Search for Long-Lived Charged Massive Particles in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

D. Acosta,[14] T. Affolder,[25] H. Akimoto,[51] M. G. Albrow,[13] D. Ambrose,[37] D. Amidei,[28] K. Anikeev,[27] J. Antos,[1] G. Apollinari,[13] T. Arisawa,[51] A. Artikov,[11] T. Asakawa,[49] W. Ashmanskas,[10] F. Azfar,[35] P. Azzi-Bacchetta,[36] N. Bacchetta,[36] H. Bachacou,[25] W. Badgett,[13] S. Bailey,[18] P. de Barbaro,[41] A. Barbaro-Galtieri,[25] V. E. Barnes,[40] B. A. Barnett,[21] S. Baroiant,[5] M. Barone,[15] G. Bauer,[27] F. Bedeschi,[38] S. Behari,[21] S. Belforte,[48] W. H. Bell,[17] G. Bellettini,[38] J. Bellinger,[52] D. Benjamin,[12] J. Bensinger,[4] A. Beretvas,[13] J. Berryhill,[10] A. Bhatti,[42] M. Binkley,[13] D. Bisello,[36] M. Bishai,[13] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[28] B. Blumenfeld,[21] S. R. Blusk,[41] A. Bocci,[42] A. Bodek,[41] G. Bolla,[40] A. Bolshov,[27] Y. Bonushkin,[6] D. Bortoletto,[40] J. Boudreau,[39] A. Brandl,[31] C. Bromberg,[29] M. Brozovic,[12] E. Brubaker,[25] N. Bruner,[31] J. Budagov,[11] H. S. Budd,[41] K. Burkett,[18] G. Busetto,[36] K. L. Byrum,[2] S. Cabrera,[12] P. Calafiura,[25] M. Campbell,[28] W. Carithers,[25] J. Carlson,[28] D. Carlsmith,[52] W. Caskey,[5] A. Castro,[3] D. Cauz,[48] A. Cerri,[38] L. Cerrito,[20] A. W. Chan,[1] P. S. Chang,[1] P. T. Chang,[1] J. Chapman,[28] C. Chen,[37] Y. C. Chen,[1] M.-T. Cheng,[1] M. Chertok,[5] G. Chiarelli,[38] I. Chirikov-Zorin,[11] G. Chlachidze,[11] F. Chlebana,[13] L. Christofek,[20] M. L. Chu,[1] J. Y. Chung,[33] W.-H. Chung,[52] Y. S. Chung,[41] C. I. Ciobanu,[33] A. G. Clark,[16] M. Coca,[41] A. P. Colijn,[13] A. Connolly,[25] M. Convery,[42] J. Conway,[44] M. Cordelli,[15] J. Cranshaw,[46] R. Culbertson,[13] D. Dagenhart,[4] S. D'Auria,[17] S. De Cecco,[43] F. DeJongh,[13] S. Dell'Agnello,[15] M. Dell'Orso,[38] S. Demers,[41] L. Demortier,[42] M. Deninno,[3] D. De Pedis,[43] P. F. Derwent,[13] T. Devlin,[44] C. Dionisi,[43] J. R. Dittmann,[13] A. Dominguez,[25] S. Donati,[38] M. D'Onofrio,[38] T. Dorigo,[36] N. Eddy,[20] K. Einsweiler,[25] E. Engels, Jr.,[39] R. Erbacher,[13] D. Errede,[20] S. Errede,[20] R. Eusebi,[41] Q. Fan,[41] H.-C. Fang,[25] S. Farrington,[17] R. G. Feild,[53] J. P. Fernandez,[40] C. Ferretti,[28] R. D. Field,[14] I. Fiori,[3] B. Flaugher,[13] L. R. Flores-Castillo,[39] G. W. Foster,[13] M. Franklin,[18] J. Freeman,[13] J. Friedman,[27] Y. Fukui,[23] I. Furic,[27] S. Galeotti,[38] A. Gallas,[32] M. Gallinaro,[42] T. Gao,[37] M. Garcia-Sciveres,[25] A. F. Garfinkel,[40] P. Gatti,[36] C. Gay,[53] D. W. Gerdes,[28] E. Gerstein,[9] S. Giagu,[43] P. Giannetti,[38] K. Giolo,[40] M. Giordani,[5] P. Giromini,[15] V. Glagolev,[11] D. Glenzinski,[13] M. Gold,[31] N. Goldschmidt,[28] J. Goldstein,[13] G. Gomez,[8] M. Goncharov,[45] I. Gorelov,[31] A. T. Goshaw,[12] Y. Gotra,[39] K. Goulianos,[42] C. Green,[40] A. Gresele,[36] G. Grim,[5] C. Grosso-Pilcher,[10] M. Guenther,[40] G. Guillian,[28] J. Guimaraes da