TOP TO CHARGED HIGGS DECAYS AND TOP PROPERTIES AT THE TEVATRON

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CDF AND DØ COLLABORATIONS

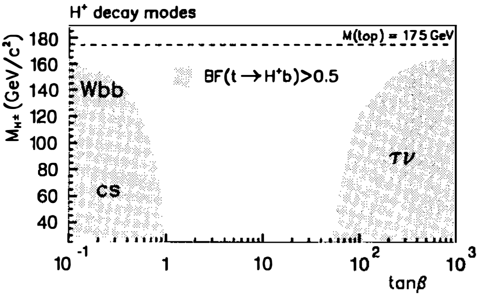
The Tevatron experiments have measured top quark properties in addition to the top quark mass and pair production cross section. These measurements are based on 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV recorded by CDF and 125 pb^{-1} of data recorded by DØ during the years 1992-95. We describe two separate techniques which exploit the top data samples to exclude large branching fractions of the top quark to a charged Higgs boson. We also determine the fraction of longitudinal W bosons produced in top quark decays to be 0.55 ± 0.34, compared to the standard model prediction of 0.71. Other top branching fraction measurements, kinematic studies, and searches for rare decays are summarized.

1 Introduction

The CDF and DØ collaborations each measure a top quark mass M_{top} of about 175 GeV/c^2 [1], and a value for the $t\bar{t}$ cross section which is consistent [2] with the theoretical range $\sigma_{t\bar{t}} = 4.7$-5.8 pb [3]. In this summary, we emphasize our recent searches for top quark decays to a charged Higgs boson ($H^{\pm}$), as well as our measurement of W-helicity fractions in top decays. Other top branching fraction measurements, kinematic studies, and searches for rare decays will be summarized.

2 Searches for Top Quark decays to a charged Higgs Boson using the Top Data

Charged Higgs bosons are interesting because they are required by supersymmetric models, and their discovery would suggest that electroweak symmetry breaking occurs in a Higgs sector containing two doublets, rather than just one as required by the minimal standard model (SM).



sample used for $H^{\pm}$ search	$\sigma_{t\bar{t}}$ in SM
CDF dilepton	$8.2^{+4.4}_{-3.4}$ pb
CDF lep.+jets (SVX b-tag)	$6.2^{+2.1}_{-1.7}$ pb
DØ lep.+jets (μ b-tag)	8.3 ± 3.6 pb
DØ lep.+jets (topological)	4.1 ± 2.1 pb

Figure 1: *(left)* Regions in the $M_{H^\pm}$ vs. tanβ plane where the branching fraction $\mathcal{B}(t \to H^{\pm}b)$ is larger than 50%. The present Tevatron data is sensitive to branching fractions of 30% or larger for this decay. At tan$\beta < 2$, H^+ decays both to $c\bar{s}$ and $W^+b\bar{b}$, where the $W^+b\bar{b}$ mode dominates for $M_{H^\pm} > 135$ GeV/c^2. At tan$\beta > 5$, H^+ decays to $\tau^+\nu$ exclusively. Table 1: *(right)* The samples used for the $H^{\pm}$ search, and the value of $\sigma_{t\bar{t}}$ extracted from the observed number of events in each channel, assuming only SM top decays. The reconstructed $\sigma_{t\bar{t}}$ in each channel is consistent with the theoretical value of about 5.0 pb.

At the Tevatron, the primary mechanism for charged Higgs production is through the top quark decay $t \to H^{\pm}b$, provided that the $H^{\pm}$ mass satisfies $M_{H^\pm} < M_{\text{top}} - M_b$. This decay competes with the SM decay $t \to W^{\pm}b$. A key parameter in the theory is tanβ, which is the ratio of vacuum expectation values of the two Higgs doublets. The parameters tanβ and $M_{H^\pm}$ determine the branching fractions for both the top quark and the charged Higgs boson. The Tevatron top data is sensitive to large branching fractions $\mathcal{B}(t \to H^{\pm}b)$, which occur for small values of tanβ (tan$\beta \leq 1$), and large values of tanβ (tan$\beta \geq 50$) - see Fig. 1.

Less than a year ago, it was believed that H^+ produced in top quark decays would decay into $c\bar{s}$ if tan$\beta < 1$, and $\tau^+\nu$ if tan$\beta > 5$. Recently it has been demonstrated that at tan$\beta < 1$, the three-body decay $H^+ \to t^*b \to W^+b\bar{b}$ competes with the decay $H^+ \to c\bar{s}$, as long as the virtual top quark t^* is produced close to its mass-shell value of about 175 GeV/c^2 [4]. Fig. 1 shows the dominant decay modes for $H^{\pm}$ in the $M_{H^\pm}$ vs. tanβ plane.

