Measurements of top-quark pair and single top total cross sections, and in-situ systematic constraints

OLGA BESSIDKAIA BYLUND
ON BEHALF OF THE ATLAS AND CMS COLLABORATIONS

Bergische Universität Wuppertal, GERMANY

Measuring the total cross sections of top-quark pair production and single top processes at high precision tests the predictions of the Standard Model and can bring better understanding of properties such as the top-quark mass, electroweak couplings, lepton universality and proton parton distribution functions. Some of the recent measurements by the ATLAS and CMS experiments at the Large Hadron Collider are outlined in this document. Experimental methods are given particular attention, particularly the determination of lepton isolation efficiencies in the ATLAS dilepton measurement of top-quark pair production.

PRESENTED AT

13th International Workshop on Top Quark Physics
Durham, UK (videoconference), 14–18 September, 2020

Copyright [2018] CERN for the benefit of the ATLAS and CMS collaborations, CC-BY-4.0 license.
Introduction  Measuring the total production cross sections of top-quark pairs ($t\bar{t}$) and in single top-quark production tests the Standard Model and can help us to better understand various properties of the top-quark, electroweak couplings and the structure of the proton. Some recent results from ATLAS [1] and CMS[2] at the LHC are outlined below, with a focus on in-situ techniques in the $t\bar{t}$ dilepton analysis by ATLAS.

Top-quark pair production in the dilepton channel (ATLAS)  Measuring $t\bar{t}$ in the dilepton channel while using innovative experimental techniques, the ATLAS experiment has pushed the precision on the measured cross section down to 2.4%. A partial Run 2 dataset of 36.1 fb$^{-1}$ collected at 13 TeV collision energy in 2015-2016 is used. In the selection, an electron-muon pair of opposite-sign charge is required along with jets, of which either one or two are $b$-tagged. The equations for the observed number of events in the 1 $b$-tag and 2 $b$-tag regions ($N_1$, $N_2$) are constructed:

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1-C_b\epsilon_b) + N_{1bkg}$$  \hspace{1cm} (1)

$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2C_b\epsilon_b^2 + N_{2bkg}$$  \hspace{1cm} (2)

and solved for $\sigma_{t\bar{t}}$ and the $b$-tagging efficiency $\epsilon_b$. The correlation coefficient $C_b$ for reconstructing and tagging the two $b$-jets is determined from simulation and $N_{1,2}^{bkg}$ denotes the background contribution. The efficiency to pass the dilepton selection $\epsilon_{e\mu}$ is determined from simulation and then corrected using data; it is lower in 2016 than in 2015. The contamination from QCD multijet events where leptons fail the isolation requirements is estimated using a selection where the cut on the isolation variable $|d_0|/\sigma_{d_0}$ has been inverted. The isolation efficiencies are corrected, accounting for this contamination, by up to 1% for electrons and 0.4% for muons, see Fig. 1.

Using the BLUE method [4, 5], the datasets from 2015 and 2016 are combined

Figure 1: The corrections for the lepton isolation efficiencies, binned in lepton transverse momentum $p_T$ and pseudorapidity $|\eta|$, for the measurement of $t\bar{t}$ in the dilepton channel by the ATLAS experiment [3]. The baseline from simulation is shown in turquoise and the corrections from data in black.

Using the BLUE method [4, 5], the datasets from 2015 and 2016 are combined
with weights of 0.49 and 0.51 respectively (note that the 2016 dataset is much larger), which improves the total sensitivity by 9% compared to treating them as one dataset. Each source of systematic uncertainty is evaluated by changing all relevant input quantities coherently and re-solving Eqs. (1), (2). The cross section is measured to be:

$$\sigma_{tt} = 826.4 \pm 3.6\text{(stat)} \pm 11.5\text{(syst)} \pm 15.7\text{(lumi)} \pm 1.9\text{(beam)} \text{pb},$$

which improves the total sensitivity by 9% compared to treating them as one dataset. Each source of systematic uncertainty is evaluated by changing all relevant input quantities coherently and re-solving Eqs. (1), (2). The cross section is measured to be:

$$\sigma_{tt} = 826.4 \pm 3.6\text{(stat)} \pm 11.5\text{(syst)} \pm 15.7\text{(lumi)} \pm 1.9\text{(beam)} \text{pb},$$

which is the most precise inclusive measurement of $t\bar{t}$ to date and in agreement with

$$\sigma_{tt}^{\text{theo}} = 832 \pm 35(\text{pdf} + \alpha_S)_{-29}^{+20}(\text{scale}) \text{pb}.$$  

The sensitivity of this measurement is limited by the precision on the luminosity, amounting to an uncertainty of 1.9% on the cross section. The total systematic uncertainty of 1.39% has the main contributions from the normalisation of the $tW$ background and the modelling uncertainties for $t\bar{t}$. The dilepton analysis is a priori sensitive to modelling uncertainties, but their impact has been reduced by measuring the lepton isolation efficiencies in-situ: when comparing the predictions from different generators, the different predictions for these efficiencies need not be included.

