2012

Search for a narrow $t\bar{t}$ resonance in $p\bar{p}$ collisions at $\sqrt{s}$= 1.96 TeV

V. M. Abazov
Joint Institute for Nuclear Research, Dubna, Russia

Kenneth A. Bloom
University of Nebraska - Lincoln, kbloom2@unl.edu

Daniel R. Claes
University of Nebraska - Lincoln, dclaes@unl.edu

Kayle DeVaughan
University of Nebraska-Lincoln

Aaron Dominguez
University of Nebraska - Lincoln, aarond@unl.edu

See next page for additional authors

Authors
V. M. Abazov, Kenneth A. Bloom, Daniel R. Claes, Kayle DeVaughan, Aaron Dominguez, Michael Eads, Ioannis Katsanos, Sudhir Malik, and Gregory Snow

PHYSICAL REVIEW D **85,** 051101(R) (2012)

Search for a narrow $t\bar{t}$ resonance in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

V. M. Abazov,[34] B. Abbott,[72] B. S. Acharya,[28] M. Adams,[48] T. Adams,[46] G. D. Alexeev,[34] G. Alkhazov,[38] A. Alton,[60,*] G. Alverson,[59] G. A. Alves,[2] M. Aoki,[47] A. Askew,[46] B. Åsman,[40] S. Atkins,[57] O. Atramentov,[64] K. Augsten,[9] C. Avila,[7] J. BackusMayes,[79] F. Badaud,[12] L. Bagby,[47] B. Baldin,[47] D. V. Bandurin,[46] S. Banerjee,[28] E. Barberis,[59] P. Baringer,[55] J. Barreto,[3] J. F. Bartlett,[47] U. Bassler,[17] V. Bazterra,[48] A. Bean,[55] M. Begalli,[3] C. Belanger-Champagne,[40] L. Bellantoni,[47] S. B. Beri,[26] G. Bernardi,[16] R. Bernhard,[21] I. Bertram,[41] M. Besançon,[17] R. Beuselinck,[42] V. A. Bezzubov,[37] P. C. Bhat,[47] V. Bhatnagar,[26] G. Blazey,[49] S. Blessing,[46] K. Bloom,[63] A. Boehnlein,[47] D. Boline,[69] E. E. Boos,[36] G. Borissov,[41] T. Bose,[58] A. Brandt,[75] O. Brandt,[22] R. Brock,[61] G. Brooijmans,[67] A. Bross,[47] D. Brown,[16] J. Brown,[16] X. B. Bu,[47] M. Buehler,[47] V. Buescher,[23] V. Bunichev,[36] S. Burdin,[41,†] T. H. Burnett,[79] C. P. Buszello,[40] B. Calpas,[14] E. Camacho-Pérez,[31] M. A. Carrasco-Lizarraga,[55] B. C. K. Casey,[47] H. Castilla-Valdez,[31] S. Chakrabarti,[69] D. Chakraborty,[49] K. M. Chan,[53] A. Chandra,[77] E. Chapon,[17] G. Chen,[55] S. Chevalier-Théry,[17] D. K. Cho,[74] S. W. Cho,[30] S. Choi,[30] B. Choudhary,[27] S. Cihangir,[47] D. Claes,[63] J. Clutter,[55] M. Cooke,[47] W. E. Cooper,[47] M. Corcoran,[77] F. Couderc,[17] M.-C. Cousinou,[14] A. Croc,[17] D. Cutts,[74] A. Das,[44] G. Davies,[42] K. De,[75] S. J. de Jong,[33] E. De La Cruz-Burelo,[31] F. Déliot,[17] R. Demina,[68] D. Denisov,[47] S. P. Denisov,[37] S. Desai,[47] C. Deterre,[17] K. DeVaughan,[63] H. T. Diehl,[47] M. Diesburg,[47] P. F. Ding,[43] A. Dominguez,[63] T. Dorland,[79] A. Dubey,[27] L. V. Dudko,[36] D. Duggan,[64] A. Duperrin,[14] S. Dutt,[26] A. Dyshkant,[49] M. Eads,[63] D. Edmunds,[61] J. Ellison,[45] V. D. Elvira,[47] Y. Enari,[16] H. Evans,[51] A. Evdokimov,[70] V. N. Evdokimov,[37] G. Facini,[59] T. Ferbel,[68] F. Fiedler,[23] F. Filthaut,[33] W. Fisher,[61] H. E. Fisk,[47] M. Fortner,[49] H. Fox,[41] S. Fuess,[47] A. Garcia-Bellido,[68] G. A. García-Guerra,[31,‡] V. Gavrilov,[35] P. Gay,[12] W. Geng,[14,61] D. Gerbaudo,[65] C. E. Gerber,[48] Y. Gershtein,[64] G. Ginther,[47,68] G. Golovanov,[34] A. Goussiou,[79] P. D. Grannis,[69] S. Greder,[18] H. Greenlee,[47] Z. D. Greenwood,[57] E. M. Gregores,[4] G. Grenier,[19] Ph. Gris,[12] J.-F. Grivaz,[15] A. Grohsjean,[17] S. Grünendahl,[47] M. W. Grünewald,[29] T. Guillemin,[15] G. Gutierrez,[47] P. Gutierrez,[72] A. Haas,[67,§] S. Hagopian,[46] J. Haley,[59] L. Han,[6] K. Harder,[43] A. Harel,[68] J. M. Hauptman,[54] J. Hays,[42] T. Head,[43] T. Hebbeker,[20] D. Hedin,[49] H. Hegab,[73] A. P. Heinson,[45] U. Heintz,[74] C. Hensel,[22] I. Heredia-De La