CDF/ANAL/TOP/PUB/7718

Measurement of the Top Quark Mass in the Dilepton Channel using the Leading-Order Differential Cross-Section at CDF II

The CDF Collaboration
URL http://www-cdf.fnal.gov
(Dated: June 27, 2005)

We present a measurement of the top quark mass in the dilepton channel using a technique in which we form a posterior probability for the mass as a product of the normalized per-event differential cross-section for leading order top quark pair production. The calculation of the differential cross section for processes which produce background events are used to reduce the impact of background events in the sample.

In $\int L = 340pb^{-1}$, we expect a statistical uncertainty of 9.4 GeV/c^2 if $M_t = 178.0$ GeV/c^2 (7.8 GeV/c^2 if $M_t = 165.0$ GeV/c^2) and a systematic uncertainty of 3.6 GeV/c^2. We measure

$$M_{top} = 165.3 \pm 6.3(\text{stat.}) \pm 3.6(\text{syst.})\ \text{GeV}/c^2$$

I. INTRODUCTION

The mass of the top quark is a free parameter of the Standard Model and is of great interest due to its exceedingly large value and the constraints it places on the mass of the Higgs boson. At the Tevatron, top quarks are primarily produced in pairs and decay to a W boson and b quark nearly 100% of the time. Of these decays, the "dilepton" channel, which includes events where both W bosons decay leptonically, has the lowest statistics but the least background contamination.

Since the number of top pairs observed at the Tevatron is small, especially in the dilepton channel, we seek to extract the maximal information from these events. To do so, we employ a natural and intuitive, though calculationally intensive technique that uses our detailed understanding of the physical production process [1–3]. In this note, we report a measurement of the top quark mass in the dilepton channel using this technique made at the CDF II detector.

II. EVENT SELECTION

This analysis is based on an integrated luminosity of 340 pb^{-1} collected with the CDF II detector between March 2002 and August 2004. The CDF II detector is a general purpose detector described elsewhere [4]. For this analysis, we select events with two high-p_T leptons, missing transverse energy ($\not\!\!E_T$) and two energetic jets coming from the hadronization of the b-quarks. We use the selection described as "DIL" in [6] to measure the cross-section in the dilepton channel.

The data are collected with an inclusive lepton trigger that requires events to have a lepton with $E_T > 18$ GeV (for an electron) or $p_T > 18$ GeV (for a muon). After full event reconstruction we require events with two leptons, both with $E_T > 20$ GeV ($p_T > 20$ GeV for muons) and at least one of which is isolated [5]. Candidate events must have at least two jets with $E_T > 15$ GeV and be measured within $|\eta| < 2.5$. We also require candidate events to have $\not\!\!E_T > 25$ GeV and in events with $\not\!\!E_T < 50$ GeV that the $\not\!\!E_T$ vector is at least 20° from the closest lepton or jet.

III. METHOD

The information contained in an event regarding the top mass can be expressed as the conditional probability $P(\mathbf{x}|M_t)$, where M_t is the top pole mass and $\mathbf{x}$ is a vector of measured event quantities. We calculate the posterior probability using the theoretical description of the $t\bar{t}$ production process expressed with respect to the measured event quantities:

$$P(\mathbf{x}|M_t) = \frac{1}{\sigma(M_t)}\frac{d\sigma(M_t)}{d\mathbf{x}}$$

where $\frac{d\sigma}{d\mathbf{x}}$ is the per-event differential cross-section.

To evaluate the probability, we integrate over quantities which are unknown because they are unmeasured by the detector, such as neutrino energies. Quark energies are not directly measured, but are estimated from the observed energies of the corresponding jets. We parametrize this uncertainty using a transfer function between quark and jet energies, $f(p, j)$, giving us the probability of measuring jet energy j given parton energy p. We form the transfer function by fitting a double Gaussian to a predicted distribution of parton-jet energy difference from simulated events. The total expression for the probability of a given pole mass for a specific event can be written as

$$P(\mathbf{x}|M_t) = \frac{1}{N}\int d\Phi_6 |\mathcal{M}_{t\bar{t}}(p; M_t)|^2 \prod_{jets} f(p_i, j_i) f_{PDF}(q_1) f_{PDF}(q_2) \tag{1}$$

where the integral is over the entire six-particle phase space, q is the vector of incoming parton-level quantities, p is the vector of resulting parton-level quantities: lepton and quark momenta, and $|\mathcal{M}_{t\bar{t}}(p; M_t)|$ is the $t\bar{t}$ production matrix element as defined in [7, 8]. The constant term in front of the integral ensures that the normalization condition for the probability:

$$\int d\mathbf{x}\ P(\mathbf{x}|M_t) = 1$$

is satisfied.

