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# Search for flavour-changing neutral current top-quark decays $t \to qZ$ in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Abstract: A search for flavour-changing neutral-current processes in top-quark decays is presented. Data collected with the ATLAS detector from proton-proton collisions at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb$^{-1}$, are analysed. The search is performed using top-quark pair events, with one top quark decaying through the $t \to qZ$ ($q = u, c$) flavour-changing neutral-current channel, and the other through the dominant Standard Model mode $t \to bW$. Only $Z$ boson decays into charged leptons and leptonic $W$ boson decays are considered as signal. Consequently, the final-state topology is characterized by the presence of three isolated charged leptons (electrons or muons), at least two jets, one of the jets originating from a $b$-quark, and missing transverse momentum from the undetected neutrino. The data are consistent with Standard Model background contributions, and at 95% confidence level the search sets observed (expected) upper limits of $1.7 \times 10^{-4}$ ($2.4 \times 10^{-4}$) on the $t \to uZ$ branching ratio and $2.4 \times 10^{-4}$ ($3.2 \times 10^{-4}$) on the $t \to cZ$ branching ratio, constituting the most stringent limits to date.

Keywords: Hadron-Hadron scattering (experiments)

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## Contents



## 1 Introduction

The top quark is the heaviest elementary particle known, with a mass $m_t = 173.3 \pm 0.8$ GeV [1]. In the Standard Model of particle physics (SM), it decays almost exclusively into $bW$ while flavour-changing neutral current (FCNC) decays such as $t \to qZ$ are forbidden at tree level. FCNC decays occur at one-loop level but are strongly suppressed by the GIM mechanism [2] with a suppression factor of 14 orders of magnitude relative to the dominant decay mode [3]. However, several SM extensions predict higher branching ratios for top-quark FCNC decays. Examples of such extensions are the quark-singlet model (QS) [4], the two-Higgs-doublet model with (FC 2HDM) or without (2HDM) flavour conservation [5], the Minimal Supersymmetric Standard Model (MSSM) [6], the MSSM with R-parity violation (RPV SUSY) [7], models with warped extra dimensions (RS) [8], or extended mirror fermion models (EMF) [9]. Reference [10] gives a comprehensive review of the various extensions of the SM that have been proposed. Table 1 provides the maximum values for the branching ratios $\mathcal{B}(t \to qZ)$ predicted by these models and compares them to the value predicted by the SM.

Experimental limits on the FCNC branching ratio $\mathcal{B}(t \to qZ)$ were established by experiments at the Large Electron-Positron collider [11–15], HERA [16], the Tevatron [17, 18], and the Large Hadron Collider (LHC) [19–22]. Before the results reported here, the most stringent limits were $\mathcal{B}(t \to uZ) < 2.2 \times 10^{-4}$ and $\mathcal{B}(t \to cZ) < 4.9 \times 10^{-4}$ at



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95% confidence level (CL), both set by the CMS Collaboration [22] using data collected at $\sqrt{s}$ = 8 TeV. For the same centre-of-mass energy, the ATLAS Collaboration derived a limit of $\mathcal{B}(t \to qZ) < 7 \times 10^{-4}$ [20]. ATLAS results obtained at $\sqrt{s}$ = 7 TeV are also available [19].

This analysis is a search for the FCNC decay $t \to qZ$ in top-quark-top-antiquark ($t\bar{t}$) events, in 36.1 fb$^{-1}$ of data collected at $\sqrt{s}$ = 13 TeV, where one top quark decays through the FCNC mode and the other through the dominant SM mode ($t \to bW$). Only $Z$ boson decays into charged leptons and leptonic $W$ boson decays are considered. The final-state topology is thus characterized by the presence of three isolated charged leptons,[1] at least two jets with exactly one being tagged as a jet containing $b$-hadrons, and missing transverse momentum from the undetected neutrino. The main sources of background events containing three prompt leptons are diboson, $t\bar{t}Z$, and $tZ$ production. Events with two or fewer prompt leptons and additional non-prompt[2] leptons are also sources of background. Besides the signal region, control regions are defined to constrain the main backgrounds. Results are obtained using a binned likelihood fit to kinematic distributions in the signal and control regions.

The article is organized as follows. A brief description of the ATLAS detector is given in section 2. The collected data samples and the simulations of signal and SM background processes are described in section 3. Section 4 presents the object definitions, while the event analysis and kinematic reconstruction are explained in section 5. Background evaluation and sources of systematic uncertainty are described in sections 6 and 7. Results are presented in section 8, and conclusions are drawn in section 9.

## 2 ATLAS detector and data samples

The ATLAS experiment [23] is a multi-purpose particle physics detector consisting of several subdetector systems, which almost fully cover the solid angle[3] around the interaction point. It is composed of an inner tracking system close to the interaction point and immersed in a 2 T axial magnetic field produced by a thin superconducting solenoid. A lead/liquid-argon (LAr) electromagnetic calorimeter, a steel/scintillator-tile hadronic calorimeter, copper/LAr hadronic endcap calorimeters, copper/LAr and tungsten/LAr forward calorimeters, and a muon spectrometer with three superconducting magnets, each one with eight toroid coils, complete the detector. A new innermost silicon pixel layer was added to the inner detector after Run 1 [24, 25]. The combination of all these systems provides charged-particle momentum measurements, together with efficient and precise lepton and

[1] In this article, lepton is used to denote an electron or muon, including those coming from leptonic $\tau$-lepton decays.

[2] Prompt leptons are leptons from the decay of $W$ or $Z$ bosons, either directly or through an intermediate $\tau \to \ell\nu\nu$ decay, or from the semileptonic decay of top quarks.

[3] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the interaction point to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$. The $\Delta R$ distance is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.



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| Model: | SM | QS | 2HDM | FC 2HDM | MSSM | RPV SUSY | RS | EMF |
|---|---|---|---|---|---|---|---|---|
| $\mathcal{B}(t \to qZ)$: | $10^{-14}$ | $10^{-4}$ | $10^{-6}$ | $10^{-10}$ | $10^{-7}$ | $10^{-6}$ | $10^{-5}$ | $10^{-6}$ |

**Table 1**. Maximum allowed FCNC $t \to qZ$ ($q = u, c$) branching ratios predicted by several models [3–10].

photon identification in the pseudorapidity range $|\eta| < 2.5$. Energy deposits over the full coverage of the calorimeters, $|\eta| < 4.9$, are used to reconstruct jets and missing transverse momentum. A two-level trigger system is used to select interesting events [26]. The first level is implemented with custom hardware and uses a subset of detector information to reduce the event rate. It is followed by a software-based trigger level to reduce the event rate to approximately 1 kHz.

In this analysis, the combined 2015 and 2016 datasets from proton-proton ($pp$) collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 36.1 fb$^{-1}$ are used. Analysed events are selected by either a single-electron or a single-muon trigger. Triggers with different transverse-momentum thresholds are used to increase the overall efficiency. The triggers using a low electron transverse momentum ($p_{\mathrm{T}}^{e}$) or muon transverse momentum ($p_{\mathrm{T}}^{\mu}$) threshold ($p_{\mathrm{T}}^{e} > 24$ GeV or $p_{\mathrm{T}}^{\mu} > 20$ GeV for 2015 data and $p_{\mathrm{T}}^{e,\mu} > 26$ GeV for 2016 data) also have isolation requirements. At high $p_{\mathrm{T}}$ the isolation requirements incur small efficiency losses which are recovered by higher-threshold triggers ($p_{\mathrm{T}}^{e} > 60$ GeV, $p_{\mathrm{T}}^{e} > 120$ GeV, or $p_{\mathrm{T}}^{\mu} > 50$ GeV for 2015 data and $p_{\mathrm{T}}^{e} > 60$ GeV, $p_{\mathrm{T}}^{e} > 140$ GeV, or $p_{\mathrm{T}}^{\mu} > 50$ GeV for 2016 data) without isolation requirements.

## 3 Signal and background simulation samples

In $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC, top quarks are produced according to the SM mainly in $t\bar{t}$ pairs with a predicted cross section of $\sigma_{t\bar{t}} = 0.83 \pm 0.05$ nb [27–32] for the top-quark mass value of 172.5 GeV used to simulate events as described in the following paragraphs; the uncertainty includes contributions from uncertainties in the factorization and renormalization scales, the parton distribution functions (PDF), the strong coupling $\alpha_{\mathrm{S}}$, and the top-quark mass. The cross section is calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms with `Top++` 2.0. The effects of PDF and $\alpha_{\mathrm{S}}$ uncertainties are calculated using the PDF4LHC prescription [33] with the MSTW 2008 68% CL NNLO [34, 35], CT10 NNLO [36, 37] and NNPDF 2.3 5f FFN [38] PDF sets and are added in quadrature to those from the renormalization and factorization scale uncertainties.