Cruz,[31] K. Herner,[60] G. Hesketh,[43,‖] M. D. Hildreth,[53] R. Hirosky,[78] T. Hoang,[46] J. D. Hobbs,[69] B. Hoeneisen,[11] M. Hohlfeld,[23] Z. Hubacek,[9,17] V. Hynek,[9] I. Iashvili,[66] Y. Ilchenko,[76] R. Illingworth,[47] A. S. Ito,[47] S. Jabeen,[74] M. Jaffré,[15] D. Jamin,[14] A. Jayasinghe,[72] R. Jesik,[42] K. Johns,[44] M. Johnson,[47] A. Jonckheere,[47] P. Jonsson,[42] J. Joshi,[26] A. W. Jung,[47] A. Juste,[39] K. Kaadze,[56] E. Kajfasz,[14] D. Karmanov,[36] P. A. Kasper,[47] I. Katsanos,[63] R. Kehoe,[76] S. Kermiche,[14] N. Khalatyan,[47] A. Khanov,[73] A. Kharchilava,[66] Y. N. Kharzheev,[34] J. M. Kohli,[26] A. V. Kozelov,[37] J. Kraus,[61] S. Kulikov,[37] A. Kumar,[66] A. Kupco,[10] T. Kurča,[19] V. A. Kuzmin,[36] J. Kvita,[8] S. Lammers,[51] G. Landsberg,[74] P. Lebrun,[19] H. S. Lee,[30] S. W. Lee,[54] W. M. Lee,[47] J. Lellouch,[16] L. Li,[45] Q. Z. Li,[47] S. M. Lietti,[5] J. K. Lim,[30] D. Lincoln,[47] J. Linnemann,[61] V. V. Lipaev,[37] R. Lipton,[47] Y. Liu,[6] A. Lobodenko,[38] M. Lokajicek,[10] R. Lopes de Sa,[69] H. J. Lubatti,[79] R. Luna-Garcia,[31,¶] A. L. Lyon,[47] A. K. A. Maciel,[2] D. Mackin,[77] R. Madar,[17] R. Magaña-Villalba,[31] S. Malik,[63] V. L. Malyshev,[34] Y. Maravin,[56] J. Martínez-Ortega,[31] R. McCarthy,[69] C. L. McGivern,[55] M. M. Meijer,[33] A. Melnitchouk,[62] D. Menezes,[49] P. G. Mercadante,[4] M. Merkin,[36] A. Meyer,[20] J. Meyer,[22] F. Miconi,[18] N. K. Mondal,[28] G. S. Muanza,[14] M. Mulhearn,[78] E. Nagy,[14] M. Naimuddin,[27] M. Narain,[74] R. Nayyar,[27] H. A. Neal,[60] J. P. Negret,[7] P. Neustroev,[38] S. F. Novaes,[5] T. Nunnemann,[24] G. Obrant,[38,‡‡] J. Orduna,[77] N. Osman,[14] J. Osta,[53] G. J. Otero y Garzón,[1] M. Padilla,[45] A. Pal,[75] N. Parashar,[52] V. Parihar,[74] S. K. Park,[30] R. Partridge,[74,§] N. Parua,[51] A. Patwa,[70] B. Penning,[47] M. Perfilov,[36] Y. Peters,[43] K. Petridis,[43] G. Petrillo,[68] P. Pétroff,[15] R. Piegaia,[1] M.-A. Pleier,[70] P. L. M. Podesta-Lerma,[31,**] V. M. Podstavkov,[47] P. Polozov,[35] A. V. Popov,[37] M. Prewitt,[77] D. Price,[51] N. Prokopenko,[37] J. Qian,[60] A. Quadt,[22] B. Quinn,[62] M. S. Rangel,[2] K. Ranjan,[27] P. N. Ratoff,[41] I. Razumov,[37] P. Renkel,[76] M. Rijssenbeek,[69] I. Ripp-Baudot,[18] F. Rizatdinova,[73] M. Rominsky,[47] A. Ross,[41] C. Royon,[17] P. Rubinov,[47] R. Ruchti,[53] G. Safronov,[35] G. Sajot,[13] P. Salcido,[49] A. Sánchez-Hernández,[31] M. P. Sanders,[24] B. Sanghi,[47] A. S. Santos,[5] G. Savage,[47] L. Sawyer,[57] T. Scanlon,[42] R. D. Schamberger,[69] Y. Scheglov,[38] H. Schellman,[50] T. Schliephake,[25] S. Schlobohm,[79] C. Schwanenberger,[43] R. Schwienhorst,[61] J. Sekaric,[55] H. Severini,[72] E. Shabalina,[22] V. Shary,[17] A. A. Shchukin,[37] R. K. Shivpuri,[27] V. Simak,[9] V. Sirotenko,[47] P. Skubic,[72] P. Slattery,[68] D. Smirnov,[53] K. J. Smith,[66] G. R. Snow,[63] J. Snow,[71] S. Snyder,[70] S. Söldner-Rembold,[43] L. Sonnenschein,[20] K. Soustruznik,[8] J. Stark,[13] V. Stolin,[35] D. A. Stoyanova,[37] M. Strauss,[72] D. Strom,[48] L. Stutte,[47] L. Suter,[43] P. Svoisky,[72] M. Takahashi,[43] A. Tanasijczuk,[1] M. Titov,[17] V. V. Tokmenin,[34] Y.-T. Tsai,[68] K. Tschann-Grimm,[69] D. Tsybychev,[69] B. Tuchming,[17] C. Tully,[65] L. Uvarov,[38] S. Uvarov,[38] S. Uzunyan,[49] R. Van Kooten,[51] W. M. van Leeuwen,[32] N. Varelas,[48] E. W. Varnes,[44] I. A. Vasilyev,[37] P. Verdier,[19] L. S. Vertogradov,[34] M. Verzocchi,[47] M. Vesterinen,[43] D. Vilanova,[17] P. Vokac,[9] H. D. Wahl,[46] M. H. L. S. Wang,[47] J. Warchol,[53] G. Watts,[79] M. Wayne,[53] M. Weber,[47,††] L. Welty-Rieger,[50] A. White,[75] D. Wicke,[25] M. R. J. Williams,[41] G. W. Wilson,[55] M. Wobisch,[57] D. R. Wood,[59] T. R. Wyatt,[43] Y. Xie,[47] R. Yamada,[47] W.-C. Yang,[43] T. Yasuda,[47] Y. A. Yatsunenko,[34] Z. Ye,[47] H. Yin,[47] K. Yip,[70] S. W. Youn,[47] J. Yu,[75] T. Zhao,[79] B. Zhou,[60] J. Zhu,[60] M. Zielinski,[68] D. Zieminska,[51] and L. Zivkovic[74]

