DØnote 5152-CONF

Measurement of the Top Quark Mass in the Dilepton Channel

The DØ Collaboration
URL http://www-d0.fnal.gov
(Dated: July 2, 2006)

We present a measurement of the top quark mass in the dilepton channel based on about 370 pb^{-1} of data collected by the DØ experiment during Run II of the Fermilab Tevatron collider. We employ two different methods to extract the top quark mass. We show that each method used obtains consistent results using ensemble tests of events generated with the DØ Monte Carlo simulation. We combine the results from both methods to obtain $m_t = 178.1 \pm 8.2$ GeV. The statistical uncertainty is 6.7 GeV and the systematic uncertainty is 4.8 GeV.

I. INTRODUCTION

The top quark mass is an important parameter in standard model[1] predictions. Loops involving top quarks provide the dominant radiative corrections to the value of the W boson mass[2], for example. Precise measurements of the W boson and top quark masses provide a constraint on the Higgs boson mass.

The measurement in the dilepton channel is statistically limited. It provides an independent measurement of the top quark mass that can be compared with the measurements in other $t\bar{t}$ decay channels, and a consistency check on the $t\bar{t}$ hypothesis in the dilepton channel.

II. THE DØ DETECTOR

The DØ detector is a typical multipurpose collider detector[3]. The central tracker employs silicon microstrips close to the beam and concentric cylinders covered with scintillating fibers in a 2 T axial magnetic field. The liquid-argon/uranium calorimeter is divided into a central section covering $|\eta| \leq 1$ and two end calorimeters extending coverage to $|\eta| \leq 4$ [4]. The muon spectrometer consists of a layer of tracking detectors and scintillation trigger counters between the calorimeter and 1.8 T toroidal magnets, followed by two similar layers outside the toroids.

III. EVENT SELECTION AND DATA SAMPLES

The event selection was developed for the measurements of the cross-section for $t\bar{t}$-production in the dilepton channel[5]. The analyses use about 370 pb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV collected with the DØ detector at the Fermilab Tevatron collider. All jets were corrected using the standard DØ jet energy scale corrections.

We select events with two well identified isolated leptons (μ or e) with transverse momentum $p_T > 15$ GeV and at least two jets with $p_T > 20$ GeV. Depending on the flavor of the leptons we distinguish $e\mu$, ee, and $\mu\mu$ events. For $e\mu$ events we require $H_T > 122$ GeV, where H_T is the scalar sum of the larger of the two lepton p_Ts and the p_Ts of the leading two jets. For ee events we require sphericity[6] > 0.15 and missing transverse momentum $\not{p}_T > 35$–40 GeV, depending on the dielectron invariant mass $m(ee)$, and we reject events with $80 < m(ee) < 100$ GeV. For $\mu\mu$ events we require inconsistency with $Z \to \mu\mu$ based on a χ^2 test, $\Delta\phi(\mu, \not{p}_T) < 175^o$. and $\not{p}_T > 35$ GeV. We tighten the $\not{p}_T$ requirement if the leading muon and $\not{p}_T$ are approximately collinear in the transverse direction.

TABLE I: Expected and observed dilepton event yield.

sample	$t\bar{t}$	WW	Z	fakes	data
no-tag	7.2	1.1	2.6	2.2	12
b-tag	9.9	0.05	0.12	0.9	14
tight	15.8	1.1	2.4	0.5	21
ℓ+track	11.3	0.02	4.4	0.4	15

For our mass measurements we use the following samples of events. The "b-tag" sample consists of events with at least one jet with a secondary vertex tag with decay length significance $\Lambda_{xy} > 7$[7]. This sample has very low backgrounds. The "no-tag" sample consists of events that have no such secondary vertex tags. The "tight" sample does not use the b-tagging information but applies a more restrictive electron selection for $e\mu$ events in order to reduce the backgrounds. All events in the tight sample are also either in the b-tag or the no-tag samples.

