Search for a Very Light CP-Odd Higgs Boson in Top Quark Decays from pp[over ¯] Collisions at sqrt[s]=1.96 TeV

T. Aaltonen *et al.* (CDF Collaboration)

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T. Aaltonen,[22] B. Álvarez González[v],[10] S. Amerio,[42] D. Amidei,[33] A. Anastassov,[37] A. Annovi,[18] J. Antos,[13] G. Apollinari,[16] J.A. Appel,[16] A. Apresyan,[47] T. Arisawa,[56] A. Artikov,[14] J. Asaadi,[52] W. Ashmanskas,[16] B. Auerbach,[59] A. Aurisano,[52] F. Azfar,[41] W. Badgett,[16] A. Barbaro-Galtieri,[27] V.E. Barnes,[47] B.A. Barnett,[24] P. Barria[ee],[45] P. Bartos,[13] M. Bauce[cc],[42] G. Bauer,[31] F. Bedeschi,[45] D. Beecher,[29] S. Behari,[24] G. Bellettini[dd],[45] J. Bellinger,[58] D. Benjamin,[15] A. Beretvas,[16] A. Bhatti,[49] M. Binkley[*],[16] D. Bisello[cc],[42] I. Bizjak[ii],[29] K.R. Bland,[5] C. Blocker,[7] B. Blumenfeld,[24] A. Bocci,[15] A. Bodek,[48] D. Bortoletto,[47] J. Boudreau,[46] A. Boveia,[12] B. Brau[a],[16] L. Brigliadori[bb],[6] A. Brisuda,[13] C. Bromberg,[34] E. Brucken,[22] M. Bucciantonio[dd],[45] J. Budagov,[14] H.S. Budd,[48] S. Budd,[23] K. Burkett,[16] G. Busetto[cc],[42] P. Bussey,[20] A. Buzatu,[32] S. Cabrera[x],[15] C. Calancha,[30] S. Camarda,[4] M. Campanelli,[34] M. Campbell,[33] F. Canelli[12],[16] A. Canepa,[44] B. Carls,[23] D. Carlsmith,[58] R. Carosi,[45] S. Carrillo[k],[17] S. Carron,[16] B. Casal,[10] M. Casarsa,[16] A. Castro[bb],[6] P. Catastini,[16] D. Cauz,[53] V. Cavaliere[ee],[45] M. Cavalli-Sforza,[4] A. Cerri[f],[27] L. Cerrito[q],[29] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[45] G. Chlachidze,[16] F. Chlebana,[16] K. Cho,[26] D. Chokheli,[14] J.P. Chou,[21] W.H. Chung,[58] Y.S. Chung,[48] C.I. Ciobanu,[43] M.A. Ciocci[ee],[45] A. Clark,[19] D. Clark,[7] G. Compostella[cc],[42] M.E. Convery,[16] J. Conway,[8] M.Corbo,[43] M. Cordelli,[18] C.A. Cox,[8] D.J. Cox,[8] F. Crescioli[dd],[45] C. Cuenca Almenar,[59] J. Cuevas[v],[10] R. Culbertson,[16] D. Dagenhart,[16] N. d'Ascenzo[t],[43] M. Datta,[16] P. de Barbaro,[48] S. De Cecco,[50] G. De Lorenzo,[4] M. Dell'Orso[dd],[45] C. Deluca,[4] L. Demortier,[49] J. Deng[c],[15] M. Deninno,[6] F. Devoto,[22] M. d'Errico[cc],[42] A. Di Canto[dd],[45] B. Di Ruzza,[45] J.R. Dittmann,[5] M. D'Onofrio,[28] S. Donati[dd],[45] P. Dong,[16] T. Dorigo,[42] K. Ebina,[56] A. Elagin,[52] A. Eppig,[33] R. Erbacher,[8] D. Errede,[23] S. Errede,[23] N. Ershaidat[aa],[43] R. Eusebi,[52] H.C. Fang,[27] S. Farrington,[41] M. Feindt,[25] J.P. Fernandez,[30] C. Ferrazza[ff],[45] R. Field,[17] G. Flanagan[r],[47] R. Forrest,[8] M.J. Frank,[5] M. Franklin,[21] J.C. Freeman,[16] I. Furic,[17] M. Gallinaro,[49] J. Galyardt,[11] J.E. Garcia,[19] A.F. Garfinkel,[47] P. Garosi[ee],[45] H. Gerberich,[23] E. Gerchtein,[16] S. Giagu[gg],[50] V. Giakoumopoulou,[3] P. Giannetti,[45] K. Gibson,[46] C.M. Ginsburg,[16] N. Giokaris,[3] P. Giromini,[18] M. Giunta,[45] G. Giurgiu,[24] V. Glagolev,[14] D. Glenzinski,[16] M. Gold,[36] D. Goldin,[52] N. Goldschmidt,[17] A. Golossanov,[16] G. Gomez,[10] G. Gomez-Ceballos,[31] M. Goncharov,[31] O. González,[30] I. Gorelov,[36] A.T. Goshaw,[15] K. Goulianos,[49] A. Gresele,[42] S. Grinstein,[4] C. Grosso-Pilcher,[12] R.C. Group,[16] J. Guimaraes