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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

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A measurement of spin correlation in $t\bar{t}$ production is presented using data collected with the ATLAS detector at the Large Hadron Collider in proton-proton collisions at a center-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 20.3 fb^{-1}. The correlation between the top and antitop quark spins is extracted from dilepton $t\bar{t}$ events by using the difference in the azimuthal angle between the two charged leptons in the laboratory frame. In the helicity basis the measured degree of correlation corresponds to $A_{\mathrm{helicity}} = 0.38 \pm 0.04$, in agreement with the standard model prediction. A search is performed for pair production of top squarks with masses close to the top quark mass decaying to predominantly right-handed top quarks and a light neutralino, the lightest supersymmetric particle. Top squarks with masses between the top quark mass and 191 GeV are excluded at the 95% confidence level.

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Detailed studies of the correlation of the spin of top and antitop quarks in $t\bar{t}$ events produced at hadron colliders are of great interest; they provide important precision tests of the predictions of the standard model (SM) and are sensitive to many new physics scenarios [1–16]. The orientations of the top and antitop quark spins are transferred to the decay products and can be measured directly via their angular distributions [3,17,17–36]. The strength of their correlation has been studied previously by the CDF and D0 collaborations in proton-antiproton scattering at 1.98 TeV [37–40] and by the ATLAS and CMS collaborations in proton-proton scattering at 7 TeV [41–43].

In this Letter the first measurement of $t\bar{t}$ spin correlation in proton-proton collisions at a center-of-mass energy of 8 TeV is presented. Because the polarization-analyzing power of the angular distributions of charged leptons from top and antitop quark decays is effectively 100% [44,45], dilepton final states of ee, $\mu\mu$, and $e\mu$ are analyzed. An observable very sensitive to $t\bar{t}$ spin correlation is the azimuthal angle $\Delta\phi$ between the charged leptons [34], which is also well measured by the ATLAS detector.

First, the measurement of $\Delta\phi$ is used to extract the spin correlation strength $A_{\mathrm{helicity}} = (N_{\mathrm{like}} - N_{\mathrm{unlike}}/N_{\mathrm{like}} + N_{\mathrm{unlike}})$, where N_{like} (N_{unlike}) is the number of events where the top quark and top antiquark spins are parallel (antiparallel) with respect to the spin quantization axis. This axis is chosen to be that of the helicity basis, using the direction of flight of the top quark in the center-of-mass frame of the $t\bar{t}$ system. Second, to study a specific model that predicts zero spin correlation, a search for supersymmetric (SUSY) top squark pair production is performed.

At the Large Hadron Collider (LHC), the SUSY partners of the top quark, the top squarks, could be produced in pairs. Models with light top squarks are particularly attractive since they provide a solution to the hierarchy problem [46–49]. In such models, the mass $m_{\tilde{t}_1}$ of the lighter top squark mass eigenstate $\tilde{t}_1$ could be close to the mass of the top quark m_t [50,51]. If the lightest SUSY particle, the neutralino $\tilde{\chi}_1^0$ (or alternatively the gravitino), is light and the top squark mass is only slightly larger than the top quark mass, two-body decays $\tilde{t}_1 \to t\tilde{\chi}_1^0$ in which the momentum of $\tilde{\chi}_1^0$ is very small can predominate [16]. The masses of all other SUSY particles are assumed to be large. In SUSY models where R parity is conserved, such as the minimal supersymmetric standard model (MSSM) [52–56], this could lead to $t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0$ intermediate states, appearing like SM $t\bar{t}$ production with additional missing transverse momentum carried away by the escaping neutralinos, making traditional searches exploiting kinematic differences as presented in Refs. [57–63] very difficult. $\tilde{t}_1\bar{\tilde{t}}_1$ events can be distinguished from SM $t\bar{t}$ events through an increase of the measured $t\bar{t}$ cross section as analyzed in Ref. [64], and since top squarks have zero spin, through measuring angular correlations sensitive to spin correlation, as analyzed in this Letter.

A description of the ATLAS detector can be found elsewhere [65]. This analysis uses proton-proton collision data with a center-of-mass energy of $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.3 fb^{-1}.

Monte Carlo (MC) simulation samples are used to evaluate the contributions, and shapes of distributions of

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kinematic variables, for signal $t\bar{t}$ events and for background processes not evaluated from complementary data samples. All MC samples are processed with the GEANT4 [66] simulation of the ATLAS detector [67] and are passed through the same analysis chain as data. The simulation includes multiple proton-proton 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.

