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Precise measurements of the top mass and direct measurement of the mass difference between top and antitop quarks at DØ

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We report on measurements of the mass using dilepton and lepton+jet data collected with the D0 detector. These results are compared to the top mass extracted from the $t\bar{t}$ cross section using higher-order quantum chromodynamics calculations. We also present a direct measurement of the mass difference between top and antitop quarks (Δm) in lepton+jets $t\bar{t}$ final states using the "matrix element" method.

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1. Introduction

The top quark is the heaviest of the heretofore observed fundamental particles, with a mass m_t a factor ≈ 35 larger than the next heaviest fermion, the bottom quark. The Standard Model predicts a scalar Higgs field that couples to fermions in proportion to their masses and, as a consequence, the top quark is the fermion that interacts most strongly with the Higgs boson. The large value of m_t suggests therefore that the top quark contributes significantly to loop corrections, affecting, for example, the mass of the W boson [1].

The large mass of the top quark opens decay channels by weak interaction which include W bosons on mass shell. This yields to a large width [2] and a lifetime that is far shorter than the hadronization time, thereby providing a clean measurement of its mass and properties directly from its decay products.

The $p\bar{p}$ Tevatron Collider, operating with $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\text{TeV}$, produces top quarks either in $t\bar{t}$ pairs with a cross section of $\approx 8\,\text{pb}$ [3, 4], or singly together with a b quark or a W boson, with a cross section of $\approx 3\,\text{pb}$ [5]. The top quark decays with a branching fraction of $> 99\%$ into a b quark and a W boson. The decay products of the latter determine the experimental signature of the events.

The following sections describe recent DØ measurements related to the mass of the top quark: measurements of m_t, based on the Neutrino Weighting and Matrix Element methods, and their combination, and a measurement of the mass difference between the top quark and its antiparticle.

2. Measurement of the mass of top quark using Neutrino Weighting

This measurement is based on $t\bar{t} \to W^-\bar{b}W^+b \to \ell^+\nu_{\bar{\ell}}\ell^-\nu_\ell b\bar{b}$ decays, where the presence of two charged leptons ($\ell = e\,\text{or}\,\mu$) in the final state labels these as "dilepton" $t\bar{t}$ events. There are 18 unknown quantities characterizing the six fermions of known mass in the final state. Twelve constraints on these arise from the measured energies and directions of the two jets from the b quarks and of the two leptons. The value of the invariant mass of the two W bosons adds two constraints, and assuming the same mass for t and $\bar{t}$ adds another constraint. The three remaining unknowns can be chosen to be the value of that mass (M_t) and the rapidities of the neutrinos (η_ν and $\eta_{\bar{\nu}}$). We define a "weight" to quantify the degree of agreement of the calculated transverse momentum of the two neutrinos, $\vec{\not{E}}_T^{\,\text{calc}}$, with the measured imbalance in transverse momentum of the event, $\vec{\not{E}}_T^{\,\text{obs}}$:

$$w\left(\eta_\nu, \eta_{\bar{\nu}}, M_\text{t}\right) = \mathrm{e}^{-\left(\frac{\not{E}_x^\text{obs} - \not{E}_x^\text{calc}}{\sqrt{2}\sigma_x^u}\right)^2} \mathrm{e}^{-\left(\frac{\not{E}_y^\text{obs} - \not{E}_y^\text{calc}}{\sqrt{2}\sigma_y^u}\right)^2}$$

where the weight is also function of the resolution of each component of $\vec{\not{E}}_T^{\,\text{obs}}$, σ_x^u and σ_y^u. The dependence on η is resolved by convolving the weight with probability distributions $\rho\left(\eta_{\nu/\bar{\nu}}\right)$, extracted from the Monte Carlo simulation (MC) of $t\bar{t}$ events:

$$w\left(M_\text{t}\right) = \int w\left(\eta_\nu, \eta_{\bar{\nu}}, M_\text{t}\right) \rho\left(\eta_\nu\right) \rho\left(\eta_{\bar{\nu}}\right) \,\mathrm{d}\eta_\nu \,\mathrm{d}\eta_{\bar{\nu}}$$

Each event i is characterised by its weight function $w(M_\text{t})$ through the weight average (μ_w^i) and RMS (σ_w^i), and is represented by these two values.

