

## Search for Second-Generation Leptoquark Pairs in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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(Received 20 October 1999)

We have searched for second-generation leptoquark (LQ) pairs in the  $\mu\mu + \text{jets}$  channel using  $94 \pm 5 \text{ pb}^{-1}$  of  $\bar{p}p$  collider data collected by the D0 experiment at the Fermilab Tevatron during 1993–1996. No evidence for a signal is observed. These results are combined with those from the

$\mu\nu + \text{jets}$  and  $\nu\nu + \text{jets}$  channels to obtain 95% confidence level (C.L.) upper limits on the LQ pair production cross section as a function of mass and  $\beta$ , the branching fraction of a LQ decay into a charged lepton and a quark. Lower limits of 200(180) GeV/ $c^2$  for  $\beta = 1(\frac{1}{2})$  are set at the 95% C.L. on the mass of scalar LQ. Mass limits are also set on vector leptoquarks as a function of  $\beta$ .

PACS numbers: 13.85.Rm, 13.85.Qk, 14.80.-j

The observed symmetry in the spectrum of fundamental particles between leptons ( $l$ ) and quarks ( $q$ ) has led to suggestions of the existence of leptoquarks (LQ) [1]. Leptoquarks would carry both lepton and quark quantum numbers, and would decay to  $lq$  systems. Although, in principle, leptoquarks could decay to any  $lq$  combinations, limits on flavor-changing neutral currents, rare lepton-family violating decays, and proton decay suggest that leptoquarks would couple only within a generation [2], implying the existence of three LQ generations analogous to the standard model fermion generations.

At the Fermilab Tevatron, leptoquarks are predicted [3] to be produced dominantly via  $q\bar{q}$  annihilation through gluon ( $g$ ) splitting,  $q\bar{q} \rightarrow g + X \rightarrow LQ\bar{L}Q + X$ . This Letter reports on an enhanced search for second-generation leptoquark pairs produced in  $\bar{p}p$  interactions at a center-of-mass energy  $\sqrt{s} = 1.8$  TeV. The experimental signature considered is when both leptoquarks decay via  $LQ \rightarrow \mu q$ , where  $q$  can be either a strange or a charm quark depending on the electric charge of the LQ. The corresponding experimental cross section is  $\beta^2 \times \sigma(\bar{p}p \rightarrow LQ\bar{L}Q)$ , where  $\beta$  is the unknown branching fraction of a LQ to a muon ( $\mu$ ) and a quark (jet).

Previous studies by the D0 [4] and CDF [5] Collaborations have considered pair production of scalar leptoquarks in  $\mu\mu + \text{jets}$  final states. These studies provide lower limits on the mass of LQs of 119 and 202 GeV/ $c^2$ , respectively, for  $\beta = 1$ . Lower limits of 160 GeV/ $c^2$  for  $\beta = 1/2$  were obtained by D0 from the  $\mu\nu + \text{jets}$  final state [6] and by CDF from the  $\mu\mu + \text{jets}$  final state [5]. For  $\beta = 0$ , D0 has obtained a lower limit of 79 GeV/ $c^2$  from the  $\nu\nu + \text{jets}$  channel [7].

This present study is complementary to previous D0 searches in the  $\mu\nu + \text{jets}$  [6] and  $\nu\nu + \text{jets}$  [7] final states, and greatly extends the previous search in the  $\mu\mu + \text{jets}$  channel [4]. The sensitivity for detection of leptoquarks is increased by considering a larger data set that uses the calorimeters to identify muon candidates, and employs several optimization techniques to enhance efficiency. These results are combined with results from other decay channels to improve mass limits on LQs. (A full description of this analysis can be found in Ref. [8].)

The D0 detector [9] consists of three major components: an inner detector for tracking charged particles, a uranium/liquid argon calorimeter for measuring electromagnetic and hadronic showers, and a muon spectrometer consisting of magnetized iron toroids and three layers of drift tubes. Jets are measured with an energy resolution of approximately  $\sigma(E)/E = 0.8/\sqrt{E}$  ( $E$  in GeV). Muons

are measured with a momentum resolution of  $\sigma(1/p) = 0.18(p - 2)/p^2 \oplus 0.003$  ( $p$  in GeV/ $c$ ).

Event samples are obtained from triggers requiring the presence of a muon candidate with transverse momentum  $p_T^\mu > 5$  GeV/ $c$  in the fiducial region  $|\eta_\mu| < 1.7$  ( $\eta \equiv -\ln[\tan(\frac{1}{2}\theta)]$ , where  $\theta$  is the polar angle of a track with respect to the  $z$  axis taken along the direction of the proton beam), and at least one jet candidate with transverse energy  $E_T^j > 8$  GeV and  $|\eta_j| < 2.5$ . The data correspond to an integrated luminosity of  $94 \pm 5$  pb $^{-1}$  collected during the 1993–1996 Tevatron collider runs at Fermilab [10].

