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Search for first-generation scalar leptoquarks in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV

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We report on a search for pair production of first-generation scalar leptoquarks (LQ) in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV using an integrated luminosity of 252 pb^{-1} collected at the Fermilab Tevatron collider by the DØ detector. We observe no evidence for LQ production in the topologies arising from $LQ\overline{LQ} \rightarrow eqeq$ and $LQ\overline{LQ} \rightarrow eq\nu q$, and derive 95% C.L. lower limits on the LQ mass as a function of β, where β is the branching fraction for $LQ \rightarrow eq$. The limits are 241 and 218 GeV/c^2 for β=1 and 0.5, respectively. These results are combined with those obtained by DØ at $\sqrt{s}$=1.8 TeV, which increases these LQ mass limits to 256 and 234 GeV/c^2.

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Several extensions of the standard model (SM) include leptoquarks (LQ) which carry color, fractional electric charge, and both lepton (l) and quark (q) quantum numbers and would decay into a lepton and a quark [1]. The H1 and ZEUS experiments at the $e^{\pm}p$ collider HERA at DESY published [2] lower limits on the mass of a first-generation LQ that depend on the unknown leptoquark-l-q Yukawa coupling λ. At the CERN LEP collider, pair production of leptoquarks could occur in e^+e^- collisions via a virtual γ or Z boson in the s-channel. At the Fermilab Tevatron collider, leptoquarks would be pair produced dominantly through $q\bar{q}$ annihilation (for $M_{\rm LQ} > 100$ GeV/c^2) and gluon fusion. Such pair production mechanisms are independent of the coupling λ. Experiments at the LEP collider [3] and at the Fermilab Tevatron collider [4, 5, 6] set lower limits on the masses of leptoquarks. In this Letter, we present a search for first-generation scalar leptoquark pairs produced in $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV for two cases: when both leptoquarks decay to an electron and a quark with a branching fraction (Br) β^2, where β is the leptoquark branching fraction into an electron and a quark, and when one of the leptoquarks decays to an electron and a quark and the other to a neutrino and a quark with Br $= 2\beta(1-\beta)$. The final states consist of two electrons and two jets ($eejj$) or of an electron, two jets, and missing transverse energy corresponding to the neutrino which escapes detection ($e\nu jj$).

The DØ detector [7] comprises three main elements. A magnetic central-tracking system, which consists of a silicon microstrip tracker and a central fiber tracker, is located within a 2 T superconducting solenoidal magnet. Three liquid-argon/uranium calorimeters, a central section (CC) covering pseudorapidities η [8] with $|\eta|$ up to ≈ 1 and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$ [9], are housed in separate cryostats. Scintillators between the CC and EC cryostats provide sampling of developing showers for $1.1 < |\eta| < 1.4$. A muon system is located outside the calorimeters.

The data used in this analysis were collected from April 2002 to March 2004. The integrated luminosity for this data sample is 252 ± 16 pb^{-1}. Events were required to pass at least one of a set of electron triggers based on the requirement of one electromagnetic trigger tower to be above threshold and on shower shape conditions. The efficiencies of the trigger combinations used in the $eejj$ and $e\nu jj$ analyses have been measured using data. They are $\sim 100\%$ for two electrons of transverse energy ($E_T^{\rm EM}$) above 25 GeV, and for one electron above 40 GeV. The small loss of events due to the trigger inefficiencies for $E_T^{\rm EM}$ below 40 GeV is taken into account using proper weighting for Monte Carlo (MC) events.

Electrons are reconstructed as calorimeter electromagnetic clusters which match a track in the central-tracking system. Electromagnetic (EM) clusters are identified by the characteristics of their energy deposition in the calorimeter. Cuts are applied on the fraction of the energy in the electromagnetic calorimeter and the isolation of the cluster in the calorimeter. EM clusters are marked as tight when they satisfy a shower shape condition and loose otherwise. Jets are reconstructed using the iterative, midpoint cone algorithm [10] with a cone size of 0.5. The energy measurement of the jets has been calibrated as a function of the jet transverse energy and η by balancing energy in photon plus jet events. The missing transverse energy ($\not\!\!E_T$) is calculated as the vector sum of the transverse energies in the calorimeter cells, removing contributions from detector noise.

