A Search for Leptoquark Bosons in \(e^-p\) Collisions at HERA

H1 Collaboration

Abstract

A search for scalar and vector leptoquarks coupling to first generation fermions is performed in the H1 experiment at the \(ep\) collider HERA. The analysis uses \(e^-p\) data collected in 1998 and 1999 at a centre-of-mass energy of 320 GeV, corresponding to an integrated luminosity of \(\sim 15 \text{ pb}^{-1}\). No evidence for the direct production of such particles is found in a data sample with a large transverse momentum final state electron or with large missing transverse momentum, and constraints on leptoquark models are established. For a Yukawa coupling of electromagnetic strength leptoquarks are excluded for masses up to \(\sim 290\) GeV. This analysis complements the leptoquark searches performed previously using data collected whilst HERA was operating with positrons instead of electrons.

To be submitted to Phys. Lett. B
G. Weber\textsuperscript{11}, M. Weber\textsuperscript{14}, D. Wegener\textsuperscript{7}, C. Werner\textsuperscript{13}, M. Werner\textsuperscript{13}, N. Werner\textsuperscript{27}, G. White\textsuperscript{17}, S. Wiesand\textsuperscript{33}, T. Wilksen\textsuperscript{10}, M. Winde\textsuperscript{35}, G.-G. Winter\textsuperscript{10}, Ch. Wisssing\textsuperscript{7}, M. Wobisch\textsuperscript{10}, E.-E. Woehrling\textsuperscript{3}, E. Wünsch\textsuperscript{10}, A.C. Wyatt\textsuperscript{21}, J. Žáček\textsuperscript{30}, J. Zálešíák\textsuperscript{30}, Z. Zhang\textsuperscript{26}, A. Zhokin\textsuperscript{23}, F. Zomer\textsuperscript{26}, J. Zsembery\textsuperscript{9}, and M. zur Nedden\textsuperscript{10}

1. I. Physikalisches Institut der RWTH, Aachen, Germany\textsuperscript{a}
2. III. Physikalisches Institut der RWTH, Aachen, Germany\textsuperscript{a}
3. School of Physics and Space Research, University of Birmingham, Birmingham, UK\textsuperscript{b}
4. Inter-University Institute for High Energies ULB-VUB, Brussels; Universitaire Instelling Antwerpen, Wilrijk; Belgium\textsuperscript{c}
5. Rutherford Appleton Laboratory, Chilton, Didcot, UK\textsuperscript{d}
6. Institute for Nuclear Physics, Krakow, Poland\textsuperscript{d}
7. Institut für Physik, Universität Dortmund, Dortmund, Germany\textsuperscript{a}
8. Joint Institute for Nuclear Research, Dubna, Russia
9. CEA, DSM/DAPNIA, CE-Saclay, Gif-sur-Yvette, France
10. DESY, Hamburg, Germany
11. II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany\textsuperscript{a}
12. Max-Planck-Institut für Kernphysik, Heidelberg, Germany\textsuperscript{a}
13. Physikalisches Institut, Universität Heidelberg, Heidelberg, Germany\textsuperscript{a}
14. Kirchhoff-Institut für Physik, Universität Heidelberg, Heidelberg, Germany\textsuperscript{a}
15. Institut für experimentelle und Angewandte Physik, Universität Kiel, Kiel, Germany\textsuperscript{a}
16. Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic\textsuperscript{e,f}
17. School of Physics and Chemistry, University of Lancaster, Lancaster, UK\textsuperscript{b}
18. Department of Physics, University of Liverpool, Liverpool, UK\textsuperscript{b}
19. Queen Mary and Westfield College, London, UK\textsuperscript{b}
20. Physics Department, University of Lund, Lund, Sweden\textsuperscript{g}
21. Physics Department, University of Manchester, Manchester, UK\textsuperscript{b}
22. CPPM, CNRS/IN2P3 - Univ Mediterranee, Marseille - France
23. Institute for Theoretical and Experimental Physics, Moscow, Russia\textsuperscript{j}
24. Lebedev Physical Institute, Moscow, Russia\textsuperscript{e,h}
25. Max-Planck-Institut für Physik, München, Germany\textsuperscript{a}
26. LAL, Université de Paris-Sud, IN2P3-CNRS, Orsay, France
27. LPNHE, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
28. LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France
29. Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic\textsuperscript{e,i}
30. Faculty of Mathematics and Physics, Charles University, Praha, Czech Republic\textsuperscript{e,i}
31. Dipartimento di Fisica Università di Roma Tre and INFN Roma 3, Roma, Italy
32. Paul Scherrer Institut, Villigen, Switzerland
33. Fachbereich Physik, Bergische Universität Gesamthochschule Wuppertal, Wuppertal, Germany\textsuperscript{a}
34. Yerevan Physics Institute, Yerevan, Armenia
35. DESY, Zeuthen, Germany\textsuperscript{a}
36. Institut für Teilchenphysik, ETH, Zürich, Switzerland\textsuperscript{j}
37. Physik-Institut der Universität Zürich, Zürich, Switzerland\textsuperscript{j}
38. Also at Physics Department, National Technical University, Zografou Campus, GR-15773
Athens, Greece

