**High transverse momentum π^0
production by π^- and π^+ on protons at 280 GeV/c**

WA70-collaboration

M.Bonesini ⁴⁾, E.Bonvin ⁵⁾, P.S.L.Booth ³⁾, D.Bortoletto ⁴⁾, L.J.Carroll ³⁾, A.J.Cass ³⁾,
D.Cavalli ⁴⁾, G.Costa ⁴⁾, M.Donnat ¹⁾, P.A.Dorsaz ¹⁾, D.N.Edwards ³⁾, J.R.Fischer ¹⁾,
L.Fluri ⁵⁾, D.Frame ²⁾, F.Gianotti ⁴⁾, S.Jack ²⁾, J.N.Jackson ³⁾, M.Kelly ³⁾,
M.N.Kienzle-Focacci ¹⁾, R.Lacock ²⁾, J.G.Lynch ²⁾, L.Mandelli ⁴⁾, M.Martin ¹⁾, L.Mathys ¹⁾,
A.Maxwell ²⁾, M.Mazzanti ⁴⁾, J.J.Myerscough ³⁾, P.J.Negus ²⁾, S.Pensotti-Rancoita ⁴⁾,
L.Perini ^{4,6)}, D.Perrin ⁵⁾, G.Polesello ⁴⁾, W.H.Range ³⁾, L.Rosselet ¹⁾, S.W.Snow ³⁾,
M.Tamborini ⁴⁾, A.S.Thompson ²⁾, R.M.Turnbull ²⁾, J.Wells ²⁾ and M.Werlen ¹⁾

Abstract

The inclusive cross sections for π^0 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 $-0.45 < x_F < 0.6$ respectively. The data are compared with leading order QCD calculations.

(Submitted to Zeitschrift fur Physik C)

1) University of Geneva, D.P.N.C., CH-1211 GENEVE, Switzerland

2) University of Glasgow, Dept. of Physics and Astronomy, GLASGOW, G12 8QQ, UK

3) University of Liverpool, Dept. of Physics, LIVERPOOL, L69 3BX, UK

4) Dipartimento di Fisica dell'Università e Sezione INFN Milano, I-20133 MILANO, Italy

5) University of Neuchâtel, CH-2000 NEUCHÂTEL, Switzerland

6) CERN, CH-1211 GENEVE 23, Switzerland

1. Introduction

In this paper results are presented on the measurement of the inclusive invariant cross sections for high transverse momentum (p_T) π^0 production by π^- and π^+ incident on protons. The data were taken in 1984 and 1985 at the CERN SPS using a liquid hydrogen target in a 280 GeV/c unseparated hadron beam. Photons and charged particles were detected with a fine grained electromagnetic calorimeter [1] and the Omega spectrometer [2] respectively.

The results have been obtained in an experiment designed to study high p_T prompt photon events [3], where a high reconstruction efficiency for π^0 s and η s over a large kinematical region is required to minimize the background in the photon sample. About 4×10^4 π^0 s were detected, with transverse momenta $4.0 < p_T < 7.0$ GeV/c and Feynman $x_F - 0.45 < x_F < 0.60$ ($x_F \equiv 2p_{\parallel} / \sqrt{s}$).

The experimental system is presented in section 2. The reconstruction and selection of events is described in section 3, while section 4 outlines the selection of high p_T π^0 s. The invariant cross sections and a discussion of systematic errors are given in section 5. A phenomenological parametrization of the data which allows a comparison of experiments performed at different energies with different acceptances is described in section 6. In section 7 the data are compared with leading order QCD calculations.

2. The experimental system

The experimental layout is shown in fig 1a. The beam was defined by three veto counters and two 11 mm diameter trigger counters ($S_1 \cdot \bar{V}_1 \cdot S_2 \cdot \bar{V}_2 \cdot \bar{V}_3$). Two beam veto counters A_1, A_2 , placed 13 m from the centre of the hydrogen target, were used to define an interacting beam particle. The beam, focussed at the centre of the target, had typically a width of 3.0 mm (FWHM), a divergence of 0.8 mrad (FWHM) and a momentum bite $\delta p/p$ of 1.8%. The average beam intensity, for both polarities, was 2×10^7 particles per 1.6 sec SPS effective pulse length, with a repetition cycle of 14.4 sec.

The combined K^- and $\bar{p}$ contamination in the negative beam was 4%. The positive beam was run with the maximum intensity allowed on the primary SPS target and, in order to enrich the π^+ fraction in the beam, an absorber consisting of 1.5 m of polyethylene and 1 m of aluminium was used. After the absorber, the ratio of $p:\pi^+:K^+$ was 77:20:3. Two differential 'CEDAR' Cerenkov counters [4], with eight photomultipliers each, were tuned to identify π^+ . A signal with at least a six-fold coincidence was required in at least one of the two CEDARs. At the beam intensity of the experiment 75% of the incident pions have this signature. In the π^+ sample, the contamination of protons is estimated to be smaller than 2%.