For both channels, the background arising from multijet events is determined from a sample of data events (QCD sample) that satisfy the main cuts used in the analysis except that each EM cluster is loose instead of tight. A QCD normalization factor is extracted for this sample in a part of the phase space where the LQ contribution is expected to be negligible. The QCD sample normalized by this factor is used to derive the multijet contribution in the relevant part of the phase space. To evaluate the Z boson/Drell-Yan (Z/DY) and the W boson background contributions, samples of MC events generated with ALPGEN [11] or PYTHIA [12] were used. Samples of PYTHIA $t\bar{t}$ events ($m_t = 175$ GeV/c^2) were used to calculate the top quark background. $LQ\overline{LQ} \rightarrow eejj$ and $LQ\overline{LQ} \rightarrow e\nu jj$ MC samples were generated using PYTHIA for LQ masses from 120 to 280 GeV/c^2 in steps of 20 GeV/c^2. All MC events were processed using a full simulation of the detector based on GEANT [13] and the complete event reconstruction. The efficiencies of the various cuts, measured using the data, were taken into account using proper weightings of the MC events.

The $eejj$ analysis requires two tight EM clusters with $E_T^{\rm EM} > 25$ GeV and at least two jets with $E_T > 20$ GeV within $|\eta| < 2.4$. At least one of the EM clusters should spatially match an isolated track and at least one should be in the CC fiducial region. The major SM background sources that mimic the $eejj$ decay of a LQ pair are multijet events (where two of the jets are misidentified as EM objects), Z/DY production, and top quark pair production. To suppress background from Z boson production, events with a di-electron mass ($M_{2\rm EM}$) compatible with the Z boson mass (80 GeV/$c^2 < M_{2\rm EM} < 102$ GeV/c^2) are rejected. Finally $S_T > 450$ GeV is also required, where S_T is the scalar sum of the transverse energies of the two electrons and the two leading jets. In Fig. 1a, the S_T distributions for data and background after applying the Z boson mass cut are shown. This choice of the cut-off has been optimized using MC signal and background events to get the best expected mass limit. The total efficiencies for a LQ signal are summarized in Table I. The multijet background is estimated from two samples of events with two EM clusters $E_T^{\rm EM} > 15$ GeV which have at least one matched track and no reconstructed jets. Both EM clusters are tight in one sample and loose in the other. The QCD normalization factor is determined by the normalization of the $M_{2\rm EM}$ distributions of the two samples below 75 GeV/c^2. The Z/DY and top quark contributions are normalized to the integrated luminosity. Table II lists the number of events in the data and the number of expected events from SM background sources.

Systematic uncertainties on the background are deter-

TABLE I: Efficiencies after all cuts and 95% C.L. upper limits on production cross section $\times$ branching fraction Br, as a function of $M_{\rm LQ}$, for the two channels.

$M_{\rm LQ}$(GeV/c^2)	$eejj$		$e\nu jj$	
	ϵ(%)	$\sigma\times$Br(pb)	ϵ(%)	$\sigma\times$Br(pb)
120	2.2±0.5	0.950	4.6±0.5	0.34
140	4.5±0.9	0.444	7.9±0.8	0.20
160	8.9±1.7	0.223	11.7±1.1	0.14
180	12.6±2.4	0.156	15.5±1.5	0.10
200	18.5±3.0	0.102	17.8±1.7	0.088
220	24.6±3.5	0.075	18.9±1.8	0.083
240	30.3±3.9	0.060	20.9±1.9	0.075
260	34.0±4.0	0.053	21.9±2.1	0.071
280	36.0±4.0	0.050	22.7±2.1	0.069

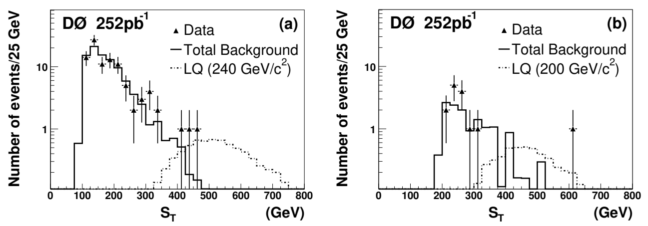

FIG. 1: The S_T distributions for the $eejj$ events (a) and $e\nu jj$ events (b) from data (triangles) compared to the SM background (solid histograms). The dot-dashed histograms are the expected distributions for a 240 GeV/c^2 LQ signal (a) and for a 200 GeV/c^2 LQ signal (b).

