PROCEEDINGS OF SCIENCE

Measurements of top quark production cross-sections with the ATLAS detector

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The LHC produces a vast sample of top quark pairs and single top quarks. Measurements of the inclusive top quark production cross-sections at the LHC have reached a precision of several percent, and test state-of-the-art QCD predictions. This review describes several recent ATLAS top-pair cross-section measurements at different centre-of-mass energies, as well as a recent combination of Run 1 measurements from both ATLAS and CMS, and the latest ATLAS s-channel single top production result with the full Run 2 data sample.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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PoS(ICHEP2022)875

1. Introduction

The study of top quark production and decay forms a central part of the physics programmes of the ATLAS [1] and CMS [2] experiments at the CERN Large Hadron Collider (LHC). Top quark production in proton–proton collisions at LHC energies is dominated by top quark-antiquark pair-production ($t\bar{t}$) via the strong interaction, with a cross-section $\sigma_{t\bar{t}}$ of about 830 pb at $\sqrt{s} = 13$ TeV. Three electroweak single-top production processes are also important, with smaller cross-sections of about 220 pb (t-channel), 70 pb (Wt) and 10 pb (s-channel). Within the Standard Model, top quarks almost always decay to a b quark and a W boson, and the final states in the detector are determined by the decay modes of the W: a charged lepton and a neutrino, or a quark-antiquark pair ($q\bar{q}$). Dileptonic final states offer the purest samples of $t\bar{t}$ events, but only 2% of $t\bar{t}$ events produce the 'golden' $e\mu$ decay mode, and 'lepton+jets' events, where one W boson decays leptonically and the other to a $q\bar{q}$ pair, are also useful. Single-top events are more challenging to select, and the measurements typically exploit the leptonic W decay mode, combined with multivariate analysis techniques to separate the signal from the dominant $t\bar{t}$ and W+jets background contributions.

2. $t\bar{t}$ cross-section measurements at $\sqrt{s} = 13$ TeV

The most precise $t\bar{t}$ cross-section measurements make use of the $e\mu$ dilepton channel, counting events with an opposite-charge $e\mu$ pair and exactly one or exactly two b-tagged jets [3]. As shown in Figure 1(left), these samples are about 88/96% pure (for one/two b-tags) in $t\bar{t}$ events, with most of the background coming from the associated production of a W boson and single top quark (Wt). The two event counts allow the product of jet reconstruction and b-tagging efficiencies to be measured from the data, minimising the associated systematic uncertainties. The remaining uncertainty is dominated by the knowledge of the integrated luminosity, and uncertainties modelling the leptonic acceptance. The result is given in Table 1, and compared to the QCD prediction calculated with the `top++` program [4] at next-to-next-to-leading order (NNLO) with next-to-next-to-leading logarithmic (NNLL) gluon resummation, using the Run 1 PDF4LHC prescription for parton distribution function (PDF) uncertainties [5]. The measurement is in excellent agreement with this prediction, and the experimental uncertainty is half that of the prediction.

ATLAS has also measured $\sigma_{t\bar{t}}$ in the lepton+jets channel, making use of events with a single electron or muon, missing transverse momentum (whose magnitude is denoted by $E_{\mathrm{T}}^{\mathrm{miss}}$) and at least four jets [6]. Three signal regions were selected, with different jet and b-tagged jet multiplicity requirements, and $t\bar{t}$ purities in the range 80–92%. The measurement was performed using a profile likelihood fit to a different discriminating variable in each signal region, *e.g.* the minimum lepton-jet invariant mass was used in the region with exactly four jets with two being b-tagged, as shown in Figure 1(right). The fit constrains the signal, background and detector uncertainties *in situ*, giving the result shown in Table 1, which is again in good agreement with the QCD prediction. The uncertainties are dominated by those from $t\bar{t}$ modelling and the jet energy scale, and the total uncertainty of 4.6% is about a factor two higher than in the $e\mu$ channel.

