Measurement of $t\bar{t}$ Spin Correlation in $p\bar{p}$ Collisions Using the CDF II Detector at the Tevatron

T. Aaltonen, B. Álvarez González, S. Amerio, D. Amidei, A. Anastassov, A. Anno, J. Antos, A. Apollinari, J.A. Appel, A. Apresyan, T. Arisawa, A. Artikov, J. Asaadi, W. Ashmanskas, B. Auerbach, A. Aurisano, F. Azfar, W. Badgett, A. Barbaro-Galtieri, V.E. Barnes, B.A. Barnett, P. Barria, P. Bartos, M. Bause, G. Bauer, F. Bedeschi, D. Beecher, S. Behari, G. Belletti, J. Bellinger, D. Benjamín, A. Beretvas, A. Bhatti, M. Binkley, D. Bisello, I. Bizjak, K.R. Bland, B. Blumenfeld, A. Bocci, A. Bodek, D. Bortoletto, J. Boudreau, A. Boveia, B. Brau, L. Brigliadori, A. Brisuda, C. Bromberg, E. Brucken, M. Bucciannoni, J. Budagov, H.S. Budd, S. Budd, K. Burkett, G. Busetto, P. Busz, A. Buzatu, C. Calancha, S. Camarda, M. Campaelli, M. Campbell, F. Canelli, A. Canepa, B. Carls, D. Carlsmith, R. Carosi, S. Carrillo, S. Carron, B. Casal, M. Casarsa, A. Castro, P. Catastini, D. Cauz, V. Cavaliere, M. Cavalli-Sforza, A. Cerri, L. Cerri, Y.C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, F. Chlebana, K. Cho, D. Chokheli, J.P. Chou, W.H. Chung, Y.S. Chung, C.I. Ciobanu, M.A. Ciocci, A. Clark, G. Compostella, M.E. Convery, J. Conway, M. Corbo, M. Cordelli, C.A. Cox, D.J. Cox, F. Crescioli, C. Cuenca Almenar, J. Cuevas, R. Culbertson, D. Dagenhart, N. d’Ascanzo, M. Datta, P. de Barbaro, S. De Cecco, G. De Lorenzo, M. Dell’Orso, C. Deluca, L. Demortier, D. Deng, M. Denimno, F. Devoto, M. d’Errico, A. Di Canto, B. Di Ruzza, J.R. Dittmann, M. D’Onofrio, S. Donati, P. Dong, M. Dorigo, T. Dorigo, K. Ebina, A. Elagin, A. Epiggy, R. Erbacher, D. Errede, S. Errede, N. Ershaidat, R. Eusebi, H.C. Fang, S. Farrington, M. Feindt, J.P. Fernandez, C. Ferrazza, R. Field, G. Flanagan, R. Forrest, M.J. Frank, M. Franklin, J.C. Freeman, Y. Funakoshi, I. Furic, M. Gallinaro, J. Galyardt, J.E. Garcia, A.F. Garfinkel, P. Garozzi, H. Gerberich, E. Gerchtein, S. Giagu, V. Giakoumopoulou, P. Giannetti, K. Gibson, C.M. Ginsburg, N. Giokaris, P. Giomini, M. Giunta, G. Giurgiu, V. Glagolev, D. Glenzinski, M. Gold, D. Goldin, N. Goldschmidt, A. Golossanov, G. Gomez, G. Gomez-Ceballos, M. Goucharov, O. González, I. Gorelov, A.T. Goshaw, K. Goulianos, A. Gresele, S. Grinstein, C. Grosso-Pilcher, R.C. Group, J. Guimarães da Costa, Z. Gunay-Unalan, C. Haber, S.R. Hahn, E. Halkiadakis, A. Hamaguchi, J.Y. Han, F. Happacher, K. Hara, D. Hare, M. Hare, R.F. Harr, K. Hatakeyama, C. Hays, M. Heck, E. Heinrich, M. Herndon, S. Hewamanage, D. Hidas, A. Hocker, W. Hopkins, D. Horn, S. Hou, R.E. Hughes, M. Hurwitz, U. Husemann, N. Hussain, M. Hussein, J. Huston, G. Intorzi, M. Iori, A. Ivanov, E. James, D. Jiang, B. Jayatilaka, E.J. Jeon, M.K. Jha, S. Jindariani, W. Johnson, M. Jones, K.K. Joo, S.Y. Jun, T.R. Junk, T. Kamon, P.E. Karchin, Y. Kato, W. Ketchum, J. Keung, V. Khotilovich, B. Kilminster, D.H. Kim, H.S. Kim, H.W. Kim, J.E. Kim, M.J. Kim, S.B. Kim, S.H. Kim, Y.K. Kim, N. Kimura, M. Kirby, S. Klimenko, K. Kondo, D.J. Kong, J. Konigsberg, A.V. Kotwal, M. Kreps, J. Kroll, D. Krop, N. Krumnack, M. Kruse, V. Krutelyov, T. Kuhn, M. Kurata, S.W. Kwong, A.T. Laasanen, S. Lami, S. Lamml, M. Lancaster, R.L. Lander, K. Lannon, A. Lath, G. Latino, I. Lazzrazzera, T. LeCompte, E. Lee, H.S. Lee, J.S. Lee, S.W. Lee, S. Leo, S. Leone, J.D. Lewis, C.-J. Lin, J. Linacre, M. Lindgren, E. Lipeles, A. Lister, D.O. Litvinsey, C. Liu, Q. Liu, T. Liu, S. Lockwitz, N.S. Lockyer, A. Logino, D. Lucchesi, J. Lueck, P. Lujan, P. Lukens, G. Lungu, J. Lys, R. Lysak, R. Madrak, K. Maeshima, K. Makhoul, P. Maksimovic, S. Malik, G. Manca, A. Manousakis-Katsikakis, F. Margaroli, C. Marino, M. Martínez, R. Martínez-Ballarín.
P. Mastrandrea, 49 M. Mathis, 23 M.E. Mattson, 57 P. Mazzanti, 6 K.S. McFarland, 47 P. McIntyre, 51 R. McNulty, 27 A. Mehta, 27 P. Mehtala, 21 A. Menzione, 44 C. Mesropian, 48 T. Miao, 15 D. Mietlicki, 32 A. Mitra, 1 H. Miyake, 53 S. Moed, 20 N. Moggi, 6 M.N. Mondragon, 15 C.S. Moon, 25 R. Moore, 15 M.J. Morello, 15 J. Morlock, 24 P. Movilla Fernandez, 15 A. Mukherjee, 15 Th. Muller, 24 P. Murat, 15 M. Mussini, 6 J. Nachtmann, 15 Y. Nagai, 53 J. Naganoma, 56 I. Nakano, 38 A. Napier, 54 J. Nett, 58 C. Neu, 60 M.S. Neubauer, 22 J. Nielsen, 26 L. Nodulman, 2 O. Norniella, 22 E. Nurse, 28 L. Oakes, 40 S.H. Oh, 14 Y.D. Oh, 25 I. Oksuzian, 60 T. Okusawa, 39 R. Orava, 21 L. Ortolan, 4 S. Pagan Griso, 41 C. Pagliarone, 52 E. Palencia, 9 V. Papadimitriou, 15 A.A. Paramonov, 2 J. Patrick, 15 G. Pauletta, 52 M. Paulini, 10 C. Paus, 30 D.E. Pellett, 7 A. Penzo, 52 T.J. Phillips, 14 G. Piacentino, 44 E. Pianori, 43 J. Pilot, 37 K. Pitts, 22 C. Plager, 8 L. Pondrom, 58 K. Potamianos, 46 O. Poukhov, 13 F. Prokoschin, 13 A. Pronko, 15 F. Pthois, 17 E. Pueschel, 10 G. Punzi, 44 J. Pursley, 58 A. Rahaman, 45 V. Ramakrishnan, 58 N. Ranjan, 46 I. Redondo, 29 P. Renton, 40 M. Rescigno, 49 F. Rimondi, 6 L. Ristori, 15 A. Robson, 19 T. Rodrigo, 9 T. Rodriguez, 43 E. Rogers, 22 S. Rolli, 54 R. Roser, 15 M. Rossi, 52 F. Rubbo, 15 F. Ruffini, 44 A. Ruiz, 9 J. Russ, 10 V. Rusu, 15 A. Safonov, 51 W.K. Sakumoto, 47 Y. Sakurai, 56 L. Santi, 52 L. Sartori, 44 K. Sato, 53 V. Saveliev, 42 A. Savoy-Navarre, 42 P. Schlabach, 15 A. Schmidt, 24 E.E. Schmidt, 15 M.P. Schmidt, 59 M. Schmitt, 36 T. Schwarz, 7 L. Scodellaro, 9 A. Scribano, 44 F. Scru, 44 A. Sedov, 46 S. Seidel, 35 Y. Seiya, 39 A. Semenov, 13 F. Sforza, 44 A. Sfyrla, 22 S.Z. Shalhout, 7 T. Shears, 27 P.F. Shepard, 15 M. Shimojima, 53 S. Shiraiishi, 11 M. Shochet, 11 