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INCLUSIVE HIGH P_T π^0 PRODUCTION FROM $\pi^\pm$ AND PROTONS AT 200 GeV/c

NA3 COLLABORATION

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ABSTRACT

We have measured the inclusive cross-section for π^0 production at large transverse momentum by 200 GeV/c positive and negative hadron beams on Carbon targets ($2.9 < P_T < 6$ GeV/c; $-0.4 < y^* < 1.2$). We used the NA3 spectrometer at the CERN SPS.

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1. INTRODUCTION

In this paper we present results on the measurement of the inclusive cross section for π^0 production. This cross-section has been determined for $P_T > 2.9$ GeV/c and in the rapidity interval $-0.4 \leq y^* \leq 1.2$, using 200 GeV positive and negative secondary beams, on a carbon target.

Two different types of triggers have been used. One type, the conversion trigger, requires the conversion of at least one photon produced at the target and the tracking of the corresponding converted e^+e^- pair in the spectrometer. The other (the calorimeter trigger), simply requires the absorption of a high P_T photon by the electromagnetic calorimeter.

The results on the π^0 inclusive cross section are obtained as part of the data analysis of an experiment performed to study direct photon production by $\pi^\pm$ and proton beams [1]. Direct photons suffer from heavy background contamination from abundant production of the π^0 . Consequently the study of all problems associated with π^0 identification, reconstruction and simulation by Monte Carlo method, is essential for the identification of the direct photon signal and for estimating the associated systematic errors.

2. EXPERIMENTAL SET-UP

The experiment was performed using the H8 (positive and negative) secondary beam at the CERN SPS. Incoming particles are identified by 2 differential Cerenkov counters (CEDARS) [2]; two additional threshold Cerenkov counters for π identification are used during positive beam runs.

The average beam intensity is $1.5 \cdot 10^7$ particles per SPS spill of 2 s; the beam flux is continuously monitored to $\pm 2\%$.

Typical proportions of identified incoming particles are : (positive) protons 57%, K^+ 4%, pions 32%, (negative) K^- 2.6%, pions 96.4% at 400 GeV primary proton energy.

The experiment was carried out using the CERN NA3 spectrometer equipped with an upgraded version of the lead scintillator electromagnetic calorimeter.

A full description of this spectrometer, in its beam dump configuration used for studying high energy muon pair production, has been already published [3].

The most significant modifications required by the new experiment are (Fig. 1) :

- a) The target consists of three identical graphite cylinders each 2 cm long (10.6 g/cm^2) mounted along the beam direction; they are 15 cm apart in order to minimize secondary interactions in the target material and ensure optimal space resolution of the reconstructed event vertex.
- b) The spectrometer was equipped with 44 MWPC planes, corresponding to a momentum resolution on charged tracks $\Delta p/p = 2 \cdot 10^{-4}$ p (GeV/c).
- c) The electromagnetic calorimeter is of the lead scintillator type; it is divided into 40 horizontal strips ($9 \times 500 \text{ cm}^2$) (20 strips in the upper, 20 in the lower part with respect to the beam horizontal plane), and segmented longitudinally in 3 stacks : γ_1 ($5 X_o$), γ_2 ($8 X_o$) and γ_3 ($12 X_o$). The horizontal strips of γ_2 and γ_3 are divided in two halves mounted symmetrically with respect to the beam line. Each half is viewed by one photomultiplier. The strips of counter γ_1 are undivided, each one being viewed at both ends by one photomultiplier, thus providing timing informations.

All γ counters are calibrated using an electron beam of known momentum before each running period. The energy resolution can be expressed as :

$$\Delta E/E = 0.004 + 0.22/\sqrt{E} \quad (E \text{ in GeV})$$

for single showers. During data taking, a relative calibration is obtained by two independent systems of light emitting diodes; the stability of the PM's gain is checked during the beam spill.

d) The segmentation of the lead scintillator calorimeter in the plane perpendicular to the beam does not generally provide a sufficient spatial resolution for electromagnetic showers; a position measuring device (shower chamber) is therefore added between γ_1 and γ_2 . It consists of two $4 \times 2 \text{ m}^2$ MWPC's, one above and one below the horizontal plane. They have analog read-out on the horizontal anode wires and on both cathodes. One cathode is segmented into vertical strips each 12 mm wide, the other is divided into independent pads of various sizes (5×5 , 10×10 , $20 \times 20 \text{ cm}^2$), the size increasing with the distance from the beam axis. The pads are particularly useful in reducing ambiguities in the geometrical reconstruction of multiparticle events.

