PRL 106, 022001 (2011) PHYSICAL REVIEW LETTERS week ending 14 JANUARY 2011

Determination of the Width of the Top Quark

V. M. Abazov,[35] B. Abbott,[73] M. Abolins,[62] B. S. Acharya,[29] M. Adams,[48] T. Adams,[46] G. D. Alexeev,[35] G. Alkhazov,[39] A. Alton,[61,*] G. Alverson,[60] G. A. Alves,[2] L. S. Ancu,[34] M. Aoki,[47] Y. Arnoud,[14] M. Arov,[57] A. Askew,[46] B. Åsman,[40] O. Atramentov,[65] C. Avila,[8] J. BackusMayes,[80] F. Badaud,[13] L. Bagby,[47] B. Baldin,[47] D. V. Bandurin,[46] S. Banerjee,[29] E. Barberis,[60] P. Baringer,[55] J. Barreto,[2] J. F. Bartlett,[47] U. Bassler,[18] V. Bazterra,[48] S. Beale,[6] A. Bean,[55] M. Begalli,[3] M. Begel,[71] C. Belanger-Champagne,[40] L. Bellantoni,[47] S. B. Beri,[27] G. Bernardi,[17] R. Bernhard,[22] I. Bertram,[41] M. Besançon,[18] R. Beuselinck,[42] V. A. Bezzubov,[38] P. C. Bhat,[47] V. Bhatnagar,[27] G. Blazey,[49] S. Blessing,[46] K. Bloom,[64] A. Boehnlein,[47] D. Boline,[70] T. A. Bolton,[56] E. E. Boos,[37] G. Borissov,[41] T. Bose,[59] A. Brandt,[76] O. Brandt,[23] R. Brock,[62] G. Brooijmans,[68] A. Bross,[47] D. Brown,[17] J. Brown,[17] X. B. Bu,[7] D. Buchholz,[50] M. Buehler,[79] V. Buescher,[24] V. Bunichev,[37] S. Burdin,[41,†] T. H. Burnett,[80] C. P. Buszello,[42] B. Calpas,[15] E. Camacho-Pérez,[32] M. A. Carrasco-Lizarraga,[32] B. C. K. Casey,[47] H. Castilla-Valdez,[32] S. Chakrabarti,[70] D. Chakraborty,[49] K. M. Chan,[53] A. Chandra,[78] G. Chen,[55] S. Chevalier-Théry,[18] D. K. Cho,[75] S. W. Cho,[31] S. Choi,[31] B. Choudhary,[28] T. Christoudias,[42] S. Cihangir,[47] D. Claes,[64] J. Clutter,[55] M. Cooke,[47] W. E. Cooper,[47] M. Corcoran,[78] F. Couderc,[18] M.-C. Cousinou,[15] A. Croc,[18] D. Cutts,[75] M. Ćwiok,[30] A. Das,[44] G. Davies,[42] K. De,[76] S. J. de Jong,[34] E. De La