da Costa,[21] Z. Gunay-Unalan,[34] C. Haber,[27] S.R. Hahn,[16] E. Halkiadakis,[51] A. Hamaguchi,[40] J.Y. Han,[48] F. Happacher,[18] K. Hara,[54] D. Hare,[51] M. Hare,[55] R.F. Harr,[57] K. Hatakeyama,[5] C. Hays,[41] M. Heck,[25] J. Heinrich,[44] M. Herndon,[58] S. Hewamanage,[5] D. Hidas,[51] A. Hocker,[16] W. Hopkins[g],[16] D. Horn,[25] S. Hou,[1] R.E. Hughes,[38] M. Hurwitz,[12] U. Husemann,[59] N. Hussain,[32] M. Hussein,[34] J. Huston,[34] G. Introzzi,[45] M. Iori[gg],[50] A. Ivanov[o],[8] E. James,[16] D. Jang,[11] B. Jayatilaka,[15] E.J. Jeon,[26] M.K. Jha,[6] S. Jindariani,[16] W. Johnson,[8] M. Jones,[47] K.K. Joo,[26] S.Y. Jun,[11] T.R. Junk,[16] T. Kamon,[52] P.E. Karchin,[57] Y. Kato[n],[40] W. Ketchum,[12] J. Keung,[44] V. Khotilovich,[52] B. Kilminster,[16] D.H. Kim,[26] H.S. Kim,[26] H.W. Kim,[26] J.E. Kim,[26] M.J. Kim,[18] S.B. Kim,[26] S.H. Kim,[54] Y.K. Kim,[12] N. Kimura,[56] S. Klimenko,[17] K. Kondo,[56] D.J. Kong,[26] J. Konigsberg,[17] A. Korytov,[17] A.V. Kotwal,[15] M. Kreps,[25] J. Kroll,[44] D. Krop,[12] N. Krumnack[l],[5] M. Kruse,[15] V. Krutelyov[d],[52] T. Kuhr,[25] M. Kurata,[54] S. Kwang,[12] A.T. Laasanen,[47] S. Lami,[45] S. Lammel,[16] M. Lancaster,[29] R.L. Lander,[8] K. Lannon[u],[38] A. Lath,[51] G. Latino[ee],[45] I. Lazzizzera,[42] T. LeCompte,[2] E. Lee,[52] H.S. Lee,[12] J.S. Lee,[26] S.W. Lee[w],[52] S. Leo[dd],[45] S. Leone,[45] J.D. Lewis,[16] C.-J. Lin,[27] J. Linacre,[41] M. Lindgren,[16] E. Lipeles,[44] A. Lister,[19] D.O. Litvintsev,[16] C. Liu,[46] Q. Liu,[47] T. Liu,[16] S. Lockwitz,[59] N.S. Lockyer,[44] A. Loginov,[59] D. Lucchesi[cc],[42] J. Lueck,[25] P. Lujan,[27] P. Lukens,[16] G. Lungu,[49] J. Lys,[27] R. Lysak,[13] R. Madrak,[16] K. Maeshima,[16] K. Makhoul,[31] P. Maksimovic,[24] S. Malik,[49] G. Manca[b],[28] A. Manousakis-Katsikakis,[3] F. Margaroli,[47] C. Marino,[25] M. Martínez,[4] R. Martínez-Ballarín,[30] P. Mastrandrea,[50] M. Mathis,[24] M.E. Mattson,[57] P. Mazzanti,[6] K.S. McFarland,[48] P. McIntyre,[52] R. McNulty[i],[28] A. Mehta,[28] P. Mehtala,[22] A. Menzione,[45] C. Mesropian,[49] T. Miao,[16] D. Mietlicki,[33] A. Mitra,[1] H. Miyake,[54] S. Moed,[21] N. Moggi,[6] M.N. Mondragon[k],[16] C.S. Moon,[26] R. Moore,[16] M.J. Morello,[16] J. Morlock,[25] P. Movilla Fernandez,[16] A. Mukherjee,[16] Th. Muller,[25] P. Murat,[16] M. Mussini[bb],[6] J. Nachtman[m],[16] Y. Nagai,[54] J. Naganoma,[56] I. Nakano,[39] A. Napier,[55] J. Nett,[58] C. Neu[z],[44] M.S. Neubauer,[23] J. Nielsen[e],[27] L. Nodulman,[2] O. Norniella,[23] E. Nurse,[29] L. Oakes,[41] S.H. Oh,[15] Y.D. Oh,[26] I. Oksuzian,[17] T. Okusawa,[40] R. Orava,[22] L. Ortolan,[4] S. Pagan Griso[cc],[42] C. Pagliarone,[53] E. Palencia[f],[10] V. Papadimitriou,[16] A.A. Paramonov,[2] J. Patrick,[16] G. Pauletta[hh],[53] M. Paulini,[11] C. Paus,[31] D.E. Pellett,[8] A. Penzo,[53] T.J. Phillips,[15] G. Piacentino,[45] E. Pianori,[44] J. Pilot,[38] K. Pitts,[23] C. Plager,[9] L. Pondrom,[58]

