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Top quark pair property measurements and $t\bar{t}+X$, using the ATLAS detector at the LHC

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Measuring the properties of the top quark has been proven to be a reliable test of the Standard Model of particle physics (SM). At the Large Hadron Collider, top quark physics has entered the era of precision measurements which allows to measure new top quark properties and to repeat other top quark properties measurements with improved precision. This article presents the measurements of top quark spin observables, charge and CP asymmetries, W boson polarisation from $t\bar{t}$ events and the cross section of $t\bar{t}$ pairs produced in association with a W or Z boson. All these measurements are using data from proton-proton collisions taken with the ATLAS detector at the Large Hadron Collider. The spin correlation $C(n,n)$ is measured for the first time and direct CP violation is measured directly for the first time in the context of b-hadron decays. The measured value of the CP mixing asymmetry A^b_{mix} presented here cannot disprove the deviation in the dimuon asymmetry seen by the DØ experiment. The W boson polarisation measurement from $t\bar{t}$ events is the most precise one to date and is used to constrain anomalous couplings at the Wtb vertex. All results are in agreement with the SM predictions.

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Introduction

Since the discovery of the top quark in 1995 [1, 2] at the Tevatron collider, measuring its properties has been proven to be a reliable test of the Standard Model of particle physics (SM). Its lifetime is shorter than the hadronisation time. Therefore, it is possible to study the top quark using perturbative QCD without having to deal with bound states and low energy QCD which is impossible with any other quark. It has the highest mass of any elementary particle in the SM of approximately 173 GeV [3]. Therefore, it may play a special role in the electroweak symmetry breaking due to its coupling to the Higgs field of approximately 1. Roughly 6 million top-antitop ($t\bar{t}$) pairs [4] have been produced during its first run between 2010 and 2013 at centre-of-mass energies of 7 and 8 TeV at the ATLAS detector [5]. During its second run roughly 30 million $t\bar{t}$ events have been produced at the ATLAS detector in 2015 and 2016. In this sense, the Large Hadron Collider (LHC) [6] at CERN is a top quark factory and top quark physics has entered the era of precision measurements. This allows to extend measurements of the top quark properties and to improve on previous measurements. This article presents new measurements of five top quark properties published since the last DIS conference in April 2016. This includes the measurements of observables related to the top spin, charge and CP asymmetries, W boson polarisation and the cross section of $t\bar{t}$ pairs produced in association with a W or Z boson ($t\bar{t}W$and $t\bar{t}Z$). All these measurements are using data from proton-proton collisions taken with the ATLAS detector at the LHC. The $t\bar{t}W$ and $t\bar{t}Z$ cross section measurement is using the dataset from 2015 corresponding to an integrated luminosity of 3.2 fb^{-1} at a centre-of-mass energy of 13 TeV. All other measurements presented here are using the dataset taken at a centre-of-mass energy of 8 TeV corresponding to an integrated luminosity of approximately 20.3 fb^{-1}

1. Top quark spin observables

The top quark decays before hadronisation takes place. Therefore, its spin information is transferred directly to its decay products. In addition to the top quark spin polarisation from weak correction and QCD absorptive parts[1], the spins of the top and antitop quarks in $t\bar{t}$ events are correlated. The angular distributions of the $t\bar{t}$ decay products can be used to probe those spin observables. Measuring the top quark spin observables gives access to the elements of the spin density matrix. The top quark spin observables are obtained from a dataset corresponding to an integrated luminosity of $20.2\,\text{fb}^{-1}$ taken with a centre-of-mass energy of 8 TeV in proton-proton collisions [7]. The W bosons from both the top and the antitop quark are required to decay leptonically. The spin observables can be obtained by using the following double differential distribution:

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+^a\,\mathrm{d}\cos\theta_-^b} = \frac{1}{4}(1+B_+^a\cos\theta_+^a+B_-^b\cos\theta_-^b-C(a,b)\cos\theta_+^a\cos\theta_-^b)\;.$$

The angle θ_+^a is measured between the direction of the lepton originating from the top quark ('-' for the antitop quark) in the $t\bar{t}$ rest frame and one of the following axes a: 'k' is the helicity axis which points in the top (antitop) quark momentum direction, 'n' is the transverse axis which is transverse to the plane described by the helicity axis and the beam axis and 'r' which is orthogonal to k and n. From this equation, 6 spin polarisation coefficients $B^a = 3 < \cos\theta^a >$ and 9 spin correlation coefficients $C(a,b) = -9 < \cos\theta_+^a\cos\theta_-^b >$ can be extracted. 10 of those 15 coefficients

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[1] The quarks and gluons in the initial state are unpolarised which means that top quarks produced in pairs are mostly unpolarised except for those contributions.

