Top physics results from ATLAS

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Abstract

Measurements of top quark production at the LHC form precision tests of the Standard Model and are a sensitive probe for new physics. Some recent results on top quark physics from the ATLAS experiment at the LHC are summarized in this document. Results of measurements of top quark charge, spin polarization, the charge asymmetry and the \(t\bar{t}\) cross section are compared with the Standard Model predictions. Results on the top quark mass measurements, which is a free parameter within the Standard Model (although it is constrained), are also shown.

Keywords: Top quark, experimental, charge, polarization, charge asymmetry, cross section, mass

1. The top quark: the heaviest fermion discovered so far

According to the Standard Model (SM), the top quark is the weak isospin partner of the b-quark, with spin \(s = \frac{1}{2}\) and a charge of \(Q = -2/3\). Its mass (Yukawa coupling with the Higgs boson) and the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements \((V_{td}, V_{ts}, V_{tb})\) are free parameters within the SM, although they are constrained (i.e., the unitarity of the CKM matrix constrains the \(V_{td}, V_{ts}, V_{tb}\) to be \(V_{td}, V_{ts} \ll V_{tb}\)).

Measurements of the top quark intrinsic properties have been carried out by the Tevatron and the LHC collaborations, giving consistent results with the SM predictions. We will detail some of the recent results from the ATLAS[1] experiment.

According to the Particle Data Group[2], the value of the top quark mass is \(M_t = 173.07 \pm 0.52 \pm 0.72\) GeV and \(\text{m}(m_t) = 160^{+5}_{-4}\) GeV. The first result is a combination of all published direct measurements done by the Tevatron experiments and is usually interpreted as the pole mass of the top quark. The second value corresponds to the \(\overline{\text{MS}}\) mass scheme and it has been extracted from the total \(t\bar{t}\) cross section.

Due to its large mass, the top-quark lifetime becomes extremely short inhibiting the formation of top quark bound states. Therefore, the top-quark polarization can be studied since the top quark transfers the spin information to its decay products and it is not diluted through hadronization effects as it happens in the case of the lighter quarks. Experimentally, the top quark is identified through the identification of its decay products: a W boson and a \(b\)-quark (in \(\sim 100\%\) of the cases since \(V_{tb} \sim 1\)). In the case of \(t\bar{t}\) production, the \(W\) bosons decay modes define the final state: dileptonic (both \(W\) bosons decay in leptons), lepton+jets (one \(W\) boson decay leptonically and the other into quarks) and fully hadronic channel (both bosons decay into quarks).

In the Standard Model the top-quark Yukawa coupling is close to one. With the strongest coupling to the Higgs boson the top quark represents an ideal laboratory for detailed tests of the Higgs mechanism. Beyond the Standard Model the top quark plays an important role in scenarios aiming to give an alternative explanation of spontaneous electroweak symmetry breaking (EWSB). The loop corrections to the Higgs boson propagator contain very large cancellations, due to the large top-quark mass. In the SM there is no symmetry which protects a strong dependence of the Higgs mass on a possible new scale. This is known as the naturalness problem. Many extensions of the Standard Model try to solve this problem and, in general, all these models expect deviations from the SM predictions in the top quark sector.

Top-quark physics is thus an interesting area for precision tests of the Standard Model but also for new physics searches.

In the following section, different top quark physics results from ATLAS, are summarized. If it is not said the opposite, all the measurements that the reader can find here have been done analysing the semileptonic \(t\bar{t}\) final state (specifically, the \(e + \text{jets}\) or \(\mu + \text{jets}\) final states). In the next section we present some of the latest results on the measurement of the intrinsic properties of the top quark (charge and spin). Also in this section, a measurement of the charge asymmetry in the \(t\bar{t}\) pair production is presented. In the third section we will cover the latest ATLAS results of the \(t\bar{t}\) production cross section measurements. In the following section, a summary on top quark mass measurements is shown. Finally, a short conclusion and a summary.

2. Top quark charge, polarization and charge asymmetry measurements

Measurement of the top-quark charge[3]

According to the SM, the top quark charge is \(Q = +2/3\). It has been measured by the ATLAS collaboration using 2.05 fb\(^{-1}\) of data at 7 TeV center-of-mass energy. The observable used to extract the charge is defined as the averaged value of:
where \( Q_{b-jet} \) is the effective \( b \)-jet charge, defined as

\[
Q_{b-jet}^i = \sum_j Q_i j \cdot \vec{p}_j / Q_i \cdot \vec{p}_i \quad (2)
\]

where \( Q_i \) and \( \vec{p}_i \) are the charge and momentum of the \( i \)-th track, \( \vec{j} \) defines the \( b \)-jet axis direction and \( k \) is a parameter which was set to be 0.5 for the best separation between \( b \)- and \( \bar{b} \)-jets mean charges.

