We summarize results of some crucial measurements of the top quark and $W/Z$ boson properties carried out by the DØ and the CDF collaborations at the Tevatron collider at Fermilab based on data collected during Run 1 (1992-96). Among the interesting properties measured are the pair-production cross section and the mass of the top quark, and the mass and the width of the $W$ boson. Searches for singly produced top quarks and for certain non-standard production and decays of the top quark, as well as studies of angular correlations in the production and decay of the top quarks are also presented. Expectations from the ongoing Run 2 of the Tevatron, presently in its second year, are discussed.

1 Introduction

Studies of the top quark and the $W$ and $Z$ bosons provide testing grounds for many important properties and calibrations of the Standard Model (SM) at large mass scales through their production rates, kinematic distributions, and decay characteristics. In the SM, $m_t$ and $m_W$ constrain $m_H$. Hence, precision measurements of these help guide the search for the SM Higgs boson. Measurement of the $W$ width provides a stringent test of the SM and helps to constrain certain scenarios beyond the SM.

The large mass of the top quark sets it apart from all other fermions. With a lifetime of $\sim 10^{-24}$ s, the top quark is expected to decay before hadronization. This gives us an opportunity to study a bare quark, free from the long-range effects of the strong interaction, such as color confinement. Studies of the top quark could also shed light on the mechanism of mass generation and mass-dependent couplings. Significant deviations from SM predictions in mass, width, decay characteristics, and kinematic distributions could lead to new physics. Furthermore, top quark decay is an excellent place to look for on-shell production of certain particles beyond the SM (e.g., $\tilde{t}$, $H^\pm$, ...) that are believed to be heavier than other SM particles.
2 The collider and the detectors

Run 1 of the Tevatron (1992-96) delivered $125 \pm 6 \text{ pb}^{-1}$ of data consisting of over $5 \times 10^{12}$ $p \bar{p}$ collisions at a center-of-mass energy of 1.8 TeV. With $\sigma(p \bar{p} \rightarrow t \bar{t}X) \approx 6 \text{ pb}$ for $m_t \approx 175 \text{ GeV}$, and $\sigma(p \bar{p} \rightarrow WX) \approx 24 \text{ nb}$, $\sim 750 t \bar{t}$ events and $\sim 3 \times 10^6 W$ events are expected to have been produced. However, these events must be detected and filtered out from a much larger number of other processes with similar signatures. The two detectors, DØ and CDF, are both modern multipurpose detectors designed to do just that. They consist of vertex detectors, precision tracking chambers, finely segmented hermetic calorimeters, muon momentum spectrometers, and fast data acquisition systems with several levels of online triggers and filters.

3 Studies of the top quark

3.1 Pair production cross section and mass measurements

At the Tevatron $p \bar{p}$ collider, most top quarks are pair-produced via the strong interaction through an intermediate gluon. This is the production channel that led to the joint discovery of the top quark by DØ and CDF in 1995. In the SM, the top quark should decay almost exclusively to a $W$ boson and a $b$ quark. Therefore, the final state of a $t \bar{t}$ decay is characterized by the decay modes of the two $W$ bosons: dilepton (BR= $\frac{1}{6}$), lepton+jets (BR= $\frac{1}{3}$), and all-jets (BR= $\frac{1}{9}$). Tagging of the $b$ quark jets using semileptonic decay modes or by isolating secondary decay vertices is a powerful means of suppressing background. All of these decay channels have been used in various studies of the properties of the top quark, including the $t \bar{t}$ production cross section of $5.7 \pm 1.6 \text{ pb}$ by the DØ collaboration and $6.5^{+1.7}_{-1.4} \text{ pb}$ by the CDF collaboration and of the top quark mass of $174.3 \pm 5.1 \text{ GeV}$ jointly by the two collaborations.

3.2 Search for single top production

A second production mode is predicted to exist, where top quarks are produced singly through an electroweak $Wtb$ vertex. Measurement of the electroweak production of single top quarks could provide the magnitude of the CKM matrix element $V_{tb}$, since the cross section is proportional to $|V_{tb}|^2$. The SM predictions for single top production cross section are $0.73 \text{ pb}$ in the $s$ channel, and $1.73 \text{ pb}$ in the $t$ channel. In addition to having a smaller cross section than that for pair production, single top production suffers from larger background contamination. Neither experiment saw conclusive evidence of signal, but were able to place upper limits on the production cross section. At 95% CL, DØ puts an upper limit of $17 \text{ pb}$ on the $s$ channel and $22 \text{ pb}$ on the $t$ channel cross section while the corresponding CDF limits are $13 \text{ pb}$ and $18 \text{ pb}$ respectively. CDF also puts a limit of $14 \text{ pb}$ on the combined cross section.

