Search for Scalar Leptoquark Pairs Decaying to Electrons and Jets in $pp$ Collisions

The DØ Collaboration *

Fermi National Accelerator Laboratory, Batavia, Illinois 60510
July 23, 1997

Abstract

We have searched for the pair production of first generation scalar leptoquarks in the $eejj$ channel using the full data set (123 pb$^{-1}$) collected with the DØ detector at the Fermilab Tevatron during 1992–1996. We observe no candidates with an expected background of approximately 0.4 events. Comparing the experimental 95% confidence level upper limit to theoretical calculations of the cross section with the assumption of a 100% branching fraction to $eq$, we set a lower limit on the mass of a first generation scalar leptoquark of 225 GeV/$c^2$. The results of this analysis rule out the interpretation of the excess of high $Q^2$ events at HERA as leptoquarks which decay exclusively to $eq$.

*Authors listed on following page.
Submitted to Physical Review Letters.
H.B. Prosper,\textsuperscript{15} S. Protopopescu,\textsuperscript{4} J. Qian,\textsuperscript{24} P.Z. Quintas,\textsuperscript{14} R. Raja,\textsuperscript{14} S. Rajagopalan,\textsuperscript{4} O. Ramirez,\textsuperscript{17} L. Rasmussen,\textsuperscript{42} S. Reucroft,\textsuperscript{29} M. Rijssenbeek,\textsuperscript{42} T. Rockwell,\textsuperscript{25} N.A. Roe,\textsuperscript{22} P. Rubinov,\textsuperscript{31} R. Ruchti,\textsuperscript{32} J. Rutherfoord,\textsuperscript{2} A. Sánchez-Hernández,\textsuperscript{11} A. Santoro,\textsuperscript{10} L. Sawyer,\textsuperscript{44} R.D. Schamberger,\textsuperscript{42} H. Schellman,\textsuperscript{31} J. Sculli,\textsuperscript{28} E. Shabalina,\textsuperscript{26} C. Shaffer,\textsuperscript{15} H.C. Shankar,\textsuperscript{43} R.K. Shivpuri,\textsuperscript{13} M. Shupe,\textsuperscript{2} H. Singh,\textsuperscript{9} J.B. Singh,\textsuperscript{34} V. Sirotenko,\textsuperscript{30} W. Smart,\textsuperscript{14} R.P. Smith,\textsuperscript{14} R. Snihur,\textsuperscript{31} G.R. Snow,\textsuperscript{27} J. Snow,\textsuperscript{33} S. Snyder,\textsuperscript{4} J. Solomon,\textsuperscript{17} P.M. Sood,\textsuperscript{34} M. Sosebee,\textsuperscript{44} N. Sotnikova,\textsuperscript{26} M. Souza,\textsuperscript{10} A.L. Spadafora,\textsuperscript{22} R.W. Stephens,\textsuperscript{44} M.L. Stevenson,\textsuperscript{22} D. Stewart,\textsuperscript{24} F. Stichelbaut,\textsuperscript{42} D.A. Stoianova,\textsuperscript{35} D. Stoker,\textsuperscript{8} M. Strauss,\textsuperscript{33} K. Streets,\textsuperscript{28} M. Strovink,\textsuperscript{22} A. Sznajder,\textsuperscript{10} P. Tamburello,\textsuperscript{23} J. Tarazi,\textsuperscript{8} M. Tartaglia,\textsuperscript{14} T.L.T. Thomas,\textsuperscript{31} J. Thompson,\textsuperscript{23} T.G. Trippe,\textsuperscript{22} P.M. Tuts,\textsuperscript{12} N. Varelas,\textsuperscript{25} E.W. Varnes,\textsuperscript{22} D. Vititoe,\textsuperscript{2} A.A. Volkov,\textsuperscript{35} A.P. Vorobiev,\textsuperscript{35} H.D. Wahl,\textsuperscript{15} G. Wang,\textsuperscript{15} J. Warchol,\textsuperscript{32} G. Watts,\textsuperscript{5} M. Wayne,\textsuperscript{32} H. Weerts,\textsuperscript{25} A. White,\textsuperscript{44} J.T. White,\textsuperscript{45} J.A. Wightman,\textsuperscript{19} S. Willis,\textsuperscript{30} S.J. Wimpenny,\textsuperscript{9} J.V.D. Wirjawan,\textsuperscript{45} J. Womersley,\textsuperscript{14} E. Won,\textsuperscript{39} D.R. Wood,\textsuperscript{29} H. Xu,\textsuperscript{5} R. Yamada,\textsuperscript{14} P. Yamin,\textsuperscript{4} C. Yanagisawa,\textsuperscript{42} J. Yang,\textsuperscript{28} T. Yasuda,\textsuperscript{29} P. Yepes,\textsuperscript{37} C. Yoshikawa,\textsuperscript{16} S. Youssef,\textsuperscript{15} J. Yu,\textsuperscript{14} Y. Yu,\textsuperscript{41} Z.H. Zhu,\textsuperscript{39} D. Zieminska,\textsuperscript{18} A. Zieminski,\textsuperscript{18} E.G. Zverev,\textsuperscript{26} and A. Zylberstejn\textsuperscript{40} (DØ Collaboration)
