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TOP PHYSICS AT CDF

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Abstract

Precision studies of top quark properties are a primary goal of the Run II physics program at the Fermilab Tevatron. Marking the first stages of this program, the CDF collaboration presents recent results on top pair production cross section, single top physics and top mass, using between 109 and 200 pb^{-1} of Run II data.

1 Introduction

Since the observation of the top quark in 1995 by the CDF [1] and D0 [2] collaborations an extensive program to characterize this heaviest and rarest quark is underway. Analyses of 110 pb^{-1} of data from the 1992-96 run of the Fermilab Tevatron ("Run I") yielded first measurements of top quark properties: a mass of 174.3±5.1 GeV/c^2 and properties generally consistent with Standard Model predictions were determined. However, the available statistics were low, only about 100 top candidates. A major physics goal of the Run II of the Tevatron, which started in early 2002, are high-statistics studies of the top quark properties. This program is unique to the Tevatron until the start of the LHC program at CERN.

The Fermilab accelerator complex underwent extensive upgrades for Run II, including an increase in the center-of-mass energy from 1.8 to 1.96 TeV, which results in a 30-40% increase in the top pair-production cross-section. Up to Spring 2004, approximately 350 pb^{-1} of data, more than three times the Run I total, have been accumulated by each experiment. For the results presented here, we have analyzed up to 200 pb^{-1} of Run II data. The CDF detector has also undergone a major upgrade [3]. A new silicon vertex tracker with larger coverage has been installed, as well as a new outer tracker and endplug calorimeter. The muon coverage has been extended. In addition, the data acquisition system and trigger system are new to accomodate the new detector elements and the decrease in Tevatron bunch crossing interval from 3.5μs to 396 ns. All systems have been commissioned and CDF is taking data with ~90% efficiency.

In this article recent results on top quark production cross-section, single top production and top mass using between 109 and 200 pb^{-1} of Run II data are presented.

2 Top Quark Production and Event Selection

Top quarks are pair-produced at the Tevatron through $q\overline{q}$ or $g\overline{g}$ annihilation with a cross-section of about 6.7 pb [4] for $m_t = 175$ GeV/c^2 and $\sqrt{s} = 1.96$ TeV. In Standard Model $t\overline{t}$ production, each top quark decays promptly to a W boson and a b quark. Each W boson decays either to a charged lepton and a neutrino, or to a quark-antiquark pair that appears in the detector as jets. The studies of top quark discussed here are either performed in the *dilepton* or in the *lepton plus jets* mode.

The dilepton channel has a branching fraction of about 11%. Its final state is characterized by two leptons with high transverse momentum (P_t) and missing energy ($\not{E}_T$) from the undetected neutrinos, as well as two jets from b quarks. This final state has the highest signal to noise ratio.

The lepton plus jets channel has a higher branching ratio, 44%, but suffers from lower signal to noise, since only one lepton is present in the final state. The final state contains one high-p_t lepton, $\not\!\!E_T$, and (nominally) four jets, two of which come from b-quarks. In practice, jets can merge or go undetected, and additional jets can result from initial- and final state radiation, so analyses of the lepton+ jets signature usually require three or more jets. The presence of b-jets in $t\bar{t}$ events provides an additional handle for selecting signal events in the lepton plus jets sample. The long lifetime of B hadrons results in secondary vertices which can be "tagged" using precision tracking. This is possible with the help of the CDFII silicon vertex detector which allows event tagging efficiencies of ~50%. In addition, b-jets can be identified through their semileptonic decays to an electron or muon. These "soft" leptons (so called to distinguish them from the primary "hard" leptons from W decay) are typically found in jets from the b fragmentation and decay.

Finally, analyses using all-jets and inclusive τ (hadronically decaying) final states are still in progress.

3 Measurements of the Top Quark Production Cross Section

Since the measurement of the $t\bar{t}$ cross section requires a detailed understanding of background normalization and shapes, event selection efficiencies and b-tagging techniques, it is a good starting point for all top physics. Most importantly, it is interesting as a test of QCD. Departures of the measurement from the NNLO calculations could indicate non-standard top production mechanisms, such as top production through decays of SUSY states.

CDF has performed measurements of the $t\bar{t}$ cross section in the dilepton and in the lepton+jets channels. It is interesting to perform the measurement in different channels and using different methods to test for consistency. Here, we present two measurements in the dilepton channel and four measurements in the lepton+jets channel.

