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We have searched for exclusive $\gamma\gamma$ production in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, using 532 pb^{-1} of integrated luminosity taken by the run II Collider Detector at Fermilab. The event signature requires two electromagnetic showers, each with transverse energy $E_T > 5$ GeV and pseudorapidity $|\eta| < 1.0$, with no other particles detected in the event. Three candidate events are observed. We discuss the consistency of the three events with $\gamma\gamma$, $\pi^0\pi^0$, or $\eta\eta$ production. The probability that other processes fluctuate to ≥ 3 events is 1.7×10^{-4}. An upper limit on the cross section of $p\bar{p} \to p + \gamma\gamma + \bar{p}$ production is set at 410 fb with 95% confidence level.

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We have searched for the "exclusive" process $p + \bar{p} \to p + \gamma\gamma + \bar{p}$ in the Collider Detector at Fermilab, CDF II, at $\sqrt{s} = 1.96$ TeV. *Exclusive* means that no other particles are produced; in our study the p and $\bar{p}$ emerge intact with small transverse momenta p_T [1] and the two photons are central with pseudorapidity, $|\eta| < 1.0$. An exclusive $\gamma\gamma$

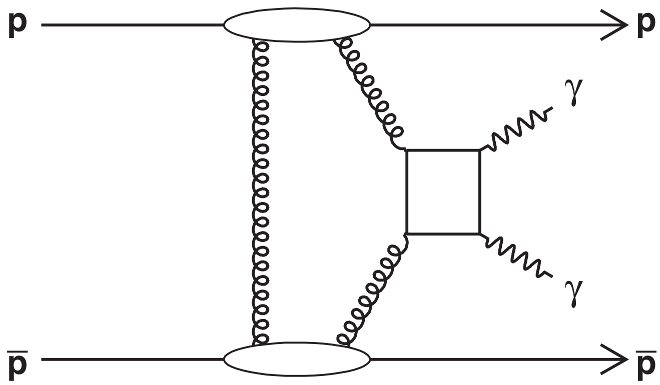

FIG. 1. The dominant diagram for central exclusive $\gamma\gamma$ production in $p\bar{p}$ collisions. The primary process is $gg \to \gamma\gamma$ through quark loops, with a screening gluon to cancel the exchanged color.

event can be produced via $gg \to \gamma\gamma$ through a quark loop, with an additional ‘‘screening’’ gluon exchanged to cancel the color of the interacting gluons, and so allow the leading hadrons to stay intact, as shown in Fig. 1. This process offers a novel possibility to test QCD and is closely related [2–5] to exclusive Higgs boson [6] production at the LHC $p + p \to p + H + p$, where the production mechanism of the Higgs boson is gg fusion through a top quark loop. In both cases the final state, $\gamma\gamma$ or H, is not strongly interacting, and thus the QCD calculation of both diagrams is similar. However, the calculation is difficult as the screening gluon has low Q^2, and other nonperturbative interactions in the same $p\bar{p}$ collision could produce additional particles. Calculations for exclusive Higgs boson production have been made using a variety of models, but these predictions cover a range of over 2 orders of magnitude [4,5]. Since the QCD part of the calculation is the same for H and $\gamma\gamma$ production, and only the calculable matrix elements $gg \to \gamma\gamma$ and $gg \to H$ are different, exclusive $\gamma\gamma$ production provides an excellent test of the theoretical predictions for H production. For exclusive production of two photons, each with transverse energy [1] $E_T^\gamma > 5$ GeV and pseudorapidity $|\eta^\gamma| < 1$, the only predicted cross sections [3] are 36 fb at the Tevatron, at $\sqrt{s} = 1.96$ TeV, and 200 fb at the LHC. The same authors predict $\sigma(p + p \to p + H + p) = 3$ fb at the LHC for a standard model Higgs boson with $M_H = 120$–140 GeV$/c^2$, claiming a factor of about three uncertainty for both processes. However, an next-to-leading order calculation has not been done, and so these uncertainties are difficult to estimate.

