The top quark plays an important role in the grand scheme of particle physics, and is also interesting on its own merits. We present recent results from CDF on top-quark physics based on $100-200 \text{pb}^{-1}$ of $p\bar{p}$ collision data. We have measured the $t\bar{t}$ cross section in different decay modes using several different techniques, and are beginning our studies of top-quark properties. New analyses for this conference include a measurement of $\sigma_{t\bar{t}}$ in the lepton-plus-jets channel using a neural net to distinguish signal and background events, and measurements of top-quark branching fractions.

Evidence for the top quark was first reported ten years ago this spring, but the properties of top, a fundamental particle in the standard model, have yet to be fully determined. There is still much to learn about the processes of production and decay, and we have not yet measured the quantum numbers of top, which are exactly predicted by the standard model. These properties are important not just for the purpose of characterizing top, but also for understanding its relationship to other particles in the model. Predictions for the mass of a standard-model Higgs boson depend very strongly on the value of the top-quark mass. Because top is so heavy, it may provide a path to new physics. The top quark must be understood in detail so that we can understand whether it is just part of the standard model, or the first hint of physics beyond it.

The top quark is an active topic of study in the CDF Collaboration, which operates a detector that records data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. The upgraded detector was commissioned in 2001, and data-taking for physics began in 2002. Since then, CDF has recorded about $200 \text{ pb}^{-1}$ of analysis-quality data in Run II, roughly double the sample of the previous data run. Here we present measurements of top-quark production rates and properties in this data sample.

Most of our studies are done with $t\bar{t}$ pairs, which are produced through the strong interaction. We typically assume that $B(t \rightarrow Wb) = 100\%$. Every $t\bar{t}$ event thus has two $W$’s, so we
classify the final states by the decays of the $W$’s. “Dilepton” events have both $W$’s decaying to $\ell\nu$; this mode has good signal to noise ($S/N \sim 1.5-3.5$), but a low detectable event rate (4-6 events/100 pb$^{-1}$). “Lepton plus jets” events have only one $W$ decaying to $\ell\nu$; the rate is higher than for dileptons (25-45 events/100 pb$^{-1}$) but this channel has worse $S/N$ ($\sim 0.3-3.0$). Regardless of how the $W$ decays, $t\bar{t}$ events have two $b$ quarks; these can be identified by displaced vertices (due to the long $b$-hadron lifetime and large mass) or soft leptons (due to the large $b$-hadron semileptonic branching fraction) embedded in the jets produced by quark hadronization.

1 Cross-Section Measurements

Before we can study the properties of the top quark, we have to isolate a sample of candidate top-quark events, and build tools to understand the rates of background events in the sample and the efficiency for top-quark selection. Our benchmark for these tools is a measurement of the $t\bar{t}$ production cross section. This production rate is predicted by QCD; a measurement that agrees with theory gives us confidence that we have some control over our tools, and that we in fact have top quarks to study.

The cross-section measurement for dileptons is straightforward because the events are so clean and the backgrounds are relatively small. CDF has two complementary dilepton cross-section measurements. One explicitly identifies the two leptons (electrons or muons), while the other identifies only one lepton and searches for an additional isolated high-$p_T$ track. The former analysis has lower background, but the latter has greater acceptance and greater sensitivity to $\tau$ decays of the $W$. The lepton-lepton analysis observes 13 events ($1\ e\bar{e}, 3\ \mu\mu, 9\ e\mu$) on 2.4 ± 0.7 background events, while the lepton-track analysis observes 19 events ($11\ e\text{-track}, 8\ \mu\text{-track}$) on 7.1 ± 1.2 background – significant signals in both cases.

