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# Search for a heavy top-quark partner in final states with two leptons with the ATLAS detector at the LHC

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## The ATLAS collaboration

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**ABSTRACT:** The results of a search for direct pair production of heavy top-quark partners in  $4.7 \text{ fb}^{-1}$  of integrated luminosity from  $pp$  collisions at  $\sqrt{s} = 7 \text{ TeV}$  collected by the ATLAS detector at the LHC are reported. Heavy top-quark partners decaying into a top quark and a neutral non-interacting particle are searched for in events with two leptons in the final state. No excess above the Standard Model expectation is observed. Limits are placed on the mass of a supersymmetric scalar top and of a spin-1/2 top-quark partner. A spin-1/2 top-quark partner with a mass between 300 GeV and 480 GeV, decaying to a top quark and a neutral non-interacting particle lighter than 100 GeV, is excluded at 95% confidence level.

**KEYWORDS:** Hadron-Hadron Scattering

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**1 Introduction**

Partners of the top quark are an ingredient of several models addressing the hierarchy problem of the Standard Model (SM). In order to stabilize the Higgs boson mass against divergent quantum corrections, these new particles should have masses close to the electroweak symmetry breaking energy scale, and thus be accessible at the LHC. One of these models is Supersymmetry (SUSY) [1–9] which naturally resolves the hierarchy problem [10–13] by introducing supersymmetric partners of the known bosons and fermions. In the MSSM [14–18], an R-parity conserving minimal supersymmetric extension of the SM, the scalar partners of right-handed and left-handed quarks,  $\tilde{q}_R$  and  $\tilde{q}_L$ , can mix to form two mass eigenstates. In this paper a search for a scalar top  $\tilde{t}_1$  which decays into a top quark and the lightest neutralino  $\tilde{\chi}_1^0$  is performed. In this model, the  $\tilde{\chi}_1^0$  is a stable particle which would escape detection.

A top-quark fermionic partner  $T$  which decays into a stable, neutral, weakly interacting particle  $A_0$  also appears in other SM extensions, such as little Higgs models with  $T$ -parity conservation [19–21] or models of Universal Extra Dimensions (UED) with Kaluza-Klein parity [22]. The production cross section at the LHC is predicted to be approximately six times higher for fermionic  $T$  [23] than for the  $\tilde{t}_1$ . Furthermore, scalar top and  $T$  decay kinematic distributions differ due to helicity effects in the decay, yielding different experimental acceptances.

Searches for these spin-1/2 heavy top-quark partners were performed by the CDF Collaboration in proton-antiproton collisions at  $\sqrt{s} = 1.96$  TeV [24], excluding at 95% confidence level (CL) top-quark partners with masses up to 400 GeV for an  $A_0$  mass lower than 70 GeV. A previous ATLAS analysis with  $1.04 \text{ fb}^{-1}$  of proton-proton collisions at  $\sqrt{s} = 7$  TeV [25] excludes a  $T$  with masses up to 420 GeV.

In this paper a search for the direct pair production of heavy top-quark partners is presented, where  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  or  $T \rightarrow tA_0$ . The final state targeted by the analysis includes two top quarks and additional missing transverse momentum  $\mathbf{p}_T^{\text{miss}}$ , with magnitude  $E_T^{\text{miss}}$ , resulting mainly from the undetected  $\tilde{\chi}_1^0$  or  $A_0$ . The present study addresses the two-lepton signature resulting from the leptonic decay of both the  $W$  bosons from the top-quark decay. The neutrinos from the  $W$  decays also contribute to the missing transverse momentum. Events with two electrons, two muons, or an electron-muon pair in the final state are selected by the analysis. To separate the signal from the large irreducible background from top-quark pair production, the  $m_{T2}$  variable [26, 27] is used. It is defined as:

$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{\text{miss}}} \left\{ \max[ m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T) ] \right\},$$

where  $m_T$  indicates the transverse mass,  $\mathbf{p}_T^{\ell_1}$  and  $\mathbf{p}_T^{\ell_2}$  are the transverse momenta of the two leptons, and  $\mathbf{q}_T$  and  $\mathbf{r}_T$  are vectors which satisfy  $\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{\text{miss}}$ . The minimization is performed over all the possible decompositions of  $\mathbf{p}_T^{\text{miss}}$ . The distribution of this variable presents a sharp kinematic limit at the  $W$  boson mass for  $t\bar{t}$  production [28, 29], whereas for the signal topology it decreases slowly towards a higher mass value, due to the presence of the two additional invisible particles produced in association with the top-quark pair. The results are interpreted in the scalar top–neutralino mass plane as well as in a generic model producing a heavy spin-1/2 top-quark partner  $T$  decaying into an invisible particle  $A_0$  and a top quark.

This analysis is sensitive to masses of the top-quark partner in excess of about 200 GeV and is thus complementary to a parallel ATLAS study reported in refs. [30, 31] optimized for scalar top masses near or below the top mass.

