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Search for flavour-changing neutral current top-quark decays to qZ in pp collision data collected with the ATLAS detector at $\sqrt{s} = 8$ TeV

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Abstract

A search for the flavour-changing neutral-current decay $t \to qZ$ is presented. Data collected by the ATLAS detector during 2012 from proton–proton collisions at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.3 fb^{-1}, are analysed. Top-quark pair-production events with one top quark decaying through the $t \to qZ$ ($q = u, c$) channel and the other through the dominant Standard Model mode $t \to bW$ are considered as signal. Only the decays of the Z boson to charged leptons and leptonic W boson decays are used. No evidence for a signal is found and an observed (expected) upper limit on the $t \to qZ$ branching ratio of 7×10^{-4} (8×10^{-4}) is set at the 95% confidence level.

1 Introduction

The top quark is the heaviest elementary particle known, with a mass $m_t = 173.21 \pm 0.51(\text{stat.}) \pm 0.71(\text{syst.})$ GeV [1]. Its lifetime is so short that, within the Standard Model (SM) of particle physics, it decays (almost exclusively to bW) before hadronisation occurs. These properties make it a particle well suited to test the predictions of the SM. In the SM, due to the GIM mechanism [2], flavour-changing neutral current (FCNC) decays such as $t \to qZ$ are forbidden at tree level. They are allowed at one-loop level, but with a suppression factor of several orders of magnitude with respect to the dominant decay mode [3]. However, several SM extensions predict higher branching ratios (BRs) for the 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 model (MSSM) [6], supersymmetry with R-parity violation ($\not{R}$ SUSY) [7] or models with warped extra dimensions (RS) [8]. For a review see Ref. [9]. The maximum values for the $t \to qZ$ BRs predicted by these models and by the SM are summarised in Table 1. Experimental limits on the FCNC $t \to qZ$ BR were established by experiments at the Large Electron Positron Collider (LEP) [10–14], HERA [15], Tevatron [16, 17] and Large Hadron Collider (LHC) [18, 19]. The most stringent limit, $\text{BR}(t \to qZ) < 5 \times 10^{-4}$, is the one from the CMS Collaboration [19] using 25 fb^{-1} of data collected at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. Previous ATLAS results obtained at $\sqrt{s} = 7$ TeV are also reported [18]. Limits on other FCNC top-quark decay BRs ($t \to qX, X = \gamma, g, H$) are reported in Refs. [10–14, 20–28].

This paper presents the ATLAS results from the search for the FCNC decay $t \to qZ$ in $t\bar{t}$ events produced at $\sqrt{s} = 8$ TeV, with one top quark decaying through the FCNC mode and the other through the SM dominant mode ($t \to bW$). Only the decays of the Z boson to charged leptons and leptonic W boson decays are considered. The final-state topology is thus characterised by the presence of three isolated charged leptons, at least two jets, and missing transverse momentum from the undetected neutrino. The paper is organised 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 Detector and data samples

The ATLAS experiment is a multi-purpose particle physics detector consisting of several sub-detector systems, which cover almost fully the solid angle[1] 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, an iron/scintillator-tile hadronic calorimeter, copper/LAr hadronic endcap calorimeter and a muon spectrometer with three superconducting magnets, each one with eight toroid coils. The forward region is covered by additional LAr calorimeters with copper and tungsten absorbers. The combination of all these systems provides

[1] 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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The ΔR distance is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Table 1: Maximum allowed FCNC $t \to qZ$ BRs as predicted by several models [3–9]

Model:	SM	QS	2HDM	FC 2HDM	MSSM	$\not R$ SUSY	RS
BR($t \to qZ$):	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}

charged-particle momentum measurements, together with efficient and precise lepton and 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 (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$). A three-level trigger system is used to select interesting events. The Level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This is followed by two software-based trigger levels which together reduce the event rate to less than 1 kHz. A detailed description of the ATLAS detector is provided in Ref. [29].

In this paper the full 2012 dataset from proton–proton (pp) collisions at $\sqrt{s} = 8$ TeV is used. The analysed events were recorded by single-electron or single-muon triggers and fulfil standard data-quality requirements. Triggers with different transverse momentum thresholds are used to increase the overall efficiency. The triggers using a low transverse momentum (p_{T}) threshold ($p_{\mathrm{T}}^{e,\mu} > 24$ GeV) also have an isolation requirement. Efficiency losses at higher p_{T} values are recovered by higher threshold triggers ($p_{\mathrm{T}}^{e} > 60$ GeV or $p_{\mathrm{T}}^{\mu} > 36$ GeV) without any isolation requirement. The integrated luminosity of the analysed data sample is 20.3 fb^{-1}.

3 Simulated samples

In the SM, top quarks are produced at the LHC mainly in pairs, with a predicted $t\bar{t}$ cross section in pp collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeVof $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb for a top-quark mass of 172.5 GeV. The cross section has been calculated at next-to-next-to leading-order (NNLO) in QCD including resummation of next-to-next-to leading logarithmic (NNLL) soft gluon terms with Top++ 2.0 [30–35]. The parton distribution function (PDF) and α_{S} uncertainties are calculated using the PDF4LHC prescription [36] with the MSTW 2008 68% CL NNLO [37, 38], CT10 NNLO [39, 40] and NNPDF 2.3 5f FFN [41] PDF sets and are added in quadrature to the renormalisation and factorisation scale uncertainties. The cross-section value for the NNLO+NNLL calculation is about 3% larger than the exact NNLO prediction implemented in HATHOR 1.5 [42].

