INCLUSIVE π^0 PRODUCTION AT THE CERN $p\bar{p}$ COLLIDER

The UA2 Collaboration

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ABSTRACT

Inclusive π^0 production has been measured at the CERN $p\bar{p}$ collider, $\sqrt{s} = 540$ GeV, for 90° production angle and in a range of transverse momenta between 1.5 and 4.5 GeV/c. The invariant production cross-section is larger than that measured at $\sqrt{s} = 53$ GeV for p - p collisions. The production of η mesons and of direct photons is also investigated.

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Introduction

The successful operation of the CERN $p\bar{p}$ Collider [1] allows the study of hadron interactions in an energy range one order of magnitude higher than previously available.

We report here results on inclusive π^0 production, the process that, at the CERN ISR, provided the first evidence for large transverse momentum secondaries [2]. The produced π^0 's are identified from two photon decays, with the photons separately measured. The total c.m. energy is $\sqrt{s} = 540$ GeV, the mean production angle is $\theta = 90^\circ$ and the π^0 transverse momentum covers the range $1.5 < p_T < 4.5$ GeV/c.

Apparatus

The detector is a large single arm spectrometer covering a solid angle of two thirds of a steradian (28° in azimuth, 68° in polar angle) around $\theta = 90^\circ$. The spectrometer is made of twelve drift chamber planes followed by a scintillator-iron-scintillator sandwich and a lead-glass wall (Figure 1). It is part of the much larger UA2 detector [3] installed in a long straight section (LSS4) of the CERN $p\bar{p}$ collider. The other detector parts are irrelevant to the present measurement and are not described here.

The lead-glass wall is located 3 m from the beam line. It is made of two arrays separated by a 30 cm gap in the middle. The wall consists of 26 vertical columns of 10 cells, staggered as shown in Figure 1 to minimize the number of cells associated with a single photon shower. Each cell is a lead-glass block, 14.5 radiation lengths deep, 15×15 cm² in cross-section, and equipped with a 5" phototube glued on the back face. Anode pulses are measured by 12-bit analog-to-digital converters (ADC). Their fast analog sum is used to trigger the data acquisition when it exceeds an energy threshold (set at 1.1 GeV for the present data).

Before installation in LSS4 each cell was calibrated at the CERN PS in a 10 GeV electron beam, and its phototube voltage was adjusted to ensure a uniform response to transverse energy over the whole detector.

At that time, data were also collected at electron energies between 1 and 10 GeV to study the linearity and resolution of energy response, the effect of the incident electron angle, and the effect of the iron converter before the lead-glass wall.

The gain and linearity of the complete electronic chain between phototube and ADC were monitored throughout the experiment. Furthermore, the calibration was maintained by sending light of xenon flash lamps via plastic fibres to each lead-glass block. The calibration remained stable to within $\pm 2\%$ during the running period.

The scintillator-iron-scintillator sandwich is located 5 cm in front of the lead-glass wall. It consists of a 2 cm thick iron plate between two scintillator hodoscopes. Each hodoscope is made of 28 vertical strips, 15 cm wide by 1 cm thick, and covers the lead-glass acceptance. The scintillators of the front hodoscope are equipped with a phototube at each end, and those of the back hodoscope are equipped with a phototube at the bottom end. Their anode pulses are measured by 10-bit ADCs.

Two scintillator arrays detecting small-angle secondaries are used to discriminate against events from sources other than beam-beam collisions. They surround the vacuum pipe, ± 10 m away from the interaction point. Each array covers one unit of rapidity around $y = \pm 4.7$. A coincidence with a signal from each is required in the trigger. The probability that a non-diffractive collision produces charged secondaries satisfying this requirement is about 60% [4]. The trigger efficiency is in fact larger because of photons from small angle π^0 decays converting in the vacuum pipe. The exact efficiency is irrelevant to the cross-section measurement because the same two small-angle arrays are used to evaluate the luminosity.

Data Reduction

For each recorded event the pattern of energy deposition in the lead-glass array is analysed and reduced to a number of clusters. Each cluster is defined as a set of adjacent cells having energies above 100 MeV. A halo contribution from surrounding cells is added to the

cluster energy. When the energy distribution within a cluster peaks in two non-adjacent cells, the cluster is split. The minimum spatial separation of two resolved clusters is about 25 cm, corresponding to the minimum photon separation resulting from a 3.25 GeV π^0 decay.

A sample of $\pi^0 \rightarrow \gamma\gamma$ candidates is obtained by retaining events having at least two clusters of more than 200 MeV in the lead-glass wall. If a track (measured in the drift chambers) points within 12 cm of a cluster center, the cluster is attributed to a charged hadron and excluded from the sample of photon candidates. This results in a loss of $2 \pm 1\%$ of real π^0 decays due to accidental track-cluster overlaps but increases the purity of the sample.

