SciPost Phys. Proc. 8, 116 (2022)

Measurement of the $t\bar{t}t\bar{t}$ production at 13 TeV with the ATLAS detector at the LHC

Ö. Oğul Öncel[1,†,⋆] on behalf of the ATLAS Collaboration

1 Physikalisches Institut, Universität Bonn, Nussallee 12, 53115 Bonn, Germany

† Now at University of Freiburg
⋆ ogul.oncel@cern.ch

Proceedings for the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects, Stony Brook University, New York, USA, 12-16 April 2021
doi:10.21468/SciPostPhysProc.8

Abstract

Two measurements and their combination for the $t\bar{t}t\bar{t}$ production cross-section analysis using 139 fb^{-1} of proton–proton collision data at a centre-of-mass energy of 13 TeV collected by the ATLAS detector at the LHC are presented. The first analysis uses the final states with either one or two opposite-sign leptons (electrons or muons). In the second analysis the final states with either two same-sign or at least three leptons are considered. With an observed (expected) significance of 4.3 (2.4) standard deviations over the background-only hypothesis, the second analysis provides the first evidence for the $t\bar{t}t\bar{t}$ process. No significant deviations from the Standard Model are observed.

Received 23-07-2021
Accepted 31-03-2022
Published 13-07-2022
doi:10.21468/SciPostPhysProc.8.116

1 Introduction

According to the Standard Model (SM), $t\bar{t}t\bar{t}$ production is a rare-process at proton–proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with a cross-section of $\sigma_{t\bar{t}t\bar{t}} = 12 \pm 2.4$ fb at next-to-leading order (NLO) in QCD including NLO electroweak corrections [1]. Various beyond the SM (BSM) models predict an enhancement of the $t\bar{t}t\bar{t}$ cross-section (see References [1-10] in [2]).

This article summarizes the two most recent measurements made by the ATLAS [3] collaboration using data collected from pp collisions at the LHC at $\sqrt{s} = 13$ TeV corresponding to 139 fb^{-1} of total integrated luminosity. Previous searches by the ATLAS [4,5] and CMS [6] collaborations are consistent with the SM. The first analysis [7] covers the final states with either one or two opposite-sign leptons (isolated electrons or muons, including those coming from τ decays) and is labeled as 1L/2LOS channel. The second analysis [8] uses the events with either two same-sign or at least three leptons and is labeled as 2LSS/3L. Finally, both channels are combined in a simultaneous fit [7].

2 1L/2LOS channel measurement

The 1L/2LOS channel comprises of about 57% of the $t\bar{t}t\bar{t}$ final states. The signature of the event features a high number of jets (N_j), with 10 (8) jets in the 1L (2LOS) channel, four of which are b-jets and could be b-tagged (N_b). This final state is almost exclusively dominated (>90%) by the irreducible background from production of $t\bar{t}$ events with additional jets ($t\bar{t}$+jets). The main challenge in the analysis is the correct estimation of this background, for which the Monte Carlo (MC) prediction is subjected to several corrections.

2.1 Background estimation

The $t\bar{t}$+jets sample is firstly corrected for three flavour fractions of the truth-matched jets not decaying from top-quarks. A profile likelihood fit is performed in 8 regions inclusive in N_j and exclusive in N_b, where the normalizations of $t\bar{t}$+≥1b , $t\bar{t}$+≥1c and $t\bar{t}$+light are simultaneously estimated. This corrected sample is then used in a sequential reweighting process of selected kinematic distributions: N_b, the number of large-radius jets, the scalar sum of all jets and lepton transverse momenta in the event (H_T), and the average distance between any pair of jets. The reweighting factors are derived from data/MC ratios in the $N_b = 2$ regions and applied to the $N_b \geq 3$ regions. Improved agreement between data and simulation is observed after these corrections.

