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CDF Findings on the Top Quark

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Abstract

The recent top quark results from the CDF experiment are presented . The cross section has been measured in the dilepton ($t\bar{t} \to e\mu, ee, \mu\mu, e\tau, \mu\tau$ + jets $+\not{E}_T$) , lepton plus jets ($t\bar{t} \to e$ or μ + jets $+\not{E}_T$), and all hadronic final states ($t\bar{t} \to \geq 6jets$). The result from all channels is $7.6^{+1.8}_{-1.5}$ pb at m_{top}=175 GeV/c^2. The direct measurement of the top quark mass in three different decay channels yields 175.3 $\pm$ 6.3 GeV/c^2. The most recent result combining the CDF and DØ numbers gives M_{top} = 173.9 $\pm$ 5.0 GeV/c^2 and $\sigma_{t\bar{t}}$ = 6.7 $\pm$ 1.3 pb (preliminary). In addition, we review the first CDF direct measurement of the CKM matrix element V_{tb}, and some top quark rare decay studies.

1 Introduction

Since the first evidence [1] and the discovery of the top quark [2],[3], the CDF Collaboration invested a lot of work to determine its production and decay properties. This paper reports the latest CDF top quark results which are based on a sample corresponding to about 110 pb^{-1} of data from the Fermilab Tevatron collider run from 1992 to 1996 (the so-called Run 1).

At the Tevatron center of mass energy $\sqrt{s}$=1.8 TeV, top quarks are produced generally in pairs from the processes $q\bar{q} \rightarrow t\bar{t}$ (in 90% of the cases) and $gg \rightarrow t\bar{t}$ (in 10% of the cases). In addition, top quarks can be produced singly, by electroweak interaction, for example W-gluon fusion and virtual W^* production in the s-channel. At the time being no signal has been observed from single top processes. We added our expectation for single top to the background when measuring the $t\bar{t}$ production cross section.

In the Standard Model, the branching ratio of the decay $t \rightarrow bW$ is nearly 100%. In addition, each of the W-bosons can decay either into a charged lepton and a neutrino (branching ratio of 1/9 for each lepton family) or into a quark pair $q\bar{q}'$ (branching ratio of 2/3). This allows us to classify the final states as:

- Dilepton final states, when both W's from the $t\bar{t}$ pair decay leptonically. These states are characterized by two high P_T charged leptons, two jets from $b\bar{b}$ quarks and significant missing transverse energy ($\not\!\!E_T$) from the neutrinos.
- Lepton+jets final states, when one W boson decays leptonically and the other one hadronically. These states contain one high P_T charged lepton, three or more jets (four or more jets will be required for the top mass analysis), and significant $\not\!\!E_T$.
- All hadronic final states, when both W's decay hadronically. These states are characterized by 6 or more jets, two of which are from b-quarks.

CDF uses all of these signatures for the top mass and production cross section measurements.

2 $t\bar{t}$ Production Cross Section

Measurement of the top quark production cross section ($\sigma_{t\bar{t}}$) is important as a check of the QCD calculation. Moreover, any deviation from the Standard Model predictions, for example top decays to final states different than Wb, or $\mathrm{t\bar{t}}$ production through a high mass intermediate state, could indicate new physics. This is the reason why CDF measured $\sigma_{\mathrm{t\bar{t}}}$ in as many channels as possible [4, 5, 6].

2.1 Dilepton Analysis

The dilepton signature is provided by the final state $\mathrm{p\bar{p}} \rightarrow \mathrm{t\bar{t}}X \rightarrow \ell^{+}\nu b\ell^{-}\bar{\nu}\bar{b}X$. Both leptons ($e$ or μ) have to be central ($|\eta| < 1.1$), oppositely charged, with $P_T > 20$ GeV and at least one of them must be isolated. To remove the background from Z decays, the events with dilepton invariant mass inside Z mass region (from 75 to 105 GeV/c^2) are rejected. The same cut is applied for the three body invariant mass ($\ell\ell\gamma$), if it is consistent with radiative Z decay. Two or more jets are required with transverse energy $E_T > 10$ GeV and $|\eta| < 2.0$. Because top dilepton events contains two neutrinos, significant missing transverse energy ($\not\!\!E_{\mathrm{T}} > 25$ GeV) is required too. If $\not\!\!E_{\mathrm{T}} < 50$ GeV, an additional cut was applied $\min(\Delta\phi(\not\!\!E_{\mathrm{T}}, leptons\ or\ jets)) > 15^0$ to reject events with a mismeasured jet or lepton.

