Search for Heavy Top-like 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[r],[16] M. Campanelli,[35] M. Campbell,[34] F. Canelli,[17] A. Canepa,[44] D. Carlsmith,[58] R. Carosi,[45] S. Carrillo[l],[18] 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[p],[30] 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[r],[7] J. Cuevas[o],[11] 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[d],[48] 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. Garberson,[10] J.E. Garcia,[45] A.F. Garfinkel,[47] K. Genser,[17] H. Gerberich,[24] D. Gerdes,[34] S. Giagu,[50] V. Giakoumopolou[a],[45] P. Giannetti,[45] K. Gibson,[46] J.L. Gimmell,[48] C.M. Ginsburg,[17] N. Giokaris[a],[15] 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[c],[10] 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[q],[52] 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[a],[15] F. Margaroli,[47] C. Marino,[26] C.P. Marino,[24] A. Martin,[59] M. Martin,[25] V. Martin[j],[21] 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[i],[29] A. Mehta,[29] P. Mehtala,[23] S. Menzemer[k],[11] 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. Necula,[16] C. Neu,[44] M.S. Neubauer,[24] J. Nielsen[f],[28] 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,[23] 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[h],[17] G. Punzi,[45] J. Pursley,[58] J. Rademacker[c],[41] 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[n],[54] 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[e],[24] R. Takashima,[39] Y. Takeuchi,[54] R. Tanaka,[39] M. Tecchio,[34] P.K. Teng,[1] K. Terashi,[49] J. Thom[g],[17] 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[l],[18] G. Velev,[17] C. Vellidis[a],[45] V. Veszpremi,[47] M. Vidal,[31] R. Vidal,[17] I. Vila,[11] R. Vilar,[11] T. Vine,[30] M. Vogel,[36] I. Volobouev[q],[28] 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[e],[44] A.B. Wicklund,[2] E. Wicklund,[17] G. Williams,[33] H.H. Williams,[44] P. Wilson,[17] B.L. Winer,[38] P. Wittich[g],[17] 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[m],[13] 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[b],[8] and S. Zucchelli[5]

(CDF Collaboration*)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[4]*Baylor University, Waco, Texas 76798*
[5]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[6]*Brandeis University, Waltham, Massachusetts 02254*
[7]*University of California, Davis, Davis, California 95616*
[8]*University of California, Los Angeles, Los Angeles, California 90024*
[9]*University of California, San Diego, La Jolla, California 92093*
[10]*University of California, Santa Barbara, Santa Barbara, California 93106*
[11]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[12]*Carnegie Mellon University, Pittsburgh, PA 15213*
[13]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[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*
[18]*University of Florida, Gainesville, Florida 32611*
[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*
[23]*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[24]*University of Illinois, Urbana, Illinois 61801*

[25] *The Johns Hopkins University, Baltimore, Maryland 21218*
[26] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[27] *Center 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*
[28] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[29] *University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[30] *University College London, London WC1E 6BT, United Kingdom*
[31] *Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[32] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[33] *Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8; and University of Toronto, Toronto, Canada M5S 1A7*
[34] *University of Michigan, Ann Arbor, Michigan 48109*
[35] *Michigan State University, East Lansing, Michigan 48824*
[36] *University of New Mexico, Albuquerque, New Mexico 87131*
[37] *Northwestern University, Evanston, Illinois 60208*
[38] *The Ohio State University, Columbus, Ohio 43210*
[39] *Okayama University, Okayama 700-8530, Japan*
[40] *Osaka City University, Osaka 588, Japan*
[41] *University of Oxford, Oxford OX1 3RH, United Kingdom*
[42] *University of Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy*
[43] *LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
[44] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[45] *Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy*
[46] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[47] *Purdue University, West Lafayette, Indiana 47907*
[48] *University of Rochester, Rochester, New York 14627*
[49] *The Rockefeller University, New York, New York 10021*
[50] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome "La Sapienza," I-00185 Roma, Italy*
[51] *Rutgers University, Piscataway, New Jersey 08855*
[52] *Texas A&M University, College Station, Texas 77843*
[53] *Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*
[54] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[55] *Tufts University, Medford, Massachusetts 02155*
[56] *Waseda University, Tokyo 169, Japan*
[57] *Wayne State University, Detroit, Michigan 48201*
[58] *University of Wisconsin, Madison, Wisconsin 53706*
[59] *Yale University, New Haven, Connecticut 06520*

(Dated: September 7, 2018)

We present the results of a search for pair production of a new heavy top-like quark t' decaying to a W boson and another quark using the CDF 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 GeV/c^2 on the mass of the t' at 95% CL assuming standard strong couplings for the t'.

PACS numbers: 12.60.Cn, 12.60.Fr,14.60.Fg,14.60.St,14.80.Cp

*With visitors from [a]University of Athens, 15784 Athens, Greece, [b]Chinese Academy of Sciences, Beijing 100864, China, [c]University of Bristol, Bristol BS8 1TL, United Kingdom, [d]University Libre de Bruxelles, B-1050 Brussels, Belgium, [e]University of California Irvine, Irvine, CA 92697, [f]University of California Santa Cruz, Santa Cruz, CA 95064, [g]Cornell University, Ithaca, NY 14853, [h]University of Cyprus, Nicosia CY-1678, Cyprus, [i]University College Dublin, Dublin 4, Ireland, [j]University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, [k]University of Heidelberg, D-69120 Heidelberg, Germany, [l]Universidad Iberoamericana, Mexico D.F., Mexico, [m]University of Manchester, Manchester M13 9PL, England, [n]Nagasaki Institute of Applied Science, Nagasaki, Japan,

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 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 sizeable radiative corrections [4], although $m(\nu_4) \approx 100$ GeV/c^2 is still consistent with electroweak data [5]. If $m(\nu_4) \gtrsim m_Z/2$ 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 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 are relaxed; the Higgs mass could be as large as 500 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 top-like 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 top-like quark which can decay to Wq, as do LH models requiring two scales ($f_{1,2}$); these have been shown to prefer a top-like 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 $t'\bar{t}' \to WqWq \to \ell\nu qqqq$. Employing a selection based on event kinematics avoids imposing a b-quark tagging requirement, which would limit our search to the decay mode $t' \to Wb$. 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 $p\bar{p}$ interaction 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 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 non-uniformity and other effects [20].

