

Measurement of the mass difference between top and antitop quarks

T. Aaltonen,²¹ S. Amerio,^{40a} D. Amidei,³² A. Anastassov,^{15,w} A. Annovi,¹⁷ J. Antos,¹² G. Apollinari,¹⁵ J. A. Appel,¹⁵ T. Arisawa,⁵³ A. Artikov,¹³ J. Asaadi,⁴⁸ W. Ashmanskas,¹⁵ B. Auerbach,² A. Aurisano,⁴⁸ F. Azfar,³⁹ W. Badgett,¹⁵ T. Bae,²⁵ A. Barbaro-Galtieri,²⁶ V. E. Barnes,⁴⁴ B. A. Barnett,²³ P. Barria,^{42c,42a} P. Bartos,¹² M. Baucé,^{40b,40a} F. Bedeschi,^{42a} S. Behari,¹⁵ G. Bellettini,^{42b,42a} J. Bellinger,⁵⁵ D. Benjamin,¹⁴ A. Beretvas,¹⁵ A. Bhatti,⁴⁶ K. R. Bland,⁵ B. Blumenfeld,²³ A. Bocci,¹⁴ A. Bodek,⁴⁵ D. Bortoletto,⁴⁴ J. Boudreau,⁴³ A. Boveia,¹¹ L. Brigliadori,^{6b,6a} C. Bromberg,³³ E. Brucken,²¹ J. Budagov,¹³ H. S. Budd,⁴⁵ K. Burkett,¹⁵ G. Busetto,^{40b,40a} P. Bussey,¹⁹ P. Butti,^{42b,42a} A. Buzatu,¹⁹ A. Calamba,¹⁰ S. Camarda,⁴ M. Campanelli,²⁸ F. Canelli,^{11,15,cc} B. Carls,²² D. Carlsmith,⁵⁵ R. Carosi,^{42a} S. Carrillo,^{16,l} B. Casal,^{9,j} M. Casarsa,^{49a} A. Castro,^{6b,6a} P. Catastini,²⁰ D. Cauz,^{49a} V. Cavaliere,²² M. Cavalli-Sforza,⁴ A. Cerri,^{26,e} L. Cerrito,^{28,r} Y. C. Chen,¹ M. Chertok,⁷ G. Chiarelli,^{42a} G. Chlachidze,¹⁵ K. Cho,²⁵ D. Chokheli,¹³ M. A. Ciocci,^{42c,42a} A. Clark,¹⁸ C. Clarke,⁵⁴ M. E. Convery,¹⁵ J. Conway,⁷ M. Corbo,¹⁵ M. Cordelli,¹⁷ C. A. Cox,⁷ D. J. Cox,⁷ M. Cremonesi,^{42a} D. Cruz,⁴⁸ J. Cuevas,^{9,y} R. Culbertson,¹⁵ N. d'Ascenzo,^{15,v} M. Datta,^{15,ee} P. De Barbaro,⁴⁵ L. Demortier,⁴⁶ M. Deninno,^{6a} F. Devoto,²¹ M. d'Errico,^{40b,40a} A. Di Canto,^{42b,42a} B. Di Ruzza,^{15,p} J. R. Dittmann,⁵ M. D'Onofrio,²⁷ S. Donati,^{42b,42a} M. Dorigo,^{49b,49a} A. Driutti,^{49a} K. Ebina,⁵³ R. Edgar,³² A. Elagin,⁴⁸ R. Erbacher,⁷ S. Errede,²² B. Esham,²² R. Eusebi,⁴⁸ S. Farrington,³⁹ J. P. Fernández Ramos,²⁹ R. Field,¹⁶ G. Flanagan,^{15,t} R. Forrest,⁷ M. Franklin,²⁰ J. C. Freeman,¹⁵ H. Frisch,¹¹ Y. Funakoshi,⁵³ A. F. Garfinkel,⁴⁴ P. Garosi,^{42c,42a} H. Gerberich,²² E. Gerchtein,¹⁵ S. Giagu,^{47a} V. Giakoumopoulou,³ K. Gibson,⁴³ C. M. Ginsburg,¹⁵ N. Giokaris,³ P. Giromini,¹⁷ G. Giurgiu,²³ V. Glagolev,¹³ D. Glenzinski,¹⁵ M. Gold,³⁵ D. Goldin,⁴⁸ A. Golossanov,¹⁵ G. Gomez,⁹ G. Gomez-Ceballos,³⁰ M. Goncharov,³⁰ O. González López,²⁹ I. Gorelov,³⁵ A. T. Goshaw,¹⁴ K. Goulianos,⁴⁶ E. Gramellini,^{6a} S. Grinstein,⁴ C. Grosso-Pilcher,¹¹ R. C. Group,^{52,15} J. Guimaraes da Costa,²⁰ S. R. Hahn,¹⁵ J. Y. Han,⁴⁵ F. Happacher,¹⁷ K. Hara,⁵⁰ M. Hare,⁵¹ R. F. Harr,⁵⁴ T. Harrington-Taber,^{15,m} K. Hatakeyama,⁵ C. Hays,³⁹ J. Heinrich,⁴¹ M. Herndon,⁵⁵ A. Hocker,¹⁵ Z. Hong,⁴⁸ W. Hopkins,^{15,f} S. Hou,¹ R. E. Hughes,³⁶ U. Husemann,⁵⁶ J. Huston,³³ G. Introzzi,^{42e,42a} M. Iori,^{47b,47a} A. Ivanov,^{7,o} E. James,¹⁵ D. Jang,¹⁰ B. Jayatilaka,¹⁵ E. J. Jeon,²⁵ S. Jindariani,¹⁵ M. Jones,⁴⁴ K. K. Joo,²⁵ S. Y. Jun,¹⁰ T. R. Junk,¹⁵ M. Kambeitz,²⁴ T. Kamon,^{25,48} P. E. Karchin,⁵⁴ A. Kasmi,⁵ Y. Kato,^{38,n} W. Ketchum,^{11,ff} J. Keung,⁴¹ B. Kilminster,^{15,cc} D. H. Kim,²⁵ H. S. Kim,²⁵ J. E. Kim,²⁵ M. J. Kim,¹⁷ S. B. Kim,²⁵ S. H. Kim,⁵⁰ Y. K. Kim,¹¹ Y. J. Kim,²⁵ N. Kimura,⁵³ M. Kirby,¹⁵ K. Knoepfel,¹⁵ K. Kondo,^{53,a} D. J. Kong,²⁵ J. Konigsberg,¹⁶ A. V. Kotwal,¹⁴ M. Kreps,²⁴ J. Kroll,⁴¹ M. Kruse,¹⁴ T. Kuhr,²⁴ M. Kurata,⁵⁰ A. T. Laasanen,⁴⁴ S. Lammel,¹⁵ M. Lancaster,²⁸ K. Lannon,^{36,x} G. Latino,^{42c,42a} H. S. Lee,²⁵ J. S. Lee,²⁵ S. Leo,^{42a} S. Leone,^{42a} J. D. Lewis,¹⁵ A. Limosani,^{14,s} E. Lipeles,⁴¹ H. Liu,⁵² Q. Liu,⁴⁴ T. Liu,¹⁵ S. Lockwitz,⁵⁶ A. Loginov,⁵⁶ D. Lucchesi,^{40b,40a} J. Lueck,²⁴ P. Lujan,²⁶ P. Lukens,¹⁵ G. Lungu,⁴⁶ J. Lys,²⁶ R. Lysak,^{12,d} R. Madrak,¹⁵ P. Maestro,^{42c,42a} S. Malik,⁴⁶ G. Manca,^{27,b} A. Manousakis-Katsikakis,³ F. Margaroli,^{47a} P. Marino,^{42d,42a} M. Martínez,⁴ K. Matera,²² M. E. Mattson,⁵⁴ A. Mazzacane,¹⁵ P. Mazzanti,^{6a} R. McNulty,^{27,i} A. Mehta,²⁷ P. Mehtala,²¹ C. Mesropian,⁴⁶ T. Miao,¹⁵ D. Mietlicki,³² A. Mitra,¹ H. Miyake,⁵⁰ S. Moed,¹⁵ N. Moggi,^{6a} C. S. Moon,²⁵ R. Moore,^{15,dd} M. J. Morello,^{42d,42a} A. Mukherjee,¹⁵ Th. Muller,²⁴ P. Murat,¹⁵ M. Mussini,^{6b,6a} J. Nachtman,^{15,m} Y. Nagai,⁵⁰ J. Naganoma,⁵³ I. Nakano,³⁷ A. Napier,⁵¹ J. Nett,⁴⁸ C. Neu,⁵² T. Nigmanov,⁴³ L. Nodulman,² S. Y. Noh,²⁵ O. Norniella,²² L. Oakes,³⁹ S. H. Oh,¹⁴ Y. D. Oh,²⁵ I. Oksuzian,⁵² T. Okusawa,³⁸ R. Orava,²¹ L. Ortolan,⁴ C. Pagliarone,^{49a} E. Palencia,^{9,e} P. Palni,³⁵ V. Papadimitriou,¹⁵ W. Parker,⁵⁵ G. Pauletta,^{49c,49a} M. Paulini,¹⁰ C. Paus,³⁰ T. J. Phillips,¹⁴ G. Piacentino,^{42a} E. Pianori,⁴¹ J. Pilot,³⁶ K. Pitts,²² C. Plager,⁸ L. Pondrom,⁵⁵ S. Poprocki,^{15,f} K. Potamianos,²⁶ F. Prokoshin,^{13,aa} A. Pranko,²⁶ F. Ptochos,^{17,g} G. Punzi,^{42b,42a} N. Ranjan,⁴⁴ I. Redondo Fernández,²⁹ P. Renton,³⁹ M. Rescigno,^{47a} T. Riddick,²⁸ F. Rimondi,^{6a,a} L. Ristori,^{42a,15} A. Robson,¹⁹ T. Rodriguez,⁴¹ S. Rolli,^{51,h} M. Ronzani,^{42b,42a} R. Roser,¹⁵ J. L. Rosner,¹¹ F. Ruffini,^{42c,42a} A. Ruiz,⁹ J. Russ,¹⁰ V. Rusu,¹⁵ A. Safonov,⁴⁸ W. K. Sakumoto,⁴⁵ Y. Sakurai,⁵³ L. Santi,^{49c,49a} K. Sato,⁵⁰ V. Saveliev,^{15,v} A. Savoy-Navarro,^{15,z} P. Schlabach,¹⁵ E. E. Schmidt,¹⁵ T. Schwarz,³² L. Scodellaro,⁹ F. Scuri,^{42a} S. Seidel,³⁵ Y. Seiya,³⁸ A. Semenov,¹³ F. Sforza,^{42b,42a} S. Z. Shalhout,⁷ T. Shears,²⁷ P. F. Shepard,⁴³ M. Shimojima,^{50,u} M. Shochet,¹¹ I. Shreyber-Tecker,³⁴ A. Simonenko,¹³ P. Sinervo,³¹ K. Sliwa,⁵¹ J. R. Smith,⁷ F. D. Snider,¹⁵ V. Sorin,⁴ H. Song,⁴³ M. Stancari,¹⁵ R. St. Denis,¹⁹ B. Stelzer,³¹ O. Stelzer-Chilton,³¹ D. Stentz,^{15,w} J. Strogas,³⁵ Y. Sudo,⁵⁰ A. Sukhanov,¹⁵ I. Suslov,¹³ K. Takemasa,⁵⁰ Y. Takeuchi,⁵⁰ J. Tang,¹¹ M. Tecchio,³² P. K. Teng,¹ J. Thom,^{15,f} E. Thomson,⁴¹ V. Thukral,⁴⁸ D. Toback,⁴⁸ S. Tokar,¹² K. Tollefson,³³ T. Tomura,⁵⁰ D. Tonelli,^{15,e} S. Torre,¹⁷ D. Torretta,¹⁵ P. Totaro,^{40a} M. Trovato,^{42d,42a} F. Ukegawa,⁵⁰ S. Uozumi,²⁵ F. Vázquez,^{16,l} G. Velev,¹⁵ C. Vellidis,¹⁵ C. Vernieri,^{42d,42a} M. Vidal,⁴⁴ R. Vilar,⁹ J. Vizán,^{9,bb} M. Vogel,³⁵ G. Volpi,¹⁷ P. Wagner,⁴¹ R. Wallny,⁸ S. M. Wang,¹ A. Warburton,³¹ D. Waters,²⁸ W. C. Wester III,¹⁵ D. Whiteson,^{41,c} A. B. Wicklund,² S. Wilbur,¹¹ H. H. Williams,⁴¹ J. S. Wilson,³² P. Wilson,¹⁵ B. L. Winer,³⁶ P. Wittich,^{15,f} S. Wolbers,¹⁵ H. Wolfe,³⁶ T. Wright,³² X. Wu,¹⁸ Z. Wu,⁵ K. Yamamoto,³⁸ D. Yamato,³⁸ T. Yang,¹⁵ U. K. Yang,^{11,q} Y. C. Yang,²⁵ W.-M. Yao,²⁶ G. P. Yeh,¹⁵ K. Yi,^{15,m} J. Yoh,¹⁵ K. Yorita,⁵³ T. Yoshida,^{38,k} G. B. Yu,¹⁴ I. Yu,²⁵ A. M. Zanetti,^{49a} Y. Zeng,¹⁴ C. Zhou,¹⁴ and S. Zucchelli^{6b,6a}

