D0 top quark mass and properties

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We present measurements of the top quark mass, the top quark width and the ratio, f, of events with correlated t and $\bar{t}$ spins to the total number of $t\bar{t}$ events. The analyzed $p\bar{p}$ collision data correspond to an integrated luminosity of 5.3-5.4 fb^{-1} collected by the D0 Collaboration at the Tevatron Collider. The top quark mass is measured in the dilepton final state resulting in $m_t = 174.0 \pm 2.4(\text{stat})\pm 1.4(\text{syst})$ GeV. The dominant systematic uncertainty from jet energy calibration is reduced by using a correction obtained from $t\bar{t} \to \ell$+jets events. The total width is extracted from the partial width $\Gamma(t \to Wb)$ and the branching fraction $B(t \to Wb)$. The resulting width is $\Gamma_t = 2.00^{+0.47}_{-0.43}$. The ratio f is evaluated using a matrix-element-based approach in both the ℓ+jets and dilepton final state. The combination provides evidence for the presence of spin correlation in $t\bar{t}$ events with a significance of more than 3 standard deviations.

1 Introduction

The top quark is the heaviest known elementary particle and completes the quark sector of the standard model (SM). It differs from the other quarks not only by its much larger mass, but also by its lifetime that is expected to be shorter than the QCD scale typical of the formation of hadronic bound states. Since the top quark decays through the electroweak interaction before it can interact through the strong interaction the spin orientation of the top quark at production is reflected in the angular distributions of the final state particles. This allows a measurement of the degree to which the spins of the top and antitop quarks are correlated, which is expected to be large in the SM.

In $p\bar{p}$ collisions, top quarks t are primarily produced in $t\bar{t}$ pairs, with each t quark decaying to a b quark with $\mathcal{B}(t \to Wb) \approx 100\%$. These events yield final states with either 0, 1, or 2 leptons from the decays of the two W bosons coming from $t\bar{t}$ decay. For the measurement of the t quark mass we consider the dilepton channel where the two leptons are electrons or muons. In addition the ℓ+jets channel, where the lepton is an electron or muon from a W boson and the second W boson decays to quarks, is used in the measurement of the degree to which the spins of the t and $\bar{t}$ quarks are correlated. The top quark width Γ_t is determined from a measurement in the dilepton and ℓ+jets channel as well as a measurement of the t-channel single top quark production cross section.

2 Event selection

The three analyses discussed in this note use common event selections for the three final states considered. In the dilepton final state events are selected to have two leptons (ee, $e\mu$, $\mu\mu$) and two or more jets. The leptons must have transverse momentum $p_T > 15$ GeV and the jets must satisfy $p_T > 20$ GeV. Electrons and jets are required to satisfy pseudorapidity $|\eta| < 2.5$, while muons must have $|\eta| < 2$. The $e\mu$ events must satisfy $H_T > 120$ GeV, where H_T is the sum of the p_T of jets and the leading lepton. In $\mu\mu$ and ee events, we further require $\not\!\!E_T$ to be significantly different from values typically found in the distribution from Z+jets events. Additionally, events in the $\mu\mu$ final state have to satisfy $\not\!\!E_T > 40$ GeV. These and all other selection criteria are detailed in [1].

In the ℓ+jets final state we require one isolated electron with $p_T > 20$ GeV and $|\eta| < 1.1$, or one isolated muon with $p_T > 20$ GeV and $|\eta| < 2.0$, as well as an imbalance in transverse momentum $\not\!\!E_T > 20(25)$ GeV for the e+jets (μ+jets) channel. In addition we require at least four jets with $p_T > 20$ GeV and $|\eta| < 2.5$; the jet with the largest transverse momentum must have $p_T > 40$ GeV. Full details are given in [2].

In order to measure the t-channel cross section events containing an isolated electron or muon, missing transverse energy and at least two jets are selected. Backgrounds is suppressed by requiring that one or two of the jets is identified as a b-jet. The discrimination between signal and background is further improved by employing multivariate analysis techniques as described in [3].

3 Measurement of the top quark mass

We analyze dilepton events using the neutrino weighting (νWT) approach. While the dilepton channel has low backgrounds, the small branching ratio into leptons means that m_t measurements from these events were statistically limited until recently [4]. Additionally, the dominant systematic uncertainty from jet energy calibration have been large compared to the ℓ+jets channel.

In ℓ+jets events two quarks originating from W boson decay yield a dijet mass signature that permits a precise calibration of jet energies [5]. Here we use the calibration obtained in the ℓ+jets channel to reduce this uncertainty. We carefully evaluate uncertainties arising from the use of this calibration in a different environment.

The consequence of two neutrinos being present in dilepton events is that the kinematics are under-constrained. The νWT technique is used to extract m_t [6]. To solve the event kinematics we integrate over the η distributions of the two neutrinos. By comparing the measured $\not\!\!E_T$ with the $\not\!\!E_T$ calculated from the assumed neutrino ηs we assign a weight to each sampling.

The probability distributions of the mean and RMS values (μ_W and σ_w) of the event weight distributions are constructed for background samples. For $t\bar{t}$ the probability distributions are generated as a function of μ_w, σ_w and m_t. We perform a binned maximum likelihood fit of the selected data events to these probability distributions.

The measurement is calibrated by performing the same extraction on pseudo experiments drawn from MC events. Systematic uncertainties are evaluated for jet energy calibration, effects of modelling of initial and final state radiation, color reconnection, higher order QCD evolution, parton distribution functions and uncertainties arising from the uncertainties on the offset and slope of the calibration from pseudo experiments.

