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Article

2005

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Collaborators: Campanelli, Mario; Clark, Allan Geoffrey; Donega, Mauro; D'Onofrio, Monica; Lister, Alison; Liu, Yanwen; Wu, Xin

How to cite

CDF Collaboration. Search for first-generation scalar leptoquarks in pp collisions at $\sqrt{s}=1.96$ TeV. In: Physical review. D. Particles, fields, gravitation, and cosmology, 2005, vol. 72, n° 05, p. 051107. doi: 10.1103/PhysRevD.72.051107

This publication URL: <https://archive-ouverte.unige.ch/unige:38314>

Publication DOI: [10.1103/PhysRevD.72.051107](https://doi.org/10.1103/PhysRevD.72.051107)

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

D. Acosta,¹⁶ J. Adelman,¹² T. Affolder,⁹ T. Akimoto,⁵⁴ M. G. Albrow,¹⁵ D. Ambrose,¹⁵ S. Amerio,⁴² D. Amidei,³³ A. Anastassov,⁵⁰ K. Anikeev,¹⁵ A. Annovi,⁴⁴ J. Antos,¹ M. Aoki,⁵⁴ G. Apollinari,¹⁵ T. Arisawa,⁵⁶ J-F. Arguin,³² A. Artikov,¹³ W. Ashmanskas,¹⁵ A. Attal,⁷ F. Azfar,⁴¹ P. Azzi-Bacchetta,⁴² N. Bacchetta,⁴² H. Bachacou,²⁸ W. Badgett,¹⁵ A. Barbaro-Galtieri,²⁸ G. J. Barker,²⁵ V. E. Barnes,⁴⁶ B. A. Barnett,²⁴ S. Baroiant,⁶ G. Bauer,³¹ F. Bedeschi,⁴⁴ S. Behari,²⁴ S. Belforte,⁵³ G. Bellettini,⁴⁴ J. Bellinger,⁵⁸ A. Belloni,³¹ E. Ben-Haim,¹⁵ D. Benjamin,¹⁴ A. Beretvas,¹⁵ T. Berry,²⁹ A. Bhatti,⁴⁸ M. Binkley,¹⁵ D. Bisello,⁴² M. Bishai,¹⁵ R. E. Blair,² C. Blocker,⁵ K. Bloom,³³ B. Blumenfeld,²⁴ A. Bocci,⁴⁸ A. Bodek,⁴⁷ G. Bolla,⁴⁶ A. Bolshov,³¹ D. Bortoletto,⁴⁶ J. Boudreau,⁴⁵ S. Bourov,¹⁵ B. Brau,⁹ C. Bromberg,³⁴ E. Brubaker,¹² J. Budagov,¹³ H. S. Budd,⁴⁷ K. Burkett,¹⁵ G. Busetto,⁴² P. Bussey,¹⁹ K. L. Byrum,² S. Cabrera,¹⁴ M. Campanelli,¹⁸ M. Campbell,³³ F. Canelli,⁷ A. Canepa,⁴⁶ M. Casarsa,⁵³ D. Carlsmith,⁵⁸ R. Carosi,⁴⁴ S. Carron,¹⁴ M. Cavalli-Sforza,³ A. Castro,⁴ P. Catastini,⁴⁴ D. Cauz,⁵³ A. Cerri,²⁸ L. Cerrito,⁴¹ J. Chapman,³³ Y. C. Chen,¹ M. Chertok,⁶ G. Chiarelli,⁴⁴ G. Chlachidze,¹³ F. Chlebana,¹⁵ I. Cho,²⁷ K. Cho,²⁷ D. Chokheli,¹³ J. P. Chou,²⁰ S. Chuang,⁵⁸ K. Chung,¹¹ W-H. Chung,⁵⁸ Y. S. Chung,⁴⁷ M. Cijliak,⁴⁴ C. I. Ciobanu,²³ M. A. Ciocci,⁴⁴ A. G. Clark,¹⁸ D. Clark,⁵ M. Coca,¹⁴ A. Connolly,²⁸ M. Convery,⁴⁸ J. Conway,⁶ B. Cooper,³⁰ K. Copic,³³ M. Cordelli,¹⁷ G. Cortiana,⁴² J. Cranshaw,⁵² J. Cuevas,¹⁰ A. Cruz,¹⁶ R. Culbertson,¹⁵ C. Currat,²⁸ D. Cyr,⁵⁸ D. Dagenhart,⁵ S. Da Ronco,⁴² S. D'Auria,¹⁹ P. de Barbaro,⁴⁷ S. De Cecco,⁴⁹ A. Deisher,²⁸ G. De Lentdecker,⁴⁷ M. Dell'Orso,⁴⁴ S. Demers,⁴⁷ L. Demortier,⁴⁸ M. Deninno,⁴ D. De Pedis,⁴⁹ P. F. Derwent,¹⁵ T. Devlin,⁵⁰ C. Dionisi,⁴⁹ J. R. Dittmann,¹⁵ P. DiTuro,⁵⁰ C. Dörr,²⁵ A. Dominguez,²⁸ S. Donati,⁴⁴ M. Donega,¹⁸ J. Donini,⁴² M. D'Onofrio,¹⁸ T. Dorigo,⁴² K. Ebina,⁵⁶ J. Efron,³⁸ J. Ehlers,¹⁸ R. Erbacher,⁶ M. Erdmann,²⁵ D. Errede,²³ S. Errede,²³ R. Eusebi,⁴⁷ H-C. Fang,²⁸ S. Farrington,²⁹ I. Fedorko,⁴⁴ W. T. Fedorko,¹² R. G. Feild,⁵⁹ M. Feindt,²⁵ J. P. Fernandez,⁴⁶ R. D. Field,¹⁶ G. Flanagan,³⁴ L. R. Flores-Castillo,⁴⁵ A. Foland,²⁰ S. Forrester,⁶ G. W. Foster,¹⁵ M. Franklin,²⁰ J. C. Freeman,²⁸ Y. Fujii,²⁶ I. Furic,¹² A. Gajjar,²⁹ M. Gallinaro,⁴⁸ J. Galyardt,¹¹ M. Garcia-Sciveres,²⁸ A. F. Garfinkel,⁴⁶ C. Gay,⁵⁹ H. Gerberich,¹⁴ D. W. Gerdes,³³ E. Gerchtein,¹¹ S. Giagu,⁴⁹ P. Giannetti,⁴⁴ A. Gibson,²⁸ K. Gibson,¹¹ C. Ginsburg,¹⁵ K. Giolo,⁴⁶ M. Giordani,⁵³ M. Giunta,⁴⁴ G. Giurgiu,¹¹ V. Glagolev,¹³ D. Glenzinski,¹⁵ M. Gold,³⁶ N. Goldschmidt,³³ D. Goldstein,⁷ J. Goldstein,⁴¹ G. Gomez,¹⁰ G. Gomez-Ceballos,¹⁰ M. Goncharov,⁵¹ O. González,⁴⁶ I. Gorelov,³⁶ A. T. Goshaw,¹⁴ Y. Gotra,⁴⁵ K. Goulianos,⁴⁸ A. Gresele,⁴² M. Griffiths,²⁹ C. Grosso-Pilcher,¹² U. Grundler,²³ J. Guimaraes da Costa,²⁰ C. Haber,²⁸ K. Hahn,⁴³ S. R. Hahn,¹⁵ E. Halkiadakis,⁴⁷ A. Hamilton,³² B-Y. Han,⁴⁷ R. Handler,⁵⁸ F. Happacher,¹⁷ K. Hara,⁵⁴ M. Hare,⁵⁵ R. F. Harr,⁵⁷ R. M. Harris,¹⁵ F. Hartmann,²⁵ K. Hatakeyama,⁴⁸ J. Hauser,⁷ C. Hays,¹⁴ H. Hayward,²⁹ B. Heinemann,²⁹ J. Heinrich,⁴³ M. Hennecke,²⁵ M. Herndon,²⁴ C. Hill,⁹ D. Hirschbuehl,²⁵ A. Hocker,¹⁵ K. D. Hoffman,¹² A. Holloway,²⁰ S. Hou,¹ M. A. Houlden,²⁹ B. T. Huffman,⁴¹ Y. Huang,¹⁴ R. E. Hughes,³⁸ J. Huston,³⁴ K. Ikado,⁵⁶ J. Incandela,⁹ G. Introzzi,⁴⁴ M. Iori,⁴⁹ Y. Ishizawa,⁵⁴ C. Issever,⁹ A. Ivanov,⁶ Y. Iwata,²² B. Iyutin,³¹ E. James,¹⁵ D. Jang,⁵⁰ B. Jayatilaka,³³ D. Jeans,⁴⁹ H. Jensen,¹⁵ E. J. Jeon,²⁷ M. Jones,⁴⁶ K. K. Joo,²⁷ S. Y. Jun,¹¹ T. Junk,²³ T. Kamon,⁵¹ J. Kang,³³ M. Karagoz Unel,³⁷ P. E. Karchin,⁵⁷ Y. Kato,⁴⁰ Y. Kemp,²⁵ R. Kephart,¹⁵ U. Kerzel,²⁵ V. Khotilovich,⁵¹ B. Kilminster,³⁸ D. H. Kim,²⁷ H. S. Kim,²³ J. E. Kim,²⁷ M. J. Kim,¹¹ M. S. Kim,²⁷ S. B. Kim,²⁷ S. H. Kim,⁵⁴ Y. K. Kim,¹² M. Kirby,¹⁴ L. Kirsch,⁵ S. Klimenko,¹⁶ M. Klute,³¹ B. Knuteson,³¹ B. R. Ko,¹⁴ H. Kobayashi,⁵⁴ D. J. Kong,²⁷ K. Kondo,⁵⁶ J. Konigsberg,¹⁶ K. Kordas,³² A. Korn,³¹ A. Korytov,¹⁶ A. V. Kotwal,¹⁴ A. Kovalev,⁴³ J. Kraus,²³ I. Kravchenko,³¹ A. Kreymer,¹⁵ J. Kroll,⁴³ M. Kruse,¹⁴ V. Krutelyov,⁵¹ S. E. Kuhlmann,² S. Kwang,¹² A. T. Laasanen,⁴⁶ S. Lai,³² S. Lami,^{44,48} S. Lammel,¹⁵ M. Lancaster,³⁰ R. Lander,⁶ K. Lannon,³⁸ A. Lath,⁵⁰ G. Latino,⁴⁴ I. Lazzizzera,⁴² C. Lecci,²⁵ T. LeCompte,² J. Lee,²⁷ J. Lee,⁴⁷ S. W. Lee,⁵¹ R. Lefèvre,³ N. Leonardo,³¹ S. Leone,⁴⁴ S. Levy,¹² J. D. Lewis,¹⁵ K. Li,⁵⁹ C. Lin,⁵⁹ C. S. Lin,¹⁵ M. Lindgren,¹⁵ E. Lipeles,⁸ T. M. Liss,²³ A. Lister,¹⁸ D. O. Litvintsev,¹⁵ T. Liu,¹⁵ Y. Liu,¹⁸ N. S. Lockyer,⁴³ A. Loginov,³⁵ M. Loretto,⁴² P. Loverre,⁴⁹ R-S. Lu,¹ D. Lucchesi,⁴² P. Lujan,²⁸ P. Lukens,¹⁵ G. Lungu,¹⁶ L. Lyons,⁴¹ J. Lys,²⁸ R. Lysak,¹ E. Lytken,⁴⁶ D. MacQueen,³² R. Madrak,¹⁵ K. Maeshima,¹⁵ P. Maksimovic,²⁴ G. Manca,²⁹ F. Margaroli,⁴ R. Marginean,¹⁵ C. Marino,²³ A. Martin,⁵⁹ M. Martin,²⁴ V. Martin,³⁷ M. Martínez,³ T. Maruyama,⁵⁴ H. Matsunaga,⁵⁴ M. Mattson,⁵⁷ P. Mazzanti,⁴ K. S. McFarland,⁴⁷ D. McGivern,³⁰ P. M. McIntyre,⁵¹ P. McNamara,⁵⁰ R. McNulty,²⁹ A. Mehta,²⁹ S. Menzemer,³¹ A. Menzione,⁴⁴ P. Merkel,⁴⁶ C. Mesropian,⁴⁸ A. Messina,⁴⁹ T. Miao,¹⁵ N. Miladinovic,⁵ J. Miles,³¹ L. Miller,²⁰ R. Miller,³⁴ J. S. Miller,³³ C. Mills,⁹ R. Miquel,²⁸ S. Miscetti,¹⁷ G. Mitselmakher,¹⁶ A. Miyamoto,²⁶ N. Moggi,⁴ B. Mohr,⁷ R. Moore,¹⁵ M. Morello,⁴⁴ P. A. Movilla Fernandez,²⁸ J. Muelmenstaedt,²⁸ A. Mukherjee,¹⁵ M. Mulhearn,³¹ T. Muller,²⁵ R. Mumford,²⁴ A. Munar,⁴³ P. Murat,¹⁵ J. Nachtman,¹⁵ S. Nahn,⁵⁹ I. Nakano,³⁹ A. Napier,⁵⁵ R. Napora,²⁴ D. Naumov,³⁶ V. Necula,¹⁶ J. Nielsen,²⁸ T. Nelson,¹⁵ C. Neu,⁴³ M. S. Neubauer,⁸ T. Nigmanov,⁴⁵ L. Nodulman,² O. Norniella,³ T. Ogawa,⁵⁶ S. H. Oh,¹⁴ Y. D. Oh,²⁷ T. Ohsugi,²²

