Combination of $tt$ cross section measurements and constraints on the mass of the top quark and its decays into charged Higgs bosons

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Combination of $t\bar{t}$ cross section measurements and constraints on the mass of the top quark and its decays into charged Higgs bosons

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We combine measurements of the top quark pair production cross section in $p\bar{p}$ collisions in the $\ell^+\ell^-$, $\ell\ell$, and $\tau\ell$ final states (where $\ell$ is an electron or muon) at a center of mass energy of $\sqrt{s} = 1.96$ TeV in 1 fb$^{-1}$ of data collected with the D0 detector. For a top quark mass of 170 GeV/$c^2$, we obtain $\sigma_{t\bar{t}} = 8.18^{+0.98}_{-0.87}$ pb in agreement with the theoretical prediction. Based on predictions from higher order quantum chromodynamics, we extract a mass for the top quark from the combined $t\bar{t}$ cross section, consistent with the world average of the top quark mass. In addition, the ratios of $t\bar{t}$ cross sections in different final states are used to set upper limits on the branching fractions $B(t \to H^+ b \to \tau^+ \nu b)$ and...
Precise measurements of the production and decay properties of the heaviest known fermion, the top quark, provide important tests of the standard model (SM) and offer a window for searches for new physics. In this paper we measure the top-antitop quark pair ($t\bar{t}$) production cross section and compare it with the SM prediction, extract the top quark pole mass from this measurement, and search for new physics in top quark decays analyzing ratios of the $t\bar{t}$ cross sections measured in different decay channels.

The inclusive $t\bar{t}$ production cross section ($\sigma_{t\bar{t}}$) is measured in different $t\bar{t}$ decay channels assuming SM branching fractions. The comparison of the results to predictions in next-to-leading order perturbative quantum chromodynamics (QCD), including higher order soft-gluon resummations [1–4], yields a direct test of the SM. Ratios of $\sigma_{t\bar{t}}$ measured in different final states are particularly sensitive to non-SM particles that may appear in top quark decays, especially if the boson in the decay is not a SM $W$ boson. An example is the decay into a charged Higgs boson ($t\to H^+b$), which, as predicted in some models [5], can compete with the SM decay $t\to W^+b$. Additionally, many experimental uncertainties cancel in the ratios. Furthermore, since $\sigma_{t\bar{t}}$ depends on the mass of the top quark ($m_t$), it can be used to extract $m_t$. Such a measurement is less accurate than direct mass measurements, but provides complementary information with different experimental and theoretical uncertainties.

Within the SM, each quark of the $t\bar{t}$ pair is expected to decay nearly 100% of the times into a $W$ boson and a $b$ quark [6]. $W$ bosons can decay hadronically into $q\bar{q}$ pairs or leptonically into $e\nu_e$, $\mu\nu_\mu$, and $\tau\nu_\tau$ with the $\tau$ in turn decaying into an electron, a muon, or hadrons, and associated neutrinos. If one of the $W$ bosons decays hadronically while the other one produces a direct electron or muon or a secondary electron or muon from $\tau$ decay, the final state is referred to as the $\ell +$ jets (or $\ell j$) channel. If both $W$ bosons decay leptonically, this leads to a dilepton final state containing a pair of electrons, a pair of muons, or an electron and a muon (the $\ell\ell$ channel), or a hadronically decaying tau accompanied either by an electron or a muon (the $\tau\ell$ channel).

Measurements of the individual $t\bar{t}$ cross sections in $\ell\ell$ and $\tau\ell$ channels using about 1 fb$^{-1}$ of $p\bar{p}$ data from the D0 detector at the Fermilab Tevatron collider at $\sqrt{s} = 1.96$ TeV are available in Ref. [7]. In the $\ell +$ jets channel, we use the same selection and background estimation as in Ref. [8], but a slightly larger data set and a unified treatment of systematic uncertainties with the $\ell\ell$ and $\tau\ell$ channels. We provide a brief summary of the event selection and analysis procedures below.

