Fermilab FERMILAB-Conf-01/381-E January 2002

# TOP RESULTS FROM THE TEVATRON

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Abstract

This paper summarizes the latest measurements of the properties of the top quark as determined by the CDF and DØ collaborations during the first run of the Fermilab Tevatron $p\bar{p}$ collider (1992-1996). Prospects for future measurements of the top quark at the upgraded Tevatron collider are also presented.

## 1 Introduction

Top quarks can be produced in $t\bar{t}$ pairs via strong interactions or singly via electroweak interactions. Within the Standard Model the top quark decays almost exclusively into a $W$ boson and a $b$-quark if $m_t > m_W + m_b$ ($|V_{tb}| \approx 1$). The decay channels are defined by the decay modes of the $W$ boson. These channels are: the dilepton channel where both $W$ bosons decay leptonically, the lepton+jets channel where one $W$ decays hadronically, one $W$ leptonically, and the all-jets channel where both $W$'s decay hadronically. Run I of the Tevatron collider saw the discovery of the top quark in 1995, by the CDF and DØ collaborations [1], and subsequent measurements of the pair production cross section and mass from all decay modes of the top. These measurements were combined to give the most precise direct measurement of the top mass and cross section. Attempts were also made to understand the properties of the $t - W - b$ vertex, measure the electroweak production cross section, and search for rare decays. The current measurements are limited by the small number of top quark produced from Run I of the Tevatron. The upcoming Run II of the Tevatron, starting mid 2001 with significants upgrades of the accelerator complex and of the CDF and DØ detectors [3], will yield considerably larger data sets and thus enable the collaborations to study the dynamics of $t\bar{t}$ production, probe the structure of $t - W - b$ vertex, and observe electroweak top production. Improved precision in the measurement of the top quark and the $W$ boson masses will lead to much more stringent constraints on the mass of the Higgs boson. These measurements will help understanding the mechanism of electroweak symmetry breaking and its relation, if any exists, to the mass of the top quark.

## 2 Cross section and mass measurements

At the Tevatron Run I(II) energy of $\sqrt{s} = 1.8(\sim 2)$ TeV, top quarks are produced predominantly in pairs through the annihilation process $q\bar{q} \to t\bar{t}$, 90(85)% of the time, and gluon fusion process $gg \to t\bar{t}$, 10(15)% of the time. Predictions on the cross section based on NLO QCD calculation range between 4.7 and 6.2 pb [2]. Some NLLO calculations have only recently appeared [4] and are not used for comparison in this paper. The electroweak cross section is approximately half of the pair production cross section (the Standard Model predicts 2.4 pb [5] [6] for the processes $q\bar{q} \to t\bar{b}$ and $qg \to qt\bar{b}$ combined, at $\sqrt{s} = 1.8$ TeV) but the higher background levels make a measurement of the cross section in this mode rather challenging. The Run I detectors, CDF [7] and DØ [8], each accumulated about 125 $\mathrm{pb}^{-1}$ of data. The

Table 1: *$t\bar{t}$ cross section measurements performed by the CDF and DØ collaborations in Run I (values are in pb).*

| experiment | CDF | DØ |
|---|---|---|
| dilepton | $8.4^{+4.5}_{-3.5}$ | $6.4 \pm 3.3$ |
| topological | | $4.1 \pm 2.1$ |
| lepton tag | $9.2 \pm 4.3$ | $8.3 \pm 3.5$ |
| SVX tag | $5.1 \pm 1.5$ | |
| all-jets | $7.6^{+3.5}_{-2.7}$ | $7.1 \pm 3.2$ |
| combined | $6.5^{+1.7}_{-1.4}$ [10] | $5.9 \pm 1.7$ [9] |

measured dilepton channel ($W's \to l\nu$, $l = e$ or $\mu$) accounts for 5% of all $t\bar{t}$ decays, the lepton+jets channel (one $W \to l\nu$, $l = e$ or $\mu$), accounts for 30% of all $t\bar{t}$ decays. In 44% of the decays both $W$'s decay to jets. In the remaining 21% of decays one or both $W$'s decay to $\tau\nu$. Since $W \to \tau\nu \to l\nu_l\nu_\tau\bar{\nu_\tau}$ decays are indistinguishable from $W \to l\nu$, both experiments include such decays as part of the dilepton or lepton+jets channels. Other channels are the $l\tau$ dilepton channel (CDF, hadronic decays of the $\tau$) and the $e\nu$ channel (DØ).

