**DIRECT PHOTON PRODUCTION IN
PROTON-ANTIPROTON INTERACTIONS AT $\sqrt{s} = 24.3$ GeV**

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UA6 Collaboration

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ABSTRACT

Direct photons have been studied in $p\bar{p}$ interactions at $\sqrt{s} = 24.3$ GeV and in the transverse momentum (p_T) range 3 to 7 GeV/c ($0.25 < x_T < 0.58$). The experiment was performed using an internal H₂ cluster jet target in the CERN $p\bar{p}$ Collider. The measured invariant cross-section is compared with recent theoretical predictions.

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Direct photons are expected to be produced in hadronic collisions [1] through three processes: gluon Compton scattering, quark-antiquark annihilations, and bremsstrahlung off a quark line. The bremsstrahlung contribution has been shown to be small [2]. In pp collisions, where direct photons were first observed [3], the main contribution has been shown to come from gluon Compton scattering [4, 5]. This is explained by the absence of valence antiquarks in the proton, which are necessary for the annihilation mechanism. Valence antiquarks in π^- , π^+ , and $\bar{p}$ allow an appreciable annihilation contribution in collisions of these particles with protons. Several experiments involving pions have been performed [6]. However, the largest annihilation contribution is expected in $p\bar{p}$ interactions owing to the increased number of annihilation channels. Only two such experiments have been performed so far, one at the CERN Intersecting Storage Rings (ISR) [7] in the x_T ($= 2 p_T/\sqrt{s}$) range $0.15 < x_T < 0.30$, and one at the CERN $p\bar{p}$ Collider [8] in the range $0.05 < x_T < 0.10$. These low- to medium- x_T photons arise from relatively low- x partons; because of the dominance of the gluon structure functions over the quark structure functions at low x , they are still produced predominantly by gluon Compton scattering. The data sample reported in this Letter covers the range of transverse momentum $3 < p_T < 7$ GeV/c, which at the $\sqrt{s}$ of this experiment (24.3 GeV) corresponds to the x_T range 0.25 to 0.58, a domain where from 40% up to 80% of the cross-section is expected to be due to quark-antiquark annihilation [9, 10].

The set-up of experiment UA6, shown in fig. 1, is located in a 12 m long straight section of the CERN Super Proton Synchrotron (SPS). It consists of a H_2 cluster jet used as an internal target, followed by a double-arm spectrometer. The angular coverage of each arm in the laboratory system is 20 to 100 mrad in polar angle and 70° in azimuth, corresponding to 1.8 sr in the $p\bar{p}$ centre-of-mass system. Direct photons are detected in the centre-of-mass rapidity (y) range of -0.40 to $+1.25$. An arm consists of: five multiwire proportional chambers (PCs), two in front and three behind a 2.3 T-m dipole magnet; an ionization chamber (dE/dx); a Li/Xe transition radiation detector; and an electromagnetic (e.m.) calorimeter.

The jet target is a vertical stream of pure hydrogen clusters, each cluster containing about 10^5 molecules, which traverses the SPS beams. The dimensions of the interaction volume are given along the beam by the length of the jet, which is 8 mm, and transverse to it by the height of the SPS beam, usually less than 1 mm, and by the overlap of the jet and beam, both of width 3 mm. The jet density of 4×10^{14} atoms per cubic centimetre is sufficiently low that particles produced in a collision have a very small probability of re-interacting. Yet, in spite of this low density, a typical number of 4×10^{10} stored antiprotons yields an instantaneous luminosity of $5.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$. This is because each antiproton traverses the jet at the SPS revolution frequency of 43.4 kHz. Since the experiment is performed during collider operation of the SPS, the beams are particularly clean, thus eliminating problems of beam halo common to intense secondary beams. Background photons due to muon bremsstrahlung, which affect direct photon experiments using pion beams, are also not relevant here. During collider operation, proton and antiproton bunches cross the jet separated by 907 ns.