39 Also at Rechenzentrum, Bergische Universität Gesamthochschule Wuppertal, Germany
40 Also at Institut für Experimentelle Kernphysik, Universität Karlsruhe, Karlsruhe, Germany
41 Also at Dept. Fis. Ap. CINVESTAV, Mérida, Yucatán, México
42 Also at University of P.J. Šafárik, Košice, Slovak Republic
43 Also at CERN, Geneva, Switzerland
44 Also at Dept. Fis. CINVESTAV, México City, México

a Supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie, FRG, under contract numbers 7AC17P, 7AC47P, 7DO55P, 7HH17I, 7HH27P, 7HD17P, 7HD27P, 7KI17I, 6MP17I and 7WT87P
b Supported by the UK Particle Physics and Astronomy Research Council, and formerly by the UK Science and Engineering Research Council
c Supported by FNRS-NFWO, IISN-IIKW
d Partially Supported by the Polish State Committee for Scientific Research, grant no. 2P0310318 and SPUB/DESY/P03/DZ-1/99, and by the German Federal Ministry of Education and Science, Research and Technology (BMBF)
e Supported by the Deutsche Forschungsgemeinschaft
f Supported by VEGA SR grant no. 2/1169/2001
g Supported by the Swedish Natural Science Research Council
h Supported by Russian Foundation for Basic Research grant no. 96-02-00019
i Supported by the Ministry of Education of the Czech Republic under the projects INGO-LA116/2000 and LN00A006, and by GA AVČR grant no B1010005
j Supported by the Swiss National Science Foundation
k Supported by CONACyT
l Partially Supported by Russian Foundation for Basic Research, grant no. 00-15-96584
The $ep$ collider HERA offers the unique possibility to search for resonant production of new particles which couple to lepton-parton pairs. Examples are leptoquarks (LQs), colour triplet bosons which appear naturally in various unifying theories beyond the Standard Model (SM). At HERA, leptoquarks could be singly produced by the fusion of the initial state lepton of energy $27.5$ GeV with a quark from the incoming proton of $920$ GeV, with masses up to the centre-of-mass energy $\sqrt{s_{ep}}$ of $320$ GeV.

This analysis presents a search for LQs coupling to first generation fermions using $e^-p$ data collected in 1998 and 1999. Collisions between electrons and protons provide a high sensitivity to LQs with fermion number $F = 2$ (i.e. LQs coupling to $e^{-}$ and a valence quark) while the production of such LQs is largely suppressed in $e^+p$ collisions where the interaction involves an antiquark. Thus this analysis complements the searches for LQs in $e^+p$ data [1, 2]. This search considers the decays $LQ \rightarrow e\bar{q}$ and $LQ \rightarrow \nu q$ which lead to final states similar to those of deep-inelastic scattering (DIS) neutral current (NC) and charged current (CC) interactions at very high squared momentum transfer $Q^2$. The integrated luminosity amounts to $15 \text{ pb}^{-1}$, an increase in statistics by a factor of about 35 compared to previous LQ searches [3, 4] in $e^-p$ collisions.

The phenomenology of LQs at HERA was discussed in detail in [1]. At HERA, LQs can be resonantly produced in the $s$-channel or exchanged in the $u$-channel between the incoming lepton and a quark coming from the proton. The amplitudes for both these processes interfere with those from DIS. We shall consider here the mass domain where the resonant $s$-channel contributions largely dominate the LQ signal cross-section.

In the $s$-channel, a LQ is produced at a mass $M = \sqrt{s_{ep}x}$ where $x$ is the momentum fraction of the proton carried by the interacting quark. When the LQ decays into an electron and a quark, the mass is reconstructed from the measured kinematics of the scattered electron, and is henceforth labelled $M_e$. Similarly when the LQ decays into a neutrino and a quark, the mass is labelled $M_h$ as it is reconstructed from the hadronic final state alone [1].

The H1 detector components most relevant to this analysis are the liquid argon calorimeter, which measures the positions and energies of charged and neutral particles over the polar angular range $4^\circ < \theta < 154^\circ$, and the inner tracking detectors which measure the angles and momenta of charged particles over the range $7^\circ < \theta < 165^\circ$. A full description of the detector can be found in [5].

