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# Studies of top quark properties at the D0 experiment

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We present an overview of selected top quark properties in lepton + jets and dilepton final states based on 1 – 4.3 $\mathrm{fb}^{-1}$ of data, collected with the D0 experiment at the Fermilab Tevatron collider. The recent measurement of the $W$ boson helicity, a search for anomalous top quark couplings, and measurements of spin correlations and forward backward color charge asymmetry are discussed.

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Since the discovery of top quark in 1995 by CDF and D0, the discovered particle is considered as a standard model (SM) top quark, mainly because its cross-section is in a reasonable agreement with QCD calculations and its measured mass is in a agreement with indirect top quark mass determinations. However the limited precision of these comparisons doesn't exclude the possibility of non SM contributions in the top quark final states, so direct measurements of top quark properties are useful to confirm its SM nature. In this article we report several recent measurements done using 1 – 4.3 $\mathrm{fb}^{-1}$ of data collected with the D0 detector [1] at the Fermilab Tevatron collider.

## 1. Model-independent measurement of the $W$ boson helicity

In the SM, the top quark decays, almost always, to a $W$ boson and $b$ quark via the $V-A$ charge current interaction. The new physics contribution may alter the fraction of the $W$ boson produced in different polarization states from SM values of $0.697 \pm 0.012$ [2] for the longitudinal helicity fraction $f_0$ and $3.6 \cdot 10^4$ [3] for the positive helicity fraction $f_+$ at the top quark mass of 172.6 GeV (the negative helicity fraction $f_-$ is fixed by the requirement $f_- + f_0 + f_+ = 1$). In this paper we report a simultaneous measurement of $f_0$ and $f_+$. This measurement uses the same procedure as reported in [4], but with a two times larger data sample of up to 2.7 $fb^{-1}$ using lepton + jets ($t\bar{t} \to \ell\nu b\bar{b}q\bar{q}'$) and dilepton ($t\bar{t} \to \ell^-\ell^+ b\bar{b}\nu\bar{\nu}$) final states.

The angular distribution of the down-type decay products of the $W$ boson (charged lepton or d, s quark) in the rest frame of the $W$ boson can be described by introducing the decay angle $\theta^*$ of the down-type fermion with respect to the top quark direction. The dependence of the distribution of $\cos\theta^*$ on the $W$ boson helicity fractions, $\omega(c) \propto 2(1-c^2) f_0 + (1-c)^2 f_- + (1+c)^2 f_+$, where $c = \cos\theta^*$, forms the basis for our measurement. $t\bar{t}$ events are simulated with the ALPGEN generator for the parton-level process (leading order) followed by PYTHIA generator for hadronization and simulation of the underlying events. Events corresponding to each of the three $W$ boson helicity states are produced by reweighting the generated $\cos\theta^*$ distributions. To extract $f_0$ and $f_+$ the template fit of $\cos\theta^*$ distribution is performed. The measured values of $f_0$ and $f_+$ fractions have the following values consistent with the SM expectation:

$$f_0 = 0.490 \pm 0.106\ (stat.) \pm 0.085\ (syst.) \qquad f_+ = 0.110 \pm 0.059\ (stat.) \pm 0.052\ (syst.)$$

More analysis details could be found in [5].

## 2. Measurement of anomalous top quark couplings

Another way to test the presence of non-SM physics is to study the $Wtb$ coupling in top pair and single top finals states. The effective Lagrangian describing the $Wtb$ interaction, including operators up to dimension five, is

$$\mathscr{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu V_{tb}(f_1^L P_L + f_1^R P_R)\, tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu} q_\nu V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)\, tW_\mu^- + h.c.\,,$$

where $M_W$ is the mass of the $W$ boson, $q_\nu$ is its four-momentum, $V_{tb}$ is the Cabibbo-Kobayashi-Maskawa matrix element, and $P_L = \frac{1}{2}(1-\gamma_5)$ ( $P_R = \frac{1}{2}(1+\gamma_5)$ ) is the left-handed (right-handed)

