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Top Quark Properties from Top Pair Events and Decays

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Over a decade since the discovery of the top quark we are still trying to unravel mysteries of the heaviest observed particle and learn more about its nature. The continuously accumulating statistics of CDF and DØ data provide the means for measuring top quark properties with ever greater precision and the opportunity to search for signs of new physics that could be manifested through subtle deviations from the standard model in the production and decays of top quarks. In the following we present a slice of the rich program in top quark physics at the Fermilab Tevatron: measurements of the properties of top quark decays and searches for unusual phenomena in events with pair produced tops. In particular, we discuss the most recent and precise CDF and DØ measurements of the transverse polarization of W bosons from top decays, branching ratios and searches for flavor-changing neutral current decays, decays into charged Higgs and invisible decays. These analyses correspond to integrated luminosities ranging from 0.9 to 2.7 fb^{-1}.

1. INTRODUCTION

The Tevatron $p\bar{p}$ collider operates at a center-of-mass energy $\sqrt{s} = 1.96$ TeV. Top quarks are produced mainly strongly in pairs and, within the standard model (SM), decay almost exclusively into a W boson and a b-quark via the weak interaction. Therefore, any deviation in the V-A structure of the $t \to Wb$ decay or evidence for more exotic final states would be indicative of new physics. Both the CDF and DØ Collaborations study the detailed kinematics of the products from $t \to Wb$ decay and search for non-SM contributions. These will be summarized in this report.

2. MEASUREMENT OF W HELICITY IN TOP DECAYS

The helicity of the W bosons in top decays is defined by the V-A structure of the tWb vertex and can be accessed through the kinematics of the W decay products. The alignment of the W spin can be characterized by the angle $\theta^\star$ between the W momentum vector in the top quark rest frame and the momentum of the down-type fermion in the W rest frame. The SM predicts the fraction of longitudinally polarized W bosons to be $f_0 \approx 70\%$, the fraction of left-handed Ws $f_- \approx 30\%$, while the right-handed fraction f_+ is greatly suppressed by the V-A structure of the decay.

The CDF Collaboration has performed three independent measurements of the longitudinal f_0 and right-handed f_+ fractions of the helicity of the W boson using lepton + jets events with at least one secondary-vertex tag (b-tag) in 1.9 fb^{-1} of data. The first method relies on the matrix element technique [1]. In this measurement, the fractions are set to $f_+ = 0$ and $f_- = 1 - f_0$. The two other techniques focus on measuring the $\cos\theta^\star$ distribution in kinematically reconstructed $t\bar{t}$ final states. In one case ("unfolding technique") the observed $\cos\theta^\star$ distribution is corrected by subtracting the background and accounting for bin-to-bin migration of $t\bar{t}$ events from true to reconstructed values of $\cos\theta^\star$. In the other analysis ("template method") templates of $\cos\theta^\star$ for $t\bar{t}$ with different W polarizations and backgrounds after event reconstruction are fitted to the data. Both analyses perform 1-parameter fits (fixing f_0 or f_+ to their SM values) and 2-parameter fits by simultaneously extracting the f_0 and f_+ fractions. The results of these two analyses have been further combined using the BLUE technique [2]. The summary of CDF results is presented in Table I.

The DØ Collaboration measures the W polarization using the template technique in 2.7 fb^{-1} of data in both dilepton and lepton + jets event topologies. The lepton + jets events are fully reconstructed, and the information in the $W \to q\bar{q}$ decays is also sampled by randomly picking the down-type quark as one of the jets associated with the W boson. Dileptons are reconstructed within their eight-fold ambiguity, and the average of $\cos\theta^\star$ for all solutions is used in the extraction of helicity. Results of DØ measurement are also given in Table I. All results are consistent with their SM values.

Table I: Summary of W helicity measurements.

Experiment	Channel	Technique	f_0	f_+
CDF	ℓ+jets	Matrix Element	0.64 ± 0.08 (stat) ± 0.07 (syst)	fixed to 0.0
CDF	ℓ+jets	$\cos\theta^\star$ Unfolding	0.38 ± 0.21 (stat) ± 0.07 (syst)	0.15 ± 0.10 (stat) ± 0.04 (syst)
	ℓ+jets	fixed f_0 or f_+	0.66 ± 0.10 (stat) ± 0.06 (syst)	0.01 ± 0.05 (stat) ± 0.03 (syst)
CDF	ℓ+jets	$\cos\theta^\star$ Template	0.65 ± 0.19 (stat) ± 0.03 (syst)	-0.03 ± 0.07 (stat) ± 0.03 (syst)
	ℓ+jets	fixed f_0 or f_+	0.59 ± 0.11 (stat) ± 0.04 (syst)	-0.04 ± 0.04 (stat) ± 0.03 (syst)
CDF	ℓ+jets	$\cos\theta^\star$ Combination	0.66 ± 0.16	-0.03 ± 0.07
	ℓ+jets	fixed f_0 or f_+	0.62 ± 0.11	-0.04 ± 0.05
DØ	$\ell\ell, \ell$+jets	$\cos\theta^\star$ Template	0.49 ± 0.11 (stat) ± 0.09 (syst)	0.11 ± 0.06 (stat) ± 0.05 (syst)