K. Potamianos,[47] O. Poukhov*,[14] F. Prokoshin[y],[14] A. Pronko,[16] F. Ptohos[h],[18] E. Pueschel,[11] G. Punzi[dd],[45] J. Pursley,[58] A. Rahaman,[46] V. Ramakrishnan,[58] N. Ranjan,[47] I. Redondo,[30] P. Renton,[41] M. Rescigno,[50] F. Rimondi[bb],[6] L. Ristori[45],[16] A. Robson,[20] T. Rodrigo,[10] T. Rodriguez,[44] E. Rogers,[23] S. Rolli,[55] R. Roser,[16] M. Rossi,[53] F. Ruffini[ee],[45] A. Ruiz,[10] J. Russ,[11] V. Rusu,[16] A. Safonov,[52] W.K. Sakumoto,[48] L. Santi[hh],[53] L. Sartori,[45] K. Sato,[54] V. Saveliev[t],[43] A. Savoy-Navarro,[43] P. Schlabach,[16] A. Schmidt,[25] E.E. Schmidt,[16] M.P. Schmidt*,[59] M. Schmitt,[37] T. Schwarz,[8] L. Scodellaro,[10] A. Scribano[ee],[45] F. Scuri,[45] A. Sedov,[47] S. Seidel,[36] Y. Seiya,[40] A. Semenov,[14] F. Sforza[dd],[45] A. Sfyrla,[23] S.Z. Shalhout,[8] T. Shears,[28] P.F. Shepard,[46] M. Shimojima[s],[54] S. Shiraishi,[12] M. Shochet,[12] I. Shreyber,[35] A. Simonenko,[14] P. Sinervo,[32] A. Sissakian*,[14] K. Sliwa,[55] J.R. Smith,[8] F.D. Snider,[16] A. Soha,[16] S. Somalwar,[51] V. Sorin,[4] P. Squillacioti,[16] M. Stanitzki,[59] R. St. Denis,[20] B. Stelzer,[32] O. Stelzer-Chilton,[32] D. Stentz,[37] J. Strologas,[36] G.L. Strycker,[33] Y. Sudo,[54] A. Sukhanov,[17] I. Suslov,[14] K. Takemasa,[54] Y. Takeuchi,[54] J. Tang,[12] M. Tecchio,[33] P.K. Teng,[1] J. Thom[g],[16] J. Thome,[11] G.A. Thompson,[23] E. Thomson,[44] P. Ttito-Guzmán,[30] S. Tkaczyk,[16] D. Toback,[52] S. Tokar,[13] K. Tollefson,[34] T. Tomura,[54] D. Tonelli,[16] S. Torre,[18] D. Torretta,[16] P. Totaro[hh],[53] M. Trovato[ff],[45] Y. Tu,[44] N. Turini[ee],[45] F. Ukegawa,[54] S. Uozumi,[26] A. Varganov,[33] E. Vataga[ff],[45] F. Vázquez[k],[17] G. Velev,[16] C. Vellidis,[3] M. Vidal,[30] I. Vila,[10] R. Vilar,[10] M. Vogel,[36] G. Volpi[dd],[45] P. Wagner,[44] R.L. Wagner,[16] T. Wakisaka,[40] R. Wallny,[9] S.M. Wang,[1] A. Warburton,[32] D. Waters,[29] M. Weinberger,[52] W.C. Wester III,[16] B. Whitehouse,[55] D. Whiteson[c],[44] A.B. Wicklund,[2] E. Wicklund,[16] S. Wilbur,[12] F. Wick,[25] H.H. Williams,[44] J.S. Wilson,[38] P. Wilson,[16] B.L. Winer,[38] P. Wittich[g],[16] S. Wolbers,[16] H. Wolfe,[38] T. Wright,[33] X. Wu,[19] Z. Wu,[5] K. Yamamoto,[40] J. Yamaoka,[15] T. Yang,[16] U.K. Yang[p],[12] Y.C. Yang,[26] W.-M. Yao,[27] G.P. Yeh,[16] K. Yi[m],[16] J. Yoh,[16] K. Yorita,[56] T. Yoshida[j],[40] G.B. Yu,[15] I. Yu,[26] S.S. Yu,[16] J.C. Yun,[16] A. Zanetti,[53] Y. Zeng,[15] and S. Zucchelli[bb6]

