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TOP PHYSICS RESULTS FROM CDF

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The top quark is by far the most massive fundamental particle observed so far, and the study of its properties is interesting for several reasons ranging from its possible special role in electroweak symmetry breaking to its sensitivity to physics beyond the Standard Model. We present recent top physics results from CDF based on 160-320 pb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV. The $t\bar{t}$ cross section and the top mass have been measured in different decay channels and using different methods. We have searched for evidence of single top production, setting upper limits on its production rate. Other results shown in this conference include studies of the polarization of W bosons from top decays, a search for charged Higgs decaying from top, and a search for additional heavy t' quarks.

1 Introduction: top at CDF

The CDF detector was upgraded [1] for Run 2 of the Tevatron, and has recorded ≈ 600 pb^{-1} of $p\bar{p}$ collision data at $\sqrt{s} = 1.96$ TeV. Top at the Tevatron is produced predominantly in $t\bar{t}$ pairs through the strong interaction (quark-antiquark annihilation or gluon gluon fusion), and it decays virtually 100% of time to Wb. The final state of a $t\bar{t}$ event therefore has two Ws and two b quarks, and the event selection at CDF is characterized by the decay mode of the W bosons. Events where both Ws decay to e or μ are called "dilepton" events. This mode has the advantage of being relatively clean, with a S/N of about 1.5 to 3.5, but it has a low rate (4-6 events/100 pb^{-1}) owing to the small leptonic branching fraction of W. Events in which one W decays to e or μ and the other decays to quarks are called "lepton + jets" events. This decay channel has a higher rate than the dilepton channel (25-45 events/100 pb^{-1}), but it has worse S/N (0.3 to 3). Since all $t\bar{t}$ events have two b quarks while only 1-2% of the dominant backgrounds contain heavy flavor, S/N can be considerably improved by identifying b quarks (b

tagging). This is done either by looking at tracks embedded in a jet which are displaced from the primary interaction point (due to the long b-hadron lifetime) or by looking for a soft lepton embedded in a jet (due to the large semileptonic decay rate of b-hadrons). Top at the Tevatron can also be produced singly through the electroweak interaction, with a predicted cross section which is about 3 times smaller than the $t\bar{t}$ cross section. Single top events contain just one W in the final state, have lower jet multiplicity and are harder to separate from the background.

2 Top Cross-Section

Measurement of the $t\bar{t}$ production cross section in the different decay modes and with different methods provides an understanding of the event selection efficiency, background contamination, event kinematics and heavy flavor content. It is the benchmark measurement to validate a sample of top events which can be used for other top quark measurements, and it is in itself a test of QCD predictions. The most accurate measurement in the dilepton channel results from the combination two complimentary analyses using approximately 200 pb^{-1}. One analysis selects events with two identified leptons (e or μ), while the other identifies one lepton and requires an additional isolated high P_T track in order to increase the acceptance at the cost of some additional background contamination. The two lepton analysis observes 13 events with a background expectation of 2.7 ± 0.7, while the lepton+track analysis observes 19 $t\bar{t}$ candidates with a background expectation of 6.9 ± 1.7. The combined analysis gives

$$\sigma_{t\bar{t}} = 7.0^{+2.4}_{-2.1}(\text{stat})^{+1.6}_{-1.1}(\text{sys}) \pm 0.4(\text{lum}) \text{ pb}.$$

In the lepton+jets decay mode several cross section measurements have been performed. The basic event selection requires one identified lepton, large missing transverse energy and 3 or energetic jets. Counting analyses require at least one of the jets to be tagged as a b-jet in order to further reduce the dominant W+jets and QCD backgrounds. The QCD and fake-tag backgrounds are derived from data, while W + heavy flavor, single top, and diboson backgrounds use a combination of data and MC. We check the background estimation in a control region of low jet multiplicity, where we expect little $t\bar{t}$ contribution, and measure the cross section the events with 3 or more jets by assigning any excess of observed events over the predicted non-top SM backgrounds to $t\bar{t}$ production. The most precise determination of the $t\bar{t}$ cross section at CDF uses ≈ 160 pb^{-1} of lepton+jets events and requires at least one jet to be b-tagged by a secondary vertex algorithm which looks at tracks associated to the jet. Additionally, the total transverse energy H_T of the event (including the missing E_T) is required to be larger than 200 GeV in the signal region. Figure 1 shows the distribution of b-tagged events and the predicted background rates as a function of jet multiplicity. A total of 48 events are observed in the 3 or more jet region over an expected background of 13.5 ± 1.8. The resulting cross section is

$$\sigma_{t\bar{t}} = 5.6^{+1.2}_{-1.1}(\text{stat})^{+0.9}_{-0.6}(\text{sys}) \text{ pb}$$

where a 6% luminosity uncertainty is included in the systematic uncertainty.

