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3 Top quark studies with the ATLAS detector

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8
9 The latest top quark studies in proton-proton collisions at a centre-of-mass energy of 7
10 and 8 TeV with the ATLAS detector are reported. We present recent results on the top
11 pair production inclusive cross-sections, top pair production differential cross-section in
12 the resolved and boosted regimes, single top-quark production cross-sections measured in
13 the t-channel, s-channel and W-boson associated processes, as well as the determination
14 of the CKM matrix element $|V_{tb}|$. The results are compared with theoretical expectations.
15 Latest ATLAS results on top properties will be also shown in terms of direct and pole
16 mass, spin correlations and charge asymmetry.

17 *Keywords:* Top quark; ATLAS; QCD.

18 *PACS numbers:*

19 Introduction

20 The large data samples collected by the ATLAS and CMS Collaborations in $p - p$
21 collisions at the CERN Large Hadron Collider (LHC) at the centre-of-mass energies
22 $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, allow one to study in detail the properties of the
23 top quark and to perform precise measurements of the inclusive and differential
24 cross-sections for top production.

25 The understanding of the production processes and properties of top quark is
26 fundamental for testing the predictions of the Standard Model (SM) and for search-
27 ing for signals of new physics. The top quark is the heaviest known elementary
28 particle and due to its large mass it decays before hadronizing; therefore, all prop-
29 erties of the top quark are preserved in the decay chain and propagated to its decay
30 products. Furthermore, its large coupling to the Higgs boson suggests that it might
31 be closely connected to electroweak symmetry breaking (see e.g. Ref.1).

32 In this contribution an overview of the most significant results, obtained by
33 the ATLAS Collaboration, on top quark properties and production mechanisms are
34 presented.

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35 1. Top-pair production

36 At the LHC, the top quarks are predominantly produced in pairs via the strong
37 interaction and through the gluon-gluon fusion process with only a small contribu-
38 tion from quark-antiquark annihilation. The precise prediction of the correspond-
39 ing inclusive and differential cross-sections is a challenge for perturbative Quantum
40 Chromodynamics (QCD) calculations. Precise measurements of these observables are
41 sensitive to the gluon parton distribution function (PDF), to the top quark mass
42 and to potential enhancements due to physics beyond the SM.

43 Within the SM, the quark top decays almost exclusively into a W boson and a
44 b quark, so the final-state topology of a $t\bar{t}$ event is governed by the decay modes
45 of the two W gauge bosons; in particular, the final states are subdivided into the
46 *dilepton channel* with both W bosons decaying leptonically, the *lepton+jets channel*
47 in which one of the W bosons decays leptonically and the other one hadronically,
48 and the all *hadronic channel* with both W bosons decaying hadronically.

49 In this section the most recent results on inclusive and differential $t\bar{t}$ cross-
50 sections are presented; for the differential cross-sections the results are presented
51 both in the resolved and boosted regimes.

52 1.1. Inclusive top-pair cross-section measurements

53 Recent ATLAS and CMS inclusive top-pair measurements using events in the dilep-
54 ton channel² and lepton+jets channel³ are summarized in figure 1 right, the results
55 are also presented as a function of the centre-of-mass energy and compared to
56 NNLO+NNLL QCD predictions^{4,5} (see figure 1 left).

57 The inclusive $t\bar{t}$ cross-section in the dilepton channel, $t\bar{t} \rightarrow e\mu\nu\bar{\nu}b\bar{b}$, have been
58 measured with the data sets collected at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The analysis
59 requires one electron and one muon with $p_T > 25$ GeV and a pseudorapidity^a
60 $\eta < 2.5$. The numbers of events with exactly one and exactly two b-tagged jets were
61 counted and used to simultaneously determine $\sigma_{t\bar{t}}$ and the efficiency to reconstruct
62 and b-tag a jet from a top quark decay, thereby minimising the associated systematic
63 uncertainties.

64 The total inclusive $t\bar{t}$ cross-sections are measured to be $\sigma_{t\bar{t}} = 182.9 \pm 3.9\%$ pb
65 and $\sigma_{t\bar{t}} = 242.4 \pm 4.3\%$ pb at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. The results
66 are consistent with recent NNLO+NNLL QCD calculations^{4–10}. The inclusive cross-
67 sections were also measured in a fiducial phase-space region to reduce the systematic
68 uncertainties associated with the acceptance estimation².

