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DIRECT PHOTON PRODUCTION FROM PIONS AND PROTONS AT 200 GeV/c

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ABSTRACT

Direct photon production has been studied by an experiment performed with the NA3 spectrometer at CERN, using incident negative and positive beams at 200 GeV/c interacting with an isoscalar Carbon target. Two different triggers have been used; one of them requires the photon conversion. The experiment is sensitive to direct photons produced with $3.0 < P_T < 6$ GeV/c and center-of-mass rapidity $-0.4 < y^* < 1.2$. Inclusive cross sections are given for incident $\pi^\pm$ and protons, and compared with second order QCD predictions; finally an estimation of the gluon structure function of the nucleon is given.

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1. INTRODUCTION

The discovery of direct high P_T photons produced in proton-proton collisions [1] has induced in recent years an intense experimental activity. In the framework of QCD, single photon production by protons is described by the gluon Compton scattering; when incoming pions are considered, the quark-antiquark annihilation:

$$q\bar{q} \rightarrow \gamma + g$$

is expected to contribute significantly to the total direct photon production. The only published measurement from incoming pions comes from an experiment at Fermilab [2], using a π^+ beam.

We present here the final results of an experiment performed at CERN SPS with the NA3 spectrometer, using incoming π^- , π^+ and proton beams at 200 GeV/c, on an isoscalar Carbon target. Preliminary results based on about 50% of the whole statistics have been already given in Ref. 3.

2. EXPERIMENTAL SET-UP AND TRIGGERS

The experiment was performed with the NA3 spectrometer (which has been extensively described in Ref. 4 in its beam dump configuration), with suitable modifications detailed in [3] and [5].

The most important modification with respect to the dimuon set-up consisted in putting a shower position measuring device inside the electromagnetic calorimeter, after the first 5 radiation lengths. This device, described in detail in Ref. 6, was a multiwire proportional chamber with an analog read-out of the pulses generated at the anode and both cathodes, measuring the shower position with an accuracy $\sigma = 3$ mm. Hereafter it will be referred to as the shower chamber.

Two different triggers were used to select high P_T direct photon candidates:

2.1 The "conversion" trigger

A lead converter (10% conversion probability) was put in front of the spectrometer in order to convert photons into e^+e^- pairs. The corresponding trigger requirements are:

- (a) a pair of tracks consistent with the e^+e^- topology, with vertical component of transverse momentum $P_{TV} > 1.85 \text{ GeV/c}$;
- (b) electromagnetic energy with $P_{TV} > 2.5 \text{ GeV/c}$ registered in the corresponding strip of the calorimeter; due to the parent-child relation, this method ensures a rejection of low $P_T \pi^0$'s at the trigger level.

2.2 The "calorimeter" trigger

The only requested condition is $P_{TV} > 3.5 \text{ GeV/c}$ measured by the calorimeter (this higher threshold was chosen in order to reduce the trigger rate to an acceptable level).

3. SIMULATION OF THE EXPERIMENT

The cross section for direct photon production is expected to be small with respect to π^0 production. An accurate Monte-Carlo simulation of π^0 and η^0 contributions to "direct photon candidates" is therefore essential to estimate the background.

3.1 Event generation

- (a) π^0 events are generated according to the parametrization of the invariant cross section determined in the present experiment:

$$E \frac{d^3\sigma}{dp^3} = A_\pi (1-x_D)^F / (P_T^2)^N \quad \text{with } x_D = \sqrt{x_T^2 + (x_{\not{T}} - x_0)^2}$$

The fitted values of A_π , x_0 , N and F can be found in Ref. 7 for incident π^+ , π^- and protons.

- (b) η^0 events are generated following the same cross-section, but with $A_\eta = 0.53 A_\pi$, from Ref. 8 and $B(\eta^0 \rightarrow \gamma\gamma) = 39\%$.
- (c) Direct photons are generated according to a parametrization of the two Born terms of the QCD annihilation and Compton scattering, and of the 2nd order graphs which will be discussed in section 6.

3.2 Simulation of the apparatus

The experimental conditions are thoroughly simulated within the frame of the CERN GEANT package [9], taking into account materials, detector responses and trigger conditions. The development of electromagnetic showers inside the calorimeter is generated using a parametrization fitted from the data obtained by electron beam calibration runs with energy ranging from 4 to 70 GeV. Special care was devoted to the simulation of the shower chamber response.

