Measurements of top quark properties in top pair production and decay at the LHC using the CMS detector.

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Abstract

Measurements are presented of the properties of top quarks in pair production and decay from proton-proton collisions at the LHC. The data were collected at centre-of-mass energies of 7 and 8 TeV by the CMS experiment during the years 2011 and 2012. The top quark-antiquark charge asymmetry is measured using the difference of the absolute rapidities of the reconstructed top and anti-top kinematics, as well as from distributions of the top quark decay products. The measurements are performed in the decay channels of the $t\bar{t}$ pair into both one and two leptons in the final state. The polarization of top quarks and top pair spin correlations are measured from the angular distributions of top quark decay products. The W-boson helicity fractions and angular asymmetries are extracted and limits on anomalous contributions to the $Wtb$ vertex are determined. The flavor content in top-quark pair events is measured using the fraction of top quarks decaying into a W-boson and a $b$-quark relative to all top quark decays, $R = B(t \rightarrow Wb) / B(t \rightarrow Wq)$, and the result is used to determine the CKM matrix element $V_{tb}$ as well as the width of the top quark resonance. All of the results are found to be in good agreement with standard model predictions.

Keywords: LHC, CMS, Top Quark, Charge Asymmetry, Spin Correlations, Polarization
1. Introduction

The top quark was discovered by the CDF and D0 collaborations in 1995 [1,2]. Perhaps the most striking feature that sets the top quark apart from the other quarks is its very large mass. At $173.34 \pm 0.76$ GeV [3], it is approximately thirty times heavier than the next heaviest bottom ($b$) quark and is the heaviest elementary particle in the Standard Model (SM). Because of this fact, it is natural to ask whether the top quark plays a special role in the SM.

The top quark contributes to radiative terms in theoretical calculations of many observables that have been measured at LEP, the Tevatron, and now the LHC. Hence precision measurements of top quark properties allow testing the SM and in particular probe the exact mechanism of the electroweak symmetry breaking.

As a consequence of its high mass, the phase space available for the top quark decay is large, resulting in an extremely short lifetime of about $10^{-25}$ seconds in the Standard Model, about an order of magnitude shorter than the characteristic hadronization time of Quantum Chromodynamics (QCD). Therefore, studies of the top quark decay open a unique window on the properties of a bare quark free from long-range effects of QCD.

In addition to being unique in the SM, the top quark plays an important role in many beyond SM physics scenarios. This constitutes one of the main motivations for the top quark physics program at the LHC. Several models predict the existence of new particles that decay predominantly into top quark pairs. In addition, precise measurements of the properties of the top quark and its interactions may reveal effects from new physics. This concerns in particular the study of differential distributions, such as the asymmetry in the rapidity distributions of top quarks and anti-quarks.

The LHC is a natural place to study top quarks. The large energy and instantaneous luminosity available at the LHC make it the true “top factory” and allow to study many aspects of the top quark very precisely. CMS [4] has developed a very comprehensive top physics program and only a subset of results focusing on studies of top quark properties in pair production events are presented here. The data used in the described measurements correspond to integrated luminosities of 5 fb$^{-1}$ and 20 fb$^{-1}$ at 7 and 8 TeV center-of-mass energies, respectively.

2. Charge Asymmetry

In the context of top pair production, the term charge asymmetry usually refers to a difference in the rapidity distributions of top quarks and anti-quarks. In the SM and at LO QCD, the charge asymmetry is exactly zero. At NLO QCD, a small asymmetry appears in the case of quark-antiquark annihilation. Measuring this asymmetry probes perturbative QCD predictions and allows to test many new physics models where top quark pairs are produced through the exchange of new heavy particles, for instance axigluons or $W’/Z’$-bosons.

Early measurements reported by the CDF and D0 collaborations suggested significantly larger forward-backward asymmetry than predicted in the SM [5,6]. Moreover, the reported discrepancy between the experimental and theoretical results was even bigger at large values of the invariant mass of the $t\bar{t}$ system ($m_{t\bar{t}}$), which could be an indication of high-mass exotic particles decaying into top quark and antiquark pairs.

