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The ATLAS Collaboration

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A search for flavour changing neutral currents in top-quark decays in pp collision data collected with the ATLAS detector at $\sqrt{s} = 7$ TeV

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Abstract: A search for flavour changing neutral current (FCNC) processes in top-quark decays by the ATLAS Collaboration is presented. Data collected from pp collisions at the LHC at a centre-of-mass energy of $\sqrt{s} = 7$ TeV during 2011, corresponding to an integrated luminosity of 2.1 fb^{-1}, were used. A search was performed for top-quark pair-production events, with one top quark decaying through the $t \to Zq$ FCNC $(q = u, c)$ channel, and the other through the Standard Model dominant mode $t \to Wb$. Only the decays of the Z boson to charged leptons and leptonic W-boson decays were considered as signal. Consequently, the final-state topology is characterised by the presence of three isolated charged leptons, at least two jets and missing transverse momentum from the undetected neutrino. No evidence for an FCNC signal was found. An upper limit on the $t \to Zq$ branching ratio of BR$(t \to Zq) < 0.73\%$ is set at the 95% confidence level.

Keywords: top physics, rare decays, flavour changing neutral currents

Contents

1 Introduction

The top quark is the heaviest known elementary particle, with a mass of $m_t = 173.2 \pm 0.9$ GeV [1]. The very large mass may provide a window onto physics beyond the Standard Model (SM). Deviations from SM predictions of the production and decay properties of the top quark provide model-independent tests for physics beyond the SM. According to the SM, the top quark decays nearly 100% of the time to a W boson and a b quark. Flavour changing neutral current (FCNC) decays are highly suppressed in the SM by the GIM mechanism [2] with a branching ratio (BR) of the order of 10^{-14}.

Several SM extensions predict a higher BR for top-quark FCNC decays. Examples of such extensions are the quark-singlet model [3–5], the two-Higgs doublet model with or without flavour-conservation [6–11], the minimal supersymmetric model [12–18], supersymmetry (SUSY) with R-parity violation [19], the topcolour-assisted technicolour model [20] or models with warped extra dimensions [21, 22]. The top-quark FCNC decay BR in these models is typically many orders of magnitude larger than the SM BR, and can be as high as $\sim 2 \times 10^{-4}$ in certain R-parity violating SUSY models.

Existing experimental limits on top-quark FCNC decays come from direct and indirect searches at the Tevatron collider [23, 24], and indirect searches at the LEP [25–30] and

HERA [31, 32] colliders, and at the LHC [33]. The best current direct search limits on the top quark FCNC branching fraction are 3.2% for both $t \to q\gamma$ [23] and $t \to Zq$ ($q = u, c$) [24].

This article reports a search for FCNC top-quark decays in $t\bar{t}$ events. Events were searched for in which either the top or antitop quark has decayed into a Z boson and a quark, $t \to Zq$, while the remaining top or antitop quark decayed through the SM $t \to Wb$ channel. Only leptonic decays of the Z and W bosons were considered, yielding a final-state topology characterised by the presence of three isolated charged leptons, at least two jets, and transverse momentum imbalance ($E_{\mathrm{T}}^{\mathrm{miss}}$) from the undetected neutrino arising from the W-boson decay. Leptons are either well-identified electron or muon candidates, selected using the full detector or, to increase signal acceptance, isolated tracks. Channels with τ leptons are not explicitly reconstructed, but reconstructed electrons and muons can arise from leptonic τ decays, and an isolated track can arise from hadronic τ decay modes.

2 Detector and data samples

The ATLAS detector [34] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector comprising a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker. The inner detector covers the pseudorapidity[1] range $|\eta| < 2.5$ and is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, and by lead/liquid-argon (LAr) electromagnetic (EM) sampling calorimeters with high granularity. An iron/scintillator-tile calorimeter provides hadronic energy measurements in the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for both EM and hadronic energy measurements up to $|\eta| < 4.9$. The calorimeter system is surrounded by a muon spectrometer incorporating three superconducting toroid magnet assemblies (one barrel and two end-caps), with bending power between 2.0 Tm and 7.5 Tm.

A three-level trigger system is used to collect data. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the rate to at most 75 kHz. This is followed by two software-based trigger levels that together reduce the event rate to $\sim$ 300 Hz. This analysis uses inclusive single-muon and single-electron triggers with p_{T} thresholds of 18 GeV for muons and 20 GeV or 22 GeV for electrons, depending on the data taking period.

Proton-proton collision data taken at $\sqrt{s} = 7$ TeV by ATLAS between March and August 2011 are used. The data sample corresponds to a total integrated luminosity of 2.1 fb^{-1} with an uncertainty of 3.7% [35, 36]. The mean number of interactions per bunch crossing was 6.2 for the full data sample.

[1]In the right-handed ATLAS coordinate system, the pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$, where the polar angle θ is measured with respect to the LHC beamline. The azimuthal angle ϕ is measured with respect to the x-axis, which points towards the centre of the LHC ring. The y-axis points upwards. Transverse momentum and energy are defined as $p_{\mathrm{T}} = p \sin\theta$ and $E_{\mathrm{T}} = E \sin\theta$, respectively.