The simulated π^0 , η^0 and direct photons are processed through the same chain of programs as real events. This allows the determination of the overall reconstruction efficiencies for both triggers; their values are displayed on Fig. 1.

4. DIRECT PHOTON SELECTION

In the following sections, only events originating from one of the three Carbon targets are considered.

Direct photon candidates cannot be isolated in the sample of events, due to the π^0 and η^0 contamination. The direct photon yield is obtained by first removing from the whole sample the events with a good π^0 or η^0 signature, and afterwards by statistically subtracting the remaining π^0 and η^0 contamination using the Monte-Carlo simulation.

We describe now the π^0 and η^0 selection criteria, separately for each trigger since experimental conditions and biases are substantially different.

4.1 π^0 and η^0 rejection in the conversion trigger

In this trigger, we benefit from the precise measurement of the e^+e^- pair in the spectrometer. The kinematical parameters of the converted photon γ_1 (transverse momentum P_{T1} , energy E_1 and direction) are therefore precisely known.

Events are rejected as "identified π^0 " or "identified η^0 " if there exists another photon γ_2 (with energy E_2 measured in the calorimeter) satisfying the following conditions:

- i) γ_2 has a transverse momentum $P_{T2} > 60$ MeV/c: this cut eliminates most of the background coming from spurious hits in the shower chamber.
 "Identified η^0 " have $P_{T2} > 480$ MeV/c;
- ii) γ_2 is found inside a cone of aperture α with respect to the converted photon γ_1 :

$$\alpha = \frac{m_{\pi^0}}{\sqrt{E_1 E_{2\min}}}$$

The value of $E_{2\min}$ has been varied from 1 to 5 GeV in order to obtain different samples of "identified π^0 ", and therefore estimate systematic errors coming from this definition. $E_{2\min}$ cannot be lower than 1 GeV, since the shower chamber efficiency drops rapidly below this value.

- iii) The invariant mass $M_{\gamma\gamma}$ of γ_1 and γ_2 is compatible, within the experimental resolution, with the π^0 or η^0 mass:

$$\begin{array}{ll} 60 < M_{\gamma\gamma} < 210 \text{ MeV}/c^2 & \text{for "identified } \pi^0\text{"} \\ 490 < M_{\gamma\gamma} < 630 \text{ MeV}/c^2 & \text{for "identified } \eta^0\text{"}. \end{array}$$

It should be noted that, for these "conversion trigger" events, the energy E_2 of the second photon is measured in the calorimeter, with a nominal resolution $\Delta E/E = 0.22/\sqrt{E}$ (E in GeV); the direction of γ_2 is found from its position measured in the shower chamber.

4.2 Calorimeter trigger

All "calorimeter trigger" events must fulfil the following conditions:

- at least one associated charged track originating in one of the Carbon targets;
- there exists at least one photon γ_1 with energy E_1 , vertical transverse momentum $P_{TV} > 3.4$ GeV/c, and center-of-mass rapidity $y^* < 0.8$ (when $y^* > 0.8$, the two photons of a π^0 coalesce into a single, non-separable cluster in the shower chamber).

Events fulfilling the above conditions are classified as "identified π^0 " if there exists another photon of energy E_2 satisfying:

$$60 < M_{\gamma\gamma} < 220 \text{ MeV}/c^2$$

and

$$\frac{|E_1 - E_2|}{E_1 + E_2} < 0.9$$

The energies E_1 and E_2 are measured in the calorimeter; the directions of the photons are determined using the interaction point and the shower position measured in the shower chamber.

4.3 Direct photon yield

As the relevant variables for direct photon physics are the reconstructed transverse momentum p_T and center-of-mass rapidity y^* , the events are classified in $[y^*, p_T]$ bins. We calculate the number N_γ of direct photons in a given bin from the expression:

$$\epsilon_{\gamma\gamma} N_\gamma = N_{TOT} - \frac{N_{\pi^0}}{\epsilon_{\pi^0\pi^0}}$$

$\epsilon_{\gamma\gamma}$ is the γ reconstruction efficiency,

N_{TOT} is the total number of events in the bin,

N_{π^0} and $\epsilon_{\pi^0\pi^0}$ are respectively the number of "identified π^0 " and the π^0 reconstruction efficiency (determined by the simulation) corresponding to the chosen set of cuts defining the "identified π^0 ", in the same bin.

