

## Measurement of $R = \mathcal{B}(t \rightarrow Wb) / \mathcal{B}(t \rightarrow Wq)$ in Top–Quark–Pair Decays using Dilepton Events and the Full CDF Run II Data Set

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We present a measurement of the ratio of the top-quark branching fractions  $R = \mathcal{B}(t \rightarrow Wb)/\mathcal{B}(t \rightarrow Wq)$ , where  $q$  represents any quark flavor, in events with two charged leptons, imbalance in total transverse energy, and at least two jets. The measurement uses proton–antiproton collision data at center-of-mass energy 1.96 TeV, corresponding to an integrated luminosity of  $8.7 \text{ fb}^{-1}$  collected with the Collider Detector at Fermilab during Run II of the Tevatron. We measure  $R$  to be  $0.87 \pm 0.07$ , and extract the magnitude of the top-bottom quark coupling to be  $|V_{tb}| = 0.93 \pm 0.04$ , assuming three generations of quarks. Under these assumptions, a lower limit of  $|V_{tb}| > 0.85(0.87)$  at 95 (90) % credibility level is set.

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In the standard model (SM) of fundamental interactions, the top–quark decay rate into a  $W$  boson and a down-type quark  $q$  ( $q = d, s, b$ ) is proportional to  $|V_{tq}|^2$ , the squared element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix [1]. In the hypothesis of three generations and unitarity for that  $3 \times 3$  matrix, and using the existing constraints on  $V_{ts}$  and  $V_{td}$ , the magnitude of the top–bottom quark coupling is  $|V_{tb}| = 0.99915_{-0.00005}^{+0.00002}$  [2, 3]. Under these assumptions, the ratio of the branching fractions

$$R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)}, \quad (1)$$

is indirectly determined by the knowledge of  $|V_{ts}|$  and  $|V_{td}|$  [2] as

$$R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.99830_{-0.00009}^{+0.00004}, \quad (2)$$

implying that the top–quark decays almost exclusively to the  $Wb$  final state. A deviation from this prediction would be an indication of non-SM physics, suggesting, for example, the existence of a fourth quark generation [4].

The branching ratio and  $|V_{tb}|$  in Eq. 2 can be determined by studying the rate of decays of pair-produced top–quarks into different quark flavors. In this article we report the measurement of  $R$  in the sample of top–quark pairs decaying leptonically ( $t\bar{t} \rightarrow W^+qW^-\bar{q} \rightarrow q\bar{q}\ell\ell\nu\bar{\nu}$ ). This method was used in previous measurements of  $R$  by the CDF [5] and the D0 [6] collaborations at the Fermilab Tevatron proton–antiproton collider. In the channel involving two charged leptons in the final state (dilepton channel), D0 measured  $R = 0.86 \pm 0.05$  [6]. Recently the CDF collaboration updated its measurement in the

channel involving a charged lepton and jets obtaining  $R = 0.94 \pm 0.09$  [7], both consistent with SM expectations.

A direct measurement of  $|V_{tb}|$  can be obtained from the single-top-quark production cross section [8], which is proportional to  $|V_{tb}|^2$ . By contrast, the branching ratio measurement reported here, based on top-pair-production, determines the size of  $|V_{tb}|$  relative to the other CKM matrix elements. While the single top measurement depends on the absolute cross section, the branching ratio measurement depends on the relative yields for 0, 1, or 2 top decays to a  $b$ -quark. In this sense the two measurements are complementary and the measurement of  $|V_{tb}|$  presented here is less dependent on either the uncertainty on the theoretical calculation of the top-quark production cross section or many experimental uncertainties associated with its measurements.

This analysis studies events with two charged leptons, either electron ( $e$ ) or muon ( $\mu$ ), two neutrinos, and two or more jets in the final state; we do not search for  $\tau$  leptons. We use the full Run II data set, corresponding to an integrated luminosity of  $8.7 \text{ fb}^{-1}$  collected with the CDF II detector [9] at the Tevatron at center-of-mass energy  $\sqrt{s} = 1.96 \text{ TeV}$ .