The measurement of the total and fiducial $t\bar{t}$ cross-sections at $\sqrt{s} = 8$ TeV in
the lepton+jets final state used a likelihood discriminant fit method. The inclusive

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

Fig. 1. (Left) Summary of the LHC and Tevatron measurements of the top-pair production cross-sections ¹¹ as a function of the centre-of-mass energy compared to the NNLO+NNLL QCD calculations. (Right) Compilation of the measurements of the top-pair production cross-sections at 8 TeV compared to the NNLO+NNLL QCD calculations.

$t\bar{t}$ production cross-section is found to be

$$\sigma_{t\bar{t}} = 258 \pm 1(stat.)_{-22}^{+21}(syst.) \pm 8(lumi.) \pm 4(beam) \text{ pb.}$$

The fiducial $t\bar{t}$ cross-section is found to be $\sigma_{t\bar{t}}^{fid} = 22.8 \pm 0.1(stat.)_{-1.9}^{+1.8}(syst.) \pm 7(lumi.) \pm 4(beam) \text{ pb}$. The uncertainties of the measurement take into account statistical, experimental and theoretical uncertainties, the knowledge of the integrated luminosity and the LHC beam energy.

An impressive experimental precision is reached by the LHC measurements. The experimental precision matches the precision reached by the NNLO+NNLL QCD calculations ^{4,5} that describe the measurements well. At $\sqrt{s} = 8 \text{ TeV}$, the ATLAS and CMS measurements are in good agreement with each other and with the theory predictions, while there is a difference of about two standard deviations at $\sqrt{s} = 7 \text{ TeV}$.

1.2. Differential $t\bar{t}$ cross-section measurements

The measurement of the single differential cross-sections for $t\bar{t}$ production allows to perform even more stringent tests of the predictions of pQCD by exploring the dynamics of the $t\bar{t}$ system. The ATLAS Collaboration has measured differential cross-sections in the lepton+jets channel both in the resolved^{12,13} and boosted¹⁴ regimes.

The measurement of the normalized differential cross-sections for top-quark pair production¹² at $\sqrt{s} = 7 \text{ TeV}$ has been performed as a function of several variables characterising the $t\bar{t}$ system: the transverse momentum of the top quark (p_T^t) and

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Fig. 2. Normalized differential cross-section as a function of the transverse momentum of the hadronically decaying top quark¹² compared with different MC generator predictions. The gray band is the total uncertainties of the data. The lower part of the figure shows the ratio of the generator predictions to the data.

the invariant mass ($m_{t\bar{t}}$), the transverse momentum ($p_T^{t\bar{t}}$) and the rapidity ($y_{t\bar{t}}$) of the $t\bar{t}$ system. Events are selected in the lepton+jets channel, requiring exactly one lepton and at least four jets with at least one of the jets tagged as originating from a b-quark. Figure 2 shows the normalised differential cross-section as a function of the transverse momentum of the hadronically decaying top quark compared with the predictions of different Monte Carlo (MC) generators. The measurements are in fair agreement with the MC predictions except in the region of the top quark high transverse momentum where the data distributions are softer than the predictions. A similar measurement has been performed by the CMS experiment and a similar behaviour is observed. A possible explanation of this difference between data and MC may be related to the gluon density of the proton.

The ATLAS Collaboration presented also the first measurement of the differential cross-sections in terms of various kinematic variables of the so called “pseudo-top-quark”¹³, defined in terms of either reconstructed detector objects or stable particles, in order to achieve a better correspondence between detector level and particle level measurements and a reduced dependence on the theoretical models. The cross-section is presented as a function of the transverse momentum and rapidity of both the hadronic and leptonic pseudo-top-quark as well as the transverse momentum, rapidity and invariant mass of the pseudo-top-quark pair system and compared with several MC models that implement NLO order or LO multi-leg matrix-element calculations. Figure 3 shows the results for the differential cross-section as a function of the $t\bar{t}$ pseudo-top-quark invariant mass $m(\hat{t}_l\hat{t}_h)$ and hadronic pseudo-top-quark $p_T(\hat{t}_h)$. The comparison is performed with various LO multi-leg MC generators and various NLO MC generators.

