Search for Supersymmetry with Gauge-Mediated Breaking in Diphoton Events with Missing Transverse Energy at CDF II

T. Aaltonen,[24] J. Adelman,[14] B. Álvarez González[v],[12] S. Amerio[dd],[44] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[49] T. Arisawa,[58] A. Artikov,[16] J. Asaadi,[54] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] W. Badgett,[18] A. Barbaro-Galtieri,[29] V.E. Barnes,[49] B.A. Barnett,[26] P. Barria[ff],[47] P. Bartos,[15] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47] D. Beecher,[31] S. Behari,[26] G. Bellettini[ee],[47] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] A. Bhatti,[51] M. Binkley,[18] D. Bisello[dd],[44] I. Bizjak[jj],[31] R.E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] D. Bortoletto,[49] J. Boudreau,[48] A. Boveia,[11] B. Brau[a],[11] A. Bridgeman,[25] L. Brigliadori[cc],[6] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H.S. Budd,[50] S. Budd,[25] K. Burkett,[18] G. Busetto[dd],[44] P. Bussey,[22] A. Buzatu,[34] K. L. Byrum,[2] S. Cabrera[x],[17] C. Calancha,[32] S. Camarda,[4] M. Campanelli,[36] M. Campbell,[35] F. Canelli[14],[18] A. Canepa,[46] B. Carls,[25] D. Carlsmith,[60] R. Carosi,[47] S. Carrillo[n],[19] S. Carron,[18] B. Casal,[12] M. Casarsa,[18] A. Castro[cc],[6] P. Catastini[ff],[47] D. Cauz,[55] V. Cavaliere[ff],[47] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito[q],[31] S.H. Chang,[28] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J.P. Chou,[23] G. Choudalakis,[33] K. Chung[o],[18] W.H. Chung,[60] Y.S. Chung,[50] T. Chwalek,[27] C.I. Ciobanu,[45] M.A. Ciocci[ff],[47] A. Clark,[21] D. Clark,[7] G. Compostella,[44] M.E. Convery,[18] J. Conway,[8] M.Corbo,[45] M. Cordelli,[20] C.A. Cox,[8] D.J. Cox,[8] F. Crescioli[ee],[47] C. Cuenca Almenar,[61] J. Cuevas[v],[12] R. Culbertson,[18] J.C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso[ee],[47] C. Deluca,[4] L. Demortier,[51] J. Deng[f],[17] M. Deninno,[6] M. d'Errico[dd],[44] A. Di Canto[ee],[47] G.P. di Giovanni,[45] B. Di Ruzza,[47] J.R. Dittmann,[5] M. D'Onofrio,[4] S. Donati[ee],[47] P. Dong,[18] T. Dorigo,[44] S. Dube,[53] K. Ebina,[58] A. Elagin,[54] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] N. Ershaidat[bb],[45] R. Eusebi,[54] H.C. Fang,[29] S. Farrington,[43] W.T. Fedorko,[14] R.G. Feild,[61] M. Feindt,[27] J.P. Fernandez,[32] C. Ferrazza[gg],[47] R. Field,[19] G. Flanagan[s],[49] R. Forrest,[8] M.J. Frank,[5] M. Franklin,[23] J.C. Freeman,[18] I. Furic,[19] M. Gallinaro,[51] J. Galyardt,[13] F. Garberson,[11] J.E. Garcia,[21] A.F. Garfinkel,[49] P. Garosi[ff],[47] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] A. Gessler,[27] S. Giagu[hh],[52] V. Giakoumopoulou,[3] P. Giannetti,[47] K. Gibson,[48] J.L. Gimmell,[50] C.M. Ginsburg,[18] N. Giokaris,[3] M. Giordani[ii],[55] P. Giromini,[20] M. Giunta,[47] G. Giurgiu,[26] V. Glagolev,[16] D. Glenzinski,[18] M. Gold,[38] N. Goldschmidt,[19] A. Golossanov,[18] G. Gomez,[12] G. Gomez-Ceballos,[33] M. Goncharov,[33] O. González,[32] I. Gorelov,[38] A.T. Goshaw,[17] K. Goulianos,[51] A. Gresele[dd],[44] S. Grinstein,[4] C. Grosso-Pilcher,[14] R.C. Group,[18] U. Grundler,[25] J. Guimaraes da Costa,[23] Z. Gunay-Unalan,[36] C. Haber,[29] K. Hahn,[33] S.R. Hahn,[18] E. Halkiadakis,[53] B.