Samples of $t\bar{t}$ events with SM spin correlation and without spin correlation are generated using MC@NLO v4.06 [68,69] interfaced to HERWIG v6.520 [70] for shower simulation and hadronization. Both samples are normalized to the NNLO cross section including next-to-next-to-leading-logarithm corrections [71,72]. The CT10 parton distribution function (PDF) set [73] is used. For the sample with no spin correlation, the parton shower simulation performs isotropic decays of the top quarks whereas the full matrix element is used for the generation of the SM spin-correlation sample. The top quark mass is set to 172.5 GeV [74]. The production of a $t\bar{t}$ pair in association with a Z or W boson is simulated using MADGRAPH 5 [75] interfaced to PYTHIA v6.426 [76] and is normalized to the next-to-leading-order (NLO) quantum chromodynamics (QCD) cross sections [77].

Backgrounds to $t\bar{t}$ events with same-flavor dilepton final states arise from the Drell-Yan $Z/\gamma^* +$ jets production process with the Z/γ^* boson decaying into e^+e^-, $\mu^+\mu^-$ and $\tau^+\tau^-$, followed by leptonic decays of the τ leptons. They are generated using the ALPGEN v2.13 [77] generator including leading-order (LO) matrix elements with up to five additional partons. The CTEQ6L1 PDF set [78] is used, and the cross section is normalized to the next-to-next-to-leading-order (NNLO) QCD prediction [79]. Parton showering and fragmentation are modeled by HERWIG, and multiparton interactions are simulated by JIMMY [80]. The "MLM" parton-jet matching scheme [81] is employed. Correction factors are derived from data in $Z/\gamma^* +$ jets-dominated control regions and applied to the predicted yields in the signal region, to account for the difference between the simulation prediction and data.

Single top quark background from associated Wt production is modeled with POWHEG-BOX r2129 [82–85] interfaced with PYTHIA using the CT10 PDF set [73] and normalized to the approximate NNLO QCD theoretical cross section [86]. Single-top Zt and WZt production is generated by MADGRAPH 5 interfaced with PYTHIA.

The diboson (WW, WZ, ZZ) backgrounds are modeled using SHERPA v1.4.1 [87] and are normalized to the theoretical calculation at NLO QCD [88].

The background arising from the misidentified and non-prompt leptons (collectively referred to as "fake leptons") is determined from a combination of MC simulation of $W +$ jets events using SHERPA, single-top events via t-channel exchange using MC@NLO + HERWIG, $t\bar{t}$ events with single-lepton final states using MC@NLO + HERWIG, and data using a technique known as the matrix method [89,90].

Top squark pair-production samples are simulated using the HERWIG + + v2.6.1 [91] generator with the CTEQ6L1 PDFs [78]. The top squarks are assumed to decay exclusively via $\tilde{t}_1 \to t\tilde{\chi}_1^0$. The corresponding mixing matrices for the top squarks and for the neutralinos are chosen such that the top quark has a right-handed polarization in 95% of the decays.

Candidate events are selected in the dilepton topology. The analysis requires events selected on-line by inclusive single-lepton triggers (e or μ). Electron candidates are reconstructed from an isolated electromagnetic calorimeter energy deposit matched to a charged-particle track in the inner detector and must pass "medium identification requirements" [92]. Muon candidates were reconstructed by combining tracks reconstructed in both the inner detector and muon spectrometer [93]. Jets are reconstructed from clusters of adjacent calorimeter cells [65,94] using the anti-k_t algorithm [95–97] with a radius parameter $R = 0.4$. Jets originating from b quarks were identified ("tagged") using a multivariate discriminant employing the long lifetime, high decay multiplicity, hard fragmentation, and high mass of B hadrons [98,99]. The missing transverse momentum (E_T^{miss}) is reconstructed as the magnitude of a vector sum of all calorimeter cell energies associated with topological clusters [100]. The following kinematic requirements are made:

(i) Electron candidates are required to have transverse momemtum of $p_T > 25$ GeV and pseudorapidity of $|\eta| < 2.47$, excluding electrons from the transition region between the barrel and end-cap calorimeters defined by $1.37 < |\eta| < 1.52$. (The pseudorapidity η is defined via the polar angle θ as $\eta = -\ln\tan(\theta/2)$ [65].) Muon candidates are required to have $p_T > 25$ 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 (after having removed the jet closest to the electron, if there are jets within a cone of $\Delta R = 0.2$ around a selected electron) with $p_T > 25$ GeV and $|\eta| < 2.5$. At least one jet must be identified as a b jet using a requirement in the multivariate discriminant corresponding to a 70% b-tagging efficiency.