I. Shreyber, 34 A. Simonenko, 13 P. Sinervo, 31 A. Sissakian, 13 K. Sliwa, 54 J.R. Smith, 7 F.D. Snider, 15 A. Soha, 15 S. Somalwar, 50 V. Sorin, 4 P. Squillacioti, 15 M. Stancari, 15 M. Stenitzki, 59 R. St. Denis, 19 B. Stelzer, 31 O. Stelzer-Chilton, 31 D. Stentz, 35 J. Strologas, 35 G.L. Strycker, 32 Y. Sudo, 53 A. Sukhanov, 16 I. Suslov, 13 K. Takemasa, 53 Y. Takeuchi, 56 J. Tang, 11 M. Tescio, 32 P.K. Teng, 1 J. Thom, 15 J. Thome, 19 A.A. Thompson, 72 E. Thomson, 43 P. Tito-Guzmán, 29 S. Tkaczyk, 15 D. Toback, 51 S. Tokar, 12 K. Tollefson, 33 T. Tomura, 53 D. Tonelli, 15 S. Torre, 17 D. Torretta, 13 P. Totaro, 52 M. Trovato, 44 Y. Tu, 43 F. Ukegawa, 53 S. Uozumi, 25 A. Varganov, 32 F. Vázquez, 16 G. Velev, 15 C. Vellidis, 3 M. Vidal, 29 I. Vila, 9 R. Vilar, 9 M. Vogel, 35 G. Volpi, 44 P. Wagner, 43 R.L. Wagner, 15 T. Wakisaka, 39 R. Wallny, 8 S.M. Wang, 1 A. Warburton, 31 D. Waters, 28 M. Weinberger, 51 W.C. Wester III, 15 B. Whitehouse, 34 D. Whiteson, 43 A.B. Wicklund, 6 E. Wicklund, 15 S. Wilbur, 11 F. Wick, 24 H.H. Williams, 43 J.S. Wilson, 37 P. Wilson, 15 B.L. Winer, 37 P. Wittich, 19 S. Wolbers, 13 H. Wolfe, 37 T. Wright, 32 X. Wu, 18 Z. Wu, 5 K. Yamamoto, 39 J. Yamaoka, 14 T. Yang, 15 U.K. Yang, 11 Y.C. Yang, 25 W.-M. Yao, 20 G.P. Yeh, 15 K. Yi, 15 J. Yoh, 15 K. Yorita, 56 T. Yoshida, 39 G.B. Yu, 14 I. Yu, 25 S.S. Yu, 15 J.C. Yun, 15 A. Zanetti, 52 Y. Zeng, 14 and S. Zucchelli 16 (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 Física d’Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain
5 Baylor University, Waco, Texas 76798, USA
6 Istituto Nazionale di Fisica Nucleare Bologna, Italy
7 University of Bologna, I-40127 Bologna, Italy
8 University of California, Davis, Davis, California 95616, USA
9 University of California, Los Angeles, Los Angeles, California 90024, USA
10 Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain
11 Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
12 Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia
13 Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
14 Duke University, Durham, North Carolina 27708, USA
15 Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
16 University of Florida, Gainesville, Florida 32611, USA
17 Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy
18 University of Geneva, CH-1211 Geneva 4, Switzerland
19 Glasgow University, Glasgow G12 8QQ, United Kingdom
20 Harvard University, Cambridge, Massachusetts 02138, USA
21 Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland
22 University of Illinois, Urbana, Illinois 61801, USA
23 The Johns Hopkins University, Baltimore, Maryland 21218, USA
24 Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany
25 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; Chonbuk National University, Jeonju 561-756, Korea
