4-26-2005

Search for first-generation scalar leptoquarks in ($p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV

V. M. Abazov
Joint Institute for Nuclear Research, Dubna, Russia

Gregory R. Snow
University of Nebraska-Lincoln, gsnow1@unl.edu

D0 Collaboration

PHYSICAL REVIEW D **71,** 071104(R) (2005)

Search for first-generation scalar leptoquarks in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

V. M. Abazov,[34] B. Abbott,[71] M. Abolins,[62] B. S. Acharya,[28] M. Adams,[49] T. Adams,[49] M. Agelou,[17] J.-L. Agram,[18] S. H. Ahn,[30] M. Ahsan,[56] G. D. Alexeev,[34] G. Alkhazov,[38] A. Alton,[61] G. Alverson,[60] G. A. Alves,[2] M. Anastasoaie,[33] T. Andeen,[51] S. Anderson,[43] B. Andrieu,[16] Y. Arnoud,[13] A. Askew,[75] B. Åsman,[39] O. Atramentov,[54] C. Autermann,[20] C. Avila,[7] F. Badaud,[12] A. Baden,[58] B. Baldin,[48] P. W. Balm,[32] S. Banerjee,[28] E. Barberis,[60] P. Bargassa,[75] P. Baringer,[55] C. Barnes,[41] J. Barreto,[2] J. F. Bartlett,[48] U. Bassler,[16] D. Bauer,[52] A. Bean,[55] S. Beauceron,[16] M. Begel,[67] A. Bellavance,[64] S. B. Beri,[26] G. Bernardi,[16] R. Bernhard,[48,*] I. Bertram,[40] M. Besançon,[17] R. Beuselinck,[41] V. A. Bezzubov,[37] P. C. Bhat,[48] V. Bhatnagar,[26] M. Binder,[24] C. Biscarat,[40] K. M. Black,[59] I. Blackler,[41] G. Blazey,[50] F. Blekman,[32] S. Blessing,[47] D. Bloch,[18] U. Blumenschein,[22] A. Boehnlein,[48] O. Boeriu,[53] T. A. Bolton,[56] F. Borcherding,[48] G. Borissov,[40] K. Bos,[32] T. Bose,[66] A. Brandt,[73] R. Brock,[62] G. Brooijmans,[66] A. Bross,[48] N. J. Buchanan,[47] D. Buchholz,[51] M. Buehler,[49] V. Buescher,[22] S. Burdin,[48] T. H. Burnett,[77] E. Busato,[16] J. M. Butler,[59] J. Bystricky,[17] W. Carvalho,[3] B. C. K. Casey,[72] N. M. Cason,[53] H. Castilla-Valdez,[31] S. Chakrabarti,[28] D. Chakraborty,[50] K. M. Chan,[67] A. Chandra,[28] D. Chapin,[72] F. Charles,[18] E. Cheu,[43] L. Chevalier,[17] D. K. Cho,[67] S. Choi,[46] B. Choudhary,[27] T. Christiansen,[24] L. Christofek,[55] D. Claes,[64] B. Clément,[18] C. Clément,[39] Y. Coadou,[5] M. Cooke,[75] W. E. Cooper,[48] D. Coppage,[55] M. Corcoran,[75] A. Cothenet,[14] M.-C. Cousinou,[14] B. Cox,[42] S. Crépé-Renaudin,[13] M. Cristetiu,[46] D. Cutts,[72] H. da Motta,[2] B. Davies,[40] G. Davies,[41] G. A. Davis,[51] K. De,[73] P. de Jong,[32] S. J. de Jong,[33] E. De La Cruz-Burelo,[31] C. De Oliveira Martins,[3] S. Dean,[42] F. Déliot,[17] M. Demarteau,[48] R. Demina,[67] P. Demine,[17] D. Denisov,[48] S. P. Denisov,[37] S. Desai,[68] H. T. Diehl,[48] M. Diesburg,[48] M. Doidge,[40] H. Dong,[68] S. Doulas,[60] L. V. Dudko,[36] L. Duflot,[15] S. R. Dugad,[28] A. Duperrin,[14] J. Dyer,[62] A. Dyshkant,[50] M. Eads,[50] D. Edmunds,[62] T. Edwards,[42] J. Ellison,[46] J. Elmsheuser,[24] J. T. Eltzroth,[73] V. D. Elvira,[48] S. Eno,[58] P. Ermolov,[36] O. V. Eroshin,[37] J. Estrada,[48] D. Evans,[41] H. Evans,[66] A. Evdokimov,[35] V. N. Evdokimov,[37] J. Fast,[48] S. N. Fatakia,[59] L. Feligioni,[59] T. Ferbel,[67] F. Fiedler,[24] F. Filthaut,[33] W. Fisher,[65] H. E. Fisk,[48] M. Fortner,[50] H. Fox,[22] W. Freeman,[48] S. Fu,[48] S. Fuess,[48] T. Gadfort,[77] C. F. Galea,[33] E. Gallas,[48] E. Galyaev,[53] C. Garcia,[67] A. Garcia-Bellido,[77] J. Gardner,[55] V. Gavrilov,[35] P. Gay,[12] D. Gelé,[18] R. Gelhaus,[46] K. Genser,[48] C. E. Gerber,[49] Y. Gershtein,[72] G. Ginther,[67] T. Golling,[21] B. Gómez,[7] K. Gounder,[48] A. Goussiou,[53] P. D. Grannis,[68] S. Greder,[18] H. Greenlee,[48] Z. D. Greenwood,[57] E. M. Gregores,[4] Ph. Gris,[12] J.