High transverse momentum prompt photon production by π^- and π^+ on protons at 280 GeV/c

WA70-collaboration

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Abstract

The inclusive cross sections for prompt photon production by π^- and π^+ on protons have been measured with a beam momentum of 280 GeV/c using a fine grained electromagnetic calorimeter and the CERN Omega spectrometer. The transverse momentum and Feynman x_F ranges covered are $4.0 < p_T < 7.0$ GeV/c and $-0.45 < x_F < 0.55$ respectively. A quantitative comparison of the prompt photon cross sections with next-to-leading order QCD predictions using Duke and Owens structure functions is performed.

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1. Introduction

Studies of high transverse momentum (p_T) photon production provide a clean check of constituent dynamics in hadronic collisions since prompt photons are produced in the primary interactions between quarks and gluons while high p_T hadron production arises from quark or gluon fragmentation. In leading order QCD prompt photon production in π^+p reactions is dominated by the "Compton scattering" process $qg \rightarrow \gamma q$ whereas π^-p reactions will also have a significant contribution from the annihilation mechanism $q\bar{q} \rightarrow \gamma g$. The prompt photon production cross sections should therefore be greater for π^-p than for π^+p collisions and the ratio of these cross sections should increase with p_T . Next-to-leading order calculations [1] have recently been carried out and now allow a quantitative comparison of QCD with experimental data.

Several experiments [2] have investigated these processes. The WA70 collaboration has accumulated data at the CERN SPS with a 280 GeV/c unseparated hadron beam using the Omega spectrometer and a fine-grained electromagnetic calorimeter. The prompt photon production cross sections have been determined for $4.0 < p_T < 7.0$ GeV/c and $-0.45 < x_F < 0.55$. The samples of π^-p and π^+p data correspond to sensitivities of 3.5 and 1.3 pbarn $^{-1}$ respectively.

The experimental system is described in section 2. The procedures used to select direct gamma events are outlined in section 3. The experimental results are presented in section 4 along with a discussion of the systematic errors and a phenomenological parametrization of the data. In section 5 the cross sections are compared with QCD.

2. The experimental system

The experiment was performed at the CERN SPS with a 280 GeV/c unseparated hadron beam, incident on a 1m long liquid hydrogen target, using the Omega Spectrometer. The experimental layout is shown in fig 1 and a detailed description is given in Ref.3.

In the negative beam the combined K^- and $\bar{p}$ contamination is 4%. In the positive beam the identification of the incident particle is provided by two "CEDAR" Cerenkov counters[4]. The identified π^+ amount to 15% of the total positive beam, with a proton contamination estimated to be smaller than 2% of the pions.

The fine-grained lead-liquid scintillator electromagnetic calorimeter(4mx4m) [5], 24 radiation lengths thick, provides a large p_T and x_F acceptance, electromagnetic shower separation down to 2 cm and efficient photon detection for energies greater than 500 MeV. The calorimeter consists of four quadrants, segmented in depth into three modules to distinguish between hadronic and electromagnetic showers. The energy resolution function of the calorimeter[5], for prompt photon candidates, is

$$(\sigma_E/E)^2 = 0.17^2/E + 0.026^2 \quad E \text{ in [GeV]}$$

A 4mx4m multiwire proportional chamber(BMWPC), placed immediately in front of the calorimeter, provides charged particle detection.

In order to resolve the spatial ambiguities of the orthogonal readout of the calorimeter for multishower events a time-of-flight (TOF) system [6] measures the transit time of the light along the scintillator elements of the first segment. This position determination has an accuracy of about 5 cm for shower energies greater than 5 GeV, and a threshold of 500 MeV for photons. This system also gives a good rejection against beam halo background and the out-of-time accidental triggers.

The trigger electronics [7] is designed to select high p_T electromagnetic showers above a given threshold, typically 3 GeV/c, in coincidence with a beam particle interacting in the liquid hydrogen target. The calorimeter is divided into 64 trigger cells and, after taking into account the light attenuation in the scintillator, the transverse energy in a trigger cell is required to be above a defined threshold. At a typical beam intensity of 2×10^7 particles per burst, the trigger rate was about 100 events per burst. A sharper p_T cut was achieved with a fast front-end microprocessor which calculated the p_T of the individual showers inside a trigger cell and reduced the rate by a factor of two.