This chamber and the electronics of its 2240 analog channels were already described [4]. The gain of the analog channels is monitored and recorded during data taking; this check and the survey of the gas composition inside the chambers allow a control of the whole detector stability within $\pm 2\%$.

The spacial resolution of the chamber has been measured to be $\sigma = 3 \text{ mm}$ for isolated showers; the two showers separation is about 3 cm, which allows the identification of symmetric π^0 decay up to energies of 110 GeV, for π^0 produced in the target 14 m upstream the shower chamber.

3. THE TRIGGERS

Two different triggers have been used :

- a) The "conversion trigger" : a lead converter ($0.15 X_0$ thick i.e. 10% conversion probability) is placed at the entrance of the spectrometer magnet in front of the CH1 chamber.

Whenever an energetic photon is converted, the event is recorded on tape, provided the following conditions are fulfilled :

- the hardware processor, associated with the triggering chambers M1 and M2 [5], recognizes a candidate for an e^+e^- topology with the vertical component of the transverse momentum $P_{Tv} > 1.85 \text{ GeV/c}$.
- the corresponding horizontal strips in the calorimeter register electromagnetic energy corresponding to a $P_{Tv} > 2.4 \text{ GeV/c}$ (2.8 GeV/c for data collected during 1982).

Since the conversion trigger depends on the M1 and M2 chamber efficiencies, the correct performance and stability of M1 and M2 have been checked throughout the experiment by recording on tape a fixed fraction of events selected by released trigger conditions; this allows a measurement and monitoring of the conversion trigger efficiency.

- b) The "calorimeter trigger" : the only requirement is that the electromagnetic energy deposition in the calorimeter corresponds to $P_{Tv} > 3.5 \text{ GeV/c}$, compatible with acceptably low trigger rate. The P_{Tv} range of the data extends up to 6 GeV/c .

4. MONTE CARLO SIMULATION

We generate π^0 mesons according to our measured differential cross section $E d^3\sigma/dp^3$ as described in sec. 6. Two different sets of parameters are used to generate π^0 produced by incident pions and protons respectively. We use an iterative procedure, taking as a starting point the parametrization of Donaldson et al. [6], for which we take into account the nuclear effects in the carbon target and in the accepted P_T

range, by using a nuclear dependence of the cross section of the type : σ (carbon) = $A^\alpha \sigma$ (proton), where $A = 12$ and $\alpha = 1.12$ [7].

The generated events are then processed through a Monte Carlo program based on the CERN GEANT package [8]. Electromagnetic interactions of photons and electrons in the experimental set-up, are simulated together with the detector responses. Electromagnetic showers in the calorimeter and in the shower chamber are parametrized in order to best fit the data obtained by electron beams between 4 and 70 GeV. The trigger conditions are simulated, and the accepted events are processed through the same analysis as experimental data.

5. DATA ANALYSIS

Conversion Trigger

Let E_1 be the energy of the converted photon as measured by the e^+e^- pair in the spectrometer. For a π^0 , the angle α between the two photons is related to their energies (E_1 and E_2) by the relation :

$$\alpha = m_{\pi^0} / \sqrt{E_1 E_2}$$

For a given converted photon, π^0 candidates are defined as $\gamma\gamma$ pairs satisfying the following cuts :

- $\alpha < \alpha_{\max}$ where $\alpha_{\max}$ corresponds to $E_2 = 5$ GeV
- $P_T > 60$ MeV/c

These cuts represent an optimum for background rejection and well matched statistical and systematic errors in the π^0 inclusive cross section determination. All showers found within a cone of 1.6 mrad around the converted photon are added to the energy E_1 , since they come from Bremsstrahlung produced by the electrons in the set-up.