Fig. 3. (Left) Differential $t\bar{t}$ cross-section as a function of the $t\bar{t}$ pseudo-top-quark invariant mass $m(t_l t_h)$. (Middle) Differential $t\bar{t}$ cross-section as a function of the hadronic $t\bar{t}$ pseudo-top-quark transverse momentum $p_T(t_h)$. (Right) Differential $t\bar{t}$ cross-section as a function of the hadronic pseudo-top-quark $p_T(t_h)$ ¹³. The data points are shown with a blue band which represents the total uncertainty (statistical and systematic) and compared with several LO multi-leg (middle) and NLO (right) MC generators.

112 The ALPGEN prediction¹⁵ do not describe correctly the cross-section as a function
 113 of $m(t_l t_h)$, in particular in the low mass region, and also in the high $p_T(t_h)$
 114 region where a similar trend is observed as for the resolved results previously dis-
 115 cussed. The NLO POWHEG(HERAPDF)+PYTHIA results¹⁶ provide the best
 116 description of all of the distributions.

Fig. 4. Fiducial particle-level differential cross-section as a function of the transverse momentum of the hadronically decaying top quark compared with different MC generators. MC samples are normalized to the NNLO+NNLL inclusive cross-section¹⁴. The gray band is the total data uncertainties. The lower part of the figure shows the ratio of the generator predictions to the data.

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117 A similar conclusion, on the description of the distribution as a function of the
118 top p_T , is obtained for the measurement¹⁴ in the boosted regime, characterized
119 by a large value of the transverse momentum of the produced top quarks. In this
120 analysis the differential cross-section is presented in the fiducial and total phase-
121 space as a function of the hadronically decaying top quark transverse momentum
122 p_T with a transverse momentum above 300 GeV and shown in fig 4. The predictions
123 of NLO and LO matrix element combined with parton shower MC generators are
124 found to generally overestimate the measured cross-sections. This measurement at
125 $\sqrt{s} = 8$ TeV has been performed by reconstructing the boosted top quarks with
126 the anti- k_t jet algorithm with the large radius parameter $R = 1.0$, and a dedicated
127 selection that exploits the rich content in the subjets of the fat jet originating from
128 the boosted top quark that increases the selection efficiency at high p_T and extends
129 the kinematics to the TeV scale. The dominant uncertainty in this measurement is
130 due to the large- R jets energy scale.

131 2. Single-top production

132 Top quarks can be produced singly via electroweak, charged-current interactions.
133 The single top cross-section in proton-proton collisions at $\sqrt{s} = 8$ TeV is about
134 half of that for top pair production mediated via the strong interaction. There are
135 three relevant single top-quark subprocesses that are distinguished at LO by the
136 virtuality of the exchanged W boson. At the LHC, the single top quark production
137 is dominated by the t-channel exchange of a virtual W boson process ($\sim 80\%$),

Fig. 5. (Left) Summary of ATLAS and CMS measurements of the single top production cross-section in various channel as a function of the centre-of-mass energy¹¹. The measurement are compared to theoretical calculation based on: NLO, NLO+NNLL and NNLO QCD predictions. (Right) Compilation of the ATLAS and CMS determination of the CKM matrix element $|V_{tb}|$ from single top quark measurements¹¹.

Fig. 6. (Left) Neural-network output-distribution. (Right) Predicted t-channel single top-quark fiducial cross-section for different LO and NLO MC generators together with the measured value²¹. The uncertainty on the prediction consists of the scale uncertainty and the uncertainty on the PDFs.

138 followed by the Wt production ($\sim 15\%$) while for the s-channel production only
 139 upper limits are given by the LHC experiments. The table below summarizes the
 140 theoretical predictions at NLO+NNLL for the cross-sections at 7, 8 and 14 TeV.

Table 1. SM predicted cross-sections

	t-channel ¹⁸	Wt -channel ¹⁹	s-channel ²⁰
7 TeV	$64.57^{+2.63}_{-1.74}$ pb	$15.74^{+1.17}_{-1.21}$ pb	$4.63^{+0.20}_{-0.18}$ pb
8 TeV	$87.76^{+3.44}_{-1.91}$ pb	22.37 ± 1.52 pb	5.61 ± 0.22 pb
14 TeV	243 ± 9 pb	$83.6^{+5.0}_{-6.8}$ pb	11.9 ± 0.6 pb

141 The single top-quark cross-section is proportional to the square of the W - t - b
 142 coupling at the production vertex. therefore, the measurement of the production
 143 cross-section constrains the absolute value of the quark-mixing matrix element¹⁷
 144 $|V_{tb}|$. It is then possible to extract $|V_{tb}|$ by dividing the measured inclusive single
 145 top cross-section by the corresponding SM prediction. The figure 5 left shows a sum-
 146 mary of the present single top production cross-section in the various channels^{21–23}
 147 compared with the NLO+NNLL theoretical predictions available at the centre-of-
 148 mas energy of 7 and 8 TeV.