The CDF II detector [9] consists of a particle spectrometer embedded in a magnetic field of 1.4 T, with inner tracking chambers surrounded by electromagnetic and hadronic calorimeters segmented into towers projecting to the interaction point, and outer muon detectors. A tracking system composed of a silicon microstrip detector located at radial distance  $r$  from the beam  $1.5 \leq r \leq 28 \text{ cm}$  and of a drift chamber at  $43 \leq r \leq 132 \text{ cm}$ , provides the reconstruction of charged-particle momentum

and trajectories with full efficiency up to pseudorapidity  $|\eta| \approx 1$  [10]. The silicon microstrip detector is essential for the detection of vertices displaced from the  $p\bar{p}$  collision point signaling the decay of long-lived particles. A three-level, online event-selection system [11] is used to select events with an  $e$  ( $\mu$ ) candidate in the central detector region of pseudorapidity  $|\eta| < 1.1$ , with  $E_T$  ( $p_T$ )  $> 18$  GeV ( $> 18$  GeV/ $c$ ), which form the data set for this analysis.

The measurement of  $R$  is based on the determination of the number of jets originated from  $b$ -quarks ( $b$ -jets) in  $t\bar{t}$  events reconstructed in the dilepton final state. The dilepton signature consists of two high- $p_T$  charged leptons ( $e$  or  $\mu$ ), large missing transverse energy  $\cancel{E}_T$  [10] due to the undetected neutrinos from the leptonic  $W$ -boson decays, and at least two hadronic jets. The identification of  $b$ -jets (*tagging*) is performed by the SECVTX algorithm [12], which reconstructs secondary vertices separated from the primary collision vertex.

In order to better exploit the subsample-dependent signal-to-background ratio, we divide the sample into nine statistically independent subsamples according to dilepton flavor ( $ee, \mu\mu, e\mu$ ) and  $b$ -tagging content (presence of 0, 1, or 2 tags).

As the number of  $b$ -jets in the event is related to the top-quark branching fraction in the  $Wb$  final state, we use the number of observed and predicted events in the various subsamples as input to a likelihood function, which is maximized to extract  $R$ .

The selection is similar to the one used by the CDF collaboration to measure the  $t\bar{t}$  cross section in the dilepton channel [13]. We select events with offline-reconstructed isolated oppositely-charged electrons ( $E_T \geq 20$  GeV) or muons ( $p_T \geq 20$  GeV/ $c$ ). The contributions due to known standard model processes other than  $t\bar{t}$  are further reduced by requiring a minimum  $\cancel{E}_T$  of 25 GeV, increased to 50 GeV if the direction of any lepton or jet is closer than  $20^\circ$  to the  $\cancel{E}_T$  direction, and  $\cancel{E}_T$  significance in excess of  $4$  (GeV) $^{1/2}$  [13] for events with same-flavor lepton pairs whose invariant mass is in a range of  $\pm 15$  GeV/ $c^2$  around the  $Z$  boson mass [2]. Jets are reconstructed using a fixed-size cone algorithm [14], with radius of 0.4 in pseudorapidity-azimuthal angle  $\eta - \phi$  space. We select events with at least two taggable [12] jets with  $E_T \geq 20$  GeV and  $|\eta| < 2$  after correcting for primary vertex position and jet energy scale. Given the large size of the top-quark mass, we require the sum of the transverse energies of the reconstructed leptons and jets,  $H_T$ , to be greater than 200 GeV.

The remaining background is composed of dibosons ( $WW, WZ, ZZ$ ), Drell-Yan (DY) events ( $\tau^+\tau^-, e^+e^-, \mu^+\mu^-$ ) with jets from initial (ISR) or final (FSR) state radiation and large  $\cancel{E}_T$  from energy mismeasurements, and associated production of  $W$  bosons with multiple jets where one of the jets is misidentified as a charged lepton (*fakes*). The contributions of SM processes producing

two real leptons are estimated using samples of events generated by Monte Carlo (MC) programs. The detector response is then simulated using a GEANT [15] based software package. A combination of data and Monte Carlo samples is used to estimate the contribution of jets misidentified as leptons [13]. Diboson processes are simulated using PYTHIA [16] and normalized to their next-to-leading order in strong interaction coupling cross sections,  $\sigma_{WW} = 11.34 \pm 0.68$  pb,  $\sigma_{WZ} = 3.47 \pm 0.21$  pb,  $\sigma_{ZZ} = 3.62 \pm 0.22$  pb [17]. Drell-Yan and  $Z \rightarrow \ell\ell$  events with associated jets are generated using ALPGEN [18], with hadronization simulated using PYTHIA.