The simulation of signal events is performed with PROTOS 2.2 [43, 44], which includes the effects of new physics at an energy scale Λ by adding dimension-six effective terms to the SM Lagrangian. The most general Ztu vertex that arises from the dimension-six operators can be parameterised including only γ^{μ} and $\sigma^{\mu\nu}q_{\nu}$ terms [45] as:

$$\begin{aligned} \mathcal{L}_{Ztu} &= -\frac{g}{2c_W}\bar{u}\gamma^{\mu}\left(X_{ut}^{\mathrm{L}}P_{\mathrm{L}} + X_{ut}^{\mathrm{R}}P_{\mathrm{R}}\right)tZ_{\mu} \\ &\quad -\frac{g}{2c_W}\bar{u}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_Z}\left(\kappa_{ut}^{\mathrm{L}}P_{\mathrm{L}} + \kappa_{ut}^{\mathrm{R}}P_{\mathrm{R}}\right)tZ_{\mu} + \text{h.c.}, \end{aligned} \tag{1}$$

where g is the electroweak coupling, c_W is the cosine of the weak mixing angle, u and t are the quark spinors, Z_{μ} is the Z boson field, P_{L} (P_{R}) is the left-handed (right-handed) projection operator, m_Z is the Z

boson mass and $q^\nu = p_t^\nu - p_u^\nu$ is the outgoing Z boson momentum. The Ztc vertex can be parameterised in a similar fashion. This vertex involves a minimum of four anomalous couplings $X_{ut}^{\mathrm{L}}, X_{ut}^{\mathrm{R}}, \kappa_{ut}^{L}, \kappa_{ut}^{R}$, which are set to 0.01 each. It was checked that the coupling choice does not affect the kinematics of the event. No impact in the kinematics is seen by comparing the $bWuZ$ and $bWcZ$ processes and the latter is used as reference. Only decays of the W and Z bosons involving charged leptons are generated at the matrix-element level by PROTOS ($Z \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ and $W \to e\nu, \mu\nu, \tau\nu$). The CTEQ6L1 [46] leading-order PDF is used. To account for higher-order contributions in the signal production, the events are reweighted to the measured $t\bar{t}$ differential cross section as a function of the transverse momentum of the $t\bar{t}$ system $(1/\sigma)(\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{t\bar{t}})$ [47]. Hadronisation is handled by PYTHIA 6.426 [48] with the Perugia2011C [49] set of tuned parameters and τ decays are processed with TAUOLA [50]. The top-quark mass is set to m_t = 172.5 GeV. Additional simulations with different parton shower parameterisations are used to estimate the systematic uncertainties on the amount of initial- and final-state radiation (ISR/FSR).

Several SM processes have final-state topologies similar to the signal, with at least three prompt charged leptons, especially WZ, ZZ, $t\bar{t}V$,[2] $t\bar{t}H$, ggH, VH, tZ and triboson (WWW, ZWW and ZZZ) production. Events with non-prompt leptons or in which at least one jet is misidentified as an isolated charged lepton (labelled as “fake leptons” throughout this paper) can also fulfil the event selection requirements. These events, typically Z+jets, $Z + \gamma$, $t\bar{t}$ and single-top, are estimated from a data-driven method using a parameterisation of the true- and fake-lepton efficiencies. Samples of simulated events of these backgrounds with fake leptons are used to cross-check the data-driven estimation. The Z+jets simulations include Z production in association with heavy-flavour quarks.

Table 2 summarises the information about the generators, parton shower and parton distribution functions used to simulate the different event samples considered in the analysis. Diboson events (WZ and ZZ, where Z means Z/γ^*) produced using SHERPA contain up to three additional partons and are selected to have leptons with $p_{\mathrm{T}} > 5$ GeV and $m_{\ell\ell} > 0.1$ GeV for the Z/γ^*. The additional WZ and ZZ samples are used for comparison. The WZ ALPGEN samples are simulated with up to five additional partons from the matrix element. The ZZ HERWIG [51] samples are selected to have one lepton with $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.8$. The simulations of $t\bar{t}Z$, $t\bar{t}W(W)$, tZ and tribosons include events with up to two extra partons in the final state. The simulated samples used to cross-check the data-driven estimation of background with fake leptons are also listed in Table 2.

Detailed and fast simulations of the detector and trigger are performed with standard ATLAS software using GEANT4 [52, 53] and ATLFASTII [53], respectively. The same offline reconstruction methods used on data are applied to the simulated samples.

4 Object reconstruction

The primary physics objects considered in this search are electrons, muons, $E_{\mathrm{T}}^{\mathrm{miss}}$, jets, and b-tagged jets. Tau leptons are not explicitly reconstructed, although the τ decay products are reconstructed as electrons, muons or jets and as an additional contribution to the missing transverse momentum.

Electron candidates are reconstructed [63] from energy deposits (clusters) in the electromagnetic calorimeter, which are then matched to reconstructed charged-particle tracks in the inner detector. The candidates are required to have a transverse energy E_{T} greater than 15 GeV and a pseudorapidity of the calorimeter cluster associated with the electron candidate $|\eta_{\mathrm{cluster}}| < 2.47$. Candidates in the transition

[2] V stands for W and Z bosons. The simulation of $t\bar{t}W$ events also includes a possible second W boson.

Table 2: Generators, parton shower, parton distribution functions and parameter tune for hadronisation used to produce simulated samples used in this analysis.

Sample	Generator	Parton shower	PDF	Tune
Samples with at least three prompt leptons:				
$t\bar{t} \to bWqZ$	PROTOS 2.2 [43]	PYTHIA 6.426 [48]	CTEQ6L1 [46]	Perugia2011C [49]
WZ	SHERPA 1.4.3 [54]	SHERPA 1.4.3	CT10 [39]	—
WZ	ALPGEN 2.14 [55]	HERWIG 6.520.2 [51]	CTEQ6L1	AUET2 [56]
ZZ	SHERPA 1.4.3	SHERPA 1.4.3	CT10	—
ZZ	HERWIG 6.5	HERWIG 6.5	CTEQ6L1	AUET2
$t\bar{t}V$, tZ, tribosons	MADGRAPH 5 1.3.33 [57]	PYTHIA 6.426	CTEQ6L1	AUET2B
$t\bar{t}H$, WH, ZH	PYTHIA 8.163 [58]	PYTHIA 8.163	CTEQ6L1	AU2 [59]
ggH	POWHEG 2 [60]	PYTHIA 8.163	CT10	AU2
Other samples:				
WW	SHERPA 1.4.3	SHERPA 1.4.3	CT10	—
Z+jets (30 GeV $< m_{\ell\ell} <$ 1 TeV)	ALPGEN 2.14	PYTHIA 6.426	CTEQ6L1	Perugia2011C
Z+jets (10 GeV $< m_{\ell\ell} <$ 60 GeV)	ALPGEN 2.14	HERWIG 6.520.2	CTEQ6L1	AUET2
$Z\gamma$	SHERPA 1.4.1	SHERPA 1.4.1	CT10	—
$t\bar{t} \to bWbW$	POWHEG 2	PYTHIA 6.426	CTEQ6L1	Perugia2011C
Single top (s, Wt channel)	MC@NLO 4.03 [61]	HERWIG 6.520.2	CT10	AUET2
Single top (t channel)	AcerMC 3.8 [62]	PYTHIA 6.426	CTEQ6L1	AUET2B

