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

S. Abachi,[12] B. Abbott,[34] M. Abolins,[23] B.S. Acharya,[41] I. Adam,[10] D.L. Adams,[35] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[37] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[39] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[7] J. Bendich,[20] S.B. Beri,[32] I. Bertram,[35] V.A. Bezzubov,[33] P.C. Bhat,[12] V. Bhatnagar,[32] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] P. Bloom,[5] A. Boehnlein,[12] N.I. Bojko,[33] F. Borcherding,[12] J. Borders,[36] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V.S. Burtovoi,[33] J.M. Butler,[12] D. Casey,[36] H. Castilla-Valdez,[9] D. Chakraborty,[39] S.-M. Chang,[27] S.V. Chekulaev,[33] L.-P. Chen,[20] W. Chen,[39] L. Chevalier,[37] S. Chopra,[32] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[39] A.R. Clark,[20] W.G. Cobau,[21] J. Cochran,[7] W.E. Cooper,[12] C. Cretsinger,[36] D. Cullen-Vidal,[4] M.A.C. Cummings,[14] D. Cutts,[4] O.I. Dahl,[20] K. De,[42] M. Demarteau,[12] R. Demina,[27] K. Denisenko,[12] N. Denisenko,[12] D. Denisov,[12] S.P. Denisov,[33] W. Dharmaratna,[13] H.T. Diehl,[12] M. Diesburg,[12] G. Di Loreto,[23] R. Dixon,[12] P. Draper,[42] J. Drinkard,[6] Y. Ducros,[37] S.R. Dugad,[41] S. Durston-Johnson,[36] D. Edmunds,[23] J. Ellison,[7] V.D. Elvira,[12,‡] R. Engelmann,[39] S. Eno,[21] G. Eppley,[35] P. Ermolov,[24] O.V. Eroshin,[33] V.N. Evdokimov,[33] S. Fahey,[23] T. Fahland,[4] M. Fatyga,[3] M.K. Fatyga,[36] J. Featherly,[3] S. Feher,[39] D. Fein,[2] T. Ferbel,[36] G. Finocchiaro,[39] H.E. Fisk,[12] Yu. Fisyak,[24] E. Flattum,[23] G.E. Forden,[2] M. Fortner,[28] K.C. Frame,[23] P. Franzini,[10] S. Fuess,[12] A.N. Galjaev,[33] E. Gallas,[42] C.S. Gao,[12,*] S. Gao,[12,*] T.L. Geld,[23] R.J. Genik II,[23] K. Genser,[12] C.E. Gerber,[12,§] B. Gibbard,[3] V. Glebov,[36] S. Glenn,[5] B. Gobbi,[29] M. Goforth,[13] A. Goldschmidt,[20] B. Gómez,[1] P.I. Goncharov,[33] H. Gordon,[3] L.T. Goss,[43] N. Graf,[3] P.D. Grannis,[39] D.R. Green,[12] J. Green,[28] H. Greenlee,[12] G. Griffin,[6] N. Grossman,[12] P. Grudberg,[20] S. Grünendahl,[36] W. Gu,[12,*] G. Guglielmo,[31] J.A. Guida,[39] J.M. Guida,[3] W. Guryn,[3] S.N. Gurzhiev,[33] P. Gutierrez,[31] Y.E. Gutnikov,[33] N.J. Hadley,[21] H. Haggerty,[12] S. Hagopian,[13] V. Hagopian,[13] K.S. Hahn,[36] R.E. Hall,[6] S. Hansen,[12] R. Hatcher,[23] J.M. Hauptman,[17] D. Hedin,[28] A.P. Heinson,[7] U. Heintz,[12] R. Hernández-Montoya,[9] T. Heuring,[13] R. Hirosky,[13] J.D. Hobbs,[12] B. Hoeneisen,[1,¶] J.S. Hoftun,[4] F. Hsieh,[22] Ting Hu,[39] Tong Hu,[16] T. Huehn,[7] S. Igarashi,[12] A.S. Ito,[12] E. James,[2] J. Jaques,[30] S.A. Jerger,[23] J.Z.-Y. Jiang,[39] T. Joffe-Minor,[29] H. Johari,[27] K. Johns,[2] M. Johnson,[12] H. Johnstad,[40] A. Jonckheere,[12] M. Jones,[14] H. Jöstlein,[12] S.Y. Jun,[29] C.K. Jung,[39] S. Kahn,[3] G. Kalbfleisch,[31] J.S. Kang,[18] R. Kehoe,[30] M.L. Kelly,[30] A. Kernan,[7] L. Kerth,[20] C.L. Kim,[18] S.K. Kim,[38] A. Klatchko,[13] B. Klima,[12] B.I. Klochkov,[33] C. Klopfenstein,[39] V.I. Klyukhin,[33] V.I. Kochetkov,[33] J.M. Kohli,[32] D. Koltick,[34] A.V. Kostritskiy,[33] J. Kotcher,[3] J. Kourlas,[26] A.V. Kozelov,[33] E.A. Kozlovski,[33] M.R. Krishnaswamy,[41] S. Krzywdzinski,[12] S. Kunori,[21] S. Lami,[39] G. Landsberg,[12] R.E. Lanou,[4] J-F. Lebrat,[37] A. Leflat,[24] H. Li,[39] J. Li,[42] Y.K. Li,[29] Q.Z. Li-Demarteau,[12] J.G.R. Lima,[8] D. Lincoln,[22] S.L. Linn,[13] J. Linnemann,[23] R. Lipton,[12] Y.C. Liu,[29] F. Lobkowicz,[36] S.C. Loken,[20] S. Lökös,[39] L. Lueking,[12] A.L. Lyon,[21] A.K.A. Maciel,[8] R.J. Madaras,[20] R. Madden,[13] I.V. Mandrichenko,[33] Ph. Mangeot,[37] S. Mani,[5] B. Mansoulié,[37] H.S. Mao,[12,*] S. Margulies,[15] R. Markeloff,[28] L. Markosky,[2] T. Marshall,[16] M.I. Martin,[12] M. Marx,[39] B. May,[29] A.A. Mayorov,[33] R. McCarthy,[39] T. McKibben,[15] J. McKinley,[23] T. McMahon,[31] H.L. Melanson,[12] J.R.T. de Mello Neto,[8] K.W. Merritt,[12] H. Miettinen,[35] A. Milder,[2] A. Mincer,[26] J.M. de Miranda,[8] C.S. Mishra,[12] M. Mohammadi-Baarmand,[39] N. Mokhov,[12] N.K. Mondal,[41] H.E. Montgomery,[12] P. Mooney,[1] M. Mudan,[26] C. Murphy,[16] C.T. Murphy,[12] F. Nang,[4] M. Narain,[12] V.S. Narasimham,[41] A. Narayanan,[2] H.A. Neal,[22] J.P. Negret,[1] E. Neis,[22] P. Nemethy,[26] D. Nešić,[4] D. Norman,[43] L. Oesch,[22] V. Oguri,[8] E. Oltman,[20] N. Oshima,[12] D. Owen,[23] P. Padley,[35] M. Pang,[17] A. Para,[12] C.H. Park,[12] Y.M. Park,[19] R. Partridge,[4] N. Parua,[41] M. Paterno,[36] J. Perkins,[42] A. Peryshkin,[12] M. Peters,[14] H. Piekarz,[13] Y. Pischalnikov,[34] A. Pluquet,[37] V.M. Podstavkov,[33] B.G. Pope,[23] H.B. Prosper,[13] S. Protopopescu,[3] D. Pušeljić,[20] J. Qian,[22] P.Z. Quintas,[12] R. Raja,[12] S. Rajagopalan,[39] O. Ramirez,[15] M.V.S. Rao,[41] P.A. Rapidis,[12] L. Rasmussen,[39] A.L. Read,[12] S. Reucroft,[27] M. Rijssenbeek,[39] T. Rockwell,[23] N.A. Roe,[20] P. Rubinov,[39] R. Ruchti,[30] S. Rusin,[24] J. Rutherfoord,[2] A. Santoro,[8] L. Sawyer,[42] R.D. Schamberger,[39] H. Schellman,[29] J. Sculli,[26] E. Shabalina,[24] C. Shaffer,[13] H.C. Shankar,[41] R.K. Shivpuri,[11] M. Shupe,[2] J.B. Singh,[32] V. Sirotenko,[28] W. Smart,[12] A. Smith,[2] R.P. Smith,[12] R. Snihur,[29] G.R. Snow,[25] S. Snyder,[39] J. Solomon,[15] P.M. Sood,[32] M. Sosebee,[42] M. Souza,[8] A.L. Spadafora,[20] R.W. Stephens,[42] M.L. Stevenson,[20] D. Stewart,[22] D.A. Stoianova,[33] D. Stoker,[6] K. Streets,[26] M. Strovink,[20] A. Taketani,[12] P. Tamburello,[21] J. Tarazi,[6] M. Tartaglia,[12] T.L. Taylor,[29] J. Teiger,[37] J. Thompson,[21] T.G. Trippe,[20] P.M. Tuts,[10] N. Varelas,[23] E.W. Varnes,[20] P.R.G. Virador,[20] D. Vititoe,[2] A.A. Volkov,[33] A.P. Vorobiev,[33] H.D. Wahl,[13] G. Wang,[13] J. Wang,[12,*] L.Z. Wang,[12,*] J. Warchol,[30] M. Wayne,[30] H. Weerts,[23] F. Wen,[13] W.A. Wenzel,[20] A. White,[42] J.T. White,[43] J.A. Wightman,[17] J. Wilcox,[27] S. Willis,[28] S.J. Wimpenny,[7] J.V.D. Wirjawan,[43] J. Womersley,[12] E. Won,[36] D.R. Wood,[12] H. Xu,[4] R. Yamada,[12] P. Yamin,[3] C. Yanagisawa,[39] J. Yang,[26] T. Yasuda,[27] C. Yoshikawa,[14] S. Youssef,[13] J. Yu,[36] Y. Yu,[38] Y. Zhang,[12,*] Y.H. Zhou,[12,*] Q. Zhu,[26] Y.S. Zhu,[12,*] Z.H. Zhu,[36] D. Zieminska,[16] A. Zieminski,[16] and A. Zylberstejn[37]

