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Improved determination of the width of the top quark

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We present an improved determination of the total width of the top quark, Γ_t, using 5.4 fb^{-1} of integrated luminosity collected by the D0 Collaboration at the Tevatron $p\bar{p}$ Collider. The total width Γ_t is extracted from the partial decay width $\Gamma(t \to Wb)$ and the branching fraction $\mathcal{B}(t \to Wb)$. $\Gamma(t \to Wb)$ is obtained from the t-channel single top-quark production cross section and $\mathcal{B}(t \to Wb)$ is measured in $t\bar{t}$ events. For a top mass of 172.5 GeV, the resulting width is $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV. This translates to a top-quark lifetime of $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s. We also extract an improved direct limit on the Cabibbo-Kobayashi-Maskawa quark-mixing matrix element $0.81 < |V_{tb}| \leq 1$ at 95% C.L. and a limit of $|V_{tb'}| < 0.59$ for a high-mass fourth-generation bottom quark assuming unitarity of the fourth-generation quark-mixing matrix.

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I. 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 [1]. Within the SM, the top quark decays almost exclusively into a W boson and a b quark. The total decay width Γ_t is therefore expected to be dominated by the partial decay width $\Gamma(t \to Wb)$. Neglecting higher-order electroweak corrections and terms of order m_b^2/m_t^2, α_s^2, and $(\alpha_s/\pi)M_W^2/m_t^2$, the partial width predicted by the SM at next-to-leading order is [2]

$$\Gamma(t \to Wb)_{\rm SM} = \frac{G_F m_t^3}{8\pi\sqrt{2}}|V_{tb}|^2\left(1 - \frac{M_W^2}{m_t^2}\right)^2\left(1 + 2\frac{M_W^2}{m_t^2}\right) \times \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right], \quad (1)$$

where m_t (m_b) is the mass of the top (bottom) quark, G_F (α_s) the Fermi (strong interaction) coupling constant, M_W the mass of the W boson, and V_{tb} the strength of the

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left-handed Wtb coupling. Setting $\alpha_s(M_Z) = 0.118$, $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}, $M_W = 80.399$ GeV, $|V_{tb}| = 1$ [1], and assuming $m_t = 172.5$ GeV, we obtain $\Gamma(t \to Wb)_{\rm SM} = 1.33$ GeV. A deviation from the theoretical prediction would indicate the presence of beyond SM (BSM) physics, including those involving BSM decays of the top quark to final states that escape detection. Examples of such BSM scenarios are the anomalous Wtb couplings [3], hadronically decaying charged Higgs bosons [4], or a fourth-generation b' quark.

The electroweak single top-quark production at the Tevatron proceeds mainly through the exchange of a virtual W boson accompanied at tree level by a b quark in the s channel [5], or by both a b and a light quark in the t channel [6,7]. A third channel, tW, in which the top quark is produced in association with a W boson, is not considered in this analysis because the expected production cross section at the Tevatron is small [8]. Figure 1 shows the tree-level Feynman diagrams for s- and t-channel production [9]. In this paper, we determine $\Gamma(t \to Wb)$ from a measurement of the t-channel single top-quark production cross section, making use of the fact that the process involves a Wtb vertex and is thus proportional to $\Gamma(t \to Wb)$. The t-channel was chosen as it has the highest production cross section at the Tevatron [8] and because BSM contributions may have different effects on the s- and t-channel cross sections. Here, we do not assume that the s-channel production rate is as predicted by the SM.

The first direct upper bound on Γ_t [10] was set by the CDF Collaboration from an analysis of the invariant mass distribution of $t\bar{t}$ candidate events using 1 fb^{-1} of integrated luminosity. The first indirect determination of Γ_t [11] was obtained by the D0 Collaboration by combining the measurement of the single top t-channel cross section using 2.3 fb^{-1} of integrated luminosity [12] and the branching fraction $\mathcal{B}(t \to Wb)$ determined from a sample of $t\bar{t}$ events in 0.9 fb^{-1} of integrated luminosity [13]. This method assumes the $W \to tb$ coupling in single top-quark production is the same as in top-quark decay.

In this paper, we apply the method of [11] in a new indirect determination of Γ_t that is based on two prior D0 measurements, both performed using 5.4 fb^{-1} of integrated luminosity: the single top-quark t-channel cross section $\sigma(p\bar{p} \to tqb + X) = 2.90 \pm 0.59({\rm stat} + {\rm syst})$ pb [14] and the ratio $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq) = 0.90 \pm 0.04$ [15], where q can be a d, s, or b quark.