To increase the acceptance for dilepton decays we also analyze a looser selection that requires only one well-identified lepton (μ or e) with $p_T > 15$ GeV and an isolated track with $p_T > 15$ GeV instead of the second lepton. The events must also have at least two jets with $p_T > 20$ GeV, at least one jet with a secondary vertex tag, and $\not{p}_T > 15$–35 GeV, depending on lepton flavor (μ,e) and the invariant mass of the lepton+track system. We call this the ℓ+track sample. Events with two well-identified leptons are vetoed from this sample so that there is no overlap between the ℓ+track sample and the other dilepton samples.

For the mass analysis we also reject two events found to be kinematically inconsistent with the $t\bar{t}$ hypothesis. The expected and observed event yields for each of the data samples are listed in Table I.

Monte Carlo samples were generated for nineteen values of the top quark mass between 120 and 230 GeV. The simulation uses ALPGEN[8] as the event generator, PYTHIA[9] for fragmentation and decay, and GEANT[10] for the detector simulation. The scale of Monte Carlo jets was increased by 3.4% on top of the nominal jet energy scale corrections. This factor was determined to make the invariant mass of the two jets from the W boson decay in lepton+jets events agree with the known W boson mass[11].

IV. MASS ANALYSIS PROCEDURE

We use only the two jets with the highest p_T in this analysis. We assign these two jets to the b and $\overline{b}$ quarks from the decay of the t and $\overline{t}$ quarks. If we assume a value m_t for the top quark mass, we can determine the pairs of t and $\overline{t}$ momenta that are consistent with the observed lepton and jet momenta and missing p_T. We call a pair of top-antitop quark momenta that is consistent with the observed event a solution. We assign a weight w to each solution.

We consider each of the two possible assignments of the two jets to the b and $\overline{b}$ quarks. For each assignment of observed momenta to the final state particles, there may be up to four solutions for each hypothesized value of the top quark mass. We account for detector resolutions by repeating the weight calculation with input values for the lepton and jet momenta that are drawn from the detector resolution functions for objects with the observed momenta. We refer to this procedure as resolution sampling. For each event we obtain a weight $W(m_t) = 1/N \times \sum_{j=1}^{N} \sum_{i=1}^{n} w_{ij}$ by summing over all n solutions and averaging over N resolution samples. This weight characterizes the likelihood that the event is produced in the decay of a $t\overline{t}$ pair as a function of m_t.

The techniques we use are similar to those used by the DØ Collaboration to measure the top quark mass in the dilepton channel using Run I data[12]. The data are analyzed using two different methods that differ in the event samples that they are based on, in the calculation of the event weight, and in the algorithm that compares the weights for the observed events to Monte Carlo predictions to extract the top quark mass.

A. Matrix-Element Weighting Technique

The matrix-element weighting technique ($\mathcal{M}$WT) follows the ideas proposed by Dalitz and Goldstein[13] and Kondo[14]. The solution weight is

$$w = f(x)f(\overline{x})p(E^*_\ell|m_t)p(E^*_{\overline{\ell}}|m_t),$$

where $f(x)$ is the parton distribution function of the proton, x and $\overline{x}$ is the momentum fraction carried by the initial (anti)quark. The quantity $p(E^*_\ell|m_t)$ is the probability that the lepton has energy E^*_ℓ in the top quark rest frame for the hypothesized top quark mass m_t[13].

For each event we use the value of the hypothesized top quark mass m_{peak} at which $W(m_t)$ reaches its maximum as the estimator for the mass of the top quark. We generate probability density functions of m_{peak} for a range of top quark masses using Monte Carlo simulations. We call these distributions templates. To compute the contribution of backgrounds to the templates, we use $Z \to \tau\tau$ and WW events generated with the full DØ Monte Carlo. Backgrounds arising from detector signals that are mistakenly identified as electrons or muons (fakes) are estimated from collider data samples.

We compare the distribution of m_{peak} for the observed events to these templates using a binned maximum likelihood fit. The likelihood is calculated as

$$L(m_t) = \prod_{i=1}^{n_{\text{bin}}} \left[\frac{n_s s_i(m_t) + n_b b_i}{n_s + n_b} \right]^{n_i},$$

where n_i is the number of data events observed in bin i, $s_i(m_t)$ is the normalized signal template contents for bin i at top quark mass m_t, b_i is the normalized background template contents for bin i. The product runs over all n_{bin} bins. The background template consists of events from all background sources added in the expected relative proportions. The signal-to-background fraction is fixed to n_s/n_b with the numbers of signal and background events (n_s, n_b) taken from Table I.

