Search for new physics in high p_T like-sign dilepton events at CDF II

T. Aaltonen,[22] B. Álvarez González[w,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,[57] A. Artikov,[14] J. Asaadi,[52] W. Ashmanskas,[16] B. Auerbach,[60] A. Aurisano,[52] F. Azfar,[41] W. Badgett,[16] A. Barbaro-Galtieri,[27] V.E. Barnes,[47] B.A. Barnett,[24] P. Barria[dd,45] P. Bartos,[13] M. Bauce[bb,42] G. Bauer,[31] F. Bedeschi,[45] D. Beecher,[29] S. Behari,[24] G. Bellettini[cc,45] J. Bellinger,[59] D. Benjamin,[15] A. Beretvas,[16] A. Bhatti,[49] M. Binkley[*,16] D. Bisello[bb,42] I. Bizjak[hh,29] K.R. Bland,[5] B. Blumenfeld,[24] A. Bocci,[15] A. Bodek,[48] D. Bortoletto,[47] J. Boudreau,[46] A. Boveia,[12] L. Brigliadori[aa,6] A. Brisuda,[13] C. Bromberg,[34] E. Brucken,[22] M. Bucciantonio[cc,45] J. Budagov,[14] H.S. Budd,[48] S. Budd,[23] K. Burkett,[16] G. Busetto[bb,42] P. Bussey,[20] A. Buzatu,[32] C. Calancha,[30] S. Camarda,[4] M. Campanelli,[29] M. Campbell,[33] F. Canelli[11,16] B. Carls,[23] D. Carlsmith,[59] R. Carosi,[45] S. Carrillo[k,17] S. Carron,[16] B. Casal,[10] M. Casarsa,[16] A. Castro[aa,6] P. Catastini,[21] D. Cauz,[53] V. Cavaliere,[23] M. Cavalli-Sforza,[4] A. Cerri[e,27] L. Cerrito[q,29] Y.C. Chen,[1] M. Chertok,[7] G. Chiarelli,[45] G. Chlachidze,[16] F. Chlebana,[16] K. Cho,[26] D. Chokheli,[14] J.P. Chou,[21] W.H. Chung,[59] Y.S. Chung,[48] C.I. Ciobanu,[43] M.A. Ciocci[dd,45] A. Clark,[19] C. Clarke,[58] G. Compostella[bb,42] M.E. Convery,[16] J. Conway,[7] M.Corbo,[43] M. Cordelli,[18] C.A. Cox,[7] D.J. Cox,[7] F. Crescioli[cc,45] C. Cuenca Almenar,[60] J. Cuevas[w,10] R. Culbertson,[16] D. Dagenhart,[16] N. d'Ascenzo[u,43] M. Datta,[16] P. de Barbaro,[48] S. De Cecco,[50] G. De Lorenzo,[4] M. Dell'Orso[cc,45] C. Deluca,[4] L. Demortier,[49] J. Deng[b,15] M. Deninno,[6] F. Devoto,[22] M. d'Errico[bb,42] A. Di Canto[cc,45] B. Di Ruzza,[45] J.R. Dittmann,[5] M. D'Onofrio,[28] S. Donati[cc,45] P. Dong,[16] M. Dorigo,[53] T. Dorigo,[42] K. Ebina,[57] A. Elagin,[52] A. Eppig,[33] R. Erbacher,[7] D. Errede,[23] S. Errede,[23] N. Ershaidat[z,43] R. Eusebi,[52] H.C. Fang,[27] S. Farrington,[41] M. Feindt,[25] J.P. Fernandez,[30] C. Ferrazza[ee,45] R. Field,[17] G. Flanagan[s,47] R. Forrest,[7] M.J. Frank,[5] M. Franklin,[21] J.C. Freeman,[16] Y. Funakoshi,[57] I. Furic,[17] M. Gallinaro,[49] J. Galyardt,[11] J.E. Garcia,[19] A.F. Garfinkel,[47] P. Garosi[dd,45] H. Gerberich,[23] E. Gerchtein,[16] S. Giagu[ff,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] S. Grinstein,[4] C. Grosso-Pilcher,[12] R.C. Group[55,16] 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,[58] K. Hatakeyama,[5] C. Hays,[41] M. Heck,[25] J. Heinrich,[44] M. Herndon,[59] S. Hewamanage,[5] D. Hidas,[51] A. Hocker,[16] W. Hopkins[f,16] D. Horn,[25] S. Hou,[1] R.E. Hughes,[38] M. Hurwitz,[12] U. Husemann,[60] N. Hussain,[32] M. Hussein,[34] J. Huston,[34] G. Introzzi,[45] M. Iori[ff,50] A. Ivanov[o,7] E. James,[16] D. Jang,[11] B. Jayatilaka,[15] E.J. Jeon,[26] M.K. Jha,[6] S. Jindariani,[16] W. Johnson,[7] M. Jones,[47] K.K. Joo,[26] S.Y. Jun,[11] T.R. Junk,[16] T. Kamon,[52] P.E. Karchin,[58] A. Kasmi,[5] 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,[57] M. Kirby,[16] S. Klimenko,[17] K. Kondo[*,57] D.J. Kong,[26] J. Konigsberg,[17] A.V. Kotwal,[15] M. Kreps,[25] J. Kroll,[44] D. Krop,[12] N. Krumnack[l,5] M. Kruse,[15] V. Krutelyov[c,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,[7] K. Lannon[v,38] A. Lath,[51] G. Latino[cc,45] T. LeCompte,[2] E. Lee,[52] H.S. Lee,[12] J.S. Lee,[26] S.W. Lee[x,52] S. Leo[cc,45] S. Leone,[45] J.D. Lewis,[16] A. Limosani[r,15] 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,[60] A. Loginov,[60] D. Lucchesi[bb,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] S. Malik,[49] G. Manca[a,28] A. Manousakis-Katsikakis,[3] F. Margaroli,[47] C. Marino,[25] M. Martínez,[4] R. Martínez-Ballarín,[30] P. Mastrandrea,[50] M.E. Mattson,[58] 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[aa,6] J. Nachtman[m,16] Y. Nagai,[54] J. Naganoma,[57] I. Nakano,[39] A. Napier,[55] J. Nett,[52] C. Neu,[56] M.S. Neubauer,[23] J. Nielsen[d,27] L. Nodulman,[2] O. Norniella,[23] E. Nurse,[29] L. Oakes,[41] S.H. Oh,[15] Y.D. Oh,[26] I. Oksuzian,[56] T. Okusawa,[40] R. Orava,[22] L. Ortolan,[4] S. Pagan Griso[bb,42] C. Pagliarone,[53] E. Palencia[e,10] V. Papadimitriou,[16] A.A. Paramonov,[2] J. Patrick,[16] G. Pauletta[gg,53] M. Paulini,[11] C. Paus,[31] D.E. Pellett,[7] A. Penzo,[53] T.J. Phillips,[15] G. Piacentino,[45] E. Pianori,[44] J. Pilot,[38] K. Pitts,[23] C. Plager,[9] L. Pondrom,[59] R. Porter,[8] K. Potamianos,[47] O. Poukhov[*,14] F. Prokoshin[y,14] A. Pronko,[16] F. Ptohos[g,18] E. Pueschel,[11] G. Punzi[cc,45] J. Pursley,[59] A. Rahaman,[46] V. Ramakrishnan,[59] N. Ranjan,[47] I. Redondo,[30] P. Renton,[41] M. Rescigno,[50] T. Riddick,[29] F. Rimondi[aa,6]