The next-to-leading-order (NLO) simulation of signal events was performed with the event generator `MG5_aMC@NLO` [39] interfaced to `Pythia8` [40] with the `A14` [41] set of tuned parameters and the `NNPDF2.3LO` PDF set [38]. Dynamic factorization and renormalization scales were used. The factorization and renormalization scales were set equal to $\sqrt{m_t^2 + (p_{\mathrm{T},t}^2 + p_{\mathrm{T},\bar{t}}^2)/2}$ where $p_{\mathrm{T},t}$ ($p_{\mathrm{T},\bar{t}}$) is the transverse momentum of the top quark (top antiquark). For the matrix element, the PDF set `NNPDF3.0NLO` [42] was used. For the



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top-quark FCNC decay, the effects of new physics at an energy scale $\Lambda$ were included by adding dimension-six effective terms to the SM Lagrangian. No differences between the kinematical distributions from the $bWuZ$ and $bWcZ$ processes are observed. Due to the different $b$-tagging mistag rates for $u$- and $c$-quarks, the signal efficiencies differ after applying requirements on the $b$-tagged jet multiplicity. Hence limits on $\mathcal{B}(t \to qZ)$ are set separately for $q = u, c$. Only decays of the $W$ and $Z$ bosons with charged leptons were generated at the matrix-element level ($Z \to e^+e^-$, $\mu^+\mu^-$, or $\tau^+\tau^-$ and $W \to e\nu$, $\mu\nu$, or $\tau\nu$).

Several SM processes have final-state topologies similar to the signal, with at least three prompt charged leptons, especially dibosons ($WZ$ and $ZZ$), $t\bar{t}V$ ($V$ is $W$ or $Z$), $t\bar{t}$ $WW$, $t\bar{t}H$, gluon-gluon fusion ($gg$F) $H$, vector-boson fusion (VBF) $H$, $VH$, $tZ$, $WtZ$, $tt\bar{t}(t)$, and triboson ($WWW$, $ZWW$ and $ZZZ$) production. The theoretical estimates for these backgrounds are further constrained by the simultaneous fit to the signal and control regions described below. Events with non-prompt leptons or events in which at least one jet is misidentified as an isolated charged lepton (labelled as non-prompt leptons throughout this article) can also fulfil the event selection requirements. These events, typically $Z$+jets (including $\gamma$ emission), $t\bar{t}$, and single-top ($Wt$), are estimated with the semi-data-driven method explained in section 6, which also uses simulated samples which for the $Z$+jets events include $Z$ production in association with heavy-flavour quarks.

Table 2 summarizes information about the generators, parton shower, and PDFs used to simulate the different event samples considered in the analysis. The associated production of a $t\bar{t}$ pair with one vector boson was generated at NLO with MG5_aMC@NLO interfaced to Pythia8 with the A14 set of tuned parameters and the NNPDF2.3LO PDF set. The $t\bar{t}Z$ and $t\bar{t}W$ samples were normalized to the NLO QCD+electroweak cross-section calculation using a fixed scale $(m_t + m_V/2)$ [43]. In the case of the $t\bar{t}Z$ sample with the $Z \to \ell^+\ell^-$ decay mode, the $Z/\gamma^*$ interference was included with the criterion $m_{\ell\ell} > 5$ GeV applied. The $t$-channel production of a single top quark in association with a $Z$ boson ($tZ$) was generated using MG5_aMC@NLO using the four-flavour PDF scheme. Production of a single top quark in the $Wt$-channel together with a $Z$ boson ($WtZ$) was generated with MG5_aMC@NLO with the parton shower simulated using Pythia8, the PDF set NNPDF2.3LO, and the A14 set of tuned parameters. The diagram removal technique [44] was employed to handle the overlap of $WtZ$ with $t\bar{t}Z$ and $t\bar{t}$ production followed by a three-body top-quark decay ($t \to WZb$). The procedure also removes the interference between $WtZ$ and these two processes. Diboson processes with four charged leptons ($4\ell$), three charged leptons and one neutrino ($\ell\ell\ell\nu$), two charged leptons and two neutrinos ($\ell\ell\nu\nu$), and diboson processes having additional hadronic contributions ($\ell\ell\ell\nu jj$, $\ell\ell\ell\ell jj$, $gg\ell\ell\ell\ell$, $\ell\ell\nu\nu jj$) were simulated using the Sherpa 2.1.1 [45] generator. The matrix elements contain all diagrams with four electroweak vertices. They were calculated for up to one ($4\ell$, $2\ell + 2\nu$) or no additional partons ($3\ell + 1\nu$) at NLO and up to three partons at LO using the Comix [46] and OpenLoops [47] matrix element generators and were merged with the Sherpa parton shower using the ME+PS@NLO prescription [46–48]. The CT10 PDF set was used in conjunction with a dedicated parton shower tuning developed by the Sherpa authors. The Higgs boson samples ($t\bar{t}H$, Higgs boson production via gluon-gluon fusion and vector boson fusion, and in association with a vector boson) were normalized to the theoretical calculations in ref. [43].



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| Sample | Generator | Parton shower | ME PDF | PS PDF | Tune parameters |
|---|---|---|---|---|---|
| $t\bar{t} \to bWqZ$ | MG5_aMC@NLO [39] | Pythia8 [40] | NNPDF3.0NLO [42] | NNPDF2.3LO [38] | A14 [41] |
| $t\bar{t}V$,$t\bar{t}H$ | MG5_aMC@NLO | Pythia8 | NNPDF3.0NLO | NNPDF2.3LO | A14 |
| $t\bar{t}Z$ (alternative) | Sherpa 2.2.0 [45] | Sherpa 2.2.0 | NNPDF3.0NNLO | NNPDF3.0NNLO | Sherpa default |
| $WZ$, $ZZ$ | Sherpa 2.1.1 | Sherpa 2.1.1 | CT10 [36] | CT10 | Sherpa default |
| $WZ$ (alternative) | Powheg-Box v2 [49] | Pythia8 | CT10nlo | CTEQ6L1 [54] | AZNLO [55] |
| $tZ$ | MG5_aMC@NLO | Pythia6 [56] | NNPDF3.0NLO | CTEQ6L1 | Perugia2012 [57] |
| $tZ$ (rad. syst.) | MG5_aMC@NLO | Pythia6 | NNPDF3.0NLO | CTEQ6L1 | P2012RadHi/Lo [57] |
| $WtZ$ | MG5_aMC@NLO | Pythia8 | NNPDF3.0NLO | NNPDF2.3LO | A14 |
| $WtZ$ (alternative) | MG5_aMC@NLO | Herwig++ [58] | CT10 | CTEQ6L1 | UE-EE-5 [59] |
| $gg$F $H$, VBF $H$ | Powheg-Box v2 | Pythia8 | CT10 | CTEQ6L1 | AZNLO |
| $WH$, $ZH$ | Pythia8 | Pythia8 | NNPDF2.3LO | NNPDF2.3LO | A14 |
| $3t$, $4t$, $t\bar{t}WW$ | MG5_aMC@NLO | Pythia8 | NNPDF3.0NLO | NNPDF2.3LO | A14 |
| Tribosons | Sherpa 2.1.1 | Sherpa 2.1.1 | CT10 | CT10 | Sherpa default |
| $Z$+jets | Powheg-Box v2, Photos++ [50] | Pythia8 | CT10 | CTEQ6L1 | AZNLO |
| $t\bar{t} \to bWbW$ | Powheg-Box v2 | Pythia8 | CT10 | NNPDF2.3LO | A14 |
| $t\bar{t} \to bWbW$ (rad. syst.) | Powheg-Box v2 | Pythia8 | CT10 | NNPDF2.3LO | A14v3cUp/Do [41] |
| $t\bar{t} \to bWbW$ (PS syst.) | Powheg-Box v2 | Herwig7 [60] | NNPDF3.0NLO | MMHT2014lo68cl [61] | H7-UE-MMHT [60] |
| $t\bar{t} \to bWbW$ (ME syst.) | MG5_aMC@NLO | Pythia8 | NNPDF3.0NLO | NNPDF2.3LO | A14 |
| $Wt$ | Powheg-Box v1 | Pythia6 | CT10f4 | CTEQ6L1 | Perugia2012 |

**Table 2**. Generators, parton shower simulation, parton distribution functions, and tune parameters used to produce simulated samples for this analysis. The acronyms ME and PS stand for matrix element and parton shower, respectively.

