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Abazov, V.M.; Balm, P.W.; Blekman, F.; Bos, K.; Peters, O.

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## Search for Narrow $t\bar{t}$ Resonances in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

V. M. Abazov,<sup>21</sup> B. Abbott,<sup>55</sup> A. Abdesselam,<sup>11</sup> M. Abolins,<sup>48</sup> V. Abramov,<sup>24</sup> B. S. Acharya,<sup>17</sup> D. L. Adams,<sup>53</sup> M. Adams,<sup>35</sup> S. N. Ahmed,<sup>20</sup> G. D. Alexeev,<sup>21</sup> A. Alton,<sup>47</sup> G. A. Alves,<sup>2</sup> E. W. Anderson,<sup>40</sup> Y. Arnoud,<sup>9</sup> C. Avila,<sup>5</sup> V. V. Babintsev,<sup>24</sup> L. Babukhadia,<sup>52</sup> T. C. Bacon,<sup>26</sup> A. Baden,<sup>44</sup> S. Baffioni,<sup>10</sup> B. Baldin,<sup>34</sup> P. W. Balm,<sup>19</sup> S. Banerjee,<sup>17</sup> E. Barberis,<sup>46</sup> P. Baringer,<sup>41</sup> J. Barreto,<sup>2</sup> J. F. Bartlett,<sup>34</sup> U. Bässler,<sup>12</sup> D. Bauer,<sup>38</sup> A. Bean,<sup>41</sup> F. Beaudette,<sup>11</sup> M. Begel,<sup>51</sup> A. Belyaev,<sup>33</sup> S. B. Beri,<sup>15</sup> G. Bernardi,<sup>12</sup> I. Bertram,<sup>25</sup> A. Besson,<sup>9</sup> R. Beuselinck,<sup>26</sup> V. A. Bezzubov,<sup>24</sup> P. C. Bhat,<sup>34</sup> V. Bhatnagar,<sup>15</sup> M. Bhattacharjee,<sup>52</sup> G. Blazey,<sup>36</sup> F. Blekman,<sup>19</sup> S. Blessing,<sup>33</sup> A. Boehnlein,<sup>34</sup> N. I. Bojko,<sup>24</sup> T. A. Bolton,<sup>42</sup> F. Borchering,<sup>34</sup> K. Bos,<sup>19</sup> T. Bose,<sup>50</sup> A. Brandt,<sup>57</sup> G. Briskin,<sup>56</sup> R. Brock,<sup>48</sup> G. Brooijmans,<sup>34</sup> A. Bross,<sup>34</sup> D. Buchholz,<sup>37</sup> M. Buehler,<sup>35</sup> V. Buescher,<sup>14</sup> V. S. Burtovoi,<sup>24</sup> J. M. Butler,<sup>45</sup> F. Canelli,<sup>51</sup> W. Carvalho,<sup>3</sup> D. Casey,<sup>48</sup> H. Castilla-Valdez,<sup>18</sup> D. Chakraborty,<sup>36</sup> K. M. Chan,<sup>51</sup> S. V. Chekulaev,<sup>24</sup> D. K. Cho,<sup>51</sup> S. Choi,<sup>32</sup> S. Chopra,<sup>53</sup> D. Claes,<sup>49</sup> A. R. Clark,<sup>28</sup> B. Connolly,<sup>33</sup> W. E. Cooper,<sup>34</sup> D. Coppage,<sup>41</sup> S. Crépe-Renaudin,<sup>9</sup> M. A. C. Cummings,<sup>36</sup> D. Cutts,<sup>56</sup> H. da Motta,<sup>2</sup> G. A. Davis,<sup>51</sup> K. De,<sup>57</sup> S. J. de Jong,<sup>20</sup> M. Demarteau,<sup>34</sup> R. Demina,<sup>51</sup> P. Demine,<sup>13</sup> D. Denisov,<sup>34</sup> S. P. Denisov,<sup>24</sup> S. Desai,<sup>52</sup> H. T. Diehl,<sup>34</sup> M. Diesburg,<sup>34</sup> S. Doulas,<sup>46</sup> L. V. Dudko,<sup>23</sup> S. Duensing,<sup>20</sup> L. Duflot,<sup>11</sup> S. R. Dugad,<sup>17</sup> A. Duperrin,<sup>10</sup> A. Dyshkant,<sup>36</sup> D. Edmunds,<sup>48</sup> J. Ellison,<sup>32</sup> J. T. Eltzroth,<sup>57</sup> V. D. Elvira,<sup>34</sup> R. Engelmann,<sup>52</sup> S. Eno,<sup>44</sup> G. Eppley,<sup>58</sup> P. Ermolov,<sup>23</sup> O. V. Eroshin,<sup>24</sup> J. Estrada,<sup>51</sup> H. Evans,<sup>50</sup> V. N. Evdokimov,<sup>24</sup> D. Fein,<sup>27</sup> T. Ferbel,<sup>51</sup> F. Filthaut,<sup>20</sup> H. E. Fisk,<sup>34</sup> F. Fleuret,<sup>12</sup> M. Fortner,<sup>36</sup> H. Fox,<sup>37</sup> S. Fu,<sup>50</sup> S. Fuess,<sup>34</sup> E. Gallas,<sup>34</sup> A. N. Galyaev,<sup>24</sup> M. Gao,<sup>50</sup> V. Gavrilov,<sup>22</sup> R. J. Genik