

Search for Heavy Toplike Quarks Using Lepton Plus Jets Events in 1.96 TeV pp Collisions

CDF Collaboration

CLARK, Allan Geoffrey (Collab.), *et al.*

Abstract

We present the results of a search for pair production of a new heavy toplike quark t' decaying to a W boson and another quark using the Collider Detector at Fermilab II detector in run II of the Tevatron pp collider. Using a data sample corresponding to 760 pb^{-1} of integrated luminosity, we fit the observed spectrum of total transverse energy and reconstructed t' quark mass to a combination of standard model processes and t' pair production. We see no evidence for $t't'$ production, and we infer a lower limit of $256 \text{ GeV}/c^2$ on the mass of the t' at 95% C.L. assuming standard strong couplings for the t' .

Reference

CDF Collaboration, CLARK, Allan Geoffrey (Collab.), *et al.* Search for Heavy Toplike Quarks Using Lepton Plus Jets Events in 1.96 TeV pp Collisions. *Physical Review Letters*, 2008, vol. 100, no. 16, p. 161803

DOI : 10.1103/PhysRevLett.100.161803

Available at:

<http://archive-ouverte.unige.ch/unige:38505>

Disclaimer: layout of this document may differ from the published version.



UNIVERSITÉ
DE GENÈVE

Search for Heavy Toplike Quarks Using Lepton Plus Jets Events in 1.96 TeV $p\bar{p}$ Collisions

