



$t\bar{t}$ Spin Correlations at D0

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The heaviest known elementary particle today, the top quark, has been discovered in 1995 by the CDF and D0 collaborations at the Tevatron collider at Fermilab. Its high mass and short lifetime, shorter than the timescale for hadronization, makes the top quark a special particle to study. Due to the short lifetime, the top quark's spin information is preserved in the decay products. In this article we discuss the studies of $t\bar{t}$ spin correlations at D0, testing the full chain from production to decay. In particular, we present a measurement using angular information and an analysis using a matrix-element based technique. The application of the matrix-element based technique to the $t\bar{t}$ dilepton and semileptonic final state resulted in the first evidence for non-vanishing $t\bar{t}$ spin correlations.

*36th International Conference on High Energy Physics,
July 4-11, 2012
Melbourne, Australia*

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1. Introduction

Discovered in 1995 by the CDF and D0 collaborations at the Tevatron proton antiproton ($p\bar{p}$) collider at Fermilab, the top quark [1, 2] is the heaviest known elementary particle today. The top quark mass is measured to be $m_t = 173.18 \pm 0.94$ GeV [3]. The lifetime of the top quark is shorter than the time scale for hadronization, therefore it is the only quark that can be studied as bare quark. Due to the short lifetime, the spin information of the top quark is preserved in its decay products. While $t\bar{t}$ pairs are produced unpolarized at the Tevatron, the correlation of the spin orientation of the top and the anti-top quark can be studied. By investigating the $t\bar{t}$ spin correlations, we can study the full chain from production to decay and thus test the couplings in production and decay for possible new physics that would change the $t\bar{t}$ spin correlation strength. In the following, two methods of measuring $t\bar{t}$ spin correlations, performed by the D0 collaboration using Tevatron Run II data, are presented. The first method explores angular distributions, while the second uses a matrix element based approach.

2. $t\bar{t}$ Spin Correlation Measurement using Angular Distributions

Despite the unpolarized production of top quark pairs at hadron colliders, the spins of the top and anti-top quark are expected to be correlated. Information on spin correlations can be extracted from the angular distribution of the final state objects. In particular, the doubly differential cross section $1/\sigma \times d^2\sigma/(d\cos\theta_1 d\cos\theta_2)$ can be written as

$$\frac{1}{\sigma} \times \frac{d^2\sigma}{(d\cos\theta_1 d\cos\theta_2)} = \frac{1}{4} \times (1A\alpha_1\alpha_2 \cos\theta_1 \cos\theta_2), \quad (2.1)$$

where A is the spin correlation strength, α_1 (α_2) is the spin analysing power of the final state fermion from the W^+ (W) boson or top (anti-top) quark decay, and θ_1 (θ_2) is the angle of the fermion in the top (antitop) quark rest frame with respect to a quantization axis. Several choices of the quantization axis are common: the helicity axis, where the reference axis is the flight direction of the top (anti-top) quark in the $t\bar{t}$ rest frame, the beam axis, where the quantization axis is the beam direction, and the off-diagonal basis, which yields the helicity axis for ultra-high energy and the beam axis at threshold. The standard model (SM) prediction of $C = A\alpha_1\alpha_2$ depends on the quantization axis and the ratio of the $t\bar{t}$ production modes. At the Tevatron $p\bar{p}$ collider with a center of mass energy of 1.96 TeV, the main $t\bar{t}$ production occurs via quark-antiquark annihilation to about 85% and only to about 15% via gluon-gluon fusion. For the measurement at D0 we consider the beam basis, yielding a SM prediction of $C = 0.78$ at next-to-leading order (NLO) quantum chromodynamics (QCD) [4]. Visually, the spin correlation strength can be considered as the number of events where top and antitop have the same spin direction minus the number of events with opposite spin direction, normalized to the total number of $t\bar{t}$ events. In leading order (LO) QCD, the spin analyzing power α is one for charged leptons and the down-type quarks from the W boson decay, and smaller for the up-type quark from the W boson decay and the b -quarks from the top decay. Due to the experimental challenge to distinguish up-type from down-type quarks, it is easiest to use charged leptons to extract spin correlations. The D0 collaboration has performed a measurement of C by studying the distribution $\cos\theta_1 \cos\theta_2$ in the dilepton final state,