Signal  $t\bar{t}$  events are modeled using the POWHEG [19] generator, with hadronization simulated using PYTHIA. A top-quark mass value of 172.5 GeV/ $c^2$ , consistent with recent measurements [20], is assumed.

Due to the high purity of the  $t\bar{t}$  signal in dilepton events, it is possible to perform a measurement of the  $t\bar{t}$  cross section in the sample without requiring  $b$ -tagging. This result, free of any assumption on  $\mathcal{B}(t \rightarrow Wb)$ , is then used to predict the yield of top-quark events in the various tagging categories. After the selection we find 286 events, which constitutes the *pretag* sample, with an expected background of  $54 \pm 7$  events. The largest background contributions are due to events containing jets misidentified as leptons and Drell-Yan events. From this we measure  $\sigma_{p\bar{p} \rightarrow t\bar{t}} = 7.64 \pm 0.55$ (stat) pb, in agreement with previous results [13].

In order to compare data and expectations in the nine subsamples we predict the amount of signal and background in each of them. In those subsamples containing one or two  $b$ -tagged jets, we estimate the number of expected background events following the same strategy used in the  $b$ -tagged dilepton cross section measurement [13]. We use these estimates to calculate the background in the subsamples with zero  $b$ -tags by subtracting their sum from the total background in the pretag sample. All background estimates are independent of  $R$ . A summary of SM expectations and observed events by tagging category is given in Table I.

The jet  $b$ -tagging efficiency is measured in MC samples using the SECVTX algorithm after checking that the identified jet originates from the hadronization of a bottom quark. This efficiency is corrected for differences between data and simulation. Mistagging occurs if jets from light-flavor quarks are mistakenly identified as coming from  $b$ -jets, and its efficiency is calculated using data templates and parametrized as a function of event variables such as jet energy and number of tracks in  $\eta$  and  $p_T$  intervals. In  $t\bar{t}$  events we find an efficiency of  $\simeq 40\%$  for tagging  $b$ -jets and a mistagging probability, of  $\simeq 1\%$ . Both efficiencies are used as inputs to the final fit. In the likelihood we include the possibility of reconstructing a third jet. The number of  $t\bar{t}$  signal events expected in each bin of the likelihood is a function of the probability for a jet to be tagged, which depends on  $R$  since a  $b$ -quark-generated

Process	Pretag	1 tag	2 tags
Dibosons	5.4±0.6	0.66±0.10	0.035±0.014
DY+LF	10.7±1.6	1.50±0.70	0.029±0.015
DY+HF	N/A	0.63±0.12	0.17±0.06
Fakes	21.8±4.3	5.6 ±1.9	1.0 ±0.5
Total background	54±7	8.3± 2.1	1.25±0.53
$t\bar{t}$ ( $\sigma=7.4$ pb)	223±20	100± 9	29±4
Total prediction	278±21	110±10	30.8±4.2
Observed	286	96	35

TABLE I: Summary of background contributions,  $t\bar{t}$  SM expectations (assuming  $|V_{tb}| = 1$ ), and data candidates by tagging categories for the 8.7 fb<sup>-1</sup> data sample. HF and LF indicate Heavy Flavor and Light Flavor jets.

jet is more likely to be  $b$ -tagged. In Fig. 1 the number of events observed in data and expected for different values of  $R$  in the different tagging categories is shown. The number of  $t\bar{t}$  events expected in each bin is obtained by multiplying the number of signal events before requiring  $b$ -tagging by the  $R$ -dependent probability of having 0, 1, or 2  $b$ -tagged jets in the event.

