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Top quark properties measurements at ATLAS and CMS

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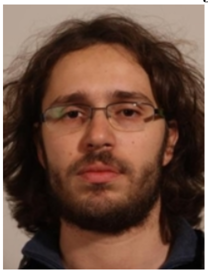

A review on recent top quark properties measurements by the ATLAS and CMS collaborations in pp collisions at the LHC is presented.

The top quark is the heaviest elementary particle, with $m_t \approx 172.5$ GeV; thanks to its high mass, it has a special place in the Standard Model (SM), and possibly in physics sectors predicted by many beyond-SM (BSM) theories. Also, it decays before hadronization, allowing for directly probing its spin information by studying its decay products. The LHC Run-2 dataset, consisting of $\approx$135 fb^{-1} (per experiment) of pp collisions at $\sqrt{s}$ =13 TeV, provides an incredible chance for precision studies on top quark properties. In the following, recent results from ATLAS and CMS are reviewed.

The measurements discussed here are relative either to top pair production ($t\bar{t}$), or to single-top production via a t-channel W boson exchange. Top quarks usually decay via $t \to Wb$, while $t \to Ws$ and $t \to Wd$ channels give very small contributions. The $t\bar{t}$ measurements discussed here use events where one W boson decays hadronically and the other via $W \to \ell\nu$ with $\ell = e$ or μ (single-lepton), or events with both W bosons decaying via $W \to \ell\nu$ with $\ell = e$ or μ (dilepton). Single-top measurements exploit leptonic decays. The datasets are collected using triggers identifying leptons with high transverse momentum (p_T). Electrons are reconstructed using a combination of tracking detectors and calorimeters, while for muons mostly tracking detectors are used. Hadrons produce jets of particles in the detectors, reconstructed using tracking detectors and calorimeters employing the anti-k_T clustering algorithm[1], with a distance parameter $R = 0.4$. Dedicated algorithms are used to identify jets associated with $b-$quarks ($b-$tagging). In some cases larger jets ($R = 0.8$ or $R = 1.0$) are used to reconstruct boosted hadronically decaying top quarks; dedicated top tagging strategies are used in this case. The presence of neutrinos in the final state is inferred from the missing transverse momentum of the event (p_T^{miss}). Many of the $t\bar{t}$ analyses discussed here perform a kinematic reconstruction, with an event-by-event measurement of the t and the $\bar{t}$ momenta, utilising available measurements of their decay products and mass constraints (m_t, m_W) with a variety of techniques.

Ref. [2] presents a measurement of the polarisation of top quarks in 36 fb^{-1} of Run-2 collisions using $t\bar{t}$ dilepton events. A coordinate system is introduced and used to express the top spin density matrix in terms of coefficients, which are then measured exploiting dedicated angular observables for the two charged leptons in the final state. Resulting normalised differential cross-sections, unfolded to parton-level, are compared with predictions: good agreement with data is found for Monte Carlo (MC) simulation with next-to-leading order (NLO) accuracy for the matrix element (ME) calculation combined with a parton shower (PS) algorithm, and for NLO SM predictions which include spin correlation effects for $t\bar{t}$ production, while significant disagreement is found when the correlation is not taken into account. Polarisation and spin-correlation coefficients are measured and found in good agreement with SM predictions. Limits are set on anomalous couplings for the top quark, evaluated with an effective field theory (EFT) approach. Statistical and systematic uncertainties are at the same level for several observables, while for others statistical effects are sub-dominant.