Cross-section measurements in the lepton-plus-jets mode fall into two categories. The first includes counting experiments, in which we predict from first principles the rate of standard-model non-$t\bar{t}$ backgrounds in the sample; any excess over that rate is considered the $t\bar{t}$ signal. Such counting experiments are only done in samples with at least one tagged $b$ jet, where the non-$t\bar{t}$ backgrounds are relatively small. The background estimates are data-driven as much as possible; estimates for rates of QCD-jet and fake-tag backgrounds are entirely derived from data, while backgrounds from $W$ plus heavy-flavor processes ($Wb\bar{b}, Wc\bar{c}, Wc$) and lower-rate processes (dibosons, single top) get assistance from Monte-Carlo information. After checking that these methods work in lepton-plus-jets samples with fewer than three jets, where we expect little $t\bar{t}$, we apply them to the lepton-plus-jets samples with at least three jets, where most of the $t\bar{t}$ events are expected. The distribution of the number of jets in $b$-tagged events is shown in Figure 1. We use two different $b$-tag techniques. In events where there is at least one jet with a displaced-vertex tag, we observe 57 events with a background prediction of 23.4 ± 3.0. In events where there is at least one jet with a lepton tag, we observe 18 events with a background prediction of 12.9 ± 2.6.

Cross-section measurements that make use of kinematic information in candidate events are in the second category. Rather than dead-reckoning the background rate, we use characteristics of the signal sample itself to help estimate the rate. We build models of kinematic variables for signal and background events, and then fit the distributions observed in the data to a sum of these models, letting the normalizations float. The estimated fraction of $t\bar{t}$ events can be converted into a cross section. Such analyses can be done with lepton-plus-jets samples where $b$ tags are not required, as we use the kinematic information to help separate signal from background instead of the tags. This exploits the large event sample, but now the backgrounds to $t\bar{t}$ are larger. With a fit to the distribution of the total transverse energy of the event ($H_T$, see Figure 2), we find that this sample has a $(13\pm 4)\%$ $t\bar{t}$ content. The signal and background $H_T$ shapes are modeled...
by Monte Carlo simulation, and systematic effects such as our understanding of the jet-energy scale and inputs to the leading-order matrix-element Monte Carlos (such as the $Q^2$ scale) limit our precision. A complementary approach is to perform this measurement in the sample of lepton-plus-jets events that include displaced-vertex-tagged jets; the energy of the leading jet is used as the kinematic variable. Now the signal-to-noise is improved, and we can use a sample of real data to model the background – the lepton-plus-jets events without $b$ tags, which should be depleted of $t\bar{t}$ events – and thus largely eliminate the systematic uncertainty due to modeling. The $t\bar{t}$ content of this sample is $(67^{+13}_{-16})\%$, where the uncertainty is now dominated by statistics. While the kinematics of $t\bar{t}$ and the dominant $W$ plus jets background process do differ, they only differ modestly, so there is very little separation in any given variable. However, these modest differences occur in many different variables. Thus, we choose several variables (jet energies, invariant masses, event shapes) that are largely uncorrelated, or have different correlations in signal and background processes, and then develop a neural network from these variables to use the information optimally. The distribution of neural-net outputs for the lepton-plus-jets sample (the same sample used in the $H_T$ analysis) is also shown in Figure 2. Now there
is much better separation between the $t\bar{t}$ signal and the backgrounds, which leads to improved statistical and systematic uncertainties. The $t\bar{t}$ fraction in this sample is $(18 \pm 3\%)$, consistent with, and more accurate than, the value measured in the $H_T$ analysis. We believe that such multivariate techniques are very promising for isolating $t\bar{t}$ and other hard-to-extract signals.

A summary of the current set of $t\bar{t}$ cross-section measurements from CDF is given in Table 1 and Figure 3 along with the current prediction from theory with $m_t = 175$ GeV. One should not perform a naive average of the values as there are correlations, and one should remember that the theory prediction has an additional $\sim 1$ pb uncertainty due to the uncertainty in $m_t$, but we do see general consistency among the measurements, and agreement with the theory prediction. This gives us confidence that we are in fact observing $t\bar{t}$ production.

In addition, CDF is searching for the production of single top quarks through the electroweak interaction; the cross section is expected to be about 3 pb. Eventually this will provide a direct measurement of $|V_{tb}|^2$. We currently set a 95% CL upper limit of 13.7 pb on the total single-top production rate.

