Search for Maximal Flavor Violating Scalars in Same-Charge Lepton Pairs in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[55] M.G. Albrow,[18] B. Álvarez González,[12] S. Amerio,[43] D. Amidei,[35] A. Anastassov,[52] A. Annovi,[20] J. Antos,[15] M. Aoki,[25] G. Apollinari,[18] A. Apresyan,[48] T. Arisawa,[57] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[53] F. Azfar,[42] P. Azzi-Bacchetta,[43] P. Azzurri,[46] N. Bacchetta,[43] W. Badgett,[18] A. Barbaro-Galtieri,[29] V.E. Barnes,[48] B.A. Barnett,[26] S. Baroiant,[8] S. Bar-Shalom,[61] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[46] P. Bednar,[15] S. Behari,[26] G. Bellettini,[46] J. Bellinger,[59] A. Belloni,[23] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] T. Berry,[30] A. Bhatti,[50] M. Binkley,[18] D. Bisello,[43] I. Bizjak,[31] R.E. Blair,[3] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[49] V. Boisvert,[49] G. Bolla,[48] A. Bolshov,[33] D. Bortoletto,[48] J. Boudreau,[47] A. Boveia,[11] B. Brau,[11] A. Bridgeman,[25] L. Brigliadori,[6] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H.S. Budd,[49] S. Budd,[25] K. Burkett,[18] G. Busetto,[43] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[3] S. Cabrera[r],[17] M. Campanelli,[36] M. Campbell,[35] F. Canelli,[18] A. Canepa,[45] D. Carlsmith,[59] R. Carosi,[46] S. Carrillo[l],[19] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro,[6] P. Catastini,[46] D. Cauz,[54] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito[p],[31] S.H. Chang,[28] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[46] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J.P. Chou,[23] G. Choudalakis,[33] S.H. Chuang,[52] K. Chung,[13] W.H. Chung,[59] Y.S. Chung,[49] C.I. Ciobanu,[25] M.A. Ciocci,[46] A. Clark,[21] D. Clark,[7] G. Compostella,[43] M.E. Convery,[18] J. Conway,[8] B. Cooper,[31] K. Copic,[35] M. Cordelli,[20] G. Cortiana,[43] F. Crescioli,[46] C. Cuenca Almenar[r],[8] J. Cuevas[o],[12] R. Culbertson,[18] J.C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[49] S. De Cecco,[51] A. Deisher,[29] G. De Lentdecker[d],[49] G. De Lorenzo,[4] M. Dell'Orso,[46] L. Demortier,[50] J. Deng,[17] M. Deninno,[6] D. De Pedis,[51] P.F. Derwent,[18] G.P. Di Giovanni,[44] C. Dionisi,[51] B. Di Ruzza,[54] J.R. Dittmann,[5] M. D'Onofrio,[4] S. Donati,[46] P. Dong,[9] J. Donini,[43] T. Dorigo,[43] S. Dube,[52] J. Efron,[39] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] R. Eusebi,[18] H.C. Fang,[29] S. Farrington,[30] W.T. Fedorko,[14] R.G. Feild,[60] M. Feindt,[27] J.P. Fernandez,[32] C. Ferrazza,[46] R. Field,[19] G. Flanagan,[48] R. Forrest,[8] S. Forrester,[8] M. Franklin,[23] J.C. Freeman,[29] I. Furic,[19] M. Gallinaro,[50] J. Galyardt,[13] F. Garberson,[11] J.E. Garcia,[46] A.F. Garfinkel,[48] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] S. Giagu,[51] V. Giakoumopoulou[a],[46] P. Giannetti,[46] K. Gibson,[47] J.L. Gimmell,[49] C.M. Ginsburg,[18] N. Giokaris[a],[16] M. Giordani,[54] P. Giromini,[20] M. Giunta,[46] V. Glagolev,[16] D. Glenzinski,[18] M. Gold,[37] N. Goldschmidt,[19] A. Golossanov,[18] G. Gomez,[12] G. Gomez-Ceballos,[33] M. Goncharov,[53] O. González,[32] I. Gorelov,[37] A.T. Goshaw,[17] K. Goulianos,[50] A. Gresele,[43] 