A. Background

The probability $P(\mathbf{x}|M_t)$ is sufficient to extract the top quark mass in an unpolluted sample. However, the top quark candidate events collected by CDF have a small fraction of background events which mimic the top quark signature. To reduce the effect of these events on the measurement, we calculate the probability $P_{bg}(\mathbf{x})$ that they were produced by a background process; we form the generalized per-event probability as

$$P(\mathbf{x}|M_t) = P_s(\mathbf{x}|M_t)p_s + P_{bg1}(\mathbf{x})p_{bg1} + P_{bg2}(\mathbf{x})p_{bg2}... \tag{2}$$

simply a sum of the probabilities for each process, weighted by their respective priors. Here, $P_s(\mathbf{x}|M_t)$ is as described in equation 1 and the $P_{bg}(\mathbf{x})$ are formed by calculating a differential cross-section for each event in a manner similar to $t\bar{t}$. The background processes for which we evaluate probabilities for in this manner are: Drell-Yan with associated jets, W pair production with associated jets and W+3 jets production where one jet is incorrectly identified as a lepton.

The weights for each term in Equation 2 are determined in part from the number of expected background events in each category. These numbers are listed in Table I.

Source	N_{ev}
WW/WZ	1.63 ± 0.22
Drell-Yan	4.92 ± 1.26
$Z \to \tau\tau$	0.80 ± 0.16
Fakes	4.21 ± 1.68
Total Background	11.6 ± 2.1
$t\bar{t}$ ($\sigma = 6.7$pb)	17.2 ± 1.4
Total SM expectation	28.8 ± 2.5
Run II Data ($\int \mathcal{L}dt = 340\text{pb}^{-1}$)	33

TABLE I: Expected signal and background events and their sources for a data sample of $\int \mathcal{L}dt = 340\text{pb}^{-1}$.

IV. PERFORMANCE IN PSEUDO-EXPERIMENTS

To test the performance of the method, we construct pseudo-experiments using Monte Carlo for generated top masses from 155 GeV/c^2 to 195 GeV/c^2. The number of signal and background events in each pseudo-experiment are Poisson fluctuated values around the *a priori* estimates given in Table I; the estimate for $t\bar{t}$ at varying masses is evolved to account for the variation of cross-section and acceptance. The response of the method for pseudo-experiments with both signal and background is shown in Figure 1. A correction, as derived from this response, is applied to the measured value in data.

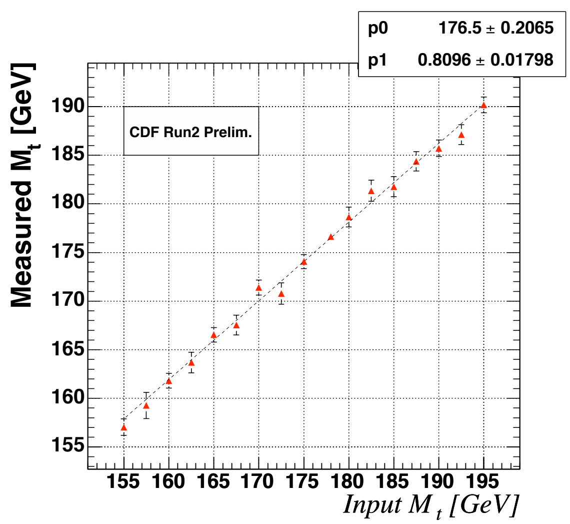

FIG. 1: Response for pseudo-experiments of signal and background events.