(CDF Collaboration)

- ¹*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
²*Argonne National Laboratory, Argonne, Illinois 60439, USA*
³*University of Athens, 157 71 Athens, Greece*
⁴*Institut de Fisica d'Altes Energies, ICREA, Universitat Autònoma de Barcelona, E-08193 Bellaterra (Barcelona), Spain*
⁵*Baylor University, Waco, Texas 76798, USA*
^{6a}*Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy*
^{6b}*University of Bologna, I-40127 Bologna, Italy*
⁷*University of California, Davis, Davis, California 95616, USA*
⁸*University of California, Los Angeles, Los Angeles, California 90024, USA*
⁹*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
¹⁰*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
¹¹*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
¹²*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
¹³*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
¹⁴*Duke University, Durham, North Carolina 27708, USA*
¹⁵*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
¹⁶*University of Florida, Gainesville, Florida 32611, USA*
¹⁷*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
¹⁸*University of Geneva, CH-1211 Geneva 4, Switzerland*
¹⁹*Glasgow University, Glasgow G12 8QQ, United Kingdom*
²⁰*Harvard University, Cambridge, Massachusetts 02138, USA*
²¹*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014 Helsinki, Finland*
²²*University of Illinois, Urbana, Illinois 61801, USA*
²³*The Johns Hopkins University, Baltimore, Maryland 21218, USA*
²⁴*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*
²⁵*Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea; Seoul National University, Seoul 151-742, Korea; Sungkyunkwan University, Suwon 440-746, Korea; Korea Institute of Science and Technology Information, Daejeon 305-806, Korea; Chonnam National University, Gwangju 500-757, Korea; Chonbuk National University, Jeonju 561-756, Korea; Ewha Womans University, Seoul 120-750, Korea*
²⁶*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
²⁷*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
²⁸*University College London, London WC1E 6BT, United Kingdom*
²⁹*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas, E-28040 Madrid, Spain*
³⁰*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
³¹*Institute of Particle Physics: McGill University, Montréal, Québec H3A 2T8, Canada; Simon Fraser University, Burnaby, British Columbia V5A 1S6, Canada; University of Toronto, Toronto, Ontario M5S 1A7, Canada; and TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*
³²*University of Michigan, Ann Arbor, Michigan 48109, USA*
³³*Michigan State University, East Lansing, Michigan 48824, USA*
³⁴*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
³⁵*University of New Mexico, Albuquerque, New Mexico 87131, USA*
³⁶*The Ohio State University, Columbus, Ohio 43210, USA*
³⁷*Okayama University, Okayama 700-8530, Japan*
³⁸*Osaka City University, Osaka 588, Japan*
³⁹*University of Oxford, Oxford OX1 3RH, United Kingdom*
^{40a}*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy*
^{40b}*University of Padova, I-35131 Padova, Italy*
⁴¹*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
^{42a}*Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy*
^{42b}*University of Pisa, I-56127 Pisa, Italy*
^{42c}*University of Siena, I-56127 Pisa, Italy*
^{42d}*Scuola Normale Superiore, I-56127 Pisa, Italy*
^{42e}*INFN Pavia and University of Pavia, I-27100 Pavia, Italy*
⁴³*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
⁴⁴*Purdue University, West Lafayette, Indiana 47907, USA*

