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Top quark properties using the ATLAS detector at the LHC

M.J. Costa on behalf of the ATLAS Collaboration[1,a]

[1] *Instituto de Física Corpuscular - Centro Mixto Consejo Superior de Investigaciones Científicas - Universidad de Valencia, Edificio Institutos de Investigación, C/Catedrático Beltrán 2, E-46980 Paterna, Spain*

Abstract.
The latest measurements of the properties of the top quark using the ATLAS experiment are presented. The top quark mass is one of the fundamental parameters of the Standard Model. A new measurement using the template method in dilepton events in which the event selection was optimised to achieve the smallest total uncertainty is presented. It is combined with a measurement on a multi-dimensional template fit that can constrain the uncertainties on the energy measurements of jets. In addition, measurements aiming to measure the mass in a well-defined scheme are presented. The top quark pair charge asymmetry is an asymmetry predicted to occur beyond leading-order QCD in the Standard Model, and may be significantly enhanced by the presence of new physics. The $t\bar{t}$ production charge asymmetry is measured inclusively and differentially using the 8 TeV ATLAS datasets in the dilepton channel and with lepton+jets events including boosted topology. Making use of the large number of top quark pairs collected, we also present measurements of the spin correlation between top and anti-top quarks and discuss their sensitivities to new physics.

1 Introduction

The top quark is the heaviest known fundamental particle, leading to important theoretical and experimental implications. The large top quark mass implies a large coupling to the Higgs boson and raises the possibility that it plays a special role in the mechanism of electroweak symmetry breaking. It also implies that the top quark decays rapidly through electroweak interactions before it can form a hadronic bound state, which provides the unique opportunity to study the properties from distributions of its decay products. It is therefore essential to measure with high precision the top quark properties using data from the ATLAS experiment [1] and confront them with the Standard Model (SM) predictions.

2 The top quark mass

The top quark mass is a free parameter of the SM which together with the W boson mass constrains the Higgs boson mass through electroweak quantum corrections, allowing for stringent tests of the SM. It is also an important input for the studies of electroweak vacuum stability.

[a] e-mail: Maria.Jose.Costa@ific.uv.es

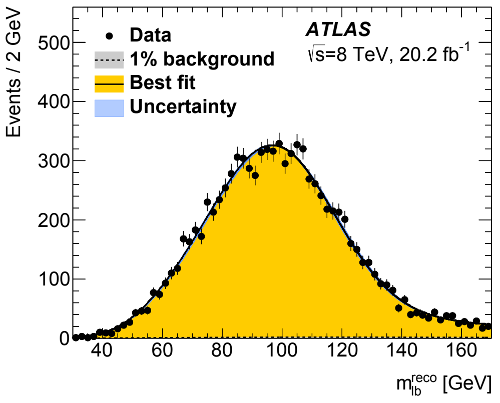

Figure 1. The reconstructed $m_{\ell b}$ observable for data together with the fitted probability density functions for background alone and for the sum of signal and background [6].

The most precise results are obtained using the template method, in particular when applied in the $t\bar{t}$ lepton+jets and dilepton channels. For a chosen observable sensitive to the top quark mass parameter (m_{top}), simulated distributions (templates) are produced using a number of discrete values of that parameter. These templates are fitted to distributions that interpolate between different input values of the top quark mass parameter. A fit to the observed data distribution is then performed to obtain the value of m_{top} that best describes data. Therefore, the mass determined with this procedure is the mass as defined in the Monte Carlo generator. It is expected that the difference between this mass definition and the pole mass is of order 1 GeV [2–4].

The measurement in the lepton+jets channel is performed using data from proton-proton collisions at $\sqrt{s} = 7$ TeV [5]. The mass is extracted from a three-dimensional template fit to the reconstructed invariant mass of the hadronic top quark decay products, the invariant mass of the two jets coming from the W boson to constrain the jet energy scale uncertainty, and an observable sensitive to the relative b-to-light jet energy scale to reduce the otherwise dominant b-jet energy scale uncertainty. The top quark mass is simultaneously determined with a global light-jet energy scale factor (JSF) and a relative b-to-light-jet energy scale factor (bJSF), accounting for residual differences of data and simulation in the light-jet and b-to-light-jet energy scale. The result obtained is $m_{\mathrm{top}} = 172.33 \pm 0.75\,(\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.02\,(\mathrm{syst})$ GeV, dominated by statistical uncertainties.