L. Ristori[45],[16] A. Robson,[20] T. Rodrigo,[10] T. Rodriguez,[44] E. Rogers,[23] S. Rolli[h],[55] R. Roser,[16] M. Rossi,[53]
F. Rubbo,[16] F. Ruffini[dd],[45] A. Ruiz,[10] J. Russ,[11] V. Rusu,[16] A. Safonov,[52] W.K. Sakumoto,[48] Y. Sakurai,[57]
L. Santi[gg],[53] L. Sartori,[45] K. Sato,[54] V. Saveliev[u],[43] A. Savoy-Navarro,[43] P. Schlabach,[16] A. Schmidt,[25]
E.E. Schmidt,[16] M.P. Schmidt[*],[60] M. Schmitt,[37] T. Schwarz,[7] L. Scodellaro,[10] A. Scribano[dd],[45] F. Scuri,[45]
A. Sedov,[47] S. Seidel,[36] Y. Seiya,[40] A. Semenov,[14] F. Sforza[cc],[45] A. Sfyrla,[23] S.Z. Shalhout,[7] T. Shears,[28]
P.F. Shepard,[46] M. Shimojima[t],[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,[7] F.D. Snider,[16] A. Soha,[16] S. Somalwar,[51] V. Sorin,[4] P. Squillacioti,[45]
M. Stancari,[16] M. Stanitzki,[60] 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[f],[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,[42]
M. Trovato[ee],[45] Y. Tu,[44] F. Ukegawa,[54] S. Uozumi,[26] A. Varganov,[33] F. Vázquez[k],[17] G. Velev,[16] C. Vellidis,[3]
M. Vidal,[30] I. Vila,[10] R. Vilar,[10] J. Vizán,[10] M. Vogel,[36] G. Volpi[cc],[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[b],[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,[57]
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[aa][6]
(CDF Collaboration[†])