(DØ Collaboration)

[1] *Universidad de los Andes, Bogotá, Colombia*
[2] *University of Arizona, Tucson, Arizona 85721*
[3] *Brookhaven National Laboratory, Upton, New York 11973*
[4] *Brown University, Providence, Rhode Island 02912*
[5] *University of California, Davis, California 95616*
[6] *University of California, Irvine, California 92717*
[7] *University of California, Riverside, California 92521*
[8] *LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[9] *CINVESTAV, Mexico City, Mexico*
[10] *Columbia University, New York, New York 10027*
[11] *Delhi University, Delhi, India 110007*
[12] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[13] *Florida State University, Tallahassee, Florida 32306*
[14] *University of Hawaii, Honolulu, Hawaii 96822*
[15] *University of Illinois at Chicago, Chicago, Illinois 60607*
[16] *Indiana University, Bloomington, Indiana 47405*
[17] *Iowa State University, Ames, Iowa 50011*
[18] *Korea University, Seoul, Korea*
[19] *Kyungsung University, Pusan, Korea*
[20] *Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720*
[21] *University of Maryland, College Park, Maryland 20742*
[22] *University of Michigan, Ann Arbor, Michigan 48109*
[23] *Michigan State University, East Lansing, Michigan 48824*
[24] *Moscow State University, Moscow, Russia*
[25] *University of Nebraska, Lincoln, Nebraska 68588*
[26] *New York University, New York, New York 10003*
[27] *Northeastern University, Boston, Massachusetts 02115*
[28] *Northern Illinois University, DeKalb, Illinois 60115*
[29] *Northwestern University, Evanston, Illinois 60208*
[30] *University of Notre Dame, Notre Dame, Indiana 46556*
[31] *University of Oklahoma, Norman, Oklahoma 73019*
[32] *University of Panjab, Chandigarh 16-00-14, India*
[33] *Institute for High Energy Physics, 142-284 Protvino, Russia*
[34] *Purdue University, West Lafayette, Indiana 47907*
[35] *Rice University, Houston, Texas 77251*
[36] *University of Rochester, Rochester, New York 14627*
[37] *CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, France*
[38] *Seoul National University, Seoul, Korea*
[39] *State University of New York, Stony Brook, New York 11794*
[40] *SSC Laboratory, Dallas, Texas 75237*
[41] *Tata Institute of Fundamental Research, Colaba, Bombay 400005, India*
[42] *University of Texas, Arlington, Texas 76019*
[43] *Texas A&M University, College Station, Texas 77843*

