archive ouverte UNIGE

http://archive-ouverte.unige.ch

Measurement of the top quark mass with the dynamical likelihood method using lepton plus jets events with *b*-tags in *pp* collisions at s√=1.96 TeV

CDF Collaboration

CAMPANELLI, Mario (Collab.), *et al*.

Abstract

This paper describes a measurement of the top quark mass, Mtop, with the dynamical likelihood method (DLM) using the CDF II detector at the Fermilab Tevatron. The Tevatron produces top/antitop (tt) pairs in pp collisions at a center-of-mass energy of 1.96 TeV. The data sample used in this analysis was accumulated from March 2002 through August 2004, which corresponds to an integrated luminosity of 318 pb−1. We use the tt candidates in the "lepton+jets" decay channel, requiring at least one jet identified as a b quark by finding a displaced secondary vertex. The DLM defines a likelihood for each event based on the differential cross section as a function of Mtop per unit phase space volume of the final partons, multiplied by the transfer functions from jet to parton energies. The method takes into account all possible jet combinations in an event, and the likelihood is multiplied event by event to derive the top quark mass by the maximum likelihood method. Using 63 tt candidates observed in the data, with 9.2 events expected from background, we measure the top quark mass to be [...]

UNIVERSITÉ
DE GENÈVE

Search for the Flavor-Changing Neutral-Current Decay $t \rightarrow Zq$ in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] M. G. Albrow,[18] B. Álvarez González,[12] S. Amerio,[44a,44b] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] P. Azzurri,[47a,47d] W. Badgett,[18] A. Barbaro-Galtieri,[29] V. E. Barnes,[49] B. A. Barnett,[26] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47a] P. Bednar,[15] D. Beecher,[31] S. Behari,[26] G. Bellettini,[47a,47b] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello,[44a,44b] I. Bizjak,[31] R. E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[49] J. Boudreau,[48] A. Boveia,[11] B. Brau,[11] A. Bridgeman,[25] L. Brigliadori,[44a] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H. S. Budd,[50] S. Budd,[25] K. Burkett,[18] G. Busetto,[44a,44b] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera,[17,q] C. Calancha,[32] M. Campanelli,[36] M. Campbell,[35] F. Canelli,[18] A. Canepa,[46] D. Carlsmith,[60] R. Carosi,[47a] S. Carrillo,[19,k] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro,[6a,6b] P. Catastini,[47a,47c] D. Cauz,[55a,55b] V. Cavaliere,[47a,47c] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito,[31,o] S. H. Chang,[28] Y. C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47a] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J. P. Chou,[23] G. Choudalakis,[33] S. H. Chuang,[53] K. Chung,[13] W. H. Chung,[60] Y. S. Chung,[50] C. I. Ciobanu,[45] M. A. Ciocci,[47a,47c] A. Clark,[21] D. Clark,[7] G. Compostella,[44a] M. E. Convery,[18] J. Conway,[8] K. Copic,[35] M. Cordelli,[20] G. Cortiana,[44a,44b] D. J. Cox,[8] F. Crescioli,[47a,47b] C. Cuenca Almenar,[8,q] J. Cuevas,[12,n] R. Culbertson,[18] J. C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52a] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso,[47a,47b] C. Deluca,[4] L. Demortier,[51] J. Deng,[17] M. Deninno,[6a] P. F. Derwent,[18] G. P. di Giovanni,[45] C. Dionisi,[52a,52b] B. Di