In order to extract  $R$  we maximize the likelihood

$$L = \prod_i \mathcal{P}(\mu_{\text{exp}}^i(R, x_j) | N_{\text{obs}}^i) \prod_j G(x_j | \bar{x}_j, \sigma_j), \quad (3)$$

where the index  $i$  runs over the nine subsamples;  $\mathcal{P}(\mu_{\text{exp}}^i(R, x_j) | N_{\text{obs}}^i)$  is the Poisson probability to observe  $N_{\text{obs}}^i$  events, given the expected value  $\mu_{\text{exp}}^i$ ; and  $G(x_j | \bar{x}_j, \sigma_j)$  are Gaussian probability density functions describing the knowledge of nuisance parameters  $x_j$ , with mean  $\bar{x}_j$  and standard deviation  $\sigma_j$ . These nuisance parameters describe luminosity, background estimates, selection acceptances, and relevant efficiencies. By using the same fit parameters for common sources of systematic uncertainties, correlations among different channels are taken into account.

In the likelihood maximization  $R$  is left as a free parameter. In addition, we evaluate the effect of several contributions not accounted for among nuisance parameters. We estimate the systematic uncertainty due to imperfect modeling of initial-state and final-state gluon radiation by varying their amount in simulated events [21] and taking as uncertainty the difference of the result with respect to the nominal one. The contribution from the jet-energy scale is estimated by varying its value by  $\pm 1$  standard deviation [21], refitting the data, and taking as uncertainty the difference of the result with respect to

the nominal result. We find

$$R = 0.871 \pm 0.045(\text{stat})_{-0.057}^{+0.058}(\text{sys}) = 0.87 \pm 0.07. \quad (4)$$

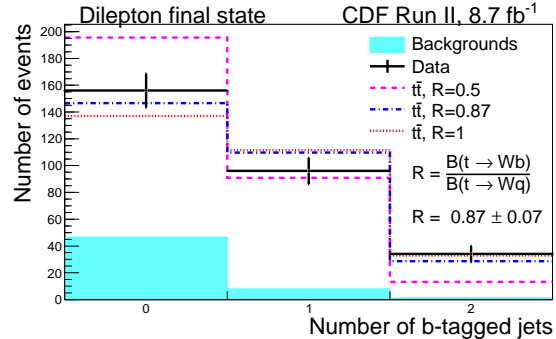


FIG. 1: Number of events observed in data and expected for various values of  $R$  as a function of identified  $b$ -jets.

To evaluate the effect of each nuisance parameter on the total systematic uncertainty, we perform the fit by individually fixing each nuisance parameter to a value corresponding to an excursion of one-standard deviation from its mean. The most important contributions to the  $R$  systematic uncertainty are reported in Table II.

Source	Syst. uncertainty
Correction to $b$ -tagging efficiency in data and MC	+0.045, -0.040
$\sigma_{t\bar{t}}$	$\pm 0.01$
Luminosity	+0.009, -0.012
Jet energy scale	+0.033, -0.025
ISR and FSR	+0.013, -0.025
Total systematic uncertainty	+0.059, -0.057
Statistical uncertainty	$\pm 0.045$
Total uncertainty	+0.074, -0.073

TABLE II: Systematic effects contributing the largest uncertainty to the measurement of  $R$ .

To determine the credibility level limit on  $R$  we follow a Bayesian statistical approach. We use a uniform prior probability density for  $R$  in the physical interval  $[0,1]$ . To obtain the posterior probability distribution for  $R$ , we integrate over all nuisance parameters using non-negative Gaussian distributions as prior probabilities. We obtain  $R > 0.73(0.76)$  at 95 (90) % credibility level. From Eq. (2) and the assumptions therein we obtain  $|V_{tb}| = 0.94 \pm 0.04$  and  $|V_{tb}| > 0.85(0.87)$  at 95 (90) % credibility level.

In summary, in this Letter we present a measurement of the ratio of the top-quark branching fractions  $R = \mathcal{B}(t \rightarrow Wb) / \mathcal{B}(t \rightarrow Wq)$  in a sample of  $t\bar{t}$  candidate events where both  $W$  bosons from the top-quarks decay into leptons ( $e$  or  $\mu$ ). The  $t\bar{t}$  are reconstructed using the CDFII detector from a dataset corresponding to 8.7 fb<sup>-1</sup> from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. The result,

$R = 0.87 \pm 0.07$ , is consistent with previous measurements by CDF [5] and D0 [6] collaborations and differs from the SM expectation by  $\approx 1.8\sigma$ .

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