Observation of Exclusive γγ Production in pp[over ¯] Collisions at sqrt[s]=1.96 TeV

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

Phys. Rev. Lett. **108**, 081801 — Published 22 February 2012

DOI: 10.1103/PhysRevLett.108.081801

Observation of Exclusive $\gamma\gamma$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

T. Aaltonen,[21] M.G. Albrow,[15] B. Álvarez González[z],[9] S. Amerio,[40] D. Amidei,[32] A. Anastassov[x],[15] A. Annovi,[17]
J. Antos,[12] G. Apollinari,[15] J.A. Appel,[15] T. Arisawa,[54] A. Artikov,[13] J. Asaadi,[49] W. Ashmanskas,[15]
B. Auerbach,[57] A. Aurisano,[49] F. Azfar,[39] W. Badgett,[15] T. Bae,[25] A. Barbaro-Galtieri,[26] V.E. Barnes,[44]
B.A. Barnett,[23] P. Barria[hh],[42] P. Bartos,[12] M. Bauce[ff],[40] F. Bedeschi,[42] S. Behari,[23] G. Bellettini[gg],[42]
J. Bellinger,[56] D. Benjamin,[14] A. Beretvas,[15] A. Bhatti,[46] D. Bisello[ff],[40] I. Bizjak,[28] K.R. Bland,[5] B. Blumenfeld,[23]
A. Bocci,[14] A. Bodek,[45] D. Bortoletto,[44] J. Boudreau,[43] A. Boveia,[11] L. Brigliadori[ee],[6] C. Bromberg,[33] E. Brucken,[21]
J. Budagov,[13] H.S. Budd,[45] K. Burkett,[15] G. Busetto[ff],[40] P. Bussey,[19] A. Buzatu,[31] A. Calamba,[10] C. Calancha,[29]
S. Camarda,[4] M. Campanelli,[28] M. Campbell,[32] F. Canelli[11],[15] B. Carls,[22] D. Carlsmith,[56] R. Carosi,[42]
S. Carrillo[m],[16] S. Carron,[15] B. Casal[k],[9] M. Casarsa,[50] A. Castro[ee],[6] P. Catastini,[20] D. Cauz,[50] V. Cavaliere,[22]
M. Cavalli-Sforza,[4] A. Cerri[f],[26] L. Cerrito[s],[28] Y.C. Chen,[1] M. Chertok,[7] G. Chiarelli,[42] G. Chlachidze,[15]
F. Chlebana,[15] K. Cho,[25] D. Chokheli,[13] W.H. Chung,[56] Y.S. Chung,[45] M.A. Ciocci[hh],[42] A. Clark,[18] C. Clarke,[55]
G. Compostella[ff],[40] M.E. Convery,[15] J. Conway,[7] M.Corbo,[15] M. Cordelli,[17] C.A. Cox,[7] D.J. Cox,[7] F. Crescioli[gg],[42]
J. Cuevas[z],[9] R. Culbertson,[15] D. Dagenhart,[15] N. d'Ascenzo[w],[15] M. Datta,[15] P. de Barbaro,[45] M. Dell'Orso[gg],[42]
L. Demortier,[46] M. Deninno,[6] F. Devoto,[21] M. d'Errico[ff],[40] A. Di Canto[gg],[42] B. Di Ruzza,[15] J.R. Dittmann,[5]
M. D'Onofrio,[27] S. Donati[gg],[42] P. Dong,[15] M. Dorigo,[50] T. Dorigo,[40] K. Ebina,[54] A. Elagin,[49] A. Eppig,[32]
R. Erbacher,[7] S. Errede,[22] N. Ershaidat[dd],[15] R. Eusebi,[49] S. Farrington,[39] M. Feindt,[24] J.P. Fernandez,[29]
R. Field,[16] G. Flanagan[u],[15] R. Forrest,[7] M.J. Frank,[5] M. Franklin,[20] J.C. Freeman,[15] Y. Funakoshi,[54] I. Furic,[16]
M. Gallinaro,[46] J.E. Garcia,[18] A.F. Garfinkel,[44] P. Garosi[hh],[42] H. Gerberich,[22] E. Gerchtein,[15] S. Giagu,[47]
V. Giakoumopoulou,[3] P. Giannetti,[42] K. Gibson,[43] C.M. Ginsburg,[15] N. Giokaris,[3] P. Giromini,[17] G. Giurgiu,[23]
V. Glagolev,[13] D. Glenzinski,[15] M. Gold,[35] D. Goldin,[49] N. Goldschmidt,[16] A. Golossanov,[15] G. Gomez,[9]
G. Gomez-Ceballos,[30] M. Goncharov,[30] O. González,[29] I. Gorelov,[35] A.T. Goshaw,[14] K. Goulianos,[46] S. Grinstein,[4]
C. Grosso-Pilcher,[11] R.C. Group[53],[15] J. Guimaraes da Costa,[20] S.R. Hahn,[15] E. Halkiadakis,[48] A. Hamaguchi,[38]
J.Y. Han,[45] F. Happacher,[17] K. Hara,[51] D. Hare,[48] M. Hare,[52] R.F. Harr,[55] K. Hatakeyama,[5] C. Hays,[39] M. Heck,[24]
J. Heinrich,[41] M. Herndon,[56] S. Hewamanage,[5] A. Hocker,[15] W. Hopkins[g],[15] D. Horn,[24] S. Hou,[1] R.E. Hughes,[36]