Tab.1 summarizes the $t\bar{t}$ cross section measurements for each of the decay channels. Two different analyses were used in the lepton+jets channel. Top pair production can be isolated by exploiting the topological characteristics of its final state (used by DØ) or by identifying a $b$-quark among the decay products. Both experiments tag $b$-quarks from their semileptonic decay (muons for DØ ; muons and electrons for CDF). CDF also tags $b-$quarks based upon the presence in the event of a secondary vertex from the decay of a long lived particle. Using all channels combined, DØ measures a cross section of $5.9 \pm 1.7$ pb [9] and CDF $6.5^{+1.7}_{-1.4}$ pb [10]. A re-analysis of the $e\mu$ channel was also performed by DØ . This analysis makes use of advanced analysis techniques such a neural networks and leads to a 10% improvement in acceptance and uncertainty for the channel in question.

Tab.2 summarizes all the measured values for the top quark mass. In the Run I the single most precise measurement comes from the lepton+jets channel, and the total combined relative uncertainty on the mass is $< 3\%$. The mass of the top affects Standard Model predictions via radiative corrections. These corrections relate, for example, the mass of the top to the mass of the $W$ and the Higgs bosons. Thus, one of the goals of Run II is to achieve improved constraints on the mass of the Higgs by performing precision measurements of the mass of the top and of the $W$ boson.

Run II of the Tevatron has begun as of March 2001. The upgraded detec-

Table 2: *Top mass measurements performed by the CDF and DØ collaborations in Run I. Of the two uncertainties associated with each of the individual measurements, the first is statistical, the second systematic (values are in GeV).*

| experiment | CDF | DØ | combined |
|---|---|---|---|
| lepton+jets | $176.1 \pm 5.1 \pm 5.3$ [11] | $173.3 \pm 5.6 \pm 5.5$ [12] | |
| dilepton | $167.4 \pm 10.3 \pm 4.8$ [13] | $168.4 \pm 12.3 \pm 3.6$ [14] | |
| all-jets | $186.0 \pm 10.0 \pm 5.7$ [15] | | |
| combined | $172.1 \pm 7.1$ | $176.1 \pm 6.6$ | $174.3 \pm 5.1$ [16] |

tors expect to accumulate 2 $\text{fb}^{-1}$ in the first two years of data taking, and a total of 15 $\text{fb}^{-1}$ by the end of 2006 (with further upgrades scheduled around 2003). With 2 $\text{fb}^{-1}$, each experiment expects to measure the $t\bar{t}$ cross section to $8-10\%$, and the top quark mass to about $2-3$ GeV. Together with an uncertainty on the $W$ mass of 40 MeV, this translates into a constraint on the mass of the Higgs, per experiment, of 80% of its value. The errors on the mass and cross section will decrease due to the enlarged data samples and the improved capabilities of both detectors. Both CDF and DØ are running with new silicon vertex detectors with improved coverage. DØ has introduced a central solenoidal field of 2 Tesla. The calibration of the jet $p_T$ scale will improve by using $Z \to b\bar{b}$ events to derive corrections specific to $b-$jets, and $W$'s hadronic decays in top events to derive corrections for light quark jets. The requirement of two $b-$tagged jets will reduce the combinatoric uncertainties for associating each jet with a final state parton in the top decay. Larger data samples will also allow more stringent comparison with theoretical predictions and their Monte Carlo implementations.

## 3 Measurements of top production properties

The measurements of some of the top production properties, other than mass and cross section, are discussed below. The results obtained with Run I data are all limited by the small statistics of the samples and much improvement is expected by the upcoming use of Run II data.