(D0 Collaboration)

[1]*Universidad de Buenos Aires, Buenos Aires, Argentina*
[2]*LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
[3]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[4]*Universidade Federal do ABC, Santo André, Brazil*
[5]*Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil*
[6]*University of Science and Technology of China, Hefei, People's Republic of China*
[7]*Universidad de los Andes, Bogotá, Colombia*
[8]*Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic*
[9]*Czech Technical University in Prague, Prague, Czech Republic*
[10]*Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[11]*Universidad San Francisco de Quito, Quito, Ecuador*
[12]*LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France*
[13]*LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France*
[14]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[15]*LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
[16]*LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France*
[17]*CEA, Irfu, SPP, Saclay, France*
[18]*IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France*
[19]*IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
[20]*III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany*
[21]*Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[22]*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[23]*Institut für Physik, Universität Mainz, Mainz, Germany*
[24]*Ludwig-Maximilians-Universität München, München, Germany*
[25]*Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[26]*Panjab University, Chandigarh, India*
[27]*Delhi University, Delhi, India*
[28]*Tata Institute of Fundamental Research, Mumbai, India*
[29]*University College Dublin, Dublin, Ireland*
[30]*Korea Detector Laboratory, Korea University, Seoul, Korea*
[31]*CINVESTAV, Mexico City, Mexico*
[32]*Nikhef, Science Park, Amsterdam, the Netherlands*
[33]*Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands*
[34]*Joint Institute for Nuclear Research, Dubna, Russia*
[35]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[36]*Moscow State University, Moscow, Russia*
[37]*Institute for High Energy Physics, Protvino, Russia*
[38]*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[39]*Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d'Altes Energies (IFAE), Barcelona, Spain*
[40]*Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden*
[41]*Lancaster University, Lancaster LA1 4YB, United Kingdom*
[42]*Imperial College London, London SW7 2AZ, United Kingdom*
[43]*The University of Manchester, Manchester M13 9PL, United Kingdom*
[44]*University of Arizona, Tucson, Arizona 85721, USA*
[45]*University of California Riverside, Riverside, California 92521, USA*
[46]*Florida State University, Tallahassee, Florida 32306, USA*
[47]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[48]*University of Illinois at Chicago, Chicago, Illinois 60607, USA*
[49]*Northern Illinois University, DeKalb, Illinois 60115, USA*
[50]*Northwestern University, Evanston, Illinois 60208, USA*
[51]*Indiana University, Bloomington, Indiana 47405, USA*
[52]*Purdue University Calumet, Hammond, Indiana 46323, USA*
[53]*University of Notre Dame, Notre Dame, Indiana 46556, USA*
[54]*Iowa State University, Ames, Iowa 50011, USA*
[55]*University of Kansas, Lawrence, Kansas 66045, USA*

