Recent highlights of top-quark physics with the ATLAS detector

C Diez Pardos, on behalf of the ATLAS collaboration
University of Siegen, Walter-Flex-Straße 3, 57072 Siegen, Germany
E-mail: diez@hep.physik.uni-siegen.de

Abstract. Highlights of the most recent top-quark measurements obtained using the full data set collected with the ATLAS experiment at the LHC at a centre-of-mass energy of 13 TeV, corresponding to 139 fb$^{-1}$ of integrated luminosity, are presented. The results include inclusive and differential cross-section measurements of the production of top-quark pairs in association with a photon or a $Z$ boson, the first evidence of four-top-quark production and a novel measurement of lepton flavour universality in top-quark topologies.

1. Introduction

The top quark is the heaviest known elementary particle and has a uniquely strong coupling to the Higgs boson. It is the only quark that decays before hadronization, giving direct access to its properties. Precise measurements of top-quark production and decay properties provide crucial information for testing the predictions of the Standard Model (SM). Additionally, various scenarios of physics beyond the SM (BSM) predict that the top quark couples to new particles. Experimentally, SM top-quark processes are a dominant source of background to many searches for BSM physics.

Top quarks decay almost exclusively via $t \rightarrow bW$ and it is the decay of the $W$ bosons that defines the final state. The measurements presented in this article are performed exploiting topologies with leptonic final states, where at least one of the $W$ bosons from the top quarks decays leptonically. These decay channels have a small branching fraction but provide cleaner final states than fully hadronic decays. The large number of top-quark events produced at the LHC gives an excellent sample of $W$ bosons to test the lepton flavour universality, to perform precise measurements of processes with very small production rates, such as top-quark pair ($t\bar{t}$) production in association with bosons, and to search for very rare SM processes. Those measurements, described in the following, are a selection of the latest top-quark results performed using the full data set recorded with the ATLAS detector [1] at the LHC between 2015 and 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 139 fb$^{-1}$. Details of additional analyses can be found elsewhere.

2. $t\bar{t}$ in association with a photon

The study of the associated production of top quarks with a high-energy photon probes the $t\gamma$ electroweak coupling. Furthermore, these topologies are sensitive, for instance, to new physics through anomalous dipole moments of the top quark and in the context of effective field theories (EFT). The latest results by the ATLAS Collaboration comprise fiducial inclusive and differential
cross-section measurements of the combined resonant $t\bar{t}\gamma$ and non-resonant $tW\gamma$ production [2]. The cross sections are measured at parton level to allow comparison with the theory calculation in [3], the first full computation of $pp \to bWbW\gamma$ at next-to-leading order (NLO) in perturbation theory.

The events are selected with exactly one electron, one muon and one photon, at least two jets, and at least one of the jets must be $b$-tagged. Events where the electrons and muons arise from the leptonic decays of $\tau$-leptons are considered as background. The fiducial inclusive cross section is measured using a profile likelihood fit to the distribution of $S_T$, defined as the scalar sum of all transverse momenta in the event, including leptons, photons, jets and missing transverse momentum. The $S_T$ distribution after the fit is shown in figure 1. The result is $\sigma_{\text{fid}} = 39.6 \pm 0.8 \text{ (stat)} \pm 2.6 \text{ (syst)} \text{ fb}$. The systematic uncertainty is dominated by modelling uncertainties. The measured cross section is in good agreement with the result of the dedicated theoretical calculation, $\sigma = 38.50 \pm 0.56 \text{ (scale)} ^{+1.04}_{-1.18} \text{ (PDF)} \text{ fb}$.

The differential cross sections, absolute and normalised to unity, are measured as functions of photon kinematic variables, angular variables related to the photon and the leptons, and angular separations between the two leptons in the event, an example of which is shown in figure 2. The results are compared with the NLO calculation and found in good agreement.

3. $t\bar{t}$ in association with a $Z$ boson
Detailed studies of $t\bar{t}$ in association with a $Z$ boson ($t\bar{t}Z$) allow scrutinising accurate theoretical calculations and can also offer sensitivity to differences between the predictions from various Monte Carlo simulations. Deviations in the coupling of the top quark to the $Z$ boson from
its SM value might hint to the existence of new effects in the electroweak symmetry breaking mechanism that could be probed in the context of EFT.