In 1985 a toroidal magnet, surrounding the beam line, was added 80 m upstream from the hydrogen target in order to deflect away from the calorimeter the muon halo which accompanied the hadron beam. These muons could simulate a high p_T trigger by producing bremsstrahlung in the calorimeter or upstream material. A set of ten scintillation counters was also positioned along the beam line to provide a signature for residual halo induced triggers.

The liquid hydrogen target, 1 m long and 25 mm in diameter, was built from low density materials in order to minimize photon conversions.

Charged track and vertex reconstruction were provided by the Omega spectrometer MWPCs [2] and two drift chamber modules (only one in 1984). To optimize the acceptance of the calorimeter, the downstream end of the target was placed at the centre of the Omega magnet; this resulted in a reduced number of Omega MWPC planes. For this experiment the Omega magnet contained thirty three MWPC planes of 2 mm pitch, thirteen vertical planes defining the y coordinate and twenty planes set at $\pm 10.14^\circ$ relative to the vertical direction defining the u and v coordinates. Two drift chamber modules with four coordinates y, u, v, y together with associated MWPC y planes were placed downstream of the Omega magnet. In addition a 4mx4m MWPC (BMWPC), with four planes u, y, v, z and a wire spacing of 4 mm, was placed immediately upstream of the calorimeter at 10.3 m from the centre of the magnet to provide charged particle identification close to the calorimeter. The Omega magnet was used at a reduced field of 1.10 T to decrease the number of "faked" high p_T triggers caused by charged particles in the calorimeter.

The electromagnetic calorimeter [1], 10.9 m from the centre of the magnet, is a sampling calorimeter using lead converters and teflon tubes filled with liquid scintillator as active elements. It consists of four quadrants (fig 1b), each 4 m^2 in area and composed of three segments 10.4 cm deep, with a total thickness of 24 radiation lengths. The scintillator tubes, arranged to give orthogonal readout, are grouped to form elements 1.07 cm wide close to the beam and 2.14 cm wide for both the outer region and for the whole of the third segment. The anode signals of the photomultipliers are digitized by 12-bit ADCs.

The position of an electromagnetic shower is measured with an accuracy of $\sigma = 0.3 \text{ cm}$. In the region of the 1.07 cm wide elements showers can be separated down to 2 cm, using mainly the information from the first segment. Fig 2a shows the probability of identifying the two γ s of the π^0 as a function of their separation in the calorimeter. This result is obtained by the Monte Carlo simulation described in section 4. Showers separated by 2.7 cm are seen to be resolved in 90% of the cases. Similarly, fig 2b shows the reconstruction efficiency for the photons of a triggering π^0 as a function of their energy. A photon can be reconstructed down to 500 MeV.

The energy resolution function of the calorimeter is found to be

$$(\sigma_E/E)^2 = c_1^2/E + c_2^2 \quad E \text{ in GeV}$$

with $c_2 \approx 0.03$ and c_1 varying from 0.17 for isolated showers to 0.28 for all showers (see [1] for details). The energy scale has been determined from the masses of π^0 and η and by comparison with electron induced showers where the electron momentum is measured by the Omega spectrometer. From these measurements, the uncertainty on the energy scale is estimated to be $\pm 0.6\%$.

A time-of-flight (TOF) system [5] is used to resolve spatial ambiguities in multi-shower events by measuring the transit time of the light in the scintillator tubes of the first segment. This system gives a spatial accuracy of about 5 cm for shower energies greater than 5 GeV. The TOF system also measures the timing of the calorimeter signals with respect to the incident beam with a precision $\sigma = 0.25 \text{ ns}$, thus providing a means of rejecting events in which there is a random coincidence between the beam interaction trigger and the high p_T calorimeter trigger.

The trigger electronics [6] is designed to select high p_T electromagnetic showers above a given threshold. An event trigger consists of a target interaction, defined by the beam counters, in coinci-

dence with a calorimeter trigger. For the calorimeter trigger, each quadrant is divided into four bands horizontally and vertically, thus defining sixteen trigger cells. The last dynode signal of each photomultiplier is weighted by a resistor to give a signal proportional to the transverse energy deposited in the scintillator. The signals inside a band are then summed and digitized through a 4-bit flash ADC. The outputs of the flash ADCs address a bank of fast memories (a look-up table) pre-programmed to determine whether the energy deposited in a given trigger cell corresponds to a transverse energy above a defined threshold. The look-up table takes into account the light attenuation in the scintillator as well as the energy balance between the two orthogonal views of the calorimeter.