Ruzza,[55a,55b] J. R. Dittmann,[5] M. D'Onofrio,[4] S. Donati,[47a,47b] P. Dong,[9] J. Donini,[44a] T. Dorigo,[44a] S. Dube,[53] J. Efron,[40] A. Elagin,[54] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] R. Eusebi,[18] H. C. Fang,[29] S. Farrington,[43] W. T. Fedorko,[14] R. G. Feild,[61] M. Feindt,[27] J. P. Fernandez,[32] C. Ferrazza,[47a,47d] R. Field,[19] G. Flanagan,[49] R. Forrest,[8] M. Franklin,[23] J. C. Freeman,[18] I. Furic,[19] M. Gallinaro,[52a] J. Galyardt,[13] F. Garberson,[11] J. E. Garcia,[47a] A. F. Garfinkel,[49] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] A. Gessler,[27] S. Giagu,[52a,52b] V. Giakoumopoulou,[3] P. Giannetti,[47a] K. Gibson,[48] J. L. Gimmell,[50] C. M. Ginsburg,[18] N. Giokaris,[3] M. Giordani,[55a,55b] P. Giromini,[20] M. Giunta,[47a,47b] G. Giurgiu,[26] V. Glagolev,[16] D. Glenzinski,[18] M. Gold,[38] N. Goldschmidt,[19] A. Golossanov,[18] G. Gomez,[12] G. Gomez-Ceballos,[33] M. Goncharov,[54] O. González,[32] I. Gorelov,[38] A. T. Goshaw,[17] K. Goulianos,[51] A. Gresele,[44a,44b] S. Grinstein,[23] C. Grosso-Pilcher,[14] R. C. Group,[18] U. Grundler,[25] J. Guimaraes da Costa,[23] Z. Gunay-Unalan,[36] C. Haber,[29] K. Hahn,[33] S. R. Hahn,[18] E. Halkiadakis,[53] B.-Y. Han,[50] J. Y. Han,[50] R. Handler,[60] F. Happacher,[20] K. Hara,[56] D. Hare,[53] M. Hare,[57] S. Harper,[43] R. F. Harr,[59] R. M. Harris,[18] M. Hartz,[48] K. Hatakeyama,[51] J. Hauser,[9] C. Hays,[43] M. Heck,[27] A. Heijboer,[46] B. Heinemann,[29] J. Heinrich,[46] C. Henderson,[33] M. Herndon,[60] J. Heuser,[27] S. Hewamanage,[5] D. Hidas,[17] C. S. Hill,[11,d] D. Hirschbuehl,[27] A. Hocker,[18] S. Hou,[1] M. Houlden,[30] S.-C. Hsu,[10] B. T. Huffman,[43] R. E. Hughes,[40] U. Husemann,[61] J. Huston,[36] J. Incandela,[11] G. Introzzi,[47a] M. Iori,[52a,52b] A. Ivanov,[8] E. James,[18] B. Jayatilaka,[17] E. J. Jeon,[28] M. K. Jha,[6a] S. Jindariani,[18] W. Johnson,[8] M. Jones,[49] K. K. Joo,[28] S. Y. Jun,[13] J. E. Jung,[28] T. R. Junk,[18] T. Kamon,[54] D. Kar,[19] P. E. Karchin,[59] Y. Kato,[42] R. Kephart,[18] J. Keung,[46] V. Khotilovich,[54] B. Kilminster,[40] D. H. Kim,[28] H. S. Kim,[28] J. E. Kim,[28] M. J. Kim,[20] S. B. Kim,[28] S. H. Kim,[56] Y. K. Kim,[14] N. Kimura,[56] L. Kirsch,[7] S. Klimenko,[19] B. Knuteson,[33] B. R. Ko,[17] S. A. Koay,[11] K. Kondo,[58] D. J. Kong,[28] J. Konigsberg,[19] A. Korytov,[19] A. V. Kotwal,[17] M. Kreps,[27] J. Kroll,[46] D. Krop,[14] N. Krumnack,[5] M. Kruse,[17] V. Krutelyov,[11] T. Kubo,[56] T. Kuhr,[27] N. P. Kulkarni,[59] M. Kurata,[56] Y. Kusakabe,[58] S. Kwang,[14] A. T. Laasanen,[49] S. Lami,[47a] S. Lammel,[18] M. Lancaster,[31] R. L. Lander,[8] K. Lannon,[40] A. Lath,[53] G. Latino,[47a,47c] I. Lazzizzera,[44a,44b] T. LeCompte,[2] E. Lee,[54] S. W. Lee,[54,p] S. Leone,[47a] J. D. Lewis,[18] C. S. Lin,[29] J. Linacre,[43] M. Lindgren,[18] E. Lipeles,[10] A. Lister,[8] D. O. Litvintsev,[18] C. Liu,[48] T. Liu,[18] N. S. Lockyer,[46] A. Loginov,[61] M. Loreti,[44a,44b] L. Lovas,[15] R.-S. Lu,[1] D. Lucchesi,[44a,44b] J. Lueck,[27] C. Luci,[52a,52b] P. Lujan,[29] P. Lukens,[18] G. Lungu,[51] L. Lyons,[43] J. Lys,[29] R. Lysak,[15] E. Lytken,[49] P. Mack,[27] D. MacQueen,[34] R. Madrak,[18] K. Maeshima,[18] K. Makhoul,[33] T. Maki,[24] P. Maksimovic,[26] S. Malde,[43] S. Malik,[31] G. Manca,[30] A. Manousakis-Katsikakis,[3] F. Margaroli,[49] C. Marino,[27] C. P. Marino,[25] A. Martin,[61] V. Martin,[22,j] M. Martínez,[4] R. Martínez-Ballarín,[32] T. Maruyama,[56] P. Mastrandrea,[52a] T. Masubuchi,[56] M. E. Mattson,[59] P. Mazzanti,[6a] K. S. McFarland,[50] P. McIntyre,[54] R. McNulty,[30,i] A. Mehta,[30] P. Mehtala,[24] A. Menzione,[47a] P. Merkel,[49] C. Mesropian,[51] T. Miao,[18] N. Miladinovic,[7] R. Miller,[36] C. Mills,[23] M. Milnik,[27] A. Mitra,[1] G. Mitselmakher,[19] H. Miyake,[56] N. Moggi,[6a] C. S. Moon,[28] R. Moore,[18] M. J. Morello,[47a,47b] J. Morlok,[27] P. Movilla Fernandez,[18] J. Mülmenstädt,[29] A. Mukherjee,[18] Th. Muller,[27] R. Mumford,[26] P. Murat,[18]