(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, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain
[5]Baylor University, Waco, Texas 76798, USA
[6]Istituto Nazionale di Fisica Nucleare Bologna, [bb]University of Bologna, I-40127 Bologna, Italy
[7]Brandeis University, Waltham, Massachusetts 02254, USA
[8]University of California, Davis, Davis, California 95616, USA
[9]University of California, Los Angeles, Los Angeles, California 90024, USA
[10]Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain
[11]Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA
[12]Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA
[13]Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia
[14]Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
[15]Duke University, Durham, North Carolina 27708, USA
[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, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany
[26]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
[27]Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
[28]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[29]University College London, London WC1E 6BT, United Kingdom
[30]Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
[31]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

[32]*Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8; Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6; University of Toronto, Toronto, Ontario, Canada M5S 1A7; and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
[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, [cc]University of Padova, I-35131 Padova, Italy*
[43]*LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
[44]*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
[45]*Istituto Nazionale di Fisica Nucleare Pisa, [dd]University of Pisa, [ee]University of Siena and [ff]Scuola Normale Superiore, I-56127 Pisa, Italy*
[46]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[47]*Purdue University, West Lafayette, Indiana 47907, USA*
[48]*University of Rochester, Rochester, New York 14627, USA*
[49]*The Rockefeller University, New York, New York 10065, USA*
[50]*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, [gg]Sapienza Università di Roma, I-00185 Roma, Italy*
[51]*Rutgers University, Piscataway, New Jersey 08855, USA*
[52]*Texas A&M University, College Station, Texas 77843, USA*
[53]*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, [hh]University of Trieste/Udine, I-33100 Udine, Italy*
[54]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[55]*Tufts University, Medford, Massachusetts 02155, USA*
[56]*Waseda University, Tokyo 169, Japan*
[57]*Wayne State University, Detroit, Michigan 48201, USA*
[58]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[59]*Yale University, New Haven, Connecticut 06520, USA*

We present the results of a search for a very light CP-odd Higgs boson a_1^0 originating from top quark decays $t \to H^\pm b \to W^{\pm(*)} a_1^0 b$, and subsequently decaying into $\tau^+\tau^-$. Using a data sample corresponding to an integrated luminosity of 2.7 fb^{-1} collected by the CDF II detector in $p\bar{p}$ collisions at 1.96 TeV, we perform a search for events containing a lepton, three or more jets, and an additional isolated track with transverse momentum in the range 3 to 20 GeV/c. Observed events are consistent with background sources, and 95% C.L. limits are set on the branching ratio of $t \to H^\pm b$ for various masses of $H^\pm$ and a_1^0.

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The Higgs boson is the last unobserved particle of the standard model (SM) [1]. In the SM the Higgs boson mass is unstable to quantum corrections. This problem is naturally solved in supersymmetric models [2]. In these

*Deceased
†With visitors from [a]University of Massachusetts Amherst, Amherst, Massachusetts 01003, [b]Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, [c]University of California Irvine, Irvine, CA 92697, [d]University of California Santa Barbara, Santa Barbara, CA 93106 [e]University of California Santa Cruz, Santa Cruz, CA 95064, [f]CERN,CH-1211 Geneva, Switzerland, [g]Cornell University, Ithaca, NY 14853, [h]University of Cyprus, Nicosia CY-1678, Cyprus, [i]University College Dublin, Dublin 4, Ireland, [j]University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017, [k]Universidad Iberoamericana, Mexico D.F., Mexico, [l]Iowa State University, Ames, IA 50011, [m]University of Iowa, Iowa City, IA 52242, [n]Kinki University, Higashi-Osaka City, Japan 577-8502, [o]Kansas State University, Manhattan, KS 66506, [p]University of Manchester, Manchester M13 9PL, England, [q]Queen Mary, University of London, London, E1 4NS, England, [r]Muons, Inc., Batavia, IL 60510, [s]Nagasaki Institute of Applied Science, Nagasaki, Japan, [t]National Research Nuclear University, Moscow, Russia, [u]University of Notre Dame, Notre Dame, IN 46556, [v]Universidad de Oviedo, E-33007 Oviedo, Spain, [w]Texas Tech University, Lubbock, TX 79609, [x]IFIC(CSIC-Universitat de Valencia), 56071 Valencia, Spain, [y]Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile, [z]University of Virginia, Charlottesville, VA 22906, [aa]Yarmouk University, Irbid 211-63, Jordan, [ii]On leave from J. Stefan Institute, Ljubljana, Slovenia,