Other analyses in the lepton+jets channel do not use b-tagging. Instead, they make use of kinematic information in the $t\bar{t}$ candidate events. Templates for different kinematic variables are built for signal and background events, and the distribution observed in the data is fit to a sum of these templates, allowing the normalizations to float. Two analyses of this type have been performed at CDF. One simply fits the H_T distribution, while the other one derives a neural net (NN) discriminant which includes information from seven different kinematic distributions. The results of such fits are shown in Figure 2. The H_T fit illustrates the difficulty of separating the top signal from the background when one does not use b-tagging. The fraction of top from

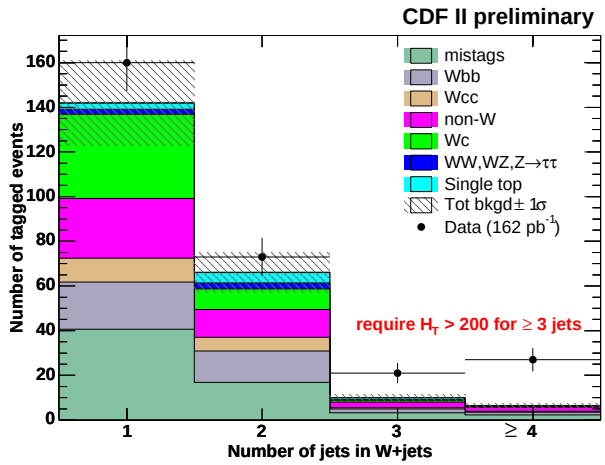

Figure 1: The number of b-tagged lepton+jets events and estimated background as a function of jet multiplicity.

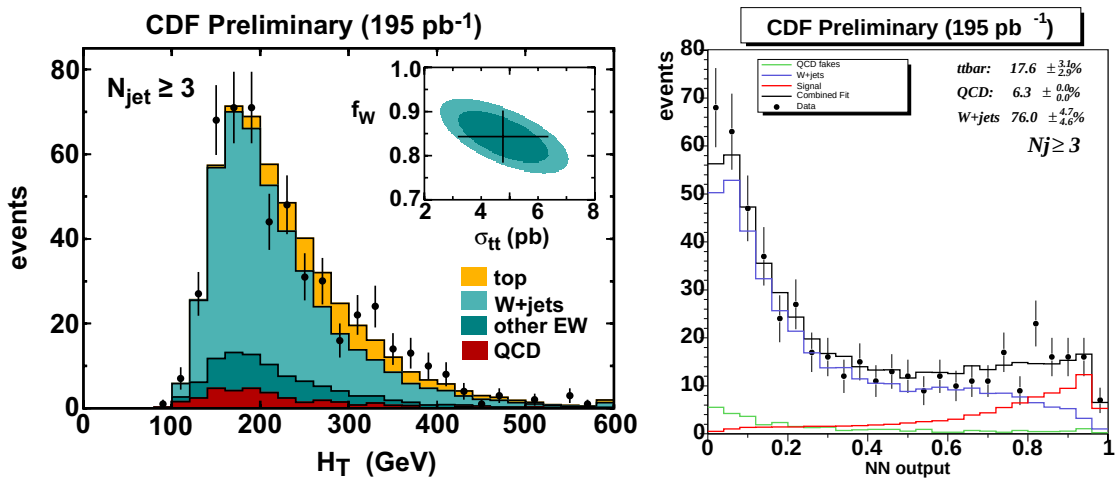

Figure 2: Distributions of H_T (left) and NN output (right) for data, top and background. Signal and background distributions are fit to the data to determine the $t\bar{t}$ fraction.