Jets are measured in the calorimeters and are reconstructed offline with a cone algorithm having radius  $\mathcal{R} \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.5$ . Candidate events must have two or more jets with  $E_T^j > 20$  GeV and  $|\eta_j| < 3.0$ .

Muon candidates reconstructed in the muon spectrometer are required to have a track that projects back to the interaction vertex. The track is required to be consistent with a muon of  $p_T^\mu > 20$  GeV/ $c$ . In addition, the muon is required to deposit energy in the calorimeters consistent with the passage of a minimum ionizing particle (MIP). To reduce backgrounds from heavy quark production, candidate muons are required to be isolated from all identified jets by  $\Delta R_{\mu j} > 0.5$  in the  $\eta$ - $\phi$  plane.

Muon candidates which are not reconstructed in the spectrometer can also be tracked in the calorimeters, where an isolated high- $p_T$  muon deposits only a small fraction of its total energy. This results in a unique energy signature consisting of energy from a MIP ( $E_{\text{MIP}}$ ) [6,11] and a large transverse energy imbalance ( $\cancel{E}_T$ ) in the calorimeters that is proportional to the muon momentum, and points in the azimuthal direction of  $E_{\text{MIP}}$ . Muon candidates in the calorimeters are required to have  $|\Delta\phi(E_{\text{MIP}} - \cancel{E}_T)| < 0.25$  rad. The kinematic quantities (e.g.,  $p_T^\mu$ ) of these candidates are calculated using the  $(\eta, \phi)$  direction of  $E_{\text{MIP}}$  and the component of the  $(\cancel{E}_T)$  along the azimuthal direction of the  $E_{\text{MIP}}$ . These muon candidates are also required to have  $p_T^\mu > 20$  GeV/ $c$ .

Dimuon candidate events are required to have at least one identified muon in the central muon spectrometer ( $|\eta_\mu| < 1.0$ ). A second muon may be identified with the muon spectrometer or the calorimeters within  $|\eta_\mu| < 1.7$ .

After obtaining a sample of  $\mu\mu + \text{jets}$  events, a selection is applied to the event topology. Heavy LQ pairs are expected to have a smaller Lorentz boost, and to decay more symmetrically, than the background events. To take advantage of these differences, the sphericity in the center-of-mass frame ( $S_{\text{c.m.}}$ ) is required to be greater than 0.05.  $S_{\text{c.m.}} \equiv 1.5(\lambda_1 + \lambda_2)$ , where  $\lambda_1 \leq \lambda_2 \leq \lambda_3$  are the normalized eigenvalues of the momentum tensor,

formed from the  $E_T$  ( $p_T$ ) of all jets (muons) in an event.  $S_{c.m.} = 0$  (1) corresponds to a linear (spherical) topology.

Leptoquark events are simulated with the ISAJET [12] Monte Carlo event generator for scalar LQ ( $S_{LQ}$ ), and with PYTHIA [13] for vector LQ ( $V_{LQ}$ ). The detection efficiencies for  $S_{LQ}$  and  $V_{LQ}$  of the same mass are found to be consistent within the uncertainties. For massive vector leptoquarks ( $m_{V_{LQ}} > 200 \text{ GeV}/c^2$ ), efficiencies are insensitive to differences between minimal vector (MV) ( $\kappa_G = 1, \lambda_G = 0$  [14]) and Yang-Mills (YM) ( $\kappa_G = \lambda_G = 0$  [14]) couplings to standard model bosons [15]. Consequently, the  $S_{LQ}$  Monte Carlo is used to represent the shapes of distributions for both  $S_{LQ}$  and  $V_{LQ}$  analyses.

The leptoquark cross sections for  $S_{LQ}$  are next-to-leading-order calculations (NLO) [16] at a renormalization scale  $\mu = m_{S_{LQ}}$ . The uncertainties are determined from the variation of the renormalization/factorization scale from  $2m_{S_{LQ}}$  to  $\frac{1}{2}m_{S_{LQ}}$ . Both types of  $V_{LQ}$  cross sections are calculated to leading order (LO) at  $\mu = m_{V_{LQ}}$  [14].