region between the barrel and endcap calorimeters with $1.37 < |\eta_{\text{cluster}}| < 1.52$ are excluded. Electron candidates in this analysis must satisfy tight quality requirements on the electromagnetic cluster and associated track which provide discrimination between isolated electrons and jets. In order to suppress multi-jet backgrounds, it is also required that there is little activity in the space surrounding the electron. Two isolation variables are employed: the energy deposited around the electron in the calorimeter in a cone of size $\Delta R = 0.2$ and the scalar sum of the p_{T} of the tracks within cone of size $\Delta R = 0.3$ around the electron. Cuts on these two quantities are used to select isolated electrons; the adopted cuts yield a 90% identification efficiency in Z boson decays to e^+e^- events from the full 2012 dataset. Additionally, the longitudinal impact parameter $|z_0|$ of the electron track with respect to the selected primary vertex of the event is required to be less than 2 mm. The closest jet if separated by $\Delta R < 0.2$ from the selected electron is removed from the event. The electron candidate is discarded if an additional selected jet is found with $\Delta R < 0.4$. A looser electron selection, used for the estimation of backgrounds with fake leptons, is defined by removing the isolation requirements.

The muon candidate reconstruction [64] is performed by finding, combining and fitting track segments in the layers of the muon chambers, starting from the outermost layer. The identified muons are then matched with tracks reconstructed in the inner detector. The candidates are refitted using the complete track information from both detector systems, and are required to satisfy $p_{\text{T}} > 15$ GeV, $|\eta| < 2.5$ and to be separated by $\Delta R > 0.4$ from any selected jet. The hit pattern in the inner detector is required to be consistent with a well-reconstructed track and the $|z_0|$ of the muon track is required to be less than 2 mm. Additionally, the sum of the momenta of tracks inside a cone around the muon candidate, with variable size such that it is smaller for higher muon p_{T} [65], must be less than 5% of the muon energy. For the estimation of backgrounds with fake leptons, a looser selection is applied by removing the isolation requirement.

Jets are reconstructed [66] from topological clusters of neighbouring calorimeter cells with significant energy deposits using the anti-k_t algorithm [67] with a radius parameter $R = 0.4$. Prior to jet finding, a local calibration scheme is applied to correct the topological cluster energies for the non-compensating response of the calorimeter, dead material and energy leakage. The corrections are obtained from simulations of charged and neutral particles. These jets are then calibrated to the hadronic energy scale using p_{T}- and η-dependent correction factors. Dedicated requirements are applied to remove the negligible fraction of events (less than 0.01%) where a jet is incorrectly reconstructed from a few noisy calorimeter cells [68]. The jets used in the analysis are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$. To reduce the number of selected jets that originate from secondary pp interactions, for jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$, the scalar sum of the p_{T} of tracks matched to a jet and originating from the primary vertex must be at least 50% of the scalar sum of the p_{T} of all tracks matched to the jet.

Jets containing b-hadrons are identified ('b-tagged') [69] 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. It is determined with simulated $t\bar{t}$ events that, for the chosen working point, the tagging efficiency for b-jets with $p_{\mathrm{T}} > 20$ GeV is 70%, while the rejection factors for light-quark or gluon jets (light jets), charm jets and τ leptons are 137, 5 and 13, respectively.

The measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$ is based [70] on the energy deposits in the calorimeter with $|\eta| < 4.9$. The energy deposits associated with reconstructed jets and electrons are calibrated accordingly. Energy deposits not associated with a reconstructed object are calibrated according to their energy sharing between the electromagnetic and hadronic calorimeters. The momentum associated with each reconstructed muon, estimated using the momentum measurement of its reconstructed track, is taken into account in the calculation of $E_{\mathrm{T}}^{\mathrm{miss}}$.

5 Event selection and kinematics

At least one of the selected leptons must be matched, with $\Delta R < 0.15$ to the appropriate trigger object and have $p_{\mathrm{T}} > 25$ GeV. The trigger efficiencies for the leptons are approximately 93% for electrons, 70% for muons with $|\eta| < 1.05$ and 86% for muons with $1.05 < |\eta| < 2.4$ [71, 72]. The events are required to have at least one primary vertex with more than four associated tracks, each with $p_{\mathrm{T}} > 400$ MeV. The primary vertex is chosen as the one with the highest $\sum p_{\mathrm{T}}^2$ over all associated tracks. Leptons from cosmic rays are rejected by removing muon pairs with large, oppositely signed transverse impact parameters ($|d_0| > 0.5$ mm) and consistent with being back-to-back in the $r - \phi$ plane. Events with noise bursts and readout errors in the LAr calorimeter are also rejected. Exactly three isolated leptons associated with the same vertex are required. The three leptons must have $|\eta| < 2.5$ and $p_{\mathrm{T}} > 15$ GeV. Two of the leptons are required to have the same flavour, opposite charge and a reconstructed mass within 15 GeV of the Z boson mass (m_Z) [1]. 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 two jets, although an additional third jet from initial- or final-state radiation is allowed. All jets are required to have $p_{\mathrm{T}} > 35$ GeV and $|\eta| < 2.5$. One or two of the jets must be b-tagged. Only one b-tagged jet is expected in the signal events, nevertheless a second one can arise from a misidentified c-jet associated with the FCNC decay of the top quark. Allowing for the additional b-tagged jet increases the signal efficiency without compromising the signal-to-background ratio.