II,<sup>25</sup> K. Genser,<sup>34</sup> C. E. Gerber,<sup>35</sup> Y. Gershtein,<sup>56</sup> G. Ginther,<sup>51</sup> B. Gómez,<sup>5</sup> P. I. Goncharov,<sup>24</sup> H. Gordon,<sup>53</sup> K. Gounder,<sup>34</sup> A. Goussiou,<sup>26</sup> N. Graf,<sup>53</sup> P. D. Grannis,<sup>52</sup> J. A. Green,<sup>40</sup> H. Greenlee,<sup>34</sup> Z. D. Greenwood,<sup>43</sup> S. Grinstein,<sup>1</sup> L. Groer,<sup>50</sup> S. Grünendahl,<sup>34</sup> S. N. Gurzhiev,<sup>24</sup> G. Gutierrez,<sup>34</sup> P. Gutierrez,<sup>55</sup> N. J. Hadley,<sup>44</sup> H. Haggerty,<sup>34</sup> S. Hagopian,<sup>33</sup> V. Hagopian,<sup>33</sup> R. E. Hall,<sup>30</sup> C. Han,<sup>47</sup> S. Hansen,<sup>34</sup> J. M. Hauptman,<sup>40</sup> C. Hebert,<sup>41</sup> D. Hedin,<sup>36</sup> J. M. Heinmiller,<sup>35</sup> A. P. Heinson,<sup>32</sup> U. Heintz,<sup>45</sup> M. D. Hildreth,<sup>39</sup> R. Hirosky,<sup>59</sup> J. D. Hobbs,<sup>52</sup> B. Hoeneisen,<sup>8</sup> J. Huang,<sup>38</sup> Y. Huang,<sup>47</sup> I. Iashvili,<sup>32</sup> R. Illingworth,<sup>26</sup> A. S. Ito,<sup>34</sup> M. Jaffré,<sup>11</sup> S. Jain,<sup>17</sup> R. Jesik,<sup>26</sup> K. Johns,<sup>27</sup> M. Johnson,<sup>34</sup> A. Jonckheere,<sup>34</sup> H. Jöstlein,<sup>34</sup> A. Juste,<sup>34</sup> W. Kahl,<sup>42</sup> S. Kahn,<sup>53</sup> E. Kajfasz,<sup>10</sup> A. M. Kalinin,<sup>21</sup> D. Karmanov,<sup>23</sup> D. Karmgard,<sup>39</sup> R. Kehoe,<sup>48</sup> A. Khanov,<sup>51</sup> A. Kharchilava,<sup>39</sup> B. Klima,<sup>34</sup> J. M. Kohli,<sup>15</sup> A. V. Kostitskiy,<sup>24</sup> J. Kotcher,<sup>53</sup> B. Kothhari,<sup>50</sup> A. V. Kozlov,<sup>24</sup> E. A. Kozlovsky,<sup>24</sup> J. Krane,<sup>40</sup> M. R. Krishnaswamy,<sup>17</sup> P. Krivkova,<sup>6</sup> S. Krzywdzinski,<sup>34</sup> M. Kubantsev,<sup>42</sup> S. Kuleshov,<sup>22</sup> Y. Kulik,<sup>34</sup> S. Kunori,<sup>44</sup> A. Kupco,<sup>7</sup> V. E. Kuznetsov,<sup>32</sup> G. Landsberg,<sup>56</sup> W. M. Lee,<sup>33</sup> A. Leflat,<sup>23</sup> F. Lehner,<sup>34,\*</sup> C. Leonidopoulos,<sup>50</sup> J. Li,<sup>57</sup> Q. Z. Li,<sup>34</sup> J. G. R. Lima,<sup>3</sup> D. Lincoln,<sup>34</sup> S. L. Linn,<sup>33</sup> J. Linnemann,<sup>48</sup> R. Lipton,<sup>34</sup> A. Lucotte,<sup>9</sup> L. Lueking,<sup>34</sup> C. Lundstedt,<sup>49</sup> C. Luo,<sup>38</sup> A. K. A. Maciel,<sup>36</sup> R. J. Madaras,<sup>28</sup> V. L. Malyshev,<sup>21</sup> V. Manankov,<sup>23</sup> H. S. Mao,<sup>4</sup> T. Marshall,<sup>38</sup> M. I. Martin,<sup>36</sup> A. A. Mayorov,<sup>24</sup> R. McCarthy,<sup>52</sup> T. McMahon,<sup>54</sup> H. L. Melanson,<sup>34</sup> M. Merkin,<sup>23</sup> K. W. Merritt,<sup>34</sup> C. Miao,<sup>56</sup> H. Miettinen,<sup>58</sup> D. Mihalcea,<sup>36</sup> N. Mokhov,<sup>34</sup> N. K. Mondal,<sup>17</sup> H. E. Montgomery,<sup>34</sup> R. W. Moore,<sup>48</sup> Y. D. Mutaf,<sup>52</sup> E. Nagy,<sup>10</sup> F. Nang,<sup>27</sup> M. Narain,<sup>45</sup> V. S. Narasimham,<sup>17</sup> N. A. Naumann,<sup>20</sup> H. A. Neal,<sup>47</sup> J. P. Negret,<sup>5</sup> A. Nomerotski,<sup>34</sup> T. Nunnemann,<sup>34</sup> D. O'Neil,<sup>48</sup> V. Oguri,<sup>3</sup> B. Olivier,<sup>12</sup> N. Oshima,<sup>34</sup> P. Padley,<sup>58</sup> K. Papageorgiou,<sup>35</sup> N. Parashar,<sup>43</sup> R. Partridge,<sup>56</sup> N. Parua,<sup>52</sup> A. Patwa,<sup>52</sup> O. Peters,<sup>19</sup> P. Pétrouff,<sup>11</sup> R. Piegaia,<sup>1</sup> B. G. Pope,<sup>48</sup> H. B. Prosper,<sup>33</sup> S. Protopopescu,<sup>53</sup> M. B. Przybycien,<sup>37,†</sup> J. Qian,<sup>47</sup> A. Quadt,<sup>51</sup> R. Raja,<sup>34</sup> S. Rajagopalan,<sup>53</sup> P. A. Rapidis,<sup>34</sup> N. W. Reay,<sup>42</sup> S. Reucroft,<sup>46</sup> M. Ridel,<sup>11</sup> M. Rijssenbeek,<sup>52</sup> F. Rizatdinova,<sup>42</sup> T. Rockwell,<sup>48</sup> C. Royon,<sup>13</sup> P. Rubinov,<sup>34</sup> R. Ruchti,<sup>39</sup> B. M. Sabirov,<sup>21</sup> G. Sajot,<sup>9</sup> A. Santoro,<sup>3</sup> L. Sawyer,<sup>43</sup> R. D. Schamberger,<sup>52</sup> H. Schellman,<sup>37</sup> A. Schwartzman,<sup>1</sup> E. Shabalina,<sup>35</sup> R. K. Shivpuri,<sup>16</sup> D. Shpakov,<sup>46</sup> M. Shupe,<sup>27</sup> R. A. Sidwell,<sup>42</sup> V. Simak,<sup>7</sup> V. Sirotenko,<sup>34</sup> P. Slattery,<sup>51</sup> R. P. Smith,<sup>34</sup> G. R. Snow,<sup>49</sup> J. Snow,<sup>54</sup> S. Snyder,<sup>53</sup> J. Solomon,<sup>35</sup> Y. Song,<sup>57</sup> V. Sorín,<sup>1</sup> M. Sosebee,<sup>57</sup> N. Sotnikova,<sup>23</sup> K. Soustruznik,<sup>6</sup> M. Souza,<sup>2</sup> N. R. Stanton,<sup>42</sup> G. Steinbrück,<sup>50</sup> D. Stoker,<sup>31</sup> V. Stolin,<sup>22</sup> A. Stone,<sup>43</sup> D. A. Stoyanova,<sup>24</sup> M. A. Strang,<sup>57</sup> M. Strauss,<sup>55</sup> M. Strovink,<sup>28</sup> L. Stutte,<sup>34</sup> A. Sznajder,<sup>3</sup> M. Talby,<sup>10</sup> W. Taylor,<sup>52</sup> S. Tentindo-Repond,<sup>33</sup> S. M. Tripathi,<sup>29</sup> T. G. Trippe,<sup>28</sup> A. S. Turcot,<sup>53</sup> P. M. Tuts,<sup>50</sup> R. Van Kooten,<sup>38</sup> V. Vaniev,<sup>24</sup> N. Varelas,<sup>35</sup> F. Villeneuve-Seguié,<sup>10</sup> A. A. Volkov,<sup>24</sup> A. P. Vorobiev,<sup>24</sup> H. D. Wahl,<sup>33</sup> Z.-M. Wang,<sup>52</sup> J. Warchol,<sup>39</sup> G. Watts,<sup>60</sup> M. Wayne,<sup>39</sup> H. Weerts,<sup>48</sup> A. White,<sup>57</sup> D. Whiteson,<sup>28</sup> D. A. Wijngaarden,<sup>20</sup> S. Willis,<sup>36</sup> S. J. Wimpenny,<sup>32</sup> J. Womersley,<sup>34</sup> D. R. Wood,<sup>46</sup> Q. Xu,<sup>47</sup> R. Yamada,<sup>34</sup> P. Yamin,<sup>53</sup> T. Yasuda,<sup>34</sup> Y. A. Yatsunenko,<sup>21</sup> K. Yip,<sup>53</sup> J. Yu,<sup>57</sup> M. Zanabria,<sup>5</sup> X. Zhang,<sup>55</sup> H. Zheng,<sup>39</sup> B. Zhou,<sup>47</sup> Z. Zhou,<sup>40</sup> M. Zielinski,<sup>51</sup> D. Zieminska,<sup>38</sup> A. Zieminski,<sup>38</sup> V. Zutshi,<sup>36</sup> E. G. Zverev,<sup>23</sup> and A. Zylberstein<sup>13</sup>