3.1 Dilepton Analyses

The dilepton channel is particularly interesting to study since in Run I some suspicious properties of the (statistically limited) signal sample were observed, such as some events with particularly high $\not\!\!E_T$, and a high fraction of $e\mu$ pairs. The dilepton channel is sufficiently clean, so that b-tagging is not required to reduce background. Backgrounds are primarily due to Drell-Yan production of lepton pairs, di-boson (WW, WZ and ZZ) production and events with a W and jets, where one of the jets is misidentified as a lepton ("fakes"). The expected Drell-Yan and fake background contribution is determined from data and di-boson background is calculated from Monte Carlo samples. We take two approaches to the analysis. To increase acceptance we first do not require lepton identification on the second lepton leg: an identified electron or muon and an isolated track, both with $p_t > 20$ GeV are selected. This gains acceptance, partly from τ leptons. In the second approach, both leptons are identified, yielding a better signal to noise ratio at the expense of acceptance. For both analyses, $\not{E}_T$ >25 GeV and at least two central jets with p_t >20 GeV are required. The understanding of the background is checked using control samples with zero jets and one jet, where the contribution from top is expected to be very small. The agreement between observation and prediction is good. Using a counting experiment the top cross section is measured for events with two or more jets. Using 200 pb^{-1} of Run II data, the preliminary result is

$$\sigma_{t\bar{t}} = 6.9^{+2.7}_{-2.4}(stat) \pm 1.2(syst) \pm 0.4(lumi)pb \tag{1}$$

for the larger acceptance dilepton sample, and

$$\sigma_{t\bar{t}} = 8.7^{+3.9}_{-2.6}(stat) \pm 1.4(syst) \pm 0.5(lumi)pb, \tag{2}$$

for the sample with two identified leptons. The lepton composition in the second sample is 1 ee, $3\mu\mu$ and 9 $e\mu$ pairs, consistent with the expectation. The two measurements give consistent measurements of the top production cross-section and were combined to yield $\sigma_{t\bar{t}} = 7.0^{+2.4}_{-2.1}(stat)^{+1.6}_{-1.1}(syst) \pm 0.4(lumi)pb$. Fig. 1 shows the number of events with zero, one and two or more jets, for data, all expected background sources and the expected top signal. Fig. 2 shows the $\not{E}_T$ distribution for data and expected background and signal contribution. We observe good agreement between the Standard Model expectation and the observation. Both figures use the larger acceptance dilepton sample.

3.2 Lepton plus Track Analyses

In the lepton plus jets channel backgrounds are larger, so b-tagging and/or kinematic information must be used to reduce them. An inclusive W sample is selecting by requiring an electron or muon with p_t >20 GeV/c and $\not{E}_T$ >20 GeV. Top is expected to appear in the sub-sample with 3 or more jets. The signal is isolated from the large W+jets background using kinematic shape templates; in particular the scalar sum of energy in the event, H_t. For 3 or more jets 519 events are observed in 200 pb^{-1} of Run II data. Fig. 3 shows the distribution of H_t for events with three or more jets, for data and expected background and signal. The top fraction from the fit is 0.13±0.04, yielding a preliminary cross- section of

$$\sigma_{t\bar{t}} = 4.7 \pm 1.6(stat) \pm 1.8(syst)pb, \tag{3}$$

The largest systematic uncertainty is due to the jet energy scale. In addition to using kinematic shapes to distinguish between background and signal, one can require at least one jet to be tagged as a b-jet. After b-tagging, the dominant backgrounds are due to mis-tags, $Wb\bar{b}$, $Wc\bar{c}$, and non-W events containing a real or fake b. Mis-tags and non-W backgrounds are estimated from QCD control samples. The W plus heavy flavor backgrounds are estimated using Monte Carlo. In the three or more jet bin we observe 35 events in 109 pb^{-1} of Run II data and extract the top fraction from a fit. It is $0.88^{+1.0}_{-1.6}$. The resulting cross-section is

$$\sigma_{t\bar{t}} = 6.9^{+1.6}_{-1.9}(stat) \pm 0.9(syst)pb, \tag{4}$$

Using just the b-tagging information and performing a counting experiment on the same dataset yields

$$\sigma_{t\bar{t}} = 4.5^{+1.4}_{-1.3}(stat) \pm 0.8(syst)pb, \tag{5}$$

We have also measured the top production cross-section using the soft lepton tag. The tagging efficiency in events with at least two jets is 15% and the false tag rate measured in QCD jets samples is 3.6% (per jet). Using $125pb^{-1}$ of Run II data, we extract the following cross section:

$$\sigma_{t\bar{t}} = 4.1^{+4.0}_{-2.8}(stat) \pm 1.9(syst)pb, \tag{6}$$

demonstrating good understanding of this tagging technique.

