



# Measurement of the Top Quark Mass in the Dilepton Channel using a Matrix Element Method with 750 pb<sup>-1</sup>

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We report a measurement of the top quark mass using events collected by the CDF II Detector from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV at the Fermilab Tevatron. We calculate a likelihood function for the top mass in events that are consistent with  $t\bar{t} \rightarrow \bar{b}\ell^-\bar{\nu}_\ell b\ell'^+\nu'_\ell$  decays. The likelihood is formed as the convolution of the leading-order matrix element and detector resolution functions. The joint likelihood is the product of likelihoods for each of 64 events collected in 750 pb<sup>-1</sup> of integrated luminosity, yielding a top quark mass,  $M_t = 164.5 \pm 4.5(\text{stat.}) \pm 3.1(\text{syst.})$  GeV/ $c^2$ .

## I. INTRODUCTION

Precision measurements of the top quark mass,  $M_t$ , place constraints on the masses of particles to which the top quark contributes radiative corrections, including the unobserved Higgs boson and particles in extensions to the standard model. At the Tevatron, top quarks are primarily produced in pairs. The dilepton channel, consisting of the decays  $t\bar{t} \rightarrow \bar{b}\ell^-\bar{\nu}_\ell b\ell'^+\nu'_\ell$ , has a small branching fraction but allows measurements which are less reliant on the calibration of the jet energy scale, the dominant systematic uncertainty, than measurements in channels with hadronic  $W$  decays. A discrepancy from other channels could indicate contributions from new processes.

The reconstruction of the top mass from dilepton events poses a particular challenge as the two neutrinos from  $W$  decays are undetected. Previous measurements in this channel [1, 2] using Run I data have calculated the mass by making several kinematic assumptions and integrating over the remaining unconstrained quantity. To extract maximum information from the small sample of dilepton events, we adapt a technique pioneered for the analysis of  $t\bar{t} \rightarrow b\ell\nu_\ell\bar{b}q\bar{q}'$  decays [3–5]. This technique uses the leading-order production cross-section and a parameterized description of the jet energy resolution. Making minimal kinematic assumptions and integrating over six unconstrained quantities, we obtain per-event likelihoods in top mass which can be directly multiplied to obtain the joint likelihood from which  $M_t$  is determined.

This method was first applied to dilepton events at CDF [6]. In this note, we report a measurement of the top quark mass in the dilepton channel using the technique in [6] using additional data collected at the CDF II detector that yields the single most precise measurement of  $M_t$  in the dilepton channel.

## II. EVENT SELECTION

This analysis is based on an integrated luminosity of  $750 \text{ pb}^{-1}$  collected with the CDF II detector between March 2002 and September 2005. The CDF II detector is a general purpose detector described elsewhere [7]. For this analysis, we select events with two high- $p_T$  leptons, missing transverse energy ( $\cancel{E}_T$ ) and two energetic jets coming from the hadronization of the  $b$ -quarks. We use the selection described as “DIL” in [9] 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  $E_T > 18 \text{ GeV}$  (for an electron) or  $p_T > 18 \text{ GeV}$  (for a muon). After full event reconstruction we require events with two leptons, both with  $E_T > 20 \text{ GeV}$  ( $p_T > 20 \text{ GeV}$  for muons) and at least one of which is isolated [8]. Candidate events must have at least two jets with  $E_T > 15 \text{ GeV}$  and be measured within  $|\eta| < 2.5$ . We also require candidate events to have  $\cancel{E}_T > 25 \text{ GeV}$  and in events with  $\cancel{E}_T < 50 \text{ GeV}$  that the  $\cancel{E}_T$  vector is at least  $20^\circ$  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,  $W(p, j)$ , 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

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

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 [10, 11]. 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 probabilities,  $P_{bg_i}(\mathbf{x})$  that they were produced by a given background process; we form the generalized per-event probability as

$$P(\mathbf{x}|M_t) = P_s(\mathbf{x}|M_t)p_s + P_{bg_1}(\mathbf{x})p_{bg_1} + P_{bg_2}(\mathbf{x})p_{bg_2}\dots \quad (2)$$

