Highlights of top-quark properties measurements at ATLAS

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Abstract

The top-quark is a fundamental particle of the Standard Model (SM) and plays an important role in Beyond the Standard Model (BSM) scenarios. It is hence important to measure its properties precisely, to reduce uncertainties on SM prediction and to constraint BSM models. The latest top-quark properties measurements performed by the ATLAS collaboration are presented. Precise measurements of the top-quark mass, top-quark width and structure of the Wtb interaction vertex, using the 8 TeV dataset, are reported. First results studying the 13 TeV dataset are also presented, which include searches for Flavour Changing Neutral Currents and measurements of the spin correlations and colour flow in $t\bar{t}$ events.

1 Introduction

The top-quark was introduced to explain CP violation in kaon decays [1] and was discovered in 1995 by the CDF and D0 collaborations [2, 3]. Top-quarks are the only quarks which can be studied outside a hadronic system, since they have the unique property of decaying before hadronization effects take place. In the Standard Model (SM) many properties of the top-quark can be predicted and the only top-quark related free parameters are its mass, m_t , and three elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which describe the strength of the top-quark electro-weak interactions. Being the top-quark branching fraction to a W boson and a b -quark around 99%, top-quarks either

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decay to one b -quark and two light quarks (hadronic decay) or to one b -quark, a lepton and a neutrino (leptonic decay). Other decay modes, involving for instance Flavour Changing Neutral Current (FCNC), are predicted to be small or strongly suppressed within the SM. In the following, a selection of the latest measurements of the top-quark properties, performed on data produced by the Large Hadron Collider (LHC) [4] and collected by the ATLAS detector [5], are reported.

2 Top-quark width

The top-quark width, Γ_t , can be computed from perturbative QCD calculations, as a function of the top-quark mass and the strong coupling constant α_s . It has been computed at the Next-to-Leading-Order (NLO) [6, 7] and NNLO [8] approximation in QCD, the latest prediction giving $\Gamma_t = 1.322$ GeV for a top-quark mass of 172.5 GeV and $\alpha_s(m_Z) = 0.1181$.

ATLAS performed a direct measurement of the top-quark width using semileptonic $t\bar{t}$ events produced from pp collisions at 8 TeV [9]. Two observables sensitive to Γ_t were chosen: the invariant mass of the system formed by the b -jet and the charged lepton from the leptonically decaying top-quark, m_{lb} , and the angular distance between the b -jet j_b and the closest light jet j_l from the hadronic top-quark decay, $\Delta R_{\min}(j_b, j_l)$. The m_{lb} observable shows good sensitivity to

Figure 1: The m_{lb} (left) and $\Delta R_{\min}(j_b, j_l)$ (right) observables used in the top-quark width direct measurement. Figure from Ref. [9].

Γ_t and is less sensitive to jet-related uncertainties compared to reconstructed masses of the hadronic decay branch. On the other hand it is beneficial to use $\Delta R_{\min}(j_b, j_l)$ in the fit, because it adds information from the hadronic top-quark side and, in the combination, reduces the leading jet-related and signal model systematic uncertainties. The distribution of the two observables used in the analysis, predicted by Monte Carlo (MC) simulations with different values for

Γ_t , are reported in Fig. 1.

A template method is used to estimate the top-quark decay width, via a binned likelihood fit to data. Templates for different top-quark decay width values were constructed by reweighting MC events with the nominal Γ_t value. The result of the fit gave

$$\Gamma_t = 1.76 \pm 0.33 \text{ (stat.) } {}^{+0.79}_{-0.68} \text{ (syst.) GeV} \quad (1)$$

which is compatible with the SM expectations for a top-quark mass of 172.5 GeV. The leading uncertainties on the measurement came from the statistically limited data sample analysed (0.3 GeV), the jet four-momenta reconstruction (${}^{+0.4}_{-0.3}$ GeV), the b -jet identification (~ 0.3 GeV) and the modelling of the hard process in the Monte Carlo generation (0.4 GeV).

3 Top-quark mass

The top-quark mass is a fundamental free parameter of the SM and its value has to be inferred from experiments. A precise determination of m_t is important in consistency checks of the SM as well as in BSM models, being the top-quark, W boson and Higgs boson masses related through radiative corrections [10]. Since in the SM quark masses are strictly related to the Higgs-quark interactions, the top-quark mass also plays an important role in the stability of the electro-weak vacuum [11].