T. Okusawa,⁴⁰ R. Oldeman,²⁹ R. Orava,²¹ W. Orejudos,²⁸ K. Osterberg,²¹ C. Pagliarone,⁴⁴ E. Palencia,¹⁰ R. Paoletti,⁴⁴ V. Papadimitriou,¹⁵ A. A. Paramonov,¹² S. Pashapour,³² J. Patrick,¹⁵ G. Pauletta,⁵³ M. Paulini,¹¹ C. Paus,³¹ D. Pellett,⁶ A. Penzo,⁵³ T. J. Phillips,¹⁴ G. Piacentino,⁴⁴ J. Piedra,¹⁰ K. T. Pitts,²³ C. Plager,⁷ L. Pondrom,⁵⁸ G. Pope,⁴⁵ X. Portell,³ O. Poukhov,¹³ N. Pounder,⁴¹ F. Prakoshyn,¹³ A. Pronko,¹⁶ J. Proudfoot,² F. Ptohos,¹⁷ G. Punzi,⁴⁴ J. Rademacker,⁴¹ M. A. Rahaman,⁴⁵ A. Rakitine,³¹ S. Rappoccio,²⁰ F. Ratnikov,⁵⁰ H. Ray,³³ B. Reisert,¹⁵ V. Rekovic,³⁶ P. Renton,⁴¹ M. Rescigno,⁴⁹ F. Rimondi,⁴ K. Rinnert,²⁵ L. Ristori,⁴⁴ W. J. Robertson,¹⁴ A. Robson,¹⁹ T. Rodrigo,¹⁰ S. Rolli,⁵⁵ R. Roser,¹⁵ R. Rossin,¹⁶ C. Rott,⁴⁶ J. Russ,¹¹ V. Rusu,¹² A. Ruiz,¹⁰ D. Ryan,⁵⁵ H. Saarikko,²¹ S. Sabik,³² A. Safonov,⁶ R. St. Denis,¹⁹ W. K. Sakumoto,⁴⁷ G. Salamanna,⁴⁹ D. Saltzberg,⁷ C. Sanchez,³ L. Santi,⁵³ S. Sarkar,⁴⁹ K. Sato,⁵⁴ P. Savard,³² A. Savoy-Navarro,¹⁵ P. Schlabach,¹⁵ E. E. Schmidt,¹⁵ M. P. Schmidt,⁵⁹ M. Schmitt,³⁷ T. Schwarz,³³ L. Scodellaro,¹⁰ A. L. Scott,⁹ A. Scribano,⁴⁴ F. Scuri,⁴⁴ A. Sedov,⁴⁶ S. Seidel,³⁶ Y. Seiya,⁴⁰ A. Semenov,¹³ F. Semeria,⁴ L. Sexton-Kennedy,¹⁵ I. Sfiligoi,¹⁷ M. D. Shapiro,²⁸ T. Shears,²⁹ P. F. Shepard,⁴⁵ D. Sherman,²⁰ M. Shimojima,⁵⁴ M. Shochet,¹² Y. Shon,⁵⁸ I. Shreyber,³⁵ A. Sidoti,⁴⁴ A. Sill,⁵² P. Sinervo,³² A. Sisakyan,¹³ J. Sjolin,⁴¹ A. Skiba,²⁵ A. J. Slaughter,¹⁵ K. Sliwa,⁵⁵ D. Smirnov,³⁶ J. R. Smith,⁶ F. D. Snider,¹⁵ R. Snihur,³² M. Soderberg,³³ A. Soha,⁶ S. V. Somalwar,⁵⁰ J. Spalding,¹⁵ M. Spezziga,⁵² F. Spinella,⁴⁴ P. Squillacioti,⁴⁴ H. Stadie,²⁵ M. Stanitzki,⁵⁹ B. Stelzer,³² O. Stelzer-Chilton,³² D. Stentz,³⁷ J. Strologas,³⁶ D. Stuart,⁹ J. S. Suh,²⁷ A. Sukhanov,¹⁶ K. Sumorok,³¹ H. Sun,⁵⁵ T. Suzuki,⁵⁴ A. Taffard,²³ R. Tafirout,³² H. Takano,⁵⁴ R. Takashima,³⁹ Y. Takeuchi,⁵⁴ K. Takikawa,⁵⁴ M. Tanaka,² R. Tanaka,³⁹ N. Tanimoto,³⁹ M. Tecchio,³³ P. K. Teng,¹ K. Terashi,⁴⁸ R. J. Tesarek,¹⁵ S. Tether,³¹ J. Thom,¹⁵ A. S. Thompson,¹⁹ E. Thomson,⁴³ P. Tipton,⁴⁷ V. Tiwari,¹¹ S. Tkaczyk,¹⁵ D. Toback,⁵¹ K. Tollefson,³⁴ T. Tomura,⁵⁴ D. Tonelli,⁴⁴ M. Tönnemann,³⁴ S. Torre,⁴⁴ D. Torretta,¹⁵ S. Tourneur,¹⁵ W. Trischuk,³² R. Tsuchiya,⁵⁶ S. Tsuno,³⁹ D. Tsybychev,¹⁶ N. Turini,⁴⁴ F. Ukegawa,⁵⁴ T. Unverhau,¹⁹ S. Uozumi,⁵⁴ D. Usynin,⁴³ L. Vacavant,²⁸ A. Vaiciulis,⁴⁷ A. Varganov,³³ S. Vejcek III,¹⁵ G. Velev,¹⁵ V. Veszpremi,⁴⁶ G. Veramendi,²³ T. Vickey,²³ R. Vidal,¹⁵ I. Vila,¹⁰ R. Vilar,¹⁰ I. Vollrath,³² I. Volobouev,²⁸ M. von der Mey,⁷ P. Wagner,⁵¹ R. G. Wagner,² R. L. Wagner,¹⁵ W. Wagner,²⁵ R. Wallny,⁷ T. Walter,²⁵ Z. Wan,⁵⁰ M. J. Wang,¹ S. M. Wang,¹⁶ A. Warburton,³² B. Ward,¹⁹ S. Waschke,¹⁹ D. Waters,³⁰ T. Watts,⁵⁰ M. Weber,²⁸ W. C. Wester III,¹⁵ B. Whitehouse,⁵⁵ D. Whiteson,⁴³ A. B. Wicklund,² E. Wicklund,¹⁵ H. H. Williams,⁴³ P. Wilson,¹⁵ B. L. Winer,³⁸ P. Wittich,⁴³ S. Wolbers,¹⁵ C. Wolfe,¹² M. Wolter,⁵⁵ M. Worcester,⁷ S. Worm,⁵⁰ T. Wright,³³ X. Wu,¹⁸ F. Würthwein,⁸ A. Wyatt,³⁰ A. Yagil,¹⁵ T. Yamashita,³⁹ K. Yamamoto,⁴⁰ J. Yamaoka,⁵⁰ C. Yang,⁵⁹ U. K. Yang,¹² W. Yao,²⁸ G. P. Yeh,¹⁵ J. Yoh,¹⁵ K. Yorita,⁵⁶ T. Yoshida,⁴⁰ I. Yu,²⁷ S. Yu,⁴³ J. C. Yun,¹⁵ L. Zanello,⁴⁹ A. Zanetti,⁵³ I. Zaw,²⁰ F. Zetti,⁴⁴ J. Zhou,⁵⁰ and S. Zucchelli⁴

