A STUDY OF THE PRODUCTION OF TWO DIRECT PHOTONS IN pp COLLISIONS AT THE CERN ISR

The Axial Field Spectrometer Collaboration

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ABSTRACT

We have studied the process $pp \rightarrow \gamma\gamma + X$ at $\sqrt{s} = 63$ GeV in the central rapidity region. We report a positive signal at 96% C.L. and a ratio $\gamma\gamma/\pi^0\pi^0 = (6.9 \pm 3.3) \times 10^{-4}$ when the transverse momentum of each photon is above 2 GeV/c, and a cross-section $d\sigma/dy dM_{\gamma\gamma} = (5.5 \pm 2.5) \times 10^{-34}$ cm²/GeV when $|y| < 0.5$, $4 < M_{\gamma\gamma} < 6$ GeV.

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1. INTRODUCTION

The production of two direct photons in hadronic interactions has been discussed before by several authors [1-2], and the process has recently been observed at the CERN Intersecting Storage Rings (ISR) [3].

The lowest order QCD process for producing a pair of direct photons [1] is the annihilation process $q\bar{q} \rightarrow \gamma\gamma$, which in the parton model involves the same structure functions as the Drell-Yan process $q\bar{q} \rightarrow e^+e^-$. The QCD process $gg \rightarrow \gamma\gamma$, proceeding via a virtual quark-loop is of higher order in α_s , but is expected nevertheless to contribute at the 15-30% level at the ISR owing to the high gluon content of the proton at small x .

We have studied the reaction $pp \rightarrow \gamma\gamma + X$ at $\sqrt{s} = 63$ GeV when each photon emerges near 90° in the centre-of-mass system with a transverse momentum of at least 1.1 GeV.

Since in our analysis we have selected $\gamma\gamma$ events not accompanied by hadrons, the background from bremsstrahlung processes should be suppressed.

2. APPARATUS AND DATA ANALYSIS

The experiment was performed with the Axial Field Spectrometer (AFS) [4]. In the configuration used the central drift chamber was surrounded by a uranium calorimeter, consisting of a 6 radiation length electromagnetic part and a 3.6 absorption length hadronic part. The calorimeter covered the full azimuth and a rapidity range varying from $|y| < 0.7$ to $|y| < 1.2$ because of the box-like construction of the detector and the beam crossing angle.

The pp data described here were taken at $\sqrt{s} = 63$ GeV in 1983, and correspond to an integrated luminosity of about $1.5 \times 10^{37} \text{ cm}^{-2}$.

For the detection of electromagnetic showers the AFS was additionally equipped with two highly segmented sodium-iodide (NaI) walls [5], each made of a group of 600 crystals in a 20×30 matrix, placed close in front of the uranium calorimeter covering a solid angle of 0.6 sr. One wall was oriented towards (NaI wall 2) and one opposite (NaI wall 1) the centre-of-mass motion, as shown in Fig. 1. The front faces of the NaI crystals are $3.5 \text{ cm} \times 3.5 \text{ cm}$; thus we were able to resolve π^0 's of momenta up to 8 GeV/c. The length of the crystals (13.8 cm) corresponds to 5.3 radiation lengths. Because the NaI walls were inside a magnetic field of 3.5 kG the light from the crystals was read out with vacuum photodiodes.

In combination with the two uranium sections behind the NaI walls, an overall resolution, varying from 9% to 6% for electrons in the range 1-4 GeV/c was measured. The minimal energy of electromagnetic showers used for this analysis was 60 MeV, compatible with the energy deposited by a minimum ionizing particle traversing a NaI block.

