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Observation of Spin Correlation in $t\bar{t}$ Events from pp Collisions at $\sqrt{s} = 7$ TeV Using the ATLAS Detector

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A measurement of spin correlation in $t\bar{t}$ production is reported using data collected with the ATLAS detector at the LHC, corresponding to an integrated luminosity of 2.1 fb^{-1} . Candidate events are selected in the dilepton topology with large missing transverse energy and at least two jets. The difference in azimuthal angle between the two charged leptons in the laboratory frame is used to extract the correlation between the top and antitop quark spins. In the helicity basis the measured degree of correlation corresponds to $A_{\text{helicity}} = 0.40^{+0.09}_{-0.08}$, in agreement with the next-to-leading-order standard model prediction. The hypothesis of zero spin correlation is excluded at 5.1 standard deviations.

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The top quark was discovered in 1995 [1,2] at the Tevatron proton-antiproton collider. The lifetime of the top quark is at least an order of magnitude shorter than the time scale for strong interactions, implying that the top quark decays before hadronization [3–7]. Therefore the spin of the top quark at production is transferred to its decay products and can be measured directly via their angular distributions [4]. While the polarization of t and \bar{t} quarks in a hadronically produced $t\bar{t}$ sample is predicted to be very small, their spins are predicted to be correlated [8–10]. In this Letter the hypothesis that the correlation of the spin of top and antitop quarks in $t\bar{t}$ events is as expected in the standard model (SM), as opposed to the hypothesis that they are uncorrelated, is tested. This tests the precise predictions of $t\bar{t}$ pair production and of top quark decay, which is expected to occur before its spin is flipped by the strong interaction [9–13]. Many scenarios of new physics beyond the SM predict different spin correlations while keeping the $t\bar{t}$ production cross section within experimental and theoretical bounds [14–18]. For example, the spin correlation measured in this Letter may differ from the SM if the $t\bar{t}$ pairs were produced via the exchange of a virtual heavy scalar Higgs boson [19] or if the top quark decayed into a scalar charged Higgs boson and a b quark ($t \rightarrow H^+ b$) [20].

At the LHC $t\bar{t}$ production occurs mostly through the $gg \rightarrow t\bar{t}$ channel. At low $t\bar{t}$ invariant mass it is dominated by the fusion of like-helicity gluon pairs which produce top quarks in the left-left or right-right helicity configurations [13]. When these decay via $t\bar{t} \rightarrow W^+ W^- b\bar{b} \rightarrow l^+ \nu l^- \bar{\nu} b\bar{b}$ they produce charged leptons which possess correlations in

azimuthal angle, $\Delta\phi$ [21], in the laboratory frame [13]. In contrast, at the Tevatron production via $q\bar{q}$ annihilation dominates. The different production mechanisms and center-of-mass energies make a measurement of the spin correlation at both colliders complementary [22]. Both the CDF and D0 Collaborations have performed measurements of the spin correlation [23–25], with a recent analysis by the D0 Collaboration reporting evidence for the presence of spin correlation in $t\bar{t}$ events with a significance of 3.1 standard deviations [26].

The azimuthal angle between charged leptons is well measured by the ATLAS detector and does not require reconstruction of the top quarks. Figure 1 shows the distribution of charged lepton $\Delta\phi$ for generated events at parton level for $\sqrt{s} = 7$ TeV, using MC@NLO [27–29] with the CTEQ6.6 parton distribution function (PDF) [30] and a top quark mass of 172.5 GeV. It compares the

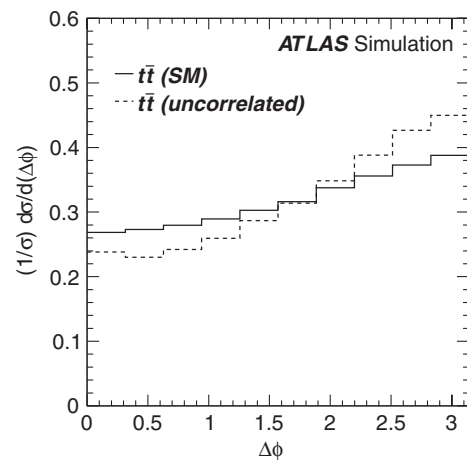


FIG. 1. Normalized reconstructed charged lepton $\Delta\phi$ distribution for generated events at parton level for $\sqrt{s} = 7$ TeV using MC@NLO. The two histograms show the SM and uncorrelated spin scenarios.