In the dilepton channel, measurements have been performed with data collected at both 7 TeV and 8 TeV center-of-mass energies [5, 6]. In this channel, the top quark mass is extracted from a one-dimensional template method, where the templates are constructed from the $m_{\ell b}$ observable, defined as per-event average invariant mass of the two lepton-b-jet systems from the decay of the top quarks (see Figure 1). Due to the underconstrained kinematics associated with the dilepton final state, no in situ constraint of the jet energy scales is performed.

The results obtained are $m_{\mathrm{top}} = 173.79 \pm 0.54\,(\mathrm{stat}) \pm 1.30\,(\mathrm{syst})$ GeV and $m_{\mathrm{top}} = 172.99 \pm 0.41\,(\mathrm{stat}) \pm 0.74\,(\mathrm{syst})$ GeV for the 7 and 8 TeV datasets respectively. The result at $\sqrt{s} = 8$ TeV is about 40% more precise than the one obtained from the $\sqrt{s} = 7$ TeV data and the most precise single result from ATLAS. The increased precision is partially driven by a better knowledge of the jet energy scale. In addition, the larger dataset at $\sqrt{s} = 8$ TeV allowed for an optimised event selection

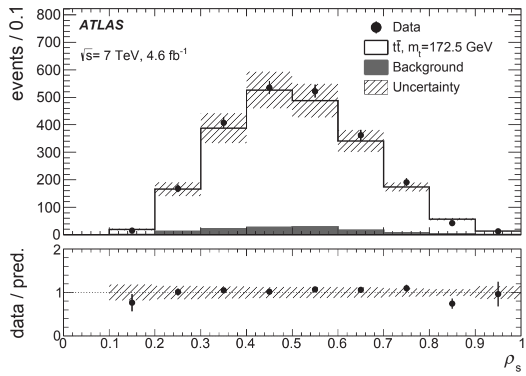

Figure 2. Number of reconstructed events as a function of $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1-\text{jet}}}}$ ($m_0 = 170$ GeV) related to the inverse of the invariant mass of the $t\bar{t}$+1-jet system. The data are compared to the signal plus background expectations [10].

significantly reducing the total systematic uncertainty, mostly due to a lower impact of the jet energy scale and theory modelling uncertainties.

These three most precise measurements obtained by ATLAS have been combined using the best linear unbiased estimate (BLUE) method [7, 8] in which both statistical and systematic uncertainties, and their correlations are taken into account. The correlations of the measurements are evaluated for each source of systematic uncertainty. Using a dedicated mapping of uncertainty categories, the combination results in $m_{\text{top}} = 172.84 \pm 0.34\,(\text{stat}) \pm 0.61\,(\text{syst})$ GeV, with a total relative precision of 0.4%, representing a 17% improvement with respect to the most precise single input measurement.

As mentioned above, the measurements presented so far correspond to the mass definition used in the Monte Carlo simulation. An alternative approach is to extract the mass from measurements of observables whose mass dependence can be calculated beyond leading-order in a perturbative expansion. With this method the top quark mass scheme is unambiguously defined in the theoretical calculations. The results obtained so far have however a lower precision.

Using this approach, the top quark pole mass has been determined from measurements of two different observables: The inclusive cross section for top quark pair production and the normalised differential cross section for $t\bar{t}$ production with at least one additional jet, $t\bar{t}$+1-jet, as a function of the inverse of the invariant mass of the $t\bar{t}$+1-jet system (see Figure 2). The top quark mass dependence for these observables is calculated at NNLO+NNLL accuracy for the former and at NLO for the latter. The differential observable presents a larger sensitivity to the top quark pole mass. Its sensitivity is due to the mass dependence of the amount of gluon radiation, with large effects in the phase space region relatively close to the $t\bar{t}$+1-jet production threshold.

The value extracted from the measurements of the inclusive $t\bar{t}$ cross section at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV is $m_{\text{top}}^{\text{pole}} = 172.9^{+2.5}_{-2.6}$ GeV [9]. From the differential measurement, the mass is measured to be $m_{\text{top}}^{\text{pole}} = 173.7 \pm 1.5\,(\text{stat}) \pm 1.4\,(\text{syst})^{+1.0}_{-0.5}\,(\text{theo})$ GeV, reaching a relative uncertainty of 1.3% [10].

3 Spin correlations in top quark pair production

Since the top quark decays before it can form hadrons, the orientations of the top and anti-top quark spins are transferred to the decay products and can be measured directly via their angular distributions.

