Search for New T' Particles in Final States with Large Jet Multiplicities and Missing Transverse Energy in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[22] B. Álvarez González,[10,x] S. Amerio,[42a] D. Amidei,[33] A. Anastassov,[37] A. Annovi,[18] J. Antos,[13] G. Apollinari,[16] J. A. Appel,[16] A. Apresyan,[47] T. Arisawa,[57] A. Artikov,[14] J. Asaadi,[52] W. Ashmanskas,[16] B. Auerbach,[60] A. Aurisano,[52] F. Azfar,[41] W. Badgett,[16] A. Barbaro-Galtieri,[27] V. E. Barnes,[47] B. A. Barnett,[24] P. Barria,[45c,45a] P. Bartos,[13] M. Bauce,[42b,42a] G. Bauer,[31] F. Bedeschi,[a61a] D. Beecher,[29] S. Behari,[24] G. Bellettini,[61b,a61a] J. Bellinger,[59] D. Benjamin,[15] M. Bentivegna,[50b,50a] A. Beretvas,[16] A. Bhatti,[49] M. Binkley,[16,a] D. Bisello,[42b,42a] I. Bizjak,[29,bb] K. R. Bland,[5] B. Blumenfeld,[24] A. Bocci,[15] A. Bodek,[48] D. Bortoletto,[47] J. Boudreau,[46] A. Boveia,[12] B. Brau,[16,b] L. Brigliadori,[6a,6b] A. Brisuda,[13] C. Bromberg,[34] E. Brucken,[22] M. Bucciantonio,[45b,45a] J. Budagov,[14] H. S. Budd,[48] S. Budd,[23] K. Burkett,[16] G. Busetto,[42b,42a] P. Bussey,[20] A. Buzatu,[32] C. Calancha,[30] S. Camarda,[4] M. Campanelli,[34] M. Campbell,[33] F. Canelli,[12,16] A. Canepa,[44] B. Carls,[23] D. Carlsmith,[59] R. Carosi,[45a] S. Carrillo,[17,l] S. Carron,[16] B. Casal,[10] M. Casarsa,[16] A. Castro,[6a,6b] P. Catastini,[16] D. Cauz,[53a] V. Cavaliere,[45b,45a] M. Cavalli-Sforza,[4] A. Cerri,[27,g] L. Cerrito,[29,r] Y. C. Chen,[1] M. Chertok,[7] G. Chiarelli,[45a] G. Chlachidze,[16] F. Chlebana,[16] K. Cho,[26] D. Chokheli,[14] J. P. Chou,[21] W. H. Chung,[59] Y. S. Chung,[48] C. I. Ciobanu,[43] M. A. Ciocci,[45c,45a] A. Clark,[19] G. Compostella,[42b,42a] M. E. Convery,[16] J. Conway,[7] M. Corbo,[43] M. Cordelli,[18] C. A. Cox,[7] D. J. Cox,[7] F. Crescioli,[45b,45a] C. Cuenca Almenar,[60] J. Cuevas,[10,x] R. Culbertson,[16] D. Dagenhart,[16] N. d'Ascenzo,[43,v] M. Datta,[16] P. de Barbaro,[48] S. De Cecco,[50a] G. De Lorenzo,[4] M. Dell'Orso,[45b,45a] C. Deluca,[4] L. Demortier,[49] J. Deng,[15,d] M. Deninno,[6a] F. Devoto,[22] M. d'Errico,[42b,42a] A. Di Canto,[45b,45a] B. Di Ruzza,[45a] J. R. Dittmann,[5] M. D'Onofrio,[28] S. Donati,[45b,45a] P. Dong,[16] M. Dorigo,[53a] T. Dorigo,[42a] K. Ebina,[57] A. Elagin,[52] A. Eppig,[33] R. Erbacher,[7] D. Errede,[23] S. Errede,[23] N. Ershaidat,[43,aa] R. Eusebi,[52] H. C. Fang,[27] S. Farrington,[41] M. Feindt,[25] J. P. Fernandez,[30] C. Ferrazza,[45d,45a] R. Field,[17] G. Flanagan,[47,t] R. Forrest,[7] M. J. Frank,[5] M. Franklin,[21] J. C. Freeman,[16] Y. Funakoshi,[57] I. Furic,[17] M. Gallinaro,[49] J. Galyardt,[11] J. E. Garcia,[19] A. F. Garfinkel,[47] P. Garosi,[45c,45a] H. Gerberich,[23] E. Gerchtein,[16] S. Giagu,[50b,50a] V. Giakoumopoulou,[3] P. Giannetti,[45a] K. Gibson,[46] C. M. Ginsburg,[16] N. Giokaris,[3] P. Giromini,[18] M. Giunta,[45a] G. Giurgiu,[24] V. Glagolev,[14] D. Glenzinski,[16] M. Gold,[36] D. Goldin,[52] N. Goldschmidt,[17] A. Golossanov,[16] G. Gomez,[10] G. Gomez-Ceballos,[31] M. Goncharov,[31] O. González,[30] I. Gorelov,[36] A. T. Goshaw,[15] K. Goulianos,[49] S. Grinstein,[4] C. Grosso-Pilcher,[12] R. C. Group,[56] J. Guimaraes