The dominant backgrounds are due to  $W$  + jets and  $Z$  + jets production, and are simulated using VECBOS [17] at the parton level and HERWIG [18] for parton fragmentation. Background due to  $WW$  production is simulated with PYTHIA [13]. Background from  $t\bar{t}$  production is simulated using HERWIG with a top quark mass of  $170 \text{ GeV}/c^2$ . Monte Carlo samples are processed through a GEANT [19] based detector simulation.

After the initial selection, there are 53 events in the data sample consistent with an estimated background of  $53 \pm 13$  events. The distribution in invariant mass ( $m_{\text{event}}$ ) calculated from all identified muons and jets is given in Fig. 1. The largest expected background is from  $W$  + jets ( $43 \pm 13$  events), where  $\cancel{E}_T$  from a neutrino is misidentified as a second muon when low-energy jets or calorimeter noise mimic the energy signature of a MIP. The other backgrounds are from  $Z$  + jets events ( $5.6 \pm 0.9$ ),  $WW$  events ( $2.3 \pm 0.9$ , consistent with previous experimental limits at D0 [20]), and  $t\bar{t}$  events ( $2.1 \pm 0.6$ ). The uncertainty in the background estimate is dominated by the statistical uncertainty of the  $W$  + jets Monte Carlo and the systematic uncertainty in the  $W$  + jets production cross section. The production estimate for  $200 \text{ GeV}/c^2$   $S_{LQ}$  passing the selection requirements is  $3.7 \pm 0.4$  events. All LQ production estimates are for  $200 \text{ GeV}/c^2$   $S_{LQ}$  at a scale  $\mu = 2m_{S_{LQ}}$ .

A neural network (NN) analysis [21] is employed to separate any possible signal from background. The NN is trained using a mixture of  $W$  + jets,  $Z$  + jets, and  $t\bar{t}$  background Monte Carlo events, and an independently generated  $S_{LQ}$  Monte Carlo sample for a mass  $m_{S_{LQ}} = 200 \text{ GeV}/c^2$ . The NN uses seven inputs [ $E_T^{j_1}, E_T^{j_2}, p_T^{\mu_1}, p_T^{\mu_2}, (E_T^{j_1} + E_T^{j_2}), m_{\text{event}}$ , and  $(E_T^{j_1} + E_T^{j_2})/\sum E_T^{j_i}$ , where jets (muons) are ordered in  $E_T$  ( $p_T$ )] and 15 nodes in a single hidden layer to calculate an output. The network output ( $D_{NN}$ ) are shown in Fig. 2.

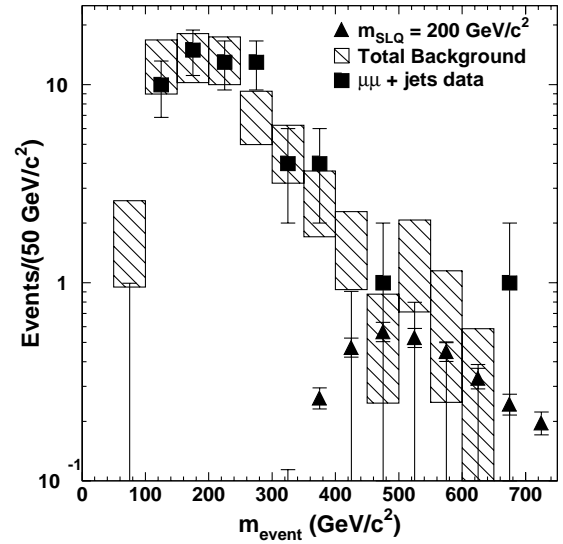


FIG. 1. Invariant mass of  $\mu\mu$  + jets events, calculated from all identified muons and jets. Hatched regions give the background estimation, square points are  $\mu\mu$  + jets data, and triangular points are the prediction for  $S_{LQ}$  from Monte Carlo. Uncertainties on bins with no data points are obtained from the 68% confidence interval.

No evidence of a signal is seen either in the  $D_{NN}$  discriminant or in any kinematic distribution. The  $D_{NN}$  selection is optimized for the calculation of limits using a measure of sensitivity [6] calculated from samples of  $S_{LQ}$  and background Monte Carlo. The requirement is set at  $D_{NN} > 0.9$ . For this selection no events are observed, consistent with an estimated background of  $0.7 \pm 0.5$  events ( $0.49 \pm 0.16$   $t\bar{t}$ ,  $0.15 \pm 0.04$   $Z$  + jets,  $0.05 \pm 0.05$   $WW$ , and  $0_{-0.0}^{+0.5}$   $W$  + jets events).  $S_{LQ}$  production is estimated at  $3.3 \pm 0.3$  events.