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,[52] A. Hamilton,[21] B.-Y. Han,[49] J.Y. Han,[49] R. Handler,[59] F. Happacher,[20] K. Hara,[55] D. Hare,[52] M. Hare,[56] S. Harper,[42] R.F. Harr,[58] R.M. Harris,[18] M. Hartz,[47] K. Hatakeyama,[50] J. Hauser,[9] C. Hays,[42] M. Heck,[27] A. Heijboer,[45] B. Heinemann,[29] J. Heinrich,[45] C. Henderson,[33] M. Herndon,[59] J. Heuser,[27] S. Hewamanage,[5] D. Hidas,[17] C.S. Hill[c],[11] D. Hirschbuehl,[27] A. Hocker,[18] S. Hou,[1] M. Houlden,[30] S.-C. Hsu,[10] B.T. Huffman,[42] R.E. Hughes,[39] U. Husemann,[60] J. Huston,[36] J. Incandela,[11] G. Introzzi,[46] M. Iori,[51] A. Ivanov,[8] B. Iyutin,[33] E. James,[18] B. Jayatilaka,[17] D. Jeans,[51] E.J. Jeon,[28] S. Jindariani,[19] W. Johnson,[8] M. Jones,[48] K.K. Joo,[28] S.Y. Jun,[13] J.E. Jung,[28] T.R. Junk,[25] T. Kamon,[53] D. Kar,[19] P.E. Karchin,[58] Y. Kato,[41] R. Kephart,[18] U. Kerzel,[27] V. Khotilovich,[53] B. Kilminster,[39] D.H. Kim,[28] H.S. Kim,[28] J.E. Kim,[28] M.J. Kim,[18] S.B. Kim,[28] S.H. Kim,[55] Y.K. Kim,[14] N. Kimura,[55] L. Kirsch,[7] S. Klimenko,[19] M. Klute,[33] B. Knuteson,[33] B.R. Ko,[17] S.A. Koay,[11] K. Kondo,[57] D.J. Kong,[28] J. Konigsberg,[19] A. Korytov,[19] A.V. Kotwal,[17] J. Kraus,[25] M. Kreps,[27] J. Kroll,[45] N. Krumnack,[5] M. Kruse,[17] V. Krutelyov,[11] T. Kubo,[55] S. E. Kuhlmann,[3] T. Kuhr,[27] N.P. Kulkarni,[58] Y. Kusakabe,[57] S. Kwang,[14] A.T. Laasanen,[48] S. Lai,[34] S. Lami,[46] S. Lammel,[18] M. Lancaster,[31] R.L. Lander,[8] K. Lannon,[39] A. Lath,[52] G. Latino,[46] I. Lazzizzera,[43] T. LeCompte,[3] J. Lee,[49] J. Lee,[28] Y.J. Lee,[28] S.W. Lee[q],[53] R. Lefèvre,[21] N. Leonardo,[33] S. Leone,[46] S. Levy,[14] J.D. Lewis,[18] C. Lin,[60] C.S. Lin,[29] J. Linacre,[42] M. Lindgren,[18] E. Lipeles,[10] A. Lister,[8] D.O. Litvintsev,[18] T. Liu,[18] N.S. Lockyer,[45] A. Loginov,[60] M. Loreti,[43] L. Lovas,[15] R.-S. Lu,[1] D. Lucchesi,[43] J. Lueck,[27] C. Luci,[51] P. Lujan,[29] P. Lukens,[18] G. Lungu,[19] L. Lyons,[42] J. Lys,[29] R. Lysak,[15] E. Lytken,[48] P. Mack,[27] D. MacQueen,[34] R. Madrak,[18] K. Maeshima,[18] K. Makhoul,[33] T. Maki,[24] P. Maksimovic,[26] S. Malde,[42] S. Malik,[31] G. Manca,[30] A. Manousakis[a],[16] F. Margaroli,[48] C. Marino,[27] C.P. Marino,[25] A. Martin,[60] M. Martin,[26] V. Martin[j],[22] M. Martínez,[4] R. Martínez-Ballarín,[32] T. Maruyama,[55] P. Mastrandrea,[51] T. Masubuchi,[55] M.E. Mattson,[58] P. Mazzanti,[6] K.S. McFarland,[49] P. McIntyre,[53] R. McNulty[i],[30]