Ref. [3] reports a direct search for an anomalous chromoelectric dipole moment (CEDM) in the top-gluon interaction vertex, i.e. a BSM source of CP violation. In this case two dedicated CP-odd observables, $\mathcal{O}_1$ and $\mathcal{O}_3$, are defined from the momenta of the top quarks, $b-$quarks and charged leptons, providing a maximal sensitivity to the effects of the anomalous coupling. The asymmetry between positive and negative values of those observables is measured in data and used to constrain the CEDM, resulting in $(0.58 \pm 0.69(\text{stat}) \pm 0.70(\text{syst})) \cdot 10^{18}$ $\mathrm{g_s}$cm (from $\mathcal{O}_1$) and $(-0.01 \pm 0.72(\text{stat}) \pm 0.58(\text{syst})) \cdot 10^{18}$ $\mathrm{g_s}$cm (from $\mathcal{O}_3$), $\mathrm{g_s}$ being the strong coupling, in agreement with SM predictions (i.e. with 0).

A powerful way of testing SM predictions is to measure asymmetries in $t\bar{t}$ production. It is symmetric at LO in QCD, but higher order and electroweak effects introduce a small asymmetry in $q\bar{q} \to t\bar{t}$, with the t ($\bar{t}$) following more often the direction of the incoming q ($\bar{q}$). At the Tevatron $q\bar{q}$ production is dominating, and the $p\bar{p}$ collisions define a preferred direction for the q ($\bar{q}$), so a forward-backward asymmetry $A_{\text{FB}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{(\Delta y>0)+N(\Delta y<0)}$, y being the rapidity and $\Delta y = y_t - y_{\bar{t}}$, can be directly measured. At the LHC $q\bar{q}$ production provides just a 10% contribution, with gg diagrams being dominant, so the effect is much smaller. Furthermore, pp collisions provide no preferred direction for q ($\bar{q}$). One solution is to exploit the different proton PDFs for quarks and anti-quarks, which result in different absolute rapidity ($|y|$) distributions for the t ($\bar{t}$). In Ref. [4] $\Delta|y| = |y_t| - |y_{\bar{t}}|$ is used to define $A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{(\Delta|y|>0)+N(\Delta|y|<0)}$, which is measured in 139 fb^{-1} of pp collisions in single-lepton events, using $R = 0.4$ jets for $m_{t\bar{t}} < 500$ GeV (resolved events) and $R = 1.0$ jets with top-tagging in the $m_{t\bar{t}} > 500$ GeV regime (boosted events). Measurements are unfolded to parton level. The inclusive result is $A_C = 0.0060 \pm 0.0011(\text{stat}) \pm 0.0010(\text{syst})$, with a 4σ significance with respect to zero. Differential measurements are also presented as a function of the longitudinal boost and of the invariant mass of the $t\bar{t}$ system. All results are in good agreement with SM predictions. Limits are set on BSM effects utilising an EFT approach. Ref. [5] presents an asymmetry measurement using 36 fb^{-1} of Run-2 collisions, in single-lepton events, with a very different approach. In this case an effective parameter $A_{\text{FB}}^{(1)}$ controlling the asymmetric part of the $q\bar{q} \to t\bar{t}$ cross-section is introduced, and it is shown that with good approximation $A_{\text{FB}}^{(1)} \approx A_{\text{FB}}$, effectively resulting in a Tevatron-style measurement. The challenge is to distinguish the sub-dominant $q\bar{q}$ production from qg and gg productions: this is obtained employing three kinematic quantities, i.e. the longitudinal boost, the invariant mass and the scattering angle of the reconstructed system. A multidimensional fit is performed for resolved and boosted events, and for a third intermediate category covering the phase space between the other two. The result is $A_{\text{FB}}^{(1)} = 0.0048^{+0.095}_{-0.087}(\text{stat})^{+0.020}_{-0.029}(\text{syst})$; limits are also set on anomalous chromoelectric and chromomagnetic moments for the top quark.