[56]*Kansas State University, Manhattan, Kansas 66506, USA*
[57]*Louisiana Tech University, Ruston, Louisiana 71272, USA*
[58]*Boston University, Boston, Massachusetts 02215, USA*
[59]*Northeastern University, Boston, Massachusetts 02115, USA*
[60]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[61]*Michigan State University, East Lansing, Michigan 48824, USA*
[62]*University of Mississippi, University, Mississippi 38677, USA*
[63]*University of Nebraska, Lincoln, Nebraska 68588, USA*
[64]*Rutgers University, Piscataway, New Jersey 08855, USA*
[65]*Princeton University, Princeton, New Jersey 08544, USA*
[66]*State University of New York, Buffalo, New York 14260, USA*
[67]*Columbia University, New York, New York 10027, USA*
[68]*University of Rochester, Rochester, New York 14627, USA*
[69]*State University of New York, Stony Brook, New York 11794, USA*
[70]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[71]*Langston University, Langston, Oklahoma 73050, USA*
[72]*University of Oklahoma, Norman, Oklahoma 73019, USA*
[73]*Oklahoma State University, Stillwater, Oklahoma 74078, USA*
[74]*Brown University, Providence, Rhode Island 02912, USA*
[75]*University of Texas, Arlington, Texas 76019, USA*
[76]*Southern Methodist University, Dallas, Texas 75275, USA*
[77]*Rice University, Houston, Texas 77005, USA*
[78]*University of Virginia, Charlottesville, Virginia 22901, USA*
[79]*University of Washington, Seattle, Washington 98195, USA*
(Received 4 November 2011; published 14 March 2012)

We report a search for a narrow $t\bar{t}$ resonance that decays into a lepton + jets final state based on an integrated luminosity of 5.3 fb^{-1} of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV collected by the D0 Collaboration at the Fermilab Tevatron Collider. We set upper limits on the production cross section of such a resonance multiplied by its branching fraction to $t\bar{t}$. We exclude a leptophobic topcolor Z' at the 95% confidence level for masses below 835 GeV (940 GeV) if its width is 1.2% (3%) of its mass. We also exclude color octet vector bosons (colorons) with masses below 775 GeV.

DOI: 10.1103/PhysRevD.85.051101 PACS numbers: 13.85.Rm, 12.60.Cn, 14.65.Ha

Narrow resonances that decay to top-antitop quark ($t\bar{t}$) pairs are predicted by many models of physics beyond the standard model. Such resonances (X) appear in grand unified theories with symmetry groups larger than SU(5) [1], as Kaluza-Klein excitations of the gluon or of the Z boson that predominantly decay to $t\bar{t}$ pairs [2,3], as axigluons [4], and in theories of new strong dynamics [5,6]. Some resonances are expected to have a large decay width and would be hard to detect over standard model $t\bar{t}$-pair production. Here we search for a $t\bar{t}$ resonance with a width that is significantly smaller than the detector resolution for reconstructing its mass.

Searches for $t\bar{t}$ resonances were previously carried out by the D0 and CDF Collaborations at the Fermilab Tevatron Collider, and no evidence was found for their production [7,8]. To extract limits for the mass M_X of a resonance, limits for cross sections were compared to predictions for a leptophobic topcolor Z' boson with width $\Gamma_X = 0.012M_{Z'}$ [6]. To simplify comparisons with previous limits, we include the same model as a reference. The lower limit for the mass of such a topcolor Z' boson published by the D0 Collaboration is 700 GeV [7] based on 0.9 fb^{-1}. The CDF Collaboration excludes Z' boson masses below 900 GeV [8] using 4.8 fb^{-1} of integrated luminosity. Both limits correspond to 95% confidence level (C.L.).

We carry out the search using lepton + jets (ℓ + jets) events in which one of the top quarks decays "leptonically," $t \to Wb \to \ell\bar{\nu}b$, and the other "hadronically," $t \to Wb \to q\bar{q}'b$ (charge conjugate states are implicitly included in our notations). This final state is characterized by an isolated charged lepton (electron or muon), imbalance in transverse momentum $\not{p}_T$ from the undetected neutrino, and jets from the fragmentation of the four quarks. The data correspond to an integrated luminosity of 5.3 fb^{-1} and were acquired by the D0 experiment at the Fermilab Tevatron Collider in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.