M. Hurwitz,[11] U. Husemann,[57] N. Hussain,[31] M. Hussein,[33] J. Huston,[33] G. Introzzi,[42] M. Iori[jj],[47] A. Ivanov[p],[7]
E. James,[15] D. Jang,[10] B. Jayatilaka,[14] E.J. Jeon,[25] S. Jindariani,[15] M. Jones,[44] K.K. Joo,[25] S.Y. Jun,[10]
T.R. Junk,[15] T. Kamon[25],[49] P.E. Karchin,[55] A. Kasmi,[5] Y. Kato[o],[38] W. Ketchum,[11] J. Keung,[41] V. Khotilovich,[49]
B. Kilminster,[15] D.H. Kim,[25] H.S. Kim,[25] J.E. Kim,[25] M.J. Kim,[17] S.B. Kim,[25] S.H. Kim,[51] Y.K. Kim,[11]
Y.J. Kim,[25] N. Kimura,[54] M. Kirby,[15] S. Klimenko,[16] K. Knoepfel,[15] K. Kondo[*],[54] D.J. Kong,[25] J. Konigsberg,[16]
A.V. Kotwal,[14] M. Kreps,[24] J. Kroll,[41] D. Krop,[11] M. Kruse,[14] V. Krutelyov[c],[49] T. Kuhr,[24] M. Kurata,[51]
S. Kwang,[11] A.T. Laasanen,[44] S. Lami,[42] S. Lammel,[15] M. Lancaster,[28] R.L. Lander,[7] K. Lannon[y],[36] A. Lath,[48]
G. Latino[hh],[42] T. LeCompte,[2] E. Lee,[49] H.S. Lee[q],[11] J.S. Lee,[25] S.W. Lee[bb],[49] S. Leo[gg],[42] S. Leone,[42] J.D. Lewis,[15]
A. Limosani[t],[14] C.-J. Lin,[26] M. Lindgren,[15] E. Lipeles,[41] A. Lister,[18] D.O. Litvintsev,[15] C. Liu,[43] H. Liu,[53] Q. Liu,[44]
T. Liu,[15] S. Lockwitz,[57] A. Loginov,[57] D. Lucchesi[ff],[40] J. Lueck,[24] P. Lujan,[26] P. Lukens,[15] G. Lungu,[46] J. Lys,[26]
R. Lysak[e],[12] R. Madrak,[15] K. Maeshima,[15] P. Maestro[hh],[42] S. Malik,[46] G. Manca[a],[27] A. Manousakis-Katsikakis,[3]
F. Margaroli,[47] C. Marino,[24] M. Martínez,[4] P. Mastrandrea,[47] K. Matera,[22] M.E. Mattson,[55] A. Mazzacane,[15]
P. Mazzanti,[6] K.S. McFarland,[45] P. McIntyre,[49] R. McNulty[j],[27] A. Mehta,[27] P. Mehtala,[21] C. Mesropian,[46]
T. Miao,[15] D. Mietlicki,[32] A. Mitra,[1] H. Miyake,[51] S. Moed,[15] N. Moggi,[6] M.N. Mondragon[m],[15] C.S. Moon,[25]
R. Moore,[15] M.J. Morello[ii],[42] J. Morlock,[24] P. Movilla Fernandez,[15] A. Mukherjee,[15] Th. Muller,[24] P. Murat,[15]
M. Mussini[ee],[6] J. Nachtman[n],[15] Y. Nagai,[51] J. Naganoma,[54] I. Nakano,[37] A. Napier,[52] J. Nett,[49] C. Neu,[53]
M.S. Neubauer,[22] J. Nielsen[d],[26] L. Nodulman,[2] S.Y. Noh,[25] O. Norniella,[22] L. Oakes,[39] S.H. Oh,[14] Y.D. Oh,[25]
I. Oksuzian,[53] T. Okusawa,[38] R. Orava,[21] L. Ortolan,[4] S. Pagan Griso[ff],[40] C. Pagliarone,[50] E. Palencia[f],[9]
V. Papadimitriou,[15] A.A. Paramonov,[2] J. Patrick,[15] G. Pauletta[kk],[50] M. Paulini,[10] C. Paus,[30] D.E. Pellett,[7]
A. Penzo,[50] T.J. Phillips,[14] G. Piacentino,[42] E. Pianori,[41] J. Pilot,[36] K. Pitts,[22] C. Plager,[8] L. Pondrom,[56]
S. Poprocki[g],[15] K. Potamianos,[44] F. Prokoshin[cc],[13] A. Pranko,[26] F. Ptohos[h],[17] G. Punzi[gg],[42] A. Rahaman,[43]
V. Ramakrishnan,[56] N. Ranjan,[44] I. Redondo,[29] P. Renton,[39] M. Rescigno,[47] T. Riddick,[28] F. Rimondi[ee],[6]
L. Ristori[42],[15] A. Robson,[19] T. Rodrigo,[9] T. Rodriguez,[41] E. Rogers,[22] S. Rolli[i],[52] R. Roser,[15] F. Ruffini[hh],[42]
A. Ruiz,[9] J. Russ,[10] V. Rusu,[15] A. Safonov,[49] W.K. Sakumoto,[45] Y. Sakurai,[54] L. Santi[kk],[50] K. Sato,[51]
V. Saveliev[w],[15] A. Savoy-Navarro[aa],[15] P. Schlabach,[15] A. Schmidt,[24] E.E. Schmidt,[15] T. Schwarz,[15] L. Scodellaro,[9]
A. Scribano[hh],[42] F. Scuri,[42] S. Seidel,[35] Y. Seiya,[38] A. Semenov,[13] F. Sforza[hh],[42] S.Z. Shalhout,[7] T. Shears,[27]

