Determination of the width of the top quark

A.A. Shchukin, 38 R.K. Shivpuri, 28 V. Simak, 10 V. Sirotenko, 47 P. Skubic, 73 P. Slattery, 69 D. Smirnov, 53
K.J. Smith, 67 G.R. Snow, 64 J. Snow, 72 S. Snyder, 71 S. Söder-Lindgreen, 43 L. Sonnenschein, 21 A. Sopczak, 41
M. Sosebee, 76 K. Soustruznik, 9 B. Spurlock, 76 J. Stark, 14 V. Stolin, 36 D.A. Stoyanova, 38 E. Strauss, 70 M. Strauss, 73
D. Strom, 48 L. Stutte, 47 P. Svoisky, 73 M. Takahashi, 43 A. Tanasijczuk, 1 W. Taylor, 6 M. Tito, 18 V.V. Tokmenin, 35
W.M. van Leeuwen, 53 N. Varelas, 48 E.W. Varnes, 44 I.A. Vasilyev, 38 P. Verdière, 20 L.S. Vertogradov, 35 M. Vezzuzi, 47
M. Vesterinen, 43 D. Vilanova, 18 P. Vint, 42 P. Vokac, 10 H.D. Wahl, 46 M.H.L. Wang, 69 J. Warchol, 53 G. Watts, 80
M. Wayne, 53 M. Weber, 47 L. Welty-Rieger, 50 M. Wetstein, 58 A. White, 76 D. Wicke, 24 M.R.J. Williams, 41
G.W. Wilson, 55 J.W. Wimpenney, 45 M. Wobisch, 57 D.R. Wood, 60 T.R. Wyatt, 63 Y. Xie, 47 C. Xu, 61 S. Yazooob, 50
R. Yamada, 47 W.-C. Yang, 43 T. Yasuda, 47 Y.A. Yatsunenko, 35 Z. Ye, 47 H. Yin, 7 K. Yip, 71 H.D. Yoo, 75

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We extract the total width of the top quark, $\Gamma_t$, from the partial decay width $\Gamma(t \to Wb)$ measured using the $t$-channel cross section for single top quark production and from the branching fraction $B(t \to Wb)$ measured in $t\bar{t}$ events using up to 2.3 fb$^{-1}$ of integrated luminosity collected by the D0 Collaboration at the Tevatron $p\bar{p}$ Collider. The result is $\Gamma_t = 1.99^{+0.69}_{-0.55}$ GeV, which translates to a top-quark lifetime of $\tau_t = (3.3^{+1.3}_{-0.3}) \times 10^{-25}$ s. Assuming a high mass fourth generation $b'$ quark and unitarity of the four-generation quark-mixing matrix, we set the first upper limit on $|V_{t'0}| < 0.63$ at 95% C.L.

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The total width, or lifetime, of the top quark is a fundamental property that has not been measured precisely so far. The top quark, like other fermions in the Standard Model (SM), decays through the electroweak interaction. But unlike $b$ and $c$ quarks, which form long-lived hadrons that can be observed through the reconstruction of displaced vertices in a tracking detector, the top quark has an extremely short lifetime.

In the SM, the total decay width of the top quark, $\Gamma_t$, is dominated by the partial decay width $\Gamma(t \to Wb)$ which, at next-to-leading order (NLO) in Quantum Chromodynamics (QCD), depends on the top quark mass $m_t$, the $W$ boson mass $M_W$, the $b$ quark mass $m_b$, the Fermi coupling constant $G_F$, the strong coupling constant $\alpha_s$ and the strength of the left-handed $Wtb$ coupling, $V_{tb}$. Neglecting higher order electroweak corrections, and terms of order $m_t^2/m_b^2$, $\alpha_s^2$, and $(\alpha_s/\pi) M_W^2/m_t^2$, the partial width becomes

$$\Gamma(t \to Wb) = \frac{G_F m_t^3}{8\pi \sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2 \frac{M_W^2}{m_t^2}\right) \times$$

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\[
\times \left[1 - \frac{2\alpha_s}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right].
\]

(1)

Setting \(\alpha_s(M_Z) = 0.118\), \(G_F = 1.16637 \times 10^{-5}\) GeV\(^{-2}\), \(M_W = 80.399\) GeV, \(|V_{tb}| = 1\), and \(m_t = 170\) GeV leads to \(\Gamma(t \to Wb)_{SM} = 1.26\) GeV. Equation (1) can be extended to include non-SM \(Wtb\) couplings. \(2\).