Selected events must contain an e or μ having $p_T > 20$ GeV/c, four or more jets with $E_T > 15$ GeV and $|\eta| < 2.0$, and missing transverse energy $\not{E}_T > 20$ 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 $\not{E}_T$

[o]University de Oviedo, E-33007 Oviedo, Spain, [p]Queen Mary, University of London, London, E1 4NS, England, [q]Texas Tech University, Lubbock, TX 79409, [r]IFIC(CSIC-Universitat de Valencia), 46071 Valencia, Spain,

in which one jet is misreconstructed as a lepton. We use observed data with non-isolated 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 $t' \to Wq$, 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 $\not\!\!E_T$ 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+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 $t' \to Wq$) 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 two 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.

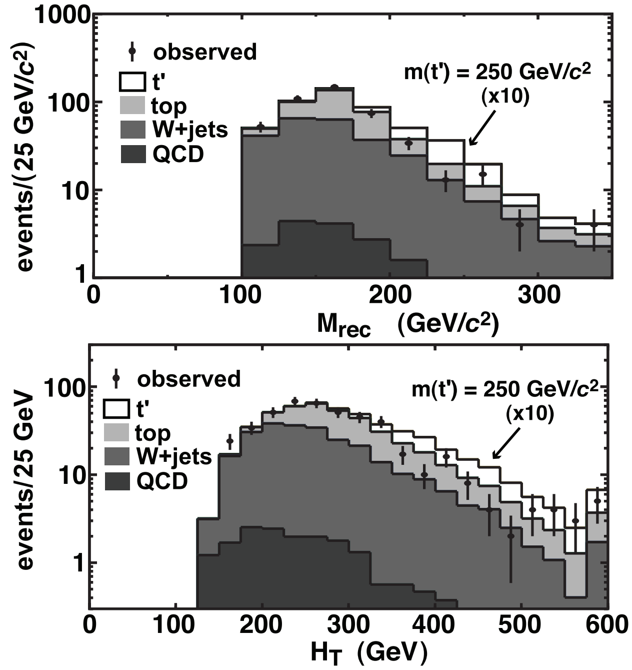

FIG. 1: Observed and predicted distributions of M_{rec} (above) and H_T (below). The predicted distribution corresponds to that for a 250 GeV/c^2 mass $t'\bar{t}'$ signal assuming a value of the cross section at ten times the theoretical one. Note that in each plot the last bin is an overflow bin, and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

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 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 $\sigma(p\bar{p} \to t'\bar{t}')$ as a function of t' mass, assuming that the branching ratio $t' \to Wq$ 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.

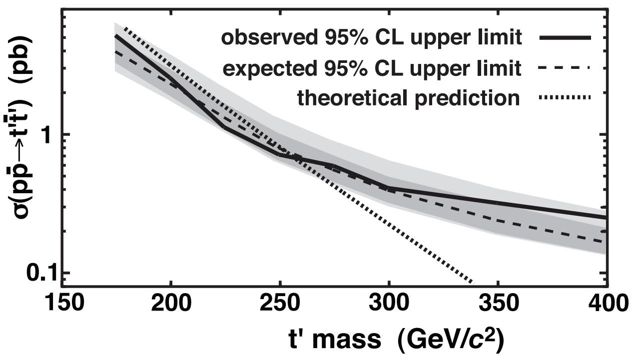

FIG. 2: Observed and expected 95% C.L. upper limits on the cross section for $t'\bar{t}'$ production as a function of t' mass. The grey bands around the median expected limit show the ±1- and ±2-standard-deviation ranges. The theoretical prediction is also shown (assuming a 100% branching ratio to Wq).

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

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

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 $B(t' \to Wq)$; this is illustrated in Figure 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.

In conclusion we present here the result of a search for a new heavy top-like 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 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, UK; 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.

[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. **0212**, 036 (2002); S. Sultansoy *et al.*, Acta Phys. Polon. B**37**, 2839 (2006).
[3] N. Borstnik *et al.*, Bled Workshops in Physics, Vol.7, No. 2 (2006).
[4] W. M. Yao *et al.* [Particle Data Group], J. Phys. G **33**, 1 (2006).
[5] G. Kribs *et al.*, 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. Rept. 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. **0408**, 61 (2004).
[15] D. E. Kaplan and M. Schmaltz, J. High Energy Phys. **0310**, 39 (2003); R. Barcelo, M. Masip, and M. Moreno-Torres, arXiv:hep-ph0701040.
[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 $\not\!\!E_T = |-\sum_i E_T^i \vec{n}_i|$ where $\vec{n}_i$ is a unit vector in the transverse plane that points from the event vertex to the ith 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-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. A **566**, 375 (2006).
[21] M. L. Mangano *et al.*, J. High Energy Phys. **0307**, 1 (2003).
[22] G. Corcella *et al.*, J. High Energy Phys. **0101**, 10 (2001).
[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. **0404**, 68 (2004).