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

T. Aaltonen, S. Amerio, D. Amidei, A. Anastassov, A. Anovi, J. Antos, G. Apollinari, J.A. Appel, T. Arisawa, A. Artikov, J. Aseaadi, W. Ashmanskas, B. Auerbach, A. Aurisano, F. Azfar, W. Badgett, T. Bae, A. Barbaro-Galtieri, V.E. Barnes, B.A. Barnett, P. Barria, P. Bartos, M. Baise, F. Bedeschi, S. Behari, J. Bellittini, D. Benjamin, A. Beretvas, A. Bhatti, K.R. Bland, B. Blumenfeld, A. Bocci, A. Bodek, D. Bortoletto, J. Boudreau, A. Boveia, L. Brigliadori, C. Bromberg, E. Brucken, J. Budagov, H.S. Budi, K. Burkett, G. Busetto, P. Bussey, P. Butiker, A. Buzatu, A. Calamba, S. Camarda, F. Canelli, B. Carls, D. Carlsmith, R. Carosi, S. Carrillo, B. Casal, M. Casarsa, A. Castro, P. Catasti, D. Cauz, V. Cavaliere, M. Cavalli-Sforza, A. Cerri, Y.C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, K. Cho, D. Chokheli, A. Clark, C. Clarke, M.E. Convery, J. Conway, M. Corbo, M. Cordelli, C.A. Cox, M. Cremonesi, D. Cruz, J. Cuevas, R. Cupertino, N. d’Ascenzo, M. Datta, P. de Barbaro, L. Demortier, M. Deninno, M. D’Onofrio, M. Dorigo, A. Drutti, R. Edgar, A. Eligain, E. Erde, B. Esham, S. Farrington, J.P. Fernández Ramos, R. Field, G. Flanagan, R. Forrest, M. Franklin, J.C. Freeman, H. Frisch, Y. Funakoshi, G. Galloni, A.F. Garfinkel, P. Garosi, H. Gerberich, E. Gerchtein, S. Giagu, V. Giakoumopoulou, K. Gibson, C.M. Ginsburg, N. Giokaris, P. Giromini, G. Giorgi, V. Glagolev, G. Glenuzski, Goldin, A. Golossanov, G. Gomez, G. Gomez-Ceballos, M. Gonclaves, G. González-López, I. Gorelov, A.T. Goshaw, K. Goulianos, C. Gross-Pihler, R.C. Group, J. Guimarães da Costa, S.R. Hahn, J.Y. Han, F. Happacher, K. Harra, M. Hare, R.F. Harr, T. Harrington-Taber, K. Hatakeyama, C. Hays, J. Heinrich, M. Herndon, A. Hocker, Z. Hong, W. Hopkins, S. Hou, R.E. Hughes, U. Husemann, M. Hussein, J. Huston, G. Intorzi, M. Iori, A. Ivanov, E. James, D. Jiang, B. Jayatilaka, E.J. Jeon, S. Jindariani, J. Jones, K.K. Joo, S.Y. Jun, T.R. Junk, M. Kambeitz, T. Kamon, P.E. Karchin, A. Kasmi, Y. Kato, W. Ketchum, J. Keung, B. Kinnsman, D.H. Kim, H.S. Kim, J.E. Kim, M.J. Kim, S.H. Kim, S.B. Kim, Y.J. Kim, Y.K. Kim, N. Kimura, M. Kirby, K. Knoepfel, K. Kondo, D.J. Kong, J. Konigsberg, A.V. Kotwal, M. Kreps, J. Kroll, M. Kruse, T. Kruh, M. Kurata, A.T. Lauanen, S. Lammel, M. Lancaster, K. Lancaster, C. Latino, G. Latino, P. Lukens, P. Maestro, S. Malik, A. Manousakis-Katsikakis, L. Marchese, F. Margaroli, P. Marino, M. Martínez, K. Materia, M.E. Mattson, A. Mazzacone, P. Mazzanti, R. McNulty, P. Mehta, C. Mesropian, T. Miao, D. Mietlicki, A. Mitra, H. Miyake, S. Moed, N. Moggi, C.S. Moon, R. Moore, M.J. Morello, A. Mukherjee, Th. Muller, P. Murat, M. Mussini, J. Nachtman, Y. Nagai, J. Naganoma, N. Nakano, A. Napier, J. Nett, C. Neu, T. Nigmanov, L. Nodulman, S.Y. Noh, N. Norniella, L. Oakes, S.H. Oh, Y.D. Oh, I. Oksuzian, T. Orava, L. Ortolan, C. Pagliarone, E. Palencia, P. Palni, V. Papadimitriou, W. Parker, P. Paletta, M. Paulini, C. Paul, T.J. Phillips, G. Piacentino, E. Pianori, F. Plotos, G. Punzi, N. Ranjan, I. Redondo Fernández, P. Renton, M. Rescigno, F. Rimondi, L. Ristori, A. Robson, T. Rodriguez, S. Rolli, M. Ronzani, R. Roser, J.L. Rosner, F. Ruffini, A. Ruiz, J. Russ, V. Rusin, W.K. Sakamoto, Y. Sakurai, L. Santi, I. Sato, V. Savileiu, A. Savoy-Navarro, P. Schlabach, E.E. Schmidt, T. Schwarzbach, L. Scodellaro, F. Scuri, S. Seidel, Y. Seiya, A. Semenov, F. Sforza, S.Z. Shelput, T. Shears, P.F. Sheppard, M. Shimomura, M. Shochet, I. Shreiber-Tecker, A. Simonenko, K. Sliwa, J.R. Smith, A. Snider, H. Song, V. Sorin, R. St. Denis, M. Stancari, D. Stentz, J. Strologas, Y. Sudoh, A. Sukhanov, I. Suslov, K. Takemasa, Y. Takeuchi, J. Tang, M. Tecchio, P.K. Teng, J. Thom, E. Thomson, V. Thukral, D. Toback, S. Tokar, T. Tollefson, T. Tomura, D. Tonelli, S. Torre, D. Torretta, P. Totaro,
We present a measurement of the ratio of the top-quark branching fractions \( R = \frac{\mathcal{B}(t \rightarrow Wb)\mathcal{B}(t \rightarrow Wq)}{\mathcal{B}(t \rightarrow Wq)/\mathcal{B}(t \rightarrow Wq)} \), 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 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.

