Search for Production of Heavy Particles Decaying to Top Quarks and Invisible Particles in $pp[\overline{p}]$ Collisions at $\sqrt{s}=1.96\text{TeV}$

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Search for Production of Heavy Particles Decaying to Top Quarks and Invisible Particles in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV
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Despite an intensive program of research [1], the precise nature of dark matter remains elusive, though it is clear that it must be long-lived on cosmological time scales. Such a long lifetime could be due to a conserved charge under an unbroken symmetry. However, none of the unbroken symmetries of the standard model (SM) suffice to provide such a charge, so it follows that dark matter must be charged under a new, unbroken symmetry. The prospects of creating dark matter at particle colliders are excellent, but only if the dark matter particles $X$ couple to standard model particles directly or indirectly. One potential mechanism is via a connector particle $Y$, which carries SM charges so
that it can be produced at particle colliders as well as carrying the new dark charge, so that it can decay to the dark matter particle, \( Y \rightarrow f + X \), where \( f \) is a SM particle. One compelling recent model \([2]\) uses an exotic fourth generation up-type quark \( T' \) as the connector particle, which decays to a top quark and dark matter, \( T' \rightarrow t + X \). Current direct and indirect bounds on such exotic quarks restrict their masses to be between 300 and 600 GeV \([2]\).

The pair production of such exotic quarks and their subsequent decay to top quarks and dark matter has a collider signal comprising of top-quark pairs \((t\bar{t})\) and missing transverse momentum \((E_T)\) due to the invisible dark matter particles. These types of signals, in general, are of great interest as they appear in numerous new physics scenarios including many dark matter motivated models, little Higgs models with \( T \)-parity conservation \([3]\) and models in which baryon and lepton numbers are gauge symmetries \([4]\). Supersymmetry, which includes a natural dark matter candidate and provides a framework for unification of the forces, also predicts a \( t\bar{t} + E_T \) signal from the decay of a supersymmetric top quark to a top quark and the lightest supersymmetric particle \([5]\), \( \tilde{t} \rightarrow t + \chi^0 \). There are currently no experimental bounds on a new heavy particle \( Y \) decaying via \( Y \rightarrow t + X \).

This Letter reports a search for such a generic signal \( t\bar{t} + E_T \) via the pair production of a heavy new particle \( T' \) with prompt decay \( T' \rightarrow t + X \). We consider the mode \( pp \rightarrow t\bar{t} + X + X \rightarrow Wb\bar{W}b + X + X \) in which one \( W \) decays leptonically (including \( \tau \) decays to \( e \) or \( \mu \)) and one decays hadronically to \( qq' \), this decay mode allows for large branching ratios while suppressing SM backgrounds. Such a signal is similar to top-quark pair production and decay, but with additional missing transverse energy due to the invisible particles.

Events were recorded by CDF II \([6]\), a general purpose detector designed to study collisions at the Fermilab Tevatron \( pp \) collider at \( \sqrt{s} = 1.96 \) TeV. A charged-particle tracking system immersed in a 1.4 T magnetic field consists of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies and drift chambers located outside the calorimeters detect muons. We use a data sample corresponding to an integrated luminosity of \( 4.8 \pm 0.3 \) fb\(^{-1}\).

The data acquisition system is triggered by \( e \) or \( \mu \) candidates \([7]\) with transverse momentum \( p_T \) \([8]\) greater than 18 GeV\( /c \). Electrons and muons are reconstructed offline and are selected if they have a pseudorapidity \( \eta \) \([8]\) magnitude less than 1.1, \( p_T \geq 20 \) GeV\( /c \) and satisfy the standard identification and isolation requirements \([7]\). Jets are reconstructed in the calorimeter using the \textsc{JETCLU} \([9]\) algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space and corrected using standard techniques \([10]\). Jets are selected if they have \( p_T \geq 15 \) GeV\( /c \) and \( |\eta| < 2.4 \).

