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

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Abstract

We have searched for second generation leptoquark (LQ) pairs in the $\mu\mu$+jets channel using 94 ± 5 pb^{-1} of $\overline{p}p$ collider data collected by the DØ experiment at the Fermilab Tevatron during 1993–1996. No evidence for a signal is observed. These results are combined with those from the $\mu\nu$+jets and $\nu\nu$+jets channels to obtain 95% confidence level (C.L.) upper limits on the LQ pair production cross section as a function of mass and β, 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 scalar LQ mass. Mass limits are also set on vector leptoquarks as a function of β.

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The apparent symmetry between leptons (l) and quarks (q) has suggested the existence of leptoquarks (LQ) in many extensions of the standard model [1]. Leptoquarks would carry both lepton and quark quantum numbers, and would decay to lq. Although leptoquarks could decay to any lq combination, limits on flavor-changing neutral currents, rare lepton-family violating decays, and proton decay suggest that leptoquarks would couple only within a single generation [2]. This implies that LQ would have three generations analogous to the fermion generations in the standard model.

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

Both scalar and vector leptoquark pairs can decay to the $\mu\mu$+jets final state. The present search is complimentary to previous DØ studies of the $\mu\nu$+jets [4] and $\nu\nu$+jets [5] decay channels, and extends a previous search in the $\mu\mu$+jets decay channel [6]. Sensitivity for the detection of leptoquarks is increased by considering a larger data set, using the calorimeter to identify muon candidates, and employing several optimization techniques to enhance efficiency. In addition, the results of this search are combined with results from the other decay channels. A detailed description of this analysis may be found in Ref. [7].

Previous studies by the DØ [6] and CDF [8] collaborations have considered scalar leptoquarks in the $\mu\mu$+jets decay channel resulting in lower mass limits of 119 GeV/c^2 and 202 GeV/c^2, respectively, for $\beta = 1$. Lower limits of 160 GeV/c^2 for $\beta = 1/2$ have been obtained by DØ from the $\mu\nu$+jets final state [4] and by CDF from the $\mu\mu$+jets final state [8]. For $\beta = 0$, DØ has obtained a lower limit of 79 GeV/c^2 from the $\nu\nu$+jets channel [5].

The DØ 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 a magnetized iron toroid 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 θ is the polar angle of a track with respect to the z–axis taken along the proton beam direction), and at least one jet candidate with transverse energy $E_T^j > 8$ GeV and $|\eta_j| < 2.5$. The data used correspond to an integrated luminosity of 94 ± 5 pb^{-1} collected during the 1993–1995 and 1996 Tevatron collider runs at Fermilab.

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

Muon candidates reconstructed in the muon spectrometer are required to have a track which projects back to the interaction vertex. The track is required to be consistent with a muon of $p_T^\mu > 20$ GeV/c and $|\eta_\mu| < 1.7$. In addition, the muon is required to deposit energy in the calorimeter consistent with the passage of a minimum ionizing particle (MIP).

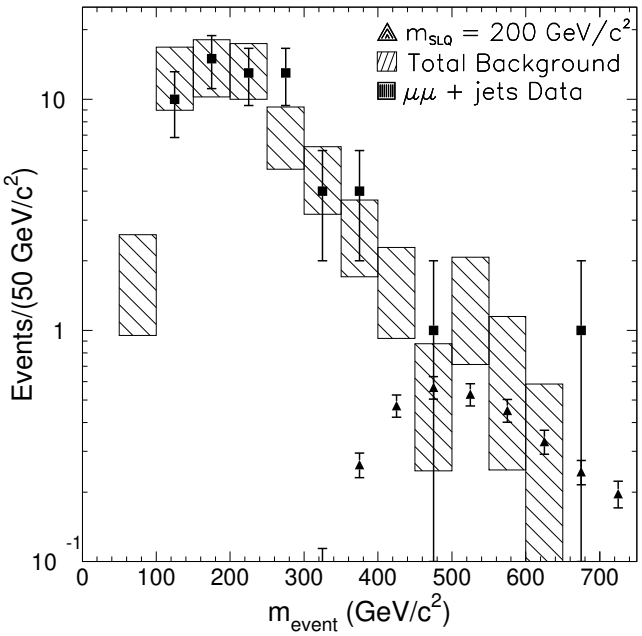

FIG. 1. Invariant mass of $\mu\mu$+jets events. The mass is calculated from all muons and jets which pass the selection criteria. In the figure the hatched regions give the background estimation, the square points are the $\mu\mu$+jets data, and the triangular points are the Monte Carlo prediction for $S_{\rm LQ}$.

