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MEASUREMENT OF THE TOP QUARK AND W BOSON MASSES

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We measure the top quark mass in $t\bar{t}$ events using up to 3.6 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV. New results are described for matrix element methods with single lepton and dilepton channels, and template methods with all-jets and dilepton channels. Standardization of systematic uncertainties has proceeded between the CDF and D0 collaborations. A combined measurement of 173.1 ± 0.6(stat) ± 1.1(syst) GeV is achieved. Fits to all measured electroweak parameters gives a Higgs boson mass 95% CL upper limit of $m_H < 163$ GeV. We also present a new measurement of the W boson mass from D0. Three different template methods are performed. Accounting for their correlations, a combined measurement of $M_W = 80.401 \pm 0.043(\mathrm{stat} + \mathrm{syst})$ GeV is obtained.

1 Introduction

The study of the top quark and W boson masses continues to be important in electroweak physics. Radiative corrections to the calculation of the W boson mass, M_W, include terms which are logarithmic in the Higgs mass, m_H, and vary as the square of the top quark mass, m_t. This allows a constraint on m_H from measurements of the other two parameters. Another source of interest in the top quark mass has been the peculiar unitary value of the corresponding Yukawa coupling, Y_t. As a result, the study of both the W boson and top quark masses are major goals of the Fermilab Tevatron program. I present recent measurements of both quantities in this paper.

Experimentally, the measurements are currently made exclusively at the Fermilab Tevatron by the D0 and CDF experiments. These are large, multipurpose collider detectors capable of low background particle identification for electrons and muons, and good momentum measurements for leptons, jets and $\not\!\!E_T$. Recorded data samples amount to 6 fb^{-1} per experiment. The measurement of m_t has been undergoing rapid improvements in precision over the last few years. Up to 3.6 fb^{-1} have been analyzed so far, which represents a ten-fold increase from data available just four years ago. Improved methods have permitted more precise measurements. Advances in the estimation of systematic effects have substantially reduced remaining uncertainties.

2 Methods of Top Quark Mass Measurement

In general, the methods used to measure the top quark mass fall into two categories (for exception, see Ref. [1]). Template methods fit a set of quantities, x_i, derived from event observables such as the measured kinematic quantities. The x_i are correlated with m_t and are compared to distributions expected from top quarks of varying mass. Often, template methods involve a kinematic reconstruction of the event by solving constraint equations, and then fitting to the solved top quark mass. Matrix element methods instead compare the observables, the x_i of this method, directly to expectations using a leading order (LO) matrix element calculation for $t\bar{t}$. In this way, event-by-event likelihoods are generated which use all of the kinematic information in an event. In each of these approaches, the background is accounted for by modeling the x_i. A probability of consistency vs. m_t is then achieved by accounting for $t\bar{t}$ and background:

$$P(x_i|m_t) = f_{top}P_{top}(x_i|m_t) + f_{bkg}P_{bkg}\,(x_i) \tag{1}$$

where P_{top} and P_{bkg} are signal and background probability densities based on x_i and a particular m_t. For matrix element approaches, P_{top} incorporates the $t\bar{t}$ matrix element. For a particular final state channel:

$$P_{top}(x_i|m_t) = \frac{1}{\sigma_{obs}(q\bar{q} \to t\bar{t} \to \text{channel}|m_t)} \times \int \sum dq_1 dq_2 f(q_1) f(q_2) \frac{(2\pi)|M|^2}{4\sqrt{(q_1 \cdot q_2)^2}} \cdot d\Phi_6 \cdot W(x_i, y) \tag{2}$$

where M is the LO matrix element, and $f(q)$ are the parton distribution functions.

