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Top quark pair property measurements using the ATLAS detector at the LHC

Stefan Kluth*
On behalf of the ATLAS collaboration
MPI für Physik
Föhringer Ring 6
80805 München / Munich
Germany
E-mail: skluth@mpp.mpg.de

Precise measurements of the properties of the top quark test the Standard Model (SM) and can be used to constrain new physics models. As it 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 dataset of the ATLAS experiment at the LHC using both the lepton+jets and dilepton channels, including a dedicated measurement for highly boosted top-quarks. The top-quark is predicted in the SM to decay almost exclusively into a W boson and a b-quark. We present a wide range of searches for non-SM top quark decays using the 13 TeV ATLAS dataset, including $t \to qH$ and $t \to qZ$ decays. In addition, measurements of the spin correlation and colour flow in $t\bar{t}$ production are presented.

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*Speaker.

1. Introduction

The mass of the top quark is 173.0 ± 0.4 GeV [2] and it is thus the heaviest known elementary particle. Among the other quarks the top quark mass is larger by more than an order of magnitude than the next-heaviest b-quark, while light (u, d, s) quarks are lighter by three to four orders of magnitude. The top quark obviously has a special rôle in the standard model (SM) of particle physics and it is one of the most important topics to better understand this rôle. Possible new physics effects mediated by e.g. supersymmetric extensions of the SM with coupling proportional to mass are naturally expected to manifest themselves in processes involving top quark production or decay.

In this contribution we discuss properties of the top quark measured in production of top quark pairs in pp collisions at the LHC with the ATLAS detector [1]. The ATLAS experiment has collected large data samples corresponding to 20/fb at 8 TeV pp centre-of-mass (cms) energy and 36/fb at 13 TeV cms energy. At the LHC top quark pair production is dominated by the process $\mathrm{pp}\to\mathrm{gg}\to\mathrm{t\bar{t}}$ with fractions of ≈80% at 8 TeV and ≈90% at 13 TeV.

2. Charge asymmetry at 8 TeV

The charge asymmetry in $\mathrm{t\bar{t}}$ decays refers to differences between the absolute values of the rapidities[1] of the top quark and the anti-top quark. At the Tevatron in $\mathrm{p\bar{p}}$ collisions a forward-backward asymmetry A_{FB} can be defined using the rapidities of the top or anti-top quark w.r.t. the incoming p direction, because the top (anti-top) rapidity distributions peak at positive (negative) rapidity values. At the LHC A_{FB} will always be zero but due to the on average larger momentum carried by valence compared with sea quarks top quarks have a more forward and anti-top quarks a more central rapidity distribution [3]. The charge asymmetry is defined as the asymmetry of the $\mathrm{t\bar{t}}$ rapidity difference $\Delta|y| = |y_\mathrm{t}| - |y_\mathrm{\bar{t}}|$ as $A_C = (N(\Delta|y| > 0) - N(\Delta|y| < 0))/(N(\Delta|y| > 0) + N(\Delta|y| < 0))$.

The ATLAS collaboration has measured A_C in three analyses using 8 TeV datasets concentrating on the final states with two leptons [4], and with a lepton and jets with exclusive jets [5] or with the boosted jets from the hadronic top decays in a large R=1 jet [6]. Exclusive jets are reconstructed using the anti-k_t algorithm with R=0.4. Leptons (e or μ) and jets are required to have transverse momentum $p_t > 25$ GeV and $|\eta| < 2.5$, in addition isolation and quality cuts are applied.

The analysis in the di-lepton channel selects final states with opposite-sign electron, muon, or electron-muon pairs, with di-lepton invariant mass $m_{ll} > 15$ GeV and in association with at least two jets. In same-flavour lepton pairs Z-boson decays are vetoed by demanding $|m_{ll} - m_Z| > 10$ GeV and at least one jet must be b-tagged. For the eμ final state the scalar sum H_T of transverse momenta p_t of the four selected objects must have $H_T > 130$ GeV. Backgrounds from Drell-Yan and single top quark production and other sources are studied in control regions using data and Monte Carlo simulation.

