An improved determination of the width of the top quark

V.M. Abazov, B. Abbott, B.S. Acharya, M. Adams, G.D. Alexeev, G. Alkhalaf, A. Alton, G. Alves, M. Aoki, A. Askew, B. Asman, S. Atkins, O. Atrakchentov, K. Augsten, C. Avila, J. Backus-Mayes, F. Badaud, L. Bagby, B. Baldin, D.V. Bandurin, S. Banerjee, E. Barberis, P. Baringer, J. Barroto, J.F. Bartlett, U. Bassler, V. Baxtiera, A. Bean, M. Begalli, C. Belanger-Champagne, L. Bellantoni, S.B. Beri, G. Bernardi, R. Bernhard, I. Bertram, M. Besançon, R. Beuselinck, V.A. Bezujobov, P.C. Bhat, S. Bhatia, V. Bhatnagar, G. Blazey, S. Blessing, K. Bloom, A. Boeheimlein, D. Boline, E.E. Boos, G. Borissov, T. Bose, A. Brandt, O. Brandt, R. Brock, G. Broojmans, A. Bross, D. Brown, J. Brown, X.B. Bu, M. Buehler, V. Buescher, V. Bunichev, S. Burdin, T.H. Burnett, C.P. Buszello, B. Calpas, E. Camacho-Pérez, M.A. Carrasco-Lizarraga, B.C.K. Casey, H. Castillo-Valdez, S. Chakrabarti, H. Chakraborthy, K.M. Chan, A. Chandra, E. Chapon, G. Chen, S. Chevalier-Théry, D.K. Cho, S.W. Cho, S. Choi, B. Choudhary, S. Chiang, D. Claes, J. Clutter, M. Cooke, W.E. Cooper, M. Corcoran, F. Couderc, M.-C. Cousinou, A. Crop, D. Cutts, A. Das, G. Davies, S.J. de Jong, E. De La Cruz-Burelo, F. Délié, R. Demina, D. Denisov, S.P. Denisov, S. Desai, C. Deterre, K. DeVaughan, H.T. Diehl, M. Diesburg, P.F. Ding, A. Dominguez, T. Dorland, A. Dubey, T. Dugan, D. Dugger, A. Duperrin, S. Dutt, A. Dyshkant, M. Eads, D. Edmunds, J. Ellison, V.D. Elvira, Y. Enari, H. Evans, A. Evdokimov, V.N. Evdokimov, G. Facini, T. Ferbel, F. Fiedler, F. Filthaut, W. Fisher, H.E. Fisk, M. Fortner, H. Fox, S. Fouess, A. Garcia-Bellido, G.A. García-Guerrero, V. Gavrilo, P. Gay, W. Geng, D. Gerbaudo, C.E. Gerber, Y. Gershtein, G. Ginther, G. Golovanov, A. Goussiou, C.P. Graf, P.D. Grannis, S. Greder, H. Greenlee, Z.D. Greenwood, E.M. Gregores, G. Grenier, Ph. Gris, J.F. Grivaz, A. Grishejev, M.W. Grümewald, T. Guillemin, G. Gutierrez, P. Guiterrez, A. Haas, S. Hagopian, J. Haley, L. Han, K. Harder, A. Harel, J.M. Hauptman, J. Hayas, T. Heege, H. Hedlin, H. Hegab, A.P. Heinson, U. Heintz, C. Hensel, I. Heredia-De La