[1]Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China
[2]Argonne National Laboratory, Argonne, Illinois 60439, USA
[3]University of Athens, 157 71 Athens, Greece
[4]Institut de Fisica d'Altes Energies, ICREA, Universitat Autonoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain
[5]Baylor University, Waco, Texas 76798, USA
[6]Istituto Nazionale di Fisica Nucleare Bologna, [aa]University of Bologna, I-40127 Bologna, Italy
[7]University of California, Davis, Davis, California 95616, USA
[8]University of California, Irvine, California 92627, 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,* [bb]*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,* [cc]*University of Pisa,*
[dd]*University of Siena and* [ee]*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,*
[ff]*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, [gg]*University of Udine, I-33100 Udine, Italy*
[54]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[55]*Tufts University, Medford, Massachusetts 02155, USA*
[56]*University of Virginia, Charlottesville, Virginia 22906, USA*
[57]*Waseda University, Tokyo 169, Japan*
[58]*Wayne State University, Detroit, Michigan 48201, USA*
[59]*University of Wisconsin, Madison, Wisconsin 53706, USA*
[60]*Yale University, New Haven, Connecticut 06520, USA*

We present a search for new physics in events with two high p_T leptons of the same electric charge, using data with an integrated luminosity of 6.1 fb^{-1}. The observed data are consistent with standard model predictions. We set 95% C.L. lower limits on the mass of doubly-charged scalars decaying to like-sign dileptons, $m_{H^{\pm\pm}} > 190 - 245$ GeV/c^2, depending on the decay mode and coupling.

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A wide variety of models of new physics predict events with two like-sign leptons, a signature which has very low backgrounds from the standard model. Examples include doubly-charged Higgs bosons [1], supersymmetry [2], heavy neutrinos [3], like-sign top quark production [4], and fourth-generation quarks [5].

CDF examined the like-sign dilepton data with integrated luminosity of 110 pb^{-1} in Run I [6] and 1 fb^{-1} in Run II [7], observing in Run II a modest excess of events above the standard model expectation (44 ob-

*Deceased
†With visitors from [a]Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, [b]University of CA Irvine, Irvine, CA 92697, USA, [c]University of CA Santa Barbara, Santa Barbara, CA 93106, USA, [d]University of CA Santa Cruz, Santa Cruz, CA 95064, USA, [e]CERN,CH-1211 Geneva, Switzerland, [f]Cornell University, Ithaca, NY 14853, USA, [g]University of Cyprus, Nicosia CY-1678, Cyprus, [h]Office of Science, U.S. Department of Energy, Washington, DC 20585, USA, [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, USA, [m]University of Iowa, Iowa City, IA 52242, USA, [n]Kinki University, Higashi-Osaka City, Japan 577-8502, [o]Kansas State University, Manhattan, KS 66506, USA, [p]University of Manchester, Manchester M13 9PL, United Kingdom, [q]Queen Mary, University of London, London, E1 4NS, United Kingdom, [r]University of Melbourne, Victoria 3010, Australia, [s]Muons, Inc., Batavia, IL 60510, USA, [t]Nagasaki Institute of Applied Science, Nagasaki, Japan, [u]National Research Nuclear University, Moscow, Russia, [v]University of Notre Dame, Notre Dame, IN 46556, USA, [w]Universidad de Oviedo, E-33007 Oviedo, Spain, [x]Texas Tech University, Lubbock, TX 79609, USA, [y]Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile, [z]Yarmouk University, Irbid 211-63, Jordan, [hh]On leave from J. Stefan Institute, Ljubljana, Slovenia,

