Direct measurement of the top quark mass in $p\bar{p}$ collisions at D0

Oleg Brandt*

on behalf of the D0 Collaboration

Universität Heidelberg, Kirchhoff-Institut für Physik, INF 227,
69120 Heidelberg, Germany
E-mail: oleg.brandt@kip.uni-heidelberg.de

The mass of the top quark is a fundamental parameter of the Standard Model and has to be determined experimentally. In these proceedings, I review recent direct measurements of the top quark mass in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the D0 experiment at the Tevatron. The measurements are performed in final states containing one and two charged leptons. I will present the legacy combination of all top quark mass measurements from the D0 experiment and their combination with results from the CDF experiment. A relative precision of down to 0.3% is attained.

*Speaker.

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1. Introduction

Since its discovery [1, 2], the determination of the top quark mass $m_t$, a fundamental parameter of the Standard Model (SM), has been one of the main goals of the CERN Large Hadron Collider (LHC) and of the Fermilab Tevatron Collider. Indeed, $m_t$ and masses of W and Higgs bosons are related through radiative corrections that provide a consistency check of the SM [3]. Furthermore, $m_t$ dominantly affects the stability of the SM Higgs potential [4]. With $m_t = 173.34 \pm 0.76$ GeV, a world-average combined precision of 0.44% has been achieved [5].

In the SM, the top quark decays to a W boson and a $b$ quark nearly 100% of the time. Thus, $t\bar{t}$ events are classified according to W boson decays as “dileptonic” ($\ell\ell$), “lepton+jets” ($\ell+\text{jets}$), or “all–jets”. In the following, I will present recent measurements in the former two channels; a full listing of $m_t$ results from the D0 can be accessed through Ref. [6].

2. Dilepton channel

The most precise single measurement of $m_t$ in the $\ell\ell$ channel at the Tevatron is performed by the D0 Collaboration using 9.7 fb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV [7]. The selection requires two isolated leptons ($e$ or $\mu$) of opposite charge, missing transverse momentum $E_T^{\text{miss}}$ due to neutrinos, $\geq 2$ jets, where at least one of which is identified as originating from a $b$ quark ($b$-tagged), and other topological selection. Leaving $m_t$ as a free parameter, $\ell\ell$ final states are kinematically under-constrained by two degrees of freedom. In this analysis, distributions in rapidities of the neutrino and the antineutrino are postulated, and a weight is calculated, which depends on the consistency of the reconstructed $\vec{p}_T^{\nu\bar{\nu}} \equiv \vec{p}_T^{\nu} + \vec{p}_T^{\bar{\nu}}$ with the measured missing transverse momentum $E_T^{\text{miss}}$ vector, as a function of $m_t$. D0 uses the first and second moment of this weight distribution to define templates and extract $m_t$, as shown in Fig. 1 (a) for the first moment $\mu_w$. To reduce the systematic uncertainty, the in situ jet energy scale (JES) calibration in the $\ell+\text{jets}$ channel derived in Ref. [10] is applied, accounting for differences in jet multiplicity, luminosity, and detector ageing. The final result reads $m_t = 173.32 \pm 1.36$(stat) $\pm 0.85$(syst) GeV. The dominant systematic uncertainties come from the knowledge of the absolute JES (0.47 GeV) and its flavour-dependence (0.36 GeV), and higher order effects on the signal modelling (0.33 GeV).

![Figure 1](image-url)
The top quark mass is also extracted using the matrix element (ME) technique using the same data and a similar selection in the $\ell\ell$ channel [8]. This technique determines the probability of observing a given event under both the $t\bar{t}$ signal and background hypotheses, as a function of $m_t$ [9]. This probability is calculated ab initio using the respective MEs of the $t\bar{t}$ signal and dominant $Z$+jets background, taking into account effects from parton showering (PS), hadronisation, and finite detector resolution. In this analysis, a SM prior is assumed for the transverse momentum distribution of the $t\bar{t}$ system, and the neutrino momenta are integrated over to overcome the challenge of the kinematically underconstrained system. After constraining the JES using $\ell$+jets channel results [10], $m_t = 173.93 \pm 1.61$(stat) $\pm 0.88$(syst) GeV is obtained, as shown in Fig. 1 (b). The systematic uncertainty is dominated by the knowledge of the absolute JES (0.46 GeV) and its flavour-dependence (0.30 GeV), $b$ quark jet identification ($b$-tagging, 0.28 GeV), and hadronisation modelling (0.32 GeV).