Pion decay in the beam produces a halo of muons ($\approx 10^5$ per burst for the negative beam). At the calorimeter, bremsstrahlung from a muon in random coincidence with an interacting beam particle can produce a false high p_T trigger. For the second half of the data taking (1985), the background due to the muon halo was reduced by the addition of veto counters and magnetised iron surrounding the beam line.

3. Data analysis

A detailed description of the data analysis has been presented in Ref.3 and only an outline is given here.

3.1 Event reconstruction

The calorimeter pattern recognition program [5] reconstructs the showers by matching the ADC amplitude information from the two orthogonal coordinates, the longitudinal centre of gravity and the TOF information. From this information different hypotheses of shower configurations within a quadrant can be constructed. Only more probable hypotheses are considered and classified by taking into account the non-associated energy and the global χ^2 formed by energy, longitudinal development and TOF information.

The charged tracks are reconstructed by the standard Omega program TRIDENT [8]. An interaction vertex is found inside the target in 90% of the events.

3.2 Prompt photon selection

Events with TOF information inconsistent with a single beam interaction in the hydrogen target are rejected as accidental triggers [3]. If more than 20% of the measured shower energy is deposited in the third segment of the calorimeter the shower is identified as hadronic[5]. A shower produced by a

charged particle in the calorimeter is identified by a track in the Omega MWPCs which extrapolates to within 5 cm of the shower position, or by a signal in the BMWPC within 3 cm of the shower. Triggers produced by the muon halo are identified in the analysis by a signature in the veto counters, or by the shower direction from the three segments of the calorimeter, or by the correspondence with a track parallel to the beam in the BMWPC, or by a TOF signal more than 1.2 ns out of time with the rest of the event. After rejection of hadronic showers, charged tracks and halo showers, a prompt photon candidate is defined as the highest p_T shower in a trigger cell satisfying the following requirements:

- The shower width corresponds to a single electromagnetic shower ($\sigma < 2$ cm).
- The shower position is inside a fiducial region extending to 5 cm from the edges of each quadrant.
- The effective mass with any other electromagnetic shower having $E > 500$ MeV is outside the π^0 mass range 70-200 MeV for all hypotheses in the trigger quadrant.
- The effective mass with any other electromagnetic shower is outside the η mass range (450-650 MeV) for showers having $E > 2.0$ GeV and asymmetry $|E_{\gamma_1} - E_{\gamma_2}| / (E_{\gamma_1} + E_{\gamma_2})$ less than 0.9. Only the most probable hypothesis is used in this cut.

3.3 Efficiency

The prompt photon efficiency and background have been determined by generating events with two different Monte Carlo programs: the LUND Monte Carlo based on QCD leading order diagrams with Lund model fragmentation [9] and a phenomenological Monte Carlo generating a π^0 , η or γ according to experimental distributions [3], and superimposing them on real events. Particles are traced to the calorimeter through a full detector simulation including materialization of γ s and secondary interactions. The longitudinal and transverse developments of electromagnetic and hadronic showers have been parametrized using experimental data. The Monte Carlo events were processed with the same chain of programs as real data. A comparison of the two Monte Carlos shows that they are compatible within statistical errors and that possible systematic effects in the prompt photon cross sections are smaller than 15%.

The effects of the system acceptance and analysis cuts on the prompt photon data vary with the data sample and beam polarity and are functions of x_F and p_T . An example of the x_F and the p_T dependence of the efficiencies is shown in fig 2. In addition to the results of the Monte Carlo calculations these efficiencies include the losses due to cuts to reject accidental triggers and muon halo background, estimated from an analysis of rejected events containing π^0 s. An indication of the relative importance of the various losses of prompt photons is presented in Table 1.

3.4 Background

The prompt photon background comes mainly from π^0 (70%), η (24%) and the electromagnetic decay of other hadrons ($\omega, \eta', \dots$). The mechanisms by which π^0 and η may simulate prompt photons are listed below.

