Measurements of the Top Quark Mass at D0

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Abstract.
We present measurements of the top quark mass based on 3.6 fb^{-1} of data collected by the D0 experiment during Run II of the Fermilab Tevatron collider. We present results in the dilepton and lepton+jets final states. We also present the measurement of the mass difference between t and $\bar{t}$ quarks observed in lepton+jets final states of $t\bar{t}$ events in 1 fb^{-1} of data.

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INTRODUCTION

The unique place in the Standard Model filled by the top quark makes precise measurements of its mass of great interest. We report preliminary top quark mass measurements using 3.6 fb^{-1} of data from the D0 experiment [1] at the Fermilab Tevatron, as well a direct measurement of the mass difference between the top quark and its antiparticle.

MEASUREMENTS OF THE TOP QUARK MASS

The most precise top quark mass measurements at D0 are currently obtained by the matrix element method [2]. In this method, a likelihood is assigned to each event of the form

$$P_{\text{evt}}(\mathbf{x};m_t,f_t) = \left[f_t P_{\text{sig}}(\mathbf{x};m_t) + (1-f_t)P_{\text{bkg}}(\mathbf{x})\right], \tag{1}$$

where $\mathbf{x}$ represents the full set of measured kinematic quantities of the event, m_t the top quark mass, and f_t is the $t\bar{t}$ signal fraction in the sample. The $t\bar{t}$ signal likelihood is then

$$P_{\text{sig}}(\mathbf{x};m_t) = \frac{1}{\sigma'(m_t)} \int_{q_1,q_2,\mathbf{y}} \sum_{\substack{\text{perm,}\\ \text{flavors}}} w_{\text{perm}}\, dq_1\, dq_2 f(q_1) f(q_2) \frac{(2\pi)^4 |\mathscr{M}|^2}{4\sqrt{(q_1\cdot q_2)^2}} d\Phi_6 W(\mathbf{x},\mathbf{y}), \tag{2}$$

where $\mathbf{y}$ is the set of parton-level kinematic variables defining the final state of the hard scatter, q_i are the momenta of the incoming partons, f is the parton distribution function, σ' is the observable cross section (including the detector efficiency), $\mathscr{M}$ is the matrix element for the hard scatter, taken from an analytic calculation [3], and W is the transfer function from a hard scatter to the measured variables. The sum is over flavors of incoming partons and assignments of jets to final-state partons; if b-tagging is used, a weight w_{perm} is applied based on this assignment. P_{bkg} is similar, except that

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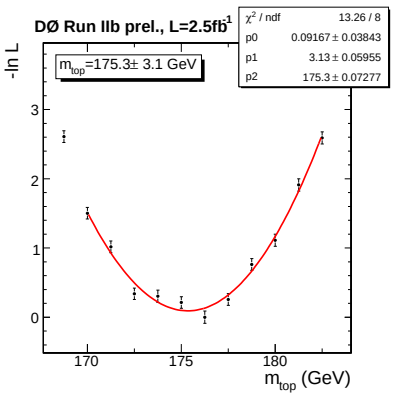

FIGURE 1. Fit for m_t to 2.5 fb^{-1} of $e\mu$ data. (Uncalibrated.)

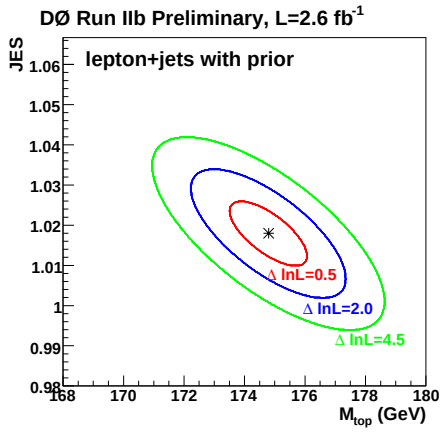

FIGURE 2. Fit for m_t and JES to 2.6 fb^{-1} of $\ell+$jets data. (Uncalibrated.)

there is no dependence on m_t and $\mathscr{M}$ is evaluated using VECBOS [4]. An estimate of m_t and its uncertainty is then extracted from the joint likelihood of a data sample via maximum likelihood. Due to approximations present in $\mathscr{M}$ and W, the mass extracted by this procedure will be systematically biased. The analysis is carried out on many simulated experiments with various input m_t; the results are used to correct the extracted m_t and its uncertainty. ALPGEN [5] is used to model the $t\bar{t}$ signal.