This search relies essentially on inclusive NC and CC DIS selections. The selection of NC-like events is identical to that presented in [1]. It requires an identified electron with transverse energy above $15$ GeV and considers the kinematic domain defined by $Q^2 > 2500$ GeV$^2$ and $0.1 < y < 0.9$, where $y = Q^2/M^2$. The inelasticity variable $y$ is related to the polar angle $\theta^*$ of the lepton in the centre-of-mass frame of the hard subprocess by $y = \frac{1}{2}(1 + \cos \theta^*)$. Since the angular distribution of the electron coming from the decay of a scalar (vector) resonance is markedly (slightly) different from that of the scattered lepton in NC DIS [1], a mass dependent cut $y > y_{\text{cut}}$ allows the signal significance to be optimized. The measured mass spectrum is compared in Fig. [1] with the NC SM prediction, obtained using a Monte-Carlo calculation [6] and the MRST parametrization [7] for the parton densities. The distributions are shown before

---

1 A fusion between an $e^+$ and a valence quark would lead to a LQ with $F = 0$.

2 The polar angle $\theta$ is defined with respect to the incident proton momentum vector (the positive $z$ axis).
Figure 1: Mass spectra of the events from the inclusive NC DIS selection for data (symbols) and DIS expectation (histograms). The data is shown before (open squares, dashed-line histogram) and after (filled dots, full-line histogram) a $y$ cut designed to maximize the significance of (a) a scalar and (b) a vector leptoquark (LQ) signal. The grey boxes indicate the $\pm 1\sigma$ uncertainty due to the systematic errors on the NC DIS expectation.

and after applying the mass dependent lower $y$ cut designed to maximize the significance of a scalar (Fig. 1a) or vector (Fig. 1b) LQ. For scalar (vector) LQs, $y_{\text{cut}}$ continuously decreases from $\sim 0.45$ ($\sim 0.25$) at 100 GeV to $\sim 0.35$ ($\sim 0.15$) at 200 GeV, reaching 0.1 (0.1) at 290 GeV. In the mass range $M_e > 62.5$ GeV and after applying the $y$ cut optimized for scalar (vector) LQ searches, 298 (514) events are observed in good agreement with the SM expectation of $297 \pm 22$ ($504 \pm 38$) events.

The selection of CC-like events follows closely that presented in [8]. In addition, a missing transverse momentum exceeding 25 GeV and $Q^2 > 2500$ GeV$^2$ are required. The domain at high $y$ where the resolution on the mass $M_h$ degrades is removed by requiring $y < 0.9$. For $M_h > 65$ GeV, 345 events are observed, in good agreement with the CC SM expectation of $350 \pm 28$ events. The observed and expected mass spectra are shown in Fig. 2.

No evidence for LQ production is observed in either data sample. Hence the data are used to set constraints on LQs which couple to first generation fermions. We use the numbers of observed and expected events within a variable mass bin, adapted to the experimental mass distribution for a given true LQ mass $M_{LQ}$, and which slides over the accessible mass range. As an example, candidate events with $M_e$ within the interval from 187 GeV to 206 GeV are used to constrain a 200 GeV LQ decaying into electrons. For LQs decaying into $\nu q$, the mass window is enlarged (to about 40 GeV for a 200 GeV LQ) to account for the mass resolution when relying on the hadronic final state. The final signal efficiencies, including the mass bin
requirement, vary with the LQ mass between 35% (20%) and 52% (45%) for scalar (vector) LQs decaying into $e_q$, and between 20% and 52% for LQs decaying into $\nu q$.

Assuming Poisson distributions for the SM background expectations and for the signal, an upper limit on the number of events coming from LQ production is obtained using a standard Bayesian prescription. This limit on the number of signal events is then translated into an upper bound on the LQ cross-section, which in turn leads to constraints on LQ models. The signal cross-section is obtained from the leading-order LQ amplitudes given in [9], corrected by multiplicative $K$-factors [10] to account for next-to-leading order QCD corrections. These corrections can enhance the LQ cross-section by $\mathcal{O}(10\%)$.