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We report on a search for second generation scalar leptoquarks with the DØ detector at the Fermilab Tevatron $p\overline{p}$ collider at $\sqrt{s} = 1.8$ TeV. This search is based on 12.7 pb^{-1} of data. Second generation leptoquarks are assumed to be produced in pairs and to decay into a muon and quark with branching ratio β or to neutrino and quark with branching ratio $(1-\beta)$. We obtain cross section times branching ratio limits as a function of leptoquark mass and set lower limits on the leptoquark mass at the 95% confidence level.

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Leptoquarks are bosons predicted [1] in many extensions of the Standard Model (SM). They carry both lepton and color quantum numbers and couple to leptons and quarks. In order to satisfy experimental constraints on flavor changing neutral currents and rare pion decays, leptoquarks are required to be left or right handed and couple to only one generation of leptons and quarks [2]. These constraints are required unless leptoquarks are considerably more massive [3] than particles the current Tevatron run can produce.

This paper reports the results of a search for second generation scalar leptoquarks. We assume leptoquarks are produced in pairs by QCD processes. At the Tevatron these processes dominate other production mechanisms which depend on the leptoquark–lepton–quark coupling. Second generation leptoquarks are assumed to decay with branching ratio β to a muon and quark and with branching ratio $(1-\beta)$ to a neutrino and quark. There are three decay signatures for pair produced second generation leptoquarks: two muons plus at least two jets, one muon plus missing transverse energy ($\not\!\!E_T$) and at least two jets, or $\not\!\!E_T$ plus two or more jets. This report gives results for limits on cross section times β^2 for the dimuon signature and cross section times $2\beta(1-\beta)$ for the single muon signature. These cross section limits are used to set limits on the second generation leptoquark mass. The data used for this analysis were taken during the Tevatron run between August 1992 and May 1993 and represent an integrated luminosity of 12.7 pb^{-1}.

Previous limits from LEP experiments exclude leptoquark masses below 45 GeV/c^2 [4]. Results from DØ and CDF on first generation scalar leptoquarks have been published [5]. The DØ limits for first generation leptoquarks are 133 GeV/c^2 and 120 GeV/c^2 for $\beta = 1.0$ and 0.5, and the CDF limits are 113 GeV/c^2 and 80 GeV/c^2 for $\beta = 1.0$ and 0.5. Experiments at HERA [6] give limits on the mass of first generation leptoquarks where their limits depend on the unknown but constrained [7] leptoquark–electron–quark coupling, which they have generally assumed to be at the strength of the electro–weak coupling.

The DØ detector, described in detail elsewhere [8], is composed of three major systems: an inner detector (without a magnetic field) for tracking charged particles within a pseudorapidity range $|\eta| < 3.5$, a calorimeter for measuring electromagnetic and hadronic showers within the range $|\eta| < 4.0$, and a muon spectrometer covering the range $|\eta| < 3.3$. The calorimeter has fine segmentation in both η and azimuth, ϕ, and measures electrons with a resolution of $15\%/\sqrt{E}$ and hadrons with a resolution of about $50\%/\sqrt{E}$. Muons are identified and their momentum, p, measured with three layers of proportional drift tubes, one before (coming from the interaction region) and two after the magnetized iron toroids. The muon momentum resolution is $\sigma(1/p) = 0.18(p-2)/p^2 \oplus 0.008$ (with p in GeV/c).

Muons are required to have an impact parameter consistent with coming from the interaction region and to have $|\eta| < 1.7$. Cosmic ray muons are removed by requiring that there are no tracks or pattern of hits back-to-back in η and ϕ. Muons are required to be well isolated from jets to reduce backgrounds from heavy quark production. A further set of requirements is defined for high quality muon identification. This includes requiring a track consistent with a minimum ionizing particle in the calorimeter and tracking chamber. The muon must hit all three layers of the muon system and have timing consistent with originating from the beam crossing. Finally, the muon must traverse a minimum field integral of 1.83 T·m of the toroid magnet.