The Yukawa couplings of $H^{\pm}$ to fermions becomes arbitrarily large in the limits tan$\beta \to 0$ and tan$\beta \to \infty$. The $t - H - b$ coupling is perturbative if $\alpha = (\text{coupling})^2/4\pi \ll 1$, which limits our search to the region $0.2 <$ tan$\beta < 175$ if 1/2 is substituted for "$\ll 1$". Outside this range, our Monte Carlo (MC) simulations and branching fraction equations become invalid.

The large Yukawa couplings also result in top quark and $H^{\pm}$ widths which become very large at the boundaries of the perturbative region of tanβ. As an example, if $M_{H^\pm} = 100$ GeV/c^2, then at tan$\beta = 0.2$, $\Gamma_{\text{top}} \approx 20$ GeV, and at tan$\beta = 175$, $\Gamma_{\text{top}} \approx 8$ GeV[5] and $\Gamma_{H^\pm} \approx 6$ GeV.

Two separate techniques are used to exclude $H^{\pm}$ using the top data. In our first approach, we note that a large $\mathcal{B}(t \to H^{\pm}b)$ suppresses $t\bar{t}$ decay rates to dilepton final states and lepton + jets final states. We use the observed number of these events and the theoretical value of $\sigma_{t\bar{t}}$ to exclude $H^{\pm}$. In our second approach, we exclude $H^{\pm}$ without assuming a value of $\sigma_{t\bar{t}}$ by exploiting the fact that a large $\mathcal{B}(t \to H^{\pm}b \to csb)$ results in a ratio of dilepton events to lepton + jets events that is much smaller than the SM value. Limits from the CDF direct search [6] for $H^{\pm} \to \tau\nu$ decays in $t\bar{t}$ events are not discussed here.

The CDF and DØ collaborations at Fermilab have established the existence of top quark pair production via the observation of events which are consistent with the SM decay $t\bar{t} \to WbW\bar{b}$. These include dilepton events which contain two isolated high-P_T e or μ, missing energy ($\not{E}_T$) and 2 or more jets, as well as lepton + jets events which contain one isolated high-P_T e or μ, $\not{E}_T$ and 3 or more jets. For this analysis, both CDF and DØ use the same event selection criteria which is used for the determination of $\sigma_{t\bar{t}}$ [2]. CDF uses its dilepton sample selection, and its lepton + jets

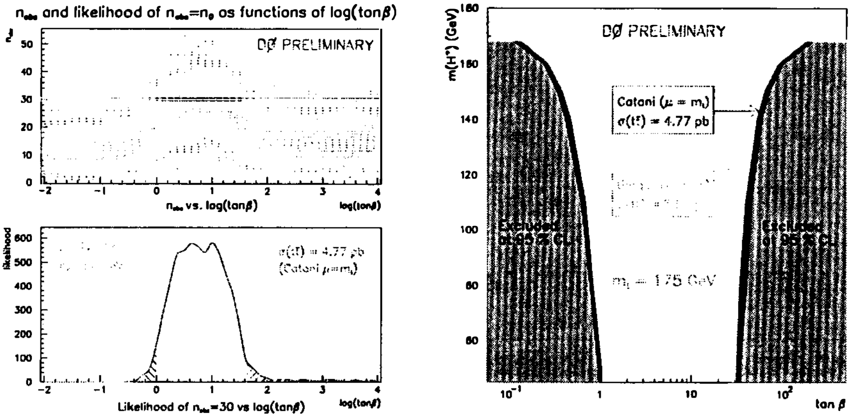


Figure 2: *Left plot:* On the top is a two-dimensional plot of the observed number of DØ lepton + jets events (30), as well as the number of events found in MC experiments vs. $\log_{10}(\tan\beta)$, for $M_{\rm top}$ = 175 GeV/c^2, $M_{H^\pm}$ = 50 GeV/c^2, and $\sigma_{t\bar{t}}$ = 4.77 pb. There are 10000 entries at each of 49 values of $\tan\beta$. On the bottom is the likelihood distribution for finding exactly 30 events, for the same set of parameters. The hatched regions on either side of the areas show the values of $\tan\beta$ which are not allowed at the 95% C.L. *Right plot:* The DØ excluded region in the $M_{H^\pm}$ vs. $\tan\beta$ plane.

selection criteria requiring the presence of a displaced-vertex b-tag (SVX tag). DØ combines its two orthogonal lepton + jets samples, one of which requires the presence of a b-tag in the form of a μ associated with one of the jets (ℓ+jets/μ), and the other which requires no μ tag but enforces stricter topological cuts (ℓ+jets). After applying these selection criteria, CDF and DØ find that the observed number of top events in each decay channel is consistent with the expected number of events, assuming that $t\bar{t}$ decays exclusively to $WbW\bar{b}$. Table 1 shows that the $\sigma_{t\bar{t}}$ extracted from each sample is consistent with the theoretical value.