26 Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
27 University of Liverpool, Liverpool L69 7ZE, United Kingdom
28 University College London, London WC1E 6BT, United Kingdom
29 Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
30 Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
31 Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3
32 University of Michigan, Ann Arbor, Michigan 48109, USA
33 Michigan State University, East Lansing, Michigan 48824, USA
34 Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
35 University of New Mexico, Albuquerque, New Mexico 87131, USA
36 Northwestern University, Evanston, Illinois 60208, USA
37 The Ohio State University, Columbus, Ohio 43210, USA
38 Okayama University, Okayama 700-8530, Japan
39 Osaka City University, Osaka 588, Japan
40 University of Oxford, Oxford OX1 3RH, United Kingdom
41 Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, University of Padova, I-35131 Padova, Italy
42 LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
43 University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
44 Istituto Nazionale di Fisica Nucleare Pisa, University of Pisa, University of Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
45 University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
46 Purdue University, West Lafayette, Indiana 47907, USA
47 University of Rochester, Rochester, New York 14627, USA
48 The Rockefeller University, New York, New York 10021, USA
49 “Sapienza” Università di Roma, I-00185 Roma, Italy
50 Rutgers University, Piscataway, New Jersey 08855, USA
51 Texas A&M University, College Station, Texas 77843, USA
52 Istituto Nazionale di Fisica Nucleare Trieste/Udine, University of Trieste/Udine, I-34100 Trieste, I-33100 Udine, Italy
53 University of Tsukuba, Tsukuba, Ibaraki 305, Japan
54 Tufts University, Medford, Massachusetts 02155, USA
55 University of Virginia, Charlottesville, Virginia 22906, USA
56 Waseda University, Tokyo 169, Japan
57 Wayne State University, Detroit, Michigan 48201, USA
58 University of Wisconsin, Madison, Wisconsin 53706, USA
59 Yale University, New Haven, Connecticut 06520, USA
60 University of Virginia, Charlottesville, VA 22906, USA
The $t\bar{t}$ spin correlation at production is a fundamental prediction of QCD and a potentially incisive test of new physics coupled to top quarks. We measure the $t\bar{t}$ spin state in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 1001 candidate events in the lepton plus jets decay channel reconstructed in the CDF II detector. In the helicity basis, for a top-quark mass of 172.5 GeV/c$^2$, we find a spin correlation coefficient $\kappa = 0.60 \pm 0.50$ (stat) $\pm 0.16$ (sys), consistent with the QCD prediction, $\kappa \approx 0.40$.

