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**SINGLE-SPIN ASYMMETRIES
AND INVARIANT CROSS SECTIONS
OF THE HIGH-TRANSVERSE-MOMENTUM
INCLUSIVE π^0 PRODUCTION IN 200 GeV/c
 pp AND $p\bar{p}$ INTERACTIONS**

(FNAL E704 Collaboration)

Submitted to *Phys.Rev.*

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Abstract

Adams D.L. et al. Single-Spin Asymmetries and Invariant Cross Sections of the High-Transverse-Momentum Inclusive π^0 Production in 200 GeV/c pp and $p\bar{p}$ Interactions: IHEP Preprint 94-88. – Protvino, 1994. – p. 18, figs. 5, tables 4, refs.: 25.

The E704 experiment at FNAL measured the π^0 inclusive and semi-inclusive single-transverse spin asymmetries in collisions of polarized proton and antiproton beams of 200 GeV/c with an unpolarized hydrogen target. The measured region was: $x_F = 0 \pm 0.15$ and $1 < p_T < 4.5$ GeV/c. The asymmetries are consistent with zero within the error bars indicating that a PQCD expectation seems confirmed and the high twist contribution to single-spin effect in π^0 production at $x_F = 0$ not be as large as was expected. Additional arguments for such a conclusion come up from the measurements of the semi-inclusive π^0 asymmetry with the detection of associated charged particles emitted opposite to the π^0 azimuthal direction. This experiment presents also high statistics inclusive π^0 cross-section data for pp and $p\bar{p}$ collisions at 200 GeV/c. The data are consistent with the parton inspired distribution functions.

Аннотация

Адамс Д.Л. и др. Односпиновые асимметрии и инвариантные сечения инклюзивного образования π^0 -мезонов с большими поперечными импульсами в pp - и $p\bar{p}$ -взаимодействиях при 200 ГэВ/с: Препринт ИФВЭ 94-88. – Протвино, 1994. – 18 с., 5 рис., 4 табл., библиогр.: 25.

В эксперименте E-704 во ФНАЛе измерены односпиновые асимметрии в инклюзивном и полуинклюзивном образовании π^0 -мезонов при взаимодействии поперечно поляризованных протонов и антипротонов с импульсом 200 ГэВ/с с неполяризованной водородной мишенью. Измерения были проведены в области $x_F = 0 \pm 0.15$ и $1 < p_T < 4.5$ ГэВ/с. Асимметрии совместимы с нулем в пределах ошибок. Это указывает на то, что ожидания пертурбативной КХТ подтверждаются, а вклад высших твистов в асимметрию в образовании π^0 -мезонов при $x_F = 0$ не так велик, как ожидалось. Дополнительные аргументы в пользу такого заключения появляются из измерений асимметрии в полуинклюзивном образовании π^0 -мезонов, когда в противоположном π^0 -мезонам азимутальном направлении регистрируются ассоциативные заряженные частицы.

В работе также представлены инвариантные сечения образования π^0 -мезонов для pp - и $p\bar{p}$ -взаимодействий при 200 ГэВ/с. Эти данные хорошо описываются в рамках партонной модели.

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1. INTRODUCTION

Interest in the single-transverse spin asymmetry has been growing recently. The discovery of a large left-right asymmetry in inclusive production of pions at 13 and 18 GeV/c [1], 24 GeV/c [2] and 40 GeV/c [3], and the hyperon polarizations [4] challenge the PQCD based model predictions. Since in these models any transverse single-spin effect is proportional to the product of the small parameters like α_S , strong coupling constant, m_q , a quark mass, and to $s^{-0.5}$, the expected spin effect becomes less than a percent at sufficiently high energy. But the data indicated spin effects of order ten percent. The ways of avoiding such contradictions were proposed in a set of theoretical papers. Examples are the model of quark-gluon correlation [5], the color string model [6], and model of un-suppressed high twist effects [7]. These approaches are promising, but they badly need the experimental data for their justifications. Moreover there are theoretical models differing in predictions of transverse asymmetry by one order of magnitude (compare [8] and [9]).

The single-transverse spin asymmetries for inclusive and semi - inclusive π^0 productions were measured in the E704 experiment at 200 GeV/c beam momentum in transverse momentum region 1 to 4.5 GeV/c. The energy and transverse momentum in this experiment were high to hope that the PQCD estimates are applicable at the highest p_T . The reliability of asymmetry data has been checked by reconstructing the inclusive cross sections and comparing them with the published data.

The paper is organized in the following way. In Sec.II the experimental set-up and Data Analysis are described. Sec.III gives the invariant cross sections for both pp and $\bar{p}p$ interactions. The single-spin asymmetries are presented in Sec.IV. Sec.V is devoted to the discussions of the presented results.