served, 33.2 ± 4.7 expected).

In this Letter, we present a study of events with like-sign dileptons with an integrated luminosity of 6.1 fb^{-1} collected by the CDF II detector. We search for a localized excess of events in a model-independent manner by comparing the observed events to the standard model prediction using a Kolmogorov-Smirnov test in several kinematic variables and assessing the statistical consistency. In addition, we set limits on a specific model: pair production of doubly-charged scalars which decay to two like-sign charged leptons [1]. These limits supersede those from CDF in 240 pb^{-1} [8] and are stronger than those from D0 in 1.1 fb^{-1} [9] and CMS in 36 pb^{-1} [10] by an order of magnitude. A companion article [11] includes interpretations for like-sign top quark production and supersymmetric processes.

Events were recorded by CDF II [12, 13], a general purpose detector designed to study collisions at the Fermilab Tevatron $p\overline{p}$ collider at $\sqrt{s} = 1.96$ TeV. A charged-particle tracking system immersed in a 1.4 T magnetic field consists of a silicon microstrip tracker and a drift chamber. Electromagnetic and hadronic calorimeters surround the tracking system and measure particle energies. Drift chambers located outside the calorimeters detect muons. We examine data taken between August 2002 and September 2010, corresponding to an integrated luminosity of 6.1 fb^{-1}.

The data acquisition system is triggered by e or μ candidates [14] with transverse momentum[13], p_T, greater than 18 GeV/c. Electrons and muons are reconstructed offline and selected if they have a pseudorapidity[13], η, magnitude less than 1.1, $p_T \geq 20$ GeV/c and satisfy the standard CDF identification and isolation requirements [14]. An additional requirement is made to suppress electrons from photon conversions, by rejecting electron candidates with a collinear intersecting reconstructed track. Jets are reconstructed in the calorimeter using the JETCLU [15] algorithm with a clustering radius of 0.4 in azimuth-pseudorapidity space [13] and calibrated [17]. Jets are selected if they have $p_T \geq 15$ GeV/c and $|\eta| < 2.4$. Missing transverse momentum [18], $\not\!\!E_T$, is reconstructed using fully corrected calorimeter and muon information [14].

We select events with at least two isolated leptons (electrons or muons), two of which have the same electric charge. The leading lepton must have $p_T > 20$ GeV/c, $|\eta| < 1.1$ and be isolated in both the calorimeter and the tracker. The second lepton must satisfy the same requirements, with the exception that it needs only have $p_T > 10$ GeV/c. We require that the two leptons come from the same primary vertex and have a dilepton invariant mass $m_{\ell\ell}$ of at least 25 GeV/c^2 to reduce backgrounds from pair production of bottom quarks. Finally, we reject events with three or more leptons if they contain a pair of opposite-sign leptons or like-signed electrons in the window, $m_{\ell\ell} \in [86, 96]$ GeV/c^2. Like-signed electrons pairs may be produced by the radiation of a hard photon, see below, which is negligible for muons. In each event, we calculate H_T, the scalar sum of the lepton p_T, the jet E_T and the missing transverse momentum.

Irreducible backgrounds to the like-sign dilepton signature with prompt like-sign leptons are rare in the SM; they are largely from WZ and ZZ production. These backgrounds are modeled using simulated events generated by PYTHIA [19] with the detector response simulated with a GEANT-based algorithm CDFSIM [20].