 Universidad de los Andes, Bogotá, Colombia
2 University of Arizona, Tucson, Arizona 85721
3 Boston University, Boston, Massachusetts 02215
4 Brookhaven National Laboratory, Upton, New York 11973
5 Brown University, Providence, Rhode Island 02912
6 Universidad de Buenos Aires, Buenos Aires, Argentina
7 University of California, Davis, California 95616
8 University of California, Irvine, California 92697
9 University of California, Riverside, California 92521
10 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
11 CINVESTAV, Mexico City, Mexico
12 Columbia University, New York, New York 10027
13 Delhi University, Delhi, India 110007
14 Fermi National Accelerator Laboratory, Batavia, Illinois 60510
15 Florida State University, Tallahassee, Florida 32306
16 University of Hawaii, Honolulu, Hawaii 96822
17 University of Illinois at Chicago, Chicago, Illinois 60607
18 Indiana University, Bloomington, Indiana 47405
19 Iowa State University, Ames, Iowa 50011
20 Korea University, Seoul, Korea
21 Kyungsung University, Pusan, Korea
22 Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720
23 University of Maryland, College Park, Maryland 20742
24 University of Michigan, Ann Arbor, Michigan 48109
25 Michigan State University, East Lansing, Michigan 48824
26 Moscow State University, Moscow, Russia
27 University of Nebraska, Lincoln, Nebraska 68588
28 New York University, New York, New York 10003
29 Northeastern University, Boston, Massachusetts 02115
30 Northern Illinois University, DeKalb, Illinois 60115
31 Northwestern University, Evanston, Illinois 60208
32 University of Notre Dame, Notre Dame, Indiana 46556
33 University of Oklahoma, Norman, Oklahoma 73019
34 University of Panjab, Chandigarh 16-00-14, India
35 Institute for High Energy Physics, 142-284 Protvino, Russia
36 Purdue University, West Lafayette, Indiana 47907
37 Rice University, Houston, Texas 77005
38 Universidade do Estado do Rio de Janeiro, Brazil
39 University of Rochester, Rochester, New York 14627
40 CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, Gif-sur-Yvette, France
41 Seoul National University, Seoul, Korea
42 State University of New York, Stony Brook, New York 11794
43 Tata Institute of Fundamental Research, Colaba, Mumbai 400005, India
44 University of Texas, Arlington, Texas 76019
45 Texas A&M University, College Station, Texas 77843
Leptoquarks (LQ) are hypothesized exotic color-triplet bosons which couple to both quarks and leptons. They appear in extended gauge theories and composite models and have attributes of both quarks and leptons such as color, fractional electric charge, and lepton and baryon quantum numbers. Leptoquarks with universal couplings to all flavors would give rise to flavor-changing neutral currents and are severely constrained by studies of low energy phenomena. Therefore, only leptoquarks which couple within a single generation are considered here. The H1 and ZEUS experiments at HERA have reported an excess of events at high \( Q^2 \) in \( e^+p \) collisions. One possible interpretation of these events is resonant production of first generation leptoquarks at a mass near 200 GeV/\( c^2 \). To date, no excess has been observed in \( e^-p \) collisions. A straightforward leptoquark explanation then requires the leptoquarks to decay to \( eq \) with a branching fraction of 100%.