In the lepton+jets channel a single lepton together with four jets is required. The selected events are separated into three signal regions depending on the number of b-tagged jets being 0, 1

[1] The rapidity $y = 1/2\ln((E+p_z)/(E-p_z))$ with particle energy E and momentum p_z along the beam axis; the pseodorapidity $\eta = -\ln(\theta/2)$ with polar angle θ.

or 2. In the analysis using lepton+jets final states with boosted hadronic top decays an anti-k_t jet with R=1 and $p_t > 300$ GeV is demanded. The substructure of this jet is analysed by reclustering the jet with R=0.3 [7].

The distributions of $\Delta|y|$ after subtraction of background are corrected to the parton level after gluon radiation and before $t\bar{t}$ decays using a response matrix derived from simulated events.

Figure 1 presents the results for A_C in the two lepton+jets analyses compared with predictions by the SM, models of new physics, and corresponding measurements of A_{FB} by D0 and CDF. The measurements are consistent with each other and exclude some models of new physics, while the SM prediction is in agreement.

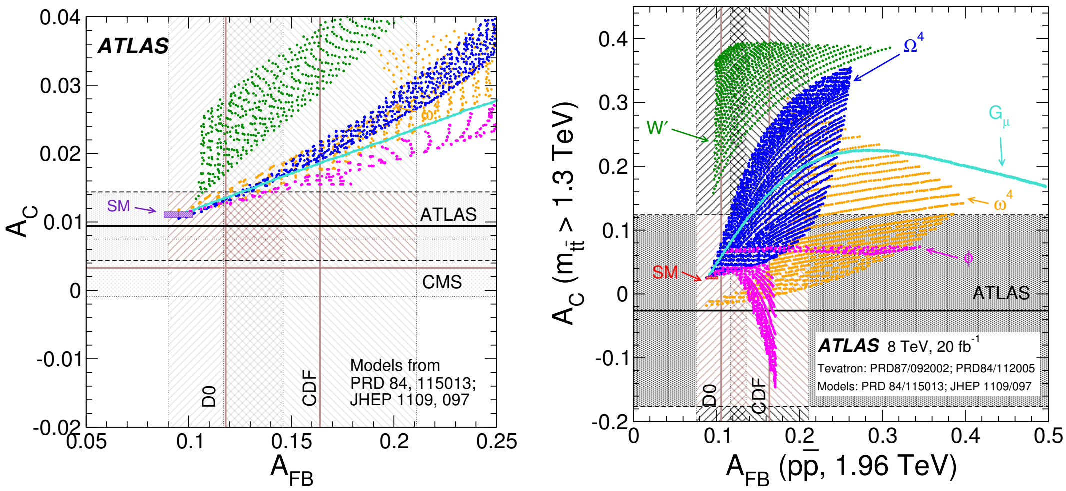

Figure 1: (left) The result for A_C from the lepton-jets analysis [5], (right) the result for A_C from the lepton+jets analysis with boosted hadronic top quarks [6]. In both plots the results are compared with A_{FB} from D0 and CDF and with predictions of various models for new physics.

3. FCNC top quark decays at 13 TeV

The theme of the analyses of rare top quark decays is flavour changing neutral currents (FCNC), which are absent in the SM. Models of new physics like supersymmetry allow for FCNC transitions and therefore such decays signal new physics. The ATLAS collaboration has published two searches for FCNC top quark decays: the first looks for the process $t \to qZ$, $q = u, c$, with a SM Z boson decaying to a lepton pair [8]; and the second concentrates on the decay $t \to qH$, $q = u, c$, and a SM Higgs boson decaying to a photon pair [9]. Both analyses are based on selection of top quark pairs, where one top quark decays in the chosen FCNC channel and the other top quark decays according to the SM.

In the search for $t \to qZ$ decays the combination of a Z boson decay to lepton pairs (e, μ) and a leptonic W decay is chosen as signal. Final states with three charged leptons, where a pair of them is consistent with a Z boson decay, and two jets, where one jet is b-tagged, are selected. In the SM one expects $\mathrm{BR}(t \to qZ) \approx 10^{-14}$ while with new physics effects values of the branching ratio of up to 10^{-4} are possible. Backgrounds to this signal definition come from production of boson pairs (WW, ZZ or WZ), or associated production of a Z boson with a $t\bar{t}$ pair or a single top. These background channels are controlled with five dedicated control regions. The complete statistical analysis yields limits for the branching ratios $\mathrm{BR(t \to uZ)} < 1.7 \cdot 10^{-4}$ and $\mathrm{BR(t \to cZ)} < 2.4 \cdot 10^{-4}$ at 95% CL. The uncertainties are dominated by effects from background and signal models.

The search for $\mathrm{t \to qH}$ selects events with one FCNC top quark decay into a qH(H$\to \gamma\gamma$) final state and a SM top quark decay with W decays to leptons (leptonic selection) or quarks (hadronic selection). The H$\to \gamma\gamma$ decay channel has a small branching ratio but together with the SM top quark decays yields a clean signal sample. The SM expectation in this analysis is $\mathrm{BR(t \to qH)} \approx 10^{-15}$ while new physics effects could allow for values of up to 10^{-3}. Backgrounds from SM processes are direct Higgs boson production, and associated production of a Higgs boson with W or Z bosons, $\mathrm{t\bar{t}}$ pairs, single top quarks, b quark pairs, or top quark W boson pairs. Higgs bosons are enriched in the sample by requiring for the di-photon invariant mass $100 < m_{\gamma\gamma} <$ 160 GeV. The SM top quark decays are selected by demanding four jets including one b-tagged jet, or one lepton, at least two jets and a transverse mass based on the charged lepton and the missing momentum $m_T > 30$ GeV. In the statistical analysis the compatibility of a possible FCNC top quark decay into a qH final state together with a SM top quark decay is tested. This is based on the invariant masses $m_{j\gamma\gamma}$ and m_{jjj} (hadronic selection) or $m_{jl\nu}$ (leptonic selection). The final result is $\mathrm{BR(t \to c(u)H)} < 2.2 \cdot 10^{-3}$ at 95% CL. The uncertainties are dominated by the effects of jet energy scale, and modeling, and by uncertainties in $\sigma_{\mathrm{t\bar{t}}}$ and $\mathrm{BR(H \to \gamma\gamma)}$. The limits from both FCNC top quark decay modes begin to reach predictions by some new physics models.

4. Spin correlations at 8 TeV

The ATLAS analysis [10] measures a set of observables sensitive to the spin structure of the $\mathrm{t\bar{t}}$ pair [11]. A coordinate system for the spin density matrix is defined by the direction k of the top quark in the $\mathrm{t\bar{t}}$ cms system, the transverse n to the plane spanned by k and the beam direction, and the transverse r to k and n. The observables are defined by the angles $\theta^a_{+(-)}$ of the lepton from the t ($\bar{t}$) decay in the t ($\bar{t}$) rest frame w.r.t. the axis a.

In the analysis the kinematics of the $\mathrm{t\bar{t}}$ system in the di-lepton final state are reconstructed using the so-called neutrino-weighting method based on the missing transverse momentum in the event and the lepton kinematics. The resulting distributions of (combinations of) angles are unfolded to either the $\mathrm{t\bar{t}}$ parton level (see above) or the particle level. Figure 2 shows as examples the distributions of the three angles $\cos\theta^a_+, a = k, n, r$ w.r.t. to the top quark corrected to the particle level. The SM is in agreement with the data for all measurements.