The dominant reducible background comes from W+jets production or $t\bar{t}$ production with semi-leptonic decays, with one prompt lepton and a second lepton due to the semi-leptonic decay of a b- or c-quark meson. This ("fake") background is described using a lepton misidentification model from inclusive jet data applied to W+jet events, validated in orthogonal jet samples and in events with like-sign dileptons but low invariant mass: $m_{\ell\ell} \in [15, 25]$ GeV/c^2.

The second largest source of background comes from processes which produce electron-positron pairs; either the electron or positron emits a hard photon leading to an asymmetric conversion (e.g. $e^-_{hard} \rightarrow e^-_{soft}\gamma \rightarrow e^-_{soft}e^-_{soft}e^+_{hard}$) where the track for the e^+_{hard} determines the charge. This mechanism is well-described by the detector simulation, and is validated in events with like-sign electron pairs which have a conversion-tagged electron. The major contributions via this mechanism are from Z/γ^*+jets and $t\bar{t}$ production with fully leptonic decays. Estimates of the backgrounds from Z/γ^*+jets processes are modeled using simulated events generated by PYTHIA normalized to data in opposite-sign events. The detector response for both Z+jets and $t\bar{t}$ processes is evaluated using CDFSIM, where, to avoid double-counting, the like-sign leptons are required to originate from the W or Z boson decays rather than from misidentified jets.

An additional contribution to the background is due to associated production of a W boson with a prompt photon. If the W boson decays to an electron (muon) and the photon converts too early to be identified as a conversion, the event can be reconstructed with a like-sign ee ($e\mu$) signature. The rate of $W\gamma$ production the efficiency for finding conversions is validated in a sample of like-sign dilepton events with a conversion-tagged electron.

Backgrounds from charge-mismeasurement are insignificant, as the charge of a particle with momentum of 100 GeV/c is typically determined with a significance greater than 5σ [16].

The dominant systematic uncertainty is the 50% uncertainty of the lepton misidentification rate, due to possible contamination of leptons from W and Z boson decays in the inclusive jet data. This gives a 20% uncertainty on the total background. Additional uncertainties are due to the jet energy scale [17], contributions from additional interactions, and descriptions of initial and fi-

TABLE I: Predicted and observed event yields in like-sign lepton events. Uncertainties included statistical and systematic contributions. Entries written as — are negigible.

Process	Total $\ell\ell$	$\mu\mu$	ee	$e\mu$
$t\bar{t}$	0.1 ± 0.1	—	—	0.1 ± 0.1
$Z \to \ell\ell$	26.6 ± 3.4	—	17.0 ± 2.8	9.7 ± 2.1
WW, WZ, ZZ	28.4 ± 1.4	7.9 ± 0.9	6.0 ± 0.4	14.5 ± 0.8
$W(\to \ell\nu)\gamma$	16.2 ± 2.4	—	8.1 ± 1.8	8.0 ± 1.8
Fake Leptons	51.6 ± 24.2	8.2 ± 5.3	22.1 ± 8.9	21.3 ± 10.6
Total	123.0 ± 24.6	16.1 ± 5.4	53.3 ± 9.5	53.6 ± 10.9
Data	145	14	66	65

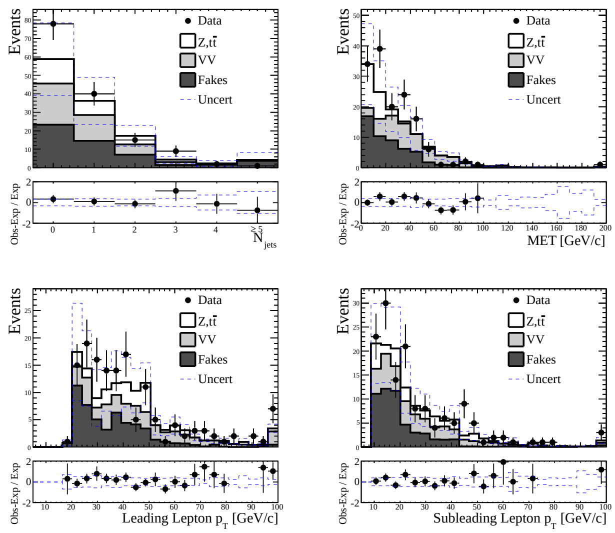

FIG. 1: Distribution of jet multiplicity, missing transverse momentum, leading lepton p_T and sub-leading lepton p_T in observed like-sign dilepton events and expected backgrounds. The VV contribution includes WW, WZ, ZZ and $W\gamma$.

nal state radiation [21] and uncertainties in the parton distribution functions [22, 23].