Missing transverse momentum \([11]\) is reconstructed using fully corrected calorimeter and muon information \([7]\). Production of \( T' \) pairs and their subsequent decays to top-quark pairs and two dark matter particles would appear as events with a charged lepton and missing transverse momentum from one leptonically decaying \( W \) and the two dark matter particles, and four jets from the two \( b \) quarks and the hadronic decay of the second \( W \) boson. We select events with at least one electron or muon, at least four jets, and large missing transverse momentum. The missing transverse energy in a signal event depends on the masses \( m_{T'} \) and \( m_X \), for each pair of signal masses we optimize for the minimum amount of missing transverse energy required (ranging from 100 GeV\( /c \) to 160 GeV\( /c \)).

We model the production and decay of \( T' \) pairs with \textsc{madgraph} \([12]\). Additional radiation, hadronization and showering are described by \textsc{pythia} \([13]\). The detector response for all simulated samples is modeled by the official CDF detector simulation.

The dominant SM background is top-quark pair production. We model this background using \textsc{pythia} \( t\bar{t} \) production with \( m_t = 172.5 \) GeV\( /c^2 \). We normalize the \( t\bar{t} \) background to the NLO cross section \([14]\), and confirm that it is well modeled by examining \( t\bar{t} \)-dominated regions in the data.

The second dominant SM background process is the associated production of \( W \) boson and jets. Samples of simulated \( W +jets \) events with light- and heavy-flavor jets are generated using the \textsc{alpgen} \([15]\) program, interfaced with the parton-shower model from \textsc{pythia}. The \( W + jets \) samples are normalized to the measured \( W \) cross section, with an additional multiplicative factor for the relative contribution of heavy- and light-flavor jets, the standard technique in measuring the top-quark pair-production cross section \([16]\). Multijet background, in which a jet is misreconstructed as a lepton, is modeled using a jet-triggered sample normalized in a background-dominated region at low missing transverse momentum. The remaining backgrounds, single top and diboson production, are modeled using \textsc{pythia} and normalized to next-to-leading order cross sections \([17]\).

We differentiate the signal events from these backgrounds by comparing the reconstructed transverse mass of the leptonically decaying \( W \) candidate,

\[
m_T^W = m_T(p_T', p_T) = \sqrt{2|p_T'||p_T|(1 - \cos [\Delta \phi (p_T', p_T)])},
\]

where \( p_T' \) is the transverse momentum of the lepton and \( p_T \) is the missing transverse momentum. In background events, the \( p_T \) comes primarily from the neutrino in \( W \rightarrow \ell \nu \) decay, and \( m_T^W \) will show a strong peak at the \( W \)-boson mass. The signal event, \( T' \rightarrow t + X \), has additional missing transverse momentum due to the invisible particles \( X \) and thus does not reconstruct the \( W \) mass in \( m_T^W \). Figure 1 shows the \( m_T^W \) distributions of the backgrounds versus the signals.
We consider several sources of systematic uncertainty on both the background rates and distributions, as well as on the expectations for the signal. Each affects the expected sensitivity to new physics expressed as an expected cross-section upper limit in the no-signal assumption. The dominant systematic uncertainties are the jet energy scale [10], contributions from additional interactions, and descriptions of initial and final state radiation [18]. In each case, we treat the unknown underlying quantity as a nuisance parameter and measure the distortion of the $m_T$ spectrum for positive and negative fluctuations. As mentioned before we optimize the minimum missing transverse energy required for each signal point, Table I compares the number of events expected with uncertainties for backgrounds and signals to data for two example missing transverse energy cuts.

We validate our modeling of the SM backgrounds in two background-dominated control regions. We validate our modeling of the large $m_T$ region in events with high missing transverse energy and exactly three jets, and validate our modeling of four-jet events in events with small missing transverse energy ($< 100 \text{ GeV}/c$). Figure 2 shows good agreement of our background modeling with data in the control regions.