The precision of the world average measurement of m_t has become dominated by systematic uncertainties. The calibration of jet energies particularly limits the achievable precision of the m_t measurement. However, top quark events offer an *in situ* dijet resonance in channels where $W \to q\bar{q}' \to jj$. As a result, measurements in these channels typically perform a simultaneous fit to the jet energy scale (through m_{jj}) and to m_t. This allows the top quark mass to be evaluated at the scale favored by the correct M_W, and the residual systematic uncertainty is reduced. Systematic uncertainties have been defined to facilitate measurement combinations. Dominant physics modeling uncertainties come from hadronization, underlying event, and the modeling of backgrounds. Major detector modeling uncertainties arise from the residual jet energy scale, and also the difference between b-jet and light-quark jet calibrations. Template methods can have significant uncertainty due to the statistical samples available for template generation.

3 All-hadronic Channel

In a $t\bar{t}$ event, both quarks are expected to decay to a W boson and a b quark. An all-hadronic ($6j$) final state results when both W bosons decay to quark pairs. Such a final state has an enormous background from QCD multijet production. This is ameliorated with the use of multiparameter discriminants and the tagging of b-jets by identification of their displaced decay vertices from long b hadron lifetimes. CDF has performed a mass analysis in 2.9 fb^{-1} of collider data using this channel [2]. To enhance their sensitivity, they have developed a further discriminant which separates quark jets from gluon jets. The resulting background reduction gives a 25% improvement in statistical uncertainty from the mass measurement.

The method of mass measurement proceeds by calculating dijet and three jet masses for each of the different assignments of jets to W bosons and b quarks. A χ^2 is calculated of these masses with respect to fitted top quark and W boson masses, as well as fitted momenta, given

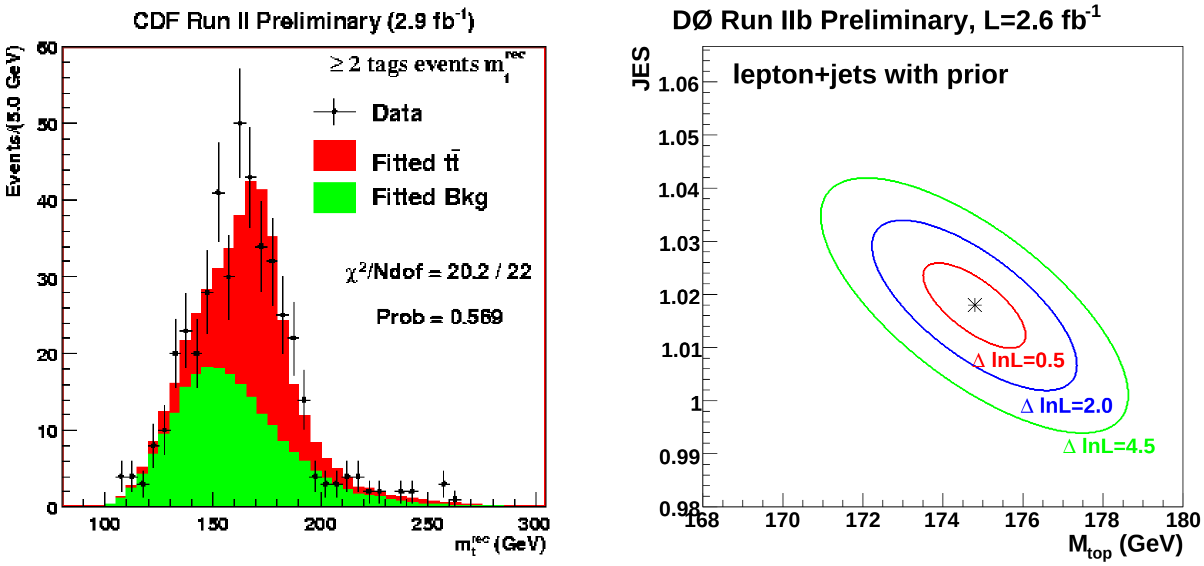

Figure 1: Left: CDF reconstructed m_t from $6j$ events. Fitted $t\bar{t}$ and background contributions are overlaid with data. Right: D0 fitted jet energy scale vs. m_t for ℓ+jets events. Contours of constant $\Delta\mathcal{L}$ are shown.

expected widths and resolutions of these parameters. The shapes of the reconstructed W boson and top quark masses are obtained by fitting shapes from the $t\bar{t}$ and background samples. These are used as templates to compare to data. The result of this fit is shown in Fig. 1. The use of the M_W constraint reduces the systematic uncertainty, but the residual jet energy scale is still a large contributor, along with color reconnection and residual bias errors.