P.F. Shepard,[43] M. Shimojima[v],[51] M. Shochet,[11] I. Shreyber-Tecker,[34] A. Simonenko,[13] P. Sinervo,[31] K. Sliwa,[52] J.R. Smith,[7] F.D. Snider,[15] A. Soha,[15] V. Sorin,[4] H. Song,[43] P. Squillacioti[hh],[42] M. Stancari,[15] R. St. Denis,[19] B. Stelzer,[31] O. Stelzer-Chilton,[31] D. Stentz[x],[15] J. Strologas,[35] G.L. Strycker,[32] Y. Sudo,[51] A. Sukhanov,[15] I. Suslov,[13] K. Takemasa,[51] Y. Takeuchi,[51] J. Tang,[11] M. Tecchio,[32] P.K. Teng,[1] J. Thom[g],[15] J. Thome,[10] G.A. Thompson,[22] E. Thomson,[41] D. Toback,[49] S. Tokar,[12] K. Tollefson,[33] T. Tomura,[51] D. Tonelli,[15] S. Torre,[17] D. Torretta,[15] P. Totaro,[40] M. Trovato[ii],[42] F. Ukegawa,[51] S. Uozumi,[25] A. Varganov,[32] F. Vázquez[m],[16] G. Velev,[15] C. Vellidis,[15] M. Vidal,[44] I. Vila,[9] R. Vilar,[9] J. Vizán,[9] M. Vogel,[35] G. Volpi,[17] P. Wagner,[41] R.L. Wagner,[15] T. Wakisaka,[38] R. Wallny,[8] S.M. Wang,[1] A. Warburton,[31] D. Waters,[28] W.C. Wester III,[15] D. Whiteson[b],[41] A.B. Wicklund,[2] E. Wicklund,[15] S. Wilbur,[11] F. Wick,[24] H.H. Williams,[41] J.S. Wilson,[36] P. Wilson,[15] B.L. Winer,[36] P. Wittich[g],[15] S. Wolbers,[15] H. Wolfe,[36] T. Wright,[32] X. Wu,[18] Z. Wu,[5] K. Yamamoto,[38] D. Yamato,[38] T. Yang,[15] U.K. Yang[r],[11] Y.C. Yang,[25] W.-M. Yao,[26] G.P. Yeh,[15] K. Yi[n],[15] J. Yoh,[15] K. Yorita,[54] T. Yoshida[l],[38] G.B. Yu,[14] I. Yu,[25] S.S. Yu,[15] J.C. Yun,[15] A. Zanetti,[50] Y. Zeng,[14] C. Zhou,[14] and S. Zucchelli[ee][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, [ee]University of Bologna, I-40127 Bologna, Italy*
[7]*University of California, Davis, Davis, California 95616, USA*
[8]*University of California, Los Angeles, Los Angeles, California 90024, USA*
[9]*Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[10]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[11]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[12]*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*
[13]*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[14]*Duke University, Durham, North Carolina 27708, USA*
[15]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
[16]*University of Florida, Gainesville, Florida 32611, USA*
[17]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[18]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[19]*Glasgow University, Glasgow G12 8QQ, United Kingdom*
[20]*Harvard University, Cambridge, Massachusetts 02138, USA*
[21]*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*
[22]*University of Illinois, Urbana, Illinois 61801, USA*
[23]*The Johns Hopkins University, Baltimore, Maryland 21218, USA*
[24]*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*
[25]*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*
[26]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[27]*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[28]*University College London, London WC1E 6BT, United Kingdom*
[29]*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
[30]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[31]*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*
[32]*University of Michigan, Ann Arbor, Michigan 48109, USA*
[33]*Michigan State University, East Lansing, Michigan 48824, USA*
[34]*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
[35]*University of New Mexico, Albuquerque, New Mexico 87131, USA*
[36]*The Ohio State University, Columbus, Ohio 43210, USA*
[37]*Okayama University, Okayama 700-8530, Japan*
[38]*Osaka City University, Osaka 588, Japan*

[39]University of Oxford, Oxford OX1 3RH, United Kingdom
[40]Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, [ff]University of Padova, I-35131 Padova, Italy
[41]University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[42]Istituto Nazionale di Fisica Nucleare Pisa, [gg]University of Pisa,
[hh]University of Siena and [ii]Scuola Normale Superiore, I-56127 Pisa, Italy
[43]University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA
[44]Purdue University, West Lafayette, Indiana 47907, USA
[45]University of Rochester, Rochester, New York 14627, USA
[46]The Rockefeller University, New York, New York 10065, USA
[47]Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1,
[jj]Sapienza Università di Roma, I-00185 Roma, Italy
[48]Rutgers University, Piscataway, New Jersey 08855, USA
[49]Texas A&M University, College Station, Texas 77843, USA
[50]Istituto Nazionale di Fisica Nucleare Trieste/Udine,
I-34100 Trieste, [kk]University of Udine, I-33100 Udine, Italy
[51]University of Tsukuba, Tsukuba, Ibaraki 305, Japan
[52]Tufts University, Medford, Massachusetts 02155, USA
[53]University of Virginia, Charlottesville, Virginia 22906, USA
[54]Waseda University, Tokyo 169, Japan
[55]Wayne State University, Detroit, Michigan 48201, USA
[56]University of Wisconsin, Madison, Wisconsin 53706, USA
[57]Yale University, New Haven, Connecticut 06520, USA