Processes other than $gg \to \gamma\gamma$ can produce an exclusive $\gamma\gamma$ final state. Contributions from $q\bar{q} \to \gamma\gamma$ and $\gamma\gamma \to \gamma\gamma$ are, respectively, <5% and <1% of $gg \to \gamma\gamma$ [3]. The dominant backgrounds to the observation of exclusive $\gamma\gamma$ events are the production of $\pi^0\pi^0$ or $\eta\eta$, with each meson decaying to two photons. No theoretical calculation of exclusive $\pi^0\pi^0$ or $\eta\eta$ production has been published; however, both cross sections are estimated [7] to be about 25% of the diphoton process, in the kinematic range of this study.

This Letter presents the first search for exclusive $\gamma\gamma$ production in hadronic interactions. We use 532 pb^{-1} integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV delivered to the CDF II detector at the Tevatron. The CDF II detector is a general purpose detector described elsewhere [8]; 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), and a solenoid providing a 1.4 Tesla magnetic field. The tracking system has nearly 100% efficiency for 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 electromagnetic and hadronic compartments. A proportional wire chamber (CES) [9] is embedded in the central electromagnetic calorimeter, $|\eta| < 1.1$, at a depth of six radiation lengths. It allows a measurement of the number and shape, in both transverse directions, of electromagnetic showers. 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 $\pi^0 \to \gamma\gamma$ and $\eta \to \gamma\gamma$. The region $3.6 < |\eta| < 5.2$ is covered by a lead-liquid scintillator calorimeter called the miniplug [10]. At higher pseudorapidities, $5.4 < |\eta| < 7.4$, scintillation counters, called beam shower counters (BSC), are located on each side of the CDF detector. Gas Čerenkov detectors covering $3.7 < |\eta| < 4.7$ determine the luminosity with a 6% uncertainty [11].

Exclusive $\gamma\gamma$ production is modeled with the EXHUME Monte Carlo generator [12], based on theoretical calculations [3,13]. Simulated single photons, and photons from π^0 and η decay, are passed through the GEANT [14] based detector simulation [15] to determine their detection efficiencies.

The event signature requires two electromagnetic showers each with transverse energy $E_T > 5$ GeV, with no other particles detected in the full CDF detector, which covers $-7.4 < \eta < +7.4$. The outgoing proton and antiproton are not detected. The event selection here follows closely that described in Ref. [16] where, using the same trigger and a similar analysis, we observed exclusive e^+e^- production. The only differences are the tracking requirements, and we restrict the $|\eta|$ coverage from ±2.0 to ±1.0. The trigger requires two electromagnetic clusters and no BSC counter-activity in the region $5.4 < |\eta| < 5.9$. The measured cross section for $|\eta^e| < 2.0$ and $p_T^e \geq 5$ GeV$/c$ (for both e^+ and e^-) is $1.6^{+0.5}_{-0.3}$(stat) $\pm$ 0.3(syst) pb (16 candidates with 1.9 ± 0.3 background), in agreement with the theoretical QED cross section of 1.71 ± 0.01 pb. Assuming the theoretical cross section to be correct, this agreement is evidence that the efficiency of the cuts we make to define exclusive processes is well understood.

For the diphoton analysis we select events containing two electromagnetic showers, each with $E_T > 5$ GeV and $|\eta| < 1.0$ and with a hadronic-to-electromagnetic energy ratio <0.058, consistent with that of a photon. We require either no tracks pointing to the showers or two adjacent tracks consistent with a photon conversion ($\gamma \to e^+e^-$). The efficiency for triggering, reconstructing, and identifying a $\gamma\gamma$ event with two photons each with $E_T^\gamma > 5$ GeV and $|\eta^\gamma| < 1$ is 0.57 ± 0.07. Cosmic ray events are rejected by requiring that the time of each shower is consistent with photons coming from a bunch crossing. The efficiency of signal events to pass this cut is 0.93 ± 0.03. We define "exclusivity" cuts that are designed to reject events having any additional particles in the range $|\eta| < 7.4$ that are not associated with the γ candidates; these cuts require no additional energy deposits ("particle signatures") above noise thresholds in the calorimeters or the BSC. We do not use track or CES information in this selection. One particle can shower and cause several "signatures." We define the exclusivity cut efficiency $\varepsilon_{\rm exc}$ as the probability that this exclusive requirement is not spoiled by another inelastic interaction in the same bunch crossing. It is measured, as explained in Ref. [16], as the fraction of bunch crossing triggers that pass the exclusivity cuts, which depends on the individual bunch-by-bunch luminosities. We find $\varepsilon_{\rm exc} = 0.086 \pm 0.001$. The total efficiency is reduced by events that contain a photon conversion or electron bremsstrahlung, which fail the exclusivity requirements, estimated to be 0.87 ± 0.09 using the EXHUME simulation. The probability of the scattered $p(\bar{p})$ depositing energy in the BSC is negligible if their p_T is less than 1.2 GeV$/c$.