The procedure which folds in the statistical and systematic errors is described in detail in [3]. The main source of experimental systematic error is the uncertainty on the electromagnetic energy scale (between 0.7% and 3%) for the NC analysis, and the uncertainty on the hadronic energy scale (2%) for the CC analysis. Furthermore, an error of $\pm 7\%$ on the DIS expectations is attributed to the limited knowledge of proton structure. An additional systematic error arises from the theoretical uncertainty on the signal cross-section, originating mainly from the uncertainties on the parton densities. This uncertainty is 7% for LQs coupling to $e^- u$, and varies between 7% at low LQ masses up to 50% around 290 GeV for LQs coupling to $e^- d$. Moreover, choosing alternatively $Q^2$ or the square of the transverse momentum of the final state lepton instead of $M_{LQ}^2$ as the hard scale at which the parton distributions are estimated yields an additional uncertainty of $\pm 7\%$ on the signal cross-section.

The phenomenological model proposed by Buchm"uller, R"uckl and Wyler (BRW) [9] de-
scribe 14 LQs. We focus here on the 7 LQs with fermion number $F = 2$ since those with $F = 0$ are better constrained using $e^+p$ data \[^1\]. In the BRW model the branching ratios $\beta_e (\beta_\nu)$ for the LQ decays into $eq (\nu q)$ are fixed and equal to 1 or 0.5 (0 or 0.5) depending on the LQ quantum numbers. The upper limits on the Yukawa coupling $\lambda$ at the $eq$ LQ vertex obtained at 95% confidence level (CL) are shown as a function of the LQ mass in Figs. 3a and b, for scalar and vector LQs respectively. The nomenclature of \[^1\] is used to label the various scalar $S_{I,L}$ $(\tilde{S}_{I,R})$ or vector $V_{I,L} (V_{I,R})$ LQ types of weak isospin $I$, which couple to a left-handed (right-handed) electron. The tilde is used to distinguish LQs which differ only by their hypercharge. For LQs decaying with an equal branching ratio into $eq$ and $\nu q$, both the NC and CC channels were combined in the derivation of the limits. However, the CC channel offers much less sensitivity to the signal than the NC channel, and thus only marginally contributes to the resulting bounds. This is due to the fact that the mass windows are larger, and that no discriminating angular cut is applied in the CC channel. Both effects yield a much larger SM background in the CC channel than in the NC case.\(^2\) For a Yukawa coupling of electromagnetic strength $\alpha_{em}$ ($\lambda = \sqrt{4\pi\alpha_{em}} \simeq 0.3$) this analysis rules out LQ masses below 275 to 290 GeV depending on the LQ type, at 95% CL. These are the most stringent direct bounds on LQs with $F = 2$.

Beyond the BRW ansatz, generic LQ models can also be considered, where other LQ decay modes are allowed such that the branching ratios $\beta_e$ and $\beta_\nu$ are free parameters. The LQ production cross-section does not depend on the total LQ width $\Gamma$ as long as $\Gamma$ is not too large. Hence the signal cross-section observable in e.g. the NC channel depends only on the Yukawa coupling and on the branching ratio $\beta_e$, and mass dependent constraints on $\beta_e$ can be set for a given value of $\lambda$. For a scalar LQ with $M_{LQ} = 295$ GeV and $\lambda = 0.3$, this approach holds as long as $\Gamma \lesssim 2$ GeV, such that the LQ total width does not exceed about four times its partial decay width into $eq$. For a scalar LQ possessing the quantum numbers of the $S_{0,R}$, which couples to $e^{-}d$ and thus cannot decay into $\nu q$, Fig. 4a shows the excluded part of the $\beta_e$-$M_{LQ}$ plane for three values of the Yukawa coupling. The domain excluded by the D0 experiment at the Tevatron \[^2\] is also shown. For a scalar LQ coupling to $e^{-}u$ (possessing the quantum numbers of the $S_{0,L}$) and for $\lambda = 0.05$, the domain of the $\beta_e$-$M_{LQ}$ ($\beta_\nu$-$M_{LQ}$) plane excluded by the NC (CC) analysis is shown in Fig. 4b. If the LQ decays into $eq$ or $\nu q$ only,\(^4\) the combination of both channels rules out the part of the plane on the left of the middle full curve, for $\lambda = 0.05$. The resulting combined bound is largely independent of the individual values of $\beta_e$ and $\beta_\nu$. Combined bounds are also shown for $\lambda = 0.03$ and $\lambda = 0.3$, for the same LQ type. For $\lambda$ greater than $\sim 0.03$, these bounds extend considerably beyond the region excluded by the D0 experiment \[^2\].

To summarize, a search for leptoquarks with fermion number $F = 2$ has been performed using the $e^{-}p$ data collected by H1 in 1998 and 1999. No signal has been observed and constraints on such LQs have been set, which extend beyond the domains excluded by other experiments. For a Yukawa coupling of electromagnetic strength, LQ masses up to 290 GeV can be ruled out. This represents the most stringent direct bound on $F = 2$ leptoquarks.