2. EXPERIMENTAL SET-UP AND DATA ANALYSIS

A polarized proton (antiproton) beam with 200 GeV/c momentum has been built at Fermilab. The polarization of the proton (antiproton) beam comes from the parity-violating decays of Λ -hyperons ($\bar{\Lambda}$). The beam transport system has been designed to minimize depolarization effects. A set of twelve dipole magnets have been used to rotate the spin direction of beam particles. A beam-tagging system determined the momentum and polarization of individual beam particles. This allowed a selection of beam particles in definite intervals of momentum and polarization. The maximal value of the proton (antiproton) polarization was 65%. A total of 13 bins described the interval between -65% to $+65\%$ polarization in 10% intervals. The same was done for scalars to count the flux of particles passing through the target. Protons (antiprotons) with polarization values between $+35\%$ and $+65\%$ were designated as "positive", those between -35% and -65% "as negative", and those between -35% and $+35\%$ "as zero" polarization. The beam - tagging system assigned a polarization value for each beam particle relative to a known trajectory. An absolute measurement of the beam polarization was necessary to confirm those values. Two independent measurements with two polarimeters have been carried out, they agreed with the expected results [10], [11].

A spin - precession rotator, loosely called a "snake", consisted of a set of magnets that changed the beam-particle polarization state from one direction to another. The design had no overall perturbation of the beam - particle trajectory; the bends and displacements of the trajectory must be canceled during passage through the snakes. A spin rotator was used in the beam line for two reasons: (1) to periodically reverse the polarization direction so that experimental systematic errors were controlled, and (2) to change the spin direction from horizontal, which was the spin component actually tagged, to vertical for experimental measurements. The net spin rotation was in the same direction for both protons and antiprotons.

Details of the channel of the polarized protons and antiprotons are described elsewhere [12]. The target was 100 cm of liquid hydrogen.

Photons from the decay of neutral mesons produced in the target were detected in the Central Electromagnetic Calorimeters CEMC1 and CEMC2 (Fig.1), located symmetrically to the left and to the right of the beam axis at 10 m from the center of the target. Each calorimeter comprised 504 lead-glass counters in an array of 21 columns by 24 rows. The dimensions of each lead-glass block were $3.81\text{ cm} \times 3.81\text{ cm} \times 18$ radiation lengths. Each array covered a polar angle of $(5.5 \pm 2.2)^\circ$ in the laboratory frame, where 5.5° corresponded

to 90° in the c.m., and azimuthal angles of $\pm 25^\circ$ with respect to the horizontal plane containing the beam axis.

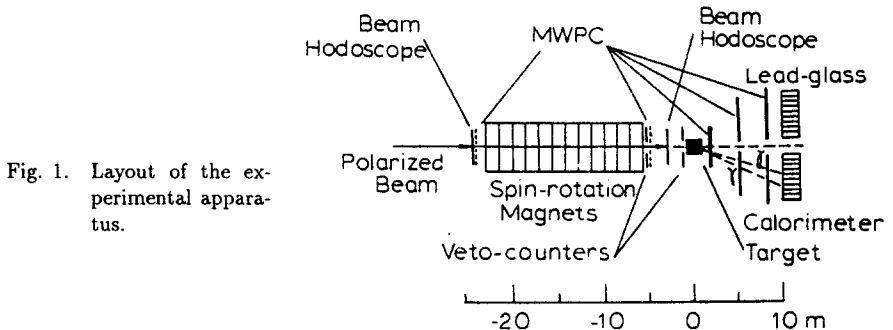


Fig. 1. Layout of the experimental apparatus.

We had a set of proportional chambers between the target and the CEMCs (Fig.1). The track reconstruction of charged particles has been done using these chambers. But this system worked only for last half of our running time during the single-spin asymmetry measurements. We used these events to calculate the asymmetry of the π^0 - production associated with charged particles.

A total of 2×10^7 events were recorded with incident protons and a total of 2×10^6 events recorded with incident antiprotons.

The calibration of the CEMC was carried out with an $E_o = 30 \text{ GeV}$ positron beam. Coefficients c_i , transforming signal amplitude A_{il} into energies E_{il}

$$E_{il} = c_i \cdot A_{il}, \quad (1)$$

were defined as a result of the calibration. Here i a counter number; l is an event number. The coefficients c_i were defined using the equations

$$\sum_l (\sum_i E_{il} - E_o)^2 = \min. \quad (2)$$

The details of the solution of these equations were described elsewhere [7]. The energy resolution 7% (FWHM) was achieved.

In our previous publication [13] the energy scale in each CEMC was based only on the calibration described above. We have recalibrated CEMC1 and CEMC2 using events with π^0 - and η -mesons. We have demanded from the γ -pairs in the effective mass regions of π^0 - and η -mesons to have the expected mass values at all p_T . The corrections to the calibration coefficients obtained earlier with the positron beam varied from 1 to 5% for different runs and different p_T . This recalibration has not practically affected the asymmetry in the p_T -range

between 1 and 3 GeV/c where statistics is enough and affected the p_T -range with poor statistics at higher p_T . In the last range a small regrouping of events into new p_T -bins due to change in the energy scale might result in significant change of asymmetry.

Signals from all counters in each set of the calorimeters were summed with appropriate weights to generate the " p_T signal" whose amplitude is approximately proportional to the p_T value deposited by detected particles in the calorimeter. This signal enabled us to select the p_T of the events and suppress the data taking of the low- p_T events. Data were taken at several p_T thresholds to enrich the statistics at higher p_T values. The highest trigger threshold was slightly beyond $p_T = 2$ GeV/c.

