

## Measurements of $t\bar{t}$ spin correlations and top quark polarization using dilepton final states in $pp$ collisions at $\sqrt{s} = 8$ TeV (Postprint)

**Authors:** Khachatryan, V. and others

**Date:** 2016-08-15T00:00:00+00:00

### Abstract

Measurements of the top quark-antiquark ( $t\bar{t}$ ) spin correlations and the top quark polarization are presented for  $t\bar{t}$  pairs produced in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The data correspond to an integrated luminosity of 19.5 inverse femtobarns collected with the CMS detector at the LHC. The measurements are performed using events with two oppositely charged leptons (electrons or muons) and two or more jets, where at least one of the jets is identified as originating from a bottom quark. The spin correlations and polarization are measured from the angular distributions of the two selected leptons, both inclusively and differentially, with respect to the invariant mass, rapidity, and transverse momentum of the  $t\bar{t}$  system. The measurements are unfolded to the parton level and found to be in agreement with predictions of the standard model. A search for new physics in the form of anomalous top quark chromo moments is performed. No evidence of new physics is observed, and exclusion limits on the real part of the chromo-magnetic dipole moment and the imaginary part of the chromo-electric dipole moment are evaluated.

### Full Text

#### Preamble

Measurements of  $t\bar{t}$  Spin Correlations and Top Quark Polarization Using Dilepton Final States in  $pp$  Collisions at  $\sqrt{s} = 8$  TeV  
The CMS Collaboration\*

#### Abstract

Measurements of the top quark-antiquark ( $t\bar{t}$ ) spin correlations and the top quark polarization are presented for  $t\bar{t}$  pairs produced in  $pp$  collisions at  $\sqrt{s} = 8$

TeV. The data correspond to an integrated luminosity of  $19.5 \text{ fb}^{-1}$  collected with the CMS detector at the LHC. The measurements are performed using events with two oppositely charged leptons (electrons or muons) and two or more jets, where at least one of the jets is identified as originating from a bottom quark. The spin correlations and polarization are measured from the angular distributions of the two selected leptons, both inclusively and differentially, with respect to the invariant mass, rapidity, and transverse momentum of the  $t\bar{t}$  system. The measurements are unfolded to the parton level and found to be in agreement with predictions of the standard model. A search for new physics in the form of anomalous top quark chromo moments is performed. No evidence of new physics is observed, and exclusion limits on the real part of the chromo-magnetic dipole moment and the imaginary part of the chromo-electric dipole moment are evaluated.

Published in *Physical Review D* as doi:10.1103/PhysRevD.93.052008. © 2016 CERN for the benefit of the CMS Collaboration. CC-BY-3.0 license.

\*See Appendix A for the list of collaboration members.

## 1 Introduction

The top quark is the heaviest known elementary particle, with mass  $m_t = 172.44 \pm 0.48 \text{ GeV}$  [1]. The top quark lifetime has been measured as  $3.29^{+0.90}_{-0.63} \times 10^{-25} \text{ s}$  [2], shorter than the hadronization timescale  $1/\Lambda_{\text{QCD}} \approx 10^{-24} \text{ s}$ , where  $\Lambda_{\text{QCD}}$  is the quantum chromodynamics (QCD) scale parameter, and also shorter than the spin decorrelation time scale  $m_t/\Lambda_{\text{QCD}}^2 \approx 10^{-21} \text{ s}$  [3]. Consequently, measurements of the angular distributions of top quark decay products give access to the spin of the top quark, allowing precise testing of perturbative QCD in the top quark-antiquark pair ( $t\bar{t}$ ) production process.

At the CERN LHC, top quarks are produced abundantly, predominantly in pairs. In the standard model (SM), top quarks from pair production have only a small net polarization arising from electroweak corrections to the QCD-dominated production process, but the pairs have significant spin correlations [4]. For low  $t\bar{t}$  invariant masses, production is dominated by the fusion of pairs of gluons with the same helicities, resulting in the creation of top quark pairs with antiparallel spins in the  $t\bar{t}$  center-of-mass frame. For larger  $t\bar{t}$  invariant masses, the dominant production is via the fusion of gluons with opposite helicities, resulting in  $t\bar{t}$  pairs with parallel spins [3]. For models beyond the SM, couplings of the top quark to new particles can alter both the top quark polarization and the strength of the spin correlations in the  $t\bar{t}$  system [4-7].

The charged lepton ( $\ell$ ) from the decay  $t \rightarrow bW^+ \rightarrow b\ell^+\nu_\ell$  is the best spin analyzer among the top quark decay products [8], and is sensitive to the top quark spin through the helicity angle  $\theta_\ell^*$ . This is the angle of the lepton in the rest frame of its parent top quark or antiquark, measured in the helicity frame (i.e., relative to the direction of the parent quark momentum in the  $t\bar{t}$  center-of-mass frame) [4].

For the decay  $t\bar{t} \rightarrow b\ell^+\nu_\ell\bar{b}\ell^-\bar{\nu}_\ell$ , the difference in azimuthal angle of the charged leptons in the laboratory frame,  $\Delta\phi_{\ell^+\ell^-}$ , is sensitive to  $t\bar{t}$  spin correlations and can be measured precisely without reconstructing the full  $t\bar{t}$  system [3]. With the  $t\bar{t}$  system fully reconstructed, the opening angle  $\phi$  between the two lepton momenta measured in the rest frames of their respective parent top quark or antiquark is directly sensitive to spin correlations, as is the product of the cosines of the helicity angles of the two leptons,  $\cos\theta_{\ell^+}^*\cos\theta_{\ell^-}^*$  [4].

Recent spin correlation and polarization measurements from the CDF, D0, and ATLAS Collaborations used template fits to angular distributions, and their results were consistent with the SM expectations [9–14]. In this analysis, the measurements are made using asymmetries in angular distributions unfolded to the parton level, allowing direct comparisons between the data and theoretical predictions. The analysis strategy is similar to that presented in Ref. [15]; however, the larger data set used here and improvements in the  $t\bar{t}$  system reconstruction techniques lead to reduced statistical uncertainty in the measurements. Furthermore, an improved unfolding technique allows for differential measurements, which were not presented in Ref. [15].

The polarization  $P^\pm$  of the top quark (antiquark) in the helicity basis is given by  $P^\pm = 2A_{P^\pm}$  [4], where the asymmetry variable  $A_{P^\pm}$  is defined as:

$$A_{P^\pm} = \frac{N(\cos\theta_{\ell^\pm}^* > 0) - N(\cos\theta_{\ell^\pm}^* < 0)}{N(\cos\theta_{\ell^\pm}^* > 0) + N(\cos\theta_{\ell^\pm}^* < 0)}$$

where the numbers of events  $N(\cos\theta_{\ell^\pm}^* > 0)$  and  $N(\cos\theta_{\ell^\pm}^* < 0)$  are counted using the helicity angle of the positively (negatively) charged lepton in each event. Assuming CP invariance, these two measurements can be combined to give the SM polarization  $P = 2A_P = (A_{P^+} + A_{P^-})$ . Alternatively, the variable  $P_{CPV} = 2A_{CPV} = (A_{P^+} - A_{P^-})$  measures possible polarization introduced by a maximally CP-violating process [4].