Applying energy–momentum conservation, the kinematics of the top quarks can be reconstructed from the corresponding decay particles. Since the neutrino from the semileptonic decay of the top quark ($t \rightarrow bW \rightarrow b\ell\nu$) is undetected, its four-momentum must be estimated. This can be done by assuming that the lepton not previously assigned to the Z boson and the b-tagged jet (labelled b-jet) originate from the W boson and SM top-quark decays, respectively, and that $E_{\mathrm{T}}^{\mathrm{miss}}$ is the neutrino's transverse momentum. The longitudinal component of the neutrino's momentum (p_z^{ν}) is then determined by minimising, without constraints, the following expression:

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

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. The central value for the masses and the widths of the top quarks and W boson are taken from reconstructed simulated signal events. This is done by matching the true particles in the simulated events to the reconstructed ones, setting the longitudinal momentum of the neutrino to the p_z of the true simulated neutrino and then performing Bukin fits[3] [73] to the masses of the matched reconstructed top quarks and W boson. The values are $m_{t_{\mathrm{FCNC}}} = 173$ GeV, $\sigma_{t_{\mathrm{FCNC}}} = 10$ GeV, $m_{t_{\mathrm{SM}}} = 168$ GeV, $\sigma_{t_{\mathrm{SM}}} = 23$ GeV, $m_W = 82$ GeV and $\sigma_W = 15$ GeV.

For each jet combination, where any jet can be assigned to j_a, while j_b must correspond to a b-tagged jet, the χ^2 minimisation gives the most probable value for p_z^{ν}. From all combinations, the one with the minimum χ^2 is chosen, along with the corresponding p_z^{ν} 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 $\epsilon_{t_{\mathrm{FCNC}}} = 79.9\%$ and $\epsilon_{t_{\mathrm{SM}}} = 56.3\%$. Figure 1 shows the p_{T} of the third lepton as well as the $E_{\mathrm{T}}^{\mathrm{miss}}$ and χ^2 distributions at this level of the analysis.

The selection of the signal region is concluded with the requirement of $\chi^2 < 6$, which optimises the sensitivity discussed in Section 8.

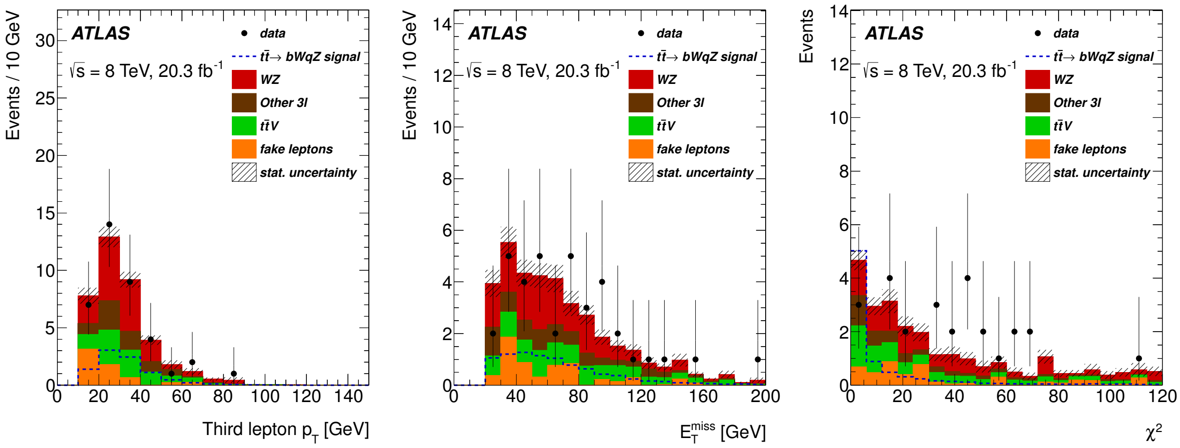
6 Background estimates

Three control regions are defined to check the agreement between data and simulated samples of the ZZ, WZ and $t\bar{t}Z$ backgrounds. No scaling factors are derived from these control regions, however they are used to estimate the background modelling uncertainties described in Section 7. The tZ contribution to the total background is expected to be smaller than the one from $t\bar{t}Z$ events [74]. Due to the similarity between the final states of tZ and signal events, there are large signal contributions to possible tZ control regions. For these reasons no control region is defined for the tZ background.

The ZZ control region is defined by requiring two pairs of leptons with the same flavour, opposite charge and a reconstructed mass within 15 GeV of the Z boson mass. The expected and observed yields are shown in Table 3 and the SHERPA sample is chosen as reference.

To study the WZ background the following control region is defined. Events are required to have three leptons, two of them with the same flavour, opposite charge and a reconstructed mass within 15 GeV of the Z boson mass. Additional requirements include the presence of at least one jet in the event with

[3] This is a piecewise function with a Gaussian function in the centre and two asymmetric tails.



(a) (b) (c)

Figure 1: Expected (filled histogram) and observed (points with error bars) distributions in the signal region before the χ^2 cut is applied for (a) p_{T} of the third lepton, (b) $E_{\mathrm{T}}^{\mathrm{miss}}$ and (c) χ^2 of the kinematics reconstruction. For comparison, distributions for the FCNC $t\bar{t} \to bWqZ$ signal (dashed line), normalised to the observed 95% CL limit reported in this paper, are also shown. Background statistical uncertainties associated with the number of events in the samples are represented by the hatched areas.

Table 3: Event yields in the ZZ control region for all significant sources of background. The ZZ `SHERPA` sample is taken as reference for the total background estimation. The first uncertainty is the statistical one associated with the number of events in the simulated samples, the second uncertainty is systematic and is described in Section 7. The entry labelled "other backgrounds" includes all the remaining backgrounds described in Section 3 and in Table 2. The signal efficiency is also shown.