Cruz, K. Herner, G. Hesketh, M.D. Hildreth, R. Hirosky, T. Hoang, J.D. Hobbs, B. Hoeineisen, M. Hohlmeier, Z. Hubble, V. Hynne, I. Iashvili, Y. Ilyenkov, R. Illingworth, A.S. Ito, J. Jabeen, M. Jaffré, D. Jamin, A. Jayasinghe, R. Jesik, K. Johns, M. Johnson, A. Jonckheere, P. Jonsson, J. Joshi, A.W. Jung, A. Juste, K. Kaadze, E. Kafkas, D. Karanov, P.A. Kasper, I. Katsanos, R. Kehoe, S. Kerniche, N. Khaltatyan, A. Khanov, A. Kharchilava, Y.N. Kharchzeev, J.M. Kohli, A.V. Kozelov, J. Kraus, S. Kulikov, A. Kumar, A. Kupec, T. Kurca, V.A. Kuzmin, S. Lammers, G. Landsberg, J. Lebrun, H.S. Lee, S.W. Lee, W.M. Lee, J. Lellouch, H. Li, L. Li, Q.Z. Li, S.M. Lietti, J.K. Lim, D. Lindon, L. Linnemann, V.V. Lipaev, R. Lipton, Y. Liu, A. Lobodenko, M. Lokajicek, R. Lopes de Sa, H.J. Lubatti, R. Luna-Garcia, A.L. Lyon, G. A.K.A. Maciel, D. Mackin, R. Madar, V.L. Malyshov, Y. Maravin, J. Martínez-Ortega, R. McCarthy, C.L. McGivney, M.M. Meijer, A. Mehnitchouk, D. Menezes, P.G. Mercadante, M. Merklin, A. Meyer, J. Meyer, F. Miconi, N.K. Mondal, G.S. Muanza, M. Mulhearn, E. Nagy, M. Naimuddin, M. Narain, R. Nayyar, H.A. Neal, J.P. Negret, P. Neustroev, S.F. Novaes, T. Nummenmaa, G. Obrant, J. Orduna, N. Osman, J. Osta, G.J. Otero y Garzón, M. Padilla, A. Pal, J. Penning, M. Perillo, Y. Peters, K. Petriddy, G. Petriulli, P. Petit, R. Piegía, M.-A. Pleier, P.L.M. Podesta-Lerma, V.M. Podstavkov, P. Polozov, A.V. Popov, M. Prewitt, D. Price, N. Prokopenko, J. Qian, A. Quadt, B. Quinn, M.S. Rangel, K. Ranjan, P.N. Ratoff, I. Razumov, P. Renkel, M. Rispens, E. Ripp-Baudot, F. Rizatdinova, M. Rominsky, A. Ross, C. Royon, P. Rubin, R. Ruchti, G. Safronov, G. Sajot, P. Salcido, A. Sánchez-Hernández, M.P. Sanders, B. Sangh, A.S. Santos, G. Savage, L. Sawyer, T. Scanlon, R.D. Schamberger, Y. Scheglov, H. Schellman, T. Schiepke, S. Schlobohm, C. Schwaneberger, R. Schwienhorst, J. Sekaric, H. Severini, E. Shabalina, V. Shary, A.A. Shchukin, K.R. Shivpuri, V. Simak, V. Sirotenko, P. Skubic, P. Slattery, D. Smirnov, K.J. Smith, G.R. Snow, J. Snow, S. Snyder, S. Söldner-Rembold, L. Sonnenschein, K. Soustruznik, J. Stark, V. Stolin, D.A. Stoyanova, M. Strauss, D. Strom, L. Stutte, L. Suter, P. Svoisky, M. Takahashi, A. Tanasijczuk, M. Titov, V.V. Tokmenin, Y.-T. Tsai, K. Tscharn-Grimm, D. Tsybychev, B. Tuchming, C. Tully, U. Uvarov, S. Uvarov, S. Uzunyan, R. Van Leeuwen, N. Varelas, E.W. Varnes, I.A. Vasilyev,
P. Verdier, L.S. Vertogradov, M. Vezzoni, P. Vokac, H.D. Wahl, M.H.L.S. Wang, J. Warchol, G. Watts, M. Wayne, M. Weber, J. Weichert, L. Welty-Rieger, A. White, D. Wicke, M.R.J. Williams, G.W. Wilson, M. Wobisch, D.R. Wood, T.R. Wyatt, Y. Xie, R. Yamada, W.-C. Yang, T. Yasuda, Y.A. Yatsunenko, W. Ye, Z. Ye, H. Yin, K. Yip, S.W. Youn, T. Zhao, B. Zhou, M. Zielinski, D. Zieminska, and L. Zivkovic (The D0 Collaboration*)