We simulate in the MC the $t\bar{t}$ signal process assuming different masses m_t of the top quark, and the most important background processes. For each of the MC samples, we form the probability for an event from this process to have specific $(\mu_w; \sigma_w)$ values, from which we obtain total background (h_{bkg}) and signal ($h_{\text{sig}}(m_{\text{t}})$) expected distributions, corresponding to assumed m_t (Fig. 2). These distributions are called "templates."

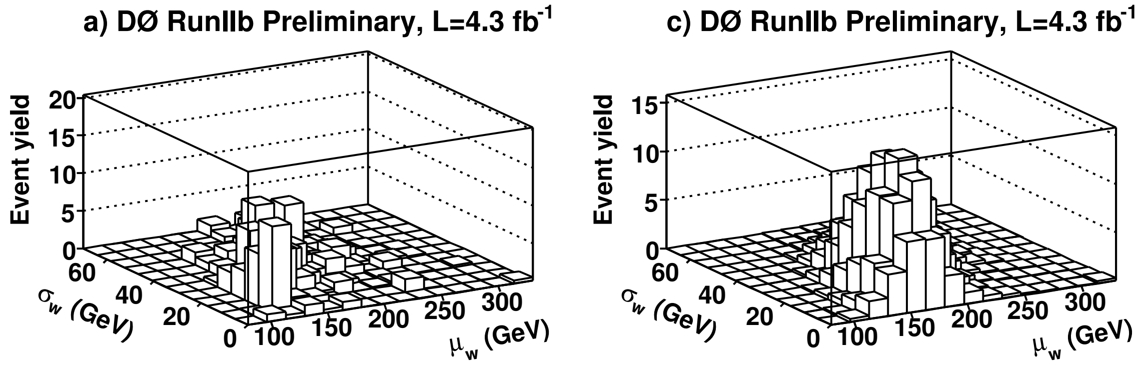

Figure 1: MC templates (h) for background and for signal (with $m_t = 175\,\text{GeV}/c^2$).

The estimator $\hat{m}_{\text{t}}$ of the top mass is extracted by comparing the distribution h_{data} for the DØ data with MC templates as function of m_t. The likelihood of a given m_t hypothesis includes the probability of each observed event to be from the signal or background processes:

$$L(m_{\text{t}}) = \prod_{i=1}^{N} f\, h_{\text{sig}} \left(\mu_w^{(i)}, \sigma_w^{(i)}; m_t \right) + (1-f)\, h_{\text{bkg}} \left(\mu_w^{(i)}, \sigma_w^{(i)} \right)$$

The two probabilities are combined through a fixed signal fraction f extracted from the simulation. The minimization of $-\log L(m_{\text{t}})$ then yields the estimator $\hat{m}_{\text{t}}$ (Fig. 2, *left*).

All analysis methods rely on approximations that can bias the result. To reduce the bias, a calibration is performed based on simulated "pseudo-experiments". Thousands of such experiments are formed from events simulated under different hypotheses on m_t, reproducing the size and composition of the observed data. The analysis is performed on each MC experiment, establishing the relation between the hypothesized m_t and the measured $\hat{m}_{\text{t}}$. This relation is found to be linear (Fig. 2, *right*) and is used to correct the measurement.

The Neutrino-Weighting method was applied to $4.3\,\text{fb}^{-1}$ of DØ data [6]. For this measurement, events are required to have one electron and one muon reconstructed with opposite electric charge. The dominant background processes are from electroweak production of single Z boson (with $Z \to \tau^+\tau^-$ and $\tau \to \ell \nu_\ell \nu_\tau$) and W^+W^-, both in association with jets, and from misreconstructed multijet events. The selected sample consists of 202 events, with an estimated signal fraction of $\approx 85\%$. The measured mass is: $m_t = 172.7 \pm 2.8(\text{stat}) \pm 2.1(\text{syst})\,\text{GeV}/c^2$. The dominant sources of systematic uncertainty are the energy scale of jets, both absolute ($1.4\,\text{GeV}/c^2$) and of jets from b quarks relative to jets from light quarks ($0.5\,\text{GeV}/c^2$), and the modelling of the $t\bar{t}$ signal ($1.0\,\text{GeV}/c^2$).