Two general methods have been used so far to measure m_t : direct mass measurements and mass measurements from cross-sections. In the former, data are compared to a template obtained from MC simulations produced with different input values of the mass parameter, m_t^{MC} . The direct mass measured in this case is defined as the value of m_t^{MC} for which the MC best describes the data. In the second method, data is compared to purely perturbative calculations, which are parametrised as a function of the top-quark mass. Top-quark masses extracted this way are measurements of the mass parameter in the theoretical Lagrangian.

Direct mass measurements so far have the highest experimental precision, with the latest results having uncertainties smaller than 1 GeV on the top-quark mass. Nevertheless, it is difficult to fully estimate theoretical uncertainties on them, since the connection between m_t^{MC} and the top-quark mass Lagrangian parameter is unknown and interpreting m_t^{MC} as the top-quark mass in the pole mass renormalization scheme could be wrong by several hundreds of MeV [12]. Cross-section mass measurements instead can be performed in a well defined theoretical framework, but on the other hand they are typically less sensitive to m_t , resulting in measurements with larger errors.

3.1 Direct top-quark mass measurement at 8 TeV

The latest top-quark mass direct measurement has been performed by ATLAS using semileptonic $t\bar{t}$ events at 8 TeV [13]. In order to reduce the impact of jet

scale factors on the measurement, they were constrained from the same data, via a simultaneous fit with the top-quark mass. The top-quark mass extracted from a MC template fit, was found to be $m_t = 172.1 \pm 0.9$ GeV, being the uncertainty dominated by MC modelling uncertainties. Such measurement was combined

Figure 2: On the left, the correlations between the systematics of the semileptonic and dileptonic direct mass measurements at 8 TeV. On the right, the effect of adding different measurements to the combination. Figure from Ref. [13].

with previous dileptonic direct top-quark mass measurements at 7 TeV and 8 TeV [14, 15]. Thanks to negative correlations between common systematics affecting the different analyses, the total error on the combined m_t was strongly reduced. The effect of including different analyses to the combination is shown in Fig. 2, where also the result of the latest ATLAS direct top-quark mass combination is shown. The final result of the combination was:

$$m_t = 172.51 \pm 0.5 \text{ GeV} \quad (2)$$

where the total error was almost halved with respect to the single most precise ATLAS top-quark mass direct measurements.

3.2 Top-quark pole mass measurement from differential cross sections

Top-quark mass measurements from cross sections used to be less precise than the direct ones, since the sensitivity of inclusive cross sections to the top-quark mass is limited. Differential cross sections, though, can exploit regions of the phase space where dependence on m_t is high.

The latest ATLAS measurement selected dileptonic $t\bar{t}$ events at 8 TeV to extract the top-quark pole mass from 8 differential cross sections [16]. Every distribution was unfolded to a fiducial volume at particle level, which shared the same phase space of existing perturbative calculation at NLO QCD [17]. The top-quark mass in the pole mass scheme was then extracted from each of the eight distributions separately, as well as in a simultaneous fit, as it is shown in

Figure 3: Top-quark pole mass values extracted from the five most sensitive differential distributions unfolded to particle level (leftmost points). The final result obtained simultaneously fitting all the eight distributions considered in Ref. [16] is shown on the right. Figure from Ref. [16].

Fig. 3. The result of the simultaneous fit was:

$$m_t^{\text{pole}} = 173.2 \pm 1.6 \text{ GeV} \quad (3)$$

which is the most precise measurement of the top-quark pole mass so far, with a relative uncertainty below 1%.

4 Study of the Wtb vertex in single-top events

In pp collisions single top-quarks can be produced via electro-weak charged currents involving the Wtb vertex. This mainly happens through the so called t -channel production mechanism, where a light quark and a b -quark collide to produce a top quark and a forward light-quark (called the spectator quark) through the exchange of space-like W boson. In the SM, the top-quarks produced via t -channel are highly polarised along the direction of the spectator quark. This has a strong influence on the angular distributions of its decay products and production asymmetries values. ATLAS measured various asymmetries distributions [18] and a triple differential decay rate [19] from data collected at 8 TeV. A cut based event selection targeting leptonic decays of the top-quarks was used to discriminate the t -channel signal from the backgrounds. Measured distributions were then unfolded to parton level, where they were compared to NNLO QCD theoretical predictions [20]. All the measurements were found to be compatible with the SM predictions, as it shown in figure Fig. 4. New physics in the Wtb vertex can be described by an effective Lagrangian with four complex parameters in a model-independent manner. The ATLAS measurements allowed to put limits on such parameters, constraining in particular possible CP violating effects in the top-quark decay.