Cruz-Burelo,[32] F. Déliot,[18] M. Demarteau,[47] R. Demina,[69] D. Denisov,[47] S. P. Denisov,[38] S. Desai,[47] K. DeVaughan,[64] H. T. Diehl,[47] M. Diesburg,[47] A. Dominguez,[64] T. Dorland,[80] A. Dubey,[28] L. V. Dudko,[37] D. Duggan,[65] A. Duperrin,[15] S. Dutt,[27] A. Dyshkant,[49] M. Eads,[64] D. Edmunds,[62] J. Ellison,[45] V. D. Elvira,[47] Y. Enari,[17] S. Eno,[58] H. Evans,[51] A. Evdokimov,[71] V. N. Evdokimov,[38] G. Facini,[60] T. Ferbel,[58,69] F. Fiedler,[24] F. Filthaut,[34] W. Fisher,[62] H. E. Fisk,[47] M. Fortner,[49] H. Fox,[41] S. Fuess,[47] T. Gadfort,[71] A. Garcia-Bellido,[69] V. Gavrilov,[36] P. Gay,[13] W. Geist,[19] W. Geng,[15,62] D. Gerbaudo,[66] C. E. Gerber,[48] Y. Gershtein,[65] G. Ginther,[47,69] G. Golovanov,[35] A. Goussiou,[80] P. D. Grannis,[70] S. Greder,[19] H. Greenlee,[47] Z. D. Greenwood,[57] E. M. Gregores,[4] G. Grenier,[20] Ph. Gris,[13] J.-F. Grivaz,[16] A. Grohsjean,[18] S. Grünendahl,[47] M. W. Grünewald,[30] F. Guo,[70] J. Guo,[70] G. Gutierrez,[47] P. Gutierrez,[73] A. Haas,[68,‡] S. Hagopian,[46] J. Haley,[60] L. Han,[7] K. Harder,[43] A. Harel,[69] J. M. Hauptman,[54] J. Hays,[42] T. Head,[43] T. Hebbeker,[21] D. Hedin,[49] H. Hegab,[74] A. P. Heinson,[45] U. Heintz,[75] C. Hensel,[23] I. Heredia-De La Cruz,[32] K. Herner,[61] G. Hesketh,[60] M. D. Hildreth,[53] R. Hirosky,[79] T. Hoang,[46] J. D. Hobbs,[70] B. Hoeneisen,[12] M. Hohlfeld,[24] S. Hossain,[73] Z. Hubacek,[10] N. Huske,[17] V. Hynek,[10] I. Iashvili,[67] R. Illingworth,[47] A. S. Ito,[47] S. Jabeen,[75] M. Jaffré,[16] S. Jain,[67] D. Jamin,[15] R. Jesik,[42] K. Johns,[44] M. Johnson,[47] D. Johnston,[64] A. Jonckheere,[47] P. Jonsson,[42] J. Joshi,[27] A. Juste,[47,§] K. Kaadze,[56] E. Kajfasz,[15] D. Karmanov,[37] P. A. Kasper,[47] I. Katsanos,[64] R. Kehoe,[77] S. Kermiche,[15] N. Khalatyan,[47] A. Khanov,[74] A. Kharchilava,[67] Y. N. Kharzheev,[35] D. Khatidze,[75] M. H. Kirby,[50] J. M. Kohli,[27] A. V. Kozelov,[38] J. Kraus,[62] A. Kumar,[67] A. Kupco,[11] T. Kurča,[20] V. A. Kuzmin,[37] J. Kvita,[9] S. Lammers,[51] G. Landsberg,[75] P. Lebrun,[20] H. S. Lee,[31] S. W. Lee,[54] W. M. Lee,[47] J. Lellouch,[17] L. Li,[45] Q. Z. Li,[47] S. M. Lietti,[5] J. K. Lim,[31] D. Lincoln,[47] J. Linnemann,[62] V. V. Lipaev,[38] R. Lipton,[47] Y. Liu,[7] Z. Liu,[6] A. Lobodenko,[39] M. Lokajicek,[11] P. Love,[41] H. J. Lubatti,[80] R. Luna-Garcia,[32,∥] A. L. Lyon,[47] A. K. A. Maciel,[2] D. Mackin,[78] R. Madar,[18] R. Magaña-Villalba,[32] S. Malik,[64] V. L. Malyshev,[35] Y. Maravin,[56] J. Martínez-Ortega,[32] R. McCarthy,[70] C. L. McGivern,[55] M. M. Meijer,[34] A. Melnitchouk,[63] D. Menezes,[49] P. G. Mercadante,[4] M. Merkin,[37] A. Meyer,[21] J. Meyer,[23] N. K. Mondal,[29] G. S. Muanza,[15] M. Mulhearn,[79] E. Nagy,[15] M. Naimuddin,[28] M. Narain,[75] R. Nayyar,[28] H. A. Neal,[61] J. P. Negret,[8] P. Neustroev,[39] S. F. Novaes,[5] T. Nunnemann,[25] G. Obrant,[39] J. Orduna,[32] N. Osman,[42] J. Osta,[53] G. J. Otero y Garzón,[1] M. Owen,[43] M. Padilla,[45] M. Pangilinan,[75] N. Parashar,[52] V. Parihar,[75] S. K. Park,[31] J. Parsons,[68] R. Partridge,[75,‡] N. Parua,[51] A. Patwa,[71] B. Penning,[47] M. Perfilov,[37] K. Peters,[43] Y. Peters,[43] G. Petrillo,[69] P. Pétroff,[16] R. Piegaia,[1] J. Piper,[62] M.-A. Pleier,[71] P. L. M. Podesta-Lerma,[32,¶] V. M. Podstavkov,[47] M.-E. Pol,[2] P. Polozov,[36] A. V. Popov,[38] M. Prewitt,[78] D. Price,[51] S. Protopopescu,[71] J. Qian,[61] A. Quadt,[23] B. Quinn,[63] M. S. Rangel,[2] K. Ranjan,[28] P. N. Ratoff,[41] I. Razumov,[38] P. Renkel,[77] P. Rich,[43] M. Rijssenbeek,[70] I. Ripp-Baudot,[19] F. Rizatdinova,[74] M. Rominsky,[47] C. Royon,[18] P. Rubinov,[47] R. Ruchti,[53] G. Safronov,[36] G. Sajot,[14] A. Sánchez-Hernández,[32] M. P. Sanders,[25] B. Sanghi,[47] A. S. Santos,[5] G. Savage,[47] L. Sawyer,[57] T. Scanlon,[42] R. D. Schamberger,[70] Y. Scheglov,[39] H. Schellman,[50] T. Schliephake,[26] S. Schlobohm,[80] C. Schwanenberger,[43] R. Schwienhorst,[62] J. Sekaric,[55] H. Severini,[73] E. Shabalina,[23] V. Shary,[18] 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. Söldner-Rembold,[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. Titov,[18] V. V. Tokmenin,[35] D. Tsybychev,[70] B. Tuchming,[18] C. Tully,[66] P. M. Tuts,[68]