(DØ Collaboration)

- <sup>1</sup>Universidad de Buenos Aires, Buenos Aires, Argentina  
<sup>2</sup>LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil  
<sup>3</sup>Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil  
<sup>4</sup>Institute of High Energy Physics, Beijing, People's Republic of China  
<sup>5</sup>Universidad de los Andes, Bogotá, Colombia  
<sup>6</sup>Charles University, Center for Particle Physics, Prague, Czech Republic  
<sup>7</sup>Institute of Physics, Academy of Sciences, Center for Particle Physics, Prague, Czech Republic  
<sup>8</sup>Universidad San Francisco de Quito, Quito, Ecuador  
<sup>9</sup>Laboratoire de Physique Subatomique et de Cosmologie, IN2P3-CNRS, Université de Grenoble 1, Grenoble, France  
<sup>10</sup>CPPM, IN2P3-CNRS, Université de la Méditerranée, Marseille, France  
<sup>11</sup>Laboratoire de l'Accélérateur Linéaire, IN2P3-CNRS, Orsay, France  
<sup>12</sup>LPNHE, Universités Paris VI and VII, IN2P3-CNRS, Paris, France  
<sup>13</sup>DAPNIA/Service de Physique des Particules, CEA, Saclay, France  
<sup>14</sup>Universität Mainz, Institut für Physik, Mainz, Germany  
<sup>15</sup>Panjab University, Chandigarh, India  
<sup>16</sup>Delhi University, Delhi, India  
<sup>17</sup>Tata Institute of Fundamental Research, Mumbai, India  
<sup>18</sup>CINVESTAV, Mexico City, Mexico  
<sup>19</sup>FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands  
<sup>20</sup>University of Nijmegen/NIKHEF, Nijmegen, The Netherlands  
<sup>21</sup>Joint Institute for Nuclear Research, Dubna, Russia  
<sup>22</sup>Institute for Theoretical and Experimental Physics, Moscow, Russia  
<sup>23</sup>Moscow State University, Moscow, Russia  
<sup>24</sup>Institute for High Energy Physics, Protvino, Russia  
<sup>25</sup>Lancaster University, Lancaster, United Kingdom  
<sup>26</sup>Imperial College, London, United Kingdom  
<sup>27</sup>University of Arizona, Tucson, Arizona 85721, USA  
<sup>28</sup>Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA  
<sup>29</sup>University of California, Davis, California 95616, USA  
<sup>30</sup>California State University, Fresno, California 93740, USA  
<sup>31</sup>University of California, Irvine, California 92697, USA  
<sup>32</sup>University of California, Riverside, California 92521, USA  
<sup>33</sup>Florida State University, Tallahassee, Florida 32306, USA  
<sup>34</sup>Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA  
<sup>35</sup>University of Illinois at Chicago, Chicago, Illinois 60607, USA  
<sup>36</sup>Northern Illinois University, DeKalb, Illinois 60115, USA  
<sup>37</sup>Northwestern University, Evanston, Illinois 60208, USA  
<sup>38</sup>Indiana University, Bloomington, Indiana 47405, USA  
<sup>39</sup>University of Notre Dame, Notre Dame, Indiana 46556, USA  
<sup>40</sup>Iowa State University, Ames, Iowa 50011, USA  
<sup>41</sup>University of Kansas, Lawrence, Kansas 66045, USA  
<sup>42</sup>Kansas State University, Manhattan, Kansas 66506, USA  
<sup>43</sup>Louisiana Tech University, Ruston, Louisiana 71272, USA  
<sup>44</sup>University of Maryland, College Park, Maryland 20742, USA  
<sup>45</sup>Boston University, Boston, Massachusetts 02215, USA  
<sup>46</sup>Northeastern University, Boston, Massachusetts 02115, USA  
<sup>47</sup>University of Michigan, Ann Arbor, Michigan 48109, USA  
<sup>48</sup>Michigan State University, East Lansing, Michigan 48824, USA  
<sup>49</sup>University of Nebraska, Lincoln, Nebraska 68588, USA  
<sup>50</sup>Columbia University, New York, New York 10027, USA  
<sup>51</sup>University of Rochester, Rochester, New York 14627, USA  
<sup>52</sup>State University of New York, Stony Brook, New York 11794, USA  
<sup>53</sup>Brookhaven National Laboratory, Upton, New York 11973, USA  
<sup>54</sup>Langston University, Langston, Oklahoma 73050, USA  
<sup>55</sup>University of Oklahoma, Norman, Oklahoma 73019, USA  
<sup>56</sup>Brown University, Providence, Rhode Island 02912, USA  
<sup>57</sup>University of Texas, Arlington, Texas 76019, USA  
<sup>58</sup>Rice University, Houston, Texas 77005, USA  
<sup>59</sup>University of Virginia, Charlottesville, Virginia 22901, USA  
<sup>60</sup>University of Washington, Seattle, Washington 98195, USA

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A search for narrow resonances that decay into  $t\bar{t}$  pairs has been performed using  $130 \text{ pb}^{-1}$  of data in the lepton + jets channel collected by the DØ detector in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$ . There is no significant deviation observed from the standard-model predictions at a top-quark mass of  $175 \text{ GeV}/c^2$ . We therefore present upper limits at the 95% confidence level on the product of the production cross section and branching fraction to  $t\bar{t}$  for narrow resonances as a function of the resonance mass  $M_X$ . These limits are used to exclude the existence of a leptophobic top-color particle with mass  $M_X < 560 \text{ GeV}/c^2$ , using a theoretical cross section for a width  $\Gamma_X = 0.012M_X$ .

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Narrow resonances decaying to  $t\bar{t}$  pairs are predicted by several theories beyond the standard model. For instance, in the top-color-assisted technicolor model [1] which combines top-color [2] and technicolor [3] models, the technicolor interactions at the electroweak scale are responsible for electroweak symmetry breaking, and extended technicolor generates the masses of all quarks and leptons except that of the top quark. The strong top-color interactions, broken near 1 TeV, induce a massive dynamical  $t\bar{t}$  condensate and all but a few GeV of the top-quark mass, and contribute little to electroweak symmetry breaking. The  $t\bar{t}$  condensate, or the heavy  $Z'$  boson, couples preferentially to the third generation. In one of the scenarios of the top-color-assisted technicolor model the heavy  $Z'$  boson couples preferentially to the third quark generation, and not to leptons (leptophobic). The cross section for the  $Z'$  boson in this model is large enough for it to be observed over a wide range of masses and widths in data available from the 1.8 TeV  $p\bar{p}$  Tevatron Collider at Fermilab.

