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Top Quark Mass from CDF

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We report on the most recent measurements of the top quark mass in three decay channels, performed by the CDF Collaboration at the Tevatron collider. We combine these results to obtain a mass value of 176.0 ± 6.5 GeV/c^2.

1 Introduction

A precise measurement of the top quark mass is an important ingredient in testing the consistency of the standard model with experimental data. In addition, precise W and top mass measurements can provide information on the mass of the Higgs boson, which is a remnant of the mechanism that gives rise to spontaneous electroweak symmetry breaking.

Within the framework of the Standard Model the top quark decays almost exclusively into a real W boson and a b quark. The observed event topology is then determined by the decay modes of the two W bosons, which can be classified into three decay channels. Decays of W boson to τ leptons are not explicitly included in the study except when they subsequently decay to an electron or a muon.

- Dilepton Channel: About 5% of the time both W bosons decay to $e\nu$ or $\mu\nu$.
- Lepton + Jets Channel: In 30% of the cases, one W boson decays to $e\nu$ or $\mu\nu$, and the other to a $q\bar{q}'$ pair.
- All Hadronic Channels: Finally 44% of the final states involve the hadronic decay of both W bosons.

Using 109 pb^{-1} of data accumulated by the CDF experiment at the Fermilab Tevatron from 1992 through 1995, we report an improved measurement of the top quark mass by combining the results from the three decay channels [1, 2, 3].

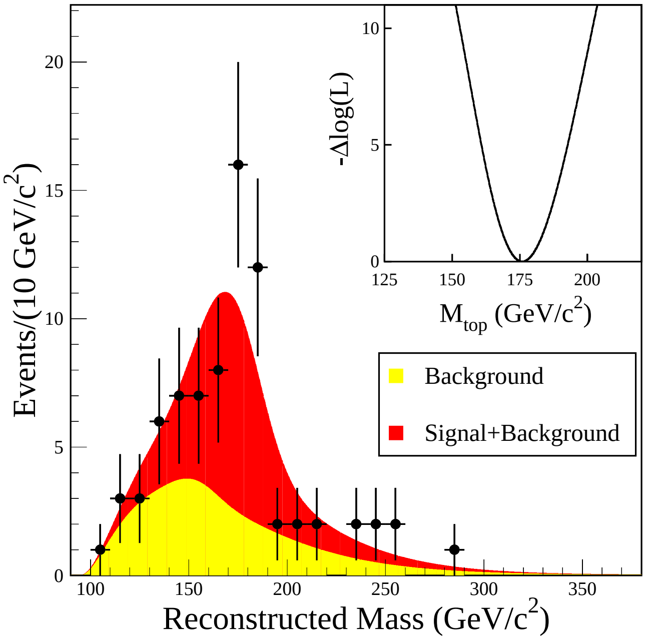

Figure 1: Reconstructed-mass distribution of the four mass subsamples combined. The data (points) are compared with the result of the combined fit (dark shading) and with the background component of the fit (light shading). The inset shows the variation of the combined negative log-likelihood with M_{top}.

2 Top Mass Measurement from Lepton + jets

The advantage of measuring a top quark mass in the Lepton + Jets channel [1] is its relatively larger branching ratio and the ability to full reconstruct the top mass on an event-to-event basis. We select events containing a single isolated electron (muon) with E_T (P_T) > 20 GeV (GeV/c) in the central region and missing transverse energy $\not{E}_T > 20$ GeV. At least four jets are required in each event, three of which must have an observed $E_T > 15$ GeV and $|\eta| < 2$ in a cone radius $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. In order to increase the acceptance, we relax the requirements on the fourth jet to be $E_T > 8$ GeV and $|\eta| < 2.4$, provided one of four leading jets is tagged by the Silicon Vertex tagging (SVX) or Soft Lepton tagging (SLT) algorithms. SVX tags are only allowed on jets with observed $E_T > 15$ GeV, while SLT tags are allowed on jets with $E_T > 8$ GeV. If no such tag is present, the fourth jet must satisfy the same E_T and η requirements as the first three. The above selection defines our mass sample, which contains 83 events.

Table 1: Subsamples used in the lepton + jets top quark mass analysis, expected background fractions, and the measured top quark mass.

