Journal of Physics: Conference Series **110** (2008) 042014 doi:10.1088/1742-6596/110/4/042014

Top quark mass measurements at D0

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Abstract. We present the most recent measurements of the mass of the top quark at D0 using proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron collider. The world average for the mass of the top quark is 170.9 ± 1.8 GeV/c^2.

1. Introduction

The top quark was discovered in 1995 [1], and its mass has been measured with increasing precision ever since. The mass of the top quark (M_t) is an interesting quantity for several reasons. First, M_t is one of the fundamental parameters of the standard model (SM). Second, the mass of the W boson (M_W) depends quadratically on M_t, and would depend quadratically on the mass of a Higgs boson (M_H) if it exists. Therefore, precise measurements of M_t and M_W can constrain the possible values of M_H. In particular, smaller values of M_t would imply smaller values of M_H.

The mass of the top quark is measured in events where a pair of top quarks is produced by a $q\bar{q}$ or gg pair. Before the top quark can hadronize, it decays nearly exclusively into a W boson and a b quark. The W boson subsequently decays into either a quark-antiquark pair or a lepton-neutrino pair. The topology of the event is therefore determined by the decays of the W bosons. The W bosons may both decay leptonically (the dilepton channel), one hadronically and one leptonically (the lepton plus jets channel), or both hadronically (the all jets channel).

2. Dilepton channel

Dilepton events have two b quarks, two charged leptons and two neutrinos. A typical event selection then requires two jets, large missing transverse energy ($\not\!\!E_T$), and two high p_T leptons (where a lepton is either an electron or muon). The presence of two leptons in the events effectively rejects backgrounds, but the low W leptonic branching fraction results in a smaller number of events in the dilepton channel. Because dilepton events have two neutrinos that are not directly measured by the detector, the kinematics of the event are underconstrained.

2.1. Neutrino weighting method

For a range of M_t hypotheses, the neutrino weighting method chooses possible values of the pseudorapidity of the two neutrinos according to the expected distribution. The distribution of the pseudorapidity of the neutrinos is only weakly correlated with M_t. The kinematics of the event are solved for each choice of the neutrino pseudorapidities, and a weight is assigned to the event based on how well the calculated $\not\!\!E_T$ agrees with the measured $\not\!\!E_T$. This process is repeated many times, varying the jet and lepton energies within their experimental resolutions.

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For each event a distribution of weights as a function M_t is constructed, and the mean and RMS of the weight distribution is calculated. A signal probability distribution function (PDF) as a function of M_t, the mean and RMS, and a background PDF as a function of the mean and RMS, is calculated using Monte Carlo (MC). A seven variable likelihood (M_t, number of signal and background events in the ee, $e\mu$, and $\mu\mu$ channels) is then maximized to estimate the top quark mass. The likelihood is the product of three terms: one that accounts for the agreement of the number of background events with the background prediction, one that accounts for the agreement of the number of signal and background events with the total number of events in the sample, and one that accounts for the agreement of the data with the signal and background PDF shapes. This measurement uses 1050 pb^{-1} of data, and finds $M_t = 172.5 \pm 5.8(\text{stat.}) \pm 3.5(\text{syst.})\text{GeV}/c^2$ [2]. The systematic uncertainty is dominated by the uncertainty on the jet energy scale (JES).

2.2. Matrix weighting method

The matrix weighting method solves the event kinematics for a range of M_t hypotheses, then assigns a weight to the solution. The weight is the product of the parton distribution functions for the two incoming partons and of the probability to observe the lepton energies in the rest frame of the top quarks. As in the neutrino weighting method, this process is repeated while varying the jet and lepton energies within their experimental resolutions. A distribution of event weights versus M_t hypothesis is constructed, and the value of M_t where the weight distribution reaches its maximum is used as the estimator of the top quark mass. Templates are then built from signal and background MC samples, and the data is fit using these templates. Using 1 fb^{-1} of data, the matrix weighting method finds $M_t = 175.2 \pm 6.1(\text{stat.}) \pm 3.4(\text{syst.})\text{GeV}/c^2$ [3].