The top quark has a special relationship with the Higgs boson in the SM. The high top mass m_t results in a very high Yukawa coupling, predicted to be $g_t^{\text{SM}} = 0.99$; BSM effects may affect this value, resulting in $\Upsilon_t = \frac{g_t}{g_t^{\text{SM}}} \neq 1$. This would alter the $t\bar{t}$ kinematics in pair production, due to contributions from virtual exchanges of Higgs bosons between the t and the $\bar{t}$. Ref. [6] and [7] present measurements of the top Yukawa coupling respectively in the single-lepton (on a 36 fb^{-1} dataset) and dilepton (on a 137 fb^{-1} dataset) channels. The sensitive observables are $m_{t\bar{t}}$ and $|\Delta y_{t\bar{t}}| = |y_t - y_{\bar{t}}|$; the dilepton analyses utilises $m_{b\bar{b}\ell\bar{\ell}}$ and $|\Delta y_{b\bar{b}\ell\bar{\ell}}|$, which are proxies for the same effects but less affected by detector uncertainties. Υ_t is measured in data with likelihood fits on those observables, resulting in $\Upsilon_t = 1.07^{+0.34}_{-0.43}$ (single-lepton) and $\Upsilon_t = 1.16^{+0.24}_{-0.35}$ (dilepton), with uncertainties dominated by systematic effects. These results are less precise than those obtained from Higgs boson measurements [8,9], but they are more general, since they do not rely on assumptions on Yukawa couplings of other particles.

Measuring the width of the top quark Γ_t is a further test for SM predictions, since BSM contributions may affect its value. Ref. [10] presents a direct measurement of Γ_t, performed on 139 fb^{-1} of pp collisions in $t\bar{t}$ dilepton events. The main observable of the analysis is the invariant mass of the $b-$quark coming from a top quark and of the charged ℓ coming from a W produced by the same top, $m_{\ell b}$. Its shape depends on the Γ_t and is used to measure its value with a template fit to data in the $e\mu$ channel. The fit is also simultaneously constraining the m_{bb} distribution in the ee and $\mu\mu$ channels in order to reduce the impact from $b-$jet related uncertainties. The result is $\Gamma_t = 1.94^{+0.52}_{-0.49}$ GeV for $m_t = 172.5$ GeV, in agreement with SM predictions, within uncertainties that are dominated by systematic effects. Results are provided also for alternative m_t hypotheses. These results are less precise but more general than those obtained from indirect constraints, which require assumptions e.g. on the value of the single-top cross section.

Ref. [11] presents a measurement of the CKM matrix elements $|V_{tx}|$ in a 36 fb^{-1} dataset using single-top t-channel events. The relative values $|V_{tb}| >> |V_{tq}|$ with $q = d, s$, thus diagrams with tWb vertices both at production and decay of the t (ST_{tWb}) are by far dominating. Contributions from events with at least one tWq vertex (ST_{tWq}) are at sub-percent level in the SM. Events are split in three categories, depending on the number of jets and how many of them are $b-$tagged, providing different sensitivities to ST_{tWb} and ST_{tWq}. A number of quantities are used to build multivariate discriminants, designed to discriminate single-top from background events and to distinguish ST_{tWb} and ST_{tWq}. The CKM elements are then measured with a maximum-likelihood fit. Results are provided for different scenarios. Assuming CKM matrix unitarity, and using $|V_{tb}|$ as the only free parameter, the measurement results in $|V_{tb}| > 0.970$ and $(|V_{td}|^2 + |V_{ts}|^2) < 0.057$ 95% CL. Assuming a heavier 4th quark generation of quarks but SM Γ_t results in $|V_{tb}| = 0.988 \pm 0.051$ and $(|V_{td}|^2 + |V_{ts}|^2) = 0.06 \pm 0.06$, while releasing the top width constraint results in $|V_{tb}| = 0.988 \pm 0.024$ and $(|V_{td}|^2 + |V_{ts}|^2) = 0.06 \pm 0.06$. The measurements, limited by systematics effects, represent a first direct and model-independent determination of the $|V_{tx}|$ terms, with respect to other existing measurements, which rely on important assumptions (e.g. on theoretical cross section calculations).

