Search for new physics in $t\bar{t} + \not\!\!E_T \to b\bar{b}q\bar{q}q\bar{q} + \not\!\!E_T$ final state in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$

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

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There are many hints, from astronomical observations and cosmological theories, for the existence of dark matter (DM) particles, which must be long-lived on cosmological time scale [1]. The long lifetime of DM can be explained by the conservation of a charge of a new symmetry. Direct-detection experiments based on ultra-low

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

A first search for the $T'\bar{T}' \rightarrow t\bar{t} + X\bar{X}$ process has been performed in the semileptonic channel: $t\bar{t} + X\bar{X} \rightarrow bW\bar{b}W + X\bar{X} \rightarrow bl\nu\bar{b}q\bar{q} + X\bar{X}$ [10]. This letter reports the first search for such a process in the all-hadronic $t\bar{t}$ decay channel, characterized by a larger branching ratio and a lower physics background rate. Events were recorded by CDF II [11] a general purpose detector designed to study collisions at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV. The tracking system consists of a cylindrical open-cell drift chamber and silicon microstrip detectors in a 1.4 T magnetic field parallel to the beam axis. Electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies and drift chambers located outside the calorimeters detect muons. Jets are reconstructed in the calorimeter using the JETCLU [12] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space [13]. The detector response for all simulated samples is modeled by a detailed CDF detector simulation. Production of T' pairs and their subsequent decays to top quark pairs and two dark matter particles would appear as events with missing transverse energy from the two dark matter particles, and six jets from the two b quarks and the hadronic decays of the two W bosons. We model the production and decay of T' pairs with the MADGRAPH Monte Carlo (MC) generator [14], and normalize to the next-to-next-to-leading order (NNLO) cross section calculation [15]. Additional radiation, hadronization and showering are described by PYTHIA [16].

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

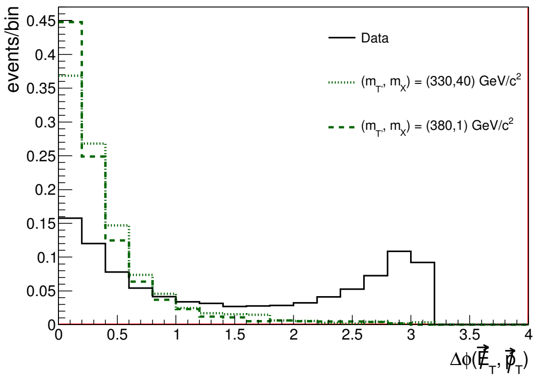

FIG. 1: Distribution of $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T)$ for the preselection data, and two scenarios with different values of $m_{T'}$ and m_X. All histograms are normalized to unit area.

energy collected in the calorimeter. Finally, we require $\sum_{jets} E_T^i > 220$ GeV to remove soft QCD events. All these cuts have been chosen to optimize the $S/\sqrt{(S+B)}$ figure of merit, where S and B are respectively the expected numbers of signal and background events. Table I shows the expected number of events in the signal region for SM backgrounds and for several signal hypothesis.

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

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

Inverting one of the event selection cuts, keeping others unchanged, allows us to define a signal-depleted control region. We use $\not{E}_T\, sig < 3\, GeV^{1/2}$, $N_{jets} = 4$ and $\not{p}_T < 20$ GeV control regions to validate the overall background modeling. The normalization factor of the QCD background is given by the average ratio of QCD events that pass the $\Delta\phi(\vec{\not{E}}_T, \vec{\not{p}}_T) < \pi/2$ cut to QCD events that fail the cut in these three control regions. Figure 2 shows good agreement of background modeling with data in these regions. We consider several sources of systematic uncertainties. The dominant components are the uncertainties on the QCD normalization factor, the jet energy scale (JES) [26] and the theoretical cross sections. We also take in account the differences of $t\bar{t}$ predicted rates using different hadron fragmentation models in the HERWIG [27] Monte Carlo, and varying initial/final state radiation and color reconnection effects [28]. The variation of the JES was found to change significantly the $\not{E}_T\, sig$ distribution in addition to its normalization, and its variation is thus taken into account. Figure 3 shows the $\not{E}_T\, sig$ distribution for expected signal events and SM backgrounds. The signal is expected to contribute significantly in the high tail of the $\not{E}_T\, sig$ distribution. There is no evidence for the presence of $T' \to t + X$ events in the data. We calculate 95% C.L. upper limits on the $T' \to t + X$ cross section, by performing a binned maximum-likelihood fit on the $\not{E}_T\, sig$ distribution. The limits are calculated using a Bayesian likelihood method with a flat prior for the signal cross-section, integrating over Gaussian priors for the systematic uncertainties. The results are shown in Table II. We convert the observed upper limits on the pair-production cross

