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The $\mu\tau$ and $e\tau$ Decays of Top Quark Pairs Produced in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.8 TeV

F. Abe et al.
The CDF Collaboration

Fermi National Accelerator Laboratory
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Distribution

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F. Abe,[17] H. Akimoto,[36] A. Akopian,[31] M. G. Albrow,[7] S. R. Amendolia,[27] D. Amidei,[20] J. Antos,[33] S. Aota,[36] G. Apollinari,[31] T. Asakawa,[36] W. Ashmanskas,[18] M. Atac,[7] F. Azfar,[26] P. Azzi-Bacchetta,[25] N. Bacchetta,[25] W. Badgett,[20] S. Bagdasarov,[31] M. W. Bailey,[22] J. Bao,[39] P. de Barbaro,[30] A. Barbaro-Galtieri,[18] V. E. Barnes,[29] B. A. Barnett,[15] M. Barone,[9] E. Barzi,[9] G. Bauer,[19] T. Baumann,[11] F. Bedeschi,[27] S. Behrends,[3] S. Belforte,[27] G. Bellettini,[27] J. Bellinger,[38] D. Benjamin,[35] J. Benlloch,[19] J. Bensinger,[3] D. Benton,[26] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] B. Bevensee,[26] A. Bhatti,[31] K. Biery,[7] M. Binkley,[7] D. Bisello,[25] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[30] W. Bokhari,[19] V. Bolognesi,[2] G. Bolla,[29] D. Bortoletto,[29] J. Boudreau,[28] L. Breccia,[2] C. Bromberg,[21] N. Bruner,[22] E. Buckley-Geer,[7] H. S. Budd,[30] K. Burkett,[20] G. Busetto,[25] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[15] C. Campagnari,[7] M. Campbell,[20] A. Caner,[27] W. Carithers,[18] D. Carlsmith,[38] A. Castro,[25] D. Cauz,[27] Y. Cen,[30] F. Cervelli,[27] P. S. Chang,[33] P. T. Chang,[33] H. Y. Chao,[33] J. Chapman,[20] M. -T. Cheng,[33] G. Chiarelli,[27] T. Chikamatsu,[36] C. N. Chiou,[33] L. Christofek,[13] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[27] E. Cocca,[27] M. Contreras,[5] J. Conway,[32] J. Cooper,[7] M. Cordelli,[9] C. Couyoumtzelis,[10] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] T. Daniels,[19] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[27] M. Dell'Orso,[27] R. Demina,[7] L. Demortier,[31] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[32] J. R. Dittmann,[6] S. Donati,[27] J. Done,[34] T. Dorigo,[25] A. Dunn,[20] N. Eddy,[20] K. Einsweiler,[18] J. E. Elias,[7] R. Ely,[18] E. Engels, Jr.,[28] D. Errede,[13] S. Errede,[13] Q. Fan,[30] G. Feild,[39] C. Ferretti,[27] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[11] M. Frautschi,[35] J. Freeman,[7] J. Friedman,[19] H. Frisch,[5] Y. Fukui,[17] S. Funaki,[36] S. Galeotti,[27] M. Gallinaro,[26] O. Ganel,[35] M. Garcia-Sciveres,[18] A. F. Garfinkel,[29] C. Gay,[11] S. Geer,[7] P. Giannetti,[27] N. Giokaris,[31] P. Giromini,[9] G. Giusti,[27] L. Gladney,[26] D. Glenzinski,[15] M. Gold,[22] J. Gonzalez,[26] A. Gordon,[11] A. T. Goshaw,[6] Y. Gotra,[25] K. Goulianos,[31] H. Grassmann,[27] L. Groer,[32] C. Grosso-Pilcher,[5] G. Guillian,[20] R. S. Guo,[33] C. Haber,[18] E. Hafen,[19] S. R. Hahn,[7] R. Hamilton,[11] R. Handler,[38] R. M. Hans,[39] F. Happacher,[9] K. Hara,[36] A. D. Hardman,[29] B. Harral,[26] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[32] E. Hayashi,[36] J. Heinrich,[26] B. Hinrichsen,[14] K. D. Hoffman,[29] M. Hohlmann,[5] C. Holck,[26] R. Hollebeek,[26] L. Holloway,[13] S. Hong,[20] G. Houk,[26] P. Hu,[28] B. T. Huffman,[28] R. Hughes,[23] J. Huston,[21] J. Huth,[11] J. Hylen,[7] H. Ikeda,[36] M. Incagli,[27] J. Incandela,[7] G. Introzzi,[27] J. Iwai,[36] Y. Iwata,[12] H. Jensen,[7] U. Joshi,[7] R. W. Kadel,[18] E. Kajfasz,[25] H. Kambara,[10] T. Kamon,[34] T. Kaneko,[36] K. Karr,[37] H. Kasha,[39] Y. Kato,[24] T. A. Keaffaber,[29] K. Kelley,[19] R. D. Kennedy,[7] R. Kephart,[7] P. Kesten,[18] D. Kestenbaum,[11] H. Keutelian,[7] F. Keyvan,[4] B. Kharadia,[13] B. J. Kim,[30] D. H. Kim,[7a] H. S. Kim,[14] S. B. Kim,[20] S. H. Kim,[36] Y. K. Kim,[18] L. Kirsch,[3] P. Koehn,[23] K. Kondo,[36] J. Konigsberg,[8] S. Kopp,[5] K. Kordas,[14] A. Korytov,[8] W. Koska,[7] E. Kovacs,[7a] W. Kowald,[6] M. Krasberg,[20] J. Kroll,[7] M. Kruse,[30] T. Kuwabara,[36] S. E. Kuhlmann,[1] E. Kuns,[32] A. T. Laasanen,[29] S. Lami,[27] S. Lammel,[7] J. I. Lamoureux,[3] M. Lancaster,[18] T. LeCompte,[1] S. Leone,[27] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[13] J. B. Liu,[30] Y. C. Liu,[33] N. Lockyer,[26] O. Long,[26] C. Loomis,[32] M. Loreti,[25] J. Lu,[34] D. Lucchesi,[27] P. Lukens,[7] S. Lusin,[38] J. Lys,[18] K. Maeshima,[7] A. Maghakian,[31] P. Maksimovic,[19] M. Mangano,[27] J. Mansour,[21] M. Mariotti,[25] J. P. Marriner,[7] A. Martin,[39] J. A. J. Matthews,[22] R. Mattingly,[19] P. McIntyre,[34] P. Melese,[31] A. Menzione,[27] E. Meschi,[27] S. Metzler,[26] C. Miao,[20] T. Miao,[7] G. Michail,[11] R. Miller,[21] H. Minato,[36] S. Miscetti,[9] M. Mishina,[17] H. Mitsushio,[36] T. Miyamoto,[36] S. Miyashita,[36] N. Moggi,[27] Y. Morita,[17] A. Mukherjee,[7] T. Muller,[16] P. Murat,[27] H. Nakada,[36] I. Nakano,[36] C. Nelson