An event is retained as " π^0 candidate" when the converted γ combined with any other γ inside the fiducial region, yields a mass value in the interval

$60 < m_{\gamma\gamma} < 210$ MeV and as " η candidate" for a mass in the interval $480 < m_{\gamma\gamma} < 620$ MeV. η candidates are selected without $\alpha_{\max}$ cut. The mass resolution at the π^0 peak is $\sigma = 17$ MeV (Fig. 3a).

The overall efficiency for π^0 detection estimated from Monte Carlo is shown in Fig. 2a, as a function of P_T . The two curves correspond to two different $P_{T\gamma}$ calorimeter thresholds used for the conversion trigger at different periods of data taking. The total number of π^0 events collected for different beam particles is listed in Table 1. The P_T scale of the events in the conversion trigger is given by the spectrometer measuring the converted electrons, and is therefore very precise.

Calorimeter Trigger

Events are required to have at least one reconstructed charged track, to ensure that they come from an interaction in the target. Afterwards we select events having at least one photon pair with the sum of their vertical transverse momenta greater than 3.4 GeV/c, corresponding to the trigger threshold. Labelling E_1 the energy of the highest P_T photon, we compute the invariant mass $M_{\gamma\gamma}$ and the asymmetry $A = |E_1 - E_2|/(E_1 + E_2)$ of each photon pair by associating to the leading photon any other photon of energy E_2 . We require $A < 0.8$, to eliminate most of the background.

In Fig. 3b we show the two photon mass spectrum thus obtained. The background at the π^0 peak is about 5% and a clear η^0 signal is also observed. The experimental mass resolution is $\sigma = 13$ MeV at the π^0 and $\sigma = 38$ MeV at the η^0 . The overall efficiency determined by Monte Carlo simulation is also shown in Fig. 2b.

For further analysis, π^0 or η^0 candidates are retained within the mass intervals defined above for the conversion trigger.

6. RESULTS

a) π^0 cross sections

The cross section for π^0 production obtained separately from the data of the conversion trigger and the calorimeter trigger are presented respectively in Table IIa and IIb. They are given for different P_T intervals, after integrating over the P_T bin and over the appropriate rapidity intervals ($-0.4 < y^* < 1.2$, for the conversion trigger; $-0.4 < y^* < 0.8$, for the calorimeter trigger) and for incident π^- , π^+ and protons.

Fig. 4a shows the ratio of the event distributions

$$\frac{d\sigma}{dP_T} (\pi^+ C \rightarrow \pi^0 X) / \frac{d\sigma}{dP_T} (\pi^- C \rightarrow \pi^0 X) \quad \text{for both types of triggers.}$$

This ratio is, within errors, compatible with 1 as expected from isospin invariance. In Fig. 4b, the ratio

$$\frac{d\sigma}{dP_T} [(\frac{\pi^+ + \pi^-}{2}) C \rightarrow \pi^0 X] / \frac{d\sigma}{dP_T} (p C \rightarrow \pi^0 X)$$

is displayed as a function of P_T , integrated over the rapidity interval $y^* = -0.4$ to 0.8 for both triggers. The increase of this ratio with P_T , already observed in previous experiments [9], is attributed to the different behaviour of the quark structure function in the pion and the proton. The ratio

$$\frac{d\sigma}{dP_T} (K^+ C \rightarrow \pi^0 X) / \frac{d\sigma}{dP_T} (\pi^+ C \rightarrow \pi^0 X)$$

shown in Fig. 4c, is independent of P_T in the range $3 \leq P_T \leq 6$ GeV/c; after integrating over P_T and y^* we find $\sigma_{K^+}/\sigma_{\pi^+} = 0.79 \pm 0.03$.

