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Precision Top-Quark Mass Measurement in the Lepton+Jets Topology in $p\bar{p}$ Collisions at $\sqrt{s}$ =1.96 TeV

A. Abulencia
University of Illinois, Urbana, Illinois 61801, USA

Kenneth A. Bloom
University of Nebraska - Lincoln, kbloom2@unl.edu

CDF Collaboration

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A. Abulencia,[23] D. Acosta,[17] J. Adelman,[13] T. Affolder,[10] T. Akimoto,[53] M. G. Albrow,[16] D. Ambrose,[16] S. Amerio,[42] D. Amidei,[33] A. Anastassov,[50] K. Anikeev,[16] A. Annovi,[44] J. Antos,[1] M. Aoki,[53] G. Apollinari,[16] J.-F. Arguin,[32] T. Arisawa,[55] A. Artikov,[14] W. Ashmanskas,[16] A. Attal,[8] F. Azfar,[41] P. Azzi-Bacchetta,[42] P. Azzurri,[44] N. Bacchetta,[42] H. Bachacou,[28] W. Badgett,[16] A. Barbaro-Galtieri,[28] V. E. Barnes,[46] B. A. Barnett,[24] S. Baroiant,[7] V. Bartsch,[30] G. Bauer,[31] F. Bedeschi,[44] S. Behari,[24] S. Belforte,[52] G. Bellettini,[44] J. Bellinger,[57] A. Belloni,[31] E. Ben-Haim,[16] D. Benjamin,[15] A. Beretvas,[16] J. Beringer,[28] T. Berry,[29] A. Bhatti,[48] M. Binkley,[16] D. Bisello,[42] M. Bishai,[16] R. E. Blair,[2] C. Blocker,[6] K. Bloom,[33] B. Blumenfeld,[24] A. Bocci,[48] A. Bodek,[47] V. Boisvert,[47] G. Bolla,[46] A. Bolshov,[31] D. Bortoletto,[46] J. Boudreau,[45] S. Bourov,[16] A. Boveia,[10] B. Brau,[10] C. Bromberg,[34] E. Brubaker,[13] J. Budagov,[14] H. S. Budd,[47] S. Budd,[23] K. Burkett,[16] G. Busetto,[42] P. Bussey,[20] K. L. Byrum,[2] S. Cabrera,[15] M. Campanelli,[19] M. Campbell,[33] F. Canelli,[8] A. Canepa,[46] D. Carlsmith,[57] R. Carosi,[44] S. Carron,[15] M. Casarsa,[52] A. Castro,[5] P. Catastini,[44] D. Cauz,[52] M. Cavalli-Sforza,[3] A. Cerri,[28] L. Cerrito,[41] S. H. Chang,[27] J. Chapman,[33] Y. C. Chen,[1] M. Chertok,[7] G. Chiarelli,[44] G. Chlachidze,[14] F. Chlebana,[16] I. Cho,[27] K. Cho,[27] D. Chokheli,[14] J. P. Chou,[21] P. H. Chu,[23] S. H. Chuang,[57] K. Chung,[12] W. H. Chung,[57] Y. S. Chung,[47] M. Ciljak,[44] C. I. Ciobanu,[23] M. A. Ciocci,[44] A. Clark,[19] D. Clark,[6] M. Coca,[15] A. Connolly,[28] M. E. Convery,[48] J. Conway,[7] B. Cooper,[30] K. Copic,[33] M. Cordelli,[18] G. Cortiana,[42] A. Cruz,[17] J. Cuevas,[11] R. Culbertson,[16] C. Currat,[28] D. Cyr,[57] S. DaRonco,[42] S. D'Auria,[20] M. D'onofrio,[19] D. Dagenhart,[6] P. de Barbaro,[47] S. De Cecco,[49] A. Deisher,[28] G. De Lentdecker,[47] M. Dell'Orso,[44] S. Demers,[47] L. Demortier,[48] J. Deng,[15] M. Deninno,[5] D. De Pedis,[49] P. F. Derwent,[16] C. Dionisi,[49] J. Dittmann,[4] P. DiTuro,[50] C. Dörr,[25] A. Dominguez,[28] S. Donati,[44] M. Donega,[19] P. Dong,[8] J. Donini,[42] T. Dorigo,[42] S. Dube,[50] K. Ebina,[55] J. Efron,[38] J. Ehlers,[19] R. Erbacher,[7] D. Errede,[23] S. Errede,[23] R. Eusebi,[47] H. C. Fang,[28] S. Farrington,[29] I. Fedorko,[44] W. T. Fedorko,[13] R. G. Feild,[58] M. Feindt,[25] J. P. Fernandez,[46] R. Field,[17] G. Flanagan,[34] L. R. Flores-Castillo,[45] A. Foland,[21] S. Forrester,[7] G. W. Foster,[16] M. Franklin,[21] J. C. Freeman,[28] Y. Fujii,[26] I. Furic,[13] A. Gajjar,[29] M. Gallinaro,[48] J. Galyardt,[12] J. E. Garcia,[44] M. Garcia