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SM prediction (solid line) to a scenario with no spin correlation between top and antitop quarks (dashed line).

The degree of correlation, A , is defined as the fractional difference between the number of events where the top and antitop quark spin orientations are aligned and those where the top quark spins have opposite alignment,

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}. \quad (1)$$

The arrows denote the spins of the top and antitop quarks with respect to a chosen quantization axis. This analysis uses a fit to templates constructed from simulated event samples to determine the amount of spin correlation from the $\Delta\phi$ distribution. The fit result is converted into a value of A in two bases: the helicity basis, using the direction of flight of the top quark in the center-of-mass frame of the $t\bar{t}$ system [31,32], and the maximal basis which is optimized for $t\bar{t}$ production from gg fusion, as described in Ref. [12]. In the helicity basis the SM correlation coefficient is calculated to be $A_{\text{helicity}}^{\text{SM}} = 0.31$ [8], and in the maximal basis $A_{\text{maximal}}^{\text{SM}} = 0.44$, evaluated at matrix-element level using MC@NLO. Theoretical uncertainties due to the variation of factorization and renormalization scales and due to PDFs are of the order of 1% including next-to-leading-order (NLO) QCD corrections in $t\bar{t}$ production and top quark decay [22].

The ATLAS detector [33] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector (ID) covering $|\eta| < 2.5$ and comprising a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, followed by a liquid argon electromagnetic sampling calorimeter (LAr) with high granularity. An iron-scintillator tile calorimeter provides hadronic energy measurements in the central rapidity region ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for both electromagnetic (EM) and hadronic energy measurements up to $|\eta| < 4.9$. The calorimeter system is surrounded by a muon spectrometer (MS) with high-precision tracking chambers covering $|\eta| < 2.7$ and separate trigger chambers. The magnetic field is provided by a barrel and two end-cap superconducting toroid magnets. A three-level trigger system is used to select events with high- p_T leptons for this analysis. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the trigger rate to 75 kHz. This is followed by two software-based trigger levels that together reduce the event rate to 200–400 Hz.

This analysis uses collision data with a center-of-mass energy of $\sqrt{s} = 7$ TeV recorded between 22 March and 22 August, 2011, corresponding to an integrated luminosity of 2.1 fb^{-1} . The luminosity is given with an uncertainty of 3.7% [34,35].

Monte Carlo (MC) simulation samples are used to evaluate the contributions, and shapes of distributions of kinematic variables, for signal $t\bar{t}$ events and background processes not evaluated from complementary data samples. All MC samples are processed with the GEANT4 [36] simulation of the ATLAS detector [37] and are passed through the same analysis chain as data. The simulation includes multiple pp interactions per bunch crossing (pileup). Events are weighted such that the distribution of the average number of interactions per bunch crossing matches that observed in data. The mean number of pileup interactions varies between 5.7 and 7.1 for the different data-taking periods.

Samples with SM spin correlation and without spin correlation are generated using MC@NLO with the CTEQ6.6 PDF set and a top quark mass of 172.5 GeV. In both cases the events are hadronized using the HERWIG shower model [38,39]. Within the statistical uncertainty of the MC generation the yields of the SM $t\bar{t}$ and uncorrelated $t\bar{t}$ samples are the same. The background MC samples are described in Ref. [40].

