Top quark properties measurement with the D0 detector

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One of the main goals of the Tevatron RunII is to look for any hints for new physics. At D0, the range of searches for new physics signals is large and one of the places we look for hints for new physics is by measuring the top quark properties. A few of these measurements are discussed in this paper.

1. Introduction

Tevatron, a $p\bar{p}$ collider with center of mass energy of about 2 TeV, is currently world’s highest energy collider in operation. It has been running quite efficiently for the last many years delivering more than $6 \text{fb}^{-1}$ integrated luminosity in RunII so far. The D0 detector has also been performing excellently. The motivation to accumulate as much luminosity as possible is not only to find Higgs and do precision measurements but also to look for new physics signals and rule out as many physics models as one can. The top quark is by far the heaviest fermion in the standard model, and thus has the strongest coupling to the Higgs boson of all standard model fermions. This makes the top quark and its interactions an ideal place to look for new physics related to electroweak symmetry breaking. In this paper, we present three analyzes which look for new physics signals in the top quark sector.

2. Measurement of CKM matrix element $V_{tb}$

Within the standard model the top quark decays to a W boson and a down-type quark $q$ ($q = d$; $s$; $b$) with a rate proportional to the squared Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{tb}|^2$. Under the assumption of three fermion families and a unitary 3x3 CKM matrix, the $V_{tb}$ elements are severely constrained [2]. However, in the presence of new physics CKM submatrix may not be a 3x3 unitary matrix and in that case $V_{tb}$ elements can significantly deviate from their standard model values. This would affect, among other things, the ratio $R$ of the top quark branching fractions, which can be expressed in terms of the CKM matrix elements as

$$R = \frac{\mathcal{B}(t \to Wb) }{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{ts}|^2 + |V_{td}|^2}.$$ 

Thus by measuring $R$ precisely we can set limit on the ratio of $|V_{tb}|^2$ to the off-diagonal matrix elements without any assumptions on the unitarity of the CKM matrix. The analysis presented here is based on data collected with the D0 detector between August 2002 and December 2005 at the Fermilab Tevatron $p\bar{p}$ collider at $\sqrt{s} = 1.96$ TeV, corresponding to an integrated luminosity of about 0.9 fb$^{-1}$. The analysis uses the top quark pair production. Within standard model top quarks decay to a W boson and a $b$ quark almost 100% of the time. For this analysis we only consider events in which one of the $W$ bosons decays into two quarks, and the other one into an electron or muon and a neutrino.

We identify $b$-jets using a neural-network tagging algorithm. We split the selected sample into subsamples according to the lepton flavor ($e$ or $\mu$), jet multiplicity (3 or $\geq 4$ jets) and number of identified $b$-jets (0, 1 or $\geq 2$), thus obtaining 12 disjoint data sets. Since the probability to tag a $tt$ event depends on the flavor of the jets, it depends on $R$. We estimate the acceptance and tagging probabilities for each of the three $tt$ decay modes $bb$, $bq$ and $qq$. Figure 1 shows tagging probabilities as a function of $R$ for $tt$ events with $\geq 4$ jets and 0, 1 and $\geq 2$ $b$ tags.

3. Anomalous $Wtb$ couplings

Anomalous $Wtb$ couplings modify the angular correlations of the top quark decay products and change the single top quark production cross section. In this paper we also present the first study of $Wtb$ couplings that combines $W$ helicity measurements in top quark decay with anomalous coupling searches in the single top quark final state.

The effective Lagrangian describing the $Wtb$ interaction including operators up to dimension five is:

$$\mathcal{L} = -\frac{g}{\sqrt{2}} b_\gamma \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W^\mu - \frac{g}{\sqrt{2}} b_i \sigma^{\mu\nu} q_i V_{tb} (f_2^L P_L + f_2^R P_R) W_i - h.c. \quad (1)$$

where $M_W$ is the mass of the $W$ boson, $q_i$ is its four-momentum, $V_{tb}$ is the Cabibbo-Kobayashi-Maskawa matrix element, and $P_L = (1 - \gamma_5)/2$ ($P_R = (1 + \gamma_5)/2$) is the left-handed (right-handed) projection operator. In the standard model, the $Wtb$ coupling is purely left-handed, and the values of the coupling form factors are $f_1^L \approx 1$, $f_2^L = f_1^R = f_2^R = 0$. For this analysis...
we assume real coupling form factors, implying CP conservation, and a spin-$\frac{1}{2}$ top quark which decays predominantly to $Wb$.