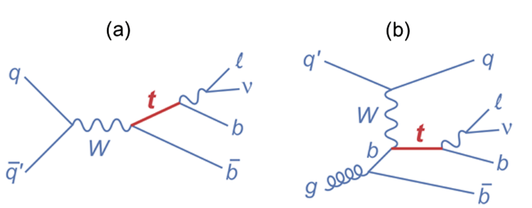

FIG. 1 (color online). Tree-level Feynman diagrams for (a) s and (b) t-channel single top-quark production.

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

$$\Gamma_p = \sigma(t - {\rm channel})\frac{\Gamma(t \to Wb)_{\rm SM}}{\sigma(t - {\rm channel})_{\rm SM}}. \qquad (2)$$

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

$$\Gamma_t = \frac{\Gamma_p}{\mathcal{B}(t \to Wb)}. \qquad (3)$$

Combining Eqs. (3) and (2), the total decay width becomes

$$\Gamma_t = \frac{\sigma(t - {\rm channel})\Gamma(t \to Wb)_{\rm SM}}{\mathcal{B}(t \to Wb)\sigma(t - {\rm channel})_{\rm SM}}, \qquad (4)$$

from which it is possible to derive the lifetime of the top quark as $\tau_t = \hbar/\Gamma_t$.

We can also use the measured value of Γ_p to probe the Wtb interaction and directly determine the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [16] element $|V_{tb}|$. A direct determination of $|V_{tb}|$, without assuming unitarity of the CKM matrix or three generations of quarks, is possible through the measurement of the total single top-quark production cross section [17]. However, this method assumes that the top quark decays exclusively to Wb, and assumes the relative production rate of s and t-channel single top production is as predicted by the SM. These two assumptions are removed when we combine the branching fraction measurement (which allows for $t \to Wd$ and $t \to Ws$ decays) and the single top cross section measured from the t-channel, independently of any assumption on the s-channel rate or on the ratio of s- to t-channel production cross sections.

II. ANALYSIS METHOD

This analysis relies on two prior D0 measurements, the single top t-channel cross section [14] and the ratio of the top-quark branching fraction [15]. Both are based on 5.4 fb^{-1} of integrated luminosity. The latter is performed by distinguishing between the standard decay mode of the top quark, $t\bar{t} \to W^+bW^-\bar{b}$ (indicated by bb), and decay modes that include light quarks ($q_l = d$, s), $t\bar{t} \to W^+bW^-\bar{q}_l$ (bq_l) and $t\bar{t} \to W^+q_lW^-\bar{q}_l$ (q_lq_l). The analysis relies on a sample of $t\bar{t}$ events in which one W boson decays into a quark and an antiquark and the other into an electron or muon and a neutrino, or events in which both W bosons decay into $\ell\nu$. In both cases, we accept events in which the W boson decayed to a τ lepton that subsequently decayed into an electron or a muon. We use a neural network b-tagging algorithm [18] to identify jets that originate from the hadronization of long-lived b hadrons (b-tagged jet) and distinguish between the bb, bq_l, and q_lq_l final states in $t\bar{t}$ decay.

The t-channel cross section measurement uses events containing an isolated electron or muon, missing transverse energy and at least two jets. Background is suppressed by requiring that one or two of the jets is identified as a b jet. The main background contributions arise from W bosons produced in association with jets and from $t\bar{t}$ pairs. We further improve the discrimination between signal and background by employing multivariate analysis techniques as described in [19]. We use 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) [14]. Single top-quark production is simulated assuming CKM matrix elements V_{tx} values (where x can be d, s, and b) obtained from a global fit to all available electroweak measurements imposing three generations and unitarity [1]. In this case, the value of $|V_{tb}| > 0.999$ results in very small contributions from Wtd or Wts vertices to the single top-quark production and decay.

Based on the t-channel output discriminant distribution, we define a binned likelihood

$$L(\mathbf{D}|\mathbf{d}) = \prod_{i=1}^{M} \frac{e^{-d_i} d_i^{D_i}}{D_i!}, \tag{5}$$

where $\mathbf{D}$ and $\mathbf{d}$ are arrays containing the observed and mean expected count for all M bins from the six different analysis channels. The mean expected count can be written in terms of the partial (Γ_p) or total (Γ_t) top-quark width as

$$\mathbf{d}\,(\Gamma_{\{p,t\}}, \sigma'_s, \mathbf{a}_t, \mathbf{a}_s, \mathbf{b}) = c_{\{p,t\}}\Gamma_{\{p,t\}}\mathbf{a}_t + \sigma'_s\mathbf{a}_s + \mathbf{b}, \tag{6}$$