[*]Visitor from Augustana College, Sioux Falls, SD, USA
[†]Visitor from The University of Liverpool, Liverpool, UK
[‡]Visitor from UPIITA-IPN, Mexico City, Mexico
[§]Visitor from SLAC, Menlo Park, CA, USA
[‖]Visitor from University College London, London, UK
[¶]Visitor from Centro de Investigacion en Computacion—IPN, Mexico City, Mexico
[**]Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico
[††]Visitor from Universität Bern, Bern, Switzerland.
[‡‡]Deceased.

The D0 detector consists of central tracking, calorimeter, and muon systems [9,10]. The central tracking system is located inside a 1.9 T superconducting solenoidal magnet. Central and forward preshower detectors are located just outside the coil and in front of the calorimeters. The liquid-argon/uranium sampling calorimeter is divided into a central section covering pseudorapidity $|\eta| < 1.1$ and two end calorimeters extending coverage up to $|\eta| \approx 4$. The calorimeter is segmented longitudinally into electromagnetic, fine hadronic, and coarse hadronic sections with increasingly coarser granularity. The muon system, located outside the calorimeter, consists of one layer of tracking detectors and scintillation trigger counters inside a 1.8 T toroidal magnet and two similar layers outside the toroids. A three-level trigger system selects events that are recorded for offline analysis.

Events must satisfy one of several trigger conditions, all requiring an electron or muon with high transverse momentum, in some cases in conjunction with one or more jets. The event selection requires one isolated lepton with $p_T >$ 20 GeV, missing transverse momentum above 20 GeV (30 GeV) for the e + jets (μ + jets) data, and at least three jets with $p_T > 20$ GeV. The leading jet must have $p_T >$ 40 GeV. We require at least one jet to be tagged as originating from the fragmentation of a b quark. Further details about the ℓ + jets event selection can be found in [11,12]. After applying these criteria, the dominant background is continuum $t\bar{t}$ production. We discriminate between continuum and resonant $t\bar{t}$ production using the invariant mass of the $t\bar{t}$ system. The ℓ + jets events are divided into four subsamples defined by lepton flavor (e, μ) and jet multiplicity (3 jets and ≥ 4 jets).

The two main standard model processes that yield an isolated lepton, $\not{p}_T$, and several jets are $t\bar{t}$ and W + jets production. The third most important background arises from multijet events in which a jet is misidentified as an electron, or a muon from heavy-flavor quark decay appears isolated, and $\not{p}_T$ is mismeasured. Single top quark, Z + jets, and diboson production can also give rise to such final states, but have much smaller yields.

We simulate $t\bar{t}$, W + jets and Z + jets production using the ALPGEN+PYTHIA event generators [13–15]. Three subsamples, $W + b\bar{b}$, $W + c\bar{c}$, and W + light-partons, are generated separately. Similarly, the Z + jets samples are divided into $Z + b\bar{b}$, $Z + c\bar{c}$, and Z + light-parton samples. We simulate single top quark production using the COMPHEP-SINGLETOP [16,17] generator and diboson (WW, WZ, and ZZ) production with PYTHIA. For all simulations, we set the top quark mass to $m_t = 172.5$ GeV and use the CTEQ6L1 parton distribution functions [18]. We simulate detector effects using GEANT-3 [19] and add randomly triggered events to all simulated events to account for multiple $p\bar{p}$ collisions in the same bunch crossing. These events are reconstructed using the same procedures as for data.

To estimate backgrounds we use either data-driven methods or simulation. We estimate the number and distribution of multijet events contained in each subsample using a control data sample [20]. We scale $t\bar{t}$ production to the theoretical approximate next-to-next-to-leading order (NNLO) prediction of $\sigma(p\bar{p} \to t\bar{t}) = 7.48^{+0.56}_{-0.72}$ pb [21]. We normalize single top quark production in the s and t channels to the NNLO cross section with next-to-NNLO threshold corrections of 3.3 pb [22]. We normalize diboson processes to their next-to-leading order (NLO) cross sections, as computed with MCFM [23], of 12.0 pb for WW, 3.7 pb for WZ, and 1.4 pb for ZZ production. We fix the relative normalization of the $Z + b\bar{b}$, $Z + c\bar{c}$, and Z + light parton samples and the relative normalizations of the $W + b\bar{b}$, $W + c\bar{c}$, and W + light parton samples to NLO predictions computed with MCFM [23]. We then normalize the inclusive Z boson production such that $\sigma(p\bar{p} \to Z) \times B(Z \to \mu^+\mu^-)$ agrees with the NNLO prediction of 256 pb [24]. We normalize the number of W + jets events such that the total number of events predicted by all background sources equals the number of events observed in each of the four subsamples before imposing the b-tagging requirement. This corresponds to increasing the total number of W + jets events expected by a factor of approximately 1.3 which is close to the NLO k-factor for W + jets production.