PACS numbers: 12.38.Qk, 14.65.Ha

In quark-pair production by the strong interaction, the quark spins are entangled according to the short distance dynamics of quantum chromodynamics (QCD) [1]. The spin state is observable in angular correlations among the quark decay products induced by the V-A (Vector minus Axial-vector) nature of the weak interaction but is typically destroyed by the depolarizing effects of hadronization before the decay can proceed. The top quark is an exception to this rule. Because of its large mass, the top-quark lifetime is shorter than the fragmentation timescale, cutting off the long distance QCD effects and transmitting the $t\bar{t}$ production configuration to the final state. Measurement of the $t\bar{t}$ spin configuration is a first look at a bare-quark pair at production. The measurement tests the fundamental predictions of QCD [1-5] and could be a sensitive discriminant of new physics coupled to top quarks [6, 7]. For example, a $t\bar{t}$ resonance appearing as an excess in the $t\bar{t}$ invariant-mass spectrum can be verified as a Kaluza-Klein graviton through measurement of the spin correlation as described in Ref. [7].

Because final state charged leptons have the strongest correlation to the top-quark spin, the $t\bar{t}$ spin correlation is usually discussed in terms of the dilepton final state $t\bar{t} \to (W^+ b)(W^- \bar{b}) \to (\ell \nu)(\ell' \bar{\nu})b\bar{b}$ [4]. This mode suffers from a small branching ratio and poor definition of the top-quark kinematics due to the presence of two undetectable neutrinos. A previous measurement of the $t\bar{t}$ spin correlation was limited to a small sample of just six events in this mode [8].

We report on a new measurement of the $t\bar{t}$ spin correlation in $p\bar{p}$ collisions at 1.96 TeV with a data sample corresponding to an integrated luminosity of 4.3 fb$^{-1}$ collected with the CDF II detector at the Fermilab Tevatron. We measure the spin correlation of pair-produced quarks for the first time in the lepton plus jets decay topology, $t\bar{t} \to (W^+ b)(W^- \bar{b}) \to (u\bar{d}b)(\ell\bar{\nu})$ or $t\bar{t} \to (W^+ b)(W^- \bar{b}) \to (\ell\nu)(u\bar{d}b)$ [9]. In this decay mode, we take advantage of a large branching ratio compared to the dilepton channel and the well-constrained $t\bar{t}$ kinematics in the lepton plus jets final state with only one neutrino. The measurement relies critically on a new technique for identifying the final state down-type quark ($d$ or $s$), which has the same spin-analyzing power as a charged lepton. We expect the spin correlation measurement to show the dominance of $t\bar{t}$ production via the $J=1$ $q\bar{q}$ annihilation channel that occurs in $\sim 85\%$ of $p\bar{p}$ collisions at the Tevatron [10].

We work in the helicity basis, where the spin-quantization axis is defined as the direction of motion of the $t$ (or $\bar{t}$) quark in the $t\bar{t}$ rest frame. There are other quantization axes which predict a larger value for the spin correlation [8], but they do not provide any significant increase in the statistical sensitivity of our approach, so we work with the simpler helicity basis. A quark is called right-handed ($t_R$)/left-handed ($t_L$) if its spin is oriented along/opposite to its direction.
of motion. In the $t\bar{t}$ rest frame the quarks move back-to-back; thus the same-spin states with $J=1$ are those with opposite helicity: $t_Ll_R$ and $t_Rl_L$. Near the energy threshold for $t\bar{t}$ production, the opposite-helicity fraction is predicted in the standard model (SM) to be $\sim 67\%$ for $t\bar{t}$ production via $q\bar{q}$ annihilation, while for top quarks with large momenta compared to the top-quark mass, helicity is approximately conserved and this fraction rises to $\sim 100\%$ \cite{1,2}. Integrating over all top-quark momenta according to the parton distribution functions and adding the small ($\sim 15\%$) $J = 0$ contribution from gluon-gluon fusion processes, we expect to find an opposite-helicity fraction \cite{1,2}:

$$F_{OH} = \frac{\sigma(t_Rl_L) + \sigma(t_Ll_R)}{\sigma(t_Rl_R) + \sigma(t_Ll_L) + \sigma(t_Rl_L) + \sigma(t_Ll_R)} \approx 0.70.$$  (1)

$F_{OH}$ is simply related to the spin correlation coefficient $\kappa$ that measures the fractional difference between the number of events in which the top-quark spins are aligned and the number of events in which they have opposite directions: $\kappa = 2F_{OH} - 1$. We thus expect $\kappa \approx 0.40$ \cite{1,2}, while for uncorrelated spins, $\kappa = 0.0$ and $F_{OH} = 0.5$.

In top-quark decays in the SM the V-A couplings fix the angular distributions of the decay products according to the polarization of the parent top quark via

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 \pm A_i \cos \theta_i),$$  (2)

where the positive/negative sign is used for right-handed/left-handed quarks, and the helicity angle $\theta_i$ is defined as the angle between the spin-quantization direction and the momentum of the decay particle in the rest frame of its parent top quark. In the V-A weak decay, the spin-analyzing-power coefficient $A_i$ is equal to +1.0 for the charged lepton or down-type quark, -0.41 for the bottom quark, and -0.31 for the neutrino or up-type quark, with the signs reversed for antitop-quark decays \cite{3}. The $t\bar{t}$ spin correlation connects the daughter helicity angles on each side of the decay. The differential cross-section in these variables is

$$\frac{1}{\sigma} \frac{d^2\sigma}{d(cos\theta_i)d(cos\theta_j)} = \frac{1 + \kappa A_i A_j \cos \theta_i \cos \theta_j}{4},$$  (3)

where $i$ and $j$ refer to top-quark and antitop-quark decay products respectively \cite{3}.

