Measurement of top quark properties at D0

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Summary. — We present a summary of the measurements of the top quark production and decay properties performed by the D0 experiment at the Fermilab Tevatron proton-antiproton collider at $\sqrt{s}=1.96$ TeV using 1 fb$^{-1}$ of data. We discuss the first simultaneous measurement of the ratio of branching fractions, $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$, with $q$ being a $d$, $s$, or $b$ quark, and the top quark pair production cross section $\sigma_{t\bar{t}}$, the first model-independent measurement of the helicity of $W$ bosons produced in the top quark decays, and the first measurement of the integrated forward-backward charge asymmetry in the production of $t\bar{t}$ pairs.

PACS 13.85.Rm – Limits on production of particles.
PACS 13.85.Qk – Inclusive production with identified leptons, photons, or other nonhadronic particles.
PACS 14.65.Ha – Top quarks.
PACS 14.70.Ha – W bosons.

1. – Introduction

The large sample of top-antitop quark pairs produced by the Fermilab Tevatron collider allows not only to perform precision measurements of such fundamental top quark characteristics as its production cross section and mass, but also to study a broad variety of top quark production and decay properties to address the question whether the top quark is indeed the particle predicted by the standard model (SM). Any deviation from the SM prediction would be an indication of the new physics. In this paper, we study the properties of top quark decay by measuring the ratio of top quark branching fractions, $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$ [1], and the W boson helicity [2]. We also report on a measurement of forward-backward ($fb$) charge asymmetry in $t\bar{t}$ production [3].

2. – Selection of $t\bar{t}$ candidates

To study top quark properties we mainly use the top quark pair decay channel where one $W$ boson from a top quark decays into two quarks, and the other one into an electron or muon and a neutrino, referred to as the lepton plus jets ($\ell$+jets) channel. We select
a data sample enriched in $t\bar{t}$ events by requiring a lepton and a jet at the trigger level. We further require at least four jets with transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$, one isolated electron (muon) with $p_T > 20$ GeV and $|\eta| < 1.1$ ($|\eta| < 2.0$), no other isolated lepton with $p_T > 15$ GeV, and missing transverse energy $E_T > 20$ GeV ($e+\text{jets}$) or $E_T > 25$ GeV ($\mu+\text{jets}$). The leading jet $p_T$ is required to exceed 40 GeV.

The dominant background in the selected sample is the production of $W$ bosons in association with heavy and light flavor jets ($W+\text{jets}$). Smaller contributions arise from $Z+\text{jets}$, diboson and single top quark production. We model $W/Z+\text{jets}$ production with the ALPGEN [4] Monte Carlo (MC) generator for the matrix element calculation and PYTHIA [5] for parton showering and hadronization. We use PYTHIA and SINGLE-TOp [6] event generators to model diboson processes and single top quark production, respectively. The sample also includes contribution from multijet events in which a jet is misidentified as an electron ($e+\text{jets}$ channel) or in which a muon originating from either a semileptonic decay of a heavy quark or an in-flight pion or kaon decay in a light flavor jet appears isolated ($\mu+\text{jets}$ channel). We determine multijet contribution from data. Details of the object identification, selection and background evaluation in $\ell+\text{jets}$ channel can be found elsewhere [7].

To improve the purity of the samples used for top quark property measurements and/or discriminate $t\bar{t}$ signal from background we use information about the presence of $b$ jets in the event. We identify $b$ jets using the algorithm which combines variables that characterize the presence and properties of secondary vertices and tracks with high impact parameter inside the jet into a neural network [8].

We also utilize kinematic information to separate $t\bar{t}$ events in the selected samples from the background. We consider kinematic variables which discriminate between the $t\bar{t}$ signal and background and combine them into a discriminant function. The selected variables are required to be well described by the background model. Neglecting the correlations between the input variables, the discriminant function can be approximated by the expression [7]:

$$D = \prod_i s_i(x_i)/b_i(x_i) / 1 + \prod_i s_i(x_i)/b_i(x_i),$$

where $s_i(x_i)$ and $b_i(x_i)$ are the normalized distributions of variable $i$ for signal and background, respectively. As constructed, the discriminant function peaks near zero for the background, and near unity for the signal. We use the discriminant distribution either to determine the fraction of $t\bar{t}$ events in a sample via a Poisson maximum-likelihood fit to data of a sum of signal and background discriminant distributions [1, 3], or to improve the purity of the samples by selecting events with high values of $D$ [2].

