

Measurements of the top quark properties in $t\bar{t}$ production using the CMS detector at the LHC

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Several recent CMS measurements of properties in top quark pair production are presented. This encompasses 8 TeV measurements of the $t\bar{t} + W$, $t\bar{t} + Z$, and $t\bar{t} + \gamma$ production cross sections, two different measurements of the charge asymmetry at 8 TeV, a 7 TeV measurement of the top quark polarization, and measurements of the top quark spin correlation in the dilepton channel at 7 TeV as well as in the μ +jets channel at 8 TeV.

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1. Introduction

In the years 2011 and 2012 the CERN LHC has been functioning as a top quark factory, enabling measurements of a variety of production properties related to this particle. This article summarizes several recent analyses of such properties in top quark pair production, with all presented analyses relying on the data recorded using the CMS detector [1].

2. Cross sections of $t\bar{t} + W$ and $t\bar{t} + Z$

The cross sections of the $t\bar{t} + W$ and $t\bar{t} + Z$ processes are interesting quantities because they could conceivably be enhanced by beyond the standard model (BSM) contributions, but also because these processes are already starting to be non-negligible backgrounds in some searches for supersymmetry. Analyses of these processes generally select events in several channels with varying numbers of charged leptons, starting at two leptons and going up to four. These different channels then contain different admixtures of the $t\bar{t} + W$ and $t\bar{t} + Z$ processes, allowing to disentangle them from one another as well as from the background contributions.

The CMS Collaboration has performed several earlier analyses of these processes that are out of scope for this summary; see references [2, 3] for details on them.

The most current analysis [4], performed on the 8 TeV data, extends the general analysis strategy described above by performing reconstructions of the measured events under the $t\bar{t} + W$ and $t\bar{t} + Z$ process hypotheses, assigning the reconstructed jets and leptons to the individual particles of the process signatures. These attempts at event reconstructions yield *match scores* quantifying the agreement of the events with the given hypotheses. The match scores are then combined with other kinematic information to train Boosted Decision Trees (BDTs) that can be used to achieve an improved separation of the background and signal processes. Such trainings are performed in a variety of channels with differing numbers of jets, b tags and charged leptons.

Performing one-dimensional fits for only the $t\bar{t} + W$ or only the $t\bar{t} + Z$ cross sections, constraining the respective other cross section to the standard model (SM) prediction, the analysis measures values of $\sigma(t\bar{t} + W) = 382^{+117}_{-102}$ fb and $\sigma(t\bar{t} + Z) = 242^{+65}_{-55}$ fb. This corresponds to significances of 4.8σ and 6.4σ , respectively, and can be compared to SM predictions of 206 fb and 203 fb [5].

The analysis uses these results in two additional ways: First, constraints on the axial-vector and vector components of the top-Z coupling are calculated and found to be in near-perfect agreement with the SM predictions. Secondly, the measured cross sections are also used to derive constraints on five Wilson coefficients for dimension-six operators in effective field theories. At the time of writing the analysis achieves the best direct constraints on those specific coefficients.

3. Cross section of $t\bar{t} + \gamma$

The most current CMS measurement of the $t\bar{t} + \gamma$ cross section [6] has been performed at 8 TeV. This analysis extracts the ratio R of the cross sections of the $t\bar{t} + \gamma$ and $t\bar{t}$ processes; this is done by performing a preselection for top quark pairs in the μ +jets decay channel and comparing the resulting yield to the one obtained when additionally the reconstruction of a photon with a transverse energy of at least 20 GeV is required. An additional correction is obtained via the

determination of the photon misidentification contribution by performing a template fit to the data distribution of the charged hadron isolation of the reconstructed photons.

Using this method the analysis measures a ratio $R = \sigma_{t\bar{t}+\gamma}/\sigma_{t\bar{t}} = (1.07 \pm 0.07(\text{stat.}) \pm 0.27(\text{syst.})) \times 10^{-2}$. This can be multiplied to the result of a general $t\bar{t}$ cross section measurement performed by CMS [7] to yield the final result of

$$\sigma_{t\bar{t}+\gamma}^{\text{CMS}} = 2.4 \pm 0.2(\text{stat.}) \pm 0.6(\text{syst.}) \text{ pb},$$

which can be compared to the SM prediction of $\sigma_{t\bar{t}+\gamma}^{\text{SM}} = 1.8 \pm 0.5 \text{ pb}$. It should be noted that all quoted values use a photon definition with the requirement $E_T^\gamma > 20 \text{ GeV}$.