1 Universidad de Buenos Aires, Buenos Aires, Argentina
2 LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3 Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4 Universidade Federal do ABC, Santo André, Brazil
5 Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6 University of Science and Technology of China, Hefei, People’s Republic of China
7 Universidad de los Andes, Bogotá, Colombia
8 Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic
9 Czech Technical University in Prague, Prague, Czech Republic
10 Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
11 Universidad San Francisco de Quito, Quito, Ecuador
12 LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
13 LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
14 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
15 LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
16 LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France
17 CEA, Ifpp, Saclay, France
18 IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
19 IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
20 III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
21 Physikalisches Institut, Universität Freiburg, Freiburg, Germany
22 II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
23 Institut für Physik, Universität Mainz, Mainz, Germany
24 Ludwig-Maximilians-Universität München, München, Germany
25 Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany
26 Panjab University, Chandigarh, India
27 Delhi University, Delhi, India
28 Tata Institute of Fundamental Research, Mumbai, India
29 University College Dublin, Dublin, Ireland
30 Korea Detector Laboratory, Korea University, Seoul, Korea
31 CINVESTAV, Mexico City, Mexico
32 Nikhef, Science Park, Amsterdam, the Netherlands
33 Radboud University Nijmegen, Nijmegen, the Netherlands and Nikhef, Science Park, Amsterdam, the Netherlands
34 Joint Institute for Nuclear Research, Dubna, Russia
35 Institute for Theoretical and Experimental Physics, Moscow, Russia
36 Moscow State Physics Institute, Moscow, Russia
37 Institute for High Energy Physics, Protvino, Russia
38 Petersburg Nuclear Physics Institute, St. Petersburg, Russia
39 Institució Catalana de Recerca i Estudis Avançats (ICREA) and Institut de Física d’Altes Energies (IFAE), Barcelona, Spain
40 Stockholm University, Stockholm and Uppsala University, Uppsala, Sweden
41 Lancaster University, Lancaster LA1 4YB, United Kingdom
42 Imperial College London, London SW7 2AZ, United Kingdom
43 The University of Manchester, Manchester M13 9PL, United Kingdom
44 University of Arizona, Tucson, Arizona 85721, USA
45 University of California Riverside, Riverside, California 92521, USA
46 Florida State University, Tallahassee, Florida 32306, USA
47 Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA
48 University of Illinois at Chicago, Chicago, Illinois 60607, USA
49 Northern Illinois University, DeKalb, Illinois 60115, USA
50 Northwestern University, Evanston, Illinois 60208, USA
51 Indiana University, Bloomington, Indiana 47405, USA
52 Purdue University Calumet, Hammond, Indiana 46323, USA
53 University of Notre Dame, Notre Dame, Indiana 46556, USA
We present an improved determination of the total width of the top quark, $\Gamma_t$, using 5.4 fb$^{-1}$ of integrated luminosity collected by the D0 Collaboration at the Tevatron $p\bar{p}$ Collider. The total width $\Gamma_t$ is extracted from the partial decay width $\Gamma(t \rightarrow Wb)$ and the branching fraction $B(t \rightarrow Wb)$. $\Gamma(t \rightarrow Wb)$ is obtained from the $t$-channel single top quark production cross section and $B(t \rightarrow Wb)$ is measured in $t\bar{t}$ events. For a top mass of 172.5 GeV, the resulting width is $\Gamma_t = 2.00^{+0.47}_{-0.45}$ 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 CKM matrix element $|V_{tb}| < 0.59$ for a high mass fourth generation bottom quark assuming unitarity of the fourth generation quark mixing matrix.