![FIG. 1. Reconstructed transverse mass of the W, $m_T$, for the standard model backgrounds, the observed data, and for three choices of ($m_T$, $m_X$).](image1)

![FIG. 2 (color online). Reconstructed transverse mass of the W, $m_T$, in signal-depleted control regions. Left, events with at least four jets and small missing transverse momentum ($< 100 \text{ GeV}/c$). Right, events with exactly three jets and large missing transverse momentum ($> 100 \text{ GeV}/c$).](image2)

**TABLE I.** Number of events, for example, signal points compared to backgrounds and data for two $E_T$ cuts after initial selection is made.

<table>
<thead>
<tr>
<th>Cut:</th>
<th>$E_T \geq 100 \text{ GeV}/c$</th>
<th>$E_T \geq 150 \text{ GeV}/c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t'T' \rightarrow tXX$ ($\text{GeV}/c^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_T$, $m_X = 300$, 90</td>
<td>22.9$^{+5.8}_{-4.7}$</td>
<td>4.1$^{+2.4}_{-2.1}$</td>
</tr>
<tr>
<td>$m_T$, $m_X = 310$, 80</td>
<td>22.6$^{+5.4}_{-4.3}$</td>
<td>6.4$^{+2.3}_{-2.0}$</td>
</tr>
<tr>
<td>$m_T$, $m_X = 330$, 70</td>
<td>17.6$^{+3.6}_{-2.6}$</td>
<td>7.3$^{+2.3}_{-2.0}$</td>
</tr>
<tr>
<td>$m_T$, $m_X = 350$, 1</td>
<td>13.1$^{+2.7}_{-2.2}$</td>
<td>6.7$^{+2.0}_{-1.9}$</td>
</tr>
<tr>
<td>$t$ &amp; $189^{+54}<em>{-50}$ &amp; 26.3$^{+11.6}</em>{-9.8}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W + jets &amp; 105$^{+31}<em>{-26}$ &amp; 16.6$^{+4.5}</em>{-3.1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single top &amp; 1.86 $^{+0.2}<em>{-0.1}$ &amp; 0.18 $^{+0.02}</em>{-0.02}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diboson &amp; 9.69 $^{+0.1}<em>{-0.1}$ &amp; 1.53 $^{+0.1}</em>{-0.1}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z + jets &amp; 4.00 $^{+0.4}<em>{-0.4}$ &amp; 0.46 $^{+0.05}</em>{-0.05}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QCD</td>
<td>0.04 $^{+0.01}_{-0.01}$</td>
<td>0.04 $^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>Total Background &amp; 310$^{+80}<em>{-71}$ &amp; 45$^{+14}</em>{-11}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data &amp; 309 &amp; 42</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
maximum-likelihood fit in the $m_T^W$ variable, allowing for systematic and statistical fluctuations via template morphing [19] which performs an interpolation in each bin as a function of the nuisance parameters. We use the likelihood-ratio ordering prescription [20] to construct classical confidence intervals in the theoretical cross section by describing expected fluctuations of statistical and systematic uncertainties on both signal and backgrounds. The observed limits are consistent with expectation in the background-only hypothesis, for a few example signal mass points we tabulate the expected and observed limits along with uncertainties on both signal and backgrounds. The observed limits are consistent with expectation in the background-only hypothesis, for a few example signal mass points we tabulate the expected and observed limits along with uncertainties on both signal and backgrounds.

In conclusion, we have searched for new physics particles $T^\prime$ decaying to top quarks with invisible particles $X$ with a detector signature of $t\bar{t} + E_T$. We calculate upper limits on the cross section of such events and exclude any dark matter model involving exotic fourth generation quark up to $m_{T^\prime} = 360 \text{ GeV}/c^2$. Our cross-section limits on the generic decay, $T^\prime \rightarrow t + X$, may be applied to the many other models that predict the production of a heavy particle $T^\prime$ decaying to top quarks and invisible particles $X$, such as the supersymmetric process $\tilde{t} \rightarrow t + \chi^0$. A similar search performed at the LHC, given its higher energy regime, would be able to provide limits on such a supersymmetric decay.