The optimization of the correct pairing of the lepton with the \( b \)-jet originated from the same top has been performed by studying the invariant mass distribution of the \( m_{lb} \) pair, as it can be seen in the Fig. 1. The \( lb \)-pairing requires events with two \( b \)-tags. Only the events that satisfy:

\[
m(l,b-jet) < m_{cut} \text{ and } m(l,b-jet) > m_{cut} \quad (3)
\]

are considered (\( m_{cut} \) is chosen to get good compromise between the efficiency and the purity of the \( lb \)-pairing method).

The final \( Q_{comb} \) distribution is shown in Fig. 2 for the muon+jets channel. This distribution, together with the equivalent for electron+jets channel, is used to get the final \( Q_{top} \) from the following expression

\[
Q_{top} = 1 + Q_{comb}^{\text{data}} \times C_b \quad (4)
\]

where the \( b \)-jet charge calibration coefficient \( C_b = Q_b / \langle Q_{comb} \rangle \) is found to be \( 4.24 \pm 0.03 \text{(stat.)} \pm 0.07 \text{(syst.)} \) when evaluated using the full \( tt \) MC sample.

The final result is

\[
Q_{top} = 0.64 \pm 0.2 \text{(stat.)} \pm 0.08 \text{(syst.)} \quad (5)
\]

which agrees with the SM prediction and excludes models that propose a heavy quark of electric charge of \(-4/3\), instead of the SM top quark, with a significance of more than 8\( \sigma \).

**Figure 1**: Lepton \( b \)-jet invariant mass spectra for the lepton and \( quarks \) (wrong pairing, dashed blue line). Figure from [3].

**Figure 2**: Data and MC comparison of the \( b \)-jet charge after the basic \( tt \) requirements for muon+jets events. The MC expectations for signal and background are normalized to 2.05 fb\(^{-1} \) using the expected cross sections. The shaded area corresponds to a combination of statistical uncertainties and uncertainties in the cross section and integrated luminosity. Figure from [3].

**Measurement of the top-quark polarization in \( tt \) production [4]**

The production of top-antitop quark pairs in proton-proton collisions through QCD interactions is a parity conserving process according to the SM which implies top quarks are produced with no polarization (only a residual polarization \( \sim 0.003 \) is generated by the weak interaction). BSM physics can induce top quark polarization. Measurements of the polarization can be obtained through its extraction from the distribution of the polar angle \( \theta \) of any of the final-state decay products, \( i \), with respect a given quantization axis:

\[
W(\cos \theta_i) = \frac{1}{2} (1 + \alpha_i P \cos \theta_i) \quad (6)
\]

where \( P \) represents the degree of polarization along the chosen quantization axis and \( \alpha_i \) is the spin-analysing power of the final state object, which is a measure of the sensitivity of the daughter particle to the spin state of the parent. At tree level, the most sensitive daughters to spin state of the top (\( \alpha_t = 1 \)) are the leptons and down-type quarks. The \( \cos \theta \) distribution has been measured for the full 2011 data set by ATLAS for the semileptonic \((e+jets, \mu+jets)\) and the dileptonic \((ee, e\mu, \mu\mu)\) channels for which the kinematics of the \( t\bar{t} \) events have been fully reconstructed. The \( \alpha_i P \) \((l \text{ indicates leptons})\) value has been extracted from the data by fitting the positive fraction of \( W(\cos \theta_i) \), \( f \), to templates where the tops are partially polarized. To produce these templates, two different assumptions about the origin of the top quark polarization are made: either the polarization is assumed to be induced by charge-parity conserving processes (CPC) or a maximal CP violation (CPV) is assumed, leading to opposite values of \( \alpha_t P \) for the top and antitop quarks. An
example of the reconstructed angular distribution is shown in Fig. 3.

Figure 3: The result of the full combined fit to the data in the dilepton channel, adding together electrons and muons with the CP-conserving polarization hypothesis. It is compared to the polarization templates used and the SM prediction of zero polarization. Positively charged leptons are on the left, and negatively charged leptons on the right. Figure from [4]

The results obtained
\[
\alpha_t P_{CP} = -0.035 \pm 0.014 \text{(stat.)} \pm 0.037 \text{(syst.)}
\]
\[
\alpha_t P_{CPV} = 0.020 \pm 0.016 \text{(stat.)} + 0.011 \text{(syst.)}
\]
show a very good agreement with the SM prediction of negligible top quark polarization.

