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Search for top quark FCNC decays to qZ in pp collision data collected by the ATLAS Detector at $\sqrt{s} = 8$ TeV

DESY - ATLAS Group

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Contents

1 Introduction

This report presents a search for the flavour-changing neutral (FCNC) current decay $t \rightarrow qZ$. The analyzed data was collected with the ATLAS detector during proton proton collisions at the LHC in 2012 with a centre-of-mass energy of $\sqrt{s} = 8\,\text{TeV}$ and an integrated luminosity of $20.3\,\text{fb}^{-1}$ [9]. The Standard Model of particle physics predicts a low branching ratio of approximately 10^{-14} [5] for the examined FCNC decay. This is why it cannot be observed at the LHC. Thus any indication of this decay in proton proton collisions would be a sign of physics beyond the Standard Model. Setting new limits on the branching ratio can also constrain several Standard Model extensions which predict higher branching fractions. Hints for certain models can be gained in case that FCNC decays are found. This work is based on an existing search for this decay channel, which uses the same data as described above. One goal of this study is to reproduce the recently presented results and improve the analysis by using a different method. In particular a different selection is employed. In this case a multivariate analysis method, here Boosted Decision Trees, is used to discriminate background from signal. This technique is tested on 8 TeV data and could be applied in searches for top quark FCNC decays with data at 13 TeV.

2 The LHC and the ATLAS detector

The Large Hadron Collider (LHC) is the world's biggest proton proton collider. It is a synchrotron accelerator with a circumference of 27 km located at CERN near Geneva in Switzerland. The energy of the proton collisions in the center of mass was 8 TeV in 2012 and is 13 TeV 2015. In the first run proton bunches were brought to collision every 50 ns at an instantaneous luminosity of around $6 \cdot 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ [9]. The four main experiments at the LHC are ATLAS, LHCb, ALICE and CMS measuring and testing the Standard Model and looking for sign of new physics.
The ATLAS detector at the LHC is a multi purpose particle detector, which is built up from layers of subdetectors in a cylindrical architecture. It is designed to find hints or physics beyond the Standard Model and to verify the current theoretical model. In the center of the detector, which covers nearly the whole solid angle, a 2 T magnet systems bends particle trajectories and allows the measurement of their momentum. The inner detector consists of two silicon detectors and a transition radiation tracker measuring charged particle trajectories. The calorimeter system consists of an electromagnetic and a hadronic calorimeter to measure the energy of the particles. The outer layer of the ATLAS detector is the muon system, which can detect muons which go through the calorimeters [9] [1].

[1]The ATLAS right-handed coordinate system has origin in the interaction point, the x-axis points to the centre of the LHC, the y-axis points up and the z-axis has the beam direction. As usual, ϕ is the azimuthal angle, measured in relation to the x axis and the polar angle θ is the angle from the positive z axis. The pseudorapidity η relates with θ by $\eta = -\ln\left(\tan\frac{\eta}{2}\right)$. The xy plane is called the transverse plane and the quantities such as the transverse momentum (p_T) or the transverse energy (E_T) are measured with respect to this plane. The ΔR distance is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ [1].

3 The Top quark

The top quark is the heaviest known elementary particle with a mass of (173.21 ± 0.51) GeV [12]. It was discovered in 1995 at the Tevatron. Due to its short lifetime of $5 \cdot 10^{-25}$ s it decays before hadronization and passes the spin information to its decay products. Therefore the top quark is a unique particle to test certain aspects of the Standard Model and search for physics beyond the Standard Model. Figure 1 shows the main processes of the top quark production. Figures a) to c) show the dominant process at the LHC which is through gluon-gluon fusion. Figure d) shows the dominant process at the Tevatron which is through quark-antiquark annihilation. Today the LHC can be considered as a top quark factory, because of its high luminosity and cross section for $t\bar{t}$ pair production. It is thus possible to study top quark production and decays with experiments like ATLAS with high statistics and precision.

