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A search for new phenomena in $t\bar{t}$ events with large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector

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A search for new phenomena in $t\bar{t}$ events with large missing transverse momentum in proton-proton collisions at a center-of-mass energy of 7 TeV is presented. The measurement is based on 1.04 fb$^{-1}$ of data collected with the ATLAS detector at the LHC. Contributions to this final state may arise from a number of standard model extensions. The results are interpreted in terms of a model where new top-quark partners are pair produced and each decay to an on-shell top (or antitop) quark and a long-lived undetected neutral particle. The data are found to be consistent with standard model expectations. A limit at 95% confidence level is set excluding a cross section times branching ratio of 1.1 pb for a top-partner mass of 420 GeV and a neutral particle mass less than 10 GeV. In a model of exotic fourth generation quarks, top-partner masses are excluded up to 420 GeV and neutral particle masses up to 140 GeV.

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The top quark holds great promise as a probe for new phenomena at the TeV scale. It has the strongest coupling to the standard model Higgs boson, and as a consequence it is the main contributor to the quadratic divergence in the Higgs boson mass. Thus, assuming the “naturalness” hypothesis of effective quantum field theory, light top partners (with masses below about 1 TeV) should correspond to one of the most robust predictions of solutions to the hierarchy problem.

In this Letter, a search is presented for pair-produced exotic top partners $T\bar{T}$, each decaying to a top quark and a stable, neutral weakly interacting particle $A_0$, which in some models may be its own antiparticle. The final state for such a process ($T\bar{T} \rightarrow t\bar{t}A_0A_0$) is identical to $t\bar{t}$, though with a larger amount of missing transverse momentum ($E_T^{\text{miss}}$) from the undetected $A_0$ pair. In supersymmetry models with $R$-parity conservation, $T$ is identified with the stop squark and $A_0$ with the lightest supersymmetric particle, the neutralino ($\chi_0$) [1] or the gravitino ($\tilde{G}$) [2]. The $t\bar{t} + E_T^{\text{miss}}$ [3] signature appears in a general set of dark matter motivated models, as well as in other standard model (SM) extensions, such as the above-mentioned supersymmetry models, little Higgs models with $T$-parity conservation [4–6], models of universal extra dimensions (UED) with Kaluza-Klein parity [7], models in which baryon and lepton number conservation arises from gauge symmetries [8], or models with third-generation scalar leptoquarks. Many of these models provide a mechanism for electroweak symmetry breaking and predict dark matter candidates, which can be identified indirectly through their large $E_T^{\text{miss}}$ signature.

The search is performed in the $t\bar{t}$ single-lepton channel where one $W$ boson produced by the top pair decays to a lepton-neutrino pair ($W \rightarrow l\nu$, including $t$ decays to $e$ or $\mu$) and the other $W$ boson decays to a pair of quarks ($W \rightarrow q\bar{q}$), resulting in a final state with an isolated lepton of high transverse momentum, four or more jets, and large $E_T^{\text{miss}}$. The observed yield in this signal region is compared with the SM expectation. In the absence of signal an upper limit on the cross-section times branching ratio BR$(T\bar{T} \rightarrow t\bar{t}A_0A_0)$ is quoted. In the model of exotic fourth generation up-type quarks [9] the $T\bar{T}$ production cross section is predicted to be approximately 6 times higher than for stop squarks with a similar mass [3], due to the multiple spin states of two $T$’s compared to scalar stops. For this model the cross-section limits are converted to an exclusion curve in the $T$ vs $A_0$ mass parameter space. A search for these exotic top-quark partners was performed in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV by the CDF Collaboration [10]. The data were found to be consistent with SM expectations. A 95% confidence level limit was set excluding a top-partner mass of 360 GeV for a neutral particle mass less than 100 GeV. A recent update by CDF in the all-jets channel excludes top-partner masses up to 400 GeV [11].

The ATLAS detector [12] consists of an inner detector tracking system (ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors inside a transition radiation tracker which provide tracking in the region $|\eta| < 2.5$ [13]. The electromagnetic calorimeter is a lead-liquid argon (LAr) detector in the barrel ($|\eta| < 1.475$) and end cap ($1.375 < |\eta| < 3.2$) regions. Hadron calorimetry is based on two different detector technologies.

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The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator and steel, while the hadronic end cap calorimeters ($1.5 < |\eta| < 3.2$) are copper and LAr. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with copper and LAr and tungsten and LAr, providing electromagnetic and hadronic energy measurements, respectively. The MS consists of three large superconducting toroids with 24 coils, a system of trigger chambers, and precision tracking chambers which provide muon momentum measurements up to $|\eta|$ of 2.7.