3.3 $W$ helicity in top decays

At the leading order, the fraction of longitudinally polarized $W$ bosons in top decays is given by

$$F_0 = \frac{\Gamma(h_W = 0)}{\Gamma(h_W = 0) + \Gamma(h_W = -1)} = \frac{m_t^2/(2m_W^2)}{1 + m_t^2/(2m_W^2)} \approx 0.70. \quad (1)$$

The large mass of the top quark exposes the longitudinal mode of the $W$ boson, possibly offering a window to electroweak symmetry breaking. The charged lepton from a $W_-$ ($W_0$) tends to move opposite (perpendicular) to the $W$ direction of motion. Consequently, the polarization of the $W$ is reflected in the $p_T$ distribution of the $e$ or $\mu$ in its leptonic decays. Fits of $h_W = 0$, $h_W = -1$, and $h_W = +1$ Monte Carlo to CDF dilepton and lepton+jets data yield $F_0(W) = 0.91 \pm 0.37 \pm 0.13$, $F_+(W) = 0.11 \pm 0.15 \pm 0.06$, consistent with SM predictions of $\sim 0.70$ and 0 respectively.
3.4 Top-antitop spin correlations

The top quark lifetime is much smaller than the timescale for hadronization which subsequently would lead to spin decorrelation. The decay products of top quarks produced in a definite spin state should therefore display angular correlations that characterize the production process. In the optimal basis, if the angle between a negatively (positively) charged lepton or \( d (\bar{d}) \) -type quark and the spin quantization axis is denoted by \( \theta_- (\theta_+) \), then the differential decay rate of the top quark can be parametrized as

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d(cos \theta_+)d(cos \theta_-)} = \frac{1 + \kappa \cos \theta_+ \cos \theta_-}{4}; \quad -1 < \kappa < 1.
\]

(2)

All information on spin correlation is contained in \( \kappa \).

For pp collisions at \( \sqrt{s} = 1.8 \) TeV, \( q\bar{q} \) annihilation through the s-channel via a spin-1 gluon is expected to account for \( \sim 90\% \) of the \( t\bar{t} \) production cross section. This leads to an expectation of \( \kappa \approx 0.9 \). An analysis of the DØ dilepton data consisting of 6 candidate events favors a positive value for \( \kappa (\kappa > -0.25 \) at 68\% CL). [8]

3.5 \( t\bar{t} \) invariant mass and kinematics

Both CDF and DØ have searched for non-SM top quark condensates in the \( t\bar{t} \) invariant mass distributions. Comparing a theoretical predictions for \( \sigma(q\bar{q} \rightarrow Z')B(Z' \rightarrow t\bar{t}) \) as functions of \( m_{Z'} \) with upper limits on the former based on data, CDF puts an lower limit of \( 3.6 \) Search for \( \text{charged Higgs} \) \( \text{Higgs} \) \( \text{of small tan} \) \( \beta \) of their lepton+jets data with SM predictions. The searches, based on leading order calculations, would lead to spin decorrelation. The decay products of top quarks produced in a definite spin state should therefore display angular correlations that characterize the production process. In the optimal basis, if the angle between a negatively (positively) charged lepton or \( d (\bar{d}) \) -type quark and the spin quantization axis is denoted by \( \theta_- (\theta_+) \), then the differential decay rate of the top quark can be parametrized as

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d(cos \theta_+)d(cos \theta_-)} = \frac{1 + \kappa \cos \theta_+ \cos \theta_-}{4}; \quad -1 < \kappa < 1.
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Studies of kinematics of \( t\bar{t} \) production and decays are important tests of QCD and electroweak theories. Both experiments have also examined distributions of various kinematic quantities for the candidate events. [8] These include transverse momenta and rapidity of individual top quarks and of the \( t\bar{t} \) system, opening angles etc. All distributions were found to be in excellent agreement with SM predictions.

3.6 Search for \( t \rightarrow H^+b \)

Charged Higgs arise in the simplest extension of the SM Higgs sector to a two-Higgs doublet model. If \( m_{H^+} < m_t - m_b \), then \( t \rightarrow H^+b \) could compete with \( t \rightarrow W^+b \) depending on \( m_{H^+} \) and \( \tan \beta \), the ratio of vacuum expectation values of the two scalar doublets. Direct searches for charged Higgs pair production at LEP have resulted in a lower limit of \( m_{H^+} > 69 \) GeV at 95\% CL. [8] The decay \( t \rightarrow H^+b \) dominates only if \( \tan \beta \) is either very large (> 40) or very small (< 0.9) and loses ground as \( m_{H^+} \) increases. Both DØ and CDF have searched for the subsequent decay \( H^+ \rightarrow \tau \nu \) which is the favored mode if \( \tan \beta > 1 \). In addition, DØ has searched the region of small \( \tan \beta \), where the favored decay mode would be \( H^+ \rightarrow c\bar{s} \), by examining the consistency of their lepton+jets data with SM predictions. The searches, based on leading order calculations, result in the exclusion of most of the \( [m_{H^+}, \tan \beta] \) parameter space where \( B(t \rightarrow H^+b) > 0.5 \).