\(^3\) This is different from the $e^+p$ case, where the CC channel significantly improves the sensitivity on the LQ production cross-section \[^1\] due to the smaller CC DIS cross-section.

\(^4\) It should be noted that $\beta_e + \beta_\nu = 1$ does not imply $\beta_e = \beta_\nu$ even when invariance under $SU(2)_L$ transformations is required. For example, when LQs belonging to a given isospin multiplet are not mass eigenstates, their mixing usually leads to different branching ratios in both channels for the physical LQ states.
**Figure 3:** Exclusion limits at 95% CL on the Yukawa coupling $\lambda$ as a function of the mass of (a) scalar and (b) vector leptoquarks (LQs) with fermion number $F = 2$ described by the BRW model. Domains above the curves are excluded by this analysis of the $e^{-}p$ data. The shaded area on each plot indicates the excluded region obtained from the $e^{+}p$ data [1], less suited for constraining $F = 2$ LQs.

**Acknowledgements**

We are grateful to the HERA machine group whose outstanding efforts have made and continue to make this experiment possible. We thank the engineers and technicians for their work in constructing and now maintaining the H1 detector, our funding agencies for financial support, the DESY technical staff for continual assistance and the DESY directorate for the hospitality which they extend to the non DESY members of the collaboration.
References

[1] C. Adloff et al. [H1 Collaboration], Eur. Phys. J. C 11 (1999) 447 [Erratum-ibid. C 14 (1999) 553] [hep-ex/9907002].

[2] J. Breitweg et al. [ZEUS Collaboration], Eur. Phys. J. C 16 (2000) 253 [hep-ex/0002038];
   J. Breitweg et al. [ZEUS Collaboration], Phys. Rev. D 63 (2001) 052002 [hep-ex/0009059].

[3] T. Ahmed et al. [H1 Collaboration], Z. Phys. C 64 (1994) 545.

[4] M. Derrick et al. [ZEUS Collaboration], Phys. Lett. B 306 (1993) 173.

[5] I. Abt et al. [H1 Collaboration], Nucl. Instrum. Meth. A 386 (1997) 310;
   R. D. Appuhn et al. [H1 SPACAL Group Collaboration], Nucl. Instrum. Meth. A 386 (1997) 397.

[6] DJANGO 6.2; G.A. Schuler and H. Spiesberger, Proc. of the Workshop Physics at HERA, W. Buchmüller and G. Ingelman (Editors), (October 1991, DESY-Hamburg) Vol. 3 p. 1419.

[7] A. D. Martin, R. G. Roberts, W. J. Stirling and R. S. Thorne, Eur. Phys. J. C 4 (1998) 463 [hep-ph/9803445].

[8] C. Adloff et al. [H1 Collaboration], Eur. Phys. J. C 19 (2001) 269 [hep-ex/0012052].

[9] W. Buchmüller, R. Rückl and D. Wyler, Phys. Lett. B 191 (1987) 442 [Erratum-ibid. B 448 (1999) 320].

[10] T. Plehn, H. Spiesberger, M. Spira and P. M. Zerwas, Z. Phys. C 74 (1997) 611 [hep-ph/9703433];
   Z. Kunszt and W. J. Stirling, Z. Phys. C 75 (1997) 453 [hep-ph/9703427].

[11] A. Djouadi, T. Köhler, M. Spira and J. Tutas, Z. Phys. C 46 (1990) 679.

[12] B. Abbott et al. [D0 Collaboration], Phys. Rev. Lett. 79 (1997) 4321 [hep-ex/9707033];
   B. Abbott et al. [D0 Collaboration], Phys. Rev. Lett. 80 (1998) 2051 [hep-ex/9710032].
Figure 4:  (a) Mass dependent exclusion limits at 95% CL on the branching ratio $\beta_e$ of a scalar leptoquark (LQ) which couples to $e^- d$ (with the quantum numbers of the $\tilde{S}_{0,R}$). (b) Domains ruled out by the combination of the NC and CC analyses, for a scalar LQ which couples to $e^- u$ (with the quantum numbers of the $S_{0,L}$) and decaying only into $e\nu$ and $\nu_q$ for three example values of the Yukawa coupling $\lambda$. The regions on the left of the full curves are excluded at 95% CL. For $\lambda = 0.05$, the part of the $\beta_{e^-}$ $M_{LQ}$ ($\beta_{\nu^-}$-$M_{LQ}$) plane on the left of the dashed (dotted) curve is excluded by the NC (CC) analysis. The branching ratios $\beta_e$ and $\beta_\nu$ are shown on the left and right axes respectively. In (a) and (b), the hatched region represents the domain excluded by the D0 experiment [12].