5. Colour flow at 13 TeV

The study of effects of colour flow using jet-pull observables by the ATLAS collaboration [12] tests long-standing predictions of perturbative QCD in a novel way. The jet pull vector $\vec{P}$ for a given jet J with constituent transverse momenta $p_{t,i}$ is defined by $\vec{P} = \sum_{i \in J} (p_{t,i}/p_{t,J}) |\Delta\vec{r}_i| \Delta\vec{r}_i$ with $\Delta\vec{r}_i = (y_i - y_J, \phi_i - \phi_J)$ w.r.t. the jet axis. The jet pull vector is calculated from charged particles after ghost association [13] to the jet reconstructed from calorimeter information. Given a pair of jets J_1 and J_2 the jet pull angle $\theta_P(J_1, J_2)$ is defined by the angle enclosed by the jet pull vector $\vec{P}_1$ of jet J_1 and the line connecting the centres of the cones of J_1 and J_2. If the two jets are produced

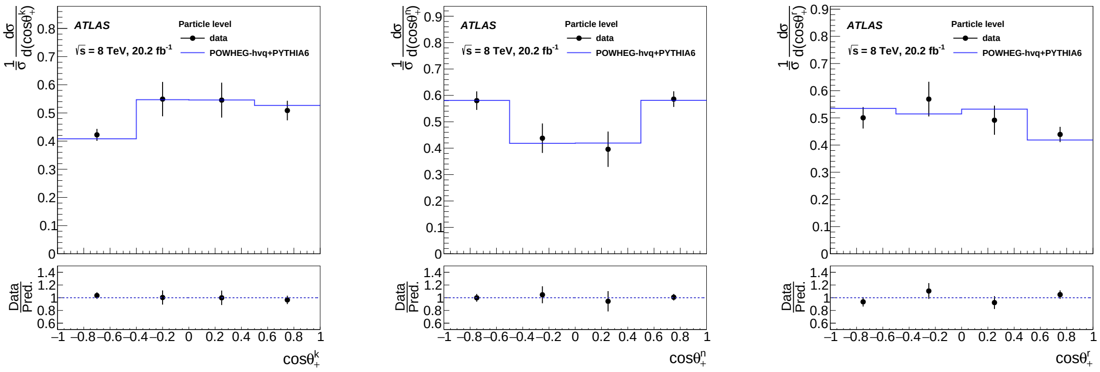

Figure 2: The three figures show the distributions of the three angles w.r.t. the top quark $\cos\theta_+^a, a = k, n, r$ unfolded to the particle level. The lines indicate the prediction by a SM Monte Carlo simulation [10].

from a colour singlet (e.g. a W boson decay to quarks), then one expects the jet pull angle to prefer small values due to enhanced production of particles from the colour field between the two quarks. For jets not directly connected to a colour singlet one does not expect enhanced particle production between the jets.

In the analysis $t\bar{t}$ events in the lepton+jets channel with one high p_t charged lepton and four jets, out of which two are b-tagged, are selected. Candidates for the jets from the hadronic W boson decay are found by taking the two highest p_t jets without a b-tag. As a control sample for jet pairs not originating from a colour singlet the two b-tagged jets are chosen. The distribution of $\theta_P(J_1^W, J_2^W)$ of the two jets associated with the hadronic W boson decay is shown after correction to the particle level in figure 3 (left). One observes a significant enhancement at small values of the jet pull angle as expected in QCD. Figure 3 (right) presents the analogous result for the jet pull angle $\theta_P(J_1^b, J_2^b)$ based on the two b-tagged jets. In this distribution (note the different vertical scale compared to figure 3 (left)) there is no evidence for enhancement at small values, also in agreement with the expectation. The data points are compared in both figures with predictions by Monte Carlo simulations. The simulation labeled "Colour-Flipped" refers to a modification in the simulation to suppress colour field effects in the hadronic W boson decays. The simulations are not in good agreement with the data for jets from W boson decays, and the agreement of the colour-flipped simulation is worse compared to the regular simulation.

6. Summary

We have reviewed several analyses of the ATLAS collaboration on properties of top quark pairs produced in pp collisions at the LHC. Three analyses provide measurements of the charge asymmetry. All measurements are consistent and the SM prediction agrees as well. FCNC decays of top quarks into qZ or qH final states where searched for and limits on the branching ratios were derived. The measurement of the complete spin density matrix in $t\bar{t}$ decays in the di-lepton channel provides a strong test of the SM, which is found to be consistent with the data. The measurement of colour flow using the jet pull angle in $t\bar{t}$ lepton+jets final states is a novel test of QCD predictions at high energies.

