DØ Note 6034-CONF

Determination of the width of the top quark

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We extract the total width of the top quark Γ_t 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 measured t-channel cross section for single top quark production in 2.3 fb^{-1} of $p\bar{p}$ data from the D0 collaboration, and $\mathcal{B}(t \to Wb)$ is extracted from a measurement of the ratio $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$ in $t\bar{t}$ events in lepton+jets channels with 0, 1 and 2 b-tags in 1 fb^{-1} of integrated luminosity. Assuming $\mathcal{B}(t \to Wq) = 1$, where q includes any kinematically accessible quark, the result is: $\Gamma_t = 2.1 \pm 0.6$ GeV which translates to a top quark lifetime of $\tau_t = (3 \pm 1) \times 10^{-25}$ s. The use of the partial width measurement alone yields the limits $\Gamma_t > 1.2$ GeV and $\tau_t < 5 \times 10^{-25}$ s, at 95% C.L.

Preliminary Results for Winter 2010 Conferences

I. INTRODUCTION

The total width, or lifetime, of the top quark is a fundamental property that has been largely unexplored. The top quark, just as other fermions in the standard model (SM), decays through the weak interaction. But unlike the b and c quarks, which form long-lived hadrons that can be detected as displaced vertices in a detector, the lifetime of the top quark (τ_t) is extremely short. Currently, the only direct limit on τ_t is from $t\bar{t}$ lepton+jets events, based on the impact parameter of the lepton's trajectory [1], which provides an upper limit $c\tau_t < 52.5$ μm at 95% C.L. For very short lifetimes, we can measure the total decay width, and then calculate the lifetime as the inverse of the width: $\tau_t = \hbar/\Gamma_t$ (in the following we use natural units $c = \hbar = 1$).

The decay width of an unstable particle can be measured with precision from its mass spectrum when the experimental resolution is better than the natural width of the particle. At leading order in the SM, the total decay width of the top quark depends on its mass m_t, the Fermi coupling constant G_F, and the strength of the left-handed Wtb coupling V_{tb}:

$$\Gamma_t^0 = \frac{G_F m_t^3}{8\pi\sqrt{2}} \times |V_{tb}|^2. \tag{1}$$

Eq. 1 can be extended to include non-SM Wtb couplings [2]. At next-to-leading order (NLO), the width is still proportional to $|V_{tb}|^2$ because the corrections that affect the coupling are negligible [3]. Neglecting terms of order m_b^2/m_t^2, α_s^2, and $(\alpha_s/\pi)M_W^2/m_t^2$, the total width becomes [4]:

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

which yields an approximate value of $\Gamma_t = 1.3$ GeV for $m_t = 170$ GeV. Since the precision of this calculation is high, the theoretical uncertainties on it can be neglected.

Consequently, because Γ_t is far smaller than the experimental resolution, it cannot be determined directly; rather one obtains only an upper limit on Γ_t that is comparable to the uncertainty on detector resolution. The first such direct upper bound was set by CDF at $\Gamma_t < 13.1$ GeV at 95% C.L. for a top mass of 175 GeV [5]. An updated result for an integrated luminosity of 4.3 fb^{-1} yields an upper bound of $\Gamma_t < 7.5$ GeV at 95% C.L., or a central value of 0.4 GeV$< \Gamma_t <$4.4 GeV at 68% C.L. [6].

Following a suggestion in Ref. [7], we determine the width of the top quark indirectly by combining the cross section for the single-top t-channel ($p\bar{p} \to tqb + X$) [8], which is proportional to the partial width $\Gamma(t \to Wb)$, with the ratio of branching fractions $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$ [9], assuming that the top quark decays into a W boson and any possible quark of flavor q, i.e. $\mathcal{B}(t \to Wq) = 1$. From the partial decay width and the branching fraction, we form the total decay width:

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

II. THEORETICAL FRAMEWORK

Electroweak single top quark production proceeds via the s-channel production and decay of a virtual W boson and the t-channel exchange of a virtual W boson [10, 11]. Both processes involve the Wtb vertex, just like the top quark decay. Thus, the measured combined single top quark cross section is proportional to the partial width $\Gamma(t \to Wb)$ of the top quark. However, contributions outside the SM have different effects on the s-channel and t-channel cross sections, and an extraction of the width from the combined single top cross section is only valid for SM couplings.