In searches for such heavy particles or narrow resonances, we seek an excess of events beyond that predicted by the standard model in the distribution of the invariant mass of  $t\bar{t}$  decay products. This excess of events would appear as a peak at the mass of the narrow resonance. Previous searches at the Tevatron have limited a leptophobic  $Z'$  boson to a mass higher than  $480 \text{ GeV}/c^2$  [4]. In this paper, we describe a direct search for narrow  $t\bar{t}$  resonances in the inclusive decay modes  $t\bar{t} \rightarrow \ell\nu + \geq 4 \text{ jets}$ , where  $\ell = \text{an electron } (e) \text{ or a muon } (\mu)$ , using  $130 \text{ pb}^{-1}$  of data recorded by the DØ experiment from 1992 to 1996. Having observed no significant deviation from the standard model, we present model-independent 95% confidence-level (C.L.) upper limits on the product of the cross section ( $\sigma_X$ ) and branching fraction ( $B$ ) to  $t\bar{t}$ , for a narrow resonance. We also present a lower limit on the resonance mass ( $M_X$ ) of the  $Z'$  boson in a particular scenario of the top-color-assisted technicolor model [1].

The DØ detector is a multipurpose particle detector designed to study  $p\bar{p}$  collisions at the Fermilab Tevatron Collider. The detector consists of three major systems: a nonmagnetic central tracking system, a uranium/liquid-argon calorimeter, and a muon spectrometer. A detailed description of the DØ detector can be found in Ref. [5].

The present search rests upon techniques developed for the measurement of the mass of the top quark at DØ in the

lepton + jets channel [6]. Because of the large mass of the top quark ( $m_t$ ), the  $t\bar{t} \rightarrow \ell\nu + \geq 4 \text{ jets}$  final state is characterized by a high- $p_T$  isolated lepton ( $e$  or  $\mu$ ) and large missing transverse energy ( $\cancel{E}_T$ ) from the undetected neutrino. Additional soft muons ( $\mu$  tags) from semileptonic decays of  $b$  and  $c$  quarks occur in  $\approx 20\%$  of  $t\bar{t}$  events but only in  $\approx 2\%$  of non- $t\bar{t}$  events [7], and therefore offer discrimination between signal and background. We consider two orthogonal classes of events for this analysis: (i) a purely topological selection of lepton + jets events denoted as  $e + \text{jets}$  and  $\mu + \text{jets}$ , where the jets are required not to contain a muon, and (ii) a selection based primarily on the presence of a muon contained within a jet ( $\mu$  tag), and additional selections on the topology of the event. These events are denoted as  $e + \text{jets}/\mu$  and  $\mu + \text{jets}/\mu$ . Details of the trigger requirements, reconstruction of events, and identification of the  $e$ ,  $\mu$ ,  $\cancel{E}_T$ , and jets can be found in Ref. [6]. The principal sources of background correspond to standard-model  $t\bar{t}$  production,  $W(\rightarrow \ell\nu) + \text{jets}$  production, and production of multijets ( $N_j \approx 5$ ), in which one of the jets is misidentified as a lepton and  $\cancel{E}_T$  stems from jet-energy mismeasurement. The contribution from all other physics sources is negligible.

In order to reduce the contribution from  $W + \text{jets}$  and multijets we apply the selections summarized in Table I. In the untagged channels, the cuts on  $E_T^W (\equiv |E_T^l| + |\cancel{E}_T|)$  and  $\eta^W$  are applied to further reduce the background from multijets. The variable  $\eta^W$  is determined by using the smaller of the two solutions for  $p_z^l$ , the longitudinal component of the neutrino momentum, obtained while performing a kinematic fit to  $W \rightarrow l\nu$  decay using the  $W$  mass as a constraint. In the tagged channels, the multijet background is further reduced by applying selections on  $\Delta\phi(\cancel{E}_T, \mu)$  which is the difference in the azimuthal angle between  $\cancel{E}_T$  and the highest- $p_T$  muon. We also apply a cut on the  $\chi^2$  from a kinematic fit to the  $t\bar{t} \rightarrow \ell\nu + \text{jets}$  hypothesis described later.

The resonance signal  $X \rightarrow t\bar{t}$  is modeled using the PHTHIA-6.1 [8] Monte Carlo (MC) event generator, with  $m_t = 175 \text{ GeV}/c^2$ , and CTEQ3M [9] parton distribution functions. Initial- and final-state radiation (ISR/FSR) is included. About 10 000 events at eight resonance masses between 400 and  $850 \text{ GeV}/c^2$  are generated, using a width  $\Gamma_X = 0.012M_X$ . This width is significantly smaller than the  $\approx 0.04M_X$  mass resolution of the DØ detector for

TABLE I. Summary of event selections. Here  $\cancel{E}_T^{\text{cal}}$  is the missing transverse energy measured just in the calorimeter.