The CDF and DØ collaborations have published the results of searches for first generation leptoquarks in \( pp \) collisions using data collected prior to 1994. The H1 and ZEUS experiments at HERA have published lower limits on the mass of a first generation leptoquark which depend on the unknown LQ-\( e-q \) coupling. Experiments at LEP have searched for leptoquarks in decays of the Z boson.

This Letter describes a search for the pair production of first generation scalar leptoquarks in the \( eejj + X \) final state using 123\( \pm 7 \) pb\(^{-1} \) of data collected at the Fermilab Tevatron with \( \sqrt{s} = 1.8 \) TeV during 1992–1996. The DØ detector and data acquisition system are described in detail in Ref. [7]. The detector consisted of three major subsystems: a uranium/liquid-argon calorimeter; central tracking detectors, including a transition radiation detector; and a muon spectrometer.

A base data sample of 101 events with two electrons and two or more jets was selected. Electrons were identified by their longitudinal and transverse shower profiles in the calorimeter and by the fraction of their energy deposited in its electromagnetic section. The electrons were required to be isolated from other energy depositions and to have pseudorapidity \(|\eta| < 1.1\) or \(1.5 < |\eta| < 2.5\). In addition, at least one electron was required to have a matching track in the central tracking detectors and to satisfy ionization requirements in the tracking chambers and transition radiation detector. Jets were reconstructed using a cone algorithm of radius \( R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.7 \), where \( \phi \) is the azimuthal angle, and required to have \(|\eta| < 2.5\). The electrons were required to be separated from jets by \( R > 0.7 \). Electrons were required to have transverse energy \( E_T^e > 20 \) GeV and jets to have \( E_T^j > 15 \) GeV. The kinematic quantities were calculated using the vertex determined by the electrons. Events whose \( ee \) invariant mass lies between \( 82 < M_{ee} < 100 \) GeV/\( c^2 \) (Z boson region) were rejected. The efficiency of the electromagnetic trigger used to collect the base data sample exceeded 99% for the leptoquark mass range addressed by this analysis.

Monte Carlo (MC) signal samples were generated for leptoquark masses between 120 and 260 GeV/\( c^2 \) using the ISAJET event generator and a detector simulation based on the GEANT program. Leptoquark production cross sections were taken from the recently available next-to-leading order (NLO) calculations of Ref. [7]. The primary backgrounds to the \( eejj \) decay mode are Drell-Yan + 2 jets production (DY), \( t\bar{t} \) production, and misidentified multijet events. Monte Carlo samples for the DY events were generated using ISAJET. The DY cross section normalization was fixed by comparing the MC events with \( Z + 2 \) jets data in the Z boson region. Top quark events were generated using the HERWIG program at a top quark mass of 170 GeV/\( c^2 \) and all dilepton final states were included. The DØ measured \( t\bar{t} \) production cross section of \( 5.5 \pm 1.8 \) pb at a top quark mass of 173.3 GeV/\( c^2 \) was used. The multijet background was estimated from a sample of events with four or more jets in which the probability for two jets or photons to be misidentified
as electrons was weighted by the number of jets in the event which passed the electron $E_T$ and $\eta$ requirements. This misidentification probability was calculated from a sample of events with three jets to be $(3.50 \pm 0.45) \times 10^{-4}$ for an electron with a reconstructed track and $(1.25 \pm 0.13) \times 10^{-3}$ for an electron without a reconstructed track. The errors on these probabilities reflect a slight dependence on the jet $E_T$ and $\eta$. The signal and background samples were required to pass the kinematic selection criteria that defined the base sample.

To search for leptoquarks, a random grid search method [?] was used to optimize cuts on the data and MC samples. Consistent results were obtained using a neural network [?]. Two criteria were used to optimize event selection, one designed for discovery and the other for limit setting. Once it became clear that the data did not contain evidence for leptoquark production, the limit setting criterion of a maximum number of signal events for a fixed number of background events was adopted. The background level chosen was 0.4 events, corresponding to a 67% probability that no such events would be observed.