Sample	Yields
ZZ (SHERPA)	87 ± 4 ± 5
ZZ (HERWIG)	85 ± 4 ± 5
Other backgrounds	0.48 ± 0.05 ± 0.08
Total background	88 ± 4 ± 5
Data	95
Signal efficiency [$\times 10^{-8}$]	5.6 ± 4.3 ± 0.1

Table 4: Event yields in the WZ control region for all significant sources of background. The WZ SHERPA sample is taken as reference for the total background estimation. The first uncertainty is the statistical one associated with the number of events in the samples, the second uncertainty is systematic and is described in Section 7. The entry labelled "other backgrounds" includes all the remaining backgrounds described in Section 3 and in Table 2. The signal efficiency is also shown.

Sample	Yields
WZ (SHERPA)	$333 \pm 5 \pm 17$
WZ (ALPGEN)	$393 \pm 6 \pm 19$
ZZ	$35 \pm 3 \pm 6$
Fake leptons	$15 \pm 3 \pm 5$
Other backgrounds	$9.5 \pm 0.3 \pm 2.4$
Total background	$392 \pm 7 \pm 19$
Data	405
Signal efficiency [$\times 10^{-4}$]	$9.8 \pm 0.1 \pm 1.0$

Table 5: Event yields in the $t\bar{t}Z$ control region for all significant sources of background. The first uncertainty is the statistical one associated with the number of events in the samples, the second uncertainty is systematic and is described in Section 7. The entry labelled "other backgrounds" includes all the remaining backgrounds described in Section 3 and in Table 2. The signal efficiency is also shown.

Sample	Yields
$t\bar{t}V$	$8.3 \pm 0.2 \pm 2.7$
tZ	$2.0 \pm 0.1 \pm 1.0$
WZ	$1.8 \pm 0.3 \pm 0.4$
Other backgrounds	$1.8 \pm 0.4 \pm 0.4$
Total background	$13.9 \pm 0.6 \pm 3.0$
Data	12
Signal efficiency [$\times 10^{-4}$]	$3.9 \pm 0.1 \pm 0.6$

$p_{\mathrm{T}} > 35$ GeV, no b-tagged jets with $p_{\mathrm{T}} > 35$ GeV and a W boson transverse mass, built with the residual lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$, greater than 50 GeV. Table 4 shows the expected and observed yields in this control region. The best estimation comes from the SHERPA prediction, which is chosen as the reference sample.

The $t\bar{t}Z$ control region is defined by requiring at least three leptons, two of them with the same flavour, opposite charge and a reconstructed mass within 15 GeV of the Z boson mass. Furthermore the events are required to have at least two jets with $p_{\mathrm{T}} > 25$ GeV and at least two b-tagged jets if there are three leptons in the event, or at least one b-tagged jet if there are four or more leptons in the event. Since the signal contribution for events with three leptons and two b-tagged jets is small, the overlap between signal and background regions is not removed, increasing the $t\bar{t}Z$ sensitivity in this control region. Table 5 shows the yields in this control region, and the background yields agree very well with the data within the given uncertainty.

Backgrounds from events which contain at least one fake lepton are estimated from data using the matrix

Table 6: Event yields in the fake-lepton control region for all significant sources of background. The first uncertainty is the statistical one associated with the number of events in the samples, the second uncertainty is systematic and is described in Section 7. The entry labelled "other backgrounds" includes all the remaining backgrounds described in Section 3 and in Table 2. The signal efficiency is also shown.

Sample	Yields
Fake leptons	$7 \pm 1 \pm 4$
WZ	$2.7 \pm 0.4 \pm 0.7$
ZZ	$1.7 \pm 0.6 \pm 0.8$
Other backgrounds	$1.7 \pm 0.1 \pm 0.6$
Total background	$13 \pm 1 \pm 4$
Data	17
Signal efficiency [$\times 10^{-4}$]	$1.77 \pm 0.06 \pm 0.20$

method [75]. This is based on the measurement of the efficiencies of real and fake loose leptons to pass the nominal selection, ϵ_R and ϵ_F, and on the selection of two orthogonal sets of events in the signal region. For the first of these sets, the nominal requirements are used for the leptonic selection, while for the second one, only the leptons which satisfy the looser selection (as described in Section 4) but without meeting the nominal requirements are considered. For the single-lepton case, the number of events with one fake nominal lepton is $N_\mathrm{F}^\mathrm{nominal} = (\epsilon_\mathrm{F}/\epsilon_\mathrm{R} - \epsilon_\mathrm{F})((\epsilon_\mathrm{R} - 1)N_\mathrm{T} + \epsilon_\mathrm{R} N_\mathrm{L})$, where N_T (N_L) represents the number of selected events in the first (second) set defined above. The method is extrapolated to the three-lepton topology, with a 8×8 matrix that is inverted using a numerical method to obtain the number of events with at least one fake lepton. The efficiencies for real and fake leptons are estimated as a function of the lepton transverse momentum by a fit of the matrix method results to two dedicated enriched samples of real and fake leptons: a sample of $Z \to \ell^+\ell^-, \ell = e, \mu$ and a same-sign dilepton sample (excluding same-flavour events with a reconstructed mass compatible with a Z boson). In both samples, in order to improve the modelling of fake leptons originating from heavy-flavour decays, only events with at least one additional b-tagged jet are considered. The efficiency ϵ_R ranges from 0.74 to 0.88 (0.80 to 0.99) and ϵ_F from 0.010 to 0.13 (0.035 to 0.18) for electrons (muons). The relevant uncertainties are calculated from the discrepancy between predicted and observed number of events in the control region detailed below.

