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On the Expectations for Leptoquarks in the Mass Range of $O(200\ \mathrm{GeV})$

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Abstract

A summary is given on the experimental bounds for the couplings and masses of scalar and vector leptoquarks associated to the first fermion generation. We investigate to which extent an interpretation of the recently reported excess of events in the large x and Q^2 range at HERA in terms of single leptoquark production is compatible with other experimental results.

1 Introduction

One of the remarkable properties of the $SU(3)_c \times SU(2)_L \times U(1)_Y$ Standard Model is the cancellation of the triangle anomalies, which is implied by the relation

$$\sum_n Q^2_{em,n} \left(Q_L - Q_R\right)_n = 0 \tag{1}$$

between the electromagnetic and the left and righthanded weak charges of the leptons and quarks for each fermion family. This relation is of fundamental importance, because it renders the Standard Model renormalizable. Although not being enforced by every possible scenario, it might be a dynamical consequence of an as yet unknow underlying theory.

In many extensions of the Standard Model new bosons, the leptoquarks $\Phi_{S,V}$, which carry both lepton and baryon number, are predicted. This applies both to Grand Unified Theories [1] as well as models based on compositeness [2] or technicolor [3]. Whereas in Grand Unified Theories leptoquarks emerge as gauge bosons with masses in the range of $O(M_{\rm GUT} \sim 10^{15}\,{\rm GeV})$ and couplings which do not conserve baryon (B) and lepton (L) number, other approaches contain also leptoquarks with B- and L-conserving couplings. These particles may have masses in the range which is accessible at the present high energy colliders.

Recently, the H1 experiment [4] at HERA observed 12 events in the range of large Bjorken x for $Q^2 > 15000\ \ {\rm GeV}^2$ expecting 4.7 events. The seven excess events of H1 cluster around $\sqrt{xs} \sim 200\,{\rm GeV}$. The ZEUS experiment [5] found 4 events for $x > 0.55$ and $y > 0.25$, where 0.9 events are expected. Still the statistics is low and further measurements are needed before firm conclusions can be drawn. If the observed excess is confirmed at larger statistics, one of the possible explanations could be single leptoquark production at a mass $M \sim \sqrt{xs}$, cf. [4].

In this note we summarize the current experimental limits on the couplings and masses for scalar and vector leptoquarks and investigate to which extent this interpretation is compatible with experimental results obtained at other high energy colliders.

2 Excluded mass ranges

Direct searches for leptoquarks were performed in e^+e^- annihilation- [6], $p\overline{p}$- [7, 8, 9], and ep scattering experiments [10]. The currently most stringent mass limits, which are independent of the fermionic couplings, were derived by the TEVATRON experiments (see [8, 9, 11]) searching for leptoquark pair production [12, 13, 14, 15]. The following mass ranges are excluded :

$$\begin{array}{lllll} M & < & 143 & \mathrm{GeV} & \text{1st generation scalar leptoquarks} \\ M & < & 141 & \mathrm{GeV} & \text{2nd generation scalar leptoquarks} \\ M & < & 99 & \mathrm{GeV} & \text{3rd generation scalar leptoquarks} \\ M & < & 170 & \mathrm{GeV} & \text{3rd generation vector leptoquarks.} \end{array} \tag{2}$$

In deriving the above bounds it was assumed that the branching fractions into the charged lepton-quark and neutrino-quark final states are equal as a working hypothesis. Rigorous theoretical predictions on the branching fractions do not exist. For leptoquarks with a purely righthanded fermion coupling, however, the decay $\Phi \rightarrow q\nu$ is not possible on tree level, leading to $Br(\Phi \rightarrow eq) \sim 1$. The H1 experiment [4] observed a high mass excess for $e + jet$ and $\nu + jet$ final states. If both effects are interpreted in terms of a leptoquark signal the branching fraction is $Br(\Phi \rightarrow eq) < 1$.