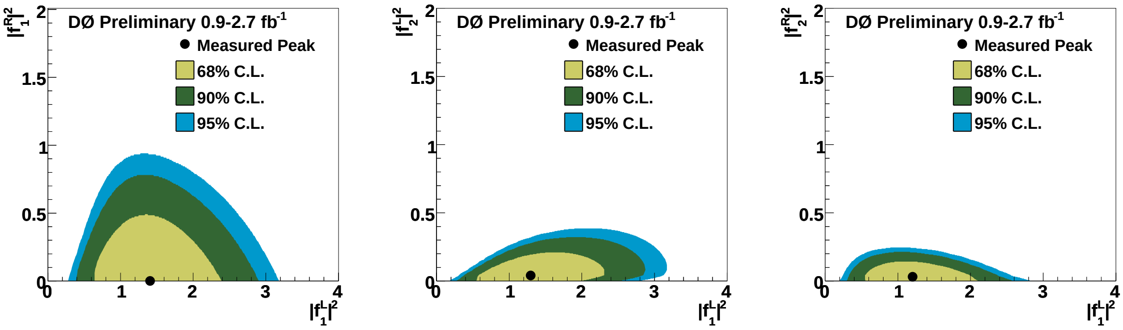


**Figure 1:** Final posterior densities for right- vs. left-handed vector coupling (left), left-handed tensor vs. left-handed vector coupling (center), and right-handed tensor vs. left-handed vector coupling (right) [8].

projection operator. We assume that CP is conserved at the $Wtb$ vertex, meaning that all the form factors $f_i^{L,R}$ are taken to be real. We also assume that the top quark has spin $\frac{1}{2}$.

Variations in the coupling form factors would mainly manifest themselves in two distinct ways that are observable at D0: by changing the rate and kinematic distributions of electroweak single top quark production, and by altering the fractions of $W$ bosons from top quark decay produced in each of the three possible helicity states. We combine information from our measurement of $W$ boson helicity fractions in $t\bar{t}$ events described in section (1) with information from measurement of single top quark production, using the general framework given in [6]. This analysis is an update of the result presented in [7] with a larger data set used in the $W$ boson helicity measurement. We use a Bayesian method to combine the $W$ helicity measurement with the results of search for anomalous $Wtb$ couplings in single top quark production. The likelihood from the $W$ helicity analysis is used as a prior to the analysis of single top anomalous couplings. The two-dimensional posterior probability density is computed as a function of $|f_1^L|^2$ and $|f_X|^2$, where $f_X$ is $f_1^R$, $f_2^L$ or $f_2^R$. These probability distributions are shown in Fig. 1. In all three scenarios we observe no anomalous contributions, and favor the left-handed hypothesis over the alternative hypothesis. More details and values of the upper limits on the anomalous couplings could be found in [8].

## 3. Spin correlation in the top quark anti-quark events

Top quark has a very short life-time of $\sim 5 \cdot 10^{-25}$ sec and decays before hadronization or depolarization, therefore transmitting its spin information to the decay products providing an unique opportunity for quark related measurements. At the Tevatron with a center-of-mass energy 1.96 TeV, the top quark anti-quark pairs are produced mainly by quark anti-quark annihilations. They are produced unpolarized, but quark and anti-quark spins are correlated. The dilepton final states have the highest sensitivity to measure the correlation between the spins of top quarks and anti-quark pairs [9]. In this analysis we are using the following three dilepton final states analyzed separately and than combined: $t\bar{t} \to e^- e^+ b\bar{b} \nu\bar{\nu}$ and $t\bar{t} \to \mu^- \mu^+ b\bar{b} \nu\bar{\nu}$ with $1.1\,fb^{-1}$ of integrated luminosity and $t\bar{t} \to e^{\pm} \mu^{\mp} b\bar{b} \nu\bar{\nu}$ with $4.2\,fb^{-1}$ of integrated luminosity.

The spin correlation in top quark pair production is analyzed by studying the double differential distribution $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$, where $\sigma$ denotes the cross section of the channel under consideration and C is a free parameter with value between -1 and and +1. In the SM the spin analyzing power of the charged leptons is +1, C represents the number of events where the quark and anti-quark spins are parallel minus the number of events where they are anti-parallel normalized by the total number of events. $\theta_1(\theta_2)$ is the angle between the lepton and the reference direction in the $t$ ($\bar{t}$) quark rest frame. The choice of spin basis determines the size of spin correlation. For the Tevatron it has been shown in [9] that an almost optimal choice for the spin basis is given by the direction of flight of one of the colliding hadrons in the $t$ ($\bar{t}$) rest frame. This, so-called, beam basis is used in this study. In order to simulate the spin correlation effects we use the PYTHIA generator (spin correlation is not implemented in it) and apply an event weight $w(\cos\theta_1, \cos\theta_2) = \frac{1}{4}(1 - C\cdot\cos\theta_1\cos\theta_2)$ calculated with parton level angles $\theta_1, \theta_2$.