The decay width of an unstable particle can be measured with precision from its mass spectrum when the experimental resolution is similar or smaller than the natural width of the particle. Because \(\Gamma_t\) is far smaller than the experimental resolution, the analysis of the invariant mass distribution yields only an upper limit on \(\Gamma_t\) that is limited by the uncertainty on the detector resolution. The first such direct upper bound of \(\Gamma_t < 13.1\) GeV was set by CDF at 95% C.L. \(4\).

Following a suggestion in Ref. \(5\), we determine the partial width \(\Gamma(t \to Wb)\) of the top quark indirectly from the single top \(t\)-channel \((p\bar{p} \to t\bar{q}b + X)\) cross section measurement \(6\), assuming that the electroweak coupling in top quark production is identical to the coupling in top quark decay. Electroweak single top quark production proceeds via \(s\)-channel production and decay of a virtual \(W\) boson, or through exchange of a virtual \(W\) boson in the \(t\)-channel \(7\). \(8\). As in the case of top quarks, both processes involve the \(Wtb\) vertex and are therefore proportional to the partial width \(\Gamma(t \to Wb)\). Since contributions outside the SM have different effects on the \(s\)-channel and \(t\)-channel cross sections, the partial width is determined focusing on the single most sensitive channel in single top quark production, the \(t\)-channel, which is illustrated in Fig. \(1\).

![FIG. 1: Representative diagram for \(t\)-channel single top quark production.](image)

From the partial decay width and the branching fraction \(B(t \to Wb)\) \(6\), we form the total decay width:

\[
\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}.
\]

(2)

In addition to the experimental measurements, this method relies on the validity of the NLO QCD calculations of the single top quark cross section and of the top quark partial decay width. In these calculations only the contributions from SM processes are considered. Any deviation of the measured total width from the theoretical prediction would therefore indicate physics beyond the SM. One example is the presence of anomalous form factors in the \(Wtb\) vertex, such as right-handed vector couplings \(10\). This would change the measured \(t\)-channel cross section and therefore the extracted partial width. It would also modify the measurement of \(B(t \to Wb)\) due to the different event kinematics which would lead to different event selection efficiencies. Another example is a charged Higgs boson \(H^+\) with a mass \(m_H < m_t - m_b\) which preferably decays via \(H^+ \to c\bar{s}\) as predicted in some supersymmetric extensions of the SM \(11\). In this case, the fusion process \(H^+b \to t\) can compete with the SM single top quark production \((W^+b \to t)\), and the decay \(t \to H^+b\) can competes with the SM decay \((t \to W^+b)\). This would enhance the measured \(t\)-channel cross section, and affect the measured branching fraction \(B(t \to Wb)\). A third example studied in more detail in this Letter is a new fourth generation \(b'\) quark.

To extract the partial width \(\Gamma(t \to Wb)\), we use the measurement of the inclusive \(t\)-channel cross section obtained from data corresponding to 2.3 fb\(^{-1}\) of integrated luminosity \(6\). Without assuming \(B(t \to Wb) = 1\) as in that publication, the cross section measurement can be expressed as

\[
\sigma(t\text{-channel}) = 3.14^{+0.94}_{-0.80} \text{ pb }.
\]

(3)

Given the linear dependence of the cross section on the partial width, we derive the partial width as

\[
\Gamma(t \to Wb) = \sigma(t\text{-channel}) \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t\text{-channel})_{SM}}.
\]

(4)

