PROCEEDINGS OF SCIENCE

Top quark pair properties and top mass measurements at the LHC

Baptiste Ravina*, **on behalf of the ATLAS and CMS collaborations**
The University of Sheffield
Hounsfield Road
S3 7RH Sheffield
United Kingdom
E-mail: baptiste.ravina@sheffield.ac.uk

Precise measurements of the properties of the top quark test the Standard Model (SM) and can be used to constrain new physics models. 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 and CMS datasets, including $t \to qH$ and $t \to qZ$. In addition, measurements of the spin correlations, charge asymmetries, top Yukawa coupling and colour flow in $t\bar{t}$ production are also discussed. The latest measurements of the top quark mass using the ATLAS and CMS experiments at the Large Hadron Collider (LHC) are surveyed. A measurement based on a multi-dimensional template fit that can constrain the uncertainties on the energy measurements of jets is presented and combined with measurements using dileptonic and all-hadronic events. In addition, an analysis of the top quark mass using leptonic kinematic variables is reviewed.

XXVII International Workshop on Deep-Inelastic Scattering and Related Subjects - DIS2019
8-12 April, 2019
Torino, Italy

*Speaker.

PoS(DIS2019)162

1. Introduction

The top quark is the heaviest known elementary particle of the Standard Model (SM) of particle physics [1]. At the Large Hadron Collider (LHC), the top quark is produced mainly in top-antitop pairs ($t\bar{t}$) through gluon fusion or quark-antiquark annihilation. Given its very short life-time, the top quark decays before hadronising, allowing one to probe its properties (e.g. spin correlation) in detail. In the SM, the top quark is predicted to decay almost exclusively into a W boson and a b-quark, yet possible new physics effects, mediated by e.g. supersymmetric extensions of the SM, challenge this prediction. Moreover, given its large mass, the top quark is generally expected to be one the most sensitive SM particles to any extension of the SM where couplings are introduced that are proportional to the particles' masses.

In this contribution, we discuss precision properties and mass measurements of the top quark, as observed in production of $t\bar{t}$ pairs in pp collisions at the LHC with the ATLAS [2] and CMS [3] detectors. These experiments have collected large data samples, corresponding to 20 fb^{-1} at $\sqrt{s} = 8$ TeV and 36 fb^{-1} at $\sqrt{s} = 13$ TeV.

2. Search for top FCNC processes at 13 TeV

Rare top quark decays, i.e. those not occurring as $t \to Wb$, may happen in the SM as tree-level-forbidden, loop-suppressed flavour-changing neutral currents (FCNC). The SM predictions for their branching ratios are typically around 10^{-14}, while supersymmetric theories or 2HDM models might bring them up to $\sim 10^{-4}$. The following subsections review the status of searches for the $t \to Zq$ process at $\sqrt{s} = 13$ TeV in the multilepton channel, as well as $t \to Hq$ for various final states, by the ATLAS and CMS experiments.

2.1 Final states with a Z boson

In the search for $t \to Zq$ decays, both ATLAS [4] and CMS [5] focus on the same final state, by selecting events with exactly three leptons (e, μ), comprising a pair of opposite-sign same-flavour (OSSF) leptons required to have an invariant mass within 10 GeV of the Z mass, and at least two jets, where one (ATLAS) or more (CMS) is b-tagged. This so-called "decay mode" signature results from $t\bar{t}$ production followed by a $t \to Zq$ interaction; CMS also considers the "production mode", where a single incoming parton decays as $q \to tZ$. There, the jet requirements are lowered to exactly one jet, which must also be b-tagged.

The main backgrounds, diboson production, non-prompt leptons (fakes), and rare top processes (tZ, $t\bar{t}Z$), are estimated in a number of dedicated control regions (CRs). The complete statistical analysis yields limits for the branching ratio $\mathrm{BR}(t \to uZ) < 1.7 \times 10^{-4} (2.4 \times 10^{-4})$ and $\mathrm{BR}(t \to cZ) < 2.4 \times 10^{-4} (4.5 \times 10^{-4})$ for ATLAS (CMS – see Figure 1). The dominant uncertainties come from the modelling and normalisation of the background processes.