The analysis is based on data recorded by the ATLAS detector in 2011 using 1.04 fb$^{-1}$ of integrated luminosity. The data were collected using electron and muon triggers. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed. Monte Carlo (MC) event samples with full ATLAS detector simulation [14] based on the GEANT4 program [15] and corrected for all known detector effects are used to model the signal process and most of the backgrounds. The multijet background is modeled using data control samples rather than the simulation. The background sources are separated into four main categories according to their importance: dilepton $\ell\ell$ (where both W bosons decay to a lepton-neutrino pair: $W \rightarrow \ell\nu$); single-lepton $\ell$ and $W +$ jets; multijet production; and other electroweak processes, such as di-boson production, single top, and jets. The $\ell\ell$ and single top samples are produced with MC@NLO [16], while the $W +$ jets and $Z +$ jets samples are generated with ALPGEN [17]. HERWIG [18] is used to simulate the parton shower and fragmentation, and JIMMY [19] is used for the underlying event simulation. The diboson background is simulated using HERWIG. The $\ell\ell$ cross section is normalized to approximate next-to-next-to-leading order (NNLO) calculations [20], the inclusive $W +$ jets and $Z +$ jets cross sections are normalized to NNLO predictions [21], and the cross sections of the other backgrounds are normalized to NLO predictions [22]. Additional corrections to the MC predictions are extracted from the data, as described below.

Electron and muon candidates are selected as for other recent ATLAS top-quark studies using the single-lepton signature [23]. Jets are reconstructed using the anti-$k_t$ algorithm with the distance parameter $R = 0.4$. To take into account the differences in calorimeter response to electrons and hadrons, a $p_T$- and $\eta$-dependent factor, derived from simulated events and validated with data, is applied to each jet to provide an average energy scale correction [25] corresponding to the energies of the reconstructed particles.

In the calorimeter, the energy deposited by particles is reconstructed in three-dimensional clusters. These clusters are calibrated according to the associated reconstructed high-$p_T$ object. The energy of these clusters is summed vectorially, and projections of this sum in the transverse plane correspond to the negative of the $E_T^{\text{miss}}$ components [26]. Clusters not associated with any high-$p_T$ object and muons reconstructed in the MS are also included in the $E_T^{\text{miss}}$ calculation.

Events are selected with exactly one isolated electron or muon that passes the following kinematic selection criteria. Electrons are required to satisfy $E_T > 25$ GeV and $|\eta| < 2.47$. Electrons in the region between the barrel and the end cap electromagnetic calorimeters ($1.37 < |\eta| < 1.52$) are removed. Muon candidates are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.5$. These selected leptons lie in the efficiency plateau of the single-lepton triggers. Only events with four or more reconstructed jets with $p_T > 25$ GeV and $|\eta| < 2.5$ are selected. To reduce the single-lepton $\ell\ell$ and $W +$ jets background, events are required to have $E_T^{\text{miss}} > 100$ GeV and $m_T > 150$ GeV, where $m_T$ is the transverse mass of the lepton and $E_T^{\text{miss}}$ [27]. Events with either a second lepton candidate with $p_T > 15$ GeV or a track with $p_T > 12$ GeV, with no other tracks with $p_T > 3$ GeV within $\Delta R = 0.4$ ($\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$), are rejected in order to reduce the contribution from $\ell\ell$ dilepton events. In particular, the isolated track veto is useful in reducing single-prong hadronic $\tau$ decays in $\ell\ell$ dilepton events. A summary of the background estimates and a comparison with the observed number of selected events passing all selection criteria are shown in Table I. A total yield of 101 $\pm$ 16 events is expected from SM sources, and 105 events are observed in data. The background composition is similar in the electron and muon channels.

The dominant background arises from $\ell\ell$ dilepton final states in which one of the leptons is not reconstructed, is outside the detector acceptance, or is a $\tau$ lepton. In all such cases, the $\ell\ell$ decay products include two high-$p_T$ neutrinos, resulting in large $E_T^{\text{miss}}$ and $m_T$ tails. In MC simulation, the second lepton veto removes 45% of the dilepton $\ell\ell$ events. In particular, the isolated track veto is useful in reducing single-prong hadronic $\tau$ decays in $\ell\ell$ dilepton events. A summary of the background estimates and a comparison with the observed number of selected events passing all selection criteria are shown in Table I. A total yield of 101 $\pm$ 16 events is expected from SM sources, and 105 events are observed in data. The background composition is similar in the electron and muon channels.