The trigger was performed in two steps. On a first level the following conditions were required: a) a coincidence between two downstream scintillation counters (beam-beam counters); b) a minimum of 2 and a maximum of 6 hits in a 44-element scintillator hodoscope (inner hodoscope) covering the central region of the intersection; c) a minimum energy deposition in the electromagnetic part of the uranium calorimeters located behind the NaI walls. Because of requirement (b), events with high charge multiplicity were excluded, so that the background due to various bremsstrahlung mechanisms was suppressed. The fraction of all inelastic collisions satisfying conditions (a) and (b) is 12%, and is approximately the same for events which turn out to be e^+e^- or $\gamma\gamma$ candidates. Since the same parton mechanisms are involved in the $\gamma\gamma$ and e^+e^- production, the $\gamma\gamma/e^+e^-$ ratio should be affected only because the electron tracks contribute to

the trigger requirement on the charge multiplicity. As explained later on, this bias has been investigated using a sample of e^+e^- events taken without requirement (b). The resulting correction amounts to 18%.

On a second level (600 ns later) the energy deposition in the NaI walls localized in 3.5° wide strips of constant azimuthal angle (corresponding to two adjacent rows of crystals) was checked, and the number of separated clusters in this projection was determined. In order to suppress the copious background of $\pi^0\pi^0$ events, only events with one and only one cluster per wall above a threshold were accepted. The trigger threshold corresponds to approximately 1 GeV. All the remaining clusters were required to be below a second threshold well above the 60 MeV level applied off-line. A coincidence of the two NaI walls was finally demanded.

An estimate of the trigger efficiency at the second level, involving the NaI walls only, was done using the EGS shower simulation code [6], and the results for isolated photons, electrons, and π^0 's are shown in Fig. 2 for wall 2.

The absolute NaI detector calibration was carried out by measuring the energy deposition of minimum ionizing particles in individual crystals. Variations in response were monitored by periodic scanning of the NaI walls with two ^{137}Cs radioactive sources. The stability of the detector electronics was frequently checked by feeding test pulses in the preamplifiers.

The raw pulse heights were corrected for pedestal shifts, and transformed to energy using individual calibration factors. The raw data were then passed through a software filter that removed events below an appropriate off-line trigger threshold. The remaining events were passed through the standard AFS off-line program chain. This includes pattern recognition in the NaI detectors and tracking and vertex reconstruction for charged particles in the drift chamber. The NaI pattern-recognition program grouped neighbouring crystals into clusters of energy corresponding to individual showers, on the basis of a 3×3 matrix. The position and energy of each individual shower was determined using a χ^2 minimization procedure, employing an average lateral shower shape which has been determined with the EGS shower simulation program [6]. The absolute energy of the showers was calculated adding the reconstructed energy deposition in the sodium iodide and in the electromagnetic and hadronic parts of the uranium calorimeter with appropriate coefficients as determined by EGS, and verified with beam tests.

To be retained for further analysis, single-shower candidates were required to lie within a fiducial area with a boundary 3.5 cm from the edge of the detectors, to have a minimum energy deposition in the NaI (450 MeV in wall 1 and 550 MeV in wall 2), a minimum energy deposition in the electromagnetic part of the uranium calorimeter (250 MeV in wall 1 and 300 MeV in wall 2), and a shower radius in the NaI wall between 7 and 30 mm. The same criteria were used for showers that were combined to form a π^0 candidate.

Single-shower events were allowed to have only one accepted shower that passed the above cuts, and π^0 events were allowed to have only two 'neutral' showers (i.e. in addition to the above requirements no tracks from the drift chamber were pointing towards them) per wall with a $\gamma\gamma$ invariant mass $90 < m_{\gamma\gamma} < 180$ MeV. The experimental mass resolution was 15 MeV. The background under the π^0 peak was estimated to be about 7%.

Single-shower and π^0 candidates with additional showers in the NaI walls with energy greater than 60 MeV were excluded. This cut reduces the background from asymmetric decays of π^0 's, and suppresses events with charged tracks in the central region. Such requirements, together with the strict multiplicity cut in the inner hodoscope imposed in the trigger, are expected to

reduce the background of $\pi^0\pi^0$ events, since charged hadrons are found experimentally [7] to be more frequently associated with π^0 's rather than with direct photons. In addition, photon pairs produced by the bremsstrahlung mechanisms, are largely vetoed.