2.2 Final states with a Higgs boson

CMS targets the final state $H \to b\bar{b}$ [6] by selecting events with exactly one lepton and at least three jets, two or more of which must be b-tagged. These are further split according to (b-)jet multiplicity into five orthogonal signal regions (SRs), and two boosted decision trees (BDTs) are trained to further enhance the signal sensitivity. The first one uses the likelihood event reconstruction and b-jet assignments to discriminate between three event hypotheses: semileptonic $t\bar{t}$ production, single-top-like tH production and $t\bar{t}$-like decay modes. A number of b-jet-related kinematic and tagging variables are then used to train the second BDT in differentiating between the κ_{Hut} and κ_{Hct} couplings. The limits at the 95% confidence level (CL) obtained in the $t \to uH$ and $t \to cH$ branching fractions are very similar, at around 0.47%.

ATLAS similarly employs a multivariate approach in the multi-lepton final state [7], targeting the $H \to WW^\star$ decay in same-sign dilepton and trilepton selections, using two BDTs to reject background and increase the sensitivity (specifically to κ_{Hut}). The diphoton final state explored in [8] targets the $H \to \gamma\gamma$ decay, constructing SRs in the all-hadronic or one-lepton final states. Higgs bosons are enriched in the sample by requiring $100 < m_{\gamma\gamma} < 160$ GeV, but this particular selection is still largely dominated by statistical uncertainties. The $H \to b\bar{b}$ selecion [9], on the other hand, is the only tHq analysis to evade this limitation. Because the large number of SRs have different background composition, these processes are more efficiently constrained. The many-b events also effectively reduce the c-tagging uncertainties by a factor two, so the fit achieves a significant reduction of the total background uncertainty.

A companion search in the $H \to \tau^+\tau^-$ channel is presented in [9], using BDTs trained on the masses and kinematics of the reconstructed final state objects, divided into four signal regions according to jet multiplicity and decay of the τ leptons. ATLAS also performs a combination of all these searches at $\sqrt{s} = 13$ TeV, yielding observed 95% CL upper limits on the $t \to Hc$ and $t \to Hu$ branching ratios of 1.1×10^{-3} and 1.2×10^{-3} (see Figure 1) respectively.

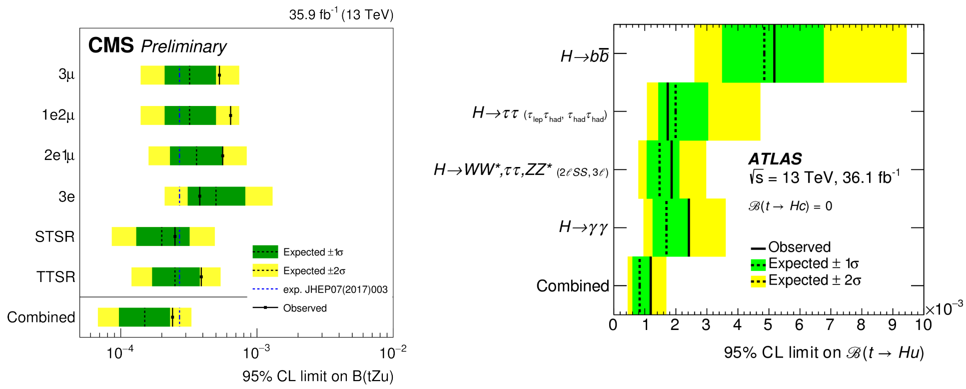

Figure 1: Left: Exclusion limits at 95% CL for each leptonic channel and signal region on the FCNC tZu branching fractions considering one non-vanishing coupling at a time. [5] Right: 95% CL upper limits on $\mathrm{BR}(t \to Hu)$ for the individual searches and their combination, assuming $\mathrm{BR}(t \to Hc) = 0$. [9]

3. Spin correlation and charge asymmetries at 13 TeV

The ATLAS analysis [10] uses a measurement of the differential $t\bar{t}$ cross-section in the $e^\pm\mu^\mp$ channel, both in $\Delta\phi(\ell^+,\ell^-)$ and $\Delta\eta(\ell^+,\ell^-)$, and made doubly-differential in bins of $M(t\bar{t})$, to provide a set of proxy distributions sensitive to the spin structure of the $t\bar{t}$ pair. A 3.2σ discrepancy with respect to the SM is observed when unfolded to parton-level, as shown in Figure 2, where a fraction of SM-like spin correlation, f_{SM}, is extracted from an inclusive binned maximum-likelihood fit as $f_{\mathrm{SM}} = 1.25 \pm 0.06$. This discrepancy persists in all bins of $M(t\bar{t})$, although with larger uncertainties due to the reconstruction efficiency of the $t\bar{t}$ system, and also in the extrapolation to the particle-level fiducial volume. Dominant systematics include the generator radiation and scale uncertainties, as well as theoretical ones deriving from the fit template.