Sciveres,[28] A. F. Garfinkel,[46] C. Gay,[58] H. Gerberich,[23] E. Gerchtein,[12] D. Gerdes,[33] S. Giagu,[49] P. Giannetti,[44] A. Gibson,[28] K. Gibson,[12] C. Ginsburg,[16] K. Giolo,[46] M. Giordani,[52] M. Giunta,[44] G. Giurgiu,[12] V. Glagolev,[14] D. Glenzinski,[16] M. Gold,[36] N. Goldschmidt,[33] J. Goldstein,[41] G. Gomez,[11] G. Gomez-Ceballos,[11] M. Goncharov,[51] O. González,[46] I. Gorelov,[36] A. T. Goshaw,[15] Y. Gotra,[45] K. Goulianos,[48] A. Gresele,[42] M. Griffiths,[29] S. Grinstein,[21] C. Grosso-Pilcher,[13] U. Grundler,[23] J. Guimaraes da Costa,[21] C. Haber,[28] S. R. Hahn,[16] K. Hahn,[43] E. Halkiadakis,[47] A. Hamilton,[32] B.-Y. Han,[47] R. Handler,[57] F. Happacher,[18] K. Hara,[53] M. Hare,[54] S. Harper,[41] R. F. Harr,[56] R. M. Harris,[16] K. Hatakeyama,[48] J. Hauser,[8] C. Hays,[15] H. Hayward,[29] A. Heijboer,[43] B. Heinemann,[29] J. Heinrich,[43] M. Hennecke,[25] M. Herndon,[57] J. Heuser,[25] D. Hidas,[15] C. S. Hill,[10] D. Hirschbuehl,[25] A. Hocker,[16] A. Holloway,[21] S. Hou,[1] M. Houlden,[29] S.-C. Hsu,[9] B. T. Huffman,[41] R. E. Hughes,[38] J. Huston,[34] K. Ikado,[55] J. Incandela,[10] G. Introzzi,[44] M. Iori,[49] Y. Ishizawa,[53] A. Ivanov,[7] B. Iyutin,[31] E. James,[16] D. Jang,[50] B. Jayatilaka,[33] D. Jeans,[49] H. Jensen,[16] E. J. Jeon,[27] M. Jones,[46] K. K. Joo,[27] S. Y. Jun,[12] T. R. Junk,[23] T. Kamon,[51] J. Kang,[33] M. Karagoz-Unel,[37] P. E. Karchin,[56] Y. Kato,[40] Y. Kemp,[25] R. Kephart,[16] U. Kerzel,[25] V. Khotilovich,[51] B. Kilminster,[38] D. H. Kim,[27] H. S. Kim,[27] J. E. Kim,[27] M. J. Kim,[12] M. S. Kim,[27] S. B. Kim,[27] S. H. Kim,[53] Y. K. Kim,[13] M. Kirby,[15] L. Kirsch,[6] S. Klimenko,[17] M. Klute,[31] B. Knuteson,[31] B. R. Ko,[15] H. Kobayashi,[53] K. Kondo,[55] D. J. Kong,[27] J. Konigsberg,[17] K. Kordas,[18] A. Korytov,[17] A. V. Kotwal,[15] A. Kovalev,[43] J. Kraus,[23] I. Kravchenko,[31] M. Kreps,[25] A. Kreymer,[16] J. Kroll,[43] N. Krumnack,[4] M. Kruse,[15] V. Krutelyov,[51] S. E. Kuhlmann,[2] Y. Kusakabe,[55] S. Kwang,[13] A. T. Laasanen,[46] S. Lai,[32] S. Lami,[44] S. Lammel,[16] M. Lancaster,[30] R. L. Lander,[7] K. Lannon,[38] A. Lath,[50] G. Latino,[44] I. Lazzizzera,[42] C. Lecci,[25] T. LeCompte,[2] J. Lee,[47] J. Lee,[27] S. W. Lee,[51] Y. J. Lee,[27] R. Lefèvre,[3] N. Leonardo,[31] S. Leone,[44] S. Levy,[13] J. D. Lewis,[16] K. Li,[58] C. Lin,[58] C. S. Lin,[16] M. Lindgren,[16] E. Lipeles,[9] T. M. Liss,[23] A. Lister,[19] D. O. Litvintsev,[16] T. Liu,[16] Y. Liu,[19] N. S. Lockyer,[43] A. Loginov,[35] M. Loreti,[42] P. Loverre,[49] R.-S. Lu,[1] D. Lucchesi,[42] P. Lujan,[28] P. Lukens,[16] G. Lungu,[17] L. Lyons,[41] J. Lys,[28] R. Lysak,[1] E. Lytken,[46] P. Mack,[25] D. MacQueen,[32] R. Madrak,[16] K. Maeshima,[16] P. Maksimovic,[24] G. Manca,[29] F. Margaroli,[5] R. Marginean,[16] C. Marino,[23] A. Martin,[58] M. Martin,[24] V. Martin,[37] M. Martínez,[3] T. Maruyama,[53] H. Matsunaga,[53] M. E. Mattson,[56] R. Mazini,[32] P. Mazzanti,[5] K. S. McFarland,[47] D. McGivern,[30] P. McIntyre,[51] P. McNamara,[50] R. McNulty,[29] A. Mehta,[29] S. Menzemer,[31] A. Menzione,[44] P. Merkel,[46] C. Mesropian,[48] A. Messina,[49] M. von der Mey,[8] T. Miao,[16] N. Miladinovic,[6] J. Miles,[31] R. Miller,[34] J. S. Miller,[33] C. Mills,[10] M. Milnik,[25] R. Miquel,[28] S. Miscetti,[18] G. Mitselmakher,[17] A. Miyamoto,[26] N. Moggi,[5] B. Mohr,[8] R. Moore,[16] M. Morello,[44] P. Movilla Fernandez,[28]