Costa,[18] R. M. Haas,[14] C. Haber,[25] S. R. Hahn,[13] E. Halkiadakis,[41] C. Hall,[18] T. Handa,[19] R. Handler,[52] F. Happacher,[15] K. Hara,[49] A. D. Hardman,[40] R. M. Harris,[13] F. Hartmann,[22] K. Hatakeyama,[42] J. Hauser,[6] J. Heinrich,[37] A. Heiss,[22] M. Hennecke,[22] M. Herndon,[21] C. Hill,[7] A. Hocker,[41] K. D. Hoffman,[10] R. Hollebeek,[37] L. Holloway,[20] S. Hou,[1] B. T. Huffman,[35] R. Hughes,[33] J. Huston,[29] J. Huth,[18] H. Ikeda,[49] J. Incandela,[7] G. Introzzi,[38] M. Iori,[43] A. Ivanov,[41] J. Iwai,[51] Y. Iwata,[19] B. Iyutin,[27] E. James,[28] M. Jones,[37] U. Joshi,[13] H. Kambara,[16] T. Kamon,[45] T. Kaneko,[49] J. Kang,[28] M. Karagoz Unel,[32] K. Karr,[50] S. Kartal,[13] H. Kasha,[53] Y. Kato,[34] T. A. Keaffaber,[40] K. Kelley,[27] M. Kelly,[28] R. D. Kennedy,[13] R. Kephart,[13] D. Khazins,[12] T. Kikuchi,[49] B. Kilminster,[41] B. J. Kim,[24] D. H. Kim,[24] H. S. Kim,[20] M. J. Kim,[9] S. B. Kim,[24] S. H. Kim,[49] T. H. Kim,[27] Y. K. Kim,[25] M. Kirby,[12] M. Kirk,[4] L. Kirsch,[4] S. Klimenko,[14] P. Koehn,[33] K. Kondo,[51] J. Konigsberg,[14] A. Korn,[27] A. Korytov,[14] K. Kotelnikov,[30] E. Kovacs,[2] J. Kroll,[37] M. Kruse,[12] V. Krutelyov,[45] S. E. Kuhlmann,[2] K. Kurino,[19] T. Kuwabara,[49] N. Kuznetsova,[13] A. T. Laasanen,[40] N. Lai,[10] S. Lami,[42] S. Lammel,[13] J. Lancaster,[12] K. Lannon,[20] M. Lancaster,[26] R. Lander,[5] A. Lath,[44] G. Latino,[31] T. LeCompte,[2] Y. Le,[21] J. Lee,[41] S. W. Lee,[45] N. Leonardo,[27] S. Leone,[38] J. D. Lewis,[13] K. Li,[53] C. S. Lin,[13] M. Lindgren,[6] T. M. Liss,[20] J. B. Liu,[41] T. Liu,[13] Y. C. Liu,[1] D. O. Litvintsev,[13] O. Lobban,[46] N. S. Lockyer,[37] A. Loginov,[30] J. Loken,[35] M. Loreti,[36] D. Lucchesi,[36] P. Lukens,[13] S. Lusin,[52] L. Lyons,[35] J. Lys,[25] R. Madrak,[18] K. Maeshima,[13] P. Maksimovic,[21] L. Malferrari,[3] M. Mangano,[38] G. Manca,[35] M. Mariotti,[36] G. Martignon,[36] M. Martin,[21] A. Martin,[53] V. Martin,[32] J. A. J. Matthews,[31] P. Mazzanti,[3] K. S. McFarland,[41] P. McIntyre,[45] M. Menguzzato,[36] A. Menzione,[38] P. Merkel,[13] C. Mesropian,[42] A. Meyer,[13] T. Miao,[13] R. Miller,[29] J. S. Miller,[28] H. Minato,[49] S. Miscetti,[15] M. Mishina,[23] G. Mitselmakher,[14] Y. Miyazaki,[34] N. Moggi,[3] E. Moore,[31] R. Moore,[28] Y. Morita,[23] T. Moulik,[40] M. Mulhearn,[27] A. Mukherjee,[13] T. Muller,[22] A. Munar,[38] P. Murat,[13] S. Murgia,[29] J. Nachtman,[6] V. Nagaslaev,[46] S. Nahn,[53] H. Nakada,[49] I. Nakano,[19] R. Napora,[21] F. Niell,[28] C. Nelson,[13] T. Nelson,[13] C. Neu,[33] M. S. Neubauer,[27] D. Neuberger,[22] C. Newman-Holmes,[13] C.-Y. P. Ngan,[27] T. Nigmanov,[39] H. Niu,[4] L. Nodulman,[2] A. Nomerotski,[14] S. H. Oh,[12] Y. D. Oh,[24] T. Ohmoto,[19] T. Ohsugi,[19] R. Oishi,[49] T. Okusawa,[34] J. Olsen,[52] W. Orejudos,[25] C. Pagliarone,[38] F. Palmonari,[38] R. Paoletti,[38] V. Papadimitriou,[46] D. Partos,[4] J. Patrick,[13] G. Pauletta,[48] M. Paulini,[9] T. Pauly,[35] C. Paus,[27] D. Pellett,[5] A. Penzo,[48] L. Pescara,[36] T. J. Phillips,[12] G. Piacentino,[38] J. Piedra,[8] K. T. Pitts,[20] A. Pompoš,[40] L. Pondrom,[52] G. Pope,[39] T. Pratt,[35] F. Prokoshin,[11] J. Proudfoot,[2] F. Ptohos,[15] O. Pukhov,[11] G. Punzi,[38] J. Rademacker,[35] A. Rakitine,[27] F. Ratnikov,[44] H. Ray,[28] D. Reher,[25] A. Reichold,[35] P. Renton,[35] M. Rescigno,[43] A. Ribon,[36] W. Riegler,[18] F. Rimondi,[3] L. Ristori,[38] M. Riveline,[47] W. J. Robertson,[12] T. Rodrigo,[8]