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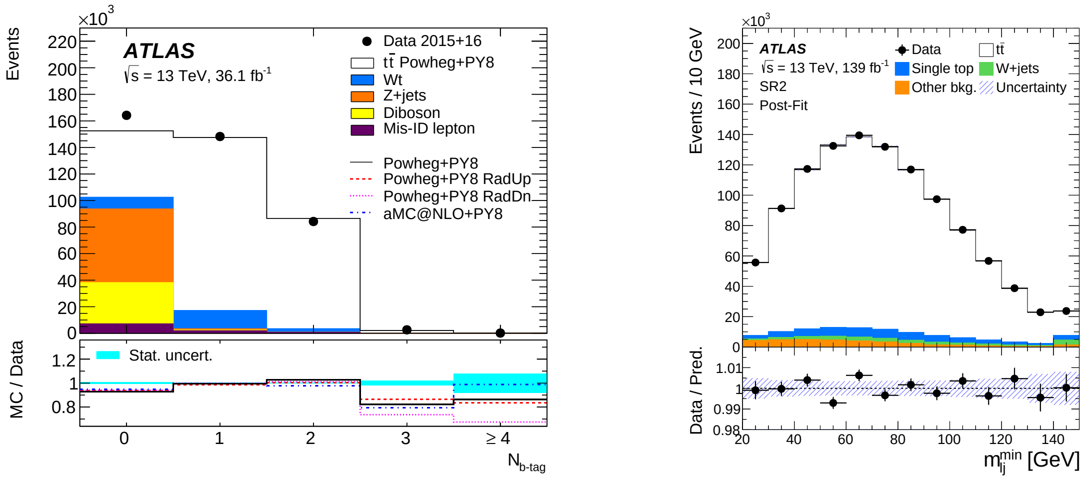

Figure 1: (left) b-tagged jet multiplicity in opposite-charge $e\mu$ events in the $\sqrt{s}$ = 13 TeV dilepton analysis [3]; (right) minimum invariant mass of a lepton-jet pair in signal region 2 of the $\sqrt{s}$ = 13 TeV lepton+jets analysis, with the data compared to the post-fit prediction [6].

$\sqrt{s}$ (TeV)	QCD prediction (pb)	Channel	Measurement (pb)	Stat. (%)	Syst. (%)	Lumi. (%)	E_{beam} (%)	Total (%)
13	$832 \pm 35^{+20}_{-29}$	$e\mu$	826 ± 20	0.4	1.4	1.9	0.2	2.4
		ℓ+jets	830 ± 38	0.1	4.3	1.7	0.2	4.6
5.02	$68.2 \pm 4.8^{+1.9}_{-2.3}$	$\ell\ell$	65.7 ± 4.9	6.8	2.5	1.8	0.3	7.5
		ℓ+jets	68.2 ± 3.1	1.3	4.2	1.6	0.3	4.5
		Comb.	67.5 ± 2.7	1.3	3.4	1.6	0.3	3.9

Table 1: Summary of predictions and measurements of the $t\bar{t}$ production cross-section at $\sqrt{s}$ = 13 TeV [3, 6] and $\sqrt{s}$ = 5.02 TeV [7]. The predictions are calculated at NNLO+NNLL in QCD with the first uncertainty corresponding to PDF and α_S uncertainties, and the second to QCD scale variations. The experimental results are given together with the breakdown of uncertainties into statistical, systematic, integrated luminosity and LHC beam energy uncertainties.

3. $t\bar{t}$ cross-section measurements at $\sqrt{s}$ = 5.02 TeV

ATLAS recorded a small 257 pb^{-1} data sample at $\sqrt{s}$ = 5.02 TeV in November 2017, giving the opportunity to measure the $t\bar{t}$ cross-section at this energy [7]. The fraction of $t\bar{t}$ events produced from $q\bar{q}$ annihilation is 25%, compared to 11% at 13 TeV, and the average Bjorken-x of the initial-state partons is larger, potentially allowing further constraints on the proton PDFs. In the dilepton analysis, the $e\mu$+b-tagged jets technique was extended to also include the same-flavour channels, using the dilepton invariant mass to separate the $t\bar{t}$ events from the dominant $Z(\rightarrow ee/\mu\mu)$+b-jets background (Figure 2(left)). The resulting measurement has a total uncertainty of 7.5%, dominated by the statistical uncertainty due to the small sample size (Table 1). In the lepton+jets channel, events with at least two jets, including at least one b-tagged jet, were selected, and divided into six regions with different jet and b-jet multiplicity requirements. In each region, a boosted decision tree (BDT) was used to separate signal and background (see *e.g.* Figure 2(right)), and a profile likelihood fit to all regions was used to determine $\sigma_{t\bar{t}}$ and constrain systematic uncertainties. The