4 Single Lepton Plus Jets Channels

Final states which provide high statistics but also reasonable background levels are those where at least one W boson from top quark decay itself decays to a lepton-neutrino ($\ell\nu$, where $\ell = e, \mu$) pair. These ℓ+jets events have been updated recently by both Tevatron experiments using matrix element approaches. D0 has selected events in 2.6 fb^{-1} of Run 2b data using a neural network b-tag selection[3]. For both the signal and background probabilities given in Eq. 1, matrix elements are used. As shown in Fig. 1, the fitted jet energy scale is 1.018 ± 0.007, which is consistent with the jet energy scale uncertainty from γ+jet events. The error is also within the expectation of pseudoexperiment tests from the Monte Carlo. The dominant systematic uncertainty comes from the relative b/light jet response uncertainty of 0.8 GeV.

Using 3.2 fb^{-1}, CDF has selected events with an exclusive four-jet selection[4]. One of these jets must satisfy a b-tag requirement. A neural network selection is performed based on 19 kinematic quantities using a quasi-Monte Carlo method to obtain uniformity in the integration. Not only is a clear separation between signal and background achieved, but the NN output is independent of top quark mass for the signal. In order to improve the mass resolution, the likelihood which comes from the mass fit is used to reject background and poorly reconstructed $t\bar{t}$ events. This is done by cutting out low peak likelihood events. The dominant uncertainty comes from the jet energy calibration.

5 Dilepton Channels

The rarest events occur when both W bosons decay to $\ell\nu$. Such dilepton (2ℓ) channels can usually attain low backgrounds without resort to b-tagging. However, there is no $W \to jj$ resonance

Table 1: Recent m_t measurements by CDF and D0 experiments. The D0 2ℓ entry combines the $e\mu$ matrix element and $ee/\mu\mu/\ell$+track template measurements. The last two entries give the combined result for each experiment for Run 1 plus Run 2 data.

Channel	Experiment	Luminosity	m_t (GeV)
$6j$	CDF	2.9 fb^{-1}	$174.8 \pm 2.4(\text{stat} + \text{JES})^{+1.2}_{-1.0}(\text{syst})$ [2]
ℓ+jets	D0	3.6 fb^{-1}	$173.7 \pm 0.8(\text{stat}) \pm 1.6(\text{syst})$ [3]
ℓ+jets	CDF	3.2 fb^{-1}	$172.1 \pm 0.9(\text{stat}) \pm 0.7(\text{JES}) \pm 1.1(\text{syst})$ [4]
2ℓ	D0	1-3.6 fb^{-1}	$174.7 \pm 2.9(\text{stat}) \pm 2.4(\text{syst})$ [5,6]
all	CDF	up to 3.2 fb^{-1}	$172.6 \pm 0.9(\text{stat}) \pm 1.2(\text{syst})$ [7]
all	D0	up to 3.6 fb^{-1}	$174.2 \pm 0.9(\text{stat}) \pm 1.5(\text{syst})$ [8]

with which to obtain an *in situ* calibration and reduce the jet energy scale uncertainty. In addition, there is an ambiguity of how the measured event $\not\!\!E_T$ corresponds to the two neutrino momenta. The dilepton analyses have been pursued in both template and matrix element approaches recently. Using $e\mu$ events in 3.6 fb^{-1} of data, D0 has employed matrix elements for both signal and background in the likelihood calculation [5]. For the latter, the largest $Z \to \tau\tau$ background is assumed for all backgrounds. This yields a measurement of $m_t = 174 \pm 3.3(\text{stat}) \pm 2.6(\text{syst})$ GeV. The main systematic uncertainties are the jet energy scale uncertainty, and the difference between b-jet and light quark jet energy scales. Hadronization and background modeling also play significant roles.