There is no forward-backward asymmetry at the LHC because the $pp$ initial state is symmetric. However, due to the proton PDF, the incoming quarks have on average more momentum compared with the anti-quarks, which means that the charge asymmetry results in a rapidity distribution of top quarks that is slightly broader than that of top anti-quarks. At large rapidities, more top quarks than anti-quarks are produced, while in the central region, more top anti-quarks than quarks are produced. Therefore, at the LHC it is common to define charge asymmetry as:

$$AC = \frac{N(\left|y_t\right| > \left|y_\bar{t}\right|) - N(\left|y_t\right| < \left|y_\bar{t}\right|)}{N(\left|y_t\right| > \left|y_\bar{t}\right|) + N(\left|y_t\right| < \left|y_\bar{t}\right|)},$$

where $\left|y_t\right|$ and $\left|y_\bar{t}\right|$ are the rapidities of the top quark and antiquark, respectively.

At CMS the measurement of $A_C$ is performed separately in top pair events with one and two charged leptons (electrons or muons) in the final state. In the single lepton analysis the presence of at least four jets is required with at least one of them tagged as originating from a $b$-quark. This final state offers better statistical precision than the dilepton analysis due to the larger hadronic branching ratio of the $W$ boson decay, however it suffers from larger backgrounds originating from $W$-jets and QCD multijet events. Using the 8 TeV dataset of 19.7 fb$^{-1}$, approximately 325,000 events are selected with the
full set of selection requirements. The expected background contamination is about 20%. The distribution of $\Delta y = |y_i - y_i^0|$ after background subtraction and unfolding to the parton level is shown in Fig. 1. The inclusive parton-level charge asymmetry measured using this distribution is found to be $A_C = 0.005 \pm 0.007^{(stat.)} \pm 0.006^{(syst.)}$, which is in good agreement with next-to-leading order (NLO) predictions $0.0102 \pm 0.0005$ [7] and $0.0111 \pm 0.0004$ [8]. The quoted uncertainty of the NLO predictions includes renormalization and factorization scale variation only.

Furthermore, differential measurements of $A_C$ in bins of the invariant mass ($m_{tt}$), rapidity ($y_{tt}$), and transverse momentum ($p_{TT}$) of the top-antitop system are performed to explore the asymmetry dependence on event kinematics. The $tt$ system reconstruction is performed on an event-by-event basis using the method described in [9]. Figure 2 shows the evolution of the unfolded value of $A_C$ in data as function of $m_{tt}$. As seen from the figure, the results are in good agreement with NLO predictions [7,8] and strongly disfavour models with an effective axial-vector coupling of the gluon. More details about the measurement can be found in [10].

![Figure 2](image-url)  
**Figure 2.** Evolution of $A_C$ in data as a function of the invariant mass of the $tt$ system in events with one charged lepton. Predictions in the SM and in the presence of potential new physics models are also shown.

The dilepton analysis [11] uses the 7 TeV dataset corresponding to 5.0 fb$^{-1}$ of integrated luminosity. The leptons are required to have opposite electric charge and the presence of at least two jets (with one of them identified as originating from a b-quark) is also requested. Approximately 10,000 top pair events are selected with a background contribution of less than 10%. The $tt$ system reconstruction is performed on an event-by-event basis using the Analytical Matrix Weighting Technique [12].

A unique feature of the dilepton final state is that one can define a lepton charge asymmetry:

$$A_C^{lep} = \frac{N(\eta_{+} > |\eta_{-}|) - N(\eta_{+} < |\eta_{-}|)}{N(\eta_{+} > |\eta_{-}|) + N(\eta_{+} < |\eta_{-}|)}$$