Data Sample	# Events	$x_b(\%)$	Top Mass (GeV/c^2)
SVX Double	5	5^{+4}_{-2}	170.1 ± 9.3
SVX Single	15	13^{+5}_{-4}	178.0 ± 7.9
SLT	14	40^{+9}_{-9}	142.1^{+33}_{-14}
No Tag	42	56^{+14}_{-17}	180.8 ± 9.0
Combined	76	-	175.9 ± 4.8

Measurement of the top quark mass begins by fitting each event in the sample to the hypotheses of $t\bar{t}$ production followed by decay in the lepton + jets channel ($t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (l^+\nu b)(q\bar{q}'\bar{b})$). There are twelve distinct ways of assigning the four leading jets to the four partons b, $\bar{b}$, q and $\bar{q}'$. In addition, there is a quadratic ambiguity in the determination of the longitudinal component of the neutrino momentum. This yields up to twenty-four different configurations for reconstructing an event according to the $t\bar{t}$ hypothesis. We require that SVX and SLT-tagged jets to be assigned to b-partons and choose the configuration with lowest χ^2. Events with lowest $\chi^2 > 10$ are rejected.

A maximum-likelihood method is used to extract a top mass measurement from a sample of events which have been reconstructed according to the $t\bar{t}$ hypothesis. An essential ingredient of the likelihood functions are the probability density $f_s(M_{rec}; m_t)$ to reconstruct a mass M_{rec} from a $t\bar{t}$ events if the true top mass is m_t, the probability density $f_b(M_{rec})$ for reconstructing a mass M_{rec} from a background events, and the background fraction x_b constrained directly from the data. The likelihood is then maximized with respect to m_t, x_b and the parameters that define the shapes of f_s and f_b.

The precision of the top quark mass measurement is expected to increase with the number of observed events, the signal-over-background ratio, and the narrowness of the reconstructed-mass distribution. Monte Carlo studies show that an optimum way to partition the sample consists of subdividing the events into the four statistically independent subsamples shown in Table 1. The table also shows the numbers of events, the expected background fraction x_b , and the fitted top mass m_t.

The reconstructed-mass distribution of the sum of the four subsamples is plotted in Figure 1. The inset shows the shape of the corresponding sum of negative log-likelihoods as a function of top mass. From this we measure $m_t = 175.9 \pm 4.8$ GeV/c^2, where the uncertainty corresponds to a half-unit change in the negative log-likelihood with respect to its minimum.

We list the systematic uncertainties in Table 2. The systematic error due to hard gluon radiation uncertainty has been revised since publication. The uncertainty is now estimated using events generated with the PYTHIA Monte Carlo[4] to isolate the effects on the top mass due to initial and final state radiation jets. In summary, we have measured the top quark mass to be $175.9 \pm 4.8 \pm 5.3$. This is the most precise determination of the top mass in a single channel.

3 Top Mass Measurement from Dilepton

We report an improved measurement of the top quark mass using dilepton events [2] originating predominantly from $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow (l^+\nu b)(l^-\bar{\nu}\bar{b})$, where $l = e$ or μ. This measurement supersedes our previously reported result in the dilepton channel[5]. The previous result was obtained by comparing data with Monte Carlo simulation of $t\bar{t}$ events for two kinematic variables, the b-jet energies and the invariant masses of the lepton and b-jet systems.

We apply the same event selection criteria as those employed in the previous mass analyses of the dilepton channel[5]. We obtain a sample of eight candidate events. The expected background of 1.3 ± 0.3 events consists of events in which a track or a jet is misidentified as a lepton (0.29 events), Drell-Yan production (0.35 events), WW production (0.24 events), $Z \rightarrow \tau\tau$ decays (0.26 events) and $Z \rightarrow \mu\mu$ decays in which μ tracks are mismeasured (0.20 events).

Each candidate event is reconstructed according to the $t\bar{t}$ decay hypothesis in the dilepton channel:

$$t \rightarrow W^+b \rightarrow \ell_1^+\nu_1 b$$
$$\bar{t} \rightarrow W^-\bar{b} \rightarrow \ell_2^-\bar{\nu}_2\bar{b}$$

The two highest E_T jets in the event are assumed to be the b-jets from top decays. We assume the b-jet mass to be 5 GeV/c^2. Because the system is underconstrained due to the two unmeasured neutrinos, we use a weighting technique to determine a function, $f(m_t)$, from which we extract a top mass value[6]. We proceed as follows. We assume a top quark mass (m_t) and the two neutrino η values (η_1, η_2) and solve for the neutrino momenta, up to a four-fold ambiguity (two $P_z(\nu)$ choices for each ν) for each of the two jet charged-lepton pairings. We then assign a weight to each solution by comparing ${\not}E_T{}^p$, the sum of the neutrino transverse momenta for that solution, to ${\not}E_T{}^m$, the measured missing transverse energy after proper correction:

$$f(m_t, \eta_1, \eta_2) = exp\left(-\frac{({\not}E_T{}^p - {\not}E_T{}^m)^2}{2\sigma^2}\right)$$