We investigate one pair of coupling form factors at a time and consider three cases, pairing the left-handed vector coupling form factor $f^L$ with each of the other three form factors. We refer to these as $(L_1, R_1)$, $(L_1, L_2)$, and $(L_1, R_2)$. For each pair under investigation we assume that the other two have the standard model values.

In this analysis we combine information from our measurement of the $W$ boson helicity fractions in $t\bar{t}$ events with information from single top quark production. We have set direct limits on anomalous top quark coupling before but those limits are based on single top quark final states only. This new measurement is based on a sample of 0.9 fb$^{-1}$ of single top candidate events and up to 2.7 fb$^{-1}$ of $t\bar{t}$ candidates collected by the D0 detector.

The $W$ boson helicity measurement, described in Ref. [5], uses events in both the $t+\text{jets}$ ($t\bar{t} \rightarrow W^+W^-b\bar{b}\rightarrow lνqq\bar{b}\bar{b}$) and dilepton ($t\bar{t} \rightarrow W^+W^-b\bar{b}\rightarrow lνl'^{\nu'}b\bar{b}$) final states, and is extracted form the distribution of $θ^*$, the angle between the down-type fermion and top quark momenta in the $W$ boson rest frame. For each pair of form factors a likelihood distribution is extracted from the $W$ helicity measurement of the decay angle distribution in top quark decays. We vary both the longitudinal and right-handed helicity fractions $f_0$ and $f_+^+$ in the fit and find the relative likelihood of any set of helicity fractions being consistent with the data. The result is presented in Fig. 3, which also demonstrates how non-SM values for the coupling form factors alter the $W$ helicity fractions.

This likelihood from the $W$ helicity analysis is then used as a prior in a Bayesian statistical analysis for the anomalous coupling search in single top quark production and decay channels, yielding a two dimensional posterior probability density as a function of both form factors. We extract limits on $f^R_1$, $f^L_2$, and $f^R_2$ by projecting the two-dimensional posterior onto the corresponding form factor axis. The $W$ boson helicity measurement is described in Ref. [5] and the helicity priors are shown in Fig. 4.

The dominant tree level Feynman diagrams for single top quark production in $p\bar{p}$ collisions are illustrated in Fig. 5. In this analysis we combine both these production modes and assume that single top quark production proceeds exclusively through $W$ boson exchange. The presence of anomalous couplings...
can change angular distributions and event kinematics as demonstrated by the $p_T$ spectrum of the charged lepton from the decay of the top quark in Fig. 6. Such differences can be used to distinguish these couplings. We use boosted decision trees to discriminate between the single top quark signal and background.

We use Bayesian statistics to compare the output distribution of the decision trees from data to expectations for single top quark production. For any pair of values of the two couplings that are considered non-zero, we compute the expected output distribution by superimposing the distributions from the two signal samples with the non-standard coupling and from the background samples in the appropriate proportions. In case of the $(L_1, L_2)$ scenario, the two amplitudes interfere, and we use a superposition of three signal samples, one with left-handed vector couplings, one with the left-handed tensor coupling only set to one, and one with both couplings set to one to take into account the effect of the interference. We then compute a likelihood as a product over all bins and channels. Here we use twelve channels defined by lepton flavor, $b$ tag multiplicity, and jet multiplicity (2, 3, or 4).

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. 7. In all three scenarios we measure approximately zero for the anomalous coupling form factors and favor the left-handed vector hypothesis over the alternative hypothesis. We compute 95% Confidence Level (C.L.) upper limits on these form fac-

Figure 3: Graphical representation of the change in $W$ boson helicity fractions away from the SM values (shown by the star) if the anomalous couplings are present.