Photons converting in the iron plate lose a fraction of their energy before entering the lead-glass wall. We correct for this loss by adding to the measured cluster energy a quantity proportional to the pulse height measured in the scintillator located immediately behind the iron plate. This correction, of 30 MeV per equivalent minimum ionising pulse height, is typically 100 MeV per converted photon. It is evaluated from a study of the dependence of the reconstructed π^0 mass on pulse height in the scintillator. The correction is consistent with measurements using an electron beam.

The invariant mass distribution of the sample of π^0 candidates is shown in Figure 2. A π^0 peak is clearly visible. The location of the interaction vertex along the beam line is ignored in the present analysis and the mass is calculated assuming that π^0 's are produced and decay at the exact center of the detector. This assumption has less than a 1% effect on the mass and cross-section evaluations.

Inclusive π^0 production

Only photon pairs having a transverse momentum exceeding 1.4 GeV/c are retained in the sample contributing to Figure 2 and used in the subsequent analysis. This ensures full trigger efficiency for single π^0 production. It rejects biased events for which a π^0 slightly below threshold is accompanied by a number of extra photons or charged hadrons. This is a strongly favoured configuration in the vicinity of the trigger threshold.

The solid line in Figure 2 is the result of a Monte Carlo calculation taking into account the lead-glass energy resolution and the finite photon shower size. A 4% readjustment of the energy scale was made to get agreement with the data. This deviation is at the level of the inaccuracy which can be expected from the extrapolation of a 10 GeV electron calibration to photons in the GeV range. For this reason we assign a 4% global uncertainty to the transverse momentum scale.

The background under the peak is 20% to 30% depending upon p_T . It is calculated, for each p_T bin separately, by interpolation from both sides of the mass peak. Uncertainties in the knowledge of the tails of the mass peak result in systematic uncertainties on the signal, that are evaluated in each bin of p_T . The ratio of systematic to statistical uncertainty varies between ~ 2 at $p_T = 1.5$ GeV/c and ~ 1 at $p_T = 3.5$ GeV/c.

There is, on the average, one extra cluster per event. But the probability that this extra cluster produces an additional pair with a mass populating the region in which the background interpolation is performed is only 10%, independent of p_T . The resulting uncertainty on the signal does not exceed 1%.

The evaluation of the π^0 production cross-section requires the knowledge of the detector acceptance and of the integrated luminosity.

The detector acceptance is obtained from the Monte-Carlo simulation. It is limited at low p_T by the solid angle over which each photon of a π^0 decay reaches the detector, and at high p_T by the increased probability that photons merge into a single cluster. The acceptance reaches its maximum, 2% of 4π , at 2.7 GeV/c. In the transverse momentum range of the present measurement it always exceeds 1% of 4π .

Integrated luminosities are evaluated from the rate of coincidences detected in the small-angle scintillator arrays. From the fluctuations measured during different running conditions we assign a 17% uncertainty to the total luminosity. This uncertainty reflects the reliability of these counters as luminosity monitors. The total integrated luminosity is $75 \mu\text{b}^{-1}$ calculated under the assumption that the non-diffractive cross-section is 38 mb (taking a total cross-section of 63 mb, an elastic cross-section of 11 mb [5], and a single-diffraction cross-section of 14 mb [6]).

The p_T -dependence of the measured invariant cross-section for inclusive π^0 production is shown in Figure 3 and in Table 1. In each bin of p_T the statistical uncertainty and the uncertainty of the background subtraction are added in quadrature.

In addition to previously mentioned corrections we have accounted for conversions occurring in the beam pipe and in the vertex detector surrounding it, causing a 9% π^0 loss, and for accidental overlaps with an extra cluster, causing a $10 \pm 3\%$ π^0 loss. Smearing resulting from the lead-glass energy resolution causes a slightly p_T -dependent increase of the measured cross-section (typically 8%) which has been corrected.

It must be noted that the requirement of a coincidence with a pair P of small-angle charged secondaries implies that the cross-section measurements listed in Table 1 are actually

$$E \frac{d^3\sigma}{dp^3} (p\bar{p} \rightarrow \pi^0 + P + \dots) \frac{\sigma_{ND}}{\sigma(p\bar{p} \rightarrow P + \dots)}$$

This becomes $E \frac{d^3\sigma}{dp^3} (p\bar{p} \rightarrow \pi^0 + \dots)$ only if there is no correlation between P and π^0 production in non-diffractive events, a reasonable assumption in the p_T range of this experiment.

The solid line of Figure 3 shows the measured pion production in $\sqrt{s} = 53$ GeV p-p collisions [7]. Preliminary ISR data indicate that it takes the same values for p- $\bar{p}$ collisions [8]. At ISR energies, for the p_T range of the present experiment, it is customary to parametrise the invariant cross-section in the form $p_T^{-n} (1-x_T)^m$ with $x_T = 2 p_T s^{-1/2}$ and typically [7] $n \simeq 8$ and $m \simeq 9$. Extrapolation to $\sqrt{s} = 540$ GeV results in an underestimate of the cross-section (dashed line, Figure 3). However this extrapolation may not be justified because the present experiment probes much lower values of x_T than at the ISR.