Candidate events are selected in the dilepton topology. Channels with τ leptons are not explicitly considered, but reconstructed leptons can arise from leptonic τ decays and are included in the signal MC samples. The full object and event selection is discussed in Ref. [40]; therefore only a brief overview is given here. The analysis requires events selected online by an inclusive single-lepton trigger (e or μ). The detailed trigger requirements vary throughout data taking, but the p_T threshold ensures that the triggered lepton candidate is in the efficiency plateau. Electron candidates are reconstructed using energy deposits in the EM calorimeter associated to reconstructed tracks of charged particles in the ID. Muon candidate reconstruction makes use of tracking in the MS and ID. Jets are reconstructed with the anti- k_r algorithm [41] with a radius parameter $R = 0.4$, starting from energy clusters of adjacent calorimeter cells. The symbol E_T^{miss} is used to denote the magnitude of the missing transverse momentum [42]. The following kinematic requirements are made:

(i) Electron candidates are required to have $p_T > 25$ GeV and $|\eta| < 2.47$, excluding electrons from the transition region between the barrel and end-cap calorimeters defined by $1.37 < |\eta| < 1.52$. Muon candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. Events must have exactly two oppositely-charged lepton candidates (e^+e^- , $\mu^+\mu^-$, $e^\pm\mu^\mp$).

(ii) Events must have at least two jets with $p_T > 25$ GeV and $|\eta| < 2.5$.

(iii) Events in the e^+e^- and $\mu^+\mu^-$ channels are required to have $m_{\ell\ell} > 15$ GeV to ensure compatibility with the MC samples and remove contributions from Υ and J/ψ production.

(iv) Events in the e^+e^- and $\mu^+\mu^-$ channels must satisfy $E_T^{\text{miss}} > 60$ GeV to suppress backgrounds from

$Z/\gamma^* + \text{jets}$ and $W + \text{jets}$ events. In addition, $m_{\ell\ell}$ must differ by at least 10 GeV from the Z -boson mass ($m_Z = 91$ GeV) to further suppress the $Z/\gamma^* + \text{jets}$ background.

(v) For the $e^\pm\mu^\mp$ channel, no E_T^{miss} or $m_{\ell\ell}$ cuts are applied. In this case, the remaining background from $Z/\gamma^*(\rightarrow\tau\tau) + \text{jets}$ production is further suppressed by requiring that the scalar sum of the p_T of all selected jets and leptons is greater than 130 GeV.

The event selection rejects $Z/\gamma^* + \text{jets}$ events with low invariant mass and those with invariant mass near the Z -boson mass. However, $Z/\gamma^* + \text{jets}$ events with an e^+e^- or $\mu^+\mu^-$ invariant mass outside of these regions can enter the signal sample when there is large E_T^{miss} , typically from mismeasurement. These events are difficult to properly model in simulations due to uncertainties on the non-Gaussian tails of the E_T^{miss} distribution, on the cross section for Z -boson production with multiple jets, and on the lepton energy resolution. The $Z/\gamma^* + \text{jets}$ background in dielectron and dimuon events is evaluated using a data-driven (DD) technique in which the MC simulation yield of $Z/\gamma^* + \text{jets}$ events is normalized to the data using a control region defined by a dilepton invariant mass within 10 GeV of the Z -boson mass [40].

The backgrounds from events with misidentified (fake) leptons, primarily from $W + \text{jets}$ events, are evaluated from data using a matrix method [43]. The matrix method makes use of the efficiency of real lepton identification and rate of lepton misidentification measured in several control regions, which are chosen to be enhanced in different sources of fake leptons [40]. Contributions from real leptons due to $W + \text{jets}$ events in the fake lepton control region are subtracted using MC simulation. Comparisons of data and MC simulation in control regions are used to tune the rates to the expected signal region composition. The fake lepton yield is then estimated by weighting each event in a sample containing one or two loosely identified leptons.

