I present recent results on top quark production and properties in $p\overline{p}$ collisions at a center of mass energy of 1.96 TeV. The measurements were performed by the CDF and D0 collaborations using approximately 3 fb$^{-1}$ of data taken during Run II at the Tevatron.

1 Introduction

The top quark was discovered at the Fermilab Tevatron Collider in 1995 and completes the quark sector of the three-generation structure of the standard model (SM). It is the heaviest known elementary particle with a mass approximately 40 times larger than that of the next heaviest quark, the bottom quark. It differs from the other quarks not only by its much larger mass, but also by its lifetime which is too short to build hadronic bound states. The top quark is one of the least-studied components of the SM, and the Tevatron, with a center of mass energy of $\sqrt{s} = 1.96$ TeV, is at present the only accelerator where it has been produced. The top quark plays an important role in the discovery of new particles, as the Higgs boson coupling to the top quark is stronger than to all other fermions. Understanding the production properties of top quark pairs is in itself a test perturbative Quantum Chromo Dynamics (pQCD), but is also a crucial ingredient in the discovery of new physics beyond the SM. In the following sections I will present studies of top quark production and decay mechanisms, both within and out of the SM predictions.

2 Studies of $t\overline{t}$ pair production mechanisms

At Tevatron energies, top quarks are produced predominantly in pairs. Within the SM, the top quark decays almost exclusively into a $W$ boson and a $b$ quark, resulting in two $W$ bosons and 2 $b$ jets in each $t\overline{t}$ pair event. The $W$ boson itself decays into one lepton and its associated neutrino, or hadronically. We have classified the $t\overline{t}$ pair decay channels as follows: the dilepton channels where both $W$ bosons decay leptonically into an electron or a muon ($ee$, $\mu\mu$, $e\mu$), the lepton + jets channels where one of the $W$ bosons decays leptonically and the other hadronically ($e$+jets, $\mu$+jets), and the all-jets channel where both $W$ bosons decay hadronically. Production cross sections have been measured in all decay channels. The lepton + jets channels have less statistics than the all-jets channel, but the background level is significantly smaller, making it the channel of choice for the measurement of top quark properties.

The total top quark pair production cross section for a hard scattering process initiated by a $p\overline{p}$ collision is a function of the top quark mass $m_t$. For a top quark mass of 175 GeV, the predicted SM $t\overline{t}$ production cross section is $6.7^{+0.7}_{-0.9}$ pb. Deviations of the measured cross section from the theoretical prediction could indicate effects beyond QCD perturbation theory. Explanations might include substantial non-perturbative effects, new

*on behalf of the CDF and the D0 collaborations
production mechanisms, or additional top quark decay modes beyond the SM. Previous measurements [5] show good agreement with the theoretical expectation within the experimental precision.

Recent results are available from both CDF and D0, and are summarized in Fig. 1 together with the theoretical predictions. As can be seen in the plots, the uncertainties on the latest experimental results are reaching the theoretical uncertainty of ≈10%.

![Figure 1: Summary of $t\bar{t}$ pair production cross section measurements at $\sqrt{s} = 1.96$ TeV from CDF (left), and D0 (right). Theoretical predictions are shown as vertical bands. The newest experimental results have reached the theoretical uncertainty of ≈10%.](image)

At leading order, $t\bar{t}$ production proceeds through the $q\bar{q} \rightarrow t\bar{t}$ and $gg \rightarrow t\bar{t}$ processes, with the $q\bar{q}$ process contributing 85% to the production cross section, and the $gg$ process contributing only 15%. NLO theoretical predictions are available [1], but suffer from large uncertainties. Measuring the relative fraction of $t\bar{t}$ events produced via a particular production mechanism provides a direct test of pQCD and may reveal the existence of $t\bar{t}$ production and decay mechanisms beyond the ones predicted by the SM [7]. CDF has studied the relative fraction of $t\bar{t}$ events produced via gluon-fusion using an azimuthal correlation of charged leptons in the $t\bar{t}$ to dilepton channel. Using 2 fb$^{-1}$ of data, CDF measures $\frac{\sigma(gg\rightarrow t\bar{t})}{\sigma(q\bar{q}\rightarrow t\bar{t})} = 0.53\pm0.36_{-0.38}^{+0.36}$. The measurement is dominated by the statistical uncertainty and is in agreement with SM expectations.

Several beyond the SM theories [8] predict the resonant production of $t\bar{t}$ pairs. Using 2.1 fb$^{-1}$ of data, D0 has studied the invariant mass spectrum in lepton + jets events using a neural network to identify b-jets. The observed spectrum is consistent with SM expectations, showing no evidence for additional resonant production mechanisms. Consequently, the data...
is used to set upper limits on $\sigma \times B(X \to \bar{t}t)$ for different hypothesized resonance masses using a Bayesian approach. Within a topcolor-assisted technicolor model, the existence of a leptophobic $Z$ boson with mass $m_{Z'} < 760$ GeV and width $\Gamma_{Z'} = 0.012 m_{Z'}$ can be excluded at 95% C.L.