- ⁴⁵*University of Rochester, Rochester, New York 14627, USA*
⁴⁶*The Rockefeller University, New York, New York 10065, USA*
^{47a}*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy*
^{47b}*Sapienza Università di Roma, I-00185 Roma, Italy*
⁴⁸*Texas A&M University, College Station, Texas 77843, USA*
^{49a}*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34127 Trieste, Italy*
^{49b}*University of Trieste, I-34127 Trieste, Italy*
^{49c}*University of Udine, I-33100 Udine, Italy*
⁵⁰*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
⁵¹*Tufts University, Medford, Massachusetts 02155, USA*
⁵²*University of Virginia, Charlottesville, Virginia 22906, USA*
⁵³*Waseda University, Tokyo 169, Japan*
⁵⁴*Wayne State University, Detroit, Michigan 48201, USA*
⁵⁵*University of Wisconsin, Madison, Wisconsin 53706, USA*
⁵⁶*Yale University, New Haven, Connecticut 06520, USA*
(Received 23 October 2012; published 18 March 2013)

We present a measurement of the mass difference between top (t) and antitop (\bar{t}) quarks using $t\bar{t}$ candidate events reconstructed in the final state with one lepton and multiple jets. We use the full data set of Tevatron $\sqrt{s} = 1.96$ TeV proton-antiproton collisions recorded by the CDF II detector, corresponding to an integrated luminosity of 8.7 fb^{-1} . We estimate event by event the mass difference to construct templates for top pair signal events and background events. The resulting mass difference distribution in data compared to signal and background templates using a likelihood fit yields $\Delta M_{\text{top}} = M_t - M_{\bar{t}} = -1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst}) \text{ GeV}/c^2$ and is in agreement with the standard model prediction of no mass difference.

DOI: [10.1103/PhysRevD.87.052013](https://doi.org/10.1103/PhysRevD.87.052013)

PACS numbers: 14.65.Ha, 13.85.Ni, 13.85.Qk, 12.15.Ff

^aDeceased.^bVisitor from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.^cVisitor from University of California Irvine, Irvine, CA 92697, USA.^dVisitor from Institute of Physics, Academy of Sciences of the Czech Republic, 182 21, Czech Republic.^eVisitor from CERN, CH-1211 Geneva, Switzerland.^fVisitor from Cornell University, Ithaca, NY 14853, USA.^gVisitor from University of Cyprus, Nicosia CY-1678, Cyprus.^hVisitor from Office of Science, U.S. Department of Energy, Washington, DC 20585, USA.ⁱVisitor from University College Dublin, Dublin 4, Ireland.^jVisitor from ETH, 8092 Zürich, Switzerland.^kVisitor from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.^lVisitor from Universidad Iberoamericana, Lomas de Santa Fe, México, C.P. 01219, Distrito Federal.^mVisitor from University of Iowa, Iowa City, IA 52242, USA.ⁿVisitor from Kinki University, Higashi-Osaka City, Japan 577-8502.^oVisitor from Kansas State University, Manhattan, KS 66506, USA.^pVisitor from Brookhaven National Laboratory, Upton, NY 11973, USA.^qVisitor from University of Manchester, Manchester M13 9PL, United Kingdom.^rVisitor from Queen Mary, University of London, London, E1 4NS, United Kingdom.^sVisitor from University of Melbourne, Victoria 3010, Australia.^tVisitor from Muons, Inc., Batavia, IL 60510, USA.^uVisitor from Nagasaki Institute of Applied Science, Nagasaki 851-0193, Japan.^vVisitor from National Research Nuclear University, Moscow 115409, Russia.^wVisitor from Northwestern University, Evanston, IL 60208, USA.^xVisitor from Notre Dame, Notre Dame, IN 46556, USA.^yVisitor from Universidad de Oviedo, E-33007 Oviedo, Spain.^zVisitor from CNRSIN2P3, Paris, F-75205 France.^{aa}Visitor from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.^{bb}Visitor from Universite catholique de Louvain, 1348 Louvain-La-Neuve, Belgium.^{cc}Visitor from University of Zürich, 8006 Zürich, Switzerland.^{dd}Visitor from Massachusetts General Hospital and Harvard Medical School, Boston, MA 02114, USA.^{ee}Visitor from Hampton University, Hampton, VA 23668, USA.^{ff}Visitor from Los Alamos National Laboratory, Los Alamos, NM 87544, USA.

The laws of the standard model of particle physics (SM) are invariant under the simultaneous transformations of charge conjugation, parity, and time reversal (*CPT*). Conservation of *CPT* is, therefore, fundamental and provides one of the most important constraints on the SM. However, examining any possibility of *CPT* violation is important, as there are well-motivated extensions of the SM allowing for *CPT* symmetry breaking [1]. In *CPT*-conserving models, particles and their antiparticles must have identical masses and widths. Thus, any mass difference between a particle and its antiparticle would indicate a violation of *CPT*. *CPT* invariance has been tested for many elementary particles such as leptons and hadrons [2,3], but not in the bare quark except for the top quark [4]. For all quarks except the top quark, direct mass measurements of bare quark are nearly impossible because the quark hadronization time scale is approximately an order of magnitude less than the quark decay time. After hadronization occurs, only the masses of hadrons are observable and give, at best, only an approximate estimate of the constituent quarks' masses. On the other hand, as the lifetime of the top quark is of the order of 10^{-24} s, it decays before hadronizing and a precision measurement of its mass and of the difference between the quark and antiquark masses can be made.