-Y. Han,[50] J.Y. Han,[50] F. Happacher,[20] K. Hara,[56] D. Hare,[53] M. Hare,[57] R.F. Harr,[59] M. Hartz,[48] K. Hatakeyama,[5] C. Hays,[43] M. Heck,[27] J. Heinrich,[46] C. Henderson,[33] M. Herndon,[60] J. Heuser,[27] S. Hewamanage,[5] D. Hidas,[53] C.S. Hill[c],[11] D. Hirschbuehl,[27] A. Hocker,[18] S. Hou,[1] M. Houlden,[30] S.-C. Hsu,[29] B.T. Huffman,[43] R.E. Hughes,[40] M. Hurwitz,[14] U. Husemann,[61] M. Hussein,[36] J. Huston,[36] J. Incandela,[11] G. Introzzi,[47] M. Iori[hh],[52] A. Ivanov[p],[8] E. James,[18] D. Jang,[13] B. Jayatilaka,[17] E.J. Jeon,[28] M.K. Jha,[6] S. Jindariani,[18] W. Johnson,[8] M. Jones,[49] K.K. Joo,[28] S.Y. Jun,[13] J.E. Jung,[28] T.R. Junk,[18] T. Kamon,[54] D. Kar,[19] P.E. Karchin,[59] Y. Kato[m],[42] R. Kephart,[18] W. Ketchum,[14] J. Keung,[46] V. Khotilovich,[54] B. Kilminster,[18] D.H. Kim,[28] H.S. Kim,[28] H.W. Kim,[28] J.E. Kim,[28] M.J. Kim,[20] S.B. Kim,[28] S.H. Kim,[56] Y.K. Kim,[14] N. Kimura,[58] L. Kirsch,[7] S. Klimenko,[19] B. Knuteson,[33] K. Kondo,[58] D.J. Kong,[28] J. Konigsberg,[19] A. Korytov,[19] A.V. Kotwal,[17] M. Kreps,[27] J. Kroll,[46] D. Krop,[14] N. Krumnack,[5] M. Kruse,[17] V. Krutelyov,[11] T. Kuhr,[27] N.P. Kulkarni,[59] M. Kurata,[56] S. Kwang,[14] A.T. Laasanen,[49] S. Lami,[47] S. Lammel,[18] M. Lancaster,[31] R.L. Lander,[8] K. Lannon[u],[40] A. Lath,[53] G. Latino[ff],[47] I. Lazzizzera[dd],[44] T. LeCompte,[2] E. Lee,[54] H.S. Lee,[14] J.S. Lee,[28] S.W. Lee[w],[54] S. Leone,[47] J.D. Lewis,[18] C.-J. Lin,[29] J. Linacre,[43] M. Lindgren,[18] E. Lipeles,[46] A. Lister,[21] D.O. Litvintsev,[18] C. Liu,[48] T. Liu,[18] N.S. Lockyer,[46] A. Loginov,[61] L. Lovas,[15] D. Lucchesi[dd],[44] J. Lueck,[27] P. Lujan,[29] P. Lukens,[18] G. Lungu,[51] J. Lys,[29] R. Lysak,[15] D. MacQueen,[34] R. Madrak,[18] K. Maeshima,[18] K. Makhoul,[33] P. Maksimovic,[26] S. Malde,[43] S. Malik,[31] G. Manca[e],[30] A. Manousakis-Katsikakis,[3] F. Margaroli,[49] C. Marino,[27] C.P. Marino,[25] A. Martin,[61] V. Martin[k],[22] M. Martínez,[4] R. Martínez-Ballarín,[32] P. Mastrandrea,[52] M. Mathis,[26] M.E. Mattson,[59] P. Mazzanti,[6] K.S. McFarland,[50] P. McIntyre,[54] R. McNulty[j],[30] A. Mehta,[30] P. Mehtala,[24] A. Menzione,[47] C. Mesropian,[51] T. Miao,[18] D. Mietlicki,[35] N. Miladinovic,[7] R. Miller,[36] C. Mills,[23] M. Milnik,[27] A. Mitra,[1] G. Mitselmakher,[19] H. Miyake,[56] S. Moed,[23] N. Moggi,[6] M.N. Mondragon[n],[18] C.S. Moon,[28] R. Moore,[18] M.J. Morello,[47] J. Morlock,[27] P. Movilla Fernandez,[18] J. Mülmenstädt,[29] A. Mukherjee,[18] Th. Muller,[27] P. Murat,[18] M. Mussini[cc],[6] J. Nachtman[o],[18] Y. Nagai,[56]