In order to calibrate the performance of our method, we generate a large number of simulated experiments for several input top quark mass values. We refer to each of these experiments as an ensemble. Each ensemble consists of as many events of each type as we have in our collider data sample. A given event is taken from the signal and background samples with probabilities that correspond to the fraction of events expected from each sample. We use a quadratic function of m_t to fit the $-\ln L$ points to thirteen mass points centered on the point with the smallest value of $-\ln L$. The distribution of measured top quark mass values from the ensemble fits gives an estimate of the parent distribution of our measurement. The ensemble test results indicate that the measured mass tracks the input mass with an offset of 1.9 GeV, which we correct for in our result. The pull widths average to 0.98 and therefore we rescale the error obtained from the fit by this factor.

The $\mathcal{M}$WT analysis uses the no-tag and b-tag samples of events. Separating out the very low-background b-tagged events improves the precision of the result. The analysis is performed with separate templates for each of the three lepton-pair flavors and separate signal-to-background fractions for events without b-tag and ≥ 1 b-tags. The joint likelihood for all events is maximized for $m_t = 176.2 \pm 9.2$ GeV as shown in Figure 1. Figure 2 shows the distributions of m_{peak} from collider data compared to the sum of Monte Carlo templates with $m_t = 180$ GeV.

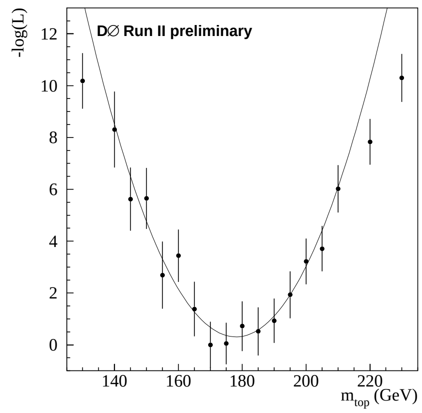

FIG. 1: Joint likelihood for all events from the $\mathcal{M}$WT analysis.

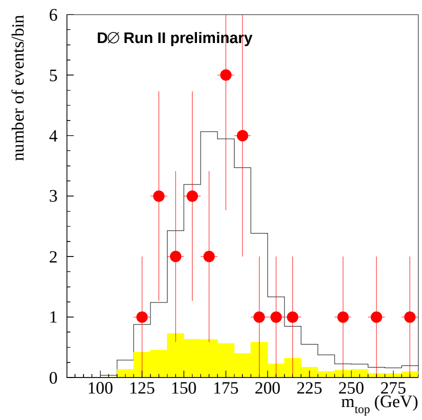

FIG. 2: Distribution of m_{peak} from the $\mathcal{M}$WT analysis of the compared to the sum of Monte Carlo templates for all channels for $m_t = 180$ GeV.

B. Neutrino Weighting Technique

The neutrino weighting technique (νWT) ignores the measured $\not{p}_T$ in reconstructing the event. Instead we assume a range of values for the pseudorapidities of the two neutrinos and the solution weight

$$w = \frac{1}{N} \sum_{i=1}^{N_\eta} \exp\left[\frac{-(\not{p}_{x_i} - \not{p}_x)^2}{2\sigma^2}\right] \exp\left[\frac{-(\not{p}_{y_i} - \not{p}_y)^2}{2\sigma^2}\right]$$

characterizes the consistency of the resulting solutions with the observed $\not{p}_T$. The sum is over the N_η sets of neutrino rapidity values, $\not{p}_{x_i}$ and $\not{p}_{y_i}$ are the x and y components of the sum of the neutrino momenta computed for set i, and σ is the measurement resolution for $\not{p}_x$ and $\not{p}_y$. We then normalize $W(m_t)$ over the range $80 < m_t < 330$ GeV and integrate it over ten bins in m_t. Every event is then characterized by a 9-component vector $\vec{W}$. We compare the vectors from the collider data events to sets of N Monte Carlo events generated with different values of m_t by computing the signal probability