3 Monte Carlo simulation samples

Monte Carlo (MC) samples were generated to model both FCNC signal events and certain backgrounds. Alternative MC samples were also generated to evaluate various systematic uncertainties. All generated events are propagated through a detailed `GEANT4` simulation [37, 38] of the ATLAS detector and are reconstructed with the same algorithms as the data. The effect of additional pp interactions in the same bunch crossing as the events of interest was simulated by superimposing additional simulated minimum-bias interactions. The effect from events in neighbouring bunch crossings was also simulated. The simulated events were reweighted such that the average number of extra interactions per crossing (pile-up) matched the data. Data-to-MC scale factors were applied to the MC samples to account for small differences in efficiencies between data and MC simulation.

3.1 Signal

Monte Carlo simulation samples of top-quark pair production, with one of the top quarks decaying through FCNC to Zq while the other decays according to the SM, were generated with `TopReX` [39]. Only decays of the W and Z bosons involving charged leptons were generated ($Z \to ee, \mu\mu, \tau\tau$ and $W \to e\nu, \mu\nu, \tau\nu$). The MRST2007 LO* [40] parton distribution function (PDF) set was used with the `TopReX` generator. All signal events were hadronized with `PYTHIA` 6.421 [41]. The masses of the top quark, W boson and Z boson were set to 172.5 GeV, 80.4 GeV and 91.2 GeV, respectively.

To study the effect of the uncertainty due to the top-quark mass, samples with top-quark masses of 170 GeV and 175 GeV were also generated. The uncertainty due to initial- and final-state radiation (ISR/FSR) was evaluated using the `AcerMC` generator [42] interfaced to `PYTHIA`, and by varying the parameters controlling ISR and FSR in a range consistent with those used in the Perugia Hard/Soft tune variations [43].

3.2 Background

Several SM processes have final-state topologies similar to the signal. These include events with three final-state charged leptons (real leptons), as well as events in which at least one jet (including jets with heavy-flavour decays) is misidentified as an isolated charged lepton ('fake leptons') and events with four leptons in which one is not reconstructed.

Diboson events (WW, WZ and ZZ) were produced using `ALPGEN` 2.13 [44]. Up to three additional partons from the matrix element were simulated, and the CTEQ6L1 [45] PDF was used. The parton shower and the underlying event were added using `HERWIG` v6.510 [46, 47] and the `JIMMY` [48] underlying event model with the AUET1 tune [49] to the ATLAS data. The `ALPGEN` program with `HERWIG` showering and the `JIMMY` underlying event model was also used to generate Z/γ+jets.

The $t\bar{t}$ and single-top events were generated using the `MC@NLO` generator v3.41 [50–52] with the CTEQ6.6 [53] PDFs [54]. The parton shower and the underlying event were added using `HERWIG` v6.510 and `JIMMY` generators as described above. The $t\bar{t}$ production cross section was normalized to the approximate next-to-next-to-leading-order (NNLO) prediction of 164.6 pb, obtained using the `HATHOR` tool [55]. The cross sections for single-top production were normalized to the approximate NNLO predictions of 64.6 pb [56], 4.6 pb [57] and 15.7 pb [58] for t-channel, s-channel and associated Wt production, respectively.

Events with $t\bar{t}$+W and $t\bar{t}$+Z production, including those with extra jets in the final state, were generated using MADGRAPH 4.4.62 [59]. Parton showering was added using PYTHIA.

All decay modes of the W and Z bosons to charged leptons were considered in the generation and simulation of the background samples used.

Backgrounds that include fake leptons were evaluated using a data-driven approach described below.

4 Object definition

The selection of leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ was close to that used for the ATLAS measurement of the $t\bar{t}$ production cross section in the dilepton channel [60]. Leptons were selected either using the full ATLAS detector, including the inner detector, calorimeter and muon spectrometer ('identified leptons' or 'ID leptons'), or using only a high quality inner detector track ('track leptons' or 'TLs'). The inclusion of TLs increased the acceptance for $W \to \tau\nu$ decays, and for electrons and muons that fail the ID lepton selection criteria. TLs were required to be distinct from ID leptons, and at most one TL per event was allowed. Signal candidates selected with three identified leptons are referred to as '3ID' events, and those selected with two identified leptons and a TL are referred to as '2ID+TL' events. The 2ID+TL events increased the signal acceptance by 22% compared to a 3ID selection alone.

ID electron candidates were reconstructed from energy deposits (clusters) in the EM calorimeter, which were then associated to reconstructed tracks of charged particles in the inner detector. Stringent quality requirements on the conditions of the EM calorimeter at the time of data taking were applied to ensure a well-measured reconstructed energy. A 'tight' selection [61] using calorimeter, tracking and combined variables, was employed to provide good separation between the signal electrons and background. Electron candidates were additionally required to have $|\eta_{\mathrm{cl}}| < 2.47$, excluding electrons in the transition region between the barrel and endcap calorimeters defined by $1.37 < |\eta_{\mathrm{cl}}| < 1.52$. The variable η_{cl} is the pseudorapidity of the energy cluster associated with the candidate.

ID muon candidate reconstruction began by searching for track segments in layers of the muon chambers. These segments were combined starting from the outermost layer, fitted to account for material effects, and matched with tracks found in the inner detector. The candidates were refitted using the complete track information from both detector systems, and were required to satisfy $|\eta| < 2.5$.