In each final state we select data samples enriched in $t\bar{t}$ events by requiring one or two isolated high transverse momentum ($p_T$) leptons for the $\ell +$ jets or $\ell\ell$ channel, respectively. At least two high $p_T$ jets are required for $\ell\ell$ and $\tau\ell$ events, and at least three for $\ell +$ jets events. Further, in all but the $e\mu$ channel, large transverse missing energy ($E_T$) is required to account for the large transverse momenta of neutrinos from $W$ boson or $\tau$ lepton decays. In the $e\mu$ final state, a requirement on the sum of the $p_T$ of the highest $p_T$ (leading) lepton and the two leading jets is imposed instead. In the $\mu\mu$ channel, the $E_T$ requirement is supplemented with a requirement on the significance of the $E_T$ measurement, estimated from the $p_T$ of muons and jets, and their expected resolutions. Additional criteria are applied on the invariant mass of the two opposite charge leptons of the same flavor in the $ee$ and $\mu\mu$ channels to reduce the dominant background from $Z/\gamma^* \to \ell^+\ell^-$ events. In the $\ell +$ jets and $\tau\ell$ channels we require a minimum azimuthal angle separation between the $E_T$ vector and the lepton $p_T$, $\Delta \phi(L,E_T)$, to reduce background from multijet events, where jets are misidentified as electron, muon, or $\tau$. Details of lepton, jet, and $E_T$ identification are provided in Refs. [9,10]. The final selection in these channels demands at least one identified $b$ jet via a neural-network-based algorithm [11]. In the $\ell +$ jets channel we separate events with one or $\approx 2b$-tagged jets due to their different signal over background ratio and systematic uncertainties.

To simplify the combination and extraction of cross section ratios, all channels are constructed to be mutually exclusive. In particular, events with two identified leptons are excluded from the $\ell +$ jets selection, and all $\tau\ell$ candidates are removed from the rest of the channels.

The compositions of the samples in the $\ell +$ jets, $\ell\ell$, and $\tau\ell$ channels are shown in Table I. $W +$ jets production dominates the background for the $\ell +$ jets events, while multijet production is the most important background in the $\tau\ell$ channel. Background in the $\ell\ell$ channels comes mainly from $Z +$ jets production. In the $\ell\ell$ channel, contributions from $W +$ jets production are part of the multijet background. The smaller contribution from diboson production is included in the category labeled “other background.” This category also includes the contribution from single top quark production in the $\ell +$ jets and $\tau\ell$ channels. The signal, $W +$ jets and $Z +$ jets backgrounds are simulated using ALPGEN [12] for the matrix element calculation and PYTHIA [13] for parton showering and hadronization. Diboson and single top backgrounds are simulated with the PYTHIA and SINGLETOP [14] generators, respectively. We estimate the multijet background from the control data samples. The difference in the ratio of $t\bar{t}$ and $W +$ jets events in the $e +$ jets and $\mu +$ jets final states is the result of the larger efficiency and misidentified lepton rate in the $e +$ jets channel compensating for the lower
lepton acceptance ($|\eta| < 1.1$) compared to the $\mu +$ jets channel ($|\eta| < 2.0$). In addition, the wider rapidity distribution of the $W +$ jets events compared to $t\bar{t}$ events increases the $W +$ jets background contribution in the $\mu +$ jets channel.

To calculate the combined cross section, we define a joint likelihood function as the product of Poisson probabilities for the 14 disjoint subsamples, as listed in Table I. Fourteen additional Poisson terms constrain the multijet background in the $\ell +$ jets and $\tau \ell$ channels. In particular, for the $\tau e$ and $\tau \mu$ channels, the multijet background is determined by counting events with an electron or muon and associated $\tau$ of the same electric charge, introducing a corresponding Poisson term per channel. In the $\ell +$ jets channel, we estimate the multijet background separately for each of the eight subchannels by using corresponding control data samples [15]. Four additional terms arise from applying this same method in evaluating the multijet background before $b$ tagging.

Each systematic uncertainty is included in the likelihood function through one free “nuisance” parameter [15]. Each of these parameters is represented by a Gaussian probability density function with zero mean and a standard deviation of one; all are allowed to float in the maximization of the likelihood function, thereby changing the central value of the measured $\sigma_{t\bar{t}}$. Correlations are taken into account by using the same nuisance parameter for a common source of systematic uncertainty in different channels scaled by the corresponding standard deviation (SD) of each individual channel. Thus, the likelihood function to be maximized is represented by the product

$$L = \prod_{i=1}^{14} P(n_i, m_i) \times \prod_{j=1}^{14} P(n_j, m_j) \times \prod_{k=1}^{K} \text{SD}_{ik} \times G(\nu_i; 0, 1),$$