## 2 The ATLAS detector

The ATLAS detector [32] consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters and a muon spectrometer with a toroidal magnetic field. The inner detector, in combination with the axial 2 T field from the solenoid, provides precision tracking of charged particles for  $|\eta| < 2.5$ , where the pseudorapidity  $\eta$  is defined in terms of the angle  $\theta$  with the beam pipe axis as  $\eta = -\ln \tan(\theta/2)$ . It consists of a silicon pixel detector, a silicon strip detector and a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . It is composed of sampling calorimeters with either liquid argon or scintillating tiles as the active media. The muon spectrometer has separate trigger and high-precision tracking chambers which provide muon trigger and measurement capabilities for  $|\eta| < 2.4$  and  $|\eta| < 2.7$  respectively.

Physics process	$\sigma \cdot \text{BR}$ [pb]	Perturbative order
$Z/\gamma^* \rightarrow \ell^+ \ell^-$	$1069 \pm 53$	NNLO
$t\bar{t}$	$167^{+17}_{-18}$	NLO+NNLL
$Wt$	$15.7 \pm 1.2$	NLO+NNLL
$t\bar{t}W$	$0.168^{+0.023}_{-0.037}$	NLO
$t\bar{t}Z$	$0.130 \pm 0.019$	NLO
$WW$	$44.4 \pm 2.8$	NLO
$WZ$	$19.1 \pm 1.3$	NLO
$ZZ$	$6.2 \pm 0.3$	NLO

**Table 1.** The most important SM background processes and their production cross sections, multiplied by the relevant branching ratios. The  $\ell$  indicates all three types of leptons ( $e, \mu, \tau$ ) summed together. The  $Z/\gamma^*$  production cross section is given for events with a di-lepton invariant mass of at least 12 GeV.

### 3 Monte Carlo samples

Monte Carlo (MC) simulated event samples are used to aid in the description of the background and to model the SUSY and spin-1/2 heavy top-quark partner signals.

Top-quark pair and  $Wt$  production are simulated with MC@NLO [33, 34], interfaced with HERWIG [35] for the fragmentation and the hadronization processes, including JIMMY [36] for the underlying event. The top-quark mass is fixed at 172.5 GeV, and the next-to-leading-order (NLO) parton distribution function (PDF) set CTEQ10 [37] is used. Additional MC samples are used to estimate the event generator systematic uncertainties: two POWHEG [38] samples, one interfaced with HERWIG and the other with PYTHIA [39]; an ALPGEN [40] sample interfaced with HERWIG and JIMMY; two ACERMC [41] samples produced with variations to the PYTHIA parton shower parameters chosen such that the two samples produce additional radiation consistent with the experimental uncertainty in the data [42, 43].

Samples of  $Z/\gamma^*$  produced in association with light- and heavy-flavour jets are generated with ALPGEN using the PDF set CTEQ6.1 [44]. Samples of  $t\bar{t}Z$  and  $t\bar{t}W$  production are generated with MADGRAPH [45] interfaced to PYTHIA. Diboson samples ( $WW, WZ, ZZ$ ) are generated with SHERPA [46]. Additional samples generated with ALPGEN and HERWIG are used for the evaluation of the event generator systematic uncertainties.

The background predictions are normalized to theoretical cross sections, including higher-order QCD corrections when available, and are compared to data in control regions populated by events produced by SM processes. Next-to-next-to-leading-order (NNLO) cross sections are used for inclusive  $Z$  boson production [47, 48]. Approximate NLO+NNLL (next-to-next-to-leading-logarithms) cross sections are used in the normalization of the  $t\bar{t}$  [49] and  $Wt$  [50] samples. NLO cross sections are used for the diboson samples [33, 51] and for the  $t\bar{t}W$  and  $t\bar{t}Z$  [52] samples. Production of  $t\bar{t}$  in association with  $b\bar{b}$  is normalized to leading order (LO) cross section [40]. Table 1 summarizes the production cross sections used in this analysis and their uncertainties.

SM processes that generate jets which are misidentified as leptons, or where a lepton from a  $b$ -hadron or  $c$ -hadron decay is selected, collectively referred to as “fake” leptons in the following, are estimated from data as described in section 6.

Scalar top signal samples are generated with HERWIG++ [53]. The mixings in the scalar top and gaugino sector are chosen to be such that the lightest scalar top is mostly the partner  $\tilde{t}_R$  of the right-handed top quark, and the lightest neutralino is almost a pure bino. Under such conditions, the scalar top is expected to decay to the lightest neutralino and a top quark with a branching ratio close to 100%, even if the decay mode to a chargino and a  $b$  quark is kinematically allowed. The effects of helicity in the decay are correctly treated by HERWIG++. Spin-1/2 heavy top-quark partner signal samples are generated with MADGRAPH [45]. Signal cross sections are calculated to NLO in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [54–56], as described in ref. [57].

The MC generator parameters have been tuned to ATLAS data [58, 59] and generated events have been processed through a detector simulation [60] based on GEANT4 [61]. Effects of multiple proton-proton interactions in the same bunch crossing (pile-up) are included, with the MC samples re-weighted so that the distribution of the average number of interactions per bunch crossing agrees with that in the data.

#### 4 Physics object reconstruction

Proton-proton interaction vertex candidates are reconstructed using the Inner Detector tracks. The vertex with the highest scalar sum of the  $p_T$  of the associated tracks is defined as the primary vertex.