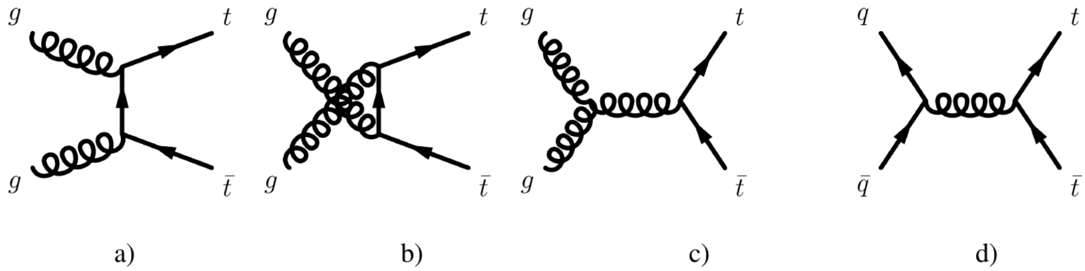


Figure 1: a)-c): Dominant top quark pair production processes through gluon-gluon fusion at the LHC. d): Dominant top quark pair through quark-antiquark annihilation at the Tevatron.

The dominant Standard Model decay of the top quark $t \to b\,W$ is shown in figure 2 a). The figure also shows several FCNC decays of the top quark. Figure b) shows $t \to q\gamma$, c) the suppressed FCNC decay $t \to qZ$ which is studied in this analysis. Figure d) shows $t \to qg$ and e) $t \to qH$ with $q = u, c$ as light quarks. The FCNC decay $t \to qZ$ is highly suppressed by the GIM-mechanism [10] and Standard Model predictions on the branching fraction are shown in table 3.1. The experimental limits on this branching fraction are shown in table 3.2.

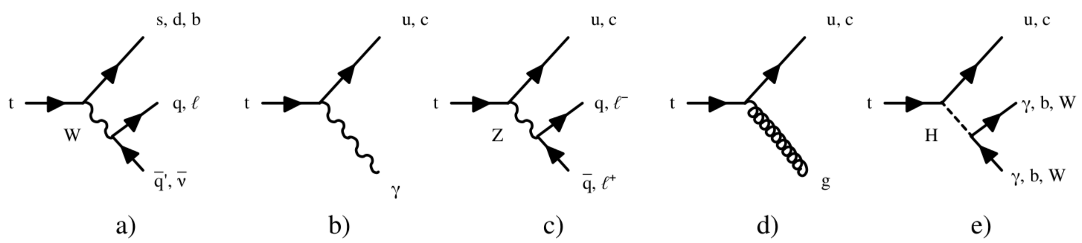


Figure 2: Top quark decays: a) Standard Model decay, b)-d) suppressed FCNC decays.

The decay channels can directly be studied by looking at their final states. This search focuses on the $t \to qZ$ decay channel. The other top quark coming from $t\bar{t}$ collisions decays through the SM dominant mode. Thus the signal studied is $t\bar{t} \to b\,W\,q\,Z$. The decay process is shown in figure 3.

Table 3.1: Theoretical values for the $t \to qZ$ branching fractions predicted by the Standard Model and Standard Model extensions. QS is the quark-singlet model, FC 2HDM is the two-Higgs doublet model with flavour conservation and 2HDM without, MSSM is the minimal supersymmetric model. R is SUSY with R parity violation and RS models with warped extra dimensions [5].

Process	SM	QS	2HDM	FC 2HDM	MSSM	R SUSY	RS
$t \to qZ$	$\sim 10^{-14}$	$\sim 10^{-4}$	$\sim 10^{-6}$	$\sim 10^{-10}$	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-5}$

Table 3.2: Experimental 95 % CL upper limits on the branching fraction of $t \to qZ$.

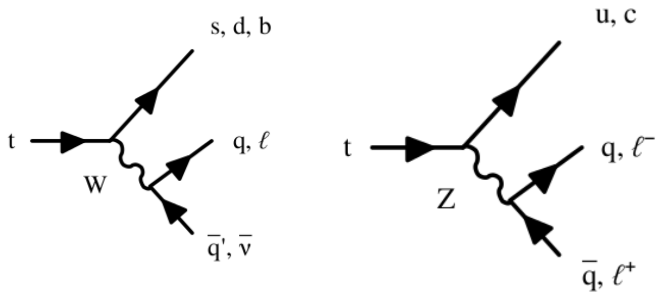
	LEP	HERA	Tevatron	LHC
BR($t \to qZ$)	7.8 % [3]	30 % [4]	3.2 % [2]	0.05 % [8]

4 Strategy

The presented search uses the three lepton decay channel because of its purity and unique signature. The existing analysis [1] applies a preselection which uses different cuts based on kinematic properties and topology of the searched decay. The goal of this study is to reproduce the yields of this preselection. After that a final selection via a quality based χ^2 cut is performed to discriminate between signal and background. This final selection uses different jet combinations and estimates a value for the missing transverse momentum of the undetected neutrino. To improve this analysis a Boosted Decision Trees is employed. For this method the preselection cut is loosened for some of the variables as described in section 6. After that the signal background classification is performed with Boosted Decision Trees and a limit on the branching fraction is calculated.