this fit is $(13 \pm 4)\%$. The NN analysis uses ≈ 195 pb^{-1} and observes 519 (pretag) events. The $t\bar{t}$ fraction is $(17.6 \pm 3.0)\%$ and the measured cross section is

$$\sigma_{t\bar{t}} = 6.7 \pm 1.1(\text{stat}) \pm 1.6(\text{sys}) \text{ pb}.$$

Several other measurements of the cross section have been performed which include two b-tagged jets, soft lepton tagging, all hadronic W decays, among others. All measurements are consistent with each other and with the theoretical prediction[2] $\sigma_{t\bar{t}}^{\text{th}} = 6.7^{+0.7}_{-0.9}$ pb for $m_t = 175$ GeV.

3 Top Mass

One of the most interesting properties of top is its huge mass, so large that its Yukawa coupling is stinkingly close to unity, making us wonder if this is just a coincidence or if top plays some special role in the electroweak symmetry breaking mechanism. The top mass is also a dominant parameter in higher order radiative corrections to several SM observables, and in particular an accurate determination of the top mass, combined with precision electroweak measurements,

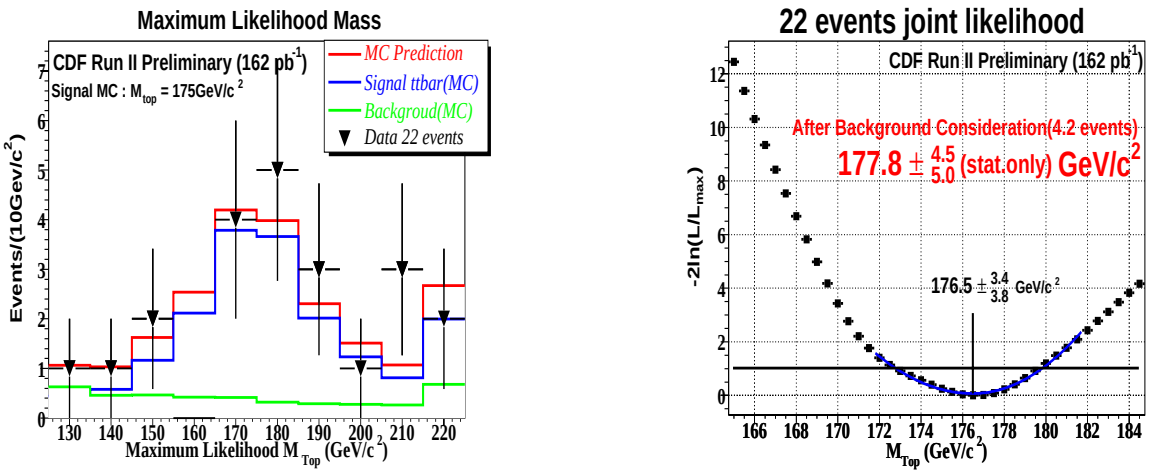

Figure 3: Maximum likelihood mass distribution for the 22 observed events (left) and combined likelihood for all 22 events (right).

helps constrain the mass of the elusive SM Higgs. CDF has measured the top mass using both dilepton and lepton+jets events. These analyses are difficult for several reasons: the final state leptons and jets observed in the detector must be matched to the $t\bar{t}$ decay partons, giving several possible assignments (only one of which is correct), the undetected neutrinos cause the event kinematics to be under-constrained, and the jet energies must be known with high accuracy. The dominant systematic uncertainty for all top mass measurements is the jet energy determination. As of the date of this conference, CDF is in the process of revising the jet energy corrections, which will result in a reduction of the systematic uncertainty of all m_t results shown here to about one half of their value. Much improved m_t results will be shown in the next round of conferences.

