

# Top-quark pair production in $p$ +Pb collisions in the ATLAS experiment

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**Abstract.** Measurements of top-quark pairs in heavy-ion collisions are expected to provide novel probes of nuclear parton distribution functions at high Bjorken- $x$  values, which are difficult to access experimentally using other available probes. In this report, the observation of top-quark pair production in proton-lead collisions at the centre-of-mass energy of 8.16 TeV in the ATLAS experiment at the LHC is discussed. Top-quark pair production is measured in the lepton+jets and the di-lepton channels, with a significance well above 5 standard deviations in each channel separately. The nuclear modification factor  $R_{pA}$  is also measured for the first time for the top-quark pair process.

## 1 Introduction

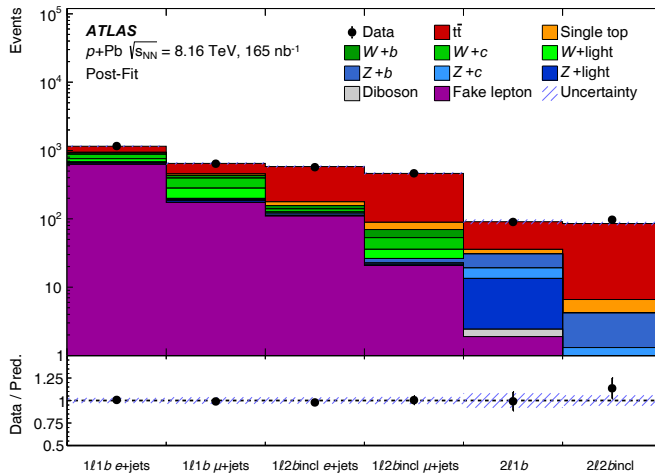
The top quark, the heaviest elementary particle, is short-lived and decays through  $t \rightarrow Wb$  with a branching ratio of almost 100%. The subsequent  $W$  boson decay may proceed leptonically ( $W \rightarrow \ell\nu_\ell$  with  $\ell = e, \mu$ ) or hadronically ( $W \rightarrow q\bar{q}$ ). At the LHC, top quarks are preferentially produced in top quark–antiquark ( $t\bar{t}$ ) pairs via gluon–gluon fusion and the pair production dominates over single-top quark production. With large integrated luminosities of proton-lead ( $p$ +Pb) and lead-lead (Pb+Pb) data recorded between 2015 and 2018 (Run 2), the observation of the  $t\bar{t}$  process becomes accessible in heavy-ion collisions for the first time at the LHC. In ultra-relativistic Pb+Pb collisions at the LHC, top quarks are expected to provide a unique tool to measure properties of the strongly interacting quark-gluon plasma (QGP). Production of  $t\bar{t}$  pairs has been observed in Pb+Pb collisions [1] recently by the ATLAS Collaboration [2]. In  $p$ +Pb collisions, top quarks provide novel probes of nuclear parton distribution functions (nPDFs), especially the gluon nPDF, which is particularly important for perturbative calculations in Quantum Chromodynamics (QCD) at the LHC energies. In this report, a first measurement of  $t\bar{t}$  production in  $p$ +Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV from the ATLAS experiment is discussed [3]. The data sample corresponds to an integrated luminosity of  $165 \text{ nb}^{-1}$ .

## 2 Event selection

Decay channels of  $t\bar{t}$  production with two opposite-sign leptons (di-lepton) or one lepton and jets ( $\ell$ +jets) are studied. Electron and muon final states are explored above an 18 GeV transverse momentum ( $p_T$ ) threshold. At least two (four) anti- $k_t$   $R = 0.4$  jets with  $p_T > 20$  GeV

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**Figure 1.** Data and predicted post-fit event yields in each of the six SRs. The background contributions, following the global fit, are depicted as filled histograms. The size of the combined statistical and systematic uncertainty in the sum of the signal and background is indicated by the blue hatched band. The ratio of the data to the sum of the signal and background is presented in the lower panel [3].

are required in di-lepton ( $\ell$ +jets) decay modes. Jets are corrected for the presence of an underlying event using a dedicated algorithm developed for heavy-ion collisions [4]. Signal events are categorised based on a number of  $b$ -tagged jets. In total, six signal regions (SR) are defined with exactly one or more than one  $b$ -tagged jets. Based on the lepton flavour, the  $\ell$ +jets SRs are further split into four regions with one electron or muon and exactly one or at least two  $b$ -tagged jets, labelled as  $1\ell 1b$   $e$ +jets,  $1\ell 2bincl$   $e$ +jets,  $1\ell 1b$   $\mu$ +jets and  $1\ell 2bincl$   $\mu$ +jets. The SRs with two leptons and exactly one or at least two  $b$ -tagged jets are labelled as  $2\ell 1b$  and  $2\ell 2bincl$ , respectively.

### 3 Background evaluation and analysis technique

In the analysis, background contributions are studied using either MC simulation ( $Z/W$ +jets bosons, single top, di-bosons) or data-driven approaches (fake leptons). The main background contribution in the di-lepton channel includes the  $Z$ +jets and single-top  $Wt$  processes. The background in the  $\ell$ +jets channel is formed mainly by  $W$ +jets events and the fake-lepton contribution.

