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$t\bar{t}$ spin correlation at the LHC

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Summary. — The ATLAS collaboration has performed a study of spin correlation in $t\bar{t}$ production from proton-proton collisions at the Large Hadron Collier (LHC) at a centre-of-mass energy of 7 TeV using $0.70\,\mathrm{fb}^{-1}$ of data. 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 is compared to the expected distributions in the Standard Model, and to the case where the top quarks are produced with uncorrelated spin. Using the helicity basis as the quantisation axis, the strength of the spin correlation between the top and antitop quark is measured to be $A_{helicity} = 0.34^{+0.15}_{-0.11}$, which is in agreement with the NLO Standard Model prediction.

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The top quark was discovered in 1995 [1,2] at the Tevatron collider and has a measured mass of 173.2 ± 0.9 GeV [3]. In addition to this high mass, the large width of the top quark of $2.00^{+0.47}_{-0.43}$ GeV [4] corresponds to a lifetime of $3.29^{+0.90}_{-0.63} \times 10^{-25}$ s, which is at least an order of magnitude shorter than the timescale for strong interactions, implying that the top quark decays before hadronisation. Thus the top quark does not form bound states before its decay, allowing the opportunity to study the properties of a bare quark [5]. Properties such as the spin correlation in the $t\bar{t}$ system are transferred to the decay products and can be measured directly via their angular distributions [6]. This would test the predictions of QCD such as whether the decay of the top quark occurs before its spin is flipped by the strong interaction or after its spin is flipped leading to a decorrelation [7]. The apparent spin correlation may differ from that expected in the SM also due to sources of new physics beyond the SM in the production of top quark pairs or in their decay. This note presents a measurement of the spin correlation in dileptonic decays at ATLAS, where the $t\bar{t}$ pairs were produced in pp collisions at the LHC at $\sqrt{s} = 7$ TeV [8].

While top quark pairs produced at hadron colliders are unpolarised, their spins are correlated. In pp collisions at the centre-of-mass energy of the LHC, top quark pair production occurs mostly through the $gg \to t\bar{t}$ channel and also through the process $q\bar{q} \to$

$t\bar{t}$. This is in contrast with the Tevatron, where top quark pair production is dominated by the $q\bar{q}$ mechanism. This, and the different centre-of-mass energy (in contrast to the LHC at the Tevatron most top quark pairs are produced at the kinematical production threshold), make a measurement of the spin correlation at the Tevatron [9] and the LHC colliders complementary [5].

In top quark decays in the SM, the V-A couplings fix the angular distribution of the decay products according to the polarisation of the parent top quark. Charged leptons are the most effective spin analysers, since they carry the full information concerning the spin of the parent top quark at LO. Therefore, here we analyze dilepton final states ($t\bar{t} \to W^+W^-b\bar{b} \to l^+\nu l^-\bar{\nu}b\bar{b}$, $l = e, \mu, \tau$, where the τ decays leptonically).

The correlation coefficient, A, is defined as the fractional difference in the number of events where the top and antitop quark spins are aligned (N_{like}) and those where the top quark spins have opposite alignment (N_{unlike}),

$$A = \frac{N_{like} - N_{unlike}}{N_{like} + N_{unlike}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}, \tag{1}$$

where the arrows denote the spins of the top and antitop quarks with respect to a quantisation axis. Results are presented in the helicity basis and the LHC maximal basis as described in [10]. It has been shown that the $\Delta\phi$ distribution between the two leptons in the laboratory frame is sensitive to the spin correlation, where $\Delta\phi = |\phi_{l^+} - \phi_{l^-}|$ [11]. This quantity is well measured by the ATLAS detector and does not require reconstruction of the top quarks (via reconstruction of the two neutrinos in the event).

In this analysis we test the hypothesis that the correlation of the spin of top and antitop quarks is as expected in the SM, as opposed to the hypothesis that they are uncorrelated, which could happen if the spins of the top quarks flip before they decay. Figure 1 (left) shows the distribution of $\Delta\phi$ at parton level for events at $\sqrt{s} = 7\,\text{TeV}$ using `MC@NLO` [12]. This compares the SM prediction (solid line) to the scenario with no spin correlation between top and antitop quarks (dashed line). We derive A in the helicity and the LHC maximal bases by fitting the observed $\Delta\phi$ distribution to a linear superposition of that expected from the SM spin correlation, and that expected with no spin correlation. The fitting procedure is used to extract the fraction of SM template (f^{SM}), which is balanced by a complementary contribution from the zero correlation template. With knowledge of the SM correlation coefficient in a particular basis, A^{SM}_{basis}, the measured spin correlation can be extracted using $A^{measured}_{basis} = A^{SM}_{basis} \cdot f^{SM}$. In the helicity basis the SM correlation coefficient is $A^{SM}_{helicity} = 0.32$ evaluated at parton level using `MC@NLO` with the CTEQ6.6 parton distribution function (PDF) [13]. The SM expectation is evaluated in the same way for the maximal basis and is found to be $A^{SM}_{maximal} = 0.44$.

The ATLAS detector is described elsewhere [14]. MC simulation samples are used to calculate the $t\bar{t}$ acceptance and to evaluate the contributions from those background processes that are difficult to estimate from complementary data samples. All MC samples are processed with the `GEANT4` [15] simulation of the ATLAS detector [16] and events are passed through the same analysis chain as the data. The generation of $t\bar{t}$ uses the `MC@NLO` MC generator [12] with the CTEQ6.6 [13] PDF set and a top quark mass of 172.5 GeV. The $t\bar{t}$ cross section is normalised to the prediction of reference [17], which employs an approximate next-to-next-to-leading order (NNLO) perturbative QCD calculation.