where $P(n, m)$ is the Poisson probability to observe $n$ events given the expectation of $m$ events. The predicted number of events in each channel is the sum of the predicted background and expected $t\bar{t}$ events, which depends on $\sigma_{t\bar{t}}$. In the product, $i$ runs over the subsamples and $j$ runs over the multijet background subsamples. The Gaussian distributions $SD_{ik} \times G(\nu_i; 0, 1)$ describe the systematic uncertainties, $K$ is the total number of independent sources of systematic uncertainty, $\nu_i$ are the individual nuisance parameters, and $SD_{ik}$ is 1 standard deviation for the source of uncertainty $k$ in subsample $i$.

Systematic uncertainties on the measured $\sigma_{t\bar{t}}$ are evaluated from sources that include electron and muon identification; $\tau$ and jet identification and energy calibration; $b$-jet identification; modeling of triggers and signal and background; and integrated luminosity. All uncertainties are treated as fully correlated among channels and between signal and background. Systematic uncertainties arising from limited statistics of data or Monte Carlo samples used in estimating signal or backgrounds are considered to be uncorrelated. A detailed discussion on systematic uncertainties can be found in Refs. [7,8]. Table II shows a breakdown of uncertainties on the combined cross section. We evaluate the effect from each source by setting all uncertainties to zero except the one in question and redoing the likelihood maximization with respect to only the corresponding nuisance parameter. Since the method allows each uncertainty to change the central value, the total uncertainty on $\sigma_{t\bar{t}}$ differs slightly from the quadratic sum of the statistical and individual systematic uncertainties. The total systematic uncertainty on $\sigma_{t\bar{t}}$ exceeds the statistical contribution. The luminosity uncertainty of 6.1% which enters into the estimation of the majority of the backgrounds and the luminosity measurement of the selected samples is the dominant source of systematic uncertainty.
from different $t\bar{t}$ decay modes. We calculate the contribution from dilepton events to the $\ell + \text{jets}$ final state as well as the contribution from dilepton and $\ell + \text{jets}$ events to the $\tau\ell$ final states using the corresponding observed cross sections in the individual channels when generating pseudodata sets.

Table III summarizes the individual $\sigma_{\ell\ell}$ measurements for the individual channels, as well as some of their combinations. Within uncertainties, all measurements are consistent with each other. The combined cross section for $\ell + \text{jets}$, $\ell\ell$, and $\tau\ell$ final states for a top quark mass of 170 GeV/$c^2$ is evaluated to be

$$\sigma_{\ell\ell} = 8.18^{+0.98}_{-0.87} \text{ pb}, \quad (2)$$

in agreement with theoretical predictions [1–4]. The uncertainty is comparable to the one on the cross section combination from different methods in the $\ell + \text{jets}$ channel performed by DØ [8]. The observed number of events in the different channels is compared to the sum of the background and combined $t\bar{t}$ signal in Fig. 1(a).

We compute ratios $R_{\ell\ell}$ of measured cross sections, $R_{\ell\ell}^{\ell\ell} = \sigma_{\ell\ell}^{\text{Data}} / \sigma_{\ell\ell}^{\text{MC}}$ and $R_{\ell\ell}^{\tau\ell\ell} = \sigma_{\ell\ell}^{\text{Data}} / \sigma_{\ell\ell}^{\text{MC} \ell\ell\ell}$, by generating pseudodata sets in the numerator and denominator in order to take into account the correlation between systematic uncertainties. $\sigma_{\ell\ell}^{\text{channel}}$ represent the measured cross sections in the corresponding channel. The pseudodata sets are created by varying the number of signal and background events around the expected number according to Poisson probabilities. All independent sources of systematic uncertainties are varied within a Gaussian distribution. Although the individual channels considered are exclusive, each channel can receive signal contributions from different $t\bar{t}$ decay modes.