(iii) Events in the e^+e^- and $\mu^+\mu^-$ channels must satisfy $E_T^{\mathrm{miss}} > 30$ GeV to suppress backgrounds from Drell–Yan $Z/\gamma^* +$ jets and $W +$ jets events.

(iv) Events in the e^+e^- and $\mu^+\mu^-$ channels are required to have $m_{\ell\ell} > 15$ GeV (where ℓ indicates e or μ) to ensure compatibility with the simulated backgrounds and to remove contributions from Υ and J/ψ production. 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 $Z/\gamma^* +$ jets background.

(v) For the $e^\pm\mu^\mp$ channel, no $E_T{}^{\mathrm{miss}}$ or $m_{\ell\ell}$ requirements are applied. In this case, the remaining background from $Z/\gamma^*(\to \tau\tau) +$ jets production is further suppressed by

TABLE I. Observed dilepton yield in data and the expected SUSY and $t\bar{t}$ signals and background contributions. Systematic uncertainties due to theoretical cross sections and systematic uncertainties evaluated for data-driven backgrounds are included in the uncertainties.

Process	Yield
$t\bar{t}$	54000^{+3400}_{-3600}
$Z/\gamma^* + \text{jets}$	2800 ± 300
tV (single top)	2600 ± 180
$t\bar{t}V$	80 ± 11
WW, WZ, ZZ	180 ± 65
Fake leptons	780 ± 780
Total non-$t\bar{t}$	6400 ± 860
Expected	60000^{+3500}_{-3700}
Observed	60424
$\tilde{t}_1\bar{\tilde{t}}_1$ ($m_{\tilde{t}_1} = 180$ GeV, $m_{\tilde{\chi}^0_1} = 1$ GeV)	7100 ± 1100

requiring that the scalar sum of the p_T of all selected jets and leptons is greater than 130 GeV.

The expected numbers of $t\bar{t}$ signal and background events are compared to data in Table I. The expected yield for top squark pair production with a top squark mass of 180 GeV and a neutralino mass of 1 GeV is also shown.

Figure 1 shows the reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels. A binned log-likelihood fit is used to extract the spin correlation from the $\Delta\phi$ distribution in data. This is done by defining a coefficient f_{SM} that measures the degree of spin correlation relative to the SM prediction. The fit includes a linear superposition of the $\Delta\phi$ distribution from the SM $t\bar{t}$ MC simulation with coefficient f_{SM}, and from the $t\bar{t}$ simulation without spin correlation 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}, leaving the $t\bar{t}$ normalization free with a fixed background normalization. The $t\bar{t}$ normalization obtained by the fit agrees with the theoretical prediction of the production cross section [71] within the uncertainties. 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 degree of $t\bar{t}$ spin correlation larger than predicted by the SM.

Systematic uncertainties are evaluated by applying the fit procedure to pseudoexperiments created from simulated samples modified to reflect the systematic variations. The fit of f_{SM} is repeated to determine the effect of each 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} [102].

The various systematic uncertainties are estimated in the same way as in Ref. [42] with the following exceptions:

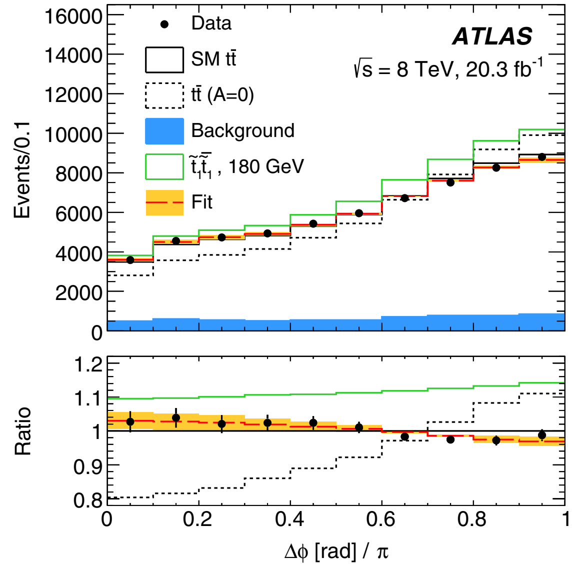

FIG. 1 (color online). Reconstructed $\Delta\phi$ distribution for the sum of the three dilepton channels. The prediction for background (blue histogram) plus SM $t\bar{t}$ production (solid black histogram) and background plus $t\bar{t}$ prediction with no spin correlation (dashed black histogram) is compared to the data and to the result of the fit to the data (red dashed histogram) with the orange band representing the total systematic uncertainty on f_{SM}. Both the SM $t\bar{t}$ and the no spin correlation $t\bar{t}$ predictions are normalized to the NNLO cross section including next-to-next-to-leading-logarithm corrections [71,72] (the theory uncertainty of 7% on this cross section is not displayed). The prediction for $\tilde{t}_1\bar{\tilde{t}}_1$ production ($m_{\tilde{t}_1} = 180$ GeV and $m_{\tilde{\chi}^0_1} = 1$ GeV) normalized to the NLO cross section including next-to-leading-logarithm corrections [101] plus SM $t\bar{t}$ production plus background is also shown (solid green histogram). The lower plot shows those distributions (except for background only) divided by the SM $t\bar{t}$ plus background prediction.