Additionally, the ratio of $t\bar{t}$ to $Z$ production is evaluated to nearly cancel the large dependency on the luminosity and constrain proton p.d.fs. Ratios of $t\bar{t}$ production at different collision energies and double ratios of $t\bar{t}$ to $Z$ production at different energies are also computed, leading to further cancellations.

**Top-quark pair production in the dilepton channel (CMS)** In the $t\bar{t}$ cross section measurement in the dilepton channel by CMS [6], in addition to $e^\pm \mu^\mp$, the opposite-sign $ee$ and $\mu\mu$ channels are considered. 35.9 fb$^{-1}$ of data collected at 13 TeV collision energy is used for the measurement. A total of 28 event categories are defined by splitting by jet and $b$-jet multiplicity in these channels: with 0, 1 or 2 $b$-tagged jets and 0, 1, 2 or at least 3 additional un-tagged jets (the no $b$-jet categories are only used for $e\mu$ events). A simultaneous template fit using all event categories is performed, fitting the transverse momentum $p_T$ of the additional jet with highest $p_T$, if defined, otherwise the event yield is fitted. A priori, the identification efficiency is known to better precision for muons than for electrons. By using the different lepton channels, the electron identification efficiency is constrained to the precision for muons. Using categories with different $b$-jet multiplicities allows constraining the efficiency for identifying and selecting a $b$-jet. The total cross section is measured to:

$$\sigma_{tt} = 803 \pm 2\text{(stat)} \pm 25\text{(syst)} \pm 20\text{(lumi)} \text{pb},$$

in agreement with theory. The main uncertainties relate to the integrated luminosity and lepton identification and isolation, with an impact of 2.5% and 2.0% respectively.

**Top-quark pair production, lepton+jets (ATLAS)** The ATLAS experiment has performed a measurement of the $t\bar{t}$ cross section in the lepton+jets channel using the full Run 2 dataset (139 fb$^{-1}$) at 13 TeV [7]. Exactly one charged lepton is required as well as at least four jets. Three event categories are defined, split by jet and $b$-jet multiplicity with: 4 jets with 1 $b$-tagged in the SR1 category, 4 jets of which 2 are...
\(b\)-tagged in SR2 and at least 5 jets of which 2 are \(b\)-tagged in SR3. The aplanarity is used as the fitting variable in SR1, the minimum invariant mass over all lepton-jet pairs in SR2 and a distance parameter between the jets in SR3. The result is:

\[ \sigma_{t\bar{t}} = 830 \pm 0.4\text{(stat)} \pm 36\text{(syst)} \pm 14\text{(lumi)} \text{ pb}, \]

with a precision of 4.6% and in agreement with the theoretical prediction. This is the most precise inclusive \(t\bar{t}\) measurement in this channel. The measurement is systematically limited, with the main uncertainties originating from parton shower systematics, followed by luminosity and final state radiation.

**Top-quark pair production with a hadronic \(\tau\) (CMS)** CMS has measured \(t\bar{t}\) production in a selection targeting a hadronically decaying \(\tau\) lepton and one electron or muon, using 35.9 \(\text{fb}^{-1}\) of data collected at 13 TeV collision energy [8]. This channel corresponds to around 5% of all \(t\bar{t}\) final states and serves as a test of lepton universality. One electron or muon, a hadronic \(\tau\) candidate of opposite-sign charge and two jets are required, of which at least one should be \(b\)-tagged. The selection is further split into categories by cutting on a distance parameter between the jets.

The \(\tau\) leptons are reconstructed with the hadron-plus-strips (HPS) algorithm. In each jet, a charged hadron is combined with other nearby charged hadrons or photons and the decay modes of the \(\tau\) are identified. Electrons and photons are clustered in strips along the bending direction of the trajectory, which enhances the identification of \(\pi^0\) mesons by taking into account the early showering of photons. A boosted decision tree (BDT) is trained to separate HPS \(\tau\) candidates from QCD multijet events. The largest background in the measurement comes from \(t\bar{t}\) events with a jet misidentified as originating from a \(\tau\). The uncertainty in the efficiency of \(\tau\) identification is 5% and has the highest impact on the precision. To extract the cross section, the transverse mass \(M_T(\ell, E_{\text{Tmiss}})\) is fitted in a profile likelihood fit, giving:

\[ \sigma_{t\bar{t}} = 781 \pm 7\text{(stat)} \pm 62\text{(syst)} \pm 20\text{(lumi)} \text{ pb}, \]

which is consistent with the Standard Model prediction. This is the first measurement of \(t\bar{t}\) production with a \(\tau\) lepton in the final state performed at 13 TeV. The ratio to \(t\bar{t}\) production in the dilepton channel is computed and found to be in agreement with lepton universality.