- a. In an asymmetric $\gamma\gamma$ decay one photon may escape detection or have its energy badly measured. This background is dominant at low p_T and negative x_F .
- b. Two nearby photons from a π^0 are not separated by pattern recognition. This background is dominant in the kinematic region $x_F > 0.4$ and $p_T > 6.0$ GeV/c.
- c. One photon is lost by conversion in the target or in the MWPCs or is wrongly identified by the pattern recognition. These backgrounds are weakly dependent on p_T and x_F , each accounting for about 10% of the total background.

The background is shown relative to the number of π^0 s generated in the Monte Carlo in fig 3 as a function of x_F and p_T . The resulting background in the prompt photon data sample, obtained by normalizing to the measured π^0 cross section [3], is shown in fig 4 for π^- and π^+ separately.

The contamination in the prompt photon sample by neutral hadrons ($n, K^0, \dots$) and charged particles is 3% with a systematic uncertainty of 5%. The muon halo background is negligible in the positive beam and in the 1985 π^- data, while it amounts to a few per cent in the 1984 π^- data in most of the kinematical region covered, reaching $20 \pm 10\%$ of the prompt photon signal for $p_T > 6.0$ GeV/c.

4. Results

4.1 Cross sections

The invariant cross sections $E \, d^3\sigma/dp^3$ for prompt photon production by π^- and π^+ averaged in p_T and x_F bins are presented in Table 2 together with their statistical and systematic errors. The p_T and x_F limits of each bin are indicated as well as their weighted averages. The p_T distributions for three x_F intervals are shown in fig 5; the x_F distributions for two p_T intervals are shown in fig 6.

The ratio of the cross sections $\sigma(\pi p \rightarrow \gamma X)/\sigma(\pi p \rightarrow \pi^0 X)$ for both beam polarities over the full x_F interval, shown in figure 7, increases as a function of p_T and is significantly higher for the π^- than for the π^+ beam.

The ratio of prompt photon production cross sections from π^- and π^+ beams is shown in fig 8 as a function of p_T in the full x_F interval. This ratio is weakly dependent on p_T , with a mean value of $2.06 \pm 0.10 \pm 0.10$ (statistical and systematic errors). The corresponding ratio for π^0 production is $1.07 \pm 0.01 \pm 0.10$ [3], consistent with the Monte Carlo value 1.06 ± 0.02 . This confirms that the higher measured prompt photon production with the π^- beam is not caused by normalization effects.

The systematic errors in the invariant cross sections are obtained by adding in quadrature the following contributions:

- uncertainty in the absolute normalization due to particle identification in the positive beam, trigger losses and rejection of accidental triggers ($\pm 6\%$)
- statistical and systematic uncertainties in the Monte Carlo and in the π^0 data used to evaluate the background (from ± 4 to $\pm 10\%$) and the efficiency factors (from ± 5 to $\pm 15\%$)
- uncertainty in hadron background ($\pm 5\%$), and muon halo background subtraction (up to $\pm 10\%$ at $p_T > 6 \text{ GeV}$)
- differences observed between the 1984 and 1985 data sets and between the data and the Monte Carlo distributions (from ± 8 to $\pm 16\%$)
- uncertainty in the energy scale of $\pm 0.6\%$, resulting in a normalization error of about $\pm 5\%$

4.2 Phenomenological fit to the data

The cross sections of Table 2 have been fitted to the same expression as that used for π^0 production[3]:

$$E \, d^3\sigma/dp^3 = C (1-x_D)^m / (p_T/p_0)^{2n}$$

$$\text{with } x_D = (x_T^2 + (x_F - x_0)^2)^{1/2}$$

$$x_T = 2 p_T / \sqrt{s} \quad \text{and } p_0 = 1 \text{ GeV}/c$$

using a least squares fit, with the normalization factor C , x_0 , m and n as free parameters. Only statistical errors were included. The results of the fit are listed in Table 3 where the parameters of π^0 production are also given for comparison.

