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Search for Second Generation Leptoquark Pairs in $\bar{\text{p}}\text{p}$ Collisions at $\sqrt{s}$ = 1.8 Tev

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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 mass of scalar LQ. Mass limits are also set on vector leptoquarks as a function of β.

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 single generation [2]. This implies the existence of three LQ generations, analogous to the fermion generations in the standard model.

At the Fermilab Tevatron, leptoquarks are predicted [3] to be produced dominantly via gluon (g) splitting, $\overline{p}p \to g + X \to LQ\overline{LQ} + X$. 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 when both leptoquarks decay via LQ $\to \mu q$, 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 $\beta^2 \times \sigma(\overline{p}p \to LQ\overline{LQ})$, where β is the unknown branching fraction of a LQ to a muon (μ) and a quark (jet).

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

The present study is complementary to previous DØ searches in the $\mu\nu$+jets [6] and $\nu\nu$+jets [7] final states, and greatly extends the previous search in the $\mu\mu$+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 detailed description of this analysis can be found in Ref. [8].)

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 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 θ 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 ± 5 pb^{-1} collected during the 1993–1995 and 1996 Tevatron collider runs at Fermilab [10].

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

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

Single muon candidates 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 ($E_{\rm MIP}$) [6,11] and a large transverse energy imbalance ($\not\!\!E_T$) in the calorimeter that is proportional to the muon momentum, and points in the azimuthal direction of the $E_{\rm MIP}$. Muon candidates are restricted to the region $|\eta| < 1.7$, and are required to have $|\Delta\phi(E_{\rm MIP}–\not\!\!E_T)| < 0.25$ radians. The kinematic quantities (e.g., p_T^μ) of these candidates are calculated using the (η, ϕ) direction of the $E_{\rm MIP}$ and the component of the $\not\!\!E_T$ along the azimuthal direction of the $E_{\rm MIP}$.

Dimuon candidate events are required to have two muons with $p_T^\mu > 20$ GeV/c. At least one muon must be 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 calorimeters.

After obtaining a sample of $\mu\mu$+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 ($\mathcal{S}_{\rm CM}$) is required to be greater than 0.05. $\mathcal{S}_{\rm CM}$ is defined as $1.5(\lambda_1 + \lambda_2)$, with $\lambda_1 \leq \lambda_2 \leq \lambda_3$ being the normalized eigenvalues of the momentum tensor. The momentum tensor is formed from the E_T (p_T) of all jets (muons) in an event, and $\mathcal{S}_{\rm CM} = 0$ (1) corresponds to a linear (spherical) topology.

Leptoquark events are simulated with the ISAJET [12] Monte Carlo event generator for scalar 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

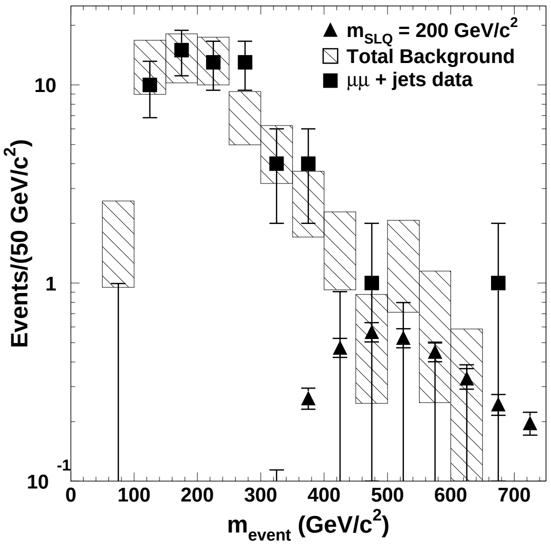

FIG. 1. Invariant mass of $\mu\mu$+jets events. The mass is calculated from all muons and jets that pass the selection criteria. The hatched regions give the background estimation, the square points are the $\mu\mu$+jets data, and the triangular points are the prediction for $S_{\rm LQ}$ from the Monte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

be consistent within the uncertainties. For massive vector leptoquarks ($m_{V_{\rm LQ}} > 200$ 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 $S_{\rm LQ}$ Monte Carlo is used to represent the shapes of distributions for both $S_{\rm LQ}$ and $V_{\rm LQ}$ analyses.

The leptoquark cross sections for $S_{\rm LQ}$ are next-to-leading-order calculations (NLO) [16] at a renormalization scale $\mu = m_{S_{\rm LQ}}$. The uncertainties are determined from variation of the renormalization/factorization scale from $2m_{S_{\rm LQ}}$ to $\frac{1}{2}m_{S_{\rm LQ}}$. Both types of $V_{\rm LQ}$ cross sections are calculated to leading-order (LO) at $\mu = m_{V_{\rm LQ}}$ [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 GeV/c^2. All Monte Carlo samples are processed through a detector simulation program based on the GEANT [19] package.

After initial selection, there are 53 events in the data sample consistent with an estimated background of 53±13 events. The distribution in invariant mass ($m_{\rm event}$) calculated from all muons and jets passing the selection criteria is given in Fig. 1. The largest expected 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 from Z+jets events (5.6±0.9), WW events (2.3±0.9, consistent with previous experimental limits at DØ [20]), and $t\bar{t}$ events (2.1±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 estimate for the production of 200 GeV/c^2 scalar leptoquarks that pass all of the previous selection requirements is 3.7±0.4 events. All leptoquark production estimates are for 200 GeV/c^2 $S_{\rm LQ}$, and use the NLO cross section at a scale $\mu = 2m_{S_{\rm LQ}}$.