3. Lepton plus jets channel

Lepton plus jets events have two b quarks, two light quarks, a charged lepton and a neutrino. A typical event selection then requires at least four jets, large $\not\!\!E_T$ and one high p_T lepton. The lepton plus jets channel has a higher yield than the dilepton channel, but also has more background. The main sources of background are W+jets events and multijet events where one jet is misidentified as a lepton. Because the lepton plus jets channel has only one neutrino, the kinematics of the event is overconstrained. With four jets in the event, there are 12 possible jet-parton assignments. Analyses in the lepton plus jets also take advantage of b-tagging information to discriminate between light-quark jets and b-quark jets. b-tagging information is used both to improve the discrimination between signal and background and to weight jet-parton assignments that are more consistent with a $t\bar{t}$ hypothesis.

3.1. Matrix element method

The matrix element method tries to maximize the use of the kinematic information in the event (denoted x) by comparing it to the matrix elements for signal and background processes (denoted y). A signal probability is defined as

$$P_{sgn}(x; M_t, \text{JES}) = \frac{1}{\sigma} \sum w_i \int T(x, y, \text{JES}) d\sigma^n(y, M_t) f(q_1) f(q_2) dq_1 dq_2, \quad (1)$$

where T is the energy resolution of the jets and lepton, $d\sigma$ is the differential cross section, and f is a parton distribution function. The jet resolution is a function of an overall JES parameter that is constrained by the mass information from the hadronically decaying W boson. A similar probability is defined for the background, where the differential cross section does not depend on M_t and where T does not depend on JES. The ten dimensional integral in Eq. 1 is performed numerically on a grid of JES and M_t. An event probability is then

$$P_{evt} = f_{sgn}P_{sgn} + (1 - f_{sgn})P_{bkg}, \tag{2}$$

and the likelihood for the sample is the product of the per-event probabilities. The likelihood is maximized with respect to the signal fraction (f_{sgn}), M_t and JES. The likelihood also contains a gaussian constraint on the value of JES whose width is the average jet energy scale uncertainty on the jets in a $t\bar{t} \rightarrow$ lepton plus jets sample. The matrix element method uses about 900 pb^{-1} and measures $M_t = 170.5 \pm 1.8(\text{stat.}) \pm 1.6(\text{JES}) \pm 1.2(\text{syst.})\text{GeV}/c^2$ [4]. The likelihood for the electron plus jets channel is shown in Fig. 1.

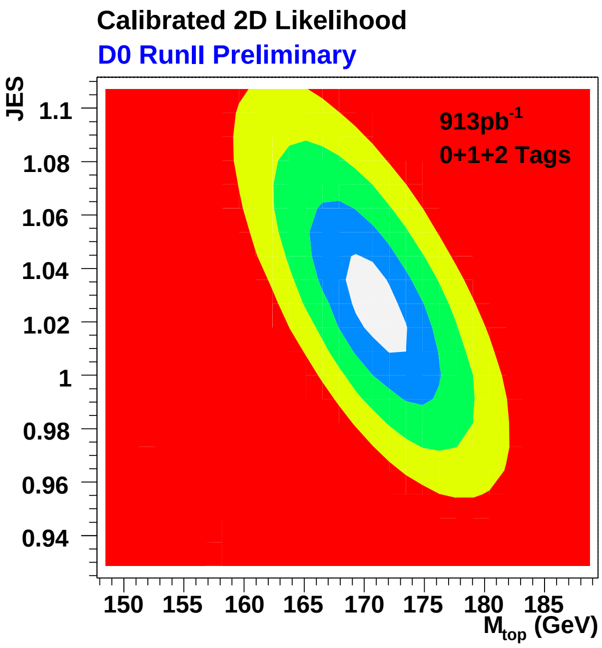

Figure 1. Likelihood for the electron plus jets channel as a function of JES and M_t using the matrix element method. The colors correspond to the 1, 2, 3 and 4 σ contours.

