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# MEASUREMENTS OF TOP QUARK PROPERTIES AT THE LHC

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The latest measurements of the top quark properties performed by the ATLAS and CMS collaborations are presented. The data from the proton-proton collisions at the LHC corresponding up to 5 fb$^{-1}$ of the integrated luminosity collected at the energy of interactions of $\sqrt{s} = 7$ TeV during 2011 and up to 20 fb$^{-1}$ collected at $\sqrt{s} = 8$ TeV during 2012 have been used. All the measurements are consistent with the theoretical predictions.

## 1 Introduction

The top quark has been discovered in 1995 by the CDF and D0 collaborations at the Tevatron [1,2]. Since then, lots of its properties have been measured there although with the limited statistical precision given by low top quark production cross-section. At the LHC, the large increase in the cross-section and in the collected luminosity resulted in about 6 millions of top quark pair events produced in both the ATLAS and CMS experiments. This allows both the precise determination of various top quark properties and also the differential measurements.

In this article, we will focus on the latest and the most precise measurements performed by the ATLAS [3] and CMS [4] experiments mostly with the full 2011 or 2012 LHC statistics. We will cover the properties related to each step in the production chain, namely the charge asymmetry, the $t\bar{t}$ spin correlations, the top quark polarization and the top quark width, the top quark branching fractions, the rare decays, and the W boson polarization. Most of the measurements mentioned below use top quark pair events. We will mention explicitly the cases where the single top quark topology is used.

We will not cover the measurements of the $t\bar{t}$ cross-section neither the top quark mass measurements which are covered in the other articles of these proceedings [5,6].

## 2 Charge asymmetry measurements

A small positive charge asymmetry is predicted at the next-to-leading order in the quantum chromodynamics, meaning the top quarks are preferentially emitted in the direction of the

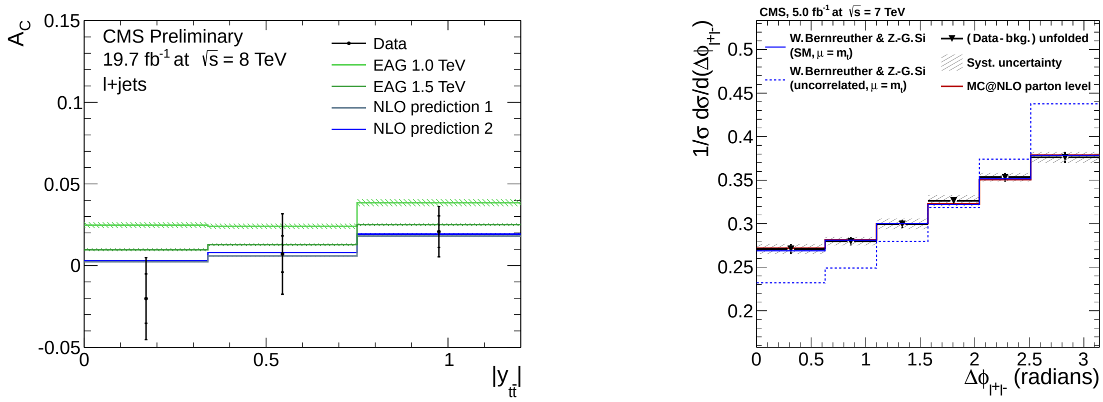


Figure 1 – The charge asymmetry as a function of $|y_{t\bar{t}}|$ from the CMS single lepton measurement [11] (left) and the $\Delta\phi_{\ell\ell}$ from the CMS spin correlation measurement [14](right).

interacting quarks. At the LHC, two observables are used for the measurement of the charge asymmetry $A_C = (N(x > 0) - N(x < 0))/(N(x > 0) + N(x < 0))$ where $x$ is either $|\Delta y_{t\bar{t}}| = |y_t| - |y_{\bar{t}}|$ or $|\Delta\eta_{\ell\ell}| = |\eta_{\ell+}| - |\eta_{\ell-}|$. The standard model (SM) prediction for $A_C^{t\bar{t}}$ ($A_C^{\ell\ell}$) is 1.23% and 1.11% (0.70% and 0.64%) at the LHC with $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively.

