PROCEEDINGS OF SCIENCE

Search for FCNC in top-quark events in ATLAS

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Searches for flavor changing neutral current (FCNC) processes in top-quark production and decays by the ATLAS Collaboration are presented. Data collected from pp collisions at the LHC at a centre-of-mass energy of $\sqrt{s} = 7$ TeV during 2011, corresponding to an integrated luminosity of 2.05 fb^{-1}, are used. In a first analysis single top-quarks produced via FCNC are searched for. Candidate events with a semileptonic top-quark decay signature are classified as signal or background-like events by using several kinematic variables as input to a neural network. No signal is observed in the neural network output distribution and a Bayesian upper limit is placed on the production cross-section. The observed upper limit is converted using a model-independent approach into upper limits on the coupling strengths $\kappa_{ugt}/\Lambda < 6.9 \cdot 10^{-3}$ TeV^{-1} and $\kappa_{cgt}/\Lambda < 1.6 \cdot 10^{-2}$ TeV^{-1}, where Λ is the new physics scale, and on the branching fractions $\mathscr{B}(t \to ug) < 5.7 \cdot 10^{-5}$ and $\mathscr{B}(t \to cg) < 2.7 \cdot 10^{-4}$. A second search is performed for top-quark pair-production events, with one top quark decaying through the $t \to Zq$ FCNC ($q = u, c$) channel, and the other through the Standard Model dominant mode $t \to Wb$. Only the decays of the Z boson to charged leptons and leptonic W-boson decays are considered as signal. No evidence for an FCNC signal is found and thus an upper limit on the $t \to Zq$ branching ratio of BR$(t \to Zq) < 0.73\%$ is set at the 95% confidence level.

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1. Flavor-changing neutral currents and the top quark

In the Standard Model (SM), flavor-changing neutral current (FCNC) processes are forbidden at tree level and highly suppressed ($\mathscr{O}(10^{-14})$) at higher orders due to the GIM mechanism [1]. Extensions of the SM with new sources of flavor predict higher rates for FCNCs involving the top quark; these extensions include new exotic quarks, new scalars, supersymmetry, or technicolor (for a review see Ref. [2]). The top-quark FCNC decay BR in these models is enhanced dramatically and can be as high as $\sim 2\times 10^{-4}$ in certain R-parity violating SUSY models.

FCNC top-quark decays can be studied directly by searching for final states with the corresponding decay particles. The $t \to qg$ mode, with $q = u,c$, is almost impossible to separate from multijet-production and a better sensitivity can be achieved in the search for anomalous single top-quark production. Here, a quark and a gluon coming from the colliding protons interact to produce a single top-quark. The most general effective Lagrangian $\mathscr{L}_{\mathrm{eff}}$ for this process can be written as:

$$\mathscr{L}_{\mathrm{eff}} = g_s \sum_{q=u,c} \frac{\kappa_{qgt}}{\Lambda} \bar{t}\sigma^{\mu\nu} T^a (f_q^L P_L + f_q^R P_R) q G^a_{\mu\nu} + h.c., \tag{1.1}$$

where the κ_{qgt} are dimensionless parameters that relate the strength of the new coupling to the strong coupling constant g_s and Λ is the new physics scale, related to the mass cutoff scale above which the effective theory breaks down.

2. Search for FCNC in single top-quark production $qg \to t$

The analysis [3] is performed using $\sqrt{s} = 7$ TeV pp-collision data recorded by ATLAS [4] in 2011 and corresponding to a total integrated luminosity of 2.05 ± 0.08 fb^{-1}.

Electron candidates are required to satisfy $p_{\mathrm{T}} > 25$ GeV and $|\eta_{\mathrm{clus}}| < 2.47$, where η_{clus} is the pseudorapidity of the cluster of energy deposits in the calorimeter. A veto is placed on candidates in the calorimeter barrel-endcap transition region, $1.37 < |\eta_{\mathrm{clus}}| < 1.52$. High-$p_{\mathrm{T}}$ electrons associated with the W-boson decay can be mimicked by hadronic jets reconstructed as electrons, electrons from decays of heavy quarks, and photon conversions. These backgrounds are suppressed via isolation criteria in a cone around the electrons. Muon candidates are required to have a transverse momentum $p_{\mathrm{T}} > 25$ GeV and to be in the pseudorapidity region of $|\eta| < 2.5$. Isolation criteria are applied to reduce background events in which a high-p_{T} muon is produced in the decay of a heavy quark. Jets are reconstructed using the anti-k_t algorithm with the distance parameter R set to 0.4, and exactly one reconstructed jet with $p_{\mathrm{T}} > 25$ GeV is required. Due to the presence of a neutrino, a missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV is required. Multijet background events are further suppressed by combined requirements on $E_{\mathrm{T}}^{\mathrm{miss}}$ and the reconstructed W-boson transverse mass. Candidate events are required to have exactly one lepton and one jet. The selected jet has to be identified as stemming from a b-quark (b-tagged).