For  $t\bar{t}$  spin correlations, the variable:

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

discriminates between correlated and uncorrelated  $t$  and  $\bar{t}$  spins, while the variable:

$$A_{c_1c_2} = \frac{N(c_1c_2 > 0) - N(c_1c_2 < 0)}{N(c_1c_2 > 0) + N(c_1c_2 < 0)}$$

where  $c_1 = \cos\theta_{\ell^+}^*$  and  $c_2 = \cos\theta_{\ell^-}^*$ , provides a direct measure of the spin correlation coefficient  $C_{\text{hel}}$  through the relationship  $C_{\text{hel}} = -4A_{c_1c_2}$  [4]. The variable:

$$A_{\cos\phi} = \frac{N(\cos\phi > 0) - N(\cos\phi < 0)}{N(\cos\phi > 0) + N(\cos\phi < 0)}$$

provides a direct measure of the spin correlation coefficient  $D$  by the relation  $D = -2A_{\cos\phi}$  [4].

In addition to the inclusive measurements, we determine the asymmetries differentially as a function of three variables describing the  $t\bar{t}$  system in the laboratory frame: its invariant mass  $M_{t\bar{t}}$ , rapidity  $y_{t\bar{t}}$ , and transverse momentum  $p_T^{t\bar{t}}$ . The results presented in this paper are based on data collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of  $19.5 \text{ fb}^{-1}$  from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$ .

## 2 The CMS Detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4  $\mu\text{s}$ . The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [16].

## 3 Event Samples

### 3.1 Object Definition and Event Selection

Events are selected using triggers that require the presence of at least two leptons (electrons or muons) with transverse momentum ( $p_T$ ) greater than 17 GeV for the highest- $p_T$  lepton and 8 GeV for the second-highest  $p_T$  lepton. The trigger efficiency per lepton, measured relative to the full offline lepton selection detailed in this section using a data sample of Drell-Yan ( $Z/\gamma^* \rightarrow \ell\ell$ ) events, is about 98% (96%) for electrons (muons), with variations at the level of several percent depending on the pseudorapidity  $\eta$  and  $p_T$  of the lepton.

The particle-flow (PF) algorithm [17, 18] is used to reconstruct and identify each individual particle with an optimized combination of information from the various elements of the CMS detector. The offline selection requires events

to have exactly two leptons of opposite charge with  $p_T > 20$  GeV and  $|\eta| < 2.4$ . Electron candidates are reconstructed starting from a cluster of energy deposits in the electromagnetic calorimeter. The cluster is then matched to a reconstructed track. The electron selection is based on the shower shape, track-cluster matching, and consistency between the cluster energy and the track momentum [19]. Muon candidates are reconstructed by performing a global fit that requires consistent hit patterns in the silicon tracker and the muon system [20].

Events with an  $e^+e^-$  or  $\mu^+\mu^-$  pair having an invariant mass,  $M_{\ell\ell}$ , within 15 GeV of the  $Z$  boson mass are removed to suppress the Drell-Yan background. For all events, we require  $M_{\ell\ell} > 20$  GeV. Leptons are required to be isolated from other activity in the event. The lepton isolation is measured using the scalar  $p_T$  sum ( $p_T^{\text{sum}}$ ) of all PF particles not associated with the lepton within a cone of radius  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ , where  $\Delta\eta$  ( $\Delta\phi$ ) is the distance in  $\eta$  ( $\phi$ ) between the directions of the lepton and the PF particle at the primary interaction vertex [21]. The average contribution of particles from additional  $pp$  interactions in the same or nearby bunch crossings (pileup) is estimated and subtracted from the  $p_T^{\text{sum}}$  quantity. The isolation requirement is  $p_T^{\text{sum}} < \min(5 \text{ GeV}, 0.15 p_T^\ell)$ , where  $p_T^\ell$  is the lepton  $p_T$ . Typical lepton identification and isolation efficiencies, measured in samples of Drell-Yan events [22], are 76% for electrons and 91% for muons, with variations at the level of several percent within the  $p_T$  and  $\eta$  ranges of the selected leptons.

The PF particles are clustered to form jets using the anti- $k_T$  clustering algorithm [23] with a distance parameter of 0.5, as implemented in the FASTJET package [24]. The contribution to the jet energy from pileup is estimated on an event-by-event basis using the jet-area method described in Ref. [25], and is subtracted from the overall jet  $p_T$ . Jets from pileup interactions are suppressed using a multivariate discriminant based on the multiplicity of objects clustered in the jet, the jet shape, and the impact parameters of the charged tracks in the jet with respect to the primary interaction vertex. The jets must be separated from the selected leptons by  $\Delta R > 0.4$ .

The selected events are required to contain at least two jets with  $p_T > 30$  GeV and  $|\eta| < 2.4$ . At least one of these jets must be consistent with containing the decay of a bottom ( $b$ ) flavored hadron, as identified using the medium operating point of the combined secondary vertex (CSV)  $b$  quark tagging algorithm [26]. We refer to such jets as  $b$ -tagged jets. The efficiency of this algorithm for  $b$  quark jets in the  $p_T$  range 30–400 GeV is 60–75% for  $|\eta| < 2.4$ . The misidentification rate for light-quark or gluon jets is approximately 1% for the chosen working point [26].

The missing transverse momentum vector  $\vec{p}_{\text{miss}}$  is defined as the projection on the plane perpendicular to the beam direction of the negative vector sum of the momenta of all reconstructed particles in the event. Its magnitude is referred to as  $E_T^{\text{miss}}$ . The calibrations that are applied to the energy measurements of jets

are propagated to a correction of  $\vec{p}_{\text{miss}}$ . The  $E_T^{\text{miss}}$  value is required to exceed 40 GeV in events with same-flavor leptons in order to further suppress the Drell-Yan background. There is no  $E_T^{\text{miss}}$  requirement for  $e^\pm\mu^\mp$  events.