5. THE RESULTS

5.1 Estimation of systematic errors

In the following, results are given with their statistical error and with an estimation of the systematic error. The latter may come from several sources:

- (a) The estimation of unrecognized π^0 and η^0 obtained by simulation. This is by far the most important source of systematic errors. Its contribution is determined by varying several cuts in the analysis. This type of systematic error is found to be strongly p_T dependent: in the conversion (resp. calorimeter) trigger, it amounts to $\sim 50\%$ for events with $p_T < 3 \text{ GeV}/c$ (resp. $4 \text{ GeV}/c$), and to $\sim 20\%$ for events with greater p_T .

This may be connected with the difficulty of simulating exactly the trigger threshold fluctuations in all strips of the calorimeter. Therefore, in the following sections, results will be given only for events with $p_T > 3$ GeV/c for the "conversion trigger", $p_T > 4$ GeV/c for the "calorimeter trigger".

(b) Other sources of systematic error are:

- luminosity normalisation error, which is 3% and affects only absolute cross section measurements;
- trigger efficiency determination (8% error in the "conversion trigger");
- Control of the calorimeter energy scale. This scale is known to $\pm 3\%$, which gives $\sim 20\%$ systematic error on the absolute cross section, due to the steep P_T dependence of γ production spectra. This error is only relevant for the "calorimeter trigger".

5.2 Direct photon cross sections

The invariant cross sections for direct photon production, integrated over the rapidity range of the experiment, are given in Table I for incoming π^+ , π^- and protons, and displayed on Fig. 2.

From these values, we give on Fig. 3 the ratio of the direct photon cross sections for the different incident particles.

We give in Fig. 4 the ratio $\sigma(\gamma)/\sigma(\pi^0)$, as a function of P_T . This presentation has been frequently used in previous publications on direct photon production [1,2].

From the cross section measurement, one can deduce the value of:

$$A = \frac{\sigma_{\pi^-}(\gamma) - \sigma_{\pi^+}(\gamma)}{\sigma_{\pi^-}(\gamma) + \sigma_{\pi^+}(\gamma)}$$

which is an estimation of the direct photon production asymmetry between incident π^- and π^+ . This quantity increases slightly with P_T and its value, averaged above $P_T = 3$ GeV/c for all data, is: $(17 \pm 7)\%$. It must be noted that recent ISR results [10] do not indicate a statistically significant difference between direct photons produced in $\bar{p}p$ and pp interactions at $\sqrt{s} = 53$ GeV. This may be due to the importance of gluon effects in direct photon production, which will be discussed in the following section.

6. COMPARISONS WITH QCD PREDICTIONS

The comparisons between the experimental results and the theoretical predictions are given in Figs. 2 and 3.

6.1 Theoretical predictions

Several authors [11,12] have computed next-to-leading QCD corrections to the basic annihilation and gluon Compton scattering diagrams. All calculations lead to important values coming from the gluon contributions, giving therefore a photon asymmetry production between π^- and π^+ (or $\bar{p}$ and p) much lower than expected from Born terms only. However, these truncated perturbative expansions do not give unique predictions, since they depend on several parameters which are not fixed by the theory:

- (a) The scales Q_s^2 (in the determination of the running coupling constant α_s) and Q_f^2 (which appears in the Q^2 evolution of structure functions) are not prescribed by perturbative QCD. These scales affect mainly the overall normalization, not the shape of the P_T spectrum.
- (b) The distribution of intrinsic transverse momentum of the interacting partons, k_T : there is no theoretical prejudice on it, and experimental results are both indirect and not precise. It is generally believed that next-to-leading QCD corrections partially reduce the need for an important intrinsic momentum. As this point is actually out of control, we neglect the intrinsic momentum in all predictions presented here.
- (c) Nucleon and pion structure functions are known from experiment only. We use the results of the analysis of Duke and Owens [13]; from deep inelastic scattering, Drell-Yan and J/ψ production experiments they have extracted two possible sets of structure functions which are referred hereafter as "0₁" and "0₂". These sets differ mainly in the x -dependence of the proton gluon structure function [$G_p(x) \sim (1-x)^6$ in "0₁" and $(1-x)^4$ in "0₂"], and in the value of the QCD Λ -parameter.

We use the calculations of P. Aurenche et al. [11] to make a comparison with our data. Predictions are done for a Carbon nucleus, supposing no nuclear effects in direct photon production; they are given after integration over the rapidity interval of our experiment. One can notice that rapidity

distributions coming from Born terms are compatible with those obtained in complete calculations; they depend almost uniquely on the choice of the structure functions.