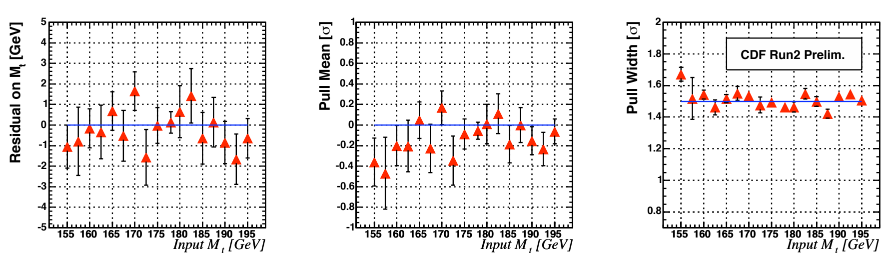

FIG. 2: Residual, pull mean, and pull width for varying top mass MC samples before scaling of statistical error

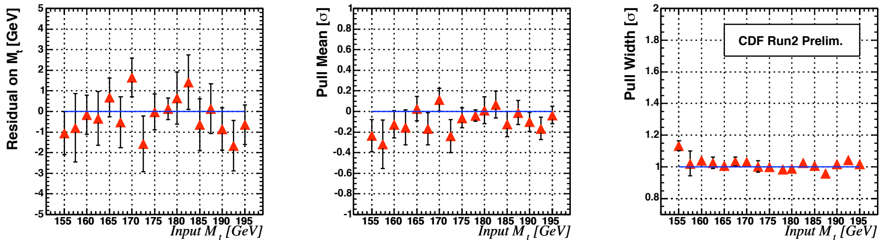

FIG. 3: Residual, pull mean, and pull width for varying top mass MC samples after scaling of statistical error

In the interest of computational tractability, several assumptions are made in the evaluation of the integrals in Equation 1. These assumptions are violated in small and understood ways in realistic events. Due to these effects, the method underestimates the statistical error as seen in the pull distribution in Figure 2. The largest contributing effects are jets coming from radiation rather than b-quark hadronization (≈20%), imperfect resolution of lepton momenta (≈10%) and imperfect resolution of jet angles (≈10%). To account for this underestimation, we scale the statistical error by a factor derived from the results of our pseudo-experiments. The resulting pull distribution after correction can be seen in Figure 3.

V. SYSTEMATIC UNCERTAINTIES

There are several sources of systematic error in our measurement which are summarized in Table II.

Source	Size (GeV/c^2)
Jet Energy Scale	2.6
Generator	1.0
Method	0.6
Sample composition uncertainty	0.7
Background MC	1.5
Background modelling	0.8
FSR modelling	0.5
ISR modelling	0.5
PDFs	1.1
Total	3.6

TABLE II: Summary of systematic errors.

The single largest source of systematic error comes from the uncertainty in the jet energy scale, which we estimate by varying the jet energy corrections by $\pm 1\sigma$ and is 2.6 GeV/c^2. The uncertainty in the Monte Carlo generator used to perform pseudo-experiments, estimated by measuring the difference in extracted the top mass from PYTHIA events and HERWIG events, amounts to 1 GeV/c^2. The uncertainty in the response correction shown in Figure 1 is estimated by varying that response by $\pm 1\sigma$ and is 0.6 GeV/c^2. The uncertainty due to initial-state (ISR) and final-state (FSR) radiation is estimated by varying the amount of ISR and FSR in simulated events and is measured to be 0.5 GeV/c^2 for both cases.

The uncertainty in background composition is estimated by varying the background estimates from Table I within their errors and amounts to 0.7 GeV/c^2. In addition, a large uncertainty comes from the limited number of Monte Carlo background events available for pseudo-experiments. To measure this uncertainty, we split each background sample into twenty pairs of disjoint sets. We measure the mass for each of the disjoint sets and take the RMS of the difference between them as an estimate of the error. Summing these, we get 1.5 GeV/c^2. We also estimate an uncertainty coming from possible imperfections in modelling the two largest sources of background: Drell-Yan and events with a "fake" lepton. This uncertainty is estimated to be 0.8 GeV/c^2

Finally, the uncertainties in the parton distribution functions (PDFs) are estimated by using different PDF sets (CTEQ5L vs. MRST72), different values of Λ_{QCD}, varying the eigenvectors of the CTEQ6M set, and varying the initial state contributions of gg and $q\bar{q}$, yielding a total uncertainty of 1.1 GeV/c^2.