theories the Higgs boson sector is more complicated. The minimal supersymmetric extension of the standard model (MSSM) contains five Higgs bosons: a light and a heavy CP-even Higgs (h and H), a CP-odd Higgs (A), and a pair of charged bosons ($H^{\pm}$). The next-to-minimal supersymmetric model (NMSSM) [3] further extends the MSSM to include an additional CP-even and CP-odd neutral Higgs bosons. In the NMSSM the lightest CP-odd Higgs a_1^0 can be below the $b\bar{b}$ threshold, so that the a_1^0 boson decays only into $\tau^+\tau^-, c\bar{c}$, or gg.

The existence of the very light a_1^0 boson has two important implications. First, the decay mode of the SM-like Higgs $h \to a_1^0 a_1^0$ becomes dominant and other SM decay rates are decreased, so that the SM-like Higgs boson avoids the LEP II direct limit [4]. The light SM-like Higgs helps to solve the naturalness and fine-tuning problems arising in the MSSM [3]. In addition, the charged Higgs boson must not be much heavier than the W boson, which helps to reconcile apparent discrepancies in the LEP lepton universality measurements [5]. Such a charged Higgs boson could appear in top quark decays $t \to H^{\pm}b$, escaping current limits [6] due to a new open decay mode $H^{\pm} \to W^{\pm^{(*)}} a_1^0$, which has not been investigated before. This motivates a search for a_1^0 bosons in decays of top quarks.

In the $p\bar{p}$ collisions at the Fermilab Tevatron the top quarks are produced mainly in pairs, and within the SM almost always decay into a W boson and a b-quark. The NMSSM scenario considered above differs from the SM process by the presence of one or two a_1^0 bosons in the final state. As the a_1^0 boson decay products are expected to have low momenta, these could remain undetected without affecting the measurements of the $t\bar{t}$ cross section and properties of the top quark.

In this Letter we report on the first search for a light CP-odd Higgs boson a_1^0 in decays of top quarks through the intermediate charged Higgs boson $t \to H^{\pm}b \to W^{\pm^{(*)}} a_1^0 b$ assuming $a_1^0 \to \tau^+\tau^-$. We analyze a data set corresponding to an integrated luminosity of 2.7 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected by the Collider Detector at Fermilab (CDF II) [7], searching in candidate $t\bar{t}$ events for the presence of low-p_T tracks [8] that could be attributed to τ-decay products.

We select candidate $t\bar{t}$ events using criteria developed for a $t\bar{t}$ cross section measurement [9]. The data events used in the analysis are collected by triggers that identify at least one high-p_T electron or muon candidate using the online data acquisition system. Subsequently, each event is required to have a single isolated e or μ with $p_T > 20$ GeV/c and $|\eta| < 2.0(1.0)$ for $e(\mu)$ [10, 11]. We require missing transverse energy $\not\!\!E_T > 20$ GeV [12], as evidence of a neutrino from the W-boson decay, and at least three jets with $E_T > 20$ GeV and $|\eta| < 2.0$, reconstructed using a fixed cone algorithm of radius $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ [13]. Backgrounds to $t\bar{t}$ production are reduced by requiring at least one of the jets to be identified as a b-quark candidate using the presence of a displaced secondary vertex [14], and by requiring the scalar sum of the transverse energy of the lepton, $\not\!\!E_T$, and jets (H_T) to be above 250 GeV. We observe 1052 events passing these selection criteria, which define a pre-signal sample.

The main contribution to the selected sample of events comes from $t\bar{t}$ production, which we model using the PYTHIA 6.216 Monte Carlo (MC) generator [15] for both SM and new physics top quark decays, assuming $m_t = 172.5$ GeV/c^2. We use an ALPGEN 2.13 [16] matrix-element generator interfaced to PYTHIA 6.325 for modeling W+jets and Z/γ^*+ jets production. Other sources of events in the pre-signal sample include diboson production (WW, WZ, ZZ) modeled with PYTHIA 6.216 MC generator, and multi-jet QCD events modeled using a data-driven approach described in [17]. The detector response in all MC samples is modeled by a GEANT3-based detector simulation [18].