### 3.2 Signal and Background Simulation

Simulated signal  $t\bar{t}$  events with a top quark mass of  $m_t = 172.5$  GeV and with SM spin correlations are generated using the MC@NLO 3.41 [27, 28] Monte Carlo (MC) event generator with the CTEQ6M parton distribution functions (PDF) [29]. The parton showering and fragmentation are performed by HERWIG 6.520 [30]. Simulations with different values of  $m_t$  and renormalization and factorization scales ( $\mu_R$  and  $\mu_F$ ) are used to evaluate the associated systematic uncertainties. Background samples of  $W + \text{jets}$ , Drell-Yan, diboson ( $WW$ ,  $WZ$ , and  $ZZ$ ), triboson, and  $t\bar{t} + \text{boson}$  events are generated with MADGRAPH 5.1.3.30 [31, 32], and normalized to the calculated next-to-leading-order (NLO) [33–37] or next-to-next-to-leading-order (NNLO) [38] cross sections. Single top quark events are generated using POWHEG 1.0 [39–43], and normalized to the theoretical NNLO cross sections [44–46]. For the background samples and an alternative  $t\bar{t}$  sample generated using POWHEG 1.0, the parton showering and fragmentation are done using PYTHIA 6.4.22 [47].

For both signal and background events, pileup interactions are simulated with PYTHIA and superimposed on the hard collisions using a pileup multiplicity distribution that reflects the luminosity profile of the analyzed data. The CMS detector response is simulated using a GEANT4-based model [48]. The simulated events are reconstructed and analyzed with the same software used to process the collision data.

The measured trigger efficiencies are used to weight the simulated events to account for the trigger requirement. Small differences between the  $b$  tagging efficiencies measured in data and simulation [26] are accounted for by using data-to-simulation correction factors to adjust the  $b$  tagging probability in simulated events, while the lepton selection efficiencies (reconstruction, identification, and isolation) are found to be consistent between data and simulation [22].

## 4 Background Estimation

Control regions (CR) are used to validate the background estimates from simulation and derive scale factors (SF) and systematic uncertainties for some background processes. Each SF multiplies the simulated background yield for the given process in the signal region (SR) to obtain the final background prediction. The CRs are designed to have similar kinematics to the SR, but with one or two selection requirements reversed, thus enhancing different SM contributions. The main CRs used in this analysis and the values of the derived SFs are summarized in Table 1.

For Drell-Yan events, the SF accounts for mismodeling of the  $E_T^{\text{miss}}$  distribution (coming largely from mismeasured jets) and mismodeling of the heavy-flavor

content. Only the latter is relevant for  $Z/\gamma^* \rightarrow \tau\tau + \text{jets}$ , where the  $E_T^{\text{miss}}$  is dominated by the well-modeled undetected neutrinos, so we omit the  $E_T^{\text{miss}}$  mismodeling in the derivation of the SF for this process. The systematic uncertainties in the SFs are taken from the envelope of the variation observed between the three dilepton flavor combinations and in various alternative CRs. The CR for single top quark production in association with a  $W$  boson ( $tW$ ) is still dominated by signal events (75%), with only a 16% contribution from  $tW$  production, which is an enhancement by a factor of 4 compared to the SR. Given the good agreement between data and simulation in this CR, we assume a SF of unity for  $tW$  production, with an uncertainty of 25% based on the recent CMS  $tW$  cross section measurement of  $23.4 \pm 5.4$  pb [49].

Contributions to the background from diboson and triboson production, as well as  $t\bar{t}$  production in association with a boson, are estimated from simulation. Recent measurements from the CMS Collaboration [50–52] indicate agreement between the predicted and measured cross sections for these processes, and we assign a systematic uncertainty of 50%.

## 5 Event Yields and Measurements at the Reconstruction Level

The expected background and observed event yields for different dilepton flavor combinations are listed in Table 2. The total predicted yield in the  $e\mu$  channel is significantly larger than for the same-flavor channels because of the additional requirements on  $E_T^{\text{miss}}$  and  $M_{\ell\ell}$  described in Section 3 that are applied to suppress the Drell–Yan background. After subtraction of the predicted background yields, the remaining yield in the data is assumed to be a signal from dileptonic  $t\bar{t}$  decays, including  $\tau$  leptons that decay leptonically. All other  $t\bar{t}$  decay modes are treated as background and are included in the  $t\bar{t} \rightarrow \ell + \text{jets}$  category. The largest background comes from  $tW$  production with dileptonic decays.

While the  $|\Delta\phi_{\ell^+\ell^-}|$  measurement relies only on the leptonic information, the measurements based on  $\cos\phi$  and  $\cos\theta_{\ell^\pm}^*$  require the reconstruction of the entire  $t\bar{t}$  system. Each signal event has two neutrinos in the final state, and there is also a twofold ambiguity in combining the  $b$  quark jets with the leptons. In the case of events with only one  $b$ -tagged jet (62% of the selected events), the untagged jet with the highest  $b$  quark likelihood from the CSV algorithm is assumed to be the second  $b$  quark jet. Analytical solutions for the two neutrino momenta are obtained from the measured  $\vec{p}_T^{\text{miss}}$  with constraints on the invariant masses of the top quark and  $W$  boson decay systems of  $m_t = 172.5$  GeV and  $m_W = 80.385$  GeV. Each event can have up to 8 possible solutions. The one most likely to represent the correct  $t\bar{t}$  configuration is chosen based on the probabilities to observe the extracted Bjorken  $x$  values of the initial-state partons and the measured lepton energies in their parent top quark rest frames [53]. For events with no physical solutions, a method is used to find a solution with the vector sum of the  $p_T$  of the two neutrinos as close as possible to the measured  $\vec{p}_T^{\text{miss}}$  [54, 55]. Nevertheless, in 16% of the events, no solutions can be found, both in

the data and the simulation. These events are not used, except in the inclusive measurement of  $|\Delta\phi_{\ell^+\ell^-}|$ .

A comparison of the distributions for the reconstructed  $t\bar{t}$  system variables  $M_{t\bar{t}}$ ,  $y_{t\bar{t}}$ , and  $p_T^{t\bar{t}}$  between data and simulation is shown in Fig. 1 [Figure 1: see original paper], where the signal yield from the simulation has been normalized to the number of signal events in the data after background subtraction. In general, the shapes of the distributions from data and simulation show reasonable agreement, with the small discrepancies covered by the systematic variations in the top quark  $p_T$  modeling, PDFs, and  $\mu_R$  and  $\mu_F$  values, which will be discussed in Section 7. A similar comparison of the angular distributions is shown in Fig. 2 [Figure 2: see original paper]. The corresponding inclusive asymmetry values, uncorrected for background, from the data and simulation are given in Table 3

## 6 Unfolding the Distributions

The observed angular distributions are distorted compared to the underlying distributions at the parton level (for which theoretical predictions exist) by the detector acceptance and resolution and the trigger and event selection efficiencies. To correct the data for these effects, we apply an unfolding procedure that yields the corrected  $|\Delta\phi_{\ell^+\ell^-}|$ ,  $\cos\phi$ ,  $c_1c_2$ , and  $\cos\theta_{\ell^\pm}^*$  distributions at the parton level. In the context of theoretical calculations and parton-shower event generators, the parton-level top quark is defined before it decays, and its kinematics include the effects of recoil from initial- and final-state radiation in the rest of the event and from final-state radiation from the top quark itself. The parton-level charged lepton, produced from the decay of the intermediate  $W$  boson, is defined before the lepton radiates any photons or the muon or tau lepton decays.