Nine events satisfied all selection criteria: 1(ee), 1($\mu\mu$) and 7(eμ). The background from WW production, $Z \rightarrow \tau\tau$, Drell-Yan and events with misidentified leptons is estimated to be 2.4 ± 0.5 events.

A specific analysis [7] is done when one of the primary leptons is an electron or muon and the second one is a τ. We identified τ leptons through their hadronic decay looking for a narrow cluster in the CDF calorimeter with low multiplicity of reconstructed tracks pointing to it. The transverse momentum cut of tau candidates is $P_T^{\tau} > 15$ GeV. Some additional kinematic cuts (for example visible transverse energy $H_T \geq 180$ GeV) to increase the signal to background ratio are applied. The selection ends with 4 candidates and an expected background of 2.0 ± 2.0 events.

2.2 Lepton Plus Jets Analysis

Lepton plus jets events have the signature $\mathrm{p\bar{p}} \rightarrow \mathrm{t\bar{t}}X \rightarrow \ell^{+}\nu bq\bar{q}'\bar{b}X$. The characteristics of this final state are the presence of one isolated central high P_T lepton (e or μ), at least three jets with E_T >15 GeV and $|\eta| \leq 2$ and significant $\not\!\!E_{\mathrm{T}}$. The dominant background is coming from direct W plus jets production ($\sim$ 67 %) and from QCD multijet events where one jet is misidentified as a lepton ($\sim$ 20 %). To increase the signal to background ratio in this channel we apply a b-jet tagging requirement, either looking for displaced vertices (Secondary Vertex Tagging, SVX) or for low P_T electrons or muons from the b-quark semileptonic decays (Soft Lepton Tagging, SLT). In case of the top quark mass analysis a fourth jet is required with $E_T > 8$ GeV if the event has at least one SVX or SLT b-tag, or $E_T > 15$ GeV if no b-tag is present.

The typical result from the "counting" of SVX tagged events is shown in Figure 1.

2.3 All Hadronic Channel Analysis

All hadronic events result from the process $\mathrm{p\bar{p}} \to \mathrm{t\bar{t}}X \to bq\bar{q}'\bar{b}q\bar{q}'X$. The signature of this process are six central jets, two of which come from b-quarks. The dominant background is QCD multijet production, which is orders of magnitude higher than the signal. To improve the signal to background ratio several tight kimematical cuts are applied. First we start requiring a high jet multiplicity ($N_{jets} \geq 5$), at least four of them with $E_T > 15$ GeV and $|\eta| \leq 2$, and a total transverse energy $\sum E_T \geq 300$ GeV, centrally deposited in the detector. Next the event aplanarity has to satisfy the condition $A \geq -0.0025 \times \sum_3^{N_{jets}} E_T(\mathrm{GeV}) + 0.54$ where the contribution from the 2 leading jets is excluded from the sum. In addition, the requirement of at least one SVX b-tag in the event is applied.

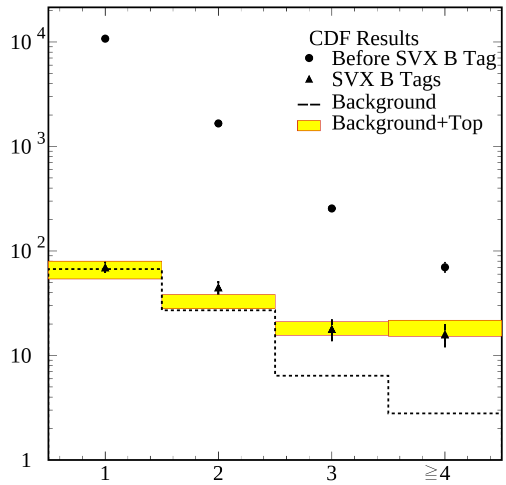

Figure 1: The result from the "counting" experiment in the case of the events with at least one SVX tag. The figure shows the number of events before tagging (points), after SVX tagging (triangles), predicted background (dashed line) and predicted top signal plus background (light shaded area).

2.4 Combined Cross Section

The acceptances, the numbers of observed events, the estimated number of background events and the measured cross sections are summarized in Table 1. We do not use in our combined result the cross section value from the τ analysis. A preliminary average of CDF and DØ results is $\sigma_{\mathrm{t\bar{t}}} = 6.7 \pm 1.3$ pb [9].

