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Latest measurements of the top quark pair production cross-section with the ATLAS detector

Leonid SERKIN* **on behalf of the ATLAS Collaboration**

INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine and ICTP, Trieste
Strada Costiera 11, Trieste 34151, Italy
E-mail: Leonid.Serkin@cern.ch

Three recent measurements of the top quark pair production cross-section $\sigma(t\bar{t})$ by the ATLAS Collaboration at the LHC are summarised: the measurement of the inclusive $\sigma(t\bar{t})$ performed using proton-proton collisions at $\sqrt{s} = 5.02$ TeV in the single-lepton and dilepton final states and their combination, the measurement of the differential $\sigma(t\bar{t})$ using boosted top quarks in the all-hadronic final state at $\sqrt{s} = 13$ TeV, and the measurement of the differential $\sigma(t\bar{t})$ using boosted top quark pair events in the lepton+jets channel at $\sqrt{s} = 13$ TeV. All the results were found to be in agreement with theoretical quantum chromodynamic calculations. The differential measurement results are compared with various Monte Carlo generators, including comparisons where the generators are reweighted to match a parton-level calculation at next-to-next-to-leading order. The reweighting improves the agreement between data and theory.

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*Speaker.

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1. Introduction

The study of top quark-antiquark ($t\bar{t}$) production in proton-proton (pp) collisions forms a central part of the physics programme of the ATLAS experiment [1] at the Large Hadron Collider (LHC). Measurements of the inclusive $t\bar{t}$ cross-section allow studies of quantum chromodynamics (QCD) at some of the highest accessible energy scales, while differential cross-section measurements provide a unique opportunity to test for deviations from the Standard Model (SM) predictions.

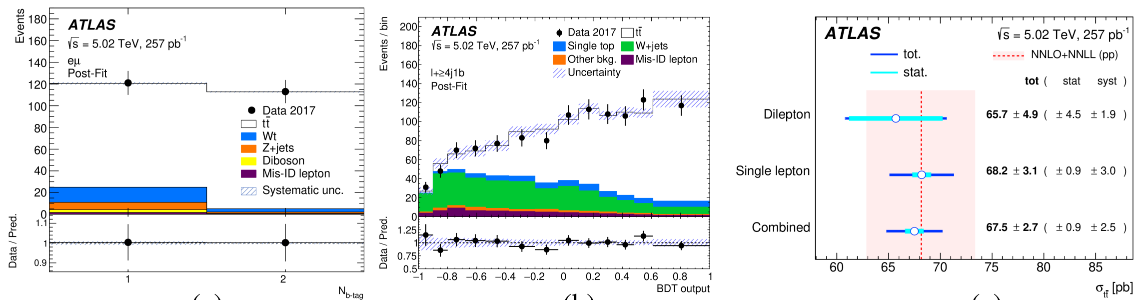
2. Measurement of inclusive $\sigma(t\bar{t})$ at $\sqrt{s} = 5.02$ TeV

The inclusive $t\bar{t}$ production cross-section $\sigma(t\bar{t})$ has been measured in pp collisions at $\sqrt{s} = 5.02$ TeV using 257 pb^{-1} of data recorded by the ATLAS experiment at the LHC in 2017 using events from both the dilepton and single-lepton channels [2].

Event samples with an opposite-charge pair of leptons, transverse-momentum imbalance arising from the presence of two neutrinos, and one or two jets tagged as likely to contain b-hadrons, shown in Figure 1(a), were used to measure the rate of $t\bar{t}$ production. The extraction technique is similar to that used in measurements of $\sigma(t\bar{t})$ using $e\mu$ events [3], but this measurement also exploits the same-flavour ee and $\mu\mu$ events and the formalism was extended to these channels.

The single-lepton event samples were defined by requiring a charged lepton, missing transverse momentum, and two or more jets with at least one of the jets tagged as being likely to contain a b-hadron. The single-lepton sample was separated into subsamples with different signal-to-background ratios, increasing the precision of the measurement. The measurement also used a multivariate technique to separate the $t\bar{t}$ signal from background events, as shown in Figure 1(b).