Top decay products can also be studied with high precision in top events. Ref. [12] presents a measurement of $R(\tau/\mu) = \frac{BR(W\to\tau\nu)}{BR(W\to\mu\nu)}$, BR being the branching ratio. This is of great interest because the LEP measurement for $R(\tau/\mu)$ shows a 2.7σ tension with SM predictions [13]. Here a 139 fb^{-1} dataset is utilised and $t\bar{t}$ dilepton events are selected, with tight cuts applied on one of the leptons, and then the measurement is performed on the other one, which is requested to be a muon. The impact parameter of the muon $|d_0|$ is used as a discriminant variable: a small $|d_0|$ value corresponds to a prompt $W \to \mu\nu$ decay, while $W \to \tau\nu$ decays have on average a larger $|d_0|$. The $|d_0|$ measurement is calibrated employing $Z \to \mu\mu$ decays. Events with two leptons with the same charge are used to control the backgrounds. The result, $R(\tau/\mu) = 0.992 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})$, is in good agreement with the SM and the most precise measurement available to date.

Ref. [14] is a new measurement of W decay BRs in $t\bar{t}$ events, performed on a 36 fb^{-1} dataset by categorising events depending on the number of jets, number of $b-$tagged jets, number and type of charged leptons (including hadronically decaying τ leptons). Kinematic variables (e.g. the sub-leading lepton p_T in $ee, e\mu, \mu\mu$ channels) are used to discriminate $W \to \ell\nu$ ($\ell =$

e, μ) from $W \to \tau\nu \to \ell\nu\nu$ ($\ell = e, \mu$) decays. BRs are extracted with a maximum likelihood estimation approach. Results for the hadronic and leptonic BRs, assuming lepton universality, are respectively $BR(W \to had) = (67.32 \pm 0.02(\text{stat}) \pm 0.23(\text{syst}))\%$ and $BR(W \to \ell\nu) = (10.89 \pm 0.01(\text{stat}) \pm 0.08(\text{syst}))\%$; BRs for the individual leptonic channels are also presented in the paper. The results are in good agreement with those from LEP [13], and have significantly better statistical precision, whereas (dominant) systematic uncertainties are at the same level. The paper presents results also for the ratios between leptonic BRs, and uses those results to perform measurements for other SM quantities, i.e. CKM matrix elements and α_s.

Finally, Ref. [15] presents a combination of ATLAS and CMS measurements for the polarisation fractions of the W boson in $t\bar{t}$ and single-top events. The measurements are performed on ≈ 20 fb^{-1} (per experiment) of LHC Run-1 pp collisions at $\sqrt{s} = 8$ TeV. The paper presents a careful assessment of the level of correlation of the systematic uncertainties for the different measurements, which is particularly challenging when considering results from different experiments. The combination results in a longitudinal polarisation fraction $F_0 = 0.693 \pm 0.009(\text{stat} + \text{bkg}) \pm 0.011(\text{syst})$ and a left-handed one $F_L = 0.315 \pm 0.006(\text{stat} + \text{bkg}) \pm 0.009(\text{syst})$, with stat+bkg representing the combination of uncertainties relative to the size of the data sample and to the background estimation. The right-handed polarisation fraction can also be measured imposing the unitarity constraint, and is found to be $F_R = -0.008 \pm 0.005(\text{stat} + \text{bkg}) \pm 0.006(\text{syst})$. All the results are in good agreement with SM predictions; limits on anomalous couplings in the tWb vertex are also presented in the paper.

In conclusion, a review of recent measurements of several properties of the top quark and of W bosons produced in top quark decays was presented. With the very high number of top quarks produced by the LHC, these measurements represent a high precision test of SM predictions, and allow for investigating potential BSM physics effects. Many measurements discussed in this overview still suffer from a sizeable statistical uncertainty, and will significantly improve when using the full Run-2 dataset or by adding data from the Run-3, which is starting in 2022. Systematic uncertainties are important for all measurements and dominant in most cases: the most relevant effects are usually those associated with hadronic jets measurements in the detector, and with modelling of the signal in simulation. The great effort the whole top physics community is devoting to improve our current knowledge on these effects will be absolutely crucial in order to maximise the information we can extract from the LHC data.

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