Since the top-quark discovery, close to three thousands of $t\bar{t}$ candidate events have been collected per experiment at the Tevatron $p\bar{p}$ collider. This sample makes measuring the top-quark mass (M_{top}) possible to an accuracy of approximately 0.5% ($M_{\text{top}} = 173.2 \pm 0.9 \text{ GeV}/c^2$) [5] and the mass difference ($\Delta M_{\text{top}} = M_t - M_{\bar{t}}$) between t and \bar{t} quarks to a comparable precision. The D0 Collaboration performed several measurements of ΔM_{top} using matrix element analyses [6,7]. The most recent D0 result, based on a 3.6 fb^{-1} data sample, reports $\Delta M_{\text{top}} = 0.8 \pm 1.9 \text{ GeV}/c^2$, consistent with zero as predicted in the SM. The CDF Collaboration performed a measurement using a 5.6 fb^{-1} data sample [8] and found $\Delta M_{\text{top}} = -3.3 \pm 1.7 \text{ GeV}/c^2$ which is also consistent with zero to within 2 standard deviations. To date, the most precise measurement is performed by the CMS Collaboration, $\Delta M_{\text{top}} = -0.44 \pm 0.53 \text{ GeV}/c^2$ [9].

This paper reports on the final CDF measurement of ΔM_{top} based on the full run II data set corresponding to an integrated luminosity of 8.7 fb^{-1} . We reconstruct the mass difference between t and \bar{t} quarks in each data event and compare its distribution with template distributions derived from Monte Carlo (MC) model simulations to estimate ΔM_{top} . This is an update of a previous measurement that used a subset of the present data [8]. In addition to the larger data sample, we improve the jet energy calibration by applying an artificial neural network to achieve better jet energy resolution [10], as in a recent measurement of M_{top} [11]. We also increase the size of the control samples and reexamine the systematic uncertainties.

In the SM, t and \bar{t} quarks decay almost exclusively into a W boson and a bottom quark ($t \rightarrow bW^+$ and $\bar{t} \rightarrow \bar{b}W^-$)

[12]. The case where one W boson decays to a charged lepton (electron or muon) and a neutrino ($W^+ \rightarrow \ell^+ \nu$ or $W^- \rightarrow \ell^- \bar{\nu}$ including the cascade decay of $W \rightarrow \tau \nu$ and $\tau \rightarrow \ell \nu$) and the other to a pair of jets defines the lepton + jets channel. To select $t\bar{t}$ candidate events in this channel, we require one electron (muon) with $E_T > 20 \text{ GeV}$ ($p_T > 20 \text{ GeV}/c$) and pseudorapidity $|\eta| < 1.1$ [13]. We also require large missing transverse energy [14] ($\cancel{E}_T > 20 \text{ GeV}$) and at least four jets. Jets are reconstructed applying a cone algorithm with radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ [15]. Besides the standard jet energy scale corrections [16], we use an artificial neural network that includes additional information to the calorimeter one, such as jet momentum from the charged particles inside the jet [10]. This additional information improves the resolution on the reconstructed jet variables, resulting in approximately a 10% improvement in statistical precision. Jets originating from b quarks are identified (tagged) using a secondary vertex tagging algorithm [17]. In order to optimize the background reduction and to improve the statistical power of the measurement, we divide the sample of $t\bar{t}$ candidates into subsamples with zero (0-tag), one (1-tag), and two or more (2-tag) b -tagged jets.

For the 0-tag events, we require exactly four *tight* jets (transverse energy $E_T > 20 \text{ GeV}$ and $|\eta| < 2.0$). In case of the 1-tag and 2-tag events, three *tight* jets and one or more *loose* jets ($E_T > 12 \text{ GeV}$ and $|\eta| < 2.4$) are required. To reduce background contributions to the 0-tag or 1-tag samples, we require the scalar sum of transverse energies in the event, $H_T = E_T^{\text{lepton}} + \cancel{E}_T + \sum_{\text{four jets}} E_T^{\text{jet}}$, to exceed 250 GeV. The H_T requirement is not applied to the 2-tag events because of the small background contribution in this subsample. We divide the 1-tag and 2-tag samples into subsamples based on the number of *tight* jets. We denote as *tight subsample* the sample requiring exactly four *tight* jets and *loose subsample* the sample consisting of the remaining events. This results in five subsamples: 0-tag, 1-tagL, 1-tagT, 2-tagL, and 2-tagT, where T and L denote *tight* and *loose* subsamples, respectively.

The primary sources of background contributions are W + jets and QCD multijet processes. To estimate the contribution of each process, we use a combination of data- and MC-based techniques described in Refs. [18,19]. For the Z + jets, diboson, single top quark, and $t\bar{t}$ events we normalize the number of simulated events using their theoretical cross sections [20–22]. We use the data-driven techniques described in Ref. [23] to estimate the QCD multijet background. The W + jets background shape is modeled using MC generated samples but the number of events is derived from the data sample by subtracting all other contributions, including the $t\bar{t}$ signal, from the data events. Table I summarizes the data sample composition. The distribution of H_T is shown in Fig. 1 for data with 0-tag and one or more b -tag (Tagged) with the predictions from our signal and background models.

TABLE I. Expected and observed numbers of signal and background events assuming a $t\bar{t}$ production cross section $\sigma_{t\bar{t}} = 7.45$ pb and $M_{\text{top}} = 172.5$ GeV/ c^2 .