A preliminary result was reported by the D0 collaboration from the analysis of Run Ib [16] yielding

$$M < 175(147)\,\mathrm{GeV} \quad \text{1st generation scalar leptoquarks, } Br(S \rightarrow eq) = 1(0.5)\ . \tag{3}$$

The above bound on 3rd generation vector leptoquarks was derived assuming the minimal vector coupling to the gluon, $\kappa_G = 1$, see section 4. For the case that the coupling of the vector leptoquark pair to the gluon is of the Yang–Mills type, $\kappa_G = 0$, the mass range $M < 225\,\mathrm{GeV}$ is excluded. Note that the bound of $M < 170\,\mathrm{GeV}$ becomes weaker considering besides the anomalous coupling κ_G a second anomalous coupling λ_G, as shown in ref. [15]. Mass limits from the TEVATRON data for vector leptoquarks associated to the first and second fermion generation were not presented yet.

3 Bounds from low energy reactions

Bounds on the leptoquark-fermion couplings from low energy reactions such as meson decays, meson-antimeson mixing, lepton decays and others were studied in refs. [17]–[19] in detail. Here the classification of leptoquarks as introduced in ref. [20] [1] was widely used.[2]

For the leptoquarks associated to the first family the bounds are [18]

$$\frac{\lambda}{e} < 0.20 \times \left(\frac{M}{200\ \mathrm{GeV}}\right) \quad \text{for the vector states } V_1, V_{1/2}, \tag{4}$$

$$\frac{\lambda}{e} < 0.40 \times \left(\frac{M}{200\ \mathrm{GeV}}\right) \quad \text{for the scalars } S_0, \tilde{S}_0, \tilde{S}_{1/2}. \tag{5}$$

The upper bound on the coupling for the other leptoquarks lies between these values. Here λ denotes either the lefthanded (λ_L) or the righthanded (λ_R) fermion coupling, and e is the electric charge. In some cases even either $\lambda_L \gg \lambda_R$ or $\lambda_R \gg \lambda_L$ has to be obeyed for $M \sim 200\,\mathrm{GeV}$, cf. [17]. Similar results were obtained in refs. [19] with a lowest bound of

$$\frac{\lambda}{e} < 0.17 \times \left(\frac{M}{200\ \mathrm{GeV}}\right)\ . \tag{6}$$

Although these bounds are partly affected by low energy hadronic matrix elements, the above numbers set a scale.

4 Single leptoquark production in ep scattering at HERA

The cross section for single leptoquark production in ep scattering $\sigma(e + q(\overline{q}) \rightarrow \Phi_{S,V})$ was calculated in refs. [22, 20, 23]. Because the leptoquark widths

$$\begin{aligned} \Gamma_S &= \frac{\lambda_S^2}{16\pi} M_S \\ \Gamma_V &= \frac{\lambda_V^2}{24\pi} M_V \end{aligned} \tag{7}$$

[1] Scalar and vector leptoquarks are denoted by S_I and V_I, respectively, where I is the weak isospin.

[2] The couplings of leptoquarks emerging in supersymmetric models with R-parity violation, cf. refs. [21], to fermion fields are described by a similar Lagrangian, containing only a few terms.

are small compared to the masses $M_{S,V}$ one may work in the narrow width approximation. The integrated leptoquark production cross section for $e^{\pm}q(\overline{q})$ scattering reads [20]

$$\sigma(eq)_{\Phi} = \frac{\pi^2}{s}\ \alpha\ \left(\frac{\lambda}{e}\right)^2 q(x = M^2/s, \langle Q^2\rangle)J(\Phi)b(\Phi)\ . \tag{8}$$

Here $\alpha = 1/128.9$ denotes the fine structure constant, $q(M^2/s)$ the quark (antiquark) density, and $b(\Phi) = Br(\Phi \rightarrow eq)$ is the branching ratio in the production channel. $J(\Phi)$ accounts for the leptoquark spin with $J(S) = 1$ and $J(V) = 2$. For $\sqrt{s} = 300.3\,\mathrm{GeV}$ the production cross sections are estimated to be