J. Naganoma,[56] K. Nakamura,[56] I. Nakano,[41] A. Napier,[57] J. Nett,[60] C. Neu[z],[46] M.S. Neubauer,[25] S. Neubauer,[27] J. Nielsen[g],[29] L. Nodulman,[2] M. Norman,[10] O. Norniella,[25] E. Nurse,[31] L. Oakes,[43] S.H. Oh,[17] Y.D. Oh,[28] I. Oksuzian,[19] T. Okusawa,[42] R. Orava,[24] K. Osterberg,[24] S. Pagan Griso[dd],[44] C. Pagliarone,[55] E. Palencia,[18] V. Papadimitriou,[18] A. Papaikonomou,[27] A.A. Paramanov,[2] B. Parks,[40] S. Pashapour,[34] J. Patrick,[18] G. Pauletta[ii],[55] M. Paulini,[13] C. Paus,[33] T. Peiffer,[27] D.E. Pellett,[8] A. Penzo,[55] T.J. Phillips,[17] G. Piacentino,[47] E. Pianori,[46] L. Pinera,[19] K. Pitts,[25] C. Plager,[9] L. Pondrom,[60] K. Potamianos,[49] O. Poukhov*,[16] F. Prokoshin[y],[16] A. Pronko,[18] F. Ptohos[i],[18] E. Pueschel,[13] G. Punzi[ee],[47] J. Pursley,[60] J. Rademacker[c],[43] A. Rahaman,[48] V. Ramakrishnan,[60] N. Ranjan,[49] I. Redondo,[32] P. Renton,[43] M. Renz,[27] M. Rescigno,[52] S. Richter,[27] F. Rimondi[cc],[6] L. Ristori,[47] A. Robson,[22] T. Rodrigo,[12] T. Rodriguez,[46] E. Rogers,[25] S. Rolli,[57] R. Roser,[18] M. Rossi,[55] R. Rossin,[11] P. Roy,[34] A. Ruiz,[12] J. Russ,[13] V. Rusu,[18] B. Rutherford,[18] H. Saarikko,[24] A. Safonov,[54] W.K. Sakumoto,[50] L. Santi[ii],[55] L. Sartori,[47] K. Sato,[56] A. Savoy-Navarro,[45] P. Schlabach,[18] A. Schmidt,[27] E.E. Schmidt,[18] M.A. Schmidt,[14] M.P. Schmidt*,[61] M. Schmitt,[39] T. Schwarz,[8] L. Scodellaro,[12] A. Scribano[ff],[47] F. Scuri,[47] A. Sedov,[49] S. Seidel,[38] Y. Seiya,[42] A. Semenov,[16] L. Sexton-Kennedy,[18] F. Sforza[ee],[47] A. Sfyrla,[25] S.Z. Shalhout,[59] T. Shears,[30] P.F. Shepard,[48] M. Shimojima[t],[56] S. Shiraishi,[14] M. Shochet,[14] Y. Shon,[60] I. Shreyber,[37] A. Simonenko,[16] P. Sinervo,[34] A. Sisakyan,[16] A.J. Slaughter,[18] J. Slaunwhite,[40] K. Sliwa,[57] J.R. Smith,[8] F.D. Snider,[18] R. Snihur,[34] A. Soha,[18] S. Somalwar,[53] V. Sorin,[4] T. Spreitzer,[34] P. Squillacioti[ff],[47] M. Stanitzki,[61] R. St. Denis,[22] B. Stelzer,[34] O. Stelzer-Chilton,[34] D. Stentz,[39] J. Strologas,[38] G.L. Strycker,[35] J.S. Suh,[28] A. Sukhanov,[19] I. Suslov,[16] A. Taffard[f],[25] R. Takashima,[41] Y. Takeuchi,[56] R. Tanaka,[41] J. Tang,[14] M. Tecchio,[35] P.K. Teng,[1] J. Thom[h],[18] J. Thome,[13] G.A. Thompson,[25] E. Thomson,[46] P. Tipton,[61] P. Ttito-Guzmán,[32] S. Tkaczyk,[18] D. Toback,[54] S. Tokar,[15] K. Tollefson,[36] T. Tomura,[56] D. Tonelli,[18] S. Torre,[20] D. Torretta,[18] P. Totaro[ii],[55] S. Tourneur,[45] M. Trovato[gg],[47] S.-Y. Tsai,[1] Y. Tu,[46] N. Turini[ff],[47] F. Ukegawa,[56] S. Uozumi,[28] N. van Remortel[b],[24] A. Varganov,[35] E. Vataga[gg],[47] F. Vázquez[n],[19] G. Velev,[18] C. Vellidis,[3] M. Vidal,[32] I. Vila,[12] R. Vilar,[12] M. Vogel,[38] I. Volobouev[w],[29] G. Volpi[ee],[47] P. Wagner,[46] R.G. Wagner,[2] R.L. Wagner,[18] W. Wagner[aa],[27] J. Wagner-Kuhr,[27] T. Wakisaka,[42] R. Wallny,[9] S.M. Wang,[1] A. Warburton,[34] D. Waters,[31] M. Weinberger,[54] J. Weinelt,[27] W.C. Wester III,[18] B. Whitehouse,[57] D. Whiteson[f],[46] A.B. Wicklund,[2] E. Wicklund,[18] S. Wilbur,[14] G. Williams,[34] H.H. Williams,[46] P. Wilson,[18] B.L. Winer,[40] P. Wittich[h],[18] S. Wolbers,[18] C. Wolfe,[14] H. Wolfe,[40] T. Wright,[35] X. Wu,[21] F. Würthwein,[10] S. Xie,[33] A. Yagil,[10] K. Yamamoto,[42] J. Yamaoka,[17] U.K. Yang[r],[14] Y.C. Yang,[28] W.M. Yao,[29] G.P. Yeh,[18] K. Yi[o],[18] J. Yoh,[18] K. Yorita,[58] T. Yoshida[l],[42] G.B. Yu,[17] I. Yu,[28] S.S. Yu,[18] J.C. Yun,[18] A. Zanetti,[55] Y. Zeng,[17] X. Zhang,[25] Y. Zheng[d],[9] and S. Zucchelli[cc6]