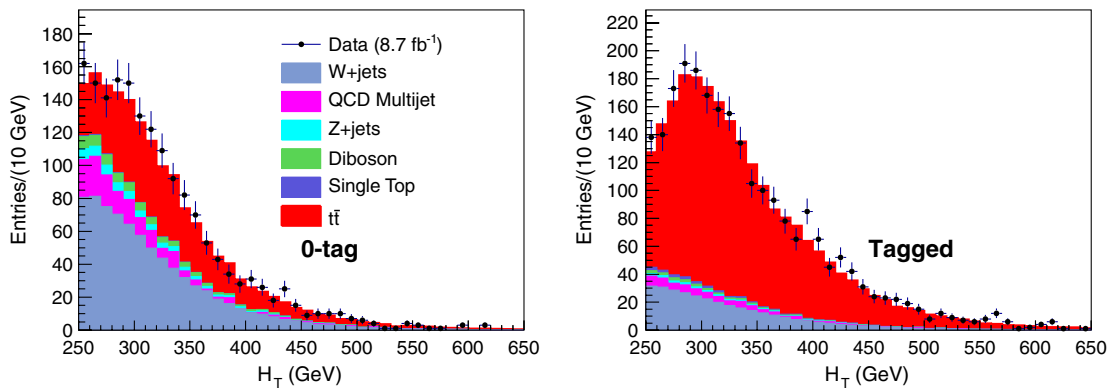
	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
$W + \text{jets}$	778 ± 219	197 ± 69	114 ± 42	11.4 ± 4.9	8.0 ± 3.4
$Z + \text{jets}$	55.7 ± 4.9	10.3 ± 1.2	6.7 ± 0.8	0.8 ± 0.2	0.5 ± 0.1
Single top	5.1 ± 0.4	11.7 ± 1.0	7.2 ± 0.6	2.2 ± 0.2	1.7 ± 0.2
Diboson	63.9 ± 5.9	11.7 ± 1.5	9.0 ± 1.2	0.9 ± 0.2	0.9 ± 0.2
QCD multijet	133 ± 107	31.7 ± 1.2	20.9 ± 16.9	4.3 ± 4.3	2.9 ± 3.5
Total background	1038 ± 244	262 ± 70	158 ± 45	19.5 ± 6.5	14.0 ± 5.0
$t\bar{t}$ signal	620 ± 83	694 ± 87	847 ± 105	188 ± 29	294 ± 45
Expected	1658 ± 257	957 ± 111	1005 ± 114	208 ± 30	308 ± 45
Observed	1712	919	1018	214	286

We assume that all selected events are lepton + jets $t\bar{t}$ events and reconstruct ΔM_{top} , event by event, using a special-purpose kinematic fitter [8]. Measured four-vectors of the lepton and jets are corrected for known effects as described in Ref. [16], and appropriate resolutions are assigned. The unclustered transverse energy (U_T) is estimated as a sum of all transverse energy in the calorimeters that is not associated with the primary lepton or with one of the leading four jets. It is used to calculate the neutrino transverse momentum. The longitudinal momentum of the neutrino is a free parameter which is effectively determined by the constraint on the invariant mass of the leptonically decaying W boson. To estimate ΔM_{top} , we define a kinematic χ^2 function,

$$\begin{aligned} \chi^2 = & \sum_{i=\ell, 4\text{jets}} (p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2 / \sigma_i^2 \\ & + \sum_{k=x,y} (U_{T_k}^{\text{fit}} - U_{T_k}^{\text{meas}})^2 / \sigma_k^2 + (M_{jj} - M_W)^2 / \Gamma_W^2 \\ & + (M_{\ell\nu} - M_W)^2 / \Gamma_W^2 + \{M_{bjj} - (M_{\text{top}}^{\text{ave}} + dm_{\text{reco}}/2)\}^2 / \Gamma_t^2 \\ & + \{M_{b\ell\nu} - (M_{\text{top}}^{\text{ave}} - dm_{\text{reco}}/2)\}^2 / \Gamma_t^2, \end{aligned} \quad (1)$$

where dm_{reco} is obtained at the lowest χ^2 and represents the reconstructed mass difference between the

hadronically and leptonically decaying top quarks, $M_{bjj} - M_{b\ell\nu}$. In Eq. (1), we constrain the lepton p_T and the four leading jets p_T to their measured values and uncertainties (σ_i). We also constrain U_T in the second term of Eq. (1). In the remaining terms, we constrain the W boson mass (M_W) to $M_W = 80.4$ GeV/ c^2 [24] and the average of t and \bar{t} masses to $M_{\text{top}}^{\text{ave}} = 172.5$ GeV/ c^2 . The quantities M_{jj} , $M_{\ell\nu}$, M_{bjj} , and $M_{b\ell\nu}$ refer to the invariant masses of the particles denoted in the subscripts. The total widths of the W boson, $\Gamma_W = 2.1$ GeV, and of the top quark, $\Gamma_t = 1.5$ GeV, are taken from Ref. [12]. We assume that the total widths of the t and \bar{t} quarks are equal. Determining the reconstructed mass difference of t and \bar{t} , Δm_t^{reco} , requires the identification of the particle type (t or \bar{t}), which is achieved using the electric charge of the lepton (Q_{lepton}), $\Delta m_t^{\text{reco}} = -Q_{\text{lepton}} \cdot dm_{\text{reco}}$. In the events with a positive (negative) lepton, t (\bar{t}) decays leptonically and \bar{t} (t) decays hadronically. Because of the different resolutions of the jets, lepton, and unclustered energy, the distribution of reconstructed mass from the hadronic top quark is different with that of the leptonic top quark. To improve the resolution of the Δm_t^{reco} and allow using the appropriate distribution in the hadronic-to-leptonic and in the leptonic-to-hadronic mass difference, we divide each subsample into the two

FIG. 1 (color online). H_T distribution for zero b -tagged (0-tag) events and one or more b -tagged (Tagged) events.

new subsamples based on the lepton charge. We then have ten subsamples in total.