### 3.1 Search for $t\bar{t}$ resonances

Studies of the $t\bar{t}$ kinematics (such as mass, $p_T$, etc.) provide a general search for heavy objects decaying into $t\bar{t}$ pairs (e.g. predicted by models of electroweak symmetry breaking through strong dynamics). Using the lepton+jets sample, both CDF

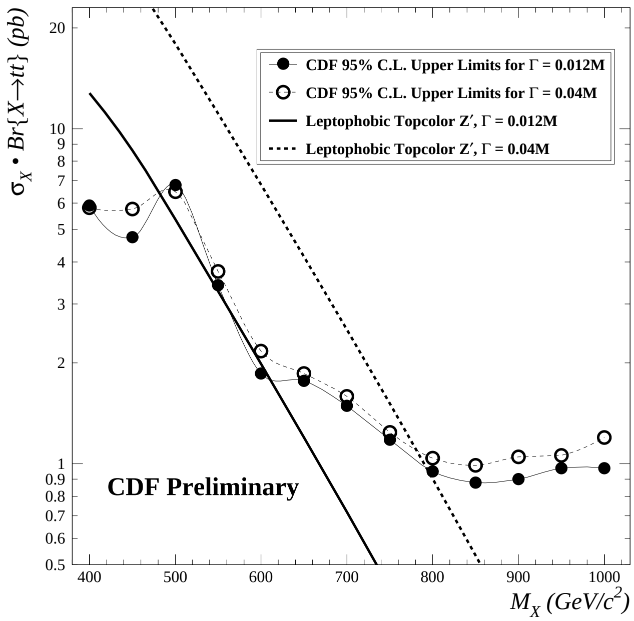


Figure 1: *The CDF* 95% *CL limits on* $\sigma \times BR(X \to t\bar{t})$ *as a function of* $M_X$ *for two different values of width. The data are compared with the prediction for a leptophobic topcolor* $Z'$ *with different widths.*

and DØ have searched for peaks in the $t\bar{t}$ mass spectrum without finding any evidence for such signals [12) 17)]. Fig.1 shows the limits on the cross section times branching ratio obtained by CDF. At the 95% confidence level (CL) the data rule out a topcolor $Z'$ with mass less than 480(780) GeV and width equal to $0.012(0.04)M_{Z'}$. In Run II, with 2 $\text{fb}^{-1}$, we expect to place limits on such narrow resonances up to about 1 TeV.

### 3.2 Top $p_T$

The top $p_T$ spectrum is an optimal tool for investigating anomalous mechanisms in $t\bar{t}$ production. DØ sees good agreement with the standard model [12)]. CDF measures [18)] the fraction of top produced in four bins of true $p_T$ and sets a model independent upper limit on the fraction of top quarks produced with $p_T > 225$ GeV of 0.114 at 95% CL. Greater statistics in Run II will allow direct comparison with various production modes.

### 3.3 $t\bar{t}$ spin correlations

The spins of top and anti-top are highly correlated in $p\bar{p} \to t\bar{t}$ production. At $\sqrt{s} = 1.8$ TeV, about 90% of the events come from $q\bar{q}$ annihilation. Top quarks decay before losing the spin information at production and the spin can be reconstructed via the decay products. The observation of spin correlation provides a way of studying a quark almost free of confinement effects, it produces a lower limit on the top width and $|V_{tb}|$, and it can be used as a probe for the appearance of new physics, which could predict different production and decay dynamics for the top quark and therefore affect the observed spin correlation. DØ makes a measurement [19] of the spin correlation using an optimal off-diagonal basis and the dilepton sample. The differential decay rate of top quarks is related to the angle $\theta_{\pm}$ of the positive/negative lepton in the off-diagonal axis of the top quark rest frame as follows: $\frac{1}{\sigma}\frac{d^2\sigma}{d(cos\theta_+)d(cos\theta_-)} = \frac{1}{4}(1+\kappa\, cos\theta_+ cos\theta_-)$. The Standard Model predicts $\kappa = 0.88$ for $t\bar{t}$ production at the Tevatron. DØ performs a binned maximum likelihood fit to the dilepton sample (shown in Fig.2) and obtains the limit: $\kappa > -0.2$ at 68% CL, in agreement with Standard Model predictions. The projections for 2 $\text{fb}^{-1}$ of Run II data are: $2.5(3.0)\sigma$ measurable effect within the dilepton(lepton+jets, double $b$-tag) sample.