Events containing $Z$ bosons + jets were simulated with Powheg-Box v2 [49] interfaced to the Pythia8 parton shower model, using Photos++ version 3.52 [50] for QED emissions from electroweak vertices and charged leptons. The generation of $t\bar{t}$ and single top quarks in the $Wt$-channel was done with Powheg-Box v2 and Powheg-Box v1, respectively. Due to the high lepton-multiplicity requirement of the event selection and to increase the sample size, the $t\bar{t}$ sample was produced by selecting only true dilepton events in the final state. The SM production of three or four top quarks and the associated production of a $t\bar{t}$ pair with two $W$ bosons were generated at LO with MG5_aMC@NLO+Pythia8. The production of three massive vector bosons with subsequent leptonic decays of all three bosons was modelled at LO with the Sherpa 2.1.1 generator. Up to two additional partons are included in the matrix element at LO.

A set of minimum-bias interactions generated with Pythia 8.186 using the A2 set of tuned parameters [51] and the MSTW2008LO [34] PDF set were overlaid on the hard-scattering event to account for additional $pp$ collisions in the same or nearby bunch crossings (pile-up). Simulated samples were reweighted to match the pile-up conditions in data. For most samples, detailed simulation of the detector and trigger system was performed with standard ATLAS software using GEANT4 [52, 53]. Fast simulation based on ATLFASTII [53] is alternatively used for a few samples dedicated to the evaluation of systematic uncertainties affecting background modelling. The same offline reconstruction methods used on data are also applied to the samples of simulated events. Simulated events are corrected so that the object identification, reconstruction, and trigger efficiencies; the energy scales; and the energy resolutions match those determined from data control samples.

## 4 Object reconstruction

The final states of interest for this search include electrons, muons, jets, $b$-tagged jets and missing transverse momentum.

Electron candidates are reconstructed [62] from energy deposits (clusters) in the electromagnetic calorimeter matched to reconstructed charged-particle tracks in the inner detector. The candidates are required to have a transverse energy $E_{\mathrm{T}} > 15$ GeV and the pseudorapidity of the calorimeter energy cluster associated with the electron candidate must satisfy $|\eta_{\mathrm{cluster}}| < 2.47$. Clusters in the transition region between the barrel and end-cap calorimeters, $1.37 \leq |\eta_{\mathrm{cluster}}| \leq 1.52$, have poorer energy resolution and are excluded. To reduce the background from non-prompt sources, electron candidates are also required to satisfy $|d_0|/\sigma(d_0) < 5$ and $|z_0 \sin(\theta)| < 0.5$ mm criteria, where $d_0$ is the transverse impact parameter, with uncertainty $\sigma(d_0)$, and $z_0$ is the longitudinal impact parameter with respect to the primary vertex (defined in section 5). The sum of transverse energies of clusters in the calorimeter within a cone of $\Delta R = 0.2$ around the electron candidate, excluding the $p_{\mathrm{T}}$ of the electron candidate, is required to be less than 6% of the electron $p_{\mathrm{T}}$. The scalar sum of particle transverse momenta around the electron candidate within a cone of min(10 GeV/$p_{\mathrm{T}}$, 0.2) must be less than 6% of the electron candidate's $p_{\mathrm{T}}$.

Muon candidates are reconstructed from tracks in the inner detector and muon spectrometer, which are combined to improve the reconstruction precision and to increase the background rejection [63]. They are required to have $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$. Muons are also required to satisfy $|d_0|/\sigma(d_0) < 3$ and $|z_0 \sin(\theta)| < 0.5$ mm criteria. Additionally, the scalar sum of particle transverse momenta around the muon candidate within a cone of min(10 GeV/$p_{\mathrm{T}}$, 0.3) must be less than 6% of the muon candidate's $p_{\mathrm{T}}$.

Jets are reconstructed from topological clusters of calorimeter cells that are noise-suppressed and calibrated to the electromagnetic scale [64] using the anti-$k_t$ algorithm [65] with a radius parameter $R = 0.4$ as implemented in FastJet [66]. Corrections that change the angles and the energy are applied to the jets, starting with a subtraction procedure that uses the jet area to estimate and remove the average energy contributed by pile-up interactions [67]. This is followed by a jet-energy-scale calibration that restores the jet energy to the mean response of a particle-level simulation by correcting variations due to jet flavour and detector geometry and data driven corrections that match the data to the simulation energy scale [68]. Jets in the analysis have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.

To reduce the number of selected jets that originate from pile-up, an additional selection criterion based on a jet-vertex tagging technique is applied. Jet-vertex tagging is a likelihood discriminant combining information from several track-based variables [69] and is only applied to jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$.

Jets containing $b$-hadrons are identified ($b$-tagged) [70, 71] using an algorithm based on multivariate techniques. It combines information from the impact parameters of displaced tracks and from topological properties of secondary and tertiary decay vertices reconstructed within the jet. Using simulated $t\bar{t}$ events, the $b$-tagging efficiency for jets originating from a $b$-quark is determined to be 77% for the chosen working point, while the rejection factors for light-flavour jets and charm jets are 134 and 6, respectively.



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The missing transverse momentum $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is the negative vector sum of the $p_{\mathrm{T}}$ of all selected and calibrated objects in the event, including a term to account for soft particles in the event that are not associated with any of the selected objects [72, 73]. To reduce contamination from pile-up interactions, the soft term is calculated from inner detector tracks matched to the selected primary vertex. The magnitude of the missing transverse momentum is $E_{\mathrm{T}}^{\mathrm{miss}}$.

To avoid double counting of single final-state objects, such as an isolated electron being reconstructed as both an electron and a jet, the following procedures are applied in the order given. Electron candidates which share a track with a muon candidate are removed. If the distance in $\Delta R$ between a jet and an electron candidate is $\Delta R < 0.2$, then the jet is dropped. If, for the same electron, multiple jets are found with this requirement, only the closest one is dropped. If the distance in $\Delta R$ between a jet and an electron is $0.2 < \Delta R < 0.4$, then the electron is dropped. If the distance in $\Delta R$ between a jet and a muon candidate is $\Delta R < 0.4$ and if the jet has more than two associated tracks, the muon is dropped; otherwise the jet is removed.

## 5 Event selection and reconstruction

Events considered in this analysis meet the following criteria. At least one of the selected leptons must be matched, with $\Delta R < 0.15$, to the appropriate trigger object and have transverse momentum greater than 25 GeV or 27 GeV for the data collected in 2015 or 2016, respectively. The events must have at least one primary vertex. The primary vertex must have at least two associated tracks, each with $p_{\mathrm{T}} > 400\,\mathrm{MeV}$. The primary vertex with the highest sum of $p_{\mathrm{T}}^2$ over all associated tracks is chosen. Exactly three isolated charged leptons with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 15$ GeV are required. The $Z$ boson candidate is reconstructed from the two leptons that have the same flavour, opposite charge, and a reconstructed mass within 15 GeV of the $Z$ boson mass ($m_Z$). If more than one compatible lepton pair is found, the one with the reconstructed mass closest to $m_Z$ is chosen as the $Z$ boson candidate. According to the signal topology, the events are then required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV and at least two jets. All jets must have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, and exactly one of the jets must be $b$-tagged.

Applying energy-momentum conservation, the kinematic properties of the top quarks are reconstructed from the corresponding decay particles by minimizing

$$\chi^2 = \frac{\left(m_{j_a\ell_a\ell_b}^{\mathrm{reco}} - m_{t_{\mathrm{FCNC}}}\right)^2}{\sigma_{t_{\mathrm{FCNC}}}^2} + \frac{\left(m_{j_b\ell_c\nu}^{\mathrm{reco}} - m_{t_{\mathrm{SM}}}\right)^2}{\sigma_{t_{\mathrm{SM}}}^2} + \frac{\left(m_{\ell_c\nu}^{\mathrm{reco}} - m_W\right)^2}{\sigma_W^2},$$

where $m_{j_a\ell_a\ell_b}^{\mathrm{reco}}$, $m_{j_b\ell_c\nu}^{\mathrm{reco}}$, and $m_{\ell_c\nu}^{\mathrm{reco}}$ are the reconstructed masses of the $qZ$, $bW$, and $\ell\nu$ systems, respectively. For each jet combination, $j_b$ corresponds to the $b$-tagged jet, while any jet can be assigned to $j_a$. Since the neutrino from the semileptonic decay of the top quark ($t \to bW \to b\ell\nu$) is undetected, its four-momentum must be estimated. This is done by assuming that the lepton not previously assigned to the $Z$ boson and the $b$-tagged jet originate from the $W$ boson and SM top-quark decay, respectively, and that $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is