 0031-9007/03/90(13)/131801(6)$20.00

S. Rolli,[50] L. Rosenson,[27] R. Roser,[13] R. Rossin,[36] C. Rott,[40] A. Roy,[40] A. Ruiz,[8] D. Ryan,[50] A. Safonov,[5] R. St. Denis,[17] W. K. Sakumoto,[41] D. Saltzberg,[6] C. Sanchez,[33] A. Sansoni,[15] L. Santi,[48] S. Sarkar,[43] H. Sato,[49] P. Savard,[47] A. Savoy-Navarro,[13] P. Schlabach,[13] E. E. Schmidt,[13] M. P. Schmidt,[53] M. Schmitt,[32] L. Scodellaro,[36] A. Scott,[6] A. Scribano,[38] A. Sedov,[40] S. Seidel,[31] Y. Seiya,[49] A. Semenov,[11] F. Semeria,[3] T. Shah,[27] M. D. Shapiro,[25] P. F. Shepard,[39] T. Shibayama,[49] M. Shimojima,[49] M. Shochet,[10] A. Sidoti,[36] J. Siegrist,[25] A. Sill,[46] P. Sinervo,[47] P. Singh,[20] A. J. Slaughter,[53] K. Sliwa,[50] F. D. Snider,[13] R. Snihur,[26] A. Solodsky,[42] J. Spalding,[13] T. Speer,[16] M. Spezziga,[46] P. Sphicas,[27] F. Spinella,[38] M. Spiropulu,[10] L. Spiegel,[13] J. Steele,[52] A. Stefanini,[38] J. Strologas,[20] F. Strumia,[16] D. Stuart,[7] A. Sukhanov,[14] K. Sumorok,[27] T. Suzuki,[49] T. Takano,[34] R. Takashima,[19] K. Takikawa,[49] P. Tamburello,[12] M. Tanaka,[49] B. Tannenbaum,[6] M. Tecchio,[28] R. J. Tesarek,[13] P. K. Teng,[1] K. Terashi,[42] S. Tether,[27] A. S. Thompson,[17] E. Thomson,[33] R. Thurman-Keup,[2] P. Tipton,[41] S. Tkaczyk,[13] D. Toback,[45] K. Tollefson,[29] D. Tonelli,[38] M. Tonnesmann,[29] H. Toyoda,[34] W. Trischuk,[47] J. F. de Troconiz,[18] J. Tseng,[27] D. Tsybychev,[14] N. Turini,[38] F. Ukegawa,[49] T. Unverhau,[17] T. Vaiciulis,[41] J. Valls,[44] A. Varganov,[28] E. Vataga,[38] S. Vejcik III,[13] G. Velev,[13] G. Veramendi,[25] R. Vidal,[13] I. Vila,[8] R. Vilar,[8] I. Volobouev,[25] M. von der Mey,[6] D. Vucinic,[27] R. G. Wagner,[2] R. L. Wagner,[13] W. Wagner,[22] N. B. Wallace,[44] Z. Wan,[44] C. Wang,[12] M. J. Wang,[1] S. M. Wang,[14] B. Ward,[17] S. Waschke,[17] T. Watanabe,[49] D. Waters,[26] T. Watts,[44] M. Weber,[25] H. Wenzel,[22] W. C. Wester III,[13] B. Whitehouse,[50] A. B. Wicklund,[2] E. Wicklund,[13] T. Wilkes,[5] H. H. Williams,[37] P. Wilson,[13] B. L. Winer,[33] D. Winn,[28] S. Wolbers,[13] D. Wolinski,[28] J. Wolinski,[29] S. Wolinski,[28] M. Wolter,[50] S. Worm,[44] X. Wu,[16] F. Würthwein,[27] J. Wyss,[38] U. K. Yang,[10] W. Yao,[25] G. P. Yeh,[13] P. Yeh,[1] K. Yi,[21] J. Yoh,[13] C. Yosef,[29] T. Yoshida,[34] I. Yu,[24] S. Yu,[37] Z. Yu,[53] J. C. Yun,[13] L. Zanello,[43] A. Zanetti,[48] F. Zetti,[25] and S. Zucchelli[3]