where $\eta_{+}$ and $\eta_{-}$ are the pseudo-rapidities of the positively and negatively charged leptons, respectively. Due to the boost of the top quarks, the direction of the daughter leptons is correlated with the direction of their mother top quark or anti-quark; therefore the information of interest is not strongly diluted in the decay chain. The advantage of this definition of asymmetry is that it is free of any ambiguities associated with $tt$ system reconstruction. The values of $A_C$ and $A_C^{lep}$ in the data unfolded to the parton level are shown in Table 1 together with the corresponding predictions by the MC@NLO Monte Carlo generator and dedicated NLO calculations [13]. The data agree well with both predictions. Figure 3 shows the inclusive distribution of $|\Delta \eta| = |\eta_{+} - |\eta_{-}|$.
in data compared to the MC@NLO prediction. The result is still statistically limited and improved precision is expected from analyzing the 8 TeV dataset.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Data (unfolded)</th>
<th>MC@NLO</th>
<th>NLO theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_C$</td>
<td>-0.010±0.017±0.008</td>
<td>0.004±0.001</td>
<td>0.0123±0.0005</td>
</tr>
<tr>
<td>$A_C^{lep}$</td>
<td>0.009±0.010±0.006</td>
<td>0.004±0.001</td>
<td>0.0070±0.0003</td>
</tr>
</tbody>
</table>

Table I. $A_C$ and $A_C^{lep}$ measured in data together with corresponding MC@NLO and dedicated NLO theory predictions. The uncertainties in data are statistical and systematic. The MC@NLO uncertainty is statistical only. The NLO theory uncertainty includes scale variation only.

Differential distributions of $A_C$ and $A_C^{lep}$ are also measured in the dilepton final state and, like in the single lepton analysis, are found to be in good agreement with the SM.

3. Spin correlations

The top quark lifetime is much shorter than the spin de-correlation timescale. Consequently, the information about the spin of the top quark at production is transferred directly to its decay products and can be accessed from their angular distribution.

In the dilepton decay $t\bar{t}\rightarrow l^+l^-b\bar{b}$ in the laboratory frame, the difference in the azimuthal angles of the charged leptons is sensitive to $t\bar{t}$ spin correlations and can be measured precisely without reconstructing the full event kinematics. Therefore, the variable:

$$A_{\Delta\phi} = \frac{N(\Delta\phi > \pi/2) - N(\Delta\phi < \pi/2)}{N(\Delta\phi > \pi/2) + N(\Delta\phi < \pi/2)}$$

provides excellent discrimination between correlated and uncorrelated top quark and anti-quark spins. The event selection used in the analysis is the same as in the charge asymmetry measurement described in Section 2. The analysis strategy is also similar - the variable is measured in the data and compared to NLO theory after background subtraction and unfolding to the parton level. CMS studies have shown that the top quark transverse momentum distribution in data is softer than in the NLO simulation. Re-weighting the top quark $p_T$ in the simulation to match the data improves modeling of the lepton and jet momentum distributions and is applied to the simulated sample used in the analysis. The simulation is used only for the unfolding, which is primarily sensitive to changes in the acceptance, where the effect of the $p_T$ re-weighting cancels in the ratio. Still, the top quark
The background subtracted and unfolded distribution of $\Delta \phi_{ll}$ is shown in Fig. 4, normalized to unit area so that it represents a parton level differential cross-section. The asymmetry determined from the parton-level distribution is also a parton-level quantity and is measured to be $A_{\Delta \phi} = 0.113 \pm 0.010 \pm 0.006 \pm 0.012$, where the uncertainties are statistical, systematic, and from top $p_T$ modeling, respectively. This measurement is compared to the NLO SM prediction of $0.115^{+0.014}_{-0.016}$ and NLO uncorrelated prediction of $0.210^{+0.013}_{-0.008}$ [14,15]. The results indicate the presence of correlation as predicted by the SM and strongly disfavor the uncorrelated case.

Figure 4. Background subtracted and unfolded distribution of $\Delta \phi_{ll}$ shown together with parton level predictions from MC@NLO and dedicated theoretical NLO calculations.

Using identical event selection and analysis techniques, we also measure the polarization ($P$) of top quarks. In the helicity basis $P$ is given by $P = 2A_P$, where:

$$A_P = \frac{N(\cos(\theta^*_l) > 0) - N(\cos(\theta^*_l) < 0)}{N(\cos(\theta^*_l) > 0) + N(\cos(\theta^*_l) < 0)}$$

Here $\theta^*_l$ is the angle of charged lepton in the rest frame of its parent top quark or antiquark, measured in the helicity basis. The measurement yields: $A_P = 0.005 \pm 0.013 \pm 0.014 \pm 0.008$, where the uncertainties are statistical, systematic, and from top $p_T$ modeling, respectively. More details can be found in [16].