For many events electromagnetic showers from two γ -quanta originated in π^0 -decay were overlapping in the CEMC. The first task of the data analysis was to reconstruct these γ -quanta, i.e., to define their energies and coordinates. The electromagnetic shower shape table was defined by averaging fluctuations of $2 \cdot 10^5$ positron events with an additional proportional chamber placed in front of the CEMC only during the calibration runs for a positron coordinate definition. This shower shape table is a two - dimensional table $E_i^T(x, y)$, where x and y are shower coordinates relatively to the center of an i -th counter. The best description of a real isolated energy cluster in the CEMC by two shower energy distribution according to the shower shape table had been looked for in each particular event. As a result, from energy deposition of two overlapping showers six parameters were defined, two energies, two x - and two y -coordinates of γ -quanta. The details of the π^0 -reconstruction algorithm are described elsewhere [14].

All combinations of photon pairs satisfying the following criteria were selected as π^0 candidates:

- 1) the energy asymmetry $A_E = |E_1 - E_2| / (E_1 + E_2)$ between the two showers was less than 0.8;
- 2) both photons were contained within a distance of more than one counter width from the edge of the calorimeter to avoid leakage of deposited energy;
- 3) the two-photon invariant mass was between 110 and 155 MeV/c² for $p_T < 2.4$ GeV/c, and between 110 and 170 MeV/c for $p_T > 2.4$ GeV/c to take into account the change of mass distribution width;
- 4) the x_F value was within ± 0.15 .

The analysis yielded about 10^6 π^0 events satisfying these conditions, produced by the beam protons tagged with average polarizations [10], [11] of +45% or -45%, and an approximately equal number produced by protons tagged with average polarization of zero. The analysis of the events produced by polarized antiprotons yielded 1.7×10^5 π^0 s.

The two-photon mass distributions are given in Fig.2. The spatial resolution (r.m.s. 1.5 mm), energy resolution (r.m.s. $\Delta E/E = 0.14/\sqrt{E}$) and target length (100 cm) contributed to an overall resolution of $\Delta m = 18 \text{ MeV}/c$ (FWHM) at $p_T \approx 1.5 \text{ GeV}/c$. The resolution deteriorated with increasing p_T because of some inefficiency of the reconstruction algorithm (increased shower overlap, leading to poorer position resolution) and was equal to $27 \text{ MeV}/c^2$ (FWHM) at $p_T \approx 3.5 \text{ GeV}/c$. The π^0 signal was extracted by fitting a gaussian signal plus a third order polynomial for a background to each mass distribution. The background had a magnitude $\approx 7\%$ at low p_T and increased up to $\approx 26\%$ at the highest p_T in the experiment. The background was mainly composed of pairs of unrelated photons. Hadronic showers were rejected approximately one order of magnitude by applying a residual cut (comparing of a shower shape in a particular event with the average electromagnetic shower shape). The mass distributions from CEMC1 and CEMC2 were identical in most p_T bins, demonstrating that the absolute calibrations and the energy resolutions were the same for the two detectors.

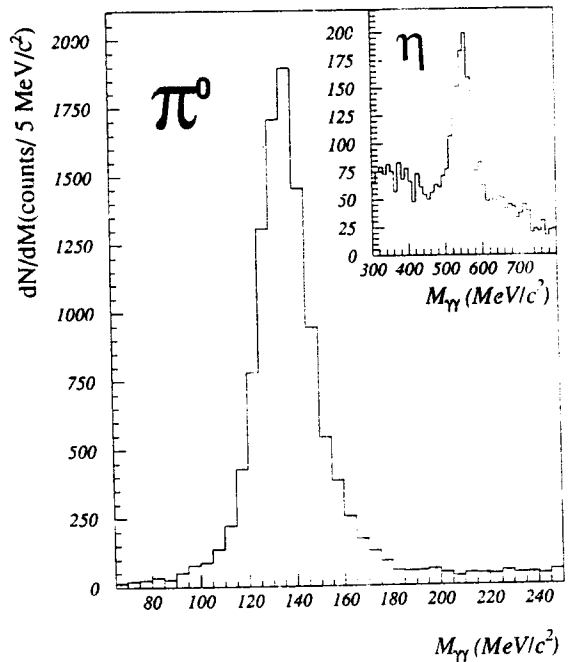


Fig. 2. The two-photon invariant-mass distributions for π^0 - and η -production by protons for $2.5 < p_T < 27 \text{ GeV}/c$.

In principle, one of the CEMC detectors, one of the two polarized parts of the beam, and polarization reversal by the spin-rotating magnets in the beam line were sufficient to determine the asymmetry. The two parts of the beam with opposite polarizations and the left-right symmetric detector apparatus represented two levels of redundancy. Consistency among the four possible methods to calculate the asymmetry provided a check of instrumental errors specific to each method. Furthermore, we calculated the false asymmetry for the events tagged with average beam polarization of zero. We did not find any false asymmetry. We have used the achieved statistical errors in the false asymmetry definitions as an estimate of point-to-point systematic errors for single-spin asymmetries. The relative systematic error proportional to A_N was estimated to be 10% and was due principally to the uncertainty in the beam polarization.

3. INVARIANT CROSS SECTIONS

In this section we present our measurements of the inclusive π^0 production cross sections averaged over x_F region from -0.15 to $+0.15$.