3. Simultaneous measurement of the ratio of branching fractions $R = \mathcal{B}(t \rightarrow Wb)/\mathcal{B}(t \rightarrow Wq)$ and $\sigma_{t\bar{t}}$.

Within the SM top quarks decay almost exclusively to a $W$ boson and a $b$ quark. This prediction is based on the requirements that there are three fermion families and the CKM matrix [9] is unitary. If these assumptions are relaxed, CKM matrix element $|V_{tb}|$ is essentially unconstrained, $|V_{tq}|$ elements can significantly deviate from their SM
values, and the ratio $R$ of the top quark branching fractions, which can be expressed as

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

can be different from unity. A precise measurement of $R$ allows to perform direct measurement, free of assumptions about the number of quark families or the unitarity of the CKM matrix, of the $|V_{tq}|$ elements via the combination with measurements of the single top quark production rates in $s$ and $t$ channels [10].

The probability for a $t\bar{t}$ event to have certain number of identified $b$ jets depends on the jet flavor, and therefore it depends on $R$. Fig 1(a) shows the fraction of events with 0, 1 and $\geq 2$ tagged jets as a function of $R$ for $t\bar{t}$ events with $\geq 4$ jets. If $R$ is close to zero, i.e., top quarks decay predominantly to $W$ bosons and light quarks, the probability to have a $t\bar{t}$ event with two $b$ tags is negligible while the probability to have no tags is close to 90%. Fig 1(b) shows the comparison of the number of data events with 0, 1 or $\geq 2$ $b$ tags to the prediction for the sum of background and $t\bar{t}$ signal with $R = 0, R = 0.5$ and $R = 1$.

![Fig. 1. – (a) Probability of $t\bar{t}$ events to have 0, 1 and $\geq 2$ $b$ tags as a function of $R$ for events with $\geq 4$ jets; (b) predicted sum of $t\bar{t}$ signal and background for $R = 0, 0.5$ and 1 compared to data in the 0, 1 and $\geq 2$ $b$ tag samples for events with $\geq 4$ jets.](image)

We measure the ratio $R$ using $\ell+$jets events with three or more jets. We split this sample into subsamples according to lepton flavor ($e$ or $\mu$), jet multiplicity (3 or $\geq 4$ jets) and number of identified $b$-jets (0, 1 or $\geq 2$), and extract $R$ and the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ simultaneously from the fit of the predicted numbers of $t\bar{t}$ signal and background events to the observed ones with 0, 1 and $\geq 2$ $b$ tags. For the events with $\geq 4$ jets and 0 $b$ tags, we include the shape of a topological discriminant in the fit. We build the discriminant function using simulated $W+$jets and $t\bar{t}$ events. For the latter we obtain a distribution for each of the three decay modes of $t\bar{t}$: $t\bar{t} \to W^+bW^-\bar{b}$, $t\bar{t} \to W^+bW^-\bar{q}_l$ (or $t\bar{t} \to W^+q_lW^-\bar{b}$) and $t\bar{t} \to W^+q_lW^-\bar{q}_l$, where $q_l$ denotes a light down-type ($d$ or $s$) quark. The systematic uncertainties are incorporated in the fit using nuisance parameters [11], each represented by a Gaussian term in the likelihood fit. The result of the fit is:

$$R = 0.97^{+0.09}_{-0.08} \text{ (stat + syst)}$$ and
\[ \sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84} \text{ (stat + syst)} \pm 0.50 \text{ (lumi) pb}, \]

for a top quark mass of 175 GeV. Fig 2 compares the distribution of the data to the sum of predicted background and measured signal for events with exactly three and \( \geq 4 \) jets. We extract a limit on \( R \) and \( |V_{tb}| \) following the Feldman-Cousins procedure [12] which yields \( R > 0.79 \) at 95% C.L. and \( |V_{tb}| > 0.89 \) at 95% C.L. The latter limit is derived assuming a unitary CKM matrix with three fermion generations. We also determine a model-independent limit of the ratio of \( |V_{tb}|^2 \) to the off-diagonal matrix elements to be \( \frac{|V_{ts}|^2}{|V_{tb}|^2 + |V_{td}|^2} > 3.8 \) at 95% C.L.