The parameter n , which characterizes the p_T dependence, has the values 3.28 and 3.76 for the π^- and π^+ beams respectively. Corresponding values for π^0 production are 4.84 and 4.74.

5. Comparison with QCD predictions

In the figures 5 to 7, the direct photon cross sections are compared with a complete next-to-leading order QCD calculation [1], using optimized perturbation theory [10] in order to resolve the renormalization and factorization scheme dependence.

Two sets of structure functions have been proposed [11], based on a compilation of deep inelastic, Drell-Yan and J/ψ production experiments. The valence quark distribution inside the pion is directly measured in Drell-Yan experiments while the gluon distribution is derived from J/ψ production in the framework of quark and gluon fusion models. The difference between the two sets arises from the uncertainty in the shape of the gluon structure function of the proton which is strongly correlated to the QCD parameter Λ . The two parametrizations, at $Q_0^2 = 4.0(\text{GeV}/c)^2$, are:

$$\text{set 1 : } \Lambda = 200 \text{ MeV}/c, \text{ soft gluon: } xG(x) \approx (1+9x)(1-x)^6$$

$$\text{set 2 : } \Lambda = 400 \text{ MeV}/c, \text{ hard gluon: } xG(x) \approx (1+9x)(1-x)^4$$

Table 4 presents a quantitative comparison of the cross sections listed in Table 2 and shown in figures 5 and 6 with theoretical predictions, taking into account statistical and systematic errors added in quadrature. The theoretical predictions are calculated only for the p_T and x_F points where the optimization method can be applied. In this framework, the use of set 1 is strongly favoured over set 2 in almost all p_T and x_F intervals. The ratio $K = (\text{data/QCD predictions})$ for set 1 structure functions is shown in fig 9 for the full x_F interval as function of p_T .

The experimental ratio $\sigma(\pi^- p \rightarrow \gamma X) / \sigma(\pi^+ p \rightarrow \gamma X)$ (fig 8) is slightly higher than the next-to-leading order optimized predictions. This ratio is not very sensitive to the difference between set 1 and set 2 in the p_T range of this experiment.

The experimental difference between $\sigma(\pi^- p \rightarrow \gamma X)$ and $\sigma(\pi^+ p \rightarrow \gamma X)$, which arises mainly from annihilation processes, is compared in fig 10 to the QCD calculations. Here the two sets of predictions differ in the assumed value of Λ . When applied to the data, for $p_T > 4.5$ GeV/c, using the combined statistical and systematic errors, the value of $\Lambda = 200$ MeV yields a χ^2 of 7.2, for 5 degrees of freedom, compared with a χ^2 of 19.0 for $\Lambda = 400$ MeV.

The data may also be compared to the QCD calculations of Ref.12 which uses a soft gluon approach to higher order calculations and allows for intrinsic transverse momentum of the interacting partons. In this calculation the absolute prediction of prompt photon production lies between the two predictions described above. The predicted ratio $\sigma(\pi^- p \rightarrow \gamma X) / \sigma(\pi^+ p \rightarrow \gamma X)$ is also below the experimental points (fig 8).

6. Conclusions

The experiment has determined the inclusive cross sections for prompt photon production by π^- and π^+ on hydrogen at 280 GeV/c, for transverse momenta p_T between 4.0 and 7.0 GeV/c and Feynman x_F between -0.45 and 0.55 .

The ratio of the cross sections for prompt photons produced by π^- and π^+ beams has a value of $2.06 \pm 0.10 \pm 0.10$ (statistical and systematic errors) and is weakly dependent on p_T .

The data are represented by the parametrization

$$E \, d^3\sigma/dp^3 = C (1-x_D)^m / (p_T/p_0)^{2n}$$

as used for π^0 production data[3]. For prompt photon production, the parameter n , which characterises the p_T dependence, is significantly smaller than that obtained for π^0 production.

A quantitative comparison of the production cross section with next-to-leading order QCD calculations [1] gives good agreement, inside the systematic errors, when optimized scales[10] with $\Lambda = 200$ MeV and a soft gluon structure function for the proton are used (set 1 of [11]). The data are incompatible with $\Lambda = 400$ MeV and a hard gluon structure function (set 2 of [11]).