0031-9007/11/106(2)/022001(7)

L. Uvarov,[39] S. Uvarov,[39] S. Uzunyan,[49] R. Van Kooten,[51] W. M. van Leeuwen,[33] N. Varelas,[48] E. W. Varnes,[44] I. A. Vasilyev,[38] P. Verdier,[20] L. S. Vertogradov,[35] M. Verzocchi,[47] M. Vesterinen,[43] D. Vilanova,[18] P. Vint,[42] P. Vokac,[10] H. D. Wahl,[46] M. H. L. S. 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] S. J. Wimpenny,[45] M. Wobisch,[57] D. R. Wood,[60] T. R. Wyatt,[43] Y. Xie,[47] C. Xu,[61] S. Yacoob,[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] S. W. Youn,[47] J. Yu,[76] S. Zelitch,[79] T. Zhao,[80] B. Zhou,[61] J. Zhu,[61] M. Zielinski,[69] D. Zieminska,[51] and L. Zivkovic[68]

(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]*Simon Fraser University, Vancouver, British Columbia, and York University, Toronto, Ontario, Canada*
[7]*University of Science and Technology of China, Hefei, People's Republic of China*
[8]*Universidad de los Andes, Bogotá, Colombia*
[9]*Charles University, Faculty of Mathematics and Physics, Center for Particle Physics, Prague, Czech Republic*
[10]*Czech Technical University in Prague, Prague, Czech Republic*
[11]*Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[12]*Universidad San Francisco de Quito, Quito, Ecuador*
[13]*LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France*
[14]*LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France*
[15]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[16]*LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
[17]*LPNHE, Universités Paris VI and VII, CNRS/IN2P3, Paris, France*
[18]*CEA, Irfu, SPP, Saclay, France*
[19]*IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France*
[20]*IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France*
[21]*III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany*
[22]*Physikalisches Institut, Universität Freiburg, Freiburg, Germany*
[23]*II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[24]*Institut für Physik, Universität Mainz, Mainz, Germany*
[25]*Ludwig-Maximilians-Universität München, München, Germany*
[26]*Fachbereich Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[27]*Panjab University, Chandigarh, India*
[28]*Delhi University, Delhi, India*
[29]*Tata Institute of Fundamental Research, Mumbai, India*
[30]*University College Dublin, Dublin, Ireland*
[31]*Korea Detector Laboratory, Korea University, Seoul, Korea*
[32]*CINVESTAV, Mexico City, Mexico*
[33]*FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands*
[34]*Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands*
[35]*Joint Institute for Nuclear Research, Dubna, Russia*
[36]*Institute for Theoretical and Experimental Physics, Moscow, Russia*
[37]*Moscow State University, Moscow, Russia*
[38]*Institute for High Energy Physics, Protvino, Russia*
[39]*Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[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*
[54]*Iowa State University, Ames, Iowa 50011, USA*
[55]*University of Kansas, Lawrence, Kansas 66045, USA*
[56]*Kansas State University, Manhattan, Kansas 66506, USA*
[57]*Louisiana Tech University, Ruston, Louisiana 71272, USA*
[58]*University of Maryland, College Park, Maryland 20742, USA*
[59]*Boston University, Boston, Massachusetts 02215, USA*
[60]*Northeastern University, Boston, Massachusetts 02115, USA*
[61]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[62]*Michigan State University, East Lansing, Michigan 48824, USA*
[63]*University of Mississippi, University, Mississippi 38677, USA*
[64]*University of Nebraska, Lincoln, Nebraska 68588, USA*
[65]*Rutgers University, Piscataway, New Jersey 08855, USA*
[66]*Princeton University, Princeton, New Jersey 08544, USA*
[67]*State University of New York, Buffalo, New York 14260, USA*
[68]*Columbia University, New York, New York 10027, USA*
[69]*University of Rochester, Rochester, New York 14627, USA*
[70]*State University of New York, Stony Brook, New York 11794, USA*
[71]*Brookhaven National Laboratory, Upton, New York 11973, USA*
[72]*Langston University, Langston, Oklahoma 73050, USA*
[73]*University of Oklahoma, Norman, Oklahoma 73019, USA*
[74]*Oklahoma State University, Stillwater, Oklahoma 74078, USA*
[75]*Brown University, Providence, Rhode Island 02912, USA*
[76]*University of Texas, Arlington, Texas 76019, USA*
[77]*Southern Methodist University, Dallas, Texas 75275, USA*
[78]*Rice University, Houston, Texas 77005, USA*
[79]*University of Virginia, Charlottesville, Virginia 22901, USA*
[80]*University of Washington, Seattle, Washington 98195, USA*
(Received 2 October 2010; published 11 January 2011)

We extract the total width of the top quark, Γ_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 $\mathcal{B}(t \to Wb)$ 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 $\tau_t = (3.3^{+1.3}_{-0.9}) \times 10^{-25}$ 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 $|V_{tb'}| < 0.63$ at 95% C.L.

DOI: 10.1103/PhysRevLett.106.022001 PACS numbers: 14.65.Ha, 12.15.Hh, 14.65.Jk

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, Γ_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 α_s, and the strength of the left-handed Wtb coupling, V_{tb}. Neglecting higher order electroweak corrections [1] 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 becomes [2]

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

where the mass corrections and the NLO QCD corrections account for a reduction of the width of about 13% and 10%, respectively. The electroweak corrections are less than 2%. Setting $\alpha_s(M_Z) = 0.118$, $G_F = 1.166\,37 \times 10^{-5}\ \text{GeV}^{-2}$, $M_W = 80.399$ GeV, $|V_{tb}| = 1$, and $m_t = 170$ GeV leads to $\Gamma(t \to Wb)_{\text{SM}} = 1.26$ GeV. Equation (1) can be extended to include non-SM Wtb couplings [3].