5 Data and simulation

The search is performed on data using the full proton proton dataset from the ATLAS detector taken between the 4th of April and 6th of December 2012 at $\sqrt{s} = 8\,\text{TeV}$. It corresponds to an integrated luminosity of $20.3\,\text{fb}^{-1}$. The events fulfill the requirements of the AllGood run list which means that all of the detector components were functioning properly. Monte Carlo simulations are used to optimize the analysis and the search for the signal decay and to estimate the fraction of background contributions in data. The simulated samples are generated with PROTOS. Only events are generated where the W and Z bosons decay leptonically. The events are hadronized using PYTHIA. The ATLAS detector and trigger simulation is done using the software GEANT4. Standard Model processes with a similar final state topology are considered as background. These are events with three real leptons, events with misidentified leptons (fakes) or events with four real leptons where one is not identified. The fake lepton events are estimated using data. This background is mostly composed of Z+jets events where two leptons come from the Z boson and one is a misidentified lepton coming from a jet. Diboson events are generated using the Monte Carlo generator SHERPA. The main contribution is from WZ process whose final state is similar to the signal decay leptonically. The jets are coming from initial state gluon radiation. ttV and triboson samples are produced using MADGRAPH adding parton showers with PYTHIA. In the case of the ttV background, the boson is most often a Z boson which decays to two leptons. The two top quarks are



(a) Standard Model decay $t \to b\,W$ **(b)** FCNC decay $t \to qZ$

Figure 3: Depicted top quark decays which are important for this search.

decaying via the Standard Model decay channel with $t \to b\,W$. Higgs background is produced with PYTHIA and POWHEG. For a detailed description of the use of the Monte Carlo generators see [1].
The most important physics objects in this search are electrons and muons, missing transverse energy from undetected neutrinos, jets and b-tagged jets. Electrons are reconstructed using the energy deposition in the electromagnetic calorimeter associated with tracking information from the inner detector. Muon reconstruction is performed with information from the muon chambers and information from the inner tracker. Jets are reconstructed using the anti-k_t algorithm [7] on energy clusters in the calorimeter. Jets coming from b quarks are identified through their longer trajectories because of longer lifetimes. The missing transverse momentum is calculated from the overall energy deposition in all calorimeter cells with $|\eta| < 4.5$ and from momenta measured with muon tracks with $|\eta| < 2.7$.

6 Preselection

The final state topology of the signal consists of three isolated leptons, one jet from a light quark, one b-tagged jet and missing momentum through the undetected neutrino. After passing the reconstruction requirements events are required to have exactly three isolated leptons coming from the same vertex. The pseudo rapidity (η) should be $|\eta| < 2.5$ and the leading lepton is required to have a transverse momentum of $p_T > 25$ GeV and the other two $p_T > 15$ GeV. Two leptons are required to have the same flavour and opposite charges as they come from the Z boson decay. Their reconstructed mass has to match the Z mass within 15 GeV. The lepton combination which matches the Z mass best is chosen. At least one of the jets must have $p_T > 35$ GeV and both jets need a $|\eta| < 2.5$. The missing transverse energy has to be $E_T^{miss} > 20$ GeV. This selection reproduces the results of the existing analysis and is called *tight* selection from now on. For the selection process using Boosted Decision Trees the missing transverse energy cut is relaxed and the leading lepton is required to have a $p_T > 15$ GeV, because these variables are provided as variables for the multivariate analysis. In figure 4 the distributions of the p_T of all jets, the good jet multiplicity, the p_T of the leading lepton and the missing transverse energy E_T^{miss} after the preselection are shown. This selection is called *loose* selection from now on. After the tight selection simulation and data show a good agreement. For comparison the signal is shown with a branching ratio of 0.05 % which corresponds to the current LHC limit on the branching ratio. Table 6.1 lists the expected number of signal and background simulation events and selected data events after preselection for the tight selection cut. The event yields after the loose selection are shown in table 6.2.