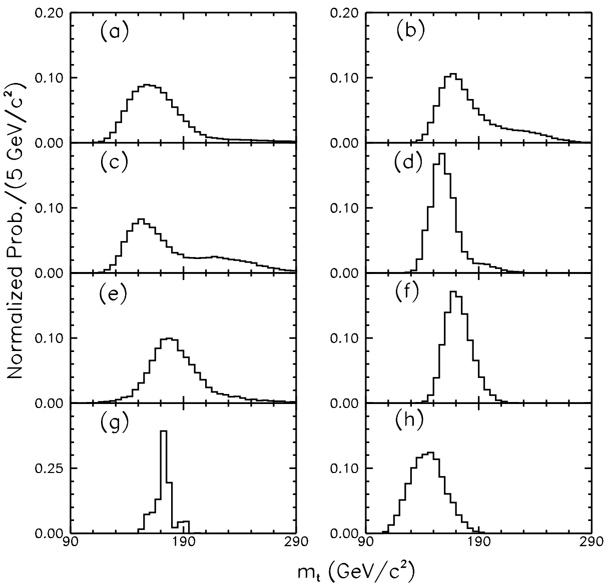

Figure 2: Weight distribution normalized to unity as a function of m_t for the eight dilepton top candidate events (a-h).

where σ is the $\not\!\!E_T$ resolution for that event.

For each choice of m_t, η_1, and η_2 we take into account the detector resolution for jets and leptons by sampling (*i.e.* fluctuating) the measured quantities many times according to their resolutions.

For each assumed top mass value we use several (100) pairs of (η_1, η_2) values, chosen from distributions obtained from the HERWIG Monte Carlo predictions[7]. They are consistent with independent Gaussian distributions with $\sigma = 1.0$ in units of η. The weight is summed for all samplings as well as over all η_1, η_2 values and all the eight possible combinations; thus for each event at each top mass, m_t, we evaluate an overall weight:

$$f(m_t) = \sum_{\eta_1,\eta_2,E_{T_i},\ell_1,\ell_2} f(m_t,\eta_1,\eta_2)$$

where E_{T_i} refers to all the jets in the event. We then compute the weight as a function of the top mass in 2.5 GeV/c^2 steps in the range 90-290 GeV/c^2.

The $f(m_t)$ distribution for each of the eight candidate events, normalized to unity, is shown in Figure 2. For each event, i, we use this distribution to determine a top mass estimate, m_i, by averaging the values of m_t corresponding to values of $f(m_t)$ greater than $f(m_t)_{max}/2$ on either side of the maximum. The m_i distribution for the eight events is shown in Figure 3, together with the Monte Carlo expectation for background alone, and top plus background normalized to the data. The inset shows the negative log-likelihood as a function of the top mass, from which we determine a top quark mass value of 167.4 ± 10.3 (stat) GeV/c^2. Including the systematic uncertainties presented in Table 2, the top quark mass is measured to be $167.4 \pm 10.3 \pm 4.8$ for the events in the dilepton channel.

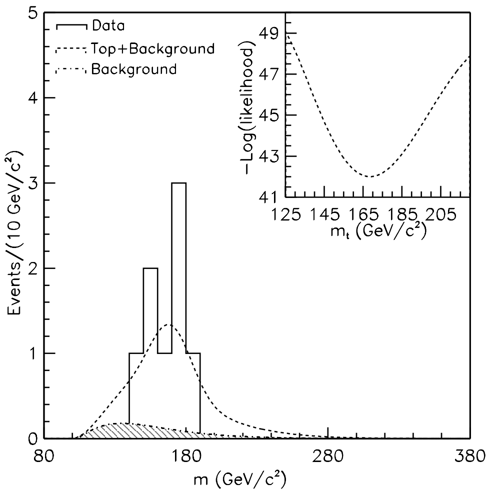

Figure 3: Reconstructed top mass for the eight dilepton events (solid). Background distribution (shaded, 1.3 events) and top Monte Carlo (6.7 events) added to background (dashed). The likelihood distribution as a function of the top mass, is shown in the inset.

4 Top Mass Measurement from all Hadronic

In this analysis [3] we select $t\bar{t}$ events in which both W bosons decay into quark-antiquark pairs, leading to an all hadronic final state. The study of this channel, with a branching ratio of about 4/9, complements the leptonic modes and the mass measurement, takes advantage of a fully reconstructed final state, but suffers a very large QCD multijet background. To reduce this background, events are required to have at least one identified SVX b-jet and to pass strict kinematic criteria that favor $t\bar{t}$ production and decay.