Combining the measurements in the three dilepton channels gives

$$m_t = 173.7 \pm 2.8(\text{stat}) \pm 1.5(\text{syst})\ \text{GeV}.$$

This is the most precise measurement of m_t in the dilepton channel to date [7].

4 Determination of the top quark width

We determine the $\Gamma(t \to Wb)$ from a measurement of the t-channel single top quark production cross section. This process involves a Wtb vertex and is thus proportional to $\Gamma(t \to Wb)$. Beyond the SM contributions may have different effects on the s- and t-channel cross sections. Here the t-channel cross section was chosen as it has the highest production cross section. The s-channel production rate is not assumed to be equal to the SM prediction.

The partial decay width $\Gamma(t \to Wb)$ can be expressed in terms of the t-channel single top quark production cross section as

$$\Gamma(t \to Wb) = \sigma(t\text{−channel}) \frac{\Gamma(t \to Wb)_{\text{SM}}}{\sigma(t\text{−channel})_{\text{SM}}}. \tag{1}$$

The total decay width Γ_t can be written in terms of the partial decay width and the branching fraction $\mathcal{B}(t \to Wb)$ as

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}. \tag{2}$$

The total decay width can be calculated by combining Eqs. 1 and 2.

The branching fraction $\mathcal{B}(t \to Wb)$ is measured by distinguishing between the standard decay mode of the t quark, $t\bar{t} \to W^+bW^-\bar{b}$, and decay modes that include light quarks. We use a neural network b-tagging algorithm [8] to identify jets that originate from the hadronization of long-lived b hadrons (b-tagged jet) and distinguish between the bb, bq and qq' final states in $t\bar{t}$ decay.

The t-channel cross section is extracted from a fit to a discriminant trained to separate the t-channel signal from the backgrounds in 6 independent analysis channels, defined according to jet multiplicity (2,3 or 4), and number of b-tagged jets (1 or 2) [9].

The main systematic uncertainties affect both the t-channel output discriminant and the measured branching fraction $\mathcal{B}(t \to Wb)$. The main systematic uncertainties arise from b-jet identification, jet energy resolution and background normalization.

The partial width is extracted using a Bayesian approach. The most probable value for the total width is defined by the peak of the probability density function and corresponds to

$$\Gamma_t = 2.00^{+0.47}_{-0.43}\text{GeV}.$$

This is the most precise determination of the width to date [10].

5 Evidence for spin correlation

A significant correlation between the direction of the spin of the top and antitop quark is expected in the SM. We present the first measurement in the ℓ+jets channel of the ratio of events, f, with correlated t and $\bar{t}$ spins to the total number of $t\bar{t}$ events. The ratio f is measured using a matrix-element-based approach in which Monte Carlo simulations with SM spin correlation and without spin correlation are compared to data.

The $t\bar{t}$ signal is modelled using the MC@NLO [11] event generator, which allows generation of $t\bar{t}$ MC samples both with and without the expected spin correlation.

To make optimal use of the kinematic information in $t\bar{t}$ events, we calculate signal probabilities P_sgn for each event using the leading-order (LO) matrix element for the hypothesis of correlated ($H = c$) and for the hypothesis of uncorrelated ($H = u$) spins. Writing P_sgn as a function of the hypotheses H as:

$$P_{\rm sgn}(x;\, H) = \frac{1}{\sigma_{obs}} \int f_{\rm PDF}(q_1) f_{\rm PDF}(q_2)\, dq_1\, dq_2 \times \frac{(2\pi)^4 |\mathcal{M}(y,H)|^2}{q_1 q_2 s} W(x,y)\, d\Phi_6,$$

with $\sigma_{\rm obs}$ being the LO $q\bar{q} \to t\bar{t}$ production cross section including selection efficiency and acceptance effects, q_1 and q_2 denoting the fraction of the proton and antiproton momentum carried by the partons, $f_{\rm PDF}$ representing the parton distribution functions, s the square of the center-of-mass energy of the colliding $p\bar{p}$ system, and $d\Phi_6$ the infinitesimal volume element of the six-body phase space. Detector resolution effects are taken into account by introducing transfer functions $W(x, y)$ that describe the probability of a partonic final state y to be measured as x. Additional details of the $P_{\rm sgn}$ calculation can be found in Ref. [12].

To distinguish between correlated and uncorrelated top quark spin hypotheses, we define, a discriminant R:

$$R = \frac{P_{\rm sgn}(x, H = c)}{P_{\rm sgn}(x, H = c) + P_{\rm sgn}(x, H = u)}.$$

The ratio f is measured by comparing templates from distributions of R for $t\bar{t}$ MC events with and without spin correlation, as well as background MC, to data. The binned maximum likelihood fit to the data is performed independently in several sub samples of varying sensitivity.

The main systematic uncertainty is the finite number of MC events used in the templates. Combining the dilepton and ℓ+jets channels we obtain

$$f = 0.85 \pm 0.29(\text{stat} + \text{syst}).$$

We can exclude $f < 0.052$ at 99.7% C.L., therefore this represents first evidence of SM spin correlation at 3.1 standard deviations [13].

6 Summary

We have presented three results measuring properties of the heaviest elementary particle, the top quark. Using dilepton events the top quark mass is measured to be $m_t = ...$ GeV [7], consistent with measurements in other channels. By combining results of two previous measurements [9, 14] we obtain the most precise determination of the top quark width $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV [10]. Distinguishing correlated and uncorrelated $t\bar{t}$ spins using a matrix-element-based approach we obtain evidence for SM like correlation of the spins [13].

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