Single-shower events with no tracks pointing towards them were classified as single photon candidates. Electrons and positrons were selected from the single-shower candidates by requiring momentum and position matching with at least one track in the drift chamber. Electrons or positrons coming from Dalitz pairs were rejected by cutting on the effective mass ($m_{ee} < 7.5$ MeV) with any other track of opposite sign. Figure 3 shows the mass spectrum of the remaining ee pairs, with an electron (positron) in each NaI wall. The peak of opposite charge electrons which dominates the spectrum is compatible, given the energy resolution of the AFS, with being entirely due to J/ψ decays.

With the trigger threshold used, the useful range for the p_T of a detected π^0 or single shower starts at about 1 GeV/c and extends up to 4 GeV/c. In this range the dominant source of single-photon candidates are the meson decays $\pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma$, and $\eta' \rightarrow \gamma\gamma$, where only one shower falls inside the detector. In addition there is a contribution from asymmetric decays where both photons are inside the detector, but one of them has a small energy and thus escapes the analysis cuts. The background caused by merged π^0 's, where the two showers are too close together to be resolved, is comparatively small in our p_T range. In order to reduce the background from meson decays, a 40 cm wide region of the electromagnetic part of the uranium calorimeter around each NaI wall was used as a veto. Events where the maximum pulse height in that region was greater than 200 MeV were rejected. A further effect of this cut is to reinforce the cut on additional showers discussed before.

The total efficiency (trigger, reconstruction and analysis cuts) was studied with Monte Carlo methods using the EGS code. The efficiencies for γ 's, e^+ 's, and π^0 's, as well as the probability of misidentifying a π^0 as a single photon, are shown in Fig. 4 for NaI wall 2. In a similar way the quality of the energy reconstruction (linearity and resolution) was obtained. The non-linearity was found to be less than 1%, and the resolution varies from 12% to 5% for 1 to 8 GeV/c, respectively.

In a further step, the acceptance for $\gamma\gamma$ and e^+e^- pairs was investigated. Possible differences could arise from the presence of the magnetic field, from different production kinematics, and from differences in reconstruction efficiency. We assumed that the $\gamma\gamma$ and e^+e^- systems are produced uniformly in rapidity and with a p_T dependence $dN/dp_T^2 \approx e^{-bp_T}$, $b = 1.4$ GeV/c⁻¹ [8]. For the $\gamma\gamma$ acceptance we assumed that the system decays isotropically, and for the e^+e^- acceptance we used a decay distribution $dN/d \cos \theta = 1 + \cos^2 \theta$, where θ is measured in the s-channel helicity frame. From Fig. 5 we may conclude that the difference between the acceptances of photon and electron pairs is of the order of 5%. Similar results were obtained also by considering different production mechanisms for $\gamma\gamma$, e.g. taking the mass spectrum and correlations as measured for $\pi^0\pi^0$ pair production [9].

In order to search for a $\gamma\gamma$ signal, we use the method introduced in Ref. [3]. The method depends on the long-range correlation between the two photons in the process $pp \rightarrow \gamma\gamma + X$, which would be azimuthally back-to-back for small intrinsic transverse momenta of the originating partons, contrasted with the essential lack of correlations in the $\gamma\gamma$ background from meson decays in reactions such as $pp \rightarrow \pi^0\pi^0 + X$, $pp \rightarrow \eta\pi^0 + X$, etc. The present experiment is in some ways a simpler case than Ref. [3], since the *single* direct photon production is very small

at the transverse momenta studied here. The only significant background we know is from meson production, mainly $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$. If π^0 production were the only source of photons, the probability of finding one π^0 falsely identified as a γ would be independent of the fate of a π^0 in the opposite hemisphere. The number of background events is then given by the single relation:

$$(N_{\gamma\gamma})_{\text{background}} = N_{\pi\gamma}N_{\gamma\pi}/N_{\pi\pi},$$

where

$N_{\gamma\gamma}$ is the number of observed $\gamma\gamma$ events;

$N_{\gamma\pi}$ is the observed number of events with a single γ detected in wall 1 and a π^0 detected in wall 2;

$N_{\pi\gamma}$ is as above with the walls interchanged;

$N_{\pi\pi}$ is the number of observed $\pi^0\pi^0$ events.