This measurement has been carried out in the $t\bar{t} \to e\mu\nu\nu b\bar{b}$ channel with 3.6 fb^{-1} of data [6]. Events are selected with an isolated, high-p_T electron and muon and two jets; there is also a requirement made on $H_T = p_T(\ell_1) + p_T(j_1) + p_T(j_2)$. This yields 154 candidate events. The expected background fraction is about 16% and is predominantly due to $Z \to \tau\tau$. The fit to the final 2.5 fb^{-1} subset of the data is shown in Fig. 1.

The result after calibration is $m_t = 174.8 \pm 3.3$ (stat.) ± 2.6 (syst.) GeV. Combined with previous D0 results from channels in which both top quarks decay to leptons [7], the result is $m_t = 174.7 \pm 2.9$ (stat.) ± 2.4 (syst.) GeV.

The analysis has also been performed in the $t\bar{t} \to \ell\nu b\bar{b}qq$ ("$\ell+$jets," where $\ell \equiv e, \mu$) channels with 3.6 fb^{-1} of data [8]. Events are required to have exactly one isolated, high-p_T electron or muon, large $\not{E}_T$, and exactly four jets, at least one of which must be identified as a b-jet. This yields 615 events with a background fraction of about 30%. Each signal event has a $W \to jj$ decay; by constraining this to the known mass of the W boson, the jet energy scale uncertainty may be reduced. This is implemented with an additional fit parameter JES, which is a multiplicative scale factor on the jet energies. A prior probability distribution for JES is included, corresponding to the results of the standard jet energy calibration. Results for the final 2.6 fb^{-1} of data are shown in Fig. 2.

The result is $m_t = 174.7 \pm 0.8$ (stat.) ± 1.6 (syst.) GeV. Combining all top quark mass measurements from D0 [9] yields $m_t = 173.2 \pm 0.9$ (stat.) ± 1.5 (syst.). The precision of this measurement is now better than 1%; also note that it is now systematics dominated.

Systematic uncertainties are summarized in Table 1. The categories shown in this table are the result of a recent effort to make the evaluation of systematics consistent across all Tevatron m_t measurements. Compared with previous analyses, two new systematics

TABLE 1. Systematic uncertainties (in GeV) for the top quark mass measurements [10].

Source	$\ell\ell$	$\ell+$jets
In-situ JES	—	±0.47
Jet e/h, b-tag, recon.	±1.32	±0.91
b modeling	±0.26	±0.07
JES control samples	±1.46	±0.84
Lepton momentum scale	±0.32	±0.18
Signal model	±0.65	±0.45
Monte Carlo model diffs.	±1.00	±0.58
Bkg. model (excl. QCD)	±0.08	±0.08
Fit method + QCD bkg.	±0.51	±0.21
Color reconnection	±0.40	±0.40
Luminosity profile	±0.00	±0.05
Total:	±2.43	±1.60

TABLE 2. Systematic uncertainties (in GeV) for the top quark mass difference measurement.

Source	
Physics modeling:	
Signal	±0.85
PDF uncertainty	±0.26
Other	±0.14
Detector modeling:	
Jet resolution	±0.39
Overall jet energy scale	±0.08
Wrong sign leptons	±0.07
$b\bar{b}$ response asymmetry	±0.42
Other	±0.22
Method:	±0.53
Total:	±1.22

have now been evaluated. "Color reconnection" arises from variations in the description of color reconnection of final-state particles [11]. "Luminosity profile" quantifies the uncertainty due to mismodeling the number of collisions per bunch crossing.