(CDF Collaboration)

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[3]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[4]*Brandeis University, Waltham, Massachusetts 02254*
[5]*University of California at Davis, Davis, California 95616*
[6]*University of California at Los Angeles, Los Angeles, California 90024*
[7]*University of California at Santa Barbara, Santa Barbara, California 93106*
[8]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[9]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15218*
[10]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[11]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[12]*Duke University, Durham, North Carolina 27708*
[13]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[14]*University of Florida, Gainesville, Florida 32611*
[15]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[16]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[17]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[18]*Harvard University, Cambridge, Massachusetts 02138*
[19]*Hiroshima University, Higashi-Hiroshima 724, Japan*
[20]*University of Illinois, Urbana, Illinois 61801*
[21]*The Johns Hopkins University, Baltimore, Maryland 21218*
[22]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[23]*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*
[24]*Center for High Energy Physics, Kyungpook National University, Taegu 702-701, Korea; Center for High Energy Physics, Seoul National University, Seoul 151-742, Korea; and Center for High Energy Physics, SungKyunKwan University, Suwon 440-746, Korea*
[25]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[26]*University College London, London WC1E 6BT, United Kingdom*
[27]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[28]*University of Michigan, Ann Arbor, Michigan 48109*
[29]*Michigan State University, East Lansing, Michigan 48824*
[30]*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
[31]*University of New Mexico, Albuquerque, New Mexico 87131*
[32]*Northwestern University, Evanston, Illinois 60208*
[33]*The Ohio State University, Columbus, Ohio 43210*
[34]*Osaka City University, Osaka 588, Japan*
[35]*University of Oxford, Oxford OX1 3RH, United Kingdom*

[36]*Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[37]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[38]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[39]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[40]*Purdue University, West Lafayette, Indiana 47907*
[41]*University of Rochester, Rochester, New York 14627*
[42]*Rockefeller University, New York, New York 10021*
[43]*Instituto Nazionale de Fisica Nucleare, Sezione di Roma, University di Roma I, "La Sapienza," I-00185 Roma, Italy*
[44]*Rutgers University, Piscataway, New Jersey 08855*
[45]*Texas A&M University, College Station, Texas 77843*
[46]*Texas Tech University, Lubbock, Texas 79409*
[47]*Institute of Particle Physics, University of Toronto, Toronto, Canada M5S 1A7*
[48]*Istituto Nazionale di Fisica Nucleare, University of Trieste/Udine, Italy*
[49]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[50]*Tufts University, Medford, Massachusetts 02155*
[51]*Waseda University, Tokyo 169, Japan*
[52]*University of Wisconsin, Madison, Wisconsin 53706*
[53]*Yale University, New Haven, Connecticut 06520*
(Received 4 December 2002; published 31 March 2003)

We report a search for the production of long-lived charged massive particles in a data sample of 90 pb^{-1} of $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions recorded by the Collider Detector at Fermilab. The search uses the muonlike penetration and anomalously high ionization energy loss signature expected for such a particle to discriminate it from backgrounds. The data are found to agree with background expectations, and cross section limits of $\mathcal{O}(1)$ pb are derived using two reference models, a stable quark and a stable scalar lepton.

DOI: 10.1103/PhysRevLett.90.131801 PACS numbers: 13.85.Rm, 12.60.Jv, 14.80.Ly

Many models for new physics introduce new particles which can be long-lived either due to a new conserved quantum number (e.g., R parity in supersymmetry) or because the decays are suppressed by kinematics or couplings [1,2]. If they are electrically charged, these particles can be detected directly. The possibility of new charged particles which are *absolutely* stable is constrained by cosmological considerations and by searches for exotic particles in stable matter [3]. However, particles which are not absolutely stable but are long-lived on an experimental scale (100 ns) are constrained only by direct searches. The most stringent limits are set by a previous search at Fermilab's Tevatron collider [4] and by searches at CERN's LEP2 collider [5] probing masses up to about 90 GeV/c^2. In this Letter, we present the results of a new search for production of long-lived charged massive particles (CHAMPs) using a data sample of 90 pb^{-1} of $\sqrt{s} = 1.8$ TeV $p\bar{p}$ collisions recorded by the Collider Detector at Fermilab (CDF) during 1994–1995. We search for particles with anomalously high ionization energy loss rate, dE/dx, which would be produced by a slow massive charged particle.