$$\sigma(eq)_{S,V} = 338\ pb\ b(\Phi)\left(\frac{\lambda}{e}\right)^2 \left\{ \begin{array}{ll} V: & \times 2 \\ S: & \times 1 \end{array} \right. \left\{ \begin{array}{ll} u: & \times 0.56...0.25 \\ \overline{u}: & \times 0.005...0.001 \\ d: & \times 0.15...0.05 \\ \overline{d}: & \times 0.014...0.003 \end{array} \right. \tag{9}$$

using the parton densities [24] for $\langle Q^2\rangle = 20000\,\mathrm{GeV}^2$ and $x = 0.4...0.5$. The integrated luminosities of the H1 and ZEUS experiment are 14 pb^{-1} and 20 pb^{-1}, respectively. If the 7 excess events of the H1 experiment [4] are interpreted in terms of a leptoquark signal, the respective fermionic couplings are found to be

$$\mathrm{H1}\ :\ (\lambda_S/e)\sqrt{b}\ : 0.06...0.09(u)\ \ 0.61...1.36(\overline{u})\ \ 0.11...0.19(d)\ \ 0.36...0.79(\overline{d}) \tag{10}$$

for leptoquark states produced in $e^+u(\overline{u})$ or $e^+d(\overline{d})$ fusion, respectively. Here, eq. (9) was used for an estimate, accounting for an acceptance of $\varepsilon = 0.8$ [4]. The values for the fermionic couplings λ_V for vector leptoquarks are given by $\lambda_V = \lambda_S/\sqrt{2}$ from the above numbers. The corresponding numbers obtained for the 3 excess events of the ZEUS experiment, at an acceptance of $\varepsilon = 0.8$ [5], are

$$\lambda_{\mathrm{ZEUS}} = 0.55\ \ \lambda_{\mathrm{H1}}. \tag{11}$$

The leptoquark couplings are found to lie in the allowed range $\lambda_S/e < 0.4$ and $\lambda_V/e < 0.2$, respectively, for the up and down quarks, while for the antiquarks they are larger and widely excluded by the bounds given in eqs. (4,5).

Since for scalar leptoquarks the y-distribution is flat, while for vector leptoquarks it behaves $\propto\ (1-y)^2$, cf. ref. [20], this distribution can in principle be used to get an information on the spin of the produced state. Although at the current statistics one cannot get a decisive answer, it is instructive to look on the y averages. As an example, one obtains for the 7 events of H1 $\langle y\rangle = 0.59 \pm 0.02$ in the range $0.4 < y < 0.9$. The average y-values for a scalar or vector leptoquark in this range are $\langle y\rangle_S = 0.65$ and $\langle y\rangle_V = 0.55$, respectively, while for the standard deep inelastic e^+p cross section $\langle y\rangle_{\mathrm{DIS}} = 0.54$ is obtained for comparison. This shows, how difficult a distinction between the different hypotheses might be, since the average value for the case of vector leptoquarks is nearly the same as for the deep inelastic sample in this range of y. At a larger statistics a χ^2-analysis may yield a definite answer.

Aside of the fusion process $e^{\pm}q(\overline{q}) \rightarrow \Phi_{S,V}$, leptoquarks should also be produced via the processes $e^{\pm}q(\overline{q}) \rightarrow g\Phi_{S,V}$ and $e^{\pm}g \rightarrow q(\overline{q})\Phi_{S,V}$. Since the gluon density is rapidly falling in the range of larger values of x, the latter reaction yields only a small contribution to the cross section for large leptoquark masses. Both processes contain a collinear singularity in the limit $p_{\perp}(\Phi_{S,V}) \rightarrow 0$, which has to be regulated for the inclusive cross section. For the differential distributions a lower cut on $p_{\perp}$ is applied. A part of these events would show an apparent two-jet signature, with one jet at a mass of $M_{S,V}$. Since the leptoquark and the final state parton are balanced in $p_\perp$, the electron is more difficult to isolate from the hadronic fragments of the leptoquark both kinematically, and possibly also due to π^0 mesons contained in the jet. For scalar leptoquark production both processes were studied in ref. [23] referring to the parton parametrization of ref. [25]. For $M_S = 200\,\mathrm{GeV}$ and $p_\perp(\Phi_S) > 5\,\mathrm{GeV}$ the integrated cross section for $eu \to g\Phi_S$ amounts to $200 \times \lambda_S^2\ pb$, i.e. $1.4/Br(\Phi \to eu)$ events, for $\mathcal{L} = 14\ pb^{-1}$ and $\lambda_S/e = 0.075$.