M. Mussini,[6a,6b] J. Nachtman,[18] Y. Nagai,[56] A. Nagano,[56] J. Naganoma,[58] K. Nakamura,[56] I. Nakano,[41] A. Napier,[57]
V. Necula,[17] C. Neu,[46] M. S. Neubauer,[25] J. Nielsen,[29,f] L. Nodulman,[2] M. Norman,[10] O. Norniella,[25] E. Nurse,[31]
L. Oakes,[43] S. H. Oh,[17] Y. D. Oh,[28] I. Oksuzian,[19] T. Okusawa,[42] R. Orava,[24] K. Osterberg,[24] S. Pagan Griso,[44a,44b]
C. Pagliarone,[47a] E. Palencia,[18] V. Papadimitriou,[18] A. Papaikonomou,[27] A. A. Paramonov,[14] B. Parks,[40] S. Pashapour,[34]
J. Patrick,[18] G. Pauletta,[55a,55b] M. Paulini,[13] C. Paus,[33] D. E. Pellett,[8] A. Penzo,[55a] T. J. Phillips,[17] G. Piacentino,[47a]
E. Pianori,[46] L. Pinera,[19] K. Pitts,[25] C. Plager,[9] L. Pondrom,[60] O. Poukhov,[16] N. Pounder,[43] F. Prakoshyn,[16] A. Pronko,[18]
J. Proudfoot,[2] F. Ptohos,[18,h] E. Pueschel,[13] G. Punzi,[47a,47b] J. Pursley,[60] J. Rademacker,[43,d] A. Rahaman,[48]
V. Ramakrishnan,[60] N. Ranjan,[49] I. Redondo,[32] B. Reisert,[18] V. Rekovic,[38] P. Renton,[43] M. Rescigno,[52a] S. Richter,[27]
F. Rimondi,[6a,6b] L. Ristori,[47a] A. Robson,[22] T. Rodrigo,[12] T. Rodriguez,[46] E. Rogers,[25] S. Rolli,[57] R. Roser,[18] M. Rossi,[55a]
R. Rossin,[11] P. Roy,[34] A. Ruiz,[12] J. Russ,[13] V. Rusu,[18] H. Saarikko,[24] A. Safonov,[54] W. K. Sakumoto,[50] O. Saltó,[4]
D. Saltzberg,[9] L. Santi,[55a,55b] S. Sarkar,[52a,52b] L. Sartori,[47a] K. Sato,[18] A. Savoy-Navarro,[45] T. Scheidle,[27] P. Schlabach,[18]
A. Schmidt,[27] E. E. Schmidt,[18] M. A. Schmidt,[14] M. P. Schmidt,[61,a] M. Schmitt,[39] T. Schwarz,[8] L. Scodellaro,[12]
A. L. Scott,[11] A. Scribano,[47a,47c] F. Scuri,[47a] A. Sedov,[49] S. Seidel,[38] Y. Seiya,[42] A. Semenov,[16] L. Sexton-Kennedy,[18]
A. Sfyrla,[21] S. Z. Shalhout,[59] T. Shears,[30] P. F. Shepard,[48] D. Sherman,[23] M. Shimojima,[56,m] S. Shiraishi,[14] M. Shochet,[14]
Y. Shon,[60] I. Shreyber,[37] A. Sidoti,[47a] P. Sinervo,[34] A. Sisakyan,[16] A. J. Slaughter,[18] J. Slaunwhite,[40] K. Sliwa,[57]
J. R. Smith,[8] F. D. Snider,[18] R. Snihur,[34] A. Soha,[8] S. Somalwar,[53] V. Sorin,[36] J. Spalding,[18] T. Spreitzer,[34]
P. Squillacioti,[47a,47c] M. Stanitzki,[61] R. St. Denis,[22] B. Stelzer,[9] O. Stelzer-Chilton,[43] D. Stentz,[39] J. Strologas,[38]
D. Stuart,[11] J. S. Suh,[28] A. Sukhanov,[19] M. Sutherland,[9] I. Suslov,[16] T. Suzuki,[56] A. Taffard,[25,e] R. Takashima,[41]
Y. Takeuchi,[56] R. Tanaka,[41] M. Tecchio,[35] P. K. Teng,[1] K. Terashi,[51] J. Thom,[18,g] A. S. Thompson,[22] G. A. Thompson,[25]
E. Thomson,[46] P. Tipton,[61] V. Tiwari,[13] S. Tkaczyk,[18] D. Toback,[54] S. Tokar,[15] K. Tollefson,[36] T. Tomura,[56] D. Tonelli,[18]
S. Torre,[20] D. Torretta,[18] P. Totaro,[55a,55b] S. Tourneur,[45] Y. Tu,[46] N. Turini,[47a,47c] F. Ukegawa,[56] S. Vallecorsa,[21]
N. van Remortel,[24,b] A. Varganov,[35] E. Vataga,[47a,47d] F. Vázquez,[19,k] G. Velev,[18] C. Vellidis,[3] V. Veszpremi,[49] M. Vidal,[32]
R. Vidal,[18] I. Vila,[12] R. Vilar,[12] T. Vine,[31] M. Vogel,[38] I. Volobouev,[29,p] G. Volpi,[47a,47b] F. Würthwein,[10] P. Wagner,[2]
R. G. Wagner,[2] R. L. Wagner,[18] J. Wagner-Kuhr,[27] W. Wagner,[27] T. Wakisaka,[42] R. Wallny,[9] S. M. Wang,[1] A. Warburton,[34]
D. Waters,[31] M. Weinberger,[54] W. C. Wester III,[18] B. Whitehouse,[57] D. Whiteson,[46,e] A. B. Wicklund,[2] E. Wicklund,[18]
G. Williams,[34] H. H. Williams,[46] P. Wilson,[18] B. L. Winer,[40] P. Wittich,[18,g] S. Wolbers,[18] C. Wolfe,[14] T. Wright,[35] X. Wu,[21]
S. M. Wynne,[30] A. Yagil,[10] K. Yamamoto,[42] J. Yamaoka,[53] U. K. Yang,[14,l] Y. C. Yang,[28] W. M. Yao,[29] G. P. Yeh,[18] J. Yoh,[18]
K. Yorita,[14] T. Yoshida,[42] G. B. Yu,[50] I. Yu,[28] S. S. Yu,[18] J. C. Yun,[18] L. Zanello,[52a,52b] A. Zanetti,[55a] I. Zaw,[23] X. Zhang,[25]
Y. Zheng,[9,c] and S. Zucchelli[6a,6b]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*University of Athens, 157 71 Athens, Greece*
[4]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[5]*Baylor University, Waco, Texas 76798, USA*
[6a]*Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy*
[6b]*University of Bologna, I-40127 Bologna, Italy*
[7]*Brandeis University, Waltham, Massachusetts 02254, USA*
[8]*University of California, Davis, Davis, California 95616, USA*
[9]*University of California, Los Angeles, Los Angeles, California 90024, USA*
[10]*University of California, San Diego, La Jolla, California 92093, USA*
[11]*University of California, Santa Barbara, Santa Barbara, California 93106, USA*
[12]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[13]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[14]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[15]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[16]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[17]*Duke University, Durham, North Carolina 27708, USA*
[18]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[19]*University of Florida, Gainesville, Florida 32611, USA*
[20]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[21]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[22]*Glasgow University, Glasgow G12 8QQ, United Kingdom*