A control region to test the performance of the fake-lepton estimation method and derive its uncertainty is defined. It requires three leptons with $p_\mathrm{T} < 50$ GeV (the third one with $p_\mathrm{T} < 30$ GeV), two of them having the same flavour, opposite charge and a reconstructed mass within 15 GeV of the Z boson mass, at least one b-tagged jet with $p_\mathrm{T} > 35$ GeV and $E_\mathrm{T}^\mathrm{miss} < 40$ GeV. As for the $t\bar{t}Z$ control region, there is a small overlap with the signal region, which is not removed in order to increase the sensitivity to the fake-lepton backgrounds. The yields are shown in Table 6 and agree well between data and expectation. As a validation of the matrix method, the background in which exactly one of the leptons is a fake lepton is also evaluated using simulated samples. The results for the signal region and different control regions are consistent between the two methods within the estimated uncertainties.

Figure 2 shows the p_T of the leading lepton for the ZZ, WZ and $t\bar{t}Z$ control regions, and the reconstructed mass of the two leptons with the same flavour and opposite charge for the fake-lepton control region.

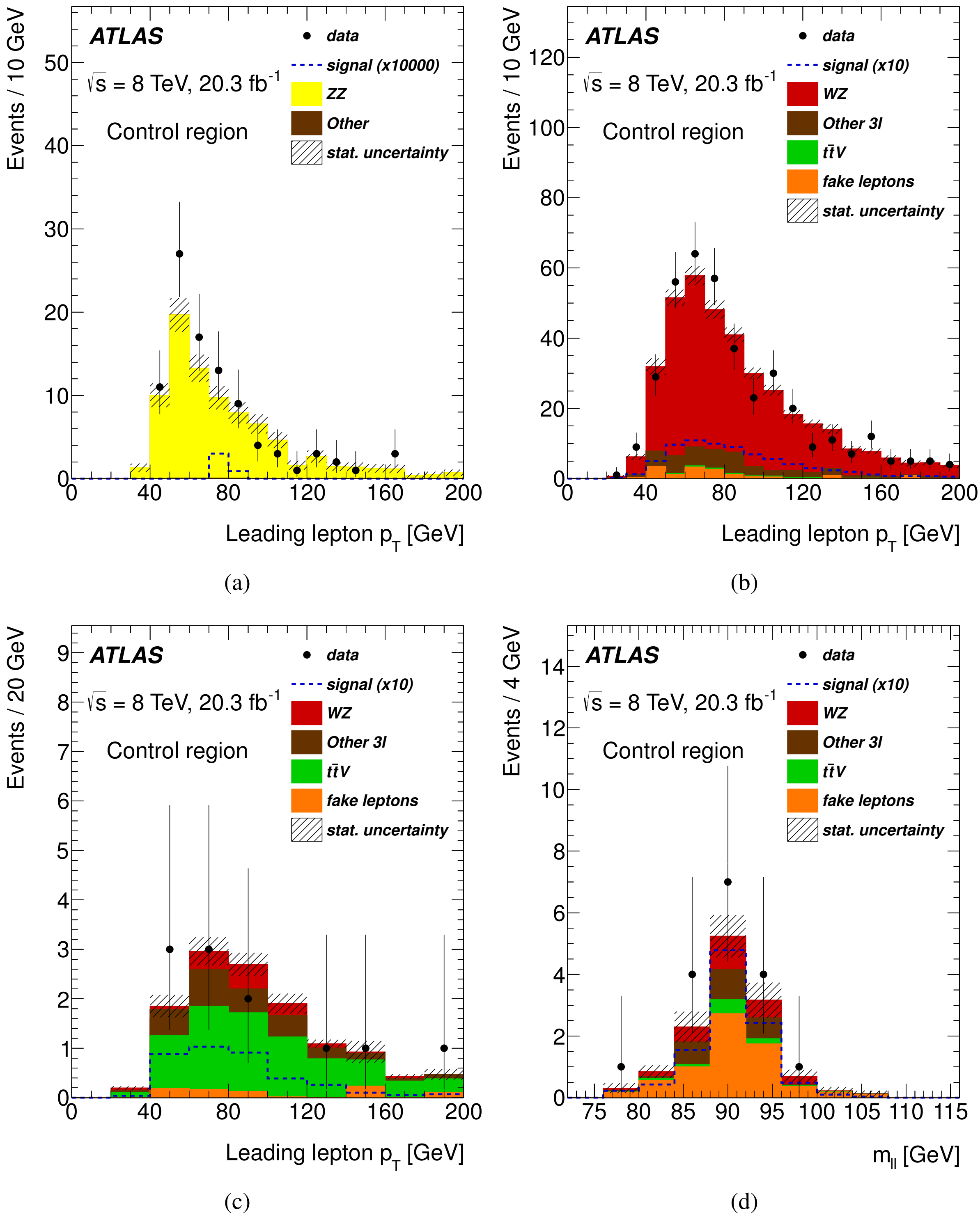


Figure 2: Expected (filled histogram) and observed (points with error bars) distributions for the p_{T} of the leading lepton in the (a) ZZ, (b) WZ and (c) $t\bar{t}Z$ control regions and (d) reconstructed mass of the two leptons with the same flavour and opposite charge in the fake-lepton control region. For comparison, distributions for the FCNC $t\bar{t} \rightarrow bWqZ$ signal (dashed line), scaled to 10^4 or 10 times the observed 95% CL limit, are also shown. Background statistical uncertainties associated with the number of events in the samples are represented by the hatched areas.

7 Systematic uncertainties

The effect of each source of systematic uncertainty is studied by independently varying the corresponding central value and propagating this through the full analysis chain. The relative impact of each type of systematic uncertainty on the total background and signal is summarised in Table 7.

The main uncertainty on the backgrounds comes from their modelling, which has the following two contributions. The level of agreement with data of the reference samples is assessed from the combination of the Poisson uncertainty on the available amount of data with the statistical uncertainty of the expected background yields in the dedicated control regions described in Section 6. The uncertainties are estimated to be 6.3%, 12%, 42% and 62%, for the WZ, ZZ, $t\bar{t}Z$ and fake-lepton backgrounds, respectively. The other contribution comes from the uncertainty on the theoretical prediction in the signal region and is estimated using the alternative WZ and ZZ simulated samples. The corresponding uncertainties are 17% and 100%, respectively. Similarly, for $t\bar{t}Z$, tZ and Higgs samples, conservative values of 30% [76, 77], 50% [74] and 15% [78] respectively, are used, in order to account for the theoretical uncertainties. The combination of all these uncertainties gives a 17% effect on the total background estimation.

