

Cross Section Constrained Top Quark Mass Measurement from Dilepton Events at the Tevatron

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We report the first top quark mass measurement that uses a cross section constraint to improve the mass determination. This measurement is made with a dilepton $t\bar{t}$ event sample collected with the CDF II detector. From a data sample corresponding to an integrated luminosity of 1.2 fb^{-1} , we measure a top quark mass of $170.7_{-3.9}^{+4.2}(\text{stat}) \pm 2.6(\text{syst}) \pm 2.4(\text{theory}) \text{ GeV}/c^2$. The measurement without the cross section constraint results in a top quark mass of $169.7_{-4.9}^{+5.2}(\text{stat}) \pm 3.1(\text{syst}) \text{ GeV}/c^2$.

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The top quark is the heaviest known elementary particle. Its mass M_t is a fundamental parameter in the standard model (SM). Together with the W -boson mass, M_t places constraints on the SM Higgs boson mass [1]. At hadron colliders, the top quarks are mainly pair produced via the strong interaction. Each top quark decays into a W -boson and a b -quark, and in the dilepton channel both W -bosons decay to a charged lepton and a neutrino. The $t\bar{t}$ dilepton events have a small branching ratio, but they have a higher purity than single-lepton or all-hadronic final states. Because the two neutrinos in the final state are not detected, the dilepton channel top mass fit is under-constrained. However, measuring the mass in this channel is important because it provides an independent measurement of M_t that can be compared to measurements in other decay channels, allowing a consistency check of the $t\bar{t}$ hypothesis in the dilepton channel. Previous measurements of M_t in the dilepton channel are described in [2, 3, 4].

According to the SM, the theoretical $t\bar{t}$ cross section $\sigma_{t\bar{t}}$ has an exponential dependence on the top mass [5, 6]. Therefore, the top mass value can be extracted from the observed event yield alone. By combining the theoretical $\sigma_{t\bar{t}}(M_t)$ dependence with the top mass determination from the event kinematics, we can use the cross section information to improve the mass measurement, as reported in this Letter.

In this novel measurement, the constraint provided by the mass dependent theoretical $t\bar{t}$ cross section is combined with a “template method” in which a top quark mass m_t^{rec} is reconstructed for each event and in which the distribution of m_t^{rec} is compared with template distributions derived from simulation. In principle, any measurement of M_t and $\sigma_{t\bar{t}}$ could be combined with the theoretical $\sigma_{t\bar{t}}(M_t)$ to obtain an improved top mass determination. However, in our analysis we include the cross section constraint while properly taking into account the top mass dependence of the acceptance and all the correlated systematic uncertainties.

The template method adopted here is an enhanced version of the “full kinematic analysis” described in [2]. The enhanced version treats b -tagged and non-tagged events separately. This separation improves the expected statistical uncertainty by 20%; this represents a significant improvement over the previous analysis, which handled b -tagged and non-tagged events as a single sample. Introducing the cross section constraint improves the expected statistical uncertainty further by 20%. In this paper, the measurement without the cross section constraint will be referred to as the “traditional” measurement. Both measurement techniques were fixed before the data were revealed.

This measurement uses data collected by the CDF II

TABLE I: Expected and observed number of events passing event selection criteria. Statistical and systematic uncertainties have been combined.

| | Expected background |
|---|---------------------|
| diboson | 5.8 ± 0.9 |
| $Z/\gamma^* \rightarrow ll, l = e, \mu, \tau$ | 10.9 ± 2.3 |
| misidentified leptons | 8.8 ± 3.9 |
| Total | 25.6 ± 5.5 |
| | Expected signal |
| $t\bar{t} (M_t = 170 \text{ GeV}/c^2)$ | 62.1 ± 4.3 |
| Total expected | 87.7 ± 8.9 |
| Data | 77 |

detector corresponding to an integrated luminosity of 1.2 fb^{-1} . The CDF II detector [7] is a multi-purpose particle detector at the $p\bar{p}$ Tevatron Collider. Charged particle trajectories are measured with a silicon microstrip detector and a drift chamber, which are immersed in a 1.4 T uniform magnetic field parallel to the beam directions. Electron, photon and hadron energies are measured with electromagnetic and hadronic calorimeters. Muons are detected with drift chambers and scintillation counter hodoscopes located outside the calorimeters. CDF employs cylindrical coordinates where θ and ϕ are the polar and azimuthal angles with respect to the proton beam. Transverse energy and momentum are defined as $E_T = E \sin \theta$ and $p_T = p \sin \theta$, where E is the energy and p is the momentum.