Assuming that the leading four jets in any event come from the four final quarks of the $t\bar{t}$ lepton + jets decay at the hard scattering level, there are 12, 6, and 2 possible jet-to-quark assignments for 0-tag, 1-tag, and 2-tag samples, respectively. The χ^2 minimization is performed for each jet-to-quark assignment, and Δm_i^{reco} is taken from the assignment that yields the lowest χ^2 (χ_{min}^2). The b -tagged (zero b -tag) events with $\chi_{\text{min}}^2 > 9.0$ ($\chi_{\text{min}}^2 > 3.0$) are rejected due to the poorly reconstructed kinematical properties. To increase the statistical power of the measurement, we employ an additional observable, $\Delta m_i^{\text{reco}(2)}$, which corresponds to the 2nd lowest χ^2 in the jet-to-quark combinatorics. Although it has a poorer sensitivity, $\Delta m_i^{\text{reco}(2)}$ provides additional information on ΔM_{top} and reduces the statistical uncertainty by approximately 10%. We use two observables (Δm_i^{reco} and $\Delta m_i^{\text{reco}(2)}$) simultaneously for the measurement.

Using MADGRAPH [25], we generate $t\bar{t}$ signal samples with ΔM_{top} between -20 and 20 GeV/c^2 in 2 GeV/c^2 intervals. Parton showering of the signal events is simulated with PYTHIA [26], and the CDF II detector is simulated using a GEANT-based software package [27].

We estimate the probability density functions (PDFs) of signal and background using the kernel density estimation [28,29]. We construct the two-dimensional PDFs that account for the correlation between Δm_i^{reco} and $\Delta m_i^{\text{reco}(2)}$. First, at discrete values of ΔM_{top} from -20 to 20 GeV/c^2 , we estimate the PDFs for the observables from the above-mentioned MADGRAPH $t\bar{t}$ samples. We interpolate the MC distributions to find PDFs for arbitrary values of ΔM_{top} using the local polynomial smoothing method [30]. Then, we fit the signal and background PDFs to the unbinned distributions observed in the data using a maximum likelihood fit [31]. Separate likelihoods are built for the ten subsamples, and the overall likelihood is obtained by multiplying them together. References [11,28] provide detailed information about this technique.

We calibrate the method using the fully simulated MC experiments. We perform 3000 simulated experiments for each of 11 equally spaced ΔM_{top} values ranging from -10 to 10 GeV/c^2 . The fit estimates and their uncertainties in the simulated experiments are found to be unbiased.

We examine a variety of systematic effects that could affect the ΔM_{top} measurement. To estimate the systematic uncertainties, we compare the results from simulated experiments in which we vary relevant parameters within 1 standard deviation. We estimate the systematic uncertainties in the assumptions of $M_{\text{top}} = 172.5$ GeV/c^2 and $\Delta M_{\text{top}} = 0.0$ GeV/c^2 . All systematic uncertainties are summarized in Table II. The dominant source of systematic uncertainty is attributed to a possible difference in the detector response between b and \bar{b} jets. To estimate this

TABLE II. Summary of systematic uncertainties on ΔM_{top} .

Source	Uncertainty (GeV/c^2)
Signal modeling	0.14
Parton showering	0.17
b and \bar{b} jets asymmetry	0.38
Higher-order effect	0.16
Jet energy scale	0.07
Parton distribution functions	0.12
b -jet energy scale	0.05
Background shape	0.20
Gluon fusion fraction	0.05
Initial and final state radiation	0.10
Finite Monte Carlo samples	0.07
Lepton energy scale	0.06
Multiple hadron interaction	0.05
Color reconnection	0.23
Total systematic uncertainty	0.59

effect, we select a $b\bar{b}$ sample by requiring exactly two b -tagged jets per event using a sample triggered on jet ($E_T > 20$ GeV). In addition, one b -tagged jet is required to contain a soft muon from leptonic decay so that the charge tendency of the b quark associated with the jet can be estimated. The energy scale of b and \bar{b} influenced jet events in data is compared with dijet MC events in which we estimate the p_T imbalance (p_T of b influenced jets minus p_T of \bar{b} influenced jets divided by average p_T) difference between the data and the MC events and obtain $-0.44 \pm 0.40\%$. To calculate the p_T imbalance difference from b and \bar{b} jets, we estimate the fraction of the b quark flavors associated with the same charge of the soft muons. We obtain the p_T imbalance difference to be $-0.73 \pm 0.67\%$ with considering incorrect charge events anticorrelatedly. We perform simulated experiments by varying the b and \bar{b} energy within their p_T imbalance difference. The possible difference of calorimeter responses between c and \bar{c} jets can be a source of systematic uncertainty. With an assumption of same asymmetry between b and \bar{b} jets as c and \bar{c} jets, we obtain a tiny uncertainty, 0.03 GeV/c^2 , which is neglected. We estimate the signal modeling uncertainty by using simulated experiments with events generated with MADGRAPH and PYTHIA. We also estimate a parton showering uncertainty by applying different showering models (PYTHIA and HERWIG [32]) to a sample generated with ALPGEN [33]. Higher-order effects are estimated using a MC@NLO generator [34]. The background shape systematic uncertainty accounts for the variation of the background composition as well as the overall background fraction. We also consider changes in the shapes by varying the Q^2 used in the calculation of hard scattering and showering. The color reconnection systematic uncertainty [35] is evaluated using the samples with and without color reconnection effects in PYTHIA tunes