Figure 4: $W$ helicity prior for right- vs left-handed vector coupling (a), left-handed tensor vs left-handed vector coupling (c), and right-handed tensor vs left-handed vector coupling (e). The $W$ helicity prior is normalized to a peak value of one and shown as equally spaced contours between zero and one.
4. Top- antitop spin correlations

Top quark physics plays an important role in testing the standard model and its possible extensions. One of the most important properties of the top quark, the spin, has not been carefully explored. While the top quarks and antiquarks produced at hadron colliders are unpolarized, their spins are correlated. Since at the Tevatron top pair production is dominated by $q\bar{q}$ scattering, a different spin correlation is analyzed compared to the LHC where top pair production is dominated by $gg$ scattering. The standard model predicts that the top quark decays before its spin flips, in contrast with the lighter quarks, which are depolarized by QCD interactions long before they fragment.
The spin of the top quark is therefore reflected by its decay products. In this analysis it is assumed that top quarks decay exactly as predicted by the standard model. Then the charged lepton from a leptonic top quark decay has a spin analyzing power of 1 at the tree level. Therefore, the dilepton final states have the highest sensitivity to measure the correlation between the spins of pair-produced top and anti-top quarks.

The observation of spin correlations would result in an upper limit on the lifetime of the top quark. This can be translated into a lower limit on the Kobayashi-Maskawa matrix element |V_{tb}|^2 without making assumptions about the number of quark generations. Moreover, many scenarios beyond the standard model predict different production and decay dynamics of the top quark, which could affect the observed spin correlation. In the analysis presented here, the double differential angular distribution is used. The double differential distribution for a measurement of spin correlations between top and antitop quark can be expressed as:

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C \cos\theta_1 \cos\theta_2),
\]

where \(\sigma\) denotes the cross section of the channel under consideration and \(C\) is a free parameter between -1 and 1 that depends on the choice of the spin basis. For this analysis the beam axis was chosen to be the spin quantization axis for which the value for the coefficient constant including NLO QCD corrections is \(C = 0.777\). For this measurement, we analyze the dileptonic decay channels where the W bosons from the top and antitop quark decay into an electron and an electron neutrino or into a muon and a muon neutrino. The ee channel with 1.1 fb^{-1}, the e\mu channel with 4.2 fb^{-1} and the \(\mu\mu\) channel with 1.1 fb^{-1} of integrated luminosity are analyzed separately and are then combined. The \(\cos\theta_1 \cos\theta_2\) distribution for the full sample is shown in Fig. 8. A likelihood fit for data gives a measured value for the spin correlation parameter \(C_{\text{meas}} = -0.09^{+0.59}_{-0.58}\) (stat + syst). The calibrated spin correlation coefficient \(C_{\text{true}} = -0.17^{+0.64}_{-0.53}\) (stat + syst) has been measured using Feldman-Cousins procedure and is shown in Fig. 9. This agrees with the standard model prediction for a spin 1/2 top quark of \(C = 0.777\) in NLO QCD within 2 standard deviations.

For analysis details please see Ref. [7].

### Table I

| Scenario Coupling | Coupling limit if \(f^+_1 = 1\) |
|-------------------|----------------------------------|
| \((L_1, R_1)\)   | \(|f^+_1|^2 = 1.27^{+0.48}_{-0.57}\) |
|                   | \(|f^+_1|^2 < 0.95\)            |
| \((L_1, L_2)\)   | \(|f^+_1|^2 = 1.27^{+0.60}_{-0.48}\) |
|                   | \(|f^+_1|^2 < 0.32\)            |
| \((L_1, R_2)\)   | \(|f^+_1|^2 = 1.04^{+0.55}_{-0.49}\) |
|                   | \(|f^+_1|^2 < 0.23\)            |

Figure 8: The \(\cos(\theta_1)\cos(\theta_2)\) distribution for full dilepton event sample. The sum of \(t\bar{t}\) signal including NLO QCD spin correlation \((C = 0.777)\) and multijet, diboson and Drell-Yan background is compared to data. The open black histogram shows the prediction without \(t\bar{t}\) spin correlation \((C = 0)\);

Figure 9: The 68%, 95%, and 99% C.L. band for \(C_{\text{true}}\) as a function of \(C_{\text{meas}}\). The thin, slanted line indicates the most probable value of \(C_{\text{true}}\) as a function of \(C_{\text{meas}}\) and represents therefore the bias of the method. The vertical black line depicts the measured value \(C_{\text{meas}} = -0.090\). The horizontal line indicates the NLO QCD value \(C_{\text{true}} = 0.777\).
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