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Top quark property measurements with ATLAS

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Summary. — This contribution covers recent results on the properties of the top quark as measured with the ATLAS detector at the Large Hadron Collider, using data collected at center-of-mass energies of 7 and 8 TeV during 2011 and 2012. Results on the $t\bar{t}$ charge asymmetry and spin correlation, and on the mass of the top quark are discussed. The most recent results expand on the first ATLAS measurements with complementary analysis channels, new observables, and direct comparisons to new physics models. No significant deviations from Standard Model predictions have been found.

PACS 14.65.Ha – Top quarks.

1. – Introduction

1˙1. *The top quark and its properties.* – The top quark is an outlier in the Standard Model (SM). It is the heaviest known fundamental particle, with a mass almost 40 times heavier than the bottom quark. Its lifetime is extremely short, approximately 0.5×10^{-24} s, so it decays before it can form any bound states and create hadrons. This provides a unique opportunity to study the properties of a free quark, and is essential for many of the measurements presented in this proceedings. The top quark has a strong potential to be tied to new physics beyond the Standard Model, and by studying in detail its properties it is possible to perform both indirect searches for new physics as well as test the predictions of particular models.

In this contribution, recent results from ATLAS on production asymmetries, the spin correlation of $t\bar{t}$ pairs, and the top quark mass will be presented. The focus of these analyses has been on expanding the scope of previous measurements in three major ways. Complementary analysis channels and additional observables have been used to offer differing sensitivities to systematic uncertainties and new physics effects. Comparisons with particular new physics models have been performed in addition to model independent tests of SM predictions.

These results use data from the ATLAS experiment [1], taken from both the 2011 and 2012 LHC runs at collision energies of 7 and 8 TeV, respectively. The LHC is a top quark factory; during these runs almost 6 million $t\bar{t}$ pairs have been produced in ATLAS. These large data sets are useful for probing in detail the properties of the top quark. Many of the measurements presented are then limited by the understanding of systematic uncertainties.

1˙2. *Top quark selection and reconstruction.* – Top quarks are produced in two main ways at the LHC – in $t\bar{t}$ pairs via the strong interaction, or single top quarks via the weak interaction. For the properties measurements presented here, $t\bar{t}$ production is used except in the case of the mass measurement in the single top t-channel production. The top decays into a W boson and a b quark (leading to a jet) nearly 100% of the time; how the W bosons decay defines the analysis channels used. In the dilepton channel, both decay to an electron or muon plus neutrino. In the $\ell +$jets channel, one does, while the other decays into a quark pair producing two additional jets. In the all-hadronic channel, six total jets are produced.

For many properties measurements, a full reconstruction of the $t\bar{t}$ topology is needed. That is, an estimate of the four momentum of each top quark and each daughter particle is necessary in order to form an observable. Two main challenges must be overcome – to estimate the momentum of the unmeasured neutrinos and to assign jets as coming from certain decay daughter quarks. A number of different methods have been used to accomplish this as described for individual analyses below.

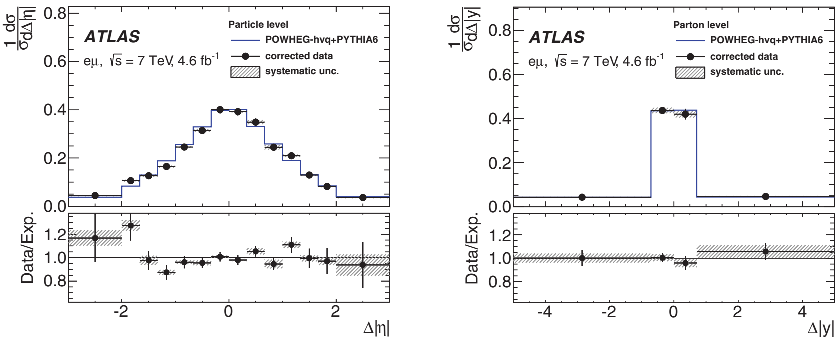
2. – Analysis results

2˙1. *Charge asymmetry.* – ATLAS has measured the charge asymmetry in $t\bar{t}$ production at 7 TeV using the dilepton channel [2]. This essentially measures to what degree the top quark is preferentially produced more forward than the antitop (*i.e.* at higher absolute value of rapidity). The $t\bar{t}$ asymmetry has been previously measured in the $\ell +$jets channel [3], but the dilepton channel also allows the measurement of the purely charged lepton based asymmetry, which though smaller is easier to measure since it does not require full event reconstruction. The mathematical form of the two asymmetries is as follows:

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta| > 0) - N(\Delta|\eta| < 0)}{N(\Delta|\eta| > 0) + N(\Delta|\eta| < 0)}, \qquad \Delta|\eta| = |\eta_{\ell+}| - |\eta_{\ell-}|, \tag{1}$$

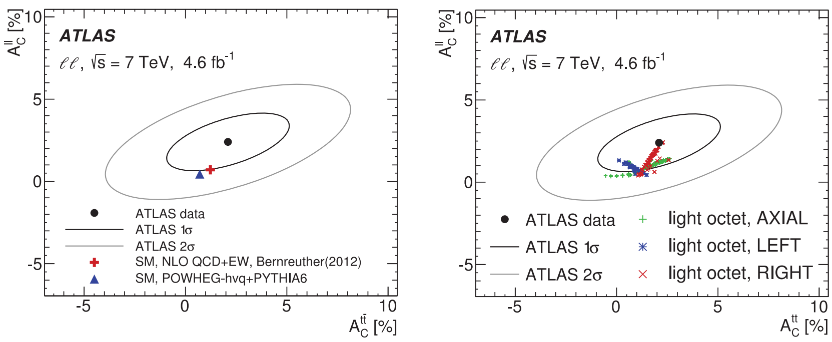
$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|. \tag{2}$$

For the $t\bar{t}$ based asymmetry, the events were reconstructed using the neutrino weighting method, which tests many hypotheses for the pseudorapidity values of the two neutrinos and chooses the one that best matches the measured missing transverse momentum. The distribution of lepton $\Delta|\eta|$ is unfolded using a bin-by-bin correction since the migration is very small. For the $t\bar{t}$ $\Delta|y|$, Fully Bayesian Unfolding has been used to obtain the final distribution at parton level. The unfolded distributions are shown in fig. 1. The asymmetries are then extracted from the unfolded distributions. The lepton based asymmetry result is $A_C^{\ell\ell} = 0.024 \pm 0.015(\text{stat.}) \pm 0.009(\text{syst.})$, and the $t\bar{t}$ result is $A_C^{t\bar{t}} = 0.021 \pm 0.025(\text{stat.}) \pm 0.017(\text{syst.})$. The results are limited by statistical uncertainties. The separate results are in agreement with the Standard Model predictions of $A_C^{\ell\ell} = 0.007$ and $A_C^{t\bar{t}} = 0.0123$. A comparison in the 2D plane including the correlation



(a) (b)

Fig. 1. – The unfolded distributions of the difference of absolute lepton pseudorapidity (a) and $t\bar{t}$ rapidity (b) in the dilepton $e\mu$ channel, from ref. [2]. The data is compared to the expected SM distribution as given in simulation. The asymmetry result is then extracted from these distributions.



(a) (b)

Fig. 2. – The results of the charge asymmetry measurement in the dilepton channel including the correlation between the lepton and $t\bar{t}$ asymmetries $A_C^{\ell\ell}$ and $A_C^{t\bar{t}}$, from ref. [2]. In (a), the result is shown to agree with SM predictions. In (b), the result is also compared to models including a light (below $t\bar{t}$ threshold) octet with various couplings.

between the two can be found in fig. 2(a). This measurement is compared to new physics models in fig. 2(b), but at the current sensitivity it is not possible to separate them.