,[7] D. Neuberger,[16] C. Newman-Holmes,[7] C-Y. P. Ngan,[19] M. Ninomiya,[36] L. Nodulman,[1] S. H. Oh,[6] K. E. Ohl,[39] T. Ohmoto,[12] T. Ohsugi,[12] R. Oishi,[36] M. Okabe,[36] T. Okusawa,[24] R. Oliveira,[26] J. Olsen,[38] C. Pagliarone,[27] R. Paoletti,[27] V. Papadimitriou,[35] S. P. Pappas,[39] N. Parashar,[27] S. Park,[7] A. Parri,[9] J. Patrick,[7] G. Pauletta,[27] M. Paulini,[18] A. Perazzo,[27] L. Pescara,[25] M. D. Peters,[18] T. J. Phillips,[6] G. Piacentino,[27] M. Pillai,[30] K. T. Pitts,[7] R. Plunkett,[7] L. Pondrom,[38] J. Proudfoot,[1] F. Ptohos,[11] G. Punzi,[27] K. Ragan,[14] D. Reher,[18] A. Ribon,[25] F. Rimondi,[2] L. Ristori,[27] W. J. Robertson,[6] T. Rodrigo,[27] S. Rolli,[37] J. Romano,[5] L. Rosenson,[19] R. Roser,[13] T. Saab,[14] W. K. Sakumoto,[30] D. Saltzberg,[5] A. Sansoni,[9] L. Santi,[27] H. Sato,[36] P. Schlabach,[7] E. E. Schmidt,[7] M. P. Schmidt,[39] A. Scribano,[27] S. Segler,[7] S. Seidel,[22] Y. Seiya,[36] G. Sganos,[14] M. D. Shapiro,[18] N. M. Shaw,[29] Q. Shen,[29] P. F. Shepard,[28] M. Shimojima,[36] M. Shochet,[5] J. Siegrist,[18] A. Sill,[35] P. Sinervo,[14] P. Singh,[28] J. Skarha,[15] K. Sliwa,[37] F. D. Snider,[15] T. Song,[20] J. Spalding,[7] T. Speer,[10] P. Sphicas,[19] F. Spinella,[27] M. Spiropulu,[11] L. Spiegel,[7] L. Stanco,[25] J. Steele,[38] A. Stefanini,[27] K. Strahl,[14] J. Strait,[7] R. Ströhmer,[7a] D. Stuart,[7] G. Sullivan,[5] K. Sumorok,[19] J. Suzuki,[36] T. Takada,[36] T. Takahashi,[24] T. Takano,[36] K. Takikawa,[36] N. Tamura,[12] B. Tannenbaum,[22] F. Tartarelli,[27] W. Taylor,[14] P. K. Teng,[33] Y. Teramoto,[24] S. Tether,[19] D. Theriot,[7] T. L. Thomas,[22] R. Thun,[20] R. Thurman-Keup,[1] M. Timko,[37] P. Tipton,[30] A. Titov,[31] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[30] A. Tollestrup,[7] H. Toyoda,[24] W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[20] J. Tseng,[19] N. Turini,[27] T. Uchida,[36] N. Uemura,[36] F. Ukegawa,[26] G. Unal,[26] J. Valls,[7a] S. C. van den Brink,[28] S. Vejcik, III,[20] G. Velev,[27] R. Vidal,[7] R. Vilar,[7a] M. Vondracek,[13] D. Vucinic,[19] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[27] A. M. Walsh,[32] C. Wang,[6] C. H. Wang,[33] J. Wang,[5] M. J. Wang,[33] Q. F. Wang,[31] A. Warburton,[14] T. Watts,[32] R. Webb,[34] C. Wei,[6] H. Wenzel,[16] W. C. Wester, III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[26] H. H. Williams,[26] P. Wilson,[5] B. L. Winer,[23]