In order to unfold the observed distributions it is necessary to choose a binning scheme. Aiming to have bins with widths well matched to the reconstruction resolution and with approximately uniform event contents, we select six bins for each parton-level angular distribution except that of  $\Delta\phi_{\ell^+\ell^-}$ . This variable depends only on the lepton momentum measurements, not on the reconstruction of the  $t\bar{t}$  system, and the superior resolution allows us to use 12 bins. For the reconstruction-level distributions we use twice as many bins as for the parton-level distributions.

The background-subtracted distribution for each variable, considered as a vector  $\vec{y}$ , is related to the underlying parton-level distribution  $\vec{x}$  through the equation  $\vec{y} = S\vec{A}\vec{x}$ , where  $A$  is a diagonal matrix describing the fraction (acceptance times efficiency) of all produced signal events that are expected to be selected in each of the measured bins, and  $S$  is a nondiagonal “smearing” matrix describing the migration of events between bins caused by imperfect detector resolution and reconstruction techniques. The  $A$  and  $S$  matrices are constructed using simulated MC@NLO  $t\bar{t}$  events. The smearing in  $\cos\phi$ ,  $c_1c_2$ , and  $\cos\theta_{\ell^\pm}^*$  can

be large in some events because of the uncertainties in the reconstruction of the  $t\bar{t}$  kinematic quantities, but the smearing matrices are still predominantly diagonal. The smearing matrix for  $|\Delta\phi_{\ell^+\ell^-}|$  is nearly diagonal because of the excellent angular resolution of the lepton momentum measurements.

To determine the parton-level angular distribution in data, we employ a regularized unfolding algorithm implemented in the TUNFOLD package [56]. The effects of large statistical fluctuations in the algorithm are greatly reduced by introducing a term in the unfolding procedure that regularizes the output distribution based on the curvature of the simulated signal distribution. In general, unfolding introduces negative correlations between adjacent bins, while regularization introduces positive correlations, and the regularization strength is optimized by minimizing the average global correlation coefficient in the unfolded distribution. The regularization strength obtained here is relatively weak, contributing at the 10% level to the total  $\chi^2$  minimized by the algorithm.

After unfolding, each distribution is normalized to unit area to give the normalized differential cross section for each variable. We use an analogous unfolding procedure to measure the normalized double-differential cross section, using three bins of  $M_{t\bar{t}}$ ,  $|y_{t\bar{t}}|$ , and  $p_T^{t\bar{t}}$  for each variable. The full covariance matrix is used in the evaluation of the statistical uncertainty in the asymmetry measured from each distribution.

## 7 Systematic Uncertainties

The systematic uncertainties coming from the detector performance and the modeling of the signal and background processes are evaluated from the difference between the nominal measurement and that obtained by repeating the unfolding procedure using simulated events with the appropriate systematic variation.

The uncertainty from the jet energy scale (JES) corrections affects the  $t\bar{t}$  final-state reconstruction, as well as the event selection. It is estimated by varying the energies of jets within their uncertainties [57], and propagating this to the  $E_T^{\text{miss}}$  value. Similarly, the jet energy resolution is varied by 2-5%, depending on the  $\eta$  of the jet [57], and the electron energy scale is varied by  $\pm 0.6\%$  ( $\pm 1.5\%$ ) for barrel (endcap) electrons (the uncertainty in muon energies is negligible), as estimated from comparisons between measured and simulated Drell-Yan events [58].

The uncertainty in the background contribution is obtained by varying the normalization of each background component by the uncertainties described in Section 4.

Many of the signal modeling and simulation uncertainties are evaluated by using weights to vary the MC@NLO  $t\bar{t}$  sample: the simulated pileup multiplicity distribution is changed within its uncertainty; the correction factors between data and simulation for the  $b$  tagging [26], trigger, and lepton selection efficiencies

are shifted up and down by their uncertainties; and the PDFs are varied using the PDF4LHC procedure [59, 60]. Previous CMS studies [61, 62] have shown that the  $p_T$  distribution of the top quark measured from data is softer than that in the NLO simulation of  $t\bar{t}$  production. Since the origin of the discrepancy is not fully understood, the change in the measurement when reweighting the MC@NLO  $t\bar{t}$  sample to match the top quark  $p_T$  spectrum in data is taken as a systematic uncertainty associated with signal modeling.

The remaining signal modeling uncertainties are separately evaluated with dedicated  $t\bar{t}$  samples:  $\mu_R$  and  $\mu_F$  are varied together up and down by a factor of 2; the top quark mass is varied by  $\pm 1$  GeV, to be consistent with the uncertainty used in other CMS measurements with the  $\sqrt{s} = 8$  TeV data set (the effect on the total systematic uncertainty of using the reduced uncertainty from the recent CMS combined  $m_t$  measurement [1] would be negligible); and the  $S$  matrix is rederived from a  $t\bar{t}$  sample generated with POWHEG and PYTHIA, while the  $A$  matrix is unchanged, in order to estimate the difference in hadronization modeling between HERWIG and PYTHIA. To avoid underestimation of systematic uncertainties caused by statistical fluctuations, which can be significant in the estimates evaluated using dedicated  $t\bar{t}$  samples, for each source of uncertainty the maximum of the estimated systematic uncertainty and the statistical uncertainty in that estimate is taken as the final systematic uncertainty.

The uncertainty in the unfolding procedure is dominated by the statistical uncertainty arising from the finite number of events in the MC@NLO  $t\bar{t}$  sample. The uncertainty owing to the unfolding regularization is evaluated by using the reconstructed distribution of a variable in data to reweight the corresponding simulated signal distribution used to regularize the curvature of the unfolded distribution. Using this method, the regularization uncertainty is found to be negligible for all measurements.

The systematic uncertainties in the inclusive asymmetry variables obtained from the unfolded distributions are summarized in Table 4. The systematic uncertainties are evaluated for each bin of the unfolded distributions, from which the covariance matrix is constructed, assuming 100% correlation or anticorrelation between bins for each individual source of uncertainty. The total systematic uncertainty is calculated by adding in quadrature the listed uncertainties.