The result of the spin correlations measurement is sensitive to new physics with anomalous $ttg$ couplings leading to a significant modification of the strength of the correlation. A model independent search is performed using an effective model of Chromo-Magnetic (CMDM) and Chromo-Electric (CEDM) Dipole Moments, as described in [17]. In the study we consider the normalized $t\bar{t}$ differential cross-section as a function of $\Delta \phi_{ll}$ (shown in Fig. 4) and search for contributions from a non-vanishing real part of the CMDM ($\text{Re}(\vec{\mu}_t)$). The $\text{Re}(\vec{\mu}_t)$ parameter can be determined using a simple fit to the data with the following function:

$$g(\Delta \phi_{ll}) = f_{SM}(\Delta \phi_{ll}) + \text{Re}(\vec{\mu}) f_{NP}(\Delta \phi_{ll}),$$

where $f_{SM}(\Delta \phi_{ll})$ and $f_{NP}(\Delta \phi_{ll})$ are contributions from the SM and new physics processes to the $\Delta \phi_{ll}$ distribution and $\text{Re}(\vec{\mu})$ is a free parameter.

The fit is the result of a $\chi^2$ minimization and is performed using MINOS [18]. The result of the fit can be seen in Fig. 5. The exclusion values are determined from the value of $\text{Re}(\vec{\mu}_t)$ extracted from the fit and the associated uncertainties. The best-fit value of $\text{Re}(\vec{\mu}_t)$ is found to be $0.037 \pm 0.041$. This accounts for the full covariance matrix of the measured distribution and additional theoretical uncertainties, namely the scale variation, which has a relatively large effect on $\Delta \phi_{ll}$. Assuming the fitted $\text{Re}(\vec{\mu}_t)$ is distributed according to a Gaussian with mean of 0.037 and width of 0.041, we find the 95% confidence level exclusion limits of $-0.043 < \text{Re}(\vec{\mu}_t) < 0.117$. 
4. Top quark branching fractions

According to the SM, the top quark decays almost exclusively to an on-shell W boson and a b-quark. The magnitude of the top-bottom charged current is proportional to $|V_{tb}|$, one of the elements in the CKM mixing matrix. Assuming unitarity of the CKM matrix, the value of $|V_{tb}|$ is expected to be very close to unity (indirect measurement yields $|V_{tb}| = 0.999146^{-0.000046}_{+0.000021}$).

Deviations from this value could indicate the presence of new physics such as for example models with more than three quark generations.

CMS measures the ratio $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$, where the denominator includes the branching fractions of the top quark to a W boson and a down-type quark (down, strange and bottom) [19]. The measurement is performed in the dilepton final state taking advantage of its high purity. The b-quark content of the events is inferred from the distribution of the number of b-tagged jets per event as a function of jet multiplicity for each of the dilepton flavor combination (electron-electron, muon-muon and electron-muon). $R$ is measured by fitting the observed b-tagged jet distribution with a parametric model that depends on the observed cross-section and efficiency of identifying b-jets. In the fit, the value of $R$ is allowed to vary without constraints. Figure 6 shows the result for each of the dilepton categories as well as the combined fit. The measured value is obtained by maximizing the profile likelihood.

The combined measurement yields $R = 1.014 \pm 0.003^{(\text{stat.})} \pm 0.032^{(\text{syst.})}$ and is in good agreement with the SM prediction. Fits in the individual dilepton channels give consistent results. The measurement is systematically limited and the main source of systematic uncertainty is the b-tagging efficiency measurement. Assuming unitarity of the CKM matrix, $R = |V_{tb}|^2$ and the value of $R$ extracted from the fit yields $|V_{tb}| = 1.007 \pm 0.016$, where the error includes both statistical and systematic components. For both $R$ and $|V_{tb}|$ we also compute confidence level intervals using the Feldman-Cousins frequentist approach. If the condition $R \leq 1$ is imposed, we obtain $R > 0.955$ at 95% confidence level. Similarly, by applying the same procedure and assuming $|V_{tb}| \leq 1$, we obtain $|V_{tb}| > 0.975$ at 95% CL.