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton $\ell\ell$</td>
<td>62 $\pm$ 15</td>
</tr>
<tr>
<td>Single-lepton $\ell\ell/W +$ jets</td>
<td>33.1 $\pm$ 3.8</td>
</tr>
<tr>
<td>Multijet</td>
<td>1.2 $\pm$ 1.2</td>
</tr>
<tr>
<td>Single top</td>
<td>3.5 $\pm$ 0.8</td>
</tr>
<tr>
<td>$Z +$ jets</td>
<td>0.9 $\pm$ 0.3</td>
</tr>
<tr>
<td>Dibosons</td>
<td>0.9 $\pm$ 0.2</td>
</tr>
<tr>
<td>Total</td>
<td>101 $\pm$ 16</td>
</tr>
<tr>
<td>Data</td>
<td>105</td>
</tr>
</tbody>
</table>
The jet techniques similar to those described in Ref. [23]. The region.

lepton channels the contribution to the signal region is
techniques exploit the fact that the lepton isolation effi-
ty from the jet energy scale [25] (approximately 5%–7% on
object identification. The largest of these uncertainties are
total integrated luminosity.

simulation, normalized to the theoretical cross section and

determined from fits to the
distributions for this combined background are extracted
from the data. First, the yield of the single-lepton back-
ground estimated from simulation is normalized in the
control region 60 GeV < m_T < 90 GeV to the data which
gives a correction of (−5 ± 3)%. Next, the shape of the m_T
distribution in MC is compared with data in various signal-
depleted control regions, where events satisfy the signal
event selection but have fewer than four jets. In these
control samples events with identified b jets, based on
lifetime b tagging [23], are rejected in order to reduce the
dilepton tH background, such that these control samples are
 dominated by W + jets events; the corresponding loss of
single-lepton tH from this b-jet veto is accounted for in
the systematic uncertainties. A comparison between data
and MC in this control region shows that MC systemati-
cally underestimates the tails of the m_T distribution above
150 GeV, and a shape correction is derived that results in a
(15 ± 10)% increase of the expected yield in the signal
region.

The multijet background is extracted from the data using
techniques similar to those described in Ref. [23]. The
techniques exploit the fact that the lepton isolation effi-
cency is different in signal and multijet events. In both
lepton channels the contribution to the signal region is
consistent with zero.

The contributions from single top, diboson production
(WW, WZ, and ZZ), and Z + jets are estimated using MC
simulation, normalized to the theoretical cross section and
total integrated luminosity.

The background yields estimated from MC simulated
events are affected by systematic uncertainties related to
the modeling of detector performance, reconstruction, and
object identification. The largest of these uncertainties are
from the jet energy scale [25] (approximately 5%–7% on
the jet p_T, including a contribution from pileup effects,
leading to an 11% uncertainty on the background event
yield), and from the performance of the second lepton veto
in dilepton tH (10%). Other uncertainties include those on
the lepton momentum scales and trigger and reconstruction
efficiencies. Lepton momentum scales and resolutions are
determined from fits to the Z-mass peak. Trigger and
reconstruction efficiencies are evaluated using tag-and-
probe measurements in Z → e^+ e^- or Z → μ^+ μ^- events.
To evaluate the effect of lepton momentum and jet energy
scale uncertainties, the E_T^{miss} and m_T are recalculated for
each uncertainty on selected objects. Other small uncer-
tainties affecting the E_T^{miss} calculation are due to multiple
pp interactions, jets with p_T below 20 GeV, and calorim-
eter clusters that are not associated to a selected object [28].
Additionally, theoretical cross-section uncertainties from
choice of scales and parton distribution functions are con-
sidered for these background sources, as are the effects of
using alternative MC generators, shower models, and ini-
tial- and final-state radiation tunings [23]. Finally, the 3.7%
uncertainty on the integrated luminosity [29] is applied to
each background source.

The systematic uncertainties applied to data-driven back-
grounds are determined from the data. The dominant un-
certainty for single-lepton backgrounds is due to the
(15 ± 10)% shape correction, and is derived from the varia-
tion in the measured correction in different control regions
and from uncertainties in the b-tagging efficiency.
The uncertainty on the single-lepton normalization of
(−5 ± 3)% includes equal contributions from limited data
statistics in the W mass region and expected differences
between the W + jets and single-lepton tH contributions to
the signal and control regions. A 100% systematic uncer-
tainty is assigned to the small estimated multijet yield.

The expected and observed event yields are consistent
within statistical and systematic uncertainties. Therefore,
the results are interpreted as a limit on the possible non-SM
contribution to the selected sample. A model involving
pair production of heavy quarklike objects (T T), each
forced to decay to a top quark and a scalar neutral A_0,
is chosen to establish these limits.