Table III. Summary of measured $\sigma_{\ell\ell}$ in different channels for $m_t = 170$ GeV/$c^2$.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sigma_{\ell\ell}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell + \text{jets}$</td>
<td>8.46$^{+0.97}_{-1.09}$</td>
</tr>
<tr>
<td>$\ell\ell$ [7]</td>
<td>7.46$^{+0.60}_{-1.37}$</td>
</tr>
<tr>
<td>$\ell + \text{jets}$ and $\ell\ell$</td>
<td>8.18$^{+0.99}_{-0.87}$</td>
</tr>
<tr>
<td>$\tau\ell$ [7]</td>
<td>7.77$^{+0.98}_{-2.00}$</td>
</tr>
<tr>
<td>$\ell + \text{jets}$, $\ell\ell$, and $\tau\ell$</td>
<td>8.18$^{+0.98}_{-0.87}$</td>
</tr>
</tbody>
</table>
using the frequentist approach of Feldman and Cousins [16].

The observed and expected (i.e., for $R_{\sigma} = 1$) limits for the tauonic and the leptophobic charged Higgs boson models are shown in Figs. 1(b) and 1(c), respectively. In the tauonic model the upper 95% C.L. limits on $B$ range from 15% to 40% for $80 \text{ GeV}/c^2 \leq M_{H^\pm} \leq 155 \text{ GeV}/c^2$, improving the limits given in [17]. For the leptophobic charged Higgs boson model, which is investigated here for the first time, the upper limit on the $B$ range is between 48% and 57% for the same mass range. Although indirect bounds as those from the measured rate of $b \to s \tau$ [18] appear stronger than the results from the direct search presented here, they can be invalidated by the presence of new physics contributions.

The interpretation of the direct measurement of the top quark mass [6] has become a subject of intense discussion in terms of its renormalization scheme [19]. The extraction of this parameter from the measured cross section provides complementary information, with different sensitivity to theoretical and experimental uncertainties, relative to direct methods that rely on kinematic details of the top quark reconstruction. Simulated samples of $t\bar{t}$ events generated at different values of the top quark mass are used to estimate the signal acceptance. The resulting measurements of $\sigma_{t\bar{t}}$ are fitted as a function of $m_t$ [2]:

$$\sigma_{t\bar{t}}(m_t) = \frac{1}{m_t^4} \left[ a + b(m_t - m_0) + c(m_t - m_0)^2 + d(m_t - m_0)^3 \right]$$

where $\sigma_{t\bar{t}}$ and $m_t$ are in pb and GeV$/c^2$, respectively, and $m_0 = 170 \text{ GeV}/c^2$ [20]. The dependence on the top quark mass is due to the mass dependence of the selection efficiencies.

We compare this parametrization to a prediction in pure next-to-leading-order (NLO) QCD [1], to a calculation including NLO QCD and all higher-order soft-gluon resummations in next-to-leading logarithms (NLL) [2], to an approximation to the next-to-next-to-leading-order (NNLO) QCD cross section that includes all next-to-next-to-leading logarithms relevant in NNLO QCD [3], and to a calculation that employs full kinematics in the double differential cross section beyond NLL using the soft anomalous dimension matrix to calculate the soft-gluon contributions at NNLO [4]. Figure 2 shows the experimental and the theoretical [1–3] $t\bar{t}$ cross sections as a function of the top quark mass.

Following the method of Refs. [7,8], we extract the most probable top quark mass values and the 68% C.L. band. Since the theoretical predictions are performed in the pole mass scheme, this defines the extracted parameter here. The results are given in Table IV. All values are in good agreement with the current world average of $171.2 \pm 2.1 \text{ GeV}/c^2$ [6].

In summary, we have combined the $t\bar{t}$ cross section measurements in $\ell +$ jets, $\ell\ell$, and $\tau +$ jets channels to measure $\sigma_{t\bar{t}} = 8.18^{+0.98}_{-0.87}$ pb for a top quark mass of $170 \text{ GeV}/c^2$. For the first time, we have also calculated ratios of cross sections as a function of the next-to-next-to-leading order efficiency.
sections and interpreted them in terms of limits on nonstandard model top quark decays into a charged Higgs boson. All results are in good agreement with the SM expectations. Finally, using different theoretical predictions given in the pole mass scheme, we have extracted the top quark mass from the combined $\sigma_{\tilde{\tau} \tilde{\tau}}$ and have found the result to be consistent with the world average top quark mass [6] from direct measurements.

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[20] We obtain $a = 6.823 \pm 0.05 \times 10^3$, $b = 1.10480 \pm 0.10^8$, $c = 8.80552 \pm 10^8$, and $d = -1.767 \times 10^5$ for Eq. (4).