The set of cuts which optimally separates signal from background was determined using a systematic search over a grid of possible cuts with the choice of grid points determined by the distributions of signal MC events. Many sets of selection criteria were explored including combinations of kinematic quantities and mass-related variables, such as transverse energy and the two $ej$ invariant masses. A cut on a single, relatively simple variable, $S_T \equiv H^e_T + H^j_T$, where $H^e_T \equiv E^e_1 + E^e_2$ and $H^j_T \equiv \sum_{\text{jets}} E^j_T$, satisfied the limit setting criterion. Approximately 0.4 background events are expected for $S_T > 350$ GeV. No events remain in the base data sample after this $S_T$ cut is applied. Figure 1 shows the $S_T$ distribution for the base data sample, the predicted background, and a MC sample of 200 GeV/$c^2$ LQ events. The highest value of $S_T$ seen in the data is 312 GeV.

For the neural network (NN) analysis, a three layer feed-forward network was constructed with two inputs, $H^e_T$ and $H^j_T$, and one output, the NN discriminant $D_{NN}$. Figure 2(a) shows the expected distribution in $H^e_T$ vs. $H^j_T$ for the 200 GeV/$c^2$ MC signal sample; Figs. 2(b) and (c) show the same distributions for the predicted background and the base data sample. The network was trained using the 200 GeV/$c^2$ LQ sample and the background samples described above. $D_{NN}$ has a range between 0 (background) and 1 (signal). Figures 2(a–c) show contours corresponding to three values of $D_{NN}$. A background of $\approx 0.4$ events is obtained by requiring $D_{NN} > 0.95$. After application of this cut, no events remain in the data. As the NN and $S_T$ analyses provide nearly identical sensitivity, only the simpler $S_T$ analysis was used for the cross section limit described in this Letter.

The background was estimated for $S_T > 350$ GeV and is given in Table 2 for the three sources.
FIG. 2. $H_T^e$ vs. $H_T^j$ for (a) 200 GeV/c² LQ events, (b) predicted background, and (c) base data sample. The area of a box is proportional to the number of events in the bin, with the total number of events normalized to $123 \text{ pb}^{-1}$.

TABLE I. Background contributions from individual sources.

<table>
<thead>
<tr>
<th>Background Source</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>DY</td>
<td>$0.18 \pm 0.04$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$0.11 \pm 0.04$</td>
</tr>
<tr>
<td>Multijet Misidentification</td>
<td>$0.16 \pm 0.02$</td>
</tr>
<tr>
<td>Total</td>
<td>$0.44 \pm 0.06$</td>
</tr>
</tbody>
</table>

The total estimated background is $0.44 \pm 0.06$ events where the error includes both statistical and systematic uncertainties. Included in the systematic error are the uncertainties in the jet energy scale, particle identification efficiency, $t\bar{t}$ production cross section, and luminosity, and the effects of the choice of parton distribution function and renormalization and factorization scale $\mu$, gluon radiation, and MC statistics.

Modeling of the $S_T$ distribution for high mass DY events was checked by studying $H_T^e$ and $H_T^j$ separately using data and MC events in the $Z$ boson mass region. The average value of $H_T^e$ for high mass DY events (which provide most of the $Z$ background) is approximately 250 GeV, corresponding to an $H_T^j$ of approximately 100 GeV for $S_T = 350$ GeV. The distribution of $H_T^j$ for high mass DY events is expected to be similar to that of $Z + 2$ jets events. Figure 3 shows the $H_T^j$ distributions for $Z + 2$ jets MC and data. In the region corresponding to the $S_T$ cut for high mass DY events ($H_T^j \approx 100$ GeV), the agreement is good.

To investigate the background further, constrained mass fits were performed on the events in

FIG. 3. The $H_T^j$ distribution for $Z + 2$ jets data (solid circles) and MC (open triangles) in the $Z$ boson mass region. For high mass DY events, $S_T = 350$ GeV corresponds to $H_T^j \approx 100$ GeV.
FIG. 4. $S_T$ vs. 3C fit mass distributions for (a) background, (b) 200 GeV/$c^2$ leptoquarks, and (c) the base data sample. The area of a box is proportional to the number of events in the bin. (d) Mass distribution of the events in the base data sample (solid circles), expected background (solid line histogram), and 200 GeV/$c^2$ leptoquarks (hatched histogram). The inset plot shows these distributions for events with $S_T > 250$ GeV.