3 Studies of top quark decays

Within the SM, the top quark decays via the V-A charged-current interaction to a $W$ boson and a $b$ quark. New physics present in the $t \to W b$ decay could become evident in the helicity of the $W$ boson originating from a top quark decay. In particular, a different Lorentz structure of the $Wtb$ interaction would alter the fractions of $W$ bosons produced in each polarization state from the SM values of $0.697 \pm 0.012$ \cite{9} for the longitudinal $f^0$ and $3.6 \times 10^{-4}$ \cite{10} for the right-handed $f^+$ polarization. The CDF and D0 collaborations have measured these fractions using as sensitive observable the cosine of the decay angle of the charged lepton in the $W$ rest frame measured with respect to the direction of motion of the $W$ boson in the top quark rest-frame. The measured fractions using 1.9 fb$^{-1}$ of CDF data \cite{11} and 2.7 fb$^{-1}$ of D0 data \cite{12} are limited by the statistics of the data samples and show no significant deviation from the SM predictions.

4 Measurement of the top quark mass

The mass of the top quark is a fundamental parameter of the SM. When combined with the $W$ mass measurement, it places constraints on the mass of the Higgs boson. Both collaborations have measured the top quark mass in different decay channels and with different methods. The most precise results are obtained in the lepton + jets channel using the Matrix Element technique \cite{13}. In this method, an event by event weight is calculated according to the quality of the agreement with the SM top quark pair and background differential cross-sections; the product of all event probabilities gives the most likely mass. The jet energy scale is constrained in-situ by the hadronic decay of the $W$ boson present in the event. A summary of all the measurements is shown in figure 2. The combined result \cite{14} of $m_{\text{top}} = 172.4 \pm 0.7 \text{(stat)} \pm 1.0 \text{(syst)}$ GeV has a precision of less than 1%.

Assuming that the top pair production is governed by the SM, the D0 collaboration extracted the top quark mass comparing the measured cross-section with a theoretical prediction \cite{15}, and obtained $m_{\text{top}} = 169.6 + 5.4 - 5.5$ GeV \cite{16}. This measurement has different experimental and theoretical uncertainties than the direct measurements; the results obtained by the two methods are in agreement with each other.

5 Single top production

The SM predicts that top quarks can be produced singly at hadron colliders \cite{17} via the electroweak interaction from the decay of an off-shell $W$ boson or fusion of a virtual $W$ boson with a $b$ quark. The SM prediction \cite{18} for the single top quark cross section for a top quark mass of 175 GeV is 0.98 $\pm$ 0.04 pb for the s-channel process $p\overline{p} \to t\bar{b}$, and 2.16 $\pm$ 0.12 pb for the t-channel process $p\overline{p} \to t\overline{q}b$. Measurement of the single top quark production cross section has been impeded by its low rate and difficult background environment compared to the top pair production. The D0 collaboration presented in 2007 the first evidence for single top quark production and the first direct measurement of $|V_{tb}|$ \cite{19,20} based on 0.9 fb$^{-1}$ of
data. More recently, the CDF collaboration has also presented evidence for single top quark production [21] in 2.2 fb$^{-1}$ of data. The summary of these results is shown in figure 2.

Events with single top quarks have also been used by both collaborations to directly measure the absolute value of the CKM matrix element $|V_{tb}|$, and to search for physics beyond the SM. In particular, the D0 collaboration searched for a charged Higgs boson $H^+$ with $180 < m_H^+ < 300$ GeV decaying to a top and a bottom quark, which would enhance the rate for the s-channel single top production and be observed as a resonance in the $m(W_{jj})$ spectrum [22]: the D0 collaboration also used the data to place constraints on the left-handed and right-handed vector and tensor $Wtb$ couplings [23]. The CDF collaboration performed a model independent search for FCNC processes in single top production, and set an upper limit on the production cross section $\sigma(u(c) + g \rightarrow t) < 1.8$ pb at the 95% C.L. limit and on the anomalous couplings that define the strength of the $gtu$ and the $tcg$ vertices [24].

6 Conclusions

The Tevatron has entered a new era of top quark precision measurements. The experimental precision on the top quark pair production cross section results has reached the theoretical uncertainty, making comparisons between different channels and methods interesting. In addition, a series of new measurements of top quark production and decay properties and searches for deviations from the SM predictions are becoming available based on the larger statistics samples collected in 3 fb$^{-1}$ of collider data. CDF and D0 have already written to

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tape more than twice the amount of data used for these results. The lepton + $\geq 3$ jets sample with two identifed $b$-jets is completely dominated by $t\bar{t}$ events. With larger data sets, as the ones that will be available at the Tevatron in the near future, even more precise measurements of top quark properties will be possible.

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