For the predicted SM \(t\)-channel cross section, we use a calculation in NLO QCD that yields \(\sigma(t\text{-channel})_{SM} = 2.14 \pm 0.18\) pb \(12\) for \(m_t = 170\) GeV. For the partial width in the SM, we use the NLO result of \(\Gamma(t \to Wb)_{SM} = 1.26\) GeV from Eq. (1) Using Eqs. (2) and (3) the total width becomes:

\[
\Gamma_t = \frac{\sigma(t\text{-channel}) \Gamma(t \to Wb)_{SM}}{\sigma(t\text{-channel})_{SM}}.
\]

(5)

The branching fraction \(B(t \to Wb)\) is determined from our previous studies of \(tt\) events with different identified \(b\) jet multiplicities. \(6\):

\[
B(t \to Wb) = 0.962^{+0.068}_{-0.066} \text{ (stat)}^{+0.064}_{-0.052} \text{ (syst)}. \]

(6)

The \(B(t \to Wb)\) measurement (Eq. (6)) is used twice: to obtain the partial width in Eqs. (3) and (4) and to derive the total width in Eq. (5).

The analysis starts with the same Bayesian Neural Network (BNN) discriminants trained to measure the \(t\)-channel cross section \(6\) in 24 independent analysis channels, separated according to data-taking period, lepton flavor (\(e\) or \(\mu\)), jet multiplicity (2, 3 or 4), and number of \(b\)-tagged jets (1 or 2). We then form a Bayesian probability density \(13\) for the partial width based on Eq. (4) This
is combined with the measurement of $B(t \to Wb)$ which is performed selecting 3 and 4 jets, and 0, 1 or 2 $b$-tags for the $e$ and $\mu$ channels. In combining the probability densities we assume that all the values of $\Gamma(t \to Wb)$ are equiprobable, which corresponds to assuming a uniform probability density for the $t$-channel cross section and for $\Gamma_t$.

Systematic uncertainties are treated in the same way as for the combination of the CDF and D0 single top quark cross section measurements. The terms included in the uncertainty calculation are:

- Uncertainty on the integrated luminosity of 6.1%.
- Uncertainties on modeling the single top quark signal, which applies only to the $t$-channel cross section and includes uncertainties from initial- and final-state radiation, scale uncertainties and parton distribution functions (PDFs).
- Uncertainties in the modeling of the $t\bar{t}$ pair production signal for the $B(t \to Wb)$ measurement, which include uncertainties from PDFs, different event generators and hadronization models. They are correlated with the $t\bar{t}$ background yield uncertainty in the $t$-channel measurement.
- Uncertainties on the background MC simulation, including the $t\bar{t}$ normalization uncertainty in the $t$-channel obtained from theoretical calculations taking into account the uncertainty on $m_t$, and for $B(t \to Wb)$ the uncertainty on the $W$+jets and heavy-flavor samples normalization.
- Detector simulation uncertainty arising from the modeling of particle identification in MC.
- Uncertainties arising from the modeling of the different background sources that are obtained using data-driven methods.
- Uncertainty on $b$-jet identification involving $b$, $c$ and light-flavor jet tagging rates and the calorimeter response to $b$-jets.
- Jet energy scale (JES) uncertainty from the calorimeter response to light jets, uncertainties from JES corrections dependent on pseudorapidity and transverse momentum and other smaller contributions.

All systematic uncertainties of the $t$-channel cross section and the $B(t \to Wb)$ measurement are assumed to be either fully correlated or uncorrelated. Table 1 shows the relative systematic uncertainties used in the $t$-channel and $B(t \to Wb)$ measurements, and displays how the correlations are treated.