Candidates for TL were defined by an inner-detector track and a series of quality cuts optimized for high efficiency and a low rate of misidentification. The track was required to have at least six pixel and/or SCT hits and at least one hit in the innermost pixel layer. The transverse distance of closest approach of the track to the beamline, d_0, was required to satisfy $|d_0| < 0.2$ mm and the uncertainty on the momentum measurement was required be less than 20%.

All leptons were required to be isolated and have high transverse momentum, p_{T}, consistent with originating from W- or Z-boson decay. Because of the requirement of three leptons in this analysis, lepton thresholds were reduced from those used in Ref. [60]. In 3ID events, the leading lepton was required to have $p_{\mathrm{T}} > 25$ GeV, and the two sub-leading leptons were required to have $p_{\mathrm{T}} > 20$ GeV. In 2ID+TL events, the TL was required to have $p_{\mathrm{T}} > 25$ GeV, and the two ID leptons in the event were required to have $p_{\mathrm{T}} > 20$ GeV. At least one ID lepton was required to have fired the trigger. To ensure good trigger efficiency with the higher electron trigger thresholds, reconstructed electrons that were associated with trigger objects were required to have $p_{\mathrm{T}} > 25$ GeV.

Lepton isolation requirements reduce backgrounds from misidentified jets and suppress the selection of leptons from heavy-flavour decays. For ID electron candidates, E_{T} deposited in the calorimeter cells but not associated to the electron was summed in a cone with radius[2] $\Delta R = 0.2$ around the electron and required to be less than 3.5 GeV. For ID muon candidates, the isolation requirement was based on both calorimeter and track information. The track isolation requirement was based on the sum of the track transverse momenta, for tracks with $p_{\mathrm{T}} > 1$ GeV in a cone with radius $\Delta R = 0.3$ centred on the muon candidate, while the calorimeter isolation requirement was based on the transverse energy in the same cone. Both the track and calorimeter sums, excluding the muon candidate, were required to be less than 4 GeV. Additionally, ID muon candidates were required to have a distance $\Delta R > 0.4$ from any jet with $p_{\mathrm{T}} > 20$ GeV, further suppressing muon candidates from heavy-flavour decays. For TLs, the track was required to be isolated from other nearby tracks following the track isolation definition above, in this case using tracks with $p_{\mathrm{T}} > 0.5$ GeV. The summed momentum cut was set to 2 GeV. ID muon candidates arising from cosmic rays were rejected by removing candidate pairs that were back-to-back in the $r - \phi$ plane and with transverse impact parameters relative to the beam axis $|d_0| > 0.5$ mm.

Jets were reconstructed with the anti-k_t algorithm [62] with a radius parameter $R = 0.4$, starting from energy clusters in the calorimeter reconstructed using the scale established for electromagnetic objects. These jets were then calibrated to the hadronic energy scale using p_{T}- and η-dependent correction factors [63]. Jets were removed if they are within $\Delta R < 0.2$ of a well-identified electron candidate, or within $\Delta R < 0.4$ of a TL. The jets used in the analysis were required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.

To suppress backgrounds in which TLs are reconstructed from fake leptons, a jet consistent with originating from a b quark was required in events with a TL. Jets were identified as b-quark candidates ('b-tagged') by an algorithm that forms a likelihood ratio of b- to light-quark jet hypotheses using several kinematic variables [64]. The cut on the combined likelihood ratio was chosen such that a b-tagging efficiency of $\approx 80\%$ per b-jet in $t\bar{t}$ candidate events was achieved.

The $E_{\mathrm{T}}^{\mathrm{miss}}$ vector was formed from the negative vector sum of the transverse momenta of the reconstructed objects (electrons, muons, jets) [65]. The contribution from cells associated with electron candidates was replaced by the calibrated transverse energy of

[2] $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

the candidate. The contribution from all ID muon candidates and calorimeter clusters (including those not belonging to a reconstructed object) was also included. TL candidates that arise from muons and leave little energy in the calorimeter are not properly included in the $E_{\mathrm{T}}^{\mathrm{miss}}$. In such events the $E_{\mathrm{T}}^{\mathrm{miss}}$ often points close to the TL direction. In these events the $E_{\mathrm{T}}^{\mathrm{miss}}$ was corrected with the p_{T} of the TL if the TL and an oppositely-charged ID muon were consistent with coming from a Z-boson decay, and if the $\Delta\phi$ between the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the TL direction was less than 0.15 and there is no ID lepton within ΔR=0.05 of the TL (in which case the correction was already included by the $E_{\mathrm{T}}^{\mathrm{miss}}$ algorithm). After all corrections, $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV was required.

5 Event selection and reconstruction

The analysis required collision data selected by an inclusive single-electron or single-muon trigger. To ensure that the event was triggered by the lepton candidates used in the analysis, one of the identified leptons and the triggered lepton were required to match within $\Delta R < 0.15$.