-F. Grivaz,[15] L. Groer,[66] S. Grünendahl,[48] M. W. Grünewald,[29] S. N. Gurzhiev,[37] G. Gutierrez,[48] P. Gutierrez,[71] A. Haas,[66] N. J. Hadley,[58] S. Hagopian,[47] I. Hall,[71] R. E. Hall,[45] C. Han,[61] L. Han,[42] K. Hanagaki,[48] K. Harder,[56] R. Harrington,[60] J. M. Hauptman,[54] R. Hauser,[62] J. Hays,[51] T. Hebbeker,[20] D. Hedin,[50] J. M. Heinmiller,[49] A. P. Heinson,[46] U. Heintz,[59] C. Hensel,[55] G. Hesketh,[60] M. D. Hildreth,[53] R. Hirosky,[76] J. D. Hobbs,[68] B. Hoeneisen,[11] M. Hohlfeld,[23] S. J. Hong,[30] R. Hooper,[72] P. Houben,[32] Y. Hu,[68] J. Huang,[52] I. Iashvili,[46] R. Illingworth,[48] A. S. Ito,[48] S. Jabeen,[55] M. Jaffré,[15] S. Jain,[71] V. Jain,[69] K. Jakobs,[22] A. Jenkins,[41] R. Jesik,[41] K. Johns,[43] M. Johnson,[48] A. Jonckheere,[48] P. Jonsson,[41] H. Jöstlein,[48] A. Juste,[48] D. Käfer,[20] W. Kahl,[56] S. Kahn,[69] E. Kajfasz,[14] A. M. Kalinin,[34] J. Kalk,[62] D. Karmanov,[36] J. Kasper,[59] D. Kau,[47] R. Kaur,[26] R. Kehoe,[74] S. Kermiche,[14] S. Kesisoglou,[72] A. Khanov,[67] A. Kharchilava,[53] Y. M. Kharzheev,[34] K. H. Kim,[30] B. Klima,[48] M. Klute,[21] J. M. Kohli,[26] M. Kopal,[71] V. M. Korablev,[37] J. Kotcher,[69] B. Kothari,[66] A. Koubarovsky,[36] A. V. Kozelov,[37] J. Kozminski,[62] S. Krzywdzinski,[48] S. Kuleshov,[35] Y. Kulik,[48] A. Kumar,[27] S. Kunori,[58] A. Kupco,[10] T. Kurča,[19] S. Lager,[39] N. Lahrichi,[17] G. Landsberg,[72] J. Lazoflores,[47] A.-C. Le Bihan,[18] P. Lebrun,[19] S. W. Lee,[30] W. M. Lee,[47] A. Leflat,[36] F. Lehner,[48,*] C. Leonidopoulos,[66] P. Lewis,[41] J. Li,[73] Q. Z. Li,[48] J. G. R. Lima,[50] D. Lincoln,[48] S. L. Linn,[47] J. Linnemann,[62] V. V. Lipaev,[37] R. Lipton,[48] L. Lobo,[41] A. Lobodenko,[38] M. Lokajicek,[10] A. Lounis,[18] H. J. Lubatti,[77] L. Lueking,[48] M. Lynker,[53] A. L. Lyon,[48] A. K. A. Maciel,[50] R. J. Madaras,[44] P. Mättig,[25] A. Magerkurth,[61] A.-M. Magnan,[13] N. Makovec,[15] P. K. Mal,[28] S. Malik,[57] V. L. Malyshev,[34] H. S. Mao,[6] Y. Maravin,[48] M. Martens,[48] S. E. K. Mattingly,[72] A. A. Mayorov,[37] R. McCarthy,[68] R. McCroskey,[43] D. Meder,[23] H. L. Melanson,[48] A. Melnitchouk,[63] A. Mendes,[14] M. Merkin,[36] K. W. Merritt,[48] A. Meyer,[20] M. Michaut,[17] H. Miettinen,[75] J. Mitrevski,[66] N. Mokhov,[48] J. Molina,[3] N. K. Mondal,[28] R. W. Moore,[5] G. S. Muanza,[19] M. Mulders,[48] Y. D. Mutaf,[68] E. Nagy,[14] M. Narain,[59] N. A. Naumann,[33] H. A. Neal,[61] J. P. Negret,[7] S. Nelson,[47] P. Neustroev,[38] C. Noeding,[22] A. Nomerotski,[48] S. F. Novaes,[4] T. Nunnemann,[24] E. Nurse,[42] V. O'Dell,[48] D. C. O'Neil,[5] V. Oguri,[3] N. Oliveira,[3] N. Oshima,[48] G. J. Otero y Garzón,[49] P. Padley,[75] N. Parashar,[57] J. Park,[30] S. K. Park,[30] J. Parsons,[66] R. Partridge,[72] N. Parua,[68] A. Patwa,[69] P. M. Perea,[46] E. Perez,[17] P. Pétroff,[15] M. Petteni,[41] L. Phaf,[32] R. Piegaia,[1] M.-A. Pleier,[67] P. L. M. Podesta-Lerma,[31] V. M. Podstavkov,[48] Y. Pogorelov,[53] B. G. Pope,[62] W. L. Prado da Silva,[3] H. B. Prosper,[47] S. Protopopescu,[69] J. Qian,[61] A. Quadt,[21] B. Quinn,[63] K. J. Rani,[28] K. Ranjan,[27] P. A. Rapidis,[48] P. N. Ratoff,[40] N. W. Reay,[56] S. Reucroft,[60] M. Rijssenbeek,[68] I. Ripp-Baudot,[18] F. Rizatdinova,[56] C. Royon,[17] P. Rubinov,[48] R. Ruchti,[53] V. I. Rud,[36] G. Sajot,[13] A. Sánchez-Hernández,[31] M. P. Sanders,[42]