6.2 Estimation of the proton gluon structure function

In the estimation of next-to-leading QCD corrections, the choice of the scale affects mainly the overall normalization. In the absence of an important intrinsic transverse momentum, the p_T dependence of the direct photon cross section in proton-nucleon collisions depends essentially on the choice of the gluon structure function in the proton. Taking a simple analytical form of the structure function:

$$xG_p(x) = A(1-x)^{N_G},$$

and varying N_G , we find that $N_G = 7$ gives an acceptable representation of our data; the error on N_G , essentially systematic, is ± 2 . This estimation of N_G is more direct than previous estimations from deep inelastic neutrino scattering [14]. It is in agreement with another direct estimation of this function, obtained by the R808 collaboration at the ISR [15] using the direct photon + jet cross section.

6.3 Comparison between experimental results and QCD predictions

The above estimation of the proton glue favours the set "0₁" of structure functions, as input for further theoretical predictions of the direct photon cross section. Recently P. Aurenche et al. [16] have prescribed an "optimized" value for the scales Q_s^2 and Q_f^2 (sect. 6.1), which is related to p_T^2 , x_T and y . They give therefore an absolute prediction of the direct photon cross section without free parameters.

We display in Figs. 2 and 3 the corresponding predictions, which are much closer to the data than for instance the predictions with $Q_s^2 = Q_f^2 = p_T^2$ used previously. One can conclude from Fig. 2 that, within the experimental errors, the predictions of Ref. 16 describe the data rather satisfactorily.

CONCLUSIONS

We have measured the cross sections of the direct photon production from incoming pions and protons on an isoscalar target at 200 GeV/c. The γ/π^0 ratio increases with P_T and amounts to $\sim 10\%$ at $p_T = 5$ GeV/c. The asymmetry in γ production between incident π^- and π^+ , averaged over the P_T range of the experiment, is $(17 \pm 7)\%$. We estimate the exponent of the gluon structure function in the proton to be $N_G = 7 \pm 2$. The direct photon cross section is consistent with available next-to-leading QCD calculations, within the systematic and statistical errors of the experiment.

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REFERENCES

- [1] P. Darriulat et al., Nucl. Phys. B110 (1976) 365;
Athens-Brookhaven-CERN Collaboration: E. Anassontzis et al.,
Zeitschrift für Physik C13 (1982) 277.
- [2] M. McLaughlin et al., Phys. Rev. Lett. 51 (1983) 971;
T. Ferbel and W.R. Molzon, Rev. Mod. Phys. 56 (1984) 181.
- [3] Proceedings of XXIIth Int. Conf. on High Energy Physics, Leipzig
(Eastern Germany), July 1984;
NA3 Collaboration: J. Badier et al., preprint CERN EP/84-101
(Aug. 1984).
- [4] NA3 Collaboration: J. Badier et al., Nucl. Instr. and Meth. 175 (1980)
319.
- [5] M. Cohen, Thesis, Université Paris Sud, May 1985,
preprint Orsay LAL 85/14;
Y. Karyotakis, Thesis, Université Paris Sud, May 1985,
LPNHE Ecole Polytechnique.
- [6] F. Costantini et al., Nucl. Instr. and Meth. 225 (1984) 463.
- [7] NA3 Collaboration: J. Badier et al., Inclusive high P_T π^0 production
at 200 GeV/c, Preprint CERN/EP 85-112, July 1985,
to be published in Zeitschrift für Physik C.
- [8] J. Povlis et al., Phys. Rev. Lett. 51 (1983) 967.
- [9] R. Brun et al., GEANT Package CERN/DD/US/86.
- [10] R-808 Collaboration: T. Åkesson et al., Phys. Lett. 158B (1985) 282.
- [11] P. Aurenche et al., Phys. Lett. 140B (1984) 87.
- [12] A.P. Contogouris et al., Direct photon production by positive and
negative pion beams, preprint Mc Gill University (Canada),
March 1985.
- [13] D.W. Duke and J.F. Owens, Phys. Rev. D30 (1984) 49;
J.F. Owens, Phys. Rev. D30 (1984) 943.
- [14] CDHS Collaboration: M. Abramowicz et al., Zeit. für Physik C 17
(1983) 283.
- [15] R.808 Collaboration: T. Åkesson et al., Contribution to the
International Europhysics Conference on High Energy Physics,
Bari (Italy), July 18-24, 1985.
- [16] P. Aurenche, R. Baier, M. Fontannaz and D. Schiff,
private communication (forthcoming paper).