2·2. *Spin correlation.* – In $t\bar{t}$ production, the individual top quarks are predicted to be very close to unpolarized, but the spin states of the top and antitop are predicted to be correlated. The Standard Model predicts an asymmetry A in the number of parallel and anti-parallel spin states. The exact value depends on the collision energy and choice of quantization axis; in the helicity basis it is about 0.3. Because the top quarks decay before hadronization, the spin state at production affects the decay angular distributions of the daughter particles. For a particular choice of quantization axis, the joint polar angular distribution is modified:

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos(\theta_+)\mathrm{d}\cos(\theta_-)} \propto 1 + A\alpha_+\alpha_-\cos(\theta_+)\cos(\theta_-), \tag{3}$$

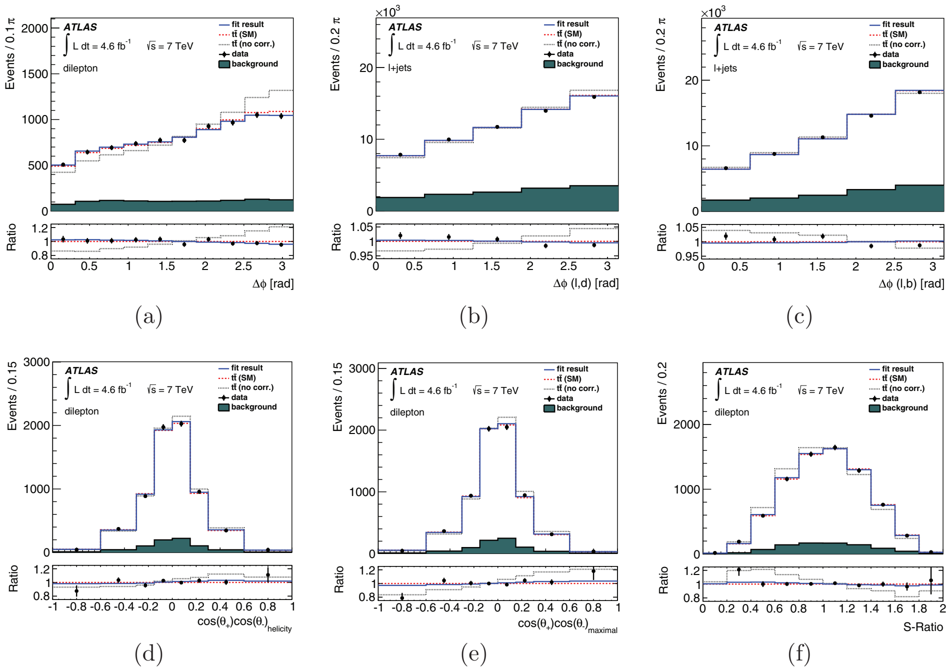


Fig. 3. – Distributions of all observables used to measure $t\bar{t}$ spin correlation, from ref. [4]. The reconstructed data is compared to predictions obtained from simulation that include either SM spin correlation, or no spin correlation. The result of the template fit to extract the measured correlation value is also shown. The $\Delta\phi$ distributions for dilepton (a), for $\ell+$jets with the down-type quark (b), and for $\ell+$jets with the b quark (c) are all shown. For the dilepton channel only, the $\cos\theta_+\cos\theta_-$ distributions in the helicity (d) and maximal (e) bases as well as the S-ratio (f) are also used.

where subscripts + and − refer to a decay daughter of the top quark and antitop quark respectively. The values α are the spin-analyzing powers of the chosen decay daughters, and are always between −1 and 1. For charged leptons, $|\alpha|$ is very close to 1. While the effect on the polar angular distributions is given above, other observables can also be used to measure spin correlation.

Following symmetry rules, there are four correlation coefficients that correspond to C and P symmetry even correlations. To cover this space, ATLAS has made measurements at 7 TeV using four observables that are each sensitive to different combinations of these coefficients [4]. The observables are as follows:

- $\Delta\phi$, the lab frame azimuthal angle between two decay daughters. This is calculated for the two charged leptons in dilepton events, and for $\Delta\phi$ between the charged lepton and the jets determined to most likely be from the b and down-type W decay quark from the hadronically decaying top quark.