The first measurements were performed at $\sqrt{s} = 7$ TeV. Both experiments unfold their results to the parton level in order to directly compare to the SM predictions. The ATLAS analysis with a single lepton in the final state measures the inclusive asymmetry $A_C^{t\bar{t}} = 0.6 \pm 1.0(stat + syst)\%$ while also performing the differential measurement in $p_T$, mass, and rapidity of $t\bar{t}$ pair [7]. The ATLAS analysis with two leptons in the final state measures inclusively both asymmetries: $A_C^{t\bar{t}} = 5.7 \pm 2.4(stat) \pm 1.5(syst)\%$ and $A_C^{\ell\ell} = 2.3 \pm 1.2(stat) \pm 0.8(syst)\%$ [8]. The CMS experiment also performs the dilepton measurement where it measures both asymmetries inclusively $A_C^{t\bar{t}} = 1.0 \pm 1.7(stat) \pm 0.8(syst)\%$, $A_C^{\ell\ell} = 0.9 \pm 1.0(stat) \pm 0.6(syst)\%$ while also measuring the $A_C^{\ell\ell}$ differentially in $p_T$, mass and rapidity of $t\bar{t}$ pair [9]. The first combination of the ATLAS and CMS charge asymmetry measurements has been already performed [10]. The method of the best linear unbiased estimate has been used. The combined inclusive measurement is $A_C^{t\bar{t}} = 0.5 \pm 0.7(stat) \pm 0.6(syst)\%$.

The CMS experiment already performed the measurement of $A_C^{t\bar{t}}$ in the single lepton channel at $\sqrt{s} = 8$ TeV inclusively ($A_C^{t\bar{t}} = 0.5 \pm 0.7(stat) \pm 0.6(syst)\%$) and also differentially in $p_T$, mass, and rapidity of $t\bar{t}$ pair, see Fig. 1 [11].

## 3 $t\bar{t}$ spin correlations and top polarization measurements

At the LHC, the top quarks are produced almost un-polarized. However, there is a correlation between the top and antitop spin. Since the top quark has a very short lifetime, the spin properties are transferred to its decay products and by analyzing them we can get the information about the top quark spin properties.

All of the ATLAS and CMS spin correlations and top polarization measurements were performed at 7 TeV. The ATLAS analyzes four spin correlations sensitive observables [12]. The fraction of the events with the SM predicted correlation $f_{SM}$ is measured (by definition, $f_{SM} = 1.0$ in SM) by comparing the data to the templates corresponding to the SM spin correlations and to no spin correlations. All four measurements are consistent with 1.0 within the uncertainties. The most precise measurement $f_{SM} = 0.87 \pm 0.11(stat) \pm 0.14(syst)$ is based on the ratio of the matrix elements for the top quark production and decay from the fusion of like-helicity gluons with the SM spin correlations and without the spin correlations.

The ATLAS analysis of the top spin polarization performs the measurements under two different hypotheses: in the charge-parity (CP) conserving scenario, the polarization of top and antitop is assumed to be the same ($P_t = P_{\bar{t}}$) while in the maximum violating CP scenario

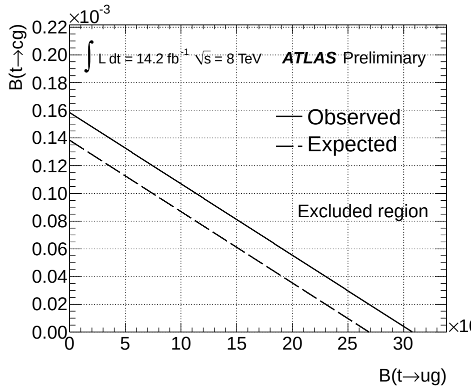


Figure 2 – The upper limits on the branching fractions in $BR(t \to ug)$ vs. $BR(t \to cg)$ plane from the ATLAS measurement [18].

the polarization is assumed to be the opposite ($P_t = -P_{\bar{t}}$). The templates for the negative and positive polarizations are compared to the data and the results are $\alpha P_t = -0.035 \pm 0.014(stat) \pm 0.037(syst)$ ($\alpha P_t = 0.020 \pm 0.016(stat)^{+0.013}_{-0.017}(syst)$) for the CP conserving (violating) case. The $\alpha$ is the spin-analyzing power of the final state object and it is very close to 1.0 for the charged leptons [13]. The result can be compared to the SM prediction of $P_{t/\bar{t}} = 0.003$.

The CMS analysis uses various asymmetry observables calculated from the distributions unfolded to the parton level which are sensitive to the $t\bar{t}$ spin correlations and the top polarization [14]. The asymmetry $A_P$ in the angle of the charged lepton in the rest frame of its parent top quark, measured in the helicity frame ($\cos\theta_\ell$) is sensitive to top polarization ($A_P = P/2$) and was measured to be $A_P = 0.005 \pm 0.013(stat) \pm 0.020(syst) \pm 0.008(top\ p_T)$. The last uncertainty is related to the top quark $p_T$ reweighting in the simulation. Two other observables are the asymmetry in the difference in the azimuthal angles of the charged leptons $\Delta\phi_{\ell\ell}$ (see Fig. 1) and the asymmetry in the product of $\cos\theta_\ell$ of the charged leptons. These are sensitive to the spin correlations. Their measured values are $A_{\Delta\phi} = 0.113 \pm 0.010(stat) \pm 0.007(syst) \pm 0.012(top\ p_T)$ and $A_{\Delta c_1 c_2} = -0.021 \pm 0.023(stat) \pm 0.027(syst) \pm 0.010(top\ p_T)$, respectively. Their latest SM predictions are 0.015 and -0.078, respectively.