Invariant cross sections $E d^3\sigma/dp^3$ were defined as follows:

$$E \frac{d^3\sigma}{dp^3} = \frac{1}{2\pi \cdot p_{max}} \cdot \left[\frac{N_{\pi^0}^H}{M^H} - \frac{N_{\pi^0}^E}{M^E} \right] \cdot \frac{1}{\varepsilon_{geom}} \cdot \frac{1}{\varepsilon_{REC}} \cdot k_{BACK} \cdot \frac{1}{\Delta p_T} \cdot \frac{1}{\Delta x_F} \cdot \frac{A}{N_A \cdot \rho l}, \quad (3)$$

where p_{max} is the maximal momentum of π^0 in the c.m. of the $pp(\bar{p}p)$ interaction ($p_{max} \approx \sqrt{s}/2$, where s is the Mandelstam variable);

$N_{\pi^0}^H, N_{\pi^0}^E$, - a number of π^0 's which survived all the selection criteria described in the Sect. II for the hydrogen and the empty targets, respectively;

M^H, M^E - beam scaler counts for the hydrogen and the empty targets, respectively;

ε_{geom} - the geometrical efficiency of the π^0 detection by the CEMC;

ε_{REC} - the efficiency of the π^0 reconstruction algorithm;

k_{BACK} - ratio of "pure" π^0 -mesons to the full number of two-gamma pairs within the chosen mass interval (the full number was π^0 -mesons plus combinatorial background);

Δp_T and Δx_F are p_T - and x_F -bins;

$\frac{N_A \rho l}{A}$ - the number of hydrogen nuclei per cm^2 .

The acceptance and the π^0 reconstruction efficiency were calculated using a Monte-Carlo program. This program generated π^0 -mesons with x_F and p_T distributions and utilized shower profiles obtained from positron beam calibration data to simulate the detector response. The Monte-Carlo generated events were analyzed with the same shower - reconstruction program as used with the real data.

We have found that the ratio of the $N_{\pi^0}^E/M^E$ to the $N_{\pi^0}^H/M^H$ was 10% and did not depend on p_T in the region of interest. ε_{geom} increased from 12% at $p_T \approx 1.5$ GeV/c up to 28% at $p_T \approx 4.5$ GeV/c (for both calorimeters). ε_{REC} decreased slowly from 72% (including $A_E = 0.8$ cut) at $p_T \approx 1.5$ GeV/c down to 66% at $p_T \approx 3.5$ GeV/c and then decreased rapidly down to 56% at $p_T \approx 4.5$ GeV/c. k_{BACK} decreased from 0.93 at $p_T \approx 1.5$ GeV/c down to 0.74 at $p_T \approx 4.5$ GeV/c. $\Delta p_T = 0.2$ GeV/c, and $\Delta x_F = 0.3$. $\frac{N_{A \cdot \rho}^{\pi^0}}{A} = 4.23 \cdot 10^{24}$ nucl/cm².

The invariant cross sections of inclusive π^0 - production in pp - and $\bar{p}p$ -interactions are presented in the Table 1 and in Fig.3 (pp only). The errors in Fig.3 are statistical only. An additional normalization uncertainty was estimated to be $\pm 10\%$ and a p_T scale uncertainty was of $\pm 1\%$. A comparison of $\bar{p}p$ and pp interactions was made. No significant differences were observed.

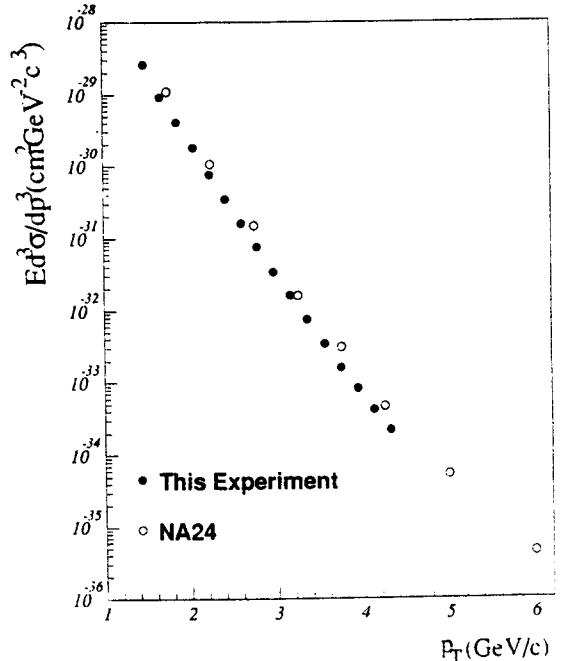


Fig. 3. The invariant cross sections for the reaction $p + p \rightarrow \pi^0 X$ at 200 GeV/c at $x_F = 0$ (black points) and at 300 GeV at $x_F = 0$ (open points).

This agreement of pp -data and $\bar{p}p$ - data is consistent with the results obtained at $\sqrt{s} = 24.3 \text{ GeV}/c$ [15]. We have measured the ratio of the spin-averaged invariant cross sections for the $\bar{p}p$ - and pp -interactions with the same electromagnetic calorimeter but in another kinematic region [16]. We have found that the ratio was close to unity when $x_F \rightarrow 0$ and $1.4 < p_T < 2.0 \text{ GeV}/c$. That is very consistent with the results of the present paper.