We search for τ-leptons from a_1^0 boson decays in $t\bar{t}$ candidate events by looking for at least one low-p_T (3 GeV/$c < p_T <$ 20 GeV/c) track in the central detector region $|\eta| < 1.1$. The track must be well-measured, i.e. it should have a sufficient number of hits in the tracking chamber. To ensure that the track is consistent with being produced in a $p\bar{p}$ collision, the distance of closest approach of the track with respect to the beam axis is required to be small. The track must also originate from the same $p\bar{p}$ interaction as the isolated lepton by requiring that $|z_{track} - z_{lepton}| < 5$ cm, where the z-coordinate corresponds to the point of the closest approach to the nominal beamline. To suppress backgrounds from jets the candidate track is required to be isolated from other tracks in the event. We sum the p_T of every well-measured track with $p_T > 0.5$ GeV/c, including the candidate track, within a cone of $\Delta R < 0.4$ around the candidate and with a z-position of origin within 5 cm of the candidate track z. We require that the ratio of the candidate track p_T to the sum p_T of tracks in the cone be at least 0.9. We also ensure that the track is not within $\Delta R < 0.4$ of the lepton (e or μ) or a jet, used to define the $t\bar{t}$ candidate.

The isolated tracks can arise from the hard parton-parton interaction producing the high-p_T lepton candidate as well as from the "underlying event" (UE). In what follows, we include in our UE definition contributions from additional simultaneous proton-antiproton collisions. Non-UE isolated tracks come from physics processes where more than one lepton is produced but only one is identified, such as from $Z/\gamma^* \to \ell^+\ell^-$ events where one lepton triggers the event, while the other one has a p_T below 20 GeV/c, or is a $\tau^{\pm}$ that leaves a low-p_T track. We use simulated events to model the track p_T spectra corresponding to leptons from the vector boson decays.

We use data to model the characteristics of UE tracks.

We analyze several different data samples to verify that the UE track p_T spectrum is independent of the data source. We select Z boson candidates by requiring events to have two leptons ("dilepton events") with an invariant mass consistent with a Z boson. We also study "lepton + jets" events by requiring only one lepton candidate, significant missing transverse energy, plus one or two jets. This data sample is dominated by events from W boson plus associated jets production. We also analyze several data samples of QCD multi-jet events collected by triggers that identify at least one jet. Each sample requires a different jet E_T threshold.

The fraction of events in which UE tracks satisfy our selection criteria is about 7.5%, and is consistent between samples within 15% relative uncertainty. The p_T spectra of the isolated tracks for different data samples normalized to the same area are shown in Fig. 1. The track p_T spectrum for lepton+jets events is corrected by subtracting contributions from tracks corresponding to real leptons from Z/γ^*, diboson, and $t\bar{t}$ events. This is done by accounting for tracks originating from a $W^\pm$ or Z boson in our MC samples, where the reconstructed track is traced back to the charged particle in the decay chain of the vector boson. In Fig. 1 both corrected and uncorrected track p_T spectra are shown. After the correction the p_T spectra agree with those from dilepton and QCD multi-jet events.

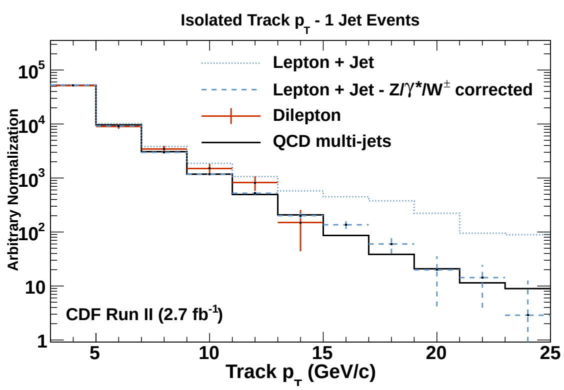

FIG. 1: The isolated track p_T spectra from lepton+jets, dilepton, and QCD multi-jet data samples for events with exactly one jet.

We tested the data to determine whether there are any correlations between the p_T spectra of isolated tracks and other parameters of the event. The only correlation we found was with the H_T of the event. We account for this correlation as described further in the text. A number of cross-checks that we performed include comparison of the UE track p_T spectra for different QCD multi-jet samples, as well as a study of dependence on the jet multiplicity, the number of primary vertices, and presence of the b-tag in the events. We observed no statistically significant difference in the track p_T spectra in these studies.

We perform the search for $t \to H^\pm b \to W^{\pm(*)} a_1^0\, b$ decays by fitting the observed isolated track p_T distribution to the combination of the UE, non-UE SM, and the new physics signal track p_T spectra. We use the UE track p_T distribution from QCD multi-jet data events to model the UE contribution, and allow the rate of UE tracks to float freely in the fit. For the MC-modeled background processes we consider isolated tracks only from the vector boson decays. In case an event has more than one track satisfying the isolation and the track quality criteria, we select the track with the highest p_T. We use the UE track p_T distribution measured in data to correct all MC track p_T spectra to account for the probability of the highest-p_T track to come from the underlying event.

