Top quark measurements at ATLAS

Sergio Grancagnolo
Humboldt University, Newtonstr 15, 12489 Berlin, Germany
E-mail: sergio.grancagnolo@cern.ch

Abstract. The top quark is the heaviest known fundamental particle. As it is the only quark that decays before it hadronizes, it allows us to probe the properties of bare quarks at the Large Hadron Collider. Highlights of a few recent precision measurements by the ATLAS Collaboration of the top quark using 13 TeV and 8 TeV collision data will be presented: top-quark pair and single top production cross sections including differential distributions will be presented alongside measurements of top-quark properties, including results using boosted top quarks, probe our understanding of top-quark production in the TeV regime. Measurements of the top-quark mass and searches for rare top quark decays are also presented.

1. Introduction
The large number of top quarks available in the data collected at various energies with the ATLAS detector [1], allows one to study properties of this particle and to measure its production and differential cross sections with high precision. This document summarises recent results in top-quark physics, organized as follows. For each analysis, motivations and overview of specific strategies are given: mass measurement in Chapter 2, properties in Chapter 3, \( t\bar{t} \) cross section in Chapter 4, and single top production in Chapter 5. Conclusions are taken in Chapter 6.

2. Top-quark mass
The mass of top quark is an important input to the global fit of electroweak parameters, cross-checking the consistency and constraining possible extensions of the Standard Model (SM). Its value has also cosmological implications, affecting the stability of the Higgs potential. The analysis presented here [2] considers the decay \( t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow \ell\nu q\bar{q}b\bar{b} \). Events are selected in a 20.2 fb\(^{-1}\) dataset collected at the collision energy of 8 TeV, by requiring exactly one isolated high-momentum lepton and at least four jets with transverse momentum \( p_T > 25 \) GeV and \( |\eta| < 2.5, \) exactly two of which contain hadrons with \( b \) quarks (\( b \)-tagging). The lepton (\( \ell \)) can be a \( \mu \) with \( p_T > 25 \) GeV or an \( e \) with transverse energy \( E_T > 25 \) GeV, also including those from a tau-lepton decay. To take into account the presence of the neutrino, minimum \( E_T^{\text{miss}} \) and \( m_W \) are required\(^2\) depending on the lepton channel.

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1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the \( z \)-axis along the beam pipe. The \( x \)-axis points from the IP to the center of the LHC ring, and the \( y \)-axis points upward. Cylindrical coordinates \((r,\phi)\) are used in the transverse plane, \( \phi \) being the azimuthal angle around the \( z \)-axis. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \).

2 The missing transverse momentum \( E_T^{\text{miss}} \) is the absolute value of the vector \( E_T^{\text{miss}} \) given by the negative vectorial sum of the transverse component of all calibrated energy deposits in the calorimeters and momentum reconstructed
The two channels (e and $\mu$) are finally merged and the preselection is further refined using a boosted decision tree (BDT) with 13 input variables. The most sensitive one is the opening angle $\Delta R$ between the two light jets associated to the $W$ boson decay. The full reconstruction of the event is performed using a kinematic fit, assuming that the best assignment of jets to partons maximises a likelihood where a common mass parameter $m_{\text{reco}}$ is associated to the leptonically and hadronically decaying top quarks. To take in account dominant effects due to jet energy scale and differences in jets originating from light or $b$ quarks, templates were generated by scaling the energy of the jets. The corresponding scale factors are determined together with $m_{\text{top}}$ in a three-dimensional final fit, resulting in $m_{\text{top}} = 172.08 \pm 0.39(\text{stat}) \pm 0.82(\text{syst})$ GeV. This is combined with previous ATLAS measurements at 7 TeV, including the orthogonal $t\bar{t} \rightarrow \text{dilepton}$ channel, taking in account all correlations. Using the best linear unbiased estimate (BLUE), the combined result is $m_{\text{top}} = 172.51 \pm 0.27(\text{stat}) \pm 0.42(\text{syst})$ GeV with a $\chi^2$ probability of 78% (Figure 1) [2].

![Figure 1](image1.png)

**Figure 1.** Comparison of combined $m_{\text{top}}$ results [2].

![Figure 2](image2.png)

**Figure 2.** Reconstructed top-quark mass in the signal region compared with a FCNC signal normalised to $BR(t \rightarrow uZ) = 0.1\%$ [3].