T. Aaltonen,²³ J. Adelman,¹³ T. Akimoto,⁵⁴ M. G. Albrow,¹⁷ B. Álvarez González,¹¹ S. Amerio,⁴² D. Amidei,³⁴ A. Anastassov,⁵¹ A. Annovi,¹⁹ J. Antos,¹⁴ M. Aoki,²⁴ G. Apollinari,¹⁷ A. Apresyan,⁴⁷ T. Arisawa,⁵⁶ A. Artikov,¹⁵ W. Ashmanskas,¹⁷ A. Attal,³ A. Aurisano,⁵² F. Azfar,⁴¹ P. Azzi-Bacchetta,⁴² P. Azzurri,⁴⁵ N. Bacchetta,⁴² W. Badgett,¹⁷ A. Barbaro-Galtieri,²⁸ V. E. Barnes,⁴⁷ B. A. Barnett,²⁵ S. Baroiant,⁷ V. Bartsch,³⁰ G. Bauer,³² P.-H. Beauchemin,³³ F. Bedeschi,⁴⁵ P. Bednar,¹⁴ S. Behari,²⁵ G. Bellettini,⁴⁵ J. Bellinger,⁵⁸ A. Belloni,²² D. Benjamin,¹⁶ A. Beretvas,¹⁷ J. Beringer,²⁸ T. Berry,²⁹ A. Bhatti,⁴⁹ M. Binkley,¹⁷ D. Bisello,⁴² I. Bizjak,³⁰ R. E. Blair,² C. Blocker,⁶ B. Blumenfeld,²⁵ A. Bocci,¹⁶ A. Bodek,⁴⁸ V. Boisvert,⁴⁸ G. Bolla,⁴⁷ A. Bolshov,³² D. Bortoletto,⁴⁷ J. Boudreau,⁴⁶ A. Boveia,¹⁰ B. Brau,¹⁰ A. Bridgeman,²⁴ L. Brigliadori,⁵ C. Bromberg,³⁵ E. Brubaker,¹³ J. Budagov,¹⁵ H. S. Budd,⁴⁸ S. Budd,²⁴ K. Burkett,¹⁷ G. Busetto,⁴² P. Bussey,²¹ A. Buzatu,³³ K. L. Byrum,² S. Cabrera,^{16,r} M. Campanelli,³⁵ M. Campbell,³⁴ F. Canelli,¹⁷ A. Canepa,⁴⁴ D. Carlsmith,⁵⁸ R. Carosi,⁴⁵ S. Carrillo,^{18,l} S. Carron,³³ B. Casal,¹¹ M. Casarsa,¹⁷ A. Castro,⁵ P. Catastini,⁴⁵ D. Cauz,⁵³ M. Cavalli-Sforza,³ A. Cerri,²⁸ L. Cerrito,^{30,p} S. H. Chang,²⁷ Y. C. Chen,¹ M. Chertok,⁷ G. Chiarelli,⁴⁵ G. Chlachidze,¹⁷ F. Chlebana,¹⁷ K. Cho,²⁷ D. Chokheli,¹⁵ J. P. Chou,²² G. Choudalakis,³² S. H. Chuang,⁵¹ K. Chung,¹² W. H. Chung,⁵⁸ Y. S. Chung,⁴⁸ C. I. Ciobanu,²⁴ M. A. Ciocci,⁴⁵ A. Clark,²⁰ D. Clark,⁶ G. Compostella,⁴² M. E. Convery,¹⁷ J. Conway,⁷ B. Cooper,³⁰ K. Copic,³⁴ M. Cordelli,¹⁹ G. Cortiana,⁴² F. Crescioli,⁴⁵ C. Cuenca Almenar,^{7,r} J. Cuevas,^{11,o} R. Culbertson,¹⁷ J. C. Cully,³⁴ D. Dagenhart,¹⁷ M. Datta,¹⁷ T. Davies,²¹ P. de Barbaro,⁴⁸ S. De Cecco,⁵⁰ A. Deisher,²⁸ G. De Lentdecker,^{48,d} G. De Lorenzo,³ M. Dell'Orso,⁴⁵ L. Demortier,⁴⁹ J. Deng,¹⁶ M. Deninno,⁵ D. De Pedis,⁵⁰ P. F. Derwent,¹⁷ G. P. Di Giovanni,⁴³ C. Dionisi,⁵⁰ B. Di Ruzza,⁵³ J. R. Dittmann,⁴ M. D'Onofrio,³ S. Donati,⁴⁵ P. Dong,⁸ J. Donini,⁴² T. Dorigo,⁴² S. Dube,⁵¹ J. Efron,³⁸ R. Erbacher,⁷ D. Errede,²⁴ S. Errede,²⁴ R. Eusebi,¹⁷ H. C. Fang,²⁸ S. Farrington,²⁹ W. T. Fedorko,¹³ R. G. Feild,⁵⁹ M. Feindt,²⁶ J. P. Fernandez,³¹ C. Ferrazza,⁴⁵ R. Field,¹⁸ G. Flanagan,⁴⁷ R. Forrest,⁷ S. Forrester,⁷ M. Franklin,²² J. C. Freeman,²⁸ I. Furic,¹⁸ M. Gallinaro,⁴⁹ J. Galyardt,¹² F. Garbers,¹⁰ J. E. Garcia,⁴⁵ A. F. Garfinkel,⁴⁷ K. Genser,¹⁷ H. Gerberich,²⁴ D. Gerdes,³⁴ S. Giagu,⁵⁰ V. Giakoumopolou,^{45,b} P. Giannetti,⁴⁵ K. Gibson,⁴⁶ J. L. Gimmell,⁴⁸ C. M. Ginsburg,¹⁷ N. Giokaris,^{15,n} M. Giordani,⁵³ P. Giromini,¹⁹ M. Giunta,⁴⁵ V. Glagolev,¹⁵ D. Glenzinski,¹⁷ M. Gold,³⁶ N. Goldschmidt,¹⁸ A. Golossanov,¹⁷ G. Gomez,¹¹ G. Gomez-Ceballos,³² M. Goncharov,⁵² O. González,³¹ I. Gorelov,³⁶ A. T. Goshaw,¹⁶ K. Goulianos,⁴⁹ A. Gresele,⁴² S. Grinstein,²² C. Grosso-Pilcher,¹³ R. C. Group,¹⁷ U. Grundler,²⁴ J. Guimaraes da Costa,²² Z. Gunay-Unalan,³⁵ C. Haber,²⁸ K. Hahn,³² S. R. Hahn,¹⁷ E. Halkiadakis,⁵¹ A. Hamilton,²⁰ B.