First Direct Bound on the Total Width of the Top Quark in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the first direct experimental bound on the total decay width of the top quark using 955 pb^{-1} of the Tevatron's $p\bar{p}$ collisions recorded by the Collider Detector at Fermilab. We identify 253 top-antitop pair candidate events. The distribution of reconstructed top quark mass from these events is fitted to templates representing different values of the top quark width. Using a confidence interval based on likelihood ratio ordering, we extract an upper limit at 95% C.L. of $\Gamma_t < 13.1$ GeV for an assumed top quark mass of 175 GeV/c^2.

PACS numbers: 14.65.Ha, 13.85.Qk, 12.15.Ff

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Due to its large mass, the top quark has the largest decay width and hence the shortest lifetime of the quarks in the standard model (SM). The total width of the top quark at the leading order is dependent on the top quark mass m_t and the Fermi coupling constant G_F: $\Gamma_t^0 = G_F m_t^3/(8\pi\sqrt{2})$. Higher order effects include the introduction of finite W boson and b quark masses (M_W, m_b), non-zero off-diagonal elements of the quark-mixing matrix, and higher order corrections in the strong coupling constant α_s. Neglecting terms of order m_b^2/m_t^2, α_s^2, and $(\alpha_s/\pi)M_W^2/m_t^2$, the width predicted in the SM at next-to-leading-order is:

$$\Gamma_t = \Gamma_t^0(1 - \frac{M_W^2}{m_t^2})^2(1 + 2\frac{M_W^2}{m_t^2})[1 - \frac{2\alpha_s}{3\pi}(\frac{2\pi^2}{3} - \frac{5}{2})].$$

The total width of the top quark is calculated to a precision of about 1% in the SM; it is approximately 1.5 GeV for $m_t = 175$ GeV/c^2 [1, 2].

A deviation from the SM prediction could indicate a significant contribution from top quark decays to non–SM particles such as $t \to bH^+$ (where H^+ is the charged Higgs boson in the supersymmetric model), or from rare SM processes such as $t \to dW^+$ and $t \to sW^+$. Although such scenarios have not been observed experimentally [3–7], a general way to rule out the presence of a large top quark decay rate to non–SM channels, including those with non-detectable final states, is through experimental constraints on Γ_t. To date, there have been no direct experimental measurements of the total width of the top quark.

The data set for the analysis presented in this paper is collected by the CDF II detector, a multipurpose particle detector for $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron. A charged particle tracking system immersed in a magnetic field consists of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers and scintillators located outside the calorimeters detect muons. The detector is described in detail elsewhere [8].

We employ a cylindrical coordinate system where θ and ϕ are the polar and azimuthal angle, respectively, with respect to the proton beam. Transverse energy and momentum are $E_T = E\sin\theta$ and $p_T = |p|\sin\theta$, respectively, where E and p are energy and momentum. Missing transverse energy, $\not\!\!E_T$, is defined as the magnitude of the vector $-\Sigma_i E_T^i \mathbf{n_i}$ where E_T^i is the magnitude of transverse energy contained in each calorimeter tower i, and $\mathbf{n_i}$ is the unit vector from the collision point to the tower in the transverse plane.

TABLE I: Event selection requirements for the 1-tag and 2-tag event samples.

Event selection category	1-tag		2-tag
E_T^e (GeV) or p_T^μ (GeV/c)		> 20	
$\not\!\!E_T$ (GeV)		> 20	
Jets 1–3 E_T (GeV)		> 15	
Jet 4 E_T (GeV)	> 15		> 8
Number of b tags	1		≥ 2

Top quarks are produced primarily by strong interaction in top-antitop ($t\bar{t}$) pairs at the Tevatron. Top quarks decay almost exclusively to a W boson and a b quark through the weak interaction in the SM. We identify candidate $t\bar{t}$ events in the "lepton + jets" channel, where one W boson decays to an electron or a muon, and a neutrino, while the other W boson decays to a quark-antiquark pair. We select events consistent with this topology, requiring a high-p_T electron or muon candidate, missing transverse energy denoting the presence of a neutrino, and four jets. Jets are reconstructed using a cone algorithm with radius $\Delta\mathrm{R} \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$. At least one jet with $E_T > 15$ GeV must be identified as a b quark candidate through the presence of a displaced vertex within the jet cone arising from the decay of a long-lived bottom hadron (b-tag). The event selection criteria are listed in Table I. Detailed information on selections is available elsewhere [9, 10].