(CDF Collaboration[†])

[1]*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2]*Argonne National Laboratory, Argonne, Illinois 60439*
[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*
[6]*Istituto Nazionale di Fisica Nucleare Bologna, [cc]University of Bologna, I-40127 Bologna, Italy*
[7]*Brandeis University, Waltham, Massachusetts 02254*
[8]*University of California, Davis, Davis, California 95616*
[9]*University of California, Los Angeles, Los Angeles, California 90024*
[10]*University of California, San Diego, La Jolla, California 92093*
[11]*University of California, Santa Barbara, Santa Barbara, California 93106*
[12]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[13]*Carnegie Mellon University, Pittsburgh, PA 15213*
[14]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[15]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[16]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[17]*Duke University, Durham, North Carolina 27708*
[18]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[19]*University of Florida, Gainesville, Florida 32611*
[20]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[21]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[22]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[23]*Harvard University, Cambridge, Massachusetts 02138*
[24]*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[25]*University of Illinois, Urbana, Illinois 61801*

[26]The Johns Hopkins University, Baltimore, Maryland 21218
[27]Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany
[28]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
[29]Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720
[30]University of Liverpool, Liverpool L69 7ZE, United Kingdom
[31]University College London, London WC1E 6BT, United Kingdom
[32]Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain
[33]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
[34]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
[35]University of Michigan, Ann Arbor, Michigan 48109
[36]Michigan State University, East Lansing, Michigan 48824
[37]Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia
[38]University of New Mexico, Albuquerque, New Mexico 87131
[39]Northwestern University, Evanston, Illinois 60208
[40]The Ohio State University, Columbus, Ohio 43210
[41]Okayama University, Okayama 700-8530, Japan
[42]Osaka City University, Osaka 588, Japan
[43]University of Oxford, Oxford OX1 3RH, United Kingdom
[44]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, [dd]University of Padova, I-35131 Padova, Italy
[45]LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France
[46]University of Pennsylvania, Philadelphia, Pennsylvania 19104
[47]Istituto Nazionale di Fisica Nucleare Pisa, [ee]University of Pisa, [ff]University of Siena and [gg]Scuola Normale Superiore, I-56127 Pisa, Italy
[48]University of Pittsburgh, Pittsburgh, Pennsylvania 15260
[49]Purdue University, West Lafayette, Indiana 47907
[50]University of Rochester, Rochester, New York 14627
[51]The Rockefeller University, New York, New York 10021
[52]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, [hh]Sapienza Università di Roma, I-00185 Roma, Italy
[53]Rutgers University, Piscataway, New Jersey 08855
[54]Texas A&M University, College Station, Texas 77843
[55]Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, [ii]University of Trieste/Udine, I-33100 Udine, Italy
[56]University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[57]Tufts University, Medford, Massachusetts 02155
[58]Waseda University, Tokyo 169, Japan
[59]Wayne State University, Detroit, Michigan 48201
[60]University of Wisconsin, Madison, Wisconsin 53706
[61]Yale University, New Haven, Connecticut 06520

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We present the results of a search for supersymmetry with gauge-mediated breaking and $\widetilde{\chi}_1^0 \to \gamma\widetilde{G}$ in the $\gamma\gamma$+missing transverse energy final state. In 2.6$\pm$0.2 fb^{-1} of $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV recorded by the CDF II detector we observe no candidate events, consistent with a standard model background expectation of 1.4$\pm$0.4 events. We set limits on the cross section at the 95% C.L. and place the world's best limit of 149 GeV/c^2 on the $\widetilde{\chi}_1^0$ mass at $\tau_{\tilde{\chi}_1^0}\ll$1 ns. We also exclude regions in the $\widetilde{\chi}_1^0$ mass-lifetime plane for $\tau_{\tilde{\chi}_1^0}\lesssim$2 ns.

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*Deceased

†With visitors from [a]University of Massachusetts Amherst,

The standard model (SM) of elementary particles has been enormously successful, but is incomplete. Theoretical motivations [1] and the observation of the '$ee\gamma\gamma$+missing transverse energy ($\not\!\!E_{\rm T}$)' [2, 3] candidate event by the CDF experiment during Run I at the Fermilab Tevatron provide a compelling rationale to search for the production and decay of new heavy particles that produce events with final state photons and $\not\!\!E_{\rm T}$ in collider experiments. Of particular theoretical interest are supersymmetry (SUSY) models with gauge-mediated SUSY-breaking (GMSB) [1]. These models solve the "naturalness problem" [4] and provide a low-mass dark matter candidate that is both consistent with inflation and astronomical observations [5]. Since many versions of these models have a similar phenomenology, we consider a scenario in which the lightest neutralino ($\tilde{\chi}_1^0$) decays almost exclusively (>96%) into a photon (γ) and a weakly interacting, stable gravitino ($\tilde{G}$). The $\tilde{G}$ gives rise to $\not\!\!E_{\rm T}$ by leaving the detector without depositing any energy [6]. In these models, the $\tilde{\chi}_1^0$ is favored to have a lifetime on the order of a nanosecond, and the $\tilde{G}$ is a warm dark matter candidate with a mass in the range $0.5<m_{\tilde{G}}<1.5$ keV/c^2 [7]. Other direct searches [8–10] have constrained the mass of the $\tilde{\chi}_1^0$ to be greater than 100 GeV/c^2 for various points in parameter space. At the Tevatron sparticle production is predicted to result primarily into gaugino pairs, and the $\tilde{\chi}_1^0$ mass ($m_{\tilde{\chi}_1^0}$) and lifetime ($\tau_{\tilde{\chi}_1^0}$) are the two most important parameters in determining the final states and their kinematics [1]. Different search strategies are required for $\tilde{\chi}_1^0$ lifetimes above and below about a nanosecond [11].