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 Γ_t is far smaller than the experimental resolution, the analysis of the invariant mass distribution yields only an upper limit on Γ_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 the CDF Collaboration 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 ($p\bar{p} \to tqb + X$) cross section measurement [6], assuming that the coupling in the production of top quarks is identical to the coupling in their decays. 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]. We measured cross sections of $3.14^{+0.94}_{-0.80}$ pb for the t channel and 1.05 ± 0.81 pb for the s channel. Our measured t-channel cross section is consistent with the standard model prediction [6].

As in the decay 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.

From the partial decay width and the branching fraction $\mathcal{B}(t \to Wb)$ [9], we form the total decay width

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{\mathcal{B}(t \to Wb)}. \tag{2}$$

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. Examples are the presence of anomalous Wtb couplings [10], hadronically decaying charged Higgs bosons as predicted in some supersymmetric extensions of the SM [11] or a fourth generation b' quark. We discuss the latter scenario in detail below.

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 $\mathcal{B}(t \to Wb) = 1$ as in that publication, the cross section measurement can be expressed as

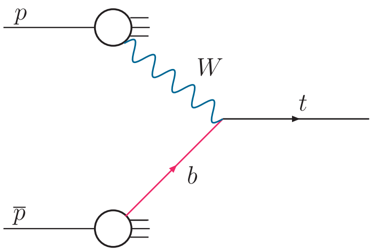

FIG. 1 (color online). Representative diagram for t-channel single top-quark production.

$$\sigma(t-\text{channel})\mathcal{B}(t \to Wb) = 3.14^{+0.94}_{-0.80}\ \text{pb}. \tag{3}$$

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

$$\Gamma(t \to Wb) = \sigma(t-\text{channel})\frac{\Gamma(t \to Wb)_{\text{SM}}}{\sigma(t-\text{channel})_{\text{SM}}}. \tag{4}$$

For the predicted SM t-channel cross section, we use a calculation in NLO QCD that yields $\sigma(t-\text{channel})_{\text{SM}} = 2.14 \pm 0.18$ pb [12] for $m_t = 170$ GeV summing up the single top and single antitop-quark production cross sections. For the partial width in the SM, we use the NLO result of $\Gamma(t \to Wb)_{\text{SM}} = 1.26$ GeV from Eq. (1). Using Eqs. (2) and (4), the total width becomes

$$\Gamma_t = \frac{\sigma(t-\text{channel})\Gamma(t \to Wb)_{\text{SM}}}{\mathcal{B}(t \to Wb)\sigma(t-\text{channel})_{\text{SM}}}. \tag{5}$$

The branching fraction $\mathcal{B}(t \to Wb)$ is determined repeating our previous analysis [9] assuming $m_t = 170$ GeV to be consistent with our t-channel cross section measurement. This correctly takes into account the mass dependence of the signal efficiency, yielding

$$\mathcal{B}(t \to Wb) = 0.962^{+0.068}_{-0.066}(\text{stat})^{+0.064}_{-0.052}(\text{syst}). \tag{6}$$

The $\mathcal{B}(t \to Wb)$ 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 discriminants trained to measure the t-channel cross section [6] in 24 independent analysis channels, separated according to the data-taking period, lepton flavor (e or μ), 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 $\mathcal{B}(t \to Wb)$ which is performed selecting 3 and 4 jets, and 0, 1, or 2 b tags for the e and μ 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 Γ_t.