	$e + \text{jets}$	$\mu + \text{jets}$	$e + \text{jets}/\mu$	$\mu + \text{jets}/\mu$
Lepton ( $l$ )	$E_T^l > 20 \text{ GeV}$ $ \eta  < 2$	$p_T^l > 20 \text{ GeV}/c$ $ \eta  < 1.7$	$E_T^l > 20 \text{ GeV}$ $ \eta  < 2$	$p_T^l > 20 \text{ GeV}/c$ $ \eta  < 1.7$
$\cancel{E}_T$	$\cancel{E}_T > 20 \text{ GeV}$ $\cancel{E}_T^{\text{cal}} > 25 \text{ GeV}$	$\cancel{E}_T > 20 \text{ GeV}$ $\cancel{E}_T^{\text{cal}} > 20 \text{ GeV}$	$\cancel{E}_T > 20 \text{ GeV}$	$\cancel{E}_T > 20 \text{ GeV}$ $\cancel{E}_T^{\text{cal}} > 20 \text{ GeV}$
Jets	$\geq 4 \text{ jets}$ $E_T > 15 \text{ GeV}$ $ \eta  < 2$	$\geq 4 \text{ jets}$ $E_T > 15 \text{ GeV}$ $ \eta  < 2$	$\geq 4 \text{ jets}$ $E_T > 15 \text{ GeV}$ $ \eta  < 2$	$\geq 4 \text{ jets}$ $E_T > 15 \text{ GeV}$ $ \eta  < 2$
$\mu$ tag	No	No	Yes	Yes
Other	$ \cancel{E}_T  +  E_T^l  > 60 \text{ GeV}$ $ \eta^W  < 2$	$ \cancel{E}_T  +  p_T^l  > 60 \text{ GeV}$ $ \eta^W  < 2$	$\cancel{E}_T > 35 \text{ GeV}$ if $\Delta\phi(\cancel{E}_T, \mu) < 25^\circ$	$\Delta\phi(\cancel{E}_T, \mu) < 170^\circ$ $ \Delta\phi(\cancel{E}_T, \mu) - 90^\circ /90^\circ < \cancel{E}_T/(45 \text{ GeV})$
Events passing above cuts and $\chi^2 < 10$	16	21	1	3

$t\bar{t}$  systems [10]. Hence, our upper limits on  $\sigma_X B$  are dominated by the detector resolution and independent of  $\Gamma_X$  for such narrow resonances and are valid for all choices of  $\Gamma_X$  that are reasonably small compared to the detector resolution. The generated events are processed through the DØGEANT detector simulation package [11] and reconstructed using the DØ event-reconstruction program.

The background is estimated from a combination of Monte Carlo simulations and collider data [6]. Standard-model  $t\bar{t}$  production is modeled using the HERWIG-5.7 [12] MC generator with a top mass  $m_t = 175 \text{ GeV}/c^2$ . The  $W + \text{jets}$  background is modeled using the VECBOS [13] parton-level event generator whose output is passed through HERWIG for QCD evolution and fragmentation. The background from multijets is estimated using signal-suppressed data samples. The selections summarized in Table I are also applied to the Monte Carlo signal and background samples.

Each event in data, as well as in the Monte Carlo signal and background samples, is fitted to a three-constraint hypothesis for the  $t\bar{t}$  production and decay:

$$t\bar{t} \rightarrow W^+ b W^- \bar{b}; \quad W^\pm \rightarrow l^\pm \nu_l; \quad W^\mp \rightarrow q \bar{q}'. \quad (1)$$

The inputs to the fit are the measured kinematic parameters of the lepton and the jets, and the missing transverse energy vector,  $\vec{\cancel{E}}_T$ . We minimize  $\chi^2 = (\mathbf{x} - \mathbf{x}^m)^T \mathbf{G} (\mathbf{x} - \mathbf{x}^m)$ , where  $\mathbf{x}^m(\mathbf{x})$  is the vector for measured (fitted) variables, and  $\mathbf{G}^{-1}$  is its error matrix [6]. The two reconstructed  $W$  boson masses are constrained to the pole mass  $M_W$  of the  $W$  boson, and the reconstructed  $t$  and  $\bar{t}$  quark masses are set to  $m_t = 173.3 \text{ GeV}/c^2$  as measured by DØ [6]. The bias introduced due to the difference in the top-quark mass used in the fit and that in the MC simulation of signal and background is negligible. Only the four highest- $E_T$  jets are used in the kinematic fit. All other jets are assumed to be due to initial-state radiation, and

are ignored. There are six (12) possible assignments of these jets to quarks in the events with (without) a  $\mu$  tag, each having two solutions for  $p_z^l$ . For every possible permutation, we apply additional parton-level and  $\eta$ -dependent jet corrections derived using data and Monte Carlo simulations [6]. We apply a loose selection on the reconstructed mass,  $M(q\bar{q})$ , of the hadronically decaying  $W$  boson,  $40 < M(q\bar{q}) < 140 \text{ GeV}/c^2$ , before the fit, to reduce computation. The results of the fit with the lowest  $\chi^2$  are used to reconstruct the invariant mass ( $M_{t\bar{t}}$ ) of the  $t\bar{t}$  system. It is observed that the jet permutation with the lowest  $\chi^2$  is the correct choice for  $\approx 20\%$  of all Monte Carlo  $t\bar{t}$  events [6]. We require  $\chi^2 < 10$  to further reduce non- $t\bar{t}$  background, whereupon summing all four classes of events 41 events are left in the data sample of which four are  $\mu$  tagged.