Jets are reconstructed from three-dimensional calorimeter energy clusters using the anti- $k_t$  jet algorithm [62, 63] with a radius parameter of 0.4. The measured jet energy is corrected for inhomogeneities, and the non-compensating nature of the calorimeter with  $p_T$ - and  $\eta$ -dependent correction factors [64]. Only jet candidates with  $p_T > 20$  GeV,  $|\eta| < 2.5$  and a “jet vertex fraction” larger than 0.75 are retained. Based on tracking information, the jet vertex fraction quantifies the fraction of a jet’s momentum that originates from the reconstructed primary vertex. The requirement on the jet vertex fraction rejects jets originating from additional proton-proton interactions occurring in the same bunch crossing. Events with any jet that fails the jet quality criteria designed to reject noise and non-collision backgrounds [64] are rejected.

Electron candidates are required to have  $p_T > 20$  GeV,  $|\eta| < 2.47$  and to satisfy “medium” electromagnetic shower shape and track selection quality criteria [65]. These preselected electrons are then required to pass “tight” quality criteria [65] which places additional requirements on the ratio of calorimetric energy to track momentum, and on the fraction of hits in the straw tube tracker that pass a higher threshold for transition radiation. The electron candidates are then required to be isolated: the scalar sum of the  $p_T$ ,  $\Sigma p_T$ , of inner detector tracks, not including the electron track, with  $p_T > 1$  GeV within a cone in the  $\eta$ - $\phi$  plane of radius  $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.2$  around the electron candidate must be less than 10% of the electron  $p_T$ .

Muon candidates are reconstructed using either a full muon spectrometer track matched to an inner detector track, or a muon spectrometer segment matched to an extrapolated inner detector track [66]. They must be reconstructed with sufficient hits in the pixel, strip and straw tube detectors. They are required to have  $p_T > 10$  GeV,  $|\eta| < 2.4$  and must have longitudinal and transverse impact parameters within 1 mm and 0.2 mm of the primary vertex, respectively. Such preselected candidates are then required to have  $\Sigma p_T < 1.8$  GeV, defined in analogy to the electron case.

Following the object reconstruction described above, overlaps between jet, electron and muon candidates are resolved. Any jet within  $\Delta R = 0.2$  of preselected electrons is discarded. Electrons or muons within  $\Delta R = 0.4$  of any remaining jet are then discarded to reject leptons from the decay of a  $b$ - or  $c$ -hadron.

The  $E_T^{\text{miss}}$  is the magnitude of the vectorial sum of the  $p_T$  of the reconstructed jets (with  $p_T > 20$  GeV and  $|\eta| < 4.5$ ) after overlap removal, preselected leptons and clusters of calorimeter cells not belonging to reconstructed physics objects [67].

A  $b$ -tagging algorithm exploiting both impact parameter and secondary vertex information [68] is used to identify jets containing a  $b$ -hadron decay. The chosen operating point has a 60% efficiency for tagging  $b$ -jets in a MC sample of  $t\bar{t}$  events, with a mis-tag probability of less than 1% for jets from light quarks and gluons.

## 5 Event selection

This search uses proton-proton collisions recorded in 2011 at a centre-of-mass energy of 7 TeV. The data are selected with a three-level trigger system. Events are accepted if they pass either a single-electron trigger reaching a plateau efficiency of about 97% for electrons with  $p_T > 25$  GeV, or a single-muon or combined muon+jet trigger which reaches a plateau efficiency of about 75% (90%) in the barrel (end-caps) for events including muons with  $p_T > 20$  GeV and jets with  $p_T > 50$  GeV. The combined muon+jet trigger is used for the data-taking periods with high instantaneous luminosity, because it is based on looser muon identification requirements than the single-muon trigger available for those periods, resulting in a higher plateau efficiency. Events are required to have a reconstructed primary vertex with five or more tracks consistent with the transverse beam spot position. Following beam, detector and data quality requirements, a total integrated luminosity of  $(4.7 \pm 0.2)$  fb<sup>-1</sup> is used, measured as described in refs. [69, 70].

Two signal regions (SRs) are defined, one for different-flavour, and one for same-flavour leptons. For both SRs events are required to have exactly two opposite-sign (OS) leptons (electrons or muons) with an invariant mass larger than 20 GeV. At least one electron or muon must have a momentum in the trigger efficiency plateau regions described above. If the event contains a third preselected electron or muon, the event is rejected. At least two jets with  $p_T > 25$  GeV, and at least one of them with  $p_T > 50$  GeV, are required. This requirement suppresses  $WW$  and  $Z/\gamma^*$ +jets backgrounds.

For the same-flavour SR, additional selections are imposed to suppress the  $Z/\gamma^*$ +jets,  $WZ$  and  $ZZ$  backgrounds, which represent a significant fraction of events with large  $m_{T2}$ . These events have large  $E_T^{\text{miss}}$ , which for the  $WZ$  process is generated by the leptonic decay

Top quark partner mass [GeV]	200	300	400	500	600
$\tilde{t}_1\tilde{t}_1$ production	0.02%	7.7%	22.0%	35.6%	43.0%
$TT$ production	-	5.3%	15.8%	27.3%	34.3%

**Table 2.** Efficiency of the  $m_{T2}$  selection, calculated after all other selection requirements applied in the SR, for signal samples with different values of the mass of the scalar top or of the spin-1/2 heavy top-quark partner. The mass of the  $\tilde{\chi}_1^0$  or  $A_0$  is zero in each case. No signal sample with mass  $m(T) = 200$  GeV has been simulated.

of the  $W$  boson, for the  $ZZ$  process by the decay of one of the  $Z$  bosons to neutrinos, and for  $Z/\gamma^*$ +jets by the tails in the jet energy resolution. The additional selections required in the same-flavour channel to suppress these backgrounds are that the invariant mass of the leptons must be outside the 71 – 111 GeV range, and at least one of the jets must be tagged as a  $b$ -jet. After these selections the background is dominated by  $t\bar{t}$ .