The total efficiency for all the above event selection criteria, for the $p + \bar{p} \to p + \gamma\gamma + \bar{p}$ process, for photons each with $E_T^\gamma > 5$ GeV and $|\eta^\gamma| < 1$, is $4.0 \pm 0.7\%$. Three events pass the selection criteria; their properties are given in Table I. The E_T values of the six electromagnetic clusters are all between 5 and 7 GeV, and the azimuthal opening angle between the two photon candidates is $\Delta\phi_{\gamma\gamma} \geq 2.9$ rad, so the $\gamma\gamma$ invariant mass exceeds 10 GeV$/c^2$. The difference from $\Delta\phi_{\gamma\gamma} = \pi$ may be attributed to the outgoing p and $\bar{p}$ transverse momenta.

TABLE I. Properties of the calorimeter showers (S) of the three candidate events: given are the E_T, the η and ϕ location, the total number of CES clusters inside the same CES chamber, $N_{\rm CES}$, and the $\chi^2_{\rm CES}$ value (a shower shape variable, explained in the text). Also given are the probabilities that a π^0 and a photon have a $\chi^2_{\rm CES}$ value smaller than that observed.

Event	S	E_T (GeV)	(η, ϕ)	$N_{\rm CES}$	$\chi^2_{\rm CES}$	$P(\pi^0)$	$P(\gamma)$
A	$A1$	6.8	(0.44, 6.11)	1	1.0	0.14	0.26
	$A2$	5.9	(0.19, 2.83)	1	1.3	0.19	0.36
B	$B1$	5.0	(−0.07, 4.86)	1	1.4	0.21	0.39
	$B2$	5.4	(0.67, 1.66)	2	⋯	⋯	⋯
C	$C1$	6.0	(−0.44, 1.66)	1	13.4	0.89	0.98
	$C2$	5.1	(0.22, 5.05)	2	2.2	0.33	0.57

Five background sources to exclusive $\gamma\gamma$ production are considered: cosmic rays, exclusive e^+e^- events where both electrons are misidentified as photons, nonexclusive events in which additional particles do not leave a signature in the detector, "quasiexclusive" events where one or both outgoing protons dissociate and the dissociation products are all very forward, beyond the detector coverage, and exclusive $\pi^0\pi^0$ or $\eta\eta$ production.

The cosmic ray background is determined to be negligible from the distribution of the arrival time of electromagnetic showers. Cosmic rays are also expected to give hits in the tracking detectors. However, a visual inspection of the event displays shows only random noise hits in the COT and the silicon detector for 5 of the 6 showers in Table I. In the sixth case, shower $B2$, an e^+e^- pair from a photon conversion is seen, with the sum of the two momenta consistent with the calorimeter shower energy.

Dielectron events [16] could be misidentified as $\gamma\gamma$ events if both electron tracks are not reconstructed or the electrons undergo energetic bremsstrahlung. This contribution is estimated from Ref. [16] to be 0.02 ± 0.02 events.

Nonexclusive events, i.e., those with central particles in addition to the two photons, may appear to be exclusive if the additional particles are not detected through inefficiency. We study this by selecting events that contain two photon candidates and no tracks in the tracking detectors (other than conversion tracks), without other requirements on the central and end-plug calorimeters. Only four events in the data sample pass these criteria: the three candidates with zero additional particle signatures, and one event with 13 signatures in the calorimeters. This background is estimated to be 0.06 ± 0.03 events by using the same shape for the distribution of additional particle signatures as in exclusive e^+e^- events [16].