We have observed exclusive $\gamma\gamma$ production in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, using data from 1.11 ± 0.07 fb^{-1} integrated luminosity taken by the Run II Collider Detector at Fermilab. We selected events with two electromagnetic showers, each with transverse energy $E_T > 2.5$ GeV and pseudorapidity $|\eta| < 1.0$, with no other particles detected in $-7.4 < \eta < +7.4$. The two showers have similar E_T and azimuthal angle separation $\Delta\phi \sim \pi$; 34 events have two charged particle tracks, consistent with the QED process $p\bar{p} \to p + e^+e^- + \bar{p}$ by two-photon exchange, while 43 events have no charged tracks. The number of these events that are exclusive $\pi^0\pi^0$ is consistent with zero and is < 15 at 95% C.L. The cross section for $p\bar{p} \to p + \gamma\gamma + \bar{p}$ with $|\eta(\gamma)| < 1.0$ and $E_T(\gamma) > 2.5$ GeV is $2.48\,^{+0.40}_{-0.35}(\mathrm{stat})\,^{+0.40}_{-0.51}(\mathrm{syst})$ pb.

PACS numbers: 12.38.Lg, 12.40.Nn, 13.85.Qk, 14.80.Bn

In proton-(anti)proton collisions, two direct high-E_T photons can be produced at leading order by $q\bar{q} \to \gamma\gamma$ and by $gg \to \gamma\gamma$ through a quark loop. In the latter case it is possible for another gluon exchange to cancel the color of the fusing gluons, allowing the (anti)proton to emerge intact with no hadrons produced. For $p\bar{p}$ collisions, this is the "exclusive" process $p\bar{p} \to p + \gamma\gamma + \bar{p}$, for which the leading order diagram is shown in Fig. 1a [1, 2]. The outgoing (anti)proton has nearly the beam momentum, and transverse momentum $p_T \lesssim 1$ GeV/c, having emitted a pair of gluons in a color singlet. There is a pseudorapidity gap $\Delta\eta > 6$ adjacent to the (anti)proton. In Regge theory this is diffractive scattering via pomeron [3, 4], $\mathbb{P}$, exchange. The cross section for $|\eta(\gamma)| < 1.0$ and transverse energy $E_T(\gamma) > 2.5$ GeV is predicted [5, 6] to be $\sigma(\gamma\gamma)_{\mathrm{exclusive}} \sim 0.2$ - 2 pb, depending on the low-x (unintegrated) gluon density. Additional uncertainties come from the cross section for $g + g \to \gamma + \gamma$, the probability that no hadrons are produced by additional parton interactions (rapidity gap survival factor and Sudakov

---

[*] 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]Institute of Physics, Academy of Sciences of the Czech Republic, Czech Republic, [f]CERN, CH-1211 Geneva, Switzerland, [g]Cornell University, Ithaca, NY 14853, USA, [h]University of Cyprus, Nicosia CY-1678, Cyprus, [i]Office of Science, U.S. Department of Energy, Washington, DC 20585, USA, [j]University College Dublin, Dublin 4, Ireland, [k]ETH, 8092 Zurich, Switzerland, [l]University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017, [m]Universidad Iberoamericana, Mexico D.F., Mexico, [n]University of Iowa, Iowa City, IA 52242, USA, [o]Kinki University, Higashi-Osaka City, Japan 577-8502, [p]Kansas State University, Manhattan, KS 66506, USA, [q]Korea University, Seoul, 136-713, Korea, [r]University of Manchester, Manchester M13 9PL, United Kingdom, [s]Queen Mary, University of London, London, E1 4NS, United Kingdom, [t]University of Melbourne, Victoria 3010, Australia, [u]Muons, Inc., Batavia, IL 60510, USA, [v]Nagasaki Institute of Applied Science, Nagasaki, Japan, [w]National Research Nuclear University, Moscow, Russia, [x]Northwestern University, Evanston, IL 60208, USA, [y]University of Notre Dame, Notre Dame, IN 46556, USA, [z]Universidad de Oviedo, E-33007 Oviedo, Spain, [aa]CNRS-IN2P3, Paris, F-75205 France, [bb]Texas Tech University, Lubbock, TX 79609, USA, [cc]Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile, [dd]Yarmouk University, Irbid 211-63, Jordan.

suppression [7]), and the probability that neither proton dissociates (e.g. $p \rightarrow p\ \pi^+\pi^-$) [5]. The calculation is also imprecise because of the low Q^2, the squared 4-momentum transfer. The total theoretical uncertainty on the cross section can be estimated to be a factor $^{\times 3}_{\div 3}$ [8]. Apart from its intrinsic interest for QCD, the process tests the theory of exclusive Higgs boson production [1, 2, 5, 8–13] $p+p \rightarrow p+H+p$, Fig. 1b, which may be detectable at the LHC. The leading order processes $gg \rightarrow \gamma\gamma$ and $gg \rightarrow H$ are calculable perturbatively, but the more uncertain elements of the exclusive processes (mainly the unintegrated gluon densities, the Sudakov suppression and the gap survival probability) are common to both (see Fig. 1). For a 120 GeV standard model Higgs boson the exclusive cross section at $\sqrt{s} = 7$ TeV is 3 fb with a factor $^{\times 3}_{\div 3}$ uncertainty [8].