A. Santoro,[3] G. Savage,[48] L. Sawyer,[57] T. Scanlon,[41] D. Schaile,[24] R. D. Schamberger,[68] H. Schellman,[51] P. Schieferdecker,[24] C. Schmitt,[25] A. A. Schukin,[37] A. Schwartzman,[65] R. Schwienhorst,[62] S. Sengupta,[47] H. Severini,[71] E. Shabalina,[49] M. Shamim,[56] V. Shary,[17] W. D. Shephard,[53] R. K. Shivpuri,[27] D. Shpakov,[60] R. A. Sidwell,[56] V. Simak,[9] V. Sirotenko,[48] P. Skubic,[71] P. Slattery,[67] R. P. Smith,[48] K. Smolek,[9] G. R. Snow,[64] J. Snow,[70] S. Snyder,[69] S. Söldner-Rembold,[42] X. Song,[50] Y. Song,[73] L. Sonnenschein,[59] A. Sopczak,[40] M. Sosebee,[73] K. Soustruznik,[8] M. Souza,[2] B. Spurlock,[73] N. R. Stanton,[56] J. Stark,[13] J. Steele,[57] G. Steinbrück,[66] K. Stevenson,[52] V. Stolin,[35] A. Stone,[49] D. A. Stoyanova,[37] J. Strandberg,[39] M. A. Strang,[73] M. Strauss,[71] R. Ströhmer,[24] D. Strom,[51] M. Strovink,[44] L. Stutte,[48] S. Sumowidagdo,[47] A. Sznajder,[3] M. Talby,[14] P. Tamburello,[43] W. Taylor,[5] P. Telford,[42] J. Temple,[43] E. Thomas,[14] B. Thooris,[17] M. Tomoto,[48] T. Toole,[58] J. Torborg,[53] S. Towers,[68] T. Trefzger,[23] S. Trincaz-Duvoid,[16] B. Tuchming,[17] C. Tully,[65] A. S. Turcot,[69] P. M. Tuts,[66] L. Uvarov,[38] S. Uvarov,[38] S. Uzunyan,[50] B. Vachon,[5] R. Van Kooten,[52] W. M. van Leeuwen,[32] N. Varelas,[49] E. W. Varnes,[43] I. A. Vasilyev,[37] M. Vaupel,[25] P. Verdier,[15] L. S. Vertogradov,[34] M. Verzocchi,[58] F. Villeneuve-Seguier,[41] J.-R. Vlimant,[16] E. Von Toerne,[56] M. Vreeswijk,[32] T. Vu Anh,[15] H. D. Wahl,[47] R. Walker,[41] L. Wang,[58] Z.-M. Wang,[68] J. Warchol,[53] M. Warsinsky,[21] G. Watts,[77] M. Wayne,[53] M. Weber,[48] H. Weerts,[62] M. Wegner,[20] N. Wermes,[21] A. White,[73] V. White,[48] D. Whiteson,[44] D. Wicke,[48] D. A. Wijngaarden,[33] G. W. Wilson,[55] S. J. Wimpenny,[46] J. Wittlin,[59] M. Wobisch,[48] J. Womersley,[48] D. R. Wood,[60] T. R. Wyatt,[42] Q. Xu,[61] N. Xuan,[53] S. Yacoob,[51] R. Yamada,[48] M. Yan,[58] T. Yasuda,[48] Y. A. Yatsunenko,[34] Y. Yen,[25] K. Yip,[69] S. W. Youn,[51] J. Yu,[73] A. Yurkewicz,[68] A. Zabi,[15] A. Zatserklyaniy,[50] M. Zdrazil,[68] C. Zeitnitz,[23] D. Zhang,[48] X. Zhang,[71] T. Zhao,[77] Z. Zhao,[61] B. Zhou,[61] J. Zhu,[58] M. Zielinski,[67] D. Zieminska,[52] A. Zieminski,[52] R. Zitoun,[68] V. Zutshi,[50] E. G. Zverev,[36] and A. Zylberstejn[17]