The theoretical uncertainties of the signal modelling, as described in Section 3, namely production cross section and ISR/FSR modelling, are found to be 5.5%.

For both the estimated signal and background event yields, experimental uncertainties resulting from detector effects are considered. The lepton reconstruction, identification and trigger efficiencies, as well as lepton momentum scales and resolutions [63, 79, 80] are considered. The overall effect on the total background yield and the signal efficiency is estimated to be 4.7% and 2.9% respectively. The effect of the jet energy scale and resolution [66, 81] uncertainties are evaluated as 7.7% and 4.9% for the background and signal, respectively. The b-tagging performance component, which includes the uncertainty of the b-, c-, mistagged- and τ-jet scale factors (the τ and charm uncertainties are highly correlated and evaluated as such) is evaluated by varying the η-, p_{T}- and flavour-dependent scale factors applied to each jet in the simulated samples. It is estimated to be 3.9% for the total background and 7.2% for the signal efficiency. The $E_{\mathrm{T}}^{\mathrm{miss}}$ scale uncertainty [70] is found to vary the total background yield and the signal efficiency by 3.2% and 1.5%, respectively. All these detector systematic uncertainties are treated as fully correlated between signal and background.

The uncertainty related to the integrated luminosity for the dataset used in this analysis is 2.8%. It is derived following the methodology described in Ref. [82]. It only affects the estimations obtained from simulated samples, therefore its impact on the total background yield estimation is 2.4%.

8 Results

Table 8 shows the expected number of background events, number of selected data events and signal efficiency after the final event selection described in Section 5. Figure 3 shows the reconstructed masses of the top quarks and Z boson after the final selection. Good agreement between data and background yields is observed at all stages of the analysis. No evidence for the $t \to qZ$ decay is found and a 95% CL upper limit on the number of signal events is derived using the modified frequentist likelihood method [83, 84].

Table 7: Summary of the impact of each type of uncertainty on the total background and signal yields. The values are shown as the relative variations from the nominal values. The statistical uncertainty associated with the number of events in the simulated samples is also shown.

Source	Background [%]	Signal [%]
Background modelling	17	—
Signal modelling	—	5.5
Leptons	4.7	2.9
Jets	7.7	4.9
b-tagging	3.9	7.2
$E_{\mathrm{T}}^{\mathrm{miss}}$	3.2	1.5
Luminosity	2.4	2.8
Statistical	8.1	1.5

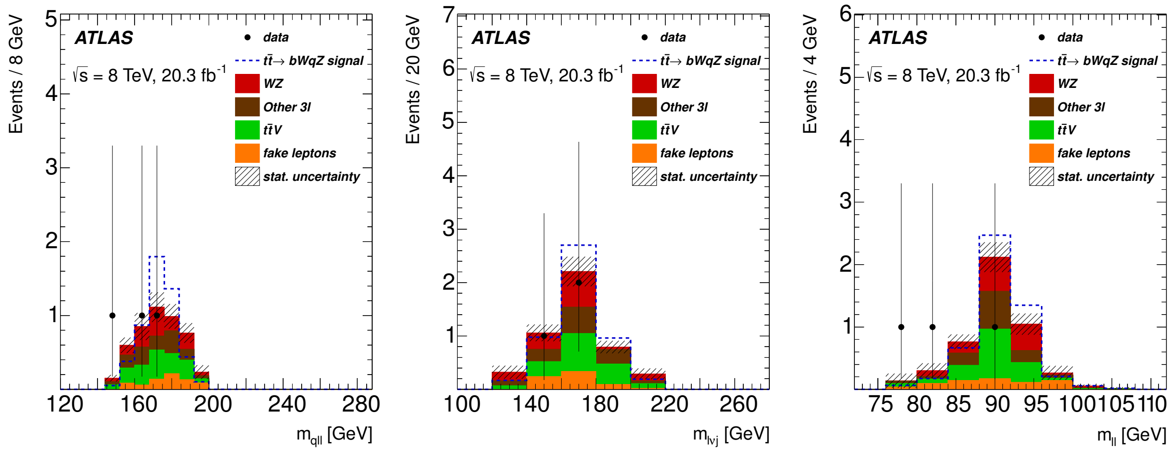
Table 8: Expected number of background events, number of selected data events and signal efficiency (normalised to all decays of the W and Z bosons), after the final selection. The first uncertainty is the statistical one associated with the number of events in the samples, the second uncertainty is systematic and is described in Section 7. The entry labelled "other backgrounds" includes all the remaining backgrounds described in Section 3 and in Table 2.

Sample	Yields
WZ	$1.3 \pm 0.2 \pm 0.6$
$t\bar{t}V$	$1.5 \pm 0.1 \pm 0.5$
tZ	$1.0 \pm 0.1 \pm 0.5$
Fake leptons	$0.7 \pm 0.3 \pm 0.4$
Other backgrounds	$0.2 \pm 0.1 \pm 0.1$
Total background	$4.7 \pm 0.4 \pm 1.0$
Data	3
Signal efficiency [$\times 10^{-4}$]	$7.8 \pm 0.1 \pm 0.8$

The test-statistic X_d, which compares the number of observed data events with background and signal expectations, is defined as:

$$X_d = n \ln\left(1 + \frac{s}{b}\right) \tag{3}$$

where n, s and b are the numbers of data, expected background and signal events, respectively. The X_d statistical test is then compared to 10^5 pseudo-experiments for the hypotheses of signal plus background (X_{s+b}) and background-only (X_b), which are obtained by replacing n with the corresponding number of events produced by each pseudo-experiment. The statistical fluctuations of the pseudo-experiments are implemented assuming that the number of events follows a Poisson distribution. All statistical and systematic uncertainties on the expected backgrounds and signal efficiencies, as described in Section 7, are taken into account and implemented assuming Gaussian distributions.