-Y. Han,⁴⁸ J. Y. Han,⁴⁸ R. Handler,⁵⁸ F. Happacher,¹⁹ K. Hara,⁵⁴ D. Hare,⁵¹ M. Hare,⁵⁵ S. Harper,⁴¹ R. F. Harr,⁵⁷ R. M. Harris,¹⁷ M. Hartz,⁴⁶ K. Hatakeyama,⁴⁹ J. Hauser,⁸ C. Hays,⁴¹ M. Heck,²⁶ A. Heijboer,⁴⁴ B. Heinemann,²⁸ J. Heinrich,⁴⁴ C. Henderson,³² M. Herndon,⁵⁸ J. Heuser,²⁶ S. Hewamanage,⁴ D. Hidas,¹⁶ C. S. Hill,^{10,c} D. Hirschbuehl,²⁶ A. Hocker,¹⁷ S. Hou,¹ M. Houlden,²⁹ S.-C. Hsu,⁹ B. T. Huffman,⁴¹ R. E. Hughes,³⁸ U. Husemann,⁵⁹ J. Huston,³⁵ J. Incandela,¹⁰ G. Introzzi,⁴⁵ M. Iori,⁵⁰ A. Ivanov,⁷ B. Iyutin,³² E. James,¹⁷ B. Jayatilaka,¹⁶ D. Jeans,⁵⁰ E. J. Jeon,²⁷ S. Jindariani,¹⁸ W. Johnson,⁷ M. Jones,⁴⁷ K. K. Joo,²⁷ S. Y. Jun,¹² J. E. Jung,²⁷ T. R. Junk,²⁴ T. Kamon,⁵² D. Kar,¹⁸ P. E. Karchin,⁵⁷ Y. Kato,⁴⁰ R. Kephart,¹⁷ U. Kerzel,²⁶ V. Khotilovich,⁵² B. Kilminster,³⁸ D. H. Kim,²⁷ H. S. Kim,²⁷ J. E. Kim,²⁷ M. J. Kim,¹⁷ S. B. Kim,²⁷ S. H. Kim,⁵⁴ Y. K. Kim,¹³ N. Kimura,⁵⁴ L. Kirsch,⁶ S. Klimenko,¹⁸ M. Klute,³² B. Knuteson,³² B. R. Ko,¹⁶ S. A. Koay,¹⁰ K. Kondo,⁵⁶ D. J. Kong,²⁷ J. Konigsberg,¹⁸ A. Korytov,¹⁸ A. V. Kotwal,¹⁶ J. Kraus,²⁴ M. Kreps,²⁶ J. Kroll,⁴⁴ N. Krumnack,⁴ M. Kruse,¹⁶ V. Krutelyov,¹⁰ T. Kubo,⁵⁴ S. E. Kuhlmann,² T. Kuhr,²⁶ N. P. Kulkarni,⁵⁷ Y. Kusakabe,⁵⁶ S. Kwang,¹³ A. T. Laasanen,⁴⁷ S. Lai,³³ S. Lami,⁴⁵ S. Lammel,¹⁷ M. Lancaster,³⁰ R. L. Lander,⁷ K. Lannon,³⁸ A. Lath,⁵¹ G. Latino,⁴⁵ I. Lazzizzera,⁴² T. LeCompte,² J. Lee,⁴⁸ J. Lee,²⁷ Y. J. Lee,²⁷ S. W. Lee,^{52,q} R. Lefèvre,²⁰ N. Leonardo,³² S. Leone,⁴⁵ S. Levy,¹³ J. D. Lewis,¹⁷ C. Lin,⁵⁹ C. S. Lin,²⁸ J. Linacre,⁴¹ M. Lindgren,¹⁷ E. Lipeles,⁹ A. Lister,⁷ D. O. Litvintsev,¹⁷ T. Liu,¹⁷ N. S. Lockyer,⁴⁴ A. Loginov,⁵⁹ M. Loreti,⁴² L. Lovas,¹⁴ R.-S. Lu,¹ D. Lucchesi,⁴² J. Lueck,²⁶ C. Luci,⁵⁰ P. Lujan,²⁸ P. Lukens,¹⁷ G. Lungu,¹⁸ L. Lyons,⁴¹ J. Lys,²⁸ R. Lysak,¹⁴ E. Lytken,⁴⁷ P. Mack,²⁶ D. MacQueen,³³ R. Madrak,¹⁷ K. Maeshima,¹⁷ K. Makhoul,³² T. Maki,²³ P. Maksimovic,²⁵ S. Malde,⁴¹ S. Malik,³⁰ G. Manca,²⁹ A. Manousakis,^{15,n} F. Margaroli,⁴⁷ C. Marino,²⁶ C. P. Marino,²⁴ A. Martin,⁵⁹ M. Martin,²⁵ V. Martin,^{21,j} M. Martínez,³ R. Martínez-Ballarín,³¹ T. Maruyama,⁵⁴ P. Mastrandrea,⁵⁰ T. Masubuchi,⁵⁴ M. E. Mattson,⁵⁷ P. Mazzanti,⁵ K. S. McFarland,⁴⁸ P. McIntyre,⁵² R. McNulty,^{29,i} A. Mehta,²⁹ P. Mehtala,²³ S. Menzemer,^{11,k} A. Menzione,⁴⁵ P. Merkel,⁴⁷ C. Mesropian,⁴⁹ A. Messina,³⁵ T. Miao,¹⁷ N. Miladinovic,⁶ J. Miles,³² R. Miller,³⁵ C. Mills,²² M. Milnik,²⁶ A. Mitra,¹ G. Mitselmakher,¹⁸ H. Miyake,⁵⁴ S. Moed,²² N. Moggi,⁵ C. S. Moon,²⁷ R. Moore,¹⁷ M. Morello,⁴⁵ P. Movilla Fernandez,²⁸ J. Mülmenstädt,²⁸ A. Mukherjee,¹⁷ Th. Muller,²⁶ R. Mumford,²⁵ P. Murat,¹⁷ M. Mussini,⁵ J. Nachtman,¹⁷ Y. Nagai,⁵⁴ A. Nagano,⁵⁴ J. Naganoma,⁵⁶ K. Nakamura,⁵⁴