The contributions from other electroweak background processes with two real leptons, such as single top, $Z \rightarrow \tau\tau$, WW , ZZ , and WZ production are determined from MC simulations normalized to the theoretical predictions. The expected numbers of signal and background events are compared to data in Table I. The number of observed events in each channel is: 477 for the e^+e^- channel, 906 for the $\mu^+\mu^-$ channel, and 2930 for the $e^\pm\mu^\mp$ channel, which dominates the total yield due to the looser selection criteria.

A binned log-likelihood fit is used to extract the spin correlation from the $\Delta\phi$ distribution in data. The fit includes a linear superposition of the distribution from SM $t\bar{t}$ MC simulation with coefficient f^{SM} , and from the uncorrelated $t\bar{t}$ MC simulation with coefficient $(1 - f^{\text{SM}})$. The e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ channels are fitted simultaneously with a common value of f^{SM} , a $t\bar{t}$ normalization that is allowed to vary (per channel) and a fixed

TABLE I. Observed dilepton yield in data and the expected signal and background composition from MC and DD samples. Systematic uncertainties are included.

$Z/\gamma^*(\rightarrow e^+e^-/\mu^+\mu^-) + \text{jets}$ (MC + DD)	64^{+11}_{-16}
$Z/\gamma^*(\rightarrow\tau\tau) + \text{jets}$ (MC)	175 ± 29
Fake leptons (DD)	160^{+140}_{-70}
Single top (MC)	197 ± 21
Diboson (MC)	148 ± 20
Total (non- $t\bar{t}$)	740^{+150}_{-80}
$t\bar{t}$ (MC)	3530^{+280}_{-340}
Total expected	4270^{+320}_{-350}
Observed	4313

background normalization. The fitted $t\bar{t}$ normalizations are in agreement with the theoretical prediction of the production cross section [44]. Negative values of f^{SM} correspond to an anticorrelation of the top and antitop quark spins. A value of $f^{\text{SM}} = 0$ implies that the spins are uncorrelated and values of $f^{\text{SM}} > 1$ indicate a larger strength of the $t\bar{t}$ spin correlation than predicted by the SM. The extraction of f^{SM} using the fitting procedure has been verified over a wide range of possible values, $-1 \leq f^{\text{SM}} \leq 2$, using MC simulation pseudoexperiments with full detector simulation.

Figure 2 shows the reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels in data. SM and uncorrelated $t\bar{t}$ MC samples are overlaid along with the expected backgrounds.

Systematic uncertainties are evaluated by applying the fit procedure to pseudoexperiments created from MC samples modified to reflect the systematic variations. The fit of f^{SM} is repeated to determine the effect of each

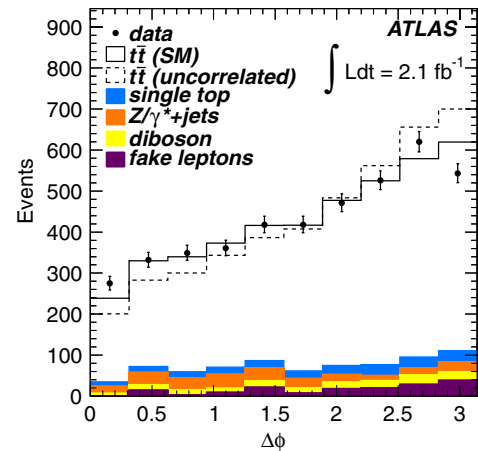


FIG. 2 (color online). Reconstructed charged lepton $\Delta\phi$ distribution for the sum of the three dilepton channels. The integrated number of events for both the SM and the uncorrelated $t\bar{t}$ samples is fixed to the value from the fit. MC background samples are normalized using their predicted cross sections and the DD method in the case of $Z/\gamma^* + \text{jets}$. The fake lepton background is evaluated from data.

systematic uncertainty using the nominal templates. The difference between the means of Gaussian fits to the results from many pseudoexperiments using nominal and modified pseudodata is taken as the systematic uncertainty on f^{SM} .