Finally, the result obtained for $R$ can be combined with the measurement of the single top-quark production cross-section in the t-channel [21] to yield an indirect determination of the top quark total width $\Gamma_t$.

$$\Gamma_t = \frac{\sigma_{t-ch.}}{B(t \rightarrow Wb)} \frac{\Gamma(t \rightarrow Wb)}{\sigma_{t-ch.}^{\text{theor.}}} ,$$

where $\sigma_{t-ch.}$ and $\sigma_{t-ch.}^{\text{theor.}}$ are the measured and theoretically calculated cross-sections for t-channel single top quark production and $\Gamma(t \rightarrow Wb)$ is the
The analysis [23] is based on 19.7 fb$^{-1}$ of integrated luminosity at a center-of-mass energy of 8 TeV. We then perform a fit to the b-tagged jet multiplicity distribution in the data leaving $\Gamma_t$ as a free parameter. The theoretical prediction for the t-channel cross-section from [20] and the CMS measured one from [21] are used in the likelihood function. After performing a maximum likelihood fit, we measure $\Gamma_t = 1.36 \pm 0.02(\text{stat.}) +0.14^{+0.01}_{-0.01} (\text{syst.})$ GeV, which is in good agreement with the theoretical prediction.

5. W helicity in top decays

The W boson helicity fractions have been of high interest to particle physicists for many years due to their sensitivity to the Wtb vertex couplings and potentially to new physics. The on-shell W bosons produced in top quark decays can have three possible helicity states – longitudinal, left-handed and right-handed. The fraction of W bosons produced in these states is here denoted as $F_0$, $F_L$ and $F_R$. In the SM the top quark decays via the V-A weak charged current interaction, which strongly suppresses right-handed W bosons. For a top quark mass of 172.8$\pm$1.3 GeV, NNLO calculations predict $F_0 = 0.687 \pm 0.005$, $F_L = 0.311 \pm 0.005$ and $F_R = 0.0017 \pm 0.0001$ [22]. A measurement that deviates significantly from these values would provide strong evidence for new physics beyond the SM.

The analysis [23] is based on 19.7 fb$^{-1}$ of integrated luminosity at a center-of-mass energy of 8 TeV. Top pair events decaying into a muon and jets are used in the measurement. At least four jets are required in each event with two of them identified as originating from a b quark. Imposing a minimum requirement on the transverse mass of the leptonically decaying W rejects the large QCD multijet background.

The helicity fractions are extracted by studying angular distributions of the top quark decay products. In the top quark rest frame, the helicity angle $\theta^*$ is defined as the angle between the down-type fermion momentum in the W boson rest frame and the W boson momentum in the top quark rest frame. In top quark pair decays with only one leptonic W boson decay the helicity angle can be defined in both decay branches – in the leptonically the down-type fermion corresponds to the charged lepton and in the hadronically to the down-type quark from the hadronic decay of the W. In this analysis, only the leptonic branch was used in the measurement.

The analysis utilizes a re-weighting method to measure the W boson helicity fractions. In the method, the simulated events are reweighted to give the combination of helicity fractions that best represents the data by maximizing a Poisson likelihood function binned in the $\cos(\theta^*)$ distribution. The distribution for the leptonic branch is shown in Fig. 7.

The measurement yields $F_0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.})$ and $F_L = 0.350 \pm 0.010(\text{stat.}) +0.024(\text{syst.})$ while fitting $F_0$ and $F_L$ simultaneously. The two fractions are strongly correlated. The right-handed helicity fraction can be then obtained from the unitarity condition $F_0 + F_L + F_R = 1$, which yields $F_R = -0.009 \pm 0.006(\text{stat.}) \pm 0.020(\text{syst.})$. All measured fractions are consistent with the predictions from the SM.

Fig. 7. Distribution of $\cos(\theta^*)$ for the leptonic branch of $t \bar{t}$ decay. A maximum likelihood fit to the data in this distribution is performed to extract the helicity fractions.

6. Summary

In the first run of the Large Hadron Collider, the CMS experiment developed a very rich physics program of top quark properties. Presented in this paper are results on charge asymmetry, $t \bar{t}$ spin correlations and top quark polarization, studies of top quark branching ratios, and W boson helicity fraction measurements. All results are compared to the theoretical predictions derived in the context of the Standard Model and found to be in good agreement with them.
References