Measurement of the top-quark pair production charge asymmetry\[5\]

At leading-order (LO), the $t\bar{t}$ production at hadron colliders is predicted to be symmetric under the exchange of top quark and antiquark. At next-to-leading-order (NLO), interferences between initial and final state gluon emission in $qg \rightarrow t\bar{t}g$ introduce to a charge asymmetry. Also, interferences between Born and NLO diagrams contribute to the asymmetries. In the case of the LHC where the two incident hadrons are both protons, the asymmetry is observed thanks to the difference on the parton distribution functions: $t\bar{t}$ production via symmetric states of charge ($qg$, $qg$) is asymmetric under top quark-antiquark exchange and, at the same time, the valence quarks carry, on average, larger momentum fraction than antiquarks from the sea, so the top quarks are produced, also on average, at higher absolute rapidities.

The value of the charge asymmetry, $A_C$, at the LHC, according to the SM is $A_C = 0.0123 \pm 0.00005[6]$ computed at NLO including EW corrections. It is defined as follows
\[
A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}
\]
where $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$. The reconstruction of this observable requires a full event reconstruction in order to determine the rapidities of the quarks. For that the full 2011 data sample has been used. The results obtained, after unfolding the events to parton level using a Bayesian unfolding procedure is:
\[
A_C = 0.006 \pm 0.010 \text{(stat.+syst)}
\]

which is compatible with the SM prediction. To gain additional sensitivity to some new physics models, the observable has been measured looking in restricted regions of phase space, as it can be seen in Fig. 4 for example. In every case, no evidence of new physics has been found.

Figure 4: Charge asymmetry distributions as a function of $m_t$ (in the figure) after unfolding, for the electron and muon channel combined, have been measured. The $A_C$ values after unfolding (points) are compared with the SM predictions (hatched grey bands) and the predictions for a color octet axigluon with a mass of 300 GeV (hatched red bands) and 7000 GeV (hatched blue bands) respectively. The bands in the theoretical predictions include scale variation uncertainties. The error bars include both the statistical and systematic uncertainties on the $A_C$ values. Figure from [5]

3. Top quark pair cross section

Top quarks at the LHC are mainly produced in pairs via strong interactions. Precise measurements of top quark pair production is one of the benchmark measurement to test the validity of the SM predictions, which are in continuous updating to increase the precision. It has been calculated at next-to-next-to leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms with top+2.0 [7, 8, 9, 10, 11, 12]. The PDF and $\alpha_s$ uncertainties were calculated using the PDF4LHC prescription [13] for different sets of PDFs[14, 15, 16, 17, 18]. The NNLO+NNLL value, as implemented in Hathor 1.5, is about 3% [19] larger than the exact NNLO prediction. The results for a top quark pole mass of $m_{top} = 172.5\text{GeV}$ are
\[
\sigma_{t\bar{t}} = 177^{+10}_{-11} pb \ (\sqrt{s} = 7\text{TeV})
\]
\[
\sigma_{t\bar{t}} = 253^{+13}_{-15} pb \ (\sqrt{s} = 8\text{TeV})
\]

In this document, we will just summarize the latest ATLAS experimental results for 7 and 8 TeV not entering in details about the many channels that have been covered and the techniques that have been developed to improve the background determination. The top quark mass considered in all the analysis is $m_{top} = 172.5\text{GeV}$, and Monte Carlo samples with this mass input are used to extract the cross section. The high precision
with theoretical predictions, the distributions are unfolded for detector effects and corrected for acceptance effects to get the parton level distributions.

For example the \( d\sigma/dm_3 \) is sensitive to the existence of new particles predicted by beyond SM theories, such as new s-channel resonances that can modify the shape of the distribution. This distribution unfolded to the parton level is shown in Fig. 7 compared with several predictions with different PDF sets. Differential distributions can be used to potentially constrain PDF. In Fig. 8 some tension of the data with the CT10 pdf set is observed in the \( d\sigma/dy_{t\bar{t}} \) distribution.

4. Top quark mass measurements

Current top-quark mass measurements are mostly based on the direct determination from the kinematic reconstruction of the invariant mass of their decay products using techniques such
as the matrix element or the template method. In this approach, the top-quark mass does not correspond to a well-defined renormalization scheme, leading to an uncertainty in its interpretation which becomes important when experimental precisions achieve $\sim 1$ GeV. In this document two such measurements are discussed.

The top-quark mass can also be extracted from indirect measurements as, for example, studying the dependence of the top-quark pair production cross section on the mass. An example of that can be seen in Ref. [22] where a pole mass value of $m_{\text{pole}} = 173.3 \pm 2.8$ is obtained. These measurements show larger uncertainties on the mass determination as a consequence of the weak sensitivity of the cross section on the top-quark mass: $\Delta \sigma_t/\sigma_t \sim 5\% \Delta m/m$. Studies of new methods that would combine an unambiguously defined mass scheme and high sensitivity to the top quark mass are ongoing. A new approach with better sensitivity is found in Ref. [23] and Ref. [24].