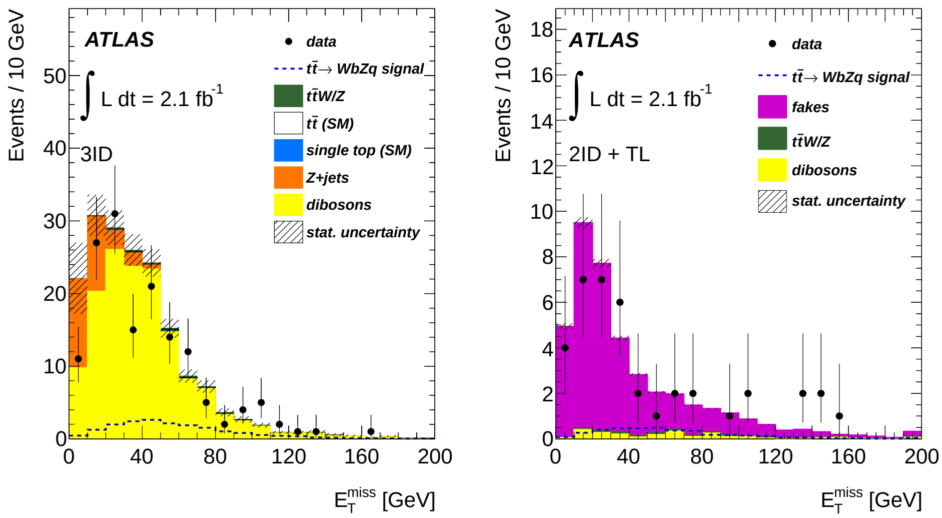
Events were required to have a primary interaction vertex with at least five tracks with $p_{\mathrm{T}} > 400$ MeV. The event was discarded if it had any jet with $p_{\mathrm{T}} > 20$ GeV that failed quality cuts designed to reject jets arising from calorimeter noise or activity inconsistent with the bunch-crossing time [63]. If an electron candidate and a muon candidate shared a track, the event was also discarded.

During part of the data-taking period, corresponding to an integrated luminosity of 0.9 fb^{-1}, an electronics failure in a small $\eta - \phi$ region of the LAr EM calorimeter created a dead region. For this subset of the data, events in data and MC simulation containing either an identified electron or a jet with $p_{\mathrm{T}} > 20$ GeV, satisfying $-0.1 < \eta < 1.5$ and $-0.9 < \phi < -0.5$ were rejected.

Events were selected as either 3ID or 2ID+TL candidates, each with thresholds described in Section 4. In both cases, all three lepton candidates were required to come from the same primary interaction vertex. In addition, signal candidates were required to have at least two jets and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV. In events selected with a TL, at least one jet was required to be b-tagged. Figure 1 shows the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for the 3ID and 2ID+TL events prior to the final selection requirements. For the 3ID case these are events with three identified leptons with at least one opposite-sign, same-flavour pair with an invariant mass consistent with a Z-boson, but no jets or $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement. In the 2ID+TL case, these are events with an opposite-sign pair and both the jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements, but no Z-boson selection.

Selected events were required to be kinematically consistent with $t\bar{t} \to WbZq$ through a χ^2 minimized with respect to jet and lepton assignments and the longitudinal momentum of the neutrino, p_z^{ν}. The χ^2 was defined as follows

$$\chi^2 = \frac{\left(m_{j_a\ell_a\ell_b}^{\mathrm{reco}} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m_{j_b\ell_c\nu}^{\mathrm{reco}} - m_t\right)^2}{\sigma_t^2} + \frac{\left(m_{\ell_c\nu}^{\mathrm{reco}} - m_W\right)^2}{\sigma_W^2} + \frac{\left(m_{\ell_a\ell_b}^{\mathrm{reco}} - m_Z\right)^2}{\sigma_Z^2}, \quad (5.1)$$



(a) (b)

Figure 1. $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions before the final selection for the (a) 3ID and (b) 2ID+TL analysis. For the 3ID case these are events with three identified leptons with at least one opposite-sign, same-flavour pair with an invariant mass consistent with a Z-boson, but no jets or $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement. In the 2ID+TL case, these are events with an opposite-sign pair and both the jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ requirements, but no Z-boson selection. The uncertainties shown are statistical only.

where $j_{a,b}$ are the two highest-p_{T} jets in the event and $\ell_{a,b,c}$ are the three lepton candidates. The constraints were defined as follows: $m_t = 172.5$ GeV, $m_W = 80.4$ GeV, $m_Z = 91.2$ GeV. The widths were derived from MC studies and set to $\sigma_t = 14$ GeV, $\sigma_W = 10$ GeV and $\sigma_Z = 3$ GeV. The transverse momentum of the neutrino was set equal to $E_{\mathrm{T}}^{\mathrm{miss}}$, and all jet and lepton assignments were tried, subject to the requirement that the Z candidate be built from same-flavour opposite-charge leptons. Any opposite-charge ID lepton–TL pair can be used as leptons from the Z-boson decay, because the TL is assumed to be the same flavour as the ID lepton. No b-jet identification was used in the reconstruction of the event kinematics. For each assignment, the value of p_z^ν was defined to be that which gave the minimum χ^2. From all combinations, the one with the smallest χ^2 was chosen along with the corresponding p_z^ν value. Events were rejected unless the reconstructed top-quark masses were within 40 GeV of m_t, the reconstructed W-boson mass was within 30 GeV of m_W, and the reconstructed Z-boson mass was within 15 GeV of m_Z. The effect of these mass cuts on the fake-TL background expectation was derived from simulation by measuring the fraction of simulated 2ID+TL background events with fake TLs that pass the χ^2 mass cuts. This fraction is $(31\pm10)\%$. Of the events that pass all other event selection requirements, 38% (29%) of the 3ID (2ID+TL) events pass the χ^2 mass cuts. The efficiency for FCNC MC events to pass the χ^2-based mass cuts is $(79 \pm 2)\%$ ($(66 \pm 2)\%$), while for background MC events it is only $(47 \pm 7)\%$ ($(33 \pm 10)\%$) for 3ID (2ID+TL) events.