Finally, for both SRs, signal candidate events are required to have a value of  $m_{T2}$  larger than 120 GeV. This requirement suppresses the remaining  $t\bar{t}$  and  $WW$  backgrounds by several orders of magnitude and was chosen to optimize the coverage of the analysis in the  $\tilde{t}_1 - \tilde{\chi}_1^0$  and  $T - A_0$  planes.

Before the  $m_{T2}$  selection,  $t\bar{t}$  production is by far the largest background. The efficiency of the  $m_{T2}$  selection for  $t\bar{t}$  events, calculated after all the other SR cuts, is 0.007%. The efficiency of the  $m_{T2}$  selection for scalar top and spin-1/2 heavy top-quark partner signal samples is given in table 2 for several values of the top-quark partner mass and for a massless  $\tilde{\chi}_1^0$  or  $A_0$ . The efficiency is smallest when  $\Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$  or  $m(T) - m(A_0)$  is close to the top quark mass, because the kinematics of the signal are then similar to those of  $t\bar{t}$  background, and it increases with increasing  $\Delta m$ . For equal masses, the spin-1/2 top-quark partner signals have a slightly lower efficiency than the scalar top signals, due to helicity effects in the decay.

## 6 Background estimation

The dominant SM background contributions to the SRs are top-quark pair and  $Z/\gamma^*$ +jets production. They are evaluated by defining a control region (CR) populated mostly by the targeted background, and using MC simulation to extrapolate from the rate measured in the CR to the expected background yield in the SR:

$$N(\text{SR}) = (N^{\text{Data}}(\text{CR}) - N_{\text{others}}(\text{CR})) \frac{N^{\text{MC}}(\text{SR})}{N^{\text{MC}}(\text{CR})}$$

where  $N^{\text{Data}}(\text{CR})$  is the number of data events observed in the CR,  $N^{\text{MC}}(\text{CR})$  and  $N^{\text{MC}}(\text{SR})$  are the number of events of the targeted background expected from MC simulation in the CR and SR respectively, and the term  $N_{\text{others}}(\text{CR})$  is the contribution from the other background sources in the CR which is estimated from MC simulation or additional control samples in data. The ratio of the number of MC events in the SR to the number of MC



Process	$t\bar{t}$ CR DF	$t\bar{t}$ CR SF
$t\bar{t}$	$68 \pm 11$	$39 \pm 11$
$t\bar{t}W + t\bar{t}Z$	$0.37 \pm 0.07$	$0.20 \pm 0.05$
$Wt$	$2.7 \pm 1.0$	$1.8 \pm 0.6$
$Z/\gamma^* + \text{jets}$	-	$3.5 \pm 1.4$
Fake leptons	$0.4 \pm 0.3$	$0.5 \pm 1.6$
Diboson	$0.49 \pm 0.14$	$0.10 \pm 0.05$
Total non- $t\bar{t}$	$4.0 \pm 1.5$	$6.1 \pm 3.7$
Total expected	$72 \pm 11$	$45 \pm 12$
Data	79	53

**Table 3.** Expected background composition and comparison of the predicted total SM event yield to the observed number of events in the top-quark control regions described in the text for the same-flavour (SF) and different-flavour (DF) selections. The expected  $Z/\gamma^* + \text{jets}$  rate in the DF channel is negligible. The quoted uncertainties include the systematic uncertainties described in section 7.

events in the CR for a given background source is referred to as the “transfer factor” in the following.

The  $t\bar{t}$  CR is defined akin to the SR, except for  $m_{T2}$ , which is required to be between 85 GeV and 100 GeV. The expected background composition of the  $t\bar{t}$  CR is given in table 3. The contamination due to fake leptons is evaluated from data with the technique described below, while all the other processes are obtained from the MC prediction. The  $t\bar{t}$  background is expected to account for 86% and 94% of the SM rate in the same-flavour and different-flavour CRs, respectively. The number of observed events is in good agreement with the expected event yields.

The systematic uncertainties on the modelling of the  $t\bar{t}$  background transfer factor due to the choice of the MC generator are assessed by comparing the baseline sample simulated with MC@NLO with the alternative samples described in section 3.

The background from  $Z/\gamma^* + \text{jets}$  is relevant for the same-flavour selection in the case of the decay channels  $Z \rightarrow ee$  or  $\mu\mu$ . For  $Z \rightarrow \tau\tau$  decays, which would contribute both to the same-flavour and the different-flavour samples, the  $m_{T2}$  distribution falls very steeply, and the number of expected events for  $m_{T2}$  in excess of 80 GeV is negligible.