- S-ratio, the ratio of matrix elements of like-helicity gluon fusion for the SM correlation case and the uncorrelated case:

$$S = \left(|\mathcal{M}|^2_{\mathrm{RR}} + |\mathcal{M}|^2_{\mathrm{LL}}\right)_{\mathrm{corr}} / \left(|\mathcal{M}|^2_{\mathrm{RR}} + |\mathcal{M}|^2_{\mathrm{LL}}\right)_{\mathrm{uncorr}}$$
$$= \frac{m_t^2\left[(t\cdot\ell^+)(t\cdot\ell^-) + (\bar{t}\cdot\ell^+)(\bar{t}\cdot\ell^-) - m_t^2(\ell^+\cdot\ell^-)\right]}{(t\cdot\ell^+)(\bar{t}\cdot\ell^-)(t\cdot\bar{t})}$$

- $\cos(\theta_+)\cos(\theta_-)$ using the helicity quantization axis.
- $\cos(\theta_+)\cos(\theta_-)$ using the maximal axis, which is calculated event-by-event to maximize the value of the SM spin correlation.

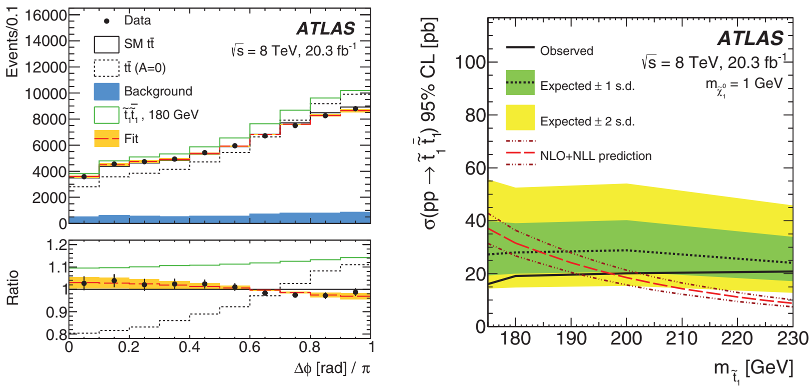
Plots of the measured distributions of these observables are found in fig. 3. For each, the spin correlation is extracted in terms of the "Standard Model fraction" from a template fit using the SM prediction and an uncorrelated simulation. A fraction of 1 corresponds to the SM prediction, while 0 gives the uncorrelated scenario. The results are summarized in table I; all results agree with the Standard Model expectation. In terms of the correlation parameter A in the helicity and maximal bases the results using the $\cos(\theta_+)\cos(\theta_-)$ observables are $A_{\mathrm{helicity}} = 0.23 \pm 0.09$ and $A_{\mathrm{maximal}} = 0.37 \pm 0.10$, compared to the SM predictions of $A^{\mathrm{SM}}_{\mathrm{helicity}} = 0.31$ and $A^{\mathrm{SM}}_{\mathrm{maximal}} = 0.44$.

A new measurement of the spin correlation at 8 TeV has also been made which expands the scope by including an interpretation of the result in terms of a limit on the production of pairs of light top superpartners decaying into top quarks and neutralinos [5]. The production of these top squarks increases the rate of $t\bar{t}$-like topologies, but by too little to be excluded by direct searches or $t\bar{t}$ cross section measurements. But top quarks produced through this method would have a different spin correlation, as shown in fig. 4. By measuring the spin correlation in the dilepton channel using $\Delta\phi$ using a similar template method as at 7 TeV, the result is $A_{\mathrm{helicity}} = 0.38 \pm 0.04$ compared to a SM prediction of $A^{\mathrm{SM}}_{\mathrm{helicity}} = 0.318$. This allows an exclusion limit to be placed on this production and decay mode; the region of top squark masses from the top mass up to 191 GeV is excluded at 95% confidence level, as shown in fig. 4(b). This excludes a region of stop masses not excluded by direct searches.

2˙3. *Top quark mass*. – Since the top quark decays before it hadronizes, its mass is directly accessible through the mass of the decay products. ATLAS has previously made its most sensitive measurements of this direct mass using the $\ell +$ jets and dilepton channels [6]. Recent results have focused on using the complementary all-hadronic and single top channels. Additionally, results have been released for the pole mass of the top quark. The theoretical interpretation of the direct mass measurements is not straightforward, and its correspondence with solid theoretical values such as the pole mass or $\overline{\mathrm{MS}}$ mass suffers from ambiguities on the order of 100 MeV. By studying production modes of the top quark, measurements of the top quark pole mass have also been made.