where σ'_s is the s-channel cross section times $\mathcal{B}(t \to Wb)$, $\mathbf{a}_t$ and $\mathbf{a}_s$ are arrays containing the product of the acceptance and the integrated luminosity in each bin for t and s processes, respectively, and $\mathbf{b}$ is an array containing the mean count of expected background events. The term $c_{\{p,t\}}$ is given by

$$c_p = \frac{\mathcal{B}(t \to Wb)\sigma(t - \text{channel})_{\text{SM}}}{\Gamma(t \to Wb)_{\text{SM}}} \tag{7}$$

or by

$$c_t = \frac{\mathcal{B}^2(t \to Wb)\sigma(t - \text{channel})_{\text{SM}}}{\Gamma(t \to Wb)_{\text{SM}}}, \tag{8}$$

when measuring the partial or total top-quark decay width, respectively. The extra $\mathcal{B}(t \to Wb)$ term with respect to Eqs. (2) and (4) is needed to remove the assumption of $\mathcal{B}(t \to Wb) = 1$ used when generating the single top quark and $t\bar{t}$ samples. We then form a Bayesian probability density for the partial or total width by integrating the expression

$$p(\Gamma_{\{p,t\}}|\mathbf{D}) = \frac{1}{\mathcal{N}} \int L(\mathbf{D}|\Gamma_{\{p,t\}}, \sigma'_s, \mathbf{a}_t, \mathbf{a}_s, \mathbf{b})\pi(\Gamma_{\{p,t\}})\pi(\sigma'_s)\pi(\mathbf{a}_t)\pi(\mathbf{a}_s)\pi(\mathbf{b})d\sigma_s d\mathbf{a}_t d\mathbf{a}_s d\mathbf{b}, \tag{9}$$

where $\pi(*)$ represent our prior knowledge of the parameters σ'_s, $\mathbf{a}_t$, $\mathbf{a}_s$, and $\mathbf{b}$ [14]. The normalization constant $\mathcal{N}$ ensures that $\int p(\Gamma_{\{p,t\}}|\mathbf{D})d\Gamma_{\{p,t\}} = 1$. The integration is performed assuming a positive and uniform probability density for $\Gamma_{\{p,t\}}$ and for σ_s. The other priors quantify our knowledge of the systematic uncertainties for the values of $\mathbf{a}_t$, $\mathbf{a}_s$, and $\mathbf{b}$. Each independent systematic source is modeled with a Gaussian of mean zero and width set to 1 standard deviation of the corresponding uncertainty.

III. SYSTEMATIC UNCERTAINTIES

The main systematic uncertainties affect the t-channel output discriminant as well as the measured branching fraction $\mathcal{B}(t \to Wb)$, and are summarized in Table I. Common systematics that affect both the discriminant and $\mathcal{B}(t \to Wb)$ are taken as 100% correlated.

The terms included in the uncertainty calculation are:

(i) Uncertainty on jet flavor identification involving b, c, and light-flavor jet tagging rates and the calorimeter response to b jets.

TABLE I. Sources of statistical and main systematic uncertainties relative to the measured value for t-channel cross section and branching fraction that affects the determination of the partial/total decay width. We list the most important uncertainties for the branching fraction and t-channel cross section measurements, respectively.

Sources	Size [%]
Uncertainties on $\mathcal{B}(t \to Wb)$	
b-jet identification	4.0
$t\bar{t}$ cross section	2.1
Integrated luminosity	1.6
Statistical uncertainty	2.3
Statistical correlation	4.2
Uncertainties on $\sigma(t - \text{channel})$	
b-jet identification	9.3
$t\bar{t}$ cross section	3.1
Integrated luminosity	5.1
W + jets normalization	8.1
Jet energy resolution	11.6
Jet energy scale	6.8
Monte Carlo statistics	6.7

(ii) Uncertainties on the modeling of the $t\bar{t}$ process used in the $\mathcal{B}(t \to Wb)$ measurement, including uncertainties from parton distribution functions, different event generators, and hadronization models. These uncertainties are correlated with the $t\bar{t}$ background yield uncertainty in the t-channel discriminant.
(iii) Uncertainty on the integrated luminosity.
(iv) Uncertainties on the normalization of the W + jets heavy-flavor contribution.
(v) Uncertainty in the jet energy scale and resolution.
(vi) The statistical uncertainty of the $\mathcal{B}(t \to Wb)$ measurement is added as systematic uncertainty. The statistical uncertainty related to the t-channel cross section is by construction included in the top-quark width posterior distributions.
(vii) A systematic uncertainty is added to account for the statistical correlation due to a small overlap between events selected to build the t-channel discriminant and those used in the $\mathcal{B}(t \to Wb)$ measurement.
(viii) Signal and background yield uncertainty because of the amount of Monte Carlo events used to construct the background and signal discriminant.