This situation is improved and the width determination is more generally valid by focusing on t-channel single top quark production alone. The t-channel production of single top quarks $q'b \to qt$ proceeds through the $W{-}b$ fusion, which can be described in the "effective W approximation" [11, 12], implied in Fig. 1.

In this approach, the W boson is treated as a parton within the proton or antiproton [13]. The kinematics of this factorization are exactly the same as in deep-inelastic scattering, but the W boson is treated as on-shell rather than as a virtual particle. Hence the virtuality (mass) of the three particles is similar to that in top quark decay. The cross section in Fig. 1 is then directly proportional to the partial width, without having to make any assumptions about the coupling [14]. Any anomalous contribution to the Wtb vertex would factorize and lead to an enhancement of the

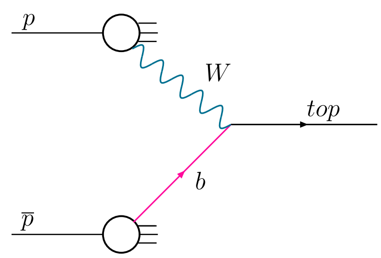

FIG. 1: Representative diagram for $W\!-\!b$ fusion.

partial width. The partial width $\Gamma(t \to Wb)$ is therefore extracted from the measurement of the t-channel $(Wb \to t)$ single top cross section rather than the combination of $s+t$ channel single top production.

The branching fraction $\mathcal{B}(t \to Wb)$ can be obtained from the measurement of $t\bar{t}$ events with 0, 1 and 2 b-tags, namely $R = \mathcal{B}(t \to Wb)/\mathcal{B}(t \to Wq)$, assuming $\mathcal{B}(t \to Wq) = 1$. The total width can then be calculated from Eq. 3.

This extraction relies on the fact that within the SM there are no flavor-changing neutral current (FCNC) interactions, and the CKM elements V_{ts} and V_{td} are very small [4]. Thus the t-channel single top production involves fusion of only the b parton with a W boson, and the decay of the top quark into a W boson and any quark is assured.

III. ANALYSIS PROCEDURE

To extract the partial width $\Gamma(t \to Wb)$, we use the measured inclusive t-channel cross section, but do not assume a branching ratio $\mathcal{B}(t \to Wb) = 1$ as in [8]:

$$\sigma(t\text{−channel})\,\mathcal{B}(t \to Wb) = 3.14^{+0.94}_{-0.80}\ \text{pb}\ , \tag{4}$$

which is obtained from 2.3 fb^{-1} of $p\bar{p}$ collision data from the D0 detector.

As $\mathcal{B}(t \to Wb)$ we use the measurement of the ratio of top quark branching fractions R for $m_t = 170$ GeV, derived with 1 fb^{-1} of data in Ref. [9]:

$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = 0.962^{+0.068}_{-0.066}(\text{stat})\ ^{+0.064}_{-0.052}(\text{syst}) \tag{5}$$

and set $\mathcal{B}(t \to Wq) = 1$.

Given the linearity between the cross section and the partial width, we derive the partial width as

$$\Gamma(t \to Wb) = \sigma(t\text{−channel})\ \frac{\Gamma(t \to Wb)_{\text{SM}}}{\sigma(t\text{−channel})_{\text{SM}}}\ . \tag{6}$$

For the predicted SM t-channel cross section we use the calculation in NLO QCD $\sigma(t\text{−channel})_{\text{SM}} = 2.15 \pm 0.24$ pb for $m_t = 170$ GeV [16]. For the partial width in the SM, we use the calculation also in NLO QCD from Eq. 2, and determine $\Gamma(t \to Wb)_{\text{SM}} = 1.26$ GeV for $\alpha_S(M_Z) = 0.118$, $G_F = 1.16637 \times 10^{-5}$ GeV^{-2}, $M_W = 80.399$ GeV and $m_t = 170$ GeV.