3. MEASUREMENT OF $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$

Within the SM, the top quark decays to a W boson and a down-type quark q ($q = d, s, b$) with a rate proportional to $|V_{tq}|^2$. The ratio R of the branching fractions of top decays to Wb relative to Wq can be expressed in terms of the CKM matrix elements as

$$R = \frac{\mathcal{B}(t \to W^+ b)}{\mathcal{B}(t \to W^+ q)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} \quad (1)$$

The average number of b-tagged jets in a $t\bar{t}$ event depends directly on the value of R and the probability of tagging a b-quark. The DØ collaboration measured R simultaneously with the $t\bar{t}$ cross section ($\sigma_{t\bar{t}}$), basing their result on the observed multiplicity distribution of b-tags shown in Fig. 1. A simultaneous likelihood fit to these two variables yields $R = 0.97\ ^{+0.09}_{-0.08}$ and $\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84}$ (stat + syst) $\pm$ 0.50 (lumi). The observed value of R is translated to a lower limit at 95% confidence level using the Feldman-Cousins ordering principle [3], giving $R > 0.79$ at 95% C.L. Assuming a unitary CKM matrix with three fermion generations yields $|V_{tb}| > 0.89$ at 95% C.L.

4. SEARCH FOR CHARGED HIGGS

Charged Higgs $H^\pm$ bosons are predicted in supersymmetric and GUT extensions of the SM. If a charged Higgs boson is sufficiently light, it can be produced in top quark decays. In the presence of a charged Higgs boson, the $t \to H^+ b$ decay would compete with the SM top quark decay $t \to W^+ b$, thereby altering the expected number of events in different final states of $t\bar{t}$. The event migration among different final states depends on the decays of $H^\pm$. Within the MSSM, $H^+ \to c\bar{s}$ dominates at low $\tan\beta$, while $H^+ \to \tau\nu$ dominates at high $\tan\beta$.

The DØ Collaboration has considered the $\mathcal{B}(H^+ \to \tau\nu) = 100\%$ and "leptophobic" $\mathcal{B}(H^+ \to c\bar{s}) = 100\%$ scenarios, and measured the $t\bar{t}$ event yields in the dilepton ($\ell = e, \mu$), the τ+ lepton, and the lepton + jets channels, which are constructed to be orthogonal to each other. For different values of $\mathcal{B}(t \to H^+ b)$ the expected and observed numbers of events in the explored final states are shown in Fig. 1. No indication was found for charged Higgs boson production in the τ or leptophobic mode. The 95% C.L. limits on $\mathcal{B}(t \to H^+ b \to \tau\nu b)$ and $\mathcal{B}(t \to H^+ b \to c\bar{s}b)$ as a function of $H^\pm$ mass are presented in Fig. 1 and Fig. 2 respectively.

The CDF Collaboration has also searched for the decays $t \to H^+ b \to c\bar{s}b$ in the lepton + jets events by fully reconstructing $t\bar{t}$ decay and exploiting the difference between the dijet mass spectra in $W \to q\bar{q}'$ and $H^+ \to c\bar{s}$ decays. The invariant dijet mass spectrum in data is presented in Fig. 2. No significant deviation from the SM is observed, and limits are set on the $\mathcal{B}(t \to H^+ b \to c\bar{s}b)$ as a function of the charged Higgs mass shown in Fig. 2.

