PROCEEDINGS OF SCIENCE

Rare top quark production in ATLAS ($t\bar{t}t\bar{t}$, tqZ, $tq\gamma$)

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The exceptionally large dataset of top quarks collected by the ATLAS experiment at the LHC during the Run 2 paves the way for more precise tests of the Standard Model in the top-quark sector. The search for rare processes involving top quarks aims at the inspection of the Standard Model in tiny corners of the phase space, looking for processes with the lowest accessible cross-sections. This document contains a review of the latest results from these searches published by the ATLAS Collaboration aiming at the measurement of $t\bar{t}t\bar{t}$, tqZ and $tq\gamma$ productions.

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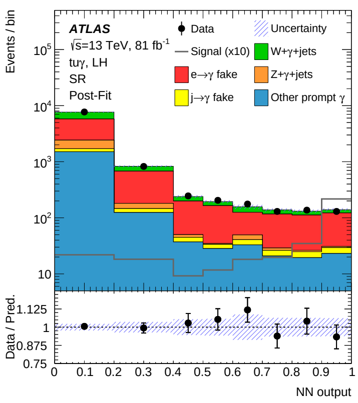
1. Introduction

The huge dataset of top quarks produced at the LHC [1] makes it a "top-quark factory". The outstanding performance of the ATLAS experiment [2], able to collect 139 fb^{-1} during the LHC Run 2, gives the chance for a deep investigation of the Standard Model (SM) in the top-quark sector to search for new physics contributions. Rare top-quark processes predicted by the SM may be significantly enhanced by new physics: in this document, the latest results from the ATLAS Collaboration are reported.

2. Flavour-changing neutral current $tq\gamma$ coupling

The ATLAS Collaboration has not yet released a result addressing the SM production of $tq\gamma$. However, a measurement of the flavour-changing neutral current (FCNC) $tq\gamma$ coupling has been performed with the partial dataset of 81 fb^{-1} [3]. The analysis tests four signal scenarios corresponding to the effective couplings of the top quark with u- and c-quarks and a left- or right-handed photon ($tu\gamma$ LH/RH, $tc\gamma$ LH/RH). The results are interpreted in terms of operators of a Next-to-Leading-Order (NLO) QCD Effective Field Theory (EFT) [5]. The events in the signal region have a single lepton and one b-jet from the top-quark decay, and one photon in the final state. The main source of irreducible background in this region is the production of a weak boson associated with one photon. This contribution is estimated with the template method: Monte Carlo simulations are used to predict the distributions, but the normalisations are included in the fit as free-floating parameters and measured in dedicated control regions. A source of reducible background is the mis-identification of an electron as a photon in the detector ($e\rightarrow\gamma$ fakes), estimated with a data-driven method. Four neural networks are trained to separate the four signal scenarios from the background and the output is used as discriminant variable in the signal region (Figure 1a). The measurement, performed with a profile likelihood fit in the signal and control regions simultaneously, shows no significant excess above the background expectation, and



(a)

Observable	Vertex	Coupling	Obs.	Exp.
$\left\|C_{\mathrm{uW}}^{(13)*} + C_{\mathrm{uB}}^{(13)*}\right\|$	$tu\gamma$	LH	0.19	$0.22^{+0.04}_{-0.03}$
$\left\|C_{\mathrm{uW}}^{(31)} + C_{\mathrm{uB}}^{(31)}\right\|$	$tu\gamma$	RH	0.27	$0.27^{+0.05}_{-0.04}$
$\left\|C_{\mathrm{uW}}^{(23)*} + C_{\mathrm{uB}}^{(23)*}\right\|$	$tc\gamma$	LH	0.52	$0.57^{+0.11}_{-0.09}$
$\left\|C_{\mathrm{uW}}^{(32)} + C_{\mathrm{uB}}^{(32)}\right\|$	$tc\gamma$	RH	0.48	$0.59^{+0.12}_{-0.09}$
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	LH	36	52^{+21}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tu\gamma$	RH	78	75^{+31}_{-21}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	LH	40	49^{+20}_{-14}
$\sigma(pp \to t\gamma)$ [fb]	$tc\gamma$	RH	33	52^{+22}_{-14}
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tu\gamma$	LH	2.8	$4.0^{+1.6}_{-1.1}$
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tu\gamma$	RH	6.1	$5.9^{+2.4}_{-1.6}$
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tc\gamma$	LH	22	27^{+11}_{-7}
$\mathcal{B}(t \to q\gamma)$ $[10^{-5}]$	$tc\gamma$	RH	18	28^{+12}_{-8}

(b)

Figure 1: (a) Comparison of the post-fit distribution of the output of the neural network in one of the signal regions with data. The distribution of the expected $tu\gamma$ (LH) signal is also shown. (b) Summary table of the limits set on the EFT operators, branching ratios and cross-sections. [3]

limits on the EFT operators, branching ratios and cross-sections are set (Figure 1b). These limits improve by up to one order of magnitude the previous results [4], being the most stringent ones to date.