[23]Harvard University, Cambridge, Massachusetts 02138, USA

[24]Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics,
FIN-00014, Helsinki, Finland

[25]University of Illinois, Urbana, Illinois 61801, USA

[26]The Johns Hopkins University, Baltimore, Maryland 21218, USA

[27]Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany

[28]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

[29]Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

[30]University of Liverpool, Liverpool L69 7ZE, United Kingdom

[31]University College London, London WC1E 6BT, United Kingdom

[32]Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain

[33]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

[34]Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8;
and University of Toronto, Toronto, Canada M5S 1A7

[35]University of Michigan, Ann Arbor, Michigan 48109, USA

[36]Michigan State University, East Lansing, Michigan 48824, USA

[37]Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia

[38]University of New Mexico, Albuquerque, New Mexico 87131, USA

[39]Northwestern University, Evanston, Illinois 60208, USA

[40]The Ohio State University, Columbus, Ohio 43210, USA

[41]Okayama University, Okayama 700-8530, Japan

[42]Osaka City University, Osaka 588, Japan

[43]University of Oxford, Oxford OX1 3RH, United Kingdom

[44a]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy

[44b]University of Padova, I-35131 Padova, Italy

[45]LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France

[46]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

[47a]Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy

[47b]University of Pisa, I-56127 Pisa, Italy

[47c]University of Siena, I-56127 Pisa, Italy

[47d]Scuola Normale Superiore, I-56127 Pisa, Italy

[48]University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA

[49]Purdue University, West Lafayette, Indiana 47907, USA

[50]University of Rochester, Rochester, New York 14627, USA

[51]The Rockefeller University, New York, New York 10021, USA

[52a]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy

[52b]Sapienza Università di Roma, I-00185 Roma, Italy

[53]Rutgers University, Piscataway, New Jersey 08855, USA

[54]Texas A&M University, College Station, Texas 77843, USA

[55a]Istituto Nazionale di Fisica Nucleare Trieste/Udine, Italy

[55b]University of Trieste/Udine, Italy

[56]University of Tsukuba, Tsukuba, Ibaraki 305, Japan

[57]Tufts University, Medford, Massachusetts 02155, USA

[58]Waseda University, Tokyo 169, Japan

[59]Wayne State University, Detroit, Michigan 48201, USA

[60]University of Wisconsin, Madison, Wisconsin 53706, USA

[61]Yale University, New Haven, Connecticut 06520, USA

We report a search for the flavor-changing neutral-current decay of the top quark $t \to Zq$ ($q = u, c$) in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using a data sample corresponding to an integrated luminosity of 1.9 fb^{-1} collected by the CDF II detector. This decay is strongly suppressed in the standard model and an observation of a signal at the Fermilab Tevatron would be an indication of physics beyond the standard model. Using $Z+ \geq 4$ jet final state candidate events, with and without an identified bottom quark jet, we obtain an upper limit of $\mathcal{B}(t \to Zq) < 3.7\%$ at 95% C.L.

Flavor-changing neutral-current (FCNC) interactions, which mediate transitions from one type of quark to another with the same electric charge, are suppressed in the standard model of particle physics (SM). FCNC processes are therefore sensitive indicators of physics beyond the SM (BSM). Presently there are only loose experimental bounds on FCNC decays of the t (top) quark [1], the heaviest known quark. While the SM branching fraction for $t \to Zq$ ($q = u, c$) is predicted to be $\mathcal{O}(10^{-14})$ [2], BSM models such as supersymmetry and quark compositeness allow branching fractions as high as $\mathcal{O}(10^{-4})$ [2,3]. An observation of the top FCNC decay $t \to Zq$ with current samples would be a strong indication of BSM physics.

In Run I, a CDF search for the $t \to Zq$ decay yielded the branching fraction upper limit $\mathcal{B}(t \to Zq) < 33\%$ (95% C.L.) [4]. The current best 95% C.L. upper limit on $\mathcal{B}(t \to Zq)$, 13.7%, was set by the L3 experiment [5] from the nonobservation of FCNC single t quark production. These analyses assumed a t quark mass of $m_t = 175$ GeV/c^2. In this Letter we also assume $m_t = 175$ GeV/c^2 and evaluate the small effect of different m_t on the result.