(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*
[4]*Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[5]*University of Alberta, Edmonton, Alberta, Canada, Simon Fraser University, Burnaby, British Columbia, Canada, York University, Toronto, Ontario, Canada, and McGill University, Montreal, Quebec, Canada*
[6]*Institute of High Energy Physics, Beijing, People's Republic of China*
[7]*Universidad de los Andes, Bogotá, Colombia*
[8]*Center for Particle Physics, Charles University, Prague, Czech Republic*
[9]*Czech Technical University, Prague, Czech Republic*
[10]*Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic*
[11]*Universidad San Francisco de Quito, Quito, Ecuador*
[12]*Laboratoire de Physique Corpusculaire, IN2P3-CNRS, Université Blaise Pascal, Clermont-Ferrand, France*
[13]*Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Universite de Grenoble 1, Grenoble, France*
[14]*CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France*
[15]*Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Orsay, France*
[16]*LPNHE, IN2P3-CNRS, Universités Paris VI and VII, Paris, France*
[17]*DAPNIA/Service de Physique des Particules, CEA, Saclay, France*
[18]*IReS, IN2P3-CNRS, Université Louis Pasteur, Strasbourg, France, and Université de Haute Alsace, Mulhouse, France*
[19]*Institut de Physique Nucléaire de Lyon, IN2P3-CNRS, Université Claude Bernard, Villeurbanne, France*
[20]*III. Physikalisches Institut A, RWTH Aachen, Aachen, Germany*
[21]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[22]*Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[23]*Institut für Physik, Universität Mainz, Mainz, Germany*
[24]*Ludwig-Maximilians-Universität München, München, Germany*
[25]*Fachbereich Physik, University of Wuppertal, Wuppertal, Germany*
[26]*Panjab University, Chandigarh, India*
[27]*Delhi University, Delhi, India*
[28]*Tata Institute of Fundamental Research, Mumbai, India*
[29]*University College Dublin, Dublin, Ireland*
[30]*Korea Detector Laboratory, Korea University, Seoul, Korea*
[31]*CINVESTAV, Mexico City, Mexico*

[32]*FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*
[33]*University of Nijmegen/NIKHEF, Nijmegen, The Netherlands*
[34]*Joint Institute for Nuclear Research, Dubna, Russia*
[35]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[36]*Moscow State University, Moscow, Russia*
[37]*Institute for High Energy Physics, Protvino, Russia*
[38]*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[39]*Lund University, Lund, Sweden, Royal Institute of Technology and Stockholm University, Stockholm, Sweden, and Uppsala University, Uppsala, Sweden*
[40]*Lancaster University, Lancaster, United Kingdom*
[41]*Imperial College, London, United Kingdom*
[42]*University of Manchester, Manchester, United Kingdom*
[43]*University of Arizona, Tucson, Arizona 85721, USA*
[44]*Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA*
[45]*California State University, Fresno, California 93740, USA*
[46]*University of California, Riverside, California 92521, USA*
[47]*Florida State University, Tallahassee, Florida 32306, USA*
[48]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[49]*University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[50]*Northern Illinois University, DeKalb, Illinois 60115, USA*
[51]*Northwestern University, Evanston, Illinois 60208, USA*
[52]*Indiana University, Bloomington, Indiana 47405, USA*
[53]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[54]*Iowa State University, Ames, Iowa 50011, USA*
[55]*University of Kansas, Lawrence, Kansas 66045, USA*
[56]*Kansas State University, Manhattan, Kansas 66506, USA*
[57]*Louisiana Tech University, Ruston, Louisiana 71272, USA*
[58]*University of Maryland, College Park, Maryland 20742, USA*
[59]*Boston University, Boston, Massachusetts 02215, USA*
[60]*Northeastern University, Boston, Massachusetts 02115, USA*
[61]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[62]*Michigan State University, East Lansing, Michigan 48824, USA*
[63]*University of Mississippi, University, Mississippi 38677, USA*
[64]*University of Nebraska, Lincoln, Nebraska 68588, USA*
[65]*Princeton University, Princeton, New Jersey 08544, USA*
[66]*Columbia University, New York, New York 10027, USA*
[67]*University of Rochester, Rochester, New York 14627, USA*
[68]*State University of New York, Stony Brook, New York 11794, USA*
[69]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[70]*Langston University, Langston, Oklahoma 73050, USA*
[71]*University of Oklahoma, Norman, Oklahoma 73019, USA*
[72]*Brown University, Providence, Rhode Island 02912, USA*
[73]*University of Texas, Arlington, Texas 76019, USA*
[74]*Southern Methodist University, Dallas, Texas 75275, USA*
[75]*Rice University, Houston, Texas 77005, USA*
[76]*University of Virginia, Charlottesville, Virginia 22901, USA*
[77]*University of Washington, Seattle, Washington 98195, USA*

(Received 13 December 2004; published 29 April 2005)

We report on a search for pair production of first-generation scalar leptoquarks (LQ) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using an integrated luminosity of 252 pb^{-1} collected at the Fermilab Tevatron collider by the D0 detector. We observe no evidence for LQ production in the topologies arising from $\text{LQ}\overline{\text{LQ}} \rightarrow eqeq$ and $\text{LQ}\overline{\text{LQ}} \rightarrow eq\nu q$, and derive 95% C.L. lower limits on the LQ mass as a function of β, where β is the branching fraction for $\text{LQ} \rightarrow eq$. The limits are 241 and 218 GeV/c^2 for $\beta = 1$ and 0.5, respectively. These results are combined with those obtained by D0 at $\sqrt{s} = 1.8$ TeV, which increases these LQ mass limits to 256 and 234 GeV/c^2.

DOI: 10.1103/PhysRevD.71.071104 PACS numbers: 14.80.−j, 13.85.Rm

*Visitor from University of Zurich, Zurich, Switzerland.