The search can be applied to several models which fall naturally into two distinct categories: weakly produced particles (e.g., new leptons), and strongly produced particles (e.g., new quarks). The lower production cross section of weakly produced particles yields a sufficient number of events only for masses $\lesssim 100$ GeV/c^2 where the background is high, while the higher cross section of strongly produced particles allows sensitivity at higher mass where the background is low. The search is made as model independent as possible, but to quantify the results we use a long-lived fourth generation quark as a reference model for a strong production search and Drell-Yan production of a long-lived slepton from gauge-mediated supersymmetry breaking (GMSB) scenarios for a weak production search.

The CDF detector, described in detail in Ref. [6], measures the trajectories (tracks) and transverse momenta [7], p_T, of charged particles in the pseudorapidity region $|\eta| < 1.1$ with the central tracking chamber (CTC) and silicon vertex detector (SVX), which are immersed in a 1.4 T solenoidal magnetic field. Up to 54 time-over-threshold measurements made by the CTC for each track determine the dE/dx with an average resolution of 13%. The charge deposited in each of the four layers of the SVX provides a second measure of the dE/dx with an average resolution of 18% [8]. Control samples with well-identified particle types are used to calibrate the dE/dx measurements at different velocities: electrons and muons from W boson decay at high velocity ($\beta\gamma > 100$), muons from J/ψ decay, and pions from K_S decay at intermediate velocity, and protons and deuterons from secondary interactions in the beam pipe at low velocity ($\beta\gamma < 1$). Figure 1 shows the comparison of these measurements to the predictions. Electromagnetic and hadronic calorimeters, located outside the superconducting solenoid, measure energy in segmented $\eta - \phi$ towers and identify electron candidates. Drift chambers for muon identification are situated outside the ≥ 5.3 interaction length ($\lambda_{\rm int}$) thick calorimeters and behind an additional $\geq 3.5\lambda_{\rm int}$ thick steel absorber.

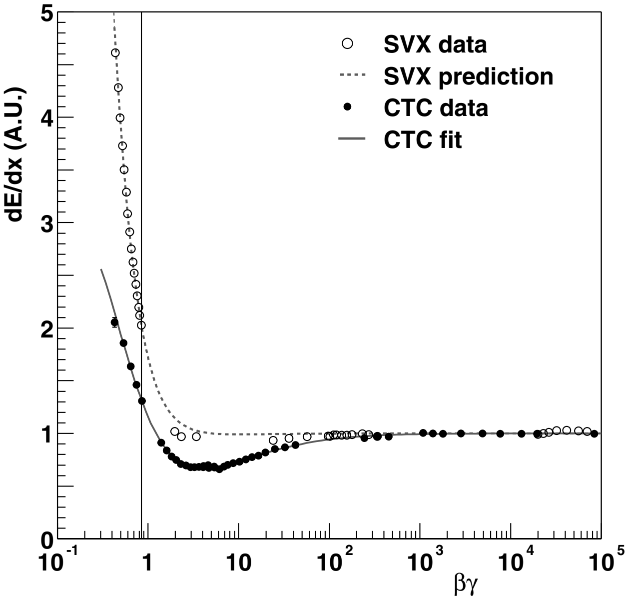

FIG. 1. dE/dx measurements in control samples are compared to predictions for SVX (open points) and CTC (solid points). The CTC prediction is a fit including detector effects. The SVX prediction is the Bethe-Bloch formula. The agreement is good in the low and high $\beta\gamma$ regions important to this search.

Three different trigger data sets are used for this search. A muon trigger selects events with hits in the muon chambers which match a track with $p_T > 12$ GeV$/c$ in the CTC within 5°. A massive particle can penetrate the calorimeters and pass the muon trigger even if it is strongly interacting because the energy lost in hadronic interactions with the relatively light nucleons is too small to initiate a shower. The CHAMP mass is > 100 times the nucleon mass so the energy available in the center-of-mass frame falls below the threshold for single pion production [9]. Only triggers in the region $|\eta| < 0.6$ are used because at larger $|\eta|$ timing requirements that assume $\beta = 1$ are used to reduce backgrounds from beam losses.

The second trigger selects events with missing transverse energy ($\not{E}_T$) > 35 GeV, which can arise since the CHAMPs will penetrate the calorimeter without fully depositing their energy [2]. This trigger also provides acceptance for events containing neutrinos, as is possible in GMSB models where CHAMPs are produced along with neutrinos from the cascade decay of a heavier particle. An electron trigger, which selects events containing electron candidates within the range $|\eta| < 1.1$ and with $E_T > 18$ GeV, provides additional acceptance for these cascade decays, as does the muon trigger, since charged leptons may be produced in these decays as well.