A. Mehta,[30] P. Mehtala,[24] S. Menzemer[k],[12] A. Menzione,[46] P. Merkel,[48] C. Mesropian,[50] A. Messina,[36] T. Miao,[18] N. Miladinovic,[7] J. Miles,[33] R. Miller,[36] C. Mills,[23] M. Milnik,[27] A. Mitra,[1] G. Mitselmakher,[19] H. Miyake,[55] S. Moed,[23] N. Moggi,[6] C.S. Moon,[28] R. Moore,[18] M. Morello,[46] P. Movilla Fernandez,[29] J. Mülmenstädt,[29] A. Mukherjee,[18] Th. Muller,[27] R. Mumford,[26] P. Murat,[18] M. Mussini,[6] J. Nachtman,[18] Y. Nagai,[55] A. Nagano,[55] J. Naganoma,[57] K. Nakamura,[55] I. Nakano,[40] A. Napier,[56] V. Necula,[17] C. Neu,[45] M.S. Neubauer,[25] J. Nielsen[f],[29] L. Nodulman,[3] M. Norman,[10] O. Norniella,[25] E. Nurse,[31] S.H. Oh,[17] Y.D. Oh,[28] I. Oksuzian,[19] T. Okusawa,[41] R. Oldeman,[30] R. Orava,[24] K. Osterberg,[24] S. Pagan Griso,[43] C. Pagliarone,[46] E. Palencia,[18] V. Papadimitriou,[18] A. Papaikonomou,[27] A.A. Paramonov,[14] B. Parks,[39] S. Pashapour,[34] J. Patrick,[18] G. Pauletta,[54] M. Paulini,[13] C. Paus,[33] D.E. Pellett,[8] A. Penzo,[54] T.J. Phillips,[17] G. Piacentino,[46] J. Piedra,[44] L. Pinera,[19] K. Pitts,[25] C. Plager,[9] L. Pondrom,[59] X. Portell,[4] O. Poukhov,[16] N. Pounder,[42] F. Prakoshyn,[16] A. Pronko,[18] J. Proudfoot,[3] F. Ptohos[h],[18] G. Punzi,[46] J. Pursley,[59] J. Rademacker[c],[42] A. Rahaman,[47] A. Rajaraman,[61] V. Ramakrishnan,[59] N. Ranjan,[48] I. Redondo,[32] B. Reisert,[18] V. Rekovic,[37] P. Renton,[42] M. Rescigno,[51] S. Richter,[27] F. Rimondi,[6] L. Ristori,[46] A. Robson,[22] T. Rodrigo,[12] E. Rogers,[25] S. Rolli,[56] R. Roser,[18] M. Rossi,[54] R. Rossin,[11] P. Roy,[34] A. Ruiz,[12] J. Russ,[13] V. Rusu,[18] H. Saarikko,[24] A. Safonov,[53] W.K. Sakumoto,[49] G. Salamanna,[51] O. Saltó,[4] L. Santi,[54] S. Sarkar,[51] L. Sartori,[46] K. Sato,[18] A. Savoy-Navarro,[44] T. Scheidle,[27] P. Schlabach,[18] E.E. Schmidt,[18] M.A. Schmidt,[14] M.P. Schmidt,[60] M. Schmitt,[38] T. Schwarz,[8] L. Scodellaro,[12] A.L. Scott,[11] A. Scribano,[46] F. Scuri,[46] A. Sedov,[48] S. Seidel,[37] Y. Seiya,[41] A. Semenov,[16] L. Sexton-Kennedy,[18] A. Sfyria,[21] S.Z. Shalhout,[58] M.D. Shapiro,[29] T. Shears,[30] P.F. Shepard,[47] D. Sherman,[23] M. Shimojima[n],[55] M. Shochet,[14] Y. Shon,[59] I. Shreyber,[21] A. Sidoti,[46] P. Sinervo,[34] A. Sisakyan,[16] A.J. Slaughter,[18] J. Slaunwhite,[39] K. Sliwa,[56] J.R. Smith,[8] F.D. Snider,[18] R. Snihur,[34] M. Soderberg,[35] A. Soha,[8] S. Somalwar,[52] V. Sorin,[36] J. Spalding,[18] F. Spinella,[46] T. Spreitzer,[34] P. Squillacioti,[46] M. Stanitzki,[60] R. St. Denis,[22] B. Stelzer,[9] O. Stelzer-Chilton,[42] D. Stentz,[38] J. Strologas,[37] D. Stuart,[11] J.S. Suh,[28] A. Sukhanov,[19] H. Sun,[56] I. Suslov,[16] T. Suzuki,[55] A. Taffard[e],[25] R. Takashima,[40] Y. Takeuchi,[55] R. Tanaka,[40] M. Tecchio,[35] P.K. Teng,[1] K. Terashi,[50] J. Thom[g],[18] A.S. Thompson,[22] G.A. Thompson,[25] E. Thomson,[45] P. Tipton,[60] V. Tiwari,[13] S. Tkaczyk,[18] D. Toback,[53] S. Tokar,[15] K. Tollefson,[36] T. Tomura,[55] D. Tonelli,[18] S. Torre,[20] D. Torretta,[18] S. Tourneur,[44] W. Trischuk,[34] Y. Tu,[45] N. Turini,[46] F. Ukegawa,[55] S. Uozumi,[55] S. Vallecorsa,[21] N. van Remortel,[24] A. Varganov,[35] E. Vataga,[37] F. Vázquez[l],[19] G. Velev,[18] C. Vellidis[a],[46] V. Veszpremi,[48] M. Vidal,[32] R. Vidal,[18] I. Vila,[12] R. Vilar,[12] T. Vine,[31] M. Vogel,[37] I. Volobouev[q],[29] G. Volpi,[46] F. Würthwein,[10] P. Wagner,[45] R.G. Wagner,[3] R.L. Wagner,[18] J. Wagner-Kuhr,[27] W. Wagner,[27] T. Wakisaka,[41] R. Wallny,[9] S.M. Wang,[1] A. Warburton,[34] D. Waters,[31] M. Weinberger,[53] W.C. Wester III,[18] B. Whitehouse,[56] D. Whiteson[e],[45] A.B. Wicklund,[3] E. Wicklund,[18] G. Williams,[34] H.H. Williams,[45] P. Wilson,[18] B.L. Winer,[39] P. Wittich[g],[18] S. Wolbers,[18] C. Wolfe,[14] T. Wright,[35] X. Wu,[21] S.M. Wynne,[30] A. Yagil,[10] K. Yamamoto,[41] J. Yamaoka,[52] T. Yamashita,[40] C. Yang,[60] U.K. Yang[m],[14] Y.C. Yang,[28] W.M. Yao,[29] G.P. Yeh,[18] J. Yoh,[18] K. Yorita,[14] T. Yoshida,[41] G.B. Yu,[49] F. Yu,[61] I. Yu,[28] S.S. Yu,[18] J.C. Yun,[18] L. Zanello,[51] A. Zanetti,[54] I. Zaw,[23] X. Zhang,[25] Y. Zheng[b],[9] and S. Zucchelli[6]

