Measurement of the top quark pair production cross section with ATLAS in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV in the single-lepton channel using semileptonic \( b \) decays

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Measurement of the top quark pair production cross section with ATLAS in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV in the single-lepton channel using semileptonic \( b \) decays

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Abstract. The cross section for top quark pair production in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV is measured using data recorded with the ATLAS detector at the Large Hadron Collider. Events are selected requiring a single high transverse momentum isolated electron or muon, missing transverse momentum and jets. Semileptonic \( b \) decays are identified by a lower momentum muon close to a jet, leading to substantially different sources of systematic uncertainty compared with other measurements. With a data sample corresponding to 4.66 fb\(^{-1}\) of integrated luminosity, the top quark pair production cross section is measured to be

\[
\sigma_{t\bar{t}} = 165 \pm 2(\text{stat.}) \pm 17(\text{syst.}) \pm 3(\text{lumi.}) \text{ pb}
\]

in agreement with theoretical predictions based on perturbative QCD and with other measurements which used different techniques or decay channels.

1. Introduction
The experimental determination of the \( t\bar{t} \) cross section is an important measurement and a test of the Standard Model (SM). Full details of this analysis are to be found in [1]. The predicted SM \( t\bar{t} \) cross section for \( pp \) collisions at a centre-of-mass energy of \( \sqrt{s} = 7 \) TeV, for a top quark mass of 172.5 GeV is \( \sigma_{t\bar{t}} = 167^{+17}_{-18} \) pb, calculated at approximate next-to-next-to-leading order (NNLO) in QCD with Hathor 1.2 [2] using the MSTW2008 NNLO parton density function (PDF) sets [3, 4] and cross checked with the next-to-leading order (NLO) and next-to-next-to-leading log (NNLL) calculation of Cacciari et al. [5] as implemented in Top++ 1.0 [6].

2. Data and simulated samples
This measurement uses data recorded by the ATLAS detector [7] between March and November 2011 at the LHC [8] corresponding to an integrated luminosity of 4.66\pm0.08 fb\(^{-1}\) [9]. The \( t\bar{t} \) signal Monte Carlo (MC) has been simulated using the MC@NLO v4.01 [10, 11] generator interfaced to Herwig [12] for parton showering and hadronisation and Jimmy [13] for the underlying event simulation. The PDF set is CT10 [14] and the top quark mass is set to 172.5 GeV. The \( W/Z+jets \) MC samples were generated using Alpgen [15] interfaced to Pythia [17]. The single top quark MC samples used MC@NLO interfaced to Herwig+Jimmy for the \( s \)-channel and \( Wt \)-channel, while the \( t \)-channel was generated using the AcerMC [16] generator interfaced to Pythia [17]. The diboson (\( WW/WZ/ZZ \)) MC samples were generated using Herwig.
3. Soft Muon Tagging (SMT) algorithm

The SMT algorithm used in this analysis relies on the presence of a reconstructed muon within a jet. The total $b \rightarrow \mu X$ branching ratio, including cascade $b \rightarrow c \rightarrow \mu X$ decays, is about 20%. The tagger uses the quality of the match between the inner detector and muon spectrometer tracks of the muon ($\chi_{\text{match}}^2$) as a discriminating variable to separate heavy flavour ($b, c$) jets from light flavoured ($u, d, s$ or gluon) ones.

Muons considered by the tagger are required to pass a series of quality cuts on the number of hits present in the various tracking subdetectors [19]. Muons are required to be with $\Delta R(\mu, \text{jet}) < 0.5$ with $|d_0| < 3$ mm, $|z_0\sin (\theta) | < 3$ mm, a transverse momentum $p_T > 4$ GeV and pseudorapidity $|\eta| < 2.5$. Muons are required to have a $\chi_{\text{match}}^2 < 3.2$ which has been optimized to provide a $b$-jet identification efficiency of 10% whilst providing a light jet rejection factor of about 200 per jet. Correction factors for simulation have been calculated as a function of $p_T$ and $\eta$ and are between 0.97 and 1 within an uncertainty ≤1%. The mistag rate is found to be 1.4±0.20 (stat. ⊕ syst.).