3. Standard Model tZq production

The SM calculation of the tZq production cross-section has small NLO QCD corrections, resulting in an accurate prediction of $\sigma_{tZq}^{\text{NLO QCD}} = 105^{+5}_{-2}$ fb [6]. The ATLAS Collaboration has performed an analysis with the full Run 2 dataset (139 fb^{-1}) [6] to test this prediction in the same phase space[1]. The analysis selects events with three leptons, of which two must be with same-flavour and opposite-sign charges and with an invariant mass in a window of 10 GeV around the Z boson mass. In addition, events must have one or two jets within $|\eta| < 4.5$ (the produced light quark is predominantly forward), of which one jet must be central ($|\eta| < 2.5$) and tagged as a b-jet. In this region, most of the irreducible background comes from $t\bar{t}Z$ and diboson events, which are estimated via the template method. Other background sources are $t\bar{t}$, tW and Z+jets processes, passing the signal selection in case an extra lepton is reconstructed in the detector. The discriminant variable in the signal region is the output of a neural network (Figure 2a), trained to classify the tZq signal against the total background. The measurement, performed via a profile likelihood fit, gives a cross-section of 97 fb with an accuracy of 14%, dominated by the statistical uncertainty. This result, that is well in agreement with the SM expectation, gives a significance of the tZq process over the background above five standard deviations. As shown in Figure 2b, the excess of data is in agreement with the tZq features, so the observation of the tZq production is claimed.

[1]The calculation requires $m_{ll} > 30$ GeV, where m_{ll} stands for the invariant mass of the two leptons coming from the Z boson decay.

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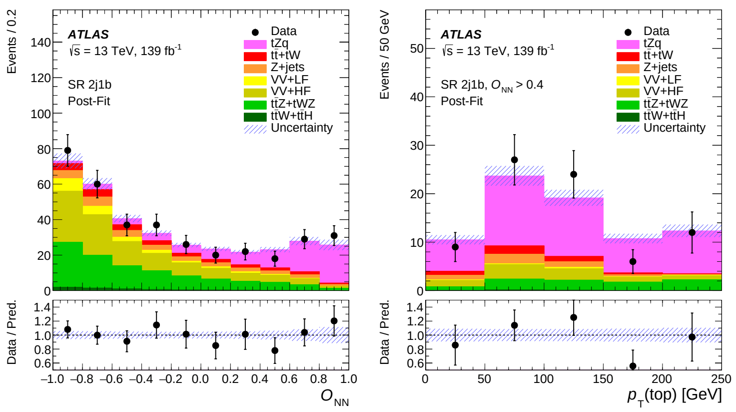

(a) **(b)**

Figure 2: Comparison of the post-fit distributions for the output of the neural network in the tZq signal region (a) and for the top-quark p_{T} in a tZq-enriched region (b) with data. [6]

4. Standard Model $t\bar{t}t\bar{t}$ production

The $t\bar{t}t\bar{t}$ production is predicted by the SM with a cross-section of 12 fb with a relative uncertainty of ±20% [7]. Previous searches in the ATLAS Collaboration resulted in a slight excess of data still compatible with the SM prediction [8, 9]. The latest results are obtained by using the full Run 2 dataset of 139 fb^{-1} [10], by selecting events with two leptons with same-sign charges or at least three leptons in the final state, corresponding to 12% of the total $t\bar{t}t\bar{t}$ events. In addition, the selected events must have at least six jets, coming from the hadronic decays of the top quarks, with at least two of them tagged as b-jets. The background composition is very complex, given the large lepton multiplicity. Leptons may come from heavy-flavour hadron decays, material conversion of photons or Dalitz decays. These are estimated via the template method. The charge of a lepton can be mis-reconstructed, providing same-sign lepton pairs. This background is estimated via a data-driven method. The irreducible background is mostly $t\bar{t}W$ production[2] associated with a large jet multiplicity, estimated via the template method. Validation regions to test the $t\bar{t}W$ modeling in different kinematic variables are built by exploiting its charge asymmetry. Two uncertainties on the modeling of $t\bar{t}W$ associated with 7 and ≥8 jets of 125% and 300%, respectively, are included in the fit as additional nuisance parameters, motivated by discrepancies observed in the validation regions (Figure 3a). The discriminant variable consists of the output of a Boosted Decision Tree (BDT) trained to separate the $t\bar{t}t\bar{t}$ signal from the total background, shown in Figure 3b. The signal strength of the $t\bar{t}t\bar{t}$ is measured in a profile likelihood fit to be twice the SM expectation, but still compatible within 1.7 standard deviations. The measured cross-section is 24^{+7}_{-6} fb. The data excess over the background is well in agreement with $t\bar{t}t\bar{t}$ features, as shown in Figure 3c, with an observed (expected) significance of 4.3 (2.4) standard deviations, yielding the first evidence for this process. The normalisation of the $t\bar{t}W$ contribution is measured to be 1.6 ± 0.3 times the SM prediction, in agreement with previous measurements in similar phase space [11].