When these results are combined with those from CDF, the new world average is $m_t = 173.1 \pm 0.6$ (stat.) ± 1.1 (syst.) GeV [10], for an overall precision of 0.75%.

TOP-ANTITOP QUARK MASS DIFFERENCE MEASUREMENT

CPT is generally believed to be a good symmetry nature; by the CPT theorem [12], it holds for any local Lorentz-invariant quantum field theory. Nevertheless, it is important to search for any violations. One implication of CPT invariance is that the mass of a particle and its antiparticle must be equal. While many precise such measurements have been made [13], those for quarks have always been indirect. The top quark is, however, unique: due to its large mass, it decays before hadronization effects become important. Thus, the masses of the top and antitop quarks can be measured directly and separately.

D0 has now performed the first direct measurement of the mass difference between a quark and its antiquark [14]. The measurement is performed in the $\ell+$jets channel using the 2002–2006 data set, comprising about 1 fb^{-1}.

The method is an extension of the matrix element method described earlier. The matrix element of (2) is modified so that the top and antitop quark masses are specified separately. For this analysis, the jet energy scale factor JES is fixed to that determined from the mass measurement. Thus, instead of (m_t, JES), we now extract $(m_t, m_{\bar{t}})$; or equivalently $(\Delta m, m_{\mathrm{sum}}) = (m_t - m_{\bar{t}}, (m_t + m_{\bar{t}})/2)$. The leptonically-decaying top quark in each event is identified as either a quark or antiquark based on the sign of the lepton. A modified version of PYTHIA [15] is used to simulate signal events with $m_t \neq m_{\bar{t}}$.

Fig. 3 shows the analysis calibration and fits to data. Combining the electron and muon channels yields $\Delta m = 3.8 \pm 3.4$ (stat.) GeV and $m_{\mathrm{sum}} = 170.9 \pm 1.5$ (stat.) GeV. The mass previously measured from this data sample was 170.6 ± 2.2 (stat.+JES) GeV [16].

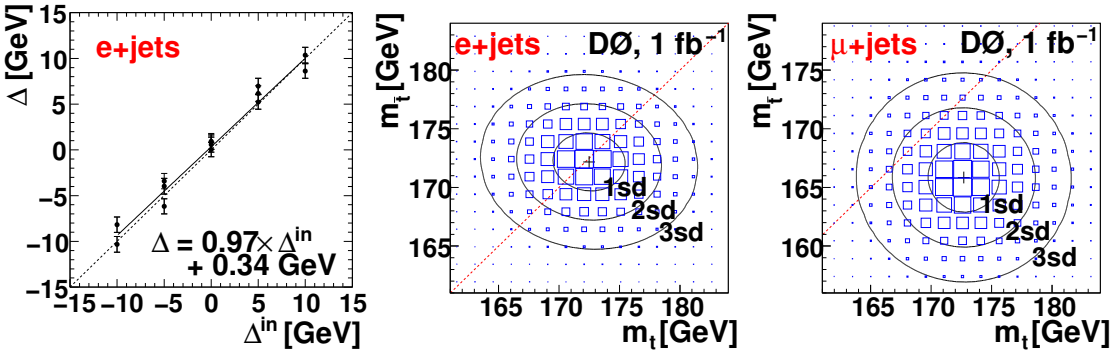

FIGURE 3. Left: Calibration curve from simulated experiments for the mass difference analysis for the $e+$jets channel. Middle and right: Fits to data.

Systematic uncertainties are summarized in Table 2. Most are common with the mass measurement analysis; they tend, however, to cancel in the difference. Many systematics are dominated by the statistics of the samples used to evaluate them. Two sources of systematics are new for this analysis. First is the uncertainty due to mismeasurements of the sign of the electron. This is evaluated by increasing the mismeasurement rate in Monte Carlo to match that seen in data. Second is the asymmetry in the calorimeter response to jets from b and $\bar{b}$ quarks. This systematic is limited by statistics.

The total systematic uncertainty for the Δm measurement is 1.2 GeV, giving a final result from 1 fb^{-1} of data of $\Delta m = 3.8 \pm 3.7$ GeV.

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