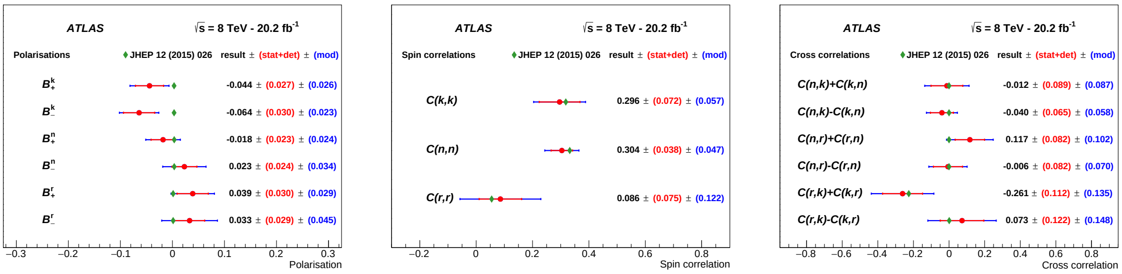

Figure 1: Measured spin observables (data points) in comparison with SM predictions at the parton level [7].

are measured for the first time. The top quark spin observables are measured on parton level in the full phase space and on particle level in a fiducial detector region. The $t\bar{t}$ reconstruction is performed using the neutrino weighting technique [8]. A fully Bayesian unfolding is performed to deal with distortions due to cuts and the detector resolution. The results on parton level are shown in Figure 1. No significant deviation from the SM expectation can be found for any spin observable. The $t\bar{t}$ spin correlation observable $C(n,n)$ is measured for the first time with 5.1σ significance.

2. Charge asymmetry in the dilepton final state of $t\bar{t}$ decays

The dominating production process for $t\bar{t}$ events at the LHC is via gluon-gluon fusion, which does not cause any $t\bar{t}$ charge asymmetries. Valence quark - sea antiquark fusion is the leading $t\bar{t}$ production process at the LHC causing $t\bar{t}$ charge asymmetries, resulting in antitop quarks being emitted more centrally in the detector on average than the top quark. This measurement is performed at a centre-of-mass energy of 8 TeV with a dataset corresponding to an integrated luminosity of $20.3\,\mathrm{fb}^{-1}$ [9]. Events are selected in which both W bosons from the $t\bar{t}$ pair decay leptonically. Two different charge asymmetries are measured, the leptonic asymmetry $A_C^{\ell\ell}$ and the $t\bar{t}$ asymmetry $A_C^{t\bar{t}}$ which are defined as

$$A_C^{\ell\ell} = \frac{N(\Delta|\eta|>0) - N(\Delta|\eta|<0)}{N(\Delta|\eta|>0) + N(\Delta|\eta|<0)} \qquad \text{and} \qquad A_C^{t\bar{t}} = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \,,$$

where $\Delta|\eta|$ is the difference between the absolute values of the pseudorapidities of the positively charged and the negatively charged lepton from the $t\bar{t}$ decay and $\Delta|y|$ is the difference between the absolute values of the rapidities of the reconstructed top and antitop quark. Those two observables are measured in inclusive and differential measurements on both parton level, using the full phase space, and on particle level in the fiducial detector region. The differential measurements are determining the two asymmetries versus the invariant mass $m_{t\bar{t}}$, the transverse momentum $p_{T,t\bar{t}}$ and the longitudinal boost $\beta_{z,t\bar{t}}$ of the $t\bar{t}$ system. A kinematic reconstruction of the $t\bar{t}$ system and fully Bayesian unfolding is performed. The results for the inclusive measurements are $A_C^{\ell\ell} = 0.008 \pm 0.006$ and $A_C^{t\bar{t}} = 0.021 \pm 0.016$ in the full phase space. The results of the differential measurement in the fiducial region are shown in Figure 2. All results are consistent with the SM predictions.