The ATLAS Collaboration has performed inclusive and differential $t\bar{t}Z$ cross-section measurements with final states requiring 3 or 4 leptons ($e, \mu$) [4]. Additional requirements based on the total number of reconstructed jets and $b$-tagged jets and on the kinematic properties of the leptons are imposed to define the signal region and several control regions to estimate the main background contributions. The dominant SM background processes in the trilepton and tetralepton regions are $WZ/ZZ$ events in association with light-flavour jets. Other important backgrounds are $tWZ$ processes and events where at least one of the reconstructed leptons is misidentified or a non-prompt lepton. The inclusive cross section is extracted performing a profile likelihood fit based on the total event yields in each signal and control regions, where the normalisation factors of $t\bar{t}Z$ and of $WZ/ZZ$+jets are treated as free parameters in the fit. The cross section is found to be $1.05 \pm 0.05$ (stat) $\pm 0.08$ (syst) pb. The dominant systematic uncertainties are the modelling of the parton shower in $t\bar{t}Z$, the modelling of the $tWZ$ and $WZ/ZZ$+jets processes and the uncertainty in $b$-tagging. The result is in good agreement with the NLO + next-to-leading log theoretical prediction, $\sigma = 0.86^{+0.07}_{-0.09}$ (scale) $\pm 0.03$ (PDF + $\alpha_S$) pb [5].

A partial event reconstruction is performed to measure kinematic properties of the $Z$ boson and the top quarks in the event. The differential measurements are presented among others as a function of kinematic variables of the $Z$ boson and the $t\bar{t}$ system and angular differences between the $Z$ boson and a top quark. Both fiducial absolute and normalised differential cross-section measurements are performed at particle and parton levels. For illustration, two distributions are shown in figure 3. The unfolded spectra from the data are found to be in good agreement with the predictions of different NLO Monte Carlo generators and theoretical predictions.

![Figure 3](image_url)

Figure 3. Absolute differential $t\bar{t}Z$ cross sections measured at particle level as a function of the transverse momentum (a) and at parton level as a function of the absolute rapidity of the $Z$ boson (b) [4]. The large difference in the y-axis scales is a result of different efficiency and acceptance corrections between the particle- and parton-level measurements, together with the branching ratio correction factor of 0.0223, which is applied only for the parton-level result.
4. Evidence for four-top-quark-production in the multilepton final state

Four-top-quark-production ($t\bar{t}t\bar{t}$) is a very rare process in the SM, with an expected cross section of about 12 fb. It is sensitive to the top-quark Yukawa coupling and its CP properties. Additionally, many models of BSM physics predict an increase in the cross section owing to the presence of hypothetical new particles that decay into top quarks or to modified couplings.

The most recent search for $t\bar{t}t\bar{t}$ by the ATLAS Collaboration is performed in events where at least two of the top quarks decay leptonically [6]. In particular, events are selected if they contain a same-sign lepton pair or at least three leptons ($e$ or $\mu$). The $t\bar{t}t\bar{t}$ topology is characterised by a large number of jets and $b$-jets in the event. Thus, jet multiplicity, jet flavour and event kinematics are used to separate the signal from the background events through a multivariate discriminant. The main irreducible backgrounds originate from $t\bar{t}$ in association with a $Z$, $W$ or Higgs boson with additional jets. The reducible ones arise mainly from events where one of the leptons has a misassigned charge and events that contain leptons from heavy-flavour decays, photon conversions or misidentified jets. Several dedicated control regions are used to determine the normalisation of various background processes.

The $t\bar{t}t\bar{t}$ production cross section is measured via a profile likelihood fit to the multivariate output distribution in the signal region and to the yields, or to the discriminating variable distributions in the four control regions. For illustration, two of the distributions are shown in figure 4. The measured cross section is $24^{+7}_{-6}$ fb, which corresponds to an observed (expected) significance with respect to the background-only hypothesis of 4.3 (2.4) standard deviations and provides evidence for this process.

Figure 4. Comparison between data and prediction after the fit (“Post-Fit”) for the distribution of the multivariate discriminant (“BDT score”) in the signal region (a) and for the sum of the transverse momenta of the leptons in the control region enriched in $t\bar{t}W$ events (b) [6]. The band includes the total uncertainty of the post-fit computation. The lower part of the plot shows the ratio of the data to the prediction.
5. Measurement of lepton flavour universality

The SM postulates the universality of the couplings of the different generations of leptons to the electroweak gauge bosons. The measurement of the ratio of the decay rate of $W$ bosons to $\tau$-leptons and muons, $R(\tau/\mu) = B(W \rightarrow \tau\nu)/B(W \rightarrow \mu\nu)$, constitutes an important test of this axiom.