Combining this result with a previous one based on $1.0\,\text{fb}^{-1}$ of data, for $5.3\,\text{fb}^{-1}$ of DØ data we obtain a mass of the top quark of

$$m_t = 173.3 \pm 2.4(\text{stat}) \pm 2.1(\text{syst})\,\text{GeV}/c^2$$

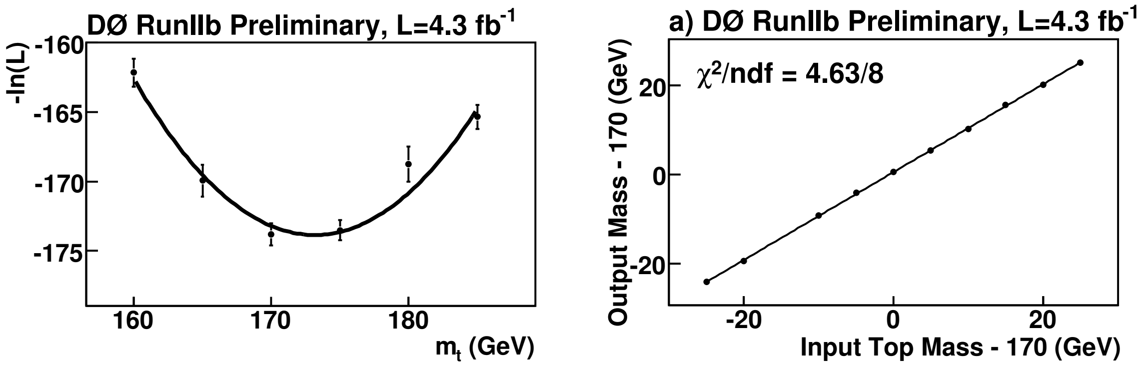

Figure 2: *(left)* likelihood and *(right)* calibration of the Neutrino-Weighting method.

3. Measurement of the mass of top quark using the Matrix-Element method

The scattering matrix for any process contains the complete information of its kinematics and can therefore be used to compare different hypotheses given the observed kinematics.

The core probability used in the Matrix Element approach is defined as:

$$P(x;m_t) = \frac{1}{\sigma(m_t)} \int \sum f(q_1)\, f(q_2)\, \sigma(y,m_t)\, \mathscr{W}(x,y) \ \ \mathrm{d}q_1\, \mathrm{d}q_2 \ \ \mathrm{d}y$$

where the parameters include the mass of top quark m_t to be measured and includes *(i)* the probability $f(q_{1,2})$ of having a specific initial state (Parton Distribution Functions), *(ii)* a matrix element $\mathscr{M}$ for a transition to a final state with configuration "y", described by the 4-momenta of all the six particles, and *(iii)* the probability $\mathscr{W}$ (Transfer Functions) that the nascent final state "y" is reconstructed as our measured set of jets and lepton objects "x".

The sum runs over all the possible initial-state ($q_{1,2}$) flavours and over all the possible pairings of reconstructed jets with the quarks and gluons from the final state y. Thus, $P(x;m_t)$ corresponds is the probability for an event from a selected process to have the kinematics we measure (x).
To calculate the probability P_{evt} to observe an event with configuration x, we consider two hypotheses: the event originates from the $t\bar{t}$ signal, or from the main background process:

$$P_{\mathrm{evt}}(x;m_t,f) \propto A(x)\left[f\,P_{\mathrm{sig}}(x;m_t) + (1-f)\,P_{\mathrm{bkg}}(x)\right]$$

We combine the two probabilities through the fraction f of signal events in our sample, and we include detector acceptance effects in $A(x)$.

We analyse events with the "dilepton" signature introduced in Sec. 2, extended to include events with two electron, two muons or an electron and a muon. We consider the signal process $t\bar{t} \to b\bar{b}\ell^+\nu_\ell\ell^-\bar{\nu}_\ell$, and the main background process, $Z + 2\,\mathrm{jets}$ with the decay $Z \to \ell^+\ell^-$ (for the $e\mu$ signature, only $Z \to \tau^+\tau^-$ as described in Sec. 2, with an additional transfer function to describe the τ decays). The matrix element for the signal process is computed analytically at Leading Order (LO), and it depends on the mass of the top quark. The matrix element for the chosen background is computed numerically (at LO) through VECBOS [7].

