Single-Spin Asymmetries in Inclusive Charged Pion Production by Transversely Polarized Antiprotons

A. Bravar,[17,*] D. L. Adams,[16] N. Akchurin,[6] N. I. Belikov,[5] B. E. Bonner,[16] J. Bystricky,[2] M. D. Corcoran,[16] J. D. Cossairt,[3] J. Cranshaw,[16,†] A. A. Derevschikov,[5] H. En'yo,[8] H. Funahashi,[8] Y. Goto,[8] O. A. Grachov,[5] D. P. Grosnick,[1] D. A. Hill,[1] T. Iijima,[8] K. Imai,[8] Y. Itow,[8,‡] K. Iwatani,[4] Yu. V. Kharlov,[5] K. Kuroda,[11] M. Laghai,[1] F. Lehar,[2] A. de Lesquen,[2] D. Lopiano,[1] F. C. Luehring,[13,§] T. Maki,[7] S. Makino,[8,**] A. Masaike,[8] Yu. A. Matulenko,[5] A. P. Meschanin,[5] A. Michalowicz,[11] D. H. Miller,[13] K. Miyake,[8] T. Nagamine,[8] F. Nessi-Tedaldi,[16,††] M. Nessi,[16,††] C. Nguyen,[16] S. B. Nurushev,[5] Y. Ohashi,[1] Y. Onel,[6] D. I. Patalakha,[5] G. Pauletta,[18] A. Penzo,[17] G. F. Rappazzo,[12] A. L. Read,[3] J. B. Roberts,[16] L. van Rossum,[2] V. L. Rykov,[5] N. Saito,[8,‡‡] G. Salvato,[12] P. Schiavon,[17] J. Skeens,[16] V. L. Solovyanov,[5] H. Spinka,[1] R. W. Stanek,[1] R. Takashima,[9] F. Takeutchi,[10] N. Tamura,[14] D. G. Underwood,[1] A. N. Vasiliev,[5] J. L. White,[16,§§] S. Yamashita,[8] A. Yokosawa,[1] T. Yoshida,[15] and A. M. Zanetti[17]

(Fermilab E704 Collaboration)

[1] *Argonne National Laboratory, Argonne, Illinois 60439*
[2] *CEA-DAPNIA/SPP, CE-Saclay, F-91191 Gif-sur-Yvette, France*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[4] *Hiroshima University, Higashi-Hiroshima 724, Japan*
[5] *Institute of High Energy Physics, 142284 Protvino, Russia*
[6] *Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242*
[7] *University of Occupational and Environmental Health, Kita-Kyushu 807, Japan*
[8] *Department of Physics, Kyoto University, Kyoto 606-01, Japan*
[9] *Kyoto University of Education, Kyoto 612, Japan*
[10] *Kyoto-Sangyo University, Kyoto 612, Japan*
[11] *Laboratoire de Physique des Particules, BP 909, 74017 Annecy-le-Vieux, France*
[12] *Dipartimento di Fisica, Università di Messina and INFN Messina, I-98100 Messina, Italy*
[13] *Physics Department, Northwestern University, Evanston, Illinois 60201*
[14] *Department of Physics, Okayama University, Okayama 800, Japan*
[15] *Osaka City University, Osaka 558, Japan*
[16] *T.W. Bonner Nuclear Laboratory, Rice University, Houston, Texas 77251*
[17] *Dipartimento di Fisica, Università di Trieste and INFN Trieste, I-34100 Trieste, Italy*
[18] *Università di Udine and INFN Udine, I-33100 Udine, Italy*

(Received 17 April 1996)

The analyzing power A_N in inclusive π^- and π^+ production has been measured with a 200 GeV/c transversely polarized antiproton beam over a wide x_F range ($0.2 \leq x_F \leq 0.9$) and at moderate p_T ($0.2 \leq p_T \leq 1.5$ GeV/c). The asymmetry A_N increases with increasing x_F from zero to large positive values for π^-'s, and decreases from zero to large negative values for π^+'s. A threshold for the onset of the asymmetry is observed about $p_T \sim 0.5$ GeV/c, below which A_N is essentially zero and above which A_N increases (decreases) with p_T for π^-'s (π^+'s) in the covered p_T range. [S0031-9007(96)01209-4]