5. Conclusions

Thanks to the outstanding performance of the LHC and the ATLAS experiment, many rare processes involving the top quark can now be measured. A first search for the $tq\gamma$ coupling has been conducted, yielding to the best limit on the corresponding ETF operators to date. The tZq production has been observed with a cross-section compatible with the SM within one standard deviation. The first evidence of $t\bar{t}t\bar{t}$ production has been established, with a cross-section compatible with the SM within 1.7 standard deviations.

References

[1] L. Evans and P. Bryant (editors), JINST 3 (2008) S08001

[2] ATLAS Collaboration, JINST 3 (2008) S08003

[2]The $t\bar{t}Z$ contribution is suppressed by a cut on the invariant mass of the $e^{\pm}e^{\mp}$ and $\mu^{\pm}\mu^{\mp}$ pairs.

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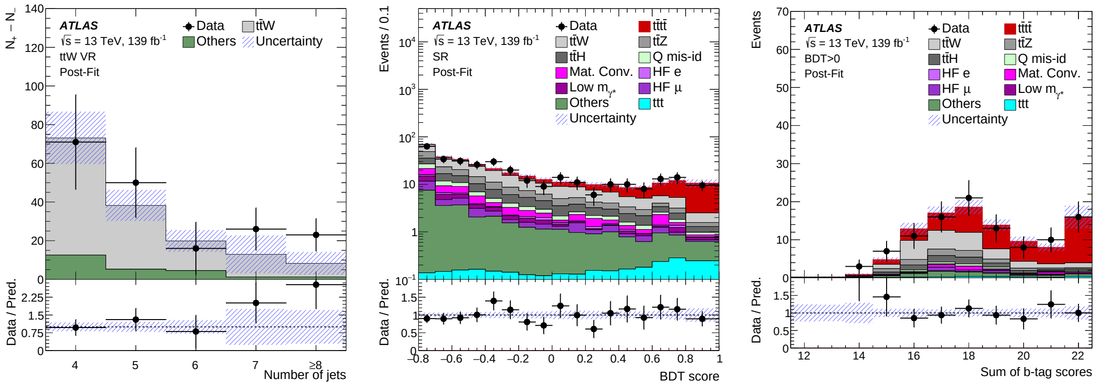

(a) (b) (c)

Figure 3: (a) Comparison of the post-fit $t\bar{t}W$ modeling with data in the validation region, as a function of jet multiplicity. Comparison with data of the post-fit distributions for the BDT output in the signal region (b) and the sum of the b-tagging scores of all jets in the event in a $t\bar{t}t\bar{t}$-enriched region (c). [10]

[3] ATLAS Collaboration, *Search for flavour-changing neutral currents in processes with one top quark and a photon using* 81 fb^{-1} *of* pp *collisions at* $\sqrt{s}$*=13 TeV with the ATLAS experiment*, Phys. Lett. B 800 (2020) 135082, arXiv:1908.08461 [hep-ex]

[4] CMS Collaboration, *Search for anomalous single top quark production in association with a photon in* pp *collisions at* $\sqrt{s}$*=8 TeV*, JHEP 04 (2016) 035, arXiv:1511.03951 [hep-ex]

[5] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, *Dimension-six terms in the Standard Model Lagrangian*, JHEP 10 (2010) 085, arXiv:1008.4884 [hep-ph]

[6] ATLAS Collaboration, *Observation of the associated production of a top quark and a Z boson in pp collisions at* $\sqrt{s}$ = 13 *TeV with the ATLAS detector*, JHEP 07 (2020) 124, arXiv:2002.07546 [hep-ex]

[7] R. Frederix, D. Pagani and M. Zaro, *Large NLO corrections in* $t\bar{t}W^{\pm}$ *and* $t\bar{t}t\bar{t}$ *hadroproduction from supposedly subleading EW contributions*. JHEP 02 (2018) 031, arXiv:1711.02116 [hep-ph]

[8] ATLAS Collaboration, *Search for new phenomena in events with same-charge leptons and b-jets in* pp *collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, JHEP 12 (2018) 039, arXiv:1807.11883 [hep-ex]

[9] ATLAS Collaboration, *Search for four-top-quark production in the single-lepton and opposite-sign dilepton final states in* pp *collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, Phys. Rev. D 99 (2019) 052009, arXiv:1811.02305 [hep-ex]

[10] ATLAS Collaboration, *Evidence for* $t\bar{t}t\bar{t}$ *production in the multilepton final state in proton-proton collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, arXiv:2007.14858 [hep-ex]

[11] ATLAS Collaboration, *Analysis of $t\bar{t}H$ and $t\bar{t}W$ production in multilepton final states with the ATLAS detector*, ATLAS-CONF-2019-045, https://cds.cern.ch/record/2693930