CMS explores the full spin density matrix in [11], extracting the 15 coefficients from individual one-dimensional differential distributions. The measured values of these coefficients are found to agree with the SM within uncertainties, with the linear combination parameter D the most sensitive (5% uncertainty), as presented in Figure 2. Only two off-diagonal elements of the C matrix are not small in the SM, and this analysis provides 3σ evidence of spin cross-correlation between the $\hat{r}$ and $\hat{k}$ axes.

CMS also performs an extraction at 13 TeV of the $t\bar{t}$ and leptonic charge asymmetries in [12], sensitive to a number of BSM scenarios such as axigluons, Z', and W' states coupling to top quarks [13]. The measured charge asymmetries and corresponding uncertainties are: $A_c^{t\bar{t}}(\text{parton level}) = 0.01 \pm 0.009$, $A_c^{t\bar{t}}(\text{particle level}) = 0.008 \pm 0.009$, and $A_c^{\ell^+\ell^-}(\text{particle level}) = 0.005 \pm 0.004$. These results are in good agreement with the SM predictions produced with the `POWHEG` and `MG5aMC@NLO` generators interfaced with `PYTHIA`, and a calculation at NLO precision in QCD and including corrections arising from mixing between QCD and electroweak diagrams, and between QCD and QED diagrams taken from [14].

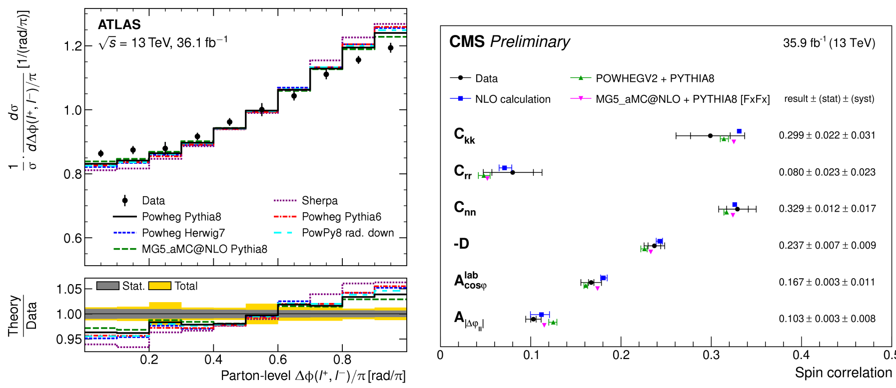

Figure 2: Left: The parton-level normalised differential cross-section in $\Delta\phi$ compared to predictions from `POWHEG`, `MadGraph5_aMC@NLO` and `SHERPA`. [10] Right: Measured spin correlation coefficients and asymmetries and their total uncertainties. [11]

4. Top Yukawa coupling and colour flow at 13 TeV

Using the lepton+jets final state because of its associated large statistics and relative ease of reconstruction of the $t\bar{t}$ system, CMS examines in [15] the possibility to extract the top Yukawa coupling from differential distributions of the $t\bar{t}$ cross-section in $M(t\bar{t})$ and $\Delta|y|(t\bar{t})$. Indeed, near the top pair production threshold, electroweak corrections grow larger and an enhanced sensitivity to Y_t (the ratio of the top Yukawa coupling to its SM prediction) is expected. Using `HATHOR` [16], these electroweak correction factors are calculated for variations of Y_t and applied to the parton-level $t\bar{t}$ distributions. The two-dimensional data distributions in the variables above are then fit to the sum of the predicted contributions in three SRs, based on jet multiplicities. A 57-bin profile likelihood scan leads to the extraction of an inclusive upper limit on the top Yukawa coupling of 1.67 at the 95% CL.

