Measurement of top quark polarization in $\ell$ lepton + jets final states

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enhanced polarizations [1]. The top quark polarization while models beyond the standard model (BSM) predict produced at the Tevatron collider are almost unpolarized, where models beyond the standard model (BSM) predict.

The standard model (SM) predicts that top quarks 

\[ \Gamma_t \approx \Gamma_{\bar{t}} \]

is the decay product (lepton, quark, or neutrino), \( \vec{\kappa} \) is its spin-analyzing power (\( \approx 0.97 \) for charged leptons, 0.96 for \( d \)-type quarks, –0.4 for \( b \)-quarks, and –0.3 for neutrinos and \( u \)-type quarks [3]), and \( \theta_{i,\vec{n}} \) is the angle between the direction of the decay product \( i \) and the quantization axis \( \vec{n} \). The mean polarizations of the top and antitop quarks are expected to be identical because of CP conservation. The \( P_{i,\vec{n}} \) can be obtained from the asymmetry of the \( \cos \theta \) distribution

\[ A_{P,\vec{n}} = \frac{N(\cos \theta_{i,\vec{n}} > 0) - N(\cos \theta_{i,\vec{n}} < 0)}{N(\cos \theta_{i,\vec{n}} > 0) + N(\cos \theta_{i,\vec{n}} < 0)}, \]

where \( N(x) \) is the number of events passing the requirement \( x \) and the polarization is then \( P_{i,\vec{n}} = 2A_{P,\vec{n}} \). The quantization axes are defined in the \( \vec{t} \) rest frame, while

\[ \cos \theta_{i,\vec{n}} = \cos \theta_{i,\hat{n}} \]

is the angle between the decay product and the quantization axis \( \hat{n} \) in the \( \vec{t} \) rest frame. This is the first measurement of top quark polarization at the Tevatron using lepton + jet final states and the first measurement of the transverse polarization in \( \vec{t} \) production. The observed distributions are consistent with standard model predictions of nearly no polarization.

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I. INTRODUCTION

The standard model (SM) predicts that top quarks produced at the Tevatron collider are almost unpolarized, while models beyond the standard model (BSM) predict enhanced polarizations [1]. The top quark polarization \( P_{\vec{n}} \) can be measured in the top quark rest frame through the angular distributions of the top quark decay products relative to some chosen axis \( \hat{n} \) [2],

\[ \frac{1}{\Gamma} \cos \theta_{i,\vec{n}} = \frac{1}{2} (1 + P_{\vec{n}} \vec{k}_i \cos \theta_{i,\hat{n}}), \]

where \( i \) is the decay product (lepton, quark, or neutrino), \( \vec{k}_i \) is its spin-analyzing power (\( \approx 1 \) for charged leptons, 0.97 for \( d \)-type quarks, –0.4 for \( b \)-quarks, and –0.3 for neutrinos and \( u \)-type quarks [3]), and \( \theta_{i,\hat{n}} \) is the angle between the direction of the decay product \( i \) and the quantization axis \( \hat{n} \). The mean polarizations of the top and antitop quarks are expected to be identical because of CP conservation. The \( P_{\vec{n}} \) can be obtained from the asymmetry of the \( \cos \theta \) distribution

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where \( N(x) \) is the number of events passing the requirement \( x \) and the polarization is then \( P_{\vec{n}} = 2A_{P,\vec{n}} \). The quantization axes are defined in the \( \vec{t} \) rest frame, while

\[ \cos \theta_{i,\vec{n}} = \cos \theta_{i,\hat{n}} \]
the decay product directions are defined after successively
boosting the particles to the \(\bar{t}t\) rest frame and then to the
parent top quark rest frame. We measure the polarization
along three quantization axes: (i) the beam axis \(\hat{n}_b\), given
by the direction of the proton beam [2]; (ii) the helicity axis
\(\hat{n}_h\), given by the direction of the parent top or antitop quark;
and (iii) the transverse axis \(\hat{n}_T\), given as perpendicular to
the production plane defined by the proton and parent top
quark directions, i.e., \(\hat{n}_p \times \hat{n}_t\) (or by \(\hat{n}_p \times \hat{n}_t\) for the
antitop quark) [4,5].