(CDF Collaboration)

¹*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*²*Argonne National Laboratory, Argonne, Illinois 60439, USA*³*Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*⁴*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*⁵*Brandeis University, Waltham, Massachusetts 02254, USA*⁶*University of California, Davis, Davis, California 95616, USA*⁷*University of California, Los Angeles, Los Angeles, California 90024, USA*⁸*University of California, San Diego, La Jolla, California 92093, USA*⁹*University of California, Santa Barbara, Santa Barbara, California 93106, USA*¹⁰*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*¹¹*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*¹²*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*¹³*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*¹⁴*Duke University, Durham, North Carolina 27708, USA*¹⁵*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*¹⁶*University of Florida, Gainesville, Florida 32611, USA*¹⁷*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*¹⁸*University of Geneva, CH-1211 Geneva 4, Switzerland*¹⁹*Glasgow University, Glasgow G12 8QQ, United Kingdom*²⁰*Harvard University, Cambridge, Massachusetts 02138, USA*²¹*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*²²*Hiroshima University, Higashi-Hiroshima 724, Japan*²³*University of Illinois, Urbana, Illinois 61801, USA*

- ²⁴The Johns Hopkins University, Baltimore, Maryland 21218, USA
²⁵Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
²⁶High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan
²⁷Center for High Energy Physics, Kyungpook National University, Taegu 702-701;
 Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746, Korea
²⁸Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
²⁹University of Liverpool, Liverpool L69 7ZE, United Kingdom
³⁰University College London, London WC1E 6BT, United Kingdom
³¹Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
³²Institute of Particle Physics, McGill University, Montréal, Canada H3A 2T8;
 and University of Toronto, Toronto, Canada M5S 1A7
³³University of Michigan, Ann Arbor, Michigan 48109, USA
³⁴Michigan State University, East Lansing, Michigan 48824, USA
³⁵Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
³⁶University of New Mexico, Albuquerque, New Mexico 87131, USA
³⁷Northwestern University, Evanston, Illinois 60208, USA
³⁸The Ohio State University, Columbus, Ohio 43210, USA
³⁹Okayama University, Okayama 700-8530, Japan
⁴⁰Osaka City University, Osaka 588, Japan
⁴¹University of Oxford, Oxford OX1 3RH, United Kingdom
⁴²University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy
⁴³University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
⁴⁴Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
⁴⁵University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
⁴⁶Purdue University, West Lafayette, Indiana 47907, USA
⁴⁷University of Rochester, Rochester, New York 14627, USA
⁴⁸The Rockefeller University, New York, New York 10021, USA
⁴⁹Istituto Nazionale di Fisica Nucleare, Sezione di Roma I, University di Roma "La Sapienza," I-00185 Roma, Italy
⁵⁰Rutgers University, Piscataway, New Jersey 08855, USA
⁵¹Texas A&M University, College Station, Texas 77843, USA
⁵²Texas Tech University, Lubbock, Texas 79409, USA
⁵³Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, Italy
⁵⁴University of Tsukuba, Tsukuba, Ibaraki 305, Japan
⁵⁵Tufts University, Medford, Massachusetts 02155, USA
⁵⁶Waseda University, Tokyo 169, Japan
⁵⁷Wayne State University, Detroit, Michigan 48201, USA
⁵⁸University of Wisconsin, Madison, Wisconsin 53706, USA
⁵⁹Yale University, New Haven, Connecticut 06520, USA
 (Received 27 June 2005; published 29 September 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 203 pb^{-1} collected at the Fermilab Tevatron collider by the CDF experiment. We observe no evidence for LQ production in the topologies arising from $LQ\bar{L}Q \rightarrow e\bar{e}q\bar{q}$ and $LQ\bar{L}Q \rightarrow e\bar{q}vq$, and derive 95% C.L. upper limits on the LQ production cross section. The results are combined with those obtained from a separately reported CDF search in the topology arising from $LQ\bar{L}Q \rightarrow \nu\bar{\nu}q\bar{q}$ and 95% C.L. lower limits on the LQ mass as a function of $\beta = \text{BR}(LQ \rightarrow e\bar{q})$ are derived. The limits are 236, 205 and 145 GeV/ c^2 for $\beta = 1$, $\beta = 0.5$ and $\beta = 0.1$, respectively.

DOI: [10.1103/PhysRevD.72.051107](https://doi.org/10.1103/PhysRevD.72.051107)

PACS numbers: 13.85.Rm, 12.60.-i, 14.80.-j

The remarkable symmetry between quarks and leptons in the standard model (SM) suggests that some more fundamental theory may exist, which allows for new interactions between them. Such interactions are mediated by a new type of particle, the leptoquark (LQ) [1] and are predicted in many extensions of the SM, e.g. grand unification, technicolor, and supersymmetry with R -parity violation [2]. A LQ carries both lepton and baryon number, is a color triplet boson with spin 0 or 1, and has fractional charge. Usually it is assumed that LQs are chiral and

couple to fermions of the same generation to accommodate experimental constraints on flavor changing neutral currents and helicity suppressed decays [3].

Previous experimental limits on LQ production are summarized in [4]. The H1 and ZEUS experiments at the e^+p collider HERA published [5] lower limits on the mass of a first-generation LQ that depend on the unknown LQ $l-q$ Yukawa coupling λ . At the LEP collider, pair production of LQs can occur in e^+e^- collisions via a virtual γ or Z boson in the s channel and lower limits have been presented in

[6]. At the Fermilab Tevatron [7–9] LQ would be predominantly pair produced through $q\bar{q}$ annihilation and gg fusion. Since the production is mediated via the strong interaction, it is independent of λ , in contrast to the searches at $e-p$ machines. The coupling strength to gluons is determined by color charges of the particles, and is model-independent in the case of scalar LQs. The production of vector LQ pairs depends on additional assumptions on LQ coupling to gluons and its cross section is typically larger than the cross section for scalar LQs production. Since the acceptance for vector and scalar LQ detection is similar, limits on the vector LQ mass will be more stringent.

In this paper, we focus on a search for first-generation scalar LQ pairs produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. A search for scalar LQ pairs decaying into $\nu\nu qq$, resulting in jets and missing transverse energy topology has been presented in [9]. Here we study alternative final state signatures, with LQs decaying into $eejj$ (final state consisting of two electrons and two jets) and LQs decaying in $evjj$ (final state consisting of an electron, two jets, and missing transverse energy). The results of the three channels are combined and presented as a function of β , the LQ branching fraction into an electron and a quark.