In [17], the ATLAS collaboration studies the effect of colour flow using jet pull observables in the semileptonic $t\bar{t}$ final state, providing a test of long-standing perturbative QCD predictions. The jet pull vector $\vec{\mathscr{P}}$ for a given jet J with constituent transverse momenta $p_{T,i}$ is defined by $\vec{\mathscr{P}} = \sum_{i\in J}(p_{T,i}/p_{T,J})|\Delta\vec{r}_i|\Delta\vec{r}_i$, with $\Delta\vec{r}_i = (y_i - y_J, \phi_i - \phi_J)$ with respect to the jet axis. Given a pair of jets J_1 and J_2, the jet pull angle $\theta_P(J_1, J_2)$ is defined as the angle enclosed by the jet pull vector $\vec{\mathscr{P}}_1$ of J_1 and the directional vector connecting the centres of the cones of J_1 and J_2. If the two jets are produced by a colour singlet (e.g. from $W \to q\bar{q}'$), the enhanced hadronic activity from the colour field between the two quarks should lead to smaller values of the jet pull angle. For non colour-connected jets (e.g. from $g \to b\bar{b}$), one expects a random (flat) distribution.

The distribution of $\theta_P(J_1^W, J_2^W)$ of the two light-jets associated with the hadronic W boson decay after correction to particle-level is shown in Figure 3. A significant enhancement at small values of θ_P is observed, consistent with the two jets being colour-connected and originating from a colour-singlet. On the other hand, Figure 3 shows no evidence of colour connection in $\theta_P(J_1^b, J_2^b)$, the two b-jets in a semileptonic $t\bar{t}$ event being colour-connected individually to the beamline. It is worth noting that no single Monte Carlo (MC) model is able to describe all distributions accurately, but that the artificially "colour-flipped" model (treating the W boson as a colour octet) performs consistently worse.

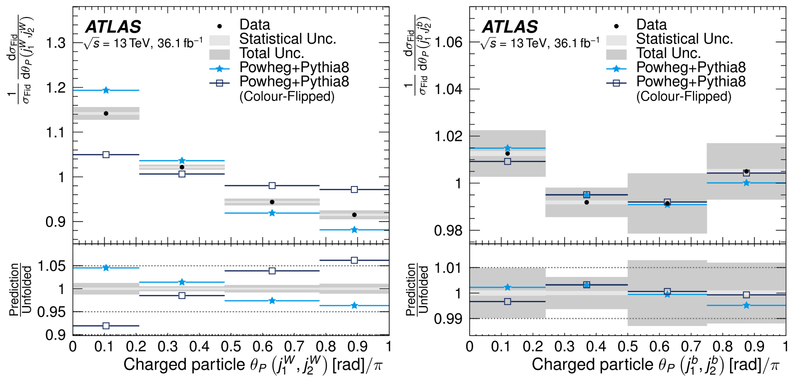

Figure 3: Normalised fiducial differential cross-sections as a function of the (left) forward pull angle for the hadronically decaying W boson daughters, (right) the forward di-b-jet-pull angle. [17]

5. Top quark mass

5.1 Indirect measurements of the pole mass at 8 TeV

The ATLAS collaboration performed two indirect measurements of the top quark pole mass at $\sqrt{s} = 8$ TeV. The first one [18] uses a simple $e^{\pm}\mu^{\mp}$ selection, with one or two b-jets, and focuses solely on leptonic observables in order to reduce the exposure to QCD modelling uncertainties that generally come with reconstructing the $t\bar{t}$ system. By looking at eight such observables (transverse momenta, energies and angles of the individual leptons and their combinations), the generator bias is also kept low during the extraction. The observed absolute and normalised cross-sections, corrected to particle-level in a suitable fiducial volume, are compared to fixed-order NLO QCD calculations (from MCFM) to explore their sensitivity to the gluon PDF and the top quark pole mass. A value of $m_t = 173.2 \pm 0.9(\text{stat.}) \pm 0.8(\text{syst.}) \pm 1.2(\text{theo.})$ GeV is extracted, dominated by the uncertainty in the choice of QCD scale.