Jets are measured in the calorimeter. They are defined by a cone algorithm with $\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.7$. Jets are corrected for calorimeter response, underlying event, and out-of-cone leakage effects. These corrections amount to about 25% and vary with jet energy and η. Jets are accepted within $|\eta| < 3.5$.

The $\not\!\!E_T$, representing the transverse energy carried by the neutrino in the single muon signature, is required to be isolated from the jets in ϕ by 0.3 radians. Also, the magnitude of the angular separation in ϕ of the muon and $\not\!\!E_T$ cannot be greater than $\pi - 0.2$. These cuts ensure that the $\not\!\!E_T$ is not an artifact of either fluctuations in the jet energy or the muon resolution. The efficiency for the muon–$\not\!\!E_T$ angle cut for single muon leptoquarks is 82$\pm$1% and 73$\pm$2% for a W boson plus jet events.

For the search in the single muon channel, the events in the data sample are required to pass a trigger with a muon transverse momentum (p_T) threshold of 8 GeV/c and a jet E_T threshold of 15 GeV. Offline, one high quality muon with $p_T > 20$ GeV/c and $|\eta| < 1.0$ is required. The $\not\!\!E_T$ is required to be greater than 25 GeV. The leptoquark signal is enhanced relative to the major physics background (W boson plus jets) by requiring two good jets with $E_T > 25$ GeV and a transverse mass (M_T) of the $\not\!\!E_T$ + muon > 95 GeV/c^2. No candidate events are left after these cuts.

Figure 1 shows the M_T distribution for three event samples: W boson plus jets Monte Carlo, single muon leptoquark Monte Carlo with a mass of 100 GeV/c^2, and the single muon data. The jet threshold has been dropped to 15 GeV for increased statistics. The vertical line indicates the M_T cut of 95 GeV/c^2. The fraction of the Monte Carlo W boson sample in Fig. 1 (a) surviving the M_T cut is 16.5$\pm$1.9% compared to 34.7$\pm$1.4% for the leptoquark signal sample shown in Fig. 1 (b). The data distribution in Fig. 1 (c) is given for a qualitative comparison.

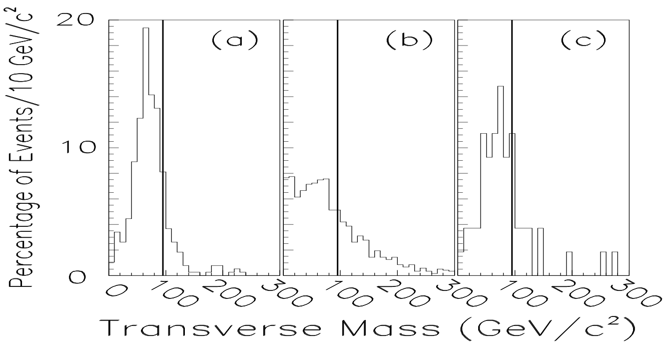

FIG. 1. M_T distributions for (a) a W$\rightarrow$ $\mu\nu$ plus jets Monte Carlo sample, (b) a 100 GeV/c^2 mass second generation leptoquark Monte Carlo sample, and (c) for a data sample obtained by the single muon signature selection with 15 GeV jets. The vertical line shows the M_T cut used in the analysis (see text for details) .

With the 25 GeV cuts on the jets, the effect of varying the transverse mass cut is shown in Table I which gives the number of expected backgrounds, the actual number of surviving events, and the total efficiency for a 100 GeV/c^2 mass leptoquark signal. For the single muon signature, the expected backgrounds come from W boson plus jets production, leptonic decays of $b\bar{b}$ pairs, Drell-Yan dimuon plus jets production where one muon is missing, and the decay of W and Z bosons into heavy quarks with semileptonic decays. Not given in the table, but added in the total, is the number of Drell-Yan dimuon plus jets backgrounds which range between 0.10 to 0.17 events with errors equal to the estimates. The background estimates reasonably account for the data.

TABLE I. The number of single muon events as a function of the M_T (GeV/c^2) cut. All other cuts are kept the same as given in the text. Also given is the number of events expected from $W \rightarrow \mu\nu$ plus jets, $b\bar{b}$, $W \rightarrow c\ s \rightarrow \mu$ plus jets, and the total expected backgrounds. The total efficiency for the 100 GeV/c^2 mass leptoquark signal is also given.