where both W bosons from the top and anti-top quark decay into a charged lepton and the associated neutrinos, using 5.4 fb^{-1} of Run II data [5]. The measurement is based on the standard $t\bar{t}$ dilepton selection [6], where two high p_T charged leptons (ee , $e\mu$ or $\mu\mu$) of opposite sign, at least two high- p_T jets and large missing transverse energy are required. The main background in this final state arises from Z -jets production, and smaller contributions form diboson production and instrumental background arising from jets faking a charged lepton.

In order to calculate θ_1 and θ_2 , the reconstruction of the full $t\bar{t}$ system is required. We use the neutrino weighting technique, as developed for precision top mass measurements [7], for this purpose. Neutrino weighting works as follows: The total dilepton final state is specified by eighteen components of momentum from the two charged leptons, two neutrinos and two b -jets, of which only twelve can be measured from the observed jets and charged leptons. Four additional constraints are provided when requiring that the invariant mass of a lepton-neutrino pair yields the known W boson mass, and the W boson and b -jet combinations yield the top quark mass. The two additional quantities that need to be specified to reconstruct the full event kinematics are extracted by sampling the pseudo-rapidity distributions of the two neutrinos, providing up to two solutions for each neutrino transverse momenta. For each solution a weight is assigned by comparing the measured value of the missing transverse energy to the calculated missing transverse energy in the reconstructed event. The resolution of the x and y components of the missing transverse energy are taken into account in the weight. Due to the possible jet assignments to the top quarks, in total eight solutions per event are possible. Detector resolutions are included in the neutrino weighting procedure by smearing the measured lepton and jet momenta according to their resolution, and by repeating the calculation for a large number of random choices.

The extraction of C from $\cos\theta_1 \cos\theta_2$ is performed by generating a sample including spin correlations at the SM value, and a sample neglecting spin correlations ($C = 0$) with the NLO Monte Carlo (MC) generator MC@NLO [8], and building templates in $\cos\theta_1 \cos\theta_2$ for both $t\bar{t}$ samples and the background, which are fitted to the data. We extract C in the beam basis as $C = 0.10 \pm 0.45$ (stat + syst), in agreement with SM predictions. Systematic uncertainties are included as nuisance parameters in the maximum likelihood fit, and the $t\bar{t}$ cross section is floated freely in order to reduce the sensitivity to normalization effects. Figure 1 shows the comparison of the predictions with and without $t\bar{t}$ spin correlations and the data in the combined dilepton final state (ee , $e\mu$ and $\mu\mu$ final states combined). The measurement is dominated by the statistical uncertainty. The CDF collaboration has measured $t\bar{t}$ spin correlation using angular distributions in the dilepton and lepton plus jets final states [9]. These measurements also show good agreement with the SM prediction.

3. $t\bar{t}$ Spin Correlation Measurement using a Matrix-Element based Approach

The measurement of $t\bar{t}$ spin correlations using angular distributions is so far limited by the statistical uncertainty. Comparing different approaches for the measurement of the top quark mass, the most precise method is the Matrix Element (ME) method, where the full event information is explored. The D0 collaboration explored the application of a ME-based approach for the first time to the measurement of $t\bar{t}$ spin correlations. We test two hypotheses against each other, in particular the hypothesis of having SM spin correlations ($H = c$) versus the hypothesis of no spin correlation

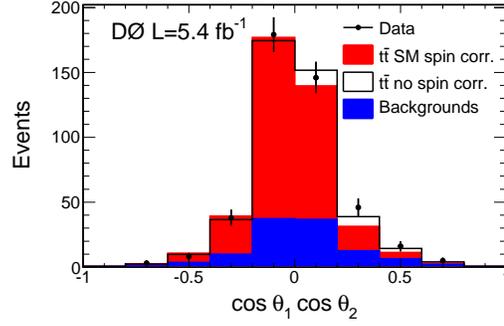


Figure 1: The distribution in $\cos \theta_1 \cos \theta_2$ for the combined dilepton channel. The expectation of the summed $t\bar{t}$ signal, including NLO QCD spin correlation ($C = 0.777$) (red) and all backgrounds (blue) is shown and are compared to data. The open histogram shows the $t\bar{t}$ prediction without spin correlation ($C = 0$) [5].