Table 6.1: Expected number of signal and background events from simulation and number of selected data events for the tight preselection cut used with χ^2 final selection.

sample	number of events
WZ	12.69 ± 1.10
$t\bar{t}V$	15.76 ± 0.36
fakes	11.67 ± 1.30
Others	10.31 ± 0.66
signal	7.856 ± 0.081
data	57

Table 6.2: Expected number of signal and background events from simulation and number of selected data events for the loose preselection cut used for the boosted decision tree final selection.

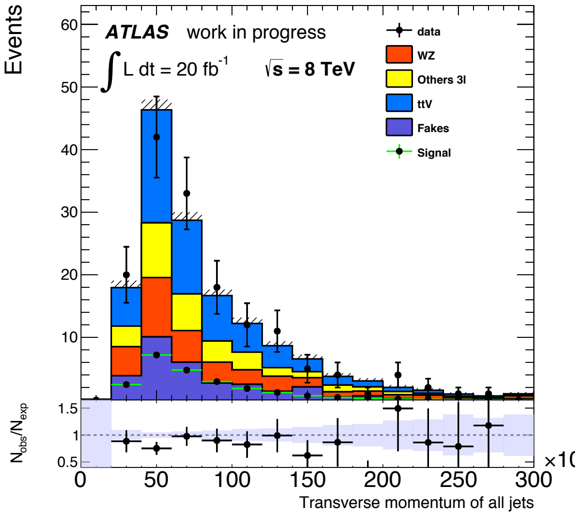
sample	number of events
WZ	13.93 ± 1.15
$t\bar{t}V$	16.90 ± 0.38
fakes	14.060 ± 1.431
Others	12.41 ± 0.86
signal	8.780 ± 0.086
data	69

7 Final selection

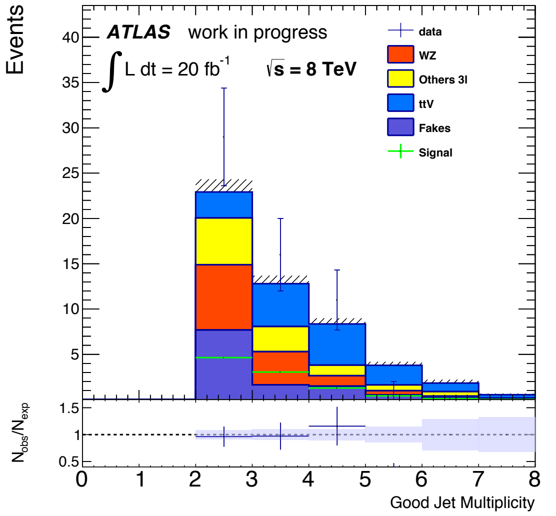
The final selection is done by using a χ^2 based cut on the one hand to reproduce the results of the former analysis. On the other hand a multivariate analysis is applied to optimize these results.

7.1 χ^2 based selection

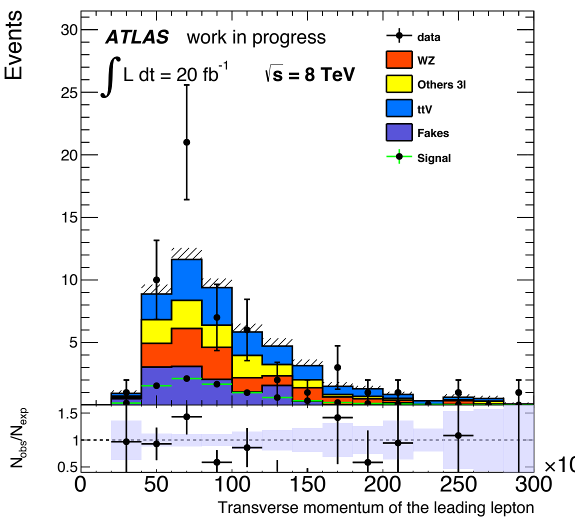
The top quark decaying through FNCN (t_{FCNC}) is reconstructed from the two leptons l_{a} and l_{b} which match the mass of the Z best and a light jet j_{a}. The top quark decaying in the Standard Model decay channel is reconstructed from the third lepton l_{c}, a b-tagged jet j_{b} and an undetected neutrino ν which has to be reconstructed. The W boson from the Standard Model decay is reconstructed from l_{c} and the neutrino. The longitudinal component of the neutrino momentum cannot be calculated from the missing transverse energy and has to be estimated through a χ^2 minimization shown in equation 1. Therefore the missing component p_{z}^{ν} is given as a variable to the χ^2 formula. The particle masses and their uncertainties obtained from a fit on simulation are compared to the reconstructed particles. All different combinations of jets are tested if there are more than two jets in the event. The minimization of χ^2 gives the missing component of the neutrino momentum and with the minimum χ^2