Other terms included in the calculation of t-channel discriminant but not mentioned in the table are:

(i) Uncertainties on modeling the single top-quark signal, including initial- and final-state radiation, scale uncertainties, and parton distribution functions.
(ii) Detector simulation uncertainty arising from the modeling of particle identification in the simulated samples.
(iii) Uncertainties arising from the modeling of the different background sources that are obtained using data-driven methods.

IV. RESULT

The expected and observed probability densities for the partial width Γ_p are shown in Fig. 2. The most probable value for the partial width is defined by the peak of the probability density function and corresponds to

$$\Gamma_p = 1.87^{+0.44}_{-0.40}\ \text{GeV}. \quad (10)$$

The expected and observed probability densities for the total width Γ_t are shown in Fig. 3. The total top-quark width is found to be

$$\Gamma_t = 2.00^{+0.47}_{-0.43}\ \text{GeV}, \quad (11)$$

which can be expressed as a top-quark lifetime of

$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}\ \text{s}. \quad (12)$$

This also translates in an upper limit to the top-quark lifetime of $\tau_t < 4.88 \times 10^{-25}$ s at 95% C.L.

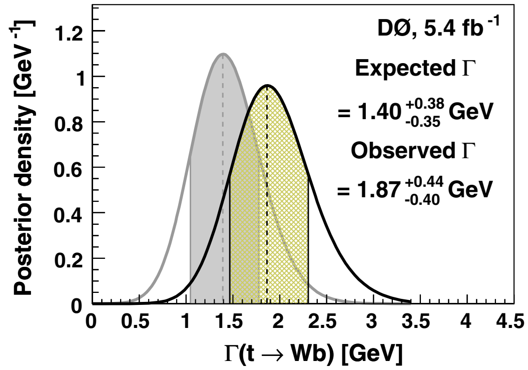

FIG. 2 (color online). Probability density for the expected and measured partial width Γ_p. The shaded areas represent 1 standard deviation centered on the most probable value.

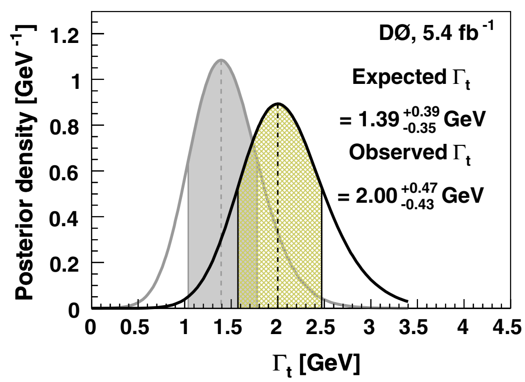

FIG. 3 (color online). Probability density for the expected and measured total width Γ_t. The shaded areas represent 1 standard deviation around the most probable value.

V. TOP-QUARK MASS DEPENDENCE

The measured branching fraction and t-channel production cross section, as well as $\Gamma(t \to Wb)_{\text{SM}}$, depend on the top-quark mass m_t. To study this dependency, we repeat the analysis using simulated $t\bar{t}$ and single top samples that were generated at different values of m_t in the range 170 to 175 GeV. The value of $\Gamma(t \to Wb)_{\text{SM}}$ is recalculated depending on m_t. Given that the dependence from m_t is small, the value and uncertainties for $\mathcal{B}(t \to Wb)$ corresponding to $m_t = 172.5$ GeV are used in all cases.

Table II summarizes the variation of the partial and total top-quark decay width as a function of m_t. The table also lists the values of $\Gamma(t \to Wb)_{\text{SM}}$ used in the analysis. The variation of the decay width with m_t follows the nonmonotonic variation observed for the t-channel cross section [14].