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the transverse momentum vector of the neutrino in the $W$ boson decay. The longitudinal component of the neutrino momentum ($p_z^\nu$) is then determined by the minimization of the $\chi^2$. The central values of the masses and the widths of the top quarks and the $W$ boson are taken from simulated signal events. This is done by matching the particles in the simulated events to the reconstructed ones, setting the longitudinal momentum of the neutrino to the $p_z$ of the simulated neutrino, and then performing Bukin fits[4] [74] to the masses of the matched reconstructed top quarks and $W$ boson. The obtained values are $m_{t_{\mathrm{FCNC}}} = 169.6$ GeV, $\sigma_{t_{\mathrm{FCNC}}} = 12.0$ GeV, $m_{t_{\mathrm{SM}}} = 167.2$ GeV, $\sigma_{t_{\mathrm{SM}}} = 24.0$ GeV, $m_W = 81.2$ GeV and $\sigma_W = 15.1$ GeV. The $\chi^2$ minimization gives the most probable value for $p_z^\nu$ for a given combination. The combination with the minimum $\chi^2$ is chosen, which fixes the assignment of reconstructed particles and the corresponding $p_z^\nu$ value. The jet from the top-quark FCNC decay is referred to as the light-quark ($q$) jet. The fractions of correct assignments between the reconstructed top quarks and the true simulated particles (evaluated as a match within a cone of size $\Delta R = 0.4$) are $\epsilon_{t_{\mathrm{FCNC}}} = 80\%$ and $\epsilon_{t_{\mathrm{SM}}} = 58\%$, where the difference comes from the fact that for the SM top-quark decay the match of the $E_{\mathrm{T}}^{\mathrm{miss}}$ with the simulated neutrino is less efficient.

The final requirements defining the signal region (SR) are $|m_{j_a\ell_a\ell_b}^{\mathrm{reco}} - 172.5\ \mathrm{GeV}| < 40$ GeV, $|m_{j_b\ell_c\nu}^{\mathrm{reco}} - 172.5\ \mathrm{GeV}| < 40$ GeV, and $|m_{\ell_c\nu}^{\mathrm{reco}} - 80.4\ \mathrm{GeV}| < 30$ GeV. Figure 1 shows the mass of the $Z$ boson candidate as well as the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the masses of both top-quark candidates for the events fulfilling these requirements. The stacked histograms show backgrounds with three prompt leptons, normalized to the theory predictions, and the scaled background from non-prompt leptons, normalized as discussed in the next section.

## 6 Background estimation and control regions

The main sources of background events containing three prompt leptons are: diboson production, $t\bar{t}Z$, and $tZ$ processes. In addition, events where one or more of the reconstructed leptons are non-prompt, either mis-reconstructed or from heavy-flavour decays, are background sources. To assess how well the data agree with the simulated samples of the expected background, five control regions (CRs) are defined and included in the final fit. This allows rescaling of the background expectations to the best fit with observed data and reduces the background uncertainties. Systematic uncertainties in the signal yield are also reduced by the final fit (section 8).

Backgrounds from events containing at least one non-prompt lepton are estimated by means of a semi-data-driven technique using dedicated selections. This technique uses the data to determine the normalization for simulated $Z$+jets and $t\bar{t}$ events with a non-prompt electron and non-prompt muon separately. In order to determine the non-prompt lepton scale factors ($\lambda^e$, $\lambda^\mu$) for simulated $Z$+jets and $t\bar{t}$ events, four regions are defined each enriched with non-prompt electrons or muons from $Z$+jets events ("light" region) or $t\bar{t}$

[4] These fits use a piecewise function with a Gaussian function in the centre and two asymmetric tails. Six parameters determine the overall normalization, the peak position, the width of the core, the asymmetry, the size of the lower tail, and the size of the higher tail. Of these, only the peak position and the width enter the $\chi^2$.

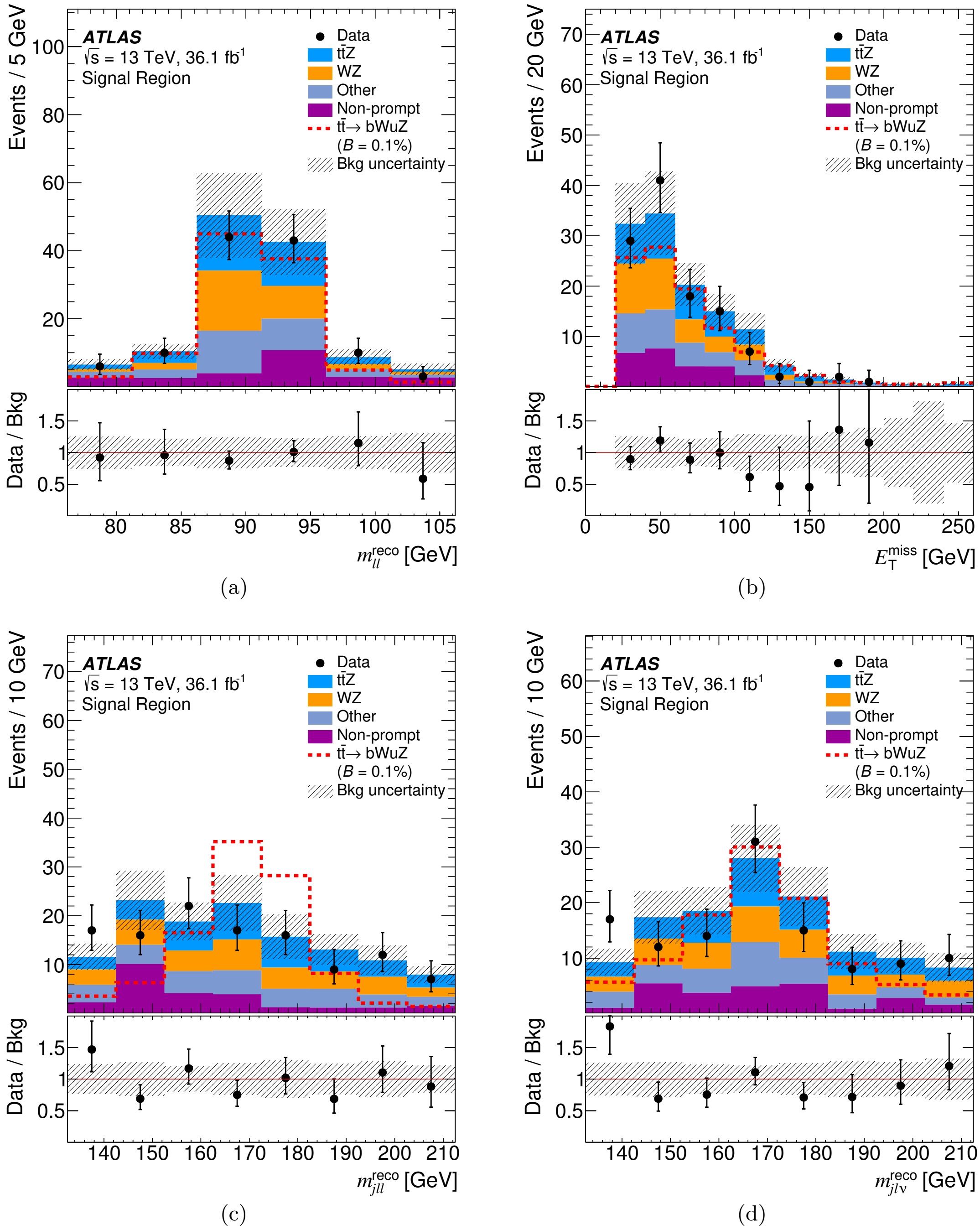


**Figure 1**. Expected (filled histogram) and observed (points with error bars) distributions in the SR before the combined fit under the background-only hypothesis of (a) the mass of the $Z$ boson candidate, (b) $E_{\mathrm{T}}^{\mathrm{miss}}$, (c) the mass of the top-quark candidate with FCNC decay, and (d) the mass of the top-quark candidate with SM decay. For comparison, distributions for the FCNC $t\bar{t} \to bWuZ$ signal (dashed line), normalized to $\mathcal{B}(t \to uZ) = 0.1\%$, are also shown. The dashed area represents the total uncertainty in the background prediction. The first (last) bin in all distributions includes the underflow (overflow). The "Other" category includes all remaining backgrounds described in section 3.