0031-9007/06/96(2)/022004(7)$23.00

J. Mülmenstädt,[28] A. Mukherjee,[16] M. Mulhearn,[31] Th. Muller,[25] R. Mumford,[24] P. Murat,[16] J. Nachtman,[16] S. Nahn,[58] I. Nakano,[39] A. Napier,[54] D. Naumov,[36] V. Necula,[17] C. Neu,[43] M. S. Neubauer,[9] J. Nielsen,[28] T. Nigmanov,[45] L. Nodulman,[2] O. Norniella,[3] T. Ogawa,[55] S. H. Oh,[15] Y. D. Oh,[27] T. Okusawa,[40] R. Oldeman,[29] R. Orava,[22] K. Osterberg,[22] C. Pagliarone,[44] E. Palencia,[11] R. Paoletti,[44] V. Papadimitriou,[16] A. Papikonomou,[25] A. A. Paramonov,[13] B. Parks,[38] S. Pashapour,[32] J. Patrick,[16] G. Pauletta,[52] M. Paulini,[12] C. Paus,[31] D. E. Pellett,[7] A. Penzo,[52] T. J. Phillips,[15] G. Piacentino,[44] J. Piedra,[11] K. Pitts,[23] C. Plager,[8] L. Pondrom,[57] G. Pope,[45] X. Portell,[3] O. Poukhov,[14] N. Pounder,[41] F. Prakoshyn,[14] A. Pronko,[16] J. Proudfoot,[2] F. Ptohos,[18] G. Punzi,[44] J. Pursley,[24] J. Rademacker,[41] A. Rahaman,[45] A. Rakitin,[31] S. Rappoccio,[21] F. Ratnikov,[50] B. Reisert,[16] V. Rekovic,[36] N. van Remortel,[22] P. Renton,[41] M. Rescigno,[49] S. Richter,[25] F. Rimondi,[5] K. Rinnert,[25] L. Ristori,[44] W. J. Robertson,[15] A. Robson,[20] T. Rodrigo,[11] E. Rogers,[23] S. Rolli,[54] R. Roser,[16] M. Rossi,[52] R. Rossin,[17] C. Rott,[46] A. Ruiz,[11] J. Russ,[12] V. Rusu,[13] D. Ryan,[54] H. Saarikko,[22] S. Sabik,[32] A. Safonov,[7] W. K. Sakumoto,[47] G. Salamanna,[49] O. Salto,[3] D. Saltzberg,[8] C. Sanchez,[3] L. Santi,[52] S. Sarkar,[49] K. Sato,[53] P. Savard,[32] A. Savoy-Navarro,[16] T. Scheidle,[25] P. Schlabach,[16] E. E. Schmidt,[16] M. P. Schmidt,[58] M. Schmitt,[37] T. Schwarz,[33] L. Scodellaro,[11] A. L. Scott,[10] A. Scribano,[44] F. Scuri,[44] A. Sedov,[46] S. Seidel,[36] Y. Seiya,[40] A. Semenov,[14] F. Semeria,[5] L. Sexton-Kennedy,[16] I. Sfiligoi,[18] M. D. Shapiro,[28] T. Shears,[29] P. F. Shepard,[45] D. Sherman,[21] M. Shimojima,[53] M. Shochet,[13] Y. Shon,[57] I. Shreyber,[35] A. Sidoti,[44] J. Siegrist,[28] A. Sill,[16] P. Sinervo,[32] A. Sisakyan,[14] J. Sjolin,[41] A. Skiba,[25] A. J. Slaughter,[16] K. Sliwa,[54] D. Smirnov,[36] J. R. Smith,[7] F. D. Snider,[16] R. Snihur,[32] M. Soderberg,[33] A. Soha,[7] S. Somalwar,[50] V. Sorin,[34] J. Spalding,[16] F. Spinella,[44] P. Squillacioti,[44] M. Stanitzki,[58] A. Staveris-Polykalas,[44] R. St. Denis,[20] B. Stelzer,[8] O. Stelzer-Chilton,[32] D. Stentz,[37] J. Strologas,[36] D. Stuart,[10] J. S. Suh,[27] A. Sukhanov,[17] K. Sumorok,[31] H. Sun,[54] T. Suzuki,[53] A. Taffard,[23] R. Tafirout,[32] R. Takashima,[39] Y. Takeuchi,[53] K. Takikawa,[53] M. Tanaka,[2] R. Tanaka,[39] M. Tecchio,[33] P. K. Teng,[1] K. Terashi,[48] S. Tether,[31] J. Thom,[16] A. S. Thompson,[20] E. Thomson,[43] P. Tipton,[47] V. Tiwari,[12] S. Tkaczyk,[16] D. Toback,[51] K. Tollefson,[34] T. Tomura,[53] D. Tonelli,[44] M. Tönnesmann,[34] S. Torre,[44] D. Torretta,[16] S. Tourneur,[16] W. Trischuk,[32] R. Tsuchiya,[55] S. Tsuno,[39] N. Turini,[44] F. Ukegawa,[53] T. Unverhau,[20] S. Uozumi,[53] D. Usynin,[43] L. Vacavant,[28] A. Vaiciulis,[47] S. Vallecorsa,[19] A. Varganov,[33] E. Vataga,[36] G. Velev,[16] G. Veramendi,[23] V. Veszpremi,[46] T. Vickey,[23] R. Vidal,[16] I. Vila,[11] R. Vilar,[11] I. Vollrath,[32] I. Volobouev,[28] F. Würthwein,[9] P. Wagner,[51] R. G. Wagner,[2] R. L. Wagner,[16] W. Wagner,[25] R. Wallny,[8] T. Walter,[25] Z. Wan,[50] M. J. Wang,[1] S. M. Wang,[17] A. Warburton,[32] B. Ward,[20] S. Waschke,[20] D. Waters,[30] T. Watts,[50] M. Weber,[28] W. C. Wester III,[16] B. Whitehouse,[54] D. Whiteson,[43] A. B. Wicklund,[2] E. Wicklund,[16] H. H. Williams,[43] P. Wilson,[16] B. L. Winer,[38] P. Wittich,[43] S. Wolbers,[16] C. Wolfe,[13] S. Worm,[50] T. Wright,[33] X. Wu,[19] S. M. Wynne,[29] S. Xie,[32] A. Yagil,[16] K. Yamamoto,[40] J. Yamaoka,[50] Y. Yamashita.,[39] C. Yang,[58] U. K. Yang,[13] W. M. Yao,[28] G. P. Yeh,[16] J. Yoh,[16] K. Yorita,[13] T. Yoshida,[40] I. Yu,[27] S. S. Yu,[43] J. C. Yun,[16] L. Zanello,[49] A. Zanetti,[52] I. Zaw,[21] F. Zetti,[44] X. Zhang,[23] J. Zhou,[50] and S. Zucchelli[5]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*
[4]*Baylor University, Waco, Texas 76798, USA*
[5]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[6]*Brandeis University, Waltham, Massachusetts 02254, USA*
[7]*University of California, Davis, Davis, California 95616, USA*
[8]*University of California, Los Angeles, Los Angeles, California 90024, USA*
[9]*University of California, San Diego, La Jolla, California 92093, USA*
[10]*University of California, Santa Barbara, Santa Barbara, California 93106, USA*
[11]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[12]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[13]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[14]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[15]*Duke University, Durham, North Carolina 27708*
[16]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[17]*University of Florida, Gainesville, Florida 32611, USA*
[18]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[19]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[20]*Glasgow University, Glasgow G12 8QQ, United Kingdom*