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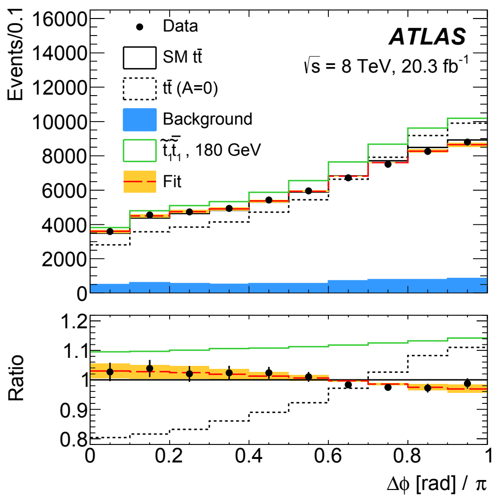

Figure 3. Reconstructed $\Delta\phi$ distribution. The prediction for background (blue histogram) plus SM $t\bar{t}$ production (solid black histogram) and background plus $t\bar{t}$ prediction with no spin correlation (dashed back histogram) is compared to data and to the result of the fit to the data (red dashed histogram) with orange band representing the total systematic uncertainty on f_{SM}. The prediction for top squark pair production plus SM $t\bar{t}$ production plus background is also shown (solid green histogram). The lower plot shows those distributions (except for background only) divided by the SM $t\bar{t}$ plus background prediction [11].

Angular distributions of charged leptons are particularly interesting because the polarisation-analysing power of the charged leptons is effectively 100%.

Within the SM QCD top quark pair production, the top quarks are expected to have a negligible polarisation, but the spins of the top and anti-top are expected to be correlated. Many scenarious of physics beyond the SM predict different spin correlations.

The latest and most precise measurements provided by ATLAS in the dilepton channel use two different observables to extract the spin correlation strength: $A_{\mathrm{helicity}} = \frac{N_{\mathrm{like}}-N_{\mathrm{unlike}}}{N_{\mathrm{like}}+N_{\mathrm{unlike}}}$, where N_{like} (N_{unlike}) is the number of events where the top quark and top anti-quark spins are parallel (anti-parallel). One of the observables is the difference in azimuthal angle $\Delta\phi$ between the two charged leptons, defined in the laboratory frame. The second measured observable is the double differential distribution of $\cos\theta_1 \cdot \theta_2$ where θ_1 and θ_2 are for each lepton the polar angle between the direction of the lepton in the top rest frame and the top quark direction in the $t\bar{t}$ center-of-mass frame.

Figure 3 shows the reconstructed $\Delta\phi$ distribution obtained using $\sqrt{s} = 8$ TeV data, compared with Monte Carlo predictions with and without spin correlations. These predictions are then used in a template fit to the data to obtain a coefficient f_{SM} that measures the degree of spin correlations with respect to the SM prediction. The extracted value is $f_{\mathrm{SM}} = 1.20 \pm 0.05\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst})$, that can be translated into $A_{\mathrm{helicity}} = 0.38 \pm 0.04$ assuming that the $t\bar{t}$ sample is composed of top quark pairs as predicted by the SM but with varying spin correlation [11]. The measurement agrees with the NLO QCD prediction to within two standard deviations.

The distribution of $\cos\theta_1 \cdot \theta_2$ is measured using $\sqrt{s} = 7$ TeV data. After background subtraction, the distribution is unfolded to parton level using an iterative Bayesian method. The unfolded distribution is in good agreement with the SM prediction and yields to $A_{\text{helicity}} = 0.315 \pm 0.061\,(\text{stat}) \pm 0.049\,(\text{syst})$ [12].

4 Charge asymmetry in top quark pair production

At leading-order, $t\bar{t}$ production is expected to be symmetric under the exchange of top and anti-top quarks. Beyond leading-order and for $q\bar{q}$ initiated processes, due to an interference between the Born and NLO diagrams and between processes with initial and final state gluon emissions, there is a connection between the direction of the top and the initial quark and between the anti-top and the initial anti-quark. At the LHC, this leads to top quarks being produced more forward and anti-top quarks more central. This effect is very small within the SM, at the 1% level, because the dominant top quark pair production is via gluon fusion, which is always symmetric. However, it can be enhanced in several BSM scenarious.