This Letter describes a search for GMSB in which gaugino pairs are produced and decay to the $\gamma\gamma+\not\!\!E_{\rm T}+X$ final state, where X denotes other high-$E_{\rm T}$ final state particles [12]. We use a dataset corresponding to an integrated luminosity of 2.6±0.2 fb^{-1} of $p\bar{p}$ collisions collected with the CDF II detector [13] at $\sqrt{s}$=1.96 TeV. This dataset is ten times larger than the one used in our previous search [8]. For the first time in this channel we use a new photon timing system [14] and a new model of the $\not\!\!E_{\rm T}$ resolution (METMODEL) [15]. These additions significantly improve our rejection of backgrounds from instrumental and non-collision sources, which allows us to considerably enhance the sensitivity of the search for large $\tilde{\chi}_1^0$ masses compared to other Tevatron searches [9]. We also extend the search by addressing $\tilde{\chi}_1^0$ lifetimes up to 2 ns, which are favored for larger $m_{\tilde{\chi}_1^0}$.

Our strategy is to select $\gamma\gamma$ candidates and optimize the search for the presence of both significant $\not\!\!E_{\rm T}$ and large total event transverse energy ($H_{\rm T}$) which would indicate the decays of heavy gauginos. We perform an *a priori* analysis based on the expected sensitivity, taking into account signal predictions and backgrounds from SM with mismeasured ("fake") $\not\!\!E_{\rm T}$, electroweak production with real $\not\!\!E_{\rm T}$, and non-collision sources.

Here we briefly describe the aspects of the detector [13] relevant to this analysis. The magnetic spectrometer consists of tracking devices inside a superconducting solenoid magnet that operates at 1.4 T. A drift chamber (COT) with 96 layers of sense wires measures the z position, time of the $p\bar{p}$ interaction, and the momenta of charged particles. The calorimeter consists of projective towers with electromagnetic (EM) and hadronic (HAD) compartments and is divided into a central part that surrounds the solenoid coil ($|\eta|<1.1$) [2] and a pair of end-plugs that cover the region $1.1<|\eta|<3.6$. The calorimeters are used to identify and measure the 4-momenta of photons, electrons, and jets (j) [16] and to provide $\not\!\!E_{\rm T}$ information. The EM calorimeter is instrumented with a timing system (EMTiming) [14] that measures the arrival time of photons.

Our analysis begins with diphoton events passing the CDF three-level trigger. The combined trigger selection efficiency is effectively 100% if both photons have $|\eta|<1.1$ and $E_{\rm T}>13$ GeV [12, 15]. Offline, both photons are required to be in the fiducial part of the calorimeter and to pass the standard CDF photon identification and isolation requirements [8], with two minor modifications to remove instrumental and electron backgrounds [15, 17]. The remaining events are dominated by SM production of $\gamma\gamma$, γj with $j\rightarrow\gamma_{fake}$, and $jj\rightarrow\gamma_{fake}\gamma_{fake}$, where γ_{fake} is any object misidentified as a photon. To minimize the number of these events with large $\not\!\!E_{\rm T}$ due to calorimeter energy mismeasurements, we remove events where the azimuthal angle between the $\not\!\!E_{\rm T}$ and the second-highest $E_{\rm T}$ photon is $|\Delta\phi|<0.3$ or if any jet points to an uninstrumented region of the calorimeter [15]. We require a primary collision vertex position with $|z_{\rm vertex}|<60$ cm in order to reduce non-collision backgrounds and to main-

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Amherst, Massachusetts 01003, [b]Universiteit Antwerpen, B-2610 Antwerp, Belgium, [c]University of Bristol, Bristol BS8 1TL, United Kingdom, [d]Chinese Academy of Sciences, Beijing 100864, China, [e]Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy, [f]University of California Irvine, Irvine, CA 92697, [g]University of California Santa Cruz, Santa Cruz, CA 95064, [h]Cornell University, Ithaca, NY 14853, [i]University of Cyprus, Nicosia CY-1678, Cyprus, [j]University College Dublin, Dublin 4, Ireland, [k]University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom, [l]University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017 [m]Kinki University, Higashi-Osaka City, Japan 577-8502 [n]Universidad Iberoamericana, Mexico D.F., Mexico, [o]University of Iowa, Iowa City, IA 52242, [p]Kansas State University, Manhattan, KS 66506 [q]Queen Mary, University of London, London, E1 4NS, England, [r]University of Manchester, Manchester M13 9PL, England, [s]Muons, Inc., Batavia, IL 60510, [t]Nagasaki Institute of Applied Science, Nagasaki, Japan, [u]University of Notre Dame, Notre Dame, IN 46556, [v]University 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]Bergische Universität Wuppertal, 42097 Wuppertal, Germany, [bb]Yarmouk University, Irbid 211-63, Jordan [jj]On leave from J. Stefan Institute, Ljubljana, Slovenia,

tain the projective nature of the photon reconstruction in the calorimeter. For events with multiple reconstructed vertices we recalculate the $E_{\rm T}$ of both photons and $\not\!\!E_{\rm T}$ values if picking a different vertex for them reduces the event $\not\!\!E_{\rm T}$.