Figure 4: Measured and predicted asymmetries (left) and deconvolved angular coefficients of the triple differential decay rate (right) in single top production. Data agree with the SM predictions within their errors. Figures from Ref. [18, 19].

5 Flavour Changing Neutral Currents

In the SM, flavour-changing neutral currents (FCNC) are expected to be experimentally unobservable, with predicted branching ratios of the order of 10^{-15} . Extensions of the SM though, can generate FCNC processes leading to signals which, if observed, would be unambiguous evidence for new physics. ATLAS searched for FCNCs in data collected during 2015 and 2016 at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb^{-1} . Two FCNC searches [21, 22] are reported in the following, looking for top-quarks decaying into a light quark (u or c type) and either a Higgs boson or a Z boson. A summary of FCNCs searches at the LHC is reported in Fig. 5.

5.1 Searches for $t \rightarrow Hq$

ATLAS looked for $t\bar{t}$ events in which one top-quark decays via $t \rightarrow Hq$ [21]. The final states targeted by this analysis were multileptonic, with either three light leptons ($3l$) or two light leptons of the same electric charge ($2lSS$). Such final states can be produced by H bosons decaying into a vector boson pair (WW^* or ZZ^*) or a pair of tau leptons, which then decay leptonically. The dominant backgrounds of such multileptonic final states come from leptons produced by hadron decays or photon conversions (the so-called *non-prompt* leptons), followed by leptons coming from $t\bar{t}V$ production.

To discriminate a possible tiny signal against the backgrounds, boosted decision trees (BDTs) were used. In total, 11 (16) observables, for the $2lSS$ ($3l$) channel, were fed to the BDT algorithm. No evidence of FCNCs was found and upper limits were set on the $\mathcal{B}(t \rightarrow Hq)$ branching fractions. At 95% confidence level (CL), they read $\mathcal{B}(t \rightarrow Hc) < 0.16\%$ and $\mathcal{B}(t \rightarrow Hu) < 0.19\%$.

Figure 5: Summary plot from Ref. [22] of the FCNC upper limits from the LHC experiments (arrows with dot), together with various SM (black lines) and BSM (coloured areas) theoretical predictions. The results presented in these proceedings corresponds to, from top to bottom, the first two and last two blue arrows.

5.2 Searches for $t \rightarrow Zq$

Another analysis performed by the ATLAS collaboration looked for $t\bar{t}$ events in which one top-quark decays producing a Z boson and a light quark [22]. Only Z bosons decaying into charged leptons and leptonic W boson decays were considered in Ref. [22]. Such choice of final state, made the largest backgrounds to be leptons from diboson, $t\bar{t}Z$ and tZ production modes, as well as *non-prompt* leptons. Control regions were defined and data driven techniques were used to estimate and constrain the main backgrounds. Good agreement between the data and SM expectations was found, and no FCNC signal was observed. The correspondent upper limits at 95%CL read $\mathcal{B}(t \rightarrow Zc) < 1.7 \times 10^{-4}$ and $\mathcal{B}(t \rightarrow Zu) < 2.4 \times 10^{-4}$, which are the strongest limits for $t \rightarrow Zq$ so far. Furthermore, effective field theory operators contributing to the $t \rightarrow Zq$ FCNC decays of the top quark were strongly constrained by this measurement.

6 Spin correlations

The spins of the top and the anti-top quarks in $t\bar{t}$ production are predicted to be correlated in the SM. Due to the unstable nature of top quarks, their spin information can be accessed through their decay products, being the lifetime of the top quark shorter than the time scale for hadronisation and much shorter than the spin decorrelation time.

In top-quark leptonic decays, the leptons carry almost all the full spin information of the parent top-quark. They are also easily identified and reconstructed by collider experiments. Hence, observables involving angular distributions of leptons are optimal to study spin-correlations in dileptonic $t\bar{t}$ events.