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| "Light" region — $e$ | "Light" region — $\mu$ | "Heavy" region — $e$ | "Heavy" region — $\mu$ |
|---|---|---|---|
| $eee$ or $e\mu\mu$, OSSF | $\mu\mu\mu$ or $\mu ee$, OSSF | $e\mu\mu$ , OS no OSSF | $\mu ee$, OS no OSSF |
| $\lvert m_{\ell\ell} - 91.2$ GeV$\rvert < 15$ GeV | $\lvert m_{\ell\ell} - 91.2$ GeV$\rvert < 15$ GeV | | |
| $\geq 1$ jet | $\geq 1$ jet | $\geq 2$ jet | $\geq 2$ jet |
| $E_{\mathrm{T}}^{\mathrm{miss}} < 40$ GeV | $E_{\mathrm{T}}^{\mathrm{miss}} < 40$ GeV | | |
| $m_{\mathrm{T}} \leq 50$ GeV | $m_{\mathrm{T}} \leq 50$ GeV | | |

**Table 3**. Selection criteria applied to derive the four scale factors of the non-prompt leptons background. OS indicates a pair of opposite-sign leptons, OSSF indicates a pair of opposite-sign, same-flavour leptons. Additionally, events with at least two jets, one of them $b$-tagged, and 20 GeV $< E_{\mathrm{T}}^{\mathrm{miss}} <$ 40 GeV in the SR are rejected from the "light" regions.

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events ("heavy" region). The selections used, which are given in table 3, make the four regions orthogonal to the CRs and SR used in the final fit (section 8). The non-prompt lepton scale factors for $Z$+jets and $t\bar{t}$ events are expected to be different due to differences in background sources and are determined by a simultaneous likelihood fit to the inclusive yields in the four regions, taking into account statistical and systematic uncertainties, leading to $\lambda^{e}_{Z+\text{jets}} = 2.2 \pm 0.8$, $\lambda^{\mu}_{Z+\text{jets}} = 1.9 \pm 0.9$, $\lambda^{e}_{t\bar{t}} = 1.1 \pm 0.3$, and $\lambda^{\mu}_{t\bar{t}} = 1.1 \pm 0.7$. These non-prompt lepton scale factors are applied to the $Z$+jets and $t\bar{t}$ samples in the CRs and SR used in the final fit (section 8). Agreement between data and expectations in the CRs is significantly improved after applying the non-prompt lepton scale factors to the simulated samples.

The $t\bar{t}Z$ CR requires exactly three leptons, two of them with the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ within 15 GeV of the $Z$ boson mass. Furthermore, the events are required to have at least four jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, two of which must be $b$-tagged.

The $WZ$ CR requires three leptons, two of them with the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ within 15 GeV of the $Z$ boson mass. Additional requirements are the presence of at least two jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, the leading jet having $p_{\mathrm{T}} > 35$ GeV, no $b$-tagged jets with $p_{\mathrm{T}} > 25$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV, and a transverse mass $m_{\mathrm{T}}^{\ell\nu} > 50$ GeV, where $m_{\mathrm{T}}^{\ell\nu}$ is calculated from the momentum of the non-$Z$ lepton and the missing transverse momentum vector.

The $ZZ$ CR requires two pairs of leptons, each with the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ within 15 GeV of the $Z$ boson mass. At least one jet with $p_{\mathrm{T}} >$ 25 GeV and $|\eta| < 2.5$, no $b$-tagged jets with $p_{\mathrm{T}} > 25$ GeV, and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV are also required.

The CR for the non-prompt lepton backgrounds requires three leptons with two of them having the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ outside 15 GeV of the $Z$ boson mass, at least one jet with $p_{\mathrm{T}} > 25$ GeV, and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV. This CR is split into two regions, with either zero (CR0) or exactly one (CR1) $b$-tagged jet.

Table 4 summarizes the selection requirements described above. The expected and observed yields in these regions, before the background fit described in section 8, are shown in table 5.

| Selection | $t\bar{t}Z$ CR | $WZ$ CR | $ZZ$ CR | Non-prompt lepton CR0 (CR1) | SR |
|---|---|---|---|---|---|
| No. leptons | 3 | 3 | 4 | 3 | 3 |
| OSSF | Yes | Yes | Yes | Yes | Yes |
| $\lvert m_{\ell\ell}^{\rm reco} - 91.2\ {\rm GeV}\rvert$ | $< 15$ GeV | $< 15$ GeV | $< 15$ GeV | $> 15$ GeV | $< 15$ GeV |
| No. jets | $\geq 4$ | $\geq 2$ | $\geq 1$ | $\geq 2$ | $\geq 2$ |
| No. $b$-tagged jets | 2 | 0 | 0 | 0 (1) | 1 |
| $E_{\rm T}^{\rm miss}$ | $> 20$ GeV | $> 40$ GeV | $> 20$ GeV | $> 20$ GeV | $> 20$ GeV |
| $m_{\rm T}^{\ell\nu}$ | — | $> 50$ GeV | — | — | — |
| $\lvert m_{\ell\nu}^{\rm reco} - 80.4\ {\rm GeV}\rvert$ | — | — | — | — | $< 30$ GeV |
| $\lvert m_{j\ell\nu}^{\rm reco} - 172.5\ {\rm GeV}\rvert$ | — | — | — | — | $< 40$ GeV |
| $\lvert m_{j\ell\ell}^{\rm reco} - 172.5\ {\rm GeV}\rvert$ | — | — | — | — | $< 40$ GeV |

**Table 4**. The selection requirements applied for the background control and signal regions. OSSF refers to the presence of a pair of opposite-sign, same-flavour leptons.

| Sample | $t\bar{t}Z$ CR | $WZ$ CR | $ZZ$ CR | Non-prompt lepton CR0 | Non-prompt lepton CR1 |
|---|---|---|---|---|---|
| $t\bar{t}Z$ | $61 \pm 9$ | $16.3 \pm 3.1$ | $0 \pm 0$ | $6.1 \pm 1.2$ | $22.1 \pm 3.2$ |
| $WZ$ | $9 \pm 9$ | $560 \pm 240$ | $0 \pm 0$ | $150 \pm 70$ | $20 \pm 9$ |
| $ZZ$ | $0.07 \pm 0.03$ | $48 \pm 11$ | $92 \pm 20$ | $58 \pm 16$ | $9.0 \pm 2.3$ |
| Non-prompt leptons | $3 \pm 6$ | $28 \pm 16$ | $0 \pm 0$ | $150 \pm 50$ | $140 \pm 70$ |
| Other backgrounds | $13.4 \pm 2.7$ | $22 \pm 5$ | $1.0 \pm 0.6$ | $17 \pm 6$ | $32 \pm 6$ |
| Total background | $87 \pm 15$ | $670 \pm 240$ | $93 \pm 20$ | $380 \pm 90$ | $230 \pm 70$ |
| Data | 81 | 734 | 87 | 433 | 260 |
| Data / Bkg | $0.94 \pm 0.19$ | $1.1 \pm 0.4$ | $0.94 \pm 0.23$ | $1.13 \pm 0.28$ | $1.1 \pm 0.4$ |

**Table 5**. Event yields in the background CRs for all significant sources of events before the combined fit under the background-only hypothesis described in section 8. The uncertainties shown include all of the systematic uncertainties described in section 7. The entry labelled "other backgrounds" includes all remaining backgrounds described in section 3 and in table 2.

## 7 Systematic uncertainties

The background fit to the CRs, described in section 8, reduces the systematic uncertainty from some sources, due to the constraints introduced by the data. The effect on shape and normalization of each source of systematic uncertainty before the fit is studied by independently varying each parameter within its estimated uncertainty and propagating this through the full analysis chain.

The main uncertainties, in both the background and signal estimations, are from theoretical normalization uncertainties and uncertainties in the modelling of background processes in the simulation.

The theoretical normalization uncertainties are estimated to be 12% for $t\bar{t}Z$, 13% for $t\bar{t}W$ [39], and 30% for $tZ$ production [75]. For dibosons, the uncertainties in the normalization of the cross section [76] and from the choice of values for the electroweak parameters [77] are added in quadrature, yielding a 12.5% uncertainty. An uncertainty of +10% and −28% is assigned to the $WtZ$ background cross section following the methodology of ref. [78]. For the remaining small backgrounds, a 50% uncertainty is assumed. The $t\bar{t}$ production cross-section uncertainties from the independent variation of the factorization and renormalization scales, the PDF choice, and $\alpha_S$ variations (see refs. [32, 33] and references therein and refs. [35, 37, 38]) give a 5% uncertainty in the signal normalization.