The signal efficiency for $t\bar{t} \rightarrow WbZq$, after all selection requirements, was determined using the TopReX sample described in Section 3 and is shown in Table 1.

6 Background evaluation

Backgrounds to this search can be divided into two categories: those with three real leptons and those with at least one fake lepton. Backgrounds with three real leptons arise from diboson (WZ and ZZ) production with additional jets, and were evaluated using the MC samples described in Section 3.2. In the case of WZ production, the required $E_{\mathrm{T}}^{\mathrm{miss}}$ comes from the neutrino from the leptonic W-boson decay. Events from ZZ decays can enter the signal region in several ways; the dominant modes are four-lepton decays with one lepton not reconstructed, giving apparent $E_{\mathrm{T}}^{\mathrm{miss}}$, and $\tau^+\tau^-$ decays with one τ decaying to e or μ and two neutrinos.

The background to 3ID candidate events, in which exactly one of the leptons is a fake lepton, was evaluated using a combination of data and MC samples. The dominant contribution in this category comes from Z+jets events, with a leptonic Z decay, in which one of the jets was misidentified as a third lepton. To evaluate this background a data-driven (DD) method was used. This method uses a control region (CR) in the ($E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\ell\ell}$) plane by selecting events with exactly two opposite-charge electrons or muons (no third ID lepton is allowed) and $|91.2\text{ GeV}-m_{\ell\ell}^{\mathrm{reco}}| < 15$ GeV in six different $E_{\mathrm{T}}^{\mathrm{miss}}$ bins from 0 GeV to $\geq$50 GeV. The Z+jets estimate in each $E_{\mathrm{T}}^{\mathrm{miss}}$ bin is then given by:

$$[N_{Z+\mathrm{jets}}^{\mathrm{Data}}]_{\mathrm{SR}} = \left[\frac{N^{\mathrm{Data}} - N_{\mathrm{Other\ backgrounds}}^{\mathrm{MC}}}{N_{Z+\mathrm{jets}}^{\mathrm{MC}}}\right]_{\mathrm{CR}} \cdot [N_{Z+\mathrm{jets}}^{\mathrm{MC}}]_{\mathrm{SR}}\,. \tag{6.1}$$

For each $E_{\mathrm{T}}^{\mathrm{miss}}$ bin considered, the corresponding background-subtracted data/simulation ratio in the CR was applied to the simulated Z+jets background in the signal regions (SR), in order to evaluate the expected number of Z+jets events in the data. To enhance the statistical power of the MC sample, the lepton selection was loosened compared to the SR lepton selection. A multiplicative factor of 0.063$\pm$0.013, corresponding to the MC probability for events with loose leptons to pass the SR lepton criteria, was applied to the final result. The remaining backgrounds with one fake lepton (dileptonic $t\bar{t}$, Wt-channel single-top and WW production) were evaluated using Monte Carlo simulation samples, described in Section 3, and the loose lepton selection and multiplicative factor above. Different DD methods and cross-checks for the one-fake-lepton background were performed. These include the matrix method [66], relaxation of $E_{\mathrm{T}}^{\mathrm{miss}}$ or lepton quality requirements, and MC simulation with fake-rate factors measured from data. These alternative methods, although statistically limited, agree with the reference DD+MC method used.

A DD method was developed to evaluate the contribution to 3ID events from multi-jet, W+jets, single-top and $t\bar{t}$ single-lepton decay events, in which two or three jets were reconstructed as leptons (2+3 fake leptons). Due to the requirement that two leptons should have the same flavour and opposite charges, the yield from these backgrounds can be extrapolated from the number of observed data events with three leptons of any flavour (e or μ), but with the same charge. Taking into account the possible charge and flavour combinations, there are 36 combinations of three leptons, in which two have the same flavour and opposite charges, and 16 combinations of three leptons with the same charge. The extrapolation factor is thus $f = 36/16 = 2.25$. No data event passed the selection after requiring three leptons with the same charge. The uncertainties in the DD backgrounds were determined using the Feldman-Cousins upper interval for a 68% C.L. [67] with no observed events (with the uncertainties multiplied by 2.25 for the 2+3 fake leptons sample). Since no events were selected with three leptons of the same charge, a multiplicative factor of 0.071 $\pm$ 0.018, to account for the final requirements of at least two jets with $p_{\mathrm{T}} > 25$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV was evaluated using MC samples and applied to the uncertainty estimate.