To reduce backgrounds from heavy quark production, candidate muons are required to be isolated from jets by $\Delta R_{\mu j} > 0.5$ in the $\eta - \phi$ plane.

Muon candidates may also be reconstructed in the hadronic calorimeter, 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 minimum ionizing energy (MIE) [4,10] and a large transverse energy imbalance ($\not\!\!E_T$) in the event proportional to the muon momentum and in the azimuthal direction of the MIE. Muon candidates are identified in the region $|\eta| < 1.7$ and are required to have $|\Delta\phi(\text{MIE}–\not\!\!E_T)| < 0.25$ radians. The kinematic quantities (e.g., p_T^μ) of these candidates are calculated using the (η, ϕ) direction of the MIE and the component of the $\not\!\!E_T$ along the azimuthal direction of the MIE.

Dimuon candidate events are required to have two muons with $p_T^\mu > 20$ GeV/c. At least one muon must be identified in the central muon spectrometer ($|\eta_\mu| < 1.0$). A second muon with $|\eta_\mu| < 1.7$ may be identified using either the muon spectrometer or the hadronic calorimeter.

After obtaining a sample of $\mu\mu$+jets events, a selection is applied to the event topology. Heavy LQ pairs would receive a smaller Lorentz boost, and would decay more symmetrically than the various backgrounds. To take advantage of these differences, the sphericity in the z-boosted center-of-mass frame ($\mathcal{S}_{\rm CM}$) [11] is required to be greater than 0.05.

Leptoquark events are simulated with the ISAJET [12] Monte Carlo event generator for scalar Yang-Mills LQ ($S_{\rm LQ}$), and with PYTHIA [13] for vector LQ (V_{LQ}). The detection efficiencies for $S_{\rm LQ}$ and $V_{\rm LQ}$ of the same mass are found to be consistent within the uncertainties. In addition, the vector leptoquark efficiencies are insensitive to the 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 for large mass [15] ($m_{V_{LQ}} > 200$ GeV/c^2). The leptoquark cross sections used for the $S_{\rm LQ}$ are from next-to-leading-order (NLO) calculations [16] at a renormalization scale $\mu = m_{S_{\rm LQ}}$, with uncertainties determined from variation of the renormalization/factorization scale from $2m_{S_{\rm LQ}}$ to $\frac{1}{2}m_{S_{\rm LQ}}$. Both $V_{\rm LQ}$ cross sections are leading-order (LO) calculations at $\mu = m_{V_{\rm LQ}}$ [14]. The $S_{\rm LQ}$ and $V_{\rm LQ}$ cross sections are shown in Table I for several LQ masses.

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

There are 53 events in the data sample after the initial selection consistent with an estimated background of 53±13 events. These are shown in Fig. 1, where $m_{\rm event}$ is the invariant mass calculated from all muons and jets passing the selection criteria described above. The largest background is from W+jets (43±13 events) where $\not\!\!E_T$ 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 5.6±0.9 Z+jets events, 2.3±0.9 WW events, and 2.1±0.6 $t\bar{t}$ events. The uncertainty in the background estimate is dominated by statistical uncertainty in the W+jets Monte Carlo sample and the systematic uncertainty in the W+jets production cross section. The production estimate for 200 GeV/c^2 scalar leptoquarks passing all of the previous selection requirements is 3.7±0.4 events. All leptoquark production estimates are for 200 GeV/c^2 scalar LQ and use the NLO cross section at a scale $\mu = 2m_{S_{\rm LQ}}$.

To separate any possible signal from the backgrounds a neural network (NN) analysis is employed [20]. The NN is trained to separate LQ events from the backgrounds using a mixture of W+jets, Z+jets, and $t\bar{t}$ background Monte Carlo, and an independently generated LQ Monte Carlo sample for a mass $m_{S_{\rm LQ}} = 200$ GeV/c^2. The NN uses seven inputs: $E_T^{j_1}$, $E_T^{j_2}$, $p_T^{\mu_1}$, $p_T^{\mu_2}$, $(E_T^{j_1} + E_T^{j_2})$, $m_{\rm event}$ 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 (known as the discriminant, D_{NN}) is shown in Fig. 2.