Data Sample	ϵ_{total}	Observed Events	Predicted Backgrounds	$\sigma_{t\bar{t}}$ (pb)
Dilepton	0.0074 ± 0.0008	9	2.4 ± 0.5	$8.2^{+4.4}_{-3.4}$
Lepton+Jets (SVX tag)	0.037 ± 0.005	34	9.2 ± 1.5	$6.2^{+2.1}_{-1.7}$
Lepton+Jets (SLT tag)	0.017 ± 0.003	40	22.6 ± 2.8	$9.2^{+4.3}_{-3.6}$
All Hadronic (1 SVX)	0.044 ± 0.010	187	142 ± 12	$9.6^{+4.4}_{-3.6}$
All Hadronic (2 SVX)	0.030 ± 0.010	157	120 ± 18	$11.5^{+7.7}_{-7.0}$
Combined				$7.6^{+1.8}_{-1.5}$
$\epsilon(\mu) + \tau$	0.085 ± 0.016	4	2.0 ± 0.4	$15.6^{+18.6}_{-13.2}$

Table 1: Summary of acceptances, number of events, expected backgrounds and cross sections for each analysis channel. The acceptances are calculated for $m_{top} = 175$ GeV/c^2.

3 Top Quark Mass Measurement

The top quark mass is a key parameter of the Standard Model. Radiative corrections induce a connection between the top quark and the W boson mass that is sensitive to the Higgs boson mass. The main goal in the Tevatron Run 1 was to determine this parameter as accurately as possible, in many different channels and ways. CDF invested a large effort in this measurement. As a result the total uncertainty has been improved from 9.8% [1] to 3.7% from the first to the final analysis of the data.

3.1 Mass Measured in the Dilepton Channel

CDF has several dilepton mass analyses. Since this sample has good signal to background ratio $\sim 7/1$ we are stimulated to invent ingenious way to reconstruct the events and extract M_{top} even though this may initially look impossible. Because of the existence of the two neutrinos from the leptonic W decays, the kinematics of the process are underconstrained. One analysis exploits the fact that the energy of the two highest E_T jets depends strongly on the top mass. From a sample of 8 candidates and expected background of 1.3±0.3 events we obtained a mass of $159 \pm 23(stat.) \pm 11(syst.)$ GeV/c^2. A second analysis uses the relation between lepton plus b-jet invariant mass and the top quark mass. The result obtained from this analysis, is $M_{top} = 163 \pm 20(stat.) \pm 9(syst.)$ GeV/c^2. A new analysis using the full event kinematics, similar to the DØ neutrino weighting method [9, 8], was developed recently. The shape of the most probable mass value distribution of the dilepton candidates is compared with Monte Carlo probability density functions for signal and background using a maximum likelihood technique. The result is $M_{top} = 167.4 \pm 10.3(stat.) \pm 4.8(syst.)$ GeV/c^2, in agreement with the previous two results but with a significantly improved statistical and systematic uncertainties.

3.2 Lepton Plus Jets Mass

The most accurate CDF top quark mass measurement comes from the lepton plus jets channel [10]. This channel sums the benefits of good signal to background ratio, the possibility to reconstruct the top quark mass event by event with a relatively small combinatoric effect, and a large branching fraction.

The applied cuts to the final state are the same as in the cross section analysis. The sample selection starts with the requirement of at least four jets and one high P_T lepton (e or μ). However, in order to increase the detector acceptance, if one of the four leading jets is tagged as a b-jet by SVX or SLT, the cut on the fourth jet is made looser $E_T > 8$ GeV. Because the lepton and jets momenta are fully measured we can obtain the transverse momentum of the neutrino from the $\not{E}_T$ in the event. We do not use the momentum balance in z-direction and we leave the neutrino p_z unmeasured. Each of the candidates is fitted to the hypothesis of $t\bar{t}X \to \ell^+\nu bq\bar{q}'\bar{b}X$. We use three kinematic constraints, following from assuming lepton plus jets topology ($M_{\ell\nu}$=M_{jj}=M_W and $M_{\ell\nu b}$=M_{jjb}). The minimized χ^2 contains itself not only constraint terms but detector resolution terms too. The fitting procedure runs over all possible combinations of assigning the four leading jets to the four partons b, $\bar{b}$ q and $\bar{q}'$. If one or more of the four leading jets are tagged as a b-jets, they are assigned to the b-partons and the number of explored combinations is correspondingly smaller. The top quark mass value which corresponds to the lowest $\chi^2 <$ 10 combination is accepted. 76 events remain after these requirements.