In order to calculate $\cos\theta_1\cos\theta_2$ parameter one needs to reconstruct all particle 4-vectors in the final state. This is not possible for the dilepton final state because of the presence of neutrino particles escaping the detection. To overcome this problem we use the Neutrino Weighting technique described in [10]. Using this technique we calculate an event weight as a mean for all possible neutrinos parameters as a function of $\cos\theta_1\cos\theta_2$. Figure 2 shows the observed and expected distributions for $\cos\theta_1\cos\theta_2$ mean value. By making a template fit of this distribution we measured the following value of the spin correlation parameter

$$C = -0.17^{+0.64}_{-0.53}(stat + syst) \ ,$$

with uncertainty dominated by the statistical component. This value could be compared with a NLO QCD expectation of $C = 0.777$ [9]. The current uncertainties of this measurement doesn't allow to distinguish between the hypotheses with spin correlation and without spin correlation, but first sensitive results could be obtained at the end of the Tevatron running. For more details see [11].

## 4. Measurement of the forward-backward color charge asymmetry of $t$ and $\bar{t}$ quarks

At leading order in quantum chromodynamics, the standard model predicts that top-pair production in $p\bar{p}$ interactions is color-charge symmetric, but at the next-to-leading order, forward-backward asymmetries of five to ten percent may be present [12]. The asymmetries arise mainly from interference between contributions symmetric and anti-symmetric under the exchange $t \to \bar{t}$, and depend strongly on the region of phase space being probed. Some extensions of the standard model may lead to a higher asymmetry. At the Tevatron, the color-charge asymmetry is observable as a forward-backward asymmetry. The difference between the reconstructed rapidities of the $t$ and $\bar{t}$ quarks, $\Delta y \equiv y_t - y_{\bar{t}}$, measures the asymmetry in $t\bar{t}(+X)$ production. We define forward and backward events by the sign of $\Delta y$ and then define the forward-backward asymmetry to be $A_{fb} = (N^{\Delta y>0} - N^{\Delta y<0})/(N^{\Delta y>0} + N^{\Delta y<0})$.

The measurement presented here is an update of the previous analysis [13] with a larger data set of $4.3\,fb^{-1}$ using the lepton + jets final state $t\bar{t} \to \ell\nu b\bar{b}q\bar{q}'$. In this measurement we are not trying to correct the asymmetry for the reconstruction effects, but compare the measurement with MC@NLO generator prediction after the full simulation chain including simulation of the detector effects and object reconstruction. The predicted asymmetry was found to be $A^{pred}_{fb} = (1^{+2}_{-1}\,(syst))\%$. The main background contribution to this final state is from $W$+jets production. To estimate this contribution we define a likelihood discriminant using variables which provide separation between

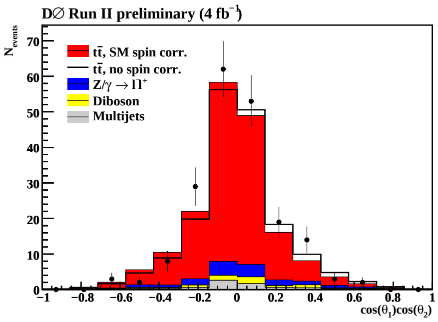


**Figure 2:** The $\cos\theta_1 \cos\theta_2$ distribution for the sum of $t\bar{t}$ signal with or without spin correlation and background in comparison with data [11].

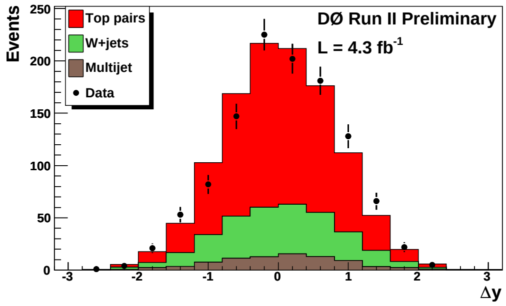


**Figure 3:** $\Delta y$ distribution for data in comparison with the sum of $t\bar{t}$ signal and background [14].

signal and $W$+jets background, are well described by the simulation and do not bias $|\Delta y|$. We extract the sample composition and the asymmetry simultaneously using a maximum likelihood fit to the distribution of events. The signal templates are derived from events generated with MC@NLO, and the $W$+jets template from events generated with ALPGEN with the jet showering performed by PYTHIA. The measured asymmetry value is found to be $(8 \pm 4)\%$. The corresponding $\Delta y$ distribution is shown in Fig. 3. Further details of this study could be found in [14].

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