TABLE CAPTION

Mean invariant cross section for direct photon production from incident π^- , π^+ and protons, in nanobarns/GeV² per Carbon nucleus.

The quantity given in the tables is:

$$\frac{1}{y_2 - y_1} \int_{y_1}^{y_2} E \frac{d^3\sigma}{dp^3} dy$$

where y_1 and y_2 are the center-of-mass rapidity limits for each trigger:

Ia) Conversion trigger $y_1 = -0.4$ $y_2 = 1.2$

Ib) Calorimeter trigger $y_1 = -0.4$ $y_2 = 0.8$

The errors are statistical only. The systematic error is estimated around 30% for the conversion trigger, $\sim 40\%$ for the calorimeter trigger.

P_T GeV/c	π^-	π^+	p
2.94	25.3 $\pm$ 4.70	23.0 $\pm$ 5.73	21.8 $\pm$ 4.32
3.09	14.4 $\pm$ 1.93	16.0 $\pm$ 2.52	7.63 $\pm$ 1.78
3.33	8.17 $\pm$ 0.85	7.39 $\pm$ 1.09	3.64 $\pm$ 0.73
3.70	2.13 $\pm$ 0.28	2.40 $\pm$ 0.39	0.98 $\pm$ 0.22
4.21	0.71 $\pm$ 0.11	0.33 $\pm$ 0.13	0.16 $\pm$ 0.066
4.98	0.085 $\pm$ 0.017	0.038 $\pm$ 0.018	0.015 $\pm$ 0.0083

Table I a)

P_T GeV/c	π^-	π^+	p
3.9	1.3 $\pm$.30	1.0 $\pm$.30	.62 $\pm$.19
4.1	1.4 $\pm$.20	.88 $\pm$.19	.44 $\pm$.11
4.3	.67 $\pm$.13	.42 $\pm$.12	.27 $\pm$.07
4.5	.32 $\pm$.09	.25 $\pm$.08	.11 $\pm$.04
4.7	.28 $\pm$.06	.083 $\pm$.055	.045 $\pm$.029
5.0	.11 $\pm$.03	.100 $\pm$.025	.047 $\pm$.013

Table I b)

FIGURE CAPTIONS

Fig. 1 Overall reconstruction efficiencies, from Monte-Carlo calculations, for a) the conversion trigger and b) the calorimeter trigger.

$\epsilon_{\gamma\gamma}$ (resp $\epsilon_{\pi^0\pi^0}$): probability of reconstructing a generated single γ (resp π^0) as a single γ (resp π^0).

$\epsilon_{\pi^0\gamma}$: probability of reconstructing a generated π^0 as a single γ .

$\epsilon_{\gamma\pi^0}$: probability of reconstructing a generated single γ as a π^0 .

The values for the conversion trigger take into account the photon conversion probability.

Fig. 2 Invariant direct photon cross section

$$\frac{1}{y_2 - y_1} \int_{y_1}^{y_2} E \frac{d^3\sigma}{dp^3} dy$$

for incident π^- , π^+ and p on a Carbon nucleus;

y_1 and y_2 are the center-of-mass rapidity limits for each trigger:

Full circles: conversion trigger, $y_1 = -0.4$, $y_2 = 1.2$;

Open circles: calorimeter trigger, $y_1 = -0.4$, $y_2 = 0.8$.

The curves are predictions from next-to-leading QCD calculations explained in the text, with the first set "O₁" of structure functions of Ref. 123

Full line: "optimized" QCD scales (see text and Ref. 16);

Dashed line: scales $Q_s^2 = Q_f^2 = p_T^2$.

Fig. 3 Ratio of direct photon cross sections for different incoming particles: (a) $\sigma_{\pi^-}(\gamma)/\sigma_{\pi^+}(\gamma)$; (b) $\sigma_{\pi^+}(\gamma)/\sigma_p(\gamma)$.

The curves are determined as in Fig.2.

Full circles: conversion trigger,

Open circles: calorimeter trigger.

Fig. 4 $\sigma(\gamma)/\sigma(\pi^0)$. The π^0 cross-section $\sigma(\pi^0)$ is taken from the fitted π^0 production spectrum found in the present experiment (Ref. 7).

a) π^- beam b) π^+ beam c) p beam

Full circles: conversion trigger,

Open circles: calorimeter trigger.

There are no theoretical curves, since the π^0 cross section is not predicted theoretically up to now.

FIG. 1

FIG. 2

FIG. 3

FIG. 4