149 The most precise ATLAS results for the t-channel production²¹ are presented
 150 in terms of fiducial and total cross-sections at $\sqrt{s} = 8$ TeV with events selected
 151 in the lepton+jets channel. Events are selected by requiring exactly two jets with
 152 one of the jets being b-tagged and the signal component is enhanced by the use
 153 of a neural-network discriminant based on the final-state observables. Figure 6 left
 154 shows the neural-network (NN) output-distribution for the combined electron and
 155 muon channel and figure 6 right shows a comparison of the fiducial cross-section

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156 with LO and NLO generators.

Using various MC generators, the fiducial cross-section can be extrapolated to the full phase-space and can be compared to the theoretical prediction. The measured value for the total cross-section in the t-channel is

$$\sigma_t = 82.6 \pm 1.2(stat.) \pm 11.4(syst.) \pm 3.1(pdf) \pm 2.3(lumi) \text{ pb}$$

157 in good agreement with the prediction available and reported in table 1. A compi-
158 lation of the relevant CKM matrix element $|V_{tb}|$ values determined in the t^{21} and
159 Wt^{22} channels is presented in figure 5 right.

160 The relative large cross-section for single top production in the t-channel allows
161 also the measurement of differential cross-section²⁴. The ATLAS collaboration has
162 measured single top differential cross-sections using the complete data sample at
163 $\sqrt{s} = 7$ TeV. The analysis strategy is very similar to the one described for the
164 fiducial and total cross-section at $\sqrt{s} = 8$ TeV, applying a cut on the neural network
165 output, a high purity region is defined to measure the differential cross-section as
166 a function of the top and antitop transverse momentum and rapidity. In figure 7
167 the measured spectrum as a function of the p_T is shown and compared to NLO
168 prediction that provide a good description of the measurement.

Fig. 7. Differential cross-section as a function of p_T and y compared to the QCD NLO calculations²⁴.

169 3. Top properties

170 In addition to the studies of the production mechanism for top pair and single
171 top production, there is at LHC an intense activity devoted to the study of the
172 properties of the top quark such as the top mass, the top charge asymmetry and
173 spin correlations.

Fig. 8. (Left) Summary of the ATLAS and CMS direct m_{top} measurements. The results are compared with the LHC and Tevatron+LHC m_{top} combinations. For each measurement, the statistical uncertainty, the jet scale factor and b-jet scale factor contributions as well as the sum of the remaining uncertainties are reported separately. The results below the line are results produced after the LHC and Tevatron+LHC combinations were performed. (Right) Summary of the measurements of the top quark pole mass, compared to direct measurements. Taken from Ref. 11.

4. Top mass measurements

Various properties of the top quark have been measured, the most precisely measured quantity being the top quark mass. It is an important parameter of the SM via its large mass and a precise measurement is an important input to fits of global electroweak parameters that help to test the internal consistency of the SM.

The measurement of the top quark mass as the invariant mass of the top quark decay products has been performed using various techniques. In ATLAS analyses, the template method is commonly used. In particular, this method is adopted in a $t\bar{t}$ dedicated measurement²⁵ performed with $\sqrt{s} = 7$ TeV data in the dilepton and lepton+jets channels and their combination. This measurement represents the most precise ATLAS result on the top quark mass determination and results in a top mass of $m_{top} = 172.99 \pm 0.91$ GeV. Another important ATLAS result come from the single top t-channel measurement²⁶ at 8 TeV. The analysis presents the first m_{top} measurement in topologies of t-channel single top enriched with $t\bar{t}$ contribution are used. This measurement yielded the value $m_{top} = 172.2 \pm 2.1$ GeV.

Thanks to the improved performance, the precise signal MC modelling and new measurement techniques, the top mass measurements becoming increasingly precise. The first world combination of m_{top} was carried out by the LHC and Tevatron experiments²⁷ and the following world average was obtained:

$$m_{top} = 173.34 \pm 0.76 \text{ GeV.}$$

Fig. 9. Summary of the charge asymmetry measurements of the ATLAS and CMS results at 7 TeV showing both the $t\bar{t}$ -based and lepton-based asymmetry measurements, compared to the respective theory predictions¹¹.