**Single top production in the \(t\)-channel (CMS)** The CMS experiment has measured the single top production cross section in the \(t\)-channel [9], using 35.9 \(\text{fb}^{-1}\) of data collected at 13 TeV. This process is charge asymmetric due to the valence quark content of the colliding protons. An electron or muon is required in the selection together with jets. In the signal-enriched category exactly one \(b\)-tagged jet and one additional jet are required. The cross sections are measured separately for top and top antiquark production by splitting the events into categories by the charge of the lepton and extracting them in a simultaneous fit. Their ratio \(R_t = \sigma_t/\sigma_{\bar{t}}\), which is sensitive to proton p.d.fs, is also determined, see Fig. [2] BDT algorithms are employed to enhance the separation of the signal from the large backgrounds consisting
Figure 2: Feynman diagrams illustrating $t$-channel production and the measured value for $R_t$ by the CMS experiment \[9\], compared to different p.d.fs.

mostly of $t\bar{t}$ and $W+\text{jets}$ events. Experimental uncertainties and uncertainties on the background rates and modelling enter as nuisance parameter in the profile likelihood fit, which allows them to be constrained. The uncertainties relating to signal modelling are not profiled to avoid propagating any constraints on them to the full phase space, where they may not be valid. The cross sections and their ratio are measured to be:

$$\sigma_t = 130 \pm 1\text{(stat)} \pm 19\text{(syst)} \text{ pb}$$
$$\sigma_{\bar{t}} = 77 \pm 1\text{(stat)} \pm 12\text{(syst)} \text{ pb} \quad , \quad R_t = 1.68 \pm 0.02\text{(stat)} \pm 0.05\text{(syst)} .$$

This is consistent with the predictions from the Standard Model:

$$\sigma_t^{\text{theo}} = 136.0^{+4.1}_{-2.9}\text{(scale)} \pm 3.5\text{(pdf + } \alpha_S) \text{ pb}$$
$$\sigma_{\bar{t}}^{\text{theo}} = 81.0^{+2.5}_{-1.7}\text{(scale)} \pm 3.2\text{(pdf + } \alpha_S) \text{ pb} \quad , \quad R_t = 1.68 .$$

### Single top combination and measurements of $tW$

ATLAS and CMS have performed a combination of single top measurements at 7 and 8 TeV \[10\] using the BLUE method. The results are summarised in Fig. 3. Since then, ATLAS also published a measurement of $tW$ production at 8 TeV in the challenging lepton+jets channel \[11\], using 20.2 $\text{fb}^{-1}$ of data, obtaining:

$$\sigma_{tW} = 26 \pm 7 \text{ pb} ,$$

with a statistical uncertainty of 4 pb. The result agrees with the theoretical prediction:

$$\sigma_{tW}^{\text{theo}} = 22.4 \pm 0.6\text{(scale)} \pm 1.4\text{(pdf)} \text{ pb} .$$

CMS reported the most precise measurement of $tW$ at 13 TeV \[12\] with 35.9 $\text{fb}^{-1}$:

$$\sigma_{tW} = 63.1 \pm 1.8\text{(stat)} \pm 6.4\text{(syst)} \pm 2.1\text{(lumi)} \text{ pb} ,$$

consistent with

$$\sigma_{tW}^{\text{theo}} = 71.7 \pm 1.8\text{(scale)} \pm 3.4\text{(pdf)} .$$
Figure 3: The combination of single top measurements by ATLAS and CMS at 7 and 8 TeV [10]. The theoretical prediction is shown in gray, the ATLAS result in blue, the CMS result in red and the combination in black.

Summary  A brief overview has been given of some recent total cross section measurements of $t\bar{t}$ and single top production by ATLAS and CMS at the LHC, with unprecedented precision reached in several channels. Particular attention is paid to the in-situ techniques in the ATLAS dilepton measurement that allows for the reduction of systematic uncertainties. A highlight from CMS is the first measurement of $t\bar{t}$ production at 13 TeV with selection targeting a $\tau$ lepton. Comparisons and combinations of the results from ATLAS and CMS help verify the results and improve the precision.

References
[1] ATLAS Collaboration, 2008 JINST 3 S08003.
[2] CMS Collaboration, 2008 JINST 3 S08004.
[3] ATLAS Collaboration, Eur.Phys.J.C 80 (2020) 6, 528.
[4] L. Lyons, D. Gibaut, P. Clifford, Nucl. Instrum. Methods A 270, 110 (1988).
[5] A. Valassi, Nucl. Instrum. Methods A 500, 391 (2003).
[6] CMS Collaboration, Eur.Phys.J.C 79 (2019) 5, 368.
[7] ATLAS Collaboration, Phys. Lett. B 810 (2020) 135797.
[8] CMS Collaboration, JHEP 02 (2020) 191.
[9] CMS Collaboration, Phys.Lett.B 800 (2020) 135042.
[10] ATLAS Collaboration and CMS Collaboration, JHEP 05 (2019) 088.

[11] ATLAS Collaboration, 2007.01554, submitted to EPJC.

[12] CMS Collaboration, JHEP 10 (2018) 117.