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  $P_{bg_i}(\mathbf{x})$  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	$N_{ev}$
$WW/WZ$	$3.63 \pm 0.72$
Drell-Yan	$7.83 \pm 3.15$
$Z \rightarrow \tau\tau$	$1.60 \pm 0.38$
Fakes	$6.29 \pm 1.11$
Total Background	$19.4 \pm 3.4$
$t\bar{t}$ ( $M_t = 175 \text{ GeV}/c^2$ )	$36.1 \pm 1.2$
Total SM expectation	$55.4 \pm 5.3$
Data ( $\int \mathcal{L} dt = 750 \text{ pb}^{-1}$ )	64

TABLE I: Expected signal and background events and their sources for a data sample of  $\int \mathcal{L} dt = 750 \text{ pb}^{-1}$ .

#### IV. PERFORMANCE IN PSEUDO-EXPERIMENTS

To test the performance of the method, we construct pseudo-experiments using Monte Carlo for generated top masses from  $155 \text{ GeV}/c^2$  to  $195 \text{ GeV}/c^2$ . 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.

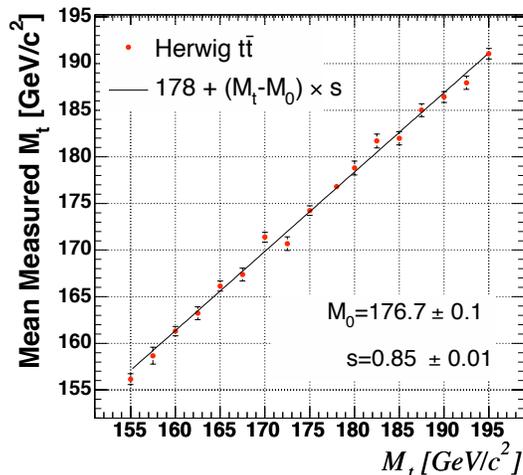


FIG. 1: Response for pseudo-experiments of signal and background events.

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. The largest contributing effects are jets coming from radiation rather than  $b$ -quark hadronization ( $\approx 20\%$ ), imperfect resolution of lepton momenta ( $\approx 10\%$ ) and imperfect resolution of jet angles ( $\approx 10\%$ ). 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 2.

#### V. SYSTEMATIC UNCERTAINTIES

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

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  $2.6 \text{ GeV}/c^2$ . The uncertainty in the Monte Carlo generator used to perform pseudo-experiments, estimated by measuring the difference in extracted the top mass from PYTHIA

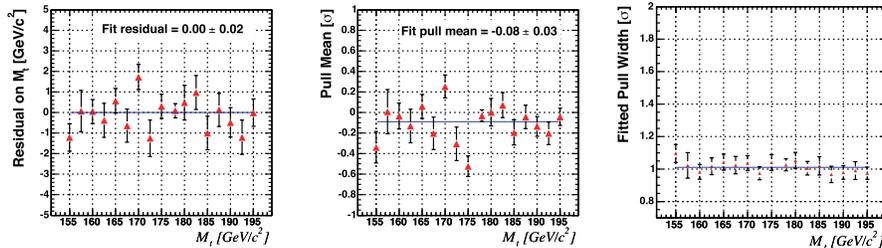


FIG. 2: Residual, pull mean, and pull width for varying top mass MC samples after scaling of statistical error by a factor of  $S = 1.49$

Source	Size ( $\text{GeV}/c^2$ )
Jet Energy Scale	2.6
Generator	0.5
Method	0.3
Sample composition uncertainty	0.7
Background MC	0.8
Background modeling	0.8
FSR modeling	0.5
ISR modeling	0.5
PDFs	0.6
Total	3.1

TABLE II: Summary of systematic errors.

events and HERWIG events, amounts to  $0.5 \text{ GeV}/c^2$ . The uncertainty in the response correction shown in Figure 1 is estimated by varying that response by  $\pm 1\sigma$  and is  $0.5 \text{ GeV}/c^2$ . 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  $0.5 \text{ GeV}/c^2$  for both cases.