For each  $M_X$  sample generated by Monte Carlo, we perform a fit based on Bayesian statistics [14] to determine the number of events expected from signal and background in the observed lepton + jets data sample. We fit [10] the data to a three-source model comprised of  $n_1$  signal events ( $X \rightarrow t\bar{t}$ ),  $n_2$  background events from standard-model  $t\bar{t}$  production, and  $n_3$  events due to the combined backgrounds from  $W + \text{jets}$  and multijets in the ratio 0.78:0.22. That ratio is based on their relative proportions in the top-quark mass analysis at DØ [6]. We define [10] a likelihood ( $L$ ) and a posterior probability  $P(n_1, n_2, n_3, M_X|D)$  for obtaining  $n_1$ ,  $n_2$ , and  $n_3$  events from the three respective sources, for a model specified by  $M_X$ . Given the observed data set  $D$ , we can write

$$P(n_1, n_2, n_3, M_X|D) = \frac{L(D|n_1, n_2, n_3, M_X)w(n_1, n_2, n_3|M_X)}{\mathcal{N}'}, \quad (2)$$

where  $w$  denotes the joint prior probability for the three-source strengths, and  $\mathcal{N}'$  is a normalization that is obtained from the requirement

TABLE II. The fitted number of events for signal,  $\langle n_1 \rangle$ , and background from standard-model  $t\bar{t}$  production,  $\langle n_2 \rangle$ , and  $W$  + jets and multijets,  $\langle n_3 \rangle$ , for different  $M_X$ . After all selections, 41 events are observed in the  $M_{t\bar{t}}$  distribution of lepton + jets data.

$M_X$ (GeV/ $c^2$ )	$\langle n_1 \rangle$	$\langle n_2 \rangle$	$\langle n_3 \rangle$	Background $\langle n_2 \rangle + \langle n_3 \rangle$
400	$9.0 \pm 7.0$	$20.5 \pm 10.8$	$13.9 \pm 10.2$	$34.4 \pm 14.9$
500	$4.9 \pm 4.2$	$22.2 \pm 11.5$	$15.3 \pm 10.5$	$37.5 \pm 15.6$
600	$4.2 \pm 3.2$	$23.7 \pm 11.6$	$15.4 \pm 10.6$	$39.0 \pm 15.7$
750	$1.6 \pm 1.6$	$26.8 \pm 11.7$	$12.6 \pm 9.9$	$39.4 \pm 15.3$

$$\int P(n_1, n_2, n_3, M_X | D) dn_1 dn_2 dn_3 = 1. \quad (3)$$

$$\langle n_j \rangle = \iiint n_j P(n_1, n_2, n_3, M_X | D) dn_1 dn_2 dn_3. \quad (5)$$

We assume Poisson statistics for the likelihood and flat priors for each of the three sources. Bayesian integration [14] over possible signal and background populations in each bin  $i$  of the  $M_{t\bar{t}}$  distribution yields the likelihood

$$L(D | n_1, n_2, n_3, M_X) = \prod_{i=1}^M \sum_{k_1, k_2, k_3=0}^{D_i} \prod_{j=1}^3 \binom{A_{ji} + k_j}{k_j} \times \frac{p_j^{k_j}}{(1 + p_j)^{A_{ji} + k_j + 1}}, \quad (4)$$

where  $D_i$  ( $A_{ji}$ ) is the number of events in bin  $i$  for data (Monte Carlo source  $j$ ); the indices  $k_j$  satisfy the multinomial constraint  $\sum_{j=1}^3 k_j = D_i$ , and  $p_j = n_j / (M + \sum_{i=1}^M A_{ji})$  is an estimate of the strength of the  $j$ th source ( $j = 1, 2, 3$ ), where  $M$  is the number of bins. The expected number of counts from any source  $j$  can be obtained from the fit as

The fitted number of events for signal ( $\langle n_1 \rangle$ ) and the two background sources ( $\langle n_2 \rangle$  and  $\langle n_3 \rangle$ ) are listed in Table II for several values of  $M_X$ . The observed  $M_{t\bar{t}}$  distribution and the corresponding distributions from the three Monte Carlo sources normalized to  $\langle n_1 \rangle$ ,  $\langle n_2 \rangle$ , and  $\langle n_3 \rangle$ , respectively, for  $M_X = 400$  GeV/ $c^2$ , are shown in Fig. 1. There is no significant deviation from the standard-model prediction. Similar agreement is observed for other choices of resonance mass.

In the absence of a signal, we proceed to set upper limits on the product of the production cross section of  $X$  and branching fraction to  $t\bar{t}$ ,  $\sigma_X B$ , by expressing  $n_1 = \mathcal{A} \mathcal{L} \sigma_X B$  in Eq. (2), where  $\mathcal{A}$  is the acceptance for  $X \rightarrow t\bar{t}$  events and  $\mathcal{L}$  is the integrated luminosity. Integrating over  $n_2$  and  $n_3$ , we define for every  $M_X$  the upper limit on  $\sigma_X B$  at the 95% confidence level as

$$\int_0^{(\sigma_X B)_{95}} P(\sigma_X B, M_X | D) d(\sigma_X B) = 0.95. \quad (6)$$

The expected shapes of distributions for background and signal, and the acceptance for signal, are subject to several sources of systematic uncertainty. The uncertainty due to the jet-energy scale is estimated by rescaling the jet energies by  $\pm(2.5\% + 0.5 \text{ GeV})$  [6] before applying any selections to the signal Monte Carlo events. For the contribution from ISR/FSR, we compare the acceptance for the signal with and without ISR/FSR (in PYTHIA). For the uncertainty from the choice of parton distribution functions, we compare the signal acceptance for the two