I. Nakano,³⁹ A. Napier,⁵⁵ V. Neclula,¹⁶ C. Neu,⁴⁴ M. S. Neubauer,²⁴ J. Nielsen,^{28,f} L. Nodulman,² M. Norman,⁹ O. Norniella,²⁴ E. Nurse,³⁰ S. H. Oh,¹⁶ Y. D. Oh,²⁷ I. Oksuzian,¹⁸ T. Okusawa,⁴⁰ R. Oldeman,²⁹ R. Orava,²³ K. Osterberg,³³ S. Pagan Griso,⁴² C. Pagliarone,⁴⁵ E. Palencia,¹⁷ V. Papadimitriou,¹⁷ A. Papaikonomou,²⁶ A. A. Paramonov,¹³ B. Parks,³⁸ S. Pashapour,³³ J. Patrick,¹⁷ G. Pauletta,⁵³ M. Paulini,¹² C. Paus,³² D. E. Pellett,⁷ A. Penzo,⁵³ T. J. Phillips,¹⁶ G. Piacentino,⁴⁵ J. Piedra,⁴³ L. Pinera,¹⁸ K. Pitts,²⁴ C. Plager,⁸ L. Pondrom,⁵⁸ X. Portell,³ O. Poukhov,¹⁵ N. Pounder,⁴¹ F. Prakoshyn,¹⁵ A. Pronko,¹⁷ J. Proudfoot,² F. Ptohos,^{17,h} G. Punzi,⁴⁵ J. Pursley,⁵⁸ J. Rademacker,^{41,c} A. Rahaman,⁴⁶ V. Ramakrishnan,⁵⁸ N. Ranjan,⁴⁷ I. Redondo,³¹ B. Reisert,¹⁷ V. Rekovic,³⁶ P. Renton,⁴¹ M. Rescigno,⁵⁰ S. Richter,²⁶ F. Rimondi,⁵ L. Ristori,⁴⁵ A. Robson,²¹ T. Rodrigo,¹¹ E. Rogers,²⁴ S. Rolli,⁵⁵ R. Roser,¹⁷ M. Rossi,⁵³ R. Rossin,¹⁰ P. Roy,³³ A. Ruiz,¹¹ J. Russ,¹² V. Rusu,¹⁷ H. Saarikko,²³ A. Safonov,⁵² W. K. Sakumoto,⁴⁸ G. Salamanna,⁵⁰ O. Saltó,³ L. Santi,⁵³ S. Sarkar,⁵⁰ L. Sartori,⁴⁵ K. Sato,¹⁷ A. Savoy-Navarro,⁴³ T. Scheidle,²⁶ P. Schlabach,¹⁷ E. E. Schmidt,¹⁷ M. A. Schmidt,¹³ M. P. Schmidt,⁵⁹ M. Schmitt,³⁷ T. Schwarz,⁷ L. Scodellaro,¹¹ A. L. Scott,¹⁰ A. Scribano,⁴⁵ F. Scuri,⁴⁵ A. Sedov,⁴⁷ S. Seidel,³⁶ Y. Seiya,⁴⁰ A. Semenov,¹⁵ L. Sexton-Kennedy,¹⁷ A. Sfyrla,²⁰ S. Z. Shalhout,⁵⁷ M. D. Shapiro,²⁸ T. Shears,²⁹ P. F. Shepard,⁴⁶ D. Sherman,²² M. Shimojima,^{54,n} M. Shochet,¹³ Y. Shon,⁵⁸ I. Shreyber,²⁰ A. Sidoti,⁴⁵ P. Sinervo,³³ A. Sisakyan,¹⁵ A. J. Slaughter,¹⁷ J. Slaunwhite,³⁸ K. Sliwa,⁵⁵ J. R. Smith,⁷ F. D. Snider,¹⁷ R. Snihur,³³ M. Soderberg,³⁴ A. Soha,⁷ S. Somalwar,⁵¹ V. Sorin,³⁵ J. Spalding,¹⁷ F. Spinella,⁴⁵ T. Spreitzer,³³ P. Squillacioti,⁴⁵ M. Stanitzki,⁵⁹ R. St. Denis,²¹ B. Stelzer,⁸ O. Stelzer-Chilton,⁴¹ D. Stentz,³⁷ J. Strologas,³⁶ D. Stuart,¹⁰ J. S. Suh,²⁷ A. Sukhanov,¹⁸ H. Sun,⁵⁵ I. Suslov,¹⁵ T. Suzuki,⁵⁴ A. Taffard,^{24,e} R. Takashima,³⁹ Y. Takeuchi,⁵⁴ R. Tanaka,³⁹ M. Tecchio,³⁴ P. K. Teng,¹ K. Terashi,⁴⁹ J. Thom,^{17,g} A. S. Thompson,²¹ G. A. Thompson,²⁴ E. Thomson,⁴⁴ P. Tipton,⁵⁹ V. Tiwari,¹² S. Tkaczyk,¹⁷ D. Toback,⁵² S. Tokar,¹⁴ K. Tollefson,³⁵ T. Tomura,⁵⁴ D. Tonelli,¹⁷ S. Torre,¹⁹ D. Torretta,¹⁷ S. Tourneur,⁴³ W. Trischuk,³³ Y. Tu,⁴⁴ N. Turini,⁴⁵ F. Ukegawa,⁵⁴ S. Uozumi,⁵⁴ S. Vallecorsa,²⁰ N. van Remortel,²³ A. Varganov,³⁴ E. Vataga,³⁶ F. Vázquez,^{18,l} G. Velev,¹⁷ C. Vellidis,^{45,a} V. Veszpremi,⁴⁷ M. Vidal,³¹ R. Vidal,¹⁷ I. Vila,¹¹ R. Vilar,¹¹ T. Vine,³⁰ M. Vogel,³⁶ I. Volobouev,^{28,q} G. Volpi,⁴⁵ F. Würthwein,⁹ P. Wagner,⁴⁴ R. G. Wagner,² R. L. Wagner,¹⁷ J. Wagner-Kuhr,²⁶ W. Wagner,²⁶ T. Wakisaka,⁴⁰ R. Wallny,⁸ S. M. Wang,¹ A. Warburton,³³ D. Waters,³⁰ M. Weinberger,⁵² W. C. Wester III,¹⁷ B. Whitehouse,⁵⁵ D. Whiteson,^{44,e} A. B. Wicklund,² E. Wicklund,¹⁷ G. Williams,³³ H. H. Williams,⁴⁴ P. Wilson,¹⁷ B. L. Winer,³⁸ P. Wittich,^{17,g} S. Wolbers,¹⁷ C. Wolfe,¹³ T. Wright,³⁴ X. Wu,²⁰ S. M. Wynne,²⁹ A. Yagil,⁹ K. Yamamoto,⁴⁰ J. Yamaoka,⁵¹ T. Yamashita,³⁹ C. Yang,⁵⁹ U. K. Yang,^{13,m} Y. C. Yang,²⁷ W. M. Yao,²⁸ G. P. Yeh,¹⁷ J. Yoh,¹⁷ K. Yorita,¹³ T. Yoshida,⁴⁰ G. B. Yu,⁴⁸ I. Yu,²⁷ S. S. Yu,¹⁷ J. C. Yun,¹⁷ L. Zanello,⁵⁰ A. Zanetti,⁵³ I. Zaw,²² X. Zhang,²⁴ Y. Zheng,^{8,b} and S. Zucchelli⁵