D. Winn,[20] D. Wolinski,[20] J. Wolinski,[21] S. Worm,[22] X. Wu,[10] J. Wyss,[25] A. Yagil,[7] W. Yao,[18] K. Yasuoka,[36] Y. Ye,[14] G. P. Yeh,[7] P. Yeh,[33] M. Yin,[6] J. Yoh,[7] C. Yosef,[21] T. Yoshida,[24] D. Yovanovitch,[7] I. Yu,[7] L. Yu,[22] J. C. Yun,[7] A. Zanetti,[27] F. Zetti,[27] L. Zhang,[38] W. Zhang,[26] and S. Zucchelli[2]

(CDF Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*
[2] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[3] *Brandeis University, Waltham, Massachusetts 02264*
[4] *University of California at Los Angeles, Los Angeles, California 90024*
[5] *University of Chicago, Chicago, Illinois 60638*
[6] *Duke University, Durham, North Carolina 28708*
[7] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8] *University of Florida, Gainesville, FL 33611*
[9] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[10] *University of Geneva, CH-1211 Geneva 4, Switzerland*
[11] *Harvard University, Cambridge, Massachusetts 02138*
[12] *Hiroshima University, Higashi-Hiroshima 724, Japan*
[13] *University of Illinois, Urbana, Illinois 61801*
[14] *Institute of Particle Physics, McGill University, Montreal H3A 2T8, and University of Toronto, Toronto M5S 1A7, Canada*
[15] *The Johns Hopkins University, Baltimore, Maryland 21218*
[16] *Universität Karlsruhe, 76128 Karlsruhe, Germany*
[17] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 315, Japan*
[18] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[19] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[20] *University of Michigan, Ann Arbor, Michigan 48109*
[21] *Michigan State University, East Lansing, Michigan 48824*
[22] *University of New Mexico, Albuquerque, New Mexico 87132*
[23] *The Ohio State University, Columbus, OH 43320*
[24] *Osaka City University, Osaka 588, Japan*
[25] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-36132 Padova, Italy*
[26] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[27] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[28] *University of Pittsburgh, Pittsburgh, Pennsylvania 15270*
[29] *Purdue University, West Lafayette, Indiana 47907*
[30] *University of Rochester, Rochester, New York 14628*
[31] *Rockefeller University, New York, New York 10021*
[32] *Rutgers University, Piscataway, New Jersey 08854*
[33] *Academia Sinica, Taipei, Taiwan 11530, Republic of China*
[34] *Texas A&M University, College Station, Texas 77843*
[35] *Texas Tech University, Lubbock, Texas 79409*
[36] *University of Tsukuba, Tsukuba, Ibaraki 315, Japan*
[37] *Tufts University, Medford, Massachusetts 02155*
[38] *University of Wisconsin, Madison, Wisconsin 53806*
[39] *Yale University, New Haven, Connecticut 06511*

We present evidence for dilepton events from $t\bar{t}$ production with one electron or muon and one hadronically decaying τ lepton from the decay $t\bar{t} \rightarrow (\ell\nu_\ell)(\tau\nu_\tau)\, b\bar{b}$, ($\ell = e, \mu$), using the Collider Detector at Fermilab (CDF). In a 109 pb^{-1} data sample of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV we expect ~ 1 signal event and a total background of ~ 2 events; we observe 4 candidate events (2 $e\tau$ and 2 $\mu\tau$). Three of these events have jets identified as b candidates, compared to an estimated background of 0.28 ± 0.02 events.

The Collider Detector at Fermilab (CDF) Collaboration [1,2] and the D0 Collaboration [3] recently established the existence of the top quark through searches for $t\bar{t}$ production with the subsequent decay $t\bar{t} \to W^+bW^-\bar{b}$. The decay modes of the two W bosons determine the observed event signature. Both experiments observed top quarks based on the "dilepton" channels in which both W bosons decay into $e\nu_e$ or $\mu\nu_\mu$, and the "lepton + jets" channel where one W boson decays into $e\nu_e$ or $\mu\nu_\mu$ and the other into quarks.

Here we present first evidence for top quark decays in the "tau dilepton" channel, where one W decays into $e\nu_e$ or $\mu\nu_\mu$ and the other into the third-generation leptons, τ and ν_τ. Consequently, the total decay chain is:

$$t\bar{t} \to W^+W^-b\bar{b} \to (\ell\nu_\ell)(\tau\nu_\tau)\, b\bar{b} \quad \hookrightarrow hadrons + \nu_\tau,$$

where ℓ stands for e or μ. This channel is of particular interest because the existence of a charged Higgs boson $H^\pm$ with $m_{H^\pm} < m_{top}$ could give rise to anomalous τ lepton production through the decay chain $t \to H^+b \to \tau^+\nu_\tau b$, which could be directly observable in this channel [4].