The selection criteria are applied to the Monte Carlo for a range of LQ masses. The leptoquark detection

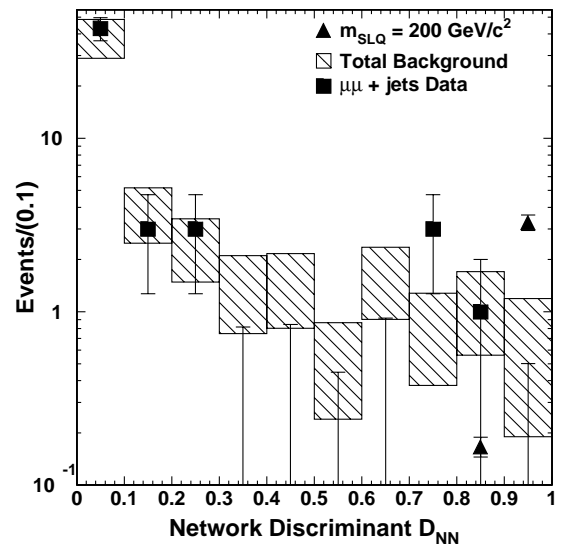


FIG. 2. Output of the neural network. The NN calculates a value for each event based on the inputs and a set of internal values determined during NN training (see text).

TABLE I. Leptoquark detection efficiencies (with statistical and systematic uncertainties) and 95% C.L. cross section limits for leptoquarks in the  $\mu\mu + \text{jets}$  channel and for the combination of all decay channels at  $\beta = \frac{1}{2}$ . Cross sections for  $S_{LQ}$  (NLO) and  $V_{LQ}$  (LO) pair production are also shown.

LQ mass (GeV/ $c^2$ )	Efficiency (%)	$\sigma_{\mu\mu+\text{jets}}^{95\%}$ (pb)	$\sigma_{\text{combined}}^{95\%}$ (pb)	$\sigma_{S_{LQ}}$ (pb)	$\sigma_{MV}$ (pb)	$\sigma_{YM}$ (pb)
140	$10.3 \pm 0.3 \pm 1.1$	0.33	0.55	1.5	20	100
160	$14.5 \pm 0.3 \pm 1.6$	0.24	0.38	0.68	8.0	50
180	$18.9 \pm 0.4 \pm 2.1$	0.18	0.31	0.32	4.0	20
200	$21.8 \pm 0.4 \pm 2.1$	0.16	0.26	0.16	2.0	10
220	$22.6 \pm 0.4 \pm 2.4$	0.15	0.26	0.08	0.90	5.0
240	$23.5 \pm 0.4 \pm 2.5$	0.15	0.24	0.04	0.45	2.5
260	$24.3 \pm 0.5 \pm 2.6$	0.15	0.24	0.02	0.25	1.2
280	$26.0 \pm 0.5 \pm 2.8$	0.13	0.22	...	0.12	0.60
300	$25.3 \pm 0.5 \pm 2.7$	0.13	0.23	...	0.06	0.35
350	$25.7 \pm 0.5 \pm 2.8$	0.13	0.23	...	...	0.06
400	$25.7 \pm 0.5 \pm 2.8$	0.13	0.22	...	...	...

efficiencies, estimated to be 10%–26% depending on the LQ mass, are listed in Table I, along with the 95% confidence level (C.L.) upper limits on the cross sections. The limits are calculated using a Bayesian approach, with a flat prior distribution for the signal cross section. The statistical and systematic uncertainties on efficiencies, integrated luminosity (5%), and background estimates are included assuming Gaussian prior distributions.

The dominant (10%) systematic uncertainty in the efficiencies is due to uncertainty in the simulation. There are also approximately equal uncertainties in the jet energy scale [22] and high- $p_T^\mu$  trigger efficiency/spectrometer resolution (6.6% and 6.4%, respectively).

Figure 3 shows the limits on the pair production cross sections for scalar and vector leptoquarks obtained from this search, corrected for the branching ratio ( $BR = \beta^2$  for  $\mu\mu + \text{jets}$ ). The results are given for  $\beta = 1$  and  $\frac{1}{2}$ .

The lower mass limits at the 95% confidence level, obtained from comparing the cross section limits with the theory cross sections at  $\mu = 2m_{S_{LQ}}$  for the  $\mu\mu + \text{jets}$  decay channel at  $\beta = 1$  (1/2), are 200 (145) GeV/ $c^2$ , 270 (225) GeV/ $c^2$ , and 325 (280) GeV/ $c^2$  for scalar, MV, and YM vector couplings, respectively.