4. Charge asymmetry in top quark pair production

The charge asymmetry in top quark pair production [8] is an effect that occurs only in production processes involving quark-antiquark-annihilation. These processes have an asymmetry in the initial state due to the higher average momentum of the quarks as compared to the antiquarks, which do not occur as valence quarks. The term *charge asymmetry* refers to effects that translate this initial-state asymmetry into a charge-dependent final-state asymmetry of the produced top quarks and antiquarks; at the LHC, the higher quark momentum is predicted to result in a wider rapidity distribution for top quarks when compared to top antiquarks.

Measurements of the charge asymmetry have received significant attention because they are sensitive to some models introducing physics beyond the SM, and because measurements at CDF have hinted at the existence of positive contributions of this kind. In recent times, however, the apparent discrepancy has become smaller as the theory predictions and measurements have converged.

The effect is measured by constructing a sensitive variable $\Delta|y| = |y_t| - |y_{\bar{t}}|$, which can be determined on an event-by-event basis. The asymmetry then is calculated as

$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}.$$

CMS has recently finished two different analyses of the charge asymmetry at 8 TeV, which pursue slightly different goals and thus can be considered to be complementary.

4.1 Measurement using unfolding

The first analysis [9] puts its focus on the highest reasonably achievable model-independence of the measurement; to this end a carefully optimized regularized unfolding technique is used to translate the reconstructed values of the sensitive variable into parton-level distributions.

The inclusive value of the charge asymmetry in the full phase space of $t\bar{t}$ production is measured to be

$$A_C = 0.0010 \pm 0.0068(\text{stat.}) \pm 0.0037(\text{syst.}),$$

which is compatible with the SM predictions of 0.0102 ± 0.0005 [10] or 0.0111 ± 0.0004 [11] and specifically does not hint at positive contributions beyond the SM expectation.

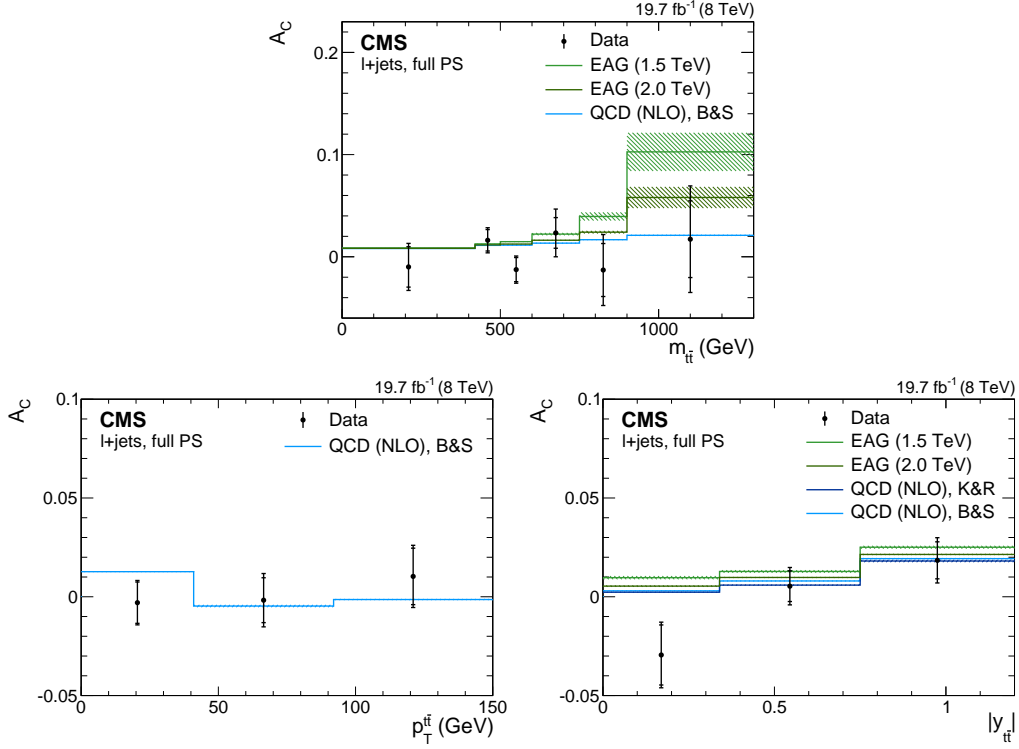


Figure 1: Measured charge asymmetry in the full phase space of top quark pair production as functions of $m_{t\bar{t}}$, $p_T^{t\bar{t}}$, and $|y_{t\bar{t}}|$. The measured values are compared to NLO calculations for the SM [10, 11], as well as to the predictions of a model featuring an effective axial-vector coupling of the gluon (EAG) [12, 13].