The event probabilities are combined in a sample likelihood:

$$L(\{x_i\};f,m_t) = \prod_i P_{\mathrm{evt}}(x_i;f,m_t)$$

The likelihood is evaluated numerically as a function of f and m_t. The maximization with respect to the parameters yields to an estimate of the mass; any bias is minimized by calibration as described in Sec. 2 (Fig. 3, *left*).

We have analysed $5.4\,\mathrm{fb}^{-1}$ of DØ data [8], selecting 73 ee, 266 $e\mu$ and 140 $\mu\mu$ events. We measure a mass (Fig. 3, *left*) of:

$$m_t = 174.0 \pm 1.8(\mathrm{stat}) \pm 2.4(\mathrm{syst})\,\mathrm{GeV}/c^2$$

The largest systematic uncertainties are same as in the Neutrino Weighting: energy scale for jets, both absolute ($1.5\,\mathrm{GeV}/c^2$) and relative for b quarks with respect to light quarks ($1.6\,\mathrm{GeV}/c^2$), and modelling of $t\bar{t}$ signal ($0.8\,\mathrm{GeV}/c^2$).

The Matrix-Element method has been applied also on a selection of events with only one electron or muon, and 4 jets ("lepton+jets"). At least one of the jets must be tagged as arising from a quark b. The main signal process is $t\bar{t} \to b\bar{b}q\bar{q}'\ell\nu_\ell$, and we choose the dominant background process of $W + 4\,\mathrm{jets}$ for the background probability.

Compared to the analysis described above for "dilepton" events, additional information is carried by the boson W decaying into quarks, that can be exploited.

We add a new parameter k_{JES} to the transfer functions for jets, to allow for a global shift of the jet energies, with constraint from the narrow width and known mass of the W boson. A global shift can be caused by the fact that the correction to the jet energy is extracted from γ+jet and two-jet events, making no distinction between jets generated by gluons and by quarks. This ignores the specificity of the analysed sample, and is normally covered by the systematic uncertainty. The k_{JES} parameter provides a recalibration (*in situ*) of the jet energy specific to the analysed sample.

The analysis of $2.6\,\mathrm{fb}^{-1}$ of DØ data [9] yields to a mass of $m_t = 176.0 \pm 1.3(\mathrm{stat{+}JES}) \pm 1.0(\mathrm{syst})\,\mathrm{GeV}/c^2$ (Fig. 3, *right*) from a selection of 312 events with an electron and 303 with a muon. The dominant sources of systematic uncertainty are the modelling of $t\bar{t}$ signal ($0.74\,\mathrm{GeV}/c^2$), the resolution on jet energy (0.32), the jet energy in simulation relative to data (0.28) and jet identification (0.26).

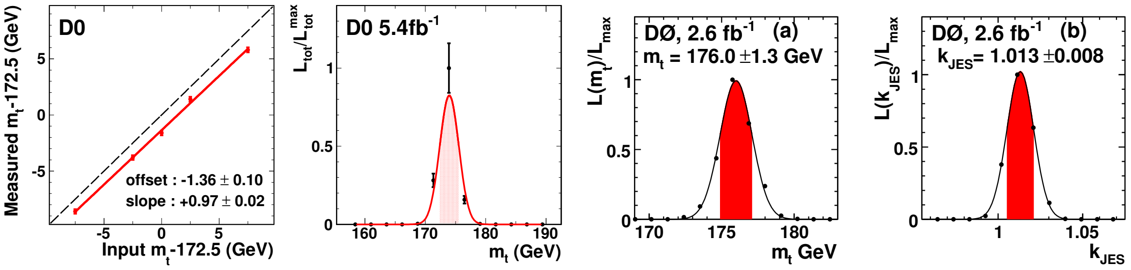

Figure 3: Calibration and likelihood for the "dilepton" sample using the Matrix-Element method. Relative likelihood of the mass of top quark and jet energy calibration for the "lepton+jet" sample using the Matrix-Element method.