(CDF Collaboration)^a¹*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*Baylor University, Waco, Texas 76798, USA*⁵*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*⁶*Brandeis University, Waltham, Massachusetts 02254, USA*⁷*University of California, Davis, Davis, California 95616, USA*⁸*University of California, Los Angeles, Los Angeles, California 90024, USA*⁹*University of California, San Diego, La Jolla, California 92093, USA*¹⁰*University of California, Santa Barbara, Santa Barbara, California 93106, USA*¹¹*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*¹²*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*¹³*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*¹⁴*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*¹⁵*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*¹⁶*Duke University, Durham, North Carolina 27708*¹⁷*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*¹⁸*University of Florida, Gainesville, Florida 32611, USA*¹⁹*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*²⁰*University of Geneva, CH-1211 Geneva 4, Switzerland*²¹*Glasgow University, Glasgow G12 8QQ, United Kingdom*²²*Harvard University, Cambridge, Massachusetts 02138, USA*²³*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*

- ²⁴University of Illinois, Urbana, Illinois 61801, USA
²⁵The Johns Hopkins University, Baltimore, Maryland 21218, USA
²⁶Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
²⁷Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea;
 Seoul National University, Seoul 151-742, Korea;
 Sungkyunkwan University, Suwon 440-746, Korea;
 Korea Institute of Science and Technology Information, Daejeon, 305-806, Korea;
 Chonnam National University, Gwangju, 500-757, 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
³¹Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
³²Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
³³Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8;
 and University of Toronto, Toronto, Canada M5S 1A7
³⁴University of Michigan, Ann Arbor, Michigan 48109, USA
³⁵Michigan State University, East Lansing, Michigan 48824, USA
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
⁴³LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
⁴⁴University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
⁴⁵Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena
 and Scuola Normale Superiore, I-56127 Pisa, Italy
⁴⁶University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
⁴⁷Purdue University, West Lafayette, Indiana 47907, USA
⁴⁸University of Rochester, Rochester, New York 14627, USA
⁴⁹The Rockefeller University, New York, New York 10021, USA
⁵⁰Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome "La Sapienza," I-00185 Roma, Italy
⁵¹Rutgers University, Piscataway, New Jersey 08855, USA
⁵²Texas A&M University, College Station, Texas 77843, 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 24 January 2008; published 22 April 2008)

We present the results of a search for pair production of a new heavy tolike quark t' decaying to a W boson and another quark using the Collider Detector at Fermilab II detector in run II of the Tevatron $p\bar{p}$ collider. Using a data sample corresponding to 760 pb^{-1} of integrated luminosity, we fit the observed spectrum of total transverse energy and reconstructed t' quark mass to a combination of standard model processes and t' pair production. We see no evidence for $t'\bar{t}'$ production, and we infer a lower limit of $256 \text{ GeV}/c^2$ on the mass of the t' at 95% C.L. assuming standard strong couplings for the t' .

DOI: [10.1103/PhysRevLett.100.161803](https://doi.org/10.1103/PhysRevLett.100.161803)

PACS numbers: 13.85.Rm, 12.60.-i, 14.65.Ha, 14.80.-j

The discovery of the top quark in 1995 [1] completed the third generation of fundamental fermions in the quark sector in the standard model (SM) of particle physics. A fourth chiral generation of massive fermions with the same quantum numbers as the known fermions is predicted in a number of models. It is favored by flavor democracy [2], for example, and arises by unifying spins and charges in the GUT $\text{SO}(1,13)$ framework [3].

Precise measurements from LEP exclude a light fourth neutrino ν_4 with mass $m(\nu_4) < m_Z/2$, where m_Z is the mass of the Z boson. On the other hand a fourth-generation neutrino cannot be too heavy due to sizable radiative corrections [4], although $m(\nu_4) \approx 100 \text{ GeV}/c^2$ is still consistent with electroweak data [5]. If $m(\nu_4) \geq m_Z/2$ the radiative corrections become small [6], such a neutrino may explain some of the astrophysical puzzles [7], and

one extra chiral family of fermions with quark masses as high as $400 \text{ GeV}/c^2$ is viable [5,8]. Additional fermion families can also be accommodated in two-Higgs-doublet scenarios and $N = 2$ SUSY models [9].

In all of the above scenarios the present bounds on the Higgs boson are relaxed; the Higgs boson mass could be as large as $500 \text{ GeV}/c^2$ with enhanced production at the Tevatron and LHC. In addition, a small mass splitting between new heavy quarks t' and b' is preferred, such that $m(b') + m(W) > m(t')$, and t' decays predominantly to Wq (a W boson and a down-type quark $q = d, s, b$) [10].

Other models with heavy exotic quarks decaying to Wq with vector couplings to the W boson are possible. Contributions to radiative corrections from such quarks with mass M decouple as $1/M^2$ and preserve the agreement with precision data. For example, the “beautiful mirrors” model [11] improves the fit to the precision electroweak observables by eliminating the observed discrepancy in the $b\bar{b}$ forward-backward asymmetry [4,12]. It introduces a new fermion doublet, a mirror copy of the standard quark doublets with a heavier version of the SM top decaying to Wb .

A heavy topline quark also appears in little Higgs (LH) models [13], which evade the hierarchy problem by introducing a minimal set of gauge and fermion fields in the context of a large-extra-dimension framework. In particular, LH models in which T parity is conserved suggest a massive topline quark which can decay to Wq , as do LH models requiring two scales ($f_{1,2}$); these have been shown to prefer a topline quark having a mass of approximately 500 GeV [14,15].