The data acquisition system consists of a VAX 780 computer, with a fast front end microprocessor MICE [7] emulating a PDP-11. The MICE reads the whole event in "cycle stealing" mode leaving time for on-line filtering. The data-taking rate was about 100 events per burst, at a nominal p_T trigger threshold of 3 GeV/c, with up to 20% dead time. A filter in MICE further selects events by making an approximate p_T calculation on individual showers, reducing the number of events written on tape by a factor of two. This filter uses a fixed point arithmetic program which associates the highest ADC cluster in each view inside the trigger cell(s) and calculates the p_T and energy balance in about 10 ms.

3. Event filters and reconstruction

The showers and charged tracks in an event are reconstructed by two separate programs. The calorimeter reconstruction program is described in [1]; the track reconstruction is performed by the standard Omega pattern recognition and geometry program TRIDENT [8].

Before complete shower reconstruction, the events are filtered using the TOF information. A fast algorithm finds the time of unambiguous showers in the event relative to the incident beam particle. Events with shower times falling into two or more clusters which differ by more than 7.5 ns are considered as an overlap of separate interactions or accidental triggers and rejected. For 70% of events, all shower times form a single cluster and the event is accepted if this time agrees with the arrival of the beam particle to within 5 ns.

The position and energy of the trigger shower computed in MICE is then examined. If the trigger shower has not deposited enough energy in segment 1 to fire the TOF, it is considered as hadronic and the event is rejected. If the TOF measurements show that the two projections of the trigger shower are uncorrelated, the event is considered an accidental trigger and rejected. The fraction of events remaining after all of these cuts is about 30%.

Showers are found by first building up shower profiles independently in the two orthogonal views, then matching the two views in order to find the shower positions. For every profile in each view, the following quantities are used for the matching: the total ADC amplitude of the three segments, their longitudinal centre of gravity (the average depth of the shower inside the calorimeter) and, for profiles with an ADC signal above the TOF threshold, the difference between the positions determined by the TOF in one view and the profile position in the other. Overlaps between profiles are allowed, every profile in one view being tested as the projection of a single shower, two showers or three showers. From this information, hypotheses of shower configurations within a quadrant are constructed. The hypotheses are classified by taking into account the non-associated energy and the global χ^2 formed by energy, longitudinal centre of gravity and TOF information. In general more than one hypothesis is acceptable, but the trigger shower is the same in 95% of the hypotheses. For the following analysis, only the best hypothesis is considered.

After the calorimeter shower reconstruction, events with either a trigger shower with $p_T > 3.0$ GeV/c or a pair of showers with effective mass smaller than 1.2 GeV and $p_T > 3.5$ GeV/c are processed through TRIDENT. The interaction vertex is defined with an accuracy varying from 2.2 cm to 1.1 cm along the target. On average the high p_T events have nine charged reconstructed tracks associated with the interaction vertex and about seventeen reconstructed showers.

4. Data analysis

The selection of high p_T π^0 s first requires that the vertex, as defined from charged tracks, is inside the volume of the target, and that there is no signal in the muon halo veto counters (1985 data only).

Residual trigger showers produced by bremsstrahlung of the muon beam halo are then rejected. They are identified by the shower direction as given by the three segments of the calorimeter or by the correspondence with a track in the BMWPC parallel to the beam or by the shower TOF signal being out of time with the rest of the event by more than 1.2 ns.

The identification of a hadronic shower is based on the energy deposited in the third segment ($E_3/E_{\text{tot}} > 0.2$). Remaining charged hadrons and electrons in the calorimeter are identified by a track in the Omega MWPCs which extrapolates to within 5 cm of a shower position, or by a signal in the BMWPC within 3 cm of a shower in the calorimeter.

After subtraction of hadrons, electrons and halo showers, a trigger shower is redefined as the highest p_T photon candidate in a trigger cell. To reconstruct a π^0 , the trigger shower is combined with each electromagnetic shower of energy greater than 500 MeV. The resulting $\gamma\gamma$ mass spectrum for a sample of data is shown in fig 3a; π^0 candidates are accepted in the $\gamma\gamma$ mass interval of 70-200 MeV. If more than one pair falls in this interval ($\leq 5\%$), the combination with the $\gamma\gamma$ effective mass nearest to the π^0 nominal mass is chosen. For this combination the decay asymmetry defined as $|E_{\gamma_1} - E_{\gamma_2}|/(E_{\gamma_1} + E_{\gamma_2})$ is shown in fig 4; events with a decay asymmetry greater than 0.9 are rejected. The π^0 mass resolution is $\sigma = 10$ MeV (fig 3b). The background under the π^0 , estimated by a linear interpolation from regions on either side of the π^0 peak, varies with p_T and x_F from 5% to 10%.