The CR for  $Z/\gamma^* + \text{jets}$  is defined with the same selections as for the SR, except for the  $Z$  boson veto selection which is reversed. The observed number of events in this CR is 11, compared to  $7.6 \pm 1.1$  expected, of which  $7.0 \pm 1.1$  are from  $Z$  boson production, where the quoted uncertainties include the systematics discussed in the next section. The transfer factor between CR and SR is evaluated with  $Z/\gamma^* + \text{jet}$  MC samples to which all the selections of the same-flavour analysis except the  $b$ -tagging requirement are applied. Detailed checks have been performed in order to verify that this transfer factor, which relates the number of events inside the  $Z$  boson peak to the number of events outside, is

stable with respect to the  $m_{T2}$  and  $b$ -tag requirements. The method is validated using an auxiliary CR dominated by  $Z/\gamma^*$ +jets events, defined in the same way as the SR except the  $b$ -jet requirement is removed. The number of predicted background events is  $7.5\pm 1.3$  (of which  $7.2\pm 1.3$  from  $Z/\gamma^*$ +jets) while the observed number is 10. The quoted uncertainty on the prediction is only statistical.

Additional SM processes yielding two isolated leptons and  $E_T^{\text{miss}}$  ( $Wt$ ,  $WW$ ,  $WZ$ ,  $ZZ$ ,  $t\bar{t}W$ ,  $t\bar{t}Z$ ) are estimated from the MC simulation. The contribution from diboson processes, particularly  $WW$  production, is about a quarter of the total background in the different-flavour signal region. The high- $m_{T2}$  population in  $WW$  production is dominated by events in which a strongly off-shell  $W$  is produced. The 18% relative difference in the number of events with  $m_{T2} > 120$  GeV between SHERPA and HERWIG before jet selection is taken as a systematic uncertainty on the simulation of the  $m_{T2}$  distribution. The 45% relative difference between SHERPA and ALPGEN in the efficiency of the jet selections integrated over the whole  $m_{T2}$  range is taken as a systematic uncertainty on the  $WWjj$  cross section.

The fake lepton background consists of semi-leptonic  $t\bar{t}$ ,  $s$ -channel and  $t$ -channel single top,  $W$ +jets and light- and heavy-flavour jet production. The contribution from this background is small (less than 10% of the total background). It is estimated from data with a method similar to that described in refs. [71, 72]. Two types of lepton identification criteria are defined for this evaluation: “tight”, corresponding to the full set of identification criteria described above, and “loose” corresponding to preselected electrons and muons. The method counts the number of observed events containing loose-loose, loose-tight, tight-loose and tight-tight lepton pairs in the SR. The probability for real leptons passing the loose selection criteria to also pass the tight selection is measured using a  $Z \rightarrow \ell\ell$  sample. The equivalent probability for fake leptons is measured from multijet-enriched control samples. From these probabilities the number of events containing a contribution from one or two fake leptons is calculated.

The procedure described above is used to estimate the fake lepton background with looser selections and extrapolated to the signal region. A systematic uncertainty is assigned to the extrapolation procedure by comparing the direct and extrapolated background estimate in various control regions.

## 7 Systematic uncertainties

Various systematic uncertainties affecting the predicted background rates in the signal regions are considered. Such uncertainties are either used directly in the evaluation of the predicted background in the SR (for diboson,  $Wt$ ,  $t\bar{t}W$  and  $t\bar{t}Z$  production), or to compute the uncertainty on the transfer factor and propagate it to the predicted event yields in the SR (for  $t\bar{t}$ ,  $Z/\gamma^*$ +jets).

The following experimental systematic uncertainties were found to be non-negligible:

**Jet energy scale and resolution.** The uncertainty on the jet energy scale (JES), derived using single particle response and test beam data, varies as a function of the jet  $p_T$  and pseudorapidity [64]. Additional systematic uncertainties arise from the dependence of the jet response on the number of interactions per bunch crossing and on

the jet flavour. The total jet energy scale uncertainty at  $p_T = 50$  GeV in the central detector region is about 5% [64]. The components of the jet energy scale uncertainty are varied by  $\pm 1\sigma$  in the MC simulation in order to obtain the resulting uncertainty in the event yield. Uncertainties related to the jet energy resolution (JER) are obtained with an in situ measurement of the jet response asymmetry in dijet events [73]. Their impact on the event yield is estimated by applying an additional smearing to the jet transverse momenta. The JES and JER variations applied to the jet momenta are propagated to the  $E_T^{\text{miss}}$ . The JES and JER relative uncertainties on the same-flavour and different-flavour signal region event yield amount to 16% and 22%, respectively.

**Calorimeter cluster energy scale and pile-up modelling.** The uncertainties related to the contribution to  $E_T^{\text{miss}}$  from the energy in the calorimeter cells not associated to electrons, muons or jets, and also from low momentum ( $7 \text{ GeV} < p_T < 25 \text{ GeV}$ ) jets, as well as the uncertainty due to the modelling of pile-up have been evaluated to amount to 6% (25%) of the same-flavor (different-flavor) event yield. The fractional uncertainty is smaller in the same-flavour channel because it has a very small impact (2%) on the estimation of the  $Z/\gamma^*$ +jets background, which is by far the largest contribution to the same-flavour channel.