(CDF Collaboration[*])

The CDF Collaboration[62]

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Informatics Institute, University of Amsterdam, Amsterdam, The Netherlands*
[3]*Argonne National Laboratory, Argonne, Illinois 60439*
[4]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[5]*Baylor University, Waco, Texas 76798*
[6]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[7]*Brandeis University, Waltham, Massachusetts 02254*
[8]*University of California, Davis, Davis, California 95616*
[9]*University of California, Los Angeles, Los Angeles, California 90024*
[10]*University of California, San Diego, La Jolla, California 92093*
[11]*University of California, Santa Barbara, Santa Barbara, California 93106*
[12]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[13]*Carnegie Mellon University, Pittsburgh, PA 15213*
[14]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[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*
[18]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[19] *University of Florida, Gainesville, Florida 32611*
[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*
[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*
[26] *The Johns Hopkins University, Baltimore, Maryland 21218*
[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*
[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*
[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*
[36] *Michigan State University, East Lansing, Michigan 48824*
[37] *University of New Mexico, Albuquerque, New Mexico 87131*
[38] *Northwestern University, Evanston, Illinois 60208*
[39] *The Ohio State University, Columbus, Ohio 43210*
[40] *Okayama University, Okayama 700-8530, Japan*
[41] *Osaka City University, Osaka 588, Japan*
[42] *University of Oxford, Oxford OX1 3RH, United Kingdom*
[43] *University of Padova, Istituto Nazionale di Fisica Nucleare,*
Sezione di Padova-Trento, I-35131 Padova, Italy
[44] *LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
[45] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[46] *Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa,*
Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
[47] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[48] *Purdue University, West Lafayette, Indiana 47907*
[49] *University of Rochester, Rochester, New York 14627*
[50] *The Rockefeller University, New York, New York 10021*
[51] *Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,*
University of Rome "La Sapienza," I-00185 Roma, Italy
[52] *Rutgers University, Piscataway, New Jersey 08855*
[53] *Texas A&M University, College Station, Texas 77843*
[54] *Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*
[55] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[56] *Tufts University, Medford, Massachusetts 02155*
[57] *Waseda University, Tokyo 169, Japan*
[58] *Wayne State University, Detroit, Michigan 48201*
[59] *University of Wisconsin, Madison, Wisconsin 53706*
[60] *Yale University, New Haven, Connecticut 06520*
[61] *University of California, Irvine 92617*
[62] *URL: http://www.cdf.fnal.gov*