The D0 Collaboration published a short study of the top
quark polarization along the helicity axis in \(p\bar{p}\) collisions
as part of the measurement of angular asymmetries of leptons
[6], but no measured value was presented. Recently, the D0 Collaboration measured the top quark polarization
along the beam axis in \(\bar{t}t\) final states with two leptons [7],
finding it to be consistent with the SM. The ATLAS and
CMS collaborations measured the top quark polarization
along the helicity axis in \(pp\) collisions, and the results are
consistent with no polarization [8,9]. The polarization at the
Tevatron and LHC are expected to be different because of
the difference in the initial states, which motivates the
measurement of the polarizations in Tevatron data [10,11].
For beam and transverse axes, the top quark polarizations in
\(p\bar{p}\) collisions are expected to be larger than those for \(pp\)
[2,4], therefore offering greater sensitivity to BSM models
with nonzero polarization.

The longitudinal polarizations along the beam and helicity axes at the Tevatron collider are predicted by the
SM to be \((-0.19 \pm 0.05)\%\) and \((-0.39 \pm 0.04)\%\) [12],
respectively, while the transverse polarization is estimated to
be \(\approx 1.1\%\) [5]. Observation of a significant departure
from the expected value would be evidence for BSM contributions to the top quark polarization [11].

We present a measurement of top quark polarization in
\(\ell^+\) jets final states of \(\bar{t}t\) production using data collected
with the D0 detector [13], corresponding to an integrated luminosity of 9.7 fb\(^{-1}\) of \(p\bar{p}\) collisions at \(\sqrt{s} = 1.96\) TeV.

The lepton is most sensitive to the polarization and is easily
identified. We therefore examine the angular distribution of
leptons. After selecting the events in the \(\ell^+\) jets final state,
we perform a kinematic fit to reconstruct the lepton angles
relative to the various axes. The resulting distributions are
fitted with mixtures of signal templates with \(+1\) and \(-1\)
polarizations to extract the observed values. The down-type
quark has an analyzing power close to unity, but its
identification is difficult. It is therefore not used in the
measurement. However, to gain statistical precision, we use
reweighted Monte Carlo (MC) down-type quark distributions
in forming signal event templates.

## II. EVENT SELECTION

Each top quark of the \(\bar{t}t\) pair decays into a \(b\) quark and a
W boson with nearly 100% probability, leading to a
W\(^+\)W\(^-\)b\(\bar{b}\) final state. In \(\ell^+\) jets events, one of the W
bosons decays leptonically and the other into quarks that
evolve into jets. The trigger selects \(\ell^+\) jets events with at
least one lepton, electron (\(e\)) or a muon (\(\mu\)). The efficiency
of the trigger is 95% or 80% for \(\bar{t}t\) events containing
reconstructed \(e\) or \(\mu\) candidates, respectively. This analysis
requires the presence of one isolated \(e\) [14] or \(\mu\) [15] with
transverse momentum \(p_T > 20\) GeV and physics pseudorapidity [16] \(|\eta| < 1.1\) or \(|\eta| < 2\), respectively. In addition,
leptons are required to originate from within 1 cm of the
primary \(p\bar{p}\) interaction vertex (PV) in the coordinate along
the beam axis. Accepted events must have a reconstructed
PV within 60 cm of the center of the detector along the beam
axis. Furthermore, we require an imbalance in transverse
momentum \(p_T > 20\) GeV, expected from the undetected
neutrino. Jets are reconstructed using an iterative cone
algorithm [17] with a cone parameter of \(R = 0.5\). Jet
energies are corrected to the particle level using calibrations
from studies of exclusive \(\gamma + \text{jet}\), \(Z + \text{jet}\), and dijet events
[18]. These calibrations account for differences in the
detector response to jets originating from gluons; \(b\) quarks;
and \(u, d, s,\) or \(c\) quarks. We require 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 [19]. In \(\mu +\) jets events,
upper limits are required on the transverse mass of the
reconstructed W boson [20] of \(M_{\text{T}}^W < 250\) GeV and \(p_T < 250\) GeV to remove events with misreconstructed muon \(p_T\).
Additional selections are applied to reduce backgrounds in
muon events and to suppress contributions from multijet
production. A detailed description of these requirements can
be found in Ref. [21]. In addition, we require the curvature
of the track associated with the lepton to be well measured
to reduce lepton charge misidentification.

