

Search for a Dark Matter Candidate Produced in Association with a Single Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We report a new search for dark matter in a data sample of an integrated luminosity of 7.7 fb^{-1} of Tevatron $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$, collected by the CDF II detector. We search for production of a dark-matter candidate, D , in association with a single top quark. We consider the hadronic decay mode of the top quark exclusively, yielding a final state of three jets with missing transverse energy. The data are consistent with the standard model; we thus set 95% confidence level upper limits on the cross section of the process $p\bar{p} \rightarrow t + D$ as a function of the mass of the dark-matter candidate. The limits are approximately 0.5 pb for a dark-matter particle with mass in the range of $0\text{--}150 \text{ GeV}/c^2$.

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Despite its successes, the standard model (SM) of particle physics leaves many important questions unanswered. For example the SM does not provide a candidate for dark matter (DM). Direct detection experiments such as DAMA [1], CoGeNT [2,3] and CRESST [4] have reported signals suggestive of DM with mass in the few GeV/c^2 range, and with coupling to the SM sector of a strength enabling its detection at collider experiments. Many beyond-the-SM theories predict DM candidates to include such coupling between the DM and SM sectors.

In the framework of effective field theories, production of a DM particle (D) in association with a single top quark at hadron colliders has been recently studied [5–7]. Here, we denote the final state containing one top quark and dark matter as a *monotop*. Such studies are also inspired by the models of monojet produced in association with missing energy used to probe gravitons [8,9]. Monotopic DM production is described by a set of Lagrangians incorporating

all possible types of DM particles (scalar, vector, fermion, etc.) and their flavor-violating interactions with quarks [10–14]. This effective theory can inclusively describe many beyond-the-SM models. For example, new physics processes with a monotopic final state can also arise from the decay of a supersymmetric squark into a neutralino and a top quark, from the decay of a vector leptoquark into a massless neutrino and a top quark, or through flavor-changing neutral interactions with a new vector state escaping detection.

In the SM, top quarks are primarily produced in pairs at particle colliders. They can also be produced singly via weak interactions, resulting in a final state consisting of a single top quark with additional lighter-flavor quarks. SM single top-quark events in the missing energy plus jets channel have been studied within the standard-model hypothesis [15]. As the beyond-the-SM monotopic theory predicts production of a single top quark in association

with a DM particle, the published SM single top-quark results do not provide any conclusive information on the existence of monotops. In addition, searches for the associated production of top quarks with DM particles have only been performed in the context of events containing a pair of top quarks [16–18]. Therefore, a dedicated search for monotops produced in colliders is needed, as the observation of monotops would be a clear sign of new physics. In this Letter, we report the first direct search for monotopic signatures at particle colliders, assuming the top quark to be produced through flavor-changing interactions of up and top quarks, in association with a DM candidate D . We assume that the D particle has a mass in the range of 0–150 GeV/ c^2 ; we do not consider decays of the D particle to up and top quarks in a higher mass range.

The top quark is short-lived and decays approximately 100% of the time into a b quark and a W boson, where $W \rightarrow l\nu, q\bar{q}'$. We consider the exclusive decay mode $t + D \rightarrow Wb + D$ in which $W \rightarrow q\bar{q}'$. This W decay mode has the largest branching ratio and it allows for the full reconstruction of the top quark. In this channel, the missing transverse energy (\cancel{E}_T) [19] can be uniquely assigned to the DM particle's passage through the detector.

Events are collected by CDF II [20], a general purpose detector used to study Tevatron $p\bar{p}$ collisions with $\sqrt{s} = 1.96$ TeV. CDF II contains a tracking system consisting of a cylindrical open-cell drift chamber and silicon microstrip detectors immersed in a 1.4 T magnetic field parallel to the beam axis. Electromagnetic and hadronic calorimeters surrounding the tracking system measure particle energies. Drift chambers and muon scintillators located outside the calorimeters identify muons. We use a data sample corresponding to an integrated luminosity of 7.7 ± 0.5 fb $^{-1}$.

We consider only those events which triggered the data acquisition system due to the presence of two calorimeter clusters and significant \cancel{E}_T . We include data recorded between 2001 and 2010. Prior to 2007, the data acquisition system \cancel{E}_T threshold was 35 GeV [15]. After an upgrade to the system [21] resulting in improved jet energy and \cancel{E}_T resolution, the requirement was lowered to $\cancel{E}_T > 30$ GeV. Jets are reconstructed using the JETCLU algorithm [22] with a clustering radius of 0.4 in azimuth-pseudorapidity space (ϕ, η) [23]. Jet energies are corrected using standard techniques [24]. Jets originating from b quarks are identified using a secondary-vertex-tagging algorithm [25].

In order to retain only those events for which the trigger system is fully efficient, we select events with $\cancel{E}_T > 50$ GeV and three jets. Exactly one jet is identified as a b jet. We require the jet transverse energy $E_T^{j_i}$, to be $E_T^{j_1} > 35$ GeV, $E_T^{j_2} > 25$ GeV, $E_T^{j_3} > 15$ GeV, where the jets j_i ($i = 1, 2, 3$) are ordered by decreasing energy. We require that either j_1 or j_2 have $|\eta| < 0.9$, and that all three jets have $|\eta| < 2.4$. We veto events with identified high- p_T electrons or muons, removing monotopic events inconsistent with a hadronically decaying top quark.