An evaluation of the effective power n_{eff} from a fit to the invariant cross-section of the form $p_T^{-n_{eff}}$ yields $n_{eff} = 5.7 \pm 0.2$. A measurement of the s-dependence of the cross-section is necessary to infer from the data an exponent which can be directly related to the nature of parton processes possibly involved in the collision.

Eta production

The $\gamma\text{-}\gamma$ mass distribution of Figure 2 shows no significant enhancement in the vicinity of the η mass. That shown in the insert is obtained by imposing stricter selection criteria on the photon pair sample : clusters must be of at most two cells, their energy must not exceed 3 GeV, there must be no more than three clusters in the lead-glass wall and the energy asymmetry must not exceed 0.4 . Under such conditions the acceptance is reduced by a factor ~ 3 but an enhancement is observed near the η mass, amounting to 53 ± 15 photon pairs above background. This is consistent with an estimate of 48 obtained from a Monte-Carlo simulation under the assumption that the inclusive cross-sections for η and π^0 productions are proportional and in the same ratio, 0.55, as measured in the ISR energy range [9].

Single photons

In order to define a photon signal from the set of energy clusters in the lead-glass wall selection criteria stricter than those for a $\pi^0 \rightarrow \gamma\gamma$ signal are necessary : the signature provided by the fixed value of the $\gamma\text{-}\gamma$ mass is now lacking. As a measure of the purity of the photon signal we use the probability ρ that no conversion occurs in the iron plate. This probability is measured to be $44 \pm 1\%$ for photons from π^0 decays used as a reference sample. This value agrees with what is expected from the thickness of the iron plate. We obtain the same value, independent of energy, if we restrict the sample of photon candidates to clusters of at most two cells associated neither with a track nor with a significant signal in front of the iron plate. Clusters of three and more cells have a higher ρ value, consistent with a small contamination of neutral hadrons, such as antineutrons.

We have compared the transverse momentum distribution of this restricted photon sample with the prediction of a Monte-Carlo simulation, using as input the measured π^0 cross-section, and assuming a p_T independent η/π^0 ratio equal to 0.55 . The dependence upon transverse momentum is well reproduced. Integrating between 1.5 and 3.0 GeV/c we observe an excess of 24 ± 58 photons, out of 1300 photons detected.

This is consistent with the absence of a significant photon production from other sources. Correcting for a possible non-linearity of the energy response of the detector (which would affect differently single photons and photon pairs) and for a possible contamination of long-lived neutral hadrons, mostly antineutrons (deduced from the measured conversion probability in the iron plate) we obtain a deficit of 46 ± 90 photons. A direct production of single photons in the ratio $\gamma/\pi^0 = 1\%$ would correspond to an excess of about 20 photons.

Conclusion

We have reported the first measurement of inclusive π^0 production from $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV. The invariant cross-section, measured at 90° and in a transverse momentum range $1.5 < p_T < 4.5$ GeV/c, has a p_T dependence which can be described by the form $p_T^{-5.7}$. It is larger than that measured at $\sqrt{s} = 53$ GeV for p-p collisions. An η signal has been observed, consistent with $\eta/\pi^0 = 0.55$ as measured at the ISR. No evidence has been found for photon sources other than π^0 and η production.

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TABLE 1

Invariant π^0 production cross-section in $p\bar{p}$ collisions at
 $\sqrt{s} = 540 \text{ GeV}$, $\theta \simeq 90^\circ$.

Transverse momentum (GeV/c)	Invariant cross-section ($\mu\text{b GeV}^{-2} \text{c}^3$)
1.51	217 ± 41
1.61	158 ± 29
1.72	108 ± 21
1.82	106 ± 14
1.92	68.4 ± 10.2
2.03	35.8 ± 8.7
2.18	31.0 ± 5.3
2.39	21.5 ± 3.0
2.60	12.3 ± 2.5
2.81	8.16 ± 1.36
3.02	5.30 ± 1.11
3.37	2.29 ± 0.44
3.89	1.02 ± 0.30
4.42	0.44 ± 0.20
Global additional uncertainties - on transverse momentum $\pm 4\%$ - on cross-section $\pm 17\%$	

FIGURE CAPTIONS.

- 1 - An exploded view of the detector. Front elements have been partly cut in order to make those in the back visible.
- 2 - Invariant mass distribution of the two-photons sample (full dots). The distribution in the insert around the η mass is for stricter cuts (see text). The result of the Monte Carlo simulation (solid lines) has been added to a hand-drawn background (dashed lines).
- 3 - The measured invariant cross-section for $p\bar{p} \rightarrow \pi^0 + \dots$ (full dots) at $\sqrt{s} = 540$ GeV is compared to that for $pp \rightarrow \pi^0 + \dots$ at $\sqrt{s} = 53$ GeV (solid line). The pp data are from Ref [4] ; in the lower p_T range the mean of π^+ and π^- cross-sections has been used. The dashed line is an extrapolation of the data of Ref [4] to Collider energy using the form $p_T^{-n} (1-x_T)^9$.

Fig. 1

Fig. 2

Fig. 3

15-9