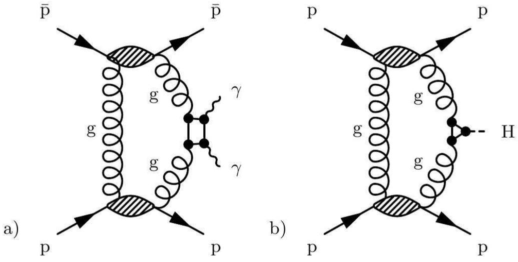

FIG. 1. Leading order diagrams for central exclusive production in $p(\bar{p})-p$ collisions: a) exclusive $\gamma\gamma$ production in $\bar{p}-p$ collisions; b) Exclusive Higgs boson production in $p-p$ collisions. Note the screening gluon that cancels the color flow from the interacting gluons.

Processes other than $gg \rightarrow \gamma\gamma$ can produce an exclusive $\gamma\gamma$ final state. Contributions from $q\bar{q} \rightarrow \gamma\gamma$ and $\gamma\gamma \rightarrow \gamma\gamma$ are respectively $< 5\%$ and $< 1\%$ of $gg \rightarrow \gamma\gamma$ [5]. Backgrounds to exclusive $\gamma\gamma$ events to be considered are $\pi^0\pi^0$ and $\eta\eta$, with each meson decaying to two photons, of which one is not detected. We also consider events where one or both protons dissociate, e.g. $p \rightarrow p\pi^+\pi^-$, to be background. These backgrounds are small.

We previously published a search for exclusive $\gamma\gamma$ production, finding three candidate events with $E_T(\gamma) > 5$ GeV and $|\eta| < 1.0$, using data from 532 pb^{-1} of integrated luminosity [14]. The prediction of Ref. [5] was $0.8^{+1.6}_{-0.5}$ events. Two events had a single narrow electromagnetic (EM) shower on each side, as expected for $\gamma\gamma$, but no observation could be claimed. This Letter reports the observation of 43 events with a contamination of $< 15\ \pi^0\pi^0$ events (at 95% C.L.), after we lowered the trigger threshold on the EM showers from 4 GeV to 2 GeV and collected data from another 1.11 fb^{-1} of integrated luminosity. We used the QED process $p+\bar{p} \rightarrow p+\gamma^*\gamma^*+\bar{p} \rightarrow p+e^+e^-+\bar{p}$ in the same data set, for which the cross section is well known, as a check of the analysis.

The data were collected by the Collider Detector at Fermilab, CDF II, at the Tevatron, with $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. The CDF II detector is a general purpose detector described elsewhere [15]; here we give a brief summary of the detector components used in this analysis. Surrounding the beam pipe is a tracking system consisting of a silicon microstrip detector, a cylindrical drift chamber (COT) [16], and a solenoid providing a 1.4 Tesla magnetic field. The tracking system is fully efficient at reconstructing isolated tracks with $p_T \geq 1$ GeV/c and $|\eta| < 1$. It is surrounded by the central and end-plug calorimeters covering the range $|\eta| < 3.6$. Both calorimeters have separate EM and hadronic compartments. A proportional wire chamber (CES) [17], with orthogonal anode wires and cathode strips, is embedded in the central EM calorimeter, covering the region of $|\eta| < 1.1$, at a depth of six radiation lengths. It allows a measurement of the number and shape, in both η and azimuth ϕ, of EM showers (clusters of wires or strips). The anode-wire pitch (in ϕ) is 1.5 cm and the cathode-strip pitch varies with η from 1.7 cm to 2.0 cm. The CES provides a means of distinguishing single photon showers from $\pi^0 \rightarrow \gamma\gamma$ up to $E_T(\pi^0) \sim 8$ GeV. The region $3.6 < |\eta| < 5.2$ is covered by a lead-liquid scintillator calorimeter called the Miniplug [18]. At higher pseudorapidities, $5.4 < |\eta| < 7.4$, scintillation counters, called beam shower counters (BSC-1/2/3), are located on each side of the CDF detector. Gas Cherenkov detectors, with 48 photomultipliers per side, covering $3.7 < |\eta| < 4.7$, detect charged particles, and were also used to determine the luminosity with a 6% uncertainty [19].

The data were recorded using a three-level on-line event selection system (trigger). At the first level we required one EM cluster with $E_T > 2$ GeV and $|\eta| < 2.1$ and no signal above noise in the BSC-1 counters ($|\eta| = 5.4-5.9$). This rapidity gap requirement rejected a large fraction of inelastic collisions as well as most events with more than one interaction (pile-up). A second EM cluster with similar properties was required at level two. A level three trigger selected events with two calorimeter showers consistent with coming from electrons or photons: i.e., passing the requirement (cut) that the ratio of shower energy in the hadronic (HAD) calorimeter to that in the EM (HAD:EM) be less than 0.125, and that the signal shape in the CES is consistent with a single shower.

We now describe the offline selection of events, with two isolated EM showers and no other particles except the outgoing p and $\bar{p}$, which were not detected. Two central, $|\eta| < 1$, EM showers were required with $E_T > 2.5$ GeV to avoid trigger threshold inefficiencies. The energy resolution is $dE/E \sim 8\%$ from test beam studies and *in situ* p/E matching for electrons. A refined HAD:EM ratio cut of $< 0.055 + 0.00045E$ was applied, as well as an acoplanarity cut of $|\pi - \Delta\phi| < 0.6$. The trigger selection efficiency for single photons was measured using data collected with an interaction trigger (minimum bias). The