TABLE II: Number of events in data compared with background expectation at different stages of the $eejj$ analysis.

	$eejj$	Z boson veto	S_T >450 GeV
Data	467	95	1
Total background	406 ± 100	92±17	0.54±0.11
Z/DY + jets	342 ± 99	41 ± 11	0.22±0.07
Multijet	59 ± 16	47 ± 13	0.27±0.08
$t\bar{t}$ production	4.7 ± 0.4	3.8 ± 0.3	0.05±0.01

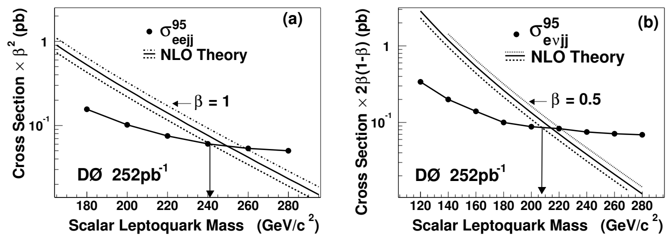

FIG. 2: The 95% C.L. limit on the experimental cross section times branching fraction as a function of LQ mass (circles) for the $eejj$ (a) and $e\nu jj$ (b) channels. The NLO theoretical cross sections [15] are plotted for different values of the renormalization scale factor: $M_{\rm LQ}$ (full line), $M_{\rm LQ}/2$ (dotted curve) and $2M_{\rm LQ}$ (dashed curve) taking into account the PDF uncertainties. A mass limit of 241 GeV/c^2 (a) and of 208 GeV/c^2 (b) for first-generation scalar leptoquarks is obtained for β=1 and β=0.5, respectively.

mined to be 15% from the QCD normalization factor and 6% from the efficiencies of the identification of electrons and jets (particle-ID). An uncertainty (26%) from the jet energy scale is determined by varying the correction factor on the calorimeter response to jets by one standard deviation. A systematic uncertainty on the Z/DY background (20%) is calculated by taking into account the differences between the two Z/DY MC samples. On the signal, the particle-ID and the limited statistics of the MC sample correspond to systematic uncertainties of 6% and 1.2% respectively. Comparing acceptances for the signal samples generated with PYTHIA using different parametrizations of parton distribution functions (PDFs) leads to an uncertainty of 5%. The uncertainty due to the jet energy scale is dependent on the LQ mass (7.3% for a LQ mass of 240 GeV/c^2). The total uncertainty on the efficiency is (17–9)% in the mass range 180–280 GeV/c^2.

The data are consistent with the expected SM background and no evidence for leptoquark production is observed in the $eejj$ channel. Thus we can set an upper limit at the 95% C.L. on the LQ pair production cross section using a Bayesian approach [14]. The limits are tabulated in Table I and shown in Fig. 2a as a function of LQ mass. To compare our experimental results with theory, we use the next-to-leading order (NLO) cross section for scalar leptoquark pair production from Ref. [15], with the CTEQ6 PDF [16]. The theoretical uncertainties correspond to the variation from $M_{\rm LQ}/2$ to $2M_{\rm LQ}$ of the renormalization scale μ used in the calculation and to the errors on the PDFs. To set a limit on the LQ mass we compare our experimental limit to the theoretical cross section for $\mu = 2M_{\rm LQ}$, which is conservative as it corresponds to the lower value of the theoretical cross section. The value of the theoretical cross section would increase by $\sim$ 7% if the PDF errors were neglected. A lower limit on the leptoquark mass of 241 GeV/c^2 is obtained for β=1.

The $e\nu jj$ analysis requires exactly one tight EM cluster ($E_T^{\rm EM}$ > 35 GeV) in the CC fiducial region which matches an isolated track spatially and kinematically. At least two jets with E_T > 25 GeV within $|\eta|$ < 2.4 and $\not\!\!E_T$ > 30 GeV are required. The main SM background sources which would mimic the $e\nu jj$ decay of a LQ pair are events with multijet production (where a jet is reconstructed as an electron and the $\not\!\!E_T$ comes from jet mismeasurements), W + 2 jets events, and top quark pair production. A veto on muons with p_T > 10 GeV/c is applied to reduce the di-lepton background from $t\bar{t}$ decays. To suppress background from W boson production, events with a transverse mass of the electron and the missing energy $M_T^{e\nu}$ < 130 GeV/c^2 are rejected. Finally S_T > 330 GeV is required, where here S_T is the sum of the transverse energies of the electron, the two

TABLE III: Number of events in data compared with background expectation at different stages of the $e\nu jj$ analysis. The values of the cuts are in GeV or in GeV/c^2.