## III. SIGNAL AND BACKGROUND SAMPLES

We simulate \(\bar{t}t\) events at the next-to-leading-order (NLO)
in perturbative QCD with the \(\text{MC@NLO}\) event generator
version 3.4 [22] and at the leading-order (LO) with \(\text{ALPGEN}\)
event generator version 2.11 [23]. Parton showering,
hadronization, and modeling of the underlying event are
performed with \(\text{HERWIG}\) [24] for \(\text{MC@NLO}\) events and with
\(\text{PYTHIA 6.4}\) [25] for \(\text{ALPGEN}\) events. The detector response is
simulated using \(\text{GEANT3}\) [26]. To model the effects of
multiple \(p\bar{p}\) interactions, the MC events are overlaid with
events from random \(p\bar{p}\) collisions with the same luminosity
distribution as the data. The main background to the \(\bar{t}t\)
signal is \(W + \text{jets}\) events, where the W boson is produced
via the electroweak interaction together with additional
partons from QCD radiation. The \(W + \text{jets}\) final state can
be split into four subsamples according to parton flavor,
\(Wb\bar{b} + \text{jets}, WC\bar{c} + \text{jets}, WC + \text{jets},\) and \(W + \text{light} \) jets,
where light refers to gluons, \(u, d,\) or \(s\) quarks. The \(W + \text{jets}\)
background is modeled with ALPGEN and PYTHIA [23,25], as is the background from Z + jets events. Other background processes include WW, WZ, and ZZ diboson productions simulated using PYTHIA and single top quark electroweak production simulated using COMPYHEP [27]. The multijet background, where a jet is misidentified as an isolated lepton, is estimated from the data using the matrix method [21,28]. We use six different BSM models [29] to study modified t̄t production: one Z′ boson model and five axigluon models with different axigluon masses and couplings (m200R, m200L, m200A, m2000R, and m2000A, where L, R, and A refer to left-handed, right-handed, and axial couplings and numbers are the particle masses in GeV). Some additional axigluon models such as m2000L are not simulated as they are excluded by other ground processes. The input variables used for the t + 3 jet kinematic discriminant are $k_T^{|m|} = \min(|p_T^{b_Q} - p_T^{h_Q}|, |p_T^{b_Q} | - |p_T^{h_Q} |)$, where $\Delta R_{ab} = \sqrt{(\eta_a - \eta_b)^2 + (\phi_a - \phi_b)^2}$ is the angular distance between the two closest jets (a and b), $\min(|p_T^{b_Q} - p_T^{h_Q}|)$ is the scalar sum of the pt of the jets and lepton; $\Delta R$ between the leading jet and the next-to-leading jet; and $\Delta R$ between the lepton and the leading jet.

The input variables for the t + ≥ 4 jet discriminant are $k_T^{|m|}$; aplanarity; $H_T^f$, centrality, $C = H_T^f/H$, where $H_T$ is the scalar sum of all jet $p_T$ values and H is the scalar sum of all jet energies; the lowest $q^2$ among the different kinematic fit solutions in each event; $(p_T^{b_Q} - p_T^{h_Q})/(p_T^{b_Q} + p_T^{h_Q})$, the relative $p_T$ difference between $b_{lep}$ and the $b$ jet candidate from the $t \rightarrow b\ell\nu$ decay, and $b_{had}$; the $b$ jet candidate from the $t \rightarrow b\ell\nu$ decay; and $m_{jj}$, the invariant mass of the two jets corresponding to the $W \rightarrow q\bar{q}'\ell$ decay.

The sample composition is determined from a simultaneous maximum-likelihood fit to the kinematic discriminant distributions. The W + jets background is normalized separately for the heavy-flavor contribution (Wb̄b + jets and Wc̄c + jets) and for the light-parton contribution (Wc + jets and W + light jets). The sample composition after implementing the selections, and fitting the maximum likelihood to data, is broken down into individual channels by lepton flavor and number of jets and summarized in Table I. The obtained t̄t yield is close to the expectations.