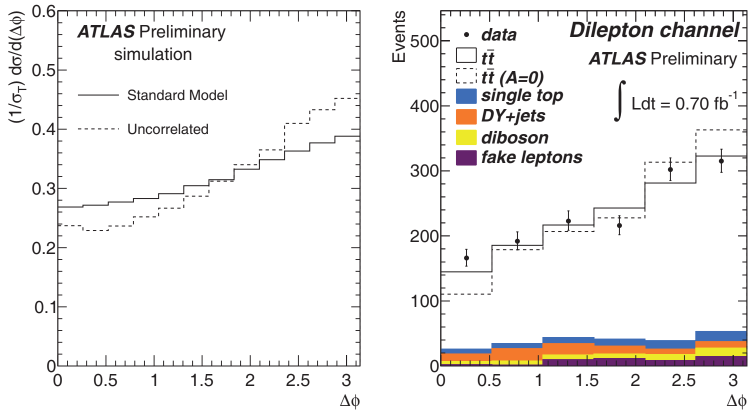

Fig. 1. – Left: distribution of $\Delta\phi$ for parton level events at $\sqrt{s} = 7\,\text{TeV}$ generated using the MC@NLO generator. The two histograms show the Standard Model and uncorrelated scenarios. Right: reconstructed lepton $\Delta\phi$ distribution for the sum of the ee, $\mu\mu$ and $e\mu$ channels [8].

Samples with SM spin correlation and without spin correlation are generated by MC@NLO which allows to switch between those different options.

Sources of background are $t\bar{t}$ single lepton+jets, single top quark and W+jets production with a non-prompt lepton arising mainly from heavy flavour decays, Z/γ^*+jets production, and diboson WW, WZ and ZZ production. They are simulated by MC generators and normalised to their theoretical cross sections as described in [18] except for the number of Z/γ^*+jets events in dielectron and dimuon events which is measured in a control region. All MC samples are generated with both in-time and out-of-time pile-up (multiple pp interactions). Another source of background is due to fake leptons (referring to both misidentified and non-prompt lepton candidates) in multijet production which is estimated from data using a matrix method [18].

Leptons are required to be isolated and have high transverse momentum, p_T, with p_T thresholds chosen to ensure events are triggered with high efficiency. Jets are reconstructed with the *anti*-k_t algorithm [19], with distance parameter $R = 0.4$, starting from energy clusters of adjacent calorimeter cells. They must be isolated from any lepton and have high p_T. Selected events must have at least two jets which are not required to be b-tagged. Each event is required to have a primary interaction vertex with at least five tracks associated to it. Further kinematic selection requirements involve the missing transverse energy (E_T^{miss}), the invariant lepton-lepton mass (m_{ll}) and the scalar p_T sum of all selected jets and leptons (H_T) and are optimised to minimise the expected total uncertainty of the measurement of the $t\bar{t}$ cross section in the dilepton channel [18] where more details can be found.

Figure 1 (right) shows the reconstructed $\Delta\phi$ distribution. for the sum of the three (ee, $e\mu$, $\mu\mu$) dilepton channels. SM and uncorrelated ($A = 0$) $t\bar{t}$ MC samples are added to the expected backgrounds. The $\Delta\phi$ distribution measured in data is overlaid.

The extraction of the spin correlation is performed using a binned likelihood fit to the $\Delta\phi$ distribution in the three channels simultaneously. The fit function is a linear superposition of the distribution expected from the SM spin correlation coefficient f^{SM} and that expected with no spin correlation with coefficient f^{UC}. A constraint is made requiring that the sum, $f^{SM} + f^{UC} = 1$. The fitting procedure has been verified over a wide range of possible values, $-1 \leq f^{SM} \leq 2$, using Monte Carlo (MC) pseudo-experiments with full simulation and reconstruction of the $t\bar{t}$ decay products. The fit was found to correctly recover the input spin correlation over the range tested.

Systematic uncertainties are evaluated using MC pseudo-experiments. The number of events in a pseudo-experiment is Poisson distributed around the expectation for signal and background from MC. We considered sources of uncertainty due to the luminosity, the finite size of the MC samples, the mis-modelling of the muon (electron) trigger, reconstruction and selection efficiencies in the simulation, the modelling of the lepton momentum scale and resolution, the jet energy scale (including uncertainties in the flavour composition of the samples, mis-measurements from nearby jets and additional uncertainties due to pileup), the jet energy resolution and reconstruction efficiency, the kinematic properties of the $t\bar{t}$ signal events (considering the choice of generator, the parton shower and fragmentation model and the modelling of initial and final state radiation, PDF, and top quark mass), the $t\bar{t}$ signal normalisation and the background estimates which use complementary data samples (including the statistical uncertainties in these methods as well as the systematic uncertainties arising from the objects and MC estimates that are used in the methods). Due to a hardware failure on 30 April 2011, a rectangular region ($\Delta\phi \times \Delta\eta = 0.2 \times 1.4$) of the ATLAS LAr calorimeter cannot be read out in a subset of the data. This impacts the electron, jet and $E_T^{\rm miss}$ reconstruction and is corrected for, including a systematic uncertainty.

The measured spin correlation is $f^{SM} = 1.06 \pm 0.21(\text{stat})^{+0.40}_{-0.27}(\text{syst})$ (compared to the SM prediction of $f^{SM} = 1$). This is used to extract $A_{helicity} = 0.34 \pm 0.07(\text{stat})^{+0.13}_{-0.09}(\text{syst})$ ($A_{helicity} = 0.32$ in the SM) and $A_{maximal} = 0.47 \pm 0.09(\text{stat})^{+0.18}_{-0.12}(\text{syst})$ ($A_{maximal} = 0.44$ in the SM) which is in agreement with the SM prediction for a spin 1/2 top quark.

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