4. Event selection

The analysis requires collision data selected by an inclusive single electron or muon trigger with offline-reconstructed candidates satisfying $p_T \geq 25$ GeV for electrons and $p_T \geq 20$ GeV for muons. Electrons are required to have $|\eta| < 2.47$ and not be in the transition region between the barrel and the endcap calorimeters (1.37 ≤ $|\eta|$ ≤ 1.52). Muon candidates are obtained by combining track segments from the layers of the muon chambers with tracks found in the inner detector within $|\eta| < 2.5$.

Leptons from $W$ decays are isolated and thus, to reduce backgrounds, both calorimeter and track isolation are required. For the electron, the cut value on the calorimeter and track variables depend on the electron $p_T$ and $\eta$ such that the isolation cut efficiency for each variable is maintained at 90%. For the muon, the calorimeter isolation is required to be < 4 GeV while the track isolation is required to be < 2.5 GeV. Leptons are also required to be separated further than an angular distance of $\Delta R = 0.4$ from any jet. Muons tagged by the SMT algorithm are not considered. Events are required to contain only one selected electron or muon.

Jets are reconstructed with the anti-$k_t$ algorithm [20, 21] with a distance parameter $R = 0.4$, calibrated at the electromagnetic (EM) scale [22]. Jets are required to have a $p_T \geq 25$ GeV, $|\eta| < 2.5$. Jets that are within $\Delta R < 0.2$ from a selected electron are rejected.

The $e$+jets channel requires that the missing transverse energy $E_T^{\text{miss}} \geq 30$ GeV and that the transverse $W$ mass, denoted $m_T(W) \geq 30$ GeV, while the $\mu$+jets channel requires that $E_T^{\text{miss}} \geq 20$ GeV and a triangular cut is performed by requesting that $E_T^{\text{miss}} + m_T(W) \geq 60$ GeV. In the analysis, events passing all selections described above with at least 3 jets are defined as “pretag” events. Pretag events with at least one jet identified as coming from a semileptonic $b$-quark decay by the SMT algorithm are referred to as “tagged”. In the $\mu$+jets channel, events for which the invariant mass of the $W$-decay muon($\mu_W$) and the $b$-tagged SMT muon($\mu_{\text{SMT}}$) is in the ranges 8 GeV ≤ $m_{\mu W} ≤ 11$ GeV and 80 GeV ≤ $m_{\mu \mu} ≤ 100$ GeV are vetoed to remove contributions from $\Upsilon$ and $Z$ dimuon decays. Additionally, to ensure that the tagged muon is not the same as the $W$-decay muon, a cut of $\Delta R(\mu_W, \mu_{\text{SMT}}) > 0.01$ is applied.

The signal selection efficiencies, found by applying the full selection described above on the simulated $t\bar{t}$ signal sample, are 1.42% in the $e$+jets channel and 2.15% in the $\mu$+jets channel.

5. Data-driven background estimation

The $W$+jets background is the dominant background since these events already contain a real lepton and significant $E_T^{\text{miss}}$. The $W$ charge asymmetry method is used to provide an overall

$$\Delta R(i,j) = \sqrt{\Delta \eta(i,j)^2 + \Delta \phi(i,j)^2},$$

where $\Delta \eta(i,j) = \eta_i - \eta_j$ and $\Delta \phi(i,j) = \phi_i - \phi_j$.
normalisation. This relies on the observation that the ratio of positively charged $W$ bosons to negatively charged $W$ bosons suffers from relatively small theoretical uncertainty [3, 23]. The final contributions are detailed in Table 1.

Multijet background events enter into the final event selection. Events in the $e$+jets analysis come mainly from photon conversions and from jets with high EM fractions. Events in the $\mu$+jets analysis come from the semileptonic decay of heavy quarks, the decay in flight of pions and kaons and from “punch-through” hadrons that are not fully absorbed within the hadronic calorimeter. Multijet estimates are obtained by considering control regions close to the signal region [24] and obtaining an SMT tagging rate. The final contributions are detailed in Table 1.