TABLE I. – *Results for $t\bar{t}$ spin correlation measurements using the various observables including both statistical and systematic uncertainties, from ref.* [4]. *The results are given in terms of the "Standard Model fraction" f_{SM}; the SM prediction for spin correlation corresponds to a value $f_{\mathrm{SM}} = 1$. All results are in agreement with the prediction.*

Observable	$f_{SM} \pm$ (stat.) $\pm$ (syst.)
$\Delta\phi$ dilepton	$1.19 \pm 0.09 \pm 0.18$
$\Delta\phi$ $\ell +$ jets	$1.12 \pm 0.11 \pm 0.22$
$\cos(\theta_+)\cos(\theta_-)$ helicity	$0.75 \pm 0.19 \pm 0.23$
$\cos(\theta_+)\cos(\theta_-)$ maximal	$0.83 \pm 0.14 \pm 0.18$
S-ratio	$0.87 \pm 0.11 \pm 0.14$

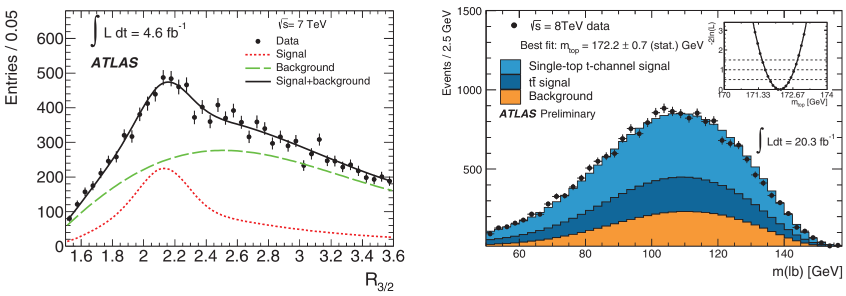


(a) (b)

Fig. 4. – The $t\bar{t}$ spin correlation as measured at 8 TeV has been used to search for the production of light top squark superpartners decaying to a top quark and neutralino, from ref. [5]. In (a), the dilepton $\Delta\phi$ distribution is shown. In addition to predictions for SM $t\bar{t}$ production and the no spin correlation scenario, a prediction including also stop pair production at $m_{\tilde{t}} = 180$ GeV is included. Using the angular and rate information together, in (b) the 95% limit on the cross section of stop pair production is shown as a function of the stop mass. Comparing to theoretical predictions gives an exclusion from the top mass up to 191 GeV.

In the all-hadronic channel, a measurement of the top quark mass has been made at 7 TeV [7]. The $t\bar{t}$ events are reconstructed with a kinematic likelihood method, and the substantial multijet background is controlled using six exclusive regions. To reduce uncertainties from jet energy measurements, the mass is extracted from a template fit to the distribution of the ratio of the 3-jet mass (top quark) to 2-jet mass (W) $R_{3/2}$, as shown in fig. 5(a). The obtained value is $m_t = 175.1 \pm 1.4(\text{stat.}) \pm 1.2(\text{syst.})$ GeV. The result shows promise for improvement with larger data sets, and will help provide additional input to a mass combination in all channels.

The mass has also been measured with a selection enriched with a neural network in t-channel single top events [8]. To avoid reconstructing the full events, the mass is



(a) (b)

Fig. 5. – Direct measurements of the top quark mass have been performed in (a) the all-hadronic $t\bar{t}$ decay channel [7], and (b) the single top t-channel [8]. In (a), a template fit to the ratio $R_{3/2}$ of the 3-jet mass to 2-jet mass is used to extract the top quark mass. In (b), a template fit is performed to the combined mass of the charged lepton and identified b-jet.