We model the signal and background contributions to the selected sample using a variety of Monte Carlo (MC) simulation programs. In our simulation we assume a top-quark mass of 172.5 GeV/ c^2 , consistent with the world's best determination [26,27]. We model monotopic DM production in the flavor-violating process ($ug \rightarrow tD$) with MADGRAPH [28]. Additional showering and hadronization are described by PYTHIA [29]. We have generated 11 signal samples assuming various DM mass in steps of 5 GeV/ c^2 from 0 to 25 GeV/ c^2 , and then in steps of 25 GeV/ c^2 from 25 to 150 GeV/ c^2 .

The event selection described above gives a data sample dominated by QCD multijet events, where the false \cancel{E}_T arises from the mismeasurement of jet energy. Simulation of this background is prohibitive due to the high production rate and large theoretical uncertainties. Instead, we use a method which relies on data and is based on a recently improved tag rate matrix (TRM) method [30]. The TRM method utilizes an estimate of the probability for QCD multijet events to have tagged jets. The probability is derived in a control region dominated by QCD multijet events. This probability is applied as a per-event weight to all events meeting our analysis selections excluding the b -jet requirement. From this sample of weighted events, we subtract the expected electroweak components (as modeled by applying the same TRM probability to simulated samples). The resulting events form our model of the QCD multijet component of the analysis data sample.

We model other physics with samples generated by MC programs. Diboson and $t\bar{t}$ production are generated by PYTHIA and normalized to the next-to-leading order (NLO) cross section predicted using the MCFM program [31,32] and the approximate next-to-next-to-leading order cross section [33], respectively. The production of W/Z plus light flavor and heavy flavor (HF) jets are simulated by ALPGEN [34] with showering and hadronization performed by PYTHIA and normalized to NLO cross sections. Single top, both s - and t - channel production, are modeled using MADGRAPH with PYTHIA and normalized to NLO cross sections [35,36].

The light flavor jets misidentified as b jets by the secondary-vertex-tagging algorithm are labeled as *mistags*. A data-driven method is used to estimate the mistag rate for the tagging algorithm [25]. We apply the mistag rate to the MC events with light flavor jets to estimate the mistag contribution.

Figure 1 shows the \cancel{E}_T distribution in a control region for events which pass our signal selection but have an identified high- p_T electron or muon.

After the selection described above, we are left with 6471 data events. We expect that approximately 70% of these events come from QCD multijet production. In order to further suppress the QCD contamination and the other SM backgrounds, we require the azimuthal distances between the \cancel{E}_T and j_2 , $\Delta\phi(\cancel{E}_T, j_2) > 0.7$, as the \cancel{E}_T in QCD

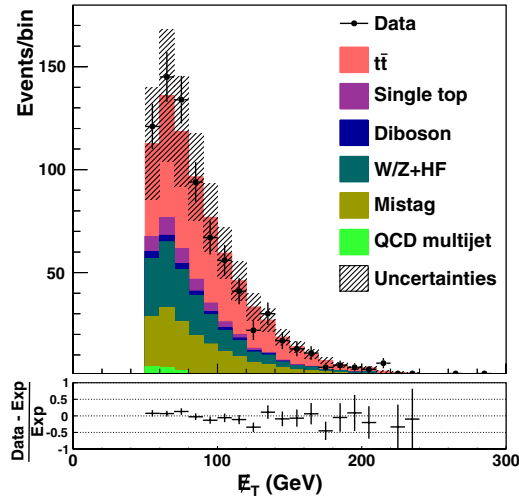


FIG. 1 (color online). The \cancel{E}_T distribution in a control region requiring an identified high- p_T lepton; the gray area represents the statistical and systematic uncertainties on the background model. The lower panel displays the difference between the data and the expected backgrounds (Exp) divided by the latter.

multijet background tends to align to the jet with less measured energy. We also require the invariant mass of the three jets to be consistent with the reconstructed top-quark mass, $110 < m_{jjj} < 200$ GeV/ c^2 , large \cancel{E}_T significance ($\cancel{E}_T / \sqrt{\sum E_T} > 3.5\sqrt{\text{GeV}}$, where $\sum E_T$ is the scalar sum of transverse energy deposited in the calorimeter) and $E_T^{\cancel{E}_T} > 25$ GeV. All selections have been chosen to optimize the significance $S/\sqrt{S+B}$, where S and B are the expected number of signal and backgrounds events, respectively. Table I shows the number of events in the signal region for the data, the number of events for SM backgrounds, and the expected signal assuming different values of the DM particle's mass. The events that fail these signal-region selections are used to form a control region that is used to validate the background models, as well as to determine the normalization of the QCD multijet background.

