Measurement of Spin Correlations in Top Pair Events in the Dilepton Channels in pp Collisions at 7 TeV

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Abstract

We present a measurement of the spin correlation of top-antitop-pair events produced in pp collisions at $\sqrt{s} = 7$ TeV. The data used by this analysis corresponds to an integrated luminosity of $5.0 \, \text{fb}^{-1}$ collected with the CMS detector at the LHC. The spin correlation in top-antitop-pair events is extracted from a fit to the angular distribution between the two selected leptons. In the helicity basis, the correlation coefficient is found to be $A_{\text{hel}} = 0.24 \pm 0.02 \pm 0.08$ and agrees with the Standard Model prediction.

1 Introduction

At the LHC, top quarks are produced abundantly, mainly in pairs by gluon fusion. The top quark mass has been measured to be $172.9 \pm 0.6 \pm 0.9 \text{ GeV}$ [1] and the width of the top quark is found to be $\Gamma_t = 2.0^{+0.7}_{-0.6} \text{ GeV}$ [1]. This implies a lifetime much shorter than the hadronization time-scale, $m_t/\Lambda_{\text{QCD}}$. Therefore, the spin of the top quark at production is transferred to its decay products and can be accessed by the distribution of angular observables. This offers the opportunity to study spin correlations of the $t\bar{t}$ pairs [2]. The investigation of spin correlation in the $t\bar{t}$ system probes the bare quark at production, and by this the top pair production processes and perturbative QCD. At the LHC, in the regime of small invariant masses of the $t\bar{t}$ systems, the production is dominated by the fusion of like-helicity gluon pairs, resulting in top pairs with aligned orientations of top and anti-top spins (RR or LL), see Fig. 1. At higher invariant $t\bar{t}$ masses, the dominant production process switches to unlike-helicity gluons, producing $t\bar{t}$ pairs in anti-aligned orientations (RL or LR), which give identical configurations than the ones produced by $q\bar{q}$ annihilation at the Tevatron [3]. In the dileptonic decay ($t\bar{t} \rightarrow l^+\nu_l^-\bar{b}b\bar{b}$), the charged leptons are correlated in azimuthal angle ($\Delta\phi_{l^+l^-}$) in the laboratory frame [3] and can be measured precisely by CMS without reconstructing the full event kinematics. CDF and D0 measured the strength of the spin correlation to be in agreement with the Standard Model expectation using template fit methods to angular distributions [4, 5, 6]. The ATLAS experiment reported a measurement of the spin correlation using $\Delta\phi_{l^+l^-}$ distributions and found it to be in agreement with next-to-leading order Standard Model predictions [7].

This analysis uses data corresponding to an integrated luminosity of $5.0 \, \text{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV, provided by the LHC and recorded with the CMS detector [8]. The measurement of the spin correlation in $t\bar{t}$ events is compared to the Standard Model expectation [9].

2 Selection

This analysis focuses on dileptonically decaying $(ee, e\mu, \mu\mu)$ top quark pairs. All events are triggered by double lepton triggers ($e$, $\mu$) and contain two isolated high energy leptons ($p_T \geq 20 \text{ GeV}$). An additional $Z$-mass-veto of $|m_{ll} - m_Z| > 15 \text{ GeV}$ and a cut on $E_T \geq 40 \text{ GeV}$ is applied on same lepton flavor events to reject Drell-Yan events. All events are also required to have an invariant lepton pair mass above 20 GeV. Two jets are required with a transverse momentum above 30 GeV, and one of them has to be $b$-tagged. A comparison of the $\Delta\phi_{l^+l^-}$ distribution of the selected events with and without spin correlations is shown in Fig. 2.

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Figure 1: Differential cross sections of different helicity states and their productions mechanisms, [10].

Figure 2: Simulated $\Delta \phi_{l^+l^-}$ distribution of selected events, with and without spin correlations.

3 Estimates of Background Processes

Two different kinds of background processes are estimated using data-driven methods. Firstly, the production of Drell-Yan events, which dominate the $e^+e^-$ and $\mu^+\mu^-$ channel. It is estimated from the number of events in data inside the $Z$-mass-veto window, scaled by the ratio of events that fail and pass this selection. Secondly, non-prompt lepton background processes are estimated using a matrix method [11], or Barlow’s event reweighting method [12]. Different dileptonic samples are constructed by loosening the lepton isolation and probabilities for prompt leptons and non-prompt leptons to be contained in these samples are introduced. The resulting system of linear equations has the number of events with two prompt-leptons ($t\bar{t}$ and Drell-Yan events) and the number of events with one or two prompt leptons as variables. Solving this system yields the expected contribution of $W$-like and QCD multijet events [13]. Other contributions, due to single top quark and diboson events, are estimated from simulation.

4 Systematic Uncertainties

Various systematic uncertainties are affecting the measurement. The dominant effects are listed below. Experimental systematic uncertainties include:

Lepton selection: Uncertainties on trigger and lepton selection (isolation and identification) affects the measurement and are estimated by changing the scale factors within their uncertainties.