Neither the D_{NN} nor any kinematic distribution shows evidence of a signal. The D_{NN} selection requirement is optimized for the calculation of limits using a measure of sensitivity [4] calculated from LQ and background Monte Carlo samples. The requirement is set to be $D_{NN} > 0.9$. For this selection no events are observed, consistent with an estimated background of 0.7±0.5 events (0.49±0.16 $t\bar{t}$, 0.15±0.04 Z+jets, 0.05±0.05 WW, and $0^{+0.5}_{-0.0}$ W+jets events). The LQ production estimate is 3.3±0.3 events.

The selection criteria are applied to the LQ Monte Carlo for a range of masses. The leptoquark detection efficiencies, estimated to be 10%-25% as a function of the LQ mass, are listed in Table I along with the 95% confidence level (C.L.) upper limits [21] on the cross sections [22]. The dominant systematic uncertainty in the efficiencies is due to uncertainty in the Monte Carlo simulation (initial and final state radiation, parton distribution function, renormalization scale and choice of generator) which contributes a 10% uncertainty. In addition, there are approximately equal contributions from uncertainty in the jet energy

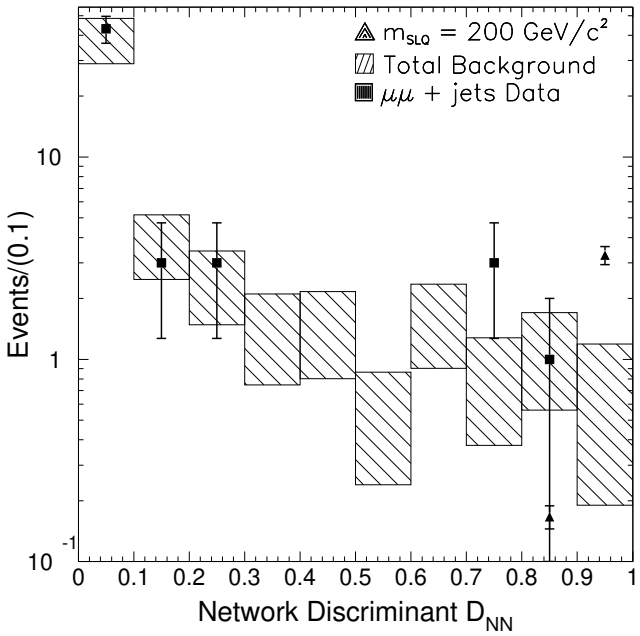

FIG. 2. Output of the neural network. The network calculates a value for each event based on the inputs (see text) and a set of internal values which are determined during network training on $S_{\rm LQ}$ and background Monte Carlo.

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

TABLE I. Leptoquark detection efficiencies (with statistical and systematic uncertainties) and 95% C.L. cross section limits for leptoquarks in the $\mu\mu$+jets channel and for the combination of all decay channels at $\beta = \frac{1}{2}$ [22]. $S_{\rm LQ}$ (NLO) and $V_{\rm LQ}$ (LO) pair production cross sections are also shown.

scale [23] and the trigger efficiency/spectrometer resolution for high-p_T muons (6.6% and 6.4% respectively).

Figure 3 shows the pair production cross section limits for scalar and vector leptoquarks obtained from this search, corrected for the branching ratio (BR = β^2 for $\mu\mu$+jets). The