An excess of $N_{\gamma\gamma}$ over this value of the background is attributed to the two direct photon process. In general, $\pi^0\pi^0$ correlations and the presence of a small amount of single direct photon production can modify this relation. In order to calculate the background including these effects, and the production of $\eta \rightarrow \gamma\gamma$, $\omega \rightarrow \pi^0\gamma$, and $\eta' \rightarrow \gamma\gamma$, a full Monte Carlo simulation of the apparatus was carried out. The results can be expressed using the ratio R of the number of events with a single detected photon to the number of events with a π^0 detected in the same p_T range in a given wall. We add the subscript γ or π to R in order to distinguish the cases where the particle in the wall under consideration is in coincidence either with a single photon (R_γ) or with a π^0 (R_π) detected in the opposite wall. The use of the double ratio R_γ/R_π allows an analysis which is manifestly insensitive to the precise values of the detection efficiencies [3]. The background is now given by

$$(N_{\gamma\gamma})_{\text{background}} = (N_{\pi\gamma} \times N_{\gamma\pi}/N_{\pi\pi}) \times (R_\gamma/R_\pi)_{\text{Monte Carlo}}.$$

We find that the effect of single direct photons is less than 0.12 for $p_T > 1.1$ GeV/c and less than 1% for $p_T > 2$ GeV/c. The effect of $\pi^0\pi^0$ correlation was studied using different models [9] and we can conclude that actually $(R_\gamma/R_\pi)_{\text{Monte Carlo}} = 1.00 \pm 0.01$. The consequence of anomalous strong correlations in $\eta\eta$ production is discussed later on.

3. RESULTS

Table 1 summarizes the results obtained. The number of e^+e^- pair events shown in this table was calculated using the selection criteria already described and selecting the sign of the charge. Since the probability of misidentifying a single shower as an electron or positron (accidental photon-track matching or photon conversion) is independent of the charge, the number of e^+e^+ and e^-e^- pair events is an estimate of the uncorrelated background.

In order to ensure the validity of the method of analysis, the number of e^+e^- pairs was also calculated in a second way. Events in which two detected single showers had a track pointing towards them were selected, without requiring an energy-momentum matching or opposite charge of the particles, and without rejecting electrons from Dalitz pairs. The background was estimated using the double ratio R_γ/R_π . The calculation is shown in Table 2. The results obtained

with the two methods, 36 ± 6.5 and 39 ± 7 events respectively, are clearly compatible within the difference of the two abstraction efficiencies for track pairs, which is expected to be 10% in favour of the second method.

The calculation of the $\gamma\gamma/\pi^0\pi^0$ ratio is shown in Table 3. The relative acceptance of a $\pi^0\pi^0$ pair and a $\gamma\gamma$ pair for the same kinematics and p_T range was calculated using a Monte Carlo program. An additional correction was made for the different effect of the inner-hodoscope multiplicity requirement at trigger level and of the additional shower cut on $\gamma\gamma$ or e^+e^- and $\pi^0\pi^0$ candidate events. This effect would depress the relative π^0/γ acceptance. It was studied by using an unbiased sample of events collected by a parallel trigger. Figure 6 shows the results for the $\gamma\gamma/\pi^0\pi^0$ ratio for each p_T threshold.

The possible contributions of some additional sources of $\gamma\gamma$ pair candidates, not included in the Monte Carlo, were evaluated. For example, using our estimate of $\gamma\gamma/\pi^0\pi^0 \approx 10^{-3}$ we evaluated the background from hadrons that interact at the very beginning of the detector, simulating single showers. In order to simulate two-photon events this would have to happen for both showers. The rejection factor for charged pions was estimated to be about 300; thus about 1% of the two-photon events could be due to this background.