The lepton angular distributions in W + jets events must be well modeled since these events form the leading background, especially in the t + 3 jet sample. We therefore use a control sample of t + 3 jet events without b tagged jets, as such events are dominated by W + jets production with > 70% contribution. This sample is not used for the polarization measurement. We reweight the W + jets MC events so that the $\cos \theta_{l,f,h}$ distributions agree with those for the control events in data with t̄t and other background components subtracted. We use the relative polarization asymmetry defined as $N_j(\cos \theta_{l,f,h}) - N_{-j}(\cos \theta_{l,f,h})/[N_j(\cos \theta_{l,f,h}) + N_{-j}(\cos \theta_{l,f,h})]$, where $j$ refers to bins of $\cos \theta_{l,f,h}$ values between 0 and 1 and $-j$ refers to bins between −1 and 0. The distributions of simulated W + jets events and subtracted data are shown in Fig. 1. The correction to MC obtained from the control sample is applied to the background templates used in our signal extraction. The corrections are 0.047 ± 0.002 for polarization along the beam axis, 0.011 ± 0.001 for the
to the expected event yield. The signal templates arise from
\( \pm \Gamma \) and \(-\Gamma \) along the chosen axis \( \hat{n} \). In the SM, assuming \( CP \) invariance, \( P_{h,1} = P_{\hat{n},2} \) and gives the relative sign factor \( \rho \) a value of +1 for the helicity axis and -1 for the beam and transverse axes [2].

A simultaneous fit is performed for the eight samples defined according to lepton flavor (\( e \) or \( \mu \)), lepton charge, and number of jets (3 or \( \geq 4 \)). The observed polarization is taken as \( P = f_+ - f_- \), where \( f_\pm \) are the fraction of events with \( P = +1 \) and -1 returned from the fit. The fitting procedure and methodological approach are verified using pseudoe
eriments for five values of polarization and through a check of consistency with predictions, using the BSM models with nonzero generated longitudinal polarizations. The fitted polarizations and the model inputs are in good agreement, as shown in Fig. 2 for the polarizations along the beam axis, thus verifying our template methodology. The distributions in the cosine of the polar angle of leptons from \( \bar{t}t \) decay for all three axes are shown in Fig. 3.

A previous measurement of top quark polarization and the forward-backward asymmetry in dilepton final states [7] noted a correlation between these two measurements. This correlation is caused by acceptance and resolution effects in the kinematic reconstruction of the events. We determine the dependence of the observed polarization on the forward-backward asymmetry at the parton level, \( A_{FB} \), using samples in which the \( t \) and \( \bar{t} \) rapidity distributions are reweighted to accommodate the polarizations. We then use a correction for the difference between the nominal MC@NLO

\( C = 0.791 \) (beam axis), both calculated at NLO in QCD and in electroweak couplings in Ref. [2]. The spin correlation factor is not known for the transverse axis, and thus we set \( C = 0 \) and assign a systematic uncertainty by varying the choice of this factor. The \( P_{\hat{n},i} \) represents the polarization state we model (here \( P_{\hat{n},i} = \pm 1 \) along the chosen axis \( \hat{n} \)).

FIG. 2. Comparison of measured and generated polarizations along the beam axis for the SM and several non-SM models. The uncertainties are statistical.
production-level $A_{FB}$ of (5.01 $\pm$ 0.03)% and the next-to-next-to-leading-order (NNLO) calculation [34] of (9.5 $\pm$ 0.7)%. The observed correction is $-0.030$ for the polarization along the beam axis, less than 0.002 for the polarization along the helicity axis, and is negligible for the transverse polarization. The uncertainty on the expected $A_{FB}$ is propagated to the measurement as part of the methodology systematic uncertainty.