Using Eqns. 3 and 6 the total width is derived as:

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

The $\mathcal{B}(t \to Wb)$ measurement from R (Eq. 5) is used twice: once to obtain the partial width in Eq. 6 from Eq. 4 and a second time to derive the total width in Eq. 7.

IV. STATISTICAL ANALYSIS

We start with the same Bayesian Neural Network (BNN) discriminants trained to measure the t-channel cross section [8] in 24 independent analysis channels separated according to the dataset 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 posterior [17, 18] for the partial width based on Eq. 6.

The measurement of the $\mathcal{B}(t \to Wb)$ is performed on data similar to the single top sample, but using data only from the first 1 fb^{-1}, for e and μ channels, 3 and 4 jets, and 0, 1 or 2 b-tags.

The analysis is performed at a top quark mass of 170 GeV. We choose a prior that is flat in $\Gamma(t \to Wb)$, which is equivalent to a prior flat in the cross section, and flat in Γ_t.

V. SYSTEMATIC UNCERTAINTIES

The systematic uncertainties are treated in the same way as for the combined Tevatron single top cross section [19]. Briefly, this includes the following:

- luminosity determination uncertainty on detector acceptance and efficiency and on the diffractive and inelastic cross sections;
- uncertainties on modeling the single top signal, which applies only to the t-channel cross section and includes uncertainties from initial and final state radiation (ISR and FSR), and parton distribution functions (PDF) descriptions;
- uncertainty for modeling top pair production signal, which includes uncertainties from different generators and hadronization models for R, and is correlated with the $t\bar{t}$ background yield in the t-channel;
- background from Monte Carlo (MC) includes for the t-channel the $t\bar{t}$ normalization uncertainty obtained from theoretical calculations taking into account the error on m_t, and for R the uncertainty on the W+jets and heavy-flavor samples normalization;
- detector-modeling uncertainty arising from the uncertainty on efficiencies for object identification and MC mismodeling of data;
- uncertainties on background from data, arising from modeling different sources using data-driven methods;
- uncertainty on b-tagging, from the b-jet identification and mistag rate and shape modeling; and
- jet-energy scale (JES) uncertainty from uncertainties in calorimeter response to light jets, uncertainties from η and p_T-dependent JES corrections, and other smaller contributions.

All systematic uncertainties of the t-channel single top cross section and the R measurement were ordered into the above categories and taken either fully correlated or fully uncorrelated. The result of this can be seen in Table I, which shows the relative systematic uncertainties used in the t-channel and R measurements, and displays how the correlation was treated.

Although the two original publications used different top masses: 170 GeV for the t-channel measurement and 175 GeV for the R measurement, we have used $m_t = 170$ GeV throughout. The value of R is quite insensitive to m_t, as expected for the ratio of two decay kinematics, and the single top t-channel measurement includes the uncertainty on m_t in the MC background modeling uncertainty for $t\bar{t}$.

VI. RESULT

The expected and observed Bayesian posterior densities for the partial width $\Gamma(t \to Wb)$ are shown in Fig. 2.

The most probable value for the partial width is given by the peak of the posterior and corresponds to

$$\Gamma(t \to Wb) = 1.90^{+0.58}_{-0.48} \text{ GeV}. \tag{8}$$

The partial width measurement alone can be used to set a lower limit on the total width. From the observed partial width posterior in Fig. 2, we obtain that $\Gamma(t \to Wb) > 1.21$ GeV at the 95% C.L. This is the lower value of the partial

Relative Systematic Uncertainties			
Sources	**t-channel**	**R measurement**	**Correlations**
Components for Normalization			
Luminosity	6.1%	0.0%	
Single top 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-tagging	2–30%	6.3%	X
Jet Energy Scale	0.1–13.1%	0.0%	

TABLE I: Sources of systematic uncertainty used as input to the determination of Γ_t, including those 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 R measurement. An "X" in the correlations column means the two sources are 100% correlated between the two measurements, and uncorrelated otherwise.