### Table 1: Summary of $t\bar{t}$ cross-section measurements from CDF. The first uncertainty is statistical, the second is systematic.

| Analysis                                      | $\sigma_{t\bar{t}}$ (pb) | $\int Ldt$ (pb) |
|-----------------------------------------------|---------------------------|-----------------|
| Dilepton – lepton-lepton                      | $8.7^{+3.9}_{-2.6} \pm 1.5$ | 193             |
| Dilepton – lepton-track                       | $6.9^{+2.7}_{-2.4} \pm 1.3$ | 200             |
| Lepton + jets – kinematic ($H_T$)             | $4.7 \pm 1.6 \pm 1.8$     | 195             |
| Lepton + jets – kinematic (NN)                | $6.7 \pm 1.1 \pm 1.5$     | 195             |
| Lepton + jets – vertex tag                    | $5.6 \pm 1.2 \pm 0.7$     | 162             |
| Lepton + jets – lepton tag                    | $4.1^{+4.0}_{-2.8} \pm 2.2$ | 126             |
| Lepton + jets – vertex tag + kinematic        | $6.0^{+1.3}_{-1.8} \pm 0.8$ | 162             |
| Theory ($m_t = 175$ GeV)$^3$                  | $6.7^{+0.6}_{-0.9}$       |                 |

2 Branching fractions

With the top-quark sample identified, we can begin to measure the properties of top quarks. For instance, we can use the cross-section measurements to study the branching fractions of top. The standard model predicts that $B(t \rightarrow Wb)$ is virtually 100%; in particular, we expect that there is always a $W$ in the decay. The $t\bar{t}$ cross-section measurements in fact assume that there are always two $W$’s in the final state; the event rates are corrected for the $W$ branching fractions to obtain the total $t\bar{t}$ cross section.

We can test this assumption by examining the ratio of measured cross sections for different $t\bar{t}$ final states, $R_\sigma = \sigma_{t\bar{t}}/\sigma_{tj}$. $R_\sigma$ should be consistent with unity if in fact the dilepton and lepton-plus-jets analyses are both examining standard-model $t\bar{t}$ production. Measuring ratios is appealing to experimenters; $R_\sigma$ will have smaller systematic uncertainties than the individual cross-section measurements as some common factors will cancel. And of course, $R_\sigma$ is independent of any theory prediction for $\sigma_{t\bar{t}}$, so we can look for new physics by looking for a deviation in the ratio, rather than by comparing a measured cross section to an uncertain theory prediction. As an example, $R_\sigma$ is sensitive to decays such as $t \rightarrow H^+b$. If this process occurs, then the mix of dilepton and lepton-plus-jets events would be different from what is expected in the standard model, and that mix is sensitive to $\tan \beta$, which controls whether the $H^+$ is more likely to decay to hadrons or to leptons.

We estimate $R_\sigma$ creating a probability distribution based on the observed event rates; this is shown in Figure 4. We find $R_\sigma = 1.45^{+0.83}_{-0.55}$, and we can limit $0.46 < R_\sigma < 4.45$ at 95% CL.
Since this is consistent with standard-model expectations, we can set limits on non-standard decays of top. These limits are by their nature model dependent, as we need to understand the efficiency to detect the non-standard decay. We find that the branching fraction to an all-hadronic $t \to Xb$ decay is less than 0.46 at 95% CL under the assumption that we detect standard and non-standard all-hadronic decays with the same efficiency.

We can also examine the other side of the branching-ratio coin – we typically assume that there is always a $b$ in each top decay, and in fact all of the cross-section measurements that use $b$ tagging depend on that assumption. We can test that hypothesis by examining the $b$-tag rates in identified $tt$ events. These rates depend both on $b = B(t \to Wb)/B(t \to Wq)$ and on the single-$b$ tagging efficiency $\epsilon$. The rates of observing two, one or zero tags in $tt$ events depend on the product $be$, as the $b$ quark must be produced and subsequently tagged:

$$N_2 \propto (be)^2 \quad N_1 \propto 2be(1 - be) \quad N_0 \propto (1 - be)^2 \Rightarrow$$

$$be = \frac{2}{N_1/N_2 + 2} = \frac{1}{2N_0/N_1 + 1}.$$ 

$be$ is thus determined by the ratios of tag rates. Since we measure the product $be$, we can either take the value of $\epsilon$ measured in calibration samples and extract $b$, or just assume the standard-model value $b = 1$ and do an in situ cross check of $\epsilon$.