The effect of the luminosity uncertainty is evaluated by scaling the number of signal and background events by the luminosity uncertainty, for backgrounds evaluated from MC simulation. Because of the finite size of the MC samples, the signal and background templates have statistical uncertainties. Each template bin is varied within its uncertainty, then f^{SM} is reevaluated. The resulting distribution for f^{SM} is fitted with a Gaussian. The width is taken as the MC simulation statistical uncertainty.

The mismodeling of the muon (electron) trigger, reconstruction, and selection efficiencies in the simulation is corrected using scale factors derived from measurements of the efficiency in data. $Z \rightarrow \mu^+ \mu^-$ ($Z \rightarrow e^+ e^-$) decays are used to obtain scale factors as a function of the kinematic variables of the leptons. Systematic uncertainties on these scale factors are evaluated by varying the selection of events used in the efficiency measurements and by checking the stability of the measurements over the course of the data-taking period. The modeling of the lepton momentum scale and resolution is studied using the reconstructed dilepton invariant mass distributions of Z/γ^* candidate events and the simulation is adjusted accordingly.

The jet energy scale, jet energy resolution, and reconstruction efficiency affect the acceptance. The jet energy scale and its uncertainty are derived by combining information from test-beam data, LHC collision data and simulation [45]. For jets within the acceptance, the jet energy scale varies in the range 4%–10% as a function of jet p_T and η , including an additional uncertainty due to multiple pp interactions. The energy resolution for jets is measured in dijet events and agrees with predictions from simulation within 10% for jets with $p_T > 30$ GeV. The jet reconstruction efficiency is evaluated using minimum bias and dijet events and depends on the p_T of the jet. Its systematic uncertainty is in the range 1%–3% based on the comparison of data and MC simulation. The uncertainties from the energy scale and resolution corrections for leptons and jets are propagated into the calculation of E_T^{miss} .

The uncertainty on the kinematic properties of the $t\bar{t}$ signal events gives rise to systematic uncertainties on the shape of the $\Delta\phi$ distribution and signal acceptance. This is evaluated by considering the choice of generator, the parton shower and fragmentation model, the modeling of initial and final state radiation (ISR/FSR), the PDF and top quark mass. The generator uncertainty is evaluated by comparing the MC@NLO predictions with those of POWHEG [46–48] interfaced to HERWIG. To estimate the uncertainty due to the parton shower modeling and fragmentation, the difference between POWHEG interfaced to HERWIG (cluster

fragmentation) and PYTHIA [49] (string fragmentation) is taken. The uncertainty due to ISR/FSR is evaluated using the ACERMC generator [50] interfaced to the PYTHIA shower model, by varying the parameters controlling ISR and FSR in a range consistent with those used in the Perugia Hard/Soft tune variations [51]. The average of the absolute values of the upward and downward variations is taken as the systematic uncertainty. The impact of the choice of PDF in simulation was studied by reweighting the MC samples to three PDF sets (CTEQ6.6, MSTW2008NLO [52], and NNPDF20 [53]) and taking the largest of either the variation interval (from the error sets) or difference between the central values of any two PDF sets [32]. The systematic uncertainty associated with the top quark mass is assessed using MC@NLO samples generated assuming different top quark masses in the range 167.5 to 177.5 GeV in increments of 2.5 GeV. The values of f^{SM} are fitted as a linear function of the top quark mass and a conservative systematic uncertainty is obtained by evaluating this function at 172.5 ± 2.5 GeV.