Figure 8 shows a summary of the top quark mass measurements entering the world combination²⁷.

It is also important to measure m_{top} using alternative approach like the comparison of NNLO+NNLL QCD calculations to the inclusive $t\bar{t}$ production cross-section measurements². Since this QCD calculation uses the pole mass scheme, the top m_{pole} can be determined. Figure 8 right summarizes the top quark pole mass measurements obtained with the $t\bar{t}$ analysis in the dilepton channel² already described and the recent measurement performed with $t\bar{t} + 1$ -jet events²⁸ and compare the results to the direct measurements, as it is visible all the results are in good agreement. Although the precision of the results of $\sim 1.5\%$ is not competitive with the direct m_{top} measurements, the results are affected by different systematic uncertainties and allows for extractions of m_{top} in theoretically well-defined mass schemes.

5. Top charge asymmetry measurement

In SM $t\bar{t}$ production the asymmetry is introduced by the higher order corrections, starting with the NLO in QCD contributions to the differential cross-sections. The asymmetry predicted in the SM is small and positive, implying that the top quark is preferentially emitted in the direction of the quark in the initial state. At the LHC, the contributions to the asymmetries are predominantly from $q\bar{q}$ and qg -initiated $t\bar{t}$ events. In the $q\bar{q}$ case, the quark is in most cases a valence quark whereas the antiquark is from the sea. The asymmetry translates to a higher boost along the beam direction for the t quark than for the $\bar{t}$ quark. The rapidity distribution reflects this effect.

The ATLAS Collaboration presented results at $\sqrt{s} = 7$ TeV performed in the dilepton²⁹ and l+jets³⁰ channels. The dilepton measurement shows results in terms

Fig. 10. (Left) Summary of the measurements of the fraction of $t\bar{t}$ events corresponding to the SM spin correlation hypothesis, f_{SM} , in the dilepton final state, using four spin correlation observables and in the lepton+jets channel. Dashed vertical line indicates the SM prediction³¹. (Right) Reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels³².

of $t\bar{t}$ charge asymmetry $A_C^{t\bar{t}}$ and leptons forward-backward asymmetry A_C^l :

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)} \quad A_C^l = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}$$

where y and η are the $t\bar{t}$ rapidity and lepton-lepton pseudorapidity respectively. The lepton+jets measurements are presented on terms of the $A_C^{t\bar{t}}$ asymmetry only.

The results are summarized in Figure 9 and are compatible with SM predictions.

6. Top Spin correlations measurement

In the SM, $t\bar{t}$ pairs are produced essentially unpolarized at hadron colliders. Nonetheless, the top quark and the antitop quark spins are correlated and the spin information transferred to the decay products and can be measured directly via their angular distributions.

Observables in the laboratory frame and in different top quark spin quantization bases can be used to measure the coefficient f_{SM} , which is connected to the number of events spin correlation as predicted by the SM. The coefficient is related to the spin correlation strength A_{helicity} defined as the differences between events where the top quark spins is parallel and antiparallel with respect to a spin quantization axis, divided by the total number of events.

In the ATLAS measurement, performed at $\sqrt{s} = 7 \text{ TeV}$ selecting dilepton and lepton+jet events³¹, the spin correlations are measured using the azimuthal difference $\Delta\phi$ between the lepton and one of the final-state jets or between the two leptons, respectively. The spin correlation strenght obtained is $A_{\text{helicity}} = 0.36 \pm 10$. Figure 10

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left shows the results obtained in terms of f_{SM} . In the figure are also presented additional measurements using observables which are different linear combinations of components in the spin density matrix of $t\bar{t}$ production. In particular, the ratio of the squares of matrix elements in the dileptonic channel is also measured. All the results are in good agreement with the SM prediction at NLO.

A new measurement of the spin correlations at 8 TeV³², with $t\bar{t}$ dilepton events, uses the difference in the azimuthal angle between the two charged leptons in the laboratory frame. The spin correlation strenght obtained is $A_{\text{helicity}} = 0.38 \pm 0.04$. In this analysis top squarks with masses between the top mass and 191 GeV are excluded at the 95% C.L.

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