To correct the data for geometrical acceptance and for the trigger, pattern recognition and overall analysis efficiencies, different Monte Carlo programs have been developed. In one, high p_T π^0 s are generated with parameters given by the fit to the present experimental data as described in section 6. The other is based on leading order QCD hard scattering diagrams with the Lund fragmentation model [9]. Particles are traced to the calorimeter through a full detector simulation, taking into account materialization of γ s and secondary interactions. The longitudinal and transverse developments of electromagnetic and hadronic showers are parametrized [10] using our experimental data. The Monte Carlo simulates the raw data information and these events are analysed with the same chain of programs as real data.

The values of the efficiency ϵ obtained in these two generations have been compared and are statistically compatible. From this comparison an upper limit for the systematic deviation has been esti-

ated: $(\epsilon_1 - \epsilon_2)/\epsilon_{\text{average}} < 0.15$. Both generations have been used to obtain a sample with statistics larger than the data by a factor of at least four in the whole p_T , x_F range. A further consistency check, which has been made with a sample obtained by superimposing π^0 s on real events in a non triggering quadrant, also shows systematic effects not exceeding 0.15.

In figures 4 and 5, the Lund Monte Carlo predictions are compared with the data for asymmetry, two γ separation and π^0 azimuthal (ϕ) distribution over the four quadrants. In the asymmetry spectrum Monte Carlo generated π^0 s and direct γ s are added in the ratio observed by this experiment. The distributions are well reproduced by Monte Carlo with the exception of the azimuthal distribution (fig 5b) which shows some differences in the four quadrants. This has been taken into account in the systematic errors.

The combined π^0 acceptance and detection efficiency depends on the beam polarity and on the experimental arrangement and is about 50% for $p_T > 4.0$ GeV/c. The main losses are due to i) the conversion of γ s inside the hydrogen target and the Omega chambers ($\simeq 13\%$), ii) the trigger and geometrical acceptance ($\simeq 12\%$) and iii) the cuts applied for the analysis ($\simeq 35\%$). Included in iii) are the losses due to the cuts to reject superimposed events (section 3) and halo induced showers. Both of these, estimated directly from an analysis of π^0 s in rejected events, result in a loss of $\simeq 25\%$. All other effects are corrected by Monte Carlo. The overall π^0 acceptance including detection efficiency is shown in fig 6 as a function of p_T and of x_F .

5. Results

The samples of π^-p and π^+p data correspond to sensitivities of 3.5 and 1.3 pbarn $^{-1}$ respectively (Table 1).

The invariant cross sections $E d^3\sigma/dp^3$ for π^0 production by π^- and π^+ averaged in p_T and x_F bins are presented in Tables 2a and 2b. The p_T and x_F limits of each bin and their weighted averages are indicated. The p_T distributions for three x_F intervals are shown in fig 7; the x_F distributions for three p_T intervals are shown in fig 8. The ratio of the π^- and π^+ cross sections is shown in fig 9 as a

function of p_T and of x_F with systematic errors relevant to this ratio; overall this ratio is $1.07 \pm 0.01 \pm 0.10$ (statistical and systematic errors respectively).

The systematic errors in the cross sections, which depend on p_T and x_F , originate from:

- uncertainty in the absolute normalization due to particle identification in the positive beam ($\pm 2\%$), trigger losses and rejections of superimposed events with TOF (added quadratically they amount to $\approx \pm 6\%$);
- statistical and systematic uncertainties of the Monte Carlo and limited size of the data samples in evaluating the correction factors (typically from ± 5 to $\pm 15\%$);
- systematic errors in the equalization of the different parts of the calorimeter have been estimated by comparing both the response of the four quadrants in the 1984 and 1985 runs and the data with Monte Carlo distributions (from ± 8 to $\pm 16\%$);
- the energy scale uncertainty of $\pm 0.6\%$ gives a systematic effect from ± 7 to $\pm 9\%$.

These contributions are combined in quadrature and given in Table 2.

6. Phenomenological fit and comparison with other experiments

The expression

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

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

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

was fitted to the data for $p_T > 4.0 \text{ GeV}/c$ and $x_F > -0.45$ using a maximum likelihood method in an x_F/p_T grid with bins of 0.025 and 0.25 GeV/c and with the normalization factor C , x_0 , m and n as free parameters (see appendix A). The results of the fits are given in Table 3 and superimposed on the data in figures 7 and 8. The parameters of this fit are strongly correlated (Table 3). The fit takes into account only statistical errors. In order to estimate the systematic effects on the fit parameters, separate fits have been performed to the 1984 and 1985 data. Systematic discrepancies observed at the edges of

the x_F distributions affect mainly the parameter m which can change by 10-15% relative to the value quoted in the table. As a consistency check, it has been verified that the fits on 1984 and 1985 data separately give cross sections which are compatible within systematic errors with those quoted in Table 2.