We present the first Tevatron Run II search for the top FCNC decay $t \to Zq$ in $t\bar{t}$ pairs. The data sample analyzed for this Letter corresponds to an integrated luminosity of 1.9 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, collected by the CDF II detector from March 2002 to May 2007. Our primary signal signature consists of the FCNC decay $t \to Zq$ ($q = u, c$) together with the dominant SM decay $\bar{t} \to W^-\bar{b}$ (charge conjugate modes are implied). We search for the Z boson via its decays $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ and for the decay of the W boson into a quark-antiquark pair. Two leptons and at least four jets of hadrons, coming from the four quarks from secondary decays, can be observed in the detector. We also allow for events in which both t quarks undergo FCNC decays.

The components of the CDF II detector relevant to this analysis are briefly described here; a more complete description can be found elsewhere [6]. The transverse momenta p_T and pseudorapidities η [7] of charged particles are measured by a silicon strip detector [8] and a 96-layer drift chamber (COT) [9] inside a 1.4 T solenoidal magnetic field. The silicon detector and the COT provide good combined reconstruction efficiency for $|\eta| < 1.2$. Electromagnetic (EM) and hadronic calorimeters measure energies of charged and neutral particles in the central ($|\eta| < 1.1$) and end-plug ($1.1 < |\eta| < 3.6$) regions. Drift chambers and scintillation counters located on the rear of the calorimeters and behind an additional steel absorber detect muons with $|\eta| < 1.0$. A three-level trigger selects events that contain electrons (muons) with $E_T > 18$ GeV ($p_T > 18$ GeV/c).

We consider several SM background processes that also result in final states with a reconstructed Z boson and four or more jets. The dominant background process is the production of Z bosons with associated jets ($Z +$ jets).

Smaller contributions come from SM $t\bar{t}$ production and the production of pairs of gauge bosons (dibosons), WZ and ZZ. The contributions from WW diboson production and from W bosons produced in association with jets are negligible.

We use the PYTHIA v6.216 Monte Carlo (MC) generator [10] to simulate the FCNC signal in $t\bar{t}$ events and all sources of SM background, except $Z +$ jets production, whose kinematic distributions we simulate with the ALPGEN MC generator [11], v2.10' interfaced to PYTHIA v6.325. Acceptance, efficiency, and kinematic distributions of signal and background are determined from the above MC simulations. We generated a full spectrum of FCNC signal MC simulations including $t\bar{t} \to ZqWb$ with $q = c$, $t\bar{t} \to ZqWb$ with $q = u$ (the probability to b-tag an FCNC signal event is reduced from 50% to 45%) where we apply the SecVtx algorithm [6] for the b-tagging, and where both top quarks decay via the FCNC mode. The amount of $t\bar{t} \to ZqZq$ relative to $t\bar{t} \to WbZq$ is adjusted according to the branching fraction $\mathcal{B}(t \to Zq)$ during the limit calculation.

The analysis proceeds in three steps. Our base selection requires a Z boson and four or more jets. An optimized event selection separates the FCNC signal from the SM backgrounds based on kinematic properties of the event. All events that pass the optimized selection are further divided into two signal regions based on whether any of the four leading jets has an identified b jet ("b-tagged region") or not ("non-b-tagged region"); those events that pass the base selection but not the optimized selection are placed in a "control" region. While only 12% of FCNC signal acceptance falls in the control region, two-thirds of the SM backgrounds are located there. We finally fit the data to one-dimensional probability density histograms ("templates") of one of the kinematic distributions (mass χ^2, see below) to derive a limit on $\mathcal{B}(t \to Zq)$. This is illustrated in Fig. 1. To reduce systematic uncertainties, the measurement is normalized to the measured event yield in SM $t\bar{t}$ production.

Our base selection chooses events with two oppositely-charged leptons of the same flavor (e or μ) and four or more jets. One lepton is required to be a central electron or muon; the other can be a forward electron or a track, as described below. The leptons must be compatible with originating from a Z boson in the mass window from 76 GeV/c^2 to 106 GeV/c^2 ($>3\sigma$ in units of CDF's Z mass resolution).

We use the standard CDF requirements for isolated electrons and muons [12]. In addition to identified electrons and muons, we double the acceptance for leptonic Z decays by allowing one of the two lepton candidates to satisfy weaker selection criteria, requiring only an isolated track which passes COT and silicon detector track quality cuts. For tracks used as electrons, if an EM calorimeter tower is associated with the track and the energy of the EM
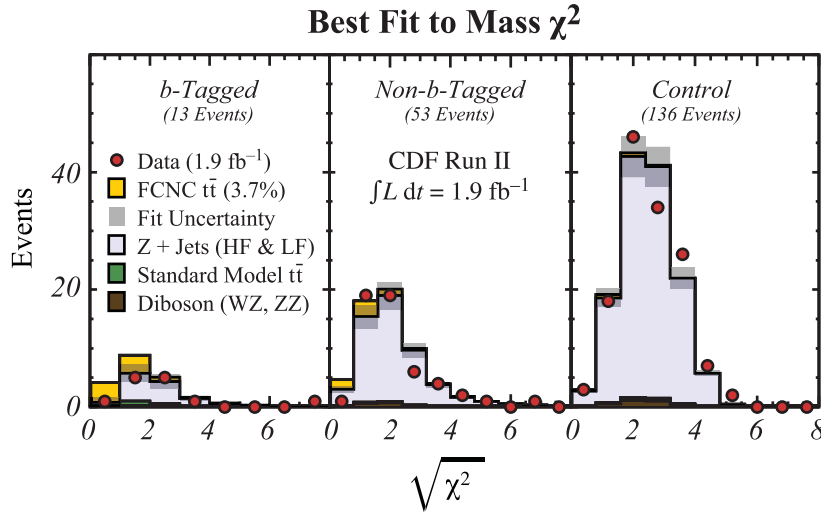
Best Fit to Mass χ^2