We divide the candidate events into two exclusive classes: one (1-tag) containing events with one b-tagged jet among the leading four, and another (2-tag) with two or more such jets. Separating these subsamples results in a more efficient use of statistical information due to their different reconstructed top mass resolution and signal-to-background ratios. Background events are expected primarily from W production in association with jets (W + jets), multijet processes where a jet is misidentified as a charged lepton and $\not\!\!E_T$ results from energy mismeasurement of the jets (non-W), and small contributions from electroweak backgrounds (EWK) composed of single top quark and diboson (WW, WZ, ZZ) production. Table II summarizes the expected sample compositions that are obtained by scaling to 955 pb^{-1} from a previous $t\bar{t}$ production analysis with 318 pb^{-1} [11].

After event selection, the analysis proceeds in three steps. First, we reconstruct a top quark mass m_t^{reco} from each event using a kinematic fitter. The width of the reconstructed mass distribution for the selected events is

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TABLE II: The sources and expected numbers of background events, and the number of events observed for the 1-tag and 2-tag event samples in our 955 pb^{-1} dataset.

Background source	1-tag	2-tag
W + jets	11.8 ± 4.2	3.4 ± 1.4
non-W	16.7 ± 2.8	2.1 ± 0.4
EWK	2.9 ± 0.6	0.2 ± 0.4
Total background events	31.4 ± 7.6	5.7 ± 2.2
Observed events	171	82

sensitive to Γ_t. The second step is a likelihood fit of the reconstructed mass distributions using simulated signal and background distributions that yields an estimator of Γ_t. Finally, we use a frequentist prescription (with Bayesian treatment of systematic uncertainties [12]) to determine a 95% C.L. upper limit on Γ_t in the physically allowed region.

We perform a χ^2 minimization to fit the momenta of the $t\bar{t}$ decay products and determine m_t^{reco} for each event using the four leading jets. We assume that the final state arises from the decay of a $t\bar{t}$ pair into W bosons and b quarks. To resolve the ambiguity arising from the different ways of assigning the jets to the four quarks, we select the assignment with the lowest χ^2 and require that b-tagged jets are assigned to b quarks. This kinematic fitter is used in other CDF analyses and is described in detail in Ref. [11]. In the χ^2 fit, both sets of W decay daughters are constrained to have the invariant mass of the W boson, and both Wb states are constrained to have the same mass. Although the top and antitop quark will likely be produced with different masses, we confirmed that there is no significant difference in the sensitivity resulting from the $m_t = m_{\bar{t}}$ condition even for a large value of Γ_t.

To distinguish between different values of Γ_t, we compare the m_t^{reco} distribution from our data to a series of samples created using the PYTHIA 6.216 event generator [13] and a full detector simulation. We use samples with $m_t = 175$ GeV/c^2 and various values of Γ_t between 0.001 GeV and 100 GeV. Although PYTHIA does not fully account for quantum interference with irreducible background diagrams and off-shell effects, for $\Gamma_t \lesssim 30$ GeV these effects are small, and the existing description is expected to be adequate [14]. W + jets background events are generated using ALPGEN 1.3 [15], with parton showering and fragmentation in HERWIG 6.504 [16]. An unbinned extended maximum likelihood fit [17] is performed using parameterized signal and background m_t^{reco} templates. As an example, Fig. 1 shows templates for the signal m_t^{reco} distribution in the 2-tag subsample at three values of Γ_t. We parameterize the m_t^{reco} distributions as a function of Γ_t. Small shifts in the mean of the templates are induced by the interplay between the top mass Breit-Wigner distribution and the parton distribution functions that preferentially produce events with low quark masses. In the likelihood fit, we constrain the background templates in the 2-tag and 1-tag samples to the levels given in Table II. The best fit value Γ_t^{fit} is the width which maximizes the likelihood.