Template methods have also been recently finalized by D0 for the three standard dilepton channels (ee, $e\mu$, $\mu\mu$) plus two b-tagged channels with loosened lepton identification requirements (e/μ+track) [6]. Because the dilepton event is underconstrained due to the two neutrinos, the kinematic reconstruction supplies an input parameter. They sample assumed neutrino rapidity distributions to provide a relative weight vs. m_t. D0 uses the moments of the weight distribution in 1 fb^{-1} to extract $m_t = 176.2 \pm 4.8(\text{stat}) \pm 2.1(\text{syst})$ GeV. D0 has also applied a template method with the same sample using partial production and decay information. These two measurements combined give $m_t = 174.8 \pm 4.4(\text{stat}) \pm 2.0(\text{syst})$ GeV.

6 World Average and Electroweak Fits

The measured value of m_t for $6j$, ℓ+jets and 2ℓ channels is given in Table 1, incorporating combinations of Run 2a and 2b results. Combined measurements for each experiment using all Run 1 and Run 2 results are also indicated. The world average top mass determined from these is $173.1 \pm 0.6(\text{stat}) \pm 1.1(\text{syst})$ GeV [9], which corresponds to $Y_t = 0.995 \pm 0.007$. In the context of the electroweak model, fitting all measured electroweak parameters including m_t yields a new constraint of the Higgs boson mass of $m_H < 163$ GeV [10] at 95% CL. The most likely value is $m_H = 90^{+36}_{-27}$ GeV (see Fig. 2), to be compared with the direct LEP2 lower limit of 114.4 GeV.

7 Measurement of the W Boson Mass

The D0 experiment has completed a preliminary, precision measurement of the W boson mass. They use 499,830 $W \to e\nu$ events obtained from 1 fb^{-1} of collider data to perform three template analyses in parallel. These use the electron p_T, the $\not\!\!E_T$ and the transverse mass calculated from these two, $m_T = \sqrt{2p_T^e p_T^\nu(1 - \cos(\phi_e - \phi_\nu))}$. This measurement requires a precise calibration of the electromagnetic calorimeter, which is provided by the 18,725 $Z \to ee$ events in this data sample. A detailed modeling of the detector response to the recoiling system is also needed.