The proton dissociation background is small since all the dissociation products must have $|\eta| > 7.4$ to escape detection in the BSC counters. There are also few excitation states available to the proton due to spin restrictions on the final state [13]. In Ref. [3] it was estimated that the dissociation background is not expected to exceed $\sim$0.1% of the exclusive signal sample, which corresponds to ≤ 0.01 events in the three-candidate sample. We take this background to be 0.01 ± 0.01 events.

Backgrounds can arise from exclusive pair production of neutral mesons, i.e., $\pi^0\pi^0$ and $\eta\eta$. One photon from the π^0 or η decay can be undetected or, in the π^0 case, the two photon showers can merge. Exclusive $\pi^0\eta$ is suppressed by isospin conservation, and $\gamma + (\pi^0/\eta)$ is forbidden by C-parity conservation. Production of $\pi^0\pi^0$ and $\eta\eta$ cannot be unambiguously distinguished from $\gamma\gamma$ production on an event-by-event basis. Since the cross sections are not well known, these backgrounds cannot be directly calculated; we discuss them later.

We therefore observe three exclusive $p + \bar{p} \to p + (\gamma\gamma/\pi^0\pi^0/\eta\eta) + \bar{p}$ candidate events with a background of 0.09 ± 0.04 events. The probability for three or more events to be observed when 0.09 ± 0.04 (assumed to be the mean and standard deviation of a gamma distribution) are expected is 1.7×10^{-4}. We set an upper limit on the cross section for exclusive $\gamma\gamma$ production, taking into account the background and its uncertainty, the signal selection efficiency, and the integrated luminosity. A Bayesian approach is used assuming a flat prior for the cross section and a gamma distribution for the uncertainties. This gives a limit on the production cross section $\sigma(p + \bar{p} \to p + \gamma\gamma + \bar{p}) < 410$ fb (for $E_T^\gamma > 5$ GeV, $|\eta^\gamma| < 1$) at 95% confidence level.

We now discuss the three candidate events as possible $\gamma\gamma$, $\pi^0\pi^0$, or $\eta\eta$ production. The selection efficiency, including exclusivity cuts, for a photon from an isolated $\pi^0 \to \gamma\gamma$ is 13% lower than that of a direct photon, while the selection efficiency for an isolated $\eta \to \gamma\gamma$ is 35% lower. Relative to $\pi^0\pi^0$ production, $\eta\eta$ detection is further suppressed by a factor of 0.15, due to the branching fraction for $\eta \to \gamma\gamma$. We therefore treat the potential background as being predominantly $\pi^0\pi^0$.

We can only distinguish between single photons, and photons from π^0 decay, using the distribution of signals on the CES strips and wires, in the module covering $\Delta\phi = 15°$ and $|\eta| < 1.1$, which contains the shower. CES clusters are formed using 11 adjacent strips or wires. We may observe two separate clusters, $N_{\rm CES} = 2$, from π^0 decay. If we observe a single cluster, $N_{\rm CES} = 1$, it could be from a π^0 if the two photon showers overlap or if one photon shower is not detected. The number of CES clusters in the three candidate events is shown in Table I. While only 12% of photons have a second CES cluster, 28% (46%) of the π^0 (η) do. From simulation the probability that one photon from $\pi^0/\eta \to \gamma\gamma$ is not detected in the CES, by ranging out or not interacting, is 0.125 ± 0.025. Single clusters from photons or π^0 can be distinguished statistically using their shape. We use the distribution of pulse heights on the wires and strips to form a variable, $\chi^2_{\rm CES}$, that compares the lateral shape with that for an electron shower. A simulated distribution of $\chi^2_{\rm CES}$ for photons and π^0's is shown in Fig. 2; it has a longer tail for π^0's than for photons, but it does not allow an event-by-event separation. Using the distributions in Fig. 2, the probability ($P(\gamma)$, $P(\pi^0)$) that a shower has a $\chi^2_{\rm CES}$ less than the observed value was calculated for the five nonconversion shower candidates. Calculated values are given in Table I.