PACS numbers: 13.88.+e, 13.85.Ni, 14.40.Aq

For the first time a high energy polarized antiproton beam was obtained at Fermilab from the parity violating decay of anti-Λ^0 hyperons [1]. Inclusive reactions measured with this beam give insight into the spin dependence of the underlying partonic processes and add new input regarding the debated question of the spin structure of polarized protons. The results from polarized lepton deep inelastic scattering [2] suggest that the overall contribution of constituent quarks to the proton helicity is small, thus implying an appreciable contribution either of sea quarks, or of gluons, or possibly of orbital angular momentum to the proton spin structure. Significant polarization effects are known to exist at medium and high energies in meson and hyperon production with hadron beams [3]: Pions produced by polarized protons show large values of the analyzing power A_N at high x_F, and hyperons produced at high x_F show large transverse polarization. A_N in inclusive pion production with polarized protons was also measured at 200 GeV/c [4,5]: The $\pi^\pm$ asymmetry shows an almost mirror symmetric dependence in x_F, where A_N increases with increasing x_F to large positive values for π^+ and decreases to large negative values for π^-. More recently, large negative values of A_N in inclusive Λ^0 production at 200 GeV/c and large x_F have also been published [6]. These effects appear already at relatively low values of the transverse momentum p_T ($p_T \sim 1.0$ GeV/c), where perturbative QCD is not expected to be applicable. Models were developed to explain and possibly correlate the spin observables in these processes using static SU(6) wave functions and spin dependent asymmetries introduced into

 0031-9007/96/77(13)/2626(4)$10.00

the quark and di-quark production and scattering amplitudes [7]. The features of the pion data are compatible with these models, based on the idea that leading valence quarks remember their polarization in the parent proton, and consistent with the interpretation of Λ^0 polarization, where quarks produced in fragmentation processes acquire a transverse polarization.

In this Letter we report on the measurement of the analyzing power A_N in inclusive π^- and π^+ production,

$$\bar{p}\uparrow + p \rightarrow \pi^-(\pi^+) + X\,,$$

using the 200 GeV/c Fermilab polarized antiproton beam incident on a 1.0 meter long liquid hydrogen target. The kinematic range covered is $0.2 \leq x_F \leq 0.9$ and $0.2 \leq p_T \leq 1.5$ GeV/c. A_N measures the left-right scattering asymmetry with respect to the beam polarization directed normal to the production plane, and positive A_N corresponds to a larger cross section for particle production to the beam left for beam polarization directed upward.

The polarized antiproton beam was obtained by selecting antiprotons from the weak decay of anti-Λ^0 particles produced in a primary target by the 800 GeV/c Tevatron extracted proton beam. The design and performance of the beam are described in Ref. [1]. Decay antiprotons are longitudinally polarized in the anti-Λ^0 decay rest frame; those emitted near $\pm 90°$ acquire a transverse polarization of $\mp 64\%$ when Lorentz boosted to the laboratory frame. The antiproton polarization, on average, was determined by tagging the trajectory in the horizontal plane at an intermediate focus of the beam line, where the momentum was also measured. The tagged polarization interval ranged from -0.65 to $+0.65$, thus allowing the simultaneous use of antiprotons of opposite polarization. Events with tagged polarization values from 0.35 to 0.65 (-0.65 to -0.35) were used in the A_N analysis and defined to have positive (negative) polarization. The average polarization was 0.45 for both signs with an estimated accuracy of ± 0.03. A spin rotator consisting of 12 dipole magnets rotated the transverse beam polarization from the horizontal to the vertical direction at the experimental target. Typical beam intensities at the target were of the order of 3×10^6 particles per 20 second Tevatron spill. About 17% were antiprotons, the rest were mainly pions from K_S^0 decays and muons, which were vetoed with two beam line Cherenkov threshold counters.