M_T	W	$b\bar{b}$	$W \rightarrow c\ s$	total bgd.	# events	ϵ_{LQ}
95	1.4±0.3	0.5±0.2	0.37±0.37	2.4±1.0	0	2.1%
85	2.2±0.5	1.0±0.3	0.37±0.37	3.7±1.3	3	2.4%
75	3.3±0.8	1.4±0.5	0.74±0.54	5.6±2.0	5	2.8%

For the dimuon signature selection, the candidate events are required to pass the same trigger as the single muon events. In the offline selection for the dimuon sample, both muons are required to be isolated and to have a p_T greater than 25 GeV/c. At least one muon is required to pass the high quality cuts, and at least one is required to have $\mid \eta \mid < 1.0$. These cuts leave 15 events in the dimuon sample. For the leptoquark signature, we require that our candidate events have at least two jets with E_T greater than 25 GeV. This jet cut significantly reduces the Drell-Yan sources of background for this signature. With this last cut no candidate events are left.

The main sources of background for the dimuon signature are Drell-Yan dimuons plus jets and leptonic decays of $b\bar{b}$ pairs. Background estimates are made for different kinematic cuts. In Table II, the background estimates for 15, 20, and 25 GeV cuts on the muons and jets in the dimuon sample are shown with the actual number of events seen. The total efficiency for the detection of a 100 GeV/c^2 mass dimuon leptoquark signal is also given. The estimated backgrounds reasonably account for the data.

TABLE II. Estimates of background contributions to the dimuon sample from Drell-Yan $\mu^+\mu^-$ with jets (including $Z \rightarrow \mu^+\mu^-$) and leptonic $b\bar{b}$ decays for the indicated threshold cuts on both the two muons and two jets. Also given is the number of dimuon plus jets events surviving these threshold cuts along with the detection efficiency for a 100 GeV/c^2 mass leptoquark signal.

jet, μ p_T(GeV)	$b\bar{b}$	Drell-Yan	# events	ϵ_{LQ}
25	0.05±0.02	1.8±0.7	0	4.8%
20	0.23±0.11	3.4±1.0	3	6.5%
15	0.77±0.38	9.9±2.1	12	8.2%

The efficiencies of the cuts used in the selection for the two signatures are determined from a study of Monte Carlo generated and collider events. The geometric acceptance and kinematic efficiency are taken from leptoquark signal Monte Carlo generated by ISAJET [9] and processed with a DØ version of the GEANT [10] detector simulator, a simulation of the DØ trigger, and DØ's standard reconstruction program. For the dimuon signature, the total efficiency ranges from 0.35% to 8.7% for leptoquark masses between 45 and 200 GeV/c^2. For the single muon signature the total efficiency ranges from 0.14% to 5.12% for the same mass range. The uncertainty on the total efficiency is 20% for the dimuon signature and 10% for the single muon signature. This uncertainty on the efficiency is dominated by the statistics of the $Z \to \mu^+\mu^-$ data sample used to calculate the efficiency of the muon quality cuts. The systematic uncertainties vary from 27% to 9% for the dimuon channel for leptoquark masses ranging from 45 to 200 GeV/c^2. These systematic uncertainties arise from a 10% jet energy scale uncertainty and a 10% and 25% uncertainty in the first and second terms of the muon p_T resolution. For the single muon signature the systematic uncertainties vary from 16% to 12% for the same mass range. For both signatures the dominant systematic effect comes from the uncertainty in the muon p_T resolution.

The 95% confidence level (CL) upper limit on cross section times branching ratio factor β^2 as a function of leptoquark mass for the dimuon signature is given in Fig. 2 (a) as the solid line. This cross section limit takes into account [11] the statistical and systematic uncertainties including a 5.4% systematic uncertainty in the integrated luminosity. The dashed line in Fig. 2 (a) is β^2 times the theoretical cross section based on ISAJET [12] using the Morfin and Tung leading order (MT-LO) parton distribution functions (pdf) [13] for $\beta = 1$. The intersection of these two curves at a leptoquark mass of 111 GeV/c^2 gives the 95% CL lower limit on the mass of a second generation leptoquark for $\beta = 1$. The 95% CL lower limit on cross section times branching ratio factor $2\beta(1-\beta)$ as a function of leptoquark mass for the single muon signature is given in Fig. 2 (b) as the solid line. Plotted as the dashed curve is $2\beta(1-\beta)$ times the theoretical cross section for $\beta = 0.5$. The single muon limit is 54 GeV/c^2.