In this Letter we present the results of a search for pair production of a new massive strongly interacting up-type quark t' with its associated antiquark, each decaying to Wq , using the large data set collected by the upgraded Collider Detector at Fermilab (CDF II) in Run II of the Tevatron. The data come from $p\bar{p}$ collisions at a center of mass energy of 1.96 TeV , corresponding to an integrated luminosity of 760 pb^{-1} .

As in the case of $t\bar{t}$ production, the case when one W decays leptonically leads to events with a lepton, a neutrino, and four quarks via the chain $t'\bar{t}' \rightarrow WqWq \rightarrow \ell\nu qqqq$. Employing a selection based on event kinematics avoids imposing a b -quark tagging requirement, which would limit our search to the decay mode $t' \rightarrow Wb$. We select events with a lepton (e or μ), missing transverse energy [16], and four or more hadronic jets. The observed distributions of the scalar sum of the transverse energy (H_T) of all reconstructed leptons, jets, and missing transverse energy in these events, together with the distribution of reconstructed t' mass (M_{rec}), allow discrimination of the $t'\bar{t}'$ signal from the standard model backgrounds discussed below.

CDF II [17] is a large general purpose detector with an overall cylindrical geometry surrounding the $p\bar{p}$ interac-

tion region. The three-dimensional trajectories of charged particles produced in $p\bar{p}$ collisions are measured using multiple layers of silicon microstrip detectors, and at outer radii with an axial-stereo wire drift chamber. The tracking system lies inside a uniform 1.4 T solenoidal magnetic field oriented along the beam direction. Outside the solenoid lie the electromagnetic and hadronic calorimeters, which are segmented in pseudorapidity (η) and azimuth in a projective “tower” geometry. Muons are identified by a system of drift chambers placed outside the calorimeter steel, which acts as an absorber for hadrons. The integrated luminosity of the $p\bar{p}$ collisions is measured using Čerenkov luminosity counters [18].

Events with a high- p_T ($18 \text{ GeV}/c$ or more) e or μ candidate are identified using high-speed trigger electronics and recorded for later analysis. The performance of the trigger and lepton identification algorithms is described in detail elsewhere [19].

Jet clustering employs an iterative cone-based technique, which associates calorimeter energy deposits within a cone of radius $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$. The energies of reconstructed jets and the missing transverse energy are corrected for detector nonuniformity and other effects [20].

Selected events must contain an e or μ having $p_T > 20 \text{ GeV}/c$, four or more jets with $E_T > 15 \text{ GeV}$ and $|\eta| < 2.0$, and missing transverse energy $\cancel{E}_T > 20 \text{ GeV}$. To ensure that leptons come from W boson decay they must be isolated; there can be no significant energy deposit within $\Delta R < 0.4$ of the lepton momentum. Also, to ensure that leptons and jets are reconstructed from the same interaction, the event vertex is required to be within 5 cm of the z position of the lepton track’s point of closest approach to the beam axis. We observe 451 events in the recorded sample.

The main SM contributions to the selected event sample come from $t\bar{t}$ events, W plus hadronic jets events, and hadronic multijet (“QCD”) events having large \cancel{E}_T in which one jet is misreconstructed as a lepton. We use observed data with nonisolated leptons to estimate the QCD contribution, following the same method as in the $t\bar{t}$ cross section measurement [19]. We use the ALPGEN [21] Monte Carlo generator to simulate W plus jets events with HERWIG [22] used for modeling parton showers, and the PYTHIA [23] event generator to simulate both $t\bar{t}$ and $t'\bar{t}'$ events. These events pass through a full detector simulation and reconstruction.

The backgrounds from single top, diboson, and Z + jets production contribute about 10% of the accepted events. However, the kinematic distributions of interest in this analysis in these processes differ negligibly from those in W + jets events, allowing use of just the W + jets simulation to model all the non- $t\bar{t}$ background with real leptons.

For each event we calculate the mass M_{rec} of the hypothetical t' and of the \bar{t}' using the same type of kinematic fit

used in a measurement of the top quark mass [24]. Of all possible lepton-jet combinations of the four highest- E_T jets, we select the one with the lowest χ^2 for the hypothesis $t' \rightarrow Wq$, having equal reconstructed t' and \bar{t}' masses, and having the W mass hypothesis satisfied by the relevant jet pair on one side and by the lepton and \cancel{E}_T on the other. This procedure selects the correct combination about 30% of the time.

We perform a binned likelihood fit of background and signal to the observed two-dimensional distribution of H_T and M_{rec} . The $t'\bar{t}'$ events would have larger H_T and M_{rec} than the backgrounds, especially as the t' mass gets larger. Fitting this two-dimensional distribution brings up to 20% more sensitivity than fitting either one alone, particularly at lower t' masses.

Imperfect knowledge of various experimental parameters leads to systematic uncertainties which degrade our sensitivity to a $t'\bar{t}'$ signal. All systematic effects are represented by Gaussian-constrained “nuisance” parameters in the likelihood. The Gaussian width is equal to the systematic uncertainty, except the rate for $W + \text{jets}$ -like events, which floats freely in the fit. We calculate the likelihood maximized with respect to the nuisance parameters as a function of a hypothetical $t'\bar{t}'$ signal cross section σ (assuming a 100% branching ratio of $t' \rightarrow Wq$) and apply Bayes’ theorem with a uniform prior in σ to obtain a 95% C.L. upper limit.