Models of Maximal Flavor Violation (MxFV) in elementary particle physics may contain at least one new scalar SU(2) doublet field $\Phi_{FV} = (\eta^0, \eta^+)$ that couples the first and third generation quarks (q_1, q_3) via a Lagrangian term $\mathcal{L}_{FV} = \xi_{13}\Phi_{FV}q_1q_3$. These models have a distinctive signature of same-charge top-quark pairs and evade flavor-changing limits from meson mixing measurements. Data corresponding to 2 fb^{-1} collected by the CDF II detector in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV are analyzed for evidence of the MxFV signature. For a neutral scalar η^0 with $m_{\eta^0} = 200$ GeV/c^2 and coupling $\xi_{13} = 1$, ~ 11 signal events are expected over a background of 2.1 ± 1.8 events. Three events are observed in the data, consistent with background expectations, and limits are set on the coupling ξ_{13} for $m_{\eta^0} = 180 - 300$ GeV/c^2.

Measurements of low energy flavor changing (FC) transitions, such as neutral meson mixing and rare B and K decays [1], largely confirm the minimal flavor violation (MFV) ansatz of the standard model's quark-mixing matrix. This suggests that any new physics that couples quark flavors must either be well aligned with the standard model couplings or mediated by particles that are too heavy to give observable deviations in current data. If the proposed new physics can be written in terms of a coupling matrix ξ_{ij} between quark flavors i and j, MFV imposes strict constraints on models that couple the top-quark to lighter quarks, namely $\xi_{31}, \xi_{13}, \xi_{32}, \xi_{23} \sim 0$.

However, there is no strong theoretical motivation for an alignment between the flavor structure of the standard model and new physics. On the contrary, theories beyond the standard model typically predict large flavor changing transitions if no additional symmetries are imposed. Moreover, new results on CP-violating asymmetries from $B_s \to J/\psi\phi$ [2, 3] suggest that new flavor structure beyond that of the CKM may be required [4].

A new class of scalar-mediated models has recently been proposed with a Lagrangian describing a scalar SU(2) doublet field $\Phi_{FV} = (\eta^0, \eta^+)$ that couple left-handed quark fields of flavor i (Q_{iL}) to right-handed up-type quark fields of flavor j (u_{jR}) with a strength ξ_{ij} [5]

$$\mathcal{L}_{FV} = \xi_{ij}\bar{Q}_{iL}\tilde{\Phi}_{FV}u_{jR} + h.c. \qquad (1)$$

This departs maximally from the MFV ansatz by allowing real $\xi_{31}, \xi_{13} \sim 1$ or $\xi_{32}, \xi_{23} \sim 1$ with all other terms zero. Contrary to previous understanding, these models are not excluded by current measurements, which constrain the products of terms in the coupling matrix, e.g., $\xi_{32} \cdot \xi_{31}$ [5], even with a light η^0 mass of $\mathcal{O}(200)$ GeV/c^2.

In the model investigated here ($\xi_{31}, \xi_{13} \sim 1$, called MxFV$_1$ in Ref. [5]), the η^0 decays with equal probability to quark-antiquark pairs $t + \bar{u}$ and $\bar{t} + u$. This leads to

a striking signal of same-charge top-quark pairs in association with light-quark jets through the processes $ug \to t\eta^0 \to tt\bar{u}$, $ug \to tt\bar{u}$ (η^0 exchange) , $u\bar{u} \to \eta^0\eta^0 \to tt\bar{u}\bar{u}$, and $uu \to tt$ (η^0 exchange) and their Hermitian conjugates. The predicted cross section is $\mathcal{O}(1)$ pb over a range of light η^0 masses, $180 - 300$ GeV/c^2.

When W bosons from both top-quarks decay leptonically ($t \to Wb \to l\nu b$), these processes have a low-background signature of two same-charge leptons, missing transverse energy ($\not{E}_T$) [6, 7], and two b jets ($\ell^\pm\ell^\pm\not{E}_Tbb$) accompanied by additional jets. Though CDF has examined its inclusive same-charge lepton dataset in smaller data subsets[8], there has not been an experimental study of the $\ell^\pm\ell^\pm\not{E}_Tbb$ final state, where many of the contributions to a $\ell^\pm\ell^\pm$ final state are suppressed by the requirement of b jet identification or large missing transverse energy. Thus, there may be new flavor-violating processes which have large cross sections, low backgrounds, and no direct experimental constraints.