VI. RESULT IN DATA

We apply the procedure described in Section III to the 33 candidate events observed in the data. After applying the corrections described in Section IV, we measure a top quark mass of

$$M_{top} = 165.3 \pm 6.3(\text{stat.})\ \text{GeV}/c^2$$

The final posterior probability density for the events in data can be seen in Figure 4.

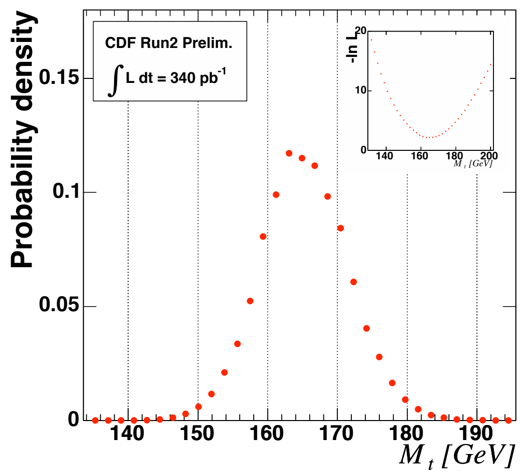

FIG. 4: Final posterior probability density as a function of the top pole mass for the 33 candidate events in data.

The measured statistical uncertainty is consistent with that measured for pseudo-experiments using M_{top} = 165 GeV/c^2 signal events (which had a mean *a priori* error of 7.8 GeV/c^2) as shown in Figure 5.

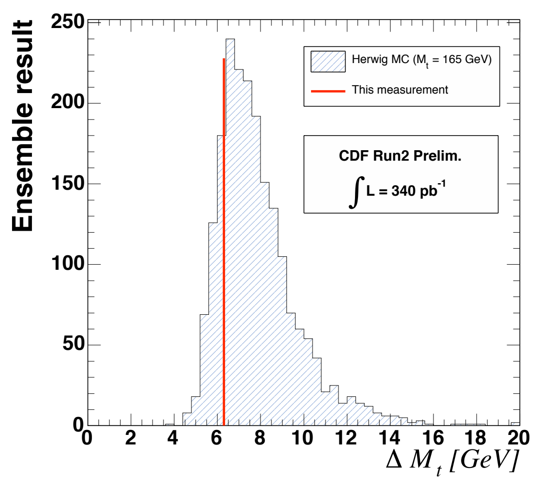

FIG. 5: Distribution of expected errors for M_t = 165 GeV/c^2. The measured error is shown as the line; 17% of pseudo-experiments yielded a smaller error.

VII. CONCLUSION

We measure the top quark mass to be

$$M_{top} = 165.3 \pm 6.3(\text{stat.}) \pm 3.6(\text{syst.})\ \text{GeV}/c^2$$

or equivalently $M_{top} = 165.3 \pm 7.3$ GeV/c^2 in dilepton events in 340 pb^{-1} of CDF II data. We have used a normalized per-event differential cross-section for leading order top quark pair production and background to form a posterior probability. The statistical power of this method allows having a relatively small error on a measurement made using a small data set such as the dilepton sample. We project that the statistical error obtained from this method by the end of Run II will be ~ 2 GeV/c^2.

Acknowledgments

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Particle Physics and Astronomy Research Council and the Royal Society, UK; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; in part by the European Community's Human Potential Programme under contract HPRN-CT-2002-00292; and the Academy of Finland.

---

[1] K. Kondo. J. Phys. Soc. Jpn. **57** (1988) 4126.
[2] J. Estrada, FERMILAB-THESIS-2001-07 (2001)
[3] F. Canelli, FERMILAB-THESIS-2003-22 (2003)
[4] D. Acosta, et al., The CDF Collaboration, Phys. Rev. D **71**, 032001 (2005)
[5] An isolated lepton is one for which no more than 10% extra energy is measured in a cone of $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} \leq 0.4$ around the lepton.
[6] D. Acosta et al., The CDF Collaboration, Phys. Rev. Lett. **93**, 142001 (2004)
[7] G. Mahlon, S. Parke, Phys. Lett. B **411**, 173 (1997)
[8] G. Mahlone, S. Parke, Phys. Rev. D **55**, 7249 (1996)