For  $A_{\Delta\phi}$ , the top quark  $p_T$  modeling uncertainty dominates; this arises from the dependence of the  $|\Delta\phi_{\ell^+\ell^-}|$  distribution shape on the top quark  $p_T$  (through the spin correlations and event kinematics); that, in turn, introduces a significant dependence of the acceptance correction on the top quark  $p_T$ . For  $A_P$ , the JES and hadronization systematic uncertainties are dominant. Both affect the reconstructed  $b$  quark jet energy, and can therefore bias the boost from the laboratory frame to the top quark center-of-mass frame, and thus the measurement of  $\cos\theta_{\ell^\pm}^*$ . For similar reasons, the same two uncertainties are large for  $A_{c_1c_2}$  and  $A_{\cos\phi}$ , which are also significantly affected by the top quark  $p_T$  modeling uncertainty through its effect on the spin correlations. For  $A_{CPV}$ , the similar systematic uncertainties in  $A_{P^+}$  and  $A_{P^-}$  largely cancel when  $A_{P^-}$  is

subtracted from  $A_{P^+}$ ; the remaining contributions to the systematic uncertainty are dominated by the statistical uncertainty in the simulation.

## 8 Results

### 8.1 Unfolded Distributions

The background-subtracted, unfolded, and normalized-to-unit-area angular distributions for the selected data events are shown in Fig. 3 [Figure 3: see original paper], along with the parton-level predictions obtained with the MC@NLO event generator and from calculations at NLO in the strong and weak gauge couplings for  $t\bar{t}$  production, with and without spin correlations [4, 63].

The measured asymmetries, obtained from the angular distributions unfolded to the parton level, are presented with their statistical and systematic uncertainties in Table 5, where they are compared to predictions from MC@NLO and the NLO calculations. Correlations between the contents of different bins, introduced by the unfolding process and from the systematic uncertainties, are accounted for in the calculation of the experimental uncertainties. The uncertainties in the NLO predictions come from varying  $\mu_R$  and  $\mu_F$  simultaneously up and down by a factor of 2. For  $A_{\cos\phi}$  and  $A_{c_1c_2}$ , these scale uncertainties are summed in quadrature with the difference between the NLO predictions from Ref. [4] when the ratio in the calculation is expanded in powers of the strong coupling constant and when the numerator and denominator are evaluated separately.

Using the relationships between the asymmetry variables and spin correlation coefficients given in Section 1, we find  $C_{\text{hel}} = 0.278 \pm 0.084$  and  $D = 0.205 \pm 0.031$ , where the uncertainties include the statistical and systematic components added in quadrature. Similarly, the CP-conserving and CP-violating components of the top quark polarization are found to be  $P = -0.022 \pm 0.058$  and  $P_{CPV} = 0.000 \pm 0.016$ , respectively. All measurements are consistent with the expectations of the SM.

The NLO predictions for  $|\Delta\phi_{\ell^+\ell^-}|$ ,  $\cos\phi$ , and  $c_1c_2$  with and without spin correlations in Table 5 are used to translate the measurements into determinations of  $f_{\text{SM}}$ , the strength of the spin correlations relative to the SM prediction, with  $f_{\text{SM}} = 1$  corresponding to the SM and  $f_{\text{SM}} = 0$  corresponding to uncorrelated events. The measurements of  $f_{\text{SM}}$  are shown in Table 6 and are derived under the assumption that the  $A$  matrix used for the unfolding is independent of spin correlations. This is found to give conservative estimates for the experimental uncertainties.

The dependence of each asymmetry on  $M_{t\bar{t}}$ ,  $|y_{t\bar{t}}|$ , and  $p_T^{t\bar{t}}$  is extracted from the measured normalized double-differential cross section, and the results are shown in Fig. 4 [Figure 4: see original paper]. The measurements are all consistent with the MC@NLO predictions, and with the SM NLO prediction for the  $M_{t\bar{t}}$  and  $|y_{t\bar{t}}|$  dependencies. No comparison is made with the NLO prediction for

the  $p_T^{t\bar{t}}$  distribution because the substantial effect of the parton shower on the  $p_T^{t\bar{t}}$  distribution means fixed-order NLO calculations are not a sufficiently good approximation of the data.

## 8.2 Limits on New Physics

Anomalous  $t\bar{t}g$  couplings can lead to a significant modification of the polarization and spin correlations in  $t\bar{t}$  events. A model-independent search can be performed using an effective model of chromo-magnetic and chromo-electric dipole moments (denoted CMDM and CEDM, respectively). This study follows the proposal in Ref. [4]. For an anomalous  $t\bar{t}g$  interaction arising from heavy-particle exchange characterized by a mass scale  $M \gg m_t$ , one can write an effective Lagrangian as:

$$\mathcal{L}_{\text{eff}} = -\hat{\mu}_t t\sigma^{\mu\nu}T^a G_{\mu\nu}^a - \hat{d}_t ti\sigma^{\mu\nu}\gamma_5 T^a G_{\mu\nu}^a$$

where  $\hat{\mu}_t$  and  $\hat{d}_t$  are the CMDM (CP-conserving) and CEDM (CP-violating) dipole moments,  $G_{\mu\nu}^a$  is the gluon field strength, and  $T^a$  are the QCD fundamental generators. It is usually preferred to define dimensionless parameters  $\hat{\mu}_t \equiv \tilde{\mu}_t g_s/2m_t$  and  $\hat{d}_t \equiv \tilde{d}_t g_s/2m_t$ , where  $g_s$  is the QCD coupling constant [4]. The parameters  $\hat{\mu}_t$  and  $\hat{d}_t$  correspond to the form factors in the timelike kinematic domain and are therefore complex quantities, here assumed to be constant. In general, both the real and imaginary parts of  $\hat{\mu}_t$  and  $\hat{d}_t$  can be determined, but the spin correlations and polarization measured in this paper are only sensitive to  $\text{Re}(\hat{\mu}_t)$  and  $\text{Im}(\hat{d}_t)$ , respectively [4].

We begin with the determination of  $\text{Re}(\hat{\mu}_t)$  using the measured normalized differential cross section  $(1/\sigma)(d\sigma/d|\Delta\phi_{\ell^+\ell^-}|)$ . In the presence of a small new physics (NP) contribution such that  $\text{Re}(\hat{\mu}_t) \ll 1$ , one can linearly expand the normalized differential cross section as [4]:

$$\frac{1}{\sigma} \frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|} = \left( \frac{1}{\sigma} \frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|} \right)_{\text{SM}} + \text{Re}(\hat{\mu}_t) \left( \frac{1}{\sigma} \frac{d\sigma}{d|\Delta\phi_{\ell^+\ell^-}|} \right)_{\text{NP}}$$

The predicted shapes of the SM and NP terms in Eq. (3) are shown in Fig. 5 [Figure 5: see original paper]. The NP term arises from interference with SM  $t\bar{t}$  production, and therefore gives both positive and negative contributions to the differential cross section.