We use data collected between 2002 and 2007 with the CDF II detector, corresponding to an integrated luminosity of 2.0 fb^{-1}. CDF II [7, 9] is a general purpose detector designed to study $p\bar{p}$ collisions at the Fermilab Tevatron. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis; the momentum resolution is $\delta p_T/p_T^2 = 0.1\%/$GeV/c. The silicon detectors provide tracking information for pseudorapidity $|\eta| < 2$ and are used to reconstruct collision and decay points. The drift chamber surrounds the silicon detectors and gives full coverage in the central pseudorapidity region $|\eta| < 1$. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers and scintillators located outside the calorimeters detect muons in the central pseudorapidity region $|\eta| < 1$. The data used in this measurement are collected with lepton triggers that require an electron or muon with $p_T > 18$ GeV/c.

To isolate the same-charge top-quarks signal, we define the $\ell^\pm\ell^\pm b\not{E}_T$ signature by requiring two same-charge reconstructed leptons (electrons or muons) in the central region of the detector, each with $p_T > 20$ GeV/c, one of which must be isolated [10]; at least one jet with $|\eta| < 2.4$ and transverse energy of at least 15 GeV identified as a b jet by the SECVTX algorithm that searches for a displaced secondary vertex [11]; and at least 20 GeV of missing transverse energy, $\not{E}_T$ [6].

To calculate the expected number of tt and $\bar{t}\bar{t}$ events, we generate events for each of the same-charge processes using CALCHEP[12] with CTEQ6M proton parton distribution functions [13] followed by parton fragmentation and hadronization by PYTHIA [14]. Detector resolution and acceptance are modeled using the GEANT-based de-

---

*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, ^{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,

tector simulation, CDFSIM [15]. Table I shows the number of expected events in our sample.

TABLE I: Production cross sections $\sigma(tt)$, $\sigma(tt\bar{u})$, and $\sigma(tt\bar{u}\bar{u})$ for each of the three same-charge top-quark processes, for $\xi_{31} = \xi_{13} = 1$ and various η^0 masses. Also given are the acceptance (ϵ) of the event selection described in the text and expected number N of $\ell^{\pm}\ell^{\pm}b\rlap{/}{E}_T$ events in our sample. The uncertainty on the cross sections is estimated to be 10%, mainly due to the choice of the renormalization scale, the choice of parton distributin functions, and the numerical integration.

	M_{η^0} [GeV/c^2]	180	190	200	225	250	300
	σ [pb]	0.50	0.45	0.41	0.33	0.27	0.19
tt	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	4.4	4.3	3.8	2.6	2.1	0.9
	σ [pb]	0.54	0.50	0.42	0.28	0.22	0.10
$tt\bar{u}$	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	4.7	3.9	3.9	3.0	2.4	1.7
	σ [pb]	0.68	0.45	0.38	0.17	0.06	0.02
$tt\bar{u}\bar{u}$	ϵ [%]	0.5	0.5	0.5	0.5	0.5	0.5
	N	5.7	3.5	3.3	1.4	0.5	0.2
Total $N(l^{\pm}l^{\pm}b\rlap{/}{E}_T)$		14.7	11.7	10.9	7.0	5.0	2.7

Backgrounds to same-charge lepton pairs come from two classes of processes. In the first class, a real lepton is paired with a jet, which is misidentified as a same-charge lepton. The second class of processes comes from a pair of real opposite-charge leptons which include an electron; a hard photon emission from an electron converts into an electron-positron pair with strongly asymmetric momenta so that only one leg is reconstructed.

Backgrounds in which the second lepton arises from a misidentified jet or the decay of a heavy quark are largely due to production of W+jets or semi-leptonic $t\bar{t}$ decays and are described using a model from jet data [16] in which the rate of lepton reconstruction in inclusive jets is measured and applied to W+jet events. The misidentification model is validated for light-quark jets by comparing the predicted and observed rates of same-charge events as a function of the missing transverse energy without a b-tag requirement. Discrepancies in rates in control regions motivate a 40% uncertainty. The selected sample may have a larger heavy flavor fraction than the jets from which the lepton misidentification model was derived. Studies in simulated events show that the rate of misidentified leptons in a heavy-flavor enriched sample may be $50 - 75\%$ higher and motivate a 100% total uncertainty on the background prediction from lepton misidentification.

Backgrounds in which the same-charge lepton is due to a hard photon emission come from Z/γ^*+jets and top-quark pairs with electron-positron decays. Estimates of the backgrounds from Z/γ^*+jets processes are made with the ALPGEN [17] simulation code matched with PYTHIA in the MLM scheme [17] for the hadronization

TABLE II: Number of expected events for each background process, and the observed same-charge lepton events with b-tag and missing transverse energy, see text.