The best CDF result comes from a "dynamic likelihood method" (DLM) analysis which uses ≈ 160 pb^{-1} of tagged lepton+jets data. Event selection requires one identified e or μ and exactly 4 jets, at least one of which is required to be tagged by the secondary vertex algorithm. A likelihood is built as a function of m_t for each event using information from leading order matrix element (LO ME) Monte Carlo and transfer functions which give the probability of observing final state jets and leptons given the LO ME partons. All parton-jet assignments are considered, with the correct assignment receiving a larger weight. The top mass is obtained by maximizing the combined likelihood of all 22 events passing the selection, and it is then corrected by a background mapping function which gives the true top mass for the measured background fraction of 19%. Figure 3 shows the maximum likelihood mass distribution for each of the 22 observed events and the resulting combined likelihood. The top mass is determined to be

$$m_t = 177.8^{+4.5}_{-5.0}(\text{stat}) \pm 6.2(\text{sys}) \text{ GeV}.$$

The top mass has also been measured using "template" analyses, in which a value for the top mass is reconstructed for each event by looping over all possible jet-parton assignments and neutrino solutions, imposing kinematic constrains, and choosing the m_t which best fits the event. The resulting m_t distribution is then compared to Monte Carlo m_t templates simulated at various top masses. The top mass is determined by maximizing a likelihood built as a function of m_t by fitting the templates to the observed distribution. This method has been used in both dilepton and lepton+jets samples. Figure 4 shows the reconstructed top mass distributions for the dilepton sample, which observes 12 events and uses ≈ 193 pb^{-1}, and for the tagged

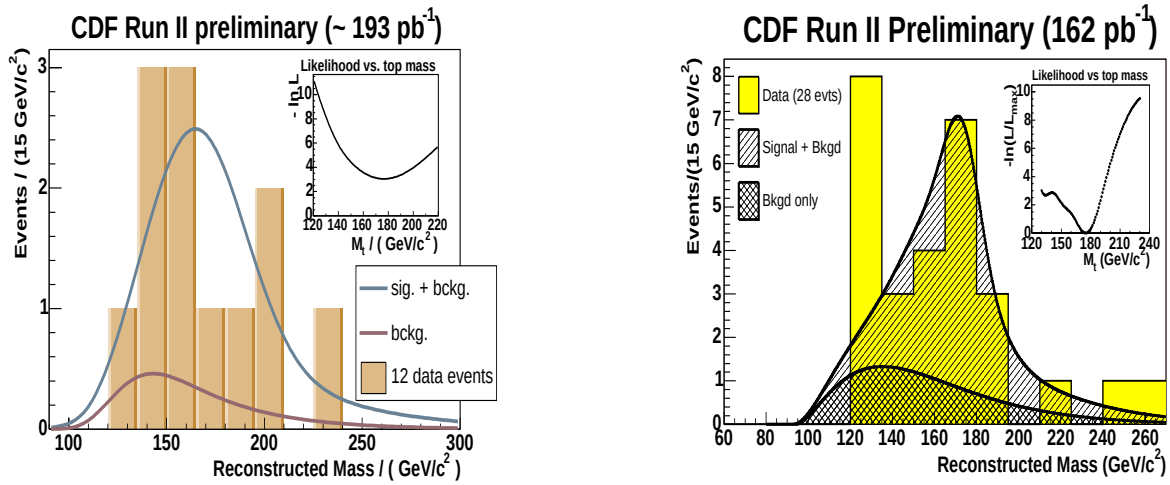

Figure 4: Reconstructed top mass distribution for the observed events in dilepton (left) and tagged lepton+jets (right) samples. Templates for signal and background are also shown. The inner figures show the likelihood as a function of m_t.

lepton+jets sample, which uses ≈ 162 pb^{-1} and observes 28 events. The figure also shows signal and background templates and the likelihood as a function of m_t. The corresponding top mass is determined to be

$$\begin{aligned} m_t &= 176.5^{+17.2}_{-16.0}(\text{stat}) \pm 6.9(\text{sys})\ \text{GeV} \\ m_t &= 174.8^{+7.1}_{-7.7}(\text{stat}) \pm 6.5(\text{sys})\ \text{GeV} \end{aligned}$$

for the dilepton and lepton+jets channels, respectively.

Several other measurements have been performed, including multivariate templates, neutrino weighting, and double tags among others.

