Top-quark production in ATLAS

Danilo Enoque Ferreira de Lima
Kelvin Building, University of Glasgow, Glasgow G12 8QQ, UK
E-mail: dferreir@mail.cern.ch

Abstract. Measurements of the top-quark production cross-sections in proton-proton collisions with the ATLAS detector at the Large Hadron Collider are presented. The measurement require no, one or two electrons or muons in the final state (hadronic, single lepton or dilepton channel). In addition, the decay modes with tau leptons are presented (channels with tau leptons). Differential measurements of $t\bar{t}$ final states are presented, in particular, measurements that are able to constrain the modelling of additional parton radiation. Measurements of single top-quark production in the $t$- and $Wt$-channels are presented and determination of the CKM matrix element $|V_{tb}|$ is discussed. In addition, the $s$-channel production is explored and limits on exotic production in single top-quark processes are discussed. This also includes the search for flavour changing neutral currents and the search for additional $W'$ bosons in the $s$-channel.

1. Introduction
The top quark is the heaviest particle in the Standard Model [1]. It decays into a $W$-boson and a $b$-quark almost exclusively. This characteristic has been explored in the measurement of its production cross-section by analysing the final states produced by the $W$-boson and the $b$-quark.

The Large Hadron Collider (LHC) [2] is a 27 km circumference synchrotron, which has a set of particle detectors which measure the final state particles in proton-proton collisions. The ATLAS [3] experiment is a general purpose detector in the LHC, which has many subdetectors, such as the Inner Detector, the Calorimeters and the Muon Spectrometer. A 2 T magnetic field bends the outgoing charged particles’ trajectory. The Inner Detector reconstructs the tracks of charged particles, which are used to measure their momentum and charge with an $|\eta| < 2.5$ coverage. The Calorimeter measures the energy of the particles with a coverage of $|\eta| < 4.9$ and, in the region of overlap with the Inner Detector, the electromagnetic calorimeter is finely granular, aiming at precision measurements for electrons and photons. The Muon Spectrometer is specifically designed to measure the momenta of muon tracks, with a coverage of $|\eta| < 2.7$. The ATLAS detector has many physics goals, such as testing the Standard Model and searching for new physics. It is designed to have $4\pi$ solid angle coverage.

In ATLAS, the top quark may be produced in top-antitop pairs or without its antiparticle in the “single-top channel”, through dominant strong and electroweak production. In the top-pair channel the final states can be classified into dilepton, if both top-quarks generate leptons in the final state; single-lepton, if only one top-quark decay product includes a lepton; or hadronic, if both top-quarks final state particles are quarks.

Results for the single-top production are also shown, with a measurement of its production in the $t$-channel, evidence for $Wt$-channel and a search for the $s$-channel.
Measurements of the top-quark production in ATLAS are shown in this document as a function of a set of observables, in different channels.

2. Top pair production

In the semileptonic final state of the $t\bar{t}$ system, the inclusive cross-section has been measured by building a likelihood-ratio discriminant $D_i$ for the signal and each background \[4\]. The likelihood functions were calculated using the lepton $\eta$, $\exp(-8 \times A)$ (where $A$ is the aplanarity), the $p_T$ of the leading jet and the $H_{T,3p}$ (a ratio of transverse to longitudinal momenta). This was carried out for the electron and muon channels. The likelihood discriminant for data and simulation is given in Figure 1, for the $\sqrt{s} = 7$ TeV analysis. To enhance heavy flavour content, at least one $b$-jet was required, using multivariate techniques for the $b$-tagging algorithm. In this analysis information from the 3, 4 and $\geq 5$ jet multiplicities was used and a cut on the transverse mass of the missing transverse energy and the lepton transverse momentum was applied to reduce the QCD-multijet background.

The $t\bar{t}$ cross-section was extracted through a maximum-likelihood fit using templates for the discriminant $D_i$, which resulted in a measurement of $\sigma_{t\bar{t}} = 179.0 \pm 3.9$(stat.) $\pm 9.0$(syst.) $\pm 6.6$(lumi.) pb. Systematic uncertainties were found to be mainly due to the generator variations (3%), followed by the jet-energy scale (2.4%).