4 Studies of the W boson

4.1 W mass measurements

CDF has used both \( W \rightarrow e\nu \) and \( W \rightarrow \mu\nu \) decays to obtain \( m_W = 80.433 \pm 0.079 \) GeV while DØ measures \( m_W = 80.483 \pm 0.084 \) GeV using the \( W \rightarrow e\nu \) channel only. [8] The two experiments have combined their results and that from the UA2 experiment to get a hadron collider average
of $m_W = 80.456 \pm 0.059$ GeV which is comparable in precision and in good agreement with the LEP result of $m_W = 80.450 \pm 0.039$ GeV.\[13\] The combined world average now stands at $m_W = 80.451 \pm 0.032$ GeV.\[14\]

4.2 Width of the W boson

Both DØ and CDF have measured $\Gamma_W$ by studying the $W$ transverse mass distribution (the direct method). The results are $\Gamma_W = 2.04 \pm 0.11$ (stat) $\pm 0.09$ (sys) GeV (CDF) and $\Gamma_W = 2.29^{+0.18}_{-0.17}$ GeV (DØ, preliminary).\[15\] These results are combined with the width extracted from the ratio of $W$ and $Z$ leptonic partial cross sections. The combined result from the Tevatron is $\Gamma_W = 2.160 \pm 0.047$ GeV.\[16\] This is the most precise measurement of the $W$ width yet, in good agreement with the LEP direct measurement of $\Gamma_W = 2.150 \pm 0.091$ GeV. The preliminary world average is $\Gamma_W = 2.158 \pm 0.042$ GeV.\[17\]

5 Future outlook

Run 2 of the Tevatron, presently in an early stage, holds much potential. The accelerator upgrade is designed to increase the center-of-mass energy by 10% (which translates to a $\sim$30% increase in $\sigma(p\bar{p} \to t\bar{t})$), and a much higher integrated luminosity: 2 fb$^{-1}$ per experiment in Run 2a, 15 fb$^{-1}$ in Run 2b. The detector upgrades will significantly improve signal efficiencies and background rejection. The number of events used for extracting the $W$ mass and width measurements by DØ in Run 2 is expected to be $\sim$430 times that in Run 1. A combined enhancement of a factor of $\sim$300 for $t\bar{t}$ events, and even greater for single top events are expected by the end of run 2. These should enable us to reduce the uncertainties on the top and $W$ mass measurements by a factor of 2 to 3. All other studies, including those on which first results have been obtained, are dominated by statistical uncertainties. These will benefit greatly from Run 2. Table 1 summarizes the current results and expectations in the near future for some of the studies of top quark physics.

Table 1: Summary of current results and future expectations on some physics topics related to the top quark.

| Top quark property | Run 1 measurement | Precision |
|-------------------|-------------------|-----------|
|                   |                   | Run 1 | Run 2a | Run 2b | LHC |
| Mass              | 174.3 $\pm$ 3.3 $\pm$ 3.9 GeV | 2.9% | 1.2% | 1.0% |
| $\sigma(t\bar{t})$ | 6.5$^{+1.7}_{-1.4}$ pb (CDF) | 25% | 10% | 5% | 5% |
| $\sigma(t\bar{t})$ | 5.9 $\pm$ 1.7 pb (DØ) |                      |       |       |       |
| $F_0(W)$          | 0.91 $\pm$ 0.37 $\pm$ 0.13 | 0.4   | 0.09 | 0.04 | 0.01 |
| $F_+(W)$          | 0.11 $\pm$ 0.15 $\pm$ 0.06 | 0.15  | 0.03 | 0.01 | 0.003 |
| $R \equiv \frac{B(t \to W^+ b)}{B(t \to W^0 q)}$ | 0.96$^{+0.31}_{-0.24}$ (3-gen.) | 30% | 4.5% | 0.8% | 0.2% |
|                   | $> 0.61$ at 90% C.L. |       |       |       |       |
| $|V_{tb}|$ from $t\bar{t}$ | 0.96$^{+0.16}_{-0.12}$ (3-gen.) | $> 0.051$ at 90% C.L. | 0.05 | 0.25 | 0.50 | 0.90 |
| $\sigma$(single top) | < 13.5 pb |       |       |       |       |
| $\Gamma(tWb)$     | – | 20% | 8% | 5% |
| $|V_{tb}|$ from single top | – | 25% | 10% | 10% |
| $B(t \to \gamma q)$ | < 0.03 (95% C.L.) | 12% | 5% | 5% |
| $B(t \to Zq)$     | < 0.32 (95% C.L.) | < 0.03 | ? | ? | ? |
|                   | $< 0.03$ (95% C.L.) | < 0.3 | < 0.02 | ? | ? |
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