The search selects charged particle tracks with $|\vec{p}| \geq 35$ GeV$/c$ and $|\eta| < 1$ which have sufficient hits in the CTC and SVX to reduce backgrounds from misreconstructed tracks. The 35 GeV$/c$ momentum cut is chosen because for lower momentum a CHAMP in the mass range of interest ($M > 100$ GeV$/c^2$) would be moving too slowly to be efficiently reconstructed. The SVX and CTC dE/dx measurements are each required to be larger than the values expected for a particle with $\beta\gamma = 0.85$. In the region $\beta\gamma \leq 0.85$, $dE/dx \propto 1/\beta^2$ to a good approximation, which allows calculation of a measured mass, $M_{dE/dx}$, from the dE/dx and the momentum. The mass resolution is measured to be 20% using a calibration sample of protons and deuterons. The search is performed for different assumed mass, M, between 100 and 270 GeV$/c^2$ with 10 GeV$/c^2$ steps. At each step, $M_{dE/dx}$ is required to be $> 0.6 \times M$, a 2σ cut. When combined with the dE/dx cut, this provides additional background rejection at lower momentum. To be considered in the weak production search, tracks must additionally pass an isolation cut requiring less than 4 GeV of calorimeter energy or total track p_T within a cone of $\sqrt{|\Delta\eta|^2 + |\Delta\phi|^2} = 0.4$ around the track.

Backgrounds arise from tracks for which the dE/dx measurement fluctuated high or included extra ionization from an unreconstructed overlapping particle. To determine the background, we use a control sample which is identical to the search sample but at lower momentum ($20 < |\vec{p}| < 35$ GeV$/c$) where the signal would not contribute. The fake rate, defined as the fraction of tracks in the control sample with dE/dx measurements high enough to correspond to $\beta\gamma \leq 0.85$, is measured to be $\mathcal{O}(10^{-4})$ for each of the different trigger data sets described above. The momentum dependence of the fake rate within the control sample matches expectations. For $|\vec{p}| < 20$ GeV$/c$, the fake rate is reduced due to residual effects of the relativistic rise slightly lowering the dE/dx of kaons in the sample. There is no significant momentum dependence for $|\vec{p}| > 25$ GeV$/c$, which allows us to extrapolate the fake rate to the high momentum signal region. The probability of a high fluctuation in the dE/dx distribution obtained from this fake rate is used to scale the number of candidate tracks, which pass all selections except the dE/dx requirement, to obtain background predictions of 12 ± 2 tracks in the muon trigger data set and 63 ± 9 in the $\not{E}_T$ trigger data set. The expected mass distribution for fake tracks in the signal region is shown in Fig. 2. It is obtained by folding the momenta of the tracks into the dE/dx distribution from the control sample with the assumption that large values of dE/dx are due to high mass particles. In the data, 12 and 45 tracks pass all cuts for the muon and $\not{E}_T$ trigger data sets, respectively. Their mass distribution, also shown in Fig. 2, shows no significant excess over the predicted background.

For the weak production search, the isolation cut reduces the background to 0.85 ± 0.25, 4.0 ± 2.8, and 0.7 ± 0.5 tracks in the muon, $\not{E}_T$, and electron trigger data sets, respectively. In the data, 0, 1, and 0 tracks are observed in these samples.

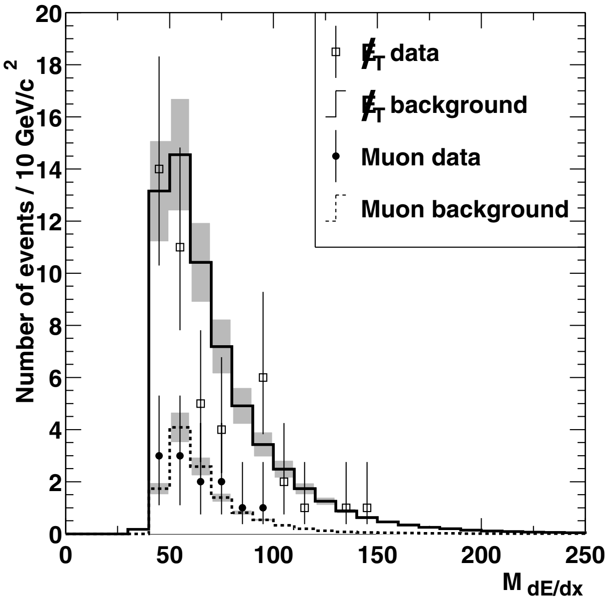

FIG. 2. Observed $M_{dE/dx}$ distribution for tracks passing all the cuts for the strong production search in the muon trigger and $\not{E}_T$ trigger data samples [10]. The curves are the expected background distributions, which have an uncertainty of about 15%, indicated by the gray bands.