Lepton energy scale: The uncertainty on the lepton energy scale, which affects mainly the $p_T$ distribution of leptons, are estimated from comparisons between data and simulated $Z$ events.

Jet energy scale and jet energy resolution: The uncertainty from the jet energy scale (JES) correction is estimated by variation of this scale within its uncertainties. The jet energy resolution (JER) is estimated similarly, by a variation depending on the $\eta$ of the jet.

Background events: The uncertainty on the normalization of background processes is considered by varying the corresponding cross section by 100%.

Pileup (PU) modeling: The uncertainty of 8% on the proton-proton cross section at the LHC energy of $\sqrt{s} = 7$ TeV influences the pileup modeling and is used to estimate the corresponding systematics.

FastSim vs. FullSim: The investigations of systematic uncertainties use a simplified detector simulation (FastSim). The observed discrepancies in respect to a detailed simulation (FullSim) are in the jet multiplicity distributions visible. This effect is accounted by comparing the $\Delta \phi_{l^+l^-}$ distributions between FastSim and FullSim.

The systematic uncertainties related to the modeling of $t\bar{t}$ signal events include:

Factorization and renormalization scales: The uncertainty related to factorization and renormalization scales is estimated by investigating dedicated MC@NLO predictions with in-/decreased scales.

Spin correlation and $\tau$ decay: Electrons and muons from $\tau$ decays are considered to be part of the signal, however the $\tau$ polarization is not taken into account in the simulation used in this analysis.
Therefore the effect of spin correlation is not properly propagated to its decay products. The corresponding uncertainty is estimated by comparing simulated events with and without excluding events containing at least one lepton from $\tau$ decay.

**Top quark mass:** The uncertainty on the top quark mass is estimated by using $t\bar{t}$ signal events with different top masses, assuming an uncertainty on the top mass of 2.5 GeV around $m_t = 172.5$ GeV.

**PDF:** The uncertainty related to PDF are estimated by a method described in Ref. [14].

## 5 Observable

The angular difference in the azimuthal plane between the two leptons coming from the W decays in $t\bar{t}$ events ($\Delta\phi_{t\bar{t}} = |\phi_t - \phi_{\bar{t}}|$) is sensitive to the spin correlation of the two top quarks. The strength of the spin correlation can be measured by the spin correlation coefficient, defined as the asymmetry between the number of $t\bar{t}$ events with spin orientation of top quarks aligned and anti-aligned, namely:

$$A = \frac{N(RR) + N(LL) - N(RL) - N(LR)}{N(RR) + N(LL) + N(RL) + N(LR)}.$$

The spin correlation coefficient is estimated from the $\Delta\phi_{t\bar{t}}$ distribution observed in data, by means of a template fit. Three different templates are considered: the simulated $\Delta\phi_{t\bar{t}}$ distributions of $t\bar{t}$ events with and without Standard Model spin correlation between the top quarks, and a $\Delta\phi_{t\bar{t}}$ distribution which describes the background events.

A binned likelihood fit method is used, to perform a simultaneous fit of the $ee$, $e\mu$ and $\mu\mu$ channels. All the events are fitted together in a single likelihood fit, but different templates are used according to the channels. The templates describing background processes are derived by simulation, and weighted according to data-driven estimates, Sec. 3, and the prediction based on simulation of single top quark and the diboson events.

Templates for $t\bar{t}$ signal events are derived from MC@NLO with and without Standard Model spin correlation. The numbers of $t\bar{t}$ signal events in each channel are parameters of the fit, as well as the fraction $f$ of events with Standard Model spin correlation.

The fit result on data is shown in Fig. 3, combining the three channels. The number of $t\bar{t}$ signal events is measured to be $1718 \pm 44$ in the $ee$ channel, $2132 \pm 50$ in the $\mu\mu$ channel and $6351 \pm 85$ in the $e\mu$ channel. The fraction of spin correlation $f$ is measured to be $0.74 \pm 0.08$ (stat.).

The systematic uncertainties are estimated using pseudo-experiments based on simulated events, that are modified according to the investigated systematic effects. The average variation of the spin correlation is used to estimate the systematic uncertainty. The effects of the systematic sources on the measurement of $f$ are presented in Tab. 1. The resulting measured value of $f$ is $0.74 \pm 0.08$ (stat.) $\pm 0.24$ (syst.).

Considering the top spin correlation predicted by MC@NLO, $A^{simu}$, the measured spin correlation coefficient is $f \times A^{simu}$. The spin correlation coefficient from MC@NLO $t\bar{t}$ signal events, in the helicity...
basis, is estimated at matrix element level and found to be $A_{hel}^{sim}=0.33$. This value of the spin correlation coefficient is close to the standard model prediction (NLO calculation) of $A_{hel}^{NLO}=0.31$ from Ref. [15], while this measurement yields a spin correlation coefficient of

$$A_{hel}^{meas} = 0.24 \pm 0.02 \text{(stat.)} \pm 0.08 \text{(syst.)}.$$

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