### 3. Top-quark properties

**3.1. Top-quark decays through flavour-changing neutral current**

Decays such as $t \rightarrow qZ$ are forbidden in the SM at tree level, and they are strongly suppressed at loop level by the GIM mechanism. Several extensions beyond the SM (BSM) predict a branching ratio (BR) order of magnitude larger for this Flavour-changing neutral current (FCNC) decay. This search considers the chain $t\bar{t} \rightarrow bW(\rightarrow \ell\nu)qZ(\rightarrow \ell\ell)$, in a 36 fb$^{-1}$ dataset collected at 13 TeV. With a similar object reconstruction as in Chapter 2, events are selected by requiring exactly three isolated charged leptons with $p_T > 15$ GeV, two of them with the same flavour and opposite charge and an invariant mass within 15 GeV of the $Z$ boson mass, at least two jets with $p_T > 25$ GeV, exactly one of them $b$-tagged, and $E_T^{\text{miss}} > 40$ GeV. Applying in tracking detectors. The $W$-boson transverse mass $m_W^{T}$ is defined as $\sqrt{2p_T E_T^{\text{miss}}(1 - \cos \phi(t, E_T^{\text{miss}}))}$. 
energy-momentum conservation, a \( \chi^2 \) is calculated from the reconstructed masses of \( qZ \), \( bW \), and \( \ell \nu \) systems. After minimisation, the assignments between reconstructed top quarks and simulated particles is around 80% for FCNC. Five additional control regions are defined and used in a simultaneous fit to better estimate background contributions and constrain systematic uncertainties. No evidence of signal events is found (Figure 2). Observed (expected) limits \( BR(t \rightarrow uZ) < 1.7 \times 10^{-4} \) (2.4 \( \times 10^{-4} \)) and \( BR(t \rightarrow cZ) < 2.3 \times 10^{-4} \) (3.2 \( \times 10^{-4} \)) are set at 95% confidence level, constraining as well corresponding effective field theory operators [3].

3.2. Charge asymmetry

The rapidity distribution of top quarks, being produced from both valence and sea quarks in the proton, is broader than that of top antiquarks, that in average have a larger momentum than sea quarks only. Asymmetries in the angular distributions in the \( q\bar{q} \rightarrow t\bar{t} \) process are introduced by higher-order effects in QCD, and they can become large at high values of the invariant mass of the \( t\bar{t} \) system in the presence of BSM contributions. The sensitive observable at LHC is the charge asymmetry: 

\[
A_C = \frac{N_{|y|<0} - N_{|y|>0}}{N_{|y|<0} + N_{|y|>0}},
\]

with \( N \) indicating the number of events with a positive or negative rapidity difference \( \Delta |y| = |y_t| - |y_{\bar{t}}| \). ATLAS and CMS combined their measurements with 5 fb\(^{-1} \) at 7 TeV and 20 fb\(^{-1} \) at 8 TeV. The final state considered is \( t\bar{t} \rightarrow \ell+\text{jets} \) as in Chapter 2. Using the BLUE method, three separate combinations are obtained. The combination of inclusive results at 7 TeV is: \( A_{\text{LHC7}} = 0.005 \pm 0.007 \text{(stat)} \pm 0.006 \text{(syst)} \). The combination of inclusive results at 8 TeV is: \( A_{\text{LHC8}} = 0.0055 \pm 0.0023 \text{(stat)} \pm 0.0025 \text{(syst)} \). The differential charge asymmetry as a function of the invariant mass of the \( t\bar{t} \) system at 8 TeV is shown in Figure 3 [4].

Figure 3. Combined ATLAS+CMS charge asymmetry in six \( t\bar{t} \) invariant-mass bins, compared with SM and BSM predictions [4].

3.3. Colour flow

In nature, only colour-neutral hadrons can be observed, and direct measurement of the quantum chromodynamics (QCD) interaction of their constituents is not possible. Quark and gluons are measured as jets, but colour connection influences jet shape, structure and event topology. The distribution of particles within a jet is related with the colour carried by corresponding partons. An observable describing this information is the pull vector, a \( p_T \)-weighted radial moment of...
the jet, computed from its constituents. For a dijet system, the pull angle between the pull vector and the vector connecting the two jets is considered (Figure 4). In the $t\bar{t} \rightarrow \ell +$ jets event topology, the jets originating from the hadronic $W$ decay are colour connected, while the two $b$-tagged jets are not.

These observables are studied using the same dataset as in Chapter 3.1, and similar object reconstruction and event selection as in Chapter 2. A corresponding one is also defined at particle level, using the Monte Carlo (MC) truth record. After bin-by-bin background subtraction, and removing effects of the detector smearing as obtained from simulation, the signal distributions are then unfolded to a particle-level spectrum, using an Iterative Bayesian (IB) method. A general good agreement is found with SM predictions, even if observables sensitive to colour flow remain poorly modelled [5].

3.4. Decay width

The decay width of the top quark is the largest of all fermions, and any deviation from SM expectation might hint to non-SM decays. The next-to-leading-order and next-to-next-to-leading-order calculation predicts $\Gamma_{\mathrm{NLO}} = 1.33$ GeV, and $\Gamma_{\mathrm{NNLO}} = 1.322$ GeV respectively [6]. The same 8 TeV dataset and a similar object reconstruction and event selection of the $t\bar{t} \rightarrow \ell +$ jets channel is performed as in Chapter 2. A likelihood-based assignment of reconstructed jets to partons is used. The events are categorised based on the flavour of the selected lepton, if they have exactly one or at least two $b$-tagged jets, and if all four associated jets have $|\eta| < 1$ or at least one has $|\eta| \geq 1$. Two observables are used in the final template fit in this eight regions. The reconstructed invariant mass $m_{tb}$ of the $b$-jet and the lepton from $t \rightarrow bW(\rightarrow \ell\nu)$, and the distance $\Delta R_{\text{min}}(j_b, j_l)$ between the $b$-jet and the closest light jet from the hadronic top decay. The signal templates are generated by reweighting events with alternative width hypotheses. The measured top decay width is $\Gamma_t = 1.76 \pm 0.33(\text{stat})^{+0.79}_{-0.68}(\text{syst})$ GeV [7].