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Figure captions

1. a) The experimental layout.

b) The electromagnetic calorimeter.

2. The photon acceptance and analysis efficiency as obtained by Monte Carlo and by the study of rejected π^0 events. The error bars indicate the overall statistical and systematic uncertainties.

a) vs p_T in the full x_F interval ($-0.45 < x_F < 0.55$).

b) vs x_F in the interval $4.0 < p_T < 5.0$ GeV/c

3. The fake γ to π^0 ratio as obtained by Monte Carlo

a) vs p_T in three x_F bins: $-0.45 < x_F < -0.15$, $-0.15 < x_F < 0.15$, $0.15 < x_F < 0.45$

b) vs x_F in the interval $4.0 < p_T < 5.0$ GeV/c

4. Fake γ background relative to γ candidates as function of p_T for all x_F and as function of x_F for the ranges $4.0 < p_T < 5.0$ GeV/c and $5.0 < p_T < 6.0$ GeV/c.

a) π^- data b) π^+ data.

5. Invariant cross sections for γ production as function of p_T for $-0.45 < x_F < -0.15$, $|x_F| < 0.15$ and $0.15 < x_F < 0.45$. The error bars are statistical only. The errors obtained by combining statistical and systematic errors in quadrature are also indicated. a) π^- data b) π^+ data.

The solid and dashed lines correspond to the predictions of second order QCD calculations [1] using optimized scale with set 1 and set 2 structure functions respectively [11].

6. Invariant cross sections for γ production as function of x_F for $4.0 < p_T < 5.0$ and $5.0 < p_T < 6.0$ GeV/c. The error bars are statistical only. The errors obtained by combining statistical and systematic errors in quadrature are also indicated. a) π^- data b) π^+ data.

The solid and dashed lines correspond to the predictions of second order QCD calculations [1] using optimized scale with set 1 and set 2 structure functions respectively [11].

7. The ratio $\sigma(\pi p \rightarrow \gamma X)/\sigma(\pi p \rightarrow \pi^0 X)$ vs p_T in the full x_F range.

a) π^- data b) π^+ data.

The error bars are statistical only. The errors obtained by combining statistical and systematic errors in quadrature are also indicated.

The solid line indicates the predictions of QCD calculations using optimized scales with set 1 structure functions. The $\pi^\pm p \rightarrow \gamma X$ theory is described in the text, the $\pi^\pm p \rightarrow \pi^0 X$ prediction is the QCD leading order calculation with the Lund fragmentation model for π^0 as described in Ref.3

8. Ratio $\sigma(\pi^- p \rightarrow \gamma X)/\sigma(\pi^+ p \rightarrow \gamma X)$ vs p_T in the full x_F range. The error bars are statistical only. The errors obtained by combining statistical and systematic errors in quadrature are also indicated.

The solid and dashed lines correspond to the predictions of second order QCD calculations [1] using optimized scales with set 1 and set 2 structure functions respectively [11]. The dashed-dotted line represents the predictions of Ref.12

9. The ratio $K = (\text{data}/\text{QCD predictions})$ described in the text for set 1 structure functions, integrated over the full x_F range. a) π^- data b) π^+ data.

10. The difference between $\pi^- p \rightarrow \gamma X$ and $\pi^+ p \rightarrow \gamma X$ invariant cross sections as a function of p_T for the full x_F range. The solid and dashed lines correspond to the predictions of second order QCD calculations [1] using optimized scales with set 1 and set 2 structure functions respectively [11].

