CDF note 10524

Observation of Exclusive $\gamma\gamma$ Production in Hadron-Hadron Collisions

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We have observed exclusive $\gamma\gamma$ production in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV, using 1.11 ± 0.07 fb^{-1} of integrated luminosity taken by the Run II Collider Detector at Fermilab. We select 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 have $\Delta\phi \sim \pi$; 34 events have two 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. From the distribution in the number of electromagnetic showers in wire chambers at shower maximum ($6X_0$) we conclude that $< 16\%$ (at 95% C.L.) of these events are exclusive $\pi^0\pi^0$. The contribution of events with $p(\bar{p})$ dissociation is negligible. The cross section of $p\bar{p} \to p + \gamma\gamma + \bar{p}$ with $|\eta(\gamma)| < 1.0$ and $E_T(\gamma) > 2.5$ GeV is $\sigma_{\gamma\gamma\ \mathrm{exclusive}}^{|\eta|<1,\mathrm{E_T}>2.5\mathrm{GeV}} = 2.48 \pm 0.42(\mathrm{stat}) \pm 0.41(\mathrm{syst})$ pb. This agrees with predictions for the process $\mathbb{P} + \mathbb{P} \to \gamma + \gamma$, where $\mathbb{P}$ is a pomeron, through an intermediate quark loop.

I. INTRODUCTION

In proton-(anti)proton collisions two direct high-p_T photons can be produced at leading order by $q\bar{q} \rightarrow \gamma\gamma$, or by $gg \rightarrow \gamma\gamma$ 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 protons to emerge intact with no hadrons produced. This is the "exclusive" process $p\bar{p} \rightarrow p+\gamma\gamma+\bar{p}$ [1, 2], Fig. 1 (middle); the protons scatter diffractively with $p_T \lesssim 1$ GeV/c [3] by pomeron, $\mathbb{P}$, exchange. It can be written $\mathbb{P}+\mathbb{P}\rightarrow \gamma + \gamma$; a purely strongly interacting initial state producing a purely electromagnetic final state via quark loops. The cross section is predicted [4, 5] to be small, $\sigma(\gamma\gamma)_{\text{exclusive}} \sim 0.7$ pb for $|\eta(\gamma)| < 1.0$ and $E_T(\gamma) >$2.5 GeV with a claimed factor $\sim$3 uncertainty. It depends on the cross section for $g + g \rightarrow \gamma + \gamma$, the skewed, unintegrated gluon distribution functions $f_g(x_1, x_2, Q^2)$, the probability of no hadron production by additional parton interactions (rapidity gap survival factor and Sudakov suppression), and the probability that neither proton dissociates (e.g. $p \rightarrow p\pi^+\pi^-$). The calculation is also imprecise because of the low Q^2, and other non-perturbative interactions in the same $p\bar{p}$ collision could produce additional particles. Apart from its intrinsic interest for QCD, the process tests the theory of exclusive Higgs boson production [1, 4, 6–8] $p + p \rightarrow p + H + p$, Fig. 1 (right), which may be detectable at the LHC.

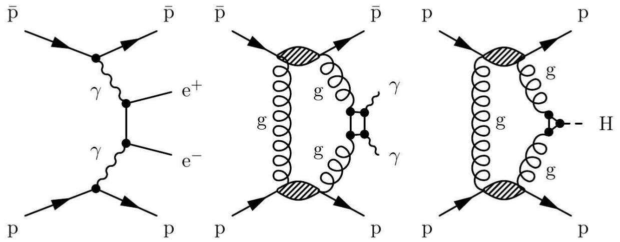

FIG. 1: Leading order diagrams for central exclusive productions at hadron colliders of $\gamma\gamma \rightarrow e^+e^-$ (left), $\mathbb{P}+\mathbb{P}\rightarrow \gamma+\gamma$ (middle) and $\mathbb{P} + \mathbb{P}\rightarrow H$ (right). The latter is feasible only at the LHC. Note the screening gluon to cancel the color flow in the QCD processes.

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 $gg \rightarrow \gamma\gamma$ [4]. Backgrounds to exclusive $\gamma\gamma$ events to be considered are $\pi^0\pi^0$ and $\eta\eta$, with each meson decaying to two photons. We will show that these backgrounds are small.

We previously presented [9] a search for exclusive $\gamma\gamma$ production, finding three candidate events with $E_T(\gamma) > 5$ GeV and $|\eta| < 1.0$. The Durham prediction [4] 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 $\pi^0\pi^0$ events of $<$ 16% (at 95% C.L.), after we lowered the trigger threshold on the EM showers from 4 GeV to 2 GeV and collected more data.