The effect of the mass dependency can be quantified by interpolating the observed Γ_t in function of top mass from Table II to the current Tevatron combination $m_t = 173.2 \pm 0.9$ GeV [20]. Adding a mass uncertainty of

TABLE II. Observed partial and total top-quark decay width as a function of the top-quark mass. We provide also the values for SM top-quark partial widths used in the analysis.

m_t (GeV)	170	172.5	175
$\Gamma(t \to Wb)_{\mathrm{SM}}$ (GeV)	1.26	1.33	1.40
$\Gamma(t \to Wb)$ (GeV)	$1.48^{+0.36}_{-0.34}$	$1.87^{+0.44}_{-0.40}$	$1.76^{+0.40}_{-0.38}$
Γ_t (GeV)	$1.63^{+0.41}_{-0.38}$	$2.00^{+0.47}_{-0.43}$	$1.96^{+0.46}_{-0.43}$

$$\delta\Gamma_t = \max_{m_t \in [172.5, 175]} |\Gamma_t(m_t) - \Gamma_t(173.2)| \approx 0.07 \text{ GeV}$$

in quadrature to the symmetrized interpolated error for $m_t = 173.2$ GeV results in a value for the total width of $\Gamma_t = 2.03 \pm 0.46$ GeV, and a value for top-quark lifetime of $\tau_t = 3.24^{+0.95}_{-0.60} \cdot 10^{-25}$ s. A lower limit on the total decay width $\Gamma_t > 1.37$ GeV at 95% C.L. can be estimated by assuming that the posterior density for Γ_t approximates a Gaussian distribution. This translates into an upper limit on the top-quark lifetime of $\tau_t < 4.82 \cdot 10^{-25}$ s at 95% C.L. Therefore, we conclude that the effect of the mass uncertainty is small with respect to the observed uncertainty obtained assuming a top-quark mass of $m_t = 172.5$ GeV.

VI. MEASUREMENT OF $|V_{tb}|$

We construct a posterior probability density for $|V_{tb}|$ by setting

$$c_{\{p,t\}}\Gamma_{\{p,t\}} = |V_{tb}|^2 \mathcal{B}(t \to Wb)\sigma(t - \text{channel})_{\mathrm{SM},|V_{tb}|=1} \quad (13)$$

in Eq. (6). A lower limit of $|V_{tb}| > 0.81$ at the 95% C.L. is obtained by restricting the prior for $|V_{tb}|^2$ to be uniform for $0 \leq |V_{tb}|^2 \leq 1$, as illustrated in Fig. 4. A systematic uncertainty on the theoretical prediction for the t-channel cross section was included in the result.

We apply the same procedure to constrain the strength of the coupling of a fourth-generation b' quark to the top quark $|V_{tb'}|$ [21]. For this measurement, we assume that $m_{b'} > m_t - m_W$, a small probability density for the b' quark to exist in protons and antiprotons, and unitarity of the four-generation quark-mixing matrix with $|V_{tb}|^2 + |V_{tb'}|^2 = 1$, and $|V_{td}|$, $|V_{ts}| \ll 1$. Using the limit on $|V_{tb}|$ and the condition $|V_{tb'}|^2 = 1 - |V_{tb}|^2$, we obtain $|V_{tb'}| < 0.59$ at the 95% C.L.

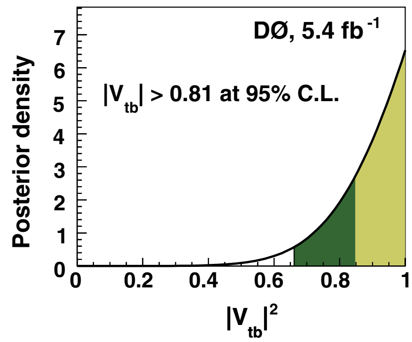

FIG. 4 (color online). Distributions of the posterior density for $|V_{tb}|^2$. The shaded (darker shaded) band indicates regions of 68% (95%) C.L.

VII. SUMMARY

We have presented an improved determination of the width of the top quark using the Bayesian techniques previously used to measure the single top-quark production cross section and an improved measurement of the branching fraction $\mathcal{B}(t \to Wb)$. The method assumes that the coupling leading to t-channel single top-quark production is identical to the coupling in the top-quark decay. We have determined the top-quark width as $\Gamma_t = 2.00^{+0.47}_{-0.43}$ GeV for $m_t = 172.5$ GeV, which corresponds to a top-quark lifetime of $\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25}$ s. These are the most precise determinations of width and lifetime to date. In addition, we set a lower limit of $|V_{tb}| > 0.81$ at the 95% C.L. without assuming that the top quark decays exclusively to Wb and with no assumption on the s- and t-channel relative production rate. We also set a limit on the strengths of the coupling for a fourth-generation b' quark to the top quark of $|V_{tb'}| < 0.59$ at 95% C.L.

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