da Costa,[21] Z. Gunay-Unalan,[34] C. Haber,[27] S. R. Hahn,[16] E. Halkiadakis,[51] A. Hamaguchi,[40] J. Y. Han,[48] F. Happacher,[18] K. Hara,[54] D. Hare,[51] M. Hare,[55] R. F. Harr,[58] K. Hatakeyama,[5] C. Hays,[41] M. Heck,[25] J. Heinrich,[44] M. Herndon,[59] S. Hewamanage,[5] D. Hidas,[51] A. Hocker,[16] W. Hopkins,[16,h] D. Horn,[25] S. Hou,[1] R. E. Hughes,[38] M. Hurwitz,[12] U. Husemann,[60] N. Hussain,[32] M. Hussein,[34] J. Huston,[34] G. Introzzi,[45a] M. Iori,[50b,50a] A. Ivanov,[7,p] E. James,[16] D. Jang,[11] B. Jayatilaka,[15] E. J. Jeon,[26] M. K. Jha,[6a] S. Jindariani,[16] W. Johnson,[7] M. Jones,[47] K. K. Joo,[26] S. Y. Jun,[11] T. R. Junk,[16] T. Kamon,[52] P. E. Karchin,[58] Y. Kato,[40,o] W. Ketchum,[12] J. Keung,[44] V. Khotilovich,[52] B. Kilminster,[16] D. H. Kim,[26] H. S. Kim,[26] H. W. Kim,[26] J. E. Kim,[26] M. J. Kim,[18] S. B. Kim,[26] S. H. Kim,[54] Y. K. Kim,[12] N. Kimura,[57] M. Kirby,[16] S. Klimenko,[17] K. Kondo,[57] D. J. Kong,[26] J. Konigsberg,[17] A. V. Kotwal,[15] M. Kreps,[25] J. Kroll,[44] D. Krop,[12] N. Krumnack,[5,m] M. Kruse,[15] V. Krutelyov,[52,e] T. Kuhr,[25] M. Kurata,[54] S. Kwang,[12] A. T. Laasanen,[47] S. Lami,[45a] S. Lammel,[16] M. Lancaster,[29] R. L. Lander,[7] K. Lannon,[38,w] A. Lath,[51] G. Latino,[45b,45a] T. LeCompte,[2] E. Lee,[52] H. S. Lee,[12] J. S. Lee,[26] S. W. Lee,[52,y] S. Leo,[45b,45a] S. Leone,[45a] J. D. Lewis,[16] A. Limosani,[15,s] C.-J. Lin,[27] J. Linacre,[41] M. Lindgren,[16] E. Lipeles,[44] A. Lister,[19] D. O. Litvintsev,[16] C. Liu,[46] Q. Liu,[47] T. Liu,[16] S. Lockwitz,[60] N. S. Lockyer,[44] A. Loginov,[60] D. Lucchesi,[42b,42a] J. Lueck,[25] P. Lujan,[27] P. Lukens,[16] G. Lungu,[49] J. Lys,[27] R. Lysak,[13] R. Madrak,[16] K. Maeshima,[16] K. Makhoul,[31] P. Maksimovic,[24] S. Malik,[49] G. Manca,[28,c] A. Manousakis-Katsikakis,[3] F. Margaroli,[47] C. Marino,[25] M. Martínez,[4] R. Martínez-Ballarín,[30] P. Mastrandrea,[50a] M. Mathis,[24] M. E. Mattson,[58] P. Mazzanti,[6a] K. S. McFarland,[48] P. McIntyre,[52] R. McNulty,[28,j] A. Mehta,[28] P. Mehtala,[22] A. Menzione,[45a] C. Mesropian,[49] T. Miao,[16] D. Mietlicki,[33] A. Mitra,[1] H. Miyake,[54] S. Moed,[21] N. Moggi,[6a] M. N. Mondragon,[16,l] C. S. Moon,[26] R. Moore,[16] M. J. Morello,[16] J. Morlock,[25] P. Movilla Fernandez,[16] A. Mukherjee,[16] Th. Muller,[25] P. Murat,[16] M. Mussini,[6a,6b] J. Nachtman,[16,n] Y. Nagai,[54] J. Naganoma,[57] I. Nakano,[39] A. Napier,[55] J. Nett,[52] C. Neu,[56] M. S. Neubauer,[23] J. Nielsen,[27,f] L. Nodulman,[2] O. Norniella,[23] E. Nurse,[29] L. Oakes,[41] S. H. Oh,[15] Y. D. Oh,[26] I. Oksuzian,[56] T. Okusawa,[40] R. Orava,[22] L. Ortolan,[4] S. Pagan Griso,[42b,42a] C. Pagliarone,[53a] E. Palencia,[10,g] V. Papadimitriou,[16] A. A. Paramonov,[2] J. Patrick,[16] G. Pauletta,[53b,53a] M. Paulini,[11] C. Paus,[31] D. E. Pellett,[7] A. Penzo,[53a] T. J. Phillips,[15] G. Piacentino,[45a] E. Pianori,[44] J. Pilot,[38] K. Pitts,[23] C. Plager,[9] L. Pondrom,[59] K. Potamianos,[47] O. Poukhov,[14,a] F. Prokoshin,[14,z] A. Pronko,[16] F. Ptohos,[18,i] E. Pueschel,[11] G. Punzi,[45b,45a] J. Pursley,[59] A. Rahaman,[46] V. Ramakrishnan,[59] N. Ranjan,[47] K. Rao,[8]