Recent results for π^- and π^+ on hydrogen at 300 GeV/c have been published [11] in the kinematic ranges $-0.65 < y < 0.52$, $1.0 < p_T < 7.5$ GeV/c; the cross sections, measured as a function of p_T only, agree with the prediction of the fit described above within 30% for $p_T > 2$ GeV/c.

The π^- data obtained in the present experiment have been compared with similar fits from previous experiments [12, 13], although it should be emphasized that they have been obtained from data in different kinematic regions. The comparison with fits to data taken at 200 GeV/c on carbon in the p_T range 3 to 6 GeV/c [13] and to data obtained at 100 and 200 GeV/c on hydrogen in the p_T range 1 to 5 GeV/c [12] are shown on fig 10. The extrapolated cross sections given by the different experiments agree within 10-20% at $x_F \approx 0$ and low p_T , but can differ by a factor two in regions of low cross section such as $p_T > 6.0$ GeV/c and at the edges of the x_F distribution.

7. Comparison with theory

The π^- data have been compared to leading order QCD, using the Lund model for fragmentation [9]. The quark and gluon structure functions are parametrized with set 1 of Duke and Owens [14]. Different choices for the Q^2 scales in the running coupling constant α_s and in the evolution of the structure functions have been tested. With "natural" scales such as

$$Q^2 = p_T^2 \quad \text{or} \quad Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$$

and with no intrinsic transverse momentum ($k_T = 0$), the predicted cross sections are approximately a factor three below experimental values. In fig 11 the ratio $K = (\text{data} / \text{predictions})$ is shown as function of p_T and x_F . Even including a k_T of 800 MeV, the discrepancy is still about a factor two.

Next-to-leading order calculations indicate that the corrections are substantial and positive [15]. In the simpler prompt photon production channel, where complete next-to-leading predictions are avail-

able, kinematically dependent “optimized Q^2 scales” [16] can be calculated [17]. The scales required for the renormalization of α_s and for the factorization have been optimized for prompt photon production, parametrized in our prompt photon kinematical domain [3] as

$$Q^2_{\text{opt}} (\text{factorization}) = 0.35 (1 - x_T) p_T^2$$

$$Q^2_{\text{opt}} (\text{renormalization}) = 0.31 p_T^2 - 1.81 p_T + 2.81$$

and used to generate high p_T π^0 events. With these scales, the comparison with the data is better, giving the ratio $K \approx 0.8$ (fig 11, A). Using these optimized scales for Q^2 in the Lund Monte Carlo the ratio of the invariant cross sections for high p_T π^0 s produced by π^- and π^+ ($p_T > 4.0$ GeV/c) is 1.06 ± 0.02 , compared with our experimental value of $1.07 \pm 0.01 \pm 0.10$.

8. Conclusions

Inclusive cross sections for π^0 production by 280 GeV/c π^- and π^+ on hydrogen have been determined in the transverse momentum and Feynman x_F ranges $4.0 < p_T < 7.0$ GeV/c and $-0.45 < x_F < 0.6$ respectively.

The ratio of the π^0 cross section for incident π^- to that for π^+ is $1.07 \pm 0.01 \pm 0.10$ averaged over these p_T and x_F ranges.

The cross sections have been fitted to the parametrization

$$E \, d^3\sigma/dp^3 = C (1 - x_D)^m / (p_T/p_0)^{2n} \quad \text{with } x_D = (x_T^2 + (x_F - x_0)^2)^{1/2}$$

The values obtained for the parameters are almost independent of beam polarity and are given in Table 3.

The data have been compared with leading order QCD calculations. The experimental cross section is higher than the predicted value by an approximate factor three. This factor changes with the definition of the Q^2 scales. On choosing “optimized” scales, determined by second order calculations on hadronic direct photon production at the same beam energy, the agreement between theory and experiment is improved.

Acknowledgements

It is a pleasure to thank the members of the Omega support group, especially W.Beusch and F.Bourgeois as well as the EA support group for their invaluable assistance throughout the experiment.

We thank J.P.Dufey, who developed the MICE acquisition system, J.Joosten and M.Letheren for their help with MICE, and members of the DD/OC support group who provided the VAX data acquisition system.