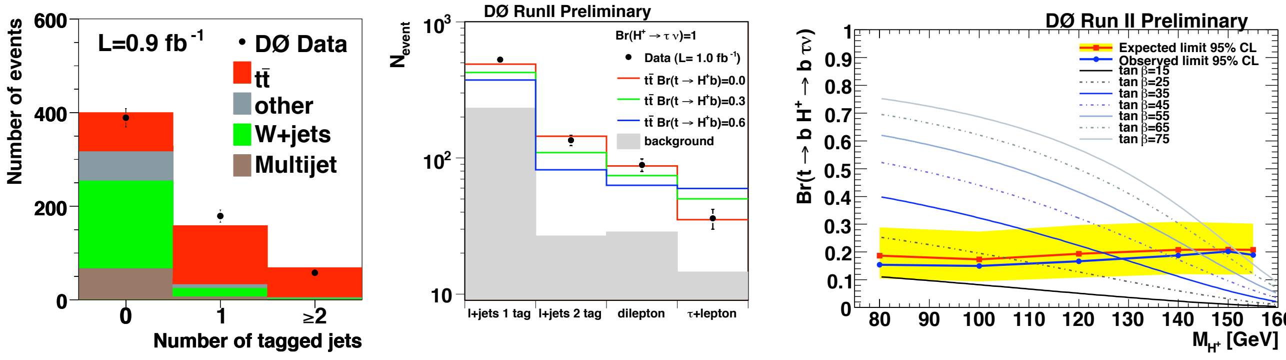

Figure 1: **LEFT:** Predicted and observed number of events with 0, 1 and $\geq$ 2 b-tags in the sample of lepton + $\geq$ 4 jets. **CENTER:** Expected (for several $\mathcal{B}(t \to H^+b)$) and observed number of events in final states of $t\bar{t}$ decays. **RIGHT:** The upper limit on $\mathcal{B}(t \to H^+b \to \tau\nu b)$ at 95% C.L. as a function of charged Higgs mass.

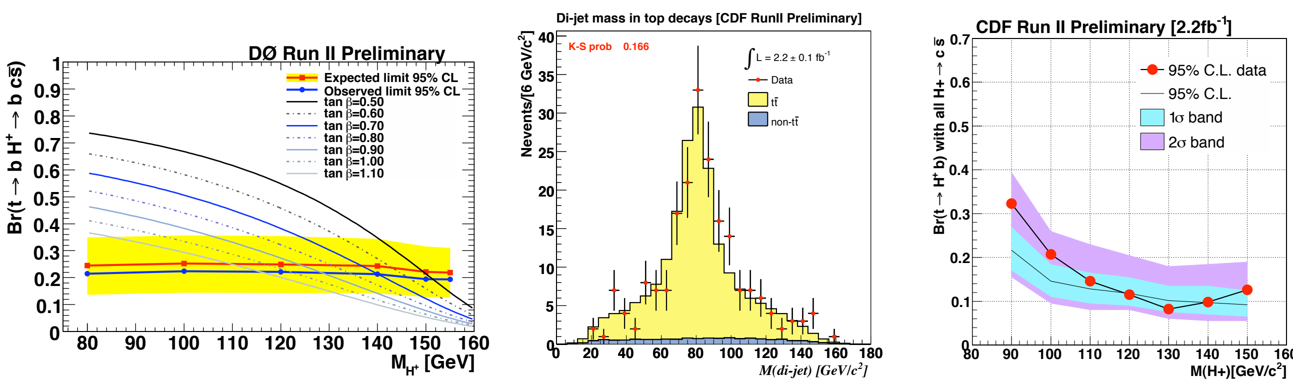

Figure 2: **LEFT:** The upper limit on the $\mathcal{B}(t \to H^+b \to c\bar{s}b)$ at 95% C.L. as a function of charged Higgs mass. **CENTER:** Distribution of di-jet mass in $t\bar{t}$ decays. **RIGHT:** The upper limit on the $\mathcal{B}(t \to H^+b)$ at 95% C.L. as a function of $m_{H^\pm}$.

5. SEARCH FOR FLAVOR-CHANGING NEUTRAL CURRENT DECAYS $t \to Zq$

In the SM, flavor-changing neutral current (FCNC) decays are highly suppressed, with expected branching fractions $\mathcal{B}(t \to Zq) \approx \mathcal{O}(10^{-14})$. In SUSY and two-Higgs doublet models branching ratios are higher, up to $\mathcal{O}(10^{-2})$ [4].

The CDF Collaboration has performed a search for FCNC top decays $t \to Zq$ using $Z \to \ell^+\ell^-(\ell = e, \mu)$ events with four and more jets and optimized selection. Events in the signal region are further classified according to availability of a secondary vertex (b-tag). A third sample is used as a control region and consists of rejected events that failed at least one of the optimized selection criteria.