Non-collision backgrounds coming from cosmic rays and beam-related effects can produce $\gamma\gamma$+$\not\!\!E_{\rm T}$ candidates, and are removed from the inclusive $\gamma\gamma$ sample using a number of techniques. Photon candidates from cosmic rays are not correlated in time with collisions. Therefore, events are removed if the timing of either photon, corrected for average path length (t_γ), indicates a non-collision source [15, 17]. Photon candidates can also be produced by beam-related muons that originate upstream of the detector (from the more intense p beam). These are suppressed using standard beam halo identification requirements [17]. A total of 38,053 inclusive $\gamma\gamma$ candidate events pass all the selection requirements.

Backgrounds to the $\gamma\gamma$+$\not\!\!E_{\rm T}$ final state from SM $\gamma\gamma$/ $\gamma\gamma_{fake}/\gamma_{fake}\gamma_{fake}$ and fake $\not\!\!E_{\rm T}$ arise due to energy mismeasurements in the calorimeter or to event reconstruction pathologies. We use the METMODEL to select events with real and significant $\not\!\!E_{\rm T}$, as part of the optimization, and to predict the contribution of SM backgrounds with fake $\not\!\!E_{\rm T}$ due to normal energy measurement fluctuations. This algorithm considers the clustered (jets) and unclustered energy in the event and calculates the probability for fluctuations in the energy measurement to produce $\not\!\!E_T^{fluct}$ equivalent to or larger than the measured $\not\!\!E_{\rm T}$, $P_{\not E_T^{fluct}\geq\not E_{\rm T}}$. This probability is then used to define a $\not\!\!E_{\rm T}$-significance as $-\log_{10}\left(P_{\not E_T^{fluct}\geq\not E_{\rm T}}\right)$. Events with true and fake $\not\!\!E_{\rm T}$ of the same value have, on average, different $\not\!\!E_{\rm T}$-significance. We use pseudo-experiments to estimate the expected $\not\!\!E_{\rm T}$-significance distribution for SM events with fake $\not\!\!E_{\rm T}$, and the number of mismeasured events above a given $\not\!\!E_{\rm T}$-significance requirement. The jets and unclustered energy are smeared according to their resolution functions in the event. The systematic uncertainty in the METMODEL is dominated by the uncertainty in the resolution functions [15].

The METMODEL does not account for reconstruction pathologies in SM events without intrinsic $\not\!\!E_{\rm T}$, such as a wrong choice of the primary interaction vertex or triphoton events with a lost photon. To obtain the prediction for this background we model SM kinematics and event reconstruction using a $\gamma\gamma$ sample generated with a PYTHIA Monte Carlo (MC) [18] that incorporates a detector simulation [19]. Since the pathologies from γj and jj sources are similar in nature, but not included directly in the simulation, we normalize the sample to the number of events in the inclusive $\gamma\gamma$ data sample. We subtract the expectations for energy mismeasurement fluctuations in the MC to avoid double counting. Uncertainties are dominated by the statistics of the MC sample, but also include the small differences between the measured response of the METMODEL to MC simulation events and real data.

Electroweak production of W and Z bosons which decay to leptons can also produce the $\gamma\gamma$+$\not\!\!E_{\rm T}$ signature where one or more of the photons can be fake, but the $\not\!\!E_{\rm T}$ is due to one or more neutrinos. To estimate the contribution from these backgrounds we use MC simulations normalized to their theoretical cross sections, taking into account all the leptonic decay modes. The Baur MC [20] is used to simulate $W\gamma$ and $Z\gamma$ production and decay where initial and final state radiation (ISR/FSR) produce W/Z+$\gamma\gamma$ events. The PYTHIA MC is used to simulate backgrounds where both photons are fakes: namely, W and Z, with photons from ISR/FSR removed, and $t\bar{t}$ sources. To minimize the dependence of our predictions on potential "MC-data" differences we scale our MC predictions to the observed number of $e\gamma$ events [15] in data where we use the same diphoton triggers and analysis selection procedures used to select the inclusive $\gamma\gamma$ sample. Uncertainties are dominated by the statistics of the MC and $e\gamma$ normalization data sample.

Non-collision backgrounds are estimated using the data. We identify a cosmic-enhanced sample by using the selected inclusive $\gamma\gamma$ sample, but requiring one of the photons to have t_γ>25 ns. Similarly, we create a beam halo-enhanced sample from events that were filtered out from our signal sample by the beam halo rejection requirements [17]. We estimate the non-collision background events in the signal region using extrapolation techniques and the measured efficiencies of the non-collision rejection requirements [15]. The uncertainties on both non-collision background estimates are dominated by the statistical uncertainty on the number of identified events. Figure 1 (top) shows the $\not\!\!E_{\rm T}$-significance distribution for the inclusive $\gamma\gamma$ sample, along with the predictions for all the backgrounds.