In the Standard Model the top branching ratio (BR) to Wb is essentially 100% and the approximate BR of W to each of $e\nu_e$, $\mu\nu_\mu$, and $\tau\nu_\tau$ is 1/9, and to $q\bar{q}'$ is 6/9. Consequently, the total BR for $t\bar{t}$ into $e\tau$ and $\mu\tau$ events is 4/81, the same as for ee, $\mu\mu$, and $e\mu$ combined. In principle, the number of dilepton events could be doubled by including τ's. However, the 64% BR [5] for τ decays into hadrons (50% one-prong and 14% three-prong decays), decreased kinematic acceptance due to the undetected ν_τ, and a τ selection that is less efficient than the e or μ selection, result in a total tau dilepton acceptance about five times smaller than that for ee, $\mu\mu$, and $e\mu$ events.

We report here on a search based on a data sample containing 109 ± 7 pb^{-1} collected with CDF during the Fermilab 1992-93 and 1994-95 Collider runs. A detailed description of the detector can be found elsewhere [6]. The components of the detector most relevant to this search are a four-layer silicon vertex detector [7], located immediately outside the beam pipe, providing precise track reconstruction used to identify secondary vertices from b and c quark decays, a central drift chamber immersed in a 1.4 T solenoidal magnetic field for tracking charged particles in the pseudorapidity [8] range $|\eta| < 1.1$, electromagnetic and hadronic calorimeters covering the range $|\eta| < 4.2$ and arranged in a projective tower geometry for identifying electrons and jets, strip chambers embedded in the electromagnetic calorimeter at a depth of approximately shower maximum for detailed shower sampling, and drift chambers outside the calorimeters in the region $|\eta| < 1.0$ for muon identification. Calorimeters also measure the missing transverse energy $\not\!\!E_T$ [8], which can indicate the presence of undetected energetic neutrinos. A three-level trigger selects inclusive electron and muon events used in this analysis.

The data sample used in this analysis comprises high-p_T inclusive lepton events that contain an electron with $E_T > 20$ GeV or a muon with $p_T > 20$ GeV/c in the central region ($|\eta| < 1.0$). The selection criteria for the primary e or μ are identical to those applied in Ref. [2].

The identification of hadronically decaying τ's is difficult due to the misidentification of the much more numerous quark or gluon jets as τ's . We use two complementary techniques for identifying τ's, one "track–based" and the other "calorimeter–based".

The track–based selection [9] accepts only one-prong τ decays. Events with an e or a μ must have an additional high-p_T ($p_T > 15$ GeV/c), central ($|\eta| < 1.0$), isolated track. The tracking isolation I_{track} is defined as Σp_T of all tracks in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ in (η, ϕ) space around the high-p_T track. A cut of $I_{track} < 1$ GeV/c discriminates between the τ signal and QCD jets. Requiring $E/p > 0.5$ ensures consistency between the energy measured in the calorimeter and the track momentum. Electrons are removed by rejecting clusters in which a large fraction of the total energy is deposited in the electromagnetic calorimeter. Tracks associated with an energy deposition consistent with that of a minimum ionizing particle are rejected as μ candidates. These cuts provide sufficient background rejection for one-prong decays, but not for three-prong decays.