Fig. 2. – Predicted and observed number of events for the measured (a) \( R \) and \( \sigma_{t\bar{t}} \) in the 0, 1 and \( \geq 2 \) \( b \) tag samples for events with (a) three jets, (b) \( \geq 4 \) jets, and (c) predicted and observed discriminant distribution in the 0 \( b \) tag sample with \( \geq 4 \) jets

4. – Measurement of the \( W \) helicity in top quark decays

In the SM the \( Wtb \) top quark decay vertex has a \( V - A \) structure which defines the fractions of \( W \) bosons produced in each polarization state to be 0.697 \pm 0.012 [13] and \( 1.6 \times 10^{-4} \) [14] for the longitudinal \( (f_0) \) and right-handed \( (f_+ \) ) fractions, respectively, for a top mass of 172.5 GeV. Any significant deviation from these values will be a signal of new physics.

We measure the \( W \) helicity by studying the distribution of the angle \( \theta^* \), defined in the \( W \) boson rest frame, between the momentum of down-type fermion (charged lepton or \( d \) or \( s \) quark) from the \( W \) boson decay and the top quark. The distributions of \( \cos \theta^* \) expected for the pure right-handed, longitudinal and left-handed \( W \)'s are shown in fig 3(a).

The data sample used in this analysis includes \( \ell+\)jets events and dilepton events where both \( W \) bosons from top quarks decay into leptons \( (e \) or \( \mu \) ). We select such events by requiring two charged leptons with opposite charge and \( p_T > 15 \) GeV, and at least two jets with \( p_T > 20 \) GeV. To increase signal purity we built a topological discriminant in each of the five channels considered \( (ee, e\mu, \mu\mu, \mu+\text{jets, e+jets}) \) using the kinematic variables listed in tab 1. Variables \( NN_{b1} \) and \( \langle NN_b \rangle \), the output value of the neural network of the leading jet and the mean of the neural network outputs of the two leading jets, respectively, include information about jet flavors into the discriminant. Thus, instead of requiring a \( b \) tag in the event corresponding to a cut on \( NN_b \), we use the full \( NN_b \) distribution and avoid a loss of efficiency due to \( b \) tag requirement. An example of the discriminant distribution in the \( e+\)jets channel is shown in fig 3(b). In
Table 1. – Summary of the multivariate selection and number of selected events for each of the \( t\bar{t} \) final states in \( W \) helicity measurement. The uncertainties are statistical only, except for the background estimates in the \( ee \) and \( \mu\mu \) channels, in which systematic uncertainties arising from imperfections in the MC model of the data are included.

| Variables used in \( D \) | \( e+\text{jets} \) | \( \mu+\text{jets} \) | \( e\mu \) | \( ee \) | \( \mu\mu \) |
|-------------------------|----------------|----------------|----------|--------|--------|
| \( C, S, A, HT, h, k_{T_{\text{min}}}^I, \langle NN_b \rangle \) | 21.1 ± 4.5 | 33.0 ± 5.2 | 9.9 ± 2.5 | 2.2 ± 0.9 | 4.8 ± 3.4 |
| \( C, S, h, \langle NN_b \rangle \) | 121 | 167 | 45 | 15 | 15 |

For each channel we select a cut on \( D \) to achieve the best expected precision for \( W \) helicity. Tab 1 lists the cut values and the composition of each sample after the cut.

Fig. 3. – (a) Distribution of the \( \cos \theta^* \) for pure left-handed (green curve), right-handed (red) and longitudinal (black) \( W \) boson helicity; (b) distribution of discriminant for signal (open histogram) and background (green) in the \( e+\text{jets} \) channel.

