# Top quark properties at CDF

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The top-quark properties are of special interest for testing standard model predictions and for indirect searches for new physics due to the large mass of the top-quark, probing very short distances, and its uniquely short life time, eliminating hadronization complexities. We present recent measurements of the top-quark decay branching ratio, constraining the $|V_{tb}|$ matrix element of the CKM matrix; of the helicity fractions of the W boson in the top-quark pair deacys in the semi-leptonic channel; of the spin correlation of the top-quark pair in the all-leptonic decay channel; and of the top-quark charge in the all-leptonic decay channel. All measurements are using CDF Run II sample

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## 1. Introduction

The top quark was discovered in 1995 by CDF and D0 experiments at Tevatron [1][2]. Since then a lot of effort are done to study this heaviest particle in the Standard Model (SM). To date most of the results agree well with the SM predictions, except the production asymmetry.

The top (anti-top) quark decays into $W^+$ ($W^-$) boson and b (anti-b) quark. Depending on how the W bosons decay, the events are selected into the lepton plus jets [LJ] channel, where only one W boson decays leptonically, and di-lepton [DIL] channel, where both W bosons decay leptonically. In the following secstions, various properties of top quark are are reported from CDF experiments for both LJ and DIL channels.

## 2. Event Selection

In both LJ and DIL channels there are either one or two neutrinos missing in the detection, which causes high missing transverse energy. The requirements of lepton(s) with high transverse momentum and high missing transverse energy are very effective in rejecting the QCD background.

The leptons are required to have transverse momentum larger than 20 GeV. And it is required that the primary lepton(s) are in the center region, $|\eta| < 2$ or smaller.

Since in case of top decay there are high energy leptons, jets and neutrinos, the total transverse energy should be high, where the total transverse energy is the sum of transverse momentum/energy of leptons, jets and the missting transverse enrgy. At CDF it is required to be greater than 200 GeV. In order to further reject the QCD background, it is useful to require that at least one jet is from b quark decay. Since b quark has large $c\tau$, one can reconstruct the secondary vertex from the tracks inside the jet and require that it is down stream of the primary vertex. This is refered to as SecVtx b tagging at CDF. For the LJ channel this is essential but in case of DIL events this is useful only to produce the purest samples of top quark.

In case of DIL events, one dominant background is from the Z boson decaying to ee or $\mu\mu$. To select the top DIL candidates it is important to suppress the Z boson events. In case of top candidates the two leptons are from W boson decay so there are larger missing transverse energy due to the two neutrinos. For the Z boson decay the missing transverse energy comes from miss measurement of the jet energy. At CDF the suppressing of Z boson events is accomplished by requiring missing transverse energy significance > 4, when the invariant mass of ee or $\mu\mu$ are within the mass range of Z boson, 76 GeV < $m_{ll}$ < 106 GeV.

The DIL events should have two or more jets due to the two b quarks. For the LJ events there are four or more jets due to the two *b* quarks and the two quark jets from the W boson decay.

## 3. Measurement of branching ratio and width

In the Standard Model, the top quark decay rate is proportional to $\left|V_{tq}\right|^2$, the Cabibbo-Kobayashi-Maskawa (CKM) matrix element. Since the assumption of three generation of quarks and the unitarity of the CKM matrix lead to $\left|V_{tb}\right|^2 = 0.99915^{+0.00003}_{-0.00005}$ [3], it can be assumed that top quark decays exclusively to Wb. A direct measurement of $|V_{tb}|^2$ matrix element can be obtained measuring the single top production cross section, but a value can be extracted from the top quark decay rate in the $t\bar{t}$ channel. It is possible to define R as the ratio of the branching fractions:

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

The measurement of R is performed using LJ data samples corresponding to 8.7 $fb^{-1}$ collected at the CDF detector at $\sqrt{s}$ =1.96 TeV. The selected samples are divided into 18 subsamples with combinations of number of jets(3,4 and $\geq$5), number of b-tag(one and two) and three lepton type, where we estimate the $t\bar{t}$ and background processes content. In order to compare the prediction to the observed data we use a Likelihood function. Our procedure simultaneously fits, by mimuzing the negative logarithm of the Likelihood for R and $\sigma(p\bar{p} \to t\bar{t})$. The fiited results for the $\sigma$ and R are 7.5±1.0 pb and 0.94±0.09 respectively, which are in agreement with the Standard Model predictions. Assuming three generation of quarks and the unitarity of the CKM matrix, we have $|V_{tb}|^2+|V_{ts}|^2+|V_{td}|^2 = 1$, leading to $R = |V_{tb}|^2$. From the fit result, the $|V_{tb}| = 0.97\pm0.05$.