II. ANALYSIS AND RESULTS

We used 1.11 fb^{-1} integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, in the Collider Detector at Fermilab, CDF II, at the Tevatron. The CDF II detector is a general purpose detector described elsewhere [10]; 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 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 electromagnetic and hadronic compartments. A proportional wire chamber (CES) [11] is embedded in the central EM calorimeter, $|\eta| < 1.1$, at a depth of six radiation lengths. It allows a measurement of the number and shape, in both θ and ϕ, 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 $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$. The region $3.6 < |\eta| < 5.2$ is covered by a lead-liquid scintillator calorimeter called the Miniplug [12]. 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 Cherenkov detectors, with 48 photomultipliers per side, covering $3.7 < |\eta| < 4.7$, determine the luminosity with a 6% uncertainty [13], and were required in this study to be empty.

The data was recorded with a level 1 trigger requiring 2 EM showers with $E_T > 2$ GeV and $|\eta| < 2.1$ and a veto on BSC-1 counters ($|\eta| = 5.4 - 5.9$). This rapidity gap requirement rejects a large fraction of inelastic collisions as well as most events with more than one interaction (pile-up). Only events with no pile-up are used. A higher level trigger imposed a Hadronic:EM ratio < 0.125, isolation cuts and a χ^2 requirement on the shape of the 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 good central EM showers were required with $E_T > 2.5$ GeV to avoid trigger threshold inefficiencies. The trigger selection efficiency for photons was measured using unbiased data, taking into account detector and reconstruction software effects, to be $55\% \pm 3\%$(syst), and estimated using samples generated by the SuperCHIC Monte Carlo [14] based on recent developments of the Durham KMR model [2]. The offline selection then requires that no activity other than these two showers (or clusters of showers) occurs in the entire detector, $|\eta| < 7.4$. We use the same procedure as in our earlier study of exclusive e^+e^- [15], searching all the calorimeters for any signal above noise levels, determined using non-interaction events. We also require the CLC counters and the more forward BSC counters to have signals consistent with noise. Events triggered only on a bunch crossing (*zero-bias*) show that the *exclusive efficiency* is $6.8\% \pm 0.4\%$(syst); this is the price paid for requiring no pile-up. We verified that the probability of a zero-bias event satisfying all the exclusivity cuts, i.e. having no detected inelastic interaction, is an exponential as a function of the bunch $\times$ bunch luminosity with intercept 0.98 ± 0.02 and a slope corresponding to 67 ± 6 mb, consistent with the inelastic $p\bar{p}$ cross section. We checked that the rate of candidate events, corrected for the exclusive efficiency, is constant during the data taking period (one year).

TABLE I: Summary of parameters for the measurement of the exclusive photon-pair cross section for a $\mathrm{E_T} > 2.5$ GeV and $|\eta| < 1.0$. Values for the e^+e^- control study are also given.

Exclusive $\gamma\gamma$	Value
Events	43
$\mathcal{L}_{\mathsf{int}}$	1.11 ± 0.07 fb^{-1}
Photon efficiency	0.40 ± 0.02 (stat)±0.03 (syst)
Exclusive efficiency	0.0680 ± 0.004 (syst)
Conversion acceptance	0.57 ± 0.06 (syst)
$\pi^0\pi^0$ background (events)	0.0, <16% (95% C.L.)
Dissociation B/G (events)	0.14 ± 0.14 (syst)
Exclusive e^+e^-	
Events	34
Electron efficiency	0.33 ± 0.01(stat)±0.02 (syst)
Radiative acceptance	0.42 ± 0.08 (syst)
Dissociation B/G (events)	3.8 ± 0.4 (stat)±0.9 (syst)

The selection of 81 events passing all cuts was made without reference to the track detectors. We found that 34 had exactly two oppositely charged tracks, 43 had no tracks in the COT, and four were in neither class. 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; we exclude these events, also from our efficiency calculation. The tracks in the two-shower events agree in all aspects with the QED process $p + \bar{p} \to p + e^+e^- + \bar{p}$ via two virtual photons, previously observed in CDF [15, 16]. The tracks' p/E and kinematic distributions are as expected after detector simulation. The mass $M(e^+e^-)$ distribution is shown in Fig. 2d, with absolute normalization. We measure the cross section $\sigma^{|\eta|<1,E_T(\gamma)>2.5\mathrm{GeV}}_{e^+e^-,\mathrm{exclusive}} = 2.88 \pm 0.59(stat) \pm 0.62(syst)$ pb, compared to 3.25 ± 0.07 pb (QED). This is a valuable control of the analysis.

The 43 events with no tracks have the kinematic properties (such as the 2-vector sum of E_T (Fig. 2c), $\pi - \Delta\phi$ (Fig. 2b), 3D opening angle, etc.) expected for exclusive $\gamma\gamma$ production by double pomeron exchange [14]. In particular the $M(\gamma\gamma)$ distribution (Fig. 2a) extending up to 15 GeV/c^2 is as expected; these plots (unlike Fig. 2d) are normalized to the same area as the SuperCHIC Monte Carlo. An important issue was whether these events could be not $\gamma\gamma$, but $\pi^0\pi^0$. Note that $\gamma\pi^0$ events are forbidden by C-parity. The CES chambers gave 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. 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 coverage. None of the 68 $e^\pm$ in our sample, with similar energies, ranged out, as expected by the detector simulation. There is no significant correlation between the numbers of found CES showers on the two sides of the event, suggesting that they are all of one class. We add the number of CES showers on both sides of the event, mostly 2 or 3 as shown in Fig. 3. 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 0.16. Since obtaining this result, a new calculation of exclusive $\pi^0\pi^0$ production [17] predicts $\sigma_{excl}(\pi^0\pi^0) = 16$ - 42 fb for $E_T(\pi^0) > 2.5$ GeV/c and $|\eta| < 1.8$, much smaller than the