I. Redondo,[30] P. Renton,[41] M. Rescigno,[50a] F. Rimondi,[6a,6b] L. Ristori,[45a,16] A. Robson,[20] T. Rodrigo,[10] T. Rodriguez,[44] E. Rogers,[23] S. Rolli,[55] R. Roser,[16] M. Rossi,[53a] F. Rubbo,[16] F. Ruffini,[45c,45a] A. Ruiz,[10] J. Russ,[11] V. Rusu,[16] A. Safonov,[52] W. K. Sakumoto,[48] Y. Sakurai,[57] L. Santi,[53b,53a] L. Sartori,[45a] K. Sato,[54] V. Saveliev,[43,v] A. Savoy-Navarro,[43] P. Schlabach,[16] A. Schmidt,[25] E. E. Schmidt,[16] M. P. Schmidt,[60,a] M. Schmitt,[37] T. Schwarz,[7] L. Scodellaro,[10] A. Scribano,[45c,45a] F. Scuri,[45a] A. Sedov,[47] S. Seidel,[36] Y. Seiya,[40] A. Semenov,[14] F. Sforza,[45b,45a] A. Sfyrla,[23] S. Z. Shalhout,[7] T. Shears,[28] P. F. Shepard,[46] M. Shimojima,[54,u] S. Shiraishi,[12] M. Shochet,[12] I. Shreyber,[35] A. Simonenko,[14] P. Sinervo,[32] A. Sissakian,[14,a] K. Sliwa,[55] J. R. Smith,[7] F. D. Snider,[16] A. Soha,[16] S. Somalwar,[51] V. Sorin,[4] P. Squillacioti,[16] M. Stancari,[16] M. Stanitzki,[60] R. St. Denis,[20] B. Stelzer,[32] O. Stelzer-Chilton,[32] D. Stentz,[37] J. Strologas,[36] G. L. Strycker,[33] Y. Sudo,[54] A. Sukhanov,[17] I. Suslov,[14] K. Takemasa,[54] Y. Takeuchi,[54] J. Tang,[12] M. Tecchio,[33] P. K. Teng,[1] J. Thom,[16,h] J. Thome,[11] G. A. Thompson,[23] E. Thomson,[44] P. Ttito-Guzmán,[30] S. Tkaczyk,[16] D. Toback,[52] S. Tokar,[13] K. Tollefson,[34] T. Tomura,[54] D. Tonelli,[16] S. Torre,[18] D. Torretta,[16] P. Totaro,[42a] M. Trovato,[45d,45a] Y. Tu,[44] F. Ukegawa,[54] S. Uozumi,[26] A. Varganov,[33] F. Vázquez,[17,l] G. Velev,[16] C. Vellidis,[3] M. Vidal,[30] I. Vila,[10] R. Vilar,[10] J. Vizán,[10] M. Vogel,[36] G. Volpi,[45b,45a] P. Wagner,[44] R. L. Wagner,[16] T. Wakisaka,[40] R. Wallny,[9] S. M. Wang,[1] A. Warburton,[32] D. Waters,[29] M. Weinberger,[52] W. C. Wester III,[16] B. Whitehouse,[55] D. Whiteson,[44,d] A. B. Wicklund,[2] E. Wicklund,[16] S. Wilbur,[12] F. Wick,[25] H. H. Williams,[44] J. S. Wilson,[38] P. Wilson,[16] B. L. Winer,[38] P. Wittich,[16,h] S. Wolbers,[16] H. Wolfe,[38] T. Wright,[33] X. Wu,[19] Z. Wu,[5] K. Yamamoto,[40] J. Yamaoka,[15] T. Yang,[16] U. K. Yang,[12,q] Y. C. Yang,[26] W.-M. Yao,[27] G. P. Yeh,[16] K. Yi,[16,n] J. Yoh,[16] K. Yorita,[57] T. Yoshida,[40,k] G. B. Yu,[15] I. Yu,[26] S. S. Yu,[16] J. C. Yun,[16] A. Zanetti,[53a] Y. Zeng,[15] and S. Zucchelli[6b,6a]