5 Single and Pair Production of Leptoquarks at TEVATRON

The single–production of leptoquarks at proton colliders[3] proceeds either through the reaction $q + g \to \Phi + e$ [27] or through charged lepton–quark (antiquark) fusion [28]. For the latter process the electron in the initial state is provided by e^+e^- pair production of a photon which is collinearly radiated off a quark of the second proton (antiproton).

The cross sections for single scalar and vector-leptoquark production in qg-fusion are [29] $\sigma \approx 0.7...1.3\ fb$ for a mass $M \sim 200\,\mathrm{GeV}$ and $(\lambda/e)\sqrt{b} = 0.075$. For the second process, the production cross section for leptoquarks at a mass $M \sim 200\,\mathrm{GeV}$ is given by

$$\sigma_\Phi \approx 0.074 pb \times \left(\frac{\lambda}{e}\right)^2 J(\Phi)\ b(\Phi)\ . \tag{12}$$

For values of $(\lambda/e)\sqrt{b} = 0.075$ the cross section amounts to $\sigma = 0.4\ fb$. These cross sections are too small to be measured at TEVATRON currently.

Complementary to single leptoquark production [4], which relies on the fermionic couplings of leptoquarks, one may consider the pair production [5] of scalar and vector leptoquarks at hadron colliders. Even if the fermionic couplings of leptoquarks are small, $\lambda/e \ll 1$, leptoquarks may be produced through quark–antiquark and gluon–gluon fusion since the couplings to the gluon are well determined. The pair production cross sections were calculated in refs. [12, 15][6] for scalar and in refs. [13, 14, 15] for vector leptoquarks by different methods. While in refs. [13] only the case of vector leptoquarks carrying a Yang–Mills type coupling and in refs. [14] as well the case of the minimal vector coupling to the gluon were considered, the general case of anomalous couplings, κ_G and λ_G, of vector leptoquarks to the gluon was delt with in ref. [15].

In figure 1 the total pair production cross section is shown for scalar leptoquarks using the CTEQ3 (LO) parametrization [24] for the parton densities. For $M \sim 200$ GeV the scalar pair production cross section amounts to $\sigma(M \sim 200\,\mathrm{GeV}) = 0.1\ pb$, taking $\mu = \sqrt{\hat{s}}$ both as the factorization and renormalization scale. Other choices as $\mu = M_S$ lead to a cross section which is larger by a factor of ~ 1.6 for $M \sim 200\,\mathrm{GeV}$, showing the scale dependence in lowest order.[7]

[3]Single leptoquark production in various other high energy reactions was studied in refs. [26].

[4]One may also search for virtual leptoquark exchange in $e^+e^- \to q\bar{q}$ and $q\bar{q} \to e^+e^-$ scattering at LEP2 and at TEVATRON, respectively. Since $\lambda_{S,V} \ll 1$, the dominant contributions come from the interference terms between the respective s-channel contributions and leptoquark exchange in the t or u channel, cf. [30]. At the current luminosities it is not possible [29] to constrain the fermionic couplings further by these reactions in the mass range $M \sim 200\,\mathrm{GeV}$.

[5]Pair production cross sections for e^+e^- annihilation, $ep-$, $\gamma\gamma-$ and $e\gamma$ scattering were calculated in refs. [31]. For a survey on the search potential, see ref. [32].

[6]For a critical discussion of other results, refs. [33], see ref. [15].

[7]A discussion on this aspect with M. Mangano is gratefully acknowledged.