Multijet events may be selected if a jet is misidentified as an isolated lepton or if the event has a non-prompt lepton that appears isolated. A binned maximum-likelihood fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution is used to estimate the multijet background normalization. A template of the multijet background is modelled using electron-like jets selected from jet-triggered collision data. The uncertainty in the multijet background normalization is estimated to be 50%.

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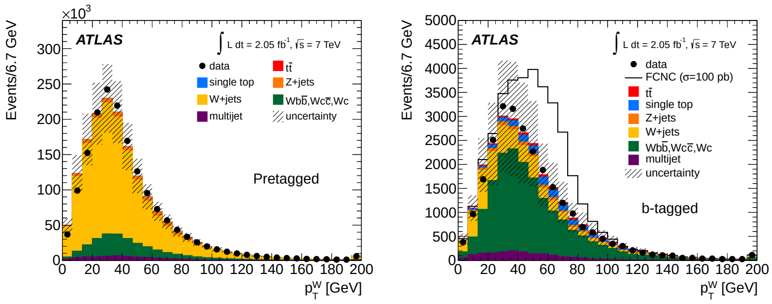

Figure 1: Data and expected distributions of the transverse momentum of the W boson, for the selection before (left) and after (right) b-tagging, for the electron and muon channel combined [3].

In the final sample, 26,223 events are observed in data compared to a SM expectation of $24{,}000 \pm 7{,}000$ events, dominated by Wc+jets events ($12{,}100 \pm 6{,}700$). Figure 1 shows good agreement between the data and expectation. Given the large uncertainty in the background and the small number of expected signal events, a neural-network classifier is used to separate signal events from background events.

The $qg \to t \to b\ell\nu$ process is characterized by three main differences from SM processes that pass the event selection cuts: (1) The top quark is produced almost without transverse momentum. (2) The W boson from the top-quark decay has a very high momentum. (3) The FCNC processes are predicted to produce four times more single top quarks than anti-top quarks, while this is at most two in SM processes.

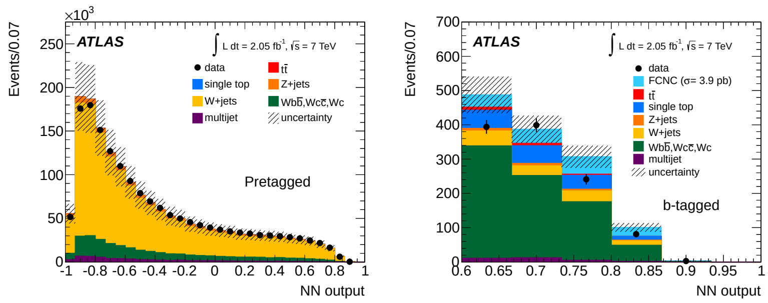

Figure 2: Neural network output distribution in the sample before requiring b-tagging (left) and in the final sample, zoomed into the signal region (right). The FCNC single top quark process is normalized to the observed limit of 3.9 pb [3].

Eleven variables are selected as input to the neural network. The three most significant variables are: the p_{T} of the W boson, the ΔR between the b-tagged jet and the lepton, and the charge of the lepton. The resulting neural network output distribution for the various processes, is shown in Figure 2. Signal-like events have output values close to 1. Good agreement between the neural network output distributions for data and simulated events is found.

Systematic uncertainties affect the signal acceptance, the normalization of the individual backgrounds, and the shape of the neural network output distributions. They lead to uncertainties in the rate estimation as well as distortions of the neural network output distribution and are implemented as such in the statistical analysis. Several sources of systematic uncertainties have been considered. The three dominant uncertainties are: (1) The uncertainty in the jet energy scale, varying between 2.5% and 8% (3.5% and 14%) in the central (forward) region, depending on jet p_{T} and η, including gluon-fraction uncertainties and mis-measurements due to close-by jets. An additional jet energy scale uncertainty of up to 2.5% is applied for b-quark jets. (2) The amount of initial and final state radiation, which is varied by modifying parameters in PYTHIA in a range comparable to those used in the Perugia Soft/Hard tune variations. (3) The b-tagging efficiencies and mis-tag rates, having uncertainties from 8–16% and 23–45%, respectively.