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
$Z \to \ell\ell$	0.01	0.02	0.02	0.1 ± 0.1
$t\bar{t}$	0.09	0.03	0.11	0.2 ± 0.1
MisID	0.6	0.71	0.50	1.8 ± 1.8
Total	0.7	0.8	0.6	2.1 ± 1.8
Data	0	1	2	3

and fragmentation and normalized to data in opposite-sign events. To validate the modeling of the rate of hard emission, we compare our prediction for the contribution of $Z \to e^+e^-$ to the observed sample of same-charge electrons or positron without a b-tag or missing transverse energy requirement. The shape and yield of the observed signal at the Z mass agrees well with the prediction. The $t\bar{t}$ backgrounds are estimated using events generated in PYTHIA at $m_t = 172$ GeV/c^2. Modeling of the $t\bar{t}$ contribution is validated by comparing predicted and observed rates of opposite-sign leptons with $\rlap{/}{E}_T$ and a b tag, where $t\bar{t}$ is expected to dominate. The detector response for both Z+jets and $t\bar{t}$ processes is evaluated using CDFSIM, where, to avoid double-counting, the same-charge leptons are required to originate from the W or Z decays rather than from misidentified jets.

Backgrounds from charge-mismeasurement are insignificant, as the charge of a particle with momentum of 100 GeV/c is typically determined with a significance greater than 5σ [18]. This is confirmed by the absence of a significant signal near the Z mass in observed same-charge muon events.

Backgrounds from diboson production WW, WZ, ZZ, $W\gamma$, and $Z\gamma$ in association with b jets are modeled with PYTHIA and BAUR[19] generators. These have non-negligible contributions to the inclusive same-charge lepton pair sample, but in the final selection they are insignificant due to the requirement of a b tag.

The final background estimate, shown in Table II, is 2.1 events with an uncertainty of 1.8 events.

From the observed number of events, one could directly measure the value of the MxFV$_1$ coupling $\xi = \xi_{31} = \xi_{13}$. To enhance precision of the measurement of the coupling, we simultaneously fit for the number of signal and background events in the data by exploiting the difference between the number of jets expected in signal and background events (see Fig. 2). Jets are required to have 15 GeV of transverse energy and $|\eta| < 2.4$. The fitted number of signal events can be transformed into an estimated value for ξ. We use a binned likelihood fit in the number of reconstructed jets which takes into account that $\sigma(ug \to t\eta^0 \to tt\bar{u}) \propto \xi^2$ while $\sigma(uu \to tt)$ and

TABLE III: 95% confidence level upper limits on the coupling ξ as a function of the mass of η^0.

Mass [GeV/c^2]	180	190	200	225	250	300
(95% C.L.) $\xi <$	0.78	0.81	0.87	1.03	1.11	1.39

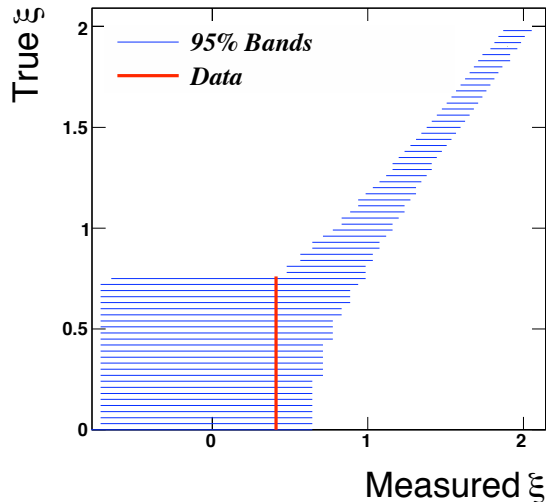$$\sigma(u\bar{u} \to \eta^0\eta^0 \to tt\bar{u}\bar{u}) \propto \xi^4.$$

FIG. 1: Following the prescription in Ref. [20], horizontal bands in measured ξ are shown which include 95% of simulated experiments, for various values of true ξ, with $m_{\eta^0} = 180$ GeV/c^2.

Following the Feldman-Cousins prescription [20], we use simulated experiments to construct bands which contain 95% of the fitted values of ξ at various true values of ξ for a mass of η^0 (Fig. 1). The simulated experiments include fluctuations in the nuisance parameters, including the uncertainty in the jet energy scale, initial and final state radiation, parton distribution functions and signal and background normalization uncertainties. The confidence band in the space of the true ξ for an individual experiment is the intersection of a line drawn at the observed ξ.

We observe 3 events, in good agreement with the background expectation. The distribution of jets can be seen in Fig. 2 for the data as well as for the signal and background for the best fit value of $\xi = 0.41$ for $m_{\eta^0} = 180$ GeV/c^2. As shown in Fig. 1, this corresponds to an upper limit $\xi < 0.78$ at 95% C.L. Table III and Fig. 3 give upper limits on the value of the coupling ξ for $m_\eta^0 = 180 - 300$ GeV/c^2.