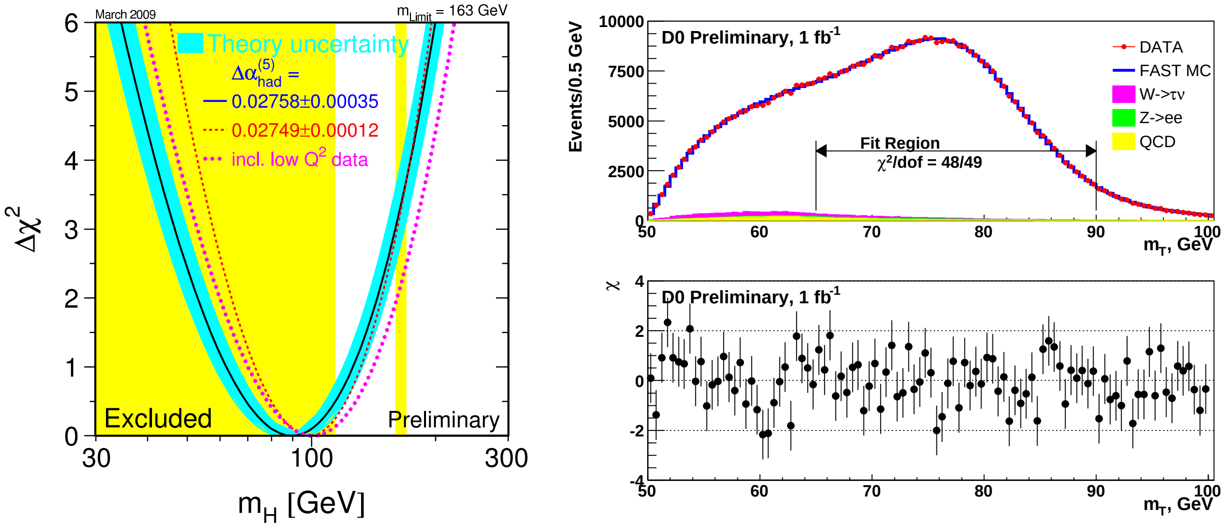

Figure 2: Left: Fit to m_H using electroweak constraints including the new world average m_t measurement. The $m_H < 163$ GeV limit, as well as the direct 95% c.l. exclusion band of $160 - 170$ GeV masses from Tevatron searches are indicated. Right: The fitted distribution of m_T in $W \to e\nu$ events in 1 fb^{-1} of D0 data. Residuals of the data relative to the fitted W boson template are shown at lower right.

The analysis proceeds by comparing the distribution of the template variables with high statistics distributions from models of signal and background. For signal, these are obtained in 10 MeV steps using RESBOS [11] and PHOTOS [12]. These templates must have 10^8 events each, so a tuned fast simulation of the detector is used. The $Z \to ee$ process is modeled in a similar fashion to facilitate a carryover of the electromagnetic calibration to the W events. A parametrized functional form for the Z boson reconstructed mass distribution is taken from GEANTed Monte Carlo samples and tuned to the data. The fit of the data to the templates in the mass range of 70 to 110 GeV yields the electron energy calibration scale and offset with $\chi^2/dof = 153/160$. Z boson events are also used to study the hadronic recoil to the W boson. A GEANTed Monte Carlo sample again provides the functional form for the detector response to the hard component. Contributions due to the spectator quarks and additional $p\bar{p}$ collisions are modeled by fitting to Z boson collider data. The backgrounds in this channel arise from $Z \to ee$ events where one electron is not identified, QCD instrumental background, and $W \to \tau\nu \to e\nu\nu$. These are modeled using an electron plus track control sample, a trigger sample with track requirements omitted, and a full GEANT Monte Carlo simulation, respectively.

The W boson mass is measured by blinding the data sample with an unknown offset for all three measurements simultaneously. The blinding was done to avoid bias by knowledge of the current world average value. The comparison of the data to the templates is performed, yielding good χ^2 for each measurement (e.g. m_T yielded $\chi^2/dof = 48/49$). Once the blinding was removed, a measurement was obtained for each method, as given in Table 2 and Fig. 2. The systematic uncertainties are dominated by a 34 MeV uncertainty due to the electron energy scale. The methods are somewhat decorrelated, and a combination yields $80.401 \pm 0.021(\text{stat}) \pm 0.038(\text{syst})$ GeV $= 80.401 \pm 0.043$ GeV [13]. This will be propagated into the world average W boson mass and electroweak fits soon.

8 Conclusions

Tevatron experiments have analyzed up to 3.6 fb^{-1} of collider data for top quark and W boson mass measurements. For the former, the all-jets channels are achieving 1.5% precision, the single leptons have surpassed the 1% precision, and even the rare dilepton events are providing

Table 2: Measurements of M_W using three different template variables. $W \rightarrow e\nu$ events in 1 $\text{fb}^{=1}$ of D0 data were used.

template variable	M_W (GeV)
m_T	$80.401 \pm 0.023(\text{stat}) \pm 0.037(\text{syst})$
$\not\!\!E_T$	$80.400 \pm 0.027(\text{stat}) \pm 0.040(\text{syst})$
p_T^e	$80.402 \pm 0.023(\text{stat}) \pm 0.044(\text{syst})$

2% precision to the top mass measurement. The world average is now $173.1 \pm 0.6(\text{stat}) \pm 1.1(\text{syst})$ GeV, which gives 0.7% precision. This update generates a new 95% CL upper limit on the Higgs boson mass of 163 GeV. The W boson mass has also been measured by D0 in the $e\nu$ channel, yielding the world's best measurement by a single experiment: $M_W = 80.401 \pm 0.043(\text{stat} + \text{syst})$ GeV.

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