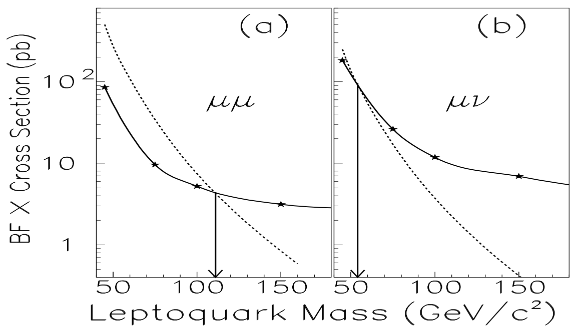

FIG. 2. The 95% CL upper limit (solid line) on the cross section as a function of the leptoquark mass for (a) the dimuon signature and (b) the single muon signature. "BF" is the branching ratio factor: β^2 for the dimuon signature and $2\beta(1-\beta)$ for the single muon signature. Also shown is the theoretical prediction (dashed line).

In Fig. 3 we show the β versus mass excluded region for the dimuon signature as the area covered by the diagonal lines. The area covered by the solid shading is the region excluded for the single muon signature. By combining the acceptance for the single muon and dimuon signatures, weighted appropriately by branching fraction, we exclude the additional region indicated by the cross hatched area. The combined mass limit for $\beta = 0.5$ is 89 GeV/c^2. The LEP limit of 45 GeV/c^2 is also given in Fig. 3. Our limit extends to a branching fraction of $\beta = 0.17$ at the LEP mass limit. CDF [14], based on the dimuon channel only, has also set limits on the mass of second generation leptoquarks of 131 and 96 GeV/c^2 for $\beta = 1.0$ and 0.5 using the cross sections from ISAJET V7.06 with CTEQ2pM pdf's. As a direct comparison, we have recomputed our mass limits with the cross sections used by CDF, and we obtain combined mass limits of 119 and 97 GeV/c^2 for $\beta = 1.0$ and 0.5. This limit is plotted in Fig. 3 as the dashed line. Using this theoretical cross section, we can exclude, compared to CDF, additional β vs mass space starting at $\beta = 0.5$ and extending down to $\beta = 0.16$ at the LEP limit.

More generally, our mass limits change 3.5 GeV/c^2 in the vicinity of 110 GeV/c^2 for every 10% change in the cross section. The variation in the cross section due to choice of pdf's is as large as 20%. Factors of four in the Q^2 scale change the cross section by about 30%. Higher order corrections [15] can have about a 10% effect in the 110 GeV/c^2 mass region.

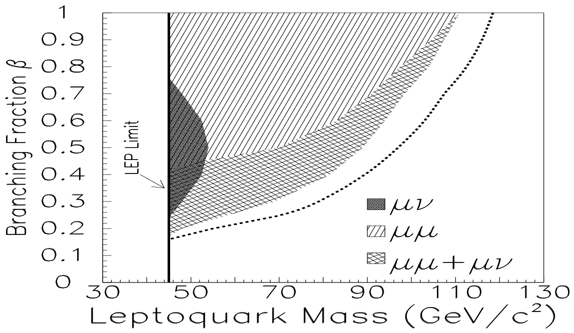

FIG. 3. The 95% CL excluded regions for the dimuon, single muon, and combined signatures. The dashed line is the combined limit using cross sections from ISAJET V7.06 with CTEQ2pM from reference [14].

In conclusion we observe no events from second generation leptoquarks. We have set limits on the mass as a function of β for the pair production of second generation leptoquarks where the cross section for their production is independent of the coupling strength of the leptoquark to a second generation lepton and quark.

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* Visitor from IHEP, Beijing, China.
‡ Visitor from CONICET, Argentina.
§ Visitor from Universidad de Buenos Aires, Argentina.
¶ Visitor from Univ. San Francisco de Quito, Ecuador.

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