

Search for Scalar Leptoquark Pairs Decaying to Electrons and Jets in $\bar{p}p$ Collisions

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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 D0 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 of eq , we set a lower limit on the mass of a first generation scalar leptoquark of $225 \text{ GeV}/c^2$. The results of this analysis rule out the interpretation of the excess of high Q^2 events at DESY HERA as leptoquarks which decay exclusively to eq . [S0031-9007(97)04714-5]

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Leptoquarks (LQ) are hypothesized exotic color-triplet bosons which couple to both quarks and leptons. They appear in extended gauge theories and composite models

[1] 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 experimentally [2,3]. Therefore, only leptoquarks which couple within a single generation are considered here. The H1 and ZEUS experiments at the DESY ep Collider (HERA) have reported an excess of events at high Q^2 in e^+p collisions [4]. One possible interpretation of these events is resonant production of first generation leptoquarks [5] at a mass near $200 \text{ GeV}/c^2$. To date, no excess has been observed in e^-p collisions [6]. A straightforward leptoquark explanation then requires the leptoquarks to decay to eq with a branching fraction of 100% [5].

The CDF and D0 collaborations have published the results of searches for first generation leptoquarks in $\bar{p}p$ collisions using data collected prior to 1994 [7]. 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 [3,6]. Experiments at LEP have searched for leptoquarks in decays of the Z boson [8].

This Letter describes a search for the pair production of first generation scalar leptoquarks [9] in the $eejj + X$ final state using $123 \pm 7 \text{ pb}^{-1}$ of data collected at the Fermilab Tevatron with $\sqrt{s} = 1.8 \text{ TeV}$ during 1992–1996. The D0 detector and data acquisition system are described in detail in Ref. [10]. 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 $\mathcal{R} \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.7$, where ϕ is the azimuthal angle, and required to have $|\eta| < 2.5$. The electrons were required to be separated from jets by $\mathcal{R} > 0.7$. Electrons were required to have transverse energy $E_T^e > 20 \text{ GeV}$ and jets to have $E_T^j > 15 \text{ GeV}$. The kinematic quantities were calculated using the vertex determined by the electrons. Events whose ee invariant mass lies between $82 < M_{ee} < 100 \text{ GeV}/c^2$ (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 $260 \text{ GeV}/c^2$ using the ISAJET [11] event generator and detector simulation based on the GEANT [12] program. Leptoquark production cross sections were taken from the recently available next-to-leading order (NLO) calculations of Ref. [13].

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 [14] program at a top quark mass of $170 \text{ GeV}/c^2$ and all dilepton final states were included. The D0 measured $t\bar{t}$ production cross section of $5.5 \pm 1.8 \text{ pb}$ at a top quark mass of $173.3 \text{ GeV}/c^2$ was used [15]. 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 η requirements. This misidentification probability was calculated from a sample of events with three jets to be $(3.50 \pm 0.35) \times 10^{-4}$ 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 η . 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 [16] was used to optimize cuts on the data and MC samples. Consistent results were obtained using a neural network [17]. Two criteria were used to optimize event selection, one designed for discovery and the other for limit setting, both based on studies of MC events. Once it became clear that the data did not contain evidence for leptoquark production, the previously determined limit setting criterion of a maximum number of signal events for a small, fixed number of background events was adopted. The background level used 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

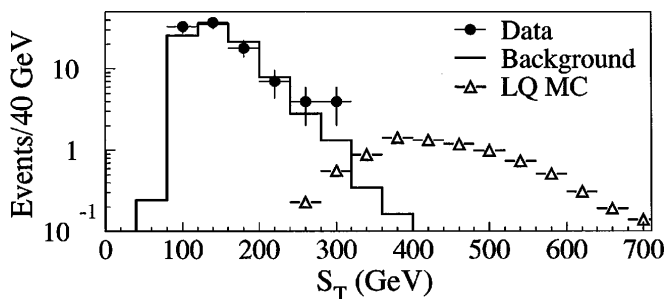


FIG. 1. S_T distributions for background (solid line histogram), data (solid circles), and $200 \text{ GeV}/c^2$ leptoquark MC events (open triangles).