since this analysis employs b tagging, the associated uncertainty is estimated by varying the relative normalizations of simulated b-jet, c-jet, and light-jet samples. The uncertainty due the choice of generator is determined by comparing the default to an alternative $t\bar{t}$ sample generated with the POWHEG-BOX generator interfaced with PYTHIA. The uncertainty due to the parton shower and hadronization model is determined by comparing two $t\bar{t}$ samples generated by ALPGEN, one interfaced with PYTHIA and the other one interfaced with HERWIG. The uncertainty on the amount of initial- and final-state radiation (ISR and FSR) in the simulated $t\bar{t}$ sample is assessed by comparing ALPGEN events, showered with PYTHIA, with varied amounts of ISR and FSR. As in Ref. [42], the size of the variation is compatible with the recent measurements of additional jet activity in $t\bar{t}$ events [103]. The Wt normalization is varied within the theoretical uncertainties of the cross-section calculation [86], and the sensitivity to the interference between Wt production and $t\bar{t}$ production at NLO is studied by comparing the predictions of POWHEG-BOX with the diagram-removal (baseline) and diagram-subtraction schemes [85,104]. As in Ref. [42], the uncertainty due to the top quark mass is evaluated but not included in the systematic uncertainties, since it would have no significant impact on the results.

The sizes of the systematic uncertainties in terms of $\Delta f_{\rm SM}$ are listed in Table II. The total systematic uncertainty is calculated by combining all systematic uncertainties in quadrature.

The measured value of $f_{\rm SM}$ for the combined fit is $1.20 \pm 0.05(\text{stat}) \pm 0.13(\text{syst})$. This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [41,42], and compares to the best previous measurement using $\Delta\phi$ of $f_{\rm SM} = 1.19 \pm 0.09(\text{stat}) \pm 0.18(\text{syst})$ [42]. It also agrees with the SM prediction to within 2 standard deviations.

This agrees with previous results from ATLAS using data at a center-of-mass energy of 7 TeV [41,42] and agrees with the SM prediction to within 2 standard deviations. An indirect extraction of $A_{\rm helicity}$ can be achieved by assuming that the $t\bar{t}$ sample is composed of top quark pairs as predicted by the SM, but with varying spin correlation. In that case, a change in the fraction $f_{\rm SM}$ leads to a linear change of $A_{\rm helicity}$ (see also Ref. [42]), and a value of the spin correlation strength in the helicity basis $A_{\rm helicity}$ at a center-of-mass energy of 8 TeV is obtained by applying the measured value of $f_{\rm SM}$ as a multiplicative factor to the SM prediction of $A_{\rm helicity}^{\rm SM} = 0.318 \pm 0.005$ [36]. This yields a measured value of $A_{\rm helicity} = 0.38 \pm 0.04$.

TABLE II. Summary of systematic uncertainties on $f_{\rm SM}$ in the combined dilepton final state.

Source of uncertainty	$\Delta f_{\rm SM}$
Detector modeling	
Lepton reconstruction	±0.01
Jet energy scale	±0.02
Jet reconstruction	±0.01
$E_T^{\rm miss}$	< 0.01
Fake leptons	< 0.01
b tagging	< 0.01
Signal and background modeling	
Renormalization and factorization scale	±0.05
MC generator	±0.03
Parton shower and fragmentation	±0.06
ISR and FSR	±0.06
Underlying event	±0.04
Color reconnection	±0.01
PDF uncertainty	±0.05
Background	±0.01
MC statistics	±0.04
Total systematic uncertainty	±0.13
Data statistics	±0.05

The measurement of the variable $\Delta\phi$ is also used to search for top squark pair production with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ decays. The present analysis is sensitive both to changes in the yield and to changes in the shape of the $\Delta\phi$ distribution caused by a potential admixture of $\tilde{t}_1\bar{\tilde{t}}_1$ with the SM $t\bar{t}$ sample. An example is shown in Fig. 1, where the effect of $\tilde{t}_1\bar{\tilde{t}}_1$ production in addition to SM $t\bar{t}$ production and backgrounds is compared to data. No evidence for $\tilde{t}_1\bar{\tilde{t}}_1$ production was found.