The uncertainties in the modelling of $t\bar{t}Z$ and $WZ$ processes in the simulation are taken from alternative generators (`Sherpa 2.2.0` and `Powheg-Box v2` interfaced to the `Pythia8`, respectively) which yield 4% and 50% uncertainties in the SR, respectively. The $WtZ$ parton-shower uncertainty is estimated as 6% in the SR by using a sample interfaced to `Herwig++` [58]. The effect of QCD radiation on the $tZ$ production process is estimated to be below 2% in the SR by using alternative `MG5_aMC@NLO_Pythia6` [56] $tZ$ samples with additional radiation. The uncertainty due to the choice of NLO generator for the $t\bar{t}$ event production is evaluated using the alternative sample generated with `MG5_aMC@NLO` interfaced to `Pythia8`. The uncertainty in the total non-prompt leptons background in the SR is 25%. To evaluate the uncertainty due to the choice of parton shower algorithm, $t\bar{t}$ samples generated using `Powheg` interfaced to `Herwig7` [60] are used, yielding 2% uncertainty in the total non-prompt leptons background in the SR. To estimate the effect of QCD radiation on the $t\bar{t}$ samples, alternative samples generated with `Powheg+Pythia8` are considered where the factorization and renormalization scales are varied up and down by a factor of two and the A14 set of tuned parameters is changed to a version that varied the `VAR3c` [41] parameter, changing the amount of QCD radiation. This leads to a 10% uncertainty in the total non-prompt leptons background in the SR. Non-prompt lepton scale factor uncertainties are considered in the estimation of the backgrounds from events containing at least one non-prompt lepton.

For both the estimated signal and background event yields, experimental uncertainties resulting from detector effects are considered, including the lepton reconstruction, identification and trigger efficiencies, as well as lepton momentum scales and resolutions [62, 79, 80]. Uncertainties of the $E_{\mathrm{T}}^{\mathrm{miss}}$ scale [72], pile-up effects, and jet-energy scale and resolution [81, 82] are also considered. The $b$-tagging uncertainty component, which includes the uncertainty of the $b$-, $c$-, mistagged- and $\tau$-jet scale factors (the $\tau$ and charm uncertainties are highly correlated and evaluated as such) is evaluated by varying the $\eta$-, $p_{\mathrm{T}}$- and flavour-dependent scale factors applied to each jet in the simulated samples. The relative impact of each type of systematic uncertainty on the total background and signal yields is summarized before and after the fit in table 6 and table 7, respectively.

The uncertainty related to the integrated luminosity for the dataset used in this analysis is 2.1%. It is derived following the methodology described in ref. [83] and only affects background estimates from simulated samples.

## 8 Results

A simultaneous fit to the SR and all CRs defined in table 4 is used to search for a signal from FCNC decays of the top quark. A maximum-likelihood fit is performed to kinematic distributions in the signal and control regions to test for the presence of signal events. Contamination of the CRs by the signal is negligible. The inclusion of the CRs in a



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| Pre-fit Source | $t\bar{t}Z$ CR | $WZ$ CR | $ZZ$ CR | Non-prompt lepton CR0 | Non-prompt lepton CR1 | SR | |
|---|---|---|---|---|---|---|---|
| | B [%] | B [%] | B [%] | B [%] | B [%] | B [%] | S [%] |
| Event modelling | 29 | 40 | 13 | 24 | 40 | 30 | 5 |
| Leptons | 2.1 | 2.4 | 3.0 | 2.6 | 2.9 | 2.6 | 1.9 |
| Jets | 6 | 8 | 15 | 10 | 4 | 9 | 4 |
| $b$-tagging | 7 | 1.5 | 0.6 | 2.3 | 3.0 | 5 | 3.4 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | 0.4 | 4 | 2.6 | 3.0 | 0.8 | 5 | 1.4 |
| Non-prompt leptons | 1.1 | 1.3 | — | 12 | 15 | 6 | — |
| Pile-up | 5 | 1.3 | 5 | 3.5 | 1.8 | 4 | 2.3 |
| Luminosity | 2.0 | 2.0 | 2.1 | 1.3 | 0.8 | 1.7 | 2.1 |

**Table 6**. Summary of the relative impact of each type of uncertainty on the total background (B) yield in the background control regions and on the background and signal (S) yields in the signal region before the combined fit under the background-only hypothesis.

| Post-fit Source | $t\bar{t}Z$ CR | $WZ$ CR | $ZZ$ CR | Non-prompt lepton CR0 | Non-prompt lepton CR1 | SR | |
|---|---|---|---|---|---|---|---|
| | B [%] | B [%] | B [%] | B [%] | B [%] | B [%] | S [%] |
| Event modelling | 22 | 10 | 11 | 9 | 23 | 18 | 5 |
| Leptons | 2.0 | 2.4 | 2.9 | 2.6 | 2.9 | 2.6 | 1.8 |
| Jets | 5 | 6 | 11 | 8 | 4 | 8 | 4 |
| $b$-tagging | 7 | 1.4 | 0.6 | 2.1 | 2.8 | 4 | 3.1 |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | 0.3 | 3.3 | 2.5 | 2.8 | 0.7 | 4 | 1.4 |
| Non-prompt leptons | 1.1 | 1.1 | — | 8 | 12 | 5 | — |
| Pile-up | 5 | 1.2 | 5 | 3.3 | 1.7 | 3.5 | 2.2 |
| Luminosity | 2.0 | 2.0 | 2.1 | 1.3 | 0.8 | 1.6 | 2.1 |

**Table 7**. Summary of the relative impact of each type of uncertainty on the total background (B) yield in the background control regions and on the background and signal (S) yields in the signal region after the combined fit under the background-only hypothesis.

combined fit with the SR constrains backgrounds and reduces systematic uncertainties. The kinematic distributions used in the fit are the $\chi^2$ of the kinematical reconstruction for the SR, the leading lepton's $p_{\mathrm{T}}$ for the non-prompt leptons and $t\bar{t}Z$ CRs, the transverse mass for the $WZ$ CR, and the reconstructed mass of the four leptons for the $ZZ$ CR.

The statistical analysis to extract the signal is based on a binned likelihood function $L(\mu, \theta)$ constructed as a product of Poisson probability terms over all bins in each considered distribution, and Gaussian constraint terms for $\theta$, a set of nuisance parameters that parameterize effects of statistical and systematic uncertainties on the signal and background expectations. The parameter $\mu$ is a multiplicative factor for the number of signal events normalized to a branching ratio $\mathcal{B}_{\mathrm{ref}}(t \to qZ) = 0.1\%$. The nuisance parameters are floated in the combined fit to adjust the expectations for signal and background according to the corresponding systematic uncertainties, and their fitted values are the adjustment that best fits the data.



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The test statistic is the profile likelihood ratio $q_\mu = -2\ln(L(\mu,\hat{\hat{\theta}}_\mu)/L(\hat{\mu},\hat{\theta}))$, where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximize the likelihood function (with the constraints $0 \leq \hat{\mu} \leq \mu$), and $\hat{\hat{\theta}}_\mu$ are the values of the nuisance parameters that maximize the likelihood function for a given value of $\mu$. This test statistic is used to measure the probability that the observed data is compatible with the background-only hypothesis (i.e. for $\mu = 0$) and to make statistical inferences about $\mu$.

The distributions used in the combined fit under the background-only hypothesis are presented in figure 2. The same distributions after the fit are presented in figure 3. Table 8 shows the expected number of background events, number of selected data events, and signal yields in the SR before and after the fit. The post-fit signal yield changes relative to the pre-fit one due to the fitted nuisance parameters. The yields in the CRs after the fit are shown in table 9. Good agreement between data and the expectation from the background-only hypothesis is observed, and no evidence of a FCNC signal is found. The upper limits on $\mathcal{B}(t \to qZ)$ are computed with the $\mathrm{CL_s}$ method [84, 85] using the asymptotic properties of $q_\mu$ [86–88] and assuming that only one FCNC mode contributes. Figure 4 shows the observed $\mathrm{CL_s}$ for $\mathcal{B}(t \to uZ)$ and $\mathcal{B}(t \to cZ)$ together with the $\pm 1\sigma$ and $\pm 2\sigma$ bands for the expected values. The 95% confidence level (CL) limit on $\mathcal{B}(t \to uZ)$ is $1.7 \times 10^{-4}$, and on $\mathcal{B}(t \to cZ)$ it is $2.4 \times 10^{-4}$. The observed and expected limits are shown in table 10. It can be seen that the observed limit is about $1\sigma$ more stringent than expected due to a smaller number of observed events in the first bin of the $\chi^2$ distribution in the SR, which is the one with the largest sensitivity to the signal.