Dileptons can also simulate diphotons because of the inefficiency of the drift chamber and the track-finding algorithm. Since this inefficiency was estimated to be less than 5% with the requirements on track quality used here, the expected contamination of the $\gamma\gamma$ signal is 0.7 events for $p_T > 1.1$ GeV/c and negligible for $p_T > 2$ GeV/c.

Uncorrelated $\eta\eta$ and $\eta'\eta'$ pairs were included in our Monte Carlo simulation, but anomalous production of full correlated $\eta\eta$ or $\eta'\eta'$ pairs (e.g. if every η or η' is always accompanied by an η or η' in the opposite side in azimuth) could create a spurious $\gamma\gamma$ signal. We estimated that complete $\eta\eta$ and $\eta'\eta'$ correlation would produce a signal that is about 3 times the observed one for $p_T > 1.1$ GeV/c but only 20% for $p_T > 2$ GeV/c.

Table 4 shows the estimate of the $\gamma\gamma$ cross-section versus the $\gamma\gamma$ invariant mass in our p_T range. This estimate was made using the measured integrated luminosity and the fact that the Monte Carlo calculated ratio of acceptances for $\gamma\gamma$ and e^+e^- events was consistent with 1 within 5% (Fig. 5).

As mentioned earlier, our trigger had two main biases: a low track multiplicity requirement in the inner hodoscope and a cut on additional showers. By using a sample of e^+e^- events taken without these biases, but otherwise in very similar conditions, we have estimated that the number of J/ψ events was suppressed by a factor of 6.3. If the same basic production mechanism does indeed apply to e^+e^- and $\gamma\gamma$, a similar strong reduction would have taken place between the inclusive and the accepted $\gamma\gamma$ events. Assuming the same track multiplicity distribution as for the e^+e^- events, the reduction for $\gamma\gamma$ events was estimated to be a factor 5.2.

Taking this into account, the final results for the inclusive $\gamma\gamma$ cross-section are shown in Fig. 7, where the previous measurements in the higher $\gamma\gamma$ mass range [3] are also given for comparison. The cross-sections in Ref. [3] are measured relative to the dilepton continuum. We note that the cross-section for mass 8–11 GeV should have a scale factor of 10^{-36} , rather than the misprinted 10^{-35} cm² as given in Ref. [3]. We have also used the information in Table 1 of Ref. [3] to obtain a cross-section for mass 4–8 GeV.

Some contribution is also expected from $C = +$ states (0^{-+} , 0^{++} , 2^{++}) of the charmonium family decaying electromagnetically into two photons. In practice, for a production cross-section

times branching ratio into $\gamma\gamma$ of the same magnitude as for J/ψ , this source could account for about 30% of the $\gamma\gamma$ signal found.

4. CONCLUSIONS

We have presented a study of the process $pp \rightarrow \gamma\gamma + X$ at $\sqrt{s} = 63$ GeV.

We report a positive signal of correlated $\gamma\gamma$ events at 86% C.L. for p_T of each photon above 1.1 GeV/c and at 96% C.L. for p_T of each photon above 2 GeV/c. When $p_T > 2$ GeV/c at most only 20% of the signal could be due to anomalous production of correlated $\eta\eta$ and/or $\eta'\eta'$ pairs.

The method of long-range p_T correlations between the two single-photon candidates was shown to have sufficient sensitivity when stringent cuts were applied to exclude events with tracks associated with photon candidates.