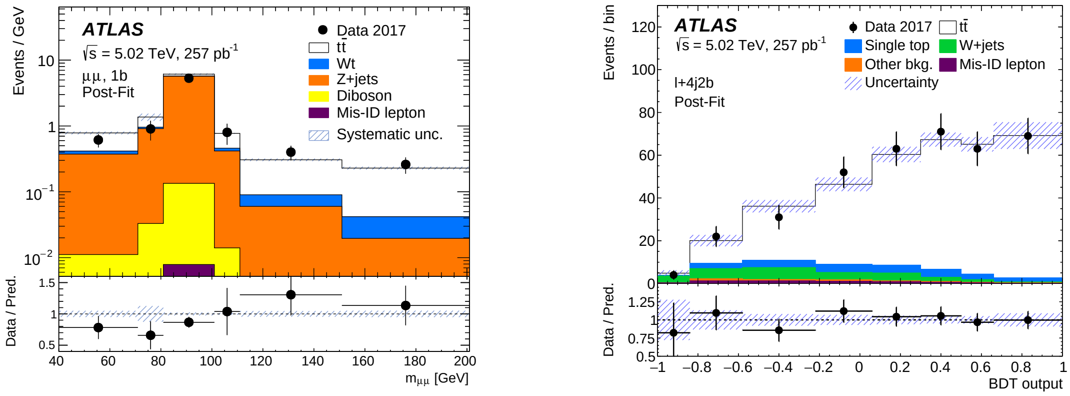

Figure 2: Illustrations of fits to determine the $t\bar{t}$ cross-section at $\sqrt{s}$ = 5.02 TeV [7]; (left) fit to the dimuon invariant mass distribution in the opposite-charge $\mu\mu$ plus one b-tagged jet sample; (right) fit to the BDT output distribution in the one lepton plus four jets sample with two b-tagged jets.

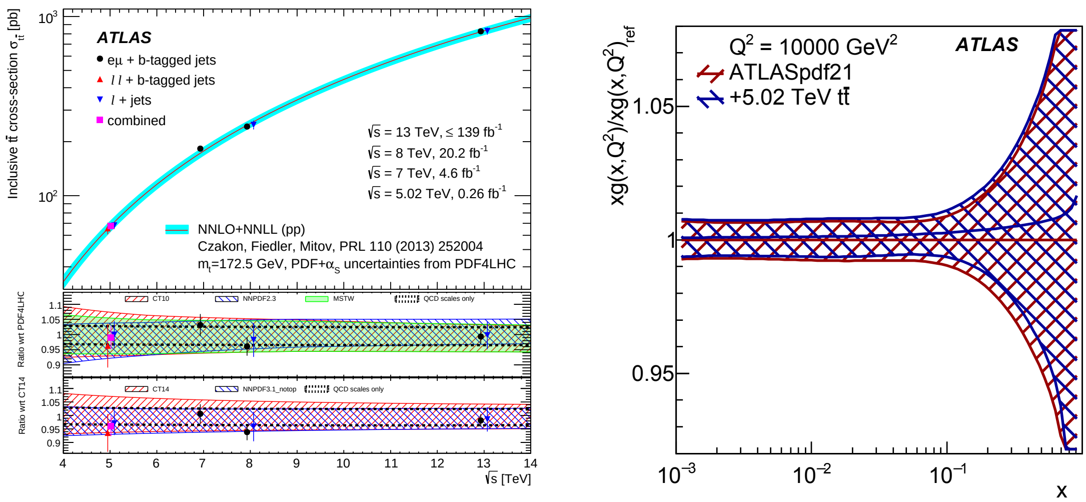

Figure 3: (left) Summary of the inclusive $t\bar{t}$ cross-section measurements from ATLAS in the dilepton and lepton+jets final states at different centre-of-mass energies, compared to QCD NNLO+NNLL predictions using various PDF sets; (right) Ratio of the gluon PDF determined using the data of the ATLASpdf21 fit plus the constraint from the $\sqrt{s}$ = 5.02 TeV $t\bar{t}$ cross-section measurement, to that from the ATLASpdf21 fit alone [7].

result (Table 1) has an uncertainty of 4.5%, slightly better than that achieved in this channel at $\sqrt{s}$ = 13 TeV, due mainly to the use of the BDTs and the smaller $t\bar{t}$ modelling uncertainties. The dilepton and single-lepton results were combined, to give a final result with an uncertainty of 3.9%, which is again in good agreement with the QCD prediction (Table 1).