A similar analysis was carried out using the $\sqrt{s} = 8$ TeV data \[5\], but building a likelihood discriminator using only the lepton $\eta$ and the transformed aplanarity. Furthermore, harder cuts on leptons ($p_T > 40$ GeV) were used to reduce the fake leptons contributions. With this setup, a likelihood fit was done to the likelihood discriminant resulting in an inclusive cross-section measurement of $\sigma_{t\bar{t}} = 241 \pm 2$(stat.) $\pm 31$(syst.) $\pm 9$(lumi.) pb. The measurement is in good agreement with the approximate NNLO calculations from HATHOR, $\sigma_{t\bar{t}}^{\text{theory}} = 238^{+22}_{-24}$ pb for a top-quark mass of $m_t = 172.5$ GeV.
An alternative $b$-tagging algorithm using leptonically decaying $b$-jets has been used to perform a single-lepton channel analysis [6]. It takes advantage of the smaller systematic uncertainty associated with this $b$-tagging algorithm, which demands a match between a muon and a $b$-jet candidate. The muon must satisfy quality cuts, including $p_T > 4$ GeV, a match criteria based on a $\chi^2$ between the Muon Spectrometer and the Inner Detector, that it has $\Delta R > 0.01$ from the $\mu$ coming from the $W$-boson decay and that it has $\Delta R < 0.5$ to the $b$-jet candidate decay. The efficiency of this $b$-jet selection is shown in Figure 2. The final measured cross-section was extracted by subtracting the background estimate and correcting for the selection efficiency, which results in a cross-section of $\sigma_{l\ell} = 165 \pm 2\text{(stat.)} \pm 17\text{(syst.)} \pm 3\text{(lumi.)} \text{pb at } \sqrt{s} = 7 \text{ TeV}$.

![Figure 3](image-url)  
**Figure 3.** Mass of the tagged $\tau$ and jet for the $\tau + e/\mu$ analysis and fitted track multiplicity for the $\tau +$ jets analysis. Statistical uncertainties are shown for data and systematic uncertainties are shown on the left, for simulation. The solid circles indicate data points and the histograms represent the simulation expectation [7] [8].

A special treatment is given to final states including the $\tau$-lepton, for the $\tau$ hadronic decay. For the $\tau + e/\mu$+ jets final state [7] at $\sqrt{s} = 7$ TeV, a set of Boosted Decision Trees are used to identify the $\tau$, separate it from electrons ($BDT_e$) and separate it from other jets ($BDT_j$). Since some backgrounds are charge symmetric, it is possible to cancel them by subtracting a set of Opposite Sign (OS) selected sample from a Same Sign (SS) sample. The final cross-section is then extracted from the $(OS - SS)$ yields after a $\chi^2$ fit to the $BDT_j$ output. The mass of the tagged $\tau +$ jet system is shown for selected events in Figure 3(a). The final measured cross-section is $\sigma_{l\ell} = 186 \pm 13\text{(stat.)}20\text{(syst.)} \pm 7\text{(lumi.)} \text{pb}$.

A $\tau +$ jet analysis [8] was also performed at $\sqrt{s} = 7$ TeV from hadronic $\tau$ decays, using a one dimensional fit to the number of tracks associated with the $\tau$ candidate, taking advantage of the fact that a $\tau$ decays preferentially into one or three charged particles. An extended binned likelihood fit was applied to fit the

![Figure 4](image-url)  
**Figure 4.** Summary of the $t\bar{t}$ cross-section measurements in the dilepton ($e/\mu$) channel at 7 TeV for each channel and the combined measurement [9].
observed events to the number of $\tau + e$. Figure 3(b) shows the track multiplicity distribution and associated fit for signal and backgrounds. The number of $\tau + e$ events were then scaled to the fraction of $\tau$ events within this selection, to extract the number of $\tau + \text{jets}$ events. At least two $b$-tagged particles, five jets and a veto on electrons or muons were applied to suppress the backgrounds. The final cross-section was measured by correcting for the efficiency of the selection, which results in $\sigma_{tt} = 194 \pm 18(\text{stat.}) \pm 46(\text{syst.}) \text{ pb}$.