A second indirect measurement [19] relies on the enhanced dependence of the cross-section of $t\bar{t}$ production in association with one hard jet on the pole mass, in the lepton+jets final state. Here, the $t\bar{t}$ system is reconstructed in order to identify the extra jet, using a minimisation criterion of the difference in the masses of the two top candidates. A distribution $\mathscr{R} = 1/\sigma_{t\bar{t}+1\text{jet}} \times \mathrm{d}\sigma_{t\bar{t}+1\text{jet}}/\mathrm{d}\rho_\text{s}$, with $\rho_\text{s} = 340\ \text{GeV}/M(t\bar{t}+1\text{jet})$, is unfolded to parton-level and compared to a fixed-order calculation at NLO. A mass $m_t = 171.1 \pm 0.4(\text{stat.}) \pm 0.9(\text{syst.})\,^{+0.7}_{-0.3}(\text{theo.})$ GeV is extracted, a factor two improvement in precision with respect to the previous measurement at 7 TeV [20], but limited mainly by the $t\bar{t}$ modelling (scale variations).

5.2 Direct measurements of the MC mass and combination at 8 TeV

Still in the semileptonic $t\bar{t}$ channel at 8 TeV, ATLAS [21] extracted the value $m_t = 172.08 \pm 0.39(\text{stat.}) \pm 0.82(\text{syst.})$ GeV for the MC top mass. The achieved total relative uncertainty of 0.53% stems from several factors. First, the optimisation of the fiducial phase-space with a BDT trained on 13 kinematic variables helped reduce the background contamination from 4% down to 1%. Second, apart from $m_\text{reco}(t)$, the variables $m_\text{reco}(\text{had.}\ W)$ and $R_\text{reco}(bq) = (p_T^{b_1} + p_T^{b_2})/(p_T^{q_1} + p_T^{q_2})$ not only help place more stringent selection cuts, but also permit the extraction of the jet energy scale factor (JSF) and the relative b-to-light energy scale factor (bJSF) from a 3D template fit, along with m_t. These effectively partially transform the jet and b-jet energy scales (JES and bJES) uncertainties into statistical ones on m_t, which can be reduced with enough data.

In the same paper, the ATLAS collaboration combines this result with previous ones in the all-hadronic and dileptonic channels, both at 7 and 8 TeV, using the BLUE framework. A combined MC top mass of $m_t = 172.69 \pm 0.25(\text{stat.}) \pm 0.41(\text{syst.})$ GeV is obtained, with a total relative uncertainty of 0.28%.

5.3 Direct measurements of the MC mass and combination at 13 TeV

At 13 TeV, the CMS collaboration [22] employs the Ideogram method in a semileptonic $t\bar{t}$ selection with exactly one lepton and at least 4 jets, of which exactly two are b-tagged, to extract the top mass and test new colour reconnection models. A joint maximum likelihood fit is used to determine m_t and JSF after a kinematic reconstruction fit, including the reconstructed W boson mass to help constrain the JES uncertainties. The "hybrid" fit, one-dimensional in m_t with a prior on JES, yields the most precise result of $m_t = 172.25 \pm 0.08(\text{stat.} + \text{JSF}) \pm 0.62(\text{syst.})$ GeV, achieving a factor two reduction in statistical uncertainties compared to the Run 1 result [23]. The systematic uncertainty here is dominated by JES, ME generator and colour reconnection.

In [24], CMS repeats a similar Ideogram fit in the all-hadronic channel, with the same "hybrid" approach yielding $m_t = 172.34 \pm 0.20(\text{stat.} + \text{JSF}) \pm 0.70(\text{syst.})$ GeV. A combination is then performed, by simultaneously fitting the two channels: $m_t(\text{comb.}) = 172.26 \pm 0.07(\text{stat.} + \text{JSF}) \pm 0.61(\text{syst.})$ GeV.