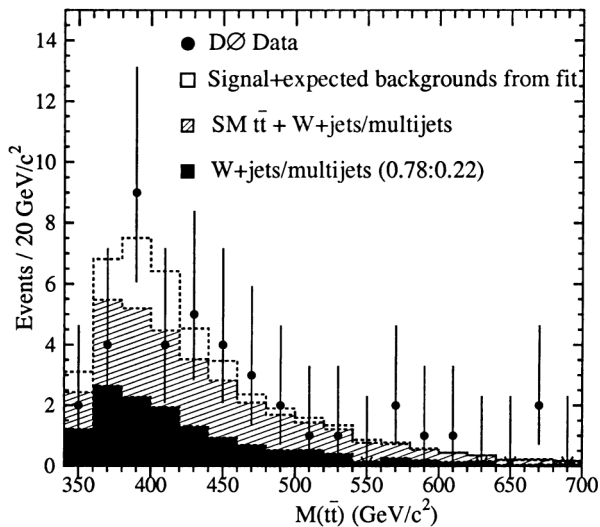


FIG. 1. Distributions of  $M_{t\bar{t}}$  obtained from the fit, for the sum of signal ( $X \rightarrow t\bar{t}$ ) and all standard-model backgrounds (open histogram), sum of all standard-model backgrounds (hatched histogram), and  $W$  + jets and multijets (solid histogram), for  $M_X = 400$  GeV/ $c^2$ . The data correspond to the dots with their statistical errors.

TABLE III. The fractional uncertainty in the product  $\mathcal{A} \mathcal{L}$  from different sources, for  $M_X = 400$  GeV/ $c^2$ .

MC statistics	3.3%
Trigger efficiency	3.6%
$e/\mu$ identification	3.8%
Luminosity	4.3%
Jet energy scale	7.4%
ISR/FSR	16.0%
Parton distribution functions	15.0%
Total	24.3%

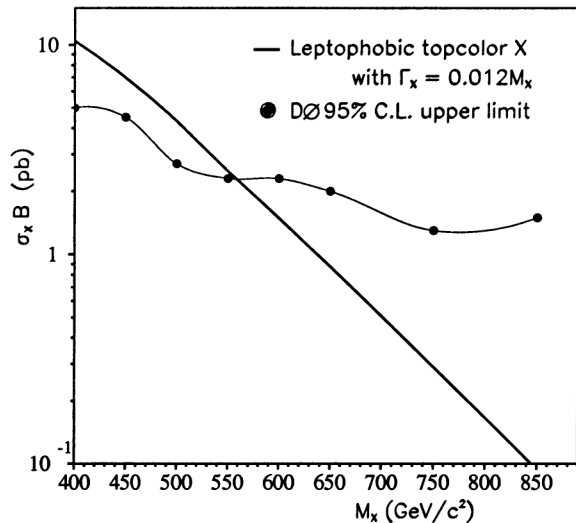


FIG. 2. The 95% C.L. upper limit on  $\sigma_X B$  as a function of resonance mass  $M_X$ . Included for reference is the  $\sigma_X B$  predicted by the top-color-assisted technicolor model for a width  $\Gamma_X = 0.012M_X$ .

parton distribution sets CTEQ3M and GRV94L [15]. We also consider the uncertainties in trigger efficiency, lepton identification, and integrated luminosity. All the sources of statistical and systematic uncertainty in the product  $\mathcal{A}\mathcal{L}$  are listed in Table III for  $M_X = 400 \text{ GeV}/c^2$  [10]. For each  $M_X$ , we convolute the posterior probability density  $P(\sigma_X B, M_X|D)$  with a Gaussian prior for  $\mathcal{A}\mathcal{L}$ , with the estimated value of  $\mathcal{A}\mathcal{L}$  as the mean of the Gaussian and its uncertainty as 1 standard deviation from the mean. The upper limits on  $\sigma_X B$  at the 95% confidence level obtained using (6), and integrating over  $\mathcal{A}\mathcal{L}$ , vary between 5.0 pb at  $M_X = 400 \text{ GeV}/c^2$  and 1.5 pb at  $M_X = 850 \text{ GeV}/c^2$ , as shown in Fig. 2. These limits are valid as long as the width of the resonance,  $\Gamma_X$ , is reasonably small compared to the DØ detector resolution. Also plotted in Fig. 2 is the theoretical prediction for  $\sigma_X B$  for a leptophobic top color of width  $\Gamma_X = 0.012M_X$  [10], which we use to exclude at the 95% C.L. the existence of the leptophobic  $Z'$  boson with mass  $M_X < 560 \text{ GeV}/c^2$ , for a width  $\Gamma_X = 0.012M_X$ .

In conclusion, after investigating  $130 \text{ pb}^{-1}$  of data, we find no statistically significant evidence for a narrow  $t\bar{t}$  resonance at  $m_t = 175 \text{ GeV}/c^2$ , and establish upper limits on  $\sigma_X B$  at the 95% C.L. for  $M_X$  between 400 and  $850 \text{ GeV}/c^2$ . We also exclude at the 95% C.L. the existence of a leptophobic  $Z'$  boson with mass  $M_X < 560 \text{ GeV}/c^2$ , for a width  $\Gamma_X = 0.012M_X$ .

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\*Visitor from University of Zurich, Zurich, Switzerland.

†Visitor from Institute of Nuclear Physics, Krakow, Poland.

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