The calorimeter–based selection [10] increases the acceptance by using both one-prong and three-prong τ decays. The selection criteria are: (i) The number of tracks with $p_T > 1$ GeV/c in a 10° cone around the calorimeter cluster center, which defines the track multiplicity associated with the cluster, must be either one or three. (ii) The track isolation I_{track} is defined as Σp_T of all tracks in a cone of $\Delta R = 0.4$ around the cluster center, excluding those that define the track multiplicity. We require $I_{track} < 1$ GeV/c. (iii) About 73% (41%) of all one(three)-prong decays are expected to be associated with at least one π^0 [5] which is identifiable in the strip chambers by searching for clusters from the decay $\pi^0 \to \gamma\gamma$. The p_T of the τ is then defined as the scalar sum of the p_T of the tracks in the 10° cone plus the E_T of any identified π^0's as measured in the electromagnetic calorimeter. We require $p_T > 15$ GeV/c and $|\eta| < 1.2$. (iv) We require $0.5 < E/p < 2.0(1.5)$ for one(three)-prongs. (v) The width σ_{cl} of a calorimeter cluster in (η, ϕ) space is defined as the second moment of the E_T distribution among the towers in a cluster. Low–multiplicity τ clusters are narrower than clusters from QCD jets: we require $\sigma_{cl} < 0.11(0.13) - 0.025(0.034) \times E_T[\mathrm{GeV}]/100$ for one(three)-prongs. (vi) Tau decays rarely involve more than 2 π^0's, so fewer than 3 π^0 candidates must be found. (vii) The invariant mass reconstructed from tracks and π^0's is required to be less than 1.8 GeV/c^2. (viii) Clusters consistent with being an e or μ are removed.

A Monte Carlo simulation ($m_{top} = 175$ GeV/c^2)

of $t\bar{t}$ production provides an estimate of the τ identification efficiencies and acceptances for tau dilepton events. We use the PYTHIA [11] Monte Carlo to generate $t\bar{t}$ events, the TAUOLA package [12], which correctly treats the τ polarization, to decay the tau lepton, and a detector simulation. We expect 29% of hadronic one-prong τ decays to produce tracks with $p_T > 15$ GeV/c and $|\eta| < 1.0$. The track–based τ selection identifies (59±4(stat)±3(syst))% of these. The calorimeter–based selection identifies (57±2(stat)±3(syst))% of the 45% of all hadronic τ decays with $p_T > 15$ GeV/c, as defined in the previous paragraph, and $|\eta| < 1.2$. The uncertainty in the number of tracks due to the underlying event and overlapping minimum bias events makes the largest contribution to the overall systematic uncertainty.

The efficiency calculation is checked using a data sample enriched in $W\to\tau\nu_\tau$ decays. Typically, a $W\to\tau\nu_\tau\to hadrons+\nu_\tau\bar{\nu}_\tau$ decay has one jet from the τ, and $\not\!\!E_T$ due to the neutrinos. A monojet sample is selected by requiring one central jet with $15 < E_T < 40$ GeV, no other jet with $E_T > 7$ GeV in $|\eta| < 4.0$, and $20 < \not\!\!E_T < 40$ GeV. Figure 1a shows the track multiplicity in this sample and in a background sample of QCD jets. The latter is normalized to the monojet sample using the bins with ≥ 4 tracks where there is a very small contribution from $W\to\tau\nu_\tau$ events. The data show a clear excess in the one-prong and three-prong bins, as expected for a sample with significant τ fraction. The $W\to\tau\nu_\tau$ content is estimated to be (45±5(stat))% by subtracting the QCD contribution. Figure 1b shows the track multiplicity after applying all cuts from the calorimeter–based τ selection (except cut i). The background in all bins is greatly

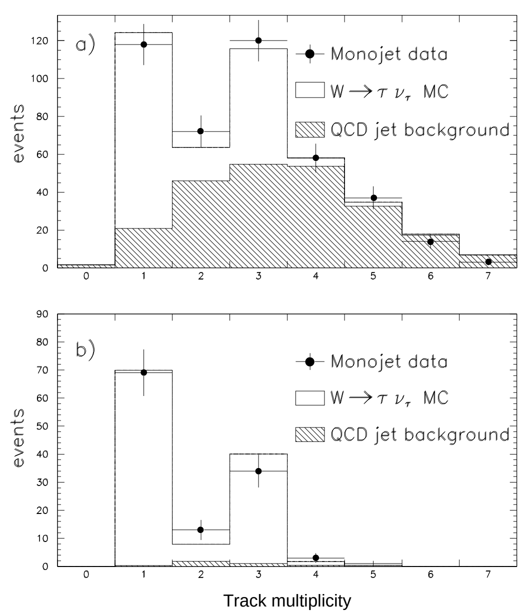

FIG. 1. Track multiplicity in the monojet data sample. a) No τ ID cuts applied. b) After applying all τ ID cuts except track multiplicity.

reduced and the data agree well with the expectation from a $W\to\tau\nu_\tau$ Monte Carlo [11]. The efficiency of all calorimeter–based τ identification cuts is measured to be (55±6(stat))%, consistent with the $W\to\tau\nu_\tau$ Monte Carlo prediction of (56±1(stat))%. The same check performed on the track–based τ selection gives similar results.