($H = u$). Per-event signal probabilities $P_{sig}(H)$ are calculated using matrix elements that include spin correlations or do not include spin correlations. For hypothesis $H = c$ we use the ME for the full process $q\bar{q} \rightarrow t\bar{t} \rightarrow W^+bW^-b \rightarrow \ell^+ \nu_\ell b \ell^- \nu_\ell \bar{b}$, averaged over the initial quarks' color and spin and summed over the final colors and spins, while for the hypothesis $H = u$, we use the ME of the same process, but neglecting the spin correlation between production and decay [10]. We can write P_{sig} as function of the hypotheses, as

$$P_{sig}(x;H) = \frac{1}{\sigma_{obs}} \int dq_1 dq_2 f_{PDF}(q_1) f_{PDF}(q_2) \frac{(2\pi)^4 |M(y,H)|^2}{q_1 q_2 s} d\Phi_6 W(x,y), \quad (3.1)$$

with σ_{obs} being the LO $q\bar{q} \rightarrow t\bar{t}$ production cross section including selection efficiency and acceptance effects, q_1 and q_2 denoting the fraction of the proton and antiproton momentum carried by the partons, f_{PDF} representing the parton distribution functions, s the square of the center of mass energy of the colliding $p\bar{p}$ system, and $d\Phi_6$ the infinitesimal volume element of the 6-body phase space. Detector resolution effects are taken into account by introducing transfer functions $W(x,y)$, that describe the probability of a partonic final state y to be measured as $x = (\tilde{p}_1, \dots, \tilde{p}_n)$, where \tilde{p}_i denote the measured four-momenta of the final state leptons and jets.

These signal probabilities are then translated into a discriminant [11]:

$$R = \frac{P_{sig}(H = c)}{P_{sig}(H = c) + P_{sig}(H = u)}. \quad (3.2)$$

Using the same D0 dataset of 5.4 fb^{-1} of dilepton events as for the measurement with angular distributions, a maximum likelihood fit of templates of R has been performed. Similar to the $t\bar{t}$ spin correlation measurement using angular distributions, we float the $t\bar{t}$ cross section freely to reduce the effect from normalization uncertainties on the measured $t\bar{t}$ spin correlations. Samples with different spin correlation content (SM value and no spin correlations) have been generated using MC@NLO MC, and we use the same samples as for the measurement using angular distributions. The ME-based approach yields an improvement of 30% in sensitivity compared to the analysis using angular distributions, resulting in $C = 0.57 \pm 0.31$ (stat + syst) [12]. The result is dominated

by statistical uncertainties. Figure 2 (left) shows the comparison of the expected distributions of the discriminant R for SM spin correlation and no spin correlation and the data.