Prior to performing the fit in the signal region, we test our procedure in the control region defined by events with one lepton plus one or two jets. In this region the dominant non-UE contribution is from $Z/\gamma^* \to e^+e^-$ or $Z/\gamma^* \to \mu^+\mu^-$ events, where the second lepton from Z/γ^* is not identified but passes our isolated track requirements, or $Z/\gamma^* \to \tau^+\tau^-$ events where one τ decays leptonically and is identified as an electron or muon, and the other one is identified as an isolated track. The lepton track p_T spectra from $Z/\gamma^\star$ decays are on average more energetic than the UE track p_T, and assuming the UE-only hypothesis an excess of events is expected in the tails of the observed isolated track p_T distribution. We test whether we are able to observe the excess of events attributed to $Z/\gamma^* \to \ell^+\ell^-$ events at the rate consistent with the expectation. The expected number of events from the $Z/\gamma^* \to \ell^+\ell^-$ process is obtained using the MC normalized to data under the Z mass peak.

We perform a log-likelihood fit to the observed isolated track p_T spectrum, with UE and Z/γ^* rates completely unconstrained, and other MC-based contributions (top and dibosons) constrained to be within their theoretical expectations. The fit is performed in the range $3 \le p_T \le 20$ GeV/c separately for events with one and two jets. The results of the fit are presented in Fig. 2. The extracted Z/γ^* contribution matches the expectations within the statistical uncertainties.

We then proceed to fit in the signal region, and employ the CL$_S$ likelihood ratio test statistic [19] to quantify the search results. The systematic uncertainties enter the CL$_S$ fit as Gaussian-constrained nuisance parameters.

The $t\bar{t}$ contribution is obtained from the data using the same technique as in the $t\bar{t}$ cross section measurement [9]. The uncertainty on the expected $t\bar{t}$ event yield is due to the lepton identification and triggering (2%), b-tagging efficiency (5%), the jet energy scale (5%), the uncertainty in the estimate of backgrounds to $t\bar{t}$ (3%), and limited data statistics (6%) accounting for the total $t\bar{t}$ normalization uncertainty of 10%.

The Z/γ^*+ heavy flavor contribution is normalized to data under the Z mass peak, with the dominant uncertainty due to limited statistics of $Z+$ tagged jet events in

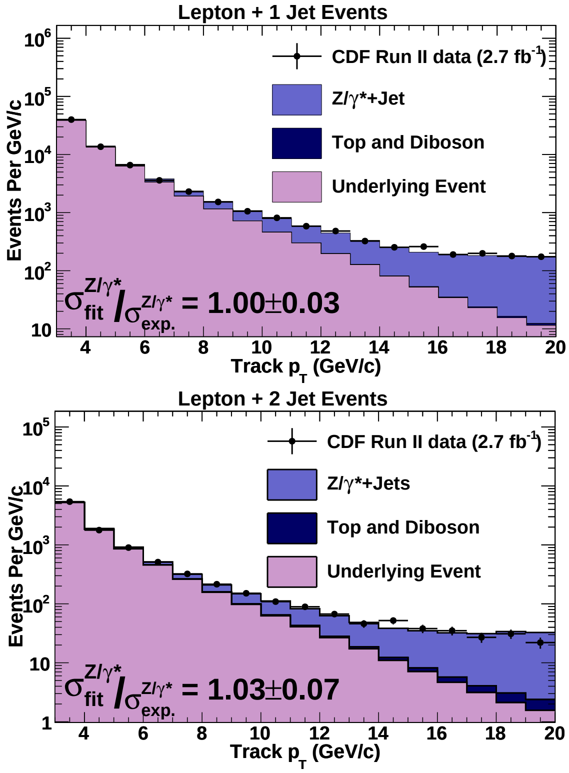

FIG. 2: The isolated track p_T spectrum fitted for Z/γ^*+jets cross section in lepton + jets data events with one jet and two jets separately. In both cases the fit results are consistent with expected Z/γ^*contribution.

data (8%). The uncertainty on the diboson (VV) background is due to NLO calculations [20] and parton distribution functions, taken conservatively to be 10%, luminosity (6%), and the jet energy scale (20%).

Since we require the isolated track not to be within a reconstructed jet, the systematic uncertainty in the jet energy scale leads to events migrating to/from the signal region, which results in an additional 3% uncertainty for all MC-based backgrounds. The uncertainty on the isolated track efficiency is 3%, and is determined using Z/γ^*events.

The largest variations in the UE isolated track p_T spectrum come from varying the H_T requirement for the candidate sample. We use the shapes obtained from multi-jet data for very low and very high H_T, and interpolate these distributions to obtain an intermediate shape. The interpolation is parametrized with a Gaussian-constrained nuisance parameter and integrated into the fit. We allow the UE track p_T distribution to change in the fit according to the value of this nuisance parameter [21].