Comparing to the 1996-1997 CDF lepton plus jets analysis this one has two major improvements:

- The new analysis splits the data into exclusive subsamples with different signal to background ratios and top mass resolutions. The Monte Carlo studies showed that an optimal partitioning is obtained with the four statistically independent categories: events with double SVX tags, events with single SVX tag, events with SLT tags but no SVX tags and finally events without tags. The information obtained for these subsamples is summarized in Table 2.

- The Monte Carlo signal probability density distributions are parameterized as a function of the reconstructed and the input top mass. The background probability density distributions are parameterized only as function of the reconstructed top mass. The likelihood of each subsample uses these parameterized signal and background probability densities to evaluate the dependencies of the likelihoods on the input top mass.

Data Sample	#Events	S/B	Top Mass (GeV/c^2)
Double SVX tagged events	5	19/1	170.1 ± 9.3
Single SVX tagged events	15	7.5/1	178.0 ± 7.9
SLT tagged events (no SVX tags)	14	2.5/1	142^{+33}_{-14}
No tagged events	42	1/1	180.8 ± 9.0
Combined	76	-	175.9 ± 4.8

Table 2: Lepton plus jets subsamples used in the top quark mass analysis, number of events in each sample, S/B ratio, and the measured top quark mass (uncertainties are statistical only). The last line shows the results from the combined likelihood fit to all four subsamples.

The results of the likelihood fit for each subsample are presented in Table 2. The combined result is shown in Figure 2. The systematic uncertainties are summarized in Table 3. All in all for events with lepton plus jets topology the top quark mass is measured to be 175.9$\pm$4.8($stat.$)$\pm$4.9($syst.$) GeV/c^2.

3.3 Determination of the Top Mass in the All Hadronic Channel

The All Hadronic Channel has the merit that all six decay objects of the process are reconstructed [6] The large QCD background and combinatorial effect require to use only the events with at least one SVX tag. In this case the data sample contains 136 events, of which 108 ± 9 are estimated to be background. The likelihood procedure mentioned previously in the lepton plus jets analysis was used to extract a top mass of 186 ± 10($stat.$)$\pm$ 8.2($syst.$) GeV/c^2. The uncertainty in the modeling of the jet energy scale and the uncertainty due to the combinatoric effect in the fitting procedure of the individual event dominate the final systematic uncertainty.

Source	Value (GeV/c^2)
Jet energy scale	4.4
Initial and final state radiation	1.8
Shape of background spectrum	1.3
b-tag bias	0.4
Parton distribution functions	0.3
Total	4.9

Table 3: The systematic uncertainties in the lepton plus jets top quark mass measurement.

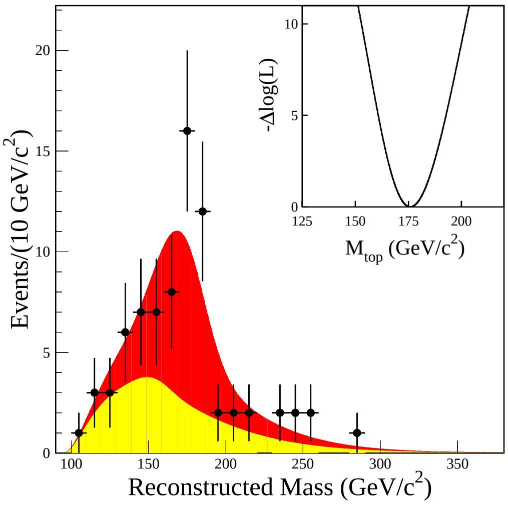

Figure 2: Reconstructed mass distribution of the 76 lepton plus jets candidates. The data (points) are compared with the result of the likelihood fit (signal+background, dark+light shaded area). The light shaded area represents the background. The insert shows the negative log $\mathcal{L}$ v.s. the input top mass.

3.4 Summary of the Top Quark Mass Measurement

Combining the three CDF measurements, corresponding to each decay topology, the top quark mass is measured to be 175.3 ± 6.3 GeV/c^2.

DØ has also combined its measurements (dilepton and lepton plus jets channels) into a single measurement of 172.1 ± 7.1 GeV/c^2 [9]. Taking into account correlations between CDF and DØ measurements, one can combine the results and obtain 173.9 ± 5.0 GeV/c^2. The Tevatron result is summarized in Figure 3.

4 Direct Measurement of V_{tb}

The CKM matrix element $|V_{tb}|$ is predicted to be very near 1 within the Standard Model. Experimentally we could measure the branching fraction $B = \Gamma(t \to Wb)/\Gamma(t \to Wq)$ which is equal to $|V_{tb}|^2$ if we assume CKM unitarity and neglect small phase space effects. Any deviation of B from one (the SM prediction) would indicate the presence of non-Standard Model processes in top decays.