The uncertainty in background composition is estimated by varying the background estimates from Table I within their errors and amounts to  $0.7 \text{ GeV}/c^2$ . 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  $0.8 \text{ GeV}/c^2$ . We also estimate an uncertainty coming from possible imperfections in modeling the two largest sources of background: Drell-Yan and events with a “fake” lepton. This uncertainty is estimated to be  $0.8 \text{ GeV}/c^2$ .

Finally, the uncertainties in the parton distribution functions (PDFs) are estimated by using different PDF sets (CTEQ5L vs. MRST72), different values of  $\Lambda_{QCD}$ , varying the eigenvectors of the CTEQ6M set, and varying the initial state contributions of  $g\bar{g}$  and  $q\bar{q}$ , yielding a total uncertainty of  $0.6 \text{ GeV}/c^2$ .

## VI. RESULT IN DATA

We apply the procedure described in Section III to the 64 candidate events observed in the data. After applying the corrections described in Section IV, we measure a top quark mass of

$$M_{top} = 164.5 \pm 4.5(\text{stat.}) \text{ GeV}/c^2$$

The final posterior probability density for the events in data can be seen in Figure 3.

The measured statistical uncertainty is consistent with that measured for pseudo-experiments using  $M_{top} = 165 \text{ GeV}/c^2$  signal events (which had a mean *a priori* error of  $5.1 \text{ GeV}/c^2$ ) as shown in Figure 4.

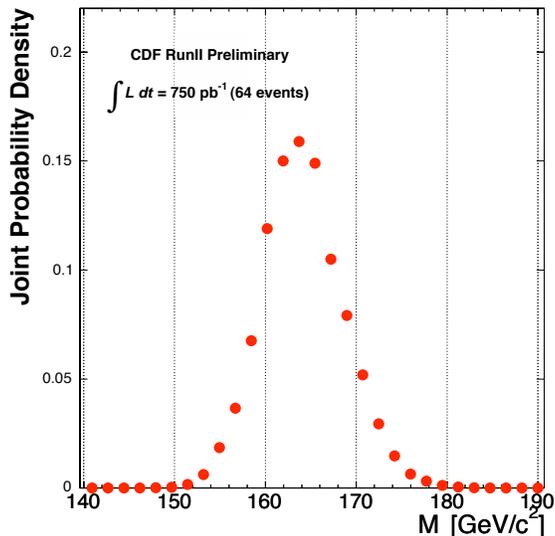


FIG. 3: Final posterior probability density as a function of the top pole mass for the 64 candidate events in data.

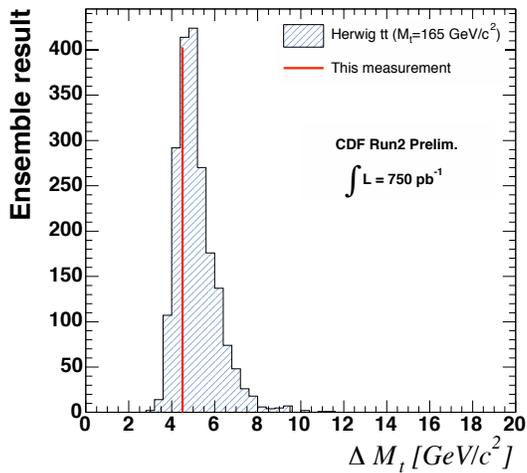


FIG. 4: Distribution of expected errors for  $M_t = 165 \text{ GeV}/c^2$ . The measured error is shown as the line; 26% of pseudo-experiments yielded a smaller error.

## VII. CONCLUSION

We measure the top quark mass to be

$$M_{top} = 164.5 \pm 4.5(\text{stat.}) \pm 3.1(\text{syst.}) \text{ GeV}/c^2$$

in dilepton events in  $750 \text{ pb}^{-1}$  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  $\sim 2 \text{ GeV}/c^2$ .

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