PACS numbers: 12.15.Hh, 13.85.Qk, 14.65.Ha

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 \( |V_{tb}|^2 \), the squared element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix \([1]\). In the hypothesis of three generations and unitarity for that 3×3 matrix, and using the existing constraints on \( V_{ts} \) and \( V_{td} \), the magnitude of the top–bottom quark coupling is \( |V_{tb}| = 0.99915^{+0.00002}_{-0.00005} \) \([2, 3]\). Under these assumptions, the ratio of the branching fractions

\[
R = \frac{\mathcal{B}(t \rightarrow Wb)}{\mathcal{B}(t \rightarrow Wq)}/\mathcal{B}(t \rightarrow Wq)
\]

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

\[
R = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = 0.99830^{+0.00004}_{-0.00009},
\]

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 \((tt \rightarrow W^+qW^-\bar{q} \rightarrow q\bar{q}\ell\ell\nu\bar{\nu})\). 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 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 ≤ \( r \) ≤ 28 cm and of a drift chamber at 43 ≤ \( r \) ≤ 132 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 $E_T$ [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 $Wb$ events reconstructed in the dilepton 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 $E_T$ of 25 GeV, increased to 50 GeV if the direction of any lepton or jet is closer than $20^\circ$ to the $\vec{E}_T$ direction, and $E_T$ 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 $E_T$ 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 generator [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 $B(t \rightarrow Wb)$, 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 ± 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 $\approx 40\%$ for tagging $b$-jets and a mistagging probability, of $\approx 1\%$. 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
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

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

where the index $i$ runs over the nine subsamples; $\mathcal{P}(\mu_{\text{exp}}(R, x_j)|N_{\text{obs}}^i)$ is the Poisson probability to observe $N_{\text{obs}}^i$ events, given the expected value $\mu_{\text{exp}}^i$; and $G(x_i | \bar{x}_j, \sigma_j)$ 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 $\pm1$ standard deviation [21], refitting the data, and taking as uncertainty the difference of the result with respect to the nominal result. We find

$$R = 0.871 \pm 0.045(\text{stat})^{+0.058}_{-0.077}(\text{syst}) = 0.87 \pm 0.07.$$

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.

| 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 |

$tt$ ($\sigma=7.4$ pb)

| Number of events | 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, $tt$ SM expectations (assuming $|V_{tb}| = 1$), and data candidates by tagging categories for the 8.7 fb$^{-1}$ data sample. HF and LF indicate Heavy Flavor and Light Flavor jets.

![Figure 1](image-url)  
**FIG. 1:** Number of events observed in data and expected for various values of $R$ as a function of identified $b$-jets.

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 $R = B(t \rightarrow Wb)/B(t \rightarrow Wq)$ 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$^{-1}$ 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 $\approx 1.8\sigma$.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, United Kingdom; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, United Kingdom; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; the Australian Research Council (ARC); and the EU community Marie Curie Fellowship Contract No. 302103.