In summary, we have measured the top production cross section in the dilepton and the lepton and jets channels, using different techniques: counting experiments, two different b-tagging techniques and shape analyses. The measurements are in good agreement with each other. Fig. 4 shows a summary of the various measurements. Note that the data sets used to extract the measurements vary in size between 109 and 200 pb^{-1}. All measurements assume a top mass of m_t=175 GeV/c^2. Work is in progress to combine all results.

4 Single Top Physics

In addition to pair production, single top quarks can be produced in weak interaction by a virtual W ("s-channel") or through Wg fusion ("t-channel"), with a total cross section of about $\sigma_{tX} = 2.9$ pb [5]. Single Top production is particularly interesting since a precise measurement of the cross section would provide a direct determination of $|V_{tb}|$. We expect a 14% uncertainty on the measurement of $|V_{tb}|$ for $L_{int} = 2fb^{-1}$ of data.

The extraction of a single top signal is more difficult than in the case of pair-produced top, because there are fewer objects in the final state and the overall event properties are less distinct from the W+jets background. The strategy is to isolate a W plus exactly two jets sample and to tag one jet as a b. Then a Likelihood fit is performed to kinematic variables. In the case of the t-channel a suitable variable is the product of lepton charge and pseudorapidity of the b-jet. For the combined search H_t is chosen. Using 162 pb^{-1} of data, the t-channel search yields an upper limit of $\sigma_t < 8.5$pb at the 95% C.L. and the combined search yields $\sigma_t < 13.7$ pb at the 95% C.L. Fig. 5 shows the fit to the data in the combined search.

5 Top Mass Measurements

The top mass is a fundamental Standard Model parameter that needs to be measured with the greatest precision possible. It is needed to determine the strength of the ttH coupling and it has a substantial effect on radiative corrections. In fact, an uncertainty of 2GeV/c^2 on the top mass would constrain the Higgs mass to 35% (assuming $m_H \sim 100$ GeV). One of the main goals of RunII is to improve on the current uncertainty. The largest contribution to the systematic uncertainty is still due to the jet energy scale. With the statistics available now the best calibration sample consists of events where a jet is recoiling against a well measured photon. Preliminary measurements of the top mass, still dominated by large systematic uncertainties have been performed using the Run II data sample. In the lepton plus 4 jet sample with at least one secondary vertex b-tagged jet a value of $m_t = 177.5^{+12.7}_{-9.4}(stat) \pm 7.1(syst) GeV/c^2$ is found using 22 candidate events shown in Fig. 6. In the dilepton channel a preliminary measurement of $m_t = 175.0^{+17.4}_{-16.9}(stat) \pm 7.9(syst) GeV/c^2$ is obtained using 6 candidate events. New results are to follow soon, as systematic uncertainties improve with new techniques and as more data is collected.

6 Conclusions

In this article, preliminary measurements of the top production cross section and top quark mass were presented, using a Run II data set about twice as large as the Run I data set. Improved measurements of these quantities will continue to be of interest. Future analyses will look beyond the baseline quantities and will result in more stringent constraints on new physics or in surprises that could point to physics beyond the Standard Model.

7 Acknowledgments

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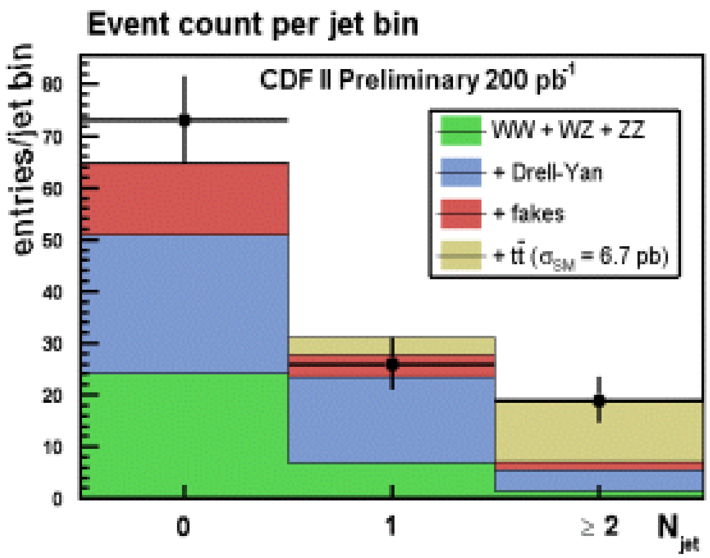

Figure 1: The number of events with zero, one and two or more jets for the Run II dilepton analysis. Shown are the data, all expected background sources and the expected top signal.