In the charged Higgs scenario, $t\bar{t}$ can decay to $WbH\bar{b}$ and $HbH\bar{b}$ instead of $WbW\bar{b}$. If $H^\pm \to cs$ or $\tau\nu$, then these two final states have much smaller efficiencies than $WbW\bar{b}$ for passing the selection criteria of the top dilepton and the lepton + jets channels. This occurs primarily because the decays $t \to H^\pm b \to \tau\nu b$ and $t \to H^\pm b \to csb$ are much less efficient for producing high-P_T electrons and muons than the decay $t \to W^\pm b$. The result is a suppression of dilepton and lepton + jets events compared to SM expectations. This is shown in Fig. 2, which plots the observed number of DØ lepton + jets events, as well as the number found in many pseudoexperiments as a function of $\log_{10}(\tan\beta)$ for $M_{H^\pm}$ = 50 GeV/c^2 and $\sigma_{t\bar{t}}$ = 4.77 pb.

To set limits for given values of $M_{H^\pm}$ and $\sigma_{t\bar{t}}$, DØ calculates the likelihood of finding the observed number of lepton + jets events (30) as a function of $\tan\beta$, using the theoretical value of $\sigma_{t\bar{t}}$ (Fig. 2). This likelihood function is then integrated to find the region of $\tan\beta$ which is allowed at the 95% C.L., shown in Fig. 2. DØ finds that $0.96(0.26) < \tan\beta < 35(96)$ for $M_{H^\pm}$ = 50(168) GeV/c^2, assuming that $M_{\rm top}$ = 175 GeV/c^2 and $\sigma_{t\bar{t}}$ = 5.53 pb. These limits extend into the non-perturbative regions of $\tan\beta$, and have been calculated without modeling large top quark and $H^\pm$ widths which are predicted at small and large values of $\tan\beta$. These limits also ignore the decay mode $H^+ \to W^+ b\bar{b}$. Currently, DØ is working to take these effects into account.

CDF sums the dilepton events and lepton + jets events, and excludes values of $M_{H^\pm}$, $\tan\beta$ and $\sigma_{t\bar{t}}$ where there exists less than a 5% chance for finding a total number of events at least as large as the observed number. The limits are shown in Fig. 3, where $\mathcal{B}(t \to H^\pm b) < 32\%$ at the 95% C.L., assuming that $\sigma_{t\bar{t}}$ = 5.0 pb and $M_{H^\pm} \leq 120$ GeV/c^2. Near $\tan\beta$ = 0.2, the top

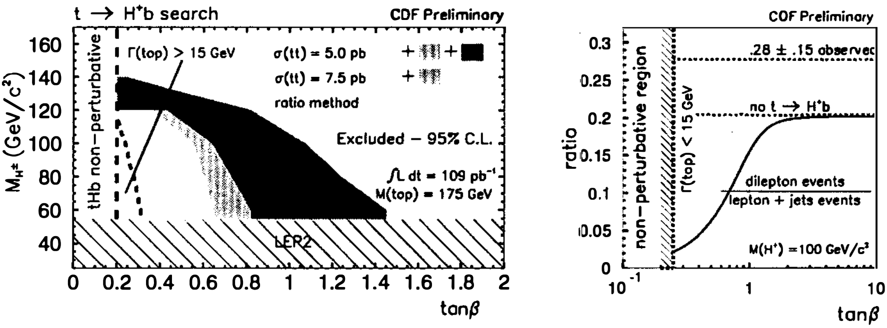


Figure 3: *Left plot:* CDF excluded regions of parameter space in the $M_{H^\pm}$ vs. tanβ plane. The best limits are obtained by assuming the theoretical value $\sigma_{t\bar{t}} = 5.0$ pb. Limits are also shown for a value which is 50% higher, $\sigma_{t\bar{t}} = 7.5$ pb. The region labelled "ratio method" is excluded by using the lepton + jets channel to measure $\sigma_{t\bar{t}}$, rather than assuming a value. This search does not apply in the region tan$\beta < 0.2$, where the $t - H - b$ coupling is non-perturbative, or in regions where the top quark width is predicted to be larger than 15 GeV. *Right plot:* The predicted ratio of dilepton events to lepton + jets events as a function of tanβ, for $M_{H^\pm} = 100$ GeV/c^2.

