L,R} = \frac{2e^4 Q_e^2 Q_q^2}{t^2} (\hat{s}^2 + u^2) + \frac{4e^2 g^2 Q_e Q_q}{t(t-m_Z^2)} (v_e \pm a_e) \times [v_q(\hat{s}^2+u^2) \mp a_q(\hat{s}^2 - u^2)] + \frac{2g^4}{(t-m_Z^2)^2} (v_e \pm a_e)^2 \times [(v_q^2 + a_q^2)(\hat{s}^2+u^2) \mp 2v_q a_q (\hat{s}^2 - u^2)], \quad (16)$$

while the interference terms between $A_{LQ}$ and $A_\gamma + A_Z$ are given by

$$2\mathrm{Re}[(A_\gamma + A_Z)A^*_{LQ}]_{L,R} = -2\bar{a}(LQ)_{L,R}$$

$$\times \frac{e^2 Q_e Q_q}{t} + \frac{g^2(v_e \pm a_e)(v_q \pm a_q)}{t-m_Z^2}, \quad LQ = S, U,$$

$$\times \frac{e^2 Q_e Q_q}{t} + \frac{g^2(v_e \pm a_e)(v_q \mp a_q)}{t-m_Z^2}, \quad LQ = V, R, \quad (17a)$$

with

$$\bar{a}(S)_{L,R} = (\lambda^2_{L,R}u^2/(u-m_S^2), \quad (17b)$$

$$\bar{a}(V)_{L,R} = 2\lambda^2_{L,R}\hat{s}^2/(u-m_V^2), \quad (17c)$$

$$\bar{a}(R)_{L,R} = \lambda^2_{L,R}\hat{s}^2(\hat{s}-m_R^2)/[(\hat{s}-m_R^2)^2 + m_R^2\Gamma_R^2], \quad (17d)$$

$$\bar{a}(U)_{L,R} = 2\lambda^2_{L,R}u^2(\hat{s}-m_U^2)/[(\hat{s}-m_U^2)^2 + m_U^2\Gamma_U^2]. \quad (17e)$$

The quadratic leptoquark terms read

$$|A_S|^2_{L,R} = \frac{1}{2} \frac{\lambda^2_{L,R}}{(u-m_S^2)^2} (\lambda_L^2 + \lambda_R^2)u^2, \quad (18a)$$

$$|A_V|^2_{L,R} = 2 \frac{\lambda^2_{L,R}}{(u-m_V^2)^2} (\lambda^2_{L,R}\hat{s}^2 + \lambda^2_{R,L}t^2), \quad (18b)$$

$$|A_R|^2_{L,R} = \frac{1}{2} \frac{\lambda^2_{L,R}}{(\hat{s}-m_R^2)^2 + m_R^2\Gamma_R^2} (\lambda_L^2 + \lambda_R^2)\hat{s}^2, \quad (18c)$$

$$|A_U|^2_{L,R} = 2 \frac{\lambda^2_{L,R}}{(\hat{s}-m_U^2)^2 + m_U^2\Gamma_U^2} (\lambda^2_{L,R}u^2 + \lambda^2_{R,L}t^2). \quad (18d)$$

Compared to eqs. (14) and (15) $s$- and $u$-channel contributions have been interchanged in eqs. (17) and (18).

Similar formulas hold for the processes $e^-q \to \nu_e q'$ and $e^+q \to \bar{\nu}_e q'$ and their charge conjugates. The expressions follow from simple substitutions in the above formulas, to wit

$$g \to \frac{e}{\sqrt{2}\sin\theta_w}, \quad Q_{e,q} \to 0,$$

$$v_{e,q}, a_{e,q} \to \tfrac{1}{2}, \quad m_Z \to m_W, \quad (19)$$

with the relevant couplings $\lambda_{L,R}$ taken from table 2. The results will explicitly be given in ref. [5].

The differential cross sections for the inclusive processes $e^\mp_{L,R}p \to e^\mp X$ pr $^{(}\bar{\nu}^{)}{}_e X$ can now be computed in standard fashion. In terms of the total squared amplitudes defined in eq. (12) one has

$$\frac{d\sigma(e^{\mp}_{L,R}p)}{dx\,dQ^2} = \frac{1}{16\pi x^2 s^2} \times \sum_q \{q(x,Q^2)\,|A(e^{\mp}_{L,R}q)|^2 + \bar{q}(x,Q^2)\,|A(e^{\mp}_{L,R}\bar{q})|^2\}, \qquad (20)$$

with the contributions from γ, Z and the various LQ's to $|A(e^-_{L,R}q)|^2 = |A(e^+_{R,L}\bar{q})|^2$ and $|(A(e^-_{L,R}\bar{q})|^2 = |A(e^+_{R,L}q)|^2$ as specified in eqs. (13)–(15) and eqs. (16)–(18), respectively. The individual scattering channels to which a given LQ contributes can readily be inferred from fig. 3 and table 2. For example, as already indicated, the scalar $S_1$ enters in $e^-u \to e^-u$ (and $e^+\bar{u} \to e^+\bar{u}$) in the $s$-channel, and in $e^-\bar{u} \to e^-\bar{u}$ (and $e^+u \to e^+u$) in the $u$-channel.

