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Search for Second Generation Leptoquark Pairs Decaying to $\mu\nu + jets$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We report on a search for second generation leptoquarks (LQ) produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the DØ detector at Fermilab. Second generation leptoquarks are assumed to be produced in pairs and to decay to either μ or ν and either a strange or a charm quark (q). Limits are placed on $\sigma(p\bar{p} \rightarrow LQ\bar{L}\bar{Q} \rightarrow \mu\nu + jets)$ as a function of the mass of the leptoquark. For equal branching ratios to μq and νq , second generation scalar leptoquarks with a mass below $160 \text{ GeV}/c^2$, vector leptoquarks with anomalous minimal vector couplings with a mass below $240 \text{ GeV}/c^2$, and vector leptoquarks with Yang-Mills couplings with a mass below $290 \text{ GeV}/c^2$, are excluded at the 95% confidence level.

Leptoquarks (LQ) are hypothetical particles that carry color, fractional electric charge, and both lepton and baryon number. They appear in several extended gauge theories and composite models beyond the standard model [1]. Leptoquarks with universal couplings to all lepton flavors would give rise to flavor-changing neutral currents, and are therefore tightly constrained by experimental data [2]. To satisfy experimental constraints on flavor-changing neutral currents, leptoquarks that couple only to second generation leptons and quarks are considered.

This Letter reports on a search for second generation leptoquark pairs produced in $p\bar{p}$ interactions at a center-of-mass energy $\sqrt{s} = 1.8$ TeV. They are assumed [3] to be produced dominantly via the strong interaction, $p\bar{p} \rightarrow g + X \rightarrow LQ\bar{L}\bar{Q} + X$. The search is conducted for the signature where one of the leptoquarks decays via $LQ \rightarrow \text{muon} + \text{quark}$ and the other via $LQ \rightarrow \text{neutrino} + \text{quark}$, where the quark may be either a strange or a charm quark. The corresponding experimental cross section is $2\beta(1-\beta) \times \sigma(p\bar{p} \rightarrow LQ\bar{L}\bar{Q})$ with β the unknown branching fraction to a charged lepton (e, μ, τ) and a quark (jet) and $(1-\beta)$ the branching fraction to a neutrino (ν) and a jet. The search considers leptoquarks with scalar or vector couplings in the $\mu\nu + \text{jets}$ final state. Additional details on this analysis may be found in reference 4. Previous studies by the D0 [5,6] and CDF [7] collaborations have considered the $\mu\mu + \text{jets}$ final state for scalar couplings, resulting in limits of 140 GeV/ c^2 and 160 GeV/ c^2 respectively for $\beta = 1/2$.

The D0 detector [8] 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 $\sigma(E) = 0.8/\sqrt{E}$ (E in GeV). Muons are measured with a momentum resolution $\sigma(1/p) = 0.18(p-2)/p^2 \oplus 0.003$ (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 the track with respect to the z axis taken along the proton beam line), and at least one jet candidate with transverse energy $E_T^j > 8$ GeV and $|\eta_j| < 2.5$. The data used for this analysis correspond to an integrated luminosity of 94 ± 5 pb $^{-1}$ collected during the 1993–1995 and 1996 Tevatron collider runs at Fermilab.

In the final event sample, muon candidates are required to have a reconstructed track originating from the interaction region consistent with a muon of $p_T^\mu > 25$ GeV/ c and $|\eta_\mu| < 0.95$. To reduce backgrounds from heavy quark production, muons must be isolated from jets ($\Delta\mathcal{R}(\mu, \text{jet}) > 0.5$ for $E_T^j > 15$ GeV, where $\Delta\mathcal{R}(\mu, \text{jet})$ is the separation between the muon and jet in the $\eta - \phi$

plane), and have energy deposition in the calorimeter consistent with that of a minimum ionizing particle. Events are required to have one muon satisfying these requirements. Events containing a second muon which satisfy these requirements, with the fiducial requirement relaxed to $|\eta_\mu| < 1.7$, are rejected.

Jets are measured in the calorimeters and are reconstructed using a cone algorithm with a radius $\mathcal{R} = 0.5$ ($\mathcal{R} \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$). Jets must be produced within $|\eta_j| < 2.0$, and have $E_T^j > 15$ GeV; with the most energetic jet in each event required to have $|\eta_j| < 1.5$.

The transverse energy of the neutrino is not directly measured, but is inferred from the energy imbalance in the calorimeters and the momentum of the reconstructed muon. Events are required to have missing transverse energy $\cancel{E}_T > 30$ GeV. To ensure that \cancel{E}_T is not dominated by mismeasurement of the muon p_T , events having \cancel{E}_T within $\pi \pm 0.1$ radians of the muon track in azimuth are rejected.