4 Single Top

Top quarks at the Tevatron can be singly produced via the weak interaction involving a Wtb vertex. The two relevant production modes are the t and s channel exchange of a virtual W boson. The predicted theoretical cross sections [3] are $\sigma_t = 0.88 \pm 0.11$ pb for the s channel and $\sigma_t = 1.98 \pm 0.25$ pb for the t channel. The single top cross section is of particular interest because it is proportional to $|V_{tb}|^2$, the square of the CKM matrix element which relates top and bottom quarks, and which has not been directly measured. Anomalously high rates of single top production would be a hint for exotic physics beyond the SM such a FCNC, W', or anomalous couplings. In addition, single top is an important background for SM Higgs searches, since the final state is the same as for $WH \to l\nu b\bar{b}$. The event selection requires an identified e or mu, high missing E_T, and two jets, one of which must be b-tagged. Two separate searches are performed using ≈ 162 pb^{-1} of data: a combined search for the s and t channel single top signal, and a separate search which measures the rates of the two single top processes separately. A maximum likelihood technique is used to extract the signal content in the data. Monte Carlo templates of an appropriate kinematic variable are built for the signal and for the $t\bar{t}$ and non-top backgrounds, and fit to the distribution observed in the data. The separate search uses a $Q \cdot \eta$ distribution which exhibits a distinct asymmetry for t channel events, where Q is the charge of the lepton and η is the pseudorapidity of the untagged jet. The combined search uses the H_T distribution. The results of the fits to the data are shown in Figure 5. No significant evidence for single top is observed in the data, and 95% C.L. upper limits are set. For the separate search,

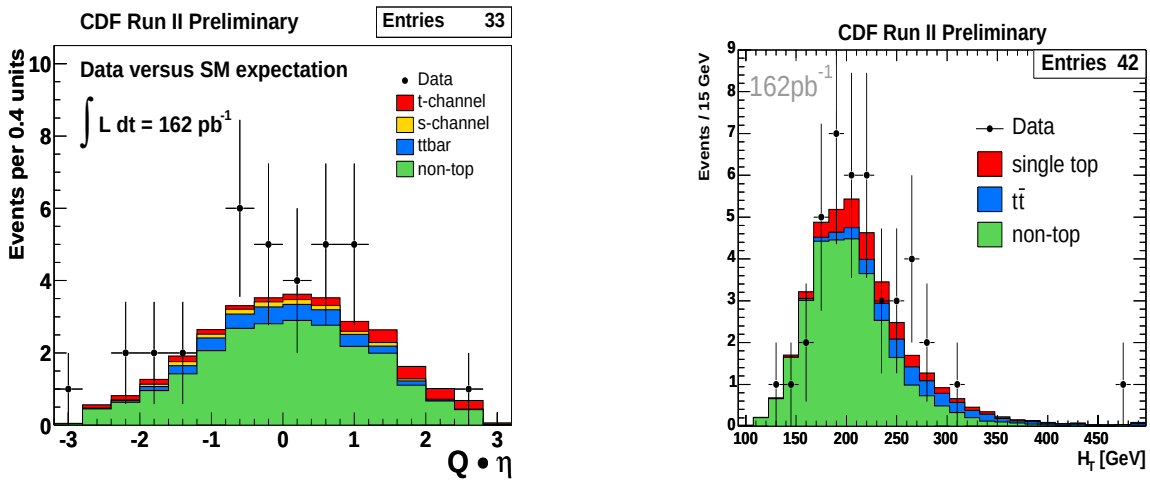

Figure 5: The $Q \cdot \eta$ distribution (left) and the H_T distribution (right) for the observed single top candidates. The solid histograms are the signal and background templates fit to the observed distribution.

we set

$$\sigma_s^{95\%CL} < 13.6 \text{ pb}$$
$$\sigma_t^{95\%CL} < 10.1 \text{ pb}$$

and for the combined search we set

$$\sigma_{s+t}^{95\%CL} < 17.8 \text{ pb}$$

CDF hopes to see evidence of single top production and to measure its production rate with a much larger data sample.