The two e.m. calorimeters [11] are of the lead/proportional-tube type. Each calorimeter consists of 30 lead plates, each plate 0.8 radiation length (X_0) thick, interleaved with alternating layers of horizontal and vertical tubes of 1 cm transverse dimension and 0.5 cm depth. The tubes are filled with a mixture of Ar (90%) + CO_2 (10%) and are operated at a gas amplification of about 1000. Each calorimeter is divided longitudinally into three identical modules of $8X_0$ each. In order to reduce the number of readout channels, the analog signals of the tubes directly behind one another are summed within a module. This preserves the fine lateral segmentation of the calorimeter, which is essential for γ/π^0 discrimination and provides three longitudinal samplings for good e.m. shower identification. The position resolution for showers was found to be 3.5 mm (r.m.s.) at 10 GeV, improving to 1.5 mm at 75 GeV. The minimum resolved two-shower separation is 2.8 cm. Test-beam

results show that the calorimeter response to electrons in the energy range 10 to 100 GeV is linear to better than 0.6%, and that the energy resolution is given by $\sigma(E)/E = 0.33/\sqrt{E}$ (E in GeV). The electronic gain of each channel was monitored using test pulses. The overall energy scale of the calorimeters was determined and adjusted off line on an hourly basis, by centring the π^0 mass peak at its known value. Before adjustment, the energy scale was found to vary, over periods of days, within $\pm 8\%$.

A set of solid-state counters, placed near 90° in the laboratory, monitored the number of recoil protons from elastic $p\bar{p}$ events. Using the optical theorem, the luminosity was determined to $\pm 4\%$. The data described in this Letter come from an integrated luminosity of 494 nb^{-1} .

A hodoscope consisting of seven horizontal scintillation counters was located between the first and second modules of each of the two calorimeters. The pulse height in these counters was proportional to the e.m. energy incident on the calorimeter. They were used as a pretrigger with a rate of a few kilohertz. These events were then analysed by a hardware processor which

- i) read the analog sum of groups of 6 adjacent calorimeter channels of the first and second modules into fast ADCs;
- ii) grouped the energy in the calorimeters into overlapping bands of 12 channels in both vertical and horizontal views;
- iii) summed each horizontal band with each vertical band;
- iv) converted the energy in each of the sums into a p_T , assuming that the energy was deposited at the geometrical intersection of the two bands;
- v) accepted the event if this p_T exceeded the minimum p_T required, typically 3 GeV/c.

In the off-line analysis, individual e.m. showers were identified in the following way. Clusters of adjacent tubes containing more than 30 MeV were formed around any seed tube containing more than $E_{\min}$ GeV. The value of $E_{\min}$ was 1.3 GeV in the first module, 0.5 GeV in the second one, and 0.2 GeV in the third. In this way, clusters were found in the horizontal and vertical views of each module. The clusters were associated module-to-module in depth when a line through the cluster centroids extrapolated to the target. The small size of the interaction volume is an advantage at this stage of the clustering. A cluster in the horizontal view was then matched to a cluster in the vertical view if their energy agreed within a range determined by test-beam data. The $E_{\min}$ requirements affected the reconstruction efficiency up to cluster energies of 10 GeV.

The distribution of the invariant mass of two clusters in the same arm shows clear π^0 and η peaks. Reconstructed π^0 's and η 's were taken to be any two-cluster combination with an invariant mass of less than $0.2 \text{ GeV}/c^2$ and between 0.40 and $0.66 \text{ GeV}/c^2$, respectively. The uncorrelated background under the π^0 and η peaks was 14% and 50%, respectively. Results on the production of these mesons using this apparatus have already been published [12].

An e.m. shower was taken to be a direct photon candidate if

- i) it was located more than 5 cm from the horizontal edges of the calorimeter and more than 15.5 cm from the vertical edges, in order to be well within the magnet aperture;
- ii) it did not reconstruct as a π^0 or η with any other shower in the same calorimeter;
- iii) no charged particle pointed to it within a radius of 1 cm (less than 3% of the candidates were rejected by this cut, most of them being Dalitz decays and conversions in the vacuum pipe);
- iv) its r.m.s. width in the first module was less than 1.35 cm (this rejects most showers originating from two photons from a π^0 which merged into a single cluster).

The raw ratio of direct photon candidates to π^0 (γ/π^0) was computed and is shown in fig. 2. The number of direct photon candidates was then corrected by subtracting single-photon candidates due to π^0 's and η 's. This was estimated using a Monte Carlo program which generated these mesons according to the parametrization of Bourquin and Gaillard [13]. The energies of the decay photons were distributed in the tubes of the simulated calorimeter by selecting showers of the appropriate

energy, angle, and tube centroid, from a bank of showers obtained from well-separated photons reconstructing to π^0 's in the data themselves. The generated events were then passed through the same analysis chain as was used for the real data. The Monte Carlo reproduced the measured π^0 's very well. For example, the energy asymmetry $|E_1 - E_2|/(E_1 + E_2)$ of the two photons from π^0 decays is plotted for both real and Monte Carlo events in fig. 3. The absolute values of the π^0 and η cross-sections were not needed in the Monte Carlo program. The program was only used to calculate the ratio of the number of π^0 's and η 's that appear as single γ 's to the number that are correctly reconstructed. The actual number of π^0 's and η 's that appear as single photons was then computed from these ratios and from the number of π^0 's and η 's reconstructed in the data. This background contribution to the γ/π^0 ratio is also shown in fig. 2. The largest contribution to the background (about 70%) is from π^0 decays in which one of the photons is not reconstructed because its energy is too small. The other sources of background — π^0 's in which the two photons coalesce and those in which one photon is outside the detector — contribute at a lower level. The contribution from η 's is only 10% of the total background. Other neutral mesons and neutral hadrons are expected to make a negligible contribution.