2.2 Signal extraction

Boosted Decision Trees (BDTs) are used to separate signal and background in six Signal Regions (SRs) that are exclusive in N_j and inclusive in N_b. In the training (testing) step LO (NLO) $t\bar{t}t\bar{t}$ signal samples are used. The background sample consists of $t\bar{t}$+jets events after applying corrections described in 2.1 and non-$t\bar{t}$ processes as predicted by the simulation. Among the 14 selected input variables, the sum of the pseudo-continuous b-tagging score [9] over the six jets with the highest score provides the strongest separation.

2.3 Fit results

In addition to the SRs, 12 Control Regions (CRs) each having less than 1% signal contamination, are used in a profile likelihood fit. For the SRs the BDT score distributions are used, while with the exception of one CR (1L, 8j, 5b) using the event count, for all CRs the H_T distributions are used. A complex decorrelation scheme is applied to $t\bar{t}$+jets correction and reweighting related uncertainties. The cross-section is measured to be

$$\sigma_{t\bar{t}t\bar{t}} = 26 \pm 8\ (\text{stat.})\ ^{+15}_{-13}(\text{syst.})\ \text{fb} = 26^{+17}_{-15}\ \text{fb} \tag{1}$$

with an observed (expected) significance of 1.9 (1.0) standard deviations. After the uncertainties in the signal modelling, the leading uncertainty is the modelling of the $t\bar{t}$+≥1b background. As exemplified in Figure 1, a good post-fit agreement between data and the simulation is observed.

3 2LSS/3L channel measurement

This channel includes approximately 13% of the $t\bar{t}t\bar{t}$ events. The signature of the event features $N_j = 8$ (6) in the 2LSS (3L) channel, four of which are b-jets. The dominant (∼75%) irreducible backgrounds of $t\bar{t}H$, $t\bar{t}W$, $t\bar{t}Z$ are followed by reducible backgrounds from non-prompt lepton (∼15%) and charge misassignment (Q mis-id) backgrounds (∼5%). The main

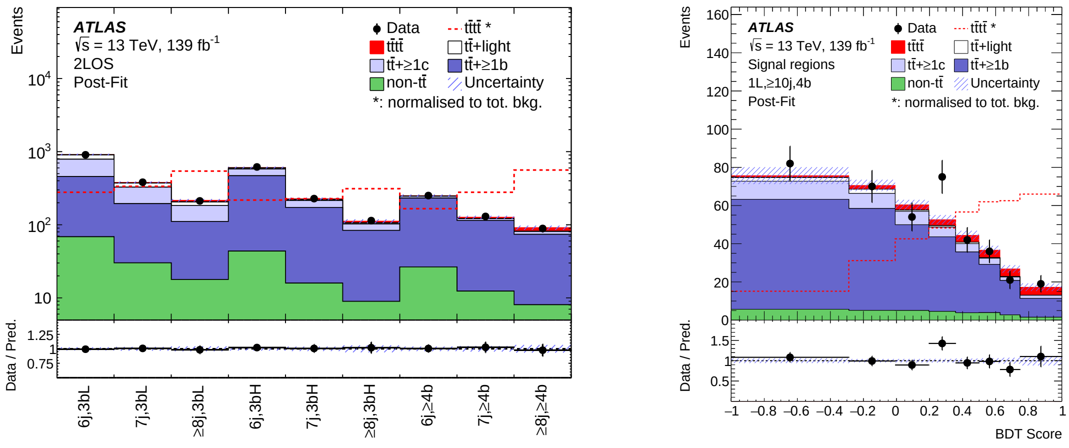


Figure 1: Post-fit agreement between data and simulation in various regions: (a) Yields for each SR and CR in 2LOS channel; (b) BDT distribution in (1L,10j,4b) SR. Shaded bands represent both statistical and systematic uncertainties [7].

challenges are the correct estimation and suppression of the $t\bar{t}W$ background, whose MC simulation modelling deteriorates with increasing jet multiplicities.

3.1 Background estimation

All irreducible backgrounds except $t\bar{t}W$ are estimated from MC simulation. Modelling of $t\bar{t}W$ in MC is difficult [10], thus its normalization factor (NF) is left as a free parameter in the fit. This parameter is constrained through a CR enriched in $t\bar{t}W$ events.