The pair production cross section for vector leptoquarks depends sizeably on the anomalous couplings κ_G and λ_G of the vector leptoquarks to the gluon, see figure 1. If the coupling would be of the Yang–Mills type, i.e. $\kappa_G = \lambda_G = 0$, the event rate could reach about 1000 events for $M \sim 200\,\mathrm{GeV}$ at each TEVATRON experiment. Even in the case of the minimal vector coupling, $\kappa_G = 1$ and $\lambda_G = 0$, the rate amounts to 100 events. Both these cases are likely to be excluded due to the event rates measured at the TEVATRON experiments. However, since a prediction on the vector couplings κ_G and λ_G does not exist, a global limit can only be derived minimizing the integrated cross section for these parameters. For a mass of $M \sim 200\,\mathrm{GeV}$ one obtains

$$\sigma_V^{min}(M = 200\,\mathrm{GeV}) = 0.20\ pb\ (Br(\Phi_V \rightarrow eq))^2 \tag{13}$$

for events with a $2e$ $2jet$ final state assuming $\mu = \sqrt{\hat{s}}$. For $\mu = M_V$ $\sigma^{min}(M = 200\,\mathrm{GeV}) = 0.29\ pb\ (Br(\Phi_V \rightarrow eq))^2$ is obtained. The corresponding anomalous couplings are $\kappa_G = 1.3$ and $\lambda_G = -0.34$.

These leading order estimates show that the pair production process of leptoquarks may yield up to 10 .. 16 signal events at an integrated luminosity of $\mathcal{L} = 100\ pb^{-1}$ for scalar leptoquarks and, in the presence of only the two anomalous couplings κ_G and λ_G, for vector leptoquarks at the minimal cross section, up to 20 .. 30 events, depending on the value of the factorization and renormalization scale [8] and the yet unknown branching ratios. The detection of the $2e$ $2jet$ final state is complicated due to different background reactions, see e.g. [34], which can only be reliably studied by the experiments themselves. Given the uncertainty in the branching fraction $Br(\Phi \rightarrow eq)$, both scalar and vector leptoquarks seem to be not yet excluded by the TEVATRON data. On the basis of the present statistics bounds on the anomalous couplings κ_G and λ_G for vector leptoquarks can be derived up to masses of $O(300\ \ \mathrm{GeV})$.

6 Conclusions

An interpretation of the recently reported excess of events in the range of high x and Q^2 at HERA in terms of single leptoquark production yields leptoquark-fermion couplings, λ_{f_i,f_j}, which are compatible with other limits, particularly those obtained from low energy reactions, for λ_{e^+u} and λ_{e^+d}. Still more statistics is needed to clearly establish an effect.

If the observed excess of events is due to leptoquarks, these states should as well be detected in the reaction channel $e^+q \rightarrow g\Phi_{S,V}$ at HERA at an increased integrated luminosity. The measurement of this reaction allows to investigate the coupling of the state Φ to gluons and provides an independent possibility to determine its spin.

The FERMILAB experiments, at a higher statistics, will be able to either clearly confirm or exclude the interpretation of the current excess of events found at HERA as being due to leptoquark production. For vector leptoquarks already at the current statistics bounds on the range of the couplings κ_G and λ_G can be derived. It is likely that both Yang-Mills type and minimal couplings of the leptoquarks to the gluon are already exluded by the observed event rates. On the other hand the TEVATRON data do not exclude scalar and vector leptoquarks, for some range in κ_G and λ_G, at a mass $M \sim 200\,\mathrm{GeV}$.

The search for leptoquark pair production at TEVATRON is complementary to the search for single leptoquark production at HERA both due to the couplings involved in the production

[8]A complete calculation of the $O(\alpha_s)$ K-factor both for scalar and vector leptoquark pair production is not yet available.

mechanism, as well as with respect to the alternative possibility to investigate the spin of the produced state in case of a confirmation of the effect.

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Note added. After completion of this paper we received the papers [35], in which similar analyses were carried out, which are found to be in mutual agreement.

