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

B. Abbott,[45] M. Abolins,[42] V. Abramov,[18] B. S. Acharya,[11] I. Adam,[44] D. L. Adams,[54] M. Adams,[28] S. Ahn,[27] V. Akimov,[16] G. A. Alves,[2] N. Amos,[41] E. W. Anderson,[34] M. M. Baarmand,[47] V. V. Babintsev,[18] L. Babukhadia,[20] A. Baden,[38] B. Baldin,[27] S. Banerjee,[11] J. Bantly,[51] E. Barberis,[21] P. Baringer,[35] J. F. Bartlett,[27] A. Belyaev,[17] S. B. Beri,[9] I. Bertram,[19] V. A. Bezzubov,[18] P. C. Bhat,[27] V. Bhatnagar,[9] M. Bhattacharjee,[47] N. Biswas,[32] G. Blazey,[29] S. Blessing,[25] P. Bloom,[22] A. Boehnlein,[27] N. I. Bojko,[18] F. Borcherding,[27] C. Boswell,[24] A. Brandt,[27] R. Breedon,[22] G. Briskin,[51] R. Brock,[42] A. Bross,[27] D. Buchholz,[30] V. S. Burtovoi,[18] J. M. Butler,[39] W. Carvalho,[2] D. Casey,[42] Z. Casilum,[47] H. Castilla-Valdez,[14] D. Chakraborty,[47] S. V. Chekulaev,[18] W. Chen,[47] S. Choi,[13] S. Chopra,[25] B. C. Choudhary,[24] J. H. Christenson,[27] M. Chung,[28] D. Claes,[43] A. R. Clark,[21] W. G. Cobau,[38] J. Cochran,[24] L. Coney,[32] W. E. Cooper,[27] D. Coppage,[35] C. Cretsinger,[46] D. Cullen-Vidal,[51] M. A. C. Cummings,[29] D. Cutts,[51] O. I. Dahl,[21] K. Davis,[20] K. De,[52] K. Del Signore,[41] M. Demarteau,[27] D. Denisov,[27] S. P. Denisov,[18] H. T. Diehl,[27] M. Diesburg,[27] G. Di Loreto,[42] P. Draper,[52] Y. Ducros,[8] L. V. Dudko,[17] S. R. Dugad,[11] A. Dyshkant,[18] D. Edmunds,[42] J. Ellison,[24] V. D. Elvira,[47] R. Engelmann,[47] S. Eno,[38] G. Eppley,[54] P. Ermolov,[17] O. V. Eroshin,[18] H. Evans,[44] V. N. Evdokimov,[18] T. Fahland,[23] M. K. Fatyga,[46] S. Feher,[27] D. Fein,[20] T. Ferbel,[46] H. E. Fisk,[27] Y. Fisyak,[48] E. Flattum,[27] G. E. Forden,[20] M. Fortner,[29] K. C. Frame,[42] S. Fuess,[27] E. Gallas,[27] A. N. Galyaev,[18] P. Gartung,[24] V. Gavrilov,[16] T. L. Geld,[42] R. J. Genik II,[42] K. Genser,[27] C. E. Gerber,[27] Y. Gershtein,[51] B. Gibbard,[48] B. Gobbi,[30] B. Gómez,[5] G. Gómez,[38] P. I. Goncharov,[18] J. L. González Solís,[14] H. Gordon,[48] L. T. Goss,[53] K. Gounder,[24] A. Goussiou,[47] N. Graf,[48] P. D. Grannis,[47] D. R. Green,[27] J. A. Green,[34] H. Greenlee,[27] S. Grinstein,[1] P. Grudberg,[21] S. Grünendahl,[27] G. Guglielmo,[50] J. A. Guida,[20] J. M. Guida,[51] A. Gupta,[11] S. N. Gurzhiev,[18] G. Gutierrez,[27] P. Gutierrez,[50] N. J. Hadley,[38] H. Haggerty,[27] S. Hagopian,[25] V. Hagopian,[25] K. S. Hahn,[46] R. E. Hall,[23] P. Hanlet,[40] S. Hansen,[27] J. M. Hauptman,[34] C. Hays,[44] C. Hebert,[35] D. Hedin,[29] A. P. Heinson,[24] U. Heintz,[39] R. Hernández-Montoya,[14] T. Heuring,[25] R. Hirosky,[28] J. D. Hobbs,[47] B. Hoeneisen,[6] J. S. Hoftun,[51] F. Hsieh,[41] Tong