We estimate the sensitivity to heavy, neutral particles that decay to photons using the GMSB reference model [6] in the mass-lifetime range, $75\leq m_{\tilde{\chi}_1^0}\leq 150$ GeV and $\tau_{\tilde{\chi}_1^0}\lesssim 2$ ns. Events from all SUSY processes considered [21] are simulated with PYTHIA followed by a detector simulation. The fraction of $\tilde{\chi}_1^0$ decays that occur in the detector volume, and thus the acceptance, depend on both the lifetime and the masses of the sparticles [11]. The total systematic uncertainty on the acceptance, after all kinematic requirements (discussed below), is estimated to be 7%, dominated by the uncertainty in the photon identification efficiency (2.5% per photon). Other significant contributions come from uncertainties on ISR/FSR (4%), jet energy measurement (2%), $\not\!\!E_{\rm T}$-significance parameterizations (1%) and parton distribution functions (PDFs, 1%).

We determine the final kinematic selection requirements by optimizing the mean expected 95% confidence level (C.L.) cross section limit using a no-signal assumption, before looking at the data in the signal region [22].

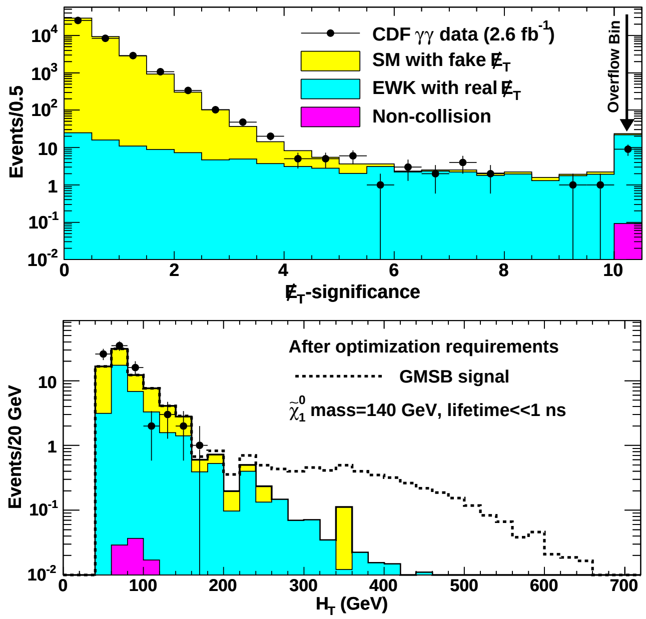

FIG. 1: The top plot shows the $\not\!\!E_{\rm T}$-significance distribution for the inclusive $\gamma\gamma$ candidate sample, along with the background predictions. The bottom plot shows the predicted $H_{\rm T}$ (total $E_{\rm T}$ of photons, jets, and $\not\!\!E_{\rm T}$) distribution after all but the final $H_{\rm T}$ requirement.

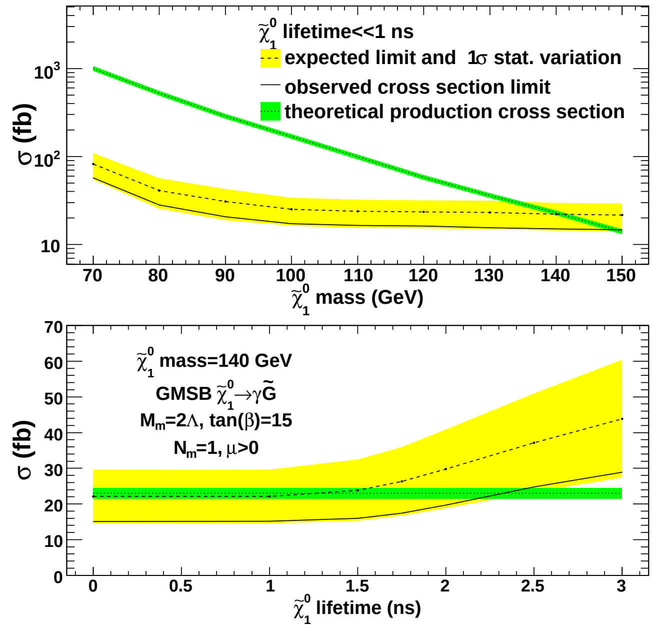

FIG. 2: The predicted and observed 95% C.L. cross section upper limits as a function of the $\widetilde{\chi}_1^0$ mass at $\tau_{\tilde{\chi}_1^0}{\ll}1$ ns (top) and as a function of the $\widetilde{\chi}_1^0$ lifetime at $m_{\tilde{\chi}_1^0}{=}140$ GeV/c^2 (bottom). Indicated in green (darker shading) is the production cross section, along with its 8.0% uncertainty-band. In yellow (lighter shading) is the RMS variation on the expected cross section limit.

To compute the predicted cross section upper limit we combine the luminosity, the acceptance, and the background estimates with their systematic uncertainties using a Bayesian method [23]. The predicted limits are optimized by simultaneously varying the selection requirements for $\not\!\!E_{\rm T}$-significance, $H_{\rm T}$ (scalar sum of $E_{\rm T}$ of photons, jets, and $\not\!\!E_{\rm T}$), and the azimuthal angle between the two leading photons, $\Delta\phi(\gamma_1,\gamma_2)$. The large $\not\!\!E_{\rm T}$-significance requirement eliminates most of the SM background with fake $\not\!\!E_{\rm T}$. GMSB production is dominated by heavy gaugino pairs which decay to high-$E_{\rm T}$ light final state particles via cascade decays. The GMSB signal has, on average, larger $H_{\rm T}$ compared to SM backgrounds so that an $H_{\rm T}$ requirement can remove these backgrounds effectively. Electroweak backgrounds with large $H_{\rm T}$ typically consist of a high-$E_{\rm T}$ photon recoiling against $W{\to}e\nu$, identified as $\gamma_{fake}\not\!\!E_{\rm T}$, which means the gauge boson decay is highly boosted. Thus, the two photon candidates in the final state are mostly back-to-back. The SM backgrounds with fake $\not\!\!E_{\rm T}$ and large H_T also have photons which are mostly back-to-back; the $\Delta\phi(\gamma_1,\gamma_2)$ requirement, therefore, reduces both these backgrounds.