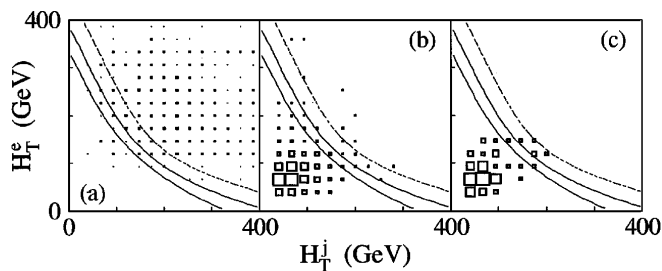


FIG. 2. H_T^e vs H_T^j for (a) 200 GeV/ c^2 LQ events, (b) predicted background, and (c) base data sample. The curved lines correspond to $D_{NN} = 0.5, 0.8,$ and 0.95 (from left to right). The area of a box is proportional to the number of events in the bin, with the total number of events normalized to 123 pb $^{-1}$.

masses. A cut on a single, relatively simple variable, $S_T \equiv H_T^e + H_T^j$, where $H_T^e \equiv E_T^{e1} + E_T^{e2}$ and $H_T^j \equiv \sum_{\text{jets}} E_T^j$, 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_T^e and H_T^j , and one output, the NN discriminant D_{NN} . Figure 2(a) shows the expected distribution in H_T^e vs H_T^j for the 200 GeV/ c^2 MC signal sample; Figs. 2(b) and 2(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)–2(c) show contours corresponding to three values of D_{NN} . A background of ≈ 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 I for the three sources. The total estimated background is 0.44 ± 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

TABLE I. Background contributions from individual sources.

Background source	Number of events
DY	0.18 ± 0.04
$t\bar{t}$	0.11 ± 0.04
Multijet misidentification	0.16 ± 0.02
Total	0.44 ± 0.06

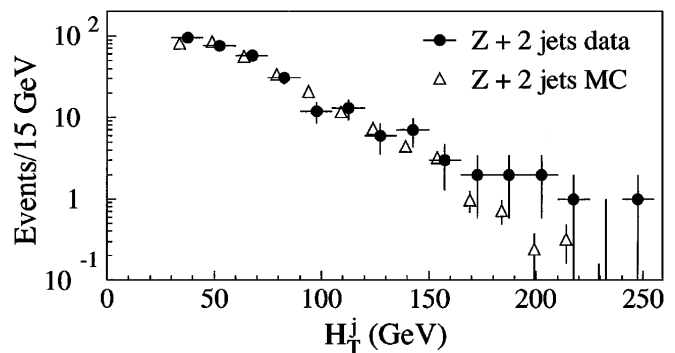


FIG. 3. The H_T^j distribution for $Z + 2$ jets data (solid circles) and MC (open triangles) in the Z boson mass region. For high mass DY events, $S_T = 350$ GeV corresponds to $H_T^j \approx 100$ GeV.

effects of the choice of parton distribution function and renormalization and factorization scale μ , 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 DY 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