Hu,[31] A. S. Ito,[27] S. A. Jerger,[42] R. Jesik,[31] T. Joffe-Minor,[30] K. Johns,[20] M. Johnson,[27] A. Jonckheere,[27] M. Jones,[26] H. Jöstlein,[27] S. Y. Jun,[30] C. K. Jung,[47] S. Kahn,[48] D. Karmanov,[17] D. Karmgard,[25] R. Kehoe,[32] S. K. Kim,[13] B. Klima,[27] C. Klopfenstein,[22] B. Knuteson,[17] W. Ko,[22] J. M. Kohli,[9] D. Koltick,[33] A. V. Kostritskiy,[18] J. Kotcher,[48] A. V. Kotwal,[44] A. V. Kozelov,[18] E. A. Kozlovsky,[18] J. Krane,[34] M. R. Krishnaswamy,[11] S. Krzywdzinski,[27] M. Kubantsev,[36] S. Kuleshov,[16] Y. Kulik,[47] S. Kunori,[38] F. Landry,[42] G. Landsberg,[51] A. Leflat,[17] J. Li,[52] Q. Z. Li,[27] J. G. R. Lima,[3] D. Lincoln,[27] S. L. Linn,[25] J. Linnemann,[42] R. Lipton,[27] A. Lucotte,[47] L. Lueking,[27] A. L. Lyon,[38] A. K. A. Maciel,[29] R. J. Madaras,[21] R. Madden,[25] L. Magaña-Mendoza,[14] V. Manankov,[17] S. Mani,[22] H. S. Mao,[4] R. Markeloff,[29] T. Marshall,[31] M. I. Martin,[27] R. D. Martin,[28] K. M. Mauritz,[34] B. May,[30] A. A. Mayorov,[18] R. McCarthy,[47] J. McDonald,[25] T. McKibben,[28] J. McKinley,[42] T. McMahon,[49] H. L. Melanson,[27] M. Merkin,[17] K. W. Merritt,[27] C. Miao,[51] H. Miettinen,[54] A. Mincer,[45] C. S. Mishra,[27] N. Mokhov,[27] N. K. Mondal,[11] H. E. Montgomery,[27] P. Mooney,[5] M. Mostafa,[1] H. da Motta,[2] C. Murphy,[28] F. Nang,[20] M. Narain,[39] V. S. Narasimham,[11] A. Narayanan,[20] H. A. Neal,[41] J. P. Negret,[5] P. Nemethy,[45] D. Norman,[53] L. Oesch,[41] V. Oguri,[3] N. Oshima,[27] D. Owen,[42] P. Padley,[54] A. Para,[27] N. Parashar,[40] Y. M. Park,[12] R. Partridge,[51] N. Parua,[7] M. Paterno,[46] B. Pawlik,[15] J. Perkins,[52] M. Peters,[26] R. Piegaia,[1] H. Piekarz,[25] Y. Pischalnikov,[33] B. G. Pope,[42] H. B. Prosper,[25] S. Protopopescu,[48] J. Qian,[41] P. Z. Quintas,[27] R. Raja,[27] S. Rajagopalan,[48] O. Ramirez,[28] N. W. Reay,[36] S. Reucroft,[40] M. Rijssenbeek,[47] T. Rockwell,[42] M. Roco,[27] P. Rubinov,[30] R. Ruchti,[32] J. Rutherfoord,[20] A. Sánchez-Hernández,[14] A. Santoro,[2] L. Sawyer,[37] R. D. Schamberger,[47] H. Schellman,[30] J. Sculli,[45] E. Shabalina,[17] C. Shaffer,[25] H. C. Shankar,[11] R. K. Shivpuri,[10] D. Shpakov,[47] M. Shupe,[20] R. A. Sidwell,[36] H. Singh,[24] J. B. Singh,[9] V. Sirotenko,[29] E. Smith,[50] R. P. Smith,[27] R. Snihur,[30] G. R. Snow,[43] J. Snow,[49] S. Snyder,[48] J. Solomon,[28] M. Sosebee,[52] N. Sotnikova,[17] M. Souza,[2] N. R. Stanton,[36] G. Steinbrück,[50] R. W. Stephens,[52] M. L. Stevenson,[21] F. Stichelbaut,[48] D. Stoker,[23] V. Stolin,[16] D. A. Stoyanova,[18] M. Strauss,[50] K. Streets,[45] M. Strovink,[21] A. Sznajder,[2] P. Tamburello,[38] J. Tarazi,[23] M. Tartaglia,[27] T. L. T. Thomas,[30] J. Thompson,[38] D. Toback,[38] T. G. Trippe,[21] P. M. Tuts,[44] V. Vaniev,[18] N. Varelas,[28] E. W. Varnes,[21] A. A. Volkov,[18] A. P. Vorobiev,[18] H. D. Wahl,[25] G. Wang,[25] J. Warchol,[32] G. Watts,[51] M. Wayne,[32] H. Weerts,[42] A. White,[52] J. T. White,[53] J. A. Wightman,[34] S. Willis,[29] S. J. Wimpenny,[24] J. V. D. Wirjawan,[53] J. Womersley,[27] D. R. Wood,[40] R. Yamada,[27] P. Yamin,[48] T. Yasuda,[40] P. Yepes,[54] K. Yip,[27] C. Yoshikawa,[26] S. Youssef,[25] J. Yu,[27] Y. Yu,[13] B. Zhang,[4] Z. Zhou,[34] Z. H. Zhu,[46] M. Zielinski,[46] D. Zieminska,[31] A. Zieminski,[31] V. Zutshi,[46] E. G. Zverev,[17] and A. Zylberstejn[8]