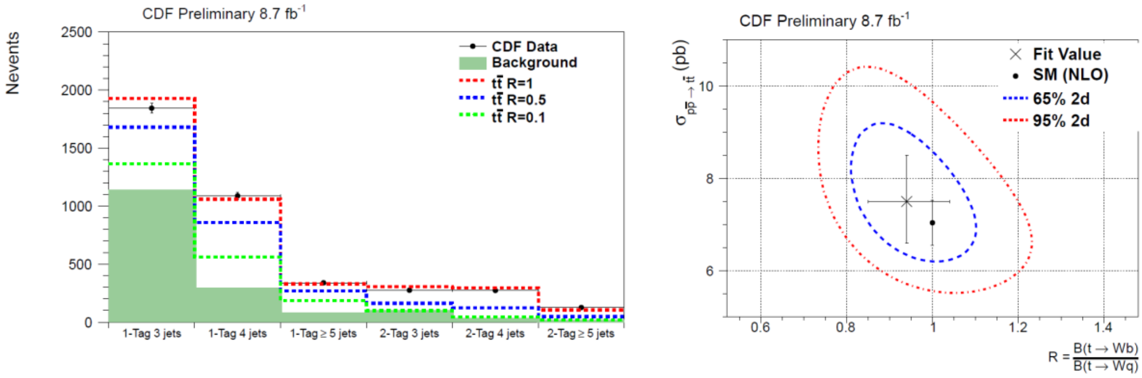


Figure 1. Data and SM expected events are compared for different values of R as a function of different final states(Left). Two dimensional contours for the combined statistical plus systematic fit(Right).

The top quark width was measured using LJ samples of 4.3 $fb^{-1}$ data. The top-quark mass and the mass of W boson that decays hadronically are reconstructed for each event and compared with templates of different top-quark widths ($\Gamma_t$) and deviations from nominal jet energy scale ($\Delta_{JES}$) to perform a simultaneous fit for both parameters, where $\Delta_{JES}$ is used for the in situ calibration of the jet energy scale. By applying a Feldman-Cousins approach, we establish an upper limit at 95% confidence level(CL) of $\Gamma_t < 7.6$ GeV and a two-sided 68% CL interval of $0.3 \text{ GeV} < \Gamma_t < 4.4$ GeV for a top-quark mass of 172.5 GeV, which are consistant with the Standard Model prediction.

## 4. Spin Correlation

The standard model predicts the top quark retain its original polarization at the production until decay, and due to the decay via parity violating weak interaction, the information of the parent top polarization is transfered to decay products. This means we can directly observe the polarization of top quark spin when it's produced, and of powerful use to a probe of $t\bar{t}$ production mechanism. The spin-spin correlation at $t\bar{t}$ production is expected to be observed through correlations between flight directions of decay products. In this analysis, we measure κ, the correlation coefficient at the $t\bar{t}$ decay in the dilepton channel, where $t\bar{t}$ is supposed to decay with the following differential cross section and decay rate:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

where $\theta_+ (\theta_-)$ denotes the angle of flight direction positive lepton(negative lepton) with respect to the quantization axis of the top (anti-top) quark.

Using 5.1 $fb^{-1}$ DIL data, we compared the distribution of reconstructed ($\cos\theta_+$, $\cos\theta_-$) and ($\cos\theta_b, \cos\theta_{\bar{b}}$) in data with SM predictions. Those distributions hardly depend on κ. Then we calculate $\kappa^{meas}$ using unbinned likelihood method for the signal template of various $\kappa^{true}$. We observed $\kappa^{meas} = 0.04 \pm 0.056$. For LJ samples of 5.3$fb^{-1}$ data, we observed $\kappa^{meas} = 0.72 \pm 0.69$. The observed κ are consistent with the one of the SM.