(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, ICREA, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[5]*Baylor University, Waco, Texas 76798, USA*
[6a]*Istituto Nazionale di Fisica Nucleare, I-40127 Bologna, Italy*
[6b]*University of Bologna, I-40127 Bologna, Italy*
[7]*University of California, Davis, Davis, California 95616, USA*
[8]*University of California, Irvine, Irvine, California 92697, USA*
[9]*University of California, Los Angeles, Los Angeles, California 90024, USA*
[10]*Instituto de Fisica de Cantabria, CSIC–University of Cantabria, 39005 Santander, Spain*
[11]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[12]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[13]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[14]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[15]*Duke University, Durham, North Carolina 27708, USA*
[16]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[17]*University of Florida, Gainesville, Florida 32611, USA*
[18]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[19]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[20]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[21]*Harvard University, Cambridge, Massachusetts 02138, USA*
[22]*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[23]*University of Illinois, Urbana, Illinois 61801, USA*
[24]*The Johns Hopkins University, Baltimore, Maryland 21218, USA*
[25]*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*
[26]*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*
[27]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[28]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[29]*University College London, London WC1E 6BT, United Kingdom*
[30]*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[31]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

[32]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
[33]University of Michigan, Ann Arbor, Michigan 48109, USA
[34]Michigan State University, East Lansing, Michigan 48824, USA
[35]Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
[36]University of New Mexico, Albuquerque, New Mexico 87131, USA
[37]Northwestern University, Evanston, Illinois 60208, USA
[38]The Ohio State University, Columbus, Ohio 43210, USA
[39]Okayama University, Okayama 700-8530, Japan
[40]Osaka City University, Osaka 588, Japan
[41]University of Oxford, Oxford OX1 3RH, United Kingdom
[42a]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, Italy
[42b]University of Padova, I-35131 Padova, Italy
[43]LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
[44]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[45a]Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy
[45b]University of Pisa, I-56127 Pisa, Italy
[45c]University of Siena, I-56127 Pisa, Italy
[45d]Scuola Normale Superiore, I-56127 Pisa, Italy
[46]University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
[47]Purdue University, West Lafayette, Indiana 47907, USA
[48]University of Rochester, Rochester, New York 14627, USA
[49]The Rockefeller University, New York, New York 10065, USA
[50a]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy
[50b]Sapienza Università di Roma, I-00185 Roma, Italy
[51]Rutgers University, Piscataway, New Jersey 08855, USA
[52]Texas A&M University, College Station, Texas 77843, USA
[53a]Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, Italy
[53b]University of Trieste/Udine, I-33100 Udine, Italy
[54]University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[55]Tufts University, Medford, Massachusetts 02155, USA
[56]University of Virginia, Charlottesville, Virginia 22906, USA
[57]Waseda University, Tokyo 169, Japan
[58]Wayne State University, Detroit, Michigan 48201, USA
[59]University of Wisconsin, Madison, Wisconsin 53706, USA
[60]Yale University, New Haven, Connecticut 06520, USA
[a61a]Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy
[61b]University of Pisa, I-56127 Pisa, Italy
(Received 20 July 2011; published 1 November 2011)

We present a search for a new particle T' decaying to a top quark via $T' \to t + X$, where X goes undetected. We use a data sample corresponding to 5.7 fb^{-1} of integrated luminosity of $p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV, collected at Fermilab Tevatron by the CDF II detector. Our search for pair production of T' is focused on the hadronic decay channel, $p\bar{p} \to T'\bar{T}' \to t\bar{t} + X\bar{X} \to bq\bar{q}\,\bar{b}\,q\bar{q} + X\bar{X}$. We interpret our results in terms of a model where T' is an exotic fourth generation quark and X is a dark matter particle. The data are consistent with standard model expectations. We set a limit on the generic production of $T'\bar{T}' \to t\bar{t} + X\bar{X}$, excluding the fourth generation exotic quarks T' at 95% confidence level up to $m_{T'} = 400\ \mathrm{GeV}/c^2$ for $m_X \leq 70\ \mathrm{GeV}/c^2$.

DOI: 10.1103/PhysRevLett.107.191803 PACS numbers: 14.65.Jk, 12.60.−i, 13.85.Rm, 14.80.−j

There are many hints, from astronomical observations and cosmological theories, for the existence of dark matter (DM) particles, which must be long lived on cosmological time scale [1]. The long lifetime of DM can be explained by the conservation of a charge of a new symmetry. Direct-detection experiments based on ultralow noise devices have recently obtained interesting results. The DAMA/LIBRA Collaboration [2], searching for annual modulation in the interaction rate due to Earth's motion through the DM galactic halo, has claimed a $\simeq 9\sigma$ observation of DM. The CoGeNT Collaboration has also reported evidence of DM [3]. If confirmed, these results would imply, unlike astronomical observations, that DM interactions with standard model (SM) particles are not only gravitational. DM interactions with SM particles could be allowed by weak interactions, or by connector particles carrying both dark and SM charges, so that they could be produced in colliders. The second hypothesis is favored in the case that DM particles have mass of a few GeV/c^2, as DAMA and CoGeNT results seems to indicate. In a recent model [4] the role of a connector particle is played by an exotic fourth generation T' quark, which is supposed to decay to a top quark and dark matter, $T' \to t + X$. The pair production of such exotic quarks and their subsequent decay has a collider signature consisting of top quark pairs ($t\bar{t}$) and missing transverse energy ($\not{E}_T$) [5] due to the invisible dark matter particles. These types of signals are of great interest as they also appear in other models containing DM candidates, such as scalar top quark production and their decay to top quarks and neutralinos [6] or top quarks and gravitinos [7], and in many other new physics scenarios such as little Higgs [8] and models where baryon and lepton numbers represent local gauge symmetries [9].