	$\not\!\!E_T > 30$	$M_T^{e\nu} > 130$	$S_T > 330$
Data	900	14	1
Total background	902 ± 211	13.9 ± 4.4	3.6 ± 1.2
W + jets	811 ± 211	10.0 ± 4.4	2.2 ± 1.2
Multijet	76 ± 7	2.3 ± 0.5	0.72 ± 0.28
$t\bar{t}$ production	14.7 ± 2.9	1.6 ± 0.37	0.70 ± 0.17

jets, and the $\not\!\!E_T$. The distribution of the variable S_T for the data and the total background is shown in Fig. 1b after applying the $M_T^{e\nu}$ cut. The choice of the cutoff has been optimized as above. The total efficiency of these cuts for a LQ signal is given in Table I. To determine the multijet background we use a data sample that passed all the preceeding cuts but with a loose EM cluster matching spatially a track. The QCD normalization factor is determined using the ratio of the number of events with $\not\!\!E_T < 10$ GeV in this and in the search samples. The W boson background is normalized to the data at transverse mass 60 GeV/c^2 $< M_T^{e\nu} <$ 100 GeV/c^2. The top quark background is normalized to the integrated luminosity using the NNLO theoretical cross section. The number of events which survive the cuts and the number of predicted background events are summarized in Table III.

Systematic uncertainties associated with the QCD normalization factor (9%) and W boson normalization factor (5.7%) are determined by the limited statistics of the samples and the choice of kinematical domain over which the normalization is done. The jet energy scale uncertainty introduces uncertainties equal to 25% for W boson production and 8.5% for the top-quark-pair production. For the W boson background an uncertainty equal to 33% is associated to the shape of the $\not\!\!E_T$ distribution. A 25% error has been included as systematic uncertainty on the top quark cross section. Finally, there is an uncertainty of 3.8% on the particle-ID acceptance. Three systematic uncertainties are determined on the signal acceptance: 3.8% comes from the uncertainty on the particle-ID, 5% is due to the jet energy scale uncertainty, and 5.4% corresponds to the acceptance variations for different PDF parameterizations.

As no excess of data over background is found in the $e\nu jj$ channel, an upper limit on the production cross section for a first-generation scalar leptoquark is derived and shown in Fig. 2b and in Table I. A comparison of these limits to theoretical calculations of the cross section [15], performed as described above, gives a lower limit on the first-generation scalar LQ mass of 208 GeV/c^2 for $\beta = 0.5$.

Combination of the limits obtained in the searches in the $eejj$ and $e\nu jj$ channels is done using a Bayesian likelihood technique [17], with correlated uncertainties taken into account. The limits on the cross sections obtained at the 95% C.L. for the combination of the two channels and different values of β are compared with the NLO LQ pair production cross section [15] and lower mass limits are derived and given, as a function of β, in Table IV and shown in Fig. 3. In Table IV are also shown the Run I mass limits based on an integrated luminosity $\sim 120\,\mathrm{pb}^{-1}$ obtained by DØ [4], using the three channels $eejj$, $e\nu jj$ and $\nu\nu jj$, and CDF [5] ($eejj$ channel). This analysis sets a 95% C.L. limit on the first-generation leptoquark mass of $M_{\mathrm{LQ}} > 218$ GeV/c^2 for β=0.5, and $M_{\mathrm{LQ}} > 241$ GeV/c^2 for β=1. The DØ Run II and Run I results are combined, using the same method, and the results are shown in Table IV and in Fig. 3. The 95% C.L. limits on the first-generation leptoquark mass are $M_{\mathrm{LQ}} > 234$ GeV/c^2 for β=0.5, and $M_{\mathrm{LQ}} > 256$ GeV/c^2 for β=1.

TABLE IV: 95% C.L. lower limits on the first-generation scalar leptoquark mass (in GeV/c^2), as a function of β. The mass limits from DØ ($eejj$, $e\nu jj$ and $\nu\nu jj$ combined) [4] and CDF ($eejj$) [5] at Run I ($\sim$ 120 pb^{-1}) are also given, as well as the limits obtained by combining the DØ Run I and Run II results.