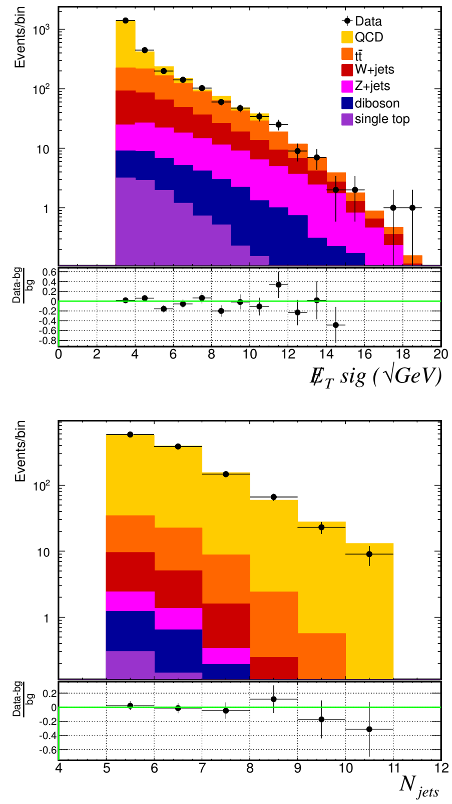

FIG. 2: Top plot shows the $\not{E}_T\, sig$ distribution in events with four jets and large $\not{E}_T$. Bottom plot shows the N_{jets} distribution in event with $5 \leq N_{jets} \leq 10$ and $\not{E}_T\, sig < 3\sqrt{GeV}$.

sections to an exclusion curve in mass parameters space $(m_{T'}, m_X)$. As shown in Fig. 4, a significant enhancement in sensitivity is obtained when comparing to the previous analysis in semi-leptonic channel.

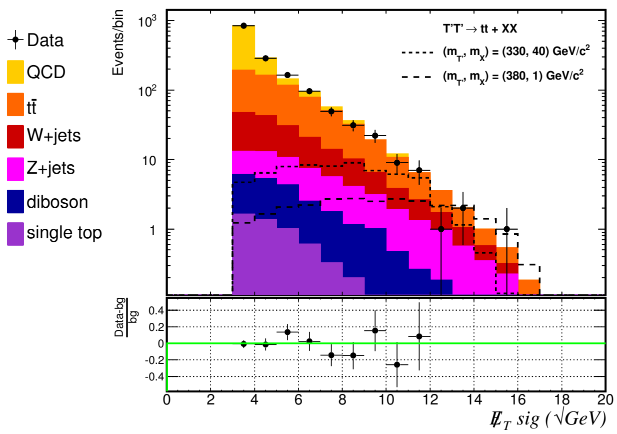

FIG. 3: $\not{E}_T$ sig distributions for the standard model backgrounds, the observed data, and for two scenarios with different values of $m_{T'}$ and m_X.

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

(mT', mX) GeV/c^2	$\sigma_{exp.95\%C.L.excl.}(pb)$	$\sigma_{obs.95\%C.L.excl.}(pb)$
(200,40)	2.02 ± 0.65	1.90
(220,40)	2.14 ± 0.75	3.00
(260,1)	0.23 ± 0.08	0.18
(280,1)	0.15 ± 0.05	0.12
(280,40)	0.18 ± 0.07	0.15
(300,1)	0.09 ± 0.03	0.09
(300,80)	0.20 ± 0.06	0.16
(300,100)	0.29 ± 0.09	0.38
(330,1)	0.05 ± 0.02	0.03
(330,100)	0.13 ± 0.04	0.18
(360,1)	0.03 ± 0.01	0.02
(360,100)	0.06 ± 0.02	0.04
(380,100)	0.06 ± 0.02	0.05
(400,1)	0.023 ± 0.008	0.016

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

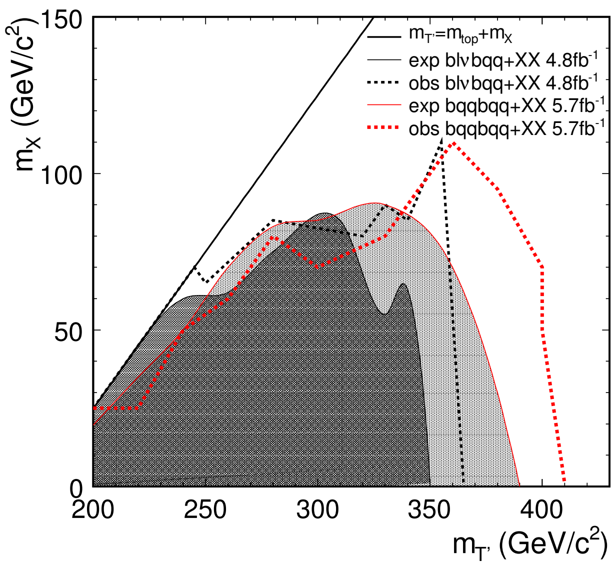

FIG. 4: Expected (exp) and observed (obs) 95% C.L. exclusion region in the $(m_{T'}, m_X)$ parameters space.

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