A first search for the $T'\bar{T}' \to t\bar{t} + X\bar{X}$ process has been performed in the semileptonic channel: $t\bar{t} + X\bar{X} \to bW\bar{b}W + X\bar{X} \to bl\nu\bar{b}q\bar{q} + X\bar{X}$ [10]. This Letter reports the first search for such a process in the all-hadronic $t\bar{t}$ decay channel, characterized by a larger branching ratio and a lower physics background rate. Events were recorded by CDF II [11], a general purpose detector designed to study collisions at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV. 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. Electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies, and drift chambers located outside the calorimeters detect muons. Jets are reconstructed in the calorimeter using the JETCLU [12] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space [13]. The detector response for all simulated samples is modeled by a detailed CDF detector simulation. Production of T' pairs and their subsequent decays to top quark pairs and two dark matter particles would appear as events with missing transverse energy from the two dark matter particles, and six jets from the two b quarks and the hadronic decays of the two W bosons. We model the production and decay of T' pairs with the MADGRAPH Monte Carlo (MC) generator [14], and normalize to the next-to-next-to-leading order (NNLO) cross-section calculation [15]. Additional radiation, hadronization and showering are described by PYTHIA [16].

We use a data sample corresponding to an integrated luminosity of $p\bar{p}$ collisions of 5.7 fb^{-1}, collected by requiring $\not{E}_T > 50$ GeV and two or more jets with transverse energy $E_T \geq 30$ GeV and $|\eta| \leq 2.4$. We then require $5 \leq N_{\text{jets}} \leq 10$, where N_{jets} is the number of jets, and where all jets satisfy the requirement $|\eta| \leq 2.4$. We also require the transverse energy E_T of the subleading jets, J_i, to be greater than 20 GeV for ($i = 3, 4, 5$) and 15 GeV for ($i > 5$). We veto events with at least one isolated electron or muon to suppress events with semileptonic $t\bar{t}$ decay. We refer to this sample as the preselection sample. At this stage of the event selection, multijet QCD background where $\not{E}_T$ arises from jet energy mismeasurement accounts for more than 95% of the expected backgrounds. The second dominant background is $t\bar{t}$ production. We model this process using PYTHIA with $m_t = 172.5$ GeV/c^2 [17], normalized to the next-to-leading order (NLO) cross section [18]. Associated production of W/Z boson and jets is also a significant background source. Samples of simulated W/Z + jets events with light- and heavy-flavor jets are generated using the ALPGEN [19] MC generator, interfaced with the parton shower model of PYTHIA. A matching scheme is applied to avoid double counting of partonic event configurations [20]. The W/Z + jets samples are normalized to the measured W and Z cross section [21]. Diboson and single top production are modeled using, respectively, PYTHIA and MADGRAPH, and normalized to NLO cross sections [21–24]. Because of the large production rate for QCD multijet events at a hadron collider and the statistics needed in order to describe this process adequately in an analysis looking for a very small signal, the Monte Carlo simulation of QCD multijet events is prohibitive. More importantly, the systematic uncertainties associated with the Monte Carlo simulation of QCD jet production are large. For these reasons, we estimate the QCD background solely from data. Similarly to $\vec{\not{E}}_T$, it is possible to define a missing transverse momentum $\vec{\not{p}}_T$ using the spectrometer as the negative vector sum of the charged particles momenta. $\vec{\not{E}}_T$ and $\vec{\not{p}}_T$ are correlated in magnitude and direction in events with undetected particles. In QCD multijet events $\vec{\not{E}}_T$ originates from the mismeasurement of a jet energy in the calorimeter, while $\vec{\not{p}}_T$ depends on fluctuations in the number of charged particles in a jet, so they are usually aligned or antialigned in dijet-like events like energetic QCD multijet events, as is shown in Fig. 1. QCD multijet events in which $\vec{\not{E}}_T$ and $\vec{\not{p}}_T$ are aligned or antialigned have the same kinematic characteristics, as we have verified studying QCD multijet samples with 2 and 3 jets [25]. We reject events with $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T) > \pi/2$, and use them to model QCD multijet events in the signal region $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T) < \pi/2$. To further suppress the QCD multijet background, we require the azimuthal distance between the directions of $\vec{\not{E}}_T$ and subleading jets, $\Delta\phi(\vec{\not{E}}_T, \vec{J}_i)$, to be greater than 0.4 for $i = 1, 2, 3$ and 0.2 for $i = 4, 5$. We also require $\not{p}_T > 20$ GeV and $\not{E}_T\text{sig} > 3$ GeV$^{1/2}$, where $\not{E}_T$sig is defined as the $\not{E}_T$ divided by the square root of the total energy collected in the calorimeter. Finally, we require $\sum_{\text{jets}} E_T^i > 220$ GeV to remove soft QCD events. All these cuts have been chosen to optimize the $S/\sqrt{(S+B)}$ figure of merit, where S and B are, respectively, the expected numbers of signal and