To measure  $\text{Re}(\hat{\mu}_t)$ , the SM and NP contributions to Eq. (3) are parametrized by polynomial functions (shown in Fig. 5), which are then used in a template fit to the measured normalized differential cross section. We use the projection in  $|\Delta\phi_{\ell^+\ell^-}|$  of the measured normalized double-differential cross section in bins of  $M_{t\bar{t}}$  to minimize the systematic uncertainty from top quark  $p_T$  modeling, as for the extraction of  $f_{\text{SM}}$ . The measurement is made under the assumption that the  $A$  matrix is unchanged by the presence of NP. Studies of the effects

of our selection criteria at the parton level show that this leads to conservative estimates of the experimental uncertainties. The fit is performed using a  $\chi^2$  minimization, accounting for both statistical and systematic uncertainties and their correlations, with  $\text{Re}(\hat{\mu}_t)$  as the only free parameter. The systematic uncertainty arising from the choice of  $\mu_R$  and  $\mu_F$  in the theoretical calculations from Ref. [4] is estimated by repeating the fit after varying both scales together up and down by a factor of 2. This constitutes the dominant source of uncertainty. The proper behavior of the fit is verified using pseudoexperiments. The result of the fit is  $\text{Re}(\hat{\mu}_t) = -0.006 \pm 0.024$  and is shown graphically in Fig. 5. The corresponding 95% confidence level (CL) interval is  $-0.053 < \text{Re}(\hat{\mu}_t) < 0.042$ .

The spin correlation coefficient  $D$  is also sensitive to  $\text{Re}(\hat{\mu}_t)$ , and the CP-violating component of the top quark polarization  $P_{CPV}$  is sensitive to  $\text{Im}(\hat{d}_t)$ . Studies of the effects of our selection criteria at the parton level show that the presence of anomalous top quark chromo moments has no significant effect on the  $A$  matrix for either of these variables, and we use this assumption in the derivation of limits on  $\text{Re}(\hat{\mu}_t)$  and  $\text{Im}(\hat{d}_t)$ .

For the  $D$  coefficient, Eq. (3) simplifies to  $D = D_{\text{SM}} + \text{Re}(\hat{\mu}_t)D_{\text{NP}}$  [4]. Using the values from Table 5, the relationship  $D = -2A_{\cos\phi}$ , and taking  $D_{\text{NP}} = -1.712 \pm 0.019$  from Ref. [4], we find  $\text{Re}(\hat{\mu}_t) = -0.014 \pm 0.020$ , with the corresponding 95% CL interval  $-0.053 < \text{Re}(\hat{\mu}_t) < 0.026$ . The constraints on  $\text{Re}(\hat{\mu}_t)$  from  $D$  are stronger than those from the  $|\Delta\phi_{\ell^+\ell^-}|$  fit because the smaller theoretical uncertainty in the SM NLO calculation of  $D$  compared to that in the  $|\Delta\phi_{\ell^+\ell^-}|$  distribution outweighs the slightly larger experimental uncertainty.

Similarly,  $P_{CPV}$  is related to  $\text{Im}(\hat{d}_t)$  via  $P_{CPV} = \text{Im}(\hat{d}_t)P_{CPV}^{\text{NP}}$ , with  $P_{CPV}^{\text{NP}} = 0.482 \pm 0.003$  [4]. We find  $\text{Im}(\hat{d}_t) = -0.001 \pm 0.034$ , with the corresponding 95% CL interval  $-0.068 < \text{Im}(\hat{d}_t) < 0.067$ .

The  $|\Delta\phi_{\ell^+\ell^-}|$  distribution is potentially sensitive to pair-produced scalar top quark partners (top squarks) that decay to produce a top quark and antiquark with no additional visible particles. The spin-zero particles transmit no spin information from the initial state to the final-state top quarks, meaning such events look much like uncorrelated  $t\bar{t}$  events. We assess the sensitivity of the measured  $|\Delta\phi_{\ell^+\ell^-}|$  distribution to pair-produced top squarks with mass equal to  $m_t$ . As seen from the measurement of  $f_{\text{SM}}$  in the last row of Table 6, the dominant source of uncertainty is the theoretical scale uncertainty in the  $|\Delta\phi_{\ell^+\ell^-}|$  distribution. The result is that no exclusion limits on top squarks can be set using the  $|\Delta\phi_{\ell^+\ell^-}|$  normalized differential cross section alone, and the additional sensitivity it would bring in combination with the inclusive measurement of the cross section would be marginal.

## 9 Summary

Measurements of the  $t\bar{t}$  spin correlations and the top quark polarization have been presented in the  $t\bar{t}$  dilepton final states ( $e^+e^-$ ,  $e^\pm\mu^\mp$ , and  $\mu^+\mu^-$ ), using an-

gular distributions unfolded to the parton level and as a function of the  $t\bar{t}$ -system variables  $M_{t\bar{t}}$ ,  $|y_{t\bar{t}}|$ , and  $p_T^{t\bar{t}}$ . The data sample corresponds to an integrated luminosity of  $19.5 \text{ fb}^{-1}$  from  $pp$  collisions at  $\sqrt{s} = 8 \text{ TeV}$ , collected by the CMS experiment at the LHC.

For the spin correlation coefficients, we measure  $C_{\text{hel}} = 0.278 \pm 0.084$  and  $D = 0.205 \pm 0.031$ . The measurements sensitive to spin correlations are translated into determinations of  $f_{\text{SM}}$ , the strength of the spin correlations relative to the SM prediction. The most precise result comes from the measurement of  $A_{\Delta\phi} = 0.095 \pm 0.006 \text{ (stat)} \pm 0.007 \text{ (syst)}$ , yielding  $f_{\text{SM}} = 1.12^{+0.12}_{-0.15}$ .

The SM (CP-conserving) top quark polarization is measured to be  $P = -0.022 \pm 0.058$ , while the CP-violating component is found to be  $P_{\text{CPV}} = 0.000 \pm 0.016$ . All measurements are in agreement with the SM expectations, and help constrain theories of physics beyond the SM.

The measured top quark spin observables are compared to theoretical predictions in order to search for hypothetical top quark anomalous couplings. No evidence of new physics is observed, and exclusion limits on the real part of the chromo-magnetic dipole moment  $\text{Re}(\hat{\mu}_t)$  and the imaginary part of the chromo-electric dipole moment  $\text{Im}(\hat{d}_t)$  are evaluated. Values outside the intervals  $-0.053 < \text{Re}(\hat{\mu}_t) < 0.026$  and  $-0.068 < \text{Im}(\hat{d}_t) < 0.067$  are excluded at the 95% confidence level, the first such measurements to date.