For each of the four possible $t\bar{t}$ helicity states, we create model templates for the distributions of $\cos \theta_i \cos \theta_d$ and $\cos \theta_t \cos \theta_b$, where the charged lepton $l$ is a decay product from one top quark in the pair and the quarks $d$ and $b$ are decay products from the other quark. We then find the relative normalization of these model templates that gives the best fit to a two-dimensional distribution of these variables in the data. The model templates account for all acceptance effects and dilutions due to event reconstruction, so that the parton-level value of $F_{OH}$ follows directly from the template fit to the data.

CDF II \cite{11} is a general purpose, azimuthally and forward-backward symmetric detector. Charged-particle directions and momenta are measured with a silicon tracker \cite{12} and a drift chamber \cite{13} in a 1.4 T solenoidal magnetic field. Electromagnetic and hadronic calorimeters \cite{14} are located beyond the solenoid and allow for jet and missing $E_T$ reconstruction. Beyond the calorimeter, muon chambers \cite{15} provide coverage for the pseudorapidity range $|\eta| \leq 1.0$. We use a cylindrical coordinate system with its origin at the center of the detector and the $z$ axis along the proton direction \cite{16}.

Lepton plus jets events are selected by requiring one electron or muon with transverse momentum of at least 20 GeV/c and $|\eta| < 1.0$, missing transverse energy of at least 20 GeV, and four or more jets with transverse energy of at least 20 GeV and $|\eta| < 2.0$, at least one of which must be tagged as a $b$ jet by the presence of a displaced secondary vertex \cite{17}. This selection yields 1001 total candidate events, 224 of which have two tagged $b$ jets.

Non-$t\bar{t}$ backgrounds are well-constrained by precision $t\bar{t}$ cross-section measurements \cite{18}, with a predicted total of $215 \pm 48$ background events. Non-$t\bar{t}$ models are checked against background-enriched sidebands with no tagged $b$ jets and are found to give very good representations of the normalizations and kinematics in all variables, including lepton and jet energies and angular distributions.

The helicity angles are determined in a complete reconstruction of the $t\bar{t}$ kinematics in $t\bar{t} \rightarrow$
\( (Wb)(Wb) \rightarrow (\ell \nu b)(udb) \), where we constrain 
\( M(\ell t) = M(ud) = 80.4 \text{ GeV}/c^2 \), the mass of the 
W boson, and \( M(\ell vb) = M(ubd) = 172.5 \text{ GeV}/c^2 \), the top-quark mass, and require any 
tagged b jets to be identified with b partons. The 
constraints were chosen to be close to the world 
averages in Ref. [19]. Each of the 24 possible 
jet-to-parton assignments is evaluated using a \( \chi^2 \) 
comparison to the four possible top-quark pair helic-
ity states: \( \bar{t}L, \bar{t}R, tL, tR \), and \( tLtR \). QCD 
interactions respect both the parity symmetry \( (P) \) and the combined symmetry of parity and 
charge conjugation \( (CP) \). Because \( CP \) transforms 
\( tLtR \rightarrow tLtL \), we can define the same-
helicity (SH) model template shape to be the 
symmetric sum of \( \sigma(tLtR) + \sigma(tLtL) \). Since \( P \) 
transforms \( tLtL \rightarrow tLtR \), we let the opposite-
helicity (OH) model template shape be the 
symmetric sum of \( \sigma(tLtL) + \sigma(tLtR) \).

