PROCEEDINGS OF SCIENCE

# 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





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Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a $Z$ boson ($t\bar{t}Z$) are presented in these proceedings. The measurements are performed using full Run 2 data that corresponds to an integrated luminosity of 139 fb$^{-1}$ and was collected with the ATLAS detector at the CERN Large Hadron Collider. The inclusive cross section, which is measured to be $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05\,(\text{stat}) \pm 0.08\,(\text{syst.})$ pb, and the differential cross section measurements are in good agreement with the Standard Model predictions.

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## 1. Introduction

Production of a top-quark-antiquark pair in association with a $Z$ boson ($t\bar{t}Z$) is a rare Standard Model (SM) process that requires large centre-of-mass energy and luminosity. The study of the $t\bar{t}Z$ system is motivated by its potential to directly probe the top-quark coupling to the $Z$ boson. In addition, the $t\bar{t}Z$ system decays to multi-lepton final states and is an important background in measurements of SM processes and beyond the Standard Model (BSM) searches. However, production of the $t\bar{t}Z$ process was only enabled at the Large Hadron Collider (LHC) [1] and has not been studied in great detail yet. Previously the inclusive $t\bar{t}Z$ cross section was measured with the ATLAS detector [2] using a subset of the LHC Run 2 data, collected in 2015 and 2016 [3] and the CMS collaboration carried out a differential cross section measurement using the 2016 and 2017 data sets [4]. These proceedings discuss the first inclusive and differential cross section measurements using full Run 2 data with the ATLAS detector [5].

## 2. Analysis channels and signal regions

The analysis is split into two analysis channels based on the number of isolated prompt leptons (electrons or muons) in the final state. The trilepton ($3\ell$) channel requires exactly three such leptons while the tetralepton ($4\ell$) channel looks for exactly four leptons. Signal regions are defined using the jet and $b$-jet multiplicities.

Two orthogonal signal regions are defined for the inclusive cross section measurement in the trilepton channel. Events with at least one $b$-tagged jet [6] and at least four jets in total are selected in the $3\ell$-$Z$-$1b4j$-PCBT region, whereas the $3\ell$-$Z$-$2b3j$-PCBT region selects events with at least two $b$-tagged jets and at least three jets in total. The orthogonality between the two regions is ensured by using pseudo-continuous $b$-tagging (PCBT) working points (WP) which allows using several different $b$-tagging efficiencies for different $b$-jets. A dedicated signal region, $3\ell$-$Z$-$2b3j$-DIFF, is used for the differential cross section measurements. This region uses a fixed $b$-tagging WP of 85% and requires at least two $b$-tags and at least three jets in total.

Four orthogonal signal regions, $4\ell$-SF-$1b$, $4\ell$-SF-$2b$, $4\ell$-DF-$1b$ and $4\ell$-DF-$2b$, are defined in the tetralepton channel. Each signal region selects events with at least two jets in total. The $1b$ signal regions require exactly one $b$-tagged jet in an event while the $2b$ regions look for events with at least two $b$-tagged jets. A fixed 85% $b$-tagging efficiency WP is used for all $b$-tagged jets. The $1b$ and $2b$ regions are divided based on the flavours of the non-$Z$ leptons into the same-flavour (SF) and different-flavour (DF) regions.

## 3. Background estimation

The $WZ/ZZ$ + jets processes are the dominant prompt lepton backgrounds of the $t\bar{t}Z$ trilepton and tetralepton channels, respectively. The normalisations of these processes are measured in the dedicated control regions. All events with $b$-tagged jets are vetoed from the $WZ$ + jets region and the $ZZ$ + jets region selects events with the missing transverse energy in the range from 20 to 40 GeV. Other selection criteria match those of the corresponding signal regions.

The 'fake' lepton background arises when different types of objects are misidentified as leptons. This background is dominated by the $t\bar{t}$ pair decays to two leptons in the current analysis. A fully

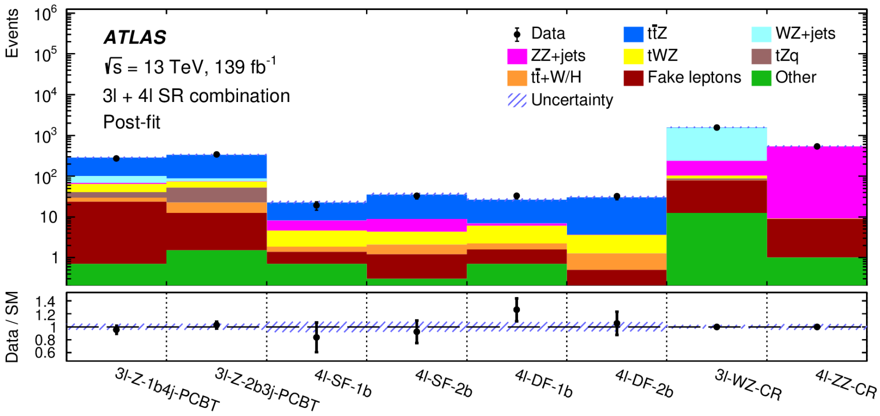


**Figure 1:** The observed and expected event yields in the trilepton and tetralepton signal regions and the $WZ/ZZ$ + jets control regions after the combined fit [5].

data-driven method, called the 'matrix' method [7, 8], is used in the analysis to estimate the contribution of fake leptons in the signal regions.