CDF is a general-purpose detector built to study the physics of $p\bar{p}$ collisions at the Tevatron accelerator at Fermilab and it is described in detail in [10]. The data used in the analysis were collected during the 2002–2003 Tevatron run II. The integrated luminosity for this data sample is $203 \pm 12.2 \text{ pb}^{-1}$. Events are selected if they pass the high E_T electron trigger, requiring one central electromagnetic trigger tower to be above threshold and a set of identification cuts on the electromagnetic cluster, track and shower profile. The efficiency of the trigger combinations used in the $eejj$ and $evjj$ analyses has been measured using $Z \rightarrow ee$ data [11,12] and it is $\sim 100\%$. Electrons are reconstructed as calorimeter electromagnetic clusters matching a track in the central region (central electrons, $|\eta| < 1.0$ [13]) or as calorimeter electromagnetic clusters only in the forward region ($1 \leq |\eta| \leq 3$). 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. The identification efficiency for a pair of central electrons is $(92.4 \pm 0.4)\%$ and for a pair of central-forward electrons is $(80 \pm 0.4)\%$ and it has been measured using $Z \rightarrow ee$ data as well. The coordinate of the lepton (also assumed to be the event coordinate) along the beam line must fall within 60 cm of the center of the detector (z_{vertex} cut) to ensure a good energy measurement in the calorimeter. This cut has an efficiency of $(95 \pm 0.1(\text{stat}) \pm 0.5(\text{syst}))\%$, and it is determined from studies with minimum bias events. The efficiencies of the identification cuts, the trigger selection and the vertex cut, are

taken into account when evaluating the signal acceptance and background estimate. Jets are reconstructed using a cone of fixed radius $R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} = 0.7$ and are required to have $|\eta| < 2.0$. Jets have been calibrated as a function of η and E_T and their energy is corrected to the parton level [14]. Neutrinos produce missing transverse energy, $\cancel{E}_T$, which is measured by balancing the calorimeter energy in the transverse plane. In the analyses we describe here, the signal selection criteria are set according to the kinematic distribution (e.g. E_T of the electrons and E_T of the jets) of decay products determined from Monte Carlo (MC) studies, optimized to eliminate background with a minimal loss of signal events [15,16].

In the dielectron and jets topology, we select events with two reconstructed isolated electrons with $E_T > 25$ GeV. At least one electron is required to be central, while the other can be central or forward. Events are further selected if there are at least two jets with $E_T > 30$ and 15 GeV. The data set selected above is dominated by QCD production of Z bosons in association with jets and $t\bar{t}$ production where both the W 's from top decay into an electron and neutrino. To reduce these backgrounds the following cuts are applied: (i) veto of events whose reconstructed dilepton mass falls in the window $76 < m_{ee} < 110 \text{ GeV}/c^2$ to remove most of the Z + jets contribution, (ii) $E_T(j_1) + E_T(j_2) > 85 \text{ GeV}$ and $E_T(e_1) + E_T(e_2) > 85 \text{ GeV}$, (iii) $\sqrt{(E_T(j_1) + E_T(j_2))^2 + (E_T(e_1) + E_T(e_2))^2} > 200 \text{ GeV}$ to remove the remaining Z + jets and top contributions. We studied the properties of the physics backgrounds by generating the process $Z + 2$ jets with ALPGEN [17] plus HERWIG [18] (to perform parton showering) and $t\bar{t}$ with PYTHIA [19], then passing them through a complete simulation of the CDF II detector based on GEANT [20] and full event reconstruction. Other backgrounds from $b\bar{b}$, $Z \rightarrow \tau\bar{\tau}$, WW are negligible due to the electron isolation and large electron and jet transverse energy requirements. To normalize the number of simulated events to data we used the theoretical cross sections for $t\bar{t}$ from [21] and for $\gamma/Z \rightarrow ee + 2$ jets from [22]. The expected number of $Z + 2$ jets events is 1.9 ± 0.4 . The expected number of $t\bar{t}$ events is 0.35 ± 0.06 events. The background arising from multijet events where a jet is mismeasured as an electron (fake) is calculated using data, for both this analysis and the one that follows. The method used relies on the assumption that the fake electron produced by a jet will be accompanied by other particles produced by the fragmentation of the jet; thus the isolation fraction of the fake electron will generally be larger than the one corresponding to a real electron. The isolation fraction is defined here as: $(E_T^{\text{cone}} - E_T^{\text{cluster}})/E_T^{\text{cluster}}$ where E_T^{cone} is the sum of the electromagnetic and hadronic transverse energies measured in all towers in a radius $R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)} = 0.4$ around the electron and E_T^{cluster} is the transverse electromagnetic energy of the electron. The phase space corresponding to the two electron isolation fractions ($eejj$) or to

one electron isolation fraction and the $\cancel{E}_T$ ($e\nu jj$) is divided in different regions. We assume that there is no correlation between the isolation of the two electrons ($eejj$) and the isolation of the electron and $\cancel{E}_T$ ($e\nu jj$). In the region where both electrons have large isolation fraction ($eejj$), or where the $\cancel{E}_T$ is small and the isolation fraction of the electron is large ($e\nu jj$) the LQ contribution is expected to be negligible. We call these background-dominated regions. With these assumptions from the ratio of the number of events in the background-dominated regions we extrapolate the contribution in the signal region. We estimate $0^{+0.7}_0$ fake events in the central-central category and 4.0 ± 2.0 in the central-forward category. The final background estimate is 6.2 ± 2.2 events. We checked the prediction of our background sources with data in a control region defined by requiring two electrons with $E_T > 25$ GeV, 2 jets with $E_T > 30$ GeV and $66 < m_{ee} < 110$ GeV/ c^2 . We observe 107 events in agreement with 113 ± 15 predicted from SM processes.