(D0 Collaboration)

[1]*Universidad de Buenos Aires, Buenos Aires, Argentina*

[2]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

[3]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

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[4]*Institute of High Energy Physics, Beijing, People's Republic of China*
[5]*Universidad de los Andes, Bogotá, Colombia*
[6]*Universidad San Francisco de Quito, Quito, Ecuador*
[7]*Institut des Sciences Nucléaires, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[8]*DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[9]*Panjab University, Chandigarh, India*
[10]*Delhi University, Delhi, India*
[11]*Tata Institute of Fundamental Research, Mumbai, India*
[12]*Kyungsung University, Pusan, Korea*
[13]*Seoul National University, Seoul, Korea*
[14]*CINVESTAV, Mexico City, Mexico*
[15]*Institute of Nuclear Physics, Kraków, Poland*
[16]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[17]*Moscow State University, Moscow, Russia*
[18]*Institute for High Energy Physics, Protvino, Russia*
[19]*Lancaster University, Lancaster, United Kingdom*
[20]*University of Arizona, Tucson, Arizona 85721*
[21]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720*
[22]*University of California, Davis, California 95616*
[23]*University of California, Irvine, California 92697*
[24]*University of California, Riverside, California 92521*
[25]*Florida State University, Tallahassee, Florida 32306*
[26]*University of Hawaii, Honolulu, Hawaii 96822*
[27]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[28]*University of Illinois at Chicago, Chicago, Illinois 60607*
[29]*Northern Illinois University, DeKalb, Illinois 60115*
[30]*Northwestern University, Evanston, Illinois 60208*
[31]*Indiana University, Bloomington, Indiana 47405*
[32]*University of Notre Dame, Notre Dame, Indiana 46556*
[33]*Purdue University, West Lafayette, Indiana 47907*
[34]*Iowa State University, Ames, Iowa 50011*
[35]*University of Kansas, Lawrence, Kansas 66045*
[36]*Kansas State University, Manhattan, Kansas 66506*
[37]*Louisiana Tech University, Ruston, Louisiana 71272*
[38]*University of Maryland, College Park, Maryland 20742*
[39]*Boston University, Boston, Massachusetts 02215*
[40]*Northeastern University, Boston, Massachusetts 02115*
[41]*University of Michigan, Ann Arbor, Michigan 48109*
[42]*Michigan State University, East Lansing, Michigan 48824*
[43]*University of Nebraska, Lincoln, Nebraska 68588*
[44]*Columbia University, New York, New York 10027*
[45]*New York University, New York, New York 10003*
[46]*University of Rochester, Rochester, New York 14627*
[47]*State University of New York, Stony Brook, New York 11794*
[48]*Brookhaven National Laboratory, Upton, New York 11973*
[49]*Langston University, Langston, Oklahoma 73050*
[50]*University of Oklahoma, Norman, Oklahoma 73019*
[51]*Brown University, Providence, Rhode Island 02912*
[52]*University of Texas, Arlington, Texas 76019*
[53]*Texas A&M University, College Station, Texas 77843*
[54]*Rice University, Houston, Texas 77005*
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We report on a search for second generation leptoquarks (LQ) produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the D0 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 $\sigma(p\overline{p} \rightarrow LQ\overline{LQ} \rightarrow \mu\nu +$ 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 GeV$/c^2$, vector leptoquarks with anomalous minimal vector couplings with a mass below 240 GeV$/c^2$, and vector leptoquarks with Yang-Mills couplings with a mass below 290 GeV$/c^2$, are excluded at the 95% confidence level.