Using the effective field theory framework developed in the TopFCNC model [89, 90] and assuming a cut-off scale $\Lambda = 1$ TeV and that only one operator has a non-zero value, the upper limits on $\mathcal{B}(t \to uZ)$ and $\mathcal{B}(t \to cZ)$ are converted to 95% CL upper limits on the moduli of the operators contributing to the FCNC decay $t \to qZ$, which are presented in table 11.

## 9 Conclusions

An analysis is performed to search for $t\bar{t}$ events with one top quark decaying through the FCNC $t \to qZ$ ($q = u, c$) channel and the other through the dominant Standard Model mode $t \to bW$, where only $Z$ boson decays into charged leptons and leptonic $W$ boson decays are considered as signal. The data were collected by the ATLAS experiment in $pp$ collisions corresponding to an integrated luminosity of 36.1 fb$^{-1}$ at the LHC at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. There is good agreement between the data and Standard Model expectations, and no evidence of a signal is found. The 95% CL limits on the $t \to qZ$ branching ratio are $\mathcal{B}(t \to uZ) < 1.7 \times 10^{-4}$ and $\mathcal{B}(t \to cZ) < 2.4 \times 10^{-4}$, improving previous ATLAS results by more than 60%. These limits constrain the values of effective field theory operators contributing to the $t \to uZ$ and $t \to cZ$ FCNC decays of the top quark.



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| Sample | Yields | |
|---|---|---|
| | Pre-fit | Post-fit |
| $t\bar{t}Z$ | $37 \pm 5$ | $37 \pm 4$ |
| $WZ$ | $32 \pm 19$ | $32 \pm 8$ |
| $ZZ$ | $6.2 \pm 3.2$ | $6.4 \pm 3.0$ |
| Non-prompt leptons | $26 \pm 11$ | $20 \pm 7$ |
| Other backgrounds | $23 \pm 4$ | $23 \pm 4$ |
| Total background | $124 \pm 26$ | $119 \pm 10$ |
| Data | 116 | 116 |
| Data / Bkg | $0.94 \pm 0.21$ | $0.97 \pm 0.12$ |
| Signal $t \to uZ$ ($\mathcal{B} = 0.1\%$) | $101 \pm 8$ | $103 \pm 8$ |
| Signal $t \to cZ$ ($\mathcal{B} = 0.1\%$) | $85 \pm 7$ | $87 \pm 7$ |

**Table 8**. Expected number of background events, number of selected data events, and number of signal events (arbitrarily normalized to a branching ratio of $\mathcal{B}(t \to qZ) = 0.1\%$) in the signal region before and after the combined fit under the background-only hypothesis. The uncertainties shown include all of the systematic uncertainties described in section 7. The entry labelled "other backgrounds" includes all remaining backgrounds described in section 3 and in table 2. The uncertainties in the post-fit yields are calculated using the full correlation matrix from the fit.

| Sample | $t\bar{t}Z$ CR | $WZ$ CR | $ZZ$ CR | Non-prompt lepton CR0 | Non-prompt lepton CR1 |
|---|---|---|---|---|---|
| $t\bar{t}Z$ | $61 \pm 6$ | $16.5 \pm 3.1$ | $0 \pm 0$ | $6.1 \pm 1.2$ | $21.9 \pm 2.9$ |
| $WZ$ | $6 \pm 4$ | $610 \pm 40$ | $0 \pm 0$ | $166 \pm 13$ | $20 \pm 5$ |
| $ZZ$ | $0.07 \pm 0.02$ | $49 \pm 9$ | $89 \pm 12$ | $59 \pm 10$ | $9.0 \pm 2.2$ |
| Non-prompt leptons | $2.0 \pm 2.3$ | $41 \pm 15$ | $0 \pm 0$ | $177 \pm 32$ | $174 \pm 21$ |
| Other backgrounds | $13.4 \pm 2.6$ | $23 \pm 5$ | $1.1 \pm 0.6$ | $19 \pm 6$ | $33 \pm 7$ |
| Total background | $82 \pm 7$ | $737 \pm 35$ | $90 \pm 12$ | $426 \pm 30$ | $258 \pm 20$ |
| Data | 81 | 734 | 87 | 433 | 260 |
| Data / Bkg | $0.99 \pm 0.14$ | $1.00 \pm 0.06$ | $0.97 \pm 0.16$ | $1.02 \pm 0.09$ | $1.01 \pm 0.10$ |

**Table 9**. Event yields in the background control regions for all significant sources of events after the combined fit under the background-only hypothesis. The uncertainties shown include all of the systematic uncertainties described in section 7. The entry labelled "other backgrounds" includes all remaining backgrounds described in section 3 and in table 2. The uncertainties in the post-fit yields are calculated using the full correlation matrix from the fit.

| | $\mathcal{B}(t \to uZ)$ | $\mathcal{B}(t \to cZ)$ |
|---|---|---|
| Observed | $1.7 \times 10^{-4}$ | $2.4 \times 10^{-4}$ |
| Expected $-1\sigma$ | $1.7 \times 10^{-4}$ | $2.2 \times 10^{-4}$ |
| Expected | $2.4 \times 10^{-4}$ | $3.2 \times 10^{-4}$ |
| Expected $+1\sigma$ | $3.4 \times 10^{-4}$ | $4.6 \times 10^{-4}$ |

**Table 10**. Observed and expected 95% CL upper limits on the FCNC top-quark decay branching ratios. The expected central value is shown together with the $\pm 1\sigma$ bands, which includes the contribution from the statistical and systematic uncertainties.



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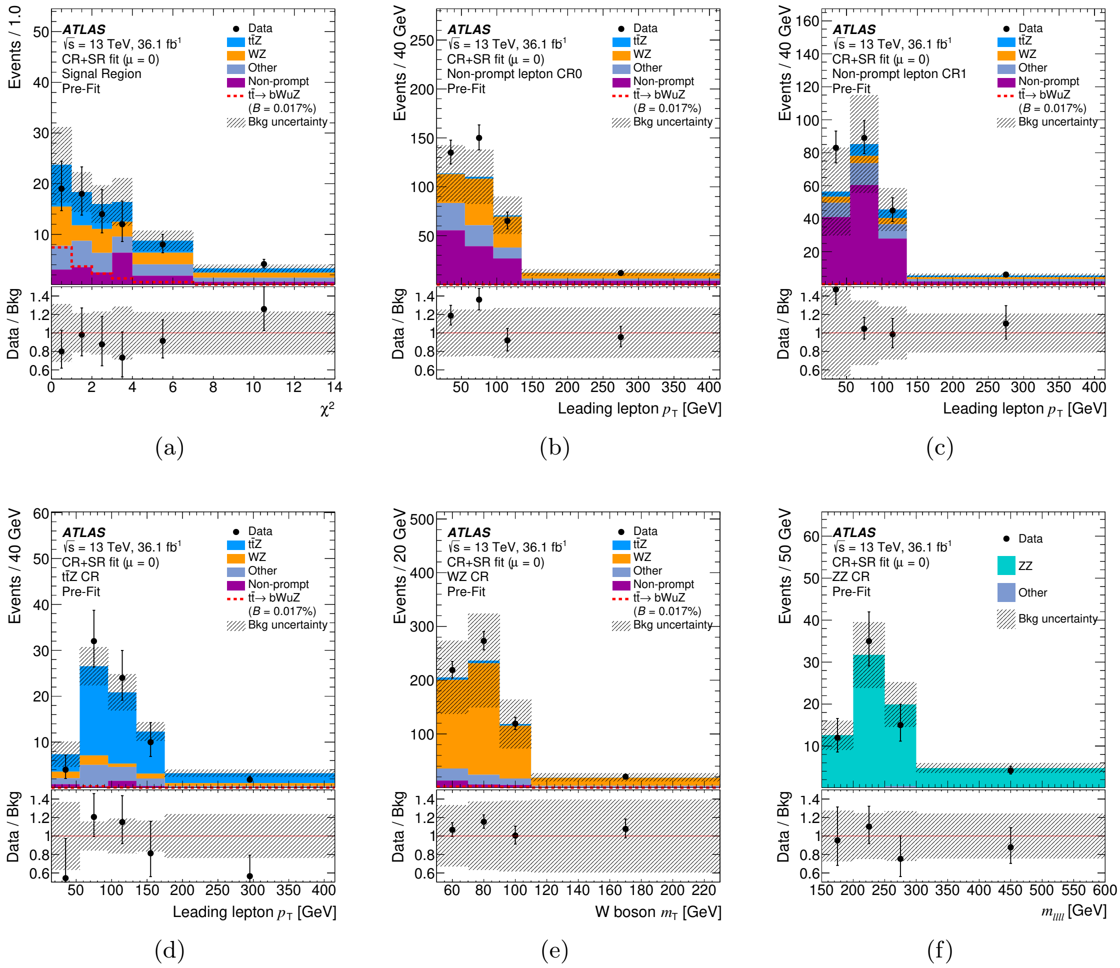