The 3C mass fit was based on the SQUAW [?] kinematic mass fitting program and required the two $e_j$ masses to be identical. Use of the fitting program improves the mass resolution by approximately 10% over a simple calculation of the $e_j$ invariant masses. Figures ??(a–c) show $S_T$ as a function of the fit mass for the estimated background, 200 GeV/$c^2$ leptoquark events, and the base data sample. The distribution from the data agrees with that of the background. The two highest mass events have low values of $S_T$ and so are unlikely to be leptoquark events. Figure ??(d) shows the one dimensional mass distributions for the same samples. Inset in Fig. ??(d) are the distributions after a cut on $S_T > 250$ GeV. As can be seen, the data are consistent with the background prediction.

The dielectron identification efficiency was determined to be $(73 \pm 4)\%$ using a sample of $Z \rightarrow ee+2$ jets events. The overall signal detection efficiency is $9–37\%$ for leptoquark masses of $120–250$ GeV/$c^2$ (Table II). We set a 95% confidence level (CL) upper limit on the cross section $\sigma$ using a Bayesian approach with a flat prior distribution for the signal cross section. The statistical and systematic uncertainties on the efficiency, the integrated luminosity, and the background estimation were included in the limit calculation with Gaussian prior distributions. The resulting upper limit on the cross section is shown in Fig. ?? together with the NLO calculation of Ref. [?), and the results are listed in Table ???. The intersection of our limit curve with the lower edge of the theory band ($\mu = 2M_{LQ}$) is at $\sigma = 0.068$ pb, leading to a lower limit on the mass of a first generation scalar leptoquark of 225 GeV/$c^2$. For a branching fraction of 100% to $eq$, this is our lower limit; inclusion of additional channels will provide increased sensitivity in the case where leptoquarks also decay to $\nu q$. 
TABLE II. The signal detection efficiency, the 95% CL upper limit on the production cross section, and the $\mu = 2M_{LQ}$ NLO cross sections from Ref. [?].

<table>
<thead>
<tr>
<th>Leptoquark Mass (GeV/c$^2$)</th>
<th>Signal Efficiency (%)</th>
<th>95% CL Upper Limit (pb)</th>
<th>NLO Theory Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>8.7 ± 1.4</td>
<td>0.170</td>
<td>3.8</td>
</tr>
<tr>
<td>160</td>
<td>20.8 ± 3.0</td>
<td>0.113</td>
<td>0.68</td>
</tr>
<tr>
<td>200</td>
<td>31.2 ± 3.8</td>
<td>0.078</td>
<td>0.16</td>
</tr>
<tr>
<td>225</td>
<td>35.7 ± 4.3</td>
<td>0.068</td>
<td>0.068</td>
</tr>
<tr>
<td>250</td>
<td>37.2 ± 4.5</td>
<td>0.066</td>
<td>0.030</td>
</tr>
</tbody>
</table>

FIG. 5. Upper limit on the leptoquark pair production cross section for 100% decay to $eq$. Also shown is the NLO calculation of Ref. [?] where the central solid line corresponds to $\mu = M_{LQ}$, and the lower and upper dashed lines to $\mu = 2M_{LQ}$ and $\mu = M_{LQ}/2$, respectively.

In conclusion, we have excluded the interpretation of the HERA high $Q^2$ events as first generation scalar leptoquarks which decay exclusively to $eq$, as expected in chiral models with no extra fermions or intergenerational mixing. Using the NLO cross section calculation of Ref. [?] with $\mu = 2M_{LQ}$, and assuming a 100% branching fraction to $eq$, the 95% CL lower limit on the mass of a first generation scalar leptoquark is 225 GeV/c$^2$.

We thank M. Krämer for discussions and detailed cross section information and J.L. Hewett and T.G. Rizzo for many useful discussions. We thank the staffs at Fermilab and collaborating institutions for their contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (U.S.A.), Commissariat à L’Energie Atomique (France), State Committee for Science and Technology and Ministry for Atomic Energy (Russia), CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), and CONICET and UBACyT (Argentina).
REFERENCES

* Visitor from IHEP, Beijing, China.
† Visitor from Universidad San Francisco de Quito, Quito, Ecuador.