As a model for $t\bar{t}$ resonance production, we use production of a Z' boson in PYTHIA, that decays exclusively to $t\bar{t}$ pairs. We consider 18 resonance mass values M_X between 350 and 1200 GeV. The intrinsic widths of the resonances are set to $\Gamma_X = 0.012 M_X$. It has been checked that kinematic differences due to a width of $\Gamma_X = 0.03 M_X$ do not affect the result.

We reconstruct the $t\bar{t}$ invariant mass, $m_{t\bar{t}}$, using up to four jets with the highest p_T, the charged lepton, and the neutrino. We determine the momentum of the neutrino by equating the neutrino p_T to the measured $\not{p}_T$ constraining the invariant mass of the charged lepton-neutrino system to the W boson mass and choosing the smaller solution of the resulting quadratic equation for the neutrino momentum component p_z along the beam direction. If there is no real solution we set neutrino $p_z = 0$ and scale the $\not{p}_T$ to satisfy the W boson mass constraint. Figure 1 shows the expected distribution of the reconstructed $m_{t\bar{t}}$ from the production of narrow $t\bar{t}$ resonances of different mass values. The detector resolution for $m_{t\bar{t}}$ varies between 65 GeV for $M_X =$ 400 GeV and 270 GeV for $M_X = 1.2$ TeV, which is much larger than the widths of the $t\bar{t}$ resonances considered.

We use the reconstructed $t\bar{t}$ mass to test for the presence of a signal in the data and to compute upper limits on the production cross section of a narrow $t\bar{t}$ resonance times branching fraction to $t\bar{t}$, σB, as a function of its mass. For each hypothesized value of the resonance mass, we fit the data to background-only and to signal + background hypotheses. For each hypothesis we also vary the systematic uncertainties given in Table I subject to a Gaussian constraint to their prior values to maximize the

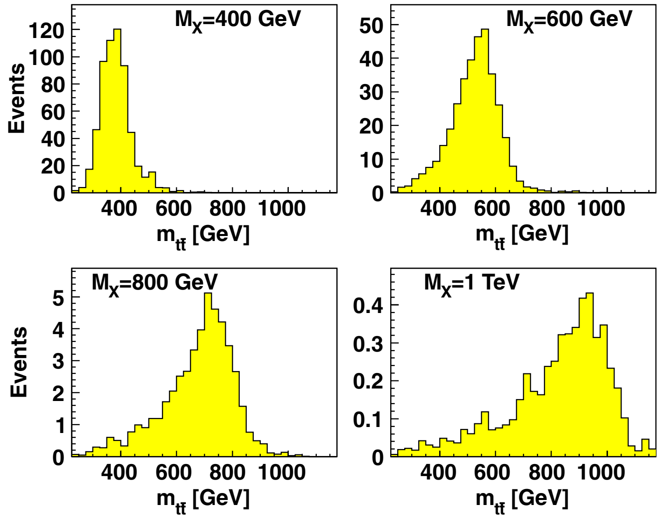

FIG. 1 (color online). Distributions of $m_{t\bar{t}}$ for resonances with mass M_X, normalized to the predicted σB from Table II.

likelihood [25]. We then use the profile likelihood ratio $L = -2\ln(P_{s+b}/P_b)$ as the test statistic, where P_{s+b} is the Poisson likelihood to observe the data under the signal + background hypothesis and P_b is the Poisson likelihood to observe the data under the background-only hypothesis. For the background-only hypothesis, we fit three components to the data. We constrain the $t\bar{t}$ production to its theoretical cross section, and the multijets background to the predicted number of events. For the other backgrounds, we constrain the relative fractions of the individual background sources to their predicted values and treat the overall normalization as a free parameter. For the signal + background fit we add σB for the resonance as a parameter to the fit.

We use the CL_s method [26] to determine the limits on σB. Using pseudoexperiments, we determine the probability to measure values of L that are larger than the value observed in the data sample if there is a $t\bar{t}$ resonance signal, CL_{s+b}, and if there is no such signal, CL_b. The value of σB for which $1 - CL_{s+b}/CL_b = 0.95$ is the 95% C.L. upper limit. We repeat this procedure at every resonance mass value.

TABLE I. Summary of systematic uncertainties above 2%. Some values vary with subsample. The numbers give the range of the uncertainties.