To calculate \( \cos \theta^* \) we reconstruct events in \( \ell+\text{jets} \) channel using a kinematic fitter. The fitter varies the four-momenta of the objects in the event within their resolutions and minimizes a \( \chi^2 \) under the following constraints: i) both \( W \) boson masses are required to be exactly 80.4 GeV; ii) the masses of two reconstructed top quarks are required to be exactly 172.5 GeV. Among possible 12 solutions we choose the one with the best \( \chi^2 \) from the kinematic fit and with the maximim probability based on \( NN_b \) values of all four jets. In the dilepton channel, the kinematics are underconstrained. We reconstruct dilepton events assuming a top quark mass of 172.5 GeV. Each event provides two entries to the \( \cos \theta^* \) distribution. Fig 4 shows the reconstructed \( \cos \theta^* \) distributions for (a) leptonic and (b) hadronic \( W \) boson decays in \( \ell+\text{jets} \) channel, and (c) for dilepton channel. Although hadronic \( W \) decays do not allow to discriminate between left-handed and right-handed \( W \) bosons, they do add information on the longitudinal \( W \) boson fraction. Including the hadronic decays in the measurement improved the sensitivity by 20%.

We extract \( f_0 \) and \( f_+ \) from the binned Poisson likelihood fit of the sum of background and right-handed, left-handed, and longitudinal helicity templates for signal to data. The
measured values of $f_0$ and $f_+$ are:

$$f_0 = 0.425 \pm 0.166\text{(stat)} \pm 0.102\text{(syst)}$$

$$f_+ = 0.119 \pm 0.090\text{(stat)} \pm 0.053\text{(syst)}$$

with a correlation factor of -0.83. Fig 5 shows the result of the fit along with the 68% and 95% C.L. contours from the fit, including all uncertainties. The measured values are consistent with the SM, as there is a 30% chance to observe a larger discrepancy given the statistical and systematic uncertainties of the measurement. If $f_+$ is fixed to the SM value, we find

$$f_+ = 0.619 \pm 0.090\text{(stat)} \pm 0.052\text{(syst)}$$

and if $f_0$ is fixed to the SM value,

$$f_+ = -0.002 \pm 0.047\text{(stat)} \pm 0.047\text{(syst)}.$$

5. Measurement of the forward-backward charge asymmetry in $t\bar{t}$ production

Leading order calculations of $t\bar{t}$ production in $p\bar{p}$ collisions predict that the kinematic distributions of a top quark pair are charge symmetric. But this symmetry is accidental. At the higher orders top pair production is expected to be charge asymmetric. In
particular, at NLO the predictions range from 5% to 10% [15]. NNLO calculations [16] are not complete but deviate significantly from the NLO predictions. But in both cases expected asymmetry is small. If new physics is present in $t\bar{t}$ production, the observed asymmetry can be much larger than that predicted by the SM, thus making the charge asymmetry measurement a probe for new physics.

A charge asymmetry in $t\bar{t}$ production can be observed as a forward-backward integrated asymmetry defined as $A_{fb} = (N_f - N_b)/(N_f + N_b)$, where $N_f$ ($N_b$) is the number of events with a positive (negative) $\Delta y$ and $\Delta y = y_t - y_{\bar{t}}$ is the signed difference between top and anti-top quark rapidities. The studies using events simulated with MC@NLO event generator [17] showed that integrated asymmetry strongly depends on the region of phase space under study. In particular, we observe large variations of asymmetry from $+8\%$ to $-3\%$ as a function of the fourth highest particle jet $p_T$. It also shows a strong dependence on the number of jets in the event.

For this measurement we select $\ell+\text{jets}$ events with at least four jets, one of which is required to be identified as a $b$ jet by the neural network algorithm. We reconstruct the kinematics of the top quark pairs using the kinematic fitter described above with the difference that top quark mass is assumed to be 170 GeV. We use the $b$-tagged and the three remaining highest $p_T$ jets in the fit, thus reducing the number of possible parton-jet assignments considered in the fit. We select the solution with the lowest $\chi^2$.

We build a discriminant to separate $t\bar{t}$ signal from the background using the following variables: i) the $p_T$ of the leading $b$-tagged jet, ii) the $\chi^2$ of the kinematic fit, iii) the invariant mass of two jets assigned to $W$ boson by the fit, and iv) $k_T^{\text{min}} = p_T^{\text{min}} R^{\text{min}}$, where $R^{\text{min}}$ is the smallest angular distance between any two jets used in kinematic fit, and $p_T^{\text{min}}$ is the smaller of these two jets’ transverse momenta.