BSC-1 gap trigger was taken to be 100% efficient as the BSC-1 trigger threshold was clearly above the noise level and the offline selection criteria. We measured an overall trigger efficiency of $\varepsilon_{\rm trig} = 92\% \pm 2\%$(syst). A weighting process was necessary due to the different slope in E_T of the minimum bias probe data compared to the signal. The trigger efficiency did not show any η or ϕ dependence for $|\eta| < 1$. Monte Carlo signal simulation data samples were generated using the SUPERCHIC program (version 1.3) [11, 20] based on recent developments of the Durham KMR model [2]. The Monte Carlo samples were passed through a simulation of the detector, CDFSIM 6.1.4.m including GEANT version 3.21/14 [21]. The systematic error was estimated by using the bin-wise uncertainty of the efficiency in the weighting process of the signal Monte Carlo sample. Taking into account a combined detector and offline reconstruction efficiency of $\varepsilon_{\rm rec} = 55\% \pm 3\%$(syst), and a photon identification efficiency of $\varepsilon_{\rm id} = 93\% \pm 1\%$(syst), we obtained a photon-pair efficiency $\varepsilon_{\rm pho} = \varepsilon^2_{\rm trig} * \varepsilon_{\rm rec} * \varepsilon^2_{\rm id} = 40\% \pm 3\%$(syst). The systematic uncertainties of the reconstruction and identification efficiency were estimated by shifting kinematical input parameters over a reasonable interval motivated by the dominating EM-energy-scale uncertainty [22]. The offline selection then required that no activity other than these two showers (or clusters of showers) occured in the entire detector, $|\eta| < 7.4$. We used the same procedure as in our earlier study of exclusive e^+e^- events [23], searching all the calorimeters for any signal above noise levels, determined using non-interaction events; 99.2% of such events have no tower (out of 480) with $E_T > 125$ MeV. We also required the CLC counters and the more forward BSC counters to have signals consistent with only noise. Events triggered only on a bunch crossing (zero-bias) showed that the exclusive efficiency, ε_{excl}, defined as the factor to be applied to the delivered luminosity to account for the requirement of no pile-up, is $\varepsilon_{excl} = 6.8\% \pm 0.4\%$(syst). The probability $P(0)$ of a zero-bias event satisfying all the exclusivity cuts, i.e., having no detected inelastic interaction, is $P(0) = A\exp(-\bar{n}) = A\exp(-L_{\rm x}\sigma_{\rm vis})$, where $L_{\rm x}$ is the single bunch crossing luminosity (cm^{-2}) and $\sigma_{\rm vis}$ is the visible cross section; $\sigma_{\rm vis} = \sigma_{\rm inel}$ if every inelastic collision is detected. We find $\sigma_{\rm vis} = 67 \pm 6$ mb. In the absence of noise (above our chosen thresholds) $A = 1.0$; we find $A = 0.98 \pm 0.02$. We checked that the rate of candidate events, corrected for the exclusive efficiency, was constant during data taking (one year). The systematic uncertainty was estimated using the spread in slope parameters from fits to data in different time periods.

TABLE I. Summary of parameters used for the measurement of the exclusive photon-pair cross section for $E_T(\gamma) > 2.5$ GeV and $|\eta(\gamma)| < 1.0$. Values for the e^+e^- control study are also given. Note that b/g stands for background.

Integrated luminosity $\mathcal{L}_{\rm int}$	1.11 ± 0.07 fb^{-1}
Exclusive efficiency	0.068 ± 0.004 (syst)
Exclusive $\gamma\gamma$	
Events	43
Photon pair efficiency	0.40 ± 0.02 (stat) $\pm\, 0.03$ (syst)
Probability of no conversions	0.57 ± 0.06 (syst)
$\pi^0\pi^0$ b/g (events)	0.0, < 15 (95% C.L.)
Dissociation b/g (events)	0.14 ± 0.14 (syst)
Exclusive e^+e^-	
Events	34
Electron pair efficiency	0.33 ± 0.01 (stat) $\pm\, 0.02$ (syst)
Probability of no radiation	0.42 ± 0.08 (syst)
Dissociation b/g (events)	3.8 ± 0.4 (stat) $\pm\, 0.9$ (syst)

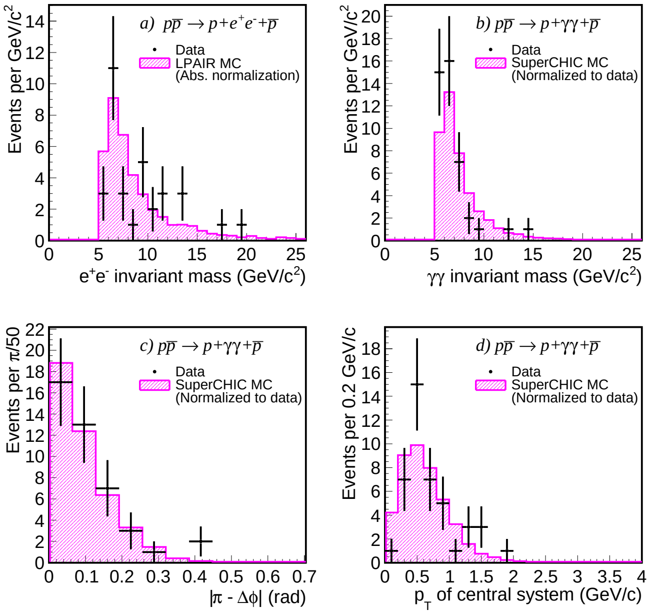

FIG. 2. The e^+e^- candidates: invariant mass distribution (a). The two-photon candidates: invariant mass distribution (b), $|\pi - \Delta\phi|$ distribution (c), and p_T distribution of the two photons (d). All error bars are statistical. The MC predictions for $\gamma\gamma$ are normalized to data. The QED prediction for e^+e^- is normalized to the delivered luminosity and efficiencies. The MC samples for the QED process were generated with the LPAIR program [25].