**$b$ -tagging efficiency and mis-tagging uncertainties.** This uncertainty is evaluated by varying the  $b$ -tagging efficiency and mis-tagging rates within the uncertainties measured in situ [68]. Since the different-flavour selection does not make use of  $b$ -tagging, this uncertainty only affects the same-flavour channel and is relatively small (about 1% of the total event yield).

**Fake-lepton background uncertainties:** an uncertainty of 33% (25%) is assigned to the fake background in the same-flavour (different-flavour) channel from the comparison of results from different CRs, with an additional 30% is taken as the systematic uncertainty due to the projection of events into the SR.

Other significant sources of uncertainty are the normalization uncertainties for processes estimated from MC simulation only, the theoretical uncertainties discussed in section 6, the limited number of data events in the CRs, the limited number of MC events, and the integrated luminosity.

A summary of the uncertainties on the total expected background in the two channels is given in table 4. The row labelled “statistics” includes the effects of the limited number of data events in the CRs and the limited number of MC events. The theoretical uncertainties include the cross section, MC generator, and initial- and final-state radiation uncertainties. They are smaller for the same-flavor channel because the theoretical uncertainty on the  $Z/\gamma^*$ +jets is relatively small (about 10%). In the opposite-flavour channel the dominant backgrounds are the top pair production, which is affected by an uncertainty of about 100% (due to the description of the high  $m_{T2}$  tail in simulation), and the diboson process whose cross section has an uncertainty of about 50%, due mostly to the poor prediction of the production in association with two (or more) jets.

Channel	SF	DF
Total event yield	1.58	0.94
JES + JER	16%	22%
$b$ -tagging	1%	–
$E_T^{\text{miss}}$ and pile-up modeling	6%	25%
Luminosity	1%	2%
Theory	14%	48%
Statistics	$\pm_{26}^{29}\%$	20%
Fake-lepton uncertainties	$\pm_0^8\%$	$\pm_0^9\%$
Total uncertainty	$\pm_{37}^{40}\%$	64%

**Table 4.** Total expected background yield and uncertainties in the same-flavour (SF) and different-flavour (DF) signal regions. Where the uncertainty is not symmetric, the upwards and downwards values are given.

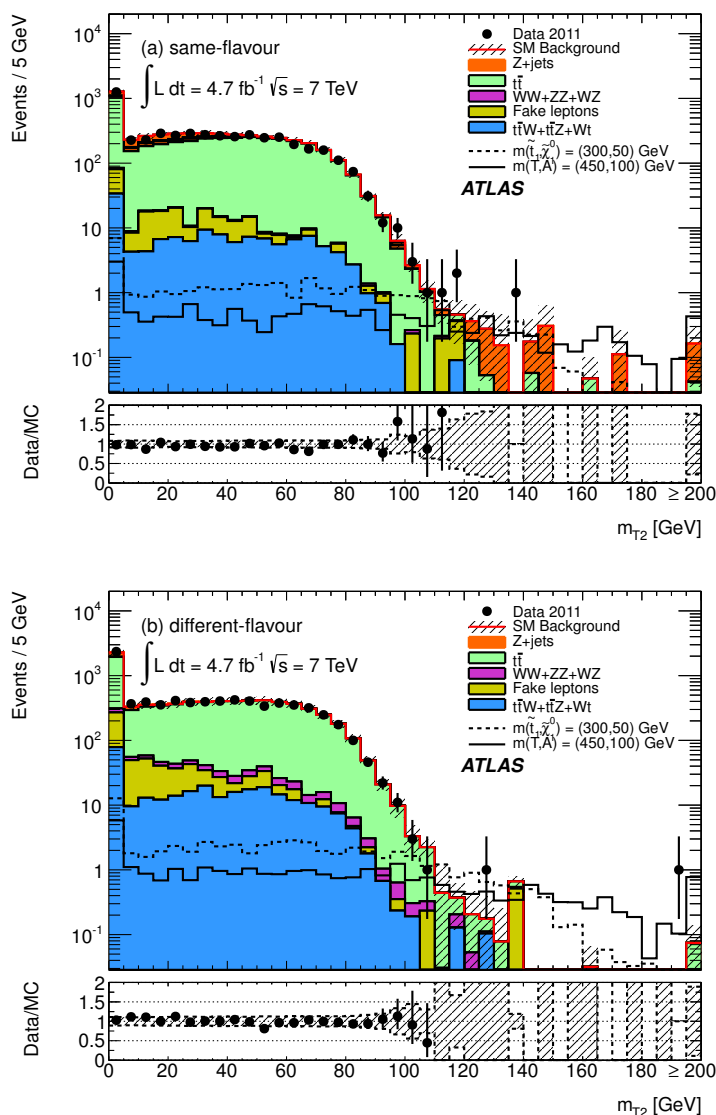
For the limit calculation, the uncertainty on the expected signal yield is also needed. The JES, JER, calorimeter energy scale and event pileup, and  $b$ -tagging uncertainties discussed above have been taken into account. The typical total uncertainty from these sources varies between 4% and 12% for the DF channel and between 7% and 22% for the SF channel, with comparable contributions from the JES, the calorimeter energy scale and pileup, and (for SF) the  $b$ -tagging uncertainties.