Top events and background have different topologies. Dilepton events from $t\bar{t}$ decays are expected to contain 2 jets from b decays. We therefore select events with $\geq$ 2 jets with $E_T > 10$ GeV and $|\eta| < 2.0$ [2]. The $\not\!\!E_T$ is corrected for muons and jets as in the dilepton analysis [1,2]. As top events are expected to have significant amount of $\not\!\!E_T$ due to undetected neutrinos, a cut is applied on the $\not\!\!E_T$ significance, defined for $e\tau$ events as $S_{\not E_T} \equiv \frac{\not E_T}{\sqrt{\Sigma E_T}}$, and as $S_{\not E_T} \equiv \frac{\not E_T}{\sqrt{\Sigma E_T + p_T^\mu}}$ for $\mu\tau$ events. Here ΣE_T is the scalar sum of the transverse energies measured in the calorimeter towers. We require $S_{\not E_T} > 3$ GeV$^{1/2}$. Due to large m_{top}, $t\bar{t}$ events exhibit large total transverse energy, H_T [13]. We require $H_T \equiv E_T^e(p_T^\mu) + p_T^\tau + \not\!\!E_T + (\sum_{jets} E_T) > 180$ GeV. Finally, the leptons must have opposite charge.

The product of all BR's, geometric and kinematic acceptance, efficiencies for trigger, lepton identification, and cuts on the event topology yields a total acceptance A_{tot} = (0.085±0.010(stat)±0.012(syst))% for the track–based selection. Using the calorimeter-based selection we find A_{tot} = (0.134±0.013(stat)±0.019(syst))%. The systematic uncertainty on A_{tot} is dominated by uncertainties on identification efficiencies for the τ (6%) and the primary lepton (7%), the top mass (6%), and the hadronic energy scale of the calorimeter (5%). Of the total one-prong events selected, 19% (38%) are expected to be found only by the track(calorimeter)–based technique, and 43% by both. Based on the $t\bar{t}$ cross section as measured by CDF from other decay modes, we expect 0.7±0.2(stat)±0.1(syst) and 1.1±0.3(stat)±0.2(syst) events from $t\bar{t}$ production in the two selections, respectively.

Table I lists the contributions from the various background sources. The dominant background is due to $Z/\gamma\to\tau^+\tau^- + jets$ events. If one τ decays leptonically and the other τ hadronically, this process can mimic the top signature. From Monte Carlo simulations we expect a background of 0.89±0.28 (1.48±0.38) events due to this process for the track(calorimeter)–based τ selection, and smaller backgrounds from WW and WZ production.

The "fake τ" background is due to $W+\geq 3$ *jets* events with one jet misidentified as a τ. We calculate the fake rates as a function of E_T by applying the τ selection criteria to jets in QCD jet samples. Applying the fake rates bin-by-bin to the E_T spectrum of all jets that could be misidentified as τ's in a $W+\geq 3$ *jets* sample gives the number of fake events. We expect 0.25±0.02 fake one-prong τ's with the track–based τ selection, and 0.78±0.04 fake one- and three-prong τ's with the calorimeter–based selection. The total expected backgrounds are 1.28±0.29 and 2.50±0.43 events, respectively.