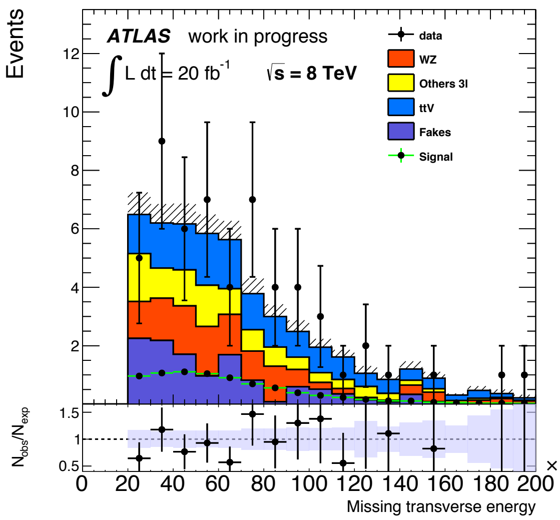
(a) p_{T} of all jets



(b) Jet multiplicity



(c) p_{T} of the leading lepton



(d) $E_{\mathrm{T}}^{\mathrm{miss}}$

Figure 4: Expected and observed distributions after the tighter preselection of the χ^2-based analysis. The signal is scaled to a branching ratio of 0.05 %. The signal is scaled to a branching ratio of 0.05 %.

and a choice for the combination of jets. The masses and uncertainties from the simulation are $m_{t_{\mathrm{FCNC}}} = 173\,\mathrm{GeV}$, $m_{t_{\mathrm{SM}}} = 168\,\mathrm{GeV}$, $m_{\mathrm{W}} = 82\,\mathrm{GeV}$, $\sigma_{t_{\mathrm{FCNC}}} = 10\,\mathrm{GeV}$, $\sigma_{t_{\mathrm{SM}}} = 23\,\mathrm{GeV}$, $\sigma_{\mathrm{W}} = 15\,\mathrm{GeV}$. A selection cut $\chi^2 < 6$ is applied, because signal events are more likely to have a small χ^2. The resulting yields are shown in table 7.1 and the χ^2 distribution in 5.

$$\chi^2 = \frac{(m^{\mathrm{reco}}_{\mathrm{j_a l_a l_b}} - m_{t_{\mathrm{FCNC}}})^2}{\sigma^2_{t_{\mathrm{FCNC}}}} + \frac{(m^{\mathrm{reco}}_{\mathrm{j_b l_c}\nu} - m_{t_{\mathrm{SM}}})^2}{\sigma^2_{t_{\mathrm{SM}}}} + \frac{(m^{\mathrm{reco}}_{\mathrm{l_c}\nu} - m_{\mathrm{W}})^2}{\sigma^2_{\mathrm{W}}} \tag{1}$$