To provide further rejection against dimuon events in which one of the muons was not identified in the spectrometer, muons are identified by a pattern of isolated energy deposited in the longitudinal segments of the hadronic calorimeter [9]. Any event where such deposited energy lies along a track originating from the interaction vertex in the region $|\eta| < 1.7$ and is within 0.25 radians in azimuth of the direction of the \cancel{E}_T vector is rejected.

Each candidate event is required to pass a selection based on the expected LQ event topology. Since the decay products of the LQ are μq or νq , the muon and neutrino in LQ pair decays come from different parent particles nearly at rest and are therefore uncorrelated. For the primary background events (e.g. $W + \text{jets}$), the two leptons have the same parent. Similar reasoning holds for the jets. Correlated backgrounds are rejected with the requirement of significant separation between the muon and \cancel{E}_T ($|\Delta\phi(\mu, \cancel{E}_T)| > 0.3$) and between the two leading jets ($\Delta\mathcal{R}(j_1, j_2) > 1.4$).

The ISAJET [10] Monte Carlo event generator is used to simulate the scalar leptoquark (S_{LQ}) signal, and PYTHIA [11] is used for the vector leptoquark (V_{LQ}) signal. The efficiencies for V_{LQ} and S_{LQ} are consistent within differences due to the choice of generator. This is verified by choosing a test point at which both scalar and vector Monte Carlo events from the same generator are compared. Therefore, efficiencies obtained from the two simulations are not distinguished. In addition, the efficiencies for vector leptoquarks are insensitive to differences between minimal vector ($\kappa_G = 1; \lambda_G = 0$ [12]) and Yang-Mills ($\kappa_G = 0; \lambda_G = 0$ [12]) couplings at large mass [6] ($M_{V_{LQ}} > 200$ GeV/ c^2). The leptoquark production cross sections used for the S_{LQ} are from next-to-leading order (NLO) calculations [13] with a renormalization scale $\mu = M_{S_{LQ}}$ and uncertainties determined from variation of the renormalization/factorization scales from $2M_{S_{LQ}}$ to $\frac{1}{2}M_{S_{LQ}}$. The V_{LQ} cross sections are leading order (LO) calculations at a scale $\mu = M_{V_{LQ}}$ [12].

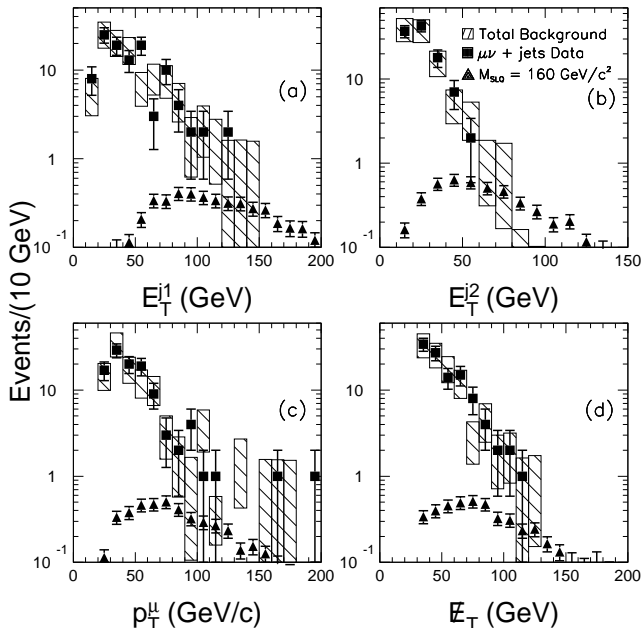


FIG. 1. Kinematic distributions for $\mu\nu + jets$ events. The quantities shown in (a)–(d) are used as inputs into the neural network (see text). The shaded regions give the background expectations, the square points are the $\mu\nu + jets$ data, and the triangular points are signal Monte Carlo.

The dominant backgrounds, from $W + jets$ and $Z + jets$, are simulated using VECBOS [14] for parton level generation and HERWIG [15] for parton fragmentation. Background due to WW production is simulated with PYTHIA [11]. Additional background from $t\bar{t}$ decays into one or more muons and two or more jets, is simulated using the HERWIG Monte Carlo program for a top quark mass of $170 \text{ GeV}/c^2$. Monte Carlo samples are processed through a detector simulation program based on the GEANT [16] package.