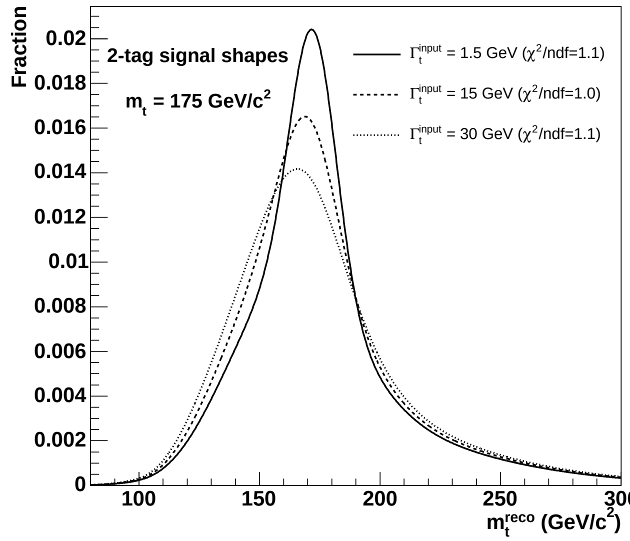

FIG. 1: The parameterized signal m_t^{reco} distributions and goodness of the parameterization are shown for the 2-tag subsample at three different values of Γ_t. The parameterization is determined in a global fit to all the 2-tag templates. The parameterized signal m_t^{reco} distributions for 1-tag are similar.

We allow negative Γ_t^{fit} values that represent m_t^{reco} distributions narrower than the nominal due to statistical fluctuations. The expected m_t^{reco} distribution for a negative Γ_t^{fit} is derived from an extrapolation of the parameterization to the unphysical region. The reconstructed top mass distributions from the data and the results of the likelihood fit are shown in Fig. 2. The data are consistent with the fitted curves with the preferred value of $\Gamma_t^{\mathrm{fit}} = -4.8$ GeV. For the data sample used in this analysis, we expect to measure a negative Γ_t^{fit} about 40% of the time and Γ_t^{fit} less than -4.8 GeV about 25% of the time if the total width is 1.5 GeV. The limit on the true value of Γ_t, however, will be constrained to the physical region.

To set a limit on the true value of Γ_t, we employ the Neyman construction [18] to ensure a coverage of at least 95%. The likelihood-ratio ordering principle due to Feldman and Cousins [19] provides a smooth transition from one-sided to two-sided limits and usually guarantees a non-empty interval. We derive the confidence belts from ensembles of simulated experiments in which signal events are selected from the simulated samples generated with different values of Γ_t. The Γ_t^{fit} distribution from each such ensemble is convoluted with a shape that represents the effects of systematic uncertainties as described below.

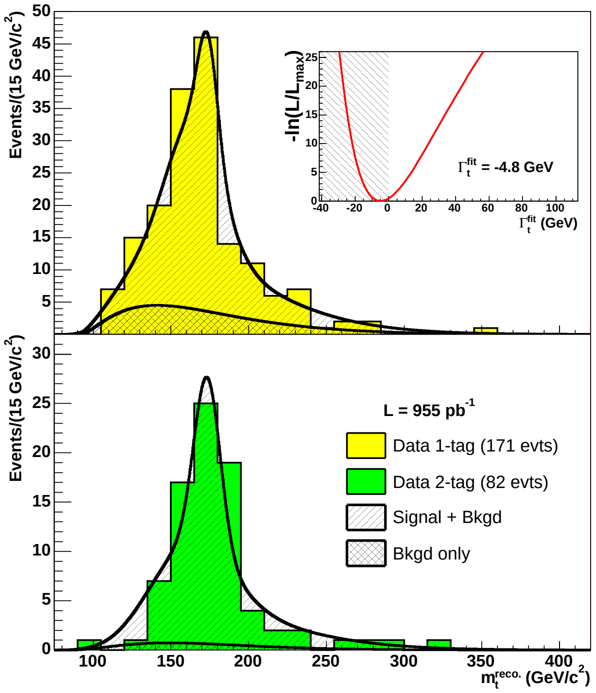

FIG. 2: The $m_t^{\rm reco}$ distribution is shown for each subsample overlaid with the expected distribution using $\Gamma_t^{\rm fit}$ and signal and background normalizations from the combined fit. A $\Gamma_t^{\rm fit}$ likelihood scan is shown in the inset; for the shaded non-physical region ($\Gamma_t^{\rm fit} < 0$), the likelihood uses $m_t^{\rm reco}$ distributions extrapolated from the parameterization to shapes with $\Gamma_t^{\rm fit} > 0$.