(a) (b) (c)

Figure 3: Expected (filled histogram) and observed (points with error bars) distributions in the signal region after the final selection is applied for the reconstructed masses of the (a) top quark from the FCNC decay, (b) top quark from the SM decay and (c) Z boson. For comparison, distributions for the FCNC $t\bar{t} \rightarrow bWqZ$ signal (dashed line), normalised to the observed 95% CL limit, are also shown. Background statistical uncertainties are represented by the hatched areas.

The CL for a given signal hypothesis s is defined as [83]:

$$1 - \mathrm{CL} = \frac{\int_0^{X_d} P_{s+b}(X)\mathrm{d}X}{\int_0^{X_d} P_b(X)\mathrm{d}X}, \tag{4}$$

where P_{s+b} and P_b are the probability density functions obtained from the pseudo-experiments for the X_{s+b} and X_b values, respectively, and are functions of s and b. The limit on the number of signal events is determined by finding the value of s corresponding to a CL of 95%. The expected limit is computed by replacing X_d with the median of the statistical test for the background hypothesis (X_b).

The limits on the number of signal events are converted into upper limits on the $t \rightarrow qZ$ branching fraction using the NNLO+NNLL calculation, and uncertainty, for the $t\bar{t}$ cross section, and constraining BR($t \rightarrow bW$) = 1 − BR($t \rightarrow qZ$). Table 9 shows the observed limit on BR($t \rightarrow qZ$) together with the expected limit and corresponding $\pm 1\sigma$ bounds. These values are calculated using the reference $t\bar{t} \rightarrow bWcZ$ sample, since it gives a more conservative result than the $t\bar{t} \rightarrow bWuZ$ sample. The smaller b-tagged jet multiplicity of the $t\bar{t} \rightarrow bWuZ$ signal sample leads to an improvement of 4% in the limit.

Figure 4 compares the 95% CL observed limit found in this analysis with the results from other FCNC searches performed by the H1, ZEUS, LEP (combined results of the ALEPH, DELPHI, L3 and OPAL collaborations), CDF, DØ and CMS collaborations. The results presented in this paper are consistent with the ones from the CMS Collaboration.

Table 9: Observed and expected 95% CL limits on the FCNC top-quark decay BRs. The expected central value is shown together with the $\pm 1\sigma$ bands, which includes the contribution from the statistical and systematic uncertainties.

Observed	7×10^{-4}
(-1σ)	6×10^{-4}
Expected	8×10^{-4}
$(+1\sigma)$	12×10^{-4}

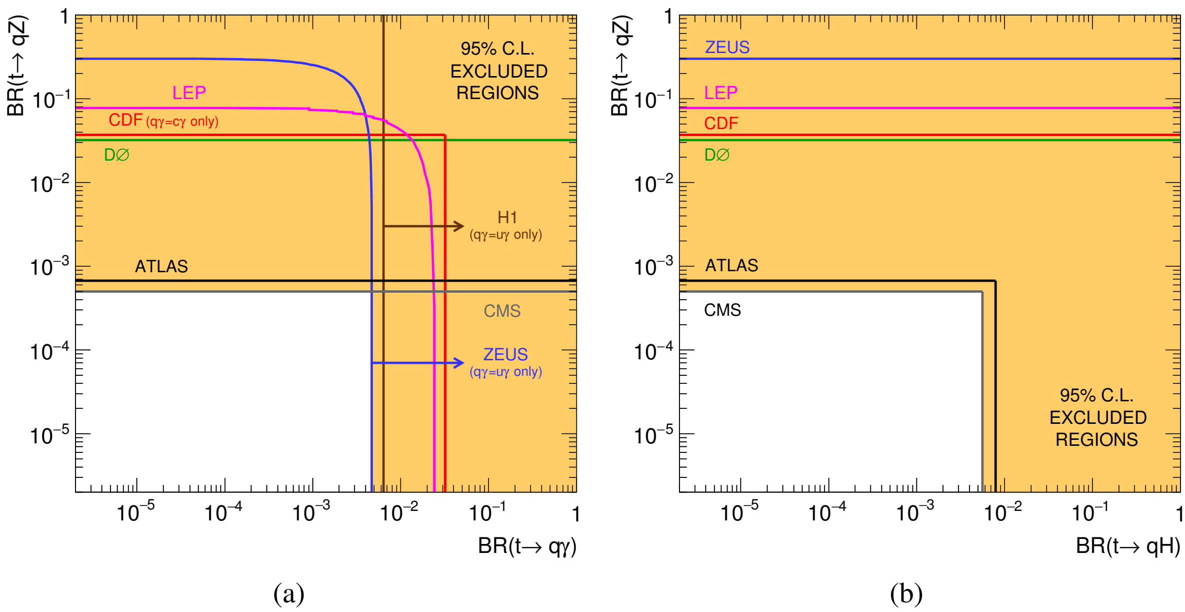


Figure 4: The current 95% CL observed limits on the (a) BR($t \to q\gamma$) vs BR($t \to qZ$) and (b) BR($t \to qH$) vs BR($t \to qZ$) planes are shown. The full lines represent the results from the ATLAS [25], CDF [16, 21] CMS [19, 27], DØ [17], H1 [20], LEP (combined results of the ALEPH, DELPHI, L3 and OPAL collaborations) [10–14] and ZEUS [15] collaborations. The ATLAS lines correspond to the limit on BR($t \to qZ$) set in this paper.

9 Conclusions

A search for the FCNC top-quark decay $t \to qZ$ in events with three leptons has been performed using LHC data collected by the ATLAS experiment at a centre-of-mass energy of $\sqrt{s} = 8$ TeV and corresponding to an integrated luminosity of 20.3 fb^{-1} recorded in 2012. No evidence for signal events is found and a 95% CL limit for the $t \to qZ$ branching fraction is established at $\mathrm{BR}(t \to qZ) < 7 \times 10^{-4}$, in agreement with the expected limit of $\mathrm{BR}(t \to qZ) < 8 \times 10^{-4}$.

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