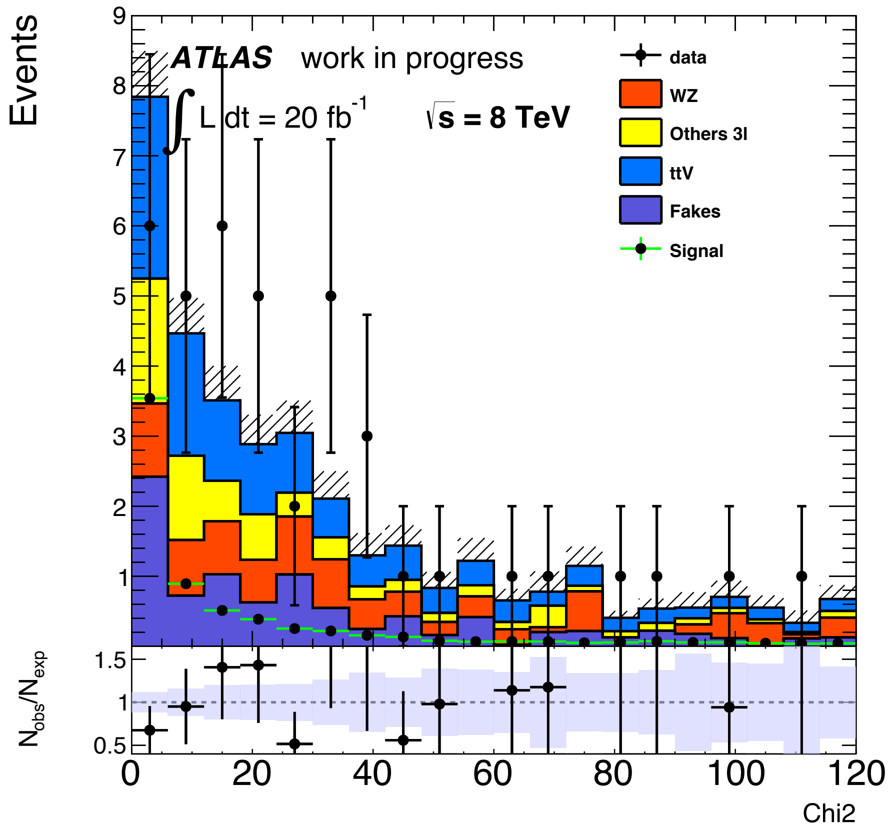


Figure 5: Distribution of χ^2. The signal is scaled to a branching ratio of 0.05 %.

7.2 BDT based selection

To apply the multivariate analysis with boosted decision trees the ROOT [6] package TMVA [11] is used. Decision trees are classifiers which are trained and tested with simulation and classify data after training. In this case the categories are background and signal. The multivariate analysis can take a multidimensional space of variables into account and thus no information is lost in comparison to the χ^2 based analysis. Observables which discriminate the main background contributions from the signal are used as BDT variables. They are derived from the topology of the different background processes. The fakes which mainly consist of a Z boson and additional jets, have no neutrino as decay product. The missing transverse

Table 7.1: Expected number of signal and background events from simulation and number of selected data events after the χ^2 cut based final selection. The signal is scaled to a branching ratio of 0.05 %.

sample	number of events
WZ	1.04 ± 0.28
$t\bar{t}V$	2.57 ± 0.15
fakes	2.42 ± 0.53
Others	1.78 ± 0.22
signal	3.540 ± 0.054
data	6

energy thus is an appropriate discriminant in this case. The detected light quark doesn't come from a top quark decay but from a radiated gluon. The angle between the Z boson and the light jet also shows separation power. In the case of the $t\bar{t}V$ background the two top quarks decay through the SM decay and an additional vector boson is produced. In most cases this is a Z boson. The reconstructed mass of the FCNC top and the number of jets and b jets are appropriate variables to distinguish this background from signal. The WZ background can also be separated by looking at the angle between the Z and the light quark, which comes from radiation. The variables which are used to discriminate between background and signal are $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{top,FCNC}}$, n_{jets}, $n_{\mathrm{b\text{-}jets}}$, $\Delta\phi(Z,q)$, χ^2, m_{W} and $\Delta\phi(l_3,b)$. $\Delta\phi(Z,q)$ and $\Delta\phi$ is the difference of the angle ϕ of the corresponding particles. The distributions of these variables for background and signal are shown in figure 6 and 7. The BDT output calculated for each event is shown in figure 3.