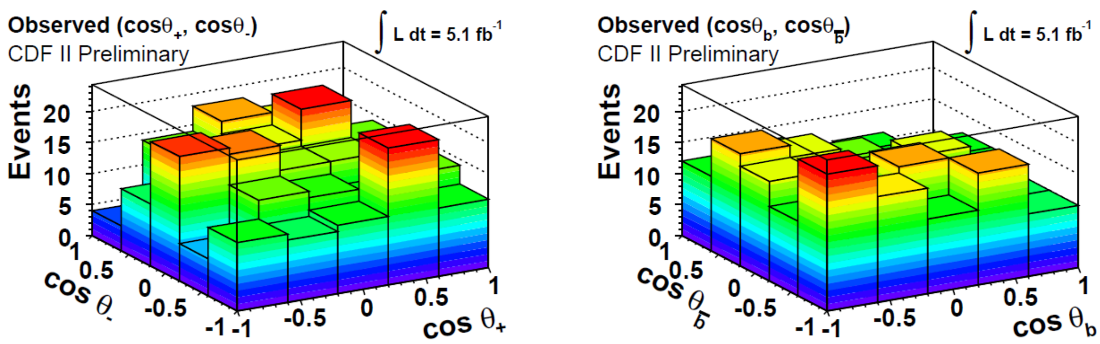


Figure 2. Distributions of ($\cos\theta_+$, $\cos\theta_-$) and ($\cos\theta_b, \cos\theta_{\bar{b}}$), which are observed in data of 5.1$fb^{-1}$.

## 5. W helicity

Measurement of the polarization of the W boson from top-quark decay provides a clean probe for testing the V −A structure of the weak interaction in the Standard Model. Due to its large mass, in the SM the top quark decays before forming a bound state via the charged current weak interaction into a $W^+$ boson and a b quark, with a branching fraction above 99%. In the SM at tree level [4], the $W^+$ boson is expected to have longitudinal polarization $f_0 = 0.696$, left-handed polarization $f_- = 0.303$, and right-handed polarization $f_+ = 3.8 \times 10^{-4}$ for a top-quark mass $m_t = 172.5$ GeV, a W boson mass $M_W = 80.4$ GeV, and a b-quark mass $m_b = 4.79$ GeV.

The uncertainties on the values of $m_t$, $M_W$ and $m_b$ change the predictions at less than 1% (relative) level. The higher-order QCD and electroweak radiative corrections modify these predictions at the 1-2% (relative) level.

The helicity fractions of the W boson from top quark decay has been measured using 5.1 $fb^{-1}$ DIL samples and 8.7 $fb^{-1}$ LJ samples. We use cos $\theta^*$ distribution to determine W boson helicity fractions, where $\theta*$ is the angle between momentum of the charged lepton (or down type quark) in the W rest frame. Since the reconstructed cos $\theta^*$ distribution is distorted from the theoretical one by many factors (selection, reconstruction, etc.), we use the template method. We get the estimate of W boson helicity fractions by comparing the cos $\theta^*$ distribution from data to the simulated cos $\theta^*$ distributions (templates) obtained for left-handed, longitudinal and right-handed W bosons respectively. The measured helicity fractions are $f_0$ = 0.71±0.18(stat.)±0.06(syst.) [DIL] , 0.726±0.066(stat.)± 0.067(syst.) [LJ] and $f_+$ = -0.07 ±0.09(stat.)±0.03(syst.) [DIL] and -0.045±0.043(stat.)± 0.058(syst.), which are in good agreement with SM predictions,