The above treatment is simplistic; we need to account for our limited acceptance for $b$ jets, for tagged jets that come from non-$tt$ events, and for tagged jets that come from non-$b$ quarks.
in $t\bar{t}$ events. We create a likelihood function that depends on the observed numbers of tags in the vertex-tagged lepton-plus-jets sample, and find the most likely value of $b\epsilon$. The resulting likelihood is shown in Figure 5. We measure the most likely value as $b\epsilon = 0.25^{+0.22}_{-0.18}$. The single-$b$ tagging efficiency is $0.45 \pm 0.05$, and thus $b = 0.54^{+0.49}_{-0.39}$ - smaller than expected, but consistent with $b = 1$. If we assume $b = 1$, we find an estimate of $\epsilon$ that is consistent with our measurements in calibration samples. In addition, we can set a lower limit of $b > 0.12$ at 95% CL. If this analysis remains exactly the same as we record more data – no change in background levels or efficiencies – we expect to set a lower limit of about 0.70 with 500 pb$^{-1}$ of integrated luminosity. Of course, we do hope to reduce our backgrounds and increase our efficiencies as we accumulate more data.

3 Mass

As stated above, measurements of the top-quark mass are of great interest right now, as predictions for the mass of the Higgs are so sensitive to it. As of the date of this conference, CDF has performed two preliminary measurements of the top mass with Run II data.

One makes use of the dilepton sample, which has very little background but low event rates. Because of the two neutrinos in the final state, estimating the top mass is an underconstrained problem, and some more information must be added. In addition, we do not know which jets to match up with which leptons in the final state, giving an additional combinatorics problem. The current CDF analysis scans over possible directions of the neutrinos, and uses the predicted $p_T$ of the $t\bar{t}$ system (taken from theory) as an event weight. Multiple solutions for the mass are possible; we choose the one with the greatest kinematic consistency with $t\bar{t}$. Using six events in 126 pb$^{-1}$ of data, we measure $m_t = 175 \pm 17_{\text{stat}} \pm 8_{\text{sys}}$ GeV, where the systematic uncertainty is dominated by our limited knowledge of the jet-energy scale.

Another mass measurement is made with the lepton-plus-jets sample. We choose the events with four jets, at least one of which is vertex-tagged. The event rates are larger here than in the dilepton mode, and while the backgrounds are also larger, they are tolerable. Now that there is only one neutrino in the final state, the problem is overconstrained. In each event, we choose the combination of jets that gives the best consistency with the $t\bar{t}$ hypothesis in a kinematic fit. With 22 events in a sample of 108 pb$^{-1}$, we measure $m_t = 178^{+13}_{-9_{\text{stat}}} \pm 7_{\text{sys}}$ GeV. Again,
the systematic uncertainty is dominated by the jet-energy scale. Improved measurements of the top-quark mass are expected shortly.

4 Outlook

At this stage of Run II at the Tevatron, there is little doubt of the top-quark signal at CDF. We have observed $t\bar{t}$ production in multiple channels (dilepton and lepton plus jets) and with multiple techniques (different $b$ taggers, counting experiments, and fits to kinematic distributions, including a new neural-net-based analysis). All of the $t\bar{t}$ cross-section measurements are consistent with the theory prediction, and with each other.

Meanwhile, studies of top-quark properties are beginning. At this conference, we presented the first Run II measurements of top-quark branching fractions. We are hard at work on the mass measurements: adding in more data, improving our techniques and reducing systematics. We hope to have new results imminently.

This is just the beginning of a broad program to characterize the top quark. At CDF, we are preparing for a variety of top-quark studies – measurements of the $W$ helicity, searches for decays to charged Higgs and for resonant $t\bar{t}$ production, and studies of angular correlations in top decay. More data and more news about top and its impact on standard and new physics are expected soon.

Acknowledgements

I thank my CDF colleagues for all of their efforts to produce these results, and the conference organizers for putting together a very pleasant week of physics and other activities.

1. “Top Quark, Last Piece in Puzzle of Matter, Appears to Be in Place,” The New York Times, Page A1, April 26, 1994.
2. See, for instance, P. Gambino, “The Top Priority: Precision Electroweak Physics from Low to High Energy,” 21st International Symposium on Lepton and Photon Interactions at High Energies (LP 03), Batavia, IL, August 2003, hep-ph/0311257
3. M. Cacciari et al., hep-ph/0303085