The efficiency to detect our signal is obtained from MC simulated LQ (PYTHIA) to account for kinematical and geometrical acceptances and it is reported in Table I for various LQ mass values. The following systematic uncertainties are considered when calculating signal acceptance and background predictions: luminosity (6%), choice of parton distribution functions (2.1%), statistical uncertainty of MC ($< 1\%$), jet energy scale ($< 1\%$), statistics of $Z \rightarrow e^+e^-$ sample (0.8%) and z_{vertex} cut (0.5%). After all selection cuts, 4 events are left in the $eejj$ channel data.

In the search in the electron and neutrino plus two jets topology, we select events with one reconstructed isolated electron with $E_T > 25$ GeV. The electron is required to be central ($|\eta| \leq 1.0$). We veto events with a second central or forward electron to be orthogonal to the previous analysis. We then select events where there is a large missing transverse energy, $\cancel{E}_T > 60$ GeV and at least two jets with $E_T > 30$ GeV in the range $|\eta| \leq 2$. This time the selected data set is dominated by QCD production of W bosons in association with jets and top quark pairs, where either both the W 's from the top pair decay into $l\nu$ and one lepton is

not identified, or one of the W s decays leptonically and the other hadronically. A small source of background is represented by $Z + 2$ jets, where one of the electrons is not identified. To reduce these backgrounds the following cuts are applied: (i) $\Delta\phi(\cancel{E}_T - \text{jet}) > 10^\circ$ to veto events where the transverse missing energy is mismeasured due to a jet pointing to a noninstrumented region of the calorimeter, (ii) $E_T(j_1) + E_T(j_2) > 80$ GeV, (iii) transverse mass of electron-neutrino system, $M_T(e\nu) > 120$ GeV/ c^2 to reduce the $W + 2$ jets contribution. We studied the properties of the $W + \text{jets}$, $t\bar{t}$ and $Z + 2$ jets backgrounds using MC simulated events (ALPGEN plus HERWIG and PYTHIA). The background from $W \rightarrow \nu_\tau\tau + 2$ jets is negligible after the final mass window cut (see below), as it is the background coming from misidentified leptons and false $\cancel{E}_T$. Our final cut consists in selecting events falling in a mass window defined around the LQ mass in the following way. We calculate the invariant mass of the electron-jet system and the transverse mass of the neutrino-jet system. Given the decay of the two LQs, there are two possible mass combinations for the electron and the neutrino with the two leading jets. We choose the combinations that minimize the difference between the electron-jet mass and the neutrino-jet transverse mass. We fit the peak of the e -jet distribution with a Gaussian, to obtain an estimate of the spread of the distribution in the signal region (σ_e), as well as the ν -jet transverse mass distribution, to obtain σ_ν . In the kinematic plane of $m(e - \text{jet})$ vs $m_T(\nu - \text{jet})$ we define the sides of rectangular boxes centered around various nominal LQ mass as $3 \times \sigma_{e,\nu}$. For each LQ mass, events are accepted if they fall inside the rectangular box. The overall selection efficiency for various LQ masses is given in Table I. We checked the simulation prediction of our background sources with data in a control region defined by requiring one electron with $E_T > 25$ GeV, $\cancel{E}_T > 35$ GeV and 2 jets with $E_T > 30$ GeV. We observe 536 events in agreement with 503 ± 22 predicted from SM processes.

The efficiency to detect our signal is obtained from MC simulated LQ data (PYTHIA). The following systematic uncertainties are considered when calculating signal acceptance and background predictions: luminosity (6%), choice of the parton distribution functions (2.1%), statistics of MC ($< 1.0\%$), jet energy scale ($< 1\%$), electron identification (0.6%), z_{vertex} cut (0.5%), QCD initial and final state radiation (1.7%). The number of events in each mass region, after all selection cuts, compared with the background expectations is reported in Table II.

In the analyses described above the number of events passing the selection cuts is consistent with the expected number of background events. The conclusion of the two searches is that there is no LQ signal: hence we derive an upper limit on the LQ production cross section at 95% confidence level. We use a Bayesian approach [23] with a flat prior for the signal cross section and Gaussian priors for acceptance and background uncertainties. The cross-

TABLE I. Efficiencies after all cuts with total error (statistical and systematic) and 95% C.L. upper limits on the production cross section $\times$ branching fraction BR, as a function of M_{LQ} , for the two channels.

M_{LQ} (GeV/ c^2)	$eejj$		$e\nu jj$	
	ϵ (%)	$\sigma \times \text{BR}$ (pb)	ϵ (%)	$\sigma \times \text{BR}$ (pb)
100	7 ± 0.5	1.11	2 ± 0.26	5.71
140	12 ± 0.5	0.25	8 ± 0.7	0.69
160	21 ± 0.8	0.14	8 ± 0.7	0.65
200	32 ± 1.2	0.09	16 ± 1.3	0.37
220	35 ± 2.0	0.08	19 ± 1.5	0.24
240	38 ± 2.0	0.07	20 ± 1.6	0.23
260	40 ± 2.0	0.07	22 ± 1.7	0.22

TABLE II. Final number of events surviving all cuts in the electron, missing energy and jets topology, compared with background expectations, as a function of the LQ mass (in GeV/c^2). Errors include statistical and systematic uncertainty.