Systematic uncertainties are treated in the same way as for the combination [14] of the CDF [15] and D0 [16] single top-quark cross section measurements. Each independent source is modeled as a Gaussian probability density function with zero mean and width corresponding to 1 standard deviation of the parameter representing the systematic uncertainty. The terms included in the uncertainty calculation are: (i) Uncertainty on the integrated luminosity of 6.1%. (ii) Uncertainties on modeling the single top-quark signal, which applies only to the t-channel cross section and includes uncertainties from

TABLE I. Sources of systematic uncertainties affecting the determination of Γ_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 $\mathcal{B}(t \to Wb)$ measurement. The sources are 100% correlated between the two measurements for rows with an "X" in the correlations column, and are uncorrelated otherwise.

Sources	$\sigma(t - \text{channel})$, %	$\mathcal{B}(t \to Wb)$, %	Correlations
Components for Normalization			
Luminosity	6.1	0.0	
Single Top Quark Signal Modeling	3.5–13.6	0.0	
Top Pair Production Signal Modeling	-	1.0	X
Other Background from MC	15.1	0.6	X
Detector Modeling	7.1	0.1	X
Components for Normalization and Shape			
Background from Data	13.7–54	1.7	X
b-Jet Identification	2–30	6.3	X
Jet Energy Scale	0.1–13.1	0.0	

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

All systematic uncertainties of the t-channel cross section and the $\mathcal{B}(t \to Wb)$ measurement are assumed to be either fully correlated or uncorrelated. Table I shows the relative systematic uncertainties used in the t-channel and $\mathcal{B}(t \to Wb)$ 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

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

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 $\Gamma(t \to Wb) > 1.21$ 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

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

Calculating the lifetime τ_t as the inverse of the total width, we determine an upper limit of $\tau_t < 5.4 \times 10^{-25}$ s. Models including an additional chiral-tensorial Wtb coupling

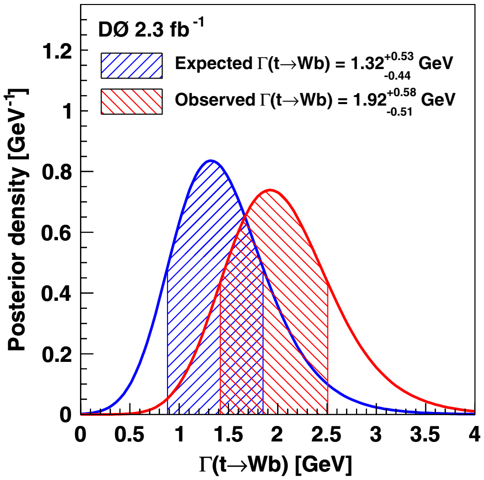

FIG. 2 (color online). Probability density for the expected and measured partial width $\Gamma(t \to Wb)$. The hatched areas represent 1 standard deviation around the most probable value.

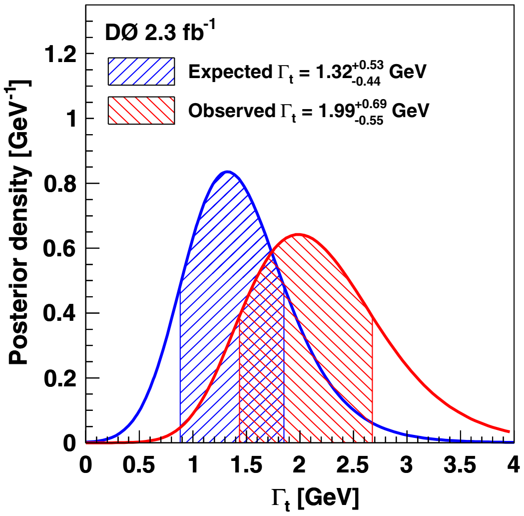

FIG. 3 (color online). Probability density for the expected and measured total width Γ_t. The hatched areas represent 1 standard deviation around the most probable value.

leading to non-SM helicity amplitudes of the top quark can be excluded by this result because they predict a partial width $\Gamma(t \to Wb) = 0.66$ GeV [17].