Several extensions of the standard model (SM) include leptoquarks (LQ) which carry color, fractional electric charge, and both lepton (l) and quark (q) quantum numbers and would decay into a lepton and a quark [1]. The H1 and ZEUS experiments at the $e^{\pm}p$ collider HERA at DESY published [2] lower limits on the mass of a first-generation LQ that depend on the unknown leptoquark-l-q Yukawa coupling λ. At the CERN LEP collider, pair production of leptoquarks could occur in e^+e^- collisions via a virtual γ or Z boson in the s channel. At the Fermilab Tevatron collider, leptoquarks would be pair produced dominantly through $q\bar{q}$ annihilation (for $M_{\rm LQ} > 100\ {\rm GeV}/c^2$) and gluon fusion. Such pair production mechanisms are independent of the coupling λ. Experiments at the LEP collider [3] and at the Fermilab Tevatron collider [4–6] set lower limits on the masses of leptoquarks. In this letter, we present a search for first-generation scalar leptoquark pairs produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV for two cases: when both leptoquarks decay to an electron and a quark with a branching fraction (Br) β^2, where β is the leptoquark branching fraction into an electron and a quark, and when one of the leptoquarks decays to an electron and a quark and the other to a neutrino and a quark with ${\rm Br} = 2\beta(1-\beta)$. The final states consist of two electrons and two jets ($eejj$) or of an electron, two jets, and missing transverse energy corresponding to the neutrino which escapes detection ($e\nu jj$).

The D0 detector [7] comprises three main elements. A magnetic central-tracking system, which consists of a silicon microstrip tracker and a central fiber tracker, is located within a 2 T superconducting solenoidal magnet. Three liquid-argon/uranium calorimeters, a central section (CC) covering pseudorapidities η [8] with $|\eta|$ up to ≈ 1 and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$ [9], are housed in separate cryostats. Scintillators between the CC and EC cryostats provide a sampling of developing showers for $1.1 < |\eta| < 1.4$. A muon system is located outside the calorimeters.

The data used in this analysis were collected from April 2002 to March 2004. The integrated luminosity for this data sample is $252 \pm 16\ {\rm pb}^{-1}$. Events were required to pass at least one of a set of electron triggers based on the requirement of one electromagnetic trigger tower to be above threshold and on shower shape conditions. The efficiencies of the trigger combinations used in the $eejj$ and $e\nu jj$ analyses have been measured using data. They are $\sim$100% for two electrons of transverse energy ($E_T^{\rm EM}$) above 25 GeV, and for one electron above 40 GeV. The small loss of events due to the trigger inefficiencies for $E_T^{\rm EM}$ below 40 GeV is taken into account using proper weighting for Monte Carlo (MC) events.

Electrons are reconstructed as calorimeter electromagnetic (EM) clusters which match a track in the central-tracking system. Electromagnetic clusters are identified by the characteristics of their energy deposition in the calorimeter. Cuts are applied on the fraction of the energy in the electromagnetic calorimeter and the isolation of the cluster in the calorimeter. EM clusters are marked as tight when they satisfy a shower shape condition and loose otherwise. Jets are reconstructed using the iterative, midpoint cone algorithm [10] with a cone size of 0.5. The energy measurement of the jets has been calibrated as a function of the jet transverse energy and η by balancing energy in photon plus jet events. The missing transverse energy ($\not{E}_T$) is calculated as the vector sum of the transverse energies in the calorimeter cells, removing contributions from detector noise.

For both channels, the background arising from multijet events is determined from a sample of data events (QCD sample) that satisfy the main cuts used in the analysis except that each EM cluster is loose instead of tight. A QCD normalization factor is extracted for this sample in a part of the phase space where the LQ contribution is expected to be negligible. The QCD sample normalized by this factor is used to derive the multijet contribution in the relevant part of the phase space. To evaluate the Z boson/Drell-Yan (Z/DY) and the W boson background contributions, samples of MC events generated with ALPGEN [11] or PYTHIA [12] were used. Samples of PYTHIA $t\bar{t}$ events ($m_t = 175\ {\rm GeV}/c^2$) were used to calculate the top quark background. ${\rm LQ}\overline{\rm LQ} \rightarrow eejj$ and ${\rm LQ}\overline{\rm LQ} \rightarrow e\nu jj$ MC samples were generated using PYTHIA for LQ masses from 120 to 280 ${\rm GeV}/c^2$ in steps of 20 ${\rm GeV}/c^2$. All MC events were processed using a full simulation of the detector based on GEANT [13] and the complete event reconstruction. The efficiencies of the various cuts, measured using the data, were taken into account using proper weightings of the MC events.

The $eejj$ analysis requires two tight EM clusters with $E_T^{\rm EM} > 25$ GeV and at least two jets with $E_T > 20$ GeV within $|\eta| < 2.4$. At least one of the EM clusters should spatially match an isolated track and at least one should be in the CC fiducial region. The major SM background sources that mimic the $eejj$ decay of a LQ pair are multijet events (where two of the jets are misidentified as EM objects), Z/DY production, and top-quark-pair production.

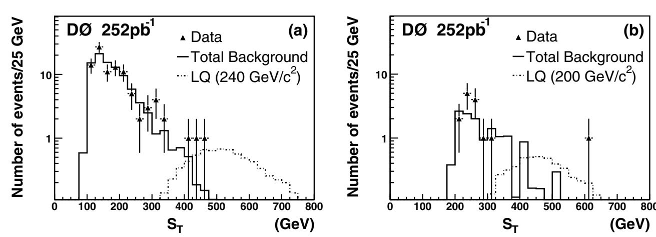

FIG. 1. The S_T distributions for the $eejj$ events (a) and $e\nu jj$ events (b) from data (triangles) compared to the SM background (solid histograms). The dot-dashed histograms are the expected distributions for a 240 ${\rm GeV}/c^2$ LQ signal (a) and for a 200 ${\rm GeV}/c^2$ LQ signal (b).