6. Systematic uncertainties and Results

For each uncertainty listed in Table 2, the combined $t\bar{t}$ cross section is recalculated by summing the $e$+jets and $\mu$+jets event yields, providing an uncertainty on the combined $t\bar{t}$ cross section. This procedure takes into account any correlation that may be present across the $e$+jets and $\mu$+jets analyses. The individual systematic uncertainties on the $t\bar{t}$ cross section are summed in quadrature to provide an overall systematic uncertainty. The dominant systematic uncertainties come from the uncertainty on the multijet and $W$+jets backgrounds and from the jet energy scale.

The number of observed and expected jets is shown in Figure 1. The cross section is calculated using:

$$\sigma_{t\bar{t}} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\int L \, dt \cdot \epsilon \cdot BR(\text{noFullHad})}$$

where $N_{\text{data}}$ and $N_{\text{bkg}}$ are the data and background yields respectively, $\epsilon$ is the signal efficiency for single-lepton and dilepton channels and $BR(\text{noFullHad}) = 0.543$ is the single-lepton branching ratio [18]. The combined $t\bar{t}$ cross section is calculated by summing the $e$+jets and $\mu$+jets event yields and is measured to be:

$$\sigma_{t\bar{t}} = 165 \pm 2(\text{stat.}) \pm 17(\text{syst.}) \pm 3(\text{lumi.}) \, \text{pb}$$

Figure 1. Number of observed and expected jets in the $e$+jets(left) and $\mu$+jets(right) analysis [1].
Table 1. Observed and estimated event yields in the pretag and tagged samples. Backgrounds are evaluated with Data Driven (DD) techniques or with MC simulation. Uncertainties are quoted as the quadratic sum of statistical and systematic contributions [1].

| Sample | Pretag | Tagged |
|--------|--------|--------|
| Data (4.66 fb$^{-1}$) | 351742 | 24105 |
| $t\bar{t}$ MC | 84000±2060 | 15060±590 |
| W+jets DD | 176500±10750 | 4520±600 |
| Multijet DD | 43200±9700 | 1930±470 |
| $Z$+jets MC | 21400$^{+3470}_{-2130}$ | 1050$^{+145}_{-105}$ |
| Single Top MC | 11430±680 | 1630±100 |
| DiBoson MC | 3220$^{+410}_{-350}$ | 100±15 |
| $t\bar{t}$ MC + Backgrounds | 340000±15000 | 24300±980 |
| Measured $t\bar{t}$ | 14900±800 |
| Selection Efficiency (%) | 3.57 ± 0.03 |

Table 2. Summary of individual relative systematic uncertainty contributions to the cross section measurement, in percent [1].

| Source | Uncertainty [%] |
|--------|-----------------|
| **Statistical Uncertainty** | ±1.0 |
| **Object selection** |  |
| Lepton energy resolution | +0.2 /-0.1 |
| Lepton reco, identification, trigger | +1.7 /-1.8 |
| Jet energy scale | +3.5 /-3.8 |
| Jet energy resolution | ±0.2 |
| Jet reconstruction efficiency | ±0.06 |
| Jet vertex fraction | +1.2 /-1.4 |
| $E_{mis}$ uncertainty | ±0.07 |
| **Background estimates** |  |
| Multijet normalisation | ±4.4 |
| W+jet normalisation | ±5.5 |
| Other bgk normalisation | ±0.1 |
| Other bgk systematics | +2.2 /-1.8 |
| **Signal simulation** |  |
| $b \rightarrow \mu X$ Branching ratio | +2.9 /-3.1 |
| Initial/Final state raditaion | ±1.5 |
| PDF | ±3.1 |
| NLO generator | ±3.2 |
| Parton shower | ±2.2 |
| **Total systematics** | ±10.5 |
| **Integrated luminosity** | ±1.8 |

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