We consider several systematic uncertainties affecting the sensitivity of this search. The dominant systematic sources are the uncertainties on multijet normalization (25.5%), the mistag rate (16.6%) and the background cross sections (6.5%–30%). We also consider uncertainties from the jet energy scale [24] (2.8%–10.7%), the luminosity measurement [37] (6%), parton density functions (2%), lepton veto (2%), b -tagging efficiency (5.2%), trigger efficiency (0.4%–0.9%), and from the initial-state and final-state radiation (4%). We also assign systematic uncertainties, based on the variation in the shape of the distribution of kinematic quantities, under a $\pm 1\sigma$ variation of the jet energy scale and the uncertainty on the efficiency of the data acquisition system.

The \cancel{E}_T is chosen to discriminate the signals from the backgrounds. The \cancel{E}_T distribution due to a DM particle of

TABLE I. Number of expected signal and background events compared to data in the signal region. The expected signals, assuming different values for the mass of the DM particle, are also presented. The errors include statistical and systematic uncertainties.

Processes	Events
$p\bar{p} \rightarrow t + D$	
$m_D = 20$ GeV/ c^2	2116.9 ± 121.4
$m_D = 75$ GeV/ c^2	232.3 ± 22.9
$m_D = 100$ GeV/ c^2	129.8 ± 12.5
$m_D = 125$ GeV/ c^2	94.5 ± 9.3
$t\bar{t}$	182.8 ± 20.2
Single top	24.3 ± 4.5
Diboson	15.7 ± 2.7
W/Z + HF	130.5 ± 33.8
Mistag	96.9 ± 39.4
QCD multijet	210.2 ± 54.5
Total background	660.2 ± 78.1
Data	592

mass of 125 GeV/ c^2 and the SM backgrounds are shown in Fig. 2. The signal is expected to contribute significantly at high values of \cancel{E}_T . We find no significant excess of signal-like events in the data analyzed, and thus proceed to set 95% confidence level (C.L.) upper limits on the monotopic DM production cross section. The limits are calculated with the \cancel{E}_T distribution as the shape discriminant using a Bayesian maximum likelihood method assuming a flat prior for the signal cross section [38]. We treat systematic uncertainties using a Bayesian marginal likelihood method. Figure 3 shows the calculated upper limits

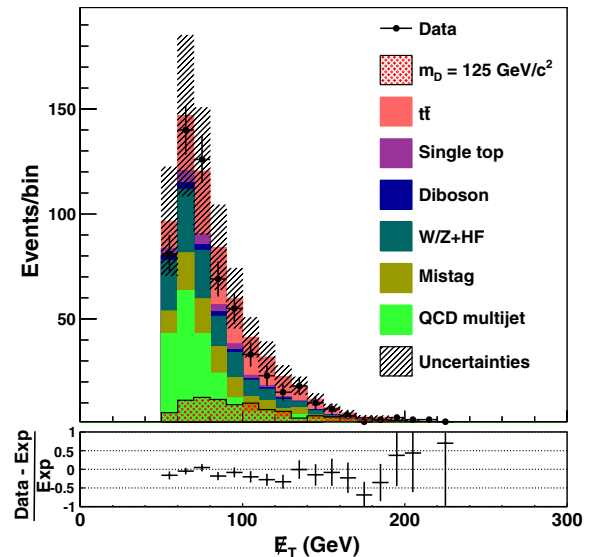


FIG. 2 (color online). The \cancel{E}_T distribution in the signal region. The data are compared to the sum of the SM contributions. The distribution of signal events with a DM mass of 125 GeV/ c^2 is also shown.

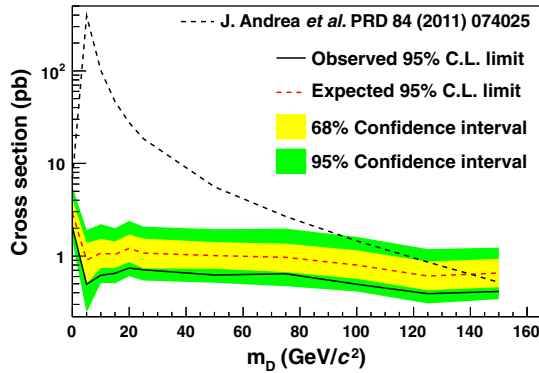


FIG. 3 (color online). Exclusion curve of the monotopic cross section as a function of the mass of DM particle.

on the monotopic cross section as a function of the mass of the DM candidate compared to the theoretical predictions.

In conclusion, we have performed the first search for the production of DM in association with a single top quark at hadron colliders. In an analysis of 7.7 fb^{-1} of CDF II data we have found that the observed data are consistent with the expectation from SM backgrounds. We set 95% C.L. upper limits on the cross section of $p\bar{p} \rightarrow D + t$ as a function of the DM mass in the range of 0–150 GeV/c^2 . Future searches for new physics in monotopic final states can probe resonant production of top quarks and DM candidates with exotic mediators. While these processes are predicted to have low production rates (making them difficult to probe with Tevatron data), they are expected to be within the reach of LHC experiments with sufficient data.

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