Figure 3(left) shows the ATLAS measurements of $\sigma_{t\bar{t}}$ at different centre-of-mass energies $\sqrt{s}$ from 5 to 13 TeV, which are in excellent agreement with QCD NNLO+NNLL predictions over the full range. Figure 3(right) shows the change in the gluon PDF when the $\sqrt{s}$ = 5.02 TeV $\sigma_{t\bar{t}}$ result is added to the ATLASpdf21 PDF fit based on previous ATLAS W, Z and $t\bar{t}$ measurements together with deep inelastic scattering data from HERA. A small decrease in the uncertainty is visible, corresponding *e.g.* to a 5% reduction at $x \approx 0.1$.

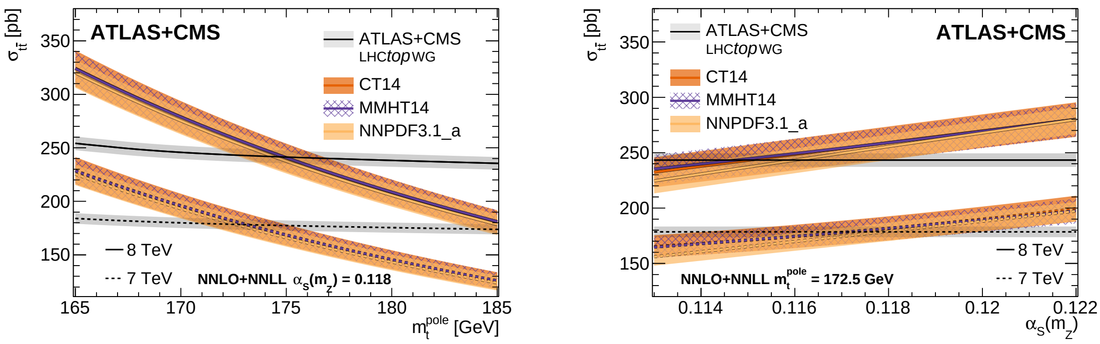

Figure 4: Dependence of the predicted and measured $t\bar{t}$ cross-sections on (left) the top quark pole mass m_t^{pole} and (right) the strong coupling α_S. The predictions are shown for various different PDF sets [8].

4. Combination of ATLAS and CMS Run 1 results

The legacy $\sigma_{t\bar{t}}$ measurements from ATLAS and CMS in the $e\mu$ channel at $\sqrt{s}$ = 7 and 8 TeV have recently been combined in a joint analysis by the two collaborations, taking into account correlated uncertainties between experiments and centre-of-mass energies [8]. The results reach a precision of about 2.5%, relatively 25–30% smaller than the individual experiment results at each $\sqrt{s}$ value, and are in good agreement with QCD predictions using recent PDF sets. Since, for a given PDF set, the $\sigma_{t\bar{t}}$ prediction depends on both the top quark pole mass m_t^{pole} and the strong coupling α_S, the results can be interpreted as measurements of one of these quantities, fixing the other via external measurements. This procedure is illustrated in Figure 4, which shows the large dependence of the $\sigma_{t\bar{t}}$ prediction on m_t^{pole} and α_S, and also the mild dependence of the measured $\sigma_{t\bar{t}}$ values on m_t^{pole}, due to changes in the predicted $t\bar{t}$ event kinematics and experimental acceptance with top quark mass (the corresponding dependence on α_S is negligible). Fitting the combined results from $\sqrt{s}$ = 7 and 8 TeV simultaneously and using a version of the NNPDF3.1 PDF set which does not include other top quark measurements gives $m_t^{\text{pole}} = 173.4^{+1.8}_{-2.0}$ GeV (assuming $\alpha_S = 0.118 \pm 0.001$) or $\alpha_S = 0.1170^{+0.0021}_{-0.0018}$ (assuming $m_t^{\text{pole}} = 172.5 \pm 1.0$ GeV). The α_S measurement is more precise than previous α_S extractions from $t\bar{t}$ events [8].