Table 1. Invariant cross sections $E d^3\sigma/dp^3$ (in $\text{cm}^2\text{GeV}^{-2}/c^3$) for inclusive π^0 production averaged over x_F range from -0.15 to 0.15. The errors are statistical and systematical. The additional systematic uncertainties are $\pm 1\%$ in the p_T scale and $\pm 10\%$ in the normalization. When calculating the ratio R of the two invariant cross sections, both statistical and systematical errors were taken into account.

$p_T, \text{GeV}/c$	$pp \rightarrow \pi^0 X$	$\bar{p}p \rightarrow \pi^0 X$	$R_{\pi^0}(\bar{p}p/pp)$
1.48	$(0.26 \pm 0.01 \pm 0.03) \times 10^{-28}$	$(0.24 \pm 0.01 \pm 0.02) \times 10^{-28}$	0.92 ± 0.13
1.67	$(0.93 \pm 0.05 \pm 0.08) \times 10^{-29}$	$(0.10 \pm 0.01 \pm 0.01) \times 10^{-28}$	1.07 ± 0.11
1.86	$(0.41 \pm 0.01 \pm 0.03) \times 10^{-29}$	$(0.48 \pm 0.01 \pm 0.04) \times 10^{-29}$	1.17 ± 0.13
2.05	$(0.18 \pm 0.01 \pm 0.01) \times 10^{-29}$	$(0.21 \pm 0.01 \pm 0.02) \times 10^{-29}$	1.17 ± 0.17
2.24	$(0.77 \pm 0.02 \pm 0.06) \times 10^{-30}$	$(0.91 \pm 0.03 \pm 0.07) \times 10^{-30}$	1.18 ± 0.14
2.42	$(0.35 \pm 0.02 \pm 0.03) \times 10^{-30}$	$(0.45 \pm 0.02 \pm 0.03) \times 10^{-30}$	1.29 ± 0.19
2.60	$(0.16 \pm 0.01 \pm 0.01) \times 10^{-30}$	$(0.21 \pm 0.01 \pm 0.01) \times 10^{-30}$	1.31 ± 0.21
2.78	$(0.75 \pm 0.02 \pm 0.05) \times 10^{-31}$	$(0.98 \pm 0.07 \pm 0.07) \times 10^{-31}$	1.31 ± 0.16
2.97	$(0.34 \pm 0.01 \pm 0.02) \times 10^{-31}$	$(0.33 \pm 0.04 \pm 0.02) \times 10^{-31}$	0.97 ± 0.16
3.16	$(0.16 \pm 0.01 \pm 0.01) \times 10^{-31}$	$(0.18 \pm 0.03 \pm 0.01) \times 10^{-31}$	1.13 ± 0.23
3.35	$(0.75 \pm 0.04 \pm 0.05) \times 10^{-32}$	$(0.71 \pm 0.20 \pm 0.05) \times 10^{-32}$	0.95 ± 0.29
3.55	$(0.34 \pm 0.02 \pm 0.03) \times 10^{-32}$		
3.74	$(0.16 \pm 0.01 \pm 0.01) \times 10^{-32}$		
3.93	$(0.83 \pm 0.09 \pm 0.09) \times 10^{-33}$		
4.12	$(0.42 \pm 0.06 \pm 0.05) \times 10^{-33}$		
4.31	$(0.22 \pm 0.04 \pm 0.03) \times 10^{-33}$		

For all p_T - bins we have broken our cross sections into three x_F - bins from $x_F = -0.15$ up to $x_F = 0.15$ with a step $\Delta x_F = 0.1$. Our data confirm well at all p_T the central plateau for inclusive π^0 -production presented in the paper [17].

Our invariant cross sections for the reaction $pp \rightarrow \pi^0 X$ are in a fair agreement with the results of the other experiments [17]-[19]. Invariant cross sections from the experiment NA24 at CERN [18] are shown in Fig.3 (open points). A wide p_T - coverage up to $p_T = 6 \text{ GeV}/c$ in this experiment allows a change of the exponential slope to be seen from 4 $(\text{GeV}/c)^{-1}$ down to lower number (about 3 $(\text{GeV}/c)^{-1}$) somewhere for p_T near 3.6 GeV/c . The E704 points also indicate this behaviour as follows. If we fit our cross section by one exponent e^{-bp_T} in the region $1.6 < p_T < 4.4 \text{ GeV}/c$, then we come up with the exponential slope

$b = (4.2 \pm 0.1) (GeV/c)^{-1}$ and $\chi^2 = 41/13$ degrees of freedom. If we fit these data by two exponents, the results are as follows: $b = (4.3 \pm 0.1) (GeV/c)^{-1}$ in the region $1.6 < p_T < 3.6 GeV/c$ and $b = (3.6 \pm 0.7) (GeV/c)^{-1}$ in the region $3.6 < p_T < 4.4 GeV/c$ and $\chi^2 = 10/11$ degrees of freedom.