[21]Harvard University, Cambridge, Massachusetts 02138, USA
[22]Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland
[23]University of Illinois, Urbana, Illinois 61801, USA
[24]The Johns Hopkins University, Baltimore, Maryland 21218, USA
[25]Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany
[26]High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan
[27]Center for High Energy Physics: Kyungpook National University, Taegu 702-701; Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746; Korea
[28]Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[29]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[30]University College London, London WC1E 6BT, United Kingdom
[31]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[32]Institute of Particle Physics: McGill University, Montréal, Canada H3A 2T8; and University of Toronto, Toronto, Canada M5S 1A7
[33]University of Michigan, Ann Arbor, Michigan 48109, USA
[34]Michigan State University, East Lansing, Michigan 48824, USA
[35]Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
[36]University of New Mexico, Albuquerque, New Mexico 87131, USA
[37]Northwestern University, Evanston, Illinois 60208, USA
[38]The Ohio State University, Columbus, Ohio 43210, USA
[39]Okayama University, Okayama 700-8530, Japan
[40]Osaka City University, Osaka 588, Japan
[41]University of Oxford, Oxford OX1 3RH, United Kingdom
[42]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, University of Padova, I-35131 Padova, Italy
[43]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[44]Istituto Nazionale di Fisica Nucleare Pisa, Universities of Pisa, Siena and Scuola Normale Superiore, I-56127 Pisa, Italy
[45]University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
[46]Purdue University, West Lafayette, Indiana 47907, USA
[47]University of Rochester, Rochester, New York 14627, USA
[48]The Rockefeller University, New York, New York 10021, USA
[49]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, University of Rome "La Sapienza", I-00185 Roma, Italy
[50]Rutgers University, Piscataway, New Jersey 08855, USA
[51]Texas A&M University, College Station, Texas 77843, USA
[52]Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy
[53]University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[54]Tufts University, Medford, Massachusetts 02155, USA
[55]Waseda University, Tokyo 169, Japan
[56]Wayne State University, Detroit, Michigan 48201, USA
[57]University of Wisconsin, Madison, Wisconsin 53706, USA
[58]Yale University, New Haven, Connecticut 06520, USA
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We report two measurements of the top-quark mass $M_{\rm top}$ using the CDF II detector at the Fermilab Tevatron in a 318 pb^{-1} data sample of $t\bar{t}$ events in the lepton + jets final state. One method uses an event-based likelihood technique resulting in $M_{\rm top} = 173.2^{+2.6}_{-2.4}(\rm stat) \pm 3.2(\rm syst)$ GeV$/c^2$ or $173.2^{+4.1}_{-4.0}$ GeV$/c^2$. The second method reconstructs a top-quark mass in each event using the measured invariant mass of the hadronically decaying W boson to constrain the jet energy scale to obtain a value for $M_{\rm top}$ of $173.5^{+3.7}_{-3.6}(\rm stat) \pm 1.3(\rm syst)$ GeV$/c^2$ or $173.5^{+3.9}_{-3.8}$ GeV$/c^2$. We take the latter, which is more precise, as our result.

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The top quark is the heaviest known elementary particle with a mass approximately 40 times that of the next-heaviest quark or lepton. Because of this comparatively large mass, top-quark studies provide insight into our understanding of mass in general, and test theories that explain the large range of quark and lepton masses. Within the context of the standard model of particle physics, the top-quark mass is related to the masses of the W boson and the Higgs boson, the latter object being the key to our understanding of the origin of mass [1]. Precision measurements of the top-quark and W boson masses test the consistency of the standard model, and in particular the

Higgs mechanism. A precision measurement of the top-quark mass is therefore a main goal of the experiments at the Fermilab Tevatron collider.

In this Letter we present two measurements of the top-quark mass in the lepton + jets decay channel. We use a sample of $t\bar{t}$ decays corresponding to 318 pb^{-1} of proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV and collected using the Collider Detector at Fermilab (CDF II) between February 2002 and August 2004. In the lepton + jets channel, $t\bar{t}$ pair production is followed by the decay of each top quark to a W boson and a b quark, the hadronic decay of one W boson, and the leptonic decay of the other. This decay channel has the largest branching fraction with good signal-to-background ratio, allowing accurate top-quark mass measurements. Events in this channel contain an electron or muon and a neutrino from the leptonic W boson decay, two quark jets from the hadronic W boson decay, and two b-quark jets.

We select events consistent with this decay topology and analyze them using two complementary methods. The first method uses an event-by-event likelihood analysis employing the leading order matrix element for $t\bar{t}$ production and decay to extract a joint likelihood as a function of the top-quark mass, M_{top}. This technique, known as the "dynamical likelihood method" or DLM, was developed by the CDF Collaboration [2] and is similar to that used by the D0 Collaboration to make the previous most precise measurement of the top-quark mass [3]. The second method, developed by the CDF Collaboration [4], reconstructs a top-quark mass, m_t^{reco}, in each event and compares the distribution of m_t^{reco} with template distributions derived from model calculations to estimate M_{top}. We have improved this "template method" by making further use of the fact that the hadronically decaying W boson daughters should form a final state whose invariant mass is consistent with the known W boson mass and width. This allows us to constrain the jet energy scale, an important uncertainty in the earlier measurements. These two methods have a top-quark mass accuracy 30% greater than earlier results, and have different statistical and systematic uncertainties.