* Deceased

† With visitors from “University of British Columbia, Vancouver, BC V6T 121, Canada, “Instituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Moncattaro (Cagliari), Italy, “University of California Irvine, Irvine, CA 92697, USA, “Institute of Physics, Academy of Sciences of the Czech Republic, 182 21, Czech Republic, “CERN, CH-1211 Geneva, Switzerland, “Cornell University, Ithaca, NY 14853, USA, “University of Cyprus, Nicosia CY-1678, Cyprus, “Office of Science, U.S. Department of Energy, Washington, DC 20585, USA, “University College Dublin, Dublin 4, Ireland, “ETH, 8092 Zürich, Switzerland, “University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017, “Universidad Iberoamericana, Lomas de Santa Fe, México, C.P. 01219, Distrito Federal, “University of Iowa, Iowa City, IA 52242, USA, “Kinki University, Higashi-Osaka City, Japan 577-8502, “Kansas State University, Manhattan, KS 66506, USA, “Brookhaven National Laboratory, Upton, NY 11973, USA, “Queen Mary, University of London, London, E1 4NS, United Kingdom, “University of Melbourne, Victoria 3010, Australia, “Mon, Inc., Batavia, IL 60510, USA, “Nagasaki Institute of Applied Science, Nagasaki 851-0193, Japan, “National Research Nuclear University, Moscow 115409, Russia, “Northwestern University, Evanston, IL 60208, USA, “University of Notre Dame, Notre Dame, IN 46556, USA, “Universidad de Oviedo, E-33007 Oviedo, Spain, “CNRS-IN2P3, Paris, F-75205 France, “Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile, “The University of Jordan, Amman 11942, Jordan, “Université catholique de Louvain, 1348 Louvain-la-Neuve, Belgium, “University of Zürich, 8006 Zürich, Switzerland, “Massachusetts General Hospital, Boston, MA 02114 USA, “Harvard Medical School, Boston, MA 02114 USA, “Hampton University, Hampton, VA 23668, USA, “Los Alamos National Laboratory, Los Alamos, NM 87544, USA, “Università degli Studi di Napoli Federico I, I-80138 Napoli, Italy”

[1] N. Cabibbo, Phys. Rev. Lett. 10, 531 (1963); M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

[2] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).

[3] A. Abulencia et al. (CDF Collaboration), Phys. Rev. Lett. 97, 242003 (2006); V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 97, 021802 (2006); R. Aaij et al. (LHCb Collaboration), Phys. Lett. B 709, 177 (2012).

[4] D. Atwood, S. K. Gupta, A. Soni, J. High Energy Phys. 06 (2012) 205.

[5] D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. 95, 102002 (2005).

[6] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 107, 121802 (2005).

[7] D. Acosta et al. (CDF Collaboration), Phys. Rev. D 87, 111101(R) (2013).

[8] V. M. Abazov et al. (D0 Collaboration), Phys. Rev. Lett. 103, 092001 (2009); T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. 103, 092002 (2009).

[9] D. Acosta et al. (CDF Collaboration), Phys. Rev. D 71, 032001 (2005).

[10] We use a cylindrical coordinate system where the z axis is along the proton beam direction, $\phi$ is the azimuthal angle, and $\theta$ is the polar angle. Pseudorapidity is $\eta = -\ln \tan(\theta/2)$, while transverse momentum is $p_T = |p| \sin \theta$, and transverse energy is $E_T = E \sin \theta$. Missing transverse energy, $E_T$, is defined as the magnitude of $-\sum_i E_{T,i} n_i$, where $n_i$ is the unit vector in the azimuthal plane that points from the beam line to the $i$th calorimeter tower.

[11] R. Downing, N. Eddy, L. Holloway, M. Kasten, H. Kim, J. Kraus, C. Marino, K. Pitts, J. Strologas, and A. Taffard, Nucl. Instrum. Methods Phys. Res., Sect. A 570, 36 (2007).

[12] D. Acosta et al. (CDF Collaboration), Phys. Rev. D 71, 052003 (2005).

[13] T. Aaltonen et al. (CDF Collaboration), Phys. Rev. D 88, 091103(R) (2013).

[14] A. Bhatti et al., Nucl. Instrum. Methods Phys. Res., Sect. A 566, 375 (2006).

[15] S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506, 250 (2003).

[16] T. Sjostrand, P. Edén, C. Friberg, L. Lönnblad, G. Miu, S. Mrenna, and E. Norrbin, Comput. Phys. Commun. 135, 238 (2001).

[17] J. M. Campbell and R. K. Ellis, Phys. Rev. D 60, 113006 (1999).

[18] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A. Polosa, J. High Energy Phys. 07 (2003) 001.

[19] S. Alioli, P. Nason, C. Oleari, and E. Re, J. High Energy Phys. 09 (2009) 111.

[20] T. Aaltonen et al. (CDF and D0 Collaborations), Phys. Rev. D 86, 092003 (2012); Tevatron electroweak working group (CDF and D0 Collaborations), arXiv:1305/3929.

[21] T. Aaltonen et al., (CDF Collaboration), Phys. Rev. D 79, 092005 (2009).