To determine the top quark mass, full kinematic reconstruction is applied to the sample of events with 6 or more jets, $E_T > 15$ GeV, $|\eta| < 2$, and at least one b-tagged jet. Events are reconstructed to the $t\bar{t} \rightarrow W^+bW^-\bar{b}$ hypothesis, where both W bosons decay into a quark pair, with each quark associated to one of the

Table 2: Systematic uncertainties on the top mass measurements (GeV/c^2)

Source	Dilep	Lep+jets	All Hadr.
Jet E_T	3.8	4.4	5.0
Gluon Radiation	3.1	2.6	1.8
Background	0.3	1.3	1.7
PDF, MC	1.1	0.5	1.0
Total	4.8	5.3	5.7

six highest E_T jets. All the combinations are tried except the SVX-tagged jet is assigned to b-partons and the combination with lowest $\chi^2 < 10$ is chosen. The data sample consist of 136 events, of which 108 ± 9 events are expected to come from background. The reconstructed 3-jet mass distribution is shown in Figure 4. The inset shows the shape of the log-likelihood as a function of top mass. From this we measure a top quark mass of $186.0 \pm 10.0 \pm 5.7$ GeV/c^2. The revised systematic uncertainties are shown in Table 2. The overall systematic error for the all-hadronic channel is reduced from 12.0 to 5.7 GeV/c^2.

5 A Combined Top Mass Measurement from CDF

The results for the three channels are combined with standard methods[8] to yield an overall CDF mass measurement. The three statistical errors are taken as uncorrelated, while the systematic errors are assumed to be either entirely correlated or uncorrelated between any two channels. The primary systematic error, that due to jet energy uncertainty, is taken as entirely correlated among all channels, as is the systematic error due to the Monte Carlo model used (mostly due to initial and final state radiation). The combined result is

$$m_t = 176.0 \pm 6.5 \text{ GeV}/c^2$$

including both statistical and systematic errors. In Table 3 we show the combined value with separate statistical and systematic errors. They are obtained by defining the combined statistical error as the sum in quadrature of the weighted individual statistical errors, and the systematic error as the difference in quadrature of the total and statistical errors. The relative contributions from the three channels are 67% for lepton plus jets, 18% for dileptons and 15% for all-hadronic.

In Run II with 2 fb^{-1} of integrated luminosity, we expect more than 1000 single tagged and about 600 double tagged $t\bar{t}$ events. It will allow us to measure the top quark mass down to approximately 2 GeV/c^2 precision.

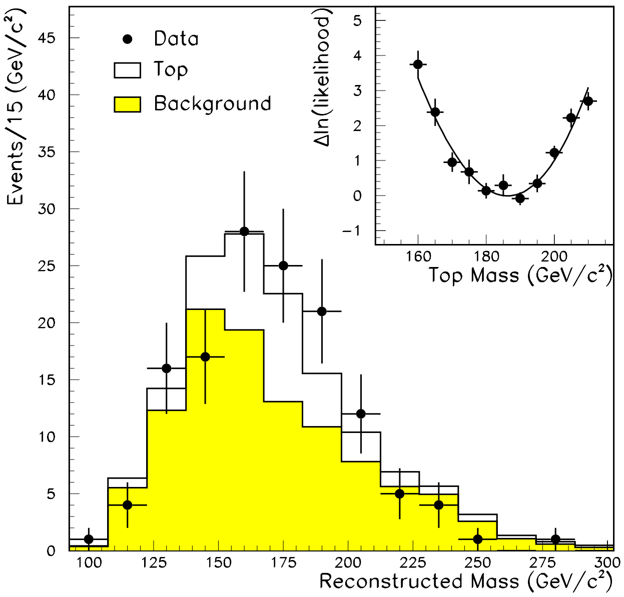

Figure 4: Reconstructed mass distribution for events with at least one b-tag. Also shown are the background distribution (shaded) and $t\bar{t}$ Monte Carlo events added to background (hollow). The inset shows the log-likelihood and the fit used to determine the top mass.

Table 3: Summary of top mass measurements with the CDF detector

Channel	Top Mass (GeV/c^2)
Lep + Jets	$175.9 \pm 4.8 \pm 5.3$
Dilepton	$167.4 \pm 10.3 \pm 4.8$
All Hadronic	$186.0 \pm 10.0 \pm 5.7$
Combined	$176.0 \pm 4.0 \pm 5.1$

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