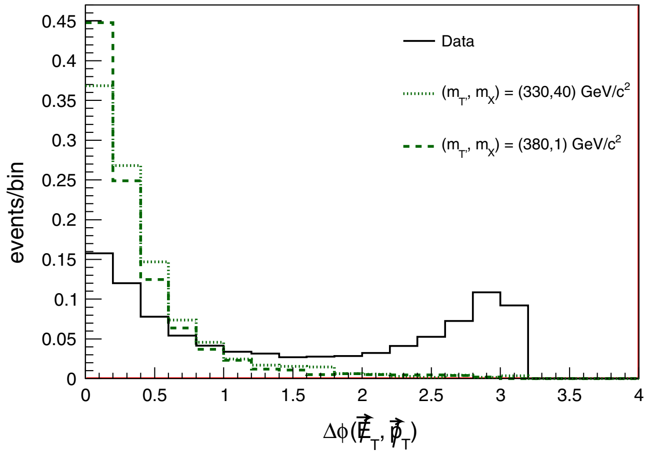

FIG. 1 (color online). Distribution of $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T)$ for the preselection data, and two scenarios with different values of $m_{T'}$ and m_X. All histograms are normalized to unit area.

background events. Table I shows the expected number of events in the signal region for SM backgrounds and for several signal hypothesis.

Inverting one of the event selection cuts, keeping others unchanged, allows us to define a signal-depleted control region. We use $\not{E}_T\mathrm{sig} < 3\ \mathrm{GeV}^{1/2}$, $N_{\mathrm{jets}} = 4$, and $\not{p}_T < 20$ GeV control regions to validate the overall background modeling. The normalization factor of the QCD background is given by the average ratio of QCD events that pass the $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T) < \pi/2$ cut to QCD events that fail the cut in these three control regions. Figure 2 shows good agreement of background modeling with data in these regions. We consider several sources of systematic uncertainties. The dominant components are the uncertainties on the QCD normalization factor, the jet energy scale (JES) [26], and the theoretical cross sections. We also take into account the differences of $t\bar{t}$ predicted rates using different hadron fragmentation models in the HERWIG [27]

TABLE I. Number of expected signal events for five benchmark scenarios compared to data and expected SM backgrounds.

$T'\bar{T}' \to t\bar{t}X\bar{X}$(hadronic) [GeV/$c^2$]	Events
$m_{T'}, m_X = 260, 80$	88.5 ± 11.9
$m_{T'}, m_X = 330, 100$	66.4 ± 8.9
$m_{T'}, m_X = 360, 100$	39.7 ± 5.3
$m_{T'}, m_X = 380, 1$	27.3 ± 3.7
$m_{T'}, m_X = 400, 1$	17.5 ± 2.3
QCD	745.4 ± 124.3
$t\bar{t}$	498.2 ± 66.8
W + jets	119.7 ± 48.4
Z + jets	39.4 ± 15.9
Diboson	17.9 ± 2.2
Single top	5.3 ± 0.8
Total background	1423 ± 150
Data	1507

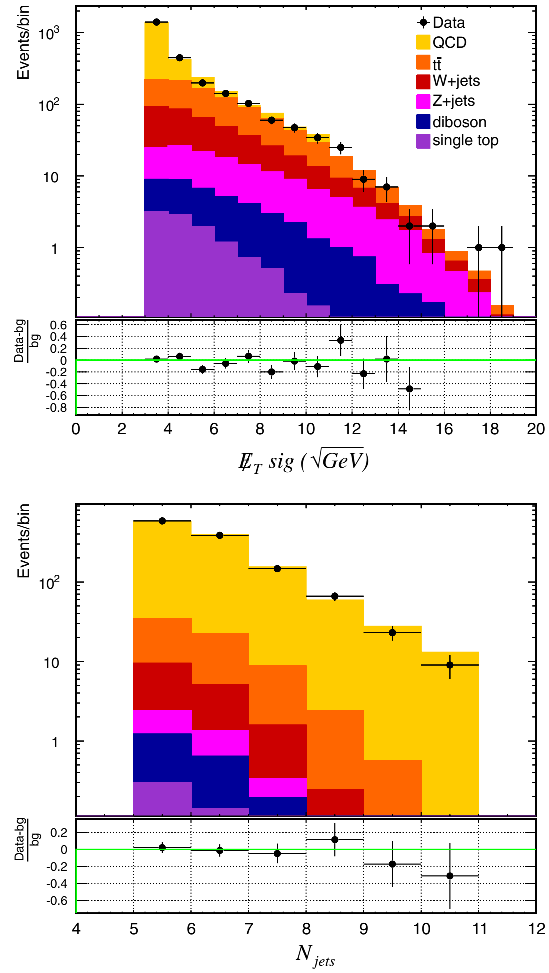

FIG. 2 (color online). Top plot shows the $\not{E}_T$sig distribution in events with four jets and large $\not{E}_T$. Bottom plot shows the N_{jets} distribution in event with $5 \le N_{\mathrm{jets}} \le 10$ and $\not{E}_T\mathrm{sig} < 3\sqrt{\mathrm{GeV}}$.