quark width is predicted to be larger than 15 GeV, which CDF has avoided modeling. CDF does not address the perturbative region tan$\beta < 0.2$. While CDF has previously excluded a region at tan$\beta > 50$ using the technique described here, some portions of this region are non-perturbative, while others involve large top and $H^\pm$ widths, so these limits need to be reevaluated.

Note that CDF is not able to set limits for $M_{H^\pm} > 140$ GeV at tan$\beta < 1$. In this region, the decay $H^\pm \to Wb\bar{b}$ dominates, resulting in $t\bar{t} \to HbW\bar{b} \to Wb\bar{b}bW\bar{b}$ and $t\bar{t} \to HbH\bar{b} \to Wb\bar{b}bW\bar{b}b\bar{b}$ events. The efficiency of these topologies to pass the selection criteria of the top dilepton and lepton + jets channels is similar to that of $t\bar{t} \to WbW\bar{b}$ decays, so that no severe deficit of $t\bar{t}$ events is predicted.

In an alternate approach to the one just described, CDF has shown that it is possible to exclude parameter space at small tanβ without assuming a value for $\sigma_{t\bar{t}}$. CDF exploits the fact that a large $\mathcal{B}(t \to H^\pm b \to csb)$ suppresses dilepton events more severely than lepton + jets events. This ratio is plotted as a function of tanβ for $M_{H^\pm} = 100$ GeV/c^2 in Fig. 3. To exclude $H^\pm$, CDF first measures $\sigma_{t\bar{t}}$ using the observed number of lepton + jets events, and then uses this $\sigma_{t\bar{t}}$ to determine the expected distribution of dilepton events, taking into account $t\bar{t}$ efficiencies that are calculated for the assumed values of $M_{H^\pm}$ and tanβ. These assumed values of $M_{H^\pm}$ and tanβ are excluded if there exists less than a 5% probability for finding a number of dilepton events at least as large as the observed number, since a deficit of dilepton events relative to lepton + jets events is predicted. For $M_{H^\pm} \leq 120$ GeV/c^2, $\mathcal{B}(t \to H^\pm b) < 72\%$ at the 95% C.L., corresponding to the region marked "ratio method" in Fig. 3. On the boundary of this excluded region, a typical central value of $\sigma_{t\bar{t}}$ is determined to be 14 pb.

3 Measurement of the W helicity fraction in top quark decays (CDF)

The SM predicts that the fraction of longitudinal W^+s produced in the top quark decay $t \to W^+b$ is $F_0 = \frac{M_{\rm top}^2}{2M_W^2 + M_{\rm top}^2} = 70.6 \pm 1.6\%$ for $M_{\rm top} = 175.6 \pm 6.8$ GeV/c^2. The other W^+ bosons are left-handed, since right-handed W^+ bosons are forbidden by helicity conservation. CDF extracts the W helicity fraction from the P_T spectrum of e and μ produced in the decay $t \to W^+b \to \ell^+\nu b$. Left-handed W^+s emit charged leptons preferentially in a direction antiparallel to the direction

data sample for W helicity analysis	number of events	background
dilepton	7	0.8 ± 0.2
$W + \geq 3$ jets, a displaced vertex b tag	34	9.2 ± 1.5
$W + \geq 4$ jets, a soft lepton b tag	14	5.6 ± 1.2
$W + \geq 4$ jets, no b tags	42	23.5 ± 6.4

Table 2: The number of observed events and the non-$t\bar{t}$ background estimate for the top samples which are used to determine the W helicity fraction in top quark decays.

of boost from the top quark rest frame to the W rest frame, while longitudinal W^+s tend to emit charged leptons perpendicular to this direction of boost. As a result, the P_T spectrum of leptons from longitudinal Ws is harder than that from left-handed Ws.

An alternate method [7] extracts F_0 from the angular distribution of charged leptons from W decay in the rest frame of the W, using $W + \geq 4$ jets events for which the kinematics are completely reconstructed. In that approach, systematic uncertainties arise to the parton combinatorics and ν reconstruction. By using the lepton P_T spectrum, the systematic error can be reduced by relying on the most accurately measured quantity in the events, and the statistical error can be reduced by extending the sample to include $W + \geq 3$ jets events and dilepton events. Although the approach relies on MC modeling of the lepton P_T spectrum from top decays, the related systematic uncertainties are small.

