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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0031-9007/11/106(19)/191801(7)

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We present a search for a new particle T' decaying to top quark via $T' \to t + X$, where X is an invisible particle. In a data sample with 4.8 fb^{-1} of integrated luminosity collected by the CDF II detector at Fermilab in $p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV, we search for pair production of T' in the lepton + jets channel, $p\bar{p} \to t\bar{t} + X + X \to \ell\nu bqq'b + X + X$. We interpret our results primarily in terms of a model where T' are exotic fourth generation quarks and X are dark matter particles. Current direct and indirect bounds on such exotic quarks restrict their masses to be between 300 and 600 GeV$/c^2$, the dark matter particle mass being anywhere below $m_{T'}$. The data are consistent with standard model expectations, and we set 95% confidence level limits on the generic production of $T'\bar{T}' \to t\bar{t} + X + X$. For the dark matter model we exclude T' at 95% confidence level up to $m_{T'} = 360$ GeV$/c^2$ for $m_X \leq 100$ GeV$/c^2$.

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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($\not{E}_t$) 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 $t\bar{t} + \not{E}_t$ signal from the decay of a supersymmetric top $\tilde{t}$ 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 $t\bar{t} + \not{E}_t$ via the pair production of a heavy new particle T' with prompt decay $T' \rightarrow t + X$. We consider the mode $p\bar{p} \rightarrow t\bar{t} + X + X \rightarrow WbWb + X + X$ in which one W decays leptonically (including τ decays to e or μ) 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 $p\bar{p}$ 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 $4.8 \pm 0.3\ \text{fb}^{-1}$.

The data acquisition system is triggered by e or μ 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 η [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 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 MADGRAPH [12]. Additional radiation, hadronization and showering are described by 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 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 ALPGEN [15] program, interfaced with the parton-shower model from 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 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,

$$m_T^W \equiv m_T(p_T^\ell, \not{p}_T) = \sqrt{2|p_T^\ell||\not{p}_T|(1 - \cos[\Delta\phi(p_T^\ell, \not{p}_T)])},$$

where p_T^ℓ is the transverse momentum of the lepton and $\not{p}_T$ is the missing transverse momentum. In background events, the $\not{p}_T$ 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.

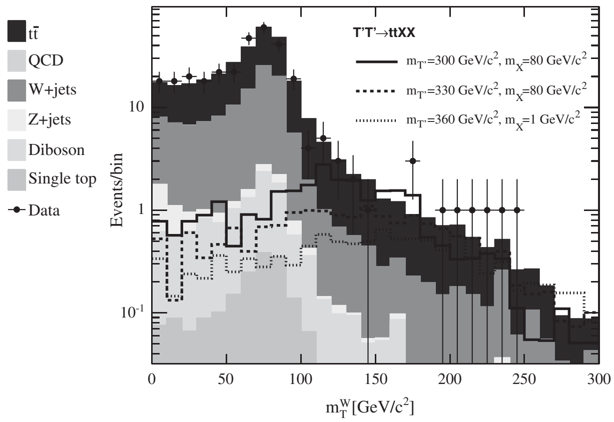

FIG. 1. Reconstructed transverse mass of the W, m_T^W, for the standard model backgrounds, the observed data, and for three choices of ($m_{T'}$, m_X).

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^W 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.

TABLE I. Number of events, for example, signal points compared to backgrounds and data for two $\not\!\!E_T$ cuts after initial selection is made.

Cut:	$\not\!\!E_T \geq 100$ GeV/c	$\not\!\!E_T \geq 150$ GeV/c
$T'T' \rightarrow ttXX$ [GeV/c^2]		
$m_{T'}$, m_X = 300, 90	$22.9^{+5.8}_{-4.7}$	$4.1^{+2.4}_{-2.1}$
$m_{T'}$, m_X = 310, 80	$22.6^{+4.9}_{-5.1}$	$6.4^{+2.3}_{-2.6}$
$m_{T'}$, m_X = 330, 70	$17.6^{+3.7}_{-3.6}$	$7.3^{+2.5}_{-2.4}$
$m_{T'}$, m_X = 350, 1	$13.1^{+2.7}_{-2.8}$	$6.7^{+2.0}_{-1.9}$
$t\bar{t}$	189^{+54}_{-50}	$26.3^{+11.6}_{-9.8}$
W + jets	105^{+31}_{-14}	$16.6^{+4.5}_{-2.1}$
Single top	1.86 ± 0.2	0.18 ± 0.02
Diboson	9.69 ± 0.1	1.53 ± 0.1
Z + jets	4.00 ± 0.4	0.46 ± 0.05
QCD	0.04 ± 0.01	0.04 ± 0.01
Total Background	310^{+80}_{-64}	45^{+14}_{-11}
Data	309	42

We validate our modeling of the SM backgrounds in two background-dominated control regions. We validate our modeling of the large m_T^W 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 GeV/c). Figure 2 shows good agreement of our background modeling with data in the control regions.