In 2ID+TL events the dominant background contribution comes from events with a fake TL. The background contribution from such events was evaluated with the same technique used in Ref. [60]: the probability of a jet being reconstructed as a track lepton was determined from a γ+jets data sample selected with photon triggers, and parameterized in a 'fake matrix' as a function of jet p_{T} and the number of primary vertices in the event, N_{vtx}. The number of primary vertices was needed in the parameterization because the fake probability is sensitive to pile-up. The fake matrix was applied to a 'parent sample' selected with all of the signal region requirements with the exception of the three leptons. Instead, two ID leptons were required. Fake probabilities from the matrix were summed for each jet in the parent sample, according to its p_{T} and N_{vtx} for each event. The resulting sum is the fake TL background contribution. Because of the b-tag requirement in events with a TL, a b-tagged jet was allowed to contribute to the sum only if there was another b-tagged jet in the event. This accounts for the fact that if a jet produced a fake TL, the remaining jet would be removed by the lepton–jet overlap removal described in Section 4. For the same reason, events with three or more jets were used to predict the number of fake TLs in events with two or more jets. The signal region required a Z-boson candidate, i.e. an opposite-charge, same-flavour lepton pair. Therefore the parent sample with two ID leptons provides three different cases:

1. Opposite-charge ID leptons
2. Two positively-charged ID leptons
3. Two negatively-charged ID leptons

In case 1, the fake TL was allowed to have either charge. In case 2 the fake TL was required to be negatively charged, and in case 3 positively charged. Three different fake matrices were constructed to account for these three cases, one in which both charges are used, and one with only negatively or positively charged TLs. When a TL and an oppositely-charged ID lepton had an invariant mass consistent with arising from a Z boson, the same-flavour requirement was automatically satisfied because the TL is taken to have the same flavour as the ID lepton. The parent sample with two ID leptons contains all sources of backgrounds that can enter the signal region with a fake TL, including those with one or two fake ID leptons. Thus the procedure predicts the full background contribution with a fake TL. A small contribution (2% of the total), evaluated from the MC simulation, was included to account for events with a 'real' TL and a fake ID lepton.

A summary of expected backgrounds and selected data events in both the 3ID lepton and 2ID+TL samples is shown in Table 1.

Table 1. Expected number of background events, number of selected data events and signal efficiency (normalized to all decays of the W and Z bosons), after the final event selection. The $t\bar{t}$ backgrounds correspond to SM decays of the top quarks. The third entry in the 2ID+TL column corresponds to the fake TL background and includes all sources of events in the left-hand column except ZZ, WZ, $t\bar{t}W$ and $t\bar{t}Z$.

	3ID	2ID+TL
ZZ and WZ	$9.5 \pm ^{4.4}$	$1.0 \pm ^{0.5}_{0.6}$
$t\bar{t}W$ and $t\bar{t}Z$	0.51 ± 0.14	0.25 ± 0.05
$t\bar{t}$, WW	0.07 ± 0.02	7.6 ± 2.2
Z+jets	1.7 ± 0.7	
Single top	0.01 ± 0.01	
2+3 fake leptons	$0.0 \pm ^{0.2}_{0.0}$	
Expected background	11.8 ± 4.4	8.9 ± 2.3
Data	8	8
Signal efficiency	$(0.205 \pm 0.024)\%$	$(0.045 \pm 0.007)\%$

Figure 2 shows the reconstructed candidate Z-boson and top-quark masses, m_{ll} and m_{llq} respectively, for the FCNC decay hypothesis in the selected candidate events, for both the 3ID and 2ID+TL data, compared with the expectations from SM backgrounds and the FCNC signal.

7 Systematic uncertainties

A number of systematic uncertainties can influence the expected number of signal and/or background events. The effect of each source of systematic uncertainty was studied by independently varying the corresponding central value by the estimated uncertainty. For each variation, the total number of expected background events and the signal efficiencies were compared with the reference values.

The measurement of the integrated luminosity has a total uncertainty of 3.7% [35, 36]. This uncertainty was considered in the analyses by changing the normalizations of the backgrounds evaluated from MC simulation. Uncertainties associated with the energy scale of light-quark jets and b-jets were studied as a function of the jet transverse momentum and pseudorapidity. These uncertainties, including the effects of pile-up, are in the range 6–10% [63]. The effects of the jet reconstruction efficiency uncertainty were studied by randomly removing about 2% of jets from the events. The effect of potential jet resolution mis-modelling in the MC simulation was evaluated by additional smearing of the reconstructed jet energies within the uncertainties. In each case, the difference with respect to