4. Top-quark pair production cross section

BSM effects can appear in $t\bar{t}$ differential distributions, while being undetected by inclusive cross section measurements. For large Lorentz boosts of the Lorentz boost of the top quarks, their decay products are collimated into a large-radius jet. This study uses 14.7 fb$^{-1}$ of data at 13 TeV looking for an all-hadronic boosted topology where both $W$ bosons decay into a pair of quarks. These jets must satisfy $p_{T,1} > 500$ GeV, $p_{T,2} > 350$ GeV, $|\eta| < 2.0$, and a top-tagging algorithm, each being also associated with a $b$-tagged jet having $p_T > 25$ GeV. No lepton with $p_T > 25$ GeV is allowed in the events selected. Background is estimated from data using nine regions defined by the number of top-tagged and $b$-tagged jets. After its subtraction, an IB unfolding technique is used to correct for detector acceptance and gives particle-level distributions of normalised cross sections for various observables, like the production angle ($\chi^{t\bar{t}} = \exp(2|y^*|)$, where $y^* = 1/2(y^{t,1} - y^{t,2})$ sensitive to $t\bar{t}$ production modelling, and the rapidity boost ($y_{B}^{t\bar{t}} = 1/2(y^{t,1} + y^{t,2})$) sensitive to parton distribution functions. The total cross section in the fiducial phase space is $\sigma^{\text{fid}}_{t\bar{t}(\text{boost})} = 374 \pm 13(\text{stat})^{+111}_{-092}(\text{syst})$ fb, in good agreement with SM predictions [8].

5. Single Top-quark production

5.1. Production in association with a $W$ boson

The $Wtb$-vertex coupling is parameterised by the $V_{tb}$ Cabibbo-Kobakashi-Maskawa matrix element and $f_W^t$ form factor. One of the three leading-order electroweak single top quark channels in the SM is the $tW$ (see Figure 5). The differential cross section is measured with the same dataset as in Chapter 3.3. The final state is required to have one $b$-tagged jet, $E_T^{\text{miss}}$, and exactly two opposite sign leptons, with an invariant mass outside $Z$-mass window if they have
the same flavour. A BDT is used to separate from $t\bar{t}$ background, optimised to reduce systematic uncertainties, with the input variable $p_T(\ell_1\ell_2E_T^{miss}b)$ giving largest separating power. Unfolding using the IB technique gives particle-level distributions of normalised cross sections for various observables, like $m_T(\ell\ell\nu\nu b)$ and $E(\ell\ell b)$. Compared to MC predictions with different generators, parton shower, hadronisation and underlying-event models, results are found in good agreement with SM predictions [9].

Figure 5. Single top production Feynman diagram in $tW$ channel and leptonic decays for both $W$ bosons [9].

Figure 6. Feynman diagram for the $tZq$ process probing the $WWZ$ vertex [10].

Figure 7. Feynman diagram for the $tZq$ process probing the $tZ$ vertex [10].

5.2. Production in association with a $Z$ boson

The rare SM single-top production process $pp \rightarrow tZq$, probes $WWZ$ and $tZ$ couplings (Figures 6, 7). It is measured using the same dataset as in Chapter 3.3. The final state contains exactly three charged leptons with $p_T > 28, 25$, and $15$ GeV respectively, two jets with $p_T > 30$ GeV, only one of them $b$-tagged. A same-flavour, opposite-sign lepton pair with invariant mass within $10$ GeV of the $Z$ boson is required. The $W$ boson is reconstructed from the remaining lepton and $E_T^{miss}$, with $m_T^W > 20$ GeV. A multivariate analysis using a three-layer neural network (NN) combines several variables into one discriminant. The output, $O_{NN}$, separate signal from background events having values closer to 1 and 0 respectively. Best separation power is given by the variable $|\eta|$ of the untagged jet. A binned likelihood fit is performed to extract the $tZq$ signal strength, maximised on the NN output, to normalise signal and background events in each bin. The measured cross section is $\sigma_{tZ(3\ell)} = 600 \pm 170$(stat) $\pm 140$(syst) fb, assuming $m_{top} = 172.5$ GeV, with a significance of 4.2$\sigma$ (5.4$\sigma$ expected) [10].

6. Conclusions

All results presented are in agreement with the SM predictions. The good performances of LHC and the high-efficiency data-taking of the experiments indicates that additional large statistics will be available in the future, and even more precision can be achieved on rare decays and property measurements sensitive to BSM effects.

References