MADGRAPH [30] is used to simulate the signal process
with the parton distribution function set CTEQ6L1 [31],
and PYTHIA [32] is used to simulate the parton shower
and fragmentation. A grid of T and A_0 masses is generated
with 300 GeV ≤ m(T) ≤ 450 GeV and 10 GeV ≤ m(A_0) ≤
150 GeV. Each sample is normalized to the cross section
calculated at approximate NNLO in QCD using HATHOR
[33], ranging from 8.0 pb for a T mass of 300 GeV to
0.66 pb for a T mass of 450 GeV. Using this grid of signal
samples, the efficiency times acceptance for the T T signal
model is parametrized as a function of the T and A_0 masses
to generate the expected signal event yield for any pair of
masses. The combined acceptance times signal selection
efficiency varies between 3% and 5% for small A_0 masses
and decreases to between 2% and 4% for larger A_0 masses.

All common systematic uncertainties for MC-based
backgrounds are applied to this signal model. These in-
clude the uncertainties on the jet energy scale, lepton
reconstruction efficiencies and scales, integrated luminos-
ity, and the dilepton veto efficiency. Overall, the systematic
uncertainty on the signal acceptance times efficiency varies
between 11% and 14%, and is largest for those samples
with a T-A_0 mass difference closest to the top quark mass.
Theoretical uncertainties on the signal cross section vary
between 10% to 15% and originate mainly from the
choice of scales (m_T/2 < μ_R = μ_F < 2m_T, where μ_R and
μ_F are the renormalization and factorization scale) and
parton distribution functions.

The E_T^{miss} and m_T distributions for data are shown in
Fig. 1 and compared with the background and signal pre-
dictions. There is no significant evidence of an excess over
the SM prediction, and the kinematics are well modeled.
As the mass difference between the region of parameter space excluded at the 95% confidence level approaches the top-quark mass, the signal region becomes indistinguishable from SM background. The last bin includes the overflow.

From the observed event yield and the predicted signal and background event yields after all cuts, a frequentist confidence interval on the signal hypothesis is calculated at the 95% confidence level versus the cross-section times branching ratio as a function of the two masses.

the cross-section times branching ratio excluded at the 95% confidence level versus $T$ mass, for an $A_0$ mass of 10 GeV. A cross-section times branching ratio of 1.1 (1.9) pb is excluded at the 95% confidence level for a $T$ mass of 420 (370) GeV and an $A_0$ mass of 10 (140) GeV. The estimated acceptance times efficiency for spin-$1/2$ $TT$ models is consistent within systematic uncertainties with that for scalar models, such as pair production of stop squarks (with a $t\bar{t}X_0\chi_0$ final state) or third-generation leptoquarks (with a $t\bar{t}v\bar{v}$, $t\bar{t}\nu$ final state). The cross-section limits presented in Fig. 3 are therefore approximately valid for such models, although the predicted cross section is typically below the current sensitivity.

In summary, in 1.04 fb$^{-1}$ of data in $pp$ collisions at a center-of-mass energy of 7 TeV, there is no evidence of an

FIG. 2 (color online). Excluded region (under the curve) at the 95% confidence level as a function of $T$ and $A_0$ masses, compared with the CDF exclusion [10,11]. Theoretical uncertainties on the $TT$ cross section are not included in the limit, but the effect of these uncertainties is shown. The gray contours show the excluded cross-section times branching ratio as a function of the two masses.

FIG. 3 (color online). Cross-section times branching ratio excluded at the 95% confidence level versus $T$ mass for an $A_0$ mass of 10 GeV. Theoretical predictions for both spin-$1/2$ and scalar $T$ pair production are also shown.
excess of events with large $E_T^{\text{miss}}$ in a sample dominated by $t\bar{t}$ events. Using a model of pair-produced quarklike objects decaying to a top quark and a heavy neutral particle, a limit is established excluding masses of these top partners up to 420 GeV and stable weakly interacting particle masses up to 140 GeV (see Fig. 2). In particular, a cross-section times branching ratio of 1.1 pb is excluded at the 95% confidence level for $m(T) = 420$ GeV and $m(A_0) = 10$ GeV. The cross-section limits are approximately valid for a number of models of new phenomena.

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[13] The azimuthal angle $\phi$ is measured around the beam axis and the polar angle $\theta$ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.
[27] The transverse mass is defined by the formula $m_T = \sqrt{p_T^2 + E_T^{\text{miss}}(1 - \cos(\phi_T - \phi_{E_T^{\text{miss}}}))}$, where $p_T$ is the $p_T$ of the muon (electron) and $\phi_T$ ($\phi_{E_T^{\text{miss}}}$) is the azimuthal angle of the lepton ($E_T^{\text{miss}}$).