A measurement of this quantity with a novel technique based on the lifetime of the $\tau$-lepton using dileptonic $t\bar{t}$ events was performed by the ATLAS Collaboration [7]. The events are selected with $b$-tagged jets and two leptons, out of which one has to be a muon. The analysis exploits the two leptonic $W$-boson decays in a tag and probe approach: in each event tag leptons are used to select the events and the probe muon is used to test whether it originates from a prompt decay. Muons that originate from $W$ bosons and those originating via intermediate $\tau$-leptons are distinguished using the muon transverse impact parameter, $|d_{\mu}^\text{IP}|$, which depends on the lifetime of the $\tau$-lepton and differences in the muon transverse momentum spectra. The shape of the $|d_{\mu}^\text{IP}|$ distribution is determined with data selecting $Z \rightarrow \mu\mu$ events for prompt muons. The major backgrounds are $Z \rightarrow \mu\mu$ events and events with muons from hadron decays. They are estimated with data in control regions, in particular from a fit to the invariant mass of the muon pair and using a same-sign dimuon control region, respectively.

The ratio is obtained from a profile likelihood fit to the selected events in the signal and control regions divided in 48 categories depending on the decay channel, the value of $|d_{\mu}^\text{IP}|$, and the value of the transverse momentum of the probe muon. An example of a $|d_{\mu}^\text{IP}|$ distribution after the fit is presented in figure 5. The value of $R(\tau/\mu)$ is found to be $0.992 \pm 0.007$ (stat) $\pm 0.011$ (syst), corresponding to a precision of 1.3%, the most precise result up to date. The result is found in agreement with the SM hypothesis of universal lepton couplings. The obtained result compared to that obtained at LEP is shown in figure 6.

Figure 5. Example of the post-fit $|d_{\mu}^\text{IP}|$ distribution in the $e\mu$ channel and for muons with transverse momenta between 5 and 10 GeV [7]. The data are represented by points and a stacked histogram represents the different simulated processes. The bottom panel shows the ratio of the data to the expectation.

Figure 6. Measured $R(\tau/\mu)$ (black circular marker) compared with the previous LEP result (red square marker) [7]. The statistical and systematic errors are shown separately and together with the total error of the measurement. The vertical dashed line indicates the SM prediction of lepton-flavour universality, with equal $W$-boson branching ratios to different lepton flavours.
6. Conclusions

Top-quark measurements provide important information about the production process as described in the SM, as well as sensitivity to possible new physics. The large data set collected with the ATLAS detector at the LHC so far allows to perform not only precise inclusive cross-section measurements of processes such as $t\bar{t}Z$ and $t\bar{t}\gamma$, which had not even been observed before the start of the LHC, but also differential measurements, which further help to improve our understanding of their modelling and to explore BSM models. Additionally, it allowed reaching evidence for $t\bar{t}t\bar{t}$ production with a $4.3\sigma$ significance and performing the most precise measurement of $R(\tau/\mu)$ to date. All results so far are consistent with the expectations of the SM.

References

[1] ATLAS Collaboration 2008 J. Instrum. 3 S08003
[2] ATLAS Collaboration 2020 J. High Energy Phys. JHEP09(2020)049 (Preprint hep-ex/2007.06946)
[3] Bevilacqua G, Hartanto H, Kraus M, Weber T and Worek M 2018 J. High Energy Phys. JHEP10(2018)158 (Preprint hep-th/1803.09916)
[4] ATLAS Collaboration 2020 Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a $Z$ boson at $\sqrt{s} = 13$ TeV with the ATLAS detector ATLAS-CONF-2020-028 URL http://cds.cern.ch/record/2725734
[5] Broggio A, Ferroglia A, Frederix R, Pagani D, Pecjak B D and Tsinikos I 2019 J. High Energy Phys. JHEP08(2019)039 (Preprint hep-ph/1907.04343)
[6] ATLAS Collaboration 2020 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 Tech. Rep. CERN-EP-2020-111 (Preprint hep-ex/2007.14858)
[7] ATLAS Collaboration 2020 Test of the universality of $\tau$ and $\mu$ lepton couplings in $W$-boson decays from $t\bar{t}$ events with the ATLAS detector Tech. Rep. CERN-EP-2020-139 (Preprint hep-ex/2007.14040)