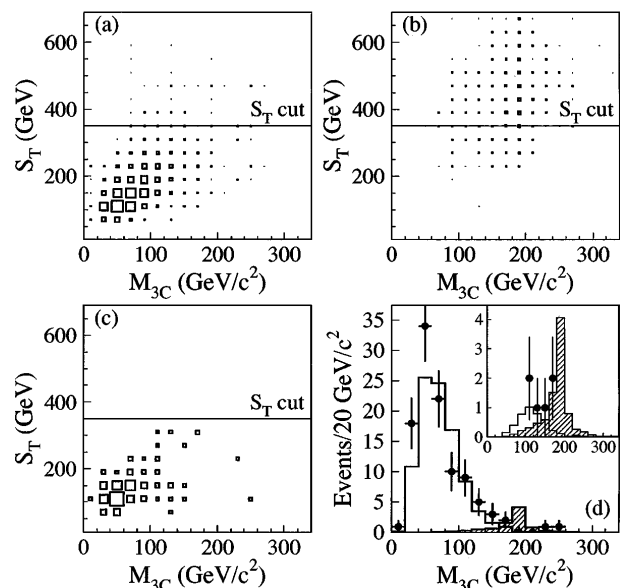


FIG. 4. S_T vs 3C fit mass distributions for (a) background, (b) 200 GeV/ c^2 leptoquarks, and (c) the base data sample. The area of a box is proportional to the number of events in the bin. (d) Mass distribution of the events in the base data sample (solid circles), expected background (solid line histogram), and 200 GeV/ c^2 leptoquarks (hatched histogram). The inset plot shows these distributions for events with $S_T > 250$ GeV.

TABLE II. The signal detection efficiency, the 95% C.L. upper limit on the production cross section, and the $\mu = 2M_{LQ}$ NLO cross sections from Ref. [13].

Leptoquark mass (GeV/c^2)	Signal efficiency (%)	95% C.L. Upper limit (pb)	NLO theory cross section (pb)
120	8.8 ± 1.4	0.300	3.8
160	20.9 ± 3.0	0.125	0.68
200	33.2 ± 4.0	0.076	0.16
225	37.7 ± 4.5	0.067	0.068
250	38.5 ± 4.7	0.066	0.030

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 the base data sample, on background samples, and on the $200 \text{ GeV}/c^2$ leptoquark signal sample. The 3C mass fit was based on the SQUAW [18] kinematic mass fitting program and required the two ej masses to be identical. Use of the fitting program improves the mass resolution by approximately 10% over a simple calculation of the ej invariant masses. Figures 4(a)–4(c) show S_T as a function of the fit mass for the estimated background, $200 \text{ GeV}/c^2$ 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 4(d) shows the one dimensional mass distributions for the same samples. Inset in Fig. 4(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 $(9\text{--}37)\%$

for leptoquark masses of $120\text{--}250 \text{ GeV}/c^2$ (Table II). We set a 95% confidence level (C.L.) upper limit on the cross section σ 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. 5 together with the NLO calculation of Ref. [13], and the results are listed in Table II. 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 $225 \text{ GeV}/c^2$. For a branching fraction of 100% to eq , this is our lower limit; inclusion of other channels will provide additional sensitivity when the branching fraction is less than 100%.

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. [13] with $\mu = 2M_{LQ}$, and assuming a 100% branching fraction to eq , the 95% C.L. lower limit on the mass of a first generation scalar leptoquark is $225 \text{ GeV}/c^2$.

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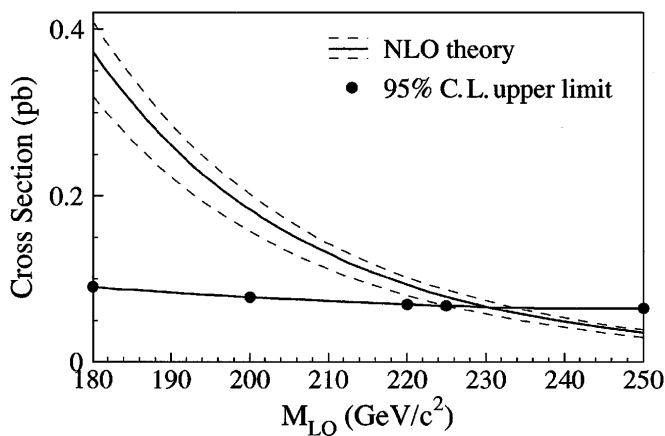


FIG. 5. Upper limit on the leptoquark pair production cross section for 100% decay to eq . Also shown is the NLO calculation of Ref. [13] where the central solid line corresponds to $\mu = M_{LQ}$, and the lower and upper dashed lines to $\mu = 2M_{LQ}$ and $\mu = M_{LQ}/2$, respectively.

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