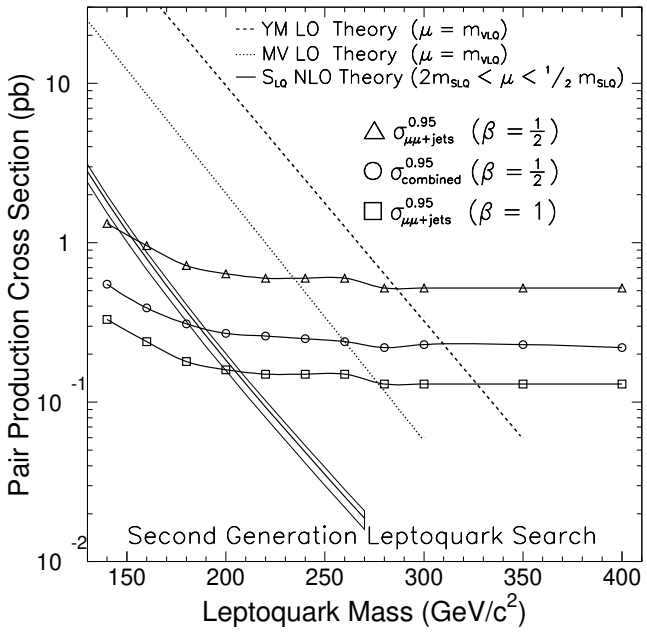

FIG. 3. 95% C.L. pair production cross section limits. Results are shown for the $\mu\mu$+jets channel for $\beta = 1, \frac{1}{2}$, and for the combination of channels at $\beta = \frac{1}{2}$.

β	Scalar (GeV/c^2)	MV (GeV/c^2)	YM (GeV/c^2)
1	200	275	325
1/2	180	260	310
0	79	160	205

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

experimental curves shown are at $\beta = 1$ and $\frac{1}{2}$. The lower mass limits from the $\mu\mu$+jets decay channel obtained from the plot 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 $\mu\mu$+jets (BR = β^2) search are combined with results from previous second generation leptoquark searches in the $\mu\nu$+jets (BR = $2\beta(1-\beta)$) [4] and $\nu\nu$ + jets (BR = $(1-\beta)^2$) [5] decay channels. Limits on the combined cross section (BR = 1) are listed in Table I, with the combination performed at $\beta = 1/2$. These limits are shown in Fig. 3 and the lower mass limits obtained are: 180 GeV/c^2 ($S_{\rm LQ}$), 310 GeV/c^2 (YM), and 260 GeV/c^2 (MV). Mass limits calculated from the combination of channels as a function of β are shown in Fig. 4 and summarized in Table II.

In conclusion a search has been performed for second generation leptoquark pairs decaying via LQ $\rightarrow \mu q$ using 94 ± 5 pb^{-1} of data collected with the DØ detector at the Fermilab Tevatron. No evidence for a signal is found and limits are set at the 95% confidence level on the mass of second generation leptoquarks. By combining the $\mu\mu$+jets results with those from previous studies of the $\mu\nu$+jets and $\nu\nu$+jets decay channels, exclusion contours are obtained which constrain the possible values of β and $m_{\rm LQ}$ for various couplings.

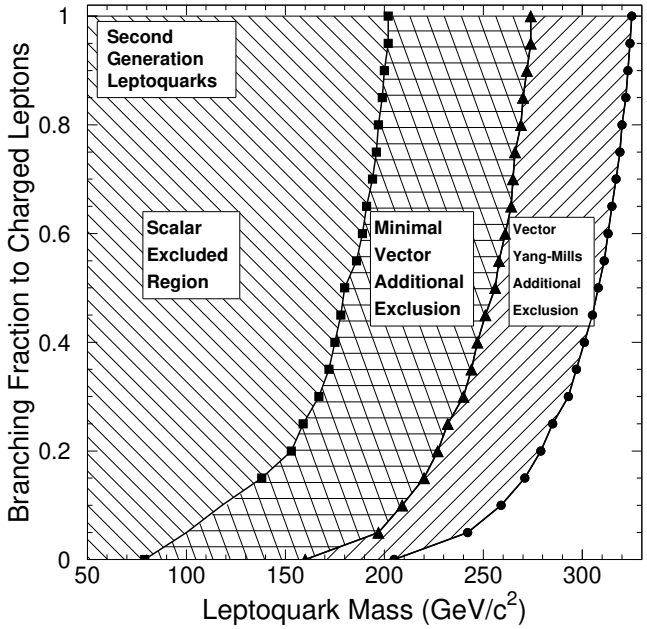

FIG. 4. The regions in the $\beta - m_{\rm LQ}$ plane excluded by combining the results of the $\mu\mu$+jets, $\mu\nu$+jets, and $\nu\nu$+jets searches. The area to the left of each curve is excluded for that coupling.

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[21] The limits are calculated using a Bayesian approach with a flat prior distribution for the signal cross section. The statistical and systematic uncertainties on the efficiencies, the integrated luminosity (5%), and the background estimate are included in the calculation assuming Gaussian prior distributions.

[22] The cross section limits for the $\mu\mu$+jets channel are independent of β, which enters only when comparing the experimental limits with the theoretical cross sections. A particular β is given for the combination since that value determines the relative contribution of each channel to the total cross section.

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