Table I shows the observed and predicted event yields. Figure 1 shows kinematic distributions of observed and predicted like-sign lepton events.

We calculate the maximum Kolmogorov-Smirnov (KS) distance for each the distributions $m_{\ell\ell}$, $\not{E}_T$, N_{jets}, lepton p_T and H_T. A large KS distance value would indicate a localized excess in one of these variables, though this test is not sensitive to discrepancies in the total yield. In each case, the standard model p-value (probability to observe a result at least this discrepant from the standard model) does not indicate significant deviation from the background-only hypothesis; see Table II.

This larger dataset does not show evidence of the excess seen in the previous analysis [7] that was based on 1 fb^{-1} of integrated luminosity. The background from misidentified leptons was calculated using a different technique, which gives a larger estimate in the original dataset than the previous analysis, though consistent within systematic uncertainties.

TABLE II: Results of KS-distance test for standard model prediction. The maximum KS distance and corresponding p-value is given for several kinematic distributions presented in this analysis.

Distribution	Total $\ell\ell$	ee	$\mu\mu$	$e\mu$
$m_{\ell\ell}$	0.11 (79%)	0.22 (47%)	0.23 (46%)	0.30 (59%)
$\not{E}_T$	0.19 (34%)	0.23 (27%)	0.24 (32%)	0.21 (69%)
N_{jets}	0.19 (56%)	0.31 (31%)	0.20 (57%)	0.21 (84%)
Lepton 1 p_T	0.16 (49%)	0.18 (47%)	0.25 (30%)	0.26 (60%)
Lepton 2 p_T	0.12 (66%)	0.21 (41%)	0.23 (33%)	0.40 (33%)
H_T	0.15 (45%)	0.22 (34%)	0.22 (32%)	0.24 (58%)

Observing no excess, we report our sensitivity in terms of limits on doubly-charge scalar bosons decaying to like-sign electron pairs, muon pairs or electron-muon pairs. Simulated events are generated with MADEVENT [24], showering and hadronization is performed by PYTHIA passed through the CDF II full detector simulation. Figure 2 shows the observed and expected standard model spectra in the $ee, \mu\mu$ and $e\mu$ channels.

The largest uncertainties on the signal model are due to energy resolution and lepton identification efficiencies, which are minor compared to the background uncertainties. In each case, we treat the unknown underlying quantity as a nuisance parameter and measure the distortion of the dilepton mass spectrum for positive and negative fluctuations.

The dilepton mass spectrum is in good agreement with the standard model prediction, and we calculate 95% confidence level upper limits on the production cross section of doubly-charged Higgs bosons, using frequentist statistics with the unified ordering scheme [25]. The Z/γ^* coupling and therefore production cross-section of the doubly-charged Higgs boson depends on whether it is a member of a singlet, doublet or triplet, as shown in Fig. 3 and Tables III and IV.

In summary, we present a search for new physics in events with two high p_T leptons of the same electric charge using data with an integrated luminosity of 6.1 fb^{-1}. The observed data are consistent with standard model predictions. We set 95% confidence level lower limits on the mass of doubly-charged scalars decaying to like-sign dileptons, $m_{H^{\pm\pm}} > 190$-245 GeV/c^2, depending on the decay mode and coupling.