3.2. Ideogram method

The ideogram method uses a kinematic fit to determine the consistency of the event with a top quark hypothesis. A likelihood is calculated for every event:

$$L(M_t, \text{JES}) = P_{evt}\left\{\int \sum w_i G(m_i, m')BW(m', M_t)dm'\right\} + (1 - P_{evt})\sum w_i BG(m_i). \tag{3}$$

P_{evt} is the probability for the event to be signal, based on a low-bias discriminant. w_i is the weight for a given jet-parton permutation and is calculated using the χ^2 of the kinematic fit and the probability that the b-tagging information of the event agrees with the jet-parton assignment. $G \cdot BW$ accounts for the width of the top quark mass and the experimental resolution on the top quark mass. It includes terms for both correct and incorrect jet-parton assignments. BG is the shape of the top quark mass hypothesis for W+jets background. The product of the per-event likelihoods is maximized with respect to JES and M_t in a 425 pb^{-1} sample, giving a result of $M_t = 173.7 \pm 4.4(\text{stat.} + \text{JES}) \pm 2.1(\text{syst.})\text{GeV}/c^2$ [5].

4. Systematics

As data samples for the top quark mass measurement surpass the 1 fb^{-1} mark, the systematic uncertainty on the top quark mass is typically as large as the statistical uncertainty in the "golden" lepton plus jets channel. The jet energy scale uncertainty can be reduced with increasing statistics via the mass constraint from the hadronically decaying W boson. The remaining systematic uncertainties are typically of the order of a few hundred MeV/c^2. The systematic uncertainties for the matrix element method are shown in Table 1 as an example. Three points warrant emphasis. First, it is no longer sufficient to quote a single jet energy scale uncertainty. In order to reduce the uncertainty due to the jet energy scale, it is necessary to understand the individual components. Second, systematic uncertainties at the level of a few hundred MeV/c^2 are now significant, therefore it is important to verify that all uncertainties are properly accounted. Finally, as the number of sources of systematic uncertainties increases, there must be coordination between CDF and D0 to ensure that measurements from the two experiments can be properly combined.

Table 1. Systematic uncertainties for the matrix element method.

Source	Uncertainty (GeV/c^2)
Signal modeling	± 0.45
Bkgd modeling	± 0.15
PDF	$^{+0.26}_{-0.40}$
b fragmentation	± 0.54
b/c semileptonic	± 0.05
JES p_T dependence	± 0.23
b response (h/e)	± 0.57
Trigger	± 0.08
Signal fraction	$^{+0.53}_{-0.24}$
QCD fraction	± 0.21
MC calibration	± 0.07
b-tagging	± 0.29
Total	± 1.20

5. Conclusion

The D0 collaboration has made excellent progress on measuring the mass of the top quark. Sophisticated analysis techniques are being used to reduce the statistical uncertainty and leading systematic uncertainties. As data samples exceed 1 fb^{-1}, the measurement will be limited by the systematic uncertainties. The CDF and D0 collaborations have combined recent measurements and obtain a world average for the mass of the top quark $M_t = 170.9 \pm 1.1(\text{stat.}) \pm 1.5(\text{syst.})\text{GeV}/c^2$ [6].

References

[1] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74** (1995) 2626; D0 Collaboration, S. Abachi *et al.*, Phys. Rev. Lett. **74** (1995) 2632.
[2] D0 Collaboration, public note 5347, supersedes the result presented at the conference.
[3] D0 Collaboration, public note 5463, supersedes the result presented at the conference: D0 Collaboration, public note 5200.
[4] D0 Collaboration, public note 5362.
[5] V. M. Abazov *et al.*, D0 Collaboration, Phys. Rev. D **75**, 092001 (2007).
[6] CDF and D0 collaborations, FERMILAB-TM-2380-E (2007), hep-ex 0703034.