### 3.4 Single top cross section

Both experiments have searched, with the Run I data samples, for electroweak production of top, via the processes $q\bar{q} \to t\bar{b}$ (s-channel $W^*$) and $qg \to qt\bar{b}$ (W-gluon fusion). Since the single top production cross section is proportional to the CKM matrix element $|V_{tb}|$, from the measurement of such cross section one can extract a measurement of the top width and a measurement of $V_{tb}$ independent from assumption on the unitarity of the CKM matrix and the number of fermion generations. A measurement of the single top cross section can also probe for anomalous couplings either through the presence of large production rates or of anomalous angular distributions. The ability of extracting a signal over an overwhelming level of background (from $t\bar{t}$, $W+$ jets, multi-jet) depends strongly on having good $b-$tagging efficiency (specially in the forward direction), and low fake lepton and fake $b-$quark jet reconstruction rates. CDF has set an upper limit of 13.5 pb [20] at 95% from a fit to the total $E_T$ spectrum of $W + 1, 2, 3$ jet events (shown in Fig.3). DØ has set a 95% CL upper limit of 39 pb on $q\bar{q} \to t\bar{b}$ production and 58 pb [21] on $qg \to qt\bar{b}$. Neural net analyses are in progress to further improve the results. In Run II, it is expected that the single top cross section will be measured with an uncertainty of

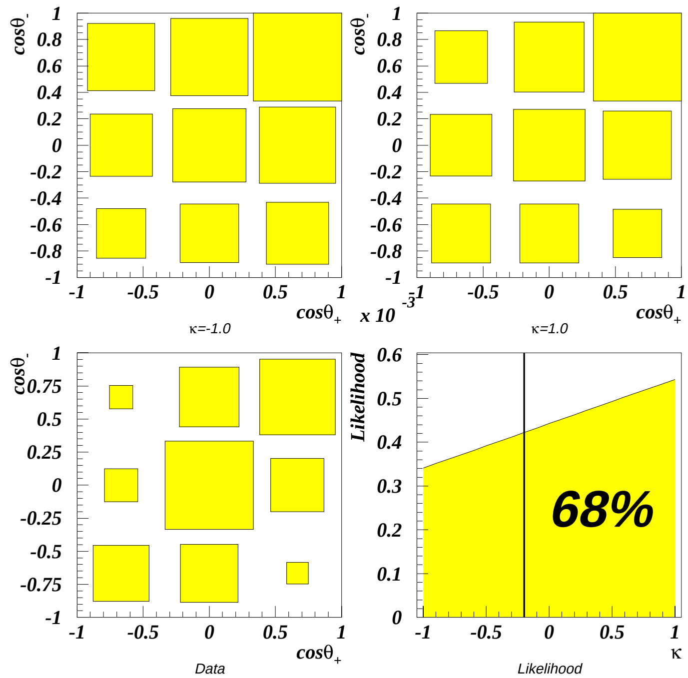


Figure 2: *Plots of probability density for $t\bar{t}$ dilepton events in $(cos\theta_+, cos\theta_-)$ space. Top left: Monte Carlo events with $\kappa = -1$; top right: with $\kappa = +1$; bottom left: DØ data; bottom right: likelihood as a function of $\kappa$.*

$20 - 30\%$.

## 4 Measurements of top decay properties

Measurements of top properties related to its decay are presented below. Run I results are discussed and prospects for more extensive Run II measurements are reviewed.