The selection of 81 events passing all cuts was made without reference to the track detectors. We found that 34 have exactly two oppositely charged tracks, 43 have no tracks in the COT, and four are in neither class. Visual inspection of the latter showed that two had photon conversions, and two were likely to be e^+e^- events with bremsstrahlung. These numbers are consistent with expectations from the detector simulation. The tracks in the 34 two-track events agree in all aspects with the QED process $p+\bar{p} \rightarrow p+e^+e^-+\bar{p}$ via two virtual photons, previously observed in CDF [23, 24]. The calorimeter shower energies are consistent with the momenta measured from the tracks. Kinematic distributions, after detector simulation, are as expected. The mass $M(e^+e^-)$ distribution is presented in Fig. 2a, together with the QED prediction normalized to the delivered luminosity and efficiencies, showing that the cross section agrees with the QED prediction in both magnitude and shape. We measured a cross section of $\sigma_{e^+e^-,\text{exclusive}}(|\eta(e)| < 1,\ E_T(e) > 2.5\,\text{GeV}) = 2.88\,^{+0.57}_{-0.48}(\text{stat}) \pm 0.63(\text{syst})$ pb, compared to 3.25 ± 0.07 pb (QED, [25]). The systematic uncertainties for the QED study are mostly identical to the photon case. Distinct from photons, electrons leave tracks in the tracking detectors and may radiate. The systematic uncertainty on the radiation probability was estimated by varying the exclusivity cuts by ±10%. This e^+e^- sample provides a valuable check of the exclusive $\gamma\gamma$ analysis.

The 43 events with no tracks have the kinematic properties expected for exclusive $\gamma\gamma$ production [20]. In particular the $M(\gamma\gamma)$ distribution (Fig. 2b) extending up to 15 GeV/c^2 is as expected, as well as the acoplanarity $\pi - \Delta\phi(\gamma\gamma)$ (Fig. 2c) and the 2-vector sum of p_T (Fig. 2d); in these plots (unlike Fig. 2a) the SUPERCHIC Monte Carlo is normalized to the same number of events as the data. An important issue is whether some of these events could be $\pi^0\pi^0$, rather than $\gamma\gamma$. Note that $\gamma\pi^0$ events are forbidden by C-parity. The CES chambers give information on the number of EM showers. The minimum opening angle $\Delta\theta_{min}$ between the two photons from π^0 decay is $2\tan^{-1}\left(\frac{m(\pi)}{p(\pi)}\right) = 3.1^\circ$ for $p(\pi) = 5$ GeV, well separated in the CES chambers, which have a granularity $< 0.5^\circ$. A π^0 can fake a γ only if one photon ranges out before the CES, or falls in an inactive region (8%) of the detector. All of the 68 $e^\pm$ events in our sample, with similar energies, had matching showers in the CES chambers. A GEANT [21] simulation predicts the probability that a photon in our energy range produces a shower to be $\gtrsim 98.3\%$. We summed the number of reconstructed CES showers in the event, mostly 2 or 3 as shown in Fig. 3 (left). The distribution agrees very well with the $\gamma\gamma$ simulation, and strongly disagrees with the $\pi^0\pi^0$ simulation. Fitting to the sum of the two components gives a best fit to the fraction $F(\pi^0\pi^0) = 0.0$, with a 95% C.L. upper limit of 15 events. Since obtaining this result, a new calculation of exclusive $\pi^0\pi^0$ production [26] predicts $\sigma_{excl}(\pi^0\pi^0) = 6$ - 24 fb for $E_T(\pi^0) > 2.5$ GeV and $|\eta| < 1.0$, $\lesssim 0.01$ of our measured exclusive $\gamma\gamma$ cross section. In the cross section calculation we take this background to be zero. Exclusive $\eta\eta$ production is also expected to be negligible. The only other significant background could be undetected proton dissociation, about 10% for the QED e^+e^- process but <1% for $\mathbb{P} + \mathbb{P} \to \gamma + \gamma$ [5, 27, 28]. The cross section for both photons with $E_T(\gamma) > 2.5$ GeV and $|\eta(\gamma)| < 1.0$ and no other produced particles is given by:

$$\sigma_{\gamma\gamma,\text{exclusive}} = \frac{N(candidates) - N(background)}{\mathcal{L}_{\text{int}}.\varepsilon.\varepsilon_{excl}},$$

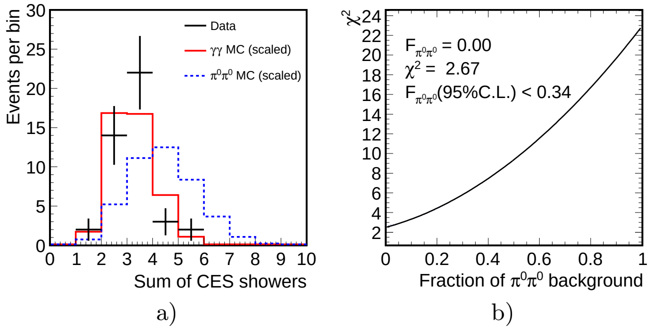

FIG. 3. Estimate of $\pi^0\pi^0$ background fraction in the candidate sample. Distribution of reconstructed CES showers per event for data compared to $\gamma\gamma$ and $\pi^0\pi^0$ Monte Carlo (a). Background fraction estimate using Pearson's χ^2 test to fit the composition hypothesis to the data distribution (b).