The signal is discriminated from background by exploring kinematic constraints present in FCNC events: $t\bar{t} \to WbZq \to q\bar{q}b\ell^+\ell^-q$. A χ^2 variable is defined using reconstructed $bq\bar{q}$ and $q\ell^+\ell^-$ masses, their uncertainties and the accepted values of the top and W mass:

$$\chi^2 = \left(\frac{m_{q\bar{q},rec} - m_W}{\sigma_{W\to q\bar{q}}}\right)^2 + \left(\frac{m_{bq\bar{q},rec} - m_t}{\sigma_{t\to bq\bar{q}}}\right)^2 + \left(\frac{m_{q\ell^+\ell^-,rec} - m_t}{\sigma_{t\to q\ell^+\ell^-}}\right)^2. \quad (2)$$

This quantifies the consistency of each event with originating from a FCNC decay. Templates of this variable are generated for the main background, and for the FCNC signal. Shape systematic uncertainties are included in the templates. The χ^2 template fit is performed simultaneously in two signal regions and the control region. Results of the fit are consistent with the χ^2 distribution for background alone. A top quark mass of 175 GeV/c^2 yields an upper limit of $\mathcal{B}(t \to Zq) < 3.7\%$ at 95% C.L. based on the Feldman-Cousins prescription (see Fig. 3).

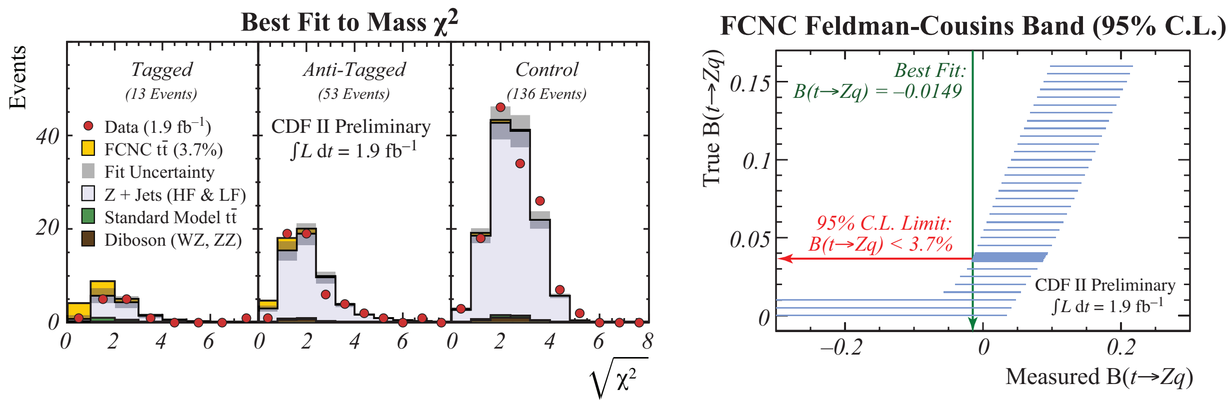

Figure 3: **LEFT:** χ^2 distribution for two signal regions, with ≥ 1 b-tag and no b-tags, and the control region. **RIGHT:** Feldman-Cousins band at 95% C.L. The measured value yields an upper limit of $\mathcal{B}(t \to Zq) < 3.7\%$ at 95% C.L.

6. SEARCH FOR INVISIBLE TOP DECAYS

The CDF Collaboration has also performed a generic search for alternative top decays by measuring the yield of the lepton + jets events with two b-tags and quantifying the deficit from the value expected for the theoretical $t\bar{t}$ production cross section. By evaluating the relative acceptance $\mathcal{R}_{WX/WW} = \mathcal{A}(t\bar{t} \to WbXY)/\mathcal{A}(t\bar{t} \to WbWb)$, where XY comprise non-standard decay, and constructing Feldman-Cousins bands that relate the true branching fraction for the considered decay to the number of observed lepton + jets events, CDF sets 95% C.L. limits on the branching ratios. Results are listed in Table II for several masses of the top quark. Invisible top decays correspond to decay products that escape detection and do not contribute to the lepton + jets final state.

Table II: 95% C.L. upper limits for branching ratios of top decays as a function of mass.

Decay	$\mathcal{R}_{WX/WW}$(%)	**Limit** (175 GeV)	**Limit** (172.5 GeV)	**Limit** (170 GeV)
$t \to Zc$	32	0.13	0.15	0.18
$t \to gc$	27	0.12	0.14	0.17
$t \to \gamma c$	18	0.11	0.12	0.15
$t \to$ invisible	0	0.09	0.10	0.12

7. CONCLUSIONS

We presented most recent CDF and DØ precision measurements of the properties of the top quark. The results are in agreement with predictions of the SM. Both experiments have set stringent limits on branching ratios for several decays beyond the SM.

References

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