With the initial data selection described above, there are 107 events, consistent with a background of 106 ± 30 events (see Fig. 1). The dominant background is $W + jets$ with 100 ± 30 events. Other backgrounds are 2.7 ± 0.7 ($Z + jets$), 2.4 ± 0.8 $t\bar{t}$, and 1.5 ± 0.6 (WW). The uncertainty in the background is dominated by the statistical uncertainty in the $W + jets$ simulation and the systematic uncertainty in the $W + jets$ cross section. The expected signal for $160 \text{ GeV}/c^2$ scalar leptoquarks is 4.8 ± 0.7 events. Signal estimations are shown for a S_{LQ} mass of $160 \text{ GeV}/c^2$ using the NLO cross section with a scale of $2M_{S_{LQ}}$.

To separate any possible signal from the backgrounds, a neural network (NN) [17] with inputs: E_T^{j1} , E_T^{j2} , p_T^μ and E_T and nine nodes in a single hidden layer is used. The network is trained on a mixture of $W + jets$, $Z + jets$ and $t\bar{t}$ background Monte Carlo events, and an independently generated signal Monte Carlo sample at a mass of $160 \text{ GeV}/c^2$. Figure 1 shows distributions of the four input quantities and Fig. 2 the network output (referred to as the discriminant, D_{NN}). No evidence of a signal is

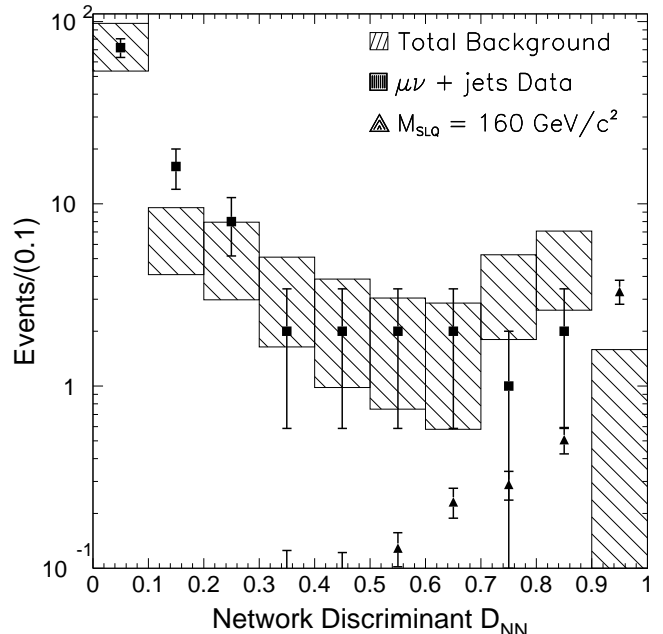


FIG. 2. Output of the neural network. The network calculates a value for each event based on the inputs (shown in Fig. 1) and a set of internal values which are determined during network training on signal and background Monte Carlo.

observed in either the discriminant distribution or any of the kinematic distributions. For setting limits, the selection on D_{NN} is optimized by maximizing a measure of sensitivity [18] defined by

$$S(D_{NN}) \equiv \sum_{k=0}^n P(k, b) M_A^{95\%}(k, b, s(M_{LQ}))$$

where $P(k, b) = e^{-b} b^k / k!$ is a Poisson coefficient with k being any possible number of observable events, b the expected mean number of background events, and $s(M_{LQ})$ the expected signal for a given leptoquark mass. $M_A^{95\%}$ is an approximate [19] mass limit at the 95% confidence level for a given k , s and b . $S(D_{NN})$ is the sum of the approximate mass limits, weighted by the probability of observing $k = 0, 1, 2, \dots, n$ ($P(n, b) < 0.05$) events for a particular choice of the D_{NN} selection criterion.

By maximizing the value of $S(D_{NN})$ a discriminant selection of $D_{NN} > 0.9$ is obtained. With this selection, no events remain in the data, which is consistent with an expected background of 0.7 ± 0.9 events. The remaining background is dominated by $t\bar{t}$ (0.6 ± 0.2 events). The uncertainty on the total background is dominated by the statistical and systematic uncertainties from $W + jets$.