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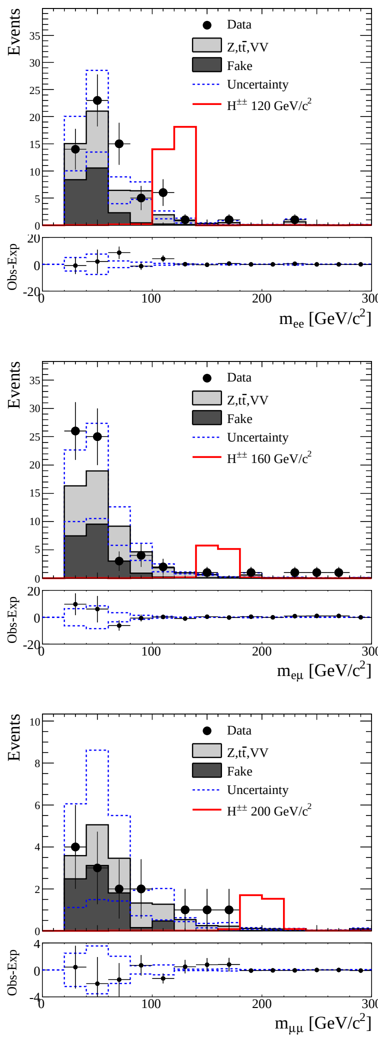

FIG. 2: The observed and expected standard model spectra in the $ee, \mu\mu$ and $e\mu$ channels. The doubly-charged Higgs boson signal is shown for typical masses. The VV contribution includes WW, WZ, ZZ and $W\gamma$.

TABLE III: For various Higgs masses, the NLO cross sections for singlet (σ_1), doublet (σ_2), triplet (σ_3) production, expected and observed 95% C.L. limits in the $ee, e\mu$ and $\mu\mu$ channels. All cross-sections are in femtobarns.

$m_{H^{\pm\pm}}$	Theory			Observed			Expected		
(GeV/c^2)	σ_1	σ_2	σ_3	σ^{95}_{ee}	$\sigma^{95}_{e\mu}$	$\sigma^{95}_{\mu\mu}$	σ^{95}_{ee}	$\sigma^{95}_{e\mu}$	$\sigma^{95}_{\mu\mu}$
100	48	55	120	12	4.2	3.1	5.7	3.8	2.8
120	23	27	55	7.4	2.3	2.2	3.3	2.6	2.2
140	11	14	26	2.0	2.2	3.4	2.4	2.2	1.6
160	6.0	7.2	14	2.4	2.2	3.2	1.5	1.9	1.4
180	3.2	3.9	7.7	2.3	2.2	2.6	1.5	1.7	1.5
200	1.8	2.2	4.2	1.2	2.4	1.6	1.5	1.4	1.5
220	1.0	1.2	2.4	2.3	3.4	1.2	1.4	1.1	1.4
240	0.6	0.7	1.4	1.7	4.4	1.2	1.4	1.1	1.3
260	0.3	0.4	0.8	1.2	4.0	1.1	1.5	1.0	1.2

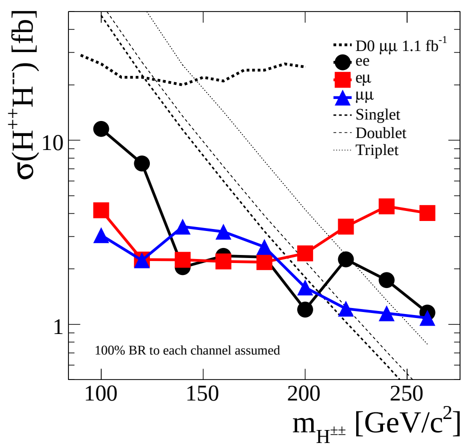

FIG. 3: Observed upper limits at 95% C.L. on the production cross-section for doubly-charged Higgs, assuming 100% branching fraction to $ee, \mu\mu$ or $e\mu$, compared to results from D0 [9]. Also shown are next-to-leading-order theoretical calculations of the cross-section, assuming the Higgs is a member of a singlet, doublet or triplet.

TABLE IV: Lower limits at 95% C.L. on $H^{\pm\pm}$ masses by channel,for singlet, doublet and triplet theories. All in units of GeV/c^2.

	Theory		
Channel	Triplet	Doublet	Singlet
ee	225	210	205
$e\mu$	210	195	190
$\mu\mu$	245	220	205

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