The data for this analysis were collected using an inclusive lepton trigger that required an electron or a muon with $p_T > 18 \text{ GeV}/c$ [8]. After the offline reconstruction, the dilepton events were selected using the DIL selection [9], which requires two oppositely charged leptons with $p_T > 20 \text{ GeV}/c$ [8], missing transverse energy [2] due to the undetected neutrinos ($\cancel{E}_T > 25 \text{ GeV}$), and at least two jets with $E_T > 15 \text{ GeV}$. The main background sources are diboson and Drell-Yan production and W +jets events where a jet is mis-reconstructed as a lepton. Additional cuts were applied to reduce the background [9]. The expected and observed numbers of events are summarized in Table I. After the event selection, the sample was divided into two subsamples with significantly different signal-to-background ratios. The b -tagged sample includes 32 events in which at least one of the jets is identified as a b -quark candidate through the presence of a displaced vertex [10]. This subsample has an expected signal-to-background ratio of 11:1. The non-tagged sample comprises 45 events in which none of the jets is identified as a b -quark candidate. In this subsample the expected signal-to-background ratio is 1:1.

Because the two neutrinos are not detected, the reconstruction of the top quark mass from dilepton events is under-constrained. Top mass reconstruction can be accomplished by considering a kinematic variable which is not observable on an event-by-event basis, but the distri-

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bution of which is predictable and independent of the top mass value. In this analysis the distribution of $p_z^{t\bar{t}}$, the longitudinal momentum of the $t\bar{t}$ system, was adopted as the variable. Monte Carlo simulations, generated with PYTHIA [11] and the CDF II detector simulation [12], indicate that the distribution of $p_z^{t\bar{t}}$ is nearly independent of the top mass, and is described by a Gaussian distribution with a mean of zero and width of 195 GeV/c. The validity of the Monte Carlo simulation was tested with data from the lepton+jets decay channel where $p_z^{t\bar{t}}$ can be explicitly reconstructed.

For each event, a top mass m_t^{rec} is reconstructed from the event kinematics as follows. The jet energies are corrected for defects in the calorimeter response, computed from Monte Carlo simulations, to correspond to the energies of the primary b -quarks. After these jet energy corrections, the two components of transverse missing momentum are taken as the sum of the neutrino transverse momentum components. Along with assumptions on the masses of the final state particles and additional constraints on $M_{W\pm} = 80.4$ GeV/c², $M_t = M_{\bar{t}}$, and $p_z^t + p_z^{\bar{t}} = p_z^{t\bar{t}}$, a top mass can be calculated [2].

A wide range of possible $p_z^{t\bar{t}}$ values is incorporated by calculating the top mass 10000 times. For each iteration, $p_z^{t\bar{t}}$ is randomly drawn from its expected distribution. Similarly, the jet energies and \cancel{E}_T are smeared according to their resolutions. For each iteration, if a solution is not found using the fixed values of M_W and M_t , solutions within $M_{W\pm} = 80.4 \pm 3.0$ GeV/c² and $M_t = M_{\bar{t}} \pm 2.0$ GeV/c² are accepted.

For a given event, we obtain two distributions of possible top quark masses, each corresponding to a different lepton-jet pairing. The pairing which has the higher fraction of solutions is selected. This choice is correct for 70% of simulated $t\bar{t}$ events. If the number of entries in this distribution is less than 100, the event is rejected. According to Monte Carlo studies, 91% of signal and 78% of background events pass this mass reconstruction requirement. The most probable value of a spline fit to the distribution selected is taken as a per-event top mass m_t^{rec} .