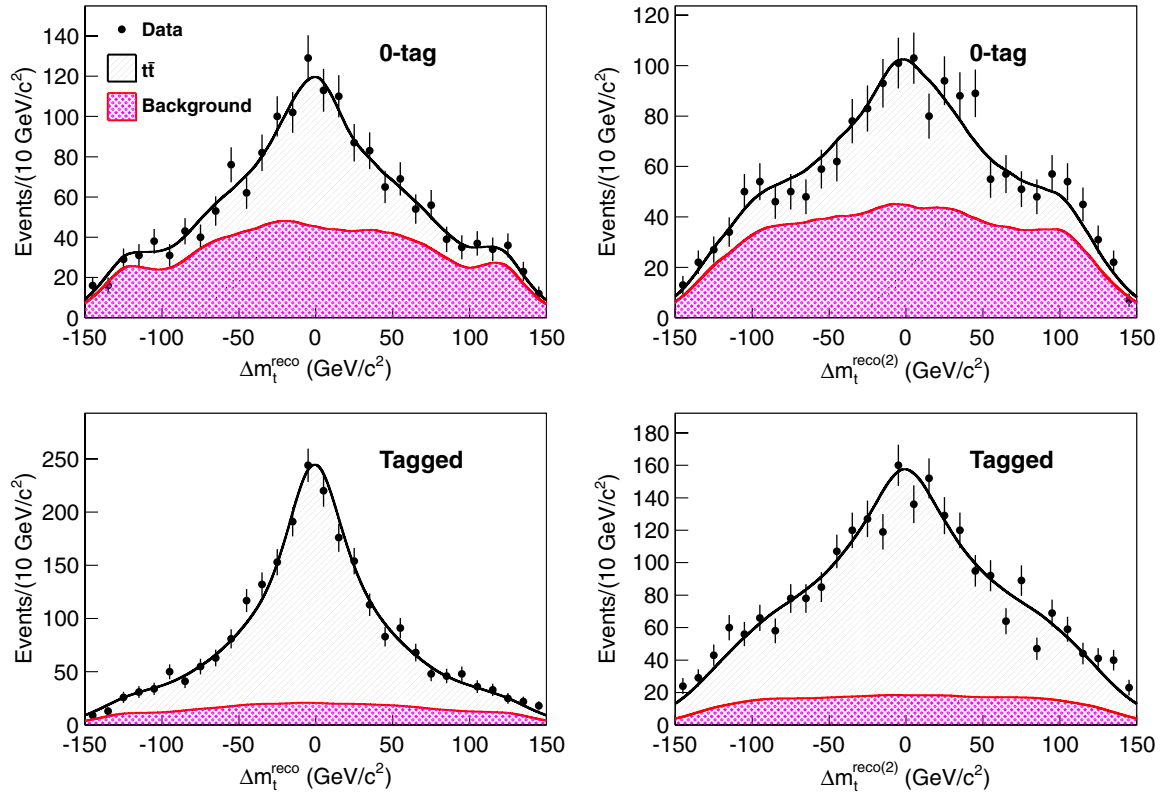


FIG. 2 (color online). Distributions of Δm_t^{reco} and $\Delta m_t^{\text{reco}(2)}$ used to extract ΔM_{top} for zero b -tagged (0-tag) events and one or more b -tagged (Tagged) events. The data are overlaid with predictions from the kernel density estimation probability distributions assuming $\Delta M_{\text{top}} = 0 \text{ GeV}/c^2$. The fitted number of signal and background events are used.

[36]. We use two samples with angular ordering for jet showers (tune A-Pro and tune ACR-Pro), the same as the nominal samples of ΔM_{top} measurement. We also have a cross check using the other two samples with p_T ordering for jet showers and new underlying-event model (*Perugia0* and *PerugiaNOCR*) and find a similar uncertainty. We vary the parameters of parton distribution functions to account for systematic effects. The jet energy scale uncertainty, the dominant uncertainty in most of the M_{top} measurements, is partially canceled in the t and \bar{t} mass difference. Other sources of systematic effects, including uncertainties in gluon radiation, multiple hadron interaction, finite size of MC samples, b -jet energy scale, and lepton energy scale, give small contributions. Because we assume the average M_{top} to be $172.5 \text{ GeV}/c^2$, the M_{top} dependence can be a possible source of systematic uncertainty. We perform the simulated experiments using different $t\bar{t}$ signal samples of M_{top} from 170.0 to $175.0 \text{ GeV}/c^2$ with $0.5 \text{ GeV}/c^2$ steps. All samples have $\Delta M_{\text{top}} = 0 \text{ GeV}/c^2$. We find the measured ΔM_{top} values, $0.01 \pm 0.08 \text{ GeV}/c^2$ in the fit, are consistent with zero. The total systematic uncertainty of $0.59 \text{ GeV}/c^2$ is calculated as a quadrature sum of the listed uncertainties. The details of systematic uncertainty evaluations are in Refs. [5,19,28].

The resulting mass difference is

$$\Delta M_{\text{top}} = -1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst}) \text{ GeV}/c^2.$$

Figure 2 shows the observed distributions of the observables used for the ΔM_{top} measurement. The density estimates for $t\bar{t}$ signal events with $\Delta M_{\text{top}} = 0 \text{ GeV}/c^2$ and for background events are overlaid.

In conclusion, we examine the mass difference between t and \bar{t} quarks in the lepton + jets channel using CDF II data corresponding to an integrated luminosity of 8.7 fb^{-1} from $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$. We measure the mass difference to be $\Delta M_{\text{top}} = M_t - M_{\bar{t}} = -1.95 \pm 1.11(\text{stat}) \pm 0.59(\text{syst}) \text{ GeV}/c^2 = -1.95 \pm 1.26 \text{ GeV}/c^2$. This result is consistent with $\Delta M_{\text{top}} = 0 \text{ GeV}/c^2$ and conservation of CPT symmetry.

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 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; and the Australian Research Council (ARC).

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