FIG. 1 (color). Mass χ^2 distribution for b-tagged and non-b-tagged signal regions and the control region. The data points as a function of $\sqrt{\chi^2}$ are compared to the SM background prediction and the expected FCNC yield at the observed 95% C.L. upper limit on the branching fraction $\mathcal{B}(t \to Zq) < 3.7\%$. The data are consistent with the background prediction.

tower is greater than the track momentum, the EM tower energy is used instead of the track momentum.

Jets are identified by energy deposited in the calorimeters within a cone of $\Delta R < 0.4$. To improve the parton energy estimate, jets are corrected for instrumental effects [13]. We select events with at least four jets with corrected $E_T > 15$ GeV and $|\eta| < 2.4$.

We separate the FCNC signal from the MC background with the help of further selection criteria in addition to the above base selection that will form the optimized selection, a mass χ^2, the transverse mass of the system, and the E_T of the four leading (highest E_T) jets.

The decay $t\bar{t} \to WbZq \to q\bar{q}'b\ell\ell q''$ contains no high-energy neutrinos; therefore, we can fully reconstruct the event kinematics. The four jets in signal events result from the b quark and the decay products of the W in the $t \to Wb$ decay, and the c or u quark from the $t \to Zq$ decay. We form all permutations of the four leading jets in the events to compare the reconstructed masses ($m_{\rm rec}$) of the W, top quark decaying to Wb, and top quark decaying to Zq. We define a mass χ^2 as

$$\chi^2 = \left(\frac{m_{W,\rm rec} - m_W}{\sigma_W} \right)^2 + \left(\frac{m_{t\to Wb,\rm rec} - m_t}{\sigma_{t\to Wb}} \right)^2$$
$$+ \left(\frac{m_{t\to Zq,\rm rec} - m_t}{\sigma_{t\to Zq}} \right)^2, \qquad (1)$$

and select the permutation with the smallest χ^2. We scale the measured four-momenta of the W and Z boson daughter particles such that the boson masses are fixed to the world average values [14] and use the scaled four-momenta to calculate the two top quark masses. The widths used are given by the standard deviations of the reconstructed masses measured in the MC simulation of FCNC events. Using the correct pairing of jets to partons, we extract $\sigma_W = 15$ GeV/c^2, $\sigma_{t\to Wb} = 24$ GeV/c^2, and $\sigma_{t\to Zq} = 21$ GeV/c^2. We expect FCNC signal events to populate the low χ^2 region and background events to result in higher

χ^2; see Fig. 1. We have verified that the components of Eq. (1) describe the data well in events with a Z boson and three jets.

Since the FCNC signal events originate from $t\bar{t}$ decays, they contain more central Z bosons and jets than background events. To exploit this, we use the transverse mass of the Z and the four leading jets, defined as $m_T = \sqrt{(\sum E_T)^2 - (\sum \vec{p}_T)^2}$, as a selection criterion. We also apply a tiered cut on the E_T of the four leading jets, as FCNC signal events contain jets with higher transverse momenta than SM background events.

We optimized these additional selection criteria for the best expected limit on $\mathcal{B}(t \to Zq)$ in the absence of a signal, using the MC simulation and a signal-depleted control region in the data ($\sqrt{\chi^2} > 3$). The optimization was performed in the blind phase of a counting experiment analysis using the first 1.1 fb^{-1} of integrated luminosity [15]. We leave the optimized selection unchanged for the full 1.9 fb^{-1} result; it requires transverse mass $m_T \geq 200$ GeV/c^2, leading jet $E_T \geq 40$ GeV, second jet $E_T \geq 30$ GeV, third jet $E_T \geq 20$ GeV, and fourth jet $E_T \geq 15$ GeV. After optimization, 88% of the FCNC signal events from the base selection fall into the two signal regions, compared to 33% of the background events. The inclusive signal acceptances for the decay $t\bar{t} \to WbZc$ ($t\bar{t} \to ZcZc$) are 0.43% (0.58%) for the b-tagged selection, 0.34% (0.86%) for the non-b-tagged selection, and 0.10% (0.16%) for the control region.

To determine the FCNC branching fraction, we take into account single or double FCNC decays of $t\bar{t}$ pairs and normalize to the event yield of a selection for the SM decay $t\bar{t} \to WbWb \to \ell\nu bq\bar{q}'b$ ("lepton + jets") requiring at least two jets to be secondary vertex b-tagged [16]. In 1.9 fb^{-1} we observe 277 $t\bar{t}$ candidate events, consistent with a production cross section of 8.8 ± 0.7(stat.) pb assuming $\mathcal{B}(t \to Wb) = 100\%$. If $t \to Zq$ decays were present, these additional $t\bar{t}$ decays are less likely to be recon-

structed in the lepton + jets mode, resulting in a measured $t\bar{t}$ production cross section smaller than the actual cross section. We correct for this effect by modifying the measured cross section based on the limit we set on $\mathcal{B}(t \to Zq)$.