4. SINGLE-SPIN ASYMMETRIES

For each selected event the transverse momentum p_T , Feynman variable x_F , and azimuthal angle φ were determined, and a six-dimensional matrix ($p_T, x_F, \varphi, SN, CEMC, POL$) was accumulated. The three additional dimensions were as follows:

SN – snake states 1 (or 2), which meant that the right or "positive" (looking downstream) side of the beam had a spin direction "up" (or "down") at the target. The left "negative" side had the opposite direction.

CEMC – 1 or 2 (depended on which CEMC was triggering).

POL – 1, 2 or 3 for "positive", "negative" and "zero" polarization regions (see description above).

The asymmetry $A_N(p_T)$ for the CEMC1 and for the right "positive" side of the beam was determined from the expression

$$\frac{[n^+(p_T, \varphi) - n^-(p_T, \varphi)]}{[n^+(p_T, \varphi) + n^-(p_T, \varphi)]} = A_N(P_T) \cdot P_{BEAM} \cdot \cos\varphi, \quad (4)$$

where n^+ and n^- are the numbers of events registered for "up" (SN = 1) and "down" (SN = 2) directions of the beam polarization, which were normalized by a flux of particles M^H passing through the target; p_{beam} - the beam polarization (about 0.46).

We calculated four sets of asymmetries with four independent combinations of calorimeter and beam polarization. We used CEMC1 and CEMC2, right and left parts of the beam with average polarizations about 46%. For each of these four methods we used two snake states, SN=1 and SN=2 to calculate n^+ and n^- in the expression (4).

The details are expressed in the Table 2.

Table 2.

CEMC	PART OF THE BEAM	Snake status, corresponding to	
		n^+	n^-
1	right	1	2
1	left	2	1
2	right	2	1
2	left	1	2

Then the final results were obtained by averaging the four asymmetries with their errors. We should mention here that all four asymmetries were in good agreement with each other (within the statistical errors).

Further analysis on the entire data sample has produced different results from a previous publication [13]. The correction of a problem with the polarization decoding, which increases the overall final data set by 30%, mostly accounts for this difference in results. In the $1 < p_T < 3 \text{ GeV}/c$ region, the current result is the same as that given previously, which is a zero asymmetry value. The statistics are large in this region, and the difference in the amount of data analyzed does not impact the asymmetry value. However, in the $3.1 < p_T < 4.6 \text{ GeV}/c$ region, where the amount of statistics is much smaller, the asymmetry values have changed to zero values. In our publication [13] we have claimed that we had seen nonzero asymmetry in this region. Also the recalibration procedure (see Sect. II) may have contributed to this change. Less than 10% of the total number of events were finally removed by different cuts on the data.

Besides the pure inclusive reaction $p \uparrow p \rightarrow \pi^0 X$ we also selected events in which at least one charged particle was observed at the azimuthal angle $\varphi = (180 \pm 30)^\circ$ relative to the produced π^0 direction. Single-spin asymmetries of inclusive π^0 -production in $p \uparrow p$ - and $\bar{p} \uparrow p$ -interactions near 90° in the c.m. are presented in the Tables 3 and 4, and in Fig.4 and 5. The errors are statistical and systematical.

Table 3. Asymmetries in the pure inclusive reaction $p \uparrow p \rightarrow \pi^{\circ}X$ (1) and in the semiinclusive reaction $p \uparrow p \rightarrow \pi^{\circ}X$ when at least one associated charged particle goes at $(180 \pm 30)^{\circ}$ relatively to the π° (2).

$p_T, GeV/c$	(1)	(2)
	$A_N, \%$	$A_N, \%$
1.09	$-0.8 \pm 0.4 \pm 0.4$	$-1.7 \pm 1.6 \pm 1.4$
1.29	$-0.7 \pm 0.5 \pm 0.4$	$-0.3 \pm 1.6 \pm 1.4$
1.48	$0.7 \pm 0.5 \pm 0.5$	$2.1 \pm 1.5 \pm 1.3$
1.67	$1.0 \pm 0.6 \pm 0.5$	$0.8 \pm 1.5 \pm 1.3$
1.86	$0.1 \pm 0.6 \pm 0.5$	$-1.2 \pm 1.6 \pm 1.4$
2.05	$-1.0 \pm 0.7 \pm 0.6$	$-2.0 \pm 1.7 \pm 1.5$
2.24	$0.6 \pm 0.9 \pm 0.8$	$-0.5 \pm 2.1 \pm 1.9$
2.42	$1.6 \pm 1.2 \pm 1.1$	$2.4 \pm 2.8 \pm 2.4$
2.60	$1.0 \pm 1.7 \pm 1.5$	$-2.9 \pm 3.8 \pm 3.3$
2.82	$-3.8 \pm 2.1 \pm 1.9$	$-9.8 \pm 4.7 \pm 4.2$
3.07	$3.2 \pm 4.1 \pm 3.6$	$4.5 \pm 9.2 \pm 8.2$
3.26	$-4.2 \pm 5.8 \pm 5.0$	$-16 \pm 13 \pm 11$
3.49	$1.1 \pm 7.2 \pm 6.3$	$-1 \pm 15 \pm 13$
3.78	$-6 \pm 12 \pm 10$	
4.12	$4 \pm 14 \pm 13$	

Table 4. Asymmetries in the pure inclusive reaction $\bar{p} \uparrow p \rightarrow \pi^{\circ}X$ (1) and in the semiinclusive reaction $\bar{p} \uparrow p \rightarrow \pi^{\circ}X$ when at least one associated charged particle goes at $(180 \pm 30)^{\circ}$ relatively to the π° (2).