Two NFs are defined for photon conversion background events where conversions emerging from interactions with the detector material (Mat. Conv.) and conversions happening before entering the detector (low $m_{\gamma*}$) are distinguished. Both processes are constrained in a single CR. Normalization of non-prompt contributions where one lepton comes from the decay of a heavy-flavour (HF) jet are also assigned two NFs that are estimated in the fit. Two CRs are defined per lepton flavour, enriched in HF→e/μ decays to constrain the corresponding NFs.

Q mis-id contributions are estimated from a separate DD estimation in a selection enriched in Z→ee and the derived rates are applied to data events with opposite charged leptons that are passing the SS2L kinematic selection.

3.2 Signal extraction

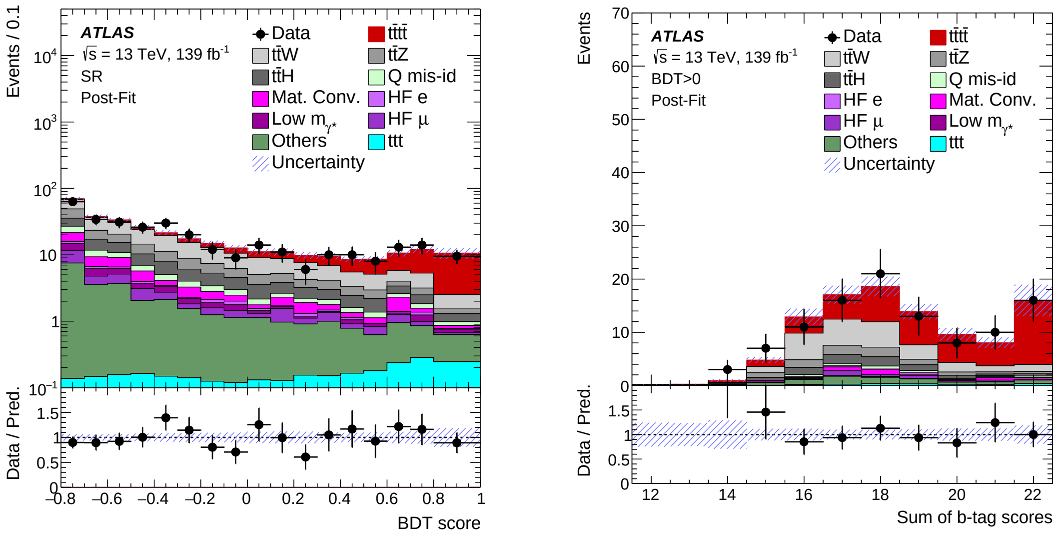
An inclusive BDT training is performed in a single SR ($N_b \geq 2$, $N_j \geq 6$, $H_T > 500$ GeV) to separate signal and background. In the training (testing) step the LO (NLO) $t\bar{t}t\bar{t}$ sample is used as the signal process. All background processes are included using their estimations from simulation. Among the 12 input variables, the sum of the pseudo-continuous b-tagging score [9] over all jets in the event provides the highest discrimination power.

3.3 Fit results

A profile likelihood fit is performed simultaneously using the SR and the four CRs. The cross-section is measured as

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5\,(\text{stat.})\,^{+5}_{-4}(\text{syst.})\ \text{fb} = 24^{+7}_{-6}\ \text{fb} \tag{2}$$

corresponding to an observed (expected) significance of 4.3 (2.4) standard deviations. This result provides the first evidence for the $t\bar{t}t\bar{t}$ process. After the theoretical uncertainty on the signal process, modelling of the $t\bar{t}W$ process has the highest impact on the uncertainty of the measurement. Good post-fit agreement between data and simulation is observed as shown in Figure 2.



(a) (b)

Figure 2: (a) The BDT distribution in the SR. (b) Sum of b-tag score in the high BDT region. Shaded bands represent both statistical and systematic uncertainties [8].