Source	resonance	$t\bar{t}$	multijets
$t\bar{t}$ cross section	-	9%	-
Multijets normalization	-	-	(30–50)%
Integrated luminosity	6.1%	6.1%	-
Monte Carlo model	-	4.3%	-
Trigger efficiency	$\leq 5\%$	$\leq 5\%$	-
b-tagging efficiency	(3–11)%	(3–5)%	-
Lepton identification	(3–4)%	(3–4)%	-
Jet energy calibration	(2–4)%	(2–5)%	-
Jet energy resolution	(3–5)%	(3–5)%	-
Jet identification	$\leq 7\%$	$\leq 10\%$	-

Table I summarizes the sources of systematic uncertainties in the normalizations of the components of the model used in the limit calculation. No uncertainties are given for the physics backgrounds other than $t\bar{t}$ production because their normalizations are free parameters of the fit. When estimating the effect of uncertainties in the jet energy scale, the jet identification efficiency, and the jet energy resolution, we vary the shape of the $m_{t\bar{t}}$ distributions. We also assign an uncertainty to the shape of the $m_{t\bar{t}}$ distribution from $t\bar{t}$ production equal to the difference between the default simulation using ALPGEN and PYTHIA and a simulation using MC@NLO and HERWIG. We also considered variations in the amount of initial and final state radiation but concluded that the resulting changes in the $m_{t\bar{t}}$ distribution were negligible relative to the uncertainties that we already consider.

Figure 2 shows the distribution of $m_{t\bar{t}}$ observed in data compared to expectations from standard model backgrounds and a 950 GeV $t\bar{t}$ resonance. We observe a small excess of events at high mass values. The excess is present in both the e + jets data and the μ + jets data. We can fit the data best with an additional resonance signal with a mass of 950 GeV and $\sigma B = 0.10 \pm 0.05$ pb. The value of $1 - CL_b$ for the data gives the probability of getting a deviation of at least the observed size at this mass value from the standard model expectation in the absence of physics beyond the standard model. We find a p value of

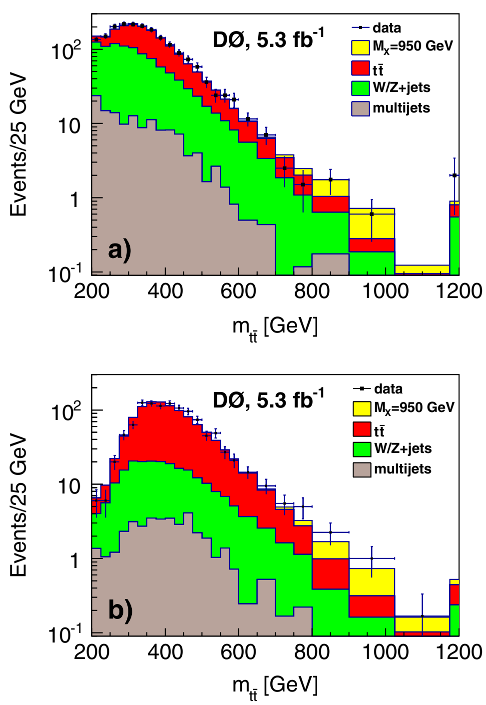

FIG. 2 (color online). Distribution of $m_{t\bar{t}}$ for events that pass the final event selection with (a) exactly 3 jets and (b) at least 4 jets, compared with expectations for standard model processes and a 950 GeV resonance signal with the best fitted $\sigma B = 0.10$ pb. The highest bin in each histogram shows the number of events with $m_{t\bar{t}} > 1175$ GeV.

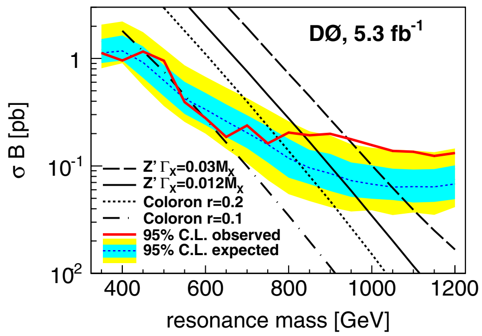

FIG. 3 (color online). Observed and expected upper limits on σB for a narrow $t\bar{t}$ resonance as a function of the resonance mass. The shaded regions around the expected limit represent the ± 1 and ± 2 standard deviation bands. The lines show predicted σB values for topcolor Z' bosons and for colorons.

0.018, corresponding to 2.1 Gaussian-equivalent standard deviations. This significance value does not take into account that the excess may have occurred at any place in the mass spectrum.