The cross-section measurements in the dilepton channel, dominated by the statistical uncertainty on data, and the single-lepton channel, dominated by systematic uncertainties, were combined to provide a more precise result. The dilepton measurement used a fit of the $t\bar{t}$ signal, background contributions, and b-tagging efficiency, while the single-lepton measurement used a binned profile-likelihood fit, resulting in post-fit uncertainty correlations that were accounted for in a combination.



(a) (b) (c)

Figure 1: Comparison between data and prediction of (a) b-tagged jet multiplicity in the dilepton $e\mu$ channel after the fit to data, (b) the BDT output distributions in the ℓ+$\geq$4j 1b region after the fit to data and (c) the summary of the measured cross-sections for the individual channels and their combination [2].

The $t\bar{t}$ cross-section value at $\sqrt{s} = 5.02$ TeV obtained from the combination of the measurements is found to be: $\sigma_{t\bar{t}} = 67.5 \pm 0.9$ (stat.) ± 2.3 (syst.) ± 1.1 (lumi.) ± 0.2 (beam) pb, with a total relative uncertainty of 3.9%. The result is consistent with the NNLO+NNLL QCD prediction of 68.2 ± 5.2 pb and with a previous measurement by the CMS Collaboration [5], but has a total uncertainty that is almost a factor of two smaller. This measurement provides additional constraints on the gluon distribution of the proton parton distribution functions at large Bjorken-x.

It is important to note that the measured $t\bar{t}$ cross-section value in the single-lepton channel, shown in Figure 1(c), represents the most precise measurement to date of $\sigma_{t\bar{t}}$ in the single-lepton channel with the ATLAS detector, as it is slightly more precise than than measurement at $\sqrt{s} = 13$ TeV [4], despite the much smaller data sample.

3. Differential $\sigma(t\bar{t})$ in boosted all-hadronic events at $\sqrt{s} = 13$ TeV

Measurements of single-, double-, and triple-differential cross-sections are presented for boosted top-quark pair-production in 139 fb^{-1} of 13 TeV pp data recorded by the ATLAS detector [6].

The top quarks are observed through their hadronic decay and reconstructed as large-radius jets with the leading jet having transverse momentum greater than 500 GeV. Kinematic distributions of top quarks and the $t\bar{t}$ system are measured by selecting boosted top-quark jets and unfolding the observed distributions to a particle-level and a parton-level fiducial phase spaces.

The fiducial phase-space cross-sections and differential cross-sections are compared with several NLO calculations with and without parton showering and hadronisation, and with a parton-level NNLO calculation. The differential cross-sections exhibit a precision of 10% – 20% and are in agreement with several NLO+PS predictions for most of the observables, as shown in Figure 2(a).

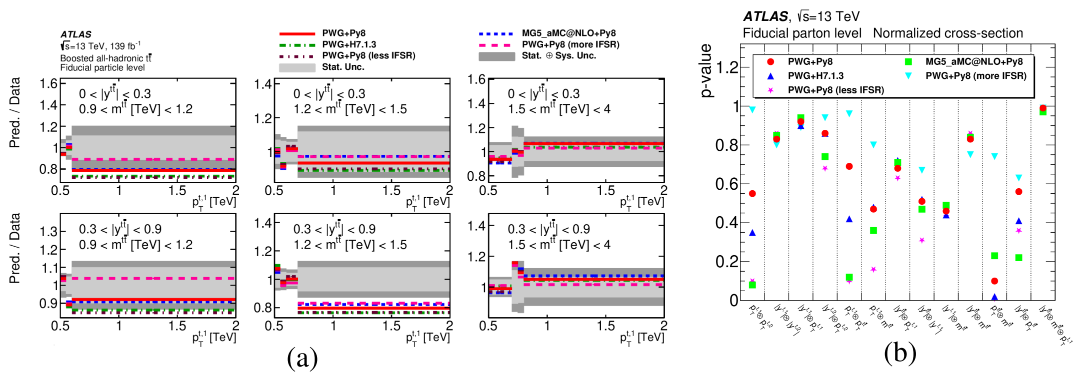


Figure 2: (a) Particle-level fiducial phase-space triple-differential cross-section as a function of the $p_{\rm T}$ of the leading top-quark jet. (b) p-values from χ^2 comparison between the measured normalised parton-level fiducial phase-space differential cross-sections and the calculations from several MC event generators [6].