The uncertainty on the signal cross sections is calculated with an envelope of cross section predictions which is defined using the 68% confidence level (CL) ranges of the CTEQ [74] (including the  $\alpha_S$  uncertainty) and MSTW [75] PDF sets, together with variations of the factorization and renormalization scales by factors of two or one half. The nominal cross section value is taken to be the midpoint of the envelope and the uncertainty assigned is half the full width of the envelope, following the PDF4LHC recommendations [76] and using the procedure described in ref. [57]. The typical cross section uncertainty is 12% for the spin-1/2 top-quark partner signal and 15% for the scalar top signal.

## 8 Results

Figure 1 shows the distributions of the  $m_{T2}$  variable for same-flavour and different-flavour events after all selection criteria are applied except the selection on  $m_{T2}$  itself. For illustration, the distributions for two signal hypotheses are also shown. The data agree with the SM background expectation within uncertainties.

Table 5 shows the expected number of events in the SR for each background source and the observed number of events. No excess of events in data is observed, and limits at 95% CL are derived on the visible cross section  $\sigma_{\text{vis}} = \sigma \times \epsilon \times \mathcal{A}$ , where  $\sigma$  is the total production cross section for the non-SM signal,  $\mathcal{A}$  is the acceptance defined by the fraction of events passing the geometric and kinematic selections at particle level, and  $\epsilon$  is the detector reconstruction, identification and trigger efficiency. Limits are set using



**Figure 1.** Distribution of  $m_{T2}$  for events passing all the signal candidate selection requirements, except that on  $m_{T2}$ , for (a) same-flavour and (b) different-flavour events. The contributions from all SM backgrounds are shown; the bands represent the total uncertainties. The components labelled “fake lepton” are estimated from data as described in the text; the other backgrounds are estimated from MC simulation with normalizations measured in control regions described in section 6 for  $t\bar{t}$  and  $Z/\gamma^*+jets$ . The distributions of the signal expected for two models considered in this paper are also shown: the dashed line corresponds to signal with a 300 GeV scalar top and a 50 GeV neutralino, while the solid line corresponds to a signal with a 450 GeV spin-1/2 top quark partner  $T$  and a 100 GeV  $A_0$  particle.

the CLs likelihood ratio prescription as described in ref. [77]. Systematic uncertainties are included in the likelihood function as nuisance parameters with a gaussian probability density function. The limits are listed in table 5.

	SF	DF
$Z/\gamma^*$ +jets ( $Z/\gamma^*$ +jets scale factor)	$1.2 \pm 0.5$ (1.27)	- -
$t\bar{t}$ ( $t\bar{t}$ scale factor)	$0.23 \pm 0.23$ (1.21)	$0.4 \pm 0.3$ (1.10)
$t\bar{t}W + t\bar{t}Z$	$0.11 \pm 0.07$	$0.19 \pm 0.12$
$WW$	$0.01^{+0.02}_{-0.01}$	$0.19 \pm 0.18$
$WZ + ZZ$	$0.05 \pm 0.05$	$0.03 \pm 0.03$
$Wt$	$0.00^{+0.17}_{-0.00}$	$0.10^{+0.18}_{-0.10}$
Fake leptons	$0.00^{+0.14}_{-0.00}$	$0.00^{+0.09}_{-0.00}$
Total SM	$1.6 \pm 0.6$	$0.9 \pm 0.6$
Observed	1	2
$m_{\tilde{t}_1} = 300 \text{ GeV}, m_{\tilde{\chi}_1^0} = 50 \text{ GeV}$	$2.2 \pm 0.3(\text{th.}) \pm 0.2(\text{exp.})$	$3.7 \pm 0.6(\text{th.}) \pm 0.3(\text{exp.})$
$m_T = 450 \text{ GeV}, m_{A_0} = 100 \text{ GeV}$	$3.1 \pm 0.4(\text{th.}) \pm 0.3(\text{exp.})$	$5.8 \pm 0.7(\text{th.}) \pm 0.5(\text{exp.})$
95% CL limit on $\sigma_{\text{vis}}^{\text{obs}}$ [fb]	0.86	1.08
95% CL limit on $\sigma_{\text{vis}}^{\text{exp}}$ [fb]	0.89	0.79