The CDF II detector [5] is a general-purpose charged and neutral particle detector located at the Tevatron collider. We employ cylindrical coordinates where θ and ϕ are the polar and azimuthal angles, respectively, with respect to the proton beam, and pseudorapidity is $\eta = -\ln\tan(\theta/2)$. Transverse energy and momentum are $E_T = E\sin\theta$ and $p_T = p\sin\theta$, respectively, where E and p are energy and momentum. The detector comprises a solenoidal charged particle spectrometer, consisting of an eight-layer silicon microstrip detector array and a cylindrical drift chamber immersed in a 1.4 T magnetic field, a segmented sampling calorimeter with acceptance up to pseudorapidity $|\eta| = 3.6$, and a set of charged particle detectors outside the calorimeter used to identify muon candidates.

TABLE I. The background composition and the number of $t\bar{t}$ candidates for events with ≥ 1 b tag, and for the subset used in the DLM analysis. Statistical and systematic uncertainties have been combined.

	≥ 1 b tag	DLM sample
Source	Expected background	
W + jets	19.6 ± 2.4	5.3 ± 1.1
Multijet	4.7 ± 0.7	3.1 ± 1.0
Other	2.3 ± 0.2	0.8 ± 0.1
Total	26.6 ± 3.0	9.2 ± 1.8
	Selected $t\bar{t}$ candidates	
Data	121	63

Events for these analyses were selected by requiring an electron or muon candidate with transverse momentum $p_T > 20$ GeV/c and $|\eta| < 1$ and missing transverse energy exceeding 20 GeV, corresponding to a high-energy neutrino candidate. The signal-to-background ratio was improved by requiring in each event the presence of four or more jets with $|\eta| < 2.0$. To reduce backgrounds further we required either (a) at least four jets with transverse energy $E_T > 21$ GeV or (b) at least three jets with $E_T > 15$ GeV and a fourth jet with $E_T > 8$ GeV with at least one jet with $E_T > 15$ GeV identified as a b-quark candidate through the presence of a displaced vertex within the jet arising from the decay of the long-lived bottom hadron (b tag). This selection resulted in 165 events that, based on our background estimates, are primarily $t\bar{t}$ events. The methods used to estimate the backgrounds are detailed in [6].

The DLM analysis uses a 63-event subset of those data defined by requiring exactly four jets with $E_T > 15$ GeV where at least one of the jets has a b tag. We have estimated the various sources of background contamination in this sample, summarized in Table I, to be 9.2 ± 1.8 events. The template method divides the 165 events into four non-overlapping subsamples with different expected m_t^{reco} distributions and background levels. Ordered by decreasing statistical power, the subsamples are (1) events with at least four jets with $E_T > 15$ GeV and one b-tagged jet ("1-tag Tight" sample with 63 events), (2) events with two or more b-tagged jets ("2-tag" sample with 25 events), (3) events with a fourth jet with 8 GeV $< E_T <$ 15 GeV and one b-tagged jet with $E_T > 15$ GeV ("1-tag Loose" sample with 33 events), and (4) events with four jets with $E_T > 21$ GeV and no b-tagged jets ("0-tag" sample with 44 events). The estimated background levels in the samples with a b tag are summarized in Table I. The background level in the 0-tag sample is determined in the subsequent fit.

Both analyses use calibrated jet energies, based on a combination of instrumental calibration and analysis of data control samples [7]. The uncertainty σ_c on the jet energy scale is the major source of uncertainty on M_{top}. For jets in the $t\bar{t}$ sample, σ_c is approximately 3% of the measured jet energy, depending on the η and p_T of the jet. The parameter Δ_{JES} is defined as the difference, averaged over all jets in the sample, between the true jet energy and our measured jet energy after calibration in units of σ_c.

The DLM technique, described in detail in [8], defines a likelihood for each event based on the differential cross section per unit phase space volume of the final state partons, $d\sigma_{t\bar{t}}/d\Phi$, as a function of M_{top}. Detector resolution effects are accounted for using $t\bar{t}$ events generated by the HERWIG Monte Carlo program [9] and full detector simulation to derive a transfer function (TF). The TF relates the transverse energies of the final state quarks, denoted by $\boldsymbol{x}$, and the observed jets. For a given event, a Monte Carlo integration is performed over the possible $t\bar{t}$ final state kinematics in the following way: we first generate a random value for the virtual mass squared of the W boson in the leptonic channel, s_W, according to the Breit-Wigner form. We identify the momentum of the electron or muon daughter with the measured value, and the neutrino transverse momentum with the measured missing transverse energy. We then generate random values for the momenta of final state quarks according to the TF probabilities. We determine the z component of the neutrino momentum, with a twofold ambiguity, using s_W as a constraint. Thus, for a given set of $\boldsymbol{x}$ and s_W, we fully determine the event kinematics, and the event likelihood as a function of M_{top} is given by

$$L(M_{top}) = N\sum_{I_j}\sum_{I_\nu}\frac{d\sigma_{t\bar{t}}}{d\Phi}(M_{top};\boldsymbol{x}, s_W), \qquad (1)$$

where the normalization factor N is independent of M_{top} for a given event, and the indices I_j and I_ν run over the parton-jet assignments and the two neutrino solutions, respectively. The event likelihood is obtained by numerically integrating over $\boldsymbol{x}$ given by the TF and s_W given by the Breit-Wigner distribution.