## 4 Measurements of other top quark properties

According to the SM, the top quark decays almost exclusively into $W$ boson and $b$ quark. The CMS measurement explores the decay of the top quark by measuring the ratio $R = BR(t \to Wb)/BR(t \to Wq)$ [15]. The multiplicity of the jets identified as coming from the hadronization of a b-quark is fitted and the result $R = 1.014 \pm 0.003(stat) \pm 0.032(syst)$ is obtained. Using this result, the CMS experiment indirectly determines (assuming 3 generations of quarks) the element of Cabibbo-Kobayashi-Maskawa matrix $|V_{tb}| > 0.975$ at 95% CL and also the top quark width by combining with the single top quark t-channel cross-section measurement $\Gamma_t = 1.36 \pm 0.02(stat)^{+0.14}_{-0.11}(syst)$ GeV.

The flavor changing neutral currents (FCNC) are highly suppressed in the SM through the GIM mechanism with the branching ratios predicted at the levels of $O(10^{-14})$. Various models beyond SM predict the enhancements of FCNC up to the level of $O(10^{-4} - 10^{-5})$. Both the ATLAS and CMS experiments look for such processes in various topologies and decays. The CMS search in the $t\bar{t}$ events with three leptons in the final state where one of top quarks is decaying through $t \to Zq$ provides the limit $BR(t \to Zq) < 0.05\%$ [16]. The anomalous $tq\gamma$ vertex is probed by the CMS experiment through the final state of single top quark and a photon. The limits are set on $BR(t \to u\gamma) < 0.016\%$ and $BR(t \to c\gamma) < 0.182\%$ [17]. The ATLAS search for the anomalous production of single top quark through $qg \to t$ provides the limit on $BR(t \to ug) < 3.1 \cdot 10^{-5}$ assuming $BR(t \to cg) = 0$ and $BR(t \to cg) < 1.6 \cdot 10^{-4}$ assuming

$BR(t \rightarrow ug) = 0$, see Fig. 2 [18].

Moreover, both ATLAS and CMS look for the Higgs boson in the top quark decay. The ATLAS experiment performs the search in $t\bar{t}$ events with one of the top quarks decaying to $qH$ with $H \rightarrow \gamma\gamma$ and sets the limit $BR(t \rightarrow Hq) < 0.79\%$ [19]. The CMS experiment performs the generic search for $\geq 3$ leptons events. The search then explores the $t\bar{t}$ production with one of the top quarks decaying into Higgs boson and sets the limit on $BR(t \rightarrow Hc) < 1.3\%$ [20]. All the limits mentioned above are at the 95% CL.

Due to the V-A nature of the electro-weak interactions and the low $b$ quark mass, there are almost no right-handed $W$ bosons in the top quark decay. The CMS experiment performed the measurement of the W boson polarization by fitting the $\cos\theta^*$ distribution where $\theta^*$ is the angle between the direction of down-type fermion from $W$ boson decay and the direction opposite to the top quark direction, both in the $W$ boson rest frame. As a result, the fraction of the top quark decays into longitudinal, left-handed, and right-handed W bosons is measured to be $F_0 = 0.659 \pm 0.015(stat) \pm 0.023(syst)$, $F_L = 0.350 \pm 0.010(stat) \pm 0.024(syst)$ and $F_R = -0.009 \pm 0.006(stat) \pm 0.020(syst)$, respectively [21]. This is in agreement with the SM prediction of $F_0 = 0.687$, $F_L = 0.311$, and $F_R = 0.002$.

## 5 Conclusions

In this article, we reviewed the current measurements of the top quark properties as performed by the ATLAS and CMS experiments. These properties are now precisely measured at the percentage level while mostly dominated by the systematic uncertainties. There are no hints of new physics in the top quark production yet. Still, many of the measurements using the full 8 TeV dataset are in the progress. In the LHC Run 2, the center-of-mass energy will be increased to 13 TeV. We should measure the properties even more differentially, focus on the systematic uncertainties and try to explore the new observables.

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