The signal efficiencies are determined using Monte Carlo simulation programs and control data samples. The muon trigger efficiency is 80.5% ± 3.0%, and the track selection efficiency is 51.3% ± 2.5%, dominated by acceptance in the SVX. The tracking efficiency decreases at low velocity, $\beta\gamma < 0.4$, due to drift time limits in the CTC track finding algorithms. This is measured with a sample of deuterons which are produced from secondary interactions in the beam pipe. The efficiencies of the cuts on the kinematic variables $|\eta|$, $|p|$, $\beta\gamma$ (dE/dx), and mass are model dependent. To set generally applicable limits, we determine these efficiencies using easily quantifiable reference models. For the strong production case we use a long-lived fourth generation quark calculated with the PYTHIA Monte Carlo program [11]. The total efficiency increases from 1.5% to 2.9% over the mass range 100–270 GeV$/c^2$ for a charge $\frac{2}{3}e$ quark (U) and from 0.8% to 1.6% for a charge $-\frac{1}{3}e$ quark (D). The charge asymmetry of the efficiency arises from the light quark (u, d, s) contributions to the fragmentation; $U\bar{s}$ and $U\bar{d}$ mesons are charged while only the $D\bar{u}$ meson is charged. Furthermore, although a massive quark would efficiently penetrate the calorimeters, the hadron containing it can undergo charge exchange from interactions in the calorimeter which replace the light quark in it, and a $\frac{2}{3}e$ quark is more likely to remain in a charged hadron and be detected by the muon chambers. The efficiency for this depends on the s quark suppression which is taken to be 30% [12]. The uncertainty from this effect, estimated by taking half of the efficiency difference obtained if every hadron is assumed to interact, is 20% for $q = \frac{1}{3}e$ and 13% for $q = \frac{2}{3}e$. Other systematic uncertainties are 4% for trigger efficiency, 5% for track selection, 4% for luminosity, and 7% from the choice of CTEQ3M [13] as the parton distribution function. The total systematic uncertainties on efficiency are 23% and 17% for $q = \frac{1}{3}e$ and $q = \frac{2}{3}e$, respectively.

Figure 3 shows the cross section limits we derive as a function of mass. From comparison with the expected cross section, we derive mass limits at a 95% confidence level of $M > 190$ GeV$/c^2$ for $q = \frac{1}{3}e$ and $M > 220$ GeV$/c^2$ for $q = \frac{2}{3}e$. The charge exchange effects described above could be different for other models. To ease comparison with other models, we include in Fig. 3 a limit calculated without these effects. These limits are based on data collected with the muon trigger. The $\not{E}_T$ trigger data set is also searched since it could provide sensitivity to signal, but the $\not{E}_T$ trigger efficiency depends critically on the calorimeter's response to a CHAMP, which is very uncertain. This makes any cross section calculations unreliable, so the $\not{E}_T$ trigger data set is not included in the limit calculation for the strong production search.

For the weak production search, the muon trigger and track quality cut efficiencies are identical to the strongly interacting case. The efficiencies of the model dependent kinematic cuts are estimated using as a reference model the Drell-Yan pair production of stable sleptons calculated with the SPYTHIA Monte Carlo program [14]. The total efficiency varies from 2.5% to 4.5% over the mass range 80–120 GeV$/c^2$. The systematic uncertainties on these efficiencies are similar to the strongly interacting case, without the charge exchange uncertainty. The cross section limits obtained for direct slepton production range

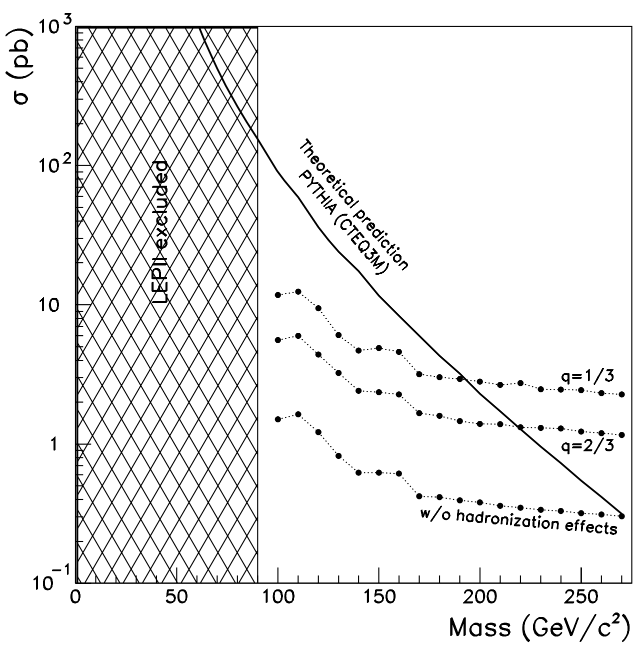

FIG. 3. Limits set at a 95% confidence level on the production cross section of long-lived fourth generation quarks are compared with the theoretical prediction.

from 1.3 pb at $M = 80$ GeV/c^2 to 0.75 pb at 120 GeV/c^2. The expected cross section is over an order of magnitude below this level of sensitivity. Stable sleptons can also be produced from cascade decays of heavier particles such as charginos. Such decays would also produce charged leptons and neutrinos, and the electron and $\not{E}_T$ trigger data samples are searched to add sensitivity to these decays. The efficiency for this is very model dependent, and we quantify it only for a single point in the GMSB parameter space which makes the three charged sleptons nearly degenerate with masses ~105 GeV/c^2, slightly above the existing limits [15]. The modified kinematics from the decays increases the efficiency to 6.7% for the muon trigger data set. Including the $\not{E}_T$ and electron triggers increases it to 8.2%. The $\not{E}_T$ trigger and isolation requirement introduce additional systematic uncertainties from the modeling of initial and final state radiation, making the total systematic uncertainty 12.5%. When cascade decays from all production modes are included, the cross section limit is lowered to 550 fb compared to the model prediction of 80 fb.