β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.
$eejj$					158	180	203	220	232	241
$e\nu jj$	169	193	203	207	208	207	203	193	169	
Comb. Run II	169	193	204	212	218	223	228	232	237	241
DØ Run I	110				204					225
DØ Runs I & II	183	206	218	227	234	239	244	248	252	256
CDF Run I										213

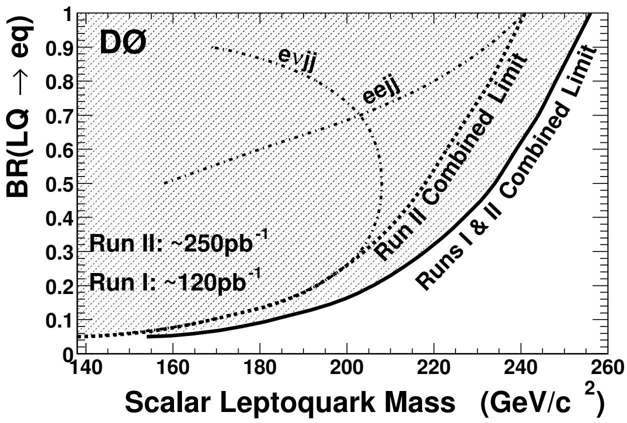

FIG. 3: Excluded regions (shaded area) at the 95% C.L. in the β versus LQ mass plane for the production of first-generation scalar leptoquarks.

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[*] Visitor from University of Zurich, Zurich, Switzerland.

[1] Darin E. Acosta and Susan K. Blessing, Ann. Rev. Nucl. Part. Sci. **49,** 389(1999) and references therein;
P. Bruce Straub, Proceedings of 31st International Conference on High Energy Physics, (ICHEP 2002), Amsterdam, The Netherlands, 24-31 Jul 2002, hep-ex/0212023.

[2] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **11**, 447 (1999); Erratum ibid. C **14** 553 (2000);
H1 Collaboration, C. Adloff *et al.*, Phys. Lett. B **523**, 234 (2001);
ZEUS Collaboration, J. Breitweg *et al.*, Eur. Phys. J. C **16**, 253 (2000);
ZEUS Collaboration, J. Breitweg *et al.*, Phys. Rev. D **63**, 052002 (2001).

[3] DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. B **446**, 6 2 (1999);
OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. B **526**, 233 (2002);
L3 Collaboration, M. Acciari *et al.*, Phys. Lett. B **489**, 81 (2000);
ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. C **12**, 183 (2000).

[4] DØ Collaboration, V. Abazov *et al.*, Phys. Rev. D **64**, 092004 (2001).

[5] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 4327 (1997).

[6] CDF Collaboration, D. Acosta *et al.*, FERMILAB-PUB-04-306-E, submitted to Phys. Rev. Lett.

[7] V. Abazov *et al.*, in preparation for submission to Nucl. Instrum. Methods Phys. Res. A; T. LeCompte and H.T. Diehl, Ann. Rev. Nucl. Part. Sci. **50**, 71 (2000).

[8] $\eta = -\ln(\tan(\theta/2)$ where θ is the polar angle measured relative to the proton beam direction.

[9] S. Abachi, *et al.*, Nucl. Instrum. Methods Phys. Res. A **338**, 185 (1994).

[10] G. Blazey, *et al.*, in Proceedings of the workshop "QCD and Weak Boson Physics in Run II", edited by U. Baur, R.K. Ellis, and D. Zeppenfeld, Batavia (2000) p. 47.

[11] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, A. Polosa, hep-ph/0206293, JHEP **0307** (2003) 001.

[12] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).

[13] R. Brun and F. Carminati, CERN Program Library Long Writeup W5013 (1993).

[14] I. Bertram *et al.*, Fermilab TM-2104 (1998).

[15] M. Krämer, *et al.*, Phys. Rev. Lett. **79,** 341 (1997).

[16] J. Pumplin *et al.*, JHEP **0207** (2002) 012;
D. Stump *et al.*, JHEP **0310** (2003) 046.

[17] C. Grosso-Pilcher, G. Landsberg, and M. Paterno, hep-ex/9810015.