5.4 Extraction of the strong coupling constant at 13 TeV

The strong coupling constant α_S and the top quark pole mass m_t cannot be measured simultaneously, since both parameters alter the predicted $\sigma_{t\bar{t}}$ in such a way that any variation of one parameter can be compensated by a variation of the other. In [25], the CMS collaboration therefore starts with a simultaneous multi-bin fit of $\sigma_{t\bar{t}}$ and the MC top mass, increasing the sensitivity to the latter free parameter by considering the distribution of the observable $\min m(\ell b)$. The fitted value of $\sigma_{t\bar{t}}$ and its uncertainty then account for the dependence on the MC top mass, and are used to extract m_t and $\alpha_S(M_Z)$ in the $\overline{\text{MS}}$ scheme with different PDF sets. The results are summarised in Figure 4, where a linear dependence is observed between the measured α_S and m_t. The main systematics are related to the inclusive cross-section measurement, as well as the choice of PDFs and scale variations.

To investigate this linear dependency further, a triply-differential cross-section measurement is performed in [26], considering the jet multiplicity, $M(t\bar{t})$ and $y(t\bar{t})$. A simultaneous extraction of α_S, m_t and PDFs (using additional HERA data) yields the values $\alpha_S(M_Z) = 0.1135^{+0.0021}_{-0.0017}(\text{total})$ and $m_t = 170.5 \pm 0.8(\text{total})$ GeV.

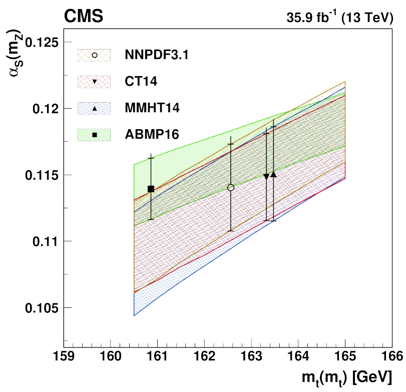

Figure 4: Values of $\alpha_S(m_Z)$ obtained in the comparison of the $\sigma_{t\bar{t}}$ measurement to the NNLO prediction using different PDFs, as a function of the $m_t(m_t)$ value used in the theoretical calculation. The results from using the different PDFs are shown by the bands with different shading. [25]

6. Summary

We have reviewed a number of analyses performed by the ATLAS and CMS collaborations, covering top quark pair properties and mass measurements at the LHC, at $\sqrt{s} = 7, 8$ and 13 TeV. FCNCs through Z and Higgs bosons in production and decay modes were sought, and competitive limits on the branching ratios were set. The distributions of proxy spin correlation observables by ATLAS in the dileptonic channel, showing a 3.2σ discrepancy with respect to the SM, have been the source of much debate in the theory community and will require further investigation. The CMS result however, focusing on the full spin density matrix, is in good agreement with the SM within uncertainties, as are its measurements of charge asymmetries. Measurements of the top Yukawa coupling and the colour flow pull angles are novel approaches to testing SM predictions at high energies. Top mass measurements, both direct and indirect, continue to be a focus of intense activity within both collaborations, and we have summarised here the latest ones, including combinations at 7 and 8 TeV and an extraction of the strong coupling constant.

References

[1] Particle Data Group. Review of particle physics. *Phys. Rev. D*, 98:030001, Aug 2018.

[2] ATLAS Collaboration. The ATLAS Experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.

[3] CMS Collaboration. The CMS experiment at the CERN LHC. *JINST*, 3:S08004, 2008.

[4] ATLAS Collaboration. Search for flavour-changing neutral current top-quark decays $t \to qZ$ in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector. *JHEP*, 07:176, 2018.

[5] CMS Collaboration. Search for flavour changing neutral currents in top quark production and decays with three-lepton final state using the data collected at $\sqrt{s}$ = 13 TeV. (CMS-PAS-TOP-17-017), 2017.

[6] CMS Collaboration. Search for the flavor-changing neutral current interactions of the top quark and the Higgs boson which decays into a pair of b quarks at $\sqrt{s} = 13\,\text{TeV}$. *JHEP*, 06:102, 2018.

[7] ATLAS Collaboration. Search for flavor-changing neutral currents in top quark decays $t \to Hc$ and $t \to Hu$ in multilepton final states in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector. *Phys. Rev. D*, 98:032002, 2018.

[8] ATLAS Collaboration. Search for top quark decays $t \to qH$, with $H \to \gamma\gamma$, in $\sqrt{s} = 13\,\text{TeV}$ pp collisions using the ATLAS detector. *JHEP*, 10:129, 2017.