The results from the  $\mu\mu + \text{jets}$  ( $BR = \beta^2$ ) search are combined with results from previous second-generation leptoquark searches in the  $\mu\nu + \text{jets}$  [ $BR = 2\beta(1 - \beta)$ ] [6] and  $\nu\nu + \text{jets}$  [ $BR = (1 - \beta)^2$ ] [7] channels. Limits on the combined cross section ( $BR = 1$ ) are listed in Table I, for  $\beta = 1/2$ . These limits are also shown in Fig. 3, and the lower mass limits obtained are 180 GeV/ $c^2$  ( $S_{LQ}$ ), 260 GeV/ $c^2$  (MV), and 310 GeV/ $c^2$  (YM), all at the 95% confidence level. Mass limits calculated from the combination of channels as a function of  $\beta$  are shown in Fig. 4 and summarized in Table II.

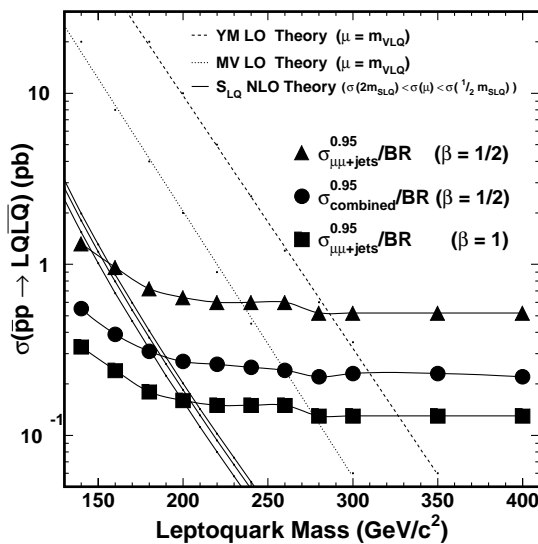


FIG. 3. 95% C.L. limits on pair production cross sections. Results are shown for the  $\mu\mu + \text{jets}$  channel ( $\sigma_{\mu\mu+\text{jets}}^{0.95}$ ) for  $\beta = 1$ ,  $\frac{1}{2}$ , and for all combined searches ( $\sigma_{\text{combined}}^{0.95}$ ) at  $\beta = \frac{1}{2}$ .

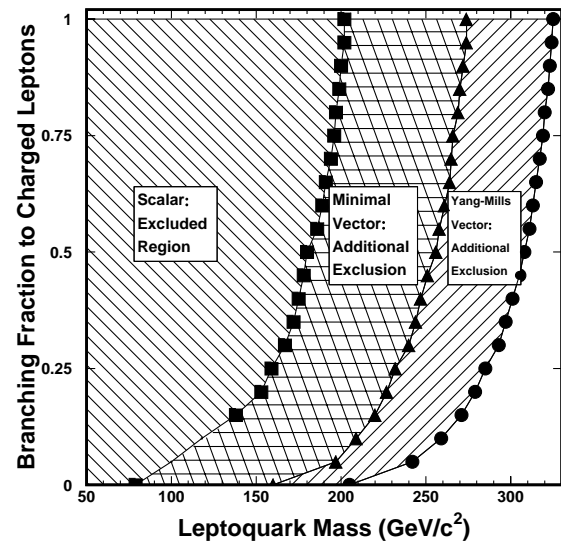


FIG. 4. The regions in the  $\beta - m_{LQ}$  plane excluded by combining the results of the  $\mu\mu + \text{jets}$ ,  $\mu\nu + \text{jets}$ , and  $\nu\nu + \text{jets}$  searches. The area to the left of each curve is excluded for that type of coupling, at the 95% confidence level.

TABLE II. Combined 95% C.L. lower mass limits for second-generation leptoquarks.

$\beta$	Scalar (GeV/ $c^2$ )	MV (GeV/ $c^2$ )	YM (GeV/ $c^2$ )
1	200	275	325
1/2	180	260	310
0	79	160	208

In conclusion, a search has been performed for second-generation leptoquark pairs decaying via  $LQ \rightarrow \mu q$  using  $94 \pm 5 \text{ pb}^{-1}$  of data. No evidence is found for a signal, and limits are set at the 95% confidence level on the mass of second-generation leptoquarks. By combining these results with those from previous studies, comprehensive limits on second-generation leptoquarks are obtained. These are shown as exclusion contours constraining the possible values of  $\beta$  and  $m_{LQ}$  by coupling.

We thank the Fermilab and collaborating institution staffs for contributions to this work, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES and CNPq (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (Korea), CONICET and UBACyT (Argentina), and the A. P. Sloan Foundation.

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