## Acknowledgments

We would like to thank W. Bernreuther and Z.-G. Si for calculating the theoretical predictions for this paper, and for studies of the effect of anomalous top quark chromo moments on the acceptance of our selection criteria at the parton level. We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development

Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie programme and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the OPUS programme of the National Science Center (Poland); the Compagnia di San Paolo (Torino); MIUR project 20108T4XTM (Italy); the Thalís and Aristeia programmes cofinanced by EU-

ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University (Thailand); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

## References

- [1] CMS Collaboration, “Measurement of the top quark mass using proton-proton data at  $\sqrt{s} = 7$  and 8 TeV” , (2015). arXiv:1509.04044. Submitted to Phys. Rev. D.
- [2] D0 Collaboration, “Improved determination of the width of the top quark” , Phys. Rev. D 85 (2012) 091104, doi:10.1103/PhysRevD.85.091104, arXiv:1201.4156.
- [3] G. Mahlon and S. J. Parke, “Spin correlation effects in top quark pair production at the LHC”, Phys. Rev. D 81 (2010) 074024, doi:10.1103/PhysRevD.81.074024, arXiv:1001.3422.
- [4] W. Bernreuther and Z.-G. Si, “Top quark spin correlations and polarization at the LHC: standard model predictions and effects of anomalous top chromo moments” , Phys. Lett. B 725 (2013) 115, doi:10.1016/j.physletb.2013.06.051, arXiv:1305.2066. [Erratum: doi:10.1016/j.physletb.2015.03.035].
- [5] D. Krohn, T. Liu, J. Shelton, and L.-T. Wang, “A polarized view of the top asymmetry”, Phys. Rev. D 84 (2011) 074034, doi:10.1103/PhysRevD.84.074034, arXiv:1105.3743.
- [6] S. Fajfer, J. F. Kamenik, and B. Melic, “Discerning new physics in  $t\bar{t}$  production using top spin observables at hadron colliders” , JHEP 08 (2012) 114, doi:10.1007/JHEP08(2012)114, arXiv:1205.0264.
- [7] J. A. Aguilar-Saavedra and M. Perez-Victoria, “ $t\bar{t}$  charge asymmetry, family and friends” , J. Phys.: Conf. Ser. 447 (2013) 012015, doi:10.1088/1742-6596/447/1/012015, arXiv:1302.6618.
- [8] A. Brandenburg, Z.-G. Si, and P. Uwer, “QCD-corrected spin analysing power of jets in decays of polarized top quarks” , Phys. Lett. B 539 (2002) 235, doi:10.1016/S0370-2693(02)02098-1, arXiv:hep-ph/0205023.
- [9] CDF Collaboration, “Measurement of  $t\bar{t}$  spin correlation in  $p\bar{p}$  collisions using the CDF II detector at the Tevatron” , Phys. Rev. D 83 (2011) 031104, doi:10.1103/PhysRevD.83.031104, arXiv:1012.3093.
- [10] D0 Collaboration, “Evidence for spin correlation in  $t\bar{t}$  production” , Phys. Rev. Lett. 108 (2012) 032004, doi:10.1103/PhysRevLett.108.032004, arXiv:1110.4194.
- [11] D0 Collaboration, “Measurement of spin correlation in  $t\bar{t}$  production using a matrix element approach” , Phys. Rev. Lett. 107 (2011) 032001, doi:10.1103/PhysRevLett.107.032001, arXiv:1104.5194.
- [12] D0 Collaboration, “Measurement of leptonic asymmetries and top-quark polarization in  $t\bar{t}$  production” , Phys. Rev. D 87 (2013) 011103, doi:10.1103/PhysRevD.87.011103, arXiv:1207.0364.
- [13] ATLAS Collaboration, “Measurement of top quark polarization

- in top-antitop events from proton-proton collisions at  $\sqrt{s} = 7$  TeV using the ATLAS detector”, Phys. Rev. Lett. 111 (2013) 232002, doi:10.1103/PhysRevLett.111.232002, arXiv:1307.6511.
- [14] ATLAS Collaboration, “Measurement of spin correlation in top-antitop quark events and search for top squark pair production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV using the ATLAS detector”, Phys. Rev. Lett. 114 (2015) 142001, doi:10.1103/PhysRevLett.114.142001, arXiv:1412.4742.
- [15] CMS Collaboration, “Measurements of  $t\bar{t}$  spin correlations and top-quark polarization using dilepton final states in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, Phys. Rev. Lett. 112 (2014) 182001, doi:10.1103/PhysRevLett.112.182001, arXiv:1311.3924.
- [16] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST 3 (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [17] CMS Collaboration, “Particle-flow event reconstruction in CMS and performance for jets, taus, and  $E_T^{\text{miss}}$ ”, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, 2009.
- [18] CMS Collaboration, “Commissioning of the particle-flow event reconstruction with the first LHC collisions recorded in the CMS detector”, CMS Physics Analysis Summary CMS-PAS-PFT-10-001, 2010.
- [19] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at  $\sqrt{s} = 8$  TeV”, JINST 10 (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [20] CMS Collaboration, “Performance of CMS muon reconstruction in  $pp$  collision events at  $\sqrt{s} = 7$  TeV”, JINST 7 (2012) P10002, doi:10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
- [21] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, JINST 9 (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
- [22] CMS Collaboration, “Search for top-squark pair production in the single-lepton final state in  $pp$  collisions at  $\sqrt{s} = 8$  TeV”, Eur. Phys. J. C 73 (2013) 2677, doi:10.1140/epjc/s10052-013-2677-2, arXiv:1308.1586.
- [23] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- $k_T$  jet clustering algorithm”, JHEP 04 (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [24] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, Eur. Phys. J. C 72 (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [25] M. Cacciari and G. P. Salam, “Pileup subtraction using jet areas”, Phys. Lett. B 659 (2008) 119, doi:10.1016/j.physletb.2007.09.077, arXiv:0707.1378.
- [26] CMS Collaboration, “Identification of  $b$ -quark jets with the CMS experiment”, JINST 8 (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.
- [27] S. Frixione and B. R. Webber, “Matching NLO QCD computations and parton shower simulations”, JHEP 06 (2002) 029, doi:10.1088/1126-6708/2002/06/029, arXiv:hep-ph/0204244.
- [28] S. Frixione, P. Nason, and B. R. Webber, “Matching NLO QCD and parton showers in heavy flavor production”, JHEP 08 (2003) 007, doi:10.1088/1126-