Combining the partial width [Eq. (7)] with $\mathcal{B}(t \to Wb)$ as in Eq. (2), we obtain the expected and observed probability densities for the total width Γ_t shown in Fig. 3. The total top-quark width is found to be

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

which can be expressed as a top-quark lifetime of

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

The determination of the top-quark width is used to set constraints on the coupling of a fourth generation b' quark to the top quark. Assuming $m_{b'} > m_t - m_W$, a small probability density for the b' quark in protons and antiprotons, and unitarity of the quark-mixing matrix, including the fourth quark generation ($|V_{tb}|^2 + |V_{tb'}|^2 = 1$, and $|V_{td}|$, $|V_{ts}| \ll 1$), the measurement of the total top-quark width can be used to extract a limit on the mixing matrix element $|V_{tb'}|$. Using a flat prior for $0 \leq |V_{tb}| \leq 1$ yields $|V_{tb'}| < 0.63$ at 95% C.L. This is the first limit on the W boson coupling to the top quark and a fourth generation b' quark.

In summary, we have presented the most precise determination of the width of the top quark. It is based on the measurement of two quantities, the partial decay width of the top quark into Wb and the branching fraction $\mathcal{B}(t \to Wb)$. 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.

We wish to thank C.-P. Yuan for fruitful discussions regarding this analysis. 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); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

---

[*] Visitor from Augustana College, Sioux Falls, SD, USA

[†] Visitor from The University of Liverpool, Liverpool, UK

[‡] Visitor from SLAC, Menlo Park, CA, USA

[§] Visitor from ICREA/IFAE, Barcelona, Spain

[‖] Visitor from Centro de Investigacion en Computacion-IPN, Mexico City, Mexico

[¶] Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico

[**] Visitor from Universität Bern, Bern, Switzerland.

[1] A. Denner and T. Sack, Nucl. Phys. **B358**, 46 (1991).

[2] M. Jezabek and J. H. Kühn, Nucl. Phys. **B314**, 1 (1989).

[3] C. R. Chen, F. Larios, and C.-P. Yuan, Phys. Lett. B **631**, 126 (2005).

[4] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **102**, 042001 (2009).

[5] D. O. Carlson and C.-P. Yuan in *Proceedings of Particle Theory and Phenomenology, International Warsaw—Kazimierz Meeting on Particle Physics and Madison Phenomenology Symposium, Ames, Iowa* (World Scientific, Singapore, 1995) p. 172.

[6] V. M. Abazov *et al.* (D0 Collaboration), Phys. Lett. B **682**, 363 (2010).

[7] S. S. D. Willenbrock and D. A. Dicus, Phys. Rev. D **34**, 155 (1986).

[8] C.-P. Yuan, Phys. Rev. D **41**, 42 (1990).

[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 $\mathcal{B}(t \to Wb)$ value used in this Letter is derived for $m_t = 170$ GeV to be consistent with the t-channel cross section measurement.

[10] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **101**, 221801 (2008).

[11] Y. Grossman, Nucl. Phys. **B426**, 355 (1994).

[12] N. Kidonakis, Phys. Rev. D **74**, 114012 (2006); N. Kidonakis (private communication) (2010). The uncertainty on the cross section includes a component which accounts for the variation of the assumed value of the top-quark mass.

[13] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. D **78**, 012005 (2008).

[14] The Tevatron Electroweak Working Group for the CDF and D0 Collaborations, arXiv:0908.2171.

[15] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **103**, 092002 (2009).

[16] V. M. Abazov *et al.* (D0 Collaboration), Phys. Rev. Lett. **103**, 092001 (2009).

[17] C. A. Nelson, arXiv:0808.2940; C. A. Nelson, Phys. Rev. D **65**, 074033 (2002).