Table I shows the signal detection efficiencies and upper limits [20] on the cross section at the 95% confidence level as a function of the leptoquark mass. The dominant systematic uncertainty on the signal efficiency is due to the simulation, (initial and final state radiation, parton distribution function, renormalization scale, choice of generator) with a 10% uncertainty. The systematic uncertainties shown include approximately equal contributions from uncertainty in the jet energy scale [21] and

LQ Mass (GeV/ c^2)	efficiency (%)	$\sigma^{95\%}$ (pb)	$BR \times \sigma_{SLQ}$ (pb)	$BR \times \sigma_{MV}$ (pb)	$BR \times \sigma_{YM}$ (pb)
100	3.7±0.2±0.6	0.94	2.8	53	430
120	5.0±0.2±0.7	0.72	2.2	23	150
140	7.2±0.3±1.1	0.47	0.75	10	50
160	10.3±0.3±1.5	0.33	0.34	4.0	25
180	12.2±0.3±1.8	0.27	0.16	2.0	10
200	13.4±0.3±2.0	0.25	0.08	1.0	5.0
220	14.1±0.3±2.1	0.24	0.04	0.45	2.5
240	15.2±0.3±2.3	0.23	0.02	0.23	1.3
260	15.5±0.3±2.3	0.22	0.01	0.13	0.60
280	16.3±0.4±2.4	0.21		0.06	0.30
300	15.7±0.4±2.3	0.22		0.03	0.18
350	16.4±0.4±2.4	0.21			0.03
400	17.2±0.4±2.6	0.20			

TABLE I. Signal detection efficiencies (with statistical and systematic uncertainty) and cross section limits (95% CL) for leptoquarks in the $\mu\nu + jets$ decay channel. Also shown for comparison are the expected cross sections for $\beta = \frac{1}{2}$. σ_{SLQ} denotes the theoretical cross section for scalar leptoquarks with a scale $2M_{SLQ}$, σ_{MV} the cross section for vector leptoquarks with anomalous minimal vector couplings, and σ_{YM} leptoquarks with vector Yang-Mills couplings.

the trigger efficiency/spectrometer resolution for high p_T muons (6.6% and 6.4% respectively). The overall systematic uncertainty for the signal efficiency is 15%.

The limits on the observed cross section are shown in Fig. 3, and are compared with the theoretical cross section times branching ratio for scalar and vector leptoquark production for $\beta = \frac{1}{2}$. Mass limits of 160 GeV/ c^2 for scalar leptoquarks and 290 (240) GeV/ c^2 for vector leptoquarks with Yang-Mills (minimal vector) couplings, are obtained at the 95% confidence level.

In conclusion, we have performed a search for second generation leptoquarks in the $\mu\nu + jets$ decay channel using $94 \pm 5 \text{ pb}^{-1}$ of data collected with the DØ detector at the Fermilab Tevatron. No evidence for a signal is seen and limits are set at the 95% confidence level on the mass of second generation leptoquarks. For equal branching fractions to μq and νq ($\beta = \frac{1}{2}$) limits of 160 GeV/ c^2 , 240 GeV/ c^2 , and 290 GeV/ c^2 for SLQ , minimal vector, and Yang-Mills vector couplings, respectively, are obtained.

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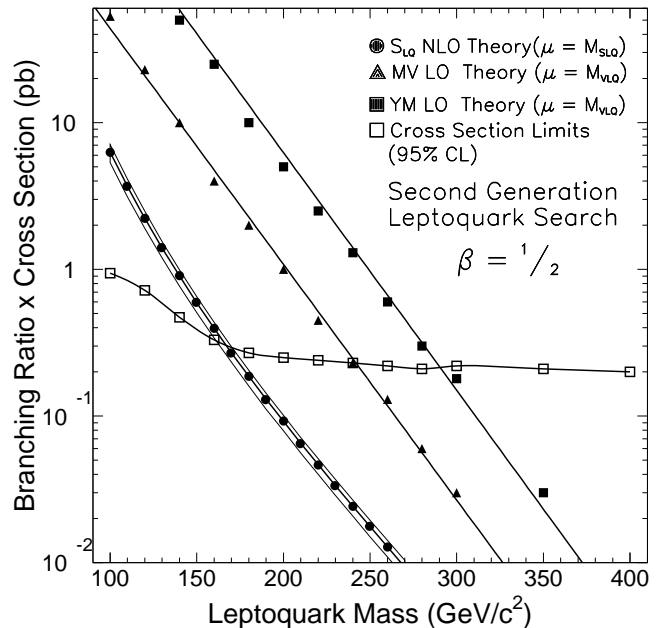


FIG. 3. Cross section limits in the $\mu\nu + jets$ channel. The V_{LQ} cross sections are leading order[12], calculated at a scale $\mu = M_{VLQ}$. The SLQ cross sections are next-to-leading order[13]. The calculation is done at a renormalization scale $\mu = M_{SLQ}$ with uncertainties obtained from variation of the renormalization/factorization scale from $2M_{SLQ}$ to $\frac{1}{2}M_{SLQ}$. For the SLQ the limit is obtained at the intersection of the experimental curve with the theoretical curve for $\mu = 2M_{SLQ}$.

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