Limits are set on the top squark pair-production cross section by fitting each bin of the $\Delta\phi$ distribution to the difference between the data and the SM prediction, varying the top squark signal strength μ. In contrast to the measurement of $f_{\rm SM}$ where the $t\bar{t}$ cross section is varied in the fit, here the $t\bar{t}$ cross section is fixed to its SM value [71]. In addition, a systematic uncertainty of 7% is introduced, composed of factorization and renormalization scale variation, top quark mass uncertainty, PDF uncertainty, and uncertainty in the measurement of the beam energy. All other sources of systematic uncertainty are identical to ones in the measurement of $f_{\rm SM}$. All shape-dependent modeling uncertainties on the SUSY signal are found to be negligible. The limits are determined using a profile likelihood ratio in the asymptotic limit [105], using nuisance parameters to account for the theoretical and experimental uncertainties.

The observed and expected limits on the top squark pair-production cross section at the 95% confidence level (C.L.) are extracted using the CL_s prescription [106] and are shown in Fig. 2. Adopting the convention of reducing the estimated SUSY production cross section by 1 standard deviation of its theoretical uncertainty (15%, coming from PDFs and QCD scale uncertainties [107]), top squark masses between the top quark mass and 191 GeV are excluded, assuming a 100% branching ratio for $\tilde{t}_1 \to t\tilde{\chi}_1^0$ and $m_{\tilde{\chi}_1^0} = 1$ GeV. The expected limit is 178 GeV. In the presented range of $m_{\tilde{t}_1}$, within the allowed phase space, varying the neutralino mass does not affect the cross-section limits by more than a few percent. If the top quarks are produced with full left-handed polarization, the expected limits change by less than 10% compared to the predominantly right-handed case.

If the $t\bar{t}$ cross-section normalization were arbitrary and not fixed to its theory prediction, the expected cross-section limit would increase by approximately 30%. If, on the other hand, the shape information of $\Delta\phi$ were not used in the fit, the expected cross-section limit would increase by 30%–40%.

The constraints on the top squark mass presented here improve previous limits in a region not explored before, to top squark masses larger than limits from Ref. [64] and to top squark masses lower than limits from analyses exploring kinematic distributions as presented in Ref. [61].

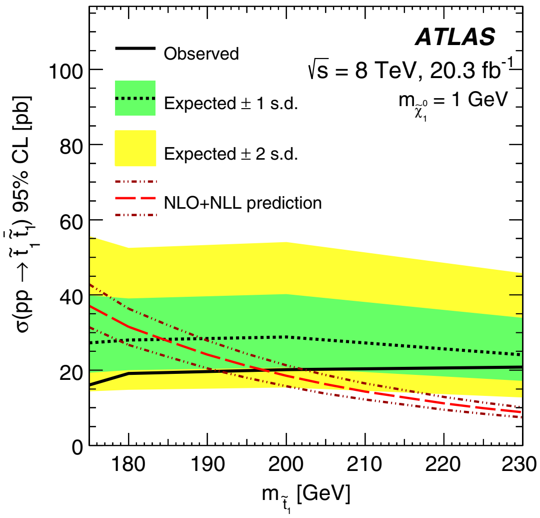

FIG. 2 (color online). Expected and observed limits at 95% C.L. on the top squark pair-production cross section as a function of $m_{\tilde{t}_1}$, for pair-produced top squarks $\tilde{t}_1$ decaying with 100% branching ratio via $\tilde{t}_1 \to t\tilde{\chi}_1^0$ to predominantly right-handed top quarks, assuming $m_{\tilde{\chi}_1^0} = 1$ GeV. The black dotted line shows the expected limit with ± 1 (green) and ± 2 (green + yellow) standard deviation contours, taking into account all uncertainties. The red dashed line shows the theoretical cross section with uncertainties. The solid black line gives the observed limit.

In conclusion, the first measurement of $t\bar{t}$ spin correlation in proton-proton scattering at a center-of-mass energy of 8 TeV at the LHC has been presented using 20.3 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 $f_{\rm SM} = 1.20 \pm 0.05(\rm stat) \pm 0.13(\rm syst)$ is consistent with the SM prediction. This represents the most precise measurement to date. The results have been used to search for pair-produced supersymmetric top squarks decaying to top quarks and light neutralinos. Assuming 100% branching ratio for the decay $\tilde{t}_1 \to t\tilde{\chi}_1^0$, and the production of predominantly right-handed top quarks, top squark masses between the top quark mass and 191 GeV are excluded at 95% C.L., which is an improvement over previous constraints.

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