The expected and observed Bayesian probability densities for the partial width $\Gamma(t \to Wb)$ 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

$$\Gamma(t \to Wb) = 1.92^{+0.58}_{-0.51} \text{ GeV}. \quad (7)$$

The measurement of the partial width alone can be used to set a lower limit on the total width. From the observed partial width probability density in Fig. 2, we obtain that $\Gamma(t \to Wb) > 1.21 \text{ GeV}$ at 95% C.L. This is the lowest value of the partial width that bounds 95% of the area of the probability density. Since the total width must be larger than the partial width, it also must satisfy

$$\Gamma_t > 1.21 \text{ GeV} \text{ at 95\% C.L.} \quad (8)$$

Calculating the lifetime $\tau_t$ as the inverse of the total width, we determine an upper limit of $\tau_t < 5.4 \times 10^{-25} \text{ s}$. Models including an additional chiral-tensorial $Wtb$ coupling leading to non-SM helicity amplitudes of the top quark can be excluded by this result because they predict a partial width $\Gamma(t \to Wb) = 0.66 \text{ GeV}$. Combining the partial width (Eq. 7) with $B(t \to Wb)$ as in Eq. 2, we obtain the expected and observed probability densities for the total width $\Gamma_t$ shown in Fig. 3. The total top quark width is found to be

$$\Gamma_t = 1.99^{+0.69}_{-0.55} \text{ GeV}, \quad (9)$$

which can be expressed as a top quark lifetime of

$$\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25} \text{ s}. \quad (10)$$

The determination of the top quark width is used to set constraints on the coupling of a fourth generation $b'$
Sources of systematic uncertainties affecting the determination of $\Gamma_t$, including sources that affect both the normalization and the shape of the final discriminant. For some uncertainties we quote the range across the different channels. In the $t$-channel cross section measurement the top pair production modeling uncertainty is included in the “Other background from MC” modeling category. It is taken as fully correlated to the “Top pair production signal modeling” uncertainty in the $B(t \to Wb)$ measurement. The sources are 100% correlated between the two measurements for rows with an “X” in the correlations column, and uncorrelated otherwise.

<table>
<thead>
<tr>
<th>Sources</th>
<th>$\sigma(t$-channel), $%$</th>
<th>$B(t \to Wb)$, $%$</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>6.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Single top quark signal modeling</td>
<td>3.5–13.6</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Top pair production signal modeling</td>
<td>—</td>
<td>1.0</td>
<td>X</td>
</tr>
<tr>
<td>Other background from MC</td>
<td>15.1</td>
<td>0.6</td>
<td>X</td>
</tr>
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<td>Detector modeling</td>
<td>7.1</td>
<td>0.1</td>
<td>X</td>
</tr>
<tr>
<td>Background from data</td>
<td>13.7–54</td>
<td>1.7</td>
<td>X</td>
</tr>
<tr>
<td>$b$-jet identification</td>
<td>2–30</td>
<td>6.3</td>
<td>X</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.1–13.1</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

TABLE I: Sources of systematic uncertainties affecting the determination of $\Gamma_t$, including sources that affect both the normalization and the shape of the final discriminant. For some uncertainties we quote the range across the different channels. In the $t$-channel cross section measurement the top pair production modeling uncertainty is included in the “Other background from MC” modeling category. It is taken as fully correlated to the “Top pair production signal modeling” uncertainty in the $B(t \to Wb)$ measurement. The sources are 100% correlated between the two measurements for rows with an “X” in the correlations column, and uncorrelated otherwise.

In summary, we have presented the most precise determination of the width of the top quark into $Wb$ and the branching fraction $B(t \to Wb)$. It is assumed that the coupling leading to $t$-channel single top quark production is identical to the coupling leading to top quark decay. The total top quark width is determined to be $\Gamma_t = 1.99^{+0.69}_{-0.55}$ GeV for $m_t = 170$ GeV, which corresponds to a top quark lifetime of $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ s. In addition, we set the first limit on a fourth-generation $b'$ quark coupling to the top quark of $|V_{tb'}| < 0.63$ at 95% C.L.

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[9] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 100, 192003 (2008). Although the original publication used a top quark mass of 175 GeV, the $B(t \to Wb)$ value used in this Letter is derived for $m_t = 170$ GeV to be consistent with the $t$-channel cross section measurement.