The data samples used in this analysis are given in Table 2. The dilepton sample is used for the determination of $\sigma_{t\bar{t}}$ [2], with the $e-e$ and $\mu - \mu$ events removed to simplify the Drell-Yan background calculation. The lepton + jets events are divided into 3 mutually orthogonal samples depending on their b-tagging status, as is done with the CDF mass analysis [1]. The channel requiring the SVX b-tag is used for the determination of $\sigma_{t\bar{t}}$ [2], and the $W + \geq 4$ jets samples are used by the mass analysis [1].

Fig. 4 shows the lepton P_T spectrum observed in the data, and the results of a likelihood fit to this distribution assuming contributions from top decays to longitudinal Ws, top decays to left-handed Ws, and non-$t\bar{t}$ background events. The fit is performed simultaneously in the dilepton and lepton + jets channels. The final result is $F_0 = 0.55 \pm 0.32(\text{stat}) \pm 0.12(\text{syst})$, compared to the SM prediction of 0.71 for $M_{\text{top}} = 175$ GeV/c^2. This result accounts for an acceptance bias; the $t\bar{t}$ kinematic acceptance in the lepton + jets channel is about 30% higher if both top quarks decay into longitudinal Ws rather than left-handed Ws. A ± 6.8 GeV ($\pm 1\sigma$) shift in the top mass results in a ± 0.10 change in the measured value of F_0, while the SM only predicts a ± 0.016 change. While the error on F_0 is completely dominated by statistics, small systematic errors arise due to uncertainty in the lepton + jets background shape (0.08), MC statistics (0.06), choice of MC generator (0.03), and choice of structure function (0.02).

4 Other top properties measured at the Tevatron - results

- **Observation of hadronic W decays in top events.** CDF has measured $M_W = 77.2 \pm 3.5(\text{stat}) \pm 2.9(\text{syst})$ GeV/c^2 in top events, with a peak significance of 3.3σ [8]. One of two methods employed identifies both b quarks and the leptonic W decay in $W + \geq 4$ jet events. M_W is reconstructed from the dijet mass of the two untagged jets.

- **A measurement of $\mathcal{B} = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$.** CDF has measured $\mathcal{B} = 0.99 \pm 0.29$ [9]. Assuming unitarity, $|V_{tb}| > 0.76$ at the 95% C.L. Without assuming unitarity, but assuming that the top quark has a zero branching fraction to a fourth generation quark, $|V_{tb}| > 0.048$ at 95% C.L.

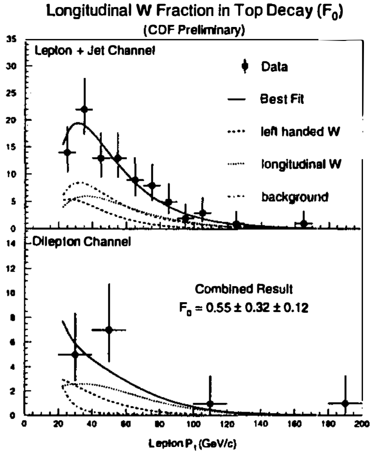


Figure 4: The best fit to the lepton P_T spectrum observed in the data, using MC predictions for top decays with left-handed and longitudinal Ws, and non-$t\bar{t}$ background shapes modeled both from MC and data. The P_T spectrum is peaked at a smaller value for left-handed Ws than for longitudinal Ws. The dilepton background, which has large contributions from $Z \to \tau\tau$ and W + jets events where a jet fakes the signature of an e or μ, produces a softer P_T spectrum than the lepton + jets background, which contributes leptons mostly from real Ws.

- **Large flavor-changing neutral current top quark branching fractions are ruled out.** CDF finds that $\mathcal{B}(t \to q\gamma) < 3.2\%$ and $\mathcal{B}(t \to qZ) < 33\%$ at the 95% C.L.[10].
- **Top quark kinematic distributions in data agree with MC predictions** for CDF and DØ data. DØ has demonstrated this agreement by calculating 13 K-S test probabilities for continuous distributions such as the top quark mass and P_T spectrums[11]. The mean of these probabilities is (53±9)%, consistent with the hypothesis that predictions for $t\bar{t}$ signal plus non-$t\bar{t}$ background adequately represent the data.

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