We check that our background calculations correctly predict the number of events in a background-dominated sample by dropping the H_T and the $S_{\not{E}_T}$ requirements and instead imposing a loose $\not{E}_T$ cut ($\not{E}_T > 15$ GeV). With these relaxed cuts we expect a total background of 5.7 ± 0.7 (9.4 ± 0.8) events, in addition to 1.3 (2.0) events from $t\bar{t}$ decays, and observe 9 (11) events in the data using the track(calorimeter)–based selection. The sum of calculated background and top contribution agrees well with the observed number of events.

Figure 2 shows $S_{\not{E}_T}$ versus $\not{E}_T$ for data events with a primary lepton and a tau candidate that passes the calorimeter–based selection cuts. After all cuts four candidate events are identified, 2 $e\tau$ and 2 $\mu\tau$ events. There is in addition one same-sign $\mu^+\tau^+$ event, consistent with the 0.78 expected background events from fake τ's. The track–based τ selection finds the same four events.

We use the presence of a soft lepton from semileptonic b decays (SLT) or of a secondary vertex (SVX) in the silicon vertex detector to identify jets from b quarks. Three of the four candidate events have b-tagged jets [2]. One event has an SLT-SLT double tag. We expect 0.16 (0.18) background events with ≥ 1 SVX (SLT) tag, for a total background including correlations of 0.28±0.02 events. The probability to observe $\geq$ 3 background events is 0.3% after b-tagging. For top signal plus background we expect 0.64±0.12(stat) (0.37±0.06(stat)) events with an SVX(SLT) tag and observe one (two) event(s).

In conclusion, we have developed a method to use τ leptons in the analysis of top decays. We observe 4 candidate events where we expect ~ 1 $t\bar{t}$ event and ~ 2 background events. In three of the events we identify jets from b quark decays, which supports the $t\bar{t}$ hypothesis. Using the numbers of estimated background and observed events in Table I ($N_{jet} \geq 2$) and the acceptances A_{tot}, we calculate a production cross section. We find $\sigma_{t\bar{t}} = 10.2^{+16.3}_{-10.2}$(stat)±1.6(syst) pb for the calorimeter–based selection and $29.1^{+26.3}_{-18.4}$(stat)±4.7(syst) pb for the track–based selection, consistent with latest measured values given the large statistical uncertainty.

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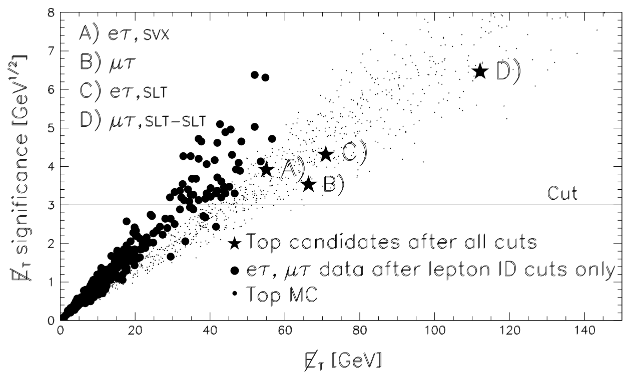

FIG. 2. The distribution of $S_{\not{E}_T}$ vs $\not{E}_T$ for events with a primary lepton and a tau candidate in the data. Three of the four final candidate events (stars) have b-tagged jets.

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TABLE I. The expected number of background and $t\bar{t}$ events and the observed events.

Selection	Track–based		Calorimeter–based	
N_{jet} ($\geq$ 10 GeV)	1	≥ 2	1	≥ 2
τ fakes	0.14±0.01	0.25±0.02	0.47±0.03	0.78±0.04
$Z/\gamma \to \tau^+\tau^-$	0.22±0.12	0.89±0.28	0.54±0.16	1.48±0.38
WW, WZ	0.14±0.06	0.14±0.08	0.20±0.09	0.24±0.10
Total Background	0.50±0.14	**1.28±0.29**	1.21±0.28	**2.50±0.43**
expected from $t\bar{t}$	0.08±0.02	0.7±0.3	0.13±0.03	1.1±0.4
observed events (b-tagged events)	1 (0)	4 (3)	0 (0)	4 (3)