**Top quark mass using a 3D template fit [25]**

This is the most precise top quark kinematical mass measurement performed by the ATLAS collaboration. This analysis uses a 3-dimensional template technique to determine the top quark mass together with two jet energy scale factors which represent large sources of uncertainty: the jet energy scale factor (JSF) and the relative $b$-jet to light-jet energy scale factor (bJSF).

The events are kinematically reconstructed using a kinematic likelihood fit which allows each jet to be assigned to its originating parton. Among the considered jet permutations, the combination which maximizes the likelihood is the chosen. After, three observables have been reconstructed and fitted at the same time: the $m_{\text{top}}^{\text{reco}}$, $m_W^{\text{reco}}$ (sensitive to the JSF) and the $R_{\text{lb}}^{\text{reco}}$ (sensitive to the bJSF). The $R_{\text{lb}}^{\text{reco}}$ observable is a ratio of the transverse momentum of the $b$-jets and the transverse momentum of the light jets coming from the W-boson. For events with one or two $b$-tagged jets:

$$R_{\text{lb}}^{\text{reco},2b} = \frac{p_T^{b_{\text{had}}_1} + p_T^{b_{\text{top}}_1}}{p_T^{W_{\text{jet}1}} + p_T^{W_{\text{jet}2}}}$$

$$R_{\text{lb}}^{\text{reco},1b} = \frac{p_T^{b_{\text{had}}_1}}{(p_T^{W_{\text{jet}1}} + p_T^{W_{\text{jet}2}})/2}$$

(12)

The best fits of the final distributions are shown in Figs. 9 and the extracted top quark mass and jet energy scales are:

$$m_{\text{top}}^{\text{reco}} = 172.31 \pm 0.75(\text{stat.}+\text{JSF}+\text{bJSF}) \pm 1.35(\text{syst}) \text{ GeV}$$

$$\text{JSF} = 1.014 \pm 0.003(\text{stat}) \pm 0.021(\text{syst})$$

$$\text{bJSF} = 1.006 \pm 0.008(\text{stat}) \pm 0.020(\text{syst})$$

(13)

Comparing with previous 2-dimensional methods, the systematic uncertainty from the bJES is now much reduced, as it is mostly absorbed in the bJSF at the cost of reduced statistical sensitivity.

**Top quark mass in dileptonic top quark pair decays [26]**

Another method used by the ATLAS collaboration to measure the top quark mass is based on the fit to templates of the $m_{\text{lb}}$ observable which is defined as the average invariant mass of the two lepton plus $b$-jet pairs in each dileptonic event. This channel presents very low background contributions ($\sim 3\%$). When using the $m_{\text{lb}}$ as estimator, events with two $b$-tagged jets are chosen where two possible assignments of the two $b$-jets to the two charged leptons are possible. For the two possible combinations, the $m_{\text{lb}}$ is constructed and the one with the minimum value is chosen, giving the correct assignment in the 77% of the cases. Finally, a likelihood fit of the template functions to the observed distribution is performed to obtain the value of the Monte Carlo mass which better describes the distribution.

The final result is:

$$m_{\text{top}} = 173.09 \pm 0.64(\text{stat}) \pm 1.50(\text{syst}) \text{ GeV}$$

(14)

obtained from the fit shown in Fig. 10.
Figure 10: Fitted $m_{\text{top}}$ distribution in data. The fitted probability density functions for the signal plus background and for the background contribution alone are also shown. The inset shows the -2 log likelihood profile as a function of the fitted top quark mass. Figure from [26].

Figure 11: Summary of the ATLAS direct top quark measurements. The results are compared to the 2013 Tevatron and LHC top combinations. For each measurement, the statistical uncertainty, the jet scale factor (JSF) and b-jet scale factor (bJSF) contributions (when applicable) as well as the sum of the remaining uncertainties are reported separately. The JSF bJSF contributions are statistical in nature and apply to analyses performing in-situ (top quark pair base) jet energy calibration procedures. Figure from [27].

Summary of direct top quark mass measurements in ATLAS

A summary of direct top quark mass measurements by ATLAS compared to the Tevatron and the LHC top mass measurement combinations is presented in Fig. 11. Compatible results between different experiments at the LHC and Tevatron are obtained. Systematic uncertainties dominate the total uncertainty. There is a lot of work ongoing within the Top LHC working group to harmonise the treatment of systematic uncertainties between the experiments.

5. Conclusions

In this document, a very short report of the top quark physics results in the ATLAS experiment has been shown. Of course, many other results and measurements have been performed in ATLAS or are in progress in this moment: single top physics, search of heavy resonances decaying in $t\bar{t}$... The results shown here present good agreement with the SM predictions considering the experimental and theoretical uncertainties. Most of the measurements are limited by systematics uncertainties. In some cases, the experimental precisions exceeds that of the theory predictions. Many more results that have not been detailed here can be seen in Ref. [27].

References