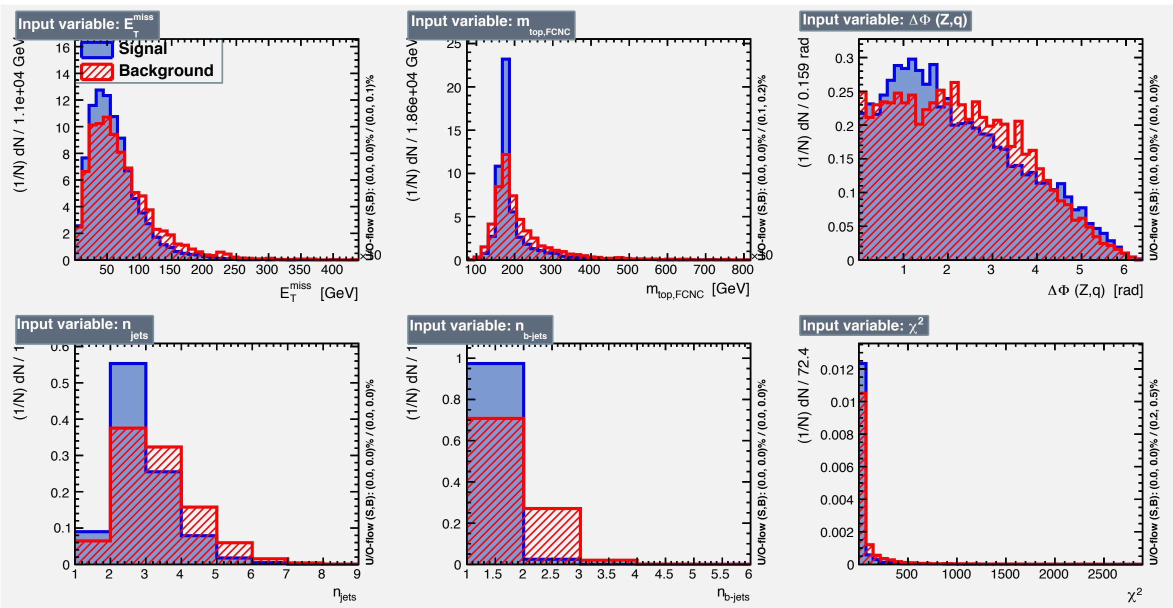


Figure 6: Boosted Decision trees discriminating variables.

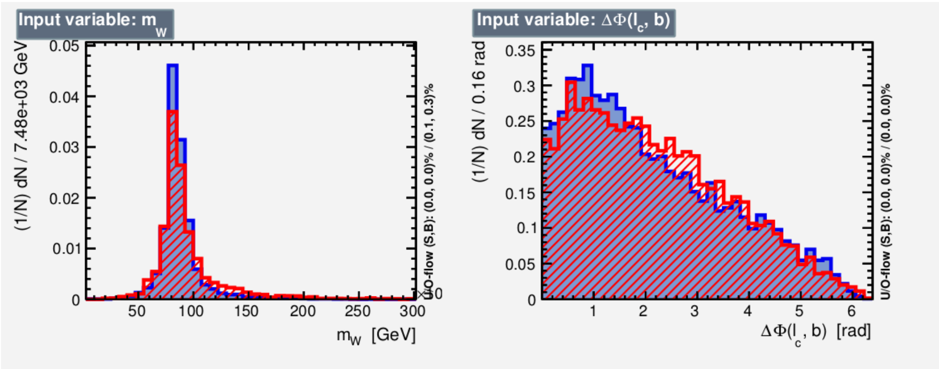


Figure 7: Boosted Decision trees discriminating variables.

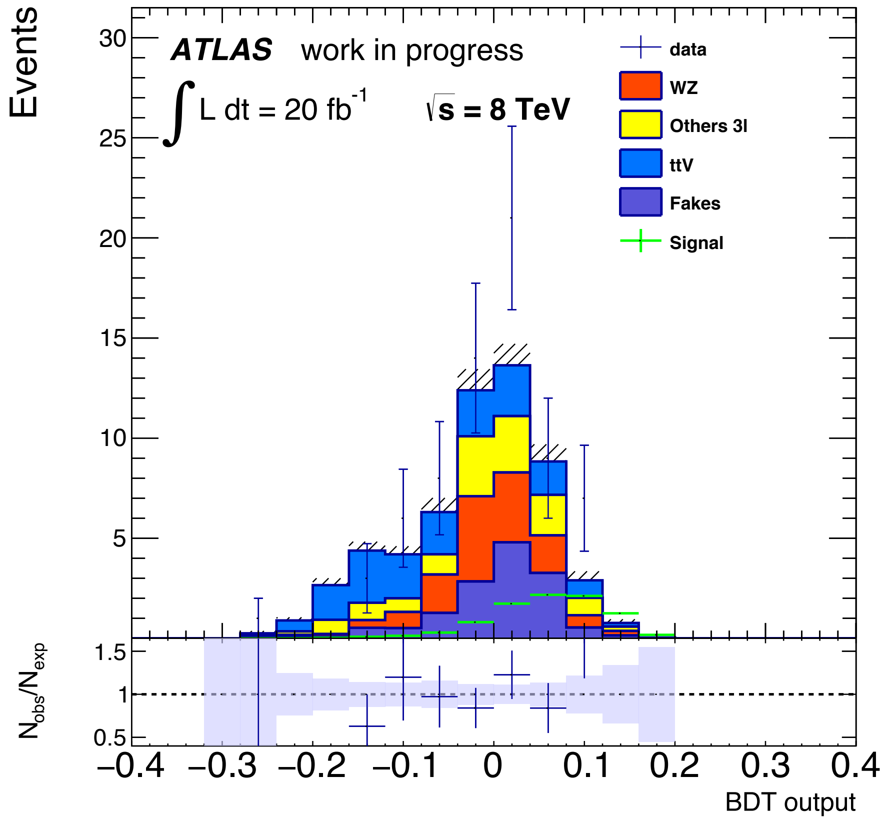


Figure 8: Distribution of the boosted decision tree output. The signal is scaled to a branching ratio of 0.05 %.