TABLE I. Efficiencies after all cuts and 95% C.L. upper limits on production cross section × branching fraction Br, as a function of M_{LQ}, for the two channels.

	eejj		*eνjj*	
M_{LQ} (GeV/c^2)	ϵ (%)	$\sigma \times$ Br (pb)	ϵ (%)	$\sigma \times$ Br (pb)
120	2.2 ± 0.5	0.950	4.6 ± 0.5	0.34
140	4.5 ± 0.9	0.444	7.9 ± 0.8	0.20
160	8.9 ± 1.7	0.223	11.7 ± 1.1	0.14
180	12.6 ± 2.4	0.156	15.5 ± 1.5	0.10
200	18.5 ± 3.0	0.102	17.8 ± 1.7	0.088
220	24.6 ± 3.5	0.075	18.9 ± 1.8	0.083
240	30.3 ± 3.9	0.060	20.9 ± 1.9	0.075
260	34.0 ± 4.0	0.053	21.9 ± 2.1	0.071
280	36.0 ± 4.0	0.050	22.7 ± 2.1	0.069

TABLE II. Number of events in data compared with background expectation at different stages of the *eejj* analysis.

	eejj	Z boson veto	$S_T > 450$ GeV
Data	467	95	1
Total background	406 ± 100	92 ± 17	0.54 ± 0.11
Z/DY + jets	342 ± 99	41 ± 11	0.22 ± 0.07
Multijet	59 ± 16	47 ± 13	0.27 ± 0.08
$t\bar{t}$ production	4.7 ± 0.4	3.8 ± 0.3	0.05 ± 0.01

To suppress background from Z boson production, events with a dielectron mass (M_{2EM}) compatible with the Z boson mass ($80 < M_{2EM} < 102$ GeV/c^2) are rejected. Finally $S_T > 450$ GeV is also required, where S_T is the scalar sum of the transverse energies of the two electrons and the two leading jets. In Fig. 1(a), the S_T distributions for data and background after applying the Z boson mass cut are shown. This choice of the cutoff has been optimized using MC signal and background events to get the best expected mass limit. The total efficiencies for a LQ signal are summarized in Table I. The multijet background is estimated from two samples of events with two EM clusters $E_T^{EM} > 15$ GeV which have at least one matched track and no reconstructed jets. Both EM clusters are tight in one sample and loose in the other. The QCD normalization factor is determined by the normalization of the M_{2EM} distributions of the two samples below 75 GeV/c^2. The Z/DY and top quark contributions are normalized to the integrated luminosity. Table II lists the number of events in the data and the number of expected events from SM background sources.

Systematic uncertainties on the background are determined to be 15% from the QCD normalization factor and 6% from the efficiencies of the identification of electrons and jets (particle ID). An uncertainty (26%) from the jet energy scale is determined by varying the correction factor on the calorimeter response to jets by 1 standard deviation. A systematic uncertainty on the Z/DY background (20%) is calculated by taking into account the differences between the two Z/DY MC samples. On the signal, the particle ID and the limited statistics of the MC sample correspond to systematic uncertainties of 6% and 1.2%, respectively. Comparing acceptances for the signal samples generated with PYTHIA using different parametrizations of parton distribution functions (PDFs) leads to an uncertainty of 5%. The uncertainty due to the jet energy scale is dependent on the LQ mass (7.3% for a LQ mass of 240 GeV/c^2). The total uncertainty on the efficiency is (17–9)% in the mass range 180–280 GeV/c^2.

The data are consistent with the expected SM background and no evidence for leptoquark production is observed in the *eejj* channel. Thus we can set an upper limit at the 95% C.L. on the LQ pair production cross section using a Bayesian approach [14]. The limits are tabulated in Table I and shown in Fig. 2(a) as a function of LQ mass. To compare our experimental results with theory, we use the next-to-leading order (NLO) cross section for scalar leptoquark pair production from Ref. [15], with the CTEQ6 PDF [16]. The theoretical uncertainties correspond to the variation from $M_{LQ}/2$ to $2M_{LQ}$ of the renormalization scale μ used in the calculation and to the errors on the PDFs. To set a limit on the LQ mass we compare our experimental limit to the theoretical cross section for

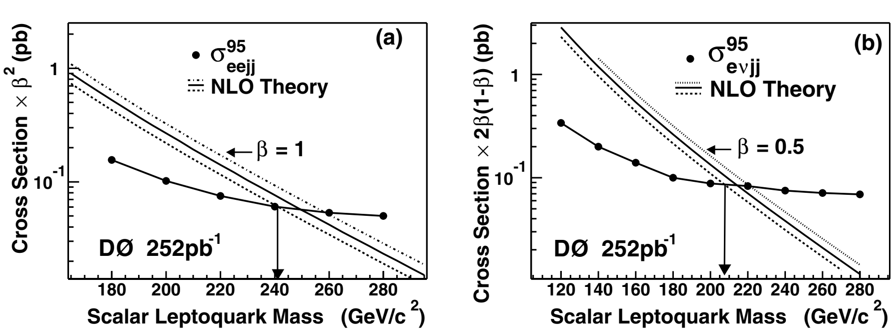

FIG. 2. The 95% C.L. limit on the experimental cross section times branching fraction as a function of LQ mass (circles) for the *eejj* (a) and *eνjj* (b) channels. The NLO theoretical cross sections [15] are plotted for different values of the renormalization scale factor: M_{LQ} (full line), $M_{LQ}/2$ (dotted curve) and $2M_{LQ}$ (dashed curve) taking into account the PDF uncertainties. A mass limit of 241 GeV/c^2 (a) and of 208 GeV/c^2 (b) for first-generation scalar leptoquarks is obtained for $\beta = 1$ and $\beta = 0.5$, respectively.