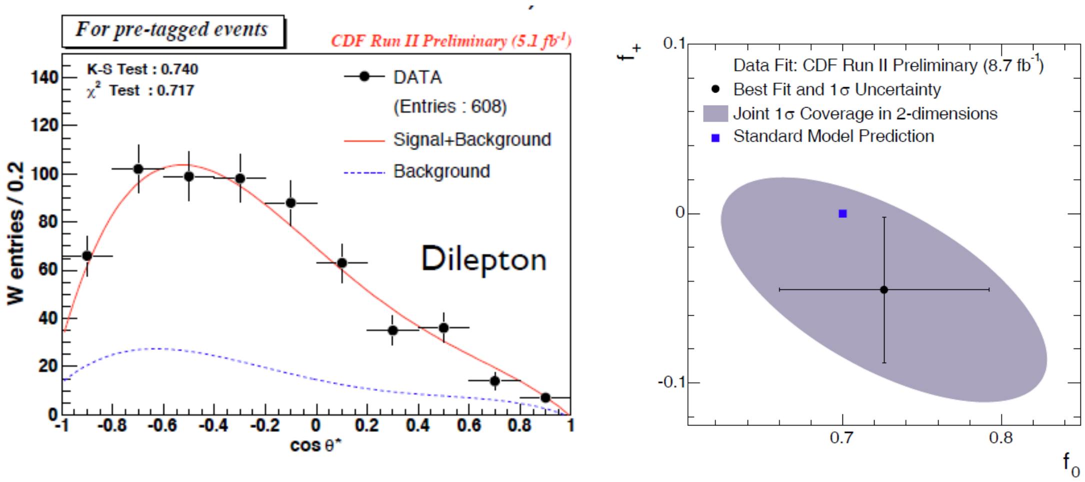


Figure 3. cos$\theta^*$ distribution comparison between data and expected signal and background for DIL samples(left). Data-fit results for simultaneous measurement of $f_0$ and $f_+$ using LJ samples(Righ).

## 6. Top quark charge

Determining whether the top quark decays into a $W^+$ and a bottom quark while the anti-top quark decays to a $W^-$ and an anti-bottom quark would ensure indirectly that the charge of the top quark is indeed +2/3 as is the charge of the top quark in the standard model. If these events were found to have an object decaying to a $W^-$ and a bottom quark, the charge of this object would be −4/3 and would not correspond to the standard model top quark. Such an hypothesis(XM) has been put forward [5] and proposes that this new particle would be an exotic quark, part of a fourth generation of quarks and leptons. These authors also calculate that the standard model top quark would be at a mass > 230 GeV.

There are three main ingredients to this analysis: determining the charge of the W (using the charge of the lepton), pairing the W with the b jet to ensure that they are from the same top decay branch and finally getting the flavor of the b jet using the Jet Charge algorithm.

We assemble these ingredients such that events where the charge of the lepton is opposite to the Jet Charge value are assigned to the SM hypothesis while events where the charge of the lepton is of the same sign as the Jet Charge value are assigned to the exotic quark hypothesis. Using $5.6\mathrm{fb}^{-1}$ of data we found 416 SM like pairs and 358 XM like pairs and the result is consistent with the Standard Model prediction, while excluding an exotic quark hypothesis with 99% confidence level.

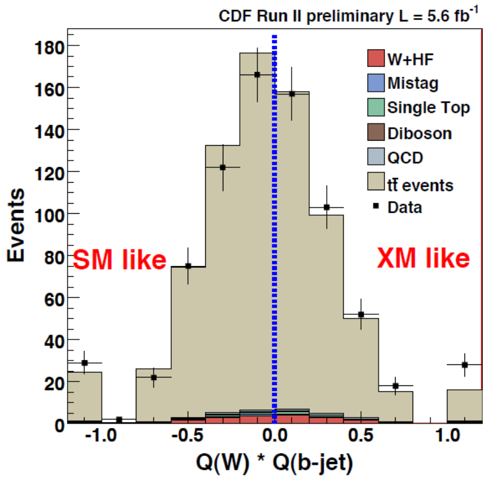


Figure 4. W charge × JetQ. SM-like pairs are on the negative side of the plot while XM-like pairs are on the positive side.

## 7. Conclusion and summary

Measurements of the top-quark decay branching ratio, constraining the $|V_{tb}|$ matrix element of the CKM matrix, the width, the helicity fractions of the W boson in the top-quark pair deacys in the semi-leptonic channel, the spin correlation of the top-quark and the top-quark charge are performed using lepton-jet and dilepton samples of CDF Run II data. All measuremets show consistency with the Standard Model predictions.

## References

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