The optimal set of requirements is slightly different for each point in the $\tau_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{\chi}_1^0}$ space considered. We choose a single set of requirements to maximize the region where the predicted production cross section at next-to-leading order [24] is above the expected 95% C.L. cross section limit. The exclusion region also takes into account the production cross section uncertainties, which are dominated by the PDFs (7%) and the renormalization scale (3%). We find the optimal set of requirements, before unblinding the signal region, to be: $\not\!\!E_{\rm T}$-significance>3, $H_{\rm T}$>200 GeV, and $\Delta\phi(\gamma_1,\gamma_2){<}\pi{-}0.35$. With these requirements we predict 1.4±0.4 background events, 0.9±0.4 of which are from electroweak sources (dominated by $Z\gamma\gamma$ production) with real $\not\!\!E_{\rm T}$, 0.5±0.2 from SM with fake $\not\!\!E_{\rm T}$, and $0.001^{+0.008}_{-0.001}$ from non-collision sources. The acceptance for $m_{\tilde{\chi}_1^0}{=}140$ GeV/c^2 and $\tau_{\tilde{\chi}_1^0}{\ll}1$ ns is estimated to be 7.8±0.6%.

No events in the data pass the final event selection. The predicted $H_{\rm T}$ distribution is shown in Fig. 1 (bottom), after all but the final $H_{\rm T}$ requirement. The data are consistent with the no-signal hypothesis and are well modeled by SM backgrounds alone. We set cross section limits as a function of $m_{\tilde{\chi}_1^0}$ and $\tau_{\tilde{\chi}_1^0}$, respectively, as shown in Fig. 2. The $m_{\tilde{\chi}_1^0}$ reach, based on the predicted and observed number of events for $\tau_{\tilde{\chi}_1^0}{\ll}1$ ns, is 141 GeV/c^2 and 149 GeV/c^2 respectively. These limits significantly extend the search sensitivity beyond the results of D0 [9], expand the results to include exclusions for $\tau_{\tilde{\chi}_1^0}{\le}2$ ns, and, when combined with the complementary limits from CDF and LEP [10, 17], cover the region shown in Fig. 3.

In conclusion, we have performed an optimized search for heavy, neutral particles that decay to photons in the

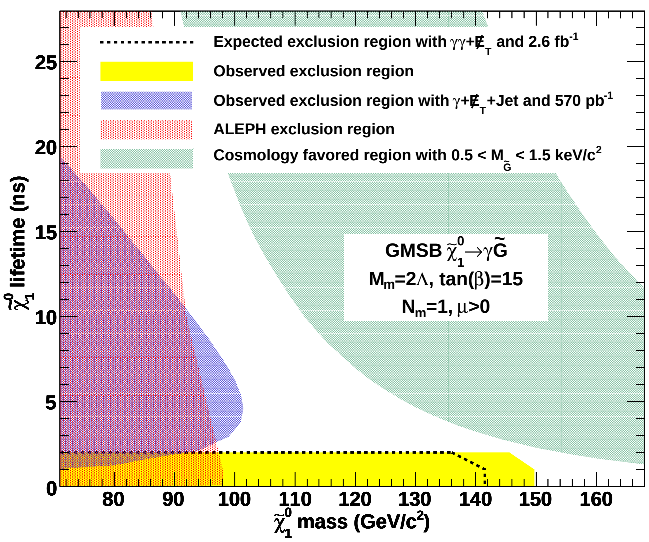

FIG. 3: The predicted and observed exclusion region along with the limit from ALEPH/LEP [10] and the CDF $\gamma+\not\!\!E_{\rm T}+jet$ 'delayed' photon analysis [17]. We have a mass reach of 141 GeV/c^2 (predicted) and 149 GeV/c^2 (observed) for lifetimes up to 1 ns. The shaded band shows the parameter space where $0.5<m_{\tilde{G}}<1.5$ keV/c^2, favored by cosmological models [7].

$\gamma\gamma+\not\!\!E_{\rm T}$ final state using 2.6±0.2 fb^{-1} of data. There is no excess of events beyond expectations. We set cross section limits using a GMSB model with $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, and find an exclusion region in the $\tau_{\tilde{\chi}_1^0}$-$m_{\tilde{\chi}_1^0}$ plane with the world's best 95% C.L. lower limit on the $\tilde{\chi}_1^0$ mass of 149 GeV/c^2 at $\tau_{\tilde{\chi}_1^0}\ll 1$ ns. By the end of Run II, with an integrated luminosity of 10 fb^{-1}, we estimate a mass reach of $\simeq$ 160 GeV/c^2 at a lifetime well below 1 ns.

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