$\mu = 2M_{\rm LQ}$, which is conservative as it corresponds to the lower value of the theoretical cross section. The value of the theoretical cross section would increase by ~7% if the PDF errors were neglected. A lower limit on the leptoquark mass of 241 GeV/c^2 is obtained for $\beta = 1$.

The $e\nu jj$ analysis requires exactly one tight EM cluster ($E_T^{\rm EM} > 35$ GeV) in the CC fiducial region which matches an isolated track spatially and kinematically. At least two jets with $E_T > 25$ GeV within $|\eta| < 2.4$ and $\not{E}_T > 30$ GeV are required. The main SM background sources which would mimic the $e\nu jj$ decay of a LQ pair are events with multijet production (where a jet is reconstructed as an electron and the $\not{E}_T$ comes from jet mismeasurements), $W + 2$ jets events, and top-quark-pair production. A veto on muons with $p_T > 10$ GeV/c is applied to reduce the dilepton background from $t\bar{t}$ decays. A cut on the invariant transverse mass of the electron and the missing energy ($M_T^{e\nu} > 130$ GeV/c^2) is applied to reduce the W boson background. Finally $S_T > 330$ GeV is required, where here S_T is the sum of the transverse energies of the electron, the two jets, and the $\not{E}_T$. The distribution of the variable S_T for the data and the total background is shown in Fig. 1(b) after applying the $M_T^{e\nu}$ cut. The choice of the cutoff has been optimized as above. The total efficiency of these cuts for a LQ signal is given in Table I. To determine the multijet background we use a data sample that passed all the preceding cuts but with a loose EM cluster spatially matching a track. The QCD normalization factor is determined using the ratio of the number of events with $\not{E}_T <$ 10 GeV in this and in the search samples. The W boson background is normalized to the data at transverse mass $60 < M_T^{e\nu} < 100$ GeV/c^2. The top quark background is normalized to the integrated luminosity using the NNLO theoretical cross section. The number of events which survive the cuts and the number of predicted background events are summarized in Table III.

Systematic uncertainties associated with the QCD normalization factor (9%) and W boson normalization factor (5.7%) are determined by the limited statistics of the samples and the choice of kinematical domain over which the normalization is done. The jet energy scale uncertainty introduces uncertainties equal to 25% for W boson production and 8.5% for the top-quark-pair production. For the W boson background an uncertainty equal to 33% is associated with the shape of the $\not{E}_T$ distribution. A 25% error has been included as systematic uncertainty on the top quark cross section. Finally, there is an uncertainty of 3.8% on the particle-ID acceptance. Three systematic uncertainties are determined on the signal acceptance: 3.8% comes from the uncertainty on the particle ID, 5% is due to the jet energy scale uncertainty, and 5.4% corresponds to the acceptance variations for different PDF parametrizations.

As no excess of data over background is found in the $e\nu jj$ channel, an upper limit on the production cross section for a first-generation scalar leptoquark is derived and shown in Fig. 2(b) and in Table I. A comparison of these limits to theoretical calculations of the cross section [15], performed as described above, gives a lower limit on the first-generation scalar LQ mass of 208 GeV/c^2 for $\beta = 0.5$.

A combination of the limits obtained in the searches in the $eejj$ and $e\nu jj$ channels is done using a Bayesian likelihood technique [17], with correlated uncertainties taken into account. The limits on the cross sections obtained at the 95% C.L. for the combination of the two channels and different values of β are compared with the NLO LQ pair production cross section [15] and lower mass limits are derived and given, as a function of β, in Table IV and shown in Fig. 3. In Table IV are also shown the run I mass limits based on an integrated luminosity ~120 pb^{-1} obtained by D0 [4], using the three channels $eejj$, $e\nu jj$ and $\nu\nu jj$, and CDF [5] ($eejj$ channel). This analysis sets a 95% C.L. limit on the first-generation leptoquark mass of $M_{\rm LQ} > 218$ GeV/c^2 for $\beta = 0.5$, and $M_{\rm LQ} >$ 241 GeV/c^2 for $\beta = 1$. The D0 run II and run I results are combined, using the same method, and the results are shown in Table IV and in Fig. 3. The 95% C.L. limits on the first-generation leptoquark mass are $M_{\rm LQ} > 234$ GeV/c^2 for $\beta = 0.5$, and $M_{\rm LQ} > 256$ GeV/c^2 for $\beta = 1$.

TABLE III. Number of events in data compared with background expectation at different stages of the $e\nu jj$ analysis. The values of the cuts are in GeV or in GeV/c^2.