Templates of reconstructed top mass distributions were created from various $t\bar{t}$ and background samples. Signal templates were generated from $t\bar{t}$ Monte Carlo samples with generated top masses ranging from 150 to 200 GeV/c², separately for b -tagged and non-tagged signal events. Diboson and $Z \rightarrow l\bar{l}$ templates were generated from Monte Carlo simulation. A template for misidentified leptons was created using data. The background templates were combined according to the expected contribution of each background source. It was observed from simulation that using the same common background template for b -tagged and non-tagged samples provides as good a performance as using separate templates. The common background template was therefore used for both subsamples.

In the traditional measurement, the top mass is extracted by comparing the reconstructed mass distribu-

tions from data to the signal and background template parametrizations (f_s and f_b , respectively) using an unbinned likelihood fit. The likelihood includes free parameters for the number of signal events n_s and background events n_b in each subsample, and for the top mass M_t . The total likelihood takes the form

$$\mathcal{L} \equiv \mathcal{L}_{b\text{-tagged}}(M_t, n_s^b, n_b^b) \times \mathcal{L}_{\text{non-tagged}}(M_t, n_s^{\text{non}}, n_b^{\text{non}}) \quad (1)$$

where each of the subsample likelihoods is:

$$\begin{aligned} \mathcal{L}_{\text{non}/b\text{-tagged}} &\equiv \mathcal{L}_{\text{shape}} \times \mathcal{L}_{\text{nev}} \times \mathcal{L}_{\text{bg}} \\ \mathcal{L}_{\text{shape}} &\equiv \prod_{i=1}^N \frac{n_s \times f_s(m_{t_i}^{rec}, M_t) + n_b \times f_b(m_{t_i}^{rec})}{n_s + n_b} \\ \mathcal{L}_{\text{nev}} &\equiv \frac{e^{-(n_s+n_b)} (n_s+n_b)^N}{N!} \\ -\ln \mathcal{L}_{\text{bg}} &\equiv \frac{(n_b - n_b^{\text{exp}})^2}{2\sigma_{n_b}^2}. \end{aligned} \quad (2)$$

In the formula, N is the number of data events in the subsample, n_b^{exp} and σ_{n_b} are the expected number of background events and its uncertainty, and $m_{t_i}^{rec}$ is the value of m_t^{rec} for the i 'th event. The top quark mass hypothesis which minimizes $-\ln(\mathcal{L})$ is taken.

To test the method, we performed Monte Carlo experiments of signal and background events. The numbers of signal and background events in each experiment were varied according to Poisson distributions using the expected mean numbers of events. According to the Monte Carlo experiments, the method is unbiased and returns appropriate uncertainties.

In 1.2 fb⁻¹ of data, 31 b -tagged and 39 non-tagged events pass the event selection criteria and have solutions for m_t^{rec} . The mass measurement from the b -tagged sample gives $M_t = 171.9_{-6.4}^{+7.2}(\text{stat.})$ GeV/c², and the measurement from the non-tagged sample gives $M_t = 166.0_{-7.9}^{+8.4}(\text{stat.})$ GeV/c². Applying the traditional method to the two subsamples with a joint likelihood, we measure $M_t = 169.7_{-4.9}^{+5.2}(\text{stat.})$ GeV/c². In 34% of Monte Carlo experiments, the statistical uncertainty was smaller than the measured statistical uncertainty from data. The reconstructed top mass distribution from data is shown in Fig. 1.

The top mass measurement can be further improved by taking into account the top mass dependence of the $t\bar{t}$ production cross section. The expected number of signal events can be expressed as

$$n_s(M_t) = \sigma_{t\bar{t}}(M_t) \cdot a(M_t) \cdot L \cdot p_{\text{mass}}^{rec}, \quad (3)$$

where $\sigma_{t\bar{t}}(M_t)$ is the theoretical $t\bar{t}$ cross section, $a(M_t)$ is the acceptance of $t\bar{t}$ events, L is the integrated luminosity, and p_{mass}^{rec} is the probability of obtaining a solution for m_t^{rec} .