7.3 Limits

The final selection cut on the BDT output is optimized to obtain the best limit on the branching ratio at 95 % confidence level. For a certain BDT output cut the limit on the branching fraction at 95 % confidence level is calculated using the TLimit tool within ROOT [6]. Figure 9 shows the expected limits on the branching fraction at 95 % confidence level with respect to the BDT cut. The minimum of the expected limit is reached for a BDT cut of 0.032 with 0.076 %. Table 7.2 presents the resulting event yields after a cut on this value. The expected limit is only based on the simulation and uses only on the background hypothesis. The observed limit using data is 0.128 % at 95 % confidence level. In the case of the χ^2 based selection the expected limit is 0.104 % at 95 % confidence level and the observed limit is 0.095 % at 95 % confidence level. It follows that the BDT cut based expected limit on the branching fraction is better than the χ^2 cut based, but the observed limit is worse through data fluctuation, because the number of events in data is slightly above the simulation after the BDT cut.

Table 7.2: Expected number of signal and background events from simulation and number of selected data events from the boosted decision tree based final selection with a BDT cut at 0.036.

sample	number of events
WZ	3.36 ± 0.54
$t\bar{t}V$	3.27 ± 0.17
fakes	4.56 ± 0.79
Others	3.54 ± 0.43
signal	6.136 ± 0.072
data	21

8 Summary

The presented search for the FCNC top quark decay to qZ in the three lepton channel with LHC data from 2012 reproduces an existing analysis. The improvement of the analysis using a loosened preselection and a multivariate analysis is promising. The expected limit on the decay is 0.076 % and the observed limit is 0.128 % at 95 % confidence level. These are above than the current LHC limit which is 0.05 % at 95 % but could be improved by optimizing the application of the Boosted Decision Trees and using larger data sets for training. Further more the new technique can be applied on searches for top quark FCNC decays on data from the LHC with a centre of mass energy of 13 TeV.

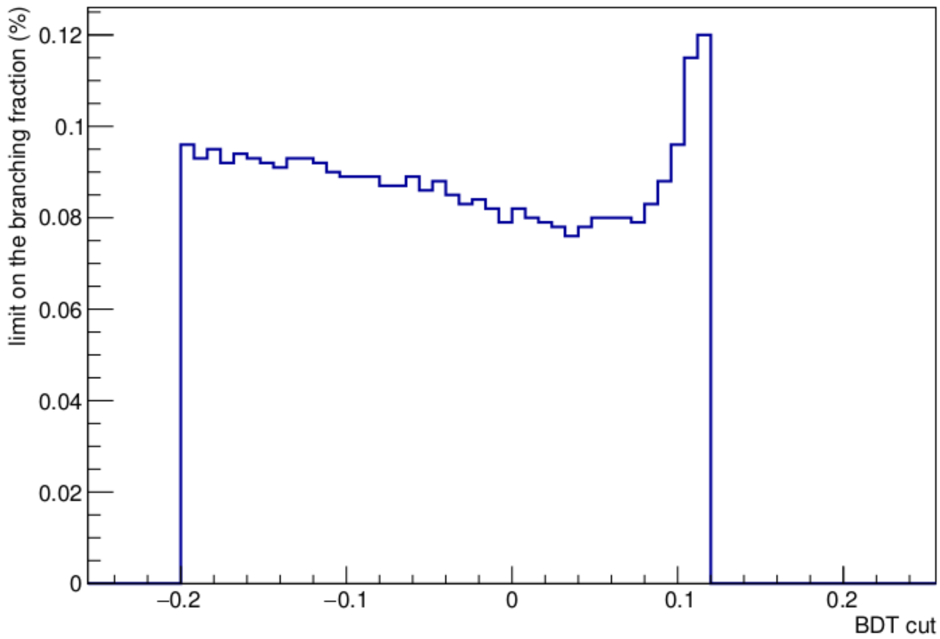


Figure 9: Limits on the branching fraction (at 95 % CL) with respect to the BDT cut

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