Measurement of top quark polarization with the D0 detector

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We present a measurement of the top quark polarization in the $t\bar{t}$ pair production in $p\bar{p}$ collisions at the Fermilab Tevatron collider at $\sqrt{s} = 1.96$ TeV. We use the full Run II data sample corresponding to 9.7 fb^{-1} of integrated luminosity recorded with the D0 detector. We consider the final state containing a lepton (electron or muon) and at least three jets. The polarization is measured through the distribution of lepton angles. We consider three different axes for the polarization measurement: the beam axis, the helicity axis, and the axis normal to the $t\bar{t}$ production plane. This is the first measurement of the transverse polarization of the top quark at a hadron collider. The observed top quark polarizations for each of the three axes are consistent with standard model predictions of nearly zero polarization.

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The standard model (SM) predicts that top quark pairs are produced almost unpolarized at the Tevatron (a small longitudinal polarization is generated by SM parity-violating weak interactions [1]), while various models beyond the SM predict non-zero polarization of the top quark pairs. The transverse polarization is allowed in strong interaction processes. The SM predictions are shown in Table 3. The top quark polarization $P_{\hat{n}}$ can be measured in the top quark rest frame through the angular distribution of the top quark decay products with respect to a chosen axis $\hat{n}$ [1, 2]: $\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2}(1+P_{\hat{n}}\kappa_i\cos\theta_{i,\hat{n}})$, where i is the decay product, κ_i its spin analyzing power (≈ 1 for ℓ, 0.97 for d-type quark, -0.4 for b-quark, and -0.3 for neutrino and u-type quark [2, 3]), and $\theta_{i,\hat{n}}$ is the angle between the direction of the decay product i and the quantization axis $\hat{n}$. The spin quantization axis choices are: the **beam axis** $\hat{b}$, given by the direction of the proton beam, the **helicity axis** $\hat{h}$, given by the direction of the parent top quark, and the **transverse axis** $\hat{t}$, given as perpendicular to the production plane defined by the proton and parent top quark directions [4, 5].

This analysis is performed using the lepton + jets final state from data collected by the D0 detector [6]. We require one isolated electron [7] or muon [8] with transverse momentum $p_T > 20$ GeV and $|\eta| < 1.1$ or $|\eta| < 2$, missing transverse momentum $\not{p}_T > 20$ GeV, at least three jets with $p_T > 20$ GeV within $|\eta| < 2.5$, and $p_T > 40$ GeV for the jet of highest p_T. At least one jet per event is required to be identified as originating from a b quark (b-tagged) through the use of a multivariate algorithm [9]. Additional selection requirements are applied same way as described in Ref. [10]. In addition, we also require that the curvature of the track associated with the lepton is well measured to reduce lepton charge misidentification.

We use Monte Carlo simulated $t\bar{t}$ events generated using the MC@NLO event generator version 3.4 [11] or the ALPGEN event generator version 2.11 [12]. Parton showering, hadronization, and underlying event modeling are performed with HERWIG [13] for MC@NLO events and with PYTHIA [14] for ALPGEN events. The detector is simulated using GEANT3 [15]. The background samples are used same as defined in Ref. [10].

A χ^2-based constrained kinematic fit is utilized to associate the observed leptons and jets with the individual top quarks as described in [16]. The kinematic fit algorithm includes a technique that allows reconstruction of events with lepton and three jets [17]. All possible combinations of objects are considered and weighted by the χ^2 of the kinematic fit solution.

To determine the sample composition we choose input variables that form a kinematic discriminant based on the approximate likelihood ratio between the $t\bar{t}$ and W+jets predictions. The input variables are selected for good separation between the $t\bar{t}$ events and the W+jets events and are required to be well modeled and not strongly correlated with one another or to the lepton polar angles. Such variables are k_T^{min},

	3 jets		≥ 4 jets	
Source	e+jets	μ+jets	e+jets	μ+jets
W+jets	1741 ± 26	1567 ± 15	339 ± 3	295 ± 3
Multijet	494 ± 7	128 ± 3	147 ± 4	49 ± 2
Other Bg	446 ± 5	378 ± 2	87 ± 1	73 ± 1
$t\bar{t}$ signal	1200 ± 25	817 ± 20	1137 ± 24	904 ± 23
Sum	3881 ± 37	2890 ± 25	1710 ± 25	1321 ± 23
Data	3872	2901	1719	1352

Table 1: Estimated number of events after selection and after determination of the sample composition from maximum-likelihood fit to the discriminant distribution. The quoted uncertainties are statistical.

aplanarity, H_T^ℓ and others described in [18]. The $\ell+3$ jet and $\ell+ \geq 4$ jet samples are each divided into 3 sub-channels according to the number of b-tagged jets: 0, 1, ≥ 2 for the sample composition fit. The zero-b-tag channels are used only to determine the sample composition and background calibration, not to measure the polarization. The sample composition is determined from a simultaneous maximum-likelihood fit to the discriminant distribution for the $t\bar{t}$ signal and W+jets background and the resulting selection is summarized in Table 1.

We need the lepton angular distributions for the W+jets events to be properly modeled, so it does not bias the final template fit, which is especially important in $\ell+3$ jet sample. To obtain a good model of the W+jets templates, we use the data in the $\ell+3$ jets and 0 b-tag control sample, which is dominated by the W+jets background with more than 70% contribution. The $t\bar{t}$ events and other background components are subtracted from data. We reweight the W+jets MC events so that the $\cos\theta_{\ell,\hat{n}}$ distribution shows good agreement with the data. The correction obtained in the control sample is propagated to the other samples.