V. SYSTEMATIC UNCERTAINITIES

We have evaluated several categories of systematic uncertainties using fully simulated events: uncertainties associated with jet reconstruction, jet energy measurement, $b$ tagging, the modeling of background and signal events, PDFs, and procedures and assumptions made in the analysis. The sources of systematic uncertainties and their contributions are listed in Table II and added in quadrature for the total uncertainty. Details about the evaluation of the uncertainties can be found in Refs. [21,31]. Additionally, we assign an uncertainty in modeling the invariant mass of the $t\bar{t}$ system ($m_{t\bar{t}}$) based on the difference in $m_{t\bar{t}}$ distributions in our signal MC and the NNLO predictions [35].

VI. RESULTS

The measured polarizations for the three spin-quantization axes are shown in Table III. Results on the longitudinal polarizations are presented in Fig. 4 and compared to SM predictions and several of the BSM models discussed previously. The measurement along the beam axis is consistent with the previous D0 result in the dilepton channel along the beam, helicity, and transverse axes and the combined polarization for beam axis with the dilepton result by the D0 Collaboration denoted as Beam—D0 comb.. The total uncertainties are obtained by adding the statistical and systematic uncertainties in quadrature.

TABLE II. Summary of the uncertainties in the measured top quark polarization along three axes. The systematic uncertainty source indicates the difference in polarization when the measurement is repeated using alternative modeling, after applying uncertainties from the employed methods, or from assumptions made in the measurement. The uncertainties are added in quadrature to form groups of systematic sources and the total uncertainty.

<table>
<thead>
<tr>
<th>Source</th>
<th>Beam</th>
<th>Helicity</th>
<th>Transverse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet reconstruction</td>
<td>±0.010</td>
<td>±0.008</td>
<td>±0.008</td>
</tr>
<tr>
<td>Jet energy measurement</td>
<td>±0.010</td>
<td>±0.023</td>
<td>±0.006</td>
</tr>
<tr>
<td>$b$ tagging</td>
<td>±0.009</td>
<td>±0.014</td>
<td>±0.005</td>
</tr>
<tr>
<td>Background modeling</td>
<td>±0.007</td>
<td>±0.021</td>
<td>±0.004</td>
</tr>
<tr>
<td>Signal modeling</td>
<td>±0.016</td>
<td>±0.020</td>
<td>±0.008</td>
</tr>
<tr>
<td>PDFs</td>
<td>±0.013</td>
<td>±0.011</td>
<td>±0.003</td>
</tr>
<tr>
<td>Methodology</td>
<td>±0.013</td>
<td>±0.007</td>
<td>±0.009</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>±0.030</td>
<td>±0.042</td>
<td>±0.017</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>±0.046</td>
<td>±0.044</td>
<td>±0.030</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>±0.055</td>
<td>±0.061</td>
<td>±0.035</td>
</tr>
</tbody>
</table>

TABLE III. Measured top quark polarization from the $t\bar{t}$ $\ell +$ jets channel along the beam, helicity, and transverse axes and the combined polarization for beam axis with the dilepton result by the D0 Collaboration denoted as Beam—D0 comb.. The total uncertainties are obtained by adding the statistical and systematic uncertainties in quadrature.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Measured polarization</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam</td>
<td>+0.070 $\pm$ 0.055</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Beam—D0 comb.</td>
<td>+0.081 $\pm$ 0.048</td>
<td>$-0.002$</td>
</tr>
<tr>
<td>Helicity</td>
<td>$-0.102$ $\pm$ 0.061</td>
<td>$-0.004$</td>
</tr>
<tr>
<td>Transverse</td>
<td>+0.040 $\pm$ 0.035</td>
<td>+0.011</td>
</tr>
</tbody>
</table>
channel [7], \( P = 0.113 \pm 0.093 \). We estimate the correlation between this result for the beam axis and that of Ref. [7] to be 5%. The combination using the method of Refs. [36,37] yields a top quark polarization along the beam axis \( P = 0.081 \pm 0.048 \).

**VII. CONCLUSION**

In summary, we measure the top quark polarization for \( t\bar{t} \) production in \( p\bar{p} \) collisions at \( \sqrt{s} = 1.96 \) TeV along several spin-quantization axes. The polarizations are consistent with SM predictions. The transverse polarization is measured for the first time. These are the most precise measurements of top quark polarization in \( p\bar{p} \) collisions.

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