The invariant cross section for π^0 production, integrated over a small interval of rapidity around the center of the rapidity plateau ($|y^* - y_o^*| < 0.2$; $y_o^* = 0$ for protons, $y_o^* = 0.2$ for $\pi^\pm$) is shown in Fig. 5a and b respectively, as a function of P_T , and shows the excellent agreement between the data corresponding to the two trigger types.

b) Systematic errors

The errors quoted in Fig. 5 and Table II are statistical only. The systematical error is estimated around $\sim 15\%$ and originates from :

- beam flux and target density measurement ($< 2\%$)
- particle identification, in the positive beam only ($\sim 3\%$)
- trigger efficiency measurement, in the conversion trigger only ($\sim 10\%$)
- calorimeter calibration, in the calorimeter trigger only, which fixes the P_T scale (at least 10% effect on the cross section).

Our results may be directly compared to the cross sections published by Povleis et al [7] at the same energy, in the same rapidity interval and for $P_T < 5$ GeV/c (positive beam only). The agreement is better than 10% for incoming π^+ ; for incoming protons our cross sections are systematically 20% lower, which is compatible within the quoted errors of the two experiments.

c) Parametrizations of the cross sections

The local slope of the P_T distribution for π^0 production may be estimated from a parametrization like $d\sigma/dP_T = A(P_T)^{-m}$. We find $m \sim 12$ for $3 < P_T < 4$ GeV/c; m varies as a function of P_T . All available data were simultaneously fitted, for each type of incident particle, by the empirical expression

$$E \frac{d^3\sigma}{dp^3} = A (1 - x_d)^F / P_T^N, \text{ where}$$

$$x_d = [x_T^2 + (x_{//} - x_o)^2]^{1/2}$$

The results of these fits are presented in Table III. Notice that part of the P_T dependence in the parametrization, is contained in the x_d variable. The result of the fit gives approximately $N \sim 9.5$.

7. CONCLUSIONS

The present experiment has determined the inclusive cross section for π^0 production by $\pi^\pm$ and protons on carbon. The data were simultaneously collected over a wide transverse momentum and rapidity intervals : $2.9 < P_T < 6$ GeV and $-0.4 < y^* < 1.2$ and with two different types of trigger : a photon conversion trigger and a calorimeter trigger. The combined use of a magnetic spectrometer and of a calorimeter has allowed a permanent check of the stability of the calorimeter, of its energy calibration and a control of systematic effects, which is essential for the analysis of direct photon production. The results obtained with both triggers are in excellent agreement.

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TABLE I

Number of events for various incident
particles and both triggers.

Incident Particle		π^-	π^+	K^-	K^+	p
Conversion Trigger	$PT > 2.9 \text{ GeV/c}; -0.4 \leq y^* \leq 1.2$	6796	3546	220	450	3374
Calorimeter Trigger	$PT > 3.8 \text{ GeV/c}; -0.4 < y^* \leq 0.8$	4685	5867	171	700	3700

TABLE II

Integrated cross section over the P_T bin and the rapidity interval :

$$\int_{P_{T1}}^{P_{T2}} \int_{Y_{\min}}^{Y_{\max}} \frac{d^2\sigma}{dy dP_T} dP_T dy \quad (\text{nb/nucleus})$$

a) Conversion trigger $-0.4 \leq y^* \leq 1.2$

P_T interval	π^-C	π^+C	PC
2.9 - 3.0	1927 $\pm$ 62	1809 $\pm$ 80	1572 $\pm$ 65
3.0 - 3.2	2175 $\pm$ 51	2112 $\pm$ 68	1677 $\pm$ 54
3.2 - 3.4	1124 $\pm$ 30	992 $\pm$ 39	794 $\pm$ 30
3.4 - 3.7	767 $\pm$ 22	756 $\pm$ 29	468 $\pm$ 20
3.7 - 4.0	289 $\pm$ 11	300 $\pm$ 16	162 $\pm$ 10
4.0 - 4.4	128 $\pm$ 7	129 $\pm$ 9	62 $\pm$ 5
4.4 - 4.8	40 $\pm$ 4	39 $\pm$ 5	13 $\pm$ 2
4.8 - 6.0	19 $\pm$ 2	14 $\pm$ 2	43 $\pm$ 10