Since the top quark mass reconstruction is dominated by the measurement of jet energy, and since our fit is largely determined by the peak and the width of the $m_t^{\rm reco}$ distribution, the uncertainties on the jet energy scale and the jet energy resolution are the dominant uncertainties in the top width measurement. The uncertainties on the jet energy scale calibration are extensively studied using a combination of simulated and data control samples [20] and amount to about 3% of the measured jet energy for jets in the $t\bar{t}$ sample. The effect on the $\Gamma_t^{\rm fit}$ distribution is single-sided, with larger $\Gamma_t^{\rm fit}$ being more likely for jet energy scale shifts in either direction. This is because the only degree of freedom in the templates is the width, and a signal template with a larger Γ_t accomodates the events with the shifted peak.

We select events with one jet and one high-p_T photon and compare their energies to study the jet energy resolution. Data and PYTHIA events show similar jet resolution of 15% − 10% for jet transverse energies between 20 GeV and 200 GeV, respectively. Taking into account statistical uncertainty of the data, we define a p_T-dependent systematic uncertainty on jet resolution of 10% − 4% to cover the difference. Then, we add Gaussian smearing with corresponding uncertainty to each jet in signal Monte Carlo events. We also study smaller systematic uncertainties in $\Gamma_t^{\rm fit}$ related to the background $m_t^{\rm reco}$ shape, Monte Carlo statistics, the Monte Carlo generator, the parton distribution functions, and other signal modeling effects [11]. The combined convolution shape, accounting for all systematic uncertainties, has a shift of -0.4 GeV and an RMS of 4.6 GeV. This can be compared to the RMS from statistical effects only: between 6.6 GeV and 10.1 GeV for simulated experiment ensembles using Γ_t of 1.5 − 30 GeV. Figure 3 shows the 95% confidence belts after including systematic uncertainties. The fitted value from data, $\Gamma_t^{\rm fit} = -4.8$ GeV, corresponds to a limit of $\Gamma_t < 13.1$ GeV at 95% C.L.

Our measurement assumes a fixed value for the top quark mass of 175 GeV/c^2. The one-dimensional likelihood is sensitive to this assumption in the same way as described above for jet energy scale uncertainties. In particular, if the top quark mass is consistent with the current world average of 172.5 ± 2.7 GeV/c^2 [21], the confidence belts would shift to higher $\Gamma_t^{\rm fit}$ values, resulting in an upper limit of Γ_t lower than what we quoted in this paper.

In summary, using 253 top-antitop pair candidate events we present the first direct experimental upper limit on the total decay width of the top quark, $\Gamma_t < 13.1$ GeV at 95% C.L. for $m_t = 175$ GeV/c^2. This corresponds to a limit on the top quark lifetime of $\tau_t > 5 \times 10^{-26}$ s. This measurement is statistically limited and its dominant systematic uncertainties are likely reducible with statistics. The precision of this measurement, therefore, will continue to improve over the course of Run II of the Tevatron.

We thank Torbjörn Sjöstrand, Stephen Mrenna, Peter Skands, Alessandro Ballestrero, and Ezio Maina for discussions related to the Monte Carlo modeling of the top quark lineshape. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Comisión Interministerial de Ciencia y Tecnología, Spain; the European Community's Human Potential Programme; the Slovak R&D Agency; and the Academy of Finland.

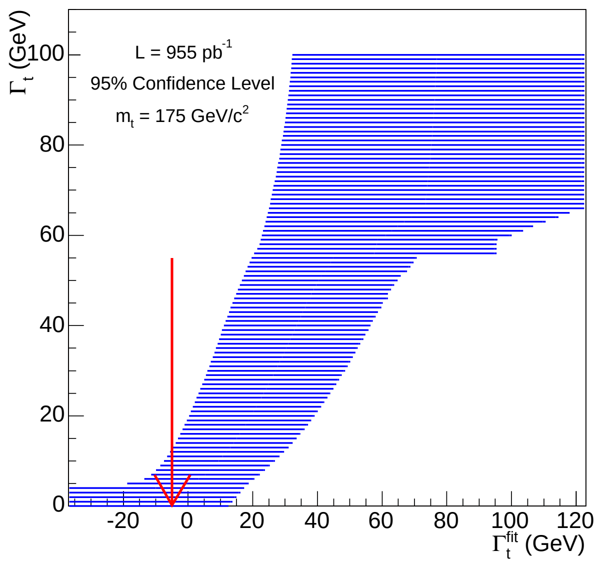

FIG. 3: The confidence band in $\Gamma_t^{\rm fit}$ for a 95% C.L. is shown. Results from simulated experiments assuming a 955 pb^{-1} dataset at different values of Γ_t are convoluted with a smearing function to account for systematic uncertainties. The fitted value from the data is indicated by an arrow.

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