We gratefully acknowledge the provision of computing facilities by CERN, CILEA, RAL and University of Geneva as well as financial support from CERN, INFN, RAL, the United Kingdom SERC and the Swiss National Foundation.

We are grateful to P.Aurenche and G.Ingelman for helpful discussions.

References

- [1] M.Bonesini et al., "A lead-liquid scintillator electromagnetic calorimeter for direct photon physics", to be published in Nucl. Inst. Meth.
- [2] W.Beusch: CERN/SPSC 77-70, SPSC/T-17 (1977)
- [3] M.Bonesini et al., "High transverse momentum prompt photon production by π^- and π^+ on protons at 280 GeV/c", to be submitted to Z. Phys..
- [4] CEDAR: C.Bovet et al.: CERN yellow report 82-13.
- [5] M.Bonesini et al., "A 1152 channel timing system for an electromagnetic calorimeter read-out", submitted to Nucl. Inst. Meth.
- [6] P.Béné et al., "High p_T trigger electronics for a large orthogonal readout electromagnetic calorimeter", to be submitted to Nucl. Inst. Meth.
- [7] MICE: J.Anthonioz-Blanc et al.: CERN-DD/81/9 and references therein.
- [8] J.C.Lasalle, F.Carena, S.Pensotti: Nucl. Inst. Meth. 176, 371 (1980).
- [9] H.U.Bengtsson, G.Engelman, T.Sjöstrand: The Lund Monte Carlo for high- p_T scattering, PYTHIA version 4.1, update of H.U.Bengtsson and G.Engelman: Comp. Phys. Comm. 34, 251 (1985); T.Sjöstrand: Jet fragmentation, JETSET version 6.2, update of T.Sjöstrand: Comp. Phys. Comm. 27, 243 (1982)
- [10] R.K.Bock, T.Hans-Kozanecka, T.P.Shah: Nucl. Inst. Meth. 186, 533 (1981); P.Andreacchio, G.Bressi, D.Zanello: CERN/EP/EHS/PH 78-14 (1978)
- [11] C.De Marzo et al.: Phys. Rev. D36, 16 (1987)
- [12] G.Donaldson et al.: Phys. Lett. 73B, 375 (1978)
- [13] J.Badier et al.: Z. Phys. C 30, 45 (1986)
- [14] D.W.Duke and J.F.Owens: Phys. Rev. D30, 49 (1984); J.F.Owens: Phys. Rev. D30, 943 (1984)
- [15] R.K.Ellis and J.C.Sexton: Nucl.Phys. B 269, 445 (1986)
- [16] P.M.Stevenson: Phys. Rev. D 23, 2916 (1981); P.Stevenson and H.Politzer: Nucl. Phys. B 277, 758 (1986);

- [17] P.Aurenche, R.Baier, A.Douiri, M.Fontannaz and D.Schiff: Phys. Lett. 140B, 87 (1984);
P.Aurenche, R.Baier, M.Fontannaz, D.Schiff: Nucl. Phys. B286, 509 (1987).

APPENDIX A

LIKELIHOOD METHOD

In order to get the normalization as a free parameter, a generalized likelihood function is constructed by convoluting a multinomial distribution with a Poisson distribution.

The multinomial distribution describes the bin to bin partition of n events in the histogram whereas the Poisson distribution gives the probability of observing just n events in total. It results in the following likelihood function:

$$L = \left(\frac{e^{-s} s^n}{n!} \right) \left(n! \prod_{i=1}^m \frac{p_i^{n_i}}{n_i!} \right) = \prod_{i=1}^m \frac{e^{-s_i} s_i^{n_i}}{n_i!}$$

where m = number of bins,

n_i = number of events observed in bin i ,

s_i = expected number of events in bin i .

s_i is a function of the parameters and includes acceptance and efficiency corrections calculated by Monte-Carlo.

$$n = \sum_{i=1}^m n_i, \quad s = \sum_{i=1}^m s_i, \quad p_i = \frac{s_i}{s}$$

Table 1:

	π^-	π^+
Number of incident particles	82.5×10^{10}	31.3×10^{10}
Number of triggers	2.9×10^6	8.7×10^5
π^0 events ($p_T > 4.0$ GeV/c)	33904	10701