A cross-section measurement has been performed using the dilepton final state [9], by selecting electrons and muons using the $\sqrt{s} = 7$ TeV data. It requires two oppositely-charged lepton candidates, two high-$p_T$ central jets, and applies constraints on the mass of the two lepton system to reduce the background contribution. A profile likelihood fit was used to estimate the cross-section in different channels and combine the results. A missing transverse energy cut was applied in the $ee$ and $\mu\mu$ channels, while an $H_T$ cut was used in the $e\mu$ channel to suppress the $Z/\gamma^* + \text{jets}$ contribution\(^1\). A summary of cross-section measurements in the dilepton final state is shown in Figure 4.

### 3. Relative $t\bar{t}$ differential cross-section measurements

Besides inclusive cross-section measurements, which have been shown before, differential cross-section measurements [10] were also done at centre-of-mass energy of $\sqrt{s} = 7$ TeV. In this context, the measurement is normalised by the inclusive cross-section and showed as a function of $X$ using \(1/\sigma_{t\bar{t}} d\sigma_{t\bar{t}}/dX\), where $X$ is the mass $m_{t\bar{t}}$, the transverse momentum $p_T$ or the rapidity $y$ of the $t\bar{t}$ system.

The analyses were performed in the semileptonic final state, which includes one $e/\mu$ lepton, a neutrino and at least four jets. Accordingly, the selection requires at least four jets and large missing transverse energy. Furthermore, a likelihood fit of the measured kinematic variables to a lowest order representation of the $t\bar{t}$ decay was used to reconstruct the $t\bar{t}$ system with the $W$-boson mass and the top-quark mass contraints. An extra requirement was applied in the likelihood to select events which are consistent with the $t\bar{t}$ decay hypothesis (on the final state of interest).

![Figure 5](image-url)  
(a) Unfolded relative cross-section binned in $m_{t\bar{t}}$.  
(b) Unfolded relative $t\bar{t}$ cross-section binned in $p_T$.

**Figure 5.** Unfolded distributions for the relative $t\bar{t}$ cross-section, comparing data and simulation predictions. The shaded band represents the systematic uncertainties on the simulation [10].

$H_T$ is defined as the scalar sum of all objects’ transverse momentum.
The measurement is performed using an unregularised unfolding procedure, subtracting the estimated background $B_i$, correcting for the acceptance $A_j$ and migration between bins $(M^{-1})_{ji}$, and using the luminosity $L$, according to Equation 1. The effect of the systematic uncertainties from the differential cross-section is reduced by the normalisation to the inclusive cross-section, but the final result is still dominated by systematic uncertainties, as can be seen in Figures 5(a) and 5(b).

$$\sigma_j = \frac{\sum_i (M^{-1})_{ji} (N_i - B_i)}{A_j L}$$ (1)

4. *$t\bar{t}$ jet multiplicity and jet veto gap fraction*

Analyses that work as a test of QCD are very important to study final state radiation. One such analysis is the measurement of the $t\bar{t}$ jet multiplicity in the semileptonic final state [11], which is particularly important since this final state is a significant background for $t\bar{t}H$, $b'\bar{b}'$ and other resonance searches. As a first step, at least three jets, at least one $b$-tagged jet, and one electron or muon with $p_T > 25$ GeV were required for a first data to simulation comparison, as shown in Figures 6(a) and 6(b) for the electron and muon channels, respectively. Missing transverse energy greater than 30 GeV and transverse mass between 2 greater than 35 GeV were also required to reduce the backgrounds contribution. A veto was applied in the second lepton with $p_T > 20$ GeV to reduce the $t\bar{t}$ dilepton background contribution. The electrons were required to be in the region given by $|\eta| < 2.47$, excluding the 1.37 < $|\eta|$ < 1.52 region, while muons used had the requirement $|\eta| < 2.5$. Isolation requirements were also applied to the leptons.