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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 $p\overline{p}$ interactions at a center-of-mass energy $\sqrt{s} = 1.8$ TeV. They are assumed [3] to be produced dominantly via the strong interaction, $p\overline{p} \to g + X \to LQ\overline{LQ} + X$. The search is conducted for the signature where one of the leptoquarks decays via LQ $\to$ muon + quark and the other via LQ $\to$ neutrino + quark, where the quark may be either a strange or a charm quark. The corresponding experimental cross section is $2\beta(1 - \beta) \times \sigma(p\overline{p} \to LQ\overline{LQ})$ 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 $\mu\nu$ + jets final state. Additional details on this analysis may be found in Ref. [4]. Previous studies by the D0 [5,6] and CDF [7] Collaborations have considered the $\mu\mu$ + 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), where $\oplus$ indicates addition in quadrature.

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 η-ϕ 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 $|\eta_j| < 1.5$. Two or more such jets are required in each event.

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 $\not\!\!E_T > 30$ GeV. To ensure that $\not\!\!E_T$ is not dominated by mismeasurement of the muon p_T, events having $\not\!\!E_T$ 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 $\not\!\!E_T$ 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 + 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 $\not\!\!E_T$ [$|\Delta\phi(\mu, \not\!\!E_T)| > 0.3$] 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] ($M_{V_{\text{LQ}}} > 200$ 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 $\mu = M_{S_{\text{LQ}}}$ and uncertainties determined from variation of the renormalization/factorization scales from $2M_{S_{\text{LQ}}}$ to $\frac{1}{2}M_{S_{\text{LQ}}}$. The V_{LQ} cross sections are leading order calculations at a scale $\mu = M_{V_{\text{LQ}}}$ [12].

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 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 GeV$/c^2$ scalar leptoquarks is 4.8 ± 0.7 events. Signal estimations are shown for a S_{LQ} mass of 160 GeV$/c^2$ using the NLO cross section with a scale of $2M_{S_{\mathrm{LQ}}}$.

To separate any possible signal from the backgrounds, a neural network (NN) [17] with inputs $E_T^{j_1}$, $E_T^{j_2}$, p_T^{μ}, and $\not{E}_T$ 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 GeV$/c^2$. Figure 1 shows distributions of the four input quantities and Fig. 2 shows the network output (referred to as the discriminant, D_{NN}). No evidence of a signal is 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

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

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

By maximizing the value of $S(D_{\mathrm{NN}})$ a discriminant selection of $D_{\mathrm{NN}} > 0.9$ 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 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%.