TABLE 2 a

 $E \frac{d^3\sigma}{dp^3} (\pi^- p \rightarrow \pi^0 X) \quad (\text{in pbarn GeV}^{-2})$
Contents of
each cell —

statist.
error
cross
section
system.
error

-0.45			50.2	13.4	9.9	5.9	3.3	1.0	0.6		
	-0.394	422.9	82.4	59.9	27.0	19.6	2.3	1.4			
-0.35		126.6	20.8	15.9	7.6	4.8	0.6	0.5			
	-0.324	385.9	164.7	89.9	29.5	19.7	2.0	1.6			
-0.30		88.5	35.7	19.2	6.5	4.6	0.6	1.7			
	-0.274	451.1	192.0	98.3	55.1	22.2	6.0	1.4			
-0.25		23.7	14.5	10.1	7.1	3.1	1.6	0.7			
	-0.224	79.3	30.4	14.9	8.6	3.8	1.3	0.5			
-0.20		22.7	15.7	11.6	7.5	3.1	1.7	1.1			
	-0.174	522.1	274.5	154.5	73.9	25.5	8.2	2.8			
-0.15		91.5	43.3	23.1	11.4	4.3	1.6	1.5			
	-0.124	22.9	16.7	11.5	7.3	4.1	1.9	0.5			
-0.10		636.4	364.7	172.8	77.2	42.8	9.1	1.5			
	-0.075	108.6	55.5	24.8	11.4	6.9	1.7	0.6			
-0.05		23.0	16.6	11.0	9.3	3.8	1.9	0.7			
	-0.025	698.3	382.8	180.7	122.2	41.0	9.6	2.5			
0		119.0	58.1	25.8	18.0	6.5	1.8	1.1			
	0.025	25.0	17.0	11.9	8.9	3.9	1.7	0.8			
0.05		870.2	439.6	218.0	120.8	46.0	9.5	2.7			
	0.075	148.2	66.7	31.1	17.7	7.2	1.7	1.3			
0.10		25.5	18.7	12.1	9.0	4.1	2.3	0.9			
	0.125	918.5	512.2	229.4	127.1	51.9	16.3	3.5			
0.15		156.5	77.7	32.7	18.6	8.1	2.9	1.6			
	0.175	25.3	18.9	12.2	9.1	4.2	1.9	0.7			
0.20		977.8	556.7	248.7	132.3	57.2	12.6	3.1			
	0.224	166.5	84.4	35.4	19.4	8.9	2.2	1.2			
0.25		26.2	18.5	13.0	9.7	4.2	2.1	0.8			
	0.274	1037.3	541.1	277.0	149.8	57.3	12.8	3.4			
0.30		176.7	82.1	39.4	21.9	8.9	2.3	1.3			
	0.324	27.2	18.7	13.3	9.0	4.3	2.2	0.8			
0.35		1088.1	549.0	282.3	133.5	58.6	15.7	3.3			
	0.374	185.4	83.3	40.2	19.6	9.2	2.8	1.2			
0.40		26.7	18.2	12.9	9.8	4.3	1.6	0.9			
	0.424	1003.1	503.5	260.4	149.9	56.5	8.8	4.3			
0.45		171.0	76.5	37.2	22.0	8.8	1.6	1.5			
	0.474	25.8	18.2	12.1	8.7	4.1	2.0	0.9			
0.50		833.9	450.9	214.7	115.9	51.5	11.4	3.7			
	0.523	142.2	68.7	30.8	17.1	8.2	2.0	1.7			
0.55		22.5	16.6	12.0	7.0	3.7	2.0	0.7			
	0.573	641.1	358.8	185.5	70.8	37.8	10.8	2.1			
0.60		109.5	54.7	26.8	10.5	6.0	2.1	0.7			
	0.632	22.3	14.5	10.3	7.1	3.4	1.6	0.9			
0.65		571.7	250.4	134.1	70.2	29.1	6.8	3.1			
	0.674	93.5	41.8	22.9	12.3	5.5	1.5	1.4			
0.70		19.8	14.4	11.2	8.6	3.5	1.7	0.5			
	0.694	413.6	234.9	138.1	75.8	27.0	7.5	1.2			
0.75		67.9	39.4	23.9	13.5	5.1	1.6	0.5			
	0.724	21.0	13.8	9.5	6.2	2.8	1.1				
0.80		396.3	181.1	83.6	42.2	15.4	2.5				
	0.774	77.7	36.2	17.2	8.9	3.5	0.6				
0.85		19.7	15.2	7.0	7.3	3.4	0.7	0.8			
	0.824	277.6	174.7	46.7	41.7	16.5	0.7	0.8			
0.90		55.0	35.4	9.7	9.1	4.1	0.2	0.4			
	0.874	24.1	14.4	10.3	6.7	3.1	1.1	0.4			
0.95		254.1	107.8	59.1	24.2	6.9	1.6	0.3			
	0.923	60.0	26.0	15.0	6.4	1.9	0.6	0.9			
1.00		40.5	13.6	9.6	10.0	3.8	2.2	0.9			
	0.973	271.4	56.0	30.2	31.8	5.4	3.1	0.9			
1.05		70.3	14.7	8.6	9.5	1.8	1.1	0.9			
x_F	$\langle x_F \rangle$	4.11	4.36	4.61	4.86	5.2	5.70	6.32			
		4.0	4.25	4.5	4.75	5.0	5.5	6.0	7.0		