where ε is the product of the trigger, reconstruction, identification, and conversion efficiencies (22.8%) in Table I. The systematic uncertainty on the conversion probability was estimated by varying the exclusivity cuts by ±10%. We find $\sigma_{\gamma\gamma,\text{excl}}\,(|\eta(\gamma)| < 1, E_T(\gamma) > 2.5\text{ GeV}) = 2.48\,^{+0.40}_{-0.35}(\text{stat})\,^{+0.40}_{-0.51}(\text{syst})$ pb. The theoretical prediction [11] is strongly dependent on the low-x gluon density, having central values 1.42 pb (MSTW08LO) or 0.35 pb (MRST99), with other uncertainties estimated to be a factor of about $^{\times 3}_{\div 3}$ [28]. A comparison of our measurment with the only theoretical prediction available to date is shown in Fig. 4. The rates of e^+e^- and $\gamma\gamma$ events with $E_T(e/\gamma) > 5$ GeV are consistent with those in our earlier studies [14, 23].

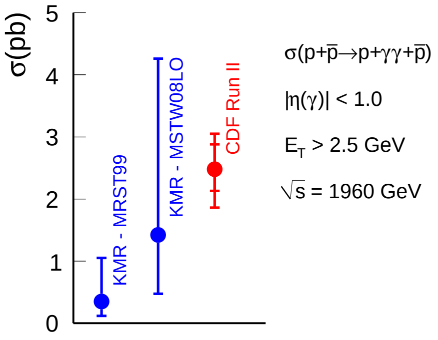

FIG. 4. Comparison of the measured cross section for the exclusive $\gamma\gamma$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with theoretical predictions [11].

In conclusion, we have observed the exclusive production of two high-E_T photons in proton-antiproton collisions, which constitutes the first observation of this process in hadron-hadron collisions. The cross section is in agreement with the only theoretical prediction, based on

$g+g \to \gamma+\gamma$, with another gluon exchanged to cancel the color and with the p and $\bar{p}$ emerging intact. If a Higgs boson exists, it should be produced by the same mechanism (see Fig. 1), and the cross sections are related.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; the Academy of Finland; and the Australian Research Council (ARC). We also thank V.A. Khoze, M.G. Ryskin and L.A. Harland-Lang for many valuable discussions.

---

[1] M.G. Albrow *et al.*, arXiv:hep-ex/0511057 (2001).

[2] V.A. Khoze, A.D. Martin, and M.G. Ryskin, Eur. Phys. J. C **23**, 311 (2002), and references therein.

[3] J.R. Forshaw and D.A. Ross, *Quantum Chromodynamics and the Pomeron*, (Cambridge University Press, Cambridge, U.K., 1997).

[4] S. Donnachie, G. Dosch, P.V. Landshoff, and O. Nachtmann, *Pomeron Physics and QCD*, (Cambridge University Press, Cambridge, U.K., 2002).

[5] V.A. Khoze *et al.*, Eur. Phys. J. C **38**, 475 (2005).

[6] V.A. Khoze, A.D. Martin, and M.G. Ryskin, Eur. Phys. J. C **14**, 525 (2000).

[7] The Sudakov factor suppresses real gluon radiation that could fill the rapidity gaps.

[8] V.A. Khoze, A.D. Martin, and M.G. Ryskin, Eur. Phys. J. C **26**, 229 (2002) and references therein.

[9] A. Bialas and P.V. Landshoff, Phys. Lett. B **256**, 540 (1991).

[10] A. Schafer, O. Nachtmann and R. Schopf, Phys. Lett. B **249**, 331 (1990).

[11] L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, and W.J. Stirling, Eur. Phys. J. C **69**, 179 (2010).

[12] T.D. Coughlin and J.R. Forshaw, J. High Energy Phys. 01 (2010) 121.

[13] M.G. Albrow, T.D. Coughlin, and J.R. Forshaw, Prog. Part. Nucl. Phys. **65**, 149 (2010).

[14] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **99**, (2007) 242002.

[15] D. Acosta *et al.* (CDF Collaboration), Phys. Rev. D **71**, 032001 (2005) and references therein; D. Amidei *et al.* (CDF Collaboration), Nucl. Instrum. Methods **350**, 73 (1994); F. Abe *et al.* (CDF Collaboration), Phys. Rev. D **50**, 2966 (1994).

[16] A. Affolder *et al.* (CDF Collaboration), Nucl. Instrum. Methods Phys. Res. Sect. A **526**, 249 (2004).

[17] L. Balka *et al.*, Nucl. Instrum. Methods A **267**, 272 (1988).

[18] M. Gallinaro *et al.*, IEEE Trans. Nucl. Sci. **52**, 879 (2005).

[19] D. Acosta *et al.*, Nucl. Instrum. Methods A **494**, 57 (2002).

[20] SUPERCHIC Monte Carlo, http://projects.hepforge.org/superchic/

[21] GEANT, detector simulation and simulation tool, CERN Program Library Long Writeup W5013 (1993).

[22] A. Bhatti *et al.* (CDF Collaboration), Nucl. Instrum. Methods A **566**, 375 (2006).

[23] A. Abulencia *et al.* (CDF Collaboration), Phys. Rev. Lett. **98**, 112001 (2007).

[24] T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **102**, 222002 (2009).

[25] J. Vermaseren, Nucl. Phys. **B229**, 347 (1983).

[26] L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin, and W.J. Stirling, Eur. Phys. J. C **71** 1714 (2011).

[27] V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. C **35**, 211 (2004).

[28] V.A. Khoze and M.G. Ryskin, private communication.