$p_T, GeV/c$	(1)	(2)
	$A_N, \%$	$A_N, \%$
1.09	$1.2 \pm 1.5 \pm 1.4$	$4.0 \pm 2.4 \pm 2.2$
1.29	$0.9 \pm 1.6 \pm 1.4$	$2.9 \pm 2.4 \pm 2.2$
1.48	$-2.6 \pm 1.8 \pm 1.6$	$-3.1 \pm 2.8 \pm 2.5$
1.67	$2.0 \pm 2.2 \pm 2.0$	$-4.7 \pm 3.6 \pm 3.3$
1.86	$-5.9 \pm 3.0 \pm 2.7$	$-3.1 \pm 5.0 \pm 4.5$
2.05	$2.2 \pm 4.2 \pm 3.8$	$12 \pm 7 \pm 6$
2.24	$-7.9 \pm 6.3 \pm 5.5$	$2 \pm 9 \pm 8$
2.42	$2.6 \pm 8.2 \pm 7.4$	$-2 \pm 14 \pm 13$
2.60	$8 \pm 12 \pm 11$	$2 \pm 18 \pm 16$
2.78	$-50 \pm 17 \pm 15$	$-50 \pm 28 \pm 25$
3.10	$-33 \pm 19 \pm 17$	$-1 \pm 33 \pm 29$

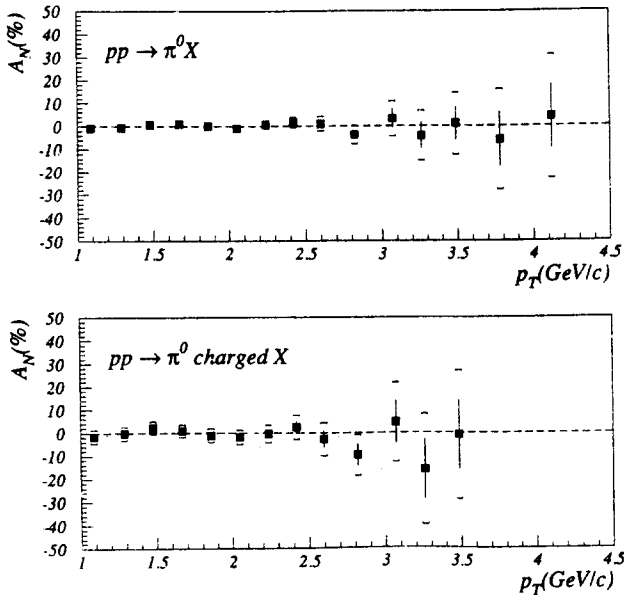


Fig. 4. The asymmetry parameter A_N as a function of p_T at $x_F = 0$ for the pure inclusive reaction $p \uparrow p \rightarrow \pi^0 X$ (a) and for the same reaction, but when at least one charged particle goes at an azimuthal angle, within $(180+30)^\circ$ relative to the π^0 (b). Statistical plus systematical errors are shown.

We have investigated the "stability" of the results in different ways.

For each run we calculated the ratio of n^+/n^- (see expression (4)) for whole the beam. The idea was in that ratio was actually the ratio of invariant cross sections at two opposite snake states and had to be near unity. We calculated the asymmetry only for the runs with this ratio within $1 \pm 2\sigma$, where σ is a statistical error of the ratio. We have not found a significant influence of this criteria on the final results. Eventually we have not used this criteria to save the number of events.

A test was made by eliminating the first 50 events in a spill and the corresponding monitor counts. It turned out that we had "killed" 25% of all events. The conclusion was that the first part of the beam spills with possible "bad structure" did not make a significant impact on the asymmetry.

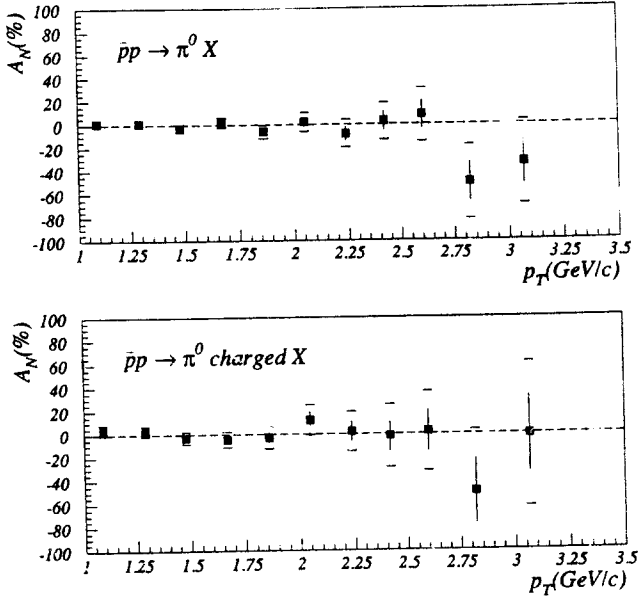


Fig. 5. The asymmetry parameter A_N as a function of p_T at $x_F = 0$ for the pure inclusive reaction $\bar{p} \uparrow p \rightarrow \pi^0 X$ (a) and for the same reaction, but when at least one charged particle goes at an azimuthal angle, $(180 + 30)^\circ$ relatively to the π^0 (b). Statistical plus systematical errors are shown.