 $\langle p_T \rangle$
(GeV/c) p_T
(GeV/c)

Table 3: *Parameters of the fit*

π^-	$C(\text{mb/GeV}^2)$ 4.9 ± 0.6	m 3.82 ± 0.07	n 4.84 ± 0.05	x_0 0.063 ± 0.002
correlation matrix	C	-0.311	$+0.960$	-0.088
	x_0	$+0.119$	-0.110	
	n	-0.561		
π^+	$C(\text{mb/GeV}^2)$ 3.6 ± 0.8	m 3.95 ± 0.12	n 4.74 ± 0.08	x_0 0.063 ± 0.004
correlation matrix	C	-0.266	$+0.956$	-0.074
	x_0	$+0.093$	-0.094	
	n	-0.533		

Figure captions

1. a) The experimental layout (in 1984 only one drift chamber was used).

b) The electromagnetic calorimeter.

2. Monte Carlo results:

a) π^0 reconstruction efficiency vs two shower distance.

b) γ reconstruction efficiency vs the γ energy for γ s of high p_T π^0 .

3. a) The $\gamma\gamma$ effective mass spectrum.

b) The π^0 mass region. The arrows indicate the cuts which define the π^0 region.

The plots are for a π^- data sample having a π^0 of $p_T \geq 4.25$ GeV/c.

4. π^0 decay asymmetry

The Lund Monte Carlo predictions (dashed line) are superimposed on a data sample (full line), taking into account direct γ contributions (shaded area). The plots are for the same data sample as in figure 3.

5. Comparison of a sample of high p_T π^0 (full line) with Monte Carlo (dashed line):

a) distance between the two showers of the π^0 .

b) azimuthal distribution (ϕ) of π^0 s in the calorimeter.

6. The combined π^0 acceptance and reconstruction efficiency as obtained by Monte Carlo and by analysis of π^0 s in rejected events. The error bars are the overall statistical and systematic uncertainties added in quadrature.

a) vs p_T in the full x_F range

FIG 1

FIG 2

b) vs x_F in the interval $4.5 < p_T < 5.0$ GeV/c

7. Invariant cross section for π^0 production as a function of p_T in three x_F bins: $-0.45 < x_F < -0.15$, $-0.15 < x_F < 0.15$, $0.15 < x_F < 0.45$.

The π^+ data are scaled down by a factor of ten. The error bars are statistical only. The error obtained by combining statistical and systematic errors in quadrature is also indicated. Superimposed on the data is the result of the phenomenological fit.

8. Invariant cross section for π^0 production as a function of x_F in the three p_T bins $4.0 < p_T < 4.5$ GeV/c, $4.5 < p_T < 5.0$ GeV/c, $5.0 < p_T < 6.0$ GeV/c.

The error bars are statistical only. The error obtained by combining statistical and systematic errors in quadrature is also indicated. Superimposed on the data is the result of the phenomenological fit.

a) π^- data b) π^+ data

9. The ratio $(\pi^- p \rightarrow \pi^0 X)/(\pi^+ p \rightarrow \pi^0 X)$ a) vs p_T in the full x_F range, b) vs x_F in the full p_T range.

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

10. Comparison of π^- data to phenomenological fits obtained by previous experiments: [12] (dashed line), [13] (full line) extrapolated to our kinematical range (statistical and systematic errors are added in quadrature and drawn on the data).

a) vs p_T integrated in the full x_F range.

b) vs x_F for $4.5 < p_T < 5.0$ GeV/c

11. Comparison with QCD

The K factor defined as $K = [\pi^- \text{ data} / \text{QCD predicted value}]$ is plotted as function of (a) p_T in the full x_F range and (b) x_F for $4.5 < p_T < 5.0$ GeV/c for different definitions of the Q^2 scales:

A) Optimized Q^2 from prompt photon analysis (see section 7)

B) $Q^2 = 2\hat{s}\hat{t}\hat{u}/(\hat{s}^2 + \hat{t}^2 + \hat{u}^2)$

C) $Q^2 = p_T^2$

D) $Q^2 = p_T^2$ and $k_T = 0.8$ GeV/c

For the scales A, B, C, $k_T = 0$ GeV/c.

The points B, C, D are shown with the statistical errors of the data and of the Monte Carlo. On points A the total errors, statistical and systematic combined in quadrature, are also indicated.

FIG 3

FIG 4

FIG 5

FIG 6

FIG 7

FIG 8

FIG 9

FIG 10

FIG 11