### 4.1 $W$ polarization

In the Standard Model the quark top is a spin 1/2 particle with pure V-A coupling to the $W$ boson, it decays to longitudinal or left-handed $W$ bosons (i.e. $W$ bosons with helicity state $h_W = 0$ or $h_W = -1$) with the ratio $F_0/F_{-1} = m_t^2/2m_W^2$. The fraction of $W$'s with 0 helicity is thus supposed to be about 75% and it can be measured using the $p_T$ distribution of leptons from $W$ decays in $t\bar{t}$ events. CDF determines [22] $F_0 = 0.91 \pm 0.39$. Fixing $F_0$ to the value predicted by Standard Model, CDF also fits a $V + A$ component ($W$ bosons with helicity +1) and finds

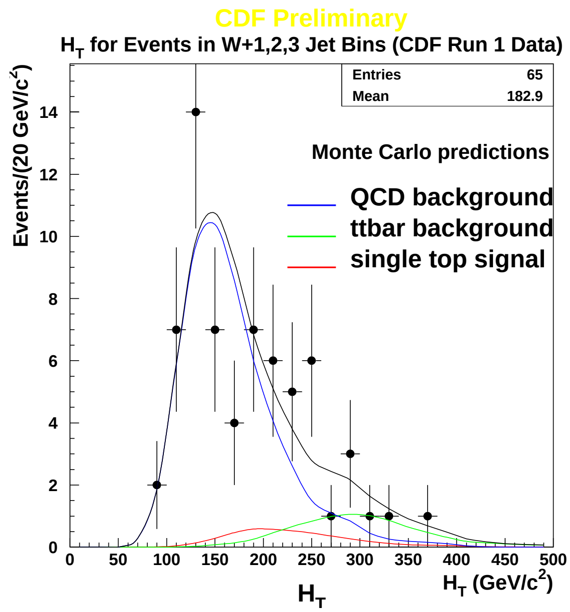


Figure 3: *The CDF fit of the* $H_T = \sum E_T$ *spectrum for* $W + 1, 2, 3$ *jet data events to the modeled signal and background components.*

$F_{+1} = 0.11 \pm 0.16$. The results are consistent with Standard Model expectations.

### 4.2 Measurement of branching fractions ratio and $V_{tb}$

The ratio of branching fractions for top quarks decaying into $b-$quarks and light quarks is measured by CDF [23] using the relative rate of lepton+jets and dilepton events with 0,1, and 2 $b-$tags and it is found to be $R = B(t \to Wb)/B(t \to Wq) = 0.94^{+0.31}_{-0.24}$. This translates, under the assumption of unitarity of the CKM matrix and the existence of 3 generations of fermions, into a measurement of $|V_{tb}| = 0.97^{+0.16}_{-0.12}$ or a lower limit of $|V_{tb}| > 0.75$ at 95% CL. The Run II projections for this measurement of $V_{tb}$ give an uncertainty of about 2% with 2 fb$^{-1}$.

### 4.3 Rare decays

Decays other than $t \to Wb$ are expected to occur, according to Standard Model, at a rate of $10^{-10}$, therefore any observation of decays such as $t \to c/u + g/\gamma/Z/H^0$, or $t \to Wb + g/\gamma/Z/H^0$ will be a definite signature for new physics. Both experiments have started searching for such signatures in Run I and are expected to continue in Run II. Run I searches for the FCNC decays $t \to Zq$ and $Z \to \gamma q$ by CDF [24] yield results which are consistent with Standard Model expectations. 95% CL limits of

33% and 3.2% respectively are placed on these two decays.

### 4.4 Search for $t \to H^+ b$

In supersymmetric (SUSY) extensions of the Standard Model, the top quark can decay to a charged Higgs boson, $H^+$, and a $b$-quark. If the phase parameter tan$\beta$ (the ratio of the vacuum expectation values of the two SUSY Higgs doublets) is low, the charged Higgs will decay to $c\bar{s}$ or $Wb\bar{b}$; if it is high, the charged Higgs will decay into $\bar{\tau}\nu_\tau$. Both DØ [25] and CDF have performed an indirect (disappearance) search for charged Higgs using the $t\bar{t}$ dilepton and lepton+jets samples (DØ uses only the latter). The selection criteria in the search are optimized for the Standard Model channel $t \to Wb$, therefore one expects the efficiencies of these criteria to be substantially smaller for $t \to H^+ b$ decays (except for the case of $H^+ \to Wb\bar{b}$). Assuming that the $t\bar{t}$ cross section has no contributions from any new physics channels, one can exclude the regions of very low acceptance (corresponding to high $BR(t \to H^+ b)$) where the observed excess of signal over background cannot be explained by $t\bar{t}$ production. Both experiments have also performed a direct search in the $H^+$ decay channel $H^+ \to \bar{\tau}\nu_\tau$ [27] [26]. As an example, the regions in $(tan\beta, m_{H^+})$ space which are excluded at 95% CL by DØ are shown in Fig.4. The limits roughly translate into an upper limit on the branching fraction of $BR(t \to H^+ b) < 0.4$ ($BR(t \to H^+ b) < 0.12$ is the prediction for Run II).