4 Combined measurement of the two channels

The combined measurement of the 1L/2LOS and 2LSS/3L final states are performed through a simultaneous profile likelihood fit on the same data set where all fit regions of both analyses are included. Due to the exclusive lepton selection the two analyses are statistically independent.

Both analyses have the same definitions of objects and use the same data set, therefore experimental uncertainties are fully correlated in the combined fit. Uncertainties related to the reducible backgrounds in the 2LSS/3L channel are treated as uncorrelated. With the exception of $t\bar{t}W$ and $t\bar{t}$, theoretical modelling uncertainties for all backgrounds and the signal process are fully correlated. Exception for the $t\bar{t}W$ and $t\bar{t}$ backgrounds are due to the relative importance and different treatment of these background processes in two analyses. The systematic uncertainties related to the normalization of $t\bar{t}W$ and modelling of the $t\bar{t}$+jets background as well as uncertainties associated with DD corrections are treated as uncorrelated. The combined cross-section is found to be

$$\sigma_{t\bar{t}t\bar{t}} = 24 \pm 4\ (\text{stat.})\ ^{+5}_{-4}(\text{syst.})\ \text{fb} = 24^{+7}_{-6}\ \text{fb} \tag{3}$$

corresponding to an observed (expected) significance of 4.7 (2.6) standard deviations. The combination has increased the significance.

5 Conclusion

Two analyses of four-top-quark production and their combined measurement is presented. Data used in the measurements is collected by the ATLAS detector from the pp collisions at the LHC with $\sqrt{s} = 13$ TeV and corresponds to a total luminosity of 139 fb^{-1}.

The first measurement is performed in final states with either one or two opposite-sign leptons and yields a measured production cross-section of 26^{+17}_{-15} fb and an observed (expected) significance of 1.9 (1.0) standard deviations. The second analysis is performed in final states with either two same-sign or at least three leptons where cross-section is found to be 24^{+7}_{-6} fb. This analysis provides the first evidence of this process with an observed (expected) significance of 4.3 (2.4) standard deviations.

A combination of both analyses is done in a simultaneous fit to all regions of both analyses taking correlations of uncertainties into account. The combined result yields a cross-section of 24^{+7}_{-6} fb with an improved observed (expected) significance of 4.7 (2.6) standard deviations. No significant deviations from the SM has been observed.

Funding information The author is funded by BMBF-Forschungsschwerpunkt 103.

References

[1] 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*, J. High Energy Phys. **02**, 031 (2018), doi:10.1007/jhep02(2018)031.

[2] G. Bevilacqua and M. Worek, *Constraining BSM physics at the LHC: four top final states with NLO accuracy in perturbative QCD*, J. High Energy Phys. **07**, 111 (2012), doi:10.1007/jhep07(2012)111.

[3] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, J. Inst. **3**, S08003 (2008), doi:10.1088/1748-0221/3/08/S08003.

[4] 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**, 052009 (2019), doi:10.1103/physrevd.99.052009.

[5] 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*, J. High Energy Phys. **12**, 039 (2018), doi:10.1007/jhep12(2018)039.

[6] CMS Collaboration, *Search for production of four top quarks in final states with same-sign or multiple leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **80**, 75 (2020), doi:10.1140/epjc/s10052-019-7593-7.

[7] ATLAS Collaboration, *Measurement of the $t\bar{t}t\bar{t}$ production cross section in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, J. High Energy Phys. **11**, 118 (2021), doi:10.1007/JHEP11(2021)118.

[8] 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*, Eur. Phys. J. C **80**, 1085 (2020), doi:10.1140/epjc/s10052-020-08509-3.

[9] ATLAS Collaboration, *ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **79**, 970 (2019), doi:10.1140/epjc/s10052-019-7450-8.

[10] R. Frederix and I. Tsinikos, *Subleading EW corrections and spin-correlation effects in $t\bar{t}W$ multi-lepton signatures*, Eur. Phys. J. C **80**, 803 (2020), doi:10.1140/epjc/s10052-020-8388-6.