The dominant top mass dependence on the expected number of events comes from the theoretical $\sigma_{t\bar{t}}$. We use a NLO calculation of $\sigma_{t\bar{t}}$ evaluated at three different top

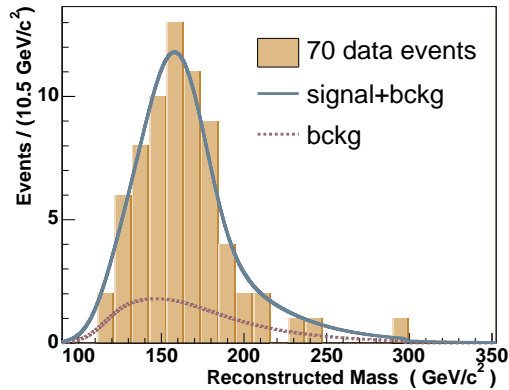


FIG. 1: Reconstructed top mass distribution from data together with the signal and background parametrizations.

masses [5]; we parametrize the mass dependence of $\sigma_{t\bar{t}}$ on the top mass using the functional form described in [6]:

$$\sigma_{t\bar{t}}(M_t) = 6.70 \cdot e^{(175-M_t)/32.29} \text{ pb.} \quad (4)$$

The acceptance $a(M_t)$ was studied using $t\bar{t}$ Monte Carlo simulation, separately for b -tagged and non-tagged samples. The Monte Carlo acceptances were corrected for trigger efficiencies and for scale factors arising from differences between data and simulation. The combined Monte Carlo acceptance corrections are between 74% and 95%, depending on the lepton flavor and pseudorapidity. The dependence of the acceptance on the top mass is linear, increasing about 30% in the top mass range of 150 to 200 GeV/c^2 . The integrated luminosity, L , is 1118 pb^{-1} for the b -tagged sample and 1189 pb^{-1} for the non-tagged sample. The two integrated luminosities are different because of the smaller data set using the silicon detector, which is required for b -tagging. The signal mass reconstruction probability, p_{mass}^{rec} , was measured to be $91 \pm 1.1\%$ for both b -tagged and non-tagged samples, and was found to be independent of the top mass.

The cross section constrained top mass measurement uses information from the reconstructed top mass distribution as well as the observed number of events. The per-event mass reconstruction method and the template parametrizations are exactly the same as in the traditional measurement. The information from the number of events is added in the likelihood function by replacing n_s in Eq. (2) with $n_s(M_t)$ from Eq. (3); thus $\mathcal{L} \equiv \mathcal{L}_{b\text{-tagged}}(M_t, n_b^b) \times \mathcal{L}_{\text{non-tagged}}(M_t, n_b^{\text{non}})$. The number of background events n_b and the top mass M_t are free fit parameters as in the likelihood function of the traditional measurement. The uncertainty in the theoretical modeling of $\sigma_{t\bar{t}}$ is not included in the likelihood; it is treated in the same way as other systematic uncertainties described below.

Simulated experiments are used to verify that the cross section constrained method is unbiased and returns appropriate uncertainties. We measure $M_t = 170.7^{+4.2}_{-3.9}(\text{stat.}) \text{ GeV}/c^2$. The statistical uncertainty is consistent with expectations: 34% of Monte Carlo experiments returned an uncertainty smaller than the uncertainty measured from data.

The sources of systematic uncertainties are summarized in Table II. The jet energy scale uncertainty is dominated by the uncertainty in jet energy corrections. This uncertainty was studied by shifting the jet energies by $\pm 1\sigma$, and half of the mass difference was taken as the systematic uncertainty. Since the jet energy corrections were determined for light quark jets, we evaluated an additional systematic uncertainty from possible differences between b jets and light quark jets [13]. The total uncertainty from the jet energy scale is 1.8 (2.9) GeV/c^2 for the cross section constrained (traditional) measurement. The cross section constrained measurement is less sensitive to the jet energy corrections because a change in the jet energy scale shifts the top mass determination from the event yield in the opposite direction to that from kinematic reconstruction. The signal modeling uncertainty is 0.9 (0.8) GeV/c^2 , and takes into account differences in parton showering between the PYTHIA [11] and HERWIG [14] Monte Carlo generators, uncertainties in initial and final state radiation modeling, and differences in parton distribution functions between MRST [15] and the full set of CTEQ6M [16] eigenvectors. Possible imperfections in modeling the $Z \rightarrow l\bar{l}$ and misidentified lepton backgrounds combine to give 0.3 (0.3) GeV/c^2 background modeling uncertainty. The uncertainty from template statistics is 0.4 (0.5) GeV/c^2 . A 1% uncertainty in the lepton p_T introduces an uncertainty of 0.2 (0.2) GeV/c^2 . The cross section constrained measurement has an additional uncertainty of $1.6 \text{ GeV}/c^2$ from the expected number of events. This uncertainty includes $1.1 \text{ GeV}/c^2$ uncertainty from the integrated luminosity, $0.5 \text{ GeV}/c^2$ from the acceptance, $0.9 \text{ GeV}/c^2$ from the expected number of background events and $0.5 \text{ GeV}/c^2$ from the mass reconstruction probability.