Monte Carlo program, and varying the initial or final state radiation and color reconnection effects [28]. The variation of the JES was found to significantly change the $\not{E}_T$sig distribution in addition to its normalization, and its variation is thus taken into account. Figure 3 shows the $\not{E}_T$sig distribution for expected signal events and SM backgrounds. The signal is expected to contribute significantly in the high tail of the $\not{E}_T$sig distribution. There is no evidence for the presence of $T' \to t + X$ events in the data. We calculate 95% C.L. upper limits on the $T' \to t + X$ cross section by performing a binned maximum-likelihood fit on the $\not{E}_T$sig distribution. The limits are calculated using a Bayesian likelihood method with a flat prior for the signal cross section, integrating over Gaussian priors for the systematic uncertainties. The results are shown in Table II. We convert the observed upper limits on the pair-production cross sections to an exclusion curve in mass parameters space $(m_{T'}, m_X)$. As shown in Fig. 4, a significant enhancement in sensitivity is obtained when comparing to the previous analysis in semileptonic channel.

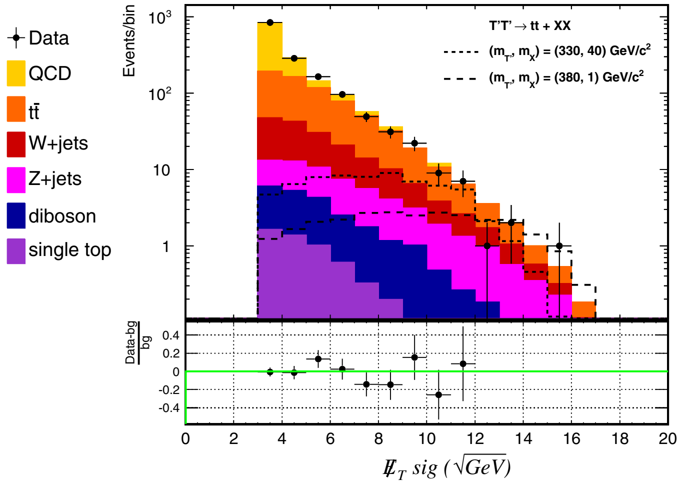

FIG. 3 (color online). $\not{E}_T$sig distributions for the standard model backgrounds, the observed data, and for two scenarios with different values of $m_{T'}$ and m_X.

In conclusion, we performed the first search for new physics in the $t\bar{t} + \not{E}_T \rightarrow b\bar{b}q\bar{q}q\bar{q} + \not{E}_T$ final state. Data are consistent with the background-only hypothesis, and we thus set a 95% C.L. upper limit on the production cross section for fermionic T' pairs decaying to top quarks and dark matter candidates X, increasing the existing mass exclusion range up to $m_{T'} = 400\ \text{GeV}/c^2$ for $m_X \leq 70\ \text{GeV}/c^2$. Finally, this study shows that the $b\bar{b}q\bar{q}q\bar{q} + \not{E}_T$ final state is the most sensitive to the generic production of top quarks plus dark matter candidates, and thus the most promising to probe the supersymmetric $\tilde{t} \rightarrow t + \chi/g$ scenarios at the LHC.

We thank Johan Alwall and Matteo Cacciari for useful discussions. We also thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean 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; the Academy of Finland; and the Australian Research Council (ARC).

TABLE II. Expected 95% C.L. upper limits on $T'T'$ production, where the uncertainty range covers 68% of the pseudoexperiments, and observed exclusion limits for representative signal points.

(mT', mX) GeV/c^2	$\sigma_{\text{expect95\%C.L.exclude}}$ (pb)	$\sigma_{\text{obs95\%C.L.exclude}}$ (pb)
(200, 40)	2.02 ± 0.65	1.90
(220, 40)	2.14 ± 0.75	3.00
(260, 1)	0.23 ± 0.08	0.18
(280, 1)	0.15 ± 0.05	0.12
(280, 40)	0.18 ± 0.07	0.15
(300, 1)	0.09 ± 0.03	0.09
(300, 80)	0.20 ± 0.06	0.16
(300, 100)	0.29 ± 0.09	0.38
(330, 1)	0.05 ± 0.02	0.03
(330, 100)	0.13 ± 0.04	0.18
(360, 1)	0.03 ± 0.01	0.02
(360, 100)	0.06 ± 0.02	0.04
(380, 100)	0.06 ± 0.02	0.05
(400, 1)	0.023 ± 0.008	0.016

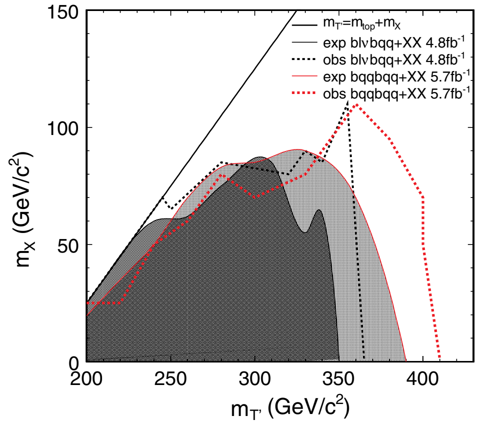

FIG. 4 (color online). Expected (exp) and observed (obs) 95% C.L. exclusion region in the $(m_{T'}, m_X)$ parameters space.