In conclusion, we find no evidence of the signature for maximal flavor violation, and set the first limits on the flavor-changing coupling between the top and up quark in such a model.
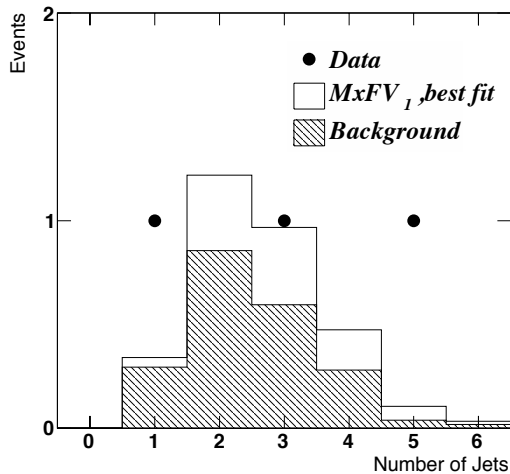
We thank the Fermilab staff and the technical staffs

FIG. 2: Jet multiplicity for background, observed data, and MxFV$_1$ signal with best-fit value of $\xi = 0.41$ for $M_{\eta^0} = 180$ GeV/c^2.
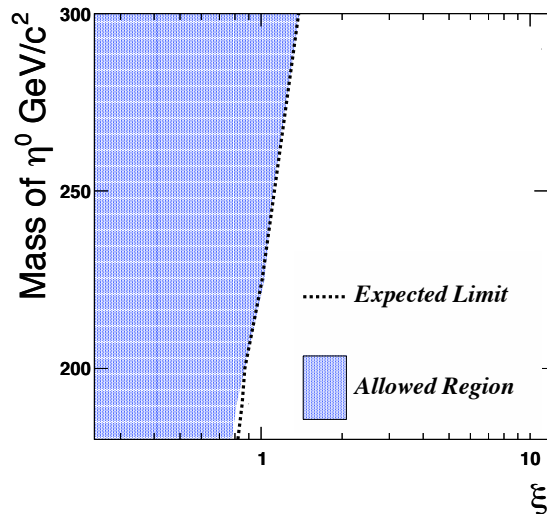

FIG. 3: Observed 95% C.L. regions in the $\xi - m_{\eta^0}$ plane.

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

[2] A. Abulencia *et al.*, Phys. Rev. Lett. **100**, 161802 (2008).

[3] V.M.Abazov *et al.* (2008), arXiv:0802.2255.

[4] Z. Ligeti *et al.*, Phys. Rev. Lett. **97**, 101801 (2006).

[5] S.Bar-Shalom and A. Rajaraman, Phys. Rev. D **77**, 095011 (2008).

[6] Missing transverse energy, $\not{E}_T$, is defined as the magnitude of the vector $-\sum_i E_T^i \vec{n}_i$ where E_T^i are the magnitudes of transverse energy contained in each calorimeter tower i, and $\vec{n}_i$ is the unit vector from the interaction vertex to the tower in the transverse (x, y) plane. $\not{E}_T$ is further corrected for the energy of identified muons.

[7] CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is $\eta \equiv -\ln(\tan(\theta/2))$, where θ is the polar angle, and ϕ is the azimuthal angle relative to the proton beam direction, while $p_T = |p| \sin\theta$, $E_T = E \sin\theta$.

[8] A. Abulencia *et al.*, Phys. Rev. Lett. **98**, 221803 (2007).

[9] D. Acosta *et al.*, Phys. Rev. D **71**, 032001 (2005).

[10] A lepton is isolated if the total E_T within a cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq 0.4$, minus the lepton E_T is $< 10\%$ of the lepton E_T.

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

[12] A. Pukhov *et al.*, Tech. Rep. 98-41/542, INP MSU (1998).

[13] J.Pumplin *et al.*,J. High Energy Phys. 07 (2002) 012.

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

[15] T. Affolder *et al.*, Nucl. Instrum. Method A **447**, 1 (2000).

[16] D. Acosta *et al.*, Phys. Rev. D **72**, 052003 (2005).

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

[18] A. Abulencia *et al.*, J. Phys. G: Nucl. Part. Phys. p. 2457 (2007).

[19] U. Bauer *et al.*, Phys Rev D **41**, 1476 (1990).

[20] G. Feldman and R. Cousins, Phys. Rev. D **57**, 3873 (1998).