\(^2\) In this context the transverse mass is defined using the lepton transverse momentum and the missing transverse energy.
The result is unfolded to account for detector effects, by subtracting the background estimate ($\vec{f}_{\text{bngd}}$) and correcting for the acceptance difference in the reconstruction-level and particle-level simulations, except for the jet multiplicity requirement ($\vec{f}_{\text{accept}}$). Corrections are also applied for events that pass the jet multiplicity requirements at reconstruction-level but not at particle-level ($\vec{f}_{\text{reco!part}}$) and events that satisfy the particle-level jet multiplicity requirement, but fail the reconstruction-level requirement. The migration between bins ($M_{\text{part}}$) is taken into account using an iterative unfolding procedure [13]. The unfolding procedure can be summarised in Equation 2.

$$\vec{N}_{\text{part}} = \vec{f}_{\text{part!reco}} \cdot M_{\text{part}} \cdot \vec{f}_{\text{reco!part}} \cdot \vec{f}_{\text{accept}} \cdot (\vec{N}_{\text{reco}} - \vec{f}_{\text{bngd}})$$  \hspace{1cm} (2)

The unfolded result is shown in Figures 7(a) and 7(b). It can be seen that MC@NLO+HERWIG underestimates the data for bins with $\geq 6$ jets, while ALPGEN+PYTHIA with the downward $\alpha_S$ variation and POWHEG+PYTHIA describe the data very well.

Another important test of extra radiation in the final state is the measurement of the “jet veto gap fraction”, defined as in Equation 3, in which $\sigma(Q_0)$ is the cross-section for the production of $t\bar{t}$ events with no additional jet with $p_T > Q_0$. The final state analysed in this study is the dilepton decay of the $t\bar{t}$ system, which includes neutrinos, two leptons (in this study $e$ or $\mu$) and two $b$-jets, with extra radiation. This particular final state is used to have a clean event selection. The results profit from a reduced systematic uncertainty because the “jet veto gap fraction” is a ratio.

$$f(Q_0) = \frac{\sigma(Q_0)}{\sigma}$$  \hspace{1cm} (3)

The jet veto gap fraction for jets within $|y| < 0.8$ for different generators is shown in Figure 8(a) and it can be seen that the MC@NLO simulation tends to produce fewer jets. Also, it can be seen from Figure 8(b), that this measurement constrains systematic uncertainties coming from ISR/FSR modelling.
The single top-quark production cross-section in the LHC is smaller than the dominant strong force mediated production of $t\bar{t}$. It can be produced through a $t$-channel, $Wt$-channel and $s$-channel diagrams, but only the $t$-channel has been observed so far.

The $t$-channel production generates a top quark with an extra quark and it has the interesting feature that it allows one to measure the production cross-section for top events and antitop events. Furthermore, the ratio between these cross-sections $R_t$ is sensitive to the extra quark’s ($u$ or $d$) Parton Distribution function. This measurement was carried out at $\sqrt{s} = 7$ TeV, finding $R_t = 1.81 \pm 0.10$(stat.) $^{+0.21}_{-0.20}$(syst.) [14]. The measurement of the single top $t$-channel at $\sqrt{s} = 8$ TeV was also done without the top/antitop separation, finding a final cross-section of $\sigma_t = 95.1 \pm 2.4$(stat.) $^{+18.0}_{-18.0}$(syst.) pb [15], in agreement with the $87.2_{-1.0}^{+2.0}$ pb approximate NNLO theoretical calculations [16].

The analysis in the $Wt$-channel at $\sqrt{s} = 7$ TeV was also performed [17] and the background-only hypothesis was excluded at 3.3$sigma$, with a cross-section measurement obtained through a maximum likelihood estimate of $\sigma_{Wt} = 16.8 \pm 2.9$(stat.)$^{+4.9}$(syst.) pb, in agreement with the approximate NNLO theoretical calculations of $15.6 \pm 0.4 \pm 1.1$ pb [16]. This allows for an estimate of the $|V_{tb}|$ CKM matrix element of $|V_{tb}| = 1.03_{-0.19}^{+0.16}$. The $s$-channel search [18] was performed at $\sqrt{s} = 7$ TeV and it leads to an observed cross-
section upper limit of 26.5 pb, while the predicted Standard Model cross-section is \(4.56\pm0.07^{+0.18}_{-0.17}\) pb [16]. Using this result a \(t\bar{t}\)-resonance search [19] was also done for a model of a right-handed \(W'_R\) with Standard Model-like couplings. Limits are set for this exotic particle as shown in the Figure 9, for \(m_{W'_R} > 1.13\) TeV at 95% Confidence Level.