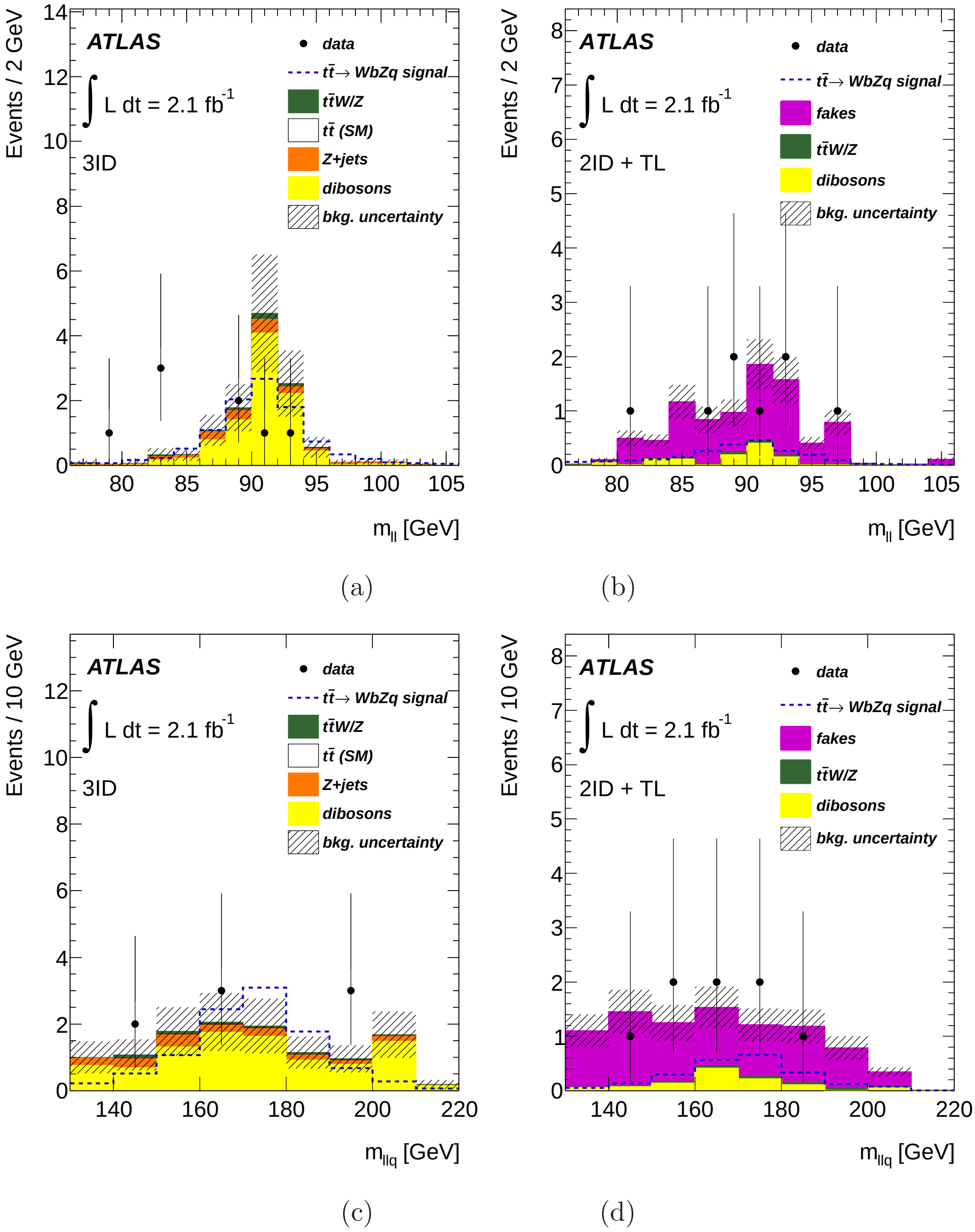


Figure 2. Expected and observed Z-boson and top-quark mass distributions for the FCNC decay hypothesis in the 3ID ((a) & (c)) and 2ID+TL ((b) & (d)) candidate events after all selection requirements. The $t\bar{t} \to WbZq$ distributions are normalized to the observed limit in each channel.

the nominal simulation was considered as the systematic uncertainty. The uncertainties due to MC modelling of the lepton trigger, reconstruction and selection efficiencies, and b-tagging efficiency, were taken into account by re-computing the predicted event yields and signal acceptance using the corresponding systematic shift. The momentum of the lepton in simulation was rescaled and smeared to correct for scale and resolution disagreements between simulated and observed data. The systematic uncertainty associated with the modelling of the momentum scale and resolution was evaluated by shifting the momentum scale and changing the smearing factors. Changes applied to electrons, muons and jets were propagated to $E_{\mathrm{T}}^{\mathrm{miss}}$. Uncertainties related to $E_{\mathrm{T}}^{\mathrm{miss}}$ were also studied: the effect of the energy in the calorimeter not associated with the above objects, and of low momentum (7 GeV $< p_{\mathrm{T}} <$ 20 GeV) jets, was studied, as well as the uncertainty due to modelling of pile-up. The effect of a hardware failure in the electromagnetic calorimeter was also considered as a systematic uncertainty (LAr readout problem) and evaluated by varying the jet thresholds used for removing events with jets directed at the dead region. The effects of ISR/FSR and top-quark mass uncertainties were evaluated using the MC samples described in Section 3. The effect of uncertainties in the PDF used for signal generation was evaluated by comparing the signal acceptance using MSTW2008LO with that from MRST2007 LO* PDFs. The systematic uncertainties related to the ZZ and WZ simulation modelling were estimated using the Berends-Giele scaling [68, 69] with an uncertainty of 24% per jet, added in quadrature. An uncertainty of 4% was included for the 0-jet bin. The ZZ and WZ cross sections were varied by their theoretical uncertainty of 5% [70]. The uncertainties on the Z+jets normalizations were derived using a data-driven method. In the 2ID+TL channel, where b-tagging was used, a systematic uncertainty associated with the heavy-flavour content of WZ+jets and ZZ+jets is included. This was evaluated by comparing `ALPGEN` and `MC@NLO`, and is small because the dominant source of b-tags in these events comes from mis-tags of light-quark jets, with a secondary component from charm jets.