The analysis exploits the dilepton and lepton plus jets samples, described previously with reference to the cross section measurement. Each one of these samples is divided into orthogonal subsamples according to the number of b-tagged jets (0, 1, or 2 tags). In case of the lepton plus jets candidates, both SVX and SLT tagging are exploited, while only events with SVX tags are considered for the dilepton sample. A maximum likelihood fit to the data yields: $B = 0.99 \pm 0.29$ or $B > 0.64(0.58)$ at 90(95)% C.L. Assuming CKM matrix unitarity, we can transform the result into $|V_{tb}| = 0.99 \pm 15$ (stat. & syst.) and into lower limit on $|V_{tb}| > 0.80(0.76)$ at 90(95) % C.L.[11].

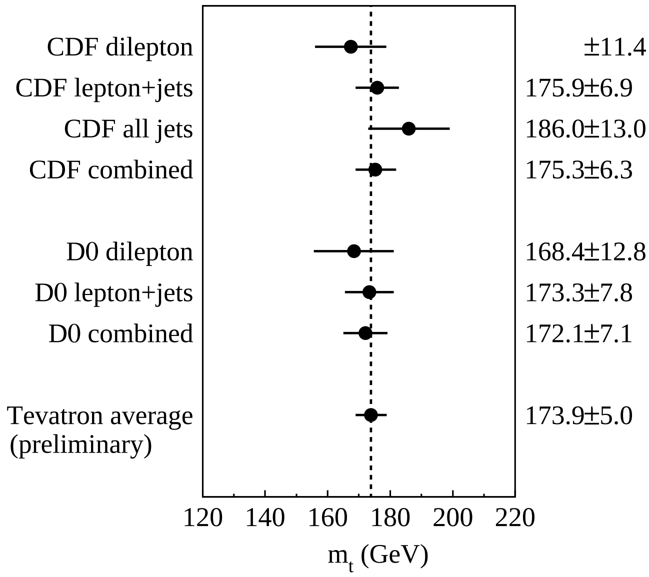

Figure 3: Combined top mass from CDF and DØ experiments.

5 CDF Search for Rare Top Decays (FCNC decays)

In the Standard Model framework the flavour changing neutral current decays (FCNC) of the top quark are suppressed by a factor of 10^{-8} to 10^{-12}. The possible FCNC top decays at a rate higher than this could be a signal for the processes beyond the SM.

The CDF search was focused on the signatures of $t \to q\gamma$ and $t \to qZ$, where q is supposed to stand for a u or c quarks. The analysis assumes that one of the top quarks in $t\bar{t}$ production could still decay to Wb, according to the SM prediction and a search is made for the rare decay of the second t-quark. We observe only two candidates, one event passed the selection criteria for $t\bar{t} \to Wbq\gamma$ and the second one passed the cuts in the case of $t\bar{t} \to WbqZ$. Taking into account the predicted background, as well as acceptances and efficiencies, we obtained the limits: $B(t \to q\gamma) < 2.9\%$ and $B(t \to qZ) < 33\%$ at the 95% C.L. [12].

6 Run 2 Prospects

A detailed overview of the Run 2 CDF physics (the next Tevatron collider run) is given in ref. [13]. We expect to measure the top quark mass with a precision of 2.5-3.5 GeV/c^2 and the total $t\bar{t}$ cross section to better than 9%. We will have the possibility of isolating the electroweak production of single top, measure $\Gamma(t \rightarrow Wb)$ with a precision of $\sim$ 26% and $|V_{tb}|$ with a precision of 13%. Finally, the top candidate sample is a fertile searching ground for new physics. A measurable fraction of unexpected events could show up, and lead us to interesting surprises.

7 Conclusions

The top quark CDF results from the Tevatron 1992-1996 run, with an integrated luminosity of 110 pb^{-1}, are presented. Using the dilepton, lepton plus jets and all hadronic channels we measured the top quark mass to be 175.3$\pm$6.3 GeV/c^2. In the same channels the combined $t\bar{t}$ production cross section is determined to be $\sigma_{t\bar{t}} = 6.7 \pm 1.3$ pb at M_{top} = 175 GeV/c^2. A first measurement of the CKM matrix element $|V_{tb}|$ is given, as well as limits on FCNC top decays, consistent with Standard Model expectations.

8 Acknowledgments

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