There is no evidence for the presence of $T' \rightarrow t + X$ events in the data. We calculate 95% C.L. upper limits on the $T' \rightarrow t + X$ cross section, by performing a binned

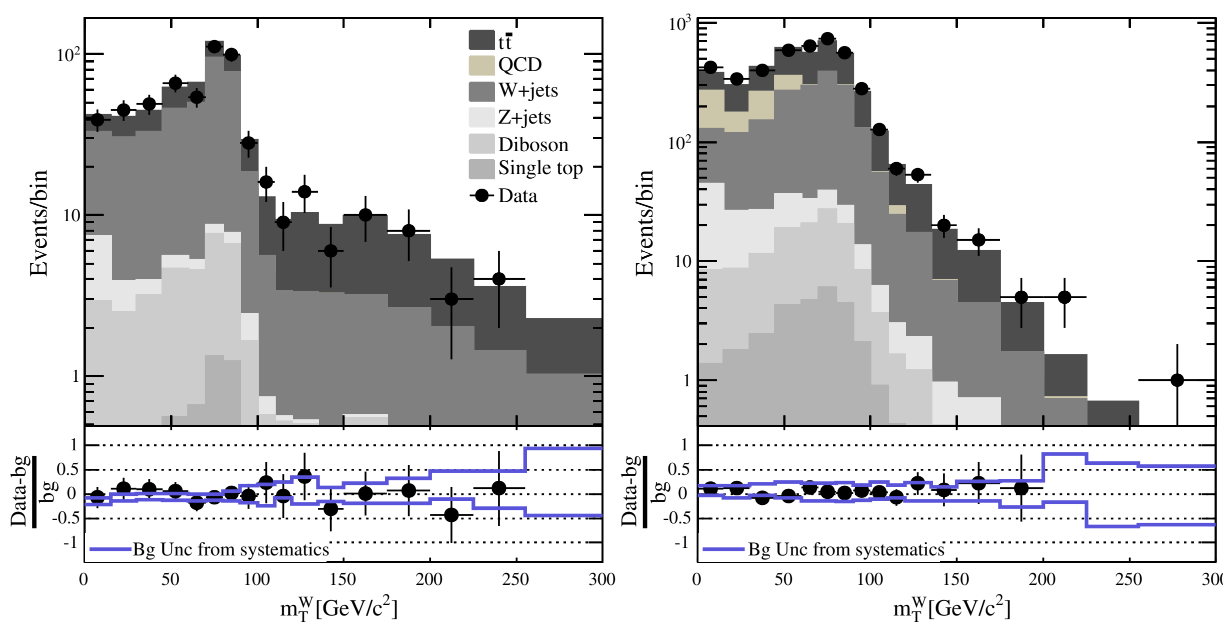

FIG. 2 (color online). Reconstructed transverse mass of the W, m_T^W, in signal-depleted control regions. Left, events with at least four jets and small missing transverse momentum (< 100 GeV/c). Right, events with exactly three jets and large missing transverse momentum (> 100 GeV/c).

TABLE II. Expected 95% C.L. upper limit on $T'\bar{T}'$ production cross section, $\sigma_{\rm exp}$, the range of expected limits which includes 68% of pseudoexperiments, and the observed limit, $\sigma_{\rm obs}$, for representative signal points in ($m_{T'}$, mX).

$m_{T'}$, m_X (GeV/c^2)	$\sigma_{\rm exp}$ [pb]	+34%	−34%	$\sigma_{\rm obs}$ [pb]
200, 1	1.31	1.86	0.83	1.21
220, 40	1.40	2.17	0.93	1.20
260, 1	0.23	0.40	0.14	0.20
280, 1	0.16	0.27	0.09	0.15
280, 20	0.18	0.29	0.11	0.17
280, 40	0.17	0.27	0.11	0.12
$m_{T'}$, m_X (GeV/c^2)	$\sigma_{\rm exp}$ [pb]	+34%	−34%	$\sigma_{\rm obs}$ [pb].
300, 100	0.34	0.51	0.24	0.39
310, 90	0.19	0.29	0.11	0.21
320, 80	0.15	0.24	0.08	0.12
350, 50	0.07	0.10	0.04	0.02
360, 110	0.09	0.19	0.05	0.09
370, 1	0.06	0.10	0.04	0.05

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 generating ensembles of simulated experiments that describe 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 (see Table II). We convert the observed upper limits on the pair-production cross sections to an exclusion curve in mass parameter space for the dark matter model involving fourth generation quarks; see Fig. 3.

In conclusion, we have searched for new physics particles T' decaying to top quarks with invisible particles X with a detector signature of $t\bar{t} + E_t$. We calculate upper

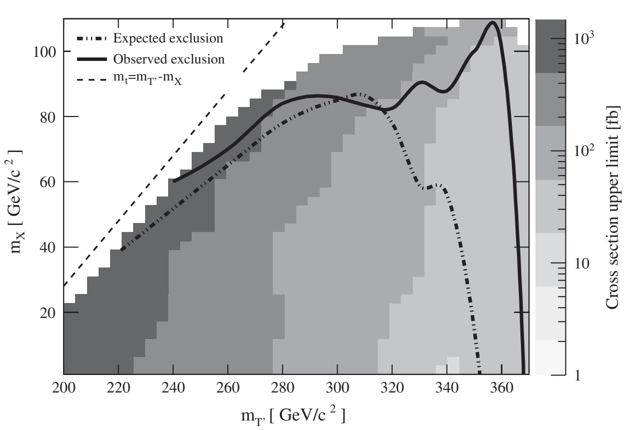

FIG. 3. Observed versus expected exclusion in ($m_{T'}$, m_X) along with the cross-section upper limits.

limits on the cross section of such events and exclude any dark matter model involving exotic fourth generation quark up to $m_{T'} = 360$ GeV$/c^2$. Our cross-section limits on the generic decay, $T' \rightarrow t + X$, may be applied to the many other models that predict the production of a heavy particle T' 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.

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