The observable used to study this effect is the forward-backward asymmetry $A_C^{t\bar{t}}$ on the distribution of the difference between the absolute rapidities of the top and anti-top quarks. For the case in which both top quarks decay leptonically, the asymmetry $A_C^{\ell\ell}$ on the distribution of the difference between absolute rapidities of the positive and negative charged leptons is also measured. This observable has a slightly diluted sensitivity but has the advantage that no reconstruction of the $t\bar{t}$ is needed.

Measurements of these two observables have been performed inclusively and differentially as a function of several kinematic variables (as the invariant mass, transverse momentum and longitudinal boost of the $t\bar{t}$ system). They have been done in the full phase space, so that they can be directly compared with the NLO QCD predictions [13, 14], and also in a fiducial region in order not to rely on extrapolations to regions of the phase space that are not within the detector acceptance.

The latest measurements are performed using the $\sqrt{s} = 8$ TeV data in the lepton+jets and dilepton channels [15–17]. For the lepton+jets channel there is a dedicated measurement in events with highly boosted top quarks with an invariant mass of the $t\bar{t}$ system in the TeV range. This kinematic region has a higher sensitivity to the SM asymmetry as well as for BSM models that introduce massive new states. The measured distributions are corrected for acceptance and detector resolution effects using a full Bayesian unfolding method.

All results are found to be compatible with the SM predictions, being the precision limited by statistics. These measurements have allowed to set limits on the masses and couplings of new particles within BSM models. The results obtained for the inclusive top quark based measurements, including also the fiducial measurement in the boosted regime, are summarised in Figure 4 and compared to the CMS measurements. Figure 5 shows the values of $A_C^{t\bar{t}}$ and $A_C^{\ell\ell}$ from the inclusive measurements in the full phase space in the dilepton channel, compared to the SM predictions and a BSM model compatible with the Tevatron results.

5 Conclusion

The latest and most precise measurements performed using Run-1 data from the ATLAS experiment of the top quark mass and angular distributions in top quark pair events sensitive to spin correlations and charge asymmetry effects have been presented. These measurements allow to probe with high precision the SM, being also sensitive to new physics effects.

The most precise measurements of the top quark mass are achieved using a template method, reaching a relative precision of 0.4% on the Monte Carlo top quark mass by combining the measurements performed in the lepton+jets and dilepton channels. Direct determinations of the pole top quark mass have also been performed, reaching a precision of 1.3%.

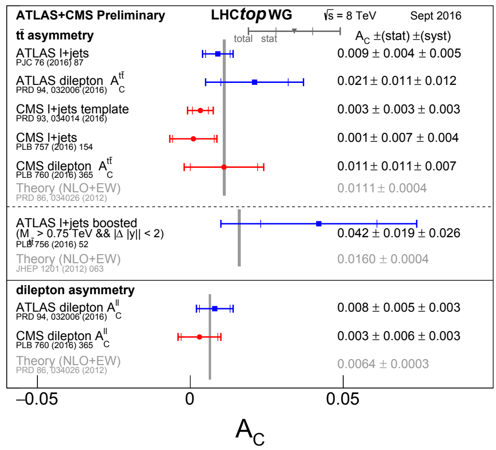

Figure 4. Summary of the charge asymmetry $A_C^{t\bar{t}}$ measurements provided by the ATLAS and CMS experiments, including both inclusive measurements and the measurement in the boosted regime in a restricted phase space region [18].

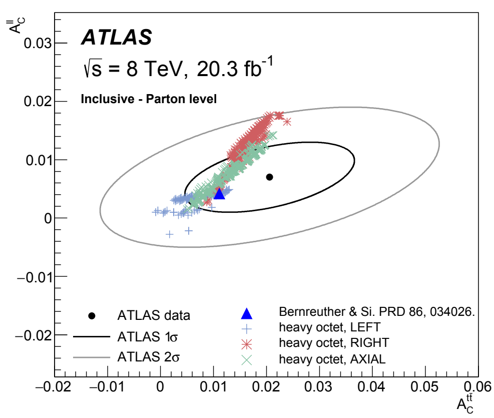

Figure 5. Comparison of the inclusive $A_C^{t\bar{t}}$ and $A_C^{\ell\ell}$ measurement values in the full phase space in the dilepton channel, compared to the SM predictions and to a benchmark BSM model with a heavy octed with mass beyond the reach of the LHC, for various couplings. Ellipses correspond to the 1σ and 2σ uncertainty of the measurement [17].

The measurements of top quark spin correlations and charge asymmetry in $t\bar{t}$ production are all compatible with the SM predictions, allowing to set limits on BSM scenarious.

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