A Bayesian statistical analysis using a binned likelihood method applied to the neural network output distributions for the electron and muon channel is performed to measure or set an upper limit on the FCNC single top-quark production cross-section.

3. Search for FCNC in top-quark decays $t \to Zq$

In a second analysis [5] a search is performed for FCNC top-quark decays in $t\bar{t}$ events, where one of the top quarks decays to a Z boson and a quark, $t \to Zq$, while the other decays through the SM $t \to Wb$ channel. Only leptonic decays of the Z and W bosons are considered, yielding a final-state topology characterized by the presence of three isolated charged leptons, at least two jets, and significant $E_{\mathrm{T}}^{\mathrm{miss}}$.

The selection of leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ is close to that used for the ATLAS measurement of the $t\bar{t}$ production cross section in the dilepton channel [6]. Events are selected with either three well-identified leptons with $p_{\mathrm{T}} > 20$ GeV (3ID) or two well-identified leptons with $p_{\mathrm{T}} > 20$ GeV and an additional track-lepton with $p_{\mathrm{T}} > 25$ GeV, which fails lepton identification (2ID+TL). In the following only the 3ID analysis is presented, since the background estimation technique for the 2ID+TL channel is described in [6] and the remaining analysis follows the main analysis.

Events are required to have a same-flavor, opposite-sign (OS) lepton pair with an invariant mass within 15 GeV of m_Z. In addition, signal candidates are required to have at least two jets and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV. Figure 3 (left) shows the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for events prior to the final selection requirements. These are events with three identified leptons with at least one opposite-sign, same-flavor pair (OSSF) with the m_Z invariant mass cut applied, but no jets or $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement.

Selected events are required to be kinematically consistent with $t\bar{t} \to WbZq$ through a χ^2 minimized with respect to jet (the two highest-p_{T}) and lepton assignments and the longitudinal momentum of the neutrino, p_z^ν. The widths are determined from simulation. All jet and lepton assignments are tried, subject to the requirement that the Z candidate be built from OSSF leptons. From all combinations, the one with the smallest χ^2 is chosen along with the corresponding p_z^ν value. Events are required to have reconstructed m_t, m_W, m_Z within respectively 40 GeV, 30 GeV, and 15 GeV, of the nominal mass. The signal efficiency for $t\bar{t} \to WbZq$, after all selection requirements, is determined to be (0.205 ± 0.025)%.

Backgrounds can be divided into two categories: those with three real leptons and those with at least one fake lepton. Backgrounds with three real leptons arise from diboson (WZ and ZZ) production with additional jets, and are evaluated using simulation. The background in which exactly one of the leptons is a fake lepton, is evaluated using a combination of data and MC samples. The dominant contribution in this category comes from Z+jets events, with a leptonic Z decay, in which

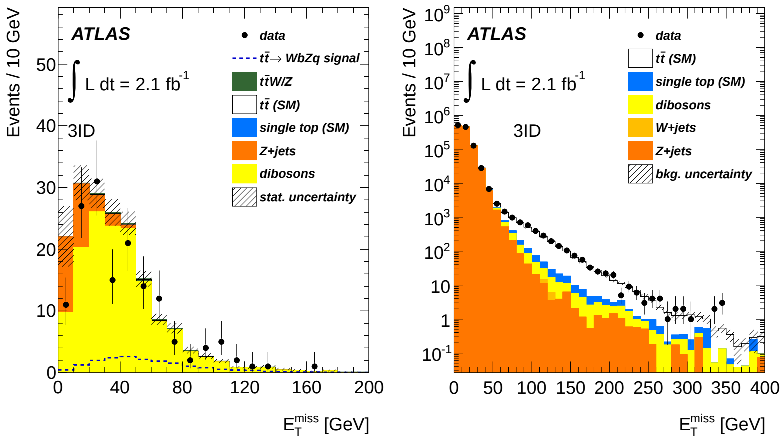

Figure 3: $E_{\mathrm{T}}^{\mathrm{miss}}$distribution for events with three identified leptons (at least one OSSF, consistent with a Z-boson), but no jets or $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement (left) and for events in a control region, defined by two same-flavor, OS leptons, consistent with a Z-boson (right). The $t\bar{t} \to WbZq$ distribution is normalized to the observed limit. [5]