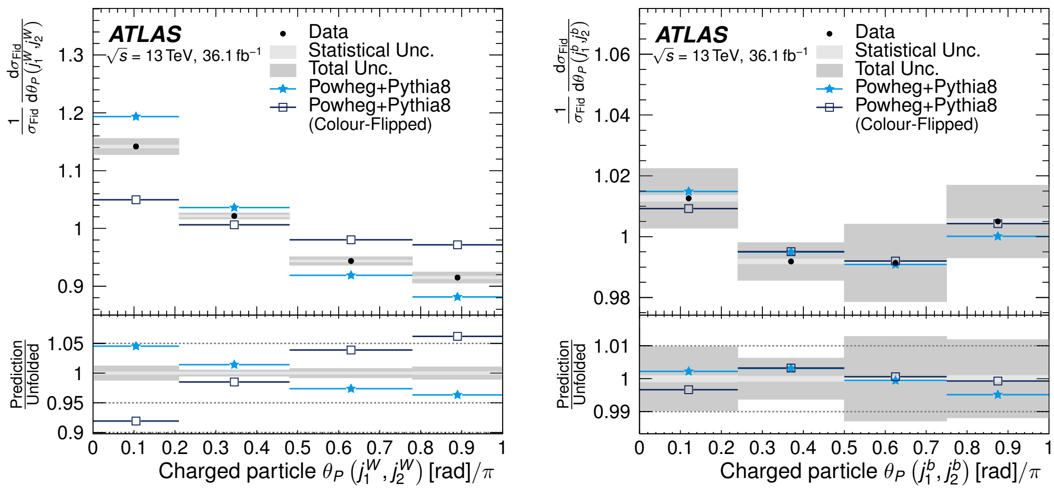

Figure 3: (left) Distribution of $\theta_P(J_1^W, J_2^W)$ of jet pairs from W boson decays. (right) Distribution of $\theta_P(J_1^b, J_2^b)$ of b-tagged jet pairs. Both distributions are corrected to the particle level and are compared with Monte Carlo simulations [12].

The space for new physics beyond the SM becomes narrower and ATLAS will continue to probe the SM using top quark pairs and other methods.

References

[1] ATLAS Collaboration (G. Aad et al.), JINST 3 (2008) S08003.

[2] Particle Data Group (M. Tanabashi et al.), Phys. Rev. D 98 (2018) 030001

[3] G. Rodrigo, in "2012 Electroweak Interactions and Unified Theories : Proceedings of the 47th Rencontres de Moriond on Electroweak Interactions and Unified Theories, La Thuile, March 3-10, 2012", E. Augé, J. Dumarchez, J.-M. Frére, L. Iconomidou-Fayard, J. Trân Thanh Vân (eds.), (2012) 295

[4] ATLAS Collaboration (G. Aad et al.), Phys. Rev. D94 (2016) 032006

[5] ATLAS Collaboration (G. Aad et al.) Eur. Phys. J. C76 (2016) 87, Erratum in Eur. Phys. J. C77 (2017) 564

[6] ATLAS Collaboration (G. Aad et al.), Phys. Lett. B756 (2016) 52

[7] ATLAS Collaboration (G. Aad et al.), JHEP 05 (2012) 128

[8] ATLAS Collaboration (M. Aaboud et al.), CERN-EP-2018-018, arXiv:1803.09923, sub. to JHEP

[9] ATLAS Collaboration (M. Aaboud et al.), JHEP 1710 (2017) 129

[10] ATLAS Collaboration (M. Aaboud et al.), JHEP 03 (2017) 113

[11] W. Berneuther, D. Heisler and Z.-G. Si, JHEP 12 (2015) 26

[12] ATLAS Collaboration (M. Aaboud et al.), CERN-EP-2018-041, arXiv:1805.02935, sub. to Eur. Phys. J. C

[13] M. Cacciari, G. P. Salam and G. Soyez, JHEP 04 (2008) 005