3. Charge and CP asymmetries in b-hadron decays from $t\bar{t}$ events

The top quark decays almost 100% of the time into a W boson and a bottom quark. Therefore, the high production rate of $t\bar{t}$ events and their distinctive signatures can be exploited to gain information of charge and CP asymmetries in the decay of the bottom quark. This measurement uses data collected at 8 TeV with a corresponding centre-of-mass energy of $20.3\,\mathrm{fb}^{-1}$ [10]. Events

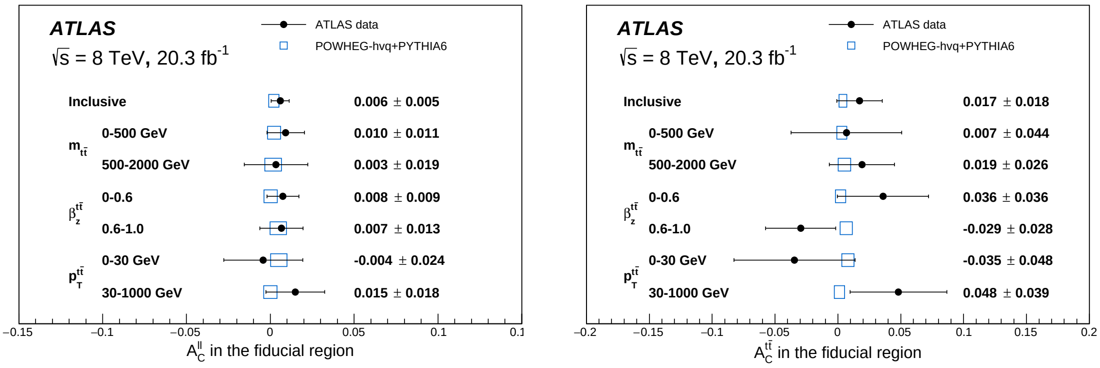

Figure 2: Results of the differential measurement for the leptonic asymmetry (left) and the $t\bar{t}$ asymmetry (right) in the fiducial region in comparison with the theoretical SM prediction [9].

are selected in which one of the W boson from the $t\bar{t}$ pair decays leptonically and the other one decays hadronically. In this measurement, 5 CP and 2 charge asymmetries are determined. These asymmetries are defined as the following:

$$A^{SS} = \frac{P(b\to\ell^+) - P(\bar{b}\to\ell^-)}{P(b\to\ell^+) + P(\bar{b}\to\ell^-)}\,, \qquad A^{OS} = \frac{P(b\to\ell^-) - P(\bar{b}\to\ell^+)}{P(b\to\ell^-) + P(\bar{b}\to\ell^+)}\,,$$

$$A^{b\ell}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to\ell^+X) - \Gamma(\bar{b}\to b\to\ell^-X)}{\Gamma(b\to\bar{b}\to\ell^+X) + \Gamma(\bar{b}\to b\to\ell^-X)}\,, \qquad A^{bc}_{\text{mix}} = \frac{\Gamma(b\to\bar{b}\to\bar{c}X) - \Gamma(\bar{b}\to b\to cX)}{\Gamma(b\to\bar{b}\to\bar{c}X) + \Gamma(\bar{b}\to b\to cX)}\,,$$

$$A^{b\ell}_{\text{dir}} = \frac{\Gamma(b\to\ell^-X) - \Gamma(\bar{b}\to\ell^+X)}{\Gamma(b\to\ell^-X) + \Gamma(\bar{b}\to\ell^+X)}\,, \qquad A^{c\ell}_{\text{dir}} = \frac{\Gamma(\bar{c}\to\ell^-X_L) - \Gamma(c\to\ell^+X_L)}{\Gamma(\bar{c}\to\ell^-X_L) + \Gamma(c\to\ell^+X_L)}\,,$$

$$A^{bc}_{\text{dir}} = \frac{\Gamma(b\to cX_L) - \Gamma(\bar{b}\to\bar{c}X_L)}{\Gamma(b\to cX_L) + \Gamma(\bar{b}\to\bar{c}X_L)}\,,$$