5 Other Top Measurements

Several other interesting top quark measurements have been and are being performed. Because $m_t > m_W$, a large fraction F_0 of W bosons produced in top decays are longitudinally polarized. The SM tree-level prediction is $F_0 = 0.703$ for $m_t = 175$ GeV. This fraction can be measured because kinematic distributions of the decay products of the W are different for the different W polarization states. Fitting the $\cos\theta^*$ distribution, where θ^* is the angle between the charged lepton momentum in the W rest frame and the boost direction from the top to the W rest frame, in a 162 pb^{-1} tagged lepton+jets sample we determine $F_0 = 0.89^{+0.30}_{-0.34}(\text{stat})\pm0.17(\text{sys})$ and $F_0 > 0.25$ 95% C.L. A similar analysis uses the p_T of the lepton to discriminate between different W polarizations. In the tagged lepton+jets sample the result is $F_0 = 0.88^{+0.12}_{-0.47}(\text{tot})$ and $F_0 > 0.24$ 95% C.L. In a 200 pb^{-1} dilepton sample we determine $F_0 < 0.52$ 95% C.L. and the combined analysis gives $F_0 = 0.27^{+0.35}_{-0.24}(\text{stat})\pm0.17(\text{sys})$ and $F_0 < 0.88$ 95% C.L. The reason for the dilepton result is an excess of events with low p_T leptons which drives the maximum likelihood for F_0 to an unphysical negative value.

A search for anomalous kinematics in top decays has been performed. All distributions agree with SM expectations except for the above mentioned excess of low p_T dilepton events, which is compatible with the SM with a 1% to 4% probability.

Top events are an interesting sample to search for physics beyond the SM. A search for charged Higgs from top decays sets tree-level limits in the MSSM (m_H,$\tan\beta$) plane which improve upon previous existing limits, and a model independent limit of BR($t \to Hb$)<0.7 at 95% C.L. is set on the top to Higgs branching fraction for charged Higgs masses of 80 GeV $< m_H <$

150 GeV. Another search for a generic 4th generation t' quark is performed using 195 pb^{-1} of data by fitting the H_T distribution in the untagged lepton + ≥ 4 jet events to different background, top, and t' signal templates generated at various t' masses. Upper limits at 95% C.L. are set on the t' cross section as a function of t' mass. The projected sensitivity of this analysis predicts setting limits on the t' mass with an integrated luminosity greater than 500 pb^{-1}.

Several branching fraction studies were performed. The rate of tau leptons in top decays is found to be in agreement with SM predictions, setting a limit of $r_\tau < 5.0$ at the 95% C.L. for the anomalous rate enhancement factor, predicted to be unity by the SM. The ratio $R = \mathrm{BR}(t \to Wb)/\mathrm{BR}(t \to Wq)$ is measured in both dilepton and lepton+jets events, setting a limit of $R > 0.62$ at 95% C.L., in agreement with the SM prediction of $R > 0.998$. The ratio of dilepton to lepton+jets cross-sections is measured to be $\sigma_{ll}/\sigma_{lj} = 1.45^{+0.83}_{-0.55}$, in agreement with the expected value of 1.

6 Conclusions and Outlook

Top quark properties are under extensive study at CDF. The $t\bar{t}$ production cross section has been measured in different top decay channels and using different techniques. All results are in agreement with one another and with the theoretical predictions, giving us confidence that indeed we have established a top signal and that we understand its backgrounds, its heavy flavor composition, and its kinematic properties. The top mass has been measured using different samples and techniques. The largest systematic uncertainty in these measurements comes from the jet energy scale determination, and much improved top mass results will be shown shortly after this conference. With larger data samples and improved jet energy measurements, the overall top mass uncertainty will soon be reduced to about 4 GeV. We have searched for electroweak production of top, setting limits on its production cross section. With much larger data samples we hope to observe a single top signal and measure its cross section. By the end of 2007, the recorded data will reach at least 2 fb^{-1}, and it could be more than double this size depending on Tevatron performance. All analyses will reduce significantly their uncertainties, and searches for new physics will significantly improve their sensitivity.

Acknowledgments

The results shown here represent a lot of work by a lot of people. I thank my CDF colleagues for their efforts to carry out these challenging physics analyses and for providing a friendly and stimulating research environment. I thank the conference organizers for a very nice and well organized week of physics. Finally, I thank the colleagues of my research institution, IFCA, for their support. This work is supported by the Ministerio de Educación y Ciencia, Spain (under contract FPA2002-01678) and by the EU (under contract HPRN-CT-2002-00292).

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