PACS numbers: 14.65.Ha, 14.65.Jk, 12.15.Hh

\section*{INTRODUCTION}

The top quark is the heaviest known elementary particle and complete 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 \cite{1}. Within the SM, the top quark decays almost exclusively into a $W$ boson and a $b$ quark. The total decay width $\Gamma_t$ is therefore expected to be dominated by the partial decay width $\Gamma(t \rightarrow Wb)$. Neglecting higher order electroweak corrections and terms of order $m_t^2/m_W^2$, $\alpha^2_s$ and $(\alpha_s/\pi)M_W^2/m_t^2$, the partial width predicted by the SM at next-to-leading order (NLO) is \cite{2}

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

(1)

where $m_t$ ($m_b$) is the mass of the top (bottom) quark, $G_F$ ($\alpha_s$) the Fermi (strong interaction) coupling constant, $M_W$ the mass of the $W$ boson, and $V_{tb}$ the strength of the 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, $|V_{tb}| = 1$ \cite{3}, and assuming $m_t = 172.5$ GeV, we obtain $\Gamma(t \rightarrow Wb)_{\text{SM}} = 1.33$ 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
...where $t \to W b$ can be 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 or by both a $b$ and a light quark in the $t$ channel. 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. Figure 1 shows the tree-level Feynman diagrams for $s$- and $t$-channel production. In this Letter, we determine $\Gamma(t \to W b)$ from a measurement of the $t$-channel single top quark production cross section, making use of the fact that the process involves a $W b$ vertex and is thus proportional to $\Gamma(t \to W b)$. The $t$-channel was chosen as it has the highest production cross section at the Tevatron 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 $\Gamma_t$ 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 $\Gamma_t$ 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 and the branching fraction $B(t \to W b)$ determined from a sample of $t\bar{t}$ events in 0.9 fb$^{-1}$ of integrated luminosity. This method assumes the $W \to t\bar{b}$ coupling in single top quark production is the same as in top quark decay.

In this Letter, we apply the method in a new indirect determination of $\Gamma_t$ 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 $\sigma(p\bar{p} \to t\bar{b}X) = 2.90 \pm 0.59$ (stat+syst) pb and the ratio $R = B(t \to W b)/B(t \to W q) = 0.90 \pm 0.04$ where $q$ can be a $d$, $s$ or $b$ quark.

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

$$\Gamma(t \to W b) = \sigma(t\text{-channel}) \frac{\Gamma(t \to W b)_{\text{SM}}}{\sigma(t\text{-channel})_{\text{SM}}}. \quad (2)$$

The total decay width $\Gamma_t$ can be written in terms of the partial decay width and the branching fraction $B(t \to W b)$ as

$$\Gamma_t = \frac{\Gamma_p}{B(t \to W b)}. \quad (3)$$

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

$$\Gamma_t = \frac{\sigma(t\text{-channel}) \Gamma(t \to W b)_{\text{SM}}}{B(t \to W b) \sigma(t\text{-channel})_{\text{SM}}}. \quad (4)$$

from which it is possible to derive the lifetime of the top quark as $\tau_t = \frac{\Gamma_t}{\Gamma}$. We can also use the measured value of $\Gamma_p$ to probe the $W tb$ interaction and directly determine the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix 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. However, this method assumes that the top quark decays exclusively to $W b$, 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 $t \to W d$ and $t \to W s$ decays) and the single top production 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.

**ANALYSIS METHOD**

This analysis relies on two prior D0 measurements, the single top $t$-channel cross section and the ratio of the top quark branching fraction. 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 $l\nu$. In both cases, we accept events in which the $W$ boson decayed to a $\tau$ lepton that subsequently decayed into an electron or a muon. We use a neural network $b$-tagging algorithm 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].

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

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

where $D$ and $d$ 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 ($\Gamma_p$) or total ($\Gamma_t$) top quark width as

$$d(\Gamma_{p,t}, \sigma', a_t, a_s, b) = c_{\{p,t\}} \Gamma_{p,t} a_t + \sigma' a_s + b$$

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

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

or by

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

when measuring the partial or total top quark decay width, respectively. The extra $\mathcal{B}(t \to Wb)$ term with respect to Eqs. [18] and [19] is necessary to remove the assumption of $\mathcal{B}(t \to Wb) = 1$ used when generating the single top $t$ and $\bar{t}t$ samples. We then form a Bayesian probability density for the partial or total width by integrating the expression

$$p(\Gamma_{p,t}|D) = \frac{1}{N} \int L(D|\Gamma_{p,t}, \sigma', a_t, a_s, b)\pi(\Gamma_{p,t})\pi(\sigma')\pi(a_t)\pi(a_s)\pi(b)d \sigma'd a_t d a_s db,$$