The analysis also performs differential measurements of the charge asymmetry as a function of $m_{t\bar{t}}$, $p_T^{t\bar{t}}$, and $y_{t\bar{t}}$, all of which are sensitive to different aspects of the charge asymmetry. The results are shown in Fig. 1; they, as well, are compatible with the SM predictions. The measured values are also compared to the predictions of a model [12, 13] featuring an effective axial-vector coupling of the gluon, which represents one of the more promising attempts at explaining the CDF results using new physics. The model can be excluded at scales of up to 1.5 TeV, whereas the explanation of the original CDF results would have required a scale of only about 1.3 TeV.

Analyses of the charge asymmetry in the full phase space of $t\bar{t}$ production necessarily require an extrapolation from the subset of events that can be measured. This extrapolation relies on SM assumptions and thus would not produce accurate results in the case of significant BSM contributions or if there is a general mismodeling of the charge asymmetry in the simulation. Acknowledging this issue, the presented analysis has also performed measurements that extrapolate to a fiducial phase space of $t\bar{t}$ production; this phase space is defined on generator level and chosen in such a way that the selection criteria of the regular analysis are emulated. As a result the necessary amount of extrapolation is reduced significantly, and due to the high similarity of the selected and fiducial phase spaces there is only a small model dependence in the remaining extrapolation. Though the fiducial results cannot be shown in detail within this article, they also are compatible with the corresponding SM predictions and do not hint at positive deviations from them.

4.2 Measurement using a template method

The second charge asymmetry analysis [14] introduces a new measurement method for this observable, relying on a template fit to the reconstructed spectrum of the sensitive variable. For this purpose the simulated SM template is symmetrized and anti-symmetrized, yielding two new templates that can be used for the fit. The scale factors obtained in the template fit to the reconstructed data then are used to calculate not only the reconstruction-level charge asymmetry, but also the one on parton level. Relying on the correct modeling of the template components, this method is slightly more model-dependent than unfolding approaches; however, it also allows for a significant reduction of the otherwise dominant statistical uncertainties.

The analysis measures a value of

$$A_C = 0.0033 \pm 0.0026(\text{stat.}) \pm 0.0033(\text{syst.}),$$

which is consistent with SM predictions – as well as with the result of the unfolding-based analysis presented above.

It should be noted that the CMS Collaboration has not yet performed differential or fiducial measurements using this technique; this leaves room for the production of additional interesting results in the future.

5. Polarization

As top quark pair production is dominated by processes of the strong interaction, which do not violate parity, the SM predictions for the top quark polarization in $t\bar{t}$ production are very small. The CMS Collaboration has measured this observable using the dilepton decay channel in events collected at a collision energy of 7 TeV [15]. The measurement relies on the angle θ_ℓ , which is defined as the angle between the top quark momentum in the $t\bar{t}$ rest frame and the momentum of the charged lepton in the top quark rest frame; this is referred to as the *helicity basis* for the polarization measurement. Unfolding the distribution of $\cos(\theta_\ell)$ and using it to calculate an asymmetry A_P , an observable is obtained that has a direct relation to the polarization $P = 2A_P$. The measurement yields a result of

$$A_P = 0.005 \pm 0.013(\text{stat.}) \pm 0.014(\text{syst.}) \pm 0.008(p_T^t),$$

with the last quoted uncertainty referring to a systematic uncertainty due to the mismodeling of the top quark p_T spectrum, as observed in another CMS measurement [16]. The result is compatible with the MC@NLO prediction of 0.000 ± 0.001 , supporting the general SM prediction of negligible polarization.

6. Top quark spin correlations

The average top quark polarization being zero does not preclude a correlation between the spins of the two top quarks in a top quark pair production event; in fact, the cross section can be parameterized as

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4} (1 + B_1 \cos\theta_1 + B_2 \cos\theta_2 + C \cos\theta_1 \cos\theta_2),$$

Table 1: Asymmetries in the top quark spin correlation measurement at 7 TeV, and the corresponding theory predictions [17, 18]. The uncertainties on the unfolded data values are, in order, the statistical, systematic, and top quark p_T uncertainties.

Asymmetry	Data (unfolded)	NLO (SM, correlated)	NLO (uncorrelated)
$A_{\Delta\phi}$	$0.113 \pm 0.010 \pm 0.006 \pm 0.012$	$0.115^{+0.014}_{-0.016}$	$0.210^{+0.013}_{-0.008}$
$A_{c_1c_2}$	$-0.021 \pm 0.023 \pm 0.025 \pm 0.010$	-0.078 ± 0.006	0

with B_1 and B_2 representing the polarizations and taking values close to zero, and C representing the spin correlation coefficient; the angles θ_i for the two leptons are defined as in Section 5. Spin correlations of significant size are predicted even by the SM [17, 18]. One example for a new process modifying the measured correlations would be stop quark pair production for stop quark masses close to the top quark mass, making this process almost indistinguishable from top quark pair production.