### 4.5 Measurement of the top quark Yukawa coupling

In the Standard Model, fermions acquire mass via Yukawa coupling to the Higgs field. Due to its heavy mass, the top quark has a Yukawa coupling $y_t = \sqrt{2}\frac{m_t}{v}$ which is about 1. The large coupling compared to other fermions has generated proposals for mechanisms of electroweak symmetry breaking which attribute a special role to top (i.e. topcolor). A direct measurement of $y_t$ is therefore of extreme interest. If the Higgs is discovered at the Tevatron, a measurement of $y_t$ via the associated Higgs production $t\bar{t}$H could be carried out using the full Run II statistics [28].

## 5 Conclusions

During the first run of the Tevatron collider, the CDF and DØ experiments have discovered the top quark, measured its mass to remarkable precision, determined the top pair production cross section and several other properties to be consistent with Standard Model expectations. The second run of the collider, which is just starting, will push the precision measurements of all top properties to effectively

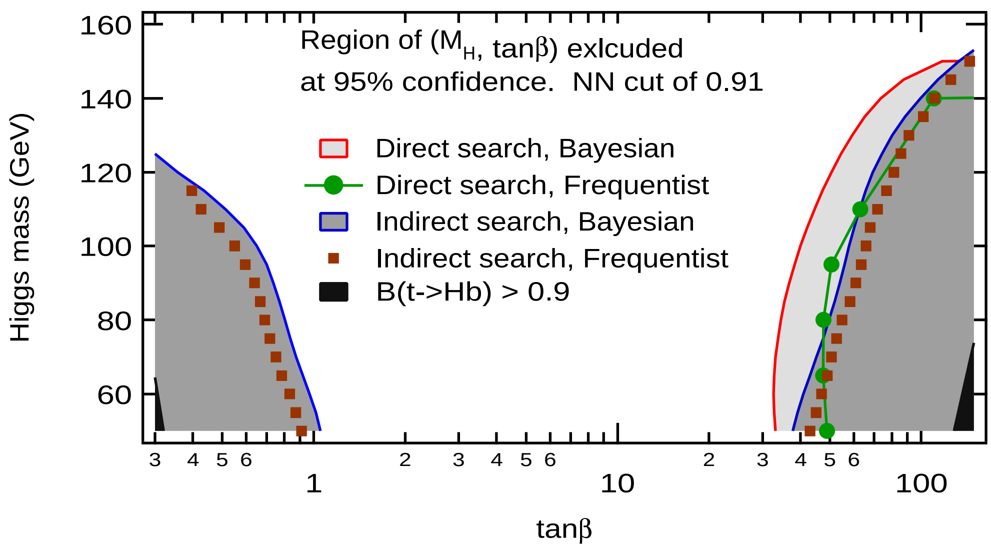


Figure 4: *The 95% CL exclusion boundaries in the* $(tan\beta, m_H^+)$ *plane for* $m_t = 175$ *GeV and* $\sigma(t\bar{t}) = 5.5$ *pb. The smaller exclusion region on the left side corresponds to the part of phase space where* $H^+ \to Wb\bar{b}$ *and the disappearance search loses its sensitivity. The NN value refers to the cut on neural net output which is used in the signal to background discrimination for the direct analysis.*

determine whether the top quark is the particle predicted by the Standard Model, whether there is new physics beyond it, and whether the top quark holds a special role in the mechanism of electroweak symmetry breaking.

## 6 Acknowledgements

I would like to thank the organizers of Les Rencontres de Physique de la Vallee d'Aoste for holding a most enjoyable and interesting meeting. I would also like to thank the members of the DØ and CDF collaborations who helped me prepare material for the talk and this paper.

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