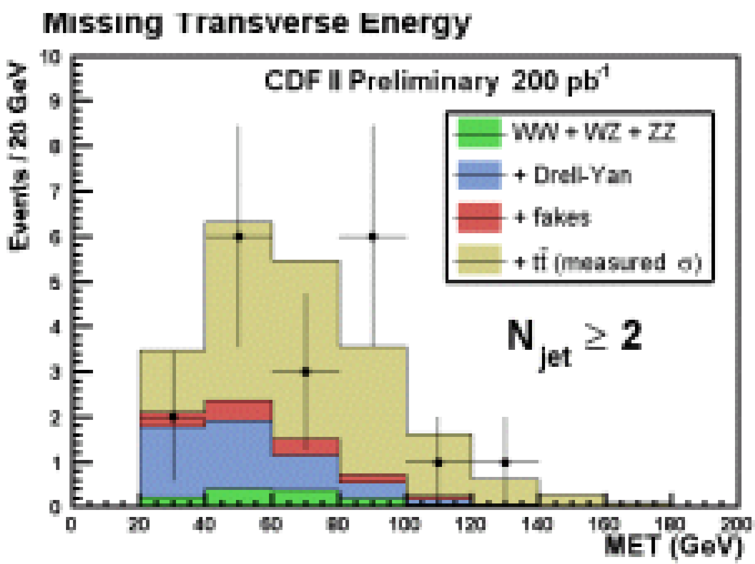

Figure 2: Run II $\not\!\!E_T$ distribution of dilepton events compared to SM expectation.

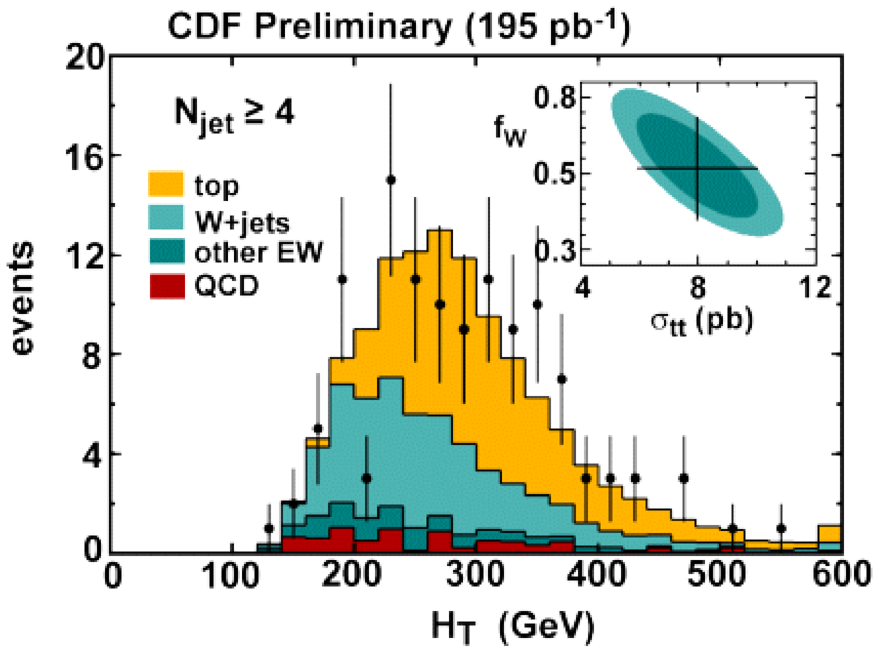

Figure 3: Run II H_t distribution of lepton+three or more jet events compared to SM expectation.