6.1 Measurement in the dilepton channel at 7 TeV

This measurement [15] uses two different approaches to gain information on the spin correlations, unfolding the reconstructed distributions of two different sensitive variables. In both cases an asymmetry is calculated from the distributions as the final quantifier of the effect.

The first sensitive variable, $\Delta\phi_{\ell^+\ell^-}$, is calculated as the difference of the ϕ coordinates of the two produced leptons in the laboratory frame. The asymmetry is calculated as

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

This variable has the advantage of not requiring a reconstruction of the top quark momenta, allowing a comparatively precise measurement of the quantity itself. This observable does not, however, allow a direct calculation of the spin correlation coefficient.

The possibility of such a direct calculation is the benefit of the second sensitive variable. It is calculated as the product of the angular variables $\cos(\theta_\ell)$, introduced in Section 5, for the two top quarks of an event. The corresponding asymmetry is

$$A_{c_1c_2} = \frac{N(\cos(\theta_\ell^+) \times \cos(\theta_\ell^-) > 0) - N(\cos(\theta_\ell^+) \times \cos(\theta_\ell^-) < 0)}{N(\cos(\theta_\ell^+) \times \cos(\theta_\ell^-) > 0) + N(\cos(\theta_\ell^+) \times \cos(\theta_\ell^-) < 0)}$$

and relates to the spin correlation coefficient as $C = -4A_{c_1c_2}$.

Table 1 shows the results of the measurements. As in Section 5, the quoted measurement uncertainties refer, in order, to the statistical, systematic, and top quark p_T mismodeling uncertainties. While the measured value of $A_{c_1c_2}$ is compatible with both the SM correlated hypothesis and the uncorrelated one within two standard deviations, $A_{\Delta\phi}$ shows near-perfect agreement with the SM prediction, and it strongly disfavors the uncorrelated hypothesis.

6.2 Measurement in the μ +jets channel at 8 TeV

In this analysis [19] a full matrix element method is used to evaluate the probabilities for the data events to occur under the SM correlated (H_{cor}) and uncorrelated (H_{uncor}) hypotheses. A test

statistic λ_{event} is calculated for each event as the ratio of the probabilities:

$$\lambda_{\text{event}} = \frac{P(H_{\text{uncor}})}{P(H_{\text{cor}})}.$$

This test statistic is used in two different ways.

The first approach is to calculate the sum of all λ_{event} values in the data sample and to perform a hypothesis test, comparing the obtained value to the predicted distributions as obtained from pseudo experiments under the SM correlated and uncorrelated hypotheses. Both the statistical and systematic errors are taken into account for these pseudo experiments. The result of the hypothesis test is a slightly better agreement with the SM correlated hypothesis than with the uncorrelated hypothesis, corresponding to agreements within 2.2 and 2.9 standard deviations, respectively.

The second approach is to perform a template fit to the distribution of λ_{event} itself. Separate templates are used for SM correlated and uncorrelated simulations of the top quark pair production process, as well as for the sum of the background contributions. An additional calibration is performed to account for biases in the obtained signal fractions that depend on the background normalization. The ratio of signal events that need to be described by the SM correlated hypothesis to obtain a best fit is found to be

$$f_{\text{calibrated}} = 0.72 \pm 0.09(\text{stat.})_{-0.13}^{+0.15}(\text{syst.}).$$

This value can be multiplied to an SM prediction of the spin correlation strength, $A_{\text{hel}}^{\text{SM}} = 0.31$ [20], to obtain a measured value of the spin correlation coefficient in the helicity basis:

$$A_{\text{hel}}^{\text{measured}} = 0.22 \pm 0.03(\text{stat.})_{-0.04}^{+0.05}(\text{syst.}).$$

7. Summary

A variety of CMS measurements of the properties in top quark pair production has been presented. The $t\bar{t} + W$ and $t\bar{t} + Z$ processes have been established at significances of 4.8σ and 6.4σ , respectively. The measured cross section of the $t\bar{t} + \gamma$ process differs from zero by about 3.7σ and is compatible with the SM prediction. The charge asymmetry in top quark pair production is measured to be compatible with the SM predictions and specifically does not hint at positive contributions from new physics. The measured values for the polarization and spin correlation of the top quarks, finally, are also found to agree with the SM predictions.

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