[a]Deceased.
[b]Visitor from University of Massachusetts Amherst, Amherst, MA 01003, USA.
[c]Visitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.
[d]Visitor from University of California Irvine, Irvine, CA 92697, USA.
[e]Visitor from University of California Santa Barbara, Santa Barbara, CA 93106, USA.
[f]Visitor from University of California Santa Cruz, Santa Cruz, CA 95064, USA.
[g]Visitor from CERN,CH-1211 Geneva, Switzerland.
[h]Visitor from Cornell University, Ithaca, NY 14853, USA.
[i]Visitor from University of Cyprus, Nicosia CY-1678, Cyprus.
[j]Visitor from University College Dublin, Dublin 4, Ireland.

[k]Visitor from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.
[l]Visitor from Universidad Iberoamericana, Mexico D.F., Mexico.
[m]Visitor from Iowa State University, Ames, IA 50011, USA.
[n]Visitor from University of Iowa, Iowa City, IA 52242, USA.
[o]Visitor from Kinki University, Higashi-Osaka City, Japan 577-8502.
[p]Visitor from Kansas State University, Manhattan, KS 66506, USA.
[q]Visitor from University of Manchester, Manchester M13 9PL, United Kingdom.
[r]Visitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.
[s]Visitor from University of Melbourne, Victoria 3010, Australia.
[t]Visitor from Muons, Inc., Batavia, IL 60510, USA.
[u]Visitor from Nagasaki Institute of Applied Science, Nagasaki, Japan.
[v]Visitor from National Research Nuclear University, Moscow, Russia.
[w]Visitor from University of Notre Dame, Notre Dame, IN 46556, USA.
[x]Visitor from Universidad de Oviedo, E-33007 Oviedo, Spain.
[y]Visitor from Texas Tech University, Lubbock, TX 79609, USA.
[z]Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.
[aa]Visitor from Yarmouk University, Irbid 211-63, Jordan.
[bb]On leave from J. Stefan Institute, Ljubljana, Slovenia.

[1] J. L. Feng, Annu. Rev. Astron. Astrophys. **48**, 495 (2010).
[2] R. Bernabei *et al.* (DAMA Collaboration), Eur. Phys. J. C **56**, 333 (2008).
[3] C. E. Aalseth *et al.* (CoGeNT Collaboration), Phys. Rev. Lett. **107**, 141301 (2011).
[4] J. Alwall, J. L. Feng, J. Kumar, and S. Su, Phys. Rev. D **81**, 114027 (2010).
[5] Missing transverse energy $\not{E}_T$ is defined as the magnitude of the vector $\vec{\not{E}}_T = -\sum_i E_T^i \vec{n}_i$, 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.
[6] J. Ellis and K. A. Olive, arXiv:1001.3651.
[7] Y. Kats and D. Shih, arXiv:1106.0030.
[8] H. C. Cheng and I. Low, J. High Energy Phys. 08 (2004) 061.
[9] P. Fileviez Perez and M. B. Wise, Phys. Rev. D **82**, 011901 (2010); **82**, 079901(E) (2010).
[10] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **106**, 191801 (2011).
[11] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005).
[12] F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **45**, 1448 (1992).
[13] 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 relative to the proton beam direction and ϕ is the azimuthal angle while $p_T = |p| \sin\theta$, $E_T = E \sin\theta$.
[14] J. Alwall *et al.*, J. High Energy Phys. 09 (2007) 028.
[15] M. Cacciari, S. Frixione, M. L. Mangano, P. Nason, and G. Ridolfi, J. High Energy Phys. 09 (2008) 127.
[16] T. Sjostrand *et al.*, Comput. Phys. Commun. **238**, 135 (2001).
[17] Tevatron Electroweak Working Group, CDF Collaboration, and D0 Collaboration, arXiv:1007.3178.
[18] R. Bonciani, S. Catani, M. L. Mangano, and P. Nason, Nucl. Phys. **B529**, 424 (1998).
[19] M. Mangano *et al.*, J. High Energy Phys. 07 (2003) 001.
[20] M. L. Mangano, M. Moretti, F. Piccinini, and M. Treccani, J. High Energy Phys. 01 (2007) 013.
[21] J. M. Campbell and R. K. Ellis, Phys. Rev. D **60**, 113006 (1999).
[22] Z. Sullivan, Phys. Rev. D **70**, 114012 (2004).
[23] B. W. Harris *et al.*, Phys. Rev. D **66**, 054024 (2002).
[24] J. M. Campbell, R. Frederix, F. Maltoni, and F. Tramontano, Phys. Rev. Lett. **102**, 182003 (2009).
[25] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **81**, 072003 (2010).
[26] A. Bhatti *et al.*, Nucl. Instrum. Methods **566**, 375 (2006).
[27] G. Corcella *et al.*, arXiv:hep-ph/0210213.
[28] P. Z. Skands, arXiv:0905.3418.