Figure 1 compares the SH and OH model tem-
plate models created with a customized version 
of the HERWIG event generation software package 
[21] that implements the angular distribution of 
Eq. 2 for the charged lepton or down-
type quark, with a tunable choice of right- or 
left-handed top quarks, and preserves all the 
other expected spin correlations [22]. We cre-
ate four different simulated samples, corresponding 
to the four possible top-quark-pair helicity states: 
\( tLtR, tLtL, tLtL, \) and \( tLtR \). QCD 
interactions respect both the parity symmetry \( (P) \) and the combined symmetry of parity and 
charge conjugation \( (CP) \). Because \( CP \) transforms 
\( tLtR \rightarrow tLtL \), we can define the same-
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symmetric sum of \( \sigma(tLtR) + \sigma(tLtL) \). Since \( P \) 
transforms \( tLtL \rightarrow tLtR \), we let the opposite-
helicity (OH) model template shape be the 
symmetric sum of \( \sigma(tLtL) + \sigma(tLtR) \).

Additional contributions to the uncertainty 
result from incomplete knowledge of the back-
ground size and shape, of the exact detector response, and of the parton distribution functions (PDF), and are estimated by performing the measurement in simulated samples with reasonable variations in the model assumptions. These systematic uncertainties are shown in Table I. The largest uncertainty, generator dependence, results from small biases seen when testing with simulated samples created using a range of event generation software packages, including HERWIG [21], PYTHIA [23], ALPGEN [24], and MADEVENT [25]. Other significant contributions come from the uncertainty of the jet energy scale (JES) during event reconstruction and uncertainty in the amount of initial and final state radiation (ISR/FSR) in our observed $tt$ events. The small variation of $F_{OH}$ with the assumed value of the top-quark mass is not included in our systematic uncertainty; our measurement assumes a mass of 172.5 GeV/$c^2$ for the top quark.

The final result of our fit to the two-dimensional distribution $\cos \theta_l \cos \theta_d$ vs. $\cos \theta_l \cos \theta_b$ is shown in Fig. 2. This figure shows one-dimensional distributions of both variables, with our data being compared to the sum of the background model, same-helicity model, and opposite-helicity model, with the model normalizations determined by our fit result. Assuming the top-quark mass is 172.5 GeV/$c^2$, we find an opposite-helicity fraction of $F_{OH} = 0.80 \pm 0.25 \text{ (stat)} \pm 0.08 \text{ (syst)}$.

Converting this to the spin correlation coefficient, using $\kappa = 2F_{OH} - 1$, yields $\kappa = 0.60 \pm 0.50 \text{ (stat)} \pm 0.16 \text{ (syst)}$.

This first measurement of the top quark-pair spin correlation in the lepton plus jets decay channel agrees well with the theoretical prediction of $\kappa \approx 0.40$ [1,3], although the statistical uncertainty is still large. Simulated experiments with larger datasets indicate that if the Tevatron dataset reaches 15 fb$^{-1}$ before the end of the Tevatron lifetime, the expected statistical uncertainty on $\kappa$ would be reduced to 0.26. This technique can thus be applied in future measurements with larger datasets collected at the Tevatron and LHC to constrain the $tt$ production spin structure or to connect with other anomalies that may show up in the reconstructable $tt$ kinematics of the lepton plus jet sample.

We thank the Fermilab staff and the technical

\begin{itemize}
\item \textbf{Table I: Systematic Uncertainties on } $F_{OH}$
\item \textbf{Systematic Uncertainty}
\item \textbf{Generator dependence} 0.060
\item \textbf{JES} 0.042
\item \textbf{ISR/FSR} 0.030
\item \textbf{Background shape} 0.023
\item \textbf{Color reconnection} 0.009
\item \textbf{PDF} 0.007
\item \textbf{Parton shower} 0.006
\item \textbf{Background size} 0.002
\item \textbf{Total uncertainty} 0.083
\end{itemize}

\begin{figure}
\begin{center}
\includegraphics[width=0.8\textwidth]{fig2}
\end{center}
\caption{Distribution of the $\cos \theta_l \cos \theta_d$ and $\cos \theta_l \cos \theta_b$ variables in data compared to the sum of our background model, the same-helicity model template, and the opposite-helicity model template. The relative normalizations of the model distributions are determined by our fit result.}
\end{figure}
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 National 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 World Class University Program, the National Research Foundation of Korea; 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 Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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