one of the jets is misidentified as a third lepton. To evaluate this background a data-driven (DD) method is used with control regions (CR) in the ($E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\ell\ell}$) plane, by selecting events with exactly two OS leptons (no third lepton is allowed) and $|m_Z - m_{\ell\ell}| < 15$ GeV in six different $E_{\mathrm{T}}^{\mathrm{miss}}$ bins from 0 GeV to $\geq$50 GeV. For each $E_{\mathrm{T}}^{\mathrm{miss}}$ bin considered, the background-subtracted data/simulation ratio in the CR is applied to the simulated Z+jets background in the signal regions, in order to evaluate the expected number of Z+jets events in data. Due to the small MC event sample after the final selection, the Z+jets background is evaluated using a loosened lepton selection and a multiplicative rejection factor of 0.063 ± 0.013 to account for the loosened selection. The remaining backgrounds with one fake lepton (dileptonic $t\bar{t}$, Wt-channel single-top and WW production) are evaluated using simulated samples. The contribution from multi-jet, W+jets, single-top and $t\bar{t}$ single-lepton decay events, where two or three jets are reconstructed as leptons, is estimated with a DD technique, making use of events with same-charge leptons. No data event passed the selection after requiring three leptons with the same charge.

The total number of expected background events is 11.8 ± 4.4, dominated by diboson events (9.5 ± 4.4). Figure 3 (right) shows good agreement in the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of data and expected backgrounds in background-dominated control region. Figure 4 shows the reconstructed candidate Z-boson and top-quark masses for the FCNC decay hypothesis in the selected candidate events, compared with the expectations from SM backgrounds and the FCNC signal.

A number of systematic uncertainties can influence the expected number of signal and/or background events. The effect of each source of systematic uncertainty is studied by independently varying the corresponding central value by the estimated uncertainty. For each variation, the total number of expected background events and the signal efficiencies are compared with the reference values. The dominant source of systematic uncertainty is the ZZ and WZ simulation modeling, which is estimated using the Berends-Giele scaling with an uncertainty of 24% per jet, added in quadrature. An uncertainty of 4% is included for the 0-jet bin. The ZZ and WZ cross sections are

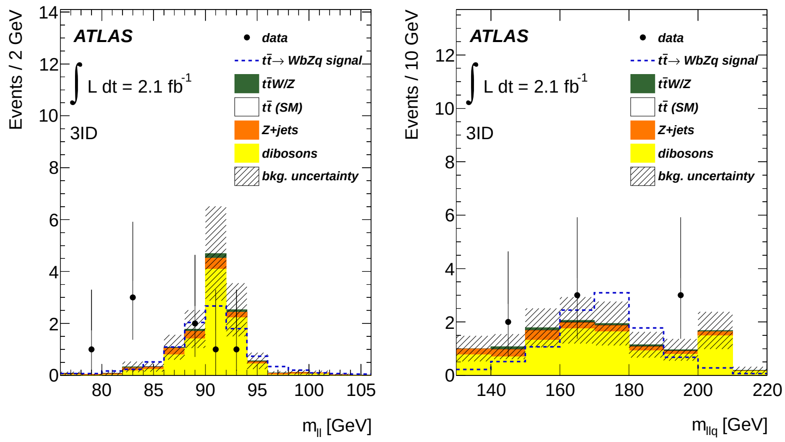

Figure 4: Z-boson (left) and top-quark mass distributions (right) for the FCNC decay hypothesis after all selection requirements. The $t\bar{t} \to WbZq$ distributions are normalized to the observed limit in each channel [5].

varied by their theoretical uncertainty of 5%. The dominant uncertainty in the 2ID+TL channel is the systematic uncertainty on the fake-TL prediction.

4. Results

A data sample selected to consist of events with an isolated electron or muon, missing transverse momentum and a b-quark jet has been used to search for FCNC production of single top-quarks at the LHC. No evidence for such processes is found and the upper limit at 95% C.L. on the production cross-section is 3.9 pb. The limit is converted into limits on the coupling constants $\kappa_{ugt}/\Lambda < 6.9\cdot 10^{-3}$ TeV^{-1} and $\kappa_{cgt}/\Lambda < 1.6\cdot 10^{-2}$ TeV^{-1}, where Λ is the new physics scale and on the branching fractions $\mathscr{B}(t \to ug) < 5.7\cdot 10^{-5}$ assuming $\mathscr{B}(t \to cg) = 0$, and $\mathscr{B}(t \to cg) < 2.7\cdot 10^{-4}$ assuming $\mathscr{B}(t \to ug) = 0$

The search for the $t \to Zq$ decay mode is performed by studying top-quark pair production with one top quark decaying according to the SM and the other according to the FCNC ($t\bar{t} \to WbZq$). No evidence for the $t \to Zq$ decay mode is found and a 95% C.L. upper limits on the number of signal events are derived using the modified frequentist (CL$_s$) likelihood method. This results in BR$(t \to Zq) < 0.73\%$, assuming BR$(t \to Wb)$+BR$(t \to Zq) = 1$.

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