The systematic uncertainty with the largest effect on the final result is that due to the 3% uncertainty on the jet energy scale. The nuisance parameter representing this effect controls how the H_T - M_{rec} distribution is modified as the jet energy scale changes within its uncertainty. We calculate the bin-by-bin dependence for each background and signal source distribution from simulated samples in which the jet energy scale has been altered from its nominal value.

Another systematic uncertainty is due to the lack of knowledge of the appropriate Q^2 scale at which the W plus jets processes should be evaluated. The magnitude of this uncertainty comes from changing the Q^2 scale by a factor of 2 up and down from the nominal choice, and assigning the larger of the two apparent shifts in σ as a systematic uncertainty. The effect of this is substantially smaller than that of the jet energy scale uncertainty. We also include along with this effect the uncertainty in the amounts of initial- and final-state radiation.

Other systematic effects include those due to a 6% uncertainty in the integrated luminosity, the 0.7% uncertainty in lepton identification efficiencies, and the 27% uncertainty in QCD background normalization. All these have a small effect on the final result.

We constrain the value of the $t\bar{t}$ production cross section in the likelihood fit to its theoretical value of 6.7 pb at 175 GeV/ c^2 [25]. We assume a 7% uncertainty in the cross section, which is predominantly due to uncertainties in the

TABLE I. The 95% C.L. upper limits on $\sigma(t'\bar{t}')$ as a function of t' mass.

Mass (GeV/ c^2)	175	200	225	250	275	300	350	400
Upper limit (pb)	5.21	2.57	1.13	0.72	0.59	0.41	0.32	0.25

parton density functions. We assume that this effect is correlated positively between the $t'\bar{t}'$ and $t\bar{t}$ production processes.

The likelihoods reveal no significant excess attributable to $t'\bar{t}'$ production, and in fact the observed distributions agree well with the zero-signal hypothesis. Table I shows the result for the 95% C.L. upper limit on $\sigma(p\bar{p} \rightarrow t'\bar{t}')$ as a function of t' mass, assuming that the branching ratio $t' \rightarrow Wq$ is 100%. Figure 1 shows the observed distributions projected onto the M_{rec} and H_T dimensions. The figures compare the observed distributions with the fit to the background plus a 250 GeV/ c^2 t' signal.

To obtain a lower bound on the mass of the t' , we compare our upper limit on σ to the theoretical cross section for a fourth-generation t' with SM couplings [25], assuming a 100% branching ratio $B(t' \rightarrow Wq)$; this is illustrated in Fig. 2. We take the point in t' mass where the observed limit crosses the theoretical cross section as the lower bound on the mass of the t' : $m(t') > 256$ GeV/ c^2 , at 95% C.L.

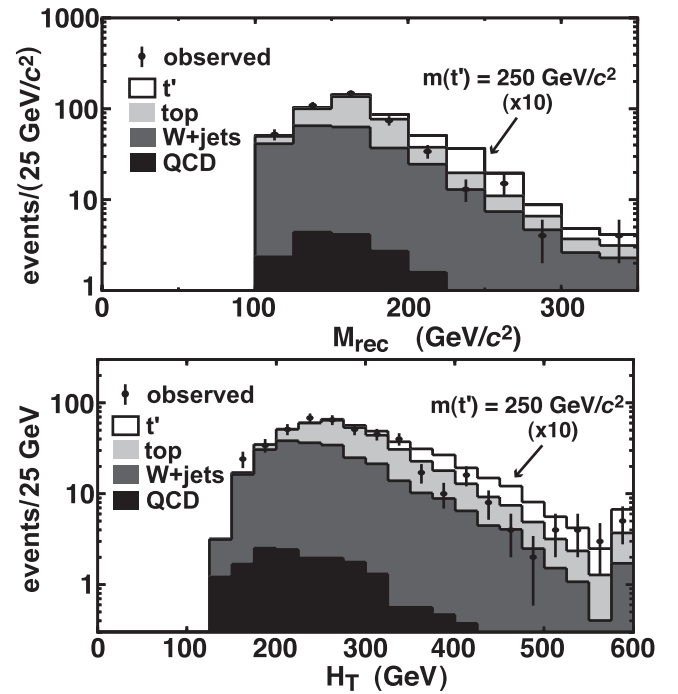


FIG. 1. Observed and predicted distributions of M_{rec} (above) and H_T (below). The predicted distribution corresponds to that for a 250 GeV/ c^2 mass $t'\bar{t}'$ signal assuming a value of the cross section at 10 times the theoretical one. Note that in each plot the last bin is an overflow bin, and that the $W + \text{jets}$ contribution also represents other similar backgrounds.

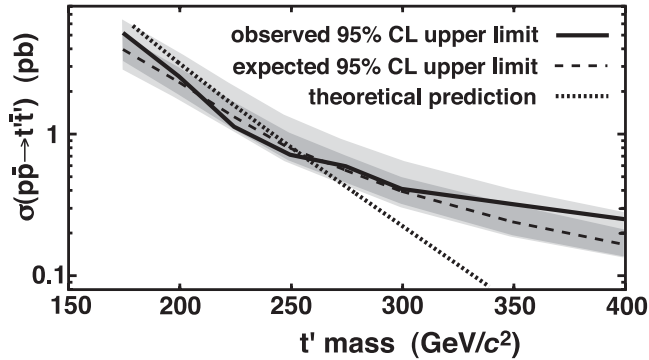


FIG. 2. Observed and expected 95% C.L. upper limits on the cross section for $t'\bar{t}'$ production as a function of t' mass. The gray bands around the median expected limit show the ± 1 - and ± 2 -standard-deviation ranges. The theoretical prediction is also shown (assuming a 100% branching ratio to Wq).