	$\not{E}_T > 30$	$M_T^{e\nu} > 130$	$S_T > 330$
Data	900	14	1
Total background	902 ± 211	13.9 ± 4.4	3.6 ± 1.2
W + jets	811 ± 211	10.0 ± 4.4	2.2 ± 1.2
Multijet	76 ± 7	2.3 ± 0.5	0.72 ± 0.28
$t\bar{t}$ production	14.7 ± 2.9	1.6 ± 0.37	0.70 ± 0.17

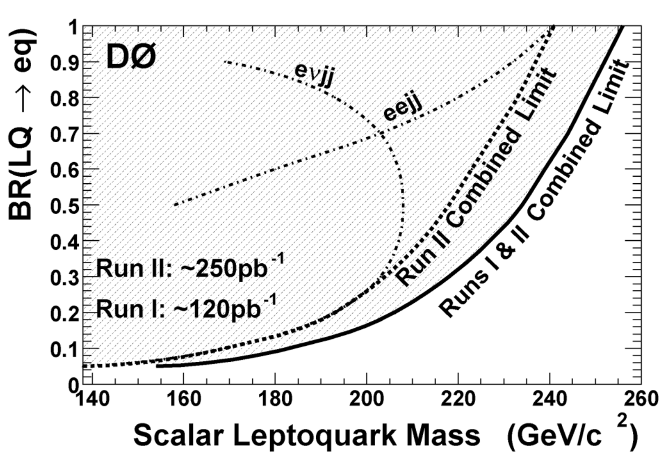

FIG. 3. Excluded regions (shaded area) at the 95% C.L. in the β versus LQ mass plane for the production of first-generation scalar leptoquarks.

TABLE IV. 95% C.L. lower limits on the first-generation scalar leptoquark mass (in GeV/c^2), as a function of β. The mass limits from D0 ($eejj$, $e\nu jj$ and $\nu\nu jj$ combined) [4] and CDF ($eejj$) [5] at run I ($\sim 120\ \mathrm{pb}^{-1}$) are also given, as well as the limits obtained by combining the D0 run I and run II results.

β	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$eejj$					158	180	203	220	232	241
$e\nu jj$	169	193	203	207	208	207	203	193	169	
D0 run II	169	193	204	212	218	223	228	232	237	241
D0 run I	110				204					225
D0 runs I & II	183	206	218	227	234	239	244	248	252	256
CDF run I										213

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à l'Energie Atomique and CNRS/Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry of Education and Science, Agency for Atomic Energy and RF President Grants Program (Russia), CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil), Departments of Atomic Energy and Science and Technology (India), Colciencias (Colombia), CONACyT (Mexico), KRF (Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (United Kingdom), Ministry of Education (Czech Republic), Canada Research Chairs Program, CFI, Natural Sciences and Engineering Research Council and WestGrid Project (Canada), BMBF and DFG (Germany), the A. P. Sloan Foundation, Research Corporation, Texas Advanced Research Program, and the Alexander von Humboldt Foundation.

[1] Darin E. Acosta and Susan K. Blessing, Annu. Rev. Nucl. Part. Sci. **49**, 389 (1999), and references therein; P. Bruce Straub, in Proceedings of the 31st International Conference on High Energy Physics, (ICHEP 2002), Amsterdam, The Netherlands, 2002 (hep-ex/0212023).

[2] H1 Collaboration, C. Adloff *et al.*, Eur. Phys. J. C **11**, 447 (1999); **14**, 553 (2000); H1 Collaboration, C. Adloff *et al.*, Phys. Lett. B **523**, 234 (2001); ZEUS Collaboration, J. Breitweg *et al.*, Eur. Phys. J. C **16**, 253 (2000); ZEUS Collaboration, J. Breitweg *et al.*, Phys. Rev. D **63**, 052002 (2001).

[3] DELPHI Collaboration, P. Abreu *et al.*, Phys. Lett. B **446**, 62 (1999); OPAL Collaboration, G. Abbiendi *et al.*, Phys. Lett. B **526**, 233 (2002); L3 Collaboration, M. Acciari *et al.*, Phys. Lett. B **489**, 81 (2000); ALEPH Collaboration, R. Barate *et al.*, Eur. Phys. J. C **12**, 183 (2000).

[4] D0 Collaboration, V. Abazov *et al.*, Phys. Rev. D **64**, 092004 (2001).

[5] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **79**, 4327 (1997).

[6] CDF Collaboration, D. Acosta *et al.*, FERMILAB Report No. FERMILAB-PUB-04-303-E, 2004.

[7] V. Abazov *et al.* (unpublished); T. LeCompte and H. T. Diehl, Annu. Rev. Nucl. Part. Sci. **50**, 71 (2000).

[8] $\eta = -\ln(\tan(\theta/2))$ where θ is the polar angle measured relative to the proton beam direction.

[9] S. Abachi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **338**, 185 (1994).

[10] G. Blazey *et al.*, in Proceedings of the Workshop "QCD and Weak Boson Physics in Run II," Batavia, 2000, edited by U. Baur, R. K. Ellis, and D. Zeppenfeld (Fermilab Report No. Fermilab-Pub-00/297), p. 47.

[11] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. Polosa, J. High Energy Phys. 07 (2003) 001.

[12] T. Sjöstrand, Comput. Phys. Commun. **82**, 74 (1994).

[13] R. Brun and F. Carminati, CERN Program Library Long Writeup No. W5013, 1993.

[14] I. Bertram *et al.*, Fermilab Report No. TM-2104, 1998.

[15] M. Krämer *et al.*, Phys. Rev. Lett. **79**, 341 (1997).

[16] J. Pumplin *et al.*, J. High Energy Phys. 07 (2002) 012; D. Stump *et al.*, J. High Energy Phys. 10 (2003) 046.

[17] C. Grosso-Pilcher, G. Landsberg, and M. Paterno, hep-ex/9810015.