In summary, we have searched for long-lived charged massive particles in 90 pb^{-1} of data at CDF. No excess over background was observed. We derive cross section limits using reference models for the two cases of strongly and weakly produced particles. In the strongly interacting case, these limits extend the excluded mass region to about 200 GeV/c^2.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. We thank S. Ambrosanio, J. L. Feng, J. F. Gunion, and P. Q. Hung for useful theoretical discussions. This work is supported by the U.S. Department of Energy and the National Science Foundation; the Natural Sciences and Engineering Research Council of Canada; the Istituto Nazionale di Fisica Nucleare of Italy; the Ministry of Education, Science and Culture of Japan; the National Science Council of the Republic of China; and the A. P. Sloan Foundation.

[1] P. H. Frampton and P. Q. Hung, Phys. Rev. D **58**, 057704 (1998); K. Enqvist, K. Mursula, and M. Roos, Nucl. Phys. **B226**, 121 (1983); Harald Fritzsch, Phys. Lett. B **78**, 611 (1978); P. Fishbane, S. Meshkov, and P. Ramond, Phys. Lett. B **134**, 81 (1984); C. Wetterich, Phys. Lett. B **167**, 325 (1986); T. Banks and M. Karliner, Nucl. Phys. **B281**, 399 (1987); G. Ingelman and C. Wetterich, Phys. Lett. B **174**, 109 (1986); J. L. Feng and T. Moroi, Phys. Rev. D **58**, 035001 (1998); S. Martin and J. Wells, Phys. Rev. D **59**, 035008 (1999); S. Ambrosanio, G. D. Kribs, and S. P. Martin, Phys. Rev. D **56**, 1761–1777 (1997); Nucl. Phys. **B516**, 55–69 (1998); H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75 (1985).

[2] H. Baer, K. Cheung, and J. F. Gunion, Phys. Rev. D **59**, 075002 (1999).

[3] P. F. Smith *et al.*, Nucl. Phys. **B149**, 525 (1979); E. Nardi and E. Roulet, Phys. Lett. B **245**, 105 (1990); R. N. Mohapatra and V. L. Teplitz, Phys. Rev. Lett. **81**, 3079–3082 (1998); R. N. Mohapatra and S. Nussinov, Phys. Rev. D **57**, 1940–1946 (1998).

[4] F. Abe *et al.*, Phys. Rev. D **46**, 1889–1894 (1992); F. Abe *et al.*, Phys. Rev. Lett. **63**, 1447 (1989).

[5] P. Achard *et al.*, Phys. Lett. B **517**, 75–85 (2001); P. Abreu *et al.*, Phys. Lett. B **478**, 65–72 (2000); R. Barate *et al.*, Eur. Phys. J. C **16**, 71–85 (2000).

[6] F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988); P. Azzi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **360**, 137 (1995).

[7] The CDF coordinate system defines the transverse momentum of a particle as $p_T \equiv |\vec{p}| \sin\theta$, where θ is the polar angle with respect to the z axis defined along the proton beam, ϕ as the azimuthal angle in the transverse plane, and pseudorapidity as $\eta \equiv -\ln(\tan\frac{\theta}{2})$.

[8] A low-end truncated mean is used for both the CTC and SVX to suppress Landau fluctuations.

[9] M. Drees and X. Tata, Phys. Lett. B **252**, 695–702 (1990).

[10] The data uncertainties are Poisson 68% C.L. intervals. G. Feldman and R. Cousins, Phys. Rev. D **57**, 3873 (1998).

[11] T. Sjostrand, Comput. Phys. Commun. **82**, 74 (1994). We use PYTHIA version 5.7.

[12] T. Affolder *et al.*, Phys. Rev. Lett. **84**, 1663 (2000); D. Buskulic *et al.*, Phys. Lett. B **361**, 221 (1995); HRS Collaboration, M. Derrick *et al.*, Phys. Lett. B **158**, 519 (1985).

[13] H. Lai *et al.*, Phys. Rev. D **51**, 4763 (1995).

[14] S. Mrenna, Comput. Phys. Commun. **101**, 232 (1997).

[15] The GMSB parameters for the point used are $N_5 = 3$, $M = 64$ TeV, $\Lambda = 32$ TeV, $\tan(\beta) = 3$, and $\mu > 0$.