3. Lepton+jets channel

The most precise single measurement of $m_t$ from the Tevatron is performed by the D0 Collaboration using $9.7$ fb$^{-1}$ of data in the $\ell$+jets channel [10] with a ME technique. The analysis was performed blinded in $m_t$. This selection requires the presence of one isolated lepton, $E_T^{\text{miss}}$, and exactly four jets with at least one $b$-tag. A new JES calibration from exclusive $\gamma$+jet, $Z$+jet, and dijet events is applied to account for differences in detector response to jets originating from a gluon, a $b$ quark, and $u,d,s$, or $c$ quarks. The overall JES $k_{\text{JES}}$ is calibrated in situ by constraining the reconstructed invariant mass of the hadronically decaying $W$ boson to $M_W = 80.4$ GeV. The likelihood over all candidate events is maximised in $(m_t, k_{\text{JES}})$ as shown in Fig. 2 (a), and $m_t = 174.98 \pm 0.58$(stat+JES) $\pm 0.49$(syst) GeV is obtained.

The estimation of systematic uncertainties is refined through an updated detector calibration, in particular improvements to the $b$-quark JES corrections [11], and using recent improvements in modeling the $t\bar{t}$ signal. Furthermore, the statistical component from limited number of MC events is eliminated by reducing the computation time of the ME technique by a factor of 90 [12].

![Figure 2](image.png)

Figure 2: (a) The likelihood in $(m_t, k_{\text{JES}})$ in the $\ell$+jets channel using the ME technique [10]. Fitted contours of equal probability are overlaid as solid lines. The maximum is marked with a cross. (b) Invariant mass of the $t\bar{t}$ system for best-fit values of $m_t$ and $k_{\text{JES}}$. In the ratio of data to SM prediction, the total systematic uncertainty is shown as a shaded band.
which results in a more precise estimation of systematic uncertainties. The dominant systematic uncertainties come from the modeling of higher-order corrections (0.15 GeV), hadronisation (0.26 GeV), and the knowledge of the JES dependence on its flavor (0.16 GeV) as well as kinematic properties of the jet not captured by \( k_{\text{JES}} \) (0.21 GeV).

4. Combined results

Measurements of \( m_t \) from D0 in a given channel in Runs I and II of the Tevatron are statistically combined, accounting for correlations between sources of systematic uncertainty. The final result reads \( m_t = 174.95 \pm 0.40 \text{(stat)} \pm 0.63 \text{(syst)} \text{ GeV} \) [13] with a \( p \)-value of 47%. A similar combination including \( m_t \) results from the CDF Collaboration in Runs I and II, as shown in Fig. 3, results in \( m_t = 174.30 \pm 0.35 \text{(stat)} \pm 0.54 \text{(syst)} \text{ GeV} \) [14], corresponding to a relative precision of 0.37% and a \( p \)-value of 46%.

Figure 3: Overview of recent \( m_t \) measurements at the Tevatron [14].

5. Conclusions

I presented recent measurements of \( m_t \), a fundamental parameter of the SM. The most precise single measurement at the Tevatron of \( m_t = 174.98 \pm 0.58 \text{(stat+JES)} \pm 0.49 \text{(syst)} \text{ GeV} \) is performed by the D0 Collaboration in the \( \ell + \text{jets} \) channel, corresponding to a relative precision of 0.43%. The combination with all other measurements from the D0 experiment results in \( m_t = 174.95 \pm 0.40 \text{(stat)} \pm 0.63 \text{(syst)} \text{ GeV} \). The Tevatron combination yields \( m_t = 174.30 \pm 0.35 \text{(stat)} \pm 0.54 \text{(syst)} \text{ GeV} \), which corresponds to a relative precision of 0.37%.
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References