We extract a limit on the branching fraction $\mathcal{B}(t \to Zq)$ from a fit to the mass χ^2 distribution using templates constructed from the MC simulated mass χ^2 distributions of the FCNC signal and the SM backgrounds (Z + jets, SM $t\bar{t}$, and dibosons). The normalization of the dominant Z + jets background is the most difficult to estimate from data and MC simulations; therefore, it is extracted from the fit. The SM $t\bar{t}$ background is normalized to the observed event yield in the lepton + jets decay mode; backgrounds from diboson production are normalized to their theoretical cross sections. Both contributions are fixed in the fit. The expected background from SM $t\bar{t}$ production and diboson production is 2.2 ± 0.2 (3.2 ± 0.2) events for the b-tagged (non-b-tagged) selection. The b-tagged, the non-b-tagged, and the control regions are fit simultaneously. We include systematic uncertainties due to the shapes of the signal and background templates by allowing the templates to change shape via a histogram interpolation technique (horizontal template morphing) [17]. The uncertainty due to the experimental jet energy scale (JES) is more than 3 times larger than any other uncertainty, and the data are most consistent with a shift of the JES; therefore, we only include JES-induced shape uncertainties in the fitting procedure.

We use the signal-depleted control region to constrain the background shape uncertainties without losing sensitivity to a small FCNC signal. Additionally we use the number of Z + jets events observed in the control region, Z_{control}, to place a loose constraint on the number of Z + jets events in the two signal regions, Z_{signal}. We constrain the ratio $\mathcal{R}_{\text{sig}} = Z_{\text{signal}}/Z_{\text{control}}$ to the value estimated by the MC simulation, $\mathcal{R}_{\text{sig}} = 0.51 \pm 0.10$ at the nominal JES. The uncertainty is conservatively estimated by varying the energy scales in the ALPGEN MC generator. We adjust $\mathcal{R}_{\text{sig}}$ as a function of the JES shift σ_{JES}, keeping the relative uncertainty of 20%. The absolute number of Z + jets background events remains unconstrained. To reflect the constraint on $\mathcal{R}_{\text{sig}}$ in the template fit,

we parametrize the number of Z + jet events passing the b-tagged and non-b-tagged signal selections, Z_{tagged} and $Z_{\text{nontagged}}$, as $Z_{\text{tagged}} = f_{\text{tag}}\mathcal{R}_{\text{sig}}Z_{\text{control}}$ and $Z_{\text{nontagged}} = (1 - f_{\text{tag}})\mathcal{R}_{\text{sig}}Z_{\text{control}}$, where f_{tag} is the fraction of Z + jets events passing the b-tagged signal selection. From the template fit to the data we measure a branching fraction $\mathcal{B}(t \to Zq) = -1.49\%$. The fit result is summarized in Table I and in Fig. 1.

We employ a Feldman-Cousins (FC) limit calculation framework that includes the handling of systematic uncertainties [18]. The FC construction is based on applying the above template fits to simulated experiments that are generated taking into account all known sources of systematic rate and shape uncertainty and their correlations (systematic uncertainties are discussed in the next paragraphs). We expect a limit of $(5.0 \pm 2.2)\%$ in the absence of signal. From the FC construction we find $\mathcal{B}(t \to Zq) < 3.7\%$ at 95% C.L.

We have studied systematic uncertainties due to shape uncertainties of the fitted templates, rate uncertainties (signal acceptance, background rate), and due to the normalization to the lepton + jets event yield. We treat the dominant source of template shape uncertainties, the experimental JES, as a free fit parameter. To account for further shape uncertainties, we measure the bias on the fitted branching fraction $\mathcal{B}(t \to Zq)$ in simulated experiments generated assuming the second largest source of shape uncertainties, the MC generator used for the Z + jets background. We simulate Z + jets events for which the vertex energy scale is varied by factors of two and assign the measured relative branching fraction bias at $\mathcal{B}(t \to Zq) = 3.7\%$ as a systematic uncertainty (5.6%).

The rate uncertainties, summarized in Table II, are divided into anticorrelated uncertainties, those which cause migration of events between b-tagged and non-b-tagged selections, and correlated uncertainties, those which simultaneously increase or decrease both selections. The signal acceptance systematic uncertainties are evaluated for the ratio of the FCNC signal acceptance to the acceptance for

TABLE I. Results of the fit to data. From the ratio of the number of Z + jet events in the signal and the control regions and the tagging fraction f_{tag}, we obtain $Z_{\text{tagged}} = 13.5$ events and $Z_{\text{nontagged}} = 53.9$ events.

Fit Parameter	Value
Branching Fraction, $\mathcal{B}(t \to Zq)$ (%)	-1.49 ± 1.52
Z + Jets Events in Control Region, Z_{control}	129.0 ± 11.1
Ratio Signal/Control Region, $\mathcal{R}_{\text{sig}}$	0.52 ± 0.07
Tagging Fraction, f_{tag}	0.20 ± 0.06
Jet Energy Scale Shift, σ_{JES}	-0.74 ± 0.43

TABLE II. Systematic uncertainties of the FCNC signal acceptance relative to the acceptance of the lepton + jets normalization mode and the background rate for the b-tagged and non-b-tagged selections. All values are percentages.