In event A both showers are single clusters with a small $\chi^2_{\rm CES}$, more consistent with originating from photons than from π^0's. In event B shower $B1$ also has a very low $\chi^2_{\rm CES}$, while shower $B2$ is a photon conversion and the $\chi^2_{\rm CES}$ method cannot be used. Two clusters in the CES are separated in ϕ, but not in η, as expected for a conversion. The sum of the two track momenta is 5.40 GeV/c, and the calorimeter energy is 5.45 ± 0.35 GeV, so if there were a second photon from a π^0 or η it would have $E_\gamma < 0.55$ GeV (95% C.L.), with a probability <10% that a π^0 or η decay would have such an energy asymmetry. Also, no additional shower is observed. Therefore events A and B clearly favor the $\gamma\gamma$ hypothesis, with three narrow single showers and one photon conversion without an accompanying shower. We cannot give an unbiased value for the $\pi^0\pi^0$ background, since this study was done *a posteriori*. In event C, one shower ($C1$) has a very large $\chi^2_{\rm CES}$ (only 2% of photon showers have a larger value), and the other shower ($C2$) has $N_{\rm CES} = 2$. Both favor the hypothesis that it is a $\pi^0\pi^0$ event. A likelihood ratio calculation, using only the $N_{\rm CES}$ and $\chi^2_{\rm CES}$ distributions, favors the $\pi^0\pi^0$ hypothesis over the $\gamma\gamma$ hypothesis by a factor of 4. For one event in three candidates to be $\pi^0\pi^0$ is compatible with the theoretical estimate [7] (about 1/5).

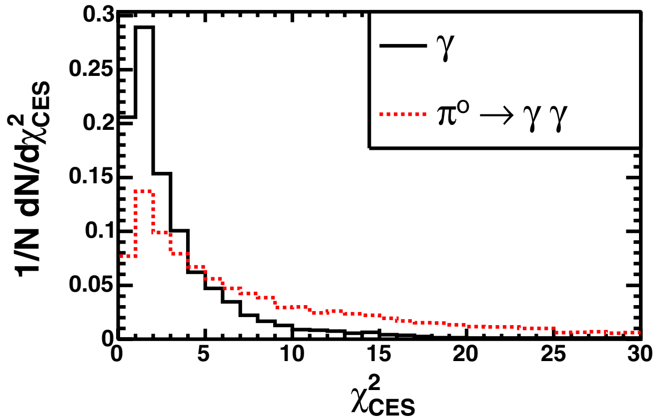

FIG. 2 (color online). The simulated distribution for $\chi^2_{\rm CES}$ for prompt photons (solid histogram), and $\pi^0 \to \gamma\gamma$ decays (dashed histogram). In all cases E_T is required to be between 5 and 7 GeV.

In conclusion, we have observed three candidate events for exclusive $\gamma\gamma$, $\pi^0\pi^0$, or $\eta\eta$ production with an expected background of 0.09 ± 0.04 events. The probability to observe three or more events when 0.09 ± 0.04 are expected from other processes is 1.7×10^{-4}, corresponding to a statistical significance of 3.7σ. Though two of the candidates are most likely to arise from $\gamma\gamma$ production, the $\pi^0\pi^0/\eta\eta$ hypotheses cannot be excluded. Therefore we report a 95% C.L. upper limit on the exclusive $\gamma\gamma$ production cross section ($E_T^\gamma > 5$ GeV, $|\eta^\gamma| < 1.0$) of 410 fb, approximately a factor of 10 higher than the prediction [3]. We note that the prediction of Ref. [3] of 36^{+72}_{-24} fb would correspond to $0.8^{+1.6}_{-0.5}$ events, compatible with our observations. This result may be used to constrain calculations of exclusive Higgs boson production at the LHC; it disfavors the highest predictions.

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[1] A cylindrical coordinate system is used with the z axis along the proton beam direction; θ is the polar angle and ϕ is the azimuthal angle. We define pseudorapidity as $\eta = -\ln\tan(\theta/2)$, transverse momentum as $p_T = |p|\sin\theta$, and transverse energy as $E_T = E\sin\theta$.

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