Qualitatively, one anticipates the following signals from leptoquarks. If $m_{LQ} < \sqrt{s}$, leptoquarks may be copiously produced via $e^{\mp}$-$^{(}\bar{q}^{)}$ fusion as quantified in fig. 2. The real production gives rise to resonance peaks in the $x$-distributions, eq. (20), of neutral (and charged) current events centered at $x = m^2_{LQ}/s$. Since the Breit–Wigner resonance cross sections obtained from eqs. (15a),(15b) and eqs. (18c),(18d) are independent of $Q^2 = -t$, apart from scaling violations through the quark densities, these peaks in $x$ should eventually become detectable by requiring sufficiently large $Q^2$ and, thereby, suppressing the standard model background. This is illustrated in fig. 4 for the case of an $S_1$ leptoquark with $m_{S_1} = 200$ GeV and the couplings of eq. (5a). While the enormous resonance in $e^-p \to e^-X$ should clearly reveal the existence of such a leptoquark, the corresponding signal in $e^+p \to e^+X$ is much smaller due to the softness of the ū-density as compared to the u-density in the proton. Of course, in a real experiment the very narrow peaks [see eq. (7)] would be smeared out by the finite resolution in $x$. In fact, in the example shown in fig. 4 practically the whole LQ signal would be contained in one $x$-bin with $\Delta x = 0.1$ around $x = 0.4$. If $m_{LQ} > \sqrt{s}$, one must search for effects arising from the exchange of virtual leptoquarks, a possibility which we will discuss in ref. [5].

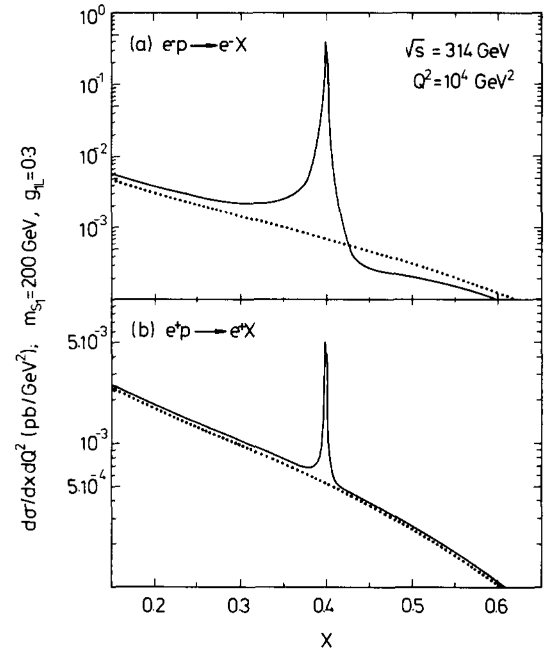


Fig. 4. Differential cross sections of unpolarized $e^-p$ (a) and $e^+p$ (b) scattering versus $x$ at $\sqrt{s} = 314$ GeV and fixed $Q^2 = 10^4$ GeV$^2$. The full curves represent the theoretical distributions if a $S_1$ leptoquark exists with $m_{S_1} = 200$ GeV and $g_{1L} = 0.3$, $g_{1R} = 0$, while the dashed curves show the standard model predictions for $m_Z = 92$ GeV and $\sin^2\theta_w = 0.229$.

In summary, the existence of leptoquarks with baryon and lepton number conserving flavour-diagonal couplings is only relatively weakly constrained by present experimental knowledge. We have given the most general SU(3)×SU(2)×U(1) invariant lagrangian describing the interactions of such leptoquarks, both scalars and vectors, with known leptons and quarks. Using this lagrangian we have computed the full differential cross sections in $x$ and $Q^2$ of $e^{\mp}p$ collisions and pointed out possible signals from leptoquarks: resonance peaks at fixed $x$ in the standard model distributions resulting from γ and Z, or W, exchange and virtual effects on cross sections and asymmetries. For coupling strengths of the order of the standard gauge couplings one can produce and detect leptoquarks at HERA almost up to the phase-space boundary, that is for masses $M_{LQ} < 300$ GeV. Heavier leptoquarks induce observable effects for masses which exceed the total ep CM energy only moderately unless the couplings are considerably stronger than gauge couplings, a possibility not excluded by experiment but theoretically rather unlikely. More interestingly, leptoquarks with $m_{LQ} \simeq 200$ GeV can be discovered for very small couplings, $g^2_{1L}/4\pi \simeq 10^{-3}\,\alpha_{em}$!

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