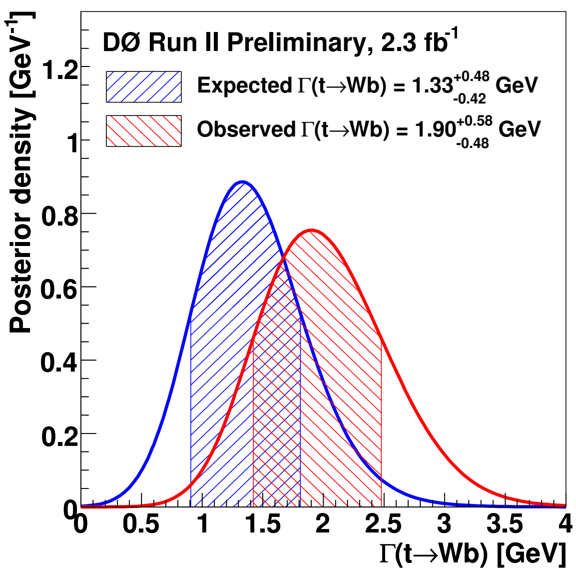

FIG. 2: Posterior probability density for the expected and measured partial width $\Gamma(t \to Wb)$. The hatched areas represent one standard deviation around the peaks.

width that contains 95% of the area of the posterior density. Since $\Gamma(t \to Wb) > 1.21$ GeV, the total width must therefore also satisfy:

$$\Gamma_t > 1.21 \text{ GeV at } 95\% \text{ C.L.} \tag{9}$$

Which translates into an upper limit on $\tau_t < 5.4 \times 10^{-25}$ s. These results are valid for any anomalous contributions which affect $W{-}b$ fusion in single top production. Certain models of non-SM helicity amplitudes of the top quark can be excluded because they predict a partial width of 0.66 GeV [20].

Finally, combining the partial width (Eq. 8) with the $\mathcal{B}(t \to Wb)$ as in Eq. 7, we obtain the expected and observed posterior densities for the total width Γ_t as shown in Fig. 3.

The total top quark width is determined to be

$$\Gamma_t = 2.05^{+0.57}_{-0.52} \text{ GeV} \quad , \tag{10}$$

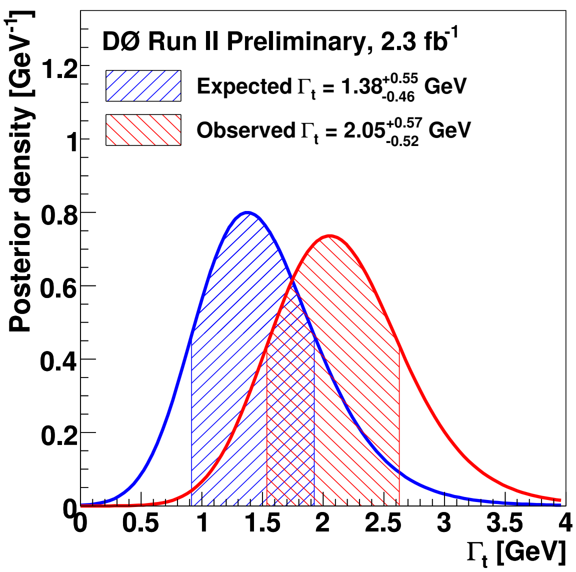

FIG. 3: Posterior probability density for the expected and measured total width Γ_t. The hatched areas represent one standard deviation around the peaks.

which can be expressed as a top quark lifetime of $\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25}$ s.

This is the most precise determination of the width of the top quark. It is based on the measurement of two quantities, the top quark partial decay width and the decay fraction. Direct measurements of the total decay width from the top quark invariant mass distribution or the decay length are independent of any model assumptions, but are limited by the experimental resolutions. Here, it is assumed that the t-channel single top production involves only the fusion of a b parton with a W boson and that the top quark decays into a W boson and any type of quark. Examples of new physics that can be probed by this result are anomalous form factors in the Wtb vertex such as right-handed vector couplings or 4th generation b' quarks.

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