Overall normalization uncertainties on the backgrounds from single top quark and diboson production are taken to be 10% [54,55] and 5% [56], respectively. The resulting uncertainty on f^{SM} is found to be negligible. The systematic uncertainties from the background evaluations derived from the data include the statistical uncertainties in these methods as well as the systematic uncertainties arising from lepton and jet identification and reconstruction, and the MC simulation estimates used. An uncertainty on the DD $Z/\gamma^* + \text{jets}$ estimation is evaluated by varying the E_T^{miss} cut in the control region by ± 5 GeV and is found to be negligible. A mismodeling of the Z-boson p_T is observed in the Z-boson dominated control region. The Z-boson p_T distribution is weighted to achieve agreement with data and the difference between the unweighted and weighted MC simulation is taken as an additional, but negligible, modeling uncertainty on f^{SM} . For the DD fake lepton background the systematic uncertainty affects the shape of the $\Delta\phi$ distribution. Systematic uncertainties are derived by adjusting the signal region composition based on uncertainties estimated from MC simulation, and by comparing data and MC samples. The different sources of fake leptons have different shapes and the change in relative flavor composition of the sample gives an estimate of the shape uncertainty.

Because of a hardware failure a small rectangular region of the LAr calorimeter could not be read out in a subset of the data (0.87 fb^{-1}). This affects the electron, jet, and E_T^{miss} reconstruction. Electrons within the affected region are rejected, as are events in which a jet with $p_T > 20$ GeV is in the affected region. The MC simulation is divided into subsamples based on the fraction of the total luminosity affected and treated in the same way as data. A systematic uncertainty is evaluated by comparing MC simulation with and without the jet and electron rejection.

TABLE II. Summary of the effect of statistical and systematic uncertainties on the measured value of f^{SM} for the combined fit.

Uncertainty source	Δf^{SM}
Data statistics	± 0.14
MC simulation template statistics	± 0.09
Luminosity	± 0.01
Lepton	± 0.01
Jet energy scale, resolution and efficiency	± 0.12
NLO generator	± 0.08
Parton shower and fragmentation	± 0.08
ISR/FSR	± 0.07
PDF uncertainty	± 0.07
Top quark mass	± 0.01
Fake leptons	$+0.16/ - 0.07$
Calorimeter readout	± 0.01
All systematics	$+0.27/ - 0.22$
Statistical + systematic	$+0.30/ - 0.26$

The effect of the systematic uncertainties in terms of Δf^{SM} are listed in Table II. The total systematic uncertainty is calculated by combining all systematic uncertainties in quadrature.

The measured value of f^{SM} for the combined fit is found to be $1.30 \pm 0.14(\text{stat})^{+0.27}_{-0.22}(\text{syst})$. This can be used to obtain a value for $A_{\text{basis}}^{\text{measured}}$ by applying it as a multiplicative factor to the NLO QCD prediction of A_{basis} using $A_{\text{basis}}^{\text{measured}} = A_{\text{basis}}^{\text{SM}} \cdot f^{\text{SM}}$, where the subscript ‘‘basis’’ indicates a chosen spin basis [11]. For the helicity basis this results in $A_{\text{helicity}} = 0.40 \pm 0.04(\text{stat})^{+0.08}_{-0.07}(\text{syst})$, and for the maximal basis $A_{\text{maximal}} = 0.57 \pm 0.06(\text{stat})^{+0.12}_{-0.10}(\text{syst})$, where the SM predictions are 0.31 and 0.44, respectively. MC simulation pseudoexperiments including systematic uncertainties are used to calculate the probability that a value of f^{SM} or larger is measured using the assumption of $f^{\text{SM}} = 0$. For the observed limit the value of f^{SM} measured in data is used and for the expected limit a value of $f^{\text{SM}} = 1$ is used. The hypothesis of zero $t\bar{t}$ spin correlation is excluded with a significance of 5.1 standard deviations. The expected significance is 4.2 standard deviations.

In conclusion, the first measurement of $t\bar{t}$ spin correlation at the LHC has been presented using 2.1 fb^{-1} of ATLAS data in the dilepton decay topology. A template fit is performed to the $\Delta\phi$ distribution and the measured value of $f^{\text{SM}} = 1.30 \pm 0.14(\text{stat})^{+0.27}_{-0.22}(\text{syst})$ is consistent with the SM prediction. The data are inconsistent with the hypothesis of zero spin correlation with a significance of 5.1 standard deviations.

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