## 4. Results of the inclusive cross section measurement

A simultaneous profile-likelihood fit to the numbers of events in the PCBT trilepton and all tetralepton signal regions as well as the $WZ/ZZ$ + jets control regions are used to extract the ratio of the measured inclusive $t\bar{t}Z$ production cross section to its corresponding SM prediction, $\mu_{t\bar{t}Z}$. Figure 1 shows the observed and expected event yields in the signal and control regions after the fit.

The $\mu_{t\bar{t}Z}$ parameter of interest is measured to be $1.19 \pm 0.06$ (stat.$\pm 0.08$ (syst.) pb corresponding to $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05$ (stat) $\pm\ 0.08$ (syst.) pb. Dominant sources of the systematic uncertainty are the $t\bar{t}Z$ parton shower and the $tWZ$ background modelling as well as $b$-tagging. The measurement is in good agreement with the NLO+NNLL predictions of $0.86^{0.07}_{0.08}$ (scale) $\pm\ 0.02$ (PDF) pb [9].

## 5. Differential cross section measurements

Absolute and normalised differential cross sections at particle and parton levels are measured using an iterative Bayesian unfolding (IBU) method [10]. In total, nine differential observables, which are sensitive to the $t\bar{t}Z$ generator modelling and BSM effects, are used.

The differential measurements with respect to the transverse momentum of the reconstructed $Z$ boson are performed by combining the differential trilepton and all tetralepton signal regions. The measured absolute differential $t\bar{t}Z$ cross sections unfolded to particle and parton levels for this observable are shown in Figure 2. The measurements are dominated by statistical uncertainties and the total uncertainty varies from 20% to 40%. Dominant sources of systematic uncertainty are associated with the $t\bar{t}Z$ modelling and $b$-tagging. The measured cross sections are compared with several NLO $t\bar{t}Z$ generators, as well as NLO+NNLL at the parton level distribution. The compatibility of the measurements with these predictions is evaluated by calculating a $\chi^2$/ndf and corresponding $p$-value. All measurements have $p$-values greater than 0.05 and, thus, show that the unfolded distributions are compatible with the predictions.



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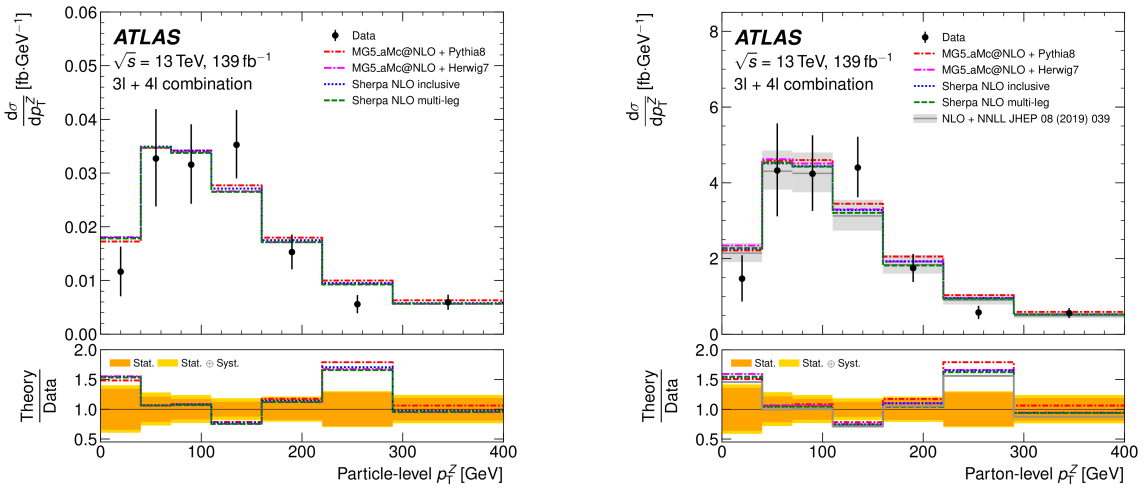


(a) (b)

**Figure 2:** Absolute differential $t\bar{t}Z$ cross sections measured at (a) particle and (b) parton level as a function of the transverse momentum of the reconstructed $Z$ boson [5].

## 6. Conclusions

The first inclusive and differential measurements of the production cross section of the $t\bar{t}Z$ process with the ATLAS detector using full Run 2 data are presented. The measured inclusive cross section of $\sigma_{t\bar{t}Z} = 0.99 \pm 0.05\,(\text{stat}) \pm 0.08\,(\text{syst.})$ pb is in good agreement with the SM prediction. The systematic uncertainty is dominated by the $t\bar{t}Z$ parton-shower and $tWZ$ modelling uncertainties as well as $b$-tagging. The differential cross sections are measured as functions of nine observables at parton and particle levels. The measurements are dominated by statistical uncertainties and good agreement with the SM predictions is observed in all cases.

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