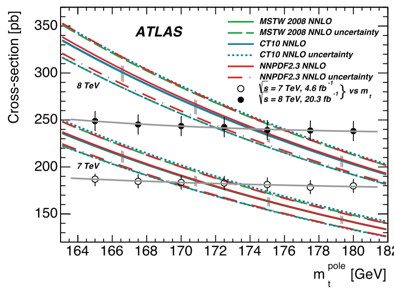


Fig. 6. – The dilepton $e\mu$ channel cross section measurements at 7 and 8 TeV are interpreted as measurements of the top quark pole mass, from ref. [9]. The intersection of the measurement dependence on the mass, and the predicted cross section as a function of pole mass can be used to determine a measured value of m_t^{pole} assuming Standard Model production.

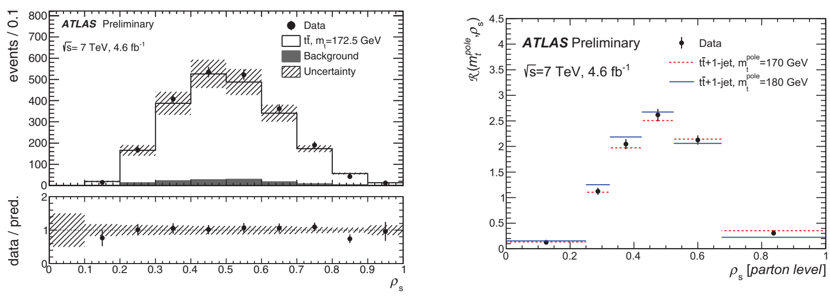
extracted from a template fit to the mass of the charged lepton and b-tagged jet, $m(\ell b)$, as shown in fig. 5(b). The result is $m_t = 172.2 \pm 0.7(\text{stat.}) \pm 2.0(\text{syst.})$ GeV. This result is dominated by systematic uncertainties.

For the determination of the pole mass, two results have been obtained. First, the cross section measurement in the dilepton $e\mu$ channel [9] can be interpreted instead as a measurement of the pole mass, as seen in fig. 6. The result is $m_t^{\text{pole}} = 172.9^{+2.5}_{-2.6}$ GeV, and it is dominated by theoretical uncertainties of approximately 2 GeV.

A more dedicated method has also been performed using the 7 TeV data using $t\bar{t}$ with one additional jet production [10]. The sensitivity of the radiation of gluons producing an additional jet to the pole mass allows a measurement from the inverse of the invariant mass of the full system. The observable used is

$$\rho_s = \frac{2 \cdot 170\,\text{GeV}}{\sqrt{s_{t\bar{t}j}}}, \tag{4}$$

and it is plotted in fig. 7(a). This distribution is unfolded using the Singular Value Decomposition (SVD) method, and then compared to theoretically predicted distribu-



(a) (b)

Fig. 7. – The pole mass of the top quark is extracted in the $t\bar{t}$ + one jet channel, from ref. [10]. The scaled inverse of the $t\bar{t}$ + jet invariant mass, $\rho_s = 2 \cdot 170\,\text{GeV}/\sqrt{s_{t\bar{t}j}}$, is reconstructed in (a). The unfolded distribution is shown in (b), compared to theoretical predictions that depend on the top pole mass; m_t^{pole} is measured from a fit to this distribution.

tions. The pole mass is extracted as a fit of these distributions to the unfolded result as shown in fig. 7(b). The result is $m_t^{\text{pole}} = 173.7 \pm 1.5(\text{stat.}) \pm 1.43(\text{syst.})^{+0.95}_{-0.49}(\text{theory})$ GeV. This result has a reduced theoretical uncertainty compared to the cross section extraction, and will also benefit from larger data sets to reduce the statistical uncertainties.

3. – Conclusions

With these recent results on the properties of the top quark, ATLAS is building upon earlier measurements and expanding the scope of tests of the Standard Model. Adding more analysis channels and observables provides complementary information and can improve future combinations of results. Top properties measurement are also being used to test specific models of new physics. Overall, many new top properties measurements are still being published using LHC Run-1 data. Top quark physics is entering a precision era, in which large data sets along with experimental expertise will combine to produce many new measurements testing the details of the Standard Model.

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