Source	Beam	Helicity	Transverse
Signal and background modeling	±0.019	±0.022	±0.009
Detector modeling	±0.017	±0.034	±0.011
Method	±0.014	±0.008	±0.005
Total systematic uncertainty	±0.030	±0.041	±0.015
Total statistical uncertainty	±0.046	±0.044	±0.030
Total uncertainty	±0.055	±0.060	±0.034

Table 2: Summary of uncertainties on the measured top quark polarization along three axes.

To measure polarization, a template fit to the reconstructed lepton $\cos\theta_{\hat{n}}$ distribution is made. The $t\bar{t}$ MC sample is only generated with zero polarization. We then obtain two templates of $+1$ and -1 polarization by reweighting the simulated $t\bar{t}$ events based on the double differential distribution:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_1 \cos\theta_2} = \frac{1}{4}(1 + \kappa_1 P_{\hat{n},1}\cos\theta_1 + \rho\,\kappa_2 P_{\hat{n},2}\cos\theta_2 - \kappa_1\kappa_2 C\cos\theta_1\cos\theta_2), \qquad (1)$$

where index 1 represents the t decay product (ℓ or d-type quark) and index 2 the $\bar{t}$ decay product, C stands for the anti-correlation factor, representing the spin correlation of the $t\bar{t}$ pair. We use the SM values $C = -0.368$ (helicity axis) and $C = 0.791$ (beam axis), both calculated at NLO in QCD and electroweak couplings [1]. The spin correlation factor is not known for the transverse axis and we set $C = 0$. In the SM with CP invariance, the relative sign factor ρ takes the value $+1$ for the helicity basis and -1 for the beam and transverse bases [1, 19]. A simultaneous fit is performed to the data using the $P = +1$ and -1 signal templates and the background template normalized to the expected background contribution. The observed polarization is taken as $P = f_+ - f_-$, where $f_\pm$ are the fractions of $P = +1$ and -1 returned in the fit. The distributions of the $\cos\theta_{\ell,\hat{n}}$ from $t\bar{t}$ decay are shown in Fig. 1.

A simultaneous measurement of the top quark polarization and the forward-backward asymmetry in the dilepton final states [20] observed a correlation between the two measurements. This correlation is due to acceptance and resolution effects in the event kinematic reconstruction. We determine the dependence of the observed polarization on the parton level forward-backward

asymmetry, A_{FB} and we perform a correction for the difference between the nominal MC@NLO production-level and the actual NNLO calculation [21].
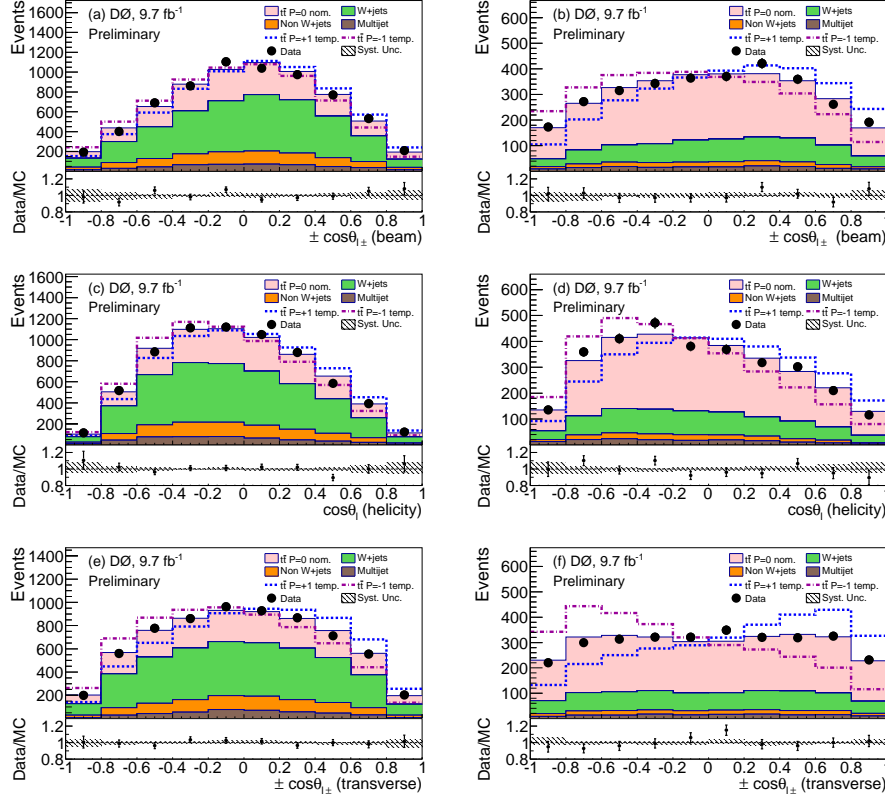

Figure 1: The combined e+jets and μ+jets $\cos\theta$ distributions for data, expected backgrounds and signal templates for $P = -1$, 0 and +1. Panels (a), (c), and (e) represent selection with exactly three jets. (b), (d), and (f) represent selection with four or more jets. The hashed area represents systematic uncertainty.

Three categories of systematic uncertainties are evaluated using fully simulated events including background contributions: modeling of signal and background events, uncertainties in the simulation of the detector response, and uncertainties in procedures used and assumptions made in the analysis as shown in Table 2. More details about the systematic uncertainties and determination can be found in [18, 22].

Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002 [23]
Helicity	-0.102 ± 0.060	-0.004 [23]
Transverse	$+0.040 \pm 0.034$	$+0.011$ [5]

Table 3: Measured top quark polarizations and the respective SM predictions.

The final measured polarizations for the three spin quantization bases are shown in Table 3. The results are consistent with zero and with the predicted SM values. The polarization along the transverse axis has been measured for the first time at a hadron collider and the longitudinal polarization results are the most precise results based on $p\bar{p}$ collisions.

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