The final γ/π^0 ratio after background subtraction and correction for acceptances is given in fig. 4. The statistical errors are shown as solid error bars; the brackets show the error after inclusion of the estimated systematic error. We consider contributions to the systematic error from the following sources:

- i) An error of $\pm 6\%$ in the number of reconstructed π^0 's; this is due to the background under the π^0 peak, leading to an error of about 10% in the ratio.
- ii) An error of about $+1\%$ in the ratio; this is due to an uncertainty in the η background. Our measurements of the η/π ratio are in the range 0.32–0.45. No other data exist at this p_T and $\sqrt{s}$. However, at $\sqrt{s} = 30.5$ GeV, this ratio has been measured [14] to be 0.42–0.55. To account for a possible mismeasurement of the η in our data, we have assigned an error of $+35\%$ to the η background.
- iii) An error of $\pm 6\%$ in the ratio arising from the maximum possible non-linearity of 0.6% in the energy scale.
- iv) Varying the values of the parameters used in the clustering algorithms, such as $E_{\min}$, within a reasonable range; this results in negligible variations in the background and acceptance estimates. Therefore no contribution from these sources has been included. The uncertainty in the detector position also contributes negligibly.

When added in quadrature, these errors combine to a total systematic error which varies between 14% at $p_T = 3$ GeV/c and 9% at 6 GeV/c.

The invariant cross-section for direct photons, evaluated at an average y of 0.4, has been computed and is shown in fig. 5. An additional systematic error of $\pm 4\%$ arising from the luminosity measurement, which cancels in the γ/π^0 ratio, has been included. By comparing the values obtained for the π^0 and the η masses, we estimate the uncertainty in the energy and p_T scales to be $\pm 1\%$. Also shown in fig. 5 are predictions by Aurenche et al. [9] using four quark flavours and Q^2 scales obtained via a ‘principle of minimal sensitivity’ [15], and by Contogouris et al. [10] using a ‘natural scale’ of $Q^2 = p_T^2$. Both calculations consider two sets of proton structure functions [16], Duke and Owens (DO) sets I and II. Set I corresponds to a soft gluon distribution of the form $(1-x)^6$ with $\Lambda = 0.2$ GeV/c, whereas set II uses a harder gluon distribution, $(1-x)^4$ with $\Lambda = 0.4$ GeV/c. The theoretical calculations agree between themselves, and the data are seen to favour the DO set I.

In conclusion, we have measured direct photon production in $p\bar{p}$ interactions at $\sqrt{s} = 24.3$ GeV. The theoretical predictions using the DO set I reproduce the invariant cross-sections. These same calculations predict that over the x_T range of 0.25 to 0.58 covered by this experiment, the annihilation

contribution increases from 40% of the direct photon cross-section to 80%. Therefore the equivalent $p\bar{p}$ cross-sections should be lower. The comparison of the data presented here with $p\bar{p}$ data obtained in our detector will be the subject of a future publication.

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Figure captions

Fig. 1 : The UA6 apparatus.

Fig. 2 : The raw γ/π^0 ratio. The dashed line is the estimate of the background contribution from π^0 's. The solid line is the sum of the π^0 and η background.

Fig. 3 : The asymmetry of the two gammas in π^0 decay, $|E_1 - E_2|/(E_1 + E_2)$. The data are the full lines; the solid circles represent the Monte Carlo. The Monte Carlo points have been normalized to the same total number of events as in the data.

Fig. 4 : The corrected γ/π^0 ratio.

Fig. 5 : The invariant cross-section for direct photon production in $p\bar{p}$ interactions at $\sqrt{s} = 24.3$ GeV, evaluated at an average $y = 0.4$. The predictions of Ref. [9] using the Duke and Owens set I (full line) and set II (dashed line) and of Ref. [10] using set I (dot-dashed line) are also shown. The prediction of Ref. [10] using set II coincides with the dashed line.

Fig. 1

Fig. 2

Fig. 3

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Fig. 5