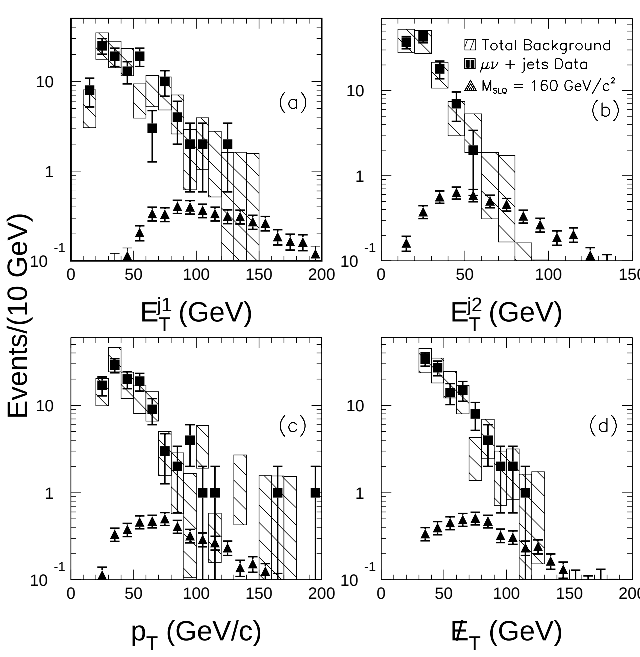

FIG. 1. Kinematic distributions for $\mu\nu$ + jets events. The quantities shown in (a)–(d) are used as inputs into the neural network (see text). The shaded regions give the background expectations, the square points are the $\mu\nu$ + jets data, and the triangular points are signal Monte Carlo.

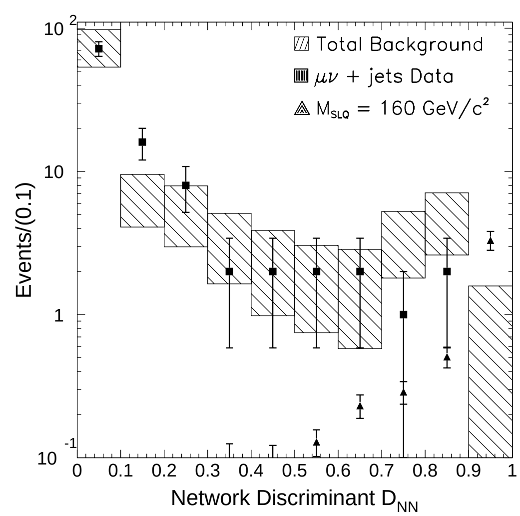

FIG. 2. Output of the neural network. The network calculates a value for each event based on the inputs (shown in Fig. 1) and a set of internal values which are determined during network training on signal and background Monte Carlo.

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

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

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 $94 \pm 5\ \mathrm{pb}^{-1}$ of data collected with the D0 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 $S_{\rm LQ}$, minimal vector, and Yang-Mills vector couplings, respectively, are obtained.

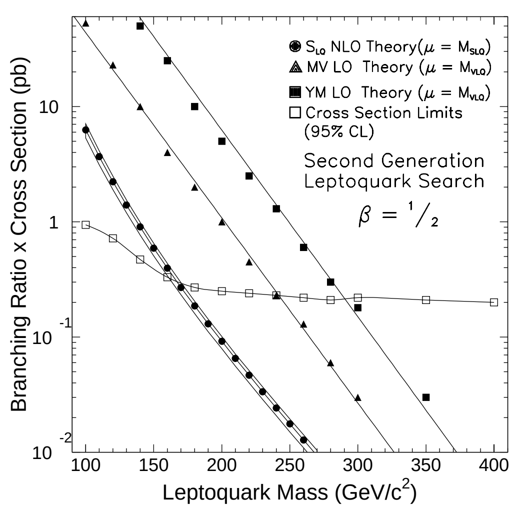

FIG. 3. Cross section limits in the $\mu\nu$ + jets channel. The $V_{\rm LQ}$ cross sections are leading order [12], calculated at a scale $\mu = M_{V_{\rm LQ}}$. The $S_{\rm LQ}$ cross sections are next-to-leading order [13]. The calculation is done at a renormalization scale $\mu = M_{S_{\rm LQ}}$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

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