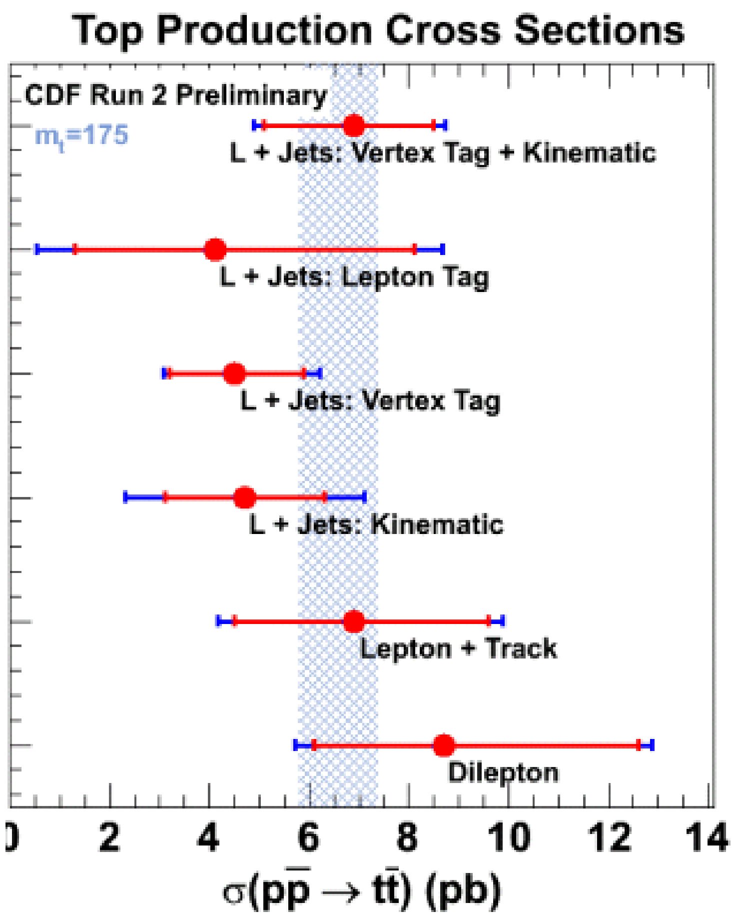

Figure 4: Summary of the top cross-section measurements. Note that the data sets used to extract the measurements vary between 109 and 200 pb^{-1}. All measurements assume a top mass of m_t=175 GeV/c^2. Work is in progress to combine all results.

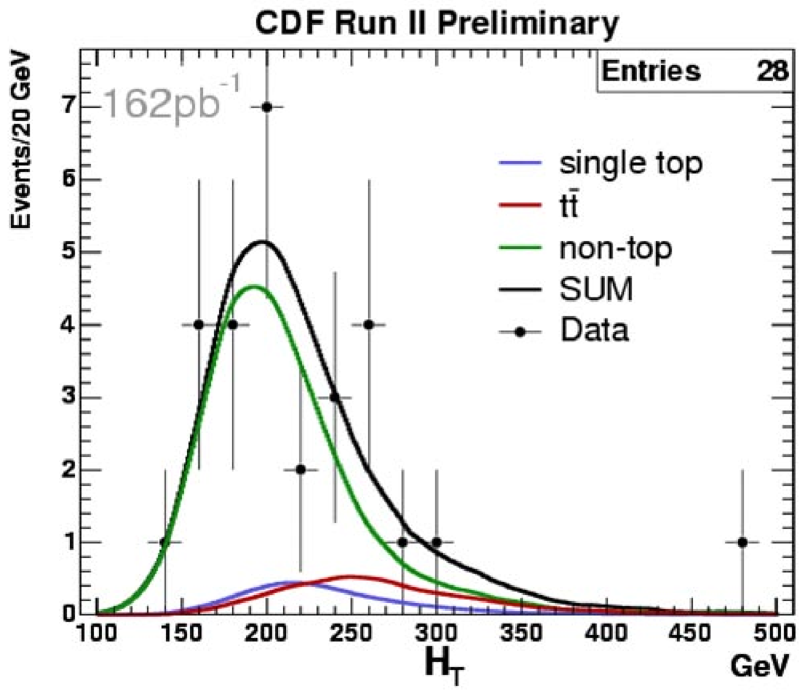

Figure 5: Run II data (points) H_t distribution compared to the expected SM background plus $t\bar{t}$ and single top production.

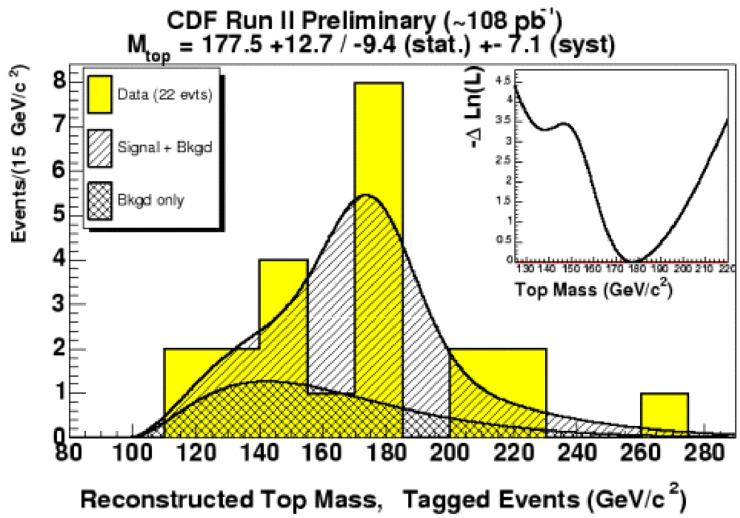

Figure 6: Reconstructed top mass using 22 vertex-tagged events from the lepton+jets sample