ATLAS analysed 36.1 fb^{-1} of data produced from pp collisions at $\sqrt{s} = 13 \text{ TeV}$ to measure the absolute azimuthal opening angle, $|\Delta\phi|$, between two charged leptons coming from the decay of top-quark pairs [23]. The measurement was performed in four intervals of the invariant mass of the $t\bar{t}$ system as well as inclusively, and unfolded to parton level and particle level. The unfolded inclusive distributions are shown in Fig. 6.

Figure 6: Normalised unfolded distributions of $|\Delta\phi|$, at particle level (left) and parton level (right). Figure from Ref. [23].

The parton level $|\Delta\phi|$ was then used to estimate the fraction of events with a SM-like spin correlation, f_{SM} , via a binned likelihood fit to a fixed order QCD prediction [24]. The spin correlation extracted from the unfolded data was found to be significantly higher than the SM expectation:

$$f_{\text{SM}} = 1.250 \pm 0.026(\text{stat}) \pm 0.063(\text{syst}) \quad (4)$$

at a confidence level of 3.7 standard deviations (3.2σ when including theoretical uncertainties). Previous measurements from ATLAS also observed such behaviour [25–28], but the uncertainties were such that the results remained consistent with the SM. The spin correlation was also found to increase as a function of the invariant mass of the $t\bar{t}$ system but, due to the larger statistical and systematic uncertainties in these regions, such effect was not significant in any individual $m_{t\bar{t}}$ bin (significance below 1.4σ).

7 Colour flow

In the decay chain of a hard-scatter event, the colour charge flows from the initial state towards stable particles. Since colour charge is conserved, connections exist between initial particles and the stable colour-neutral hadrons, and they can be studied by weighted angular moments derived from jet constituents. For a given jet j with transverse momentum p_T^j , the jet-pull vector can be defined as:

$$\vec{\mathcal{P}}(j) = \sum_{i \in j} \frac{|\vec{\Delta r}_i| \cdot p_T^i}{p_T^j} \vec{\Delta r}_i \quad (5)$$

where i are the constituents of j . Given two jets j_1 and j_2 , the jet-pull angle $\theta_P(j_1, j_2)$ can also be defined as the angle between the jet-pull vector and the vector connecting the two jet axes.

Figure 7: The four jet-pull observables measured in [29], unfolded to particle level.

ATLAS measured jet-pull observables in $t\bar{t}$ events using 36.1 fb^{-1} of pp collision data at $\sqrt{13} \text{ TeV}$ [29]. In total four observables were measured, as shown in Fig. 7: the jet-pull magnitudes and angles of the jets from the hadronic W boson, and the jet-pull angle between the two b -jets from top-quark decay. The measured observables were corrected for detector effects and compared to a variety of MC simulations. While good agreement was found for some combinations of predictions and observables, none of the simulations was found to described well the data across all observables.

8 Summary

In these proceedings, a selection of the latest measurements of the top-quark properties performed by the ATLAS collaboration has been presented. Almost all the analyses which study the 8 TeV dataset produced by the LHC have been published, while the first measurements on data collected at 13 TeV during 2015 and 2016 started to be available.

The 8 TeV analyses presented in this proceedings performed measurements of the top-quark width in Section 2, of the top-quark mass in Section 3, and of the Wtb interaction vertex in Section 4. Such measurements take advantage of the high knowledge of the ATLAS behaviour acquired during the Run 1 of the LHC, and therefore have a high precision. Typically, the largest uncertainties affecting such measurements come from jet-related systematics and MC modelling.

The 13 TeV analyses studied early Run 2 data looking for new physics in the top-quark sector and for potential $t\bar{t}$ MC mismodelling. In Section 5 searches for top-quarks decaying into a light quark and a Z or H boson were presented, were no evidence for such FCNC signal was observed. The studies on spin correlations between top-quarks produced in $t\bar{t}$ events were reported in Section 6. It was measured that the fraction of spin correlated top-quarks is higher than the SM prediction, with a 3.7σ (3.2σ when including the theoretical error) significance. Finally, in Section 7, measurements of observables sensitive to colour connections in $t\bar{t}$ events were presented. Different MC simulations were compared to data and it was found that none of the MC prediction studied could describe all the measured observables at the same time.

With more data being collected by the ATLAS detector during the Run 2 of the LHC, top-quark properties measurements are entering the precision era. A reduction of the uncertainty on the presented measurements is foreseen, which would improve top-quark physics understanding.

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