We extract the $t\bar{t}$ content and $A_{fb}$ simultaneously by performing a maximum-likelihood fit of the sum of backgrounds and backward and forward signal to the discriminant distribution in data and to the sign of the reconstructed $\Delta y$. Forward and backward signal have the same discriminant distribution but different sign of the reconstructed $\Delta y$. The fitted sample composition compared to the discriminant distribution in data for events with $\geq 4$ jets is shown in fig 6. We measure asymmetry for events with $\geq 4$, $= 4$ and $\geq 5$ jets. We find $A_{fb} = (12 \pm 8\%)$, $A_{fb} = (19 \pm 9\%)$, and $A_{fb} = (-16^{+15}_{-17})\%$, respectively, consistent with the NLO predictions from MC@NLO.

![Fig. 6. – Distribution of the discriminant for data and a sum of $t\bar{t}$ signal and background for events reconstructed as forward ($\Delta y_{\text{reco}} > 0$) (a) and backward ($\Delta y_{\text{reco}} < 0$) (b).](image-url)
such comparison. We have chosen the latter option since correction can reduce sensitivity to the effects beyond the SM. We define the asymmetry at the particle level as

$$A_{fb}(\Delta y) = \frac{g(\Delta y) - g(-\Delta y)}{g(\Delta y) + g(-\Delta y)},$$

where $g$ is the probability density for generated $|\Delta y|$ within the acceptance. Since the measured asymmetry can be diluted due to misreconstruction of the event kinematics or misidentification of the lepton charge the predicted reconstructed asymmetry is given by

$$A_{fb}^{\text{pred}} = \int_0^\infty A_{fb}(\Delta y) D(\Delta y) [g(\Delta y) + g(-\Delta y)] d\Delta y$$

where $D$ is the dilution function. It is defined as $D = 2P - 1$, where $P$ is the probability to reconstruct the correct sign of $\Delta y$. This function is determined using simulated $t\bar{t}$ events passed through the full reconstruction chain. Dilution represents the fraction of asymmetry visible in the detector and is parameterized as

$$D(|\Delta y|) = c_0 \ln(1 + c_1 |\Delta y| + c_2 |\Delta y|^2),$$

where the parameters depend on the number of jets in the event. The dependence of the dilution function on $|\Delta y|$ introduces model dependence into any correction of $A_{fb}$ from the observed to the particle-level asymmetry as they depend on the model’s $A_{fb}(\Delta y)$ shape. An example of the dilution function is shown in fig 7(a) and the parameters can be found in [3].

A contribution from the new physics can affect the $t\bar{t}$ forward-backward charge asymmetry. Here we consider the sensitivity of the measurement to $t\bar{t}$ production via heavy neutral gauge bosons ($Z'$) decaying predominantly to quarks. We study the scenario where the coupling between the $Z'$ boson and the quarks is proportional to that of $Z$ boson and the quarks, and the interference effects with the SM $t\bar{t}$ production are negligible. Unlike the direct searches of $Z'$ [18] the asymmetry measurement is sensitive to the production of both narrow and wide resonances. We simulated $t\bar{t}$ events produced via narrow $Z'$ resonance as in [18] using PYTHIA and found large positive asymmetries ranging from 13% to 35% depending on the resonance mass. We predict the distribution of $A_{fb}$ as a function of the fraction of $t\bar{t}$ events produced via $Z'$ for each $Z'$ mass and set limits following the Feldman-Cousins procedure [12] (see fig 7(b)).

6. – Summary

In summary, we have presented the measurements of the production and decay properties of the top quark. All measurements are consistent with the SM. The large data set collected at the Tevatron will allow more precise measurements of the top quark properties in the near future and facilitate searches for new physics in the top quark sector.

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(a) (b)

Fig. 7. – (a) The geometric dilution and its uncertainty band as a function of generated $|\Delta y|$ for the standard model $t\bar{t}$ production and $\geq 4$ jets; (b) 95% C.L. limits on the fraction of $t\bar{t}$ produced via a $Z'$ resonance as a function of the $Z'$ mass. Expected (observed) limits are shown by the dashed (solid) curve. Shaded bands correspond to one and two standard deviations from the expected limit. The excluded region is hatched.