b) Calorimeter trigger $-0.4 \leq y^* \leq 0.8$

P_T interval	π^-C	π^+C	PC
3.8 - 4.0	140.5 $\pm$ 3.5	144.5 $\pm$ 3	82.3 $\pm$ 2.3
4.0 - 4.2	67.4 $\pm$ 1.8	72.9 $\pm$ 1.9	37.4 $\pm$ 1.3
4.2 - 4.4	37.5 $\pm$ 1.4	42.2 $\pm$ 1.4	19.4 $\pm$ 0.78
4.4 - 4.6	21.0 $\pm$ 1.0	23.7 $\pm$ 0.9	9.4 $\pm$ 0.6
4.6 - 4.8	11.0 $\pm$ 0.7	12.5 $\pm$ 0.6	4.7 $\pm$ 0.4
4.8 - 5.0	6.0 $\pm$ 0.5	5.6 $\pm$ 0.4	2.3 $\pm$ 0.2
5.0 - 5.2	3.5 $\pm$ 0.4	4.0 $\pm$ 0.4	1.0 $\pm$ 0.2
5.2 - 5.4	1.7 $\pm$ 0.3	1.9 $\pm$ 0.2	0.95 $\pm$ 0.07
5.4 - 5.6	1.4 $\pm$ 0.2	1.0 $\pm$ 0.2	0.25 $\pm$ 0.07

TABLE III

Values of the parameters x_o , F and N obtained by a maximum of likelihood fit to the form

$$E \frac{d^3\sigma}{dp^3} = A(1 - x_d)^F / P_T^N \quad \text{where } x_d = (x_T^2 + (x_{//} - x_o)^2)^{1/2}$$

	x_o	F	N	$A(\text{mb})$
$\pi^- C \rightarrow \pi^0 X$	0.120 ± 0.004	4.73 ± 0.19	9.62 ± 0.16	154.8
$\pi^+ C \rightarrow \pi^0 X$	0.127 ± 0.004	4.89 ± 0.20	9.70 ± 0.18	196.0
$PC \rightarrow \pi^0 X$	0.043 ± 0.005	6.51 ± 0.28	10.10 ± 0.24	457

(A is the ratio between the number of events and the integral of the parametrization over the kinematical range corrected by the acceptance and efficiencies. The value of A is very sensitive to a variation of the parameters within errors. The systematic error on A is estimated to 15%).

FIGURE CAPTIONS

Fig. 1 Experimental set-up of the NA3 direct photon experiment.

Fig. 2 Overall efficiency for π^0 detection estimated by Monte Carlo as a function of P_T for the conversion trigger (a) and the calorimeter trigger (b).

Fig. 3 Two photons mass spectrum. The mass spectrum in the η^0 mass region is shown in the insert for non- π^0 events.
a) conversion trigger b) Calorimeter trigger

Fig. 4 Cross section ratio, as a function of P_T for both triggers

$$a) \quad \frac{d\sigma}{dP_T} (\pi^+ C \rightarrow \pi^0 X) / \frac{d\sigma}{dP_T} (\pi^- C \rightarrow \pi^0 X)$$

$$b) \quad \frac{d\sigma}{dP_T} [(\frac{\pi^+ + \pi^-}{2}) C \rightarrow \pi^0 + X] / \frac{d\sigma}{dP_T} (pC \rightarrow \pi^0 X)$$

$$c) \quad \frac{d\sigma}{dP_T} (K^+ C \rightarrow \pi^0 + X) / \frac{d\sigma}{dP_T} (\pi^+ C \rightarrow \pi^0 X)$$

Fig. 5 Invariant cross section for π^0 production, integrated over a small interval of rapidity around the center of the rapidity plateau $|y^* - y_o^*| < 0.2$

$$a) \quad \text{protons} \quad y_o^* = 0$$

$$b) \quad \pi^\pm \quad y_o^* = 0.2$$

The errors are statistical only.

FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5