The expected event yields in the signal region are presented in Table I. The first row in the table represents the numbers of expected and observed events before the isolated track requirement. The second row shows the event

Events per 2.7 fb^{-1}

$t\bar{t}$	QCD,W	VV	Z/γ^*	UE	Total	Data
805	215	11	19	-	1049	1052
2.6±0.3	-	0.1±0.0	0.7±0.1	79±12	83±12	70

TABLE I: Expected event yields in 2.7 fb^{-1} before the track requirement (first row), and with at least one isolated track (second row) with 3 GeV/$c < p_T <$ 20 GeV/c. In the second row events are categorized based on the origin of the isolated track. The number of UE events is the expected number of events before the fit to the track p_T spectrum.

yields after the isolated track requirement, where events are categorized based on the origin of the isolated track. The quoted event yield due to the UE corresponds to the expected rate, while the actual normalization is obtained from the fit to the isolated track p_T spectrum in data, as can be seen in Fig. 3.

Figure 3 shows that the data are well described by SM background sources. We set 95% confidence level (C.L.) upper limits on the branching ratio of $t \to H^+ b$ under the assumption that the branching ratios $\mathcal{B}(a_1^0 \to \tau^+\tau^-) =$ 100% and $\mathcal{B}(H^\pm \to W^\pm a_1^0) =$ 100%. The expected and observed 95% C.L. limits as a function of $m_{H^\pm}$ and $m_{a_1^0}$ are shown in Fig. 4. For a given mass of CP-odd Higgs boson a_1^0 we exclude the branching ratios of $\mathcal{B}(t \to H^+ b)$ above the respective curve shown in the plot. For an a_1^0 boson with mass of 9 GeV/c^2, we exclude a $\mathcal{B}(t \to H^+ b) > 0.20$ at 95% C.L. for H^+ masses between 90 and 160 GeV/c^2. These are the first limits on the branching ratio of $t \to H^+ b$ in this decay mode.

In conclusion, we have presented a search for non-SM top decays $t \to H^\pm b \to W^{\pm(*)} a_1^0 b$ within the NMSSM scenario using a data sample corresponding to 2.7 fb^{-1} of integrated luminosity in 1.96 TeV $p\bar{p}$ collisions. We see no evidence of τ's from light Higgs a_1^0 decays, and set the world's first limits on the branching ratio of $t \to H^+ b$ in this mode, assuming $\mathcal{B}(a_1^0 \to \tau^+\tau^-) =$ 100% and $\mathcal{B}(H^\pm \to W^\pm a_1^0) =$ 100%.

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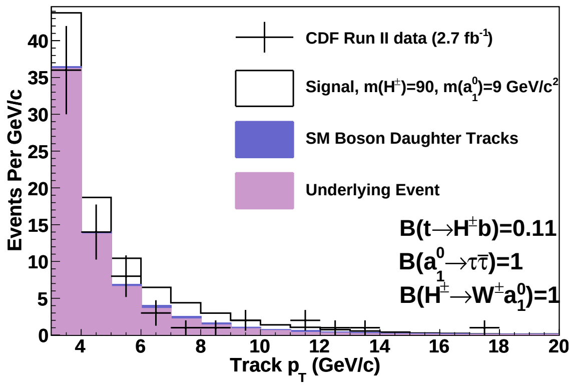

FIG. 3: The isolated track p_T spectrum. The contribution from non-SM top decays corresponds to an example scenario that is excluded at 95% C.L.

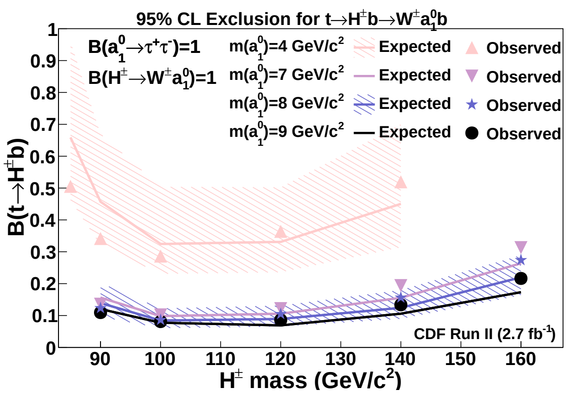

FIG. 4: Observed and expected limits (with $\pm 1\ \sigma$ error band) on the branching ratio of $t \to H^+ b$.

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[12] The missing transverse energy is defined as $\not{E}_T = |\vec{\not{E}}_T| = |-\sum_i E_T^i \vec{n}_i|$ where $\vec{n}_i$ is a unit vector in the plane transverse to the beam direction pointing from the event vertex to the i-th calorimeter tower. The missing transverse energy is corrected for the escaping muon momenta when muon candidates are present.

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