Combining this with our previous result on $1.0\,\mathrm{fb}^{-1}$, we find

$$m_t = 174.9 \pm 1.1(\mathrm{stat{+}JES}) \pm 1.0(\mathrm{syst})\,\mathrm{GeV}/c^2$$

PoS(EPS-HEP2011)351

4. Combination of measurements of the mass of the top quark from DØ

We have combined the measurement of the mass of the top quark from up to 5.4 fb^{-1} DØ data including analyses of events with one lepton, two leptons and one lepton and an isolated track. The correlation among the measurements is taken into account by using the Best Linear Unbiased Estimator technique [10]. This yields a measurement of the mass of the top quark from DØ [11] of

$$m_t = 175.08 \pm 0.77(\text{stat}) \pm 1.25(\text{syst})\,\text{GeV}/c^2$$

5. Measurement of the difference of mass of t and $\bar{t}$

Lorentz-invariant, local quantum-field theories, such as the Standard Model, are invariant under CPT transformations. A consequence of this invariance is that each particle and its antiparticle must have the same mass. This has been confirmed by experiments for many elementary and even composite particles, e.g. electrons, pions, kaons, nucleons and heavy baryons. On the other hand, this difference can't be measured for light quarks, as they create bound states before they can be detected. The top quark is the exception, in that it decays before binding. From the decay products of the top quark it is possible to measure more directly characteristics of the $t\bar{t}$ pair, such as the correlation of their spin and the difference in their mass.

The Matrix-Element method has been adapted to measure the difference in mass between the top quark and antiquark. This analysis is based on the same selection of events as in the measurement described in Sec. 3 for events with one lepton and jets. The event generator PYTHIA [12] has been modified to generate quarks t and $\bar{t}$ of different mass, while leaving all other characteristics the same. The event probability is now function of the two independent masses, m_t and $m_{\bar{t}}$, which are rotated into the difference $m_t - m_{\bar{t}}$ and average value $m_{\text{top}} = \frac{m_t + m_{\bar{t}}}{2}$. The *in situ* calibration from the former measurement is not used in this study.

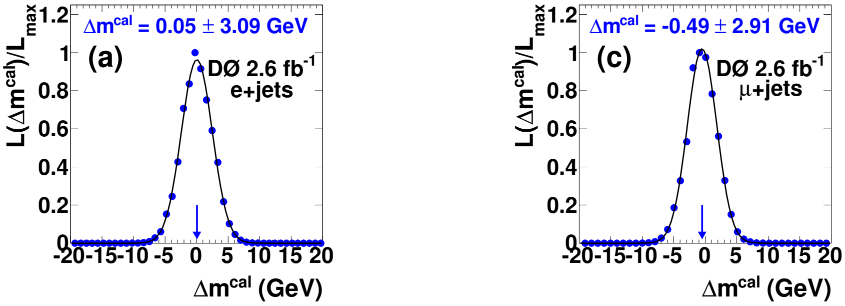

Figure 4: Relative likelihood of the mass difference $\Delta m = m_t - m_{\bar{t}}$ from events with *(left)* an electron and *(right)* a muon.

The analysis of 2.6 fb^{-1} of DØ data [13] yields to a mass difference: $m_t - m_{\bar{t}} = -0.2 \pm 2.1(\text{stat}) \pm 0.5(\text{syst})\,\text{GeV}/c^2$ (see Fig. 5 for results separately for events with e and μ), which combined with the previous result on 1.0 fb^{-1} of DØ data yields:

$$m_t - m_{\bar{t}} = 0.84 \pm 1.81(\text{stat}) \pm 0.48(\text{syst})\,\text{GeV}/c^2$$

6. Summary

The mass of the top quark is an important parameter of the Standard Model. Constant improvements in the analyses, and increases in the amount of available data, have achieved a precision on m_t of $< 1\%$ for DØ alone, and at the threshold of $1\,\mathrm{GeV}/c^2$, when combined with the CDF measurement. The results presented here rely on up to $5.4\,\mathrm{fb}^{-1}$ of data, while almost twice as much data is now recorded at both DØ and CDF. However, the measurement is already limited by systematic uncertainties, which are the current challenge. The measurements from different selections are all consistent, and also the difference between t and $\bar{t}$ masses is within expectations of CPT invariance.

We have presented measurements based on the direct reconstruction of the mass of the top quark from its decay products, which achieve remarkable precision, calibrated through simulation. This binds the interpretation of our m_t measurement to its interpretation in the simulation. DØ has also performed an indirect measurement [14], exploiting the dependence of the production cross section of $t\bar{t}$ on the mass, which compares different hypotheses on the nature of the measured mass.

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