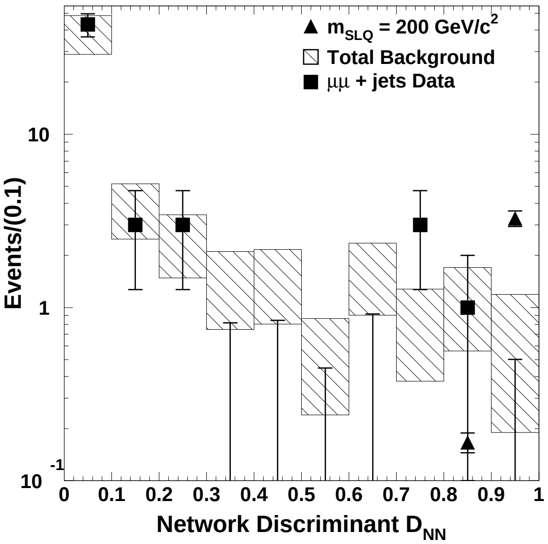

FIG. 2. Output of the neural network. The network calculates a value for each event based on the inputs (see text) and a set of internal values which are determined during network training on $S_{\rm LQ}$ and background Monte Carlo.

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 $S_{\rm LQ}$ 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 (D_{NN}) is shown in Fig. 2.

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 $S_{\rm LQ}$ 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±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 estimate for 200 GeV/c^2 $S_{\rm LQ}$ production is 3.3±0.3 events.

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

LQ Mass (GeV/c^2)	Efficiency (%)	$\sigma^{95\%}_{\mu\mu+\mathrm{jets}}$ (pb)	$\sigma^{95\%}_{\mathrm{combined}}$ (pb)	$\sigma_{S_{\mathrm{LQ}}}$ (pb)	σ_{MV} (pb)	σ_{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 $\beta = \frac{1}{2}$. Cross sections for S_{LQ} (NLO) and V_{LQ} (LO) pair production are also shown.

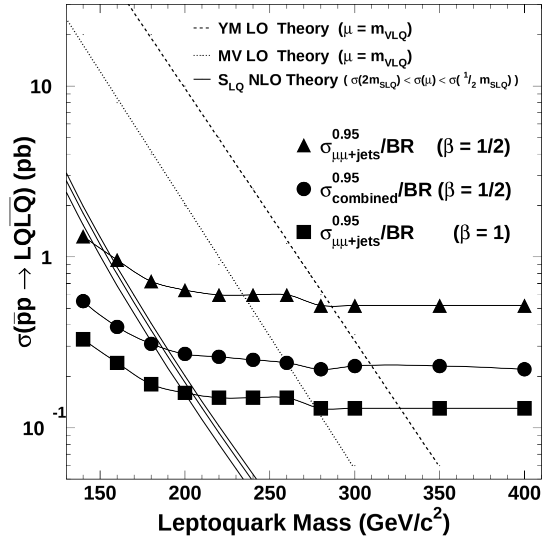

FIG. 3. 95% C.L. limits on pair production cross sections. Results are shown for the $\mu\mu$+jets channel ($\sigma^{0.95}_{\mu\mu+\mathrm{jets}}$) for $\beta = 1, \frac{1}{2}$, and for all combined searches ($\sigma^{0.95}_{\mathrm{combined}}$) at $\beta = \frac{1}{2}$.

statistical and systematic uncertainties on the efficiencies, the integrated luminosity (5%), and the background estimate are included in the calculation assuming Gaussian prior distributions. It should be noted that the cross section limits for the $\mu\mu$+jets channel are independent of β, which enters only when comparing experimental limits with theory. A particular β is given for the combined result since that value determines the relative contribution of each channel to the total cross section.

The dominant (10%) systematic uncertainty in the efficiencies is due to uncertainty in the simulation. In addition, there are approximately equal uncertainties in the jet energy scale [22] and the trigger efficiency/spectrometer resolution for high-p_T muons (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 = β^2 for $\mu\mu$+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 $\mu\mu$+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.

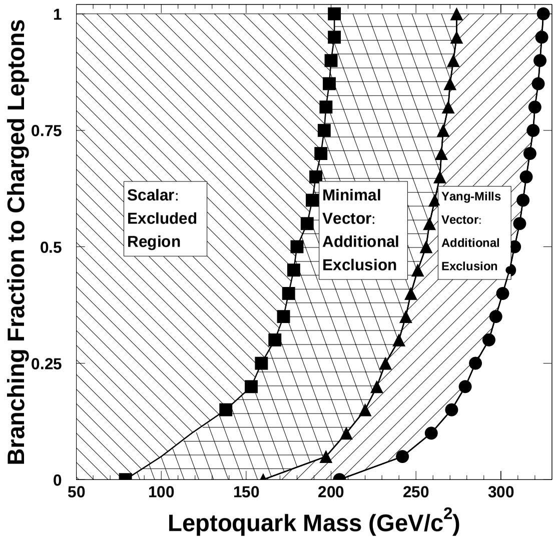

FIG. 4. The regions in the $\beta - m_{\mathrm{LQ}}$ plane excluded by combining the results of the $\mu\mu$+jets, $\mu\nu$+jets, and $\nu\nu$+jets searches. The area to the left of each curve is excluded for that type of coupling, at the 95% confidence level.

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.

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 = $2\beta(1-\beta)$) [6] and $\nu\nu$+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 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 → μq using 94 ± 5 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 β and m_{LQ} by coupling.

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