where A^{SS} and A^{OS} are the two charge asymmetries, A^{xy}_{mix} are the CP asymmetries in the mixing and A^{xy}_{dir} are direct CP asymmetries. The probability of the quark q decaying into a particle f and not its charge conjugated counterpart is described by $P(q\to f)$ and Γ describes the decay width for the corresponding process. Bottom quark, charm quark and charged lepton are denoted by b, c and ℓ. Hadronic states with no leptons and with both light and charm quarks (only light quarks) are denoted by X (X_L). In order to determine the charge of the bottom quark during its production, the charge from the leptonically decaying W boson is used. The charge of the bottom quark during its decay is determined by measuring the charge of a soft muon identified to emerge from the bottom quark decay, using the so called soft-muon heavy-flavour tagging technique [11, 12]. The data are unfolded to a well defined fiducial space. The results are $A^{SS} = -0.007 \pm 0.008$, $A^{OS} = 0.004 \pm 0.005$, $A^{b}_{\text{mix}} = -0.025 \pm 0.028$, $A^{b\ell}_{\text{dir}} = 0.005 \pm 0.005$, $A^{c\ell}_{\text{dir}} = 0.010 \pm 0.010$ and $A^{bc}_{\text{dir}} = -0.010 \pm 0.011$, where $A^{b}_{\text{mix}} \equiv A^{b\ell}_{\text{mix}} \equiv A^{bc}_{\text{mix}}$ assuming no direct CP violation. The measured value of A^{b}_{mix} can neither disprove the SM expectation nor the deviation in the dimuon asymmetry seen by the DØ experiment [13]. The direct CP violation has been measured for the first time in this context, improving the existing limits of indirect measurements. All results are consistent with the SM.

4. W boson polarisation in $t\bar{t}$ events

Within the model of an effective field theory [14], the SM Lagrangian at the Wtb vertex can be expanded using anomalous couplings V_L, V_R, g_L and g_R:

$$\mathscr{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}\ .$$

Those anomalous couplings are $V_L \approx 1$ and $V_R \approx g_L \approx g_R \approx 0$ at the SM. Measuring the polarisation of the W boson from the top quark decay is an opportunity to constrain the coupling V_R, g_L and g_R. This particular measurement [15] uses a dataset corresponding to an integrated luminosity of 20.2 fb^{-1} taken at a centre-of-mass energy of 8 TeV and using the lepton+jets decay channel of $t\bar{t}$ pairs. The longitudinal W boson polarisation F_0 as well as its left and right handed polarisation F_L and F_R can be obtained by measuring the angle θ^* between the momentum direction of the analyser (lepton or down type quark from W decay) and the inverse b-quark momentum direction in the W boson rest frame using the differential cross section

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right)F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_L + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_R\ .$$

The $t\bar{t}$ pair reconstruction is performed via a kinematic likelihood approach using the KLFitter framework [16]. Three templates using Monte Carlo $t\bar{t}$ samples reweighted to F_0 only, F_L only and F_R only plus the background samples are fitted to the measured $\cos\theta^*$ distribution in data. The best result is $F_0 = 0.709 \pm 0.019$, $F_L = 0.299 \pm 0.015$ and $F_R = -0.008 \pm 0.014$ which is obtained from events with at least two b-tagged jets using the leptonic analyser. This is the most precise W boson polarisation measurement to date. The results are in agreement with the SM predictions. Anomalous Wtb couplings are constrained in one- and two-dimensional fits using the EFTfitter framework [17]. The 95% CL intervals from the one-dimensional fits are $[-0.24, 0.31]$ for V_R, $[-0.14, 0.11]$ for g_L and $[-0.02, 0.06], [0.74, 0.78]$ for g_R. The results from the two-dimensional fits are shown in Figure 3.

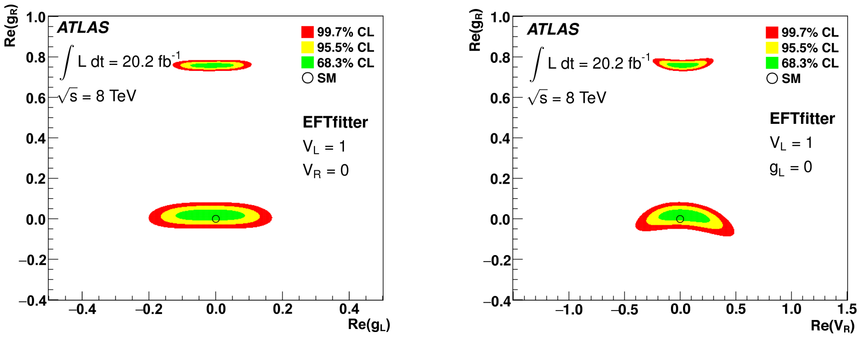

Figure 3: Two-dimensional limits on the anomalous left- and right-handed tensor couplings (left) and on the right-handed vector and tensor couplings (right) [15].