5. Single top production in the s-channel

The s-channel single top production mode, $q\bar{q} \to t\bar{b}$ followed by $t \to Wb \to \ell\nu b$ gives rise to a final state with an electron or muon, E_T^{miss}, and exactly two b-tagged jets. The small predicted cross-section of $\sigma_{s\text{-chan}} = 10.3 \pm 0.4$ pb and large background from $t\bar{t}$ and W+b-jets events makes this analysis particularly challenging. The recent ATLAS analysis of the full Run 2 data sample [9] made use of a matrix element method to calculate the compatibility of the kinematics of each selected event with the signal or various background hypotheses, expressed as a per-event signal probability $P(S|X)$. After validating the modelling of $P(S|X)$ in background-dominated regions, the results of the profile likelihood fit to the $P(S|X)$ distribution in the signal region are shown in Figure 5. The signal-to-background ratio in the highest-purity bin is about 10%, and the largest uncertainties come from the normalisation of the $t\bar{t}$ background and the jet energy scale. The result of $\sigma_{s\text{-chan}} = 8.2 \pm 0.6(\text{stat})^{+3.4}_{-2.8}(\text{syst})$ pb has a significance of 3.3 standard deviations above

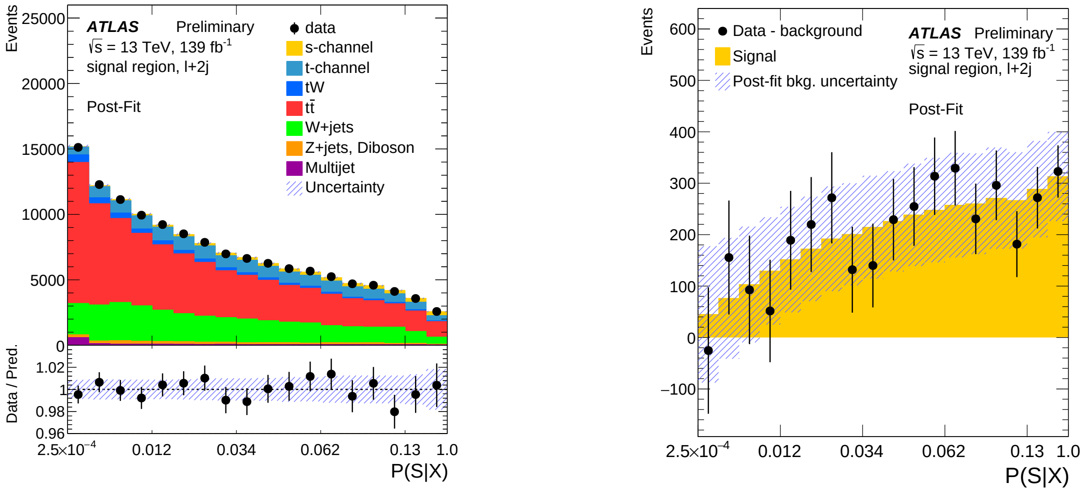

Figure 5: (left) Distribution of the discriminant $P(S|X)$ in the signal region after the fit to data, and (right) after background subtraction, comparing the data to the fitted signal component, in the $\sqrt{s}$ = 13 TeV s-channel single top analysis [9].

the background-only hypothesis, similar to the result obtained at $\sqrt{s}$ = 8 TeV, where the dataset is smaller but the signal-to-background ratio is more favourable.

6. Conclusion

Inclusive $t\bar{t}$ cross-section studies are reaching maturity at LHC Run 2, with individual ATLAS measurements having uncertainties as small as 2.4%. All measurements are in good agreement with the QCD NNLO+NNLL predictions, and can be interpreted to constrain PDFs, or to extract values for m_t^{pole} or α_S, limited by the uncertainties on the theoretical predictions (in particular QCD scale uncertainties). Single top cross-section measurements are still typically limited by the experimental systematic uncertainties, and full Run 2 results in the t and Wt channels are still to come.

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