**Figure 2**. Expected (filled histogram) and observed (points with error bars) distributions before the combined fit under the background-only hypothesis of (a) the $\chi^2$ of the kinematical reconstruction in the SR; (b) $p_{\mathrm{T}}$ of the leading lepton in the non-prompt lepton CR with $b$-tag veto; (c) $p_{\mathrm{T}}$ of the leading lepton in the non-prompt lepton CR with $b$-tag; (d) $p_{\mathrm{T}}$ of the leading lepton in the $t\bar{t}Z$ CR; (e) the transverse mass in the $WZ$ CR and (f) the reconstructed mass of the four leptons in the $ZZ$ CR. For comparison, distributions for the FCNC $t\bar{t} \to bWuZ$ signal (dashed line), normalized to the observed limit, are also shown. The "Other" category includes all remaining backgrounds described in section 3. The dashed area represents the total uncertainty in the background prediction.

| Operator | Observed | Expected |
|---|---|---|
| $\lvert C_{uB}^{(31)}\rvert$ | 0.25 | 0.30 |
| $\lvert C_{uW}^{(31)}\rvert$ | 0.25 | 0.30 |
| $\lvert C_{uB}^{(32)}\rvert$ | 0.30 | 0.34 |
| $\lvert C_{uW}^{(32)}\rvert$ | 0.30 | 0.34 |

**Table 11**. Observed and expected 95% CL upper limits on the moduli of the operators contributing to the FCNC decays $t \to uZ$ and $t \to cZ$ within the TopFCNC model for a new-physics energy scale $\Lambda = 1$ TeV.

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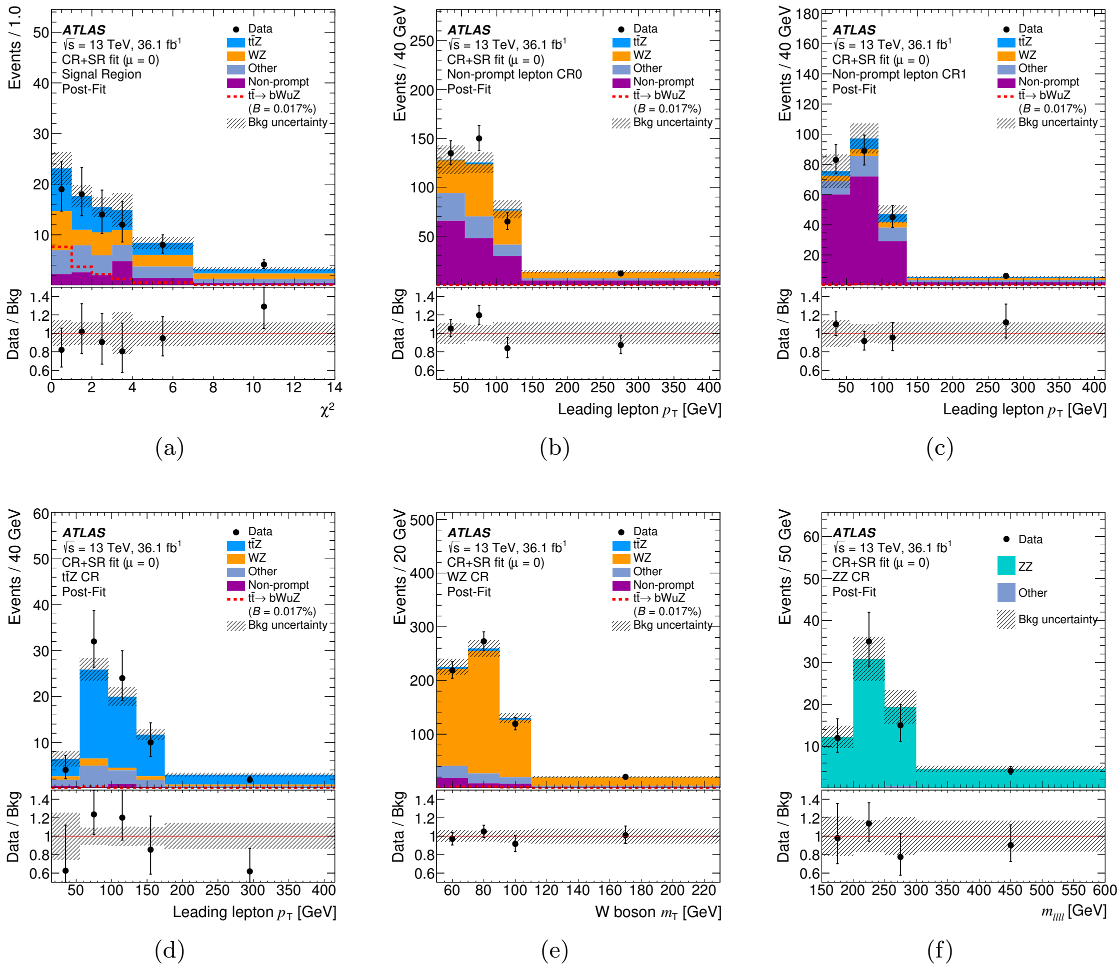


**Figure 3**. Expected (filled histogram) and observed (points with error bars) distributions after the combined fit under the background-only hypothesis of (a) the $\chi^2$ of the kinematical reconstruction in the SR; (b) $p_{\mathrm{T}}$ of the leading lepton in the non-prompt lepton CR with $b$-tag veto; (c) $p_{\mathrm{T}}$ of the leading lepton in the non-prompt lepton CR with $b$-tag; (d) $p_{\mathrm{T}}$ of the leading lepton in the $t\bar{t}Z$ CR; (e) the transverse mass in the $WZ$ CR and (f) the reconstructed mass of the four leptons in the $ZZ$ CR. For comparison, distributions for the FCNC $t\bar{t} \to bWuZ$ signal (dashed line), normalized to the observed limit, are also shown. The "Other" category includes all remaining backgrounds described in section 3. The dashed area represents the total uncertainty in the background prediction.

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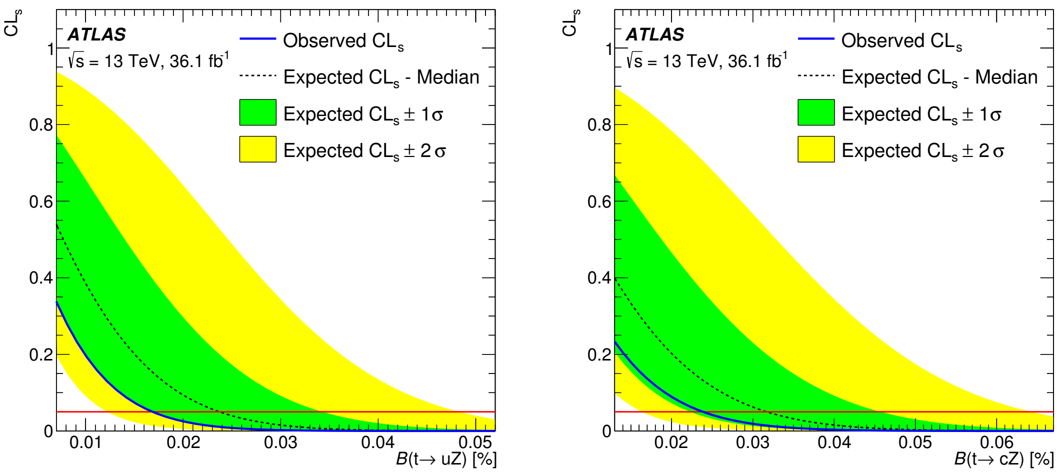


(a) (b)

**Figure 4**. (a) $\mathrm{CL_s}$ vs $\mathcal{B}(t \to uZ)$ and (b) $\mathrm{CL_s}$ vs $\mathcal{B}(t \to cZ)$ taking into account systematic and statistical uncertainties. The observed $\mathrm{CL_s}$ values (solid line) are compared to the expected (median) $\mathrm{CL_s}$ values under the background-only hypothesis (dashed line). The surrounding shaded bands correspond to the 68% and 95% CL intervals around the expected $\mathrm{CL_s}$ values, denoted by $\pm 1\sigma$ and $\pm 2\sigma$, respectively. The solid line at $\mathrm{CL_s} = 0.05$ denotes the threshold below which the hypothesis is excluded at 95% CL.


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