Mass	$W + 2$ jets	Top	$Z + 2$ jets	Total	Data
120	1.5 ± 0.9	3.3 ± 0.5	0.06 ± 0.01	4.9 ± 1.0	6
140	1.5 ± 0.9	3.1 ± 0.6	0.08 ± 0.02	4.7 ± 1.0	4
160	2.5 ± 1.1	2.8 ± 0.6	0.08 ± 0.02	5.4 ± 1.2	4
180	2.5 ± 1.1	2.4 ± 0.5	0.08 ± 0.02	5.0 ± 1.2	4
200	2.5 ± 1.1	2.0 ± 0.5	0.07 ± 0.02	4.6 ± 1.2	4
220	2.0 ± 1.0	1.6 ± 0.3	0.06 ± 0.02	3.7 ± 1.1	2
240	2.0 ± 1.0	1.1 ± 0.3	0.06 ± 0.02	3.1 ± 1.0	2
260	1.5 ± 1.0	0.8 ± 0.3	0.04 ± 0.02	2.4 ± 0.9	2

section limits are tabulated in Table I and the mass limits are tabulated in Table III. To compare our experimental results with the theoretical expectation, we use the next-to-leading order cross section for scalar LQ pair production from [24] with CTEQ6 parton distribution functions [25]. The theoretical uncertainties correspond to the variations from $M_{\text{LQ}}/2$ to $2M_{\text{LQ}}$ of the renormalization scale μ used in the calculation. To set a limit on the LQ mass we compare our 95% C.L. upper experimental limit to the theoretical cross section for $\mu = 2M_{\text{LQ}}$, which is conservative as it corresponds to the lower value of the theoretical cross section. We find lower limits on $M(\text{LQ})$ at $235 \text{ GeV}/c^2$ ($\beta = 1$) and $176 \text{ GeV}/c^2$ ($\beta = 0.5$). To obtain the best limit, we have combined the results from the two decay channels just described with the result of a search for LQ in the case where the LQ pair decays to neutrino and quark with branching ratio $\text{BR}(\text{LQ} \rightarrow \nu q) = 1.0$ [9]. The individual channel analyses are in fact optimized for fixed values of β (1, 0.5, 0) while in the combined analysis, due to the contributions of the different decay channels, the signal acceptance can be naturally expressed as a function of β . As for the treatment of uncertainties, the searches in the $eejj$ and $evjj$ channel

TABLE III. 95% C.L. lower limits on the first-generation scalar LQ mass (in GeV/c^2), as a function of β . The limit from CDF [8] ($eejj$) run I ($\sim 120 \text{ pb}^{-1}$) is also given.

β	$eejj$	$evjj$	$\nu\nu jj$	Combined	CDF run I
0.01	<100	<100	116	126	...
0.05	<100	<100	112	134	...
0.1	<100	144	<80	145	...
0.2	<100	158	<80	163	...
0.3	114	167	<80	180	...
0.4	165	174	<80	193	...
0.5	183	176	<80	205	...
0.6	197	174	<80	215	...
0.7	207	167	<80	222	...
0.8	216	158	<80	227	...
0.9	226	144	<80	231	...
1.0	235	<100	<80	236	213

use common criteria and sometimes apply the same kind of requirements so the uncertainties in the acceptances have been considered correlated. When calculating the limit combination including the $\nu\nu jj$ channel the uncertainties have been considered uncorrelated. For each β value a 95% C.L. upper limit on the expected number of events is returned for each mass, and by comparing this to the theoretical expectation, lower limits on the LQ mass are set. The combined limit as a function of β is shown in Fig. 1, together with the individual channel limits. The combined mass limits are also tabulated in Table III.

In conclusion, we have performed a search for pair production of first-generation scalar LQs using 203 pb^{-1} of proton-antiproton collision data recorded by the CDF experiment during run II of the Tevatron. The results from all the final state signatures are combined and no evidence of LQs production is observed. Assuming that a scalar LQ decays to electron and quark with variable branching ratio β we exclude LQs with masses below $236 \text{ GeV}/c^2$ for $\beta = 1$, $205 \text{ GeV}/c^2$ for $\beta = 0.5$ and $145 \text{ GeV}/c^2$ for $\beta = 0.1$.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Found-

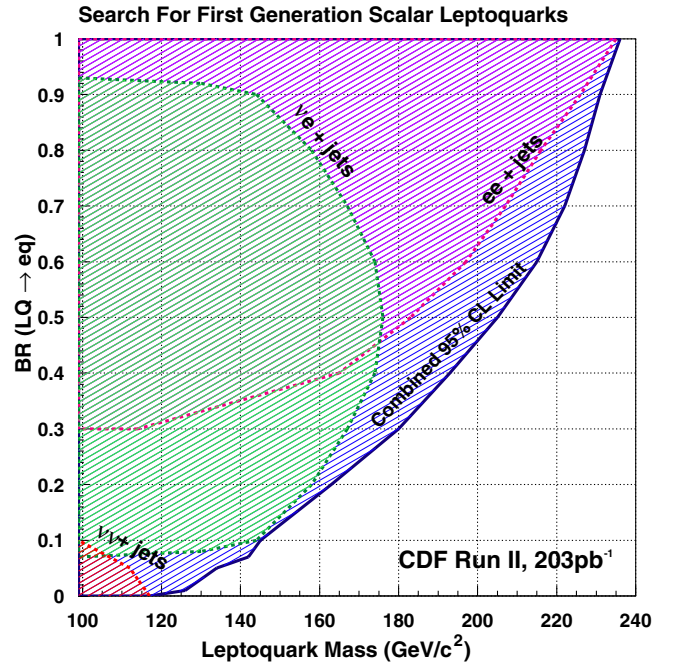


FIG. 1 (color online). LQ mass exclusion regions at 95% C.L. as a function of $\text{BR}(\text{LQ} \rightarrow eq)$.

ation; the A. P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian

Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; and in part by the European Community's Human Potential Programme under Contract No. HPRN-CT-20002, Probe for New Physics.

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