While the dilepton final state is the easiest to perform spin correlation measurements, the D0 collaboration extended the ME-based measurement to the lepton plus jets final state. The selection of semileptonic $t\bar{t}$ events is based on the $t\bar{t}$ cross section measurement using 5.3 fb^{-1} of data [13]. We restrict the sample to events with at least four jets, of which at least two have to be identified as b -jets, using a neural network based b -tagger that combines variables characterizing the properties of secondary vertices and tracks displaced with respect to the primary interaction vertex [14]. In order to get the right assignment of final state objects to the top and anti-top, four permutations of jets are included: two corresponding to the choice of which b -jet corresponds to the top and anti-top quark, and two corresponding to the assignment of one of the non- b -jets to the down-type quark from the W boson decay. To optimize the measurement, we then split the events into four regions with higher and lower sensitivity. In particular, we distinguish events according to whether exactly four or more than four jets are present, and whether the invariant mass of the two non- b -jets is close or far away from the known W boson mass. The first split is motivated by the fact that for more than four jets, it is more likely to include wrong jet permutations, while the second split is motivated due to a higher probability of having picked the wrong jet pair if the invariant mass is far from the W boson mass. Even though the complication of not knowing the down-type jet reduces the sensitivity of the measurement in the lepton plus jets final state by about half, the larger dataset, about twice as high as in the dilepton final state, yields a sensitivity to spin correlations in the lepton plus jets final state similar to the one in the dilepton final state. Figure 2 (right) shows the expectation of signal and background for SM $t\bar{t}$ spin correlations and no spin correlations compared to the data. For the combined fit in the dilepton and lepton plus jets channel, we measure $C = 0.66 \pm 0.23$ (stat + syst) [15], which provides the first evidence for non-vanishing $t\bar{t}$ spin correlations.

All measurements of $t\bar{t}$ spin correlations are in agreement with the NLO SM prediction. Independent of the method, the uncertainties of the results are all dominated by the statistical uncertainty. So far only half of the full Tevatron data sample has been analysed (5.4 and 5.3 fb^{-1} respectively), and at least a factor of $\sqrt{2}$ of improvement on the uncertainty can be expected for the final $t\bar{t}$ spin correlation measurement from D0. Including improvements on the methods the uncertainty should reduce even further.

4. Conclusion and Outlook

The measurement of $t\bar{t}$ spin correlations provides a test of new physics in the full chain from production to decay. Only recently, the Tevatron data samples became large enough to extract sensitive $t\bar{t}$ spin correlation measurements. Several approaches have been explored to measure the spin correlations strength, in particular a template method using angular distributions, and a new matrix-element based approach. The application of the latter to dilepton and lepton plus jets $t\bar{t}$ final states resulted in the first evidence for non-vanishing $t\bar{t}$ spin correlations. As the results from Tevatron and LHC are complementary due to different $t\bar{t}$ production modes dominating, the exploration of $t\bar{t}$ spin correlation provides one of Tevatron's legacies. An important remaining achievement is the exploration of the full Tevatron dataset.

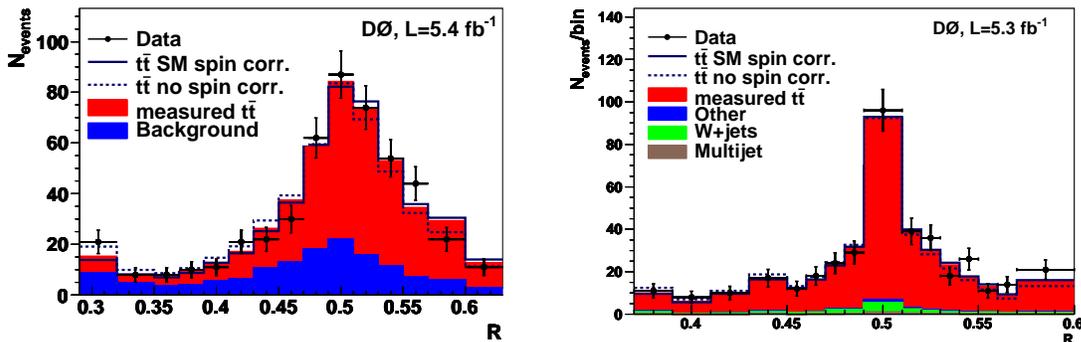


Figure 2: The distribution of the discriminant R for the combined dilepton (left) and lepton plus jets (right) final state. The expectation for $t\bar{t}$ signal and all backgrounds is shown with SM spin correlation (full line) and without spin correlation (dashed line) [12, 15].

Acknowledgements

I thank my collaborators from D0 for their help in preparing the presentation and this article. I also thank the staffs at Fermilab and collaborating institutions, and acknowledge the support from the Helmholtz association.

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