In conclusion, we present here the result of a search for a new heavy toplike quark t' decaying to Wq , using a data sample from 760 pb^{-1} integrated luminosity of $p\bar{p}$ collisions at 1.96 TeV center of mass energy. Our fit of the observed H_T - M_{rec} distribution reveals no excess from $t'\bar{t}'$ production, and so we conclude that the mass of the t' , if it exists, must exceed $256 \text{ GeV}/c^2$ at 95% C.L. or the t' must decay to a different final state.

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 Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, U.K.; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme; the Slovak R&D Agency; and the Academy of Finland.

^aVisitor from University of Athens, 15784 Athens, Greece.

^bVisitor from Chinese Academy of Sciences, Beijing 100864, China.

^cVisitor from University of Bristol, Bristol BS8 1TL, United Kingdom.

^dVisitor from University Libre de Bruxelles, B-1050 Brussels, Belgium.

^eVisitor from University of CA Irvine, Irvine, CA 92697, USA.

^fVisitor from University of CA Santa Cruz, Santa Cruz, CA 95064, USA.

^gVisitor from Cornell University, Ithaca, NY 14853, USA.

^hVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.

ⁱVisitor from University College Dublin, Dublin 4, Ireland.

^jVisitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

^kVisitor from University of Heidelberg, D-69120 Heidelberg, Germany.

^lVisitor from Universidad Iberoamericana, Mexico D.F., Mexico.

^mVisitor from University of Manchester, Manchester M13 9PL, England.

ⁿVisitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.

^oVisitor from University de Oviedo, E-33007 Oviedo, Spain.

^pVisitor from Queen Mary, University of London, London, E1 4NS, England.

^qVisitor from Texas Tech University, Lubbock, TX 79409, USA.

^rVisitor from IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain.

- [1] F. Abe *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **74**, 2626 (1995); S. Abachi *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **74**, 2632 (1995).
- [2] J. Silva-Marcos, *J. High Energy Phys.* **12** (2002) 036; S. Sultansoy *et al.*, *Acta Phys. Pol. B* **37**, 2839 (2006).
- [3] N. Borstnik *et al.*, in *Bled Workshops in Physics* (DMFA-Zaloznistvo, Ljubljana, 2006), Vol. 7, No. 2 (arXiv:hep-ph/0612250).
- [4] W. M. Yao *et al.* (Particle Data Group), *J. Phys. G* **33**, 1 (2006).
- [5] G. Kribs *et al.*, Report No. ANL-HEP-PR-07-39, 2007.
- [6] M. Maltoni *et al.*, *Phys. Lett. B* **476**, 107 (2000).
- [7] D. Fargion *et al.*, *JETP Lett.* **69**, 434 (1999).
- [8] L. Okun *et al.*, *Phys. Lett. B* **529**, 111 (2002).
- [9] H.-J. He, N. Polonsky, and S. Su, *Phys. Rev. D* **64**, 053004 (2001).
- [10] P. Frampton, P. Hung, and M. Sher, *Phys. Rep.* **330**, 263 (2000).
- [11] D. Choudhury, T.M.P. Tait, and C.E.M. Wagner, *Phys. Rev. D* **65**, 053002 (2002).
- [12] M. Chanowitz, *Phys. Rev. Lett.* **87**, 231802 (2001).
- [13] T. Han *et al.*, *Phys. Lett. B* **563**, 191 (2003); B. A. Dobrescu and C. T. Hill, *Phys. Rev. Lett.* **81**, 2634 (1998).
- [14] H. C. Cheng and I. Low, *J. High Energy Phys.* **08** (2004) 61.
- [15] D. E. Kaplan and M. Schmaltz, *J. High Energy Phys.* **10** (2003) 39; R. Barcelo, M. Masip, and M. Moreno-Torres, *Nucl. Phys.* **B782**, 159 (2007).
- [16] We use a cylindrical coordinate system about the beam axis in which θ is the polar angle and ϕ is the azimuthal angle. We define the pseudorapidity η of a particle's three-momentum as $\eta \equiv -\ln(\tan\frac{\theta}{2})$. The transverse energy and momentum are defined as $E_T = E \sin\theta$ and $p_T = p \sin\theta$.

where E is the energy measured by the calorimeter and p is the momentum measured in the tracking system. The missing transverse energy is defined as $\cancel{E}_T = |-\sum_i E_T^i \vec{n}_i|$ where \vec{n}_i is a unit vector in the transverse plane that points from the event vertex to the i th calorimeter tower.

- [17] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
- [18] S. Klimenko, J. Konigsberg, and T. M. Liss, FERMILAB Report No. FERMILAB-FN-0741, 2003.
- [19] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **72**, 052003 (2005).
- [20] A. Bhatti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **566**, 375 (2006).
- [21] M. L. Mangano *et al.*, J. High Energy Phys. 07 (2003) 1.
- [22] G. Corcella *et al.*, J. High Energy Phys. 01 (2001) 10.
- [23] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001), and references therein.
- [24] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. D **73**, 032003 (2006).
- [25] M. Cacciari *et al.*, J. High Energy Phys. 04 (2004) 68; production cross sections for larger t' masses were provided by the authors.