$$f_s(\vec{W}|m_t) = \frac{1}{N}\sum_{i=1}^{N}\prod_{j=1}^{9}\frac{\exp[-(W_i - W_{ji}^{MC})^2/2h^2]}{\int_0^1 \exp[-(W' - W_{ji}^{MC})^2/2h^2]dW'},$$

where $\vec{W}_j^{MC}$ is the vector of weights from MC event j. The resolution parameter h is optimized using Monte Carlo studies. We compute a similar probability $f_b(\vec{W})$ for backgrounds and combine them in the likelihood

$$L(m_t, \overline{n}_b, n) = G(n_b - \overline{n}_b, \sigma)P(n_s + n_b, n)\prod_{i=1}^{n}\left[\frac{n_s f_s(\vec{W}_i|m_t) + n_b f_b(\vec{W}_i)}{n_s + n_b}\right]$$

which we optimize with respect to m_t, the number of signal events n_s and the number of background events n_b. G is a gaussian constraint on the difference between n_b and the expected number of background events $\overline{n}_b$, and P is a poisson constraint on $n_s + n_b$ to the number of events n observed in data.

The νWT analysis uses the tight sample and the ℓ+track sample. The analysis is performed with separate templates for all three lepton-pair flavors in the tight sample and the two lepton flavors in the ℓ+track sample. We fit the $-\ln L$ points for values of m_t within 20 GeV of the point with the smallest value of $-\ln L$ with a quadratic function of m_t. The performance of the νWT algorithm is checked using ensemble tests as described for the $\mathcal{M}$WT algorithm. The average measured values of m_t track the input values within 1-2%. For the νWT analysis, the joint likelihood of all events is minimized at $m_t = 179.5 \pm 7.4$ GeV (Fig. 3).

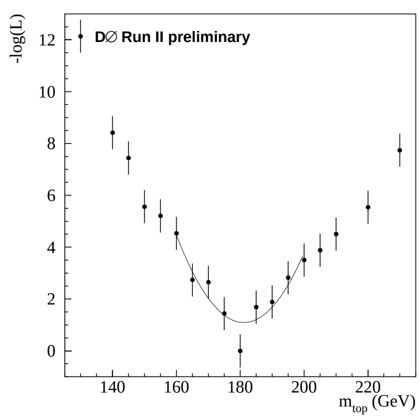

FIG. 3: Joint likelihood for all events from the νWT analysis.

We also use ensemble tests to study the size of systematic uncertainties (see Table II). All systematic uncertainties add in quadrature to 3.9 GeV. The uncertainty in the calibration of the jet energy scale of 4.1% gives rise to the dominant systematic uncertainty in the measurement.

V. RESULTS

We follow the method for combining correlated measurements from [15] in combining the results from the $\mathcal{M}$WT and νWT analyses. We determine the statistical correlation between the two measurements using ensemble tests. The correlation factor between the two analyses is 0.35. The systematic uncertainties from each source in Table II are taken to be completely correlated between the two analyses. The results of the combination are also listed in Table II.

In conclusion, we measure the top quark mass in the dilepton channel. We obtain $m_t = 178.1 \pm 6.7(stat) \pm 4.8(syst)$ GeV as our best estimate of the top quark mass. This is in good agreement with the world average $m_t = 172.5 \pm 2.3$ GeV[16], based on Run I and Run II data collected by CDF and DØ.

Acknowledgements

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP

TABLE II: Summary of dilepton mass measurements.

	$\mathcal{M}$WT	νWT	combined
top quark mass	176.2	179.5	178.1 GeV
statistical uncertainty	9.2	7.4	6.7 GeV
systematic uncertainty	3.9	5.6	4.8 GeV
jet energy scale	3.6	4.8	4.3 GeV
parton distribution functions	0.9	0.7	0.8 GeV
gluon radiation	0.8	2.0	1.5 GeV
background	0.2	1.4	0.9 GeV
heavy flavor content	—	0.6	0.3 GeV
calibration	—	0.2	0.1 GeV
template statistics	0.8	1.0	0.9 GeV
jet resolution	—	0.6	0.3 GeV
muon resolution	—	0.4	0.2 GeV
total uncertainty	10.0	9.3	8.2 GeV

and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); Research Corporation; Alexander von Humboldt Foundation; and the Marie Curie Program.

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