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

### 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:

- Uncertainty on jet flavor identification involving $b$, $c$ and light-flavor jet tagging rates and the calorimeter-

| 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 |

| 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 the most important uncertainties for the branching fraction and $t$-channel cross section measurements, respectively.
The total width \( \Gamma \) of the top quark is found to be 

\[
\Gamma_t = 2.00^{\pm0.47}_{-0.43} \text{ GeV},
\]

which can be expressed as a top quark lifetime of

\[
\tau_t = (3.29^{+0.30}_{-0.63}) \times 10^{-25} \text{ s}.
\]

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

**TOP QUARK MASS DEPENDENCE**

The measured branching fraction and t-channel production cross section, as well as \( \Gamma(t \rightarrow Wb)_{\text{SM}} \), depend on the top quark mass \( m_t \). To study this dependency, we repeat the analysis using simulated \( tt \) and single top samples that were generated at different values of \( m_t \) in the range 170 to 175 GeV. The value of \( \Gamma(t \rightarrow Wb)_{\text{SM}} \) is recalculated depending on \( m_t \). Given that the dependence from \( m_t \) is small, the value and uncertainties for \( B(t \rightarrow Wb) \) corresponding to \( m_t = 172.5 \text{ GeV} \) 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 non-monotonic variation observed for the $t$-channel cross section [14].

The effect of the mass dependency can be quantified by interpolating the observed $\Gamma_t$ in function of top mass from Table III to the current Tevatron combination $m_t = 173.2 \pm 0.9$ GeV [29]. Adding a mass uncertainty of $\delta\Gamma_t = \max_{m_t \in [172.5, 175]} |\Gamma_t(m_t) - \Gamma_t(173.2)| \approx 0.07$ 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 $\tau_t = 3.24^{+0.95}_{-0.69} \times 10^{-25}$ 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 $\Gamma_t$ approximates a Gaussian distribution. This translates into an upper limit on the top quark lifetime of $\tau_t < 4.82 \times 10^{-25}$ 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.

**MEASUREMENT OF $|V_{tb}|$**

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

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

in Eq. [13]. 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 $|V_{tb'}|$. 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.

**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 $B(t \to Wb)$. 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.

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); NRF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).
[1] K. Nakamura et al. (Particle Data Group) J. Phys G 37, 075021 (2010).
[2] M. Jezabek and J. H. Kühn, Nucl. Phys. B 314, 1 (1989).
[3] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 101, 221801 (2008).
[4] Y. Grossman, Nucl. Phys. B 426, 355 (1994).
[5] S. Cortese and R. Petronzio, Phys. Lett. B 253, 494 (1991).
[6] S. S. D. Willenbrock and D. A. Dicus, Phys. Rev. D 34, 155 (1986).
[7] C.-P. Yuan, Phys. Rev. D 41, 42 (1990).
[8] N. Kidonakis, Phys. Rev. D 74, 114012 (2006). The cross sections for the single top quark processes \( m_t = 172.5 \text{ GeV} \) are 1.04 ± 0.04 pb (s channel), 2.26 ± 0.12 pb (t channel), and 0.28 ± 0.06 pb (tW channel).
[9] Unless otherwise stated, charge-conjugate states are implied.
[10] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 102, 042001 (2009).
[11] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 106, 022001 (2011).

[12] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 682, 363 (2010).
[13] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 100, 192003 (2008). Although the original publication used \( m_t = 175 \text{ GeV} \), the \( B(t \to Wb) \) value used in this Letter is derived for \( m_t = 170 \text{ GeV} \) to be consistent with the t-channel cross section measurement.
[14] V. M. Abazov et al. (D0 Collaboration), Phys. Lett. B 705, 313 (2011).
[15] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 107, 121802 (2011).
[16] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
[17] G. V. Jikia and S.R. Slabospitsky, Phys. Lett. B 295, 136 (1992).
[18] V. M. Abazov et al. (D0 Collaboration), Nucl. Instrum. Methods in Phys. Res. Sect. A 620, 490 (2010).
[19] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. D 78, 012005 (2008).
[20] The Tevatron Electroweak Working Group for the CDF and D0 Collaborations, arXiv:1107.3395 [hep-ex].