[9] ATLAS Collaboration. Search for top-quark decays $t \to qH$ with $36\,\text{fb}^{-1}$ of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector. *JHEP*, 2019(5):123, May 2019.

[10] ATLAS Collaboration. Measurements of top-quark pair spin correlations in the $e\mu$ channel at $\sqrt{s} = 13\,\text{TeV}$ using pp collisions in the ATLAS detector. *Eur. Phys. J.*, 2019.

[11] CMS Collaboration. Measurement of the top quark polarization and $\mathrm{t\bar{t}}$ spin correlations in dilepton final states at $\sqrt{s} = 13$ TeV. (CMS-PAS-TOP-18-006), 2018.

[12] CMS Collaboration. Measurements of $t\bar{t}$ differential cross sections in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ using events containing two leptons. *JHEP*, 02:149, 2019.

[13] J. A. Aguilar-Saavedra and M. Pérez-Victoria. Simple models for the top asymmetry: constraints and predictions. *JHEP*, 2011(9), September 2011.

[14] Werner Bernreuther, Dennis Heisler, and Zong-Guo Si. A set of top quark spin correlation and polarization observables for the LHC: Standard model predictions and new physics contributions. *JHEP*, 2015(12):1–36, December 2015.

[15] CMS Collaboration. Constraining the top quark Yukawa coupling from $\mathrm{t\bar{t}}$ differential cross sections in the lepton+jets final state in proton-proton collisions at $\sqrt{s} = 13$ TeV. (CMS-PAS-TOP-17-004), 2019.

[16] M. Aliev, H. Lacker, U. Langenfeld, S. Moch, P. Uwer, and M. Wiedermann. HATHOR – HAdronic top and heavy quarks crOss section calculatoR. *Computer Physics Communications*, 182(4):1034–1046, April 2011.

[17] ATLAS Collaboration. Measurement of colour flow using jet-pull observables in $t\bar{t}$ events with the ATLAS experiment at $\sqrt{s} = 13\,\text{TeV}$. *Eur. Phys. J. C*, 78:847, 2018.

PoS(DIS2019)162

[18] ATLAS Collaboration. Measurement of lepton differential distributions and the top quark mass in $t\bar{t}$ production in pp collisions at $\sqrt{s} = 8\,\text{TeV}$ with the ATLAS detector. *Eur. Phys. J. C*, 77:804, 2017.

[19] ATLAS Collaboration. Measurement of the top-quark mass in $t\bar{t}+1$-jet events collected with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV. (arXiv:1905.02302. CERN-EP-2019-059), 2019.

[20] ATLAS Collaboration. Determination of the top-quark pole mass using $t\bar{t}+1$-jet events collected with the ATLAS experiment in 7 TeV pp collisions. *JHEP*, 10:121, 2015.

[21] ATLAS Collaboration. Measurement of the top quark mass in the $t\bar{t} \rightarrow$ lepton+jets channel from $\sqrt{s} = 8\,\text{TeV}$ ATLAS data and combination with previous results. *Eur. Phys. J. C*, 79:290, 2019.

[22] CMS Collaboration. Measurement of the top quark mass with lepton+jets final states using pp collisions at $\sqrt{s} = 13\,\text{TeV}$. *Eur. Phys. J. C*, 78:891, 2018.

[23] CMS Collaboration. Measurement of the top quark mass using proton–proton data at $\sqrt{s} = 7$ and 8 TeV. *Phys. Rev. D*, 93:072004, 2016.

[24] CMS Collaboration. Measurement of the top quark mass in the all-jets final state at $\sqrt{s} = 13$ tev and combination with the lepton+jets channel. *Eur. Phys. J. C*, 79(4), April 2019.

[25] CMS Collaboration. Measurement of the $t\bar{t}$ production cross section, the top quark mass, and the strong coupling constant using dilepton events in pp collisions at $\sqrt{s} = 13$ TeV. *Eur. Phys. J. C*, 79(5):368, Apr 2019.

[26] CMS Collaboration. Measurement of $\mathrm{t\bar{t}}$ normalised multi-differential cross sections in pp collisions at $\sqrt{s} = 13$ TeV, and simultaneous determination of the strong coupling strength, top quark pole mass, and parton distribution functions. (arXiv:1904.05237. CMS-TOP-18-004-003), Apr 2019.