5. $t\bar{t}W$ and $t\bar{t}Z$ cross sections

The $t\bar{t}$ production in association with a Z boson ($t\bar{t}Z$) can be used to determine the coupling of the Z boson to the top quark. This can further be used to constrain anomalous tZ couplings and to measure the third component of the weak isospin of the top quark. The $t\bar{t}Z$ process is usually measured together with the $t\bar{t}$ production in association with a W boson ($t\bar{t}W$). The $t\bar{t}W$ process could be used to constrain parton density functions in the future because the W boson is only produced via couplings to initial state quarks in this process. Both $t\bar{t}W$ and $t\bar{t}Z$ can also be used to study the electroweak symmetry breaking, are indicators for a lot of theories for physics beyond the SM and are important backgrounds for analyses like $t\bar{t}H$ and SUSY in the multilepton channels. The measurement of $t\bar{t}W$ and $t\bar{t}Z$ cross sections presented here are using a dataset with an integrated luminosity of 3.2 fb^{-1} taken at a centre-of-mass energy of 13 TeV [18]. The analysis is divided into three different channels: one channel requiring exactly two muons of the same sign (2μSS channel) which is sensitive to $t\bar{t}W$, another channel requiring exactly three leptons (trilepton channel) which is both sensitive to $t\bar{t}W$ and $t\bar{t}Z$ and a channel requiring exactly four leptons (tetralepton channel) being sensitive to $t\bar{t}Z$. Most backgrounds are estimated using Monte Carlo samples except for the misidentified leptons from hadronic processes, called 'fake leptons'. In the 2μSS and trilepton channel, the fake lepton background is estimated using the fully data driven matrix method [19]. In the tetralepton channel, scale factors are estimated from data and finally applied to the MC background to get the correct fake background yields. The post fit yields are shown on the left hand side in Figure 4. The cross sections from the one dimensional fit are $\sigma_{t\bar{t}W} = 1.5 \pm 0.8$ pb and $\sigma_{t\bar{t}Z} = 0.9 \pm 0.3$ pb. The result of the two dimensional fit is shown on the right hand side of Figure 4. The results are consistent with the SM predictions.

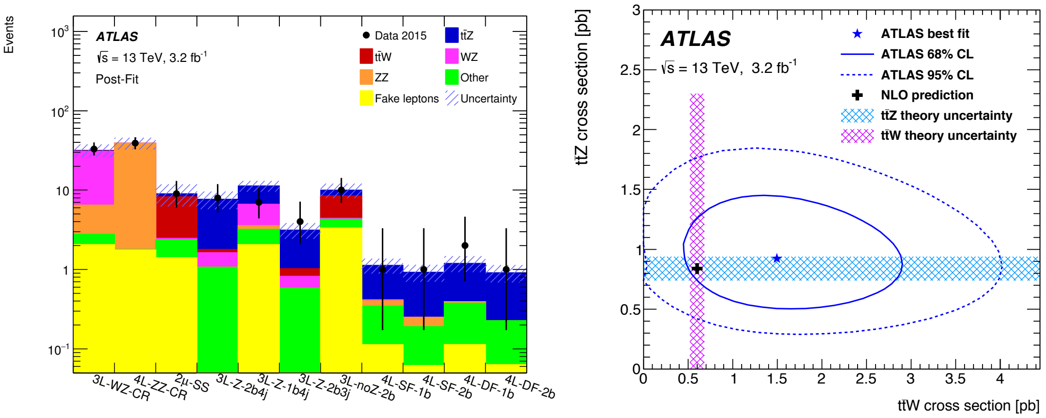

Figure 4: Left: post-fit yields for the WZ and ZZ control regions, as well as all signal regions. Right: result of the two dimensional fit of the $t\bar{t}W$ and $t\bar{t}Z$ cross sections compared with the SM prediction [18].

Conclusion

Five different measurements of the top quark properties including a measurement of the $t\bar{t}W$ and $t\bar{t}Z$ cross sections are presented using data taken with the ATLAS detector. The spin correlation $C(n,n)$ is extracted for the first time and direct CP violation is measured directly for the first time in the context of b-hadron decays. The measured value of the CP mixing asymmetry A^b_{mix} presented here cannot disprove the deviation in the dimuon asymmetry seen by the DØ experiment. The W boson polarisation measurement from $t\bar{t}$ events is the most precise one to date and is used to constrain anomalous couplings at the Wtb vertex. All results are in agreement with the SM predictions.

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