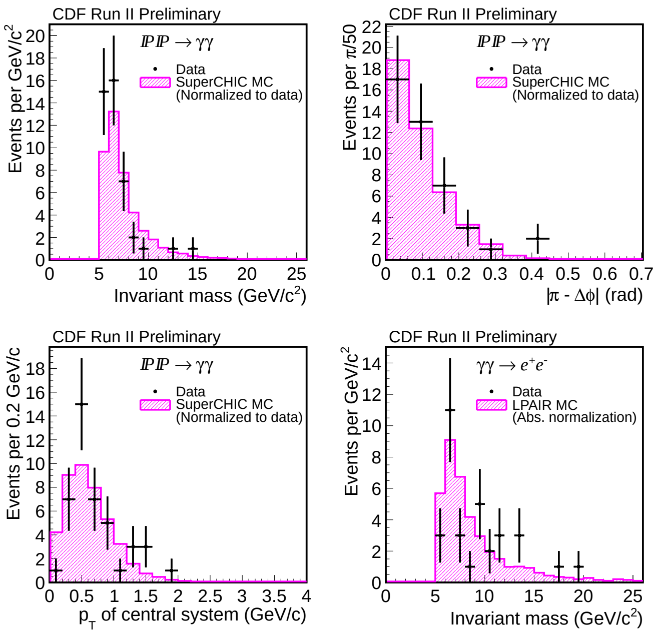

FIG. 2: Two-photon candidates: (a) Invariant mass distribution (b) $|\pi - \Delta\phi|$ distribution (c) p_T distribution of the central system. The invariant mass distribution of e^+e^- is shown in (d). All error bars are statistical. The MC predictions are normalized to data for $\gamma\gamma$ and are absolutely normalized for e^+e^-.

diphoton process. In the cross section calculation we will take this background to be zero.

Exclusive $\eta\eta$ production is also expected to be negligible, and most would not pass our exclusivity cuts as $\Delta\theta_{min}$ is larger by a factor of 4. The only other significant background could be undetected proton dissociation, about 10% for the QED e^+e^- process but <1% for $I\!P + I\!P \to \gamma + \gamma$. To give a cross section for the 43 exclusive $\gamma\gamma$ candidtates

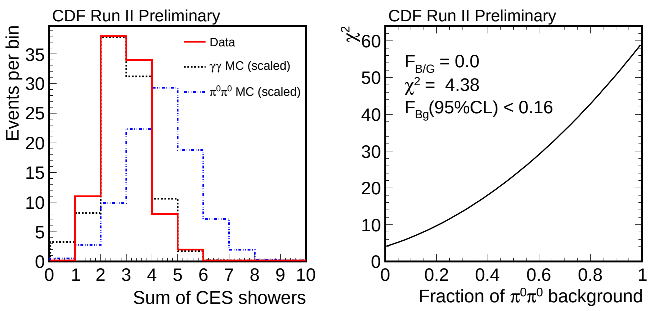

FIG. 3: Estimation of $\pi^0\pi^0$ background fraction in the candidate sample. Left: Distribution of reconstructed CES showers per event for data compared to $\gamma\gamma$ and $\pi^0\pi^0$ Monte Carlo. Right: Background fraction estimate using Pearson's χ^2 test to fit the composition hypothesis to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

we correct for the efficiencies of trigger, reconstruction, identification, and conversions (combined, 26.7%) and the exclusivity efficiency 6.8%. We find $\sigma_{\gamma\gamma,\mathrm{excl}}^{|\eta|<1, E_T(\gamma)>2.5\mathrm{GeV}} = 2.48 \pm 0.42(stat) \pm 0.41(syst)$ pb. The theory prediction [6] is strongly dependent on the gluon PDF, having central values 1.42 pb (MSTW08LO) or 0.35 pb (MRST99), with other uncertainties estimated to be a factor of $\sim\stackrel{\times}{\div} 3$[18]. The rates of e^+e^- and $\gamma\gamma$ events with $E_T(e/\gamma) > 5$ GeV are consistent with those in our earlier studies [9, 15].

III. CONCLUSION

We have made the first observation of the exclusive production of two high-E_T photons in hadron-hadron collisions. The cross section is in agreement with (but somewhat higher than) the only theoretical prediction, based on the double pomeron process $\mathbb{P}+\mathbb{P}\rightarrow \gamma + \gamma$. If a Higgs boson exists it should be produced by the same mechanism; this measurement constrains that cross section.

Acknowledgments

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