Systematic Uncertainty	Acceptance		Background	
	b	Non-b	b	Non-b
ID, Trig, and PDF	1.0	1.0	1.5	1.5
Initial/Final State Rad.	4.8	5.5	$\cdots$	$\cdots$
Z Helicity	3.4	3.6	$\cdots$	$\cdots$
Total Correlated	6.2	6.1	6.2	6.2
b-Tagging	5.6	16.1	3.2	2.5
$\mathcal{B}(t \to Zc)$ vs $\mathcal{B}(t \to Zu)$	4.5	4.5	$\cdots$	$\cdots$
Total Anti-Correlated	7.2	16.7	3.2	2.5

the event selection used in the lepton + jets normalization mode. Background rate uncertainties affect only the smaller SM $t\bar{t}$ and diboson backgrounds. The rate of the dominant Z + jets background in the control region is a free parameter in the fit; therefore, we do not assign systematic uncertainties for this.

Normalization to the lepton + jets event yields in the $t\bar{t}$ production cross section analysis removes nearly all uncertainties depending directly on luminosity. Many other systematic uncertainties also partially cancel. We absorb the statistical and systematic uncertainties of the $t\bar{t}$ production cross section measurement as part of the systematic uncertainty (7.8%).

In conclusion, we have searched for the top quark flavor-changing neutral-current decay $t \rightarrow Zq$ in events with a Z boson and four or more jets using CDF Run II data corresponding to 1.9 fb^{-1} of integrated luminosity. The data are consistent with the SM background prediction, and we set an upper limit on the branching fraction $\mathcal{B}(t \rightarrow Zq)$ of 3.7% at 95% C.L. at a top quark mass of 175 GeV/c^2. Assuming a top quark mass of 170 GeV/c^2, the 95% C.L. upper limit is 4.1%. Compared with the previous world's best limit of 13.7% by the L3 experiment [5] at LEP2, and the previous Tevatron upper limit of 33%, as reported by CDF Run I [4], our reported limit of 3.7% represents a substantial improvement.

[a]Deceased.

[b]Visitor from Universiteit Antwerpen, B-2610 Antwerp, Belgium.

[c]Visitor from Chinese Academy of Sciences, Beijing 100864, China.

[d]Visitor from University of Bristol, Bristol BS8 1TL, United Kingdom.

[e]Visitor from University of California Irvine, Irvine, CA 92697, USA.

[f]Visitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.

[g]Visitor from Cornell University, Ithaca, NY 14853, USA.

[h]Visitor from University of Cyprus, Nicosia CY-1678, Cyprus.

[i]Visitor from University College Dublin, Dublin 4, Ireland.

[j]Visitor from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

[k]Visitor from Universidad Iberoamericana, Mexico D.F., Mexico.

[l]Visitor from University of Manchester, Manchester M13 9PL, United Kingdom.

[m]Visitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.

[n]Visitor from University de Oviedo, E-33007 Oviedo, Spain.

[o]Visitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.

[p]Visitor from Texas Tech University, Lubbock, TX 79409, USA.

[q]Visitor from IFIC (CSIC-Universitat de Valencia), 46071 Valencia, Spain.

[1] H. Fritzsch, Phys. Lett. B **224**, 423 (1989).

[2] J. A. Aguilar-Saavedra, Acta Phys. Pol. B **35**, 2695 (2004).

[3] F. Larios, R. Martínez, and M. A. Pérez, Int. J. Mod. Phys. A **21**, 3473 (2006).

[4] F. Abe *et al.* (CDF Collaboration), Phys. Rev. Lett. **80**, 2525 (1998).

[5] P. Achard *et al.* (L3 Collaboration), Phys. Lett. B **549**, 290 (2002).

[6] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 052003 (2005).

[7] In the CDF geometry, θ is the polar angle with respect to the proton beam axis (positive z direction), and ϕ is the azimuthal angle. The pseudorapidity is $\eta = -\ln[\tan(\theta/2)]$.

[8] A. Sill *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **447**, 1 (2000); T. Affolder *et al.*, *ibid.* **453**, 84 (2000); C. S. Hill *et al.*, *ibid.* **511**, 118 (2003).

[9] T. Affolder *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **526**, 249 (2004).

[10] T. Sjöstrand *et al.*, Comput. Phys. Commun. **135**, 238 (2001).

[11] M. L. Mangano *et al.*, J. High Energy Phys. 07 (2003) 001.

[12] A. Abulencia *et al.* (CDF Collaboration), J. Phys. G **34**, 2457 (2007).

[13] A. Bhatti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **566**, 375 (2006).

[14] W.-M. Yao *et al.*, J. Phys. G **33**, 1 (2006).

[15] For the 1.1 fb^{-1} blind analysis, we obtain a 95% C.L. limit of $\mathcal{B}(t \rightarrow Zq) < 10.4\%$ (expected limit: 6.8%), consistent with a 1σ upward fluctuation of the expected SM backgrounds.

[16] D. Sherman, Ph.D. thesis, Harvard University, 2007.

[17] A. L. Read, Nucl. Instrum. Methods Phys. Res., Sect. A **425**, 357 (1999).

[18] D. Acosta *et al.*, Phys. Rev. Lett. **95**, 102002 (2005).