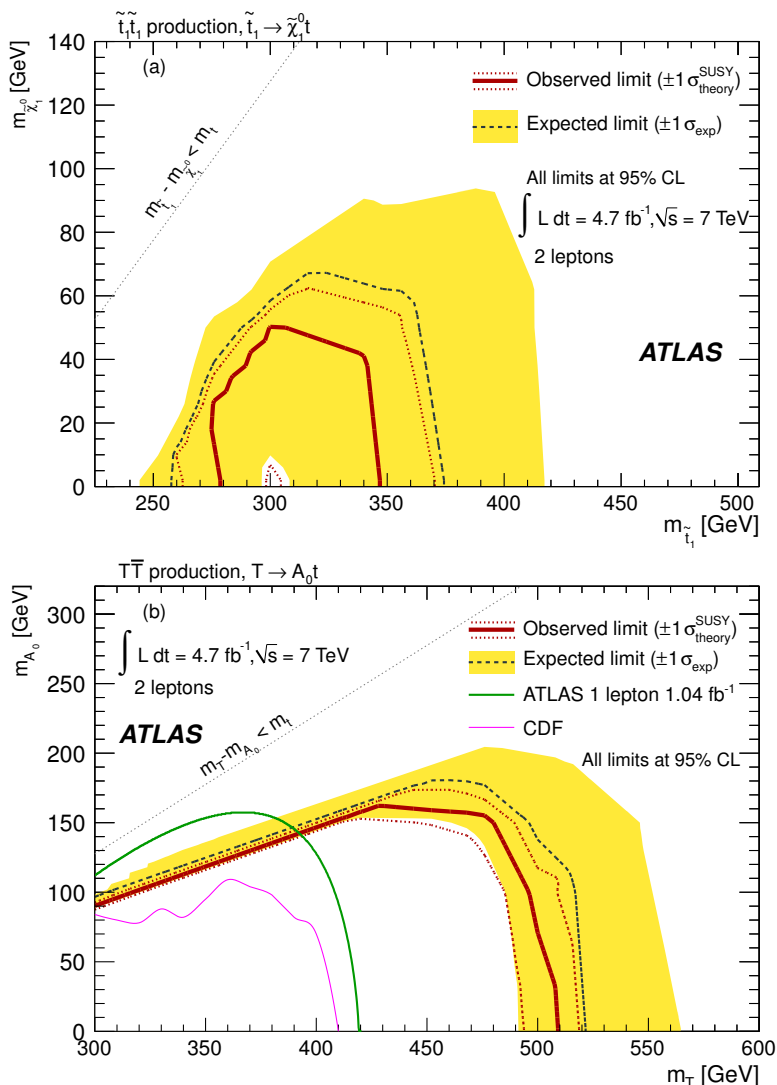
**Table 5.** Number of expected SM background events and number of observed events for the same-flavour (SF) and different-flavour (DF) signal regions. The quoted errors are the total uncertainties on the expected rates. For  $Z/\gamma^*$ +jets and  $t\bar{t}$  the ratio between the estimate based on the control region and the MC prediction (scale factor) is also reported. Dashes indicate negligible background expectations. The expected yield for two signal models is also shown, with the associated theoretical and experimental uncertainties. Observed and expected upper limits at 95% confidence level on  $\sigma_{\text{vis}} = \sigma \times \epsilon \times \mathcal{A}$  are also shown.

The results obtained are used to derive limits on the mass of a pair-produced heavy top-quark partner decaying into a top quark and a weakly interacting particle with 100% branching ratio. The limits are derived in the plane defined by the masses of the two particles for two scenarios: a model with a scalar top  $\tilde{t}_1$  and a spin-1/2 neutralino  $\tilde{\chi}_1^0$  and one with a spin-1/2 top-quark partner  $T$  and a scalar boson  $A_0$ .

In both scenarios, the limits are derived after combining the same-flavour and different-flavour channels. Uncertainties on the detector response, cross section, luminosity and MC statistics are taken into account. The limits are shown in figure 2 for the scalar top and spin-1/2 top-quark partner models. Using a signal cross section one standard deviation below the central value, a spin-1/2 top-quark partner  $T$  with a mass between 300 GeV and 480 GeV (if the  $A_0$  mass is lower than 100 GeV) is excluded at 95% CL. The region of the mass plane which is excluded is smaller for scalar top production, because of the lower production cross section. A scalar top of mass close to 300 GeV and a nearly massless neutralino is excluded at 95% CL.

## 9 Conclusions

A search for a heavy partner of the top quark, which decays into a top quark and an invisible particle, has been performed using  $4.7 \text{ fb}^{-1}$  of pp collision data at  $\sqrt{s} = 7 \text{ TeV}$



**Figure 2.** Expected and observed 95% CL limits (a) in the  $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$  model as a function of the scalar top and neutralino masses, and (b) in the  $T \rightarrow tA_0$  model as a function of the spin-1/2 top-quark partner  $T$  and  $A_0$  masses. The dashed line and the shaded band are the expected limit and its  $\pm 1\sigma$  uncertainty, respectively. The thick solid line is the observed limit for the central value of the signal cross section. The expected and observed limits do not include the effect of the theoretical uncertainties on the signal cross section. The dotted lines show the effect on the observed limit of varying the signal cross section by  $\pm 1\sigma$  of the theoretical uncertainty. The curve labelled “ATLAS 1 lepton 1.04 fb<sup>-1</sup>” is the previous ATLAS limit from ref. [25] using the one lepton channel while the curve labelled “CDF” is from ref. [24].

produced by the LHC and taken by the ATLAS detector. The number of observed events has been found to be consistent with the Standard Model expectation.

Limits have been derived on a spin-1/2 heavy top-quark partner decaying to a top quark and a heavy neutral particle. A spin-1/2 top-quark partner mass between 300 GeV and 480 GeV is excluded at 95% CL for a heavy neutral particle mass below 100 GeV.



This result extends the previously published limits in this scenario [25]. A supersymmetric scalar top  $\tilde{t}_1$  with a mass of 300 GeV decaying to a top quark and a massless neutralino is also excluded at 95% CL.

The present result complements those from other ATLAS direct scalar top pair production searches [30, 31, 78, 79] addressing different signatures with either both scalar top decaying to a chargino and a  $b$  quark [30, 31] or with both scalar top decaying to a neutralino and a top quark and the subsequent top quark decays yielding zero or one lepton in the final state [78, 79].

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