Observables sensitive to gluon radiation are not well described by most NLO+PS MC calculations. Agreement with the nominal Powheg+Pythia 8 calculation improves after reweighting [7] those to the NNLO calculation. These observations point to the need for NNLO+PS MC calculations, as well as a better understanding of initial- and final-state radiation. The comparison between the measured cross-sections and a variety of MC calculations is quantified by calculating χ^2 values employing the covariance matrix and by calculating the p-values, as shown in Figure 2(b).

This measurement represents the most precise differential cross-section measured in the boosted $t\bar{t}$ all-hadronic final state, with uncertainties being a factor of two smaller than in previous ATLAS measurements [8], and up to a factor of four smaller in the region with top-quark $p_{\mathrm{T}} > 1$ TeV.

4. Differential $\sigma(t\bar{t})$ in boosted single-lepton events at $\sqrt{s} = 13$ TeV

Measurements of differential cross-sections in $t\bar{t}$ events where the hadronically decaying top quark has $p_{\mathrm{T}} > 355$ GeV and the other top quark decays into $\ell\nu b$ are presented using 139 fb^{-1} of data collected by the ATLAS experiment during pp collisions at the LHC [9].

The analysis introduces a novel technique to use the invariant mass of the selected large-radius jet from the hadronically decaying top quark to reduce the impact of jet energy scale uncertainties, shown in Figure 3(a), and significantly improves the precision compared to the previous ATLAS publication [10]. The fiducial cross-section, shown in Figure 3(b), is measured to be 1.267 ± 0.005 (stat.) ± 0.053 (syst.) pb, with a relative precision of 4.2%. The result exceeds the relative precision of NNLO+NNLL calculations and reaches the same level of precision as in the resolved topologies.

The cross-section is measured differentially as a function of variables characterising the $t\bar{t}$ system and additional radiation in the events. These measurements are compared with various NLO+PS MC generators. No single generator is able to describe all the measured variables well. Applying parton-level reweighting [7] to match NNLO in QCD predictions gives better agreement with the data for all generators, as shown in Figure 3(c), indicating that these corrections are relevant given the precision of the measurements.

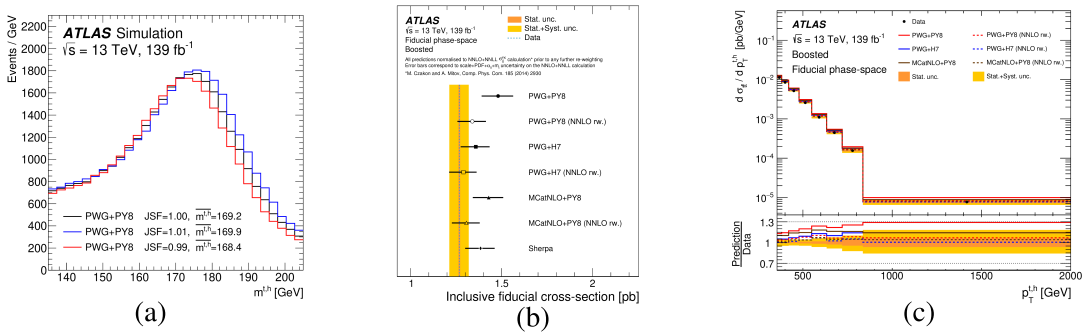


Figure 3: (a) Distribution of the invariant mass of the top-tagged jet for three example values of the jet energy scale factor. (b) Measured fiducial cross-section at particle level compared with several NLO predictions. (c) Differential measurement as a function of the hadronic top quark p_{T} compared with predictions from the NLO generators with and without the NNLO reweighting [9].

5. Summary

A new high-precision measurement of the $t\bar{t}$ production cross-section at $\sqrt{s} = 5.02$ TeV was released by the ATLAS Collaboration at the LHC, improving the total uncertainty almost by a factor of two with respect to the measurement by the CMS Collaboration. The differential measurements clearly show that reweighting the MC predictions to the NNLO parton-level prediction gives significantly better agreement between data and predictions, and that better description of data could be obtained with a full NNLO plus parton shower MC model.

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