TABLE II: Summary of systematic uncertainties for the traditional (T) and cross section constrained (C) measurements.

| Systematic Source | ΔM_t (GeV/c^2) | |
|---------------------------|-----------------------------------|-----|
| | T | C |
| Jet energy scale | 2.9 | 1.8 |
| Signal modeling | 0.8 | 0.9 |
| Background modeling | 0.3 | 0.3 |
| Template statistics | 0.5 | 0.4 |
| Lepton p_T | 0.2 | 0.2 |
| Expected number of events | n.a | 1.6 |
| Total | 3.1 | 2.6 |

The uncertainty in the theoretical $\sigma_{t\bar{t}}(M_t = 175 \text{ GeV}/c^2)$ is $^{+0.71}_{-0.88} \text{ pb}$ [5]. We propagated this uncertainty to the top mass by changing the number of

signal events in the Monte Carlo experiments. The estimated uncertainty on the top mass is $2.4 \text{ GeV}/c^2$. Simulation studies show that this cross section constrained top mass measurement is not very sensitive to the probability shape of the theoretical $\sigma_{t\bar{t}}$ uncertainty. Figure 2 shows the cross section constrained top mass measurement in the $M_t - \sigma_{t\bar{t}}$ plane. The extracted top mass from the cross section measurement [17] only is $178.3_{-8.0}^{+10.1}(\text{exp})_{-5.8}^{+4.0}(\text{theory}) \text{ GeV}/c^2$, consistent within about one standard deviation with the result from the traditional analysis.

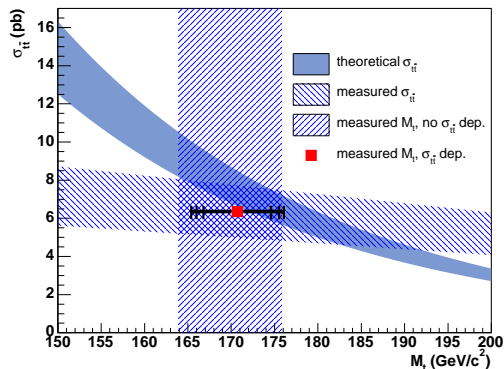


FIG. 2: The measured cross section constrained top mass is shown in the $M_t - \sigma_{t\bar{t}}$ plane. The innermost error bars correspond to the statistical uncertainty, the middle ones the statistical+systematic uncertainty, and the outermost error bars show the statistical+systematic+theory uncertainty. The hatched areas mark the traditional top mass measurement and the $\sigma_{t\bar{t}}$ measurement in the dilepton channel with statistical+systematic uncertainties.

In summary, we have introduced a new way to improve the template top mass measurement in the dilepton channel by using a theoretical cross section constraint. With this measurement, we compare the reconstructed top mass distribution to templates and the observed number of events to expectation. In 1.2 fb^{-1} of data collected by the CDF II detector, we measure a top quark mass of $170.7_{-3.9}^{+4.2}(\text{stat}) \pm 2.6(\text{syst}) \pm 2.4(\text{theory}) \text{ GeV}/c^2$. This measurement is in good agreement with the top mass measurement made without a cross section constraint, which gives $169.7_{-4.9}^{+5.2}(\text{stat}) \pm 3.1(\text{syst}) \text{ GeV}/c^2$, and with top quark mass measurements made in other decay channels [18, 19, 20].

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