The dominant source of systematic uncertainty for the 3ID channel is the ZZ and WZ simulation modelling. The other sources have effects at most of the same magnitude as the statistical uncertainty. The dominant uncertainty in the 2ID+TL channel is the systematic uncertainty on the fake-TL prediction, because 90% of the expected background arises from this source. This was determined to be 20% by comparing predicted and observed events with TLs in control regions dominated by fake TLs [60].

The resulting uncertainties for the backgrounds and signal acceptance are shown in Table 2. Because almost 90% of the 2ID+TL background evaluation is data-driven, the 2ID+TL analysis has a smaller relative background systematic uncertainties in most categories, compared to the 3ID analysis.

8 Limit evaluation

Good agreement between data and expected background yields was observed, as shown in Table 1. No evidence for the $t \to Zq$ decay mode was found and 95% C.L. upper limits on the number of signal events were derived using the modified frequentist ($\mathrm{CL_s}$) likelihood method [71, 72]. The statistical fluctuations of the pseudo-experiments were performed using Poisson distributions. All statistical and systematic uncertainties of the expected backgrounds and signal efficiencies were taken into account, as described in Section 7 and were implemented assuming Gaussian distributions [71]. The systematic uncertainties of

Table 2. Relative changes in the expected number of background events and signal yield for different sources of systematic uncertainties. The contributions from the ZZ and WZ event generator apply only to the simulated background samples.

	3ID		2ID+TL	
Source	Background	Signal	Background	Signal
Luminosity	4%	4%	<1%	4%
Electron trigger	4%	1%	<1%	<1%
Electron reconstruction modelling	10%	3%	<1%	2%
Muon trigger	3%	1%	<1%	<1%
Muon reconstruction modelling	7%	1%	<1%	1%
TL reconstruction modelling	—	—	2%	1%
Jet energy scale	11%	1%	1%	1%
Jet reconstruction efficiency	5%	2%	<1%	<1%
Jet energy resolution	1%	3%	1%	4%
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	4%	1%	<1%	<1%
LAr readout problem	3%	1%	<1%	1%
Pile-up	4%	<1%	<1%	<1%
b-tagging	—	—	1%	6%
Top quark mass	<1%	2%	—	3%
$\sigma_{t\bar{t}}$	<1%	8%	—	8%
ISR/FSR	<1%	3%	—	6%
PDFs	—	3%	—	3%
ZZ and WZ shape	33%	—	5%	—
ZZ and WZ cross section	4%	—	<1%	—
ZZ and WZ heavy-flavour content	—	—	<1%	—
Fake leptons	1%	—	17%	—
Total	38%	12%	18%	15%

the ZZ, WZ and signal acceptance were considered to be fully correlated between the 3ID and 2ID+TL channels, while all other sources of uncertainties (statistical or systematic) were considered uncorrelated. The limits on the number of signal events were converted into upper limits on the corresponding BRs using the approximate NNLO calculation, and its uncertainty, for the $t\bar{t}$ cross section ($\sigma_{t\bar{t}} = 165^{+11}_{-16}$ pb) [73], and constraining BR($t \to Wb$) = 1−BR($t \to Zq$). The observed 95% C.L. upper limit on the FCNC $t \to Zq$ BR is 0.82% (3.2%) taking the 3ID (2ID+TL) events and background evaluation alone, and 0.73% when the 3ID and 2ID+TL results are combined. Table 3 shows the observed and expected limits in the absence of signal for the 3ID and 2ID+TL channels, as well as for the combination. Also shown are the $\pm 1\sigma$ expected limits.

Table 3. The expected and observed 95% C.L. upper limits on the FCNC top quark decay $t \to Zq$ BR. The $\pm 1\sigma$ expected limits include both statistical and systematic uncertainties.

channel	observed	(-1σ)	expected	$(+1\sigma)$
3ID	0.81%	0.63%	0.95%	1.4%
2ID+TL	3.2%	2.15%	3.31%	4.9%
Combination	0.73%	0.61%	0.93%	1.4%

9 Conclusions

A search for FCNC decays of top quarks produced in pairs was performed using data collected by the ATLAS experiment at a centre-of-mass energy of $\sqrt{s} = 7$ TeV and corresponding to an integrated luminosity of 2.1 fb^{-1}. The search for the $t \to qZ$ decay mode was performed by studying top-quark pair production with one top quark decaying according to the Standard Model and the other according to the FCNC ($t\bar{t} \to bWqZ$). No evidence for such a signal was found. An observed limit at 95% C.L. on the $t \to qZ$ FCNC top-quark decay branching fraction was set at BR$(t \to qZ) < 0.73\%$, assuming BR$(t \to bW)$+BR$(t \to qZ) = 1$. The observed limit is compatible with the expected sensitivity, assuming that the data are described correctly by the Standard Model, of BR$(t \to qZ) < 0.93\%$.

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