We 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 World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

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**TABLE II.** Expected 95% C.L. upper limit on $T^\prime T^\prime$ production cross section, $\sigma_{\text{exp}}$, the range of expected limits which includes 68% of pseudoeperiments, and the observed limit, $\sigma_{\text{obs}}$, for representative signal points in $(m_T^W, m_X)$.

<table>
<thead>
<tr>
<th>$m_T^W$, $m_X$ (GeV/$c^2$)</th>
<th>$\sigma_{\text{exp}}$ [pb]</th>
<th>+34%</th>
<th>-34%</th>
<th>$\sigma_{\text{obs}}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>200, 1</td>
<td>1.31</td>
<td>1.86</td>
<td>0.83</td>
<td>1.21</td>
</tr>
<tr>
<td>220, 40</td>
<td>1.40</td>
<td>2.17</td>
<td>0.93</td>
<td>1.20</td>
</tr>
<tr>
<td>260, 1</td>
<td>0.23</td>
<td>0.40</td>
<td>0.14</td>
<td>0.20</td>
</tr>
<tr>
<td>280, 1</td>
<td>0.16</td>
<td>0.27</td>
<td>0.09</td>
<td>0.15</td>
</tr>
<tr>
<td>280, 20</td>
<td>0.18</td>
<td>0.29</td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td>280, 40</td>
<td>0.17</td>
<td>0.27</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>300, 100</td>
<td>0.34</td>
<td>0.51</td>
<td>0.24</td>
<td>0.39</td>
</tr>
<tr>
<td>310, 90</td>
<td>0.19</td>
<td>0.29</td>
<td>0.11</td>
<td>0.21</td>
</tr>
<tr>
<td>320, 80</td>
<td>0.15</td>
<td>0.24</td>
<td>0.08</td>
<td>0.12</td>
</tr>
<tr>
<td>350, 50</td>
<td>0.07</td>
<td>0.10</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>360, 110</td>
<td>0.09</td>
<td>0.19</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>370, 1</td>
<td>0.06</td>
<td>0.10</td>
<td>0.04</td>
<td>0.05</td>
</tr>
</tbody>
</table>

---

**FIG. 3.** Observed versus expected exclusion in $(m_T^W, m_X)$ along with the cross-section upper limits.

---

aDeceased.
bWith visitors from University of Massachusetts Amherst, Amherst, MA 01003, USA.
cWith visitors from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.
dWith visitors from University of California Irvine, Irvine, CA 92697, USA.
eWith visitors from University of California Santa Barbara, Santa Barbara, CA 93106, USA.
fWith visitors from University of California Santa Cruz, Santa Cruz, CA 95064, USA.
gWith visitors from CERN,CH-1211 Geneva, Switzerland.
hWith visitors from Cornell University, Ithaca, NY 14853, USA.
iWith visitors from University of Cyprus, Nicosia CY-1678, Cyprus.
jWith visitors from University College Dublin, Dublin 4, Ireland.
kWith visitors from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.
lWith visitors from Universidad Iberoamericana, Mexico D.F., Mexico.
mWith visitors from Iowa State University, Ames, IA 50011, USA.
nWith visitors from University of Iowa, Iowa City, IA 52242, USA.
With visitors from Kinki University, Higashi-Osaka City, Japan 577-8502.

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With visitors from Yarmouk University, Irbid 211-63, Jordan.

On leave from J. Stefan Institute, Ljubljana, Slovenia.


8 CDF uses a cylindrical coordinate system with the z axis along the proton beam axis. Pseudorapidity is \( \eta = -\ln(\tan(\theta/2)) \), where \( \theta \) is the polar angle relative to the proton beam direction, and \( \phi \) is the azimuthal angle while \( \rho_T = |p| \sin \theta, E_T = E \sin \theta. \)


11 Missing transverse momentum, \( E_T \), is defined as the magnitude of the vector \( -\sum E_T \vec{n}_i \) where \( E_T \) 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.