Using a binned profile likelihood fit in six SRs simultaneously, the signal strength defined as a ratio of the measured-to-predicted cross-sections, is extracted. The  $H_T^{\ell,j}$  variable, defined as the scalar sum of  $p_T$  of leptons and jets in the event, is used for the fit. In the fit, systematic uncertainties are represented by nuisance parameters. The signal significance exceeds  $5\sigma$  in each channel, marking a first observation of  $t\bar{t}$  production in the di-lepton channel in heavy-ion collisions at the LHC. Figure 1 shows data and predicted post-fit yields in each of the SRs. Event yields predicted by the fit and the observed ones are in good agreement.

## 4 Results

The measured signal strength is translated to the inclusive  $t\bar{t}$  production cross-section, which amounts to:

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0 \text{ (stat.)}_{-4.4}^{+4.8} \text{ (syst.) nb.} \quad (1)$$

The combined relative uncertainty is 9% and is dominated by the systematic contribution. The measurement features the most precise inclusive cross-section value for  $t\bar{t}$  production in  $p$ +Pb collisions to date. The left panel of Figure 2 shows a comparison of the observed inclusive  $t\bar{t}$  cross-section with the measurement by CMS [5]. The two results are in agreement within 1.4 standard deviations. Also the most precise combined measurement of the  $t\bar{t}$  production cross-section in proton-proton ( $pp$ ) collisions at  $\sqrt{s} = 8$  TeV from the ATLAS and CMS Collaborations [6] is shown. It is extrapolated to the centre-of-mass energy of the  $p$ +Pb system. The measured cross-section is also compared with predictions obtained with the next-to-next-to-leading order (NNLO) calculations in QCD using four state-of-the-art nPDF sets. The largest discrepancy is found for the nNNPDF30 nPDF set [7] which does not include the recent Run-2 LHC data for light hadrons and quarkonia production from  $p$ +Pb collisions [8]. The remaining nPDF sets are in good agreement with the measured cross-section value.

The nuclear modification factor ( $R_{pA}$ ) for  $t\bar{t}$  production is extracted for the first time using the measured  $\sigma_{t\bar{t}}$  value and the extrapolated  $pp$  cross-section at 8 TeV. It amounts to:

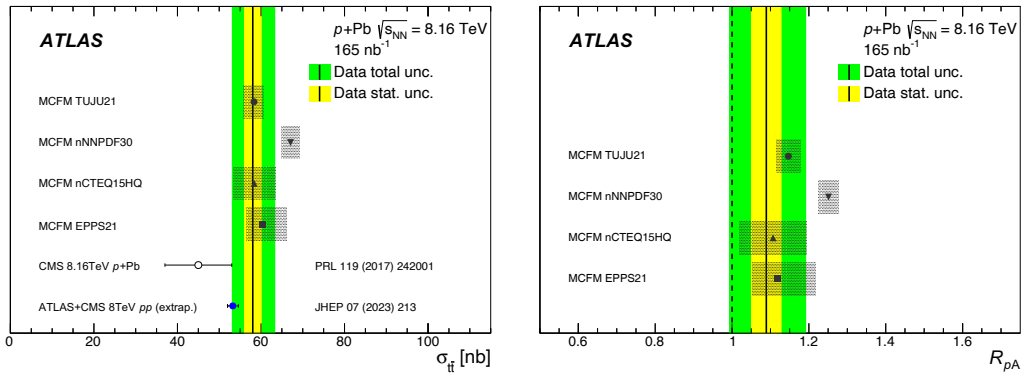
$$R_{pA} = 1.090 \pm 0.039 \text{ (stat.)}_{-0.087}^{+0.094} \text{ (syst.).} \quad (2)$$

All uncertainties are assumed to be uncorrelated in the cross-section measurements in  $p$ +Pb and  $pp$ . The  $R_{pA}$  value is shown in the right panel of Figure 2. The central value of  $R_{pA}$  is one standard deviation above unity, hinting at the expected enhancement of  $t\bar{t}$  production in  $p$ +Pb collisions in comparison to the  $pp$  system. The relative uncertainty of the measurement amounts to 9% and is dominated by the systematic component due to modelling of  $t\bar{t}$  production and background estimation from fake leptons in the  $\ell$ +jet channel. The  $R_{pA}$  is also compared to other measurements and theoretical predictions for the signal process involving different nPDF sets. The uncertainty associated with the baseline PDF for  $pp$  interactions is considered fully correlated in the predictions and cancels out in the ratio. The resulting uncertainty represents the uncertainty on nPDF. All nPDF calculations result in  $R_{pA}$  values above unity. A good agreement is found between the measured and predicted  $R_{pA}$ . The largest difference of more than one standard deviation above the measured  $R_{pA}$  value is observed for the nNNPDF30 prediction.

## 5 Conclusions

A first measurement of  $t\bar{t}$  production in  $p$ +Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV per nucleon pair from the ATLAS experiment was reported. Di-lepton and lepton+jets decay modes with electrons and muons were analysed. Background contributions from various processes were identified and evaluated. The inclusive  $t\bar{t}$  production cross-section and nuclear modification factor were measured. They were compared with the NNLO calculations in QCD based on the state-of-the-art nPDF sets. In general, a good agreement was found.

This measurement paves a new way to constrain nPDFs in the high Bjorken- $x$  region. As such it is also an important milestone for measurements involving the extraction of properties of the QGP in Pb+Pb collisions at the LHC.



**Figure 2.** Inclusive cross-section (left) and nuclear modification factor (right) for  $t\bar{t}$  production in  $p$ +Pb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV [3].

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