Figure 1 shows the distribution of the top-quark mass value at the point of maximum likelihood in each event compared with the expectation from simulated events. An inset shows the joint log likelihood as a function of M_{top}, formed by multiplying the likelihoods of the individual events together. We account for the presence of background events by evaluating the shift of -1.4 GeV$/c^2$ they make in the measured top-quark mass. From the joint likelihood we infer $M_{top} = 173.2^{+2.6}_{-2.4}$(stat) GeV$/c^2$, where the uncertainty is only statistical. The systematic uncertainty due to the jet energy scale is estimated as the shift in M_{top} arising from a $\pm 1\sigma_c$ change in jet energies, and is 3.0 GeV$/c^2$.

The template method is described in detail in [10]. We perform a χ^2 minimization to fit the parton momenta from the $t\bar{t}$ daughters and determine m_t^{reco} for each event, assuming that the final state arises from the decay of a $t\bar{t}$ pair into W bosons and b quarks. We use only the four leading jets in the mass reconstruction. In the χ^2 fit, both sets of W decay daughters are constrained to have the invariant mass of the W boson, and both Wb states are constrained to have the same mass. The ambiguity arising from the different ways of assigning the jets to the four quarks is resolved by selecting the assignment with the lowest χ^2, taking into account the b-tagging information. We construct a histogram of m_t^{reco} for each subsample, discarding events with $\chi^2 > 9$, corresponding to poorly reconstructed or background events.

The parameter Δ_{JES} is determined within this event sample by removing the W boson mass constraints, and

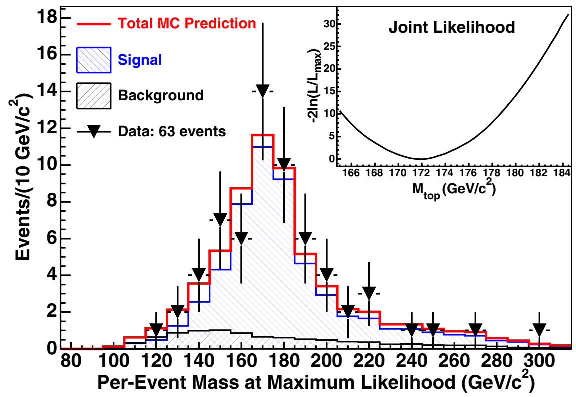

FIG. 1 (color online). The value of the top-quark mass at the maximum of the DLM likelihood is plotted for each event. Data events (points) are compared to an expected distribution (histogram) comprising simulated $t\bar{t}$ ($M_{top} = 172.5$ GeV$/c^2$) and background events. The last bin includes events with masses > 305 GeV$/c^2$. The inset shows the joint log likelihood for the 63 events, before accounting for the presence of background.

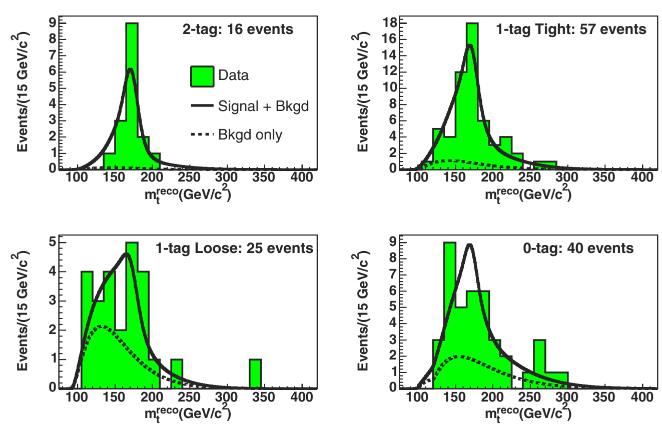

FIG. 2 (color online). The m_t^{reco} distribution of the template method is shown for each subsample overlaid with the expected distribution using M_{top}, Δ_{JES}, and signal and background normalizations from the combined fit. The events with $\chi^2 > 9$ have been excluded from each subsample.