- 6708/2003/08/007, arXiv:hep-ph/0305252.
- [29] J. Pumplin et al., “New generation of parton distributions with uncertainties from global QCD analysis” , JHEP 07 (2002) 012, doi:10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.
- [30] G. Corcella et al., “HERWIG 6: an event generator for hadron emission reactions with interfering gluons (including supersymmetric processes)” , JHEP 01 (2001) 010, doi:10.1088/1126-6708/2001/01/010, arXiv:hep-ph/0011363.
- [31] J. Alwall et al., “MADGRAPH 5: going beyond” , JHEP 06 (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.
- [32] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations” , JHEP 07 (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [33] J. M. Campbell and R. K. Ellis, “MCFM for the Tevatron and the LHC” , Nucl. Phys. Proc. Suppl. 205-206 (2010) 10, doi:10.1016/j.nuclphysbps.2010.08.011, arXiv:1007.3492.
- [34] J. M. Campbell, R. K. Ellis, and C. Williams, “Vector boson pair production at the LHC” , JHEP 07 (2011) 018, doi:10.1007/JHEP07(2011)018, arXiv:1105.0020.
- [35] R. Frederix et al., “Four-lepton production at hadron colliders: aMC@NLO predictions with theoretical uncertainties” , JHEP 02 (2012) 099, doi:10.1007/JHEP02(2012)099, arXiv:1110.4738.
- [36] J. M. Campbell and R. K. Ellis, “ $t\bar{t}W^\pm$  production and decay at NLO” , JHEP 07 (2012) 052, doi:10.1007/JHEP07(2012)052, arXiv:1204.5678.
- [37] M. V. Garzelli, A. Kardos, C. G. Papadopoulos, and Z. Trocsanyi, “ $t\bar{t}W^\pm$  and  $t\bar{t}Z$  hadroproduction at NLO accuracy in QCD with Parton Shower and Hadronization Effects” , JHEP 11 (2012) 056, doi:10.1007/JHEP11(2012)056, arXiv:1208.2665.
- [38] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, “W Physics at the LHC with FEWZ 2.1” , Comput. Phys. Commun. 184 (2013) 208, doi:10.1016/j.cpc.2012.09.005, arXiv:1201.5896.
- [39] P. Nason, “A new method for combining NLO QCD with shower Monte Carlo algorithms” , JHEP 11 (2004) 040, doi:10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
- [40] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method” , JHEP 11 (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [41] S. Alioli, P. Nason, C. Oleari, and E. Re, “NLO single-top production matched with shower in POWHEG: s- and t-channel contributions” , JHEP 09 (2009) 111, doi:10.1088/1126-6708/2009/09/111, arXiv:0907.4076. [Erratum: doi:10.1007/JHEP02(2010)011].
- [42] S. Alioli, P. Nason, C. Oleari, and E. Re, “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX” , JHEP 06 (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.
- [43] E. Re, “Single-top  $tW$ -channel production matched with parton showers using the POWHEG method” , Eur. Phys. J. C 71 (2011) 1547,

- doi:10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
- [44] N. Kidonakis, “Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production”, *Phys. Rev. D* 83 (2011) 091503, doi:10.1103/PhysRevD.83.091503, arXiv:1103.2792.
- [45] N. Kidonakis, “NNLL resummation for s-channel single top quark production”, *Phys. Rev. D* 81 (2010) 054028, doi:10.1103/PhysRevD.81.054028, arXiv:1001.5034.
- [46] N. Kidonakis, “Two-loop soft anomalous dimensions for single top quark associated production with a  $W^-$  or  $H^-$ ”, *Phys. Rev. D* 82 (2010) 054018, doi:10.1103/PhysRevD.82.054018, arXiv:1005.4451.
- [47] T. Sjöstrand, S. Mrenna, and P. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* 05 (2006) 026, doi:10.1088/1126-6708/2006/05/026, arXiv:0706.2334.
- [48] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [49] CMS Collaboration, “Observation of the associated production of a single top quark and a  $W$  boson in  $pp$  collisions at  $\sqrt{s} = 8$  TeV”, *Phys. Rev. Lett.* 112 (2014) 231802, doi:10.1103/PhysRevLett.112.231802, arXiv:1401.2942.
- [50] CMS Collaboration, “Measurement of the sum of  $WW$  and  $WZ$  production with  $W$ +dijet events in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, *Eur. Phys. J. C* 73 (2013) 2283, doi:10.1140/epjc/s10052-013-2283-3, arXiv:1210.7544.
- [51] CMS Collaboration, “Measurement of  $WZ$  and  $ZZ$  production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV in final states with  $b$ -tagged jets”, *Eur. Phys. J. C* 74 (2014) 2973, doi:10.1140/epjc/s10052-014-2973-5, arXiv:1403.3047.
- [52] CMS Collaboration, “Observation of top quark pairs produced in association with a vector boson in  $pp$  collisions at  $\sqrt{s} = 8$  TeV”, *JHEP* 01 (2016) 096, doi:10.1007/JHEP01(2016)096, arXiv:1510.01131.
- [53] CMS Collaboration, “Measurement of the  $t\bar{t}$  production cross section and the top quark mass in the dilepton channel in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, *JHEP* 07 (2011) 049, doi:10.1007/JHEP07(2011)049, arXiv:1105.5661.
- [54] R. H. Dalitz and G. R. Goldstein, “Analysis of top-antitop production and dilepton decay events and the top quark mass”, *Phys. Lett. B* 287 (1992) 225, doi:10.1016/0370-2693(92)91904-N.
- [55] B. A. Betchart, R. Demina, and A. Harel, “Analytic solutions for neutrino momenta in decay of top quarks”, *Nucl. Instrum. Meth. A* 736 (2014) 169, doi:10.1016/j.nima.2013.10.039, arXiv:1305.1878.
- [56] S. Schmitt, “TUnfold, an algorithm for correcting migration effects in high energy physics”, *JINST* 7 (2012) T10003, doi:10.1088/1748-0221/7/10/T10003, arXiv:1205.6201.
- [57] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* 6 (2011) P11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.
- [58] CMS Collaboration, “Energy calibration and resolution of the CMS electromagnetic calorimeter in  $pp$  collisions at  $\sqrt{s} = 7$  TeV”, *JINST* 8 (2013) P09009, doi:10.1088/1748-0221/8/09/P09009, arXiv:1306.2016.
- [59] S. Alekhin et al., “The PDF4LHC Working Group interim report”, (2011). arXiv:1101.0536.

- [60] M. Botje et al., “The PDF4LHC Working Group interim recommendations” , (2011). arXiv:1101.0538.
- [61] CMS Collaboration, “Measurement of differential top-quark pair production cross sections in  $pp$  collisions at  $\sqrt{s} = 7$  TeV” , Eur. Phys. J. C 73 (2013) 2339, doi:10.1140/epjc/s10052-013-2339-4, arXiv:1211.2220.
- [62] CMS Collaboration, “Measurement of the differential cross section for top quark pair production in  $pp$  collisions at  $\sqrt{s} = 8$  TeV” , Eur. Phys. J. C 75 (2015) 542, doi:10.1140/epjc/s10052-015-3709-x, arXiv:1505.04480.
- [63] W. Bernreuther and Z.-G. Si, “Distributions and correlations for top quark pair production and decay at the Tevatron and LHC” , Nucl. Phys. B 837 (2010) 90, doi:10.1016/j.nuclphysb.2010.05.001, arXiv:1003.3926.

## Appendix A: The CMS Collaboration

*The author list appears in the original document and is preserved in its entirety.*

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv – Machine translation. Verify with original.*