We have used a pseudorapidity η instead of the Feynman variable x_F . We integrated over $|\eta| < 0.4$ - region instead of $|x_F| < 0.15$ - region. It did not affect the result at all, because the small CEMC calorimeters could accept only rather sharp x_F -distributions around $x_F = 0$, and the asymmetry did not change very rapidly with deviation from 90° in the c.m.

5. DISCUSSIONS

As was mentioned in the Sect. III, by analysing our cross section measured up to $p_T \sim 4.5 \text{ GeV}/c$ and the NA24 data [18] measured up to $p_T \sim 6 \text{ GeV}/c$, we have concluded that there is a slope break in the π^0 inclusive production cross sections in pp -collisions somewhere near $p_T \sim 3.6 \text{ GeV}/c$. In the previous polarization data (for example, in the measurements of the polarization in the charge - exchange exclusive reactions $\pi^- + p \uparrow \rightarrow \pi^0$ (or $\eta(550)$, or $\omega(783)$, or $f(1270) + n$), it has been found [20]-[23] that there is a strong correlation between cross section and asymmetry behaviour. In the place of a slope break in a cross section there is always a peculiarity in the asymmetry behaviour.

We now compare the present results for the p_T -dependence of A_N in π^0 production by 200-GeV polarized protons with the results from four previous measurements of inclusive pion production at $x_F = 0$ and $p_T < 3 \text{ GeV}/c$, with transversely polarized proton targets or beams at initial energies from 13 to 40 GeV. The Brookhaven experiment [1] had studied π^+ production at 13.3 GeV and 18.5 GeV with the AGS polarized proton beam incident on an unpolarized target. The CERN-PS [2] and Serpukhov [3] experiments had measured π^0 production on polarized proton targets by 24-GeV protons and 40-GeV negative pions, respectively. In all of these experiments the asymmetry was small at low p_T and then rose to relatively large positive values. A positive sign of A_N corresponds to a larger production cross-section to the beam-left (beam-right) when the beam (target) proton spin is vertically-upward. The similarity between π^+ and π^0 production asymmetries may be expected considering that both involve valence u -quark scattering. It had been noticed [3] that, at energies from 13.3 to 40 GeV, the rise of A_N to large positive values occurred at fixed values of the transverse scaling variable $x_T = 0.4$.

This x_T -value was interpreted [3] as a point x_T^0 , where the relative flip-nonflip phase goes to zero and probably changes sign. This scaling of the single-spin asymmetry phase seems to be clearly supported by the experimental data in the beam momentum range from 13 to 40 GeV/c.

The experimental data on $A_N(0, p_T)$ in this experiment do not exhibit a structure around the predicted point $p_T \approx 4 \text{ GeV}/c$, however the p_T dependence of the production cross section $Ed^3\sigma/dp_T$ at $x_F = 0$ shows a change of the exponential slope near $p_T = 3.6 \text{ GeV}/c$. It can indicate that there is some peculiarity in the asymmetry behaviour, that may be the asymmetry phase scaling. By extrapolating this x_T^0 -scaling seen at low energies to the energy of 200 GeV, one can expect that the asymmetry should start to rise up from zero values somewhere near $p_T = 4 \text{ GeV}/c$.

What we have observed in the asymmetry measurements is as follows. The asymmetry is zero for single inclusive π^0 -production in pp -interactions in the $1 < p_T < 3 \text{ GeV}/c$ region within the accuracy of up to 2%. At larger p_T , the errors grow from 5% at $p_T \approx 3.3 \text{ GeV}/c$ up to 15% at $p_T \approx 4.1 \text{ GeV}/c$. The statistics are too poor to make a definite conclusion about nonzero asymmetry, though in our previous publication with the preliminary results [13] we claimed that we have seen positive asymmetry.

No significant difference was observed when we selected events with additional charged particles (at least one), going at $(180 \pm 30)^\circ$ relatively to the π^0 .

It was based on an idea that by using the criteria described above we should enrich hard parton-parton interactions and the asymmetry would not be diluted by soft processes, but the asymmetry remained equal to zero.

For $\bar{p} \uparrow p$ -interactions, the statistics are an order of magnitude less. The asymmetry is equal to zero within statistical accuracy in the $1 < p_T < 3 \text{ GeV}/c$ region, except the two last points (3 and 1.5 standard deviations from zero).

In the model for inclusive processes based on the \hat{U} -matrix it is predicted that asymmetry decreases with the energy increased [24]. The expected value of asymmetry in this model is at the level of a few percents at 200 GeV, that does not contradict with our results.

Observations of small or zero asymmetry at large p_T agree with the recent calculation of a twist-3 effect [9], and also with the model of an orbiting valence quark around a polarization axis that produces zero asymmetry at $x_F = 0$, but a large asymmetry at large x_F [25].

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