6. Summary
The ATLAS Collaboration has used different techniques to estimate the top-quark production cross-section in different scenarios. The cross-section of the dominant \(t\bar{t}\) production process has been measured for dileptonic and semileptonic final states, which also included a cross-check study, using an uncorrelated tagger (Soft Muon Tagger).

Extra radiation in the semileptonic final state and the dileptonic final states are studied in the \(t\bar{t}+\) jets analysis and the jet veto gap fraction study. The jet veto gap fraction analysis was used to constrain the AcerMC variations. Smaller variations were used to compare with the \(t\bar{t}+\) jets analysis. The results of the \(t\bar{t}+\) jets analysis are consistent with the jet veto gap fraction analysis. The former is also important to understand the main background for many searches, while the latter constrains the ISR/FSR systematic uncertainty in the generators by \(\sim 50\%\).

The single top-quark production has also been studied in the \(t-, Wt-\) and \(s\)-channels, which were used to estimate the \(|V_{tb}|\) CKM matrix element, in agreement to the world average of \(|V_{tb}| = 0.999146^{+0.000021}_{-0.000046}\) [20], and set limits for the \(s\)-channel cross-section and for a model for a right-handed \(W'_R \to tb\). The cross-section in the \(t\)-channel was measured and evidence for the \(Wt\)-channel was found.

Other recent results from ATLAS, complementary to the ones shown, include the measurement of the \(t\bar{t}\) all hadronic cross section [21] and a search for single top-quark Flavour Changing Neutral Currents [22].

References
[1] J. R. Incandela et al., Prog. Part. Nucl. Phys. 63 (2009) 239-292.
[2] O. S. Bruning, (Ed.), P. Collier, (Ed.), P. Lebrun, (Ed.), S. Myers, (Ed.), R. Ostojic, (Ed.), J. Poole, (Ed.) and P. Proudlock, (Ed.), CERN-2004-003-V-1.
[3] The ATLAS Collaboration, ATLAS Detector Status and Physics Startup Plans, JINST 3 S08003 (2008).
[4] The ATLAS Collaboration, ATLAS-CONF-2011-121.
[5] The ATLAS Collaboration, ATLAS-CONF-2012-149.
[6] The ATLAS Collaboration, ATLAS-CONF-2012-131.
[7] The ATLAS Collaboration, Phys. Lett. B 717 (2012) 89-108.
[8] The ATLAS Collaboration, arXiv:1211.7205.
[9] The ATLAS Collaboration, JHEP 1205 (2012) 059.
[10] The ATLAS Collaboration, arXiv 1207.5644.
[11] The ATLAS Collaboration, ATLAS-CONF-2012-155.
[12] The ATLAS Collaboration, Eur. Phys. J. C72 (2012) 2043.
[13] G. D'Agostini, Nucl. Instr. and Meth. A 362 (1995) 487.
[14] The ATLAS Collaboration, ATLAS-CONF-2012-122.
[15] The ATLAS Collaboration, ATLAS-CONF-2012-056.
[16] N. Kidonakis, arXiv: 1210.7813.
[17] The ATLAS Collaboration, Phys. Lett. B 716 (2012) 142-159.
[18] The ATLAS Collaboration, ATLAS-CONF-2011-118.
[19] The ATLAS Collaboration, Phys. Rev. Lett. 109 (2012) 081801.
[20] J. Beringer et al. (PDG), Phys. Rev. D86, 010001 (2012).
[21] The ATLAS Collaboration, ATLAS-CONF-2012-031.
[22] The ATLAS Collaboration, arXiv 1203.0529.