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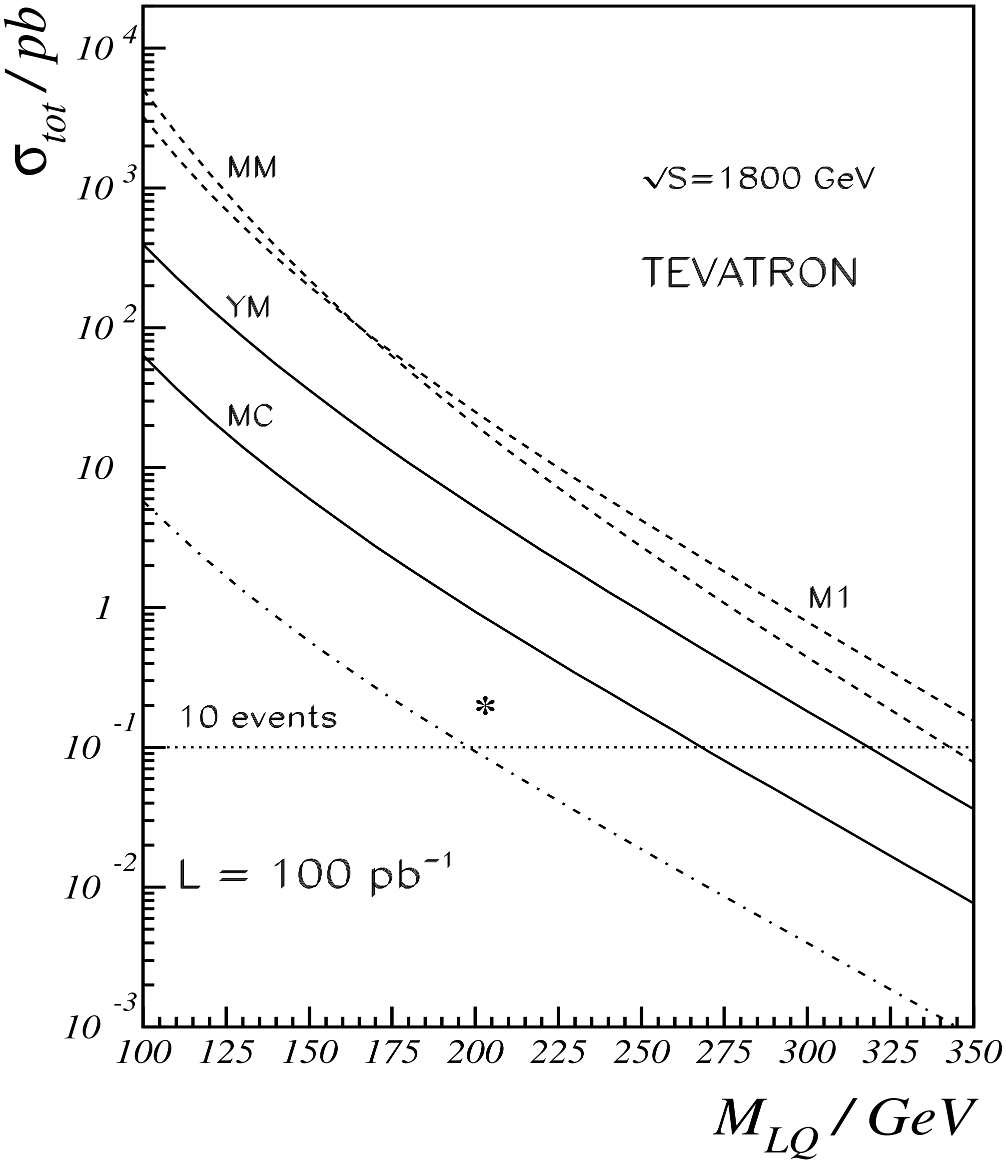

Figure 1: Integrated cross sections for scalar vector leptoquark pair production at the TEVATRON, $\sqrt{s}$ = 1.8 TeV choosing the renormalization and factorization scale by $\mu = \sqrt{\hat{s}}$. Dash-dotted line : scalar leptoquarks; fill lines : YM : Yang-Mills type coupling $\kappa_G = \lambda_G \equiv 0$; MC : minmal vector coupling $\kappa_G = 1, \lambda_G = 0$; dashed lines : other choices for the anomalous couplings : MM : $\kappa_G = \lambda_G = -1$, M1 : $\kappa_G = -1, \lambda_G = +1$. The asterisk denotes the minimum of the pairproduction cross section for vector leptoquarks with respect to the anomalous couplings at $M_V = 200$ GeV.