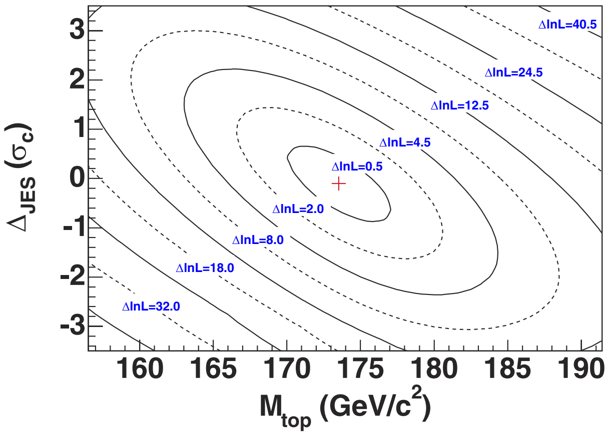

FIG. 3 (color online). Contours of the template method likelihood are shown in the M_{top}-Δ_{JES} plane for the combined fit to all four subsamples. The crosshair shows the best fit point. Contours are given at intervals of $\Delta \ln L$, the change in log likelihood from its maximum.

identifying for each event all pairs of jets that would be consistent with the W boson final state. We form histograms of the invariant masses of these jet pairs for each of the four event subsamples and compare these with what we expect given the precisely known W boson mass [11].

We use these eight histograms to measure simultaneously M_{top} and Δ_{JES}. An unbinned likelihood fit is performed to parametrized signal templates taken from simulated $t\bar{t}$ events generated using different values of M_{top} and Δ_{JES}, and background templates derived from studies of the relevant background processes. We include in the fit a Gaussian constraint ($\Delta_{JES} = 0 \pm 1\sigma_c$) from the extrinsic jet energy calibrations, and we constrain the background rates in the 2-tag, 1-tag Tight, and 1-tag Loose samples to the estimated background rates within their uncertainties. The background level in the 0-tag sample is determined to be $15.7^{+8.0}_{-7.1}$(stat) events by the fit using the differences in predicted signal and background mass distributions.

The four reconstructed top-quark mass distributions and the results of the fit are shown in Fig. 2, where we also show the background contributions. In all cases, we see agreement between the observed data distributions and the fitted curves. We obtain $M_{top} = 173.5^{+3.7}_{-3.6}$(stat) GeV/$c^2$, where the uncertainty is statistical and incorporates the uncertainty due to the jet energy scale, which we estimate contributes ~2.5 GeV/c^2. Figure 3 shows the likelihood in the M_{top}-Δ_{JES} plane. If we do not constrain Δ_{JES} to the nominal value of zero, we obtain $\Delta_{JES} = -0.25 \pm 1.22\sigma_c$, which indicates our nominal jet energy calibrations are in good agreement with information provided by the W boson mass peak in the $t\bar{t}$ decay. This also demonstrates that the constraint on Δ_{JES} from the W boson decay has comparable precision to the jet energy calibration.

TABLE II. The systematic uncertainties for the two analyses.

Systematic	DLM ΔM_{top} (GeV/c^2)	Template ΔM_{top} (GeV/c^2)
Jet energy scale	3.0	[~2.5][a]
ISR/FSR	0.6	0.7
PDFs	0.5	0.3
Modeling	0.7	0.9
Method	0.5	0.6
Total	3.2	1.3

[a]The uncertainty due to the jet energy scale is included in the uncertainty reported by the likelihood fit.

There are a number of additional systematic uncertainties that affect both analyses: initial state and final state radiation uncertainties (ISR/FSR), uncertainties arising from the parton distribution functions (PDFs), and uncertainties arising from modeling of the background processes, the choice of event generators, and b-jet fragmentation, decays, and color connections (modeling) [12,13]. Table II summarizes these uncertainties.

The DLM method has additional uncertainties that arise from the use of transfer functions and from the procedure that corrects the measured mass for the presence of background (method). Together with the jet energy scale and other common sources noted above, the systematic uncertainty on the DLM mass measurement is 3.2 GeV/c^2.

The template method has additional uncertainties arising from the statistical precision of the templates themselves and approximations made in treating Δ_{JES} as a single parameter affecting all jets coherently (method). The total systematic uncertainty on the template mass measurement is 1.3 GeV/c^2.

In summary, we have presented two new measurements of the top-quark mass. The analysis using the DLM method results in $M_{top} = 173.2 + ^{+2.6}_{-2.4}$(stat) $\pm$ 3.2(syst) GeV/c^2; the analysis using the template technique results in $M_{top} = 173.5\,^{+3.7}_{-3.6}$(stat) $\pm$ 1.3(syst) GeV/c^2. There is a large statistical correlation between these measurements given the common data sample, so that we quote as a result only the more accurate measurement, the template method result of $M_{top} = 173.5\,^{+3.9}_{-3.8}$ GeV/c^2. This provides the most precise single measurement of this important physical parameter. In comparison, the previous most precise measurement was $M_{top} = 180.1 \pm 5.3$ GeV/c^2 [3] and the world average was $M_{top} = 178.0 \pm 4.3$ GeV/c^2 [14].

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