Table 1: Estimates of prompt photon losses

a) From the analysis of π^0 events

Accidental triggers	10%
Halo muons	10%
Hadrons and electrons	3%

b) From Monte Carlo

γ conversion	7%
Geometrical acceptances and fiducial cuts	12%
Fake π^0 or η	10%

$$E \frac{d^3\sigma}{dp^3} (\pi^- p \rightarrow \gamma X) \quad (\text{in pbarn GeV}^{-2})$$

	statist.
CROSS	error
section	system
	error

[illegible]
$$E \frac{d^3\sigma}{dp^3} (\pi^+ p \rightarrow \gamma X) \quad (\text{in pbarn GeV}^{-2})$$

	statist.
CROSS	error
section	system
	error

p_T (GeV/c)	→	4.0	4.25	4.5	4.75	5.0	5.5	6.0	7.0				
$\langle p_T \rangle$ (GeV/c)	→	4.11	4.36	4.61	4.86	5.21	5.71	6.34					
$x_F = -0.45$													
$\langle x_F \rangle = -0.328$		19.3	7.2	11.4	4.6	11.0	3.6	6.6	2.6	1.8	0.9		
			7.4		3.9		2.6		1.3		0.4		
-0.25		47.3	7.1	40.7	5.7	18.8	3.7	9.8	2.8	5.5	1.4	2.2	0.8
-0.139			10.3		6.9		3.1		1.7		0.8	0.8	0.3
-0.05													
0.051		44.0	7.1	35.7	6.0	18.5	4.1	17.8	3.5	8.0	1.6	2.3	0.9
			10.2		6.9		3.7		2.7		1.1	0.3	0.1
0.15		51.3	8.7	28.2	6.0	17.5	4.5	5.8	2.8	5.6	1.6	0.6	0.5
0.240			11.6		5.5		3.5		1.4		0.9	0.1	0.1
0.35		22.3	9.5	32.6	7.5	10.4	4.9	2.9	2.7	3.6	1.7		
0.430			9.9		7.6		3.4		1.5		0.9		
0.55													

Table 3: Parameters of the fit

π^- data	$C(\text{mb}/\text{GeV}^2)$	m	n	x_0
π^0	4.9 ± 0.6	3.82 ± 0.07	4.84 ± 0.05	0.063 ± 0.002
γ	$(5.7 \pm 1.6)10^{-3}$	3.34 ± 0.19	3.28 ± 0.11	0.056 ± 0.007
correlation coefficients for γ	C x_0 n	0.520 0.188 0.754	0.952 0.150	0.116

π^+ data	$C(\text{mb}/\text{GeV}^2)$	m	n	x_0
π^0	3.6 ± 0.8	3.95 ± 0.12	4.74 ± 0.08	0.063 ± 0.004
γ	$(9.1 \pm 10.3)10^{-3}$	2.96 ± 0.58	3.76 ± 0.33	0.039 ± 0.023
correlation coefficients for γ	C x_0 n	0.376 -0.155 -0.054	0.900 0.089	0.027

Table 4: Comparison with QCD theory.

π^- data	set 1 $\chi^2/\text{d.o.f}$	set 2 $\chi^2/\text{d.o.f}$
Table 2	38.0/65	338/51
$-0.45 < x_F < -0.15$	7.20/7	14.43/7
$-0.15 < x_F < 0.15$	2.36/7	83.85/7
$0.15 < x_F < 0.45$	7.88/7	91.89/7
$4. < p_T < 5. \text{ GeV}/c$	11.2/20	181.8/20
$5. < p_T < 6. \text{ GeV}/c$	17.2/10	108.9/10

π^+ data	set 1 $\chi^2/\text{d.o.f}$	set 2 $\chi^2/\text{d.o.f}$
Table 2	20.1/35	226.6/35
$-0.45 < x_F < -0.15$	1.2/7	12.6/7
$-0.15 < x_F < 0.15$	2.8/7	94.7/7
$0.15 < x_F < 0.45$	7.4/7	76.6/7
$4. < p_T < 5. \text{ GeV}/c$	6.8/10	130.0/10
$5. < p_T < 6. \text{ GeV}/c$	4.2/10	38.2/10

FIG 1

FIG 2

FIG 3

FIG 4

FIG 5

a) $\pi^- p \rightarrow \gamma X$

b) $\pi^+ p \rightarrow \gamma X$

FIG 6

FIG 7

FIG 8

FIG 9

$$\sigma(\pi^- p \rightarrow \gamma X) - \sigma(\pi^+ p \rightarrow \gamma X)$$

FIG 10