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Table 1Statistics of the observed events and $\gamma\gamma/e^+e^-$ ratio

p_T requirement	$p_T > 1.1 \text{ GeV}/c$	$p_T > 2 \text{ GeV}/c$
Observed events:		
$\gamma\gamma$	3199	73
$\gamma\pi^0$	3206	141
$\pi^0\gamma$	2112	91
$\pi^0\pi^0$	2246	258
R_γ/R_π observed	1.06 ± 0.04	1.47 ± 0.28
R_γ/R_π Monte Carlo	1.00 ± 0.01	1.00 ± 0.01
Background to $\gamma\gamma$	3015 ± 110	50 ± 7
Signal $\gamma\gamma$	184 ± 124	23 ± 11
e^+e^- events	39	3
e^+e^+ or e^-e^- events	3	0
e^+e^- signal	36 ± 6.5	3 ± 1.7
Estimated e^+e^- continuum	6.2 ± 1.2	3 ± 1.7
Abstraction efficiency for track pairs	0.64	0.64
Suppression factor due to the inner hodoscope multiplicity requirement and the cut on additional showers = 5.2/6.3 (see text)	0.82	0.82
$\gamma\gamma/e^+e^-$ cont.	15 ± 12	4.0 ± 3.0

Table 2Statistics of the e^+e^- events

p_T requirement	$p_T > 1.1 \text{ GeV}/c$
Observed events with an associated track to each shower:	
ee	46
$e\pi^0$	142
π^0e	112
$\pi^0\pi^0$	2246
R_γ/R_π observed	6.5 ± 1.3
Background to ee	7.0 ± 0.9
Signal e^+e^-	39 ± 7

Table 3Estimate of the $\gamma\gamma/\pi^0\pi^0$ ratio

p_T requirement	$p_T > 1.1 \text{ GeV}/c$	$p_T > 2 \text{ GeV}/c$
Signal $\gamma\gamma$	184 ± 124	23 ± 11
$\pi^0\pi^0$ events	2246	258
Relative $\pi^0\pi^0/\gamma\gamma$ acceptance	0.025	0.062
Relative suppression factor due to the inner hodoscope multiplicity requirement and the cut on additional showers	8.0	8.0
$\gamma\gamma/\pi^0\pi^0$ ratio	$(2.6 \pm 1.7) \times 10^{-4}$	$(6.9 \pm 3.3) \times 10^{-4}$

Table 4Estimate of the $\gamma\gamma$ cross-section

Mass range	$2.2 < M_{\gamma\gamma} < 4 \text{ GeV}$	$4 < M_{\gamma\gamma} < 6 \text{ GeV}$
Integrated luminosity	$1.5 \times 10^{37} \text{ cm}^{-2}$	$1.5 \times 10^{37} \text{ cm}^{-2}$
$\gamma\gamma$ acceptance	0.0038	0.0075
$\gamma\gamma$ events	161 ± 124	23 ± 11
Suppression factor due to the inner hodoscope multiplicity requirement and the cut on additional showers	5.2	5.2
$\gamma\gamma$ cross-section $d\sigma/dy dM, y < 0.5$ (cm^2/GeV)	$(8.3 \pm 6.1) \times 10^{-33}$	$(5.5 \pm 2.5) \times 10^{-34}$

Figure captions

- Fig. 1 Experimental set-up as seen from above.
- Fig. 2 Second-level trigger efficiency in NaI wall 2, evaluated with EGS.
- Fig. 3 Observed electron-pair mass spectrum. The invariant mass is calculated using the momenta measured with the drift chamber. The spectrum is not corrected for geometrical acceptance or trigger efficiency.
- Fig. 4 Total efficiency (second-level trigger and reconstruction efficiency) in NaI wall 2, evaluated with EGS.
- Fig. 5 Acceptance and reconstruction efficiency as a function of the invariant mass for $\gamma\gamma$ and e^+e^- pairs.
- Fig. 6 Measured $\gamma\gamma/\pi^0\pi^0$ ratio in this experiment and in Ref. [3].
- Fig. 7 Measured $\gamma\gamma$ cross-section in this experiment and in Ref. [3]. The superimposed line represents the Drell-Yan dilepton continuum [8].

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7