Figure 3 and Table II display the resulting limits for σB compared to the limits expected in the absence of a narrow $t\bar{t}$ resonance. Superimposed on the cross section limits are predictions for σB of topcolor Z' bosons [6] with $\Gamma_X = 0.012 M_X$ ($0.03 M_X$) that exclusively decay to $t\bar{t}$. The expected mass limits for such Z' bosons are 920 (1045) GeV. The observed cross section limit allows us to exclude such Z' bosons at the 95% C.L. for masses below 835 (940) GeV. We also superimpose the predicted σB for a color octet vector boson (coloron), which would decay to $t\bar{t}$ with a branching fraction of about $1/6$ and have a width substantially below 1% of its mass. We include two curves, for different values of the coupling to light quarks $r = 0.1$ and 0.2 [27]. This could, for example, be a Kaluza-Klein gluon. We can exclude such a coloron for $r = 0.2$ with masses below 775 GeV.

In our previous publication [7], we computed a Bayesian limit on σB for a $t\bar{t}$ resonance. For reference, we have repeated the same calculation using a subset of the data sample reported in this paper, corresponding to 4.3 fb^{-1}, and find results consistent with the limits on σB given in Fig. 3. We also find that our results are independent of the couplings of the $t\bar{t}$ resonance (pure vector, pure axial-vector, or standard model Z-like) and are therefore valid for any narrow resonance that decays to a $t\bar{t}$ final state.

TABLE II. Observed and expected 95% C.L. limits for σB and values predicted for a topcolor Z' with $\Gamma_X = 0.012 M_X$, $m_t = 172.5$ GeV and CTEQ6L1 parton distribution functions used as a reference in previous publications.

M_X	Z' prediction	expected limit	observed limit
(GeV)	(pb)	(pb)	(pb)
350	7.85	1.13	1.13
400	12.79	1.18	0.96
450	8.59	0.92	1.16
500	5.35	0.62	0.95
550	3.32	0.42	0.39
600	2.03	0.34	0.28
650	1.24	0.26	0.19
700	0.76	0.20	0.24
750	0.46	0.16	0.16
800	0.28	0.12	0.20
850	0.17	0.10	0.19
900	0.11	0.08	0.20
950	0.059	0.07	0.18
1000	0.034	0.07	0.16
1050	0.020	0.06	0.14
1100	0.012	0.06	0.14
1150	0.0069	0.06	0.12
1200	0.0041	0.07	0.13

In conclusion, we searched for production of a narrow $t\bar{t}$ resonance in the lepton + jets channel. We do not observe a signal consistent with the production of such a resonance, although we observe a slight excess of events around 950 GeV. We set upper limits on the cross section times branching fraction for production of such a resonance for masses between 350 and 1200 GeV. We interpret our results to set lower mass limits on topcolor Z' bosons and colorons.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

[1] A. Leike, Phys. Rep. **317**, 143 (1999).
[2] B. Lillie, L. Randall, and L.-T. Wang, J. High Energy Phys. 09 (2007) 074.
[3] T. G. Rizzo, Phys. Rev. D **61**, 055005 (2000).
[4] L. M. Sehgal and M. Wanninger, Phys. Lett. B **200**, 211 (1988).
[5] C. T. Hill and S. J. Parke, Phys. Rev. D **49**, 4454 (1994).

[6] R. M. Harris, C. T. Hill, and S. J. Parke, arXiv:hep-ph/9911288.
[7] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **668**, 98 (2008).
[8] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. D **84**, 072004 (2011).
[9] S. Abachi *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **338**, 185 (1994).
[10] V. M. Abazov *et al.* (D0 Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **565**, 463 (2006).
[11] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **107**, 082001 (2011).
[12] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **84**, 012008 (2011).
[13] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. D. Polosa, J. High Energy Phys. 07 (2003) 001.
[14] T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys. 05 (2006) 026.
[15] S. Hoeche *et al.*, arXiv:hep-ph/0602031.
[16] E. E. Boos, V. E. Bunichev, L. V. Dudko, V. I. Savrin, and A. V. Sherstnev, Phys. At. Nucl. **69**, 1317 (2006).
[17] E. Boos *et al.* (CompHEP Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **534**, 250 (2004).
[18] J. Pumplin *et al.*, J. High Energy Phys. 07 (2002) 012.
[19] R. Brun and F. Carminati, CERN Program Library Long Writeup Report No. W5013, 1993.
[20] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **76**, 092007 (2007).
[21] S. Moch and P. Uwer, Phys. Rev. D **78**, 034003 (2008).
[22] N. Kidonakis and R. Vogt, Phys. Rev. D **78**, 074005 (2008).
[23] J. Campbell and R. K. Ellis, Phys. Rev. D **65**, 113007 (2002).
[24] R. Hamberg, W. van Neerven, and T. Matsuura, Nucl. Phys. **B359**, 343 (1991).
[25] W. Fisher, Report No. FERMILAB-TM-2386-E.
[26] T. Junk, Nucl. Instrum. Methods Phys. Res., Sect. A **434**, 435 (1999).
[27] B. A. Dobrescu, K. Kong, and R. Mahbubani, J. High Energy Phys. 06 (2009) 001; B. A. Dobrescu (private communication).