The pions produced at the target were measured with a large forward spectrometer described in Refs. [4] and [6]. The reconstruction of charged tracks produced at the target was done with two telescopes of multiwire proportional chamber modules, 5 upstream and 5 downstream of a 3-Tm $\int B dl$ dipole magnet, which was used for momentum measurement. Identification of the charged pions produced at the target was accomplished with a 25 meter long threshold Cherenkov counter, C1, located downstream of the analyzing magnet. C1 was filled with helium gas, and its gas pressure was set so that it would count pions with $P_\pi \geq 40$ GeV/c ($x_F \geq 0.2$) but not protons or kaons. The π^- and π^+ data were taken in separate runs with inverted polarities of the analyzing magnet. The trigger required antiproton beam definition [1] and pion identification. A simple trigger using three hodoscopes downstream of the analyzing magnet in conjunction with fast programmable electronics selected events where the hodoscope hit patterns were compatible with at least one high momentum ($P > 40$ GeV/c) trajectory from the target. Charged pions were tagged with C1. Background events due to noninteracting beam particles were reduced by using a beam veto located at the downstream end of the spectrometer.

The reconstruction efficiency of the offline tracking program was found to be better than 85% for a single track. The position resolution on the production point of a track in the target was better than 1 mm in the transverse plane and a few centimeters along the beam axis. It was required that selected tracks matched the beam track in the target volume within the measured track resolution and that they traversed the C1 fiducial volume determined by its mirrors. These selections were found to be independent of the kinematical variables x_F and p_T. The background due to misidentified particles and particle production other than at the target was found to be less than 5% in the selected sample.

The analyzing power A_N was determined from the measured yields of pions produced in a well defined azimuthal angular interval around the beam axis using vertically polarized antiprotons of both polarization signs:

$$A_N = \frac{1}{P_B \langle \cos\phi \rangle} \frac{N\uparrow - N\downarrow}{N\uparrow + N\downarrow}\,.$$

P_B is the beam polarization, and ϕ is the azimuthal angle between the beam polarization axis directed upward and the normal to the production plane. The selected azimuthal angular interval was $\pm 45°$ from the horizontal plane to the beam right, giving $\langle \cos\phi \rangle \approx -0.90$. $N\uparrow$ ($N\downarrow$) is the number of pions produced for positive (negative) spin orientation of the beam antiprotons at the target, normalized to the corresponding beam flux. $N\uparrow$ was obtained by combining events having positive tagged polarization and negative spin rotator polarity with events having negative tagged polarization and positive spin rotator polarity. $N\downarrow$ was obtained from events with equal tagged polarization sign and spin rotator polarity.

A number of consistency checks were performed to establish that the asymmetry results were free of systematic effects. This asymmetry, to a good accuracy, is independent of detection and reconstruction efficiencies, since pion yields were measured with the same apparatus and both polarizations simultaneously. We evaluated the *false* asymmetries by averaging over opposite spin rotator states or over both tagged polarization signs. The average beam polarization was zero for these sets of events. These asymmetries were found to be consistent with zero (*false*

TABLE I. A_N data for $\bar{p}\uparrow + p \rightarrow \pi^- + X$ and $\bar{p}\uparrow + p \rightarrow \pi^+ + X$ as a function of x_F. The reported errors are statistical (first error) and systematic (second error).

x_F	A_N %	$\langle p_T(\mathrm{GeV/c})\rangle$	No. of events
	$\bar{p}\uparrow + p \rightarrow \pi^- + X$		
0.2–0.3	1.1 ± 2.6 ± 0.1	0.38	9386
0.3–0.4	1.4 ± 2.0 ± 0.1	0.48	14 707
0.4–0.5	5.3 ± 2.2 ± 0.4	0.51	11 688
0.5–0.7	11.9 ± 2.5 ± 1.0	0.61	9466
0.7–0.9	21.8 ± 6.7 ± 1.8	0.81	1267
	$\bar{p}\uparrow + p \rightarrow \pi^+ + X$		
0.2–0.3	2.0 ± 2.6 ± 0.2	0.38	8851
0.3–0.4	1.1 ± 2.2 ± 0.1	0.46	12 167
0.4–0.5	−6.1 ± 2.7 ± 0.5	0.55	8339
0.5–0.7	−14.8 ± 3.3 ± 1.2	0.66	5264
0.7–0.9	−34 ± 11 ± 3	0.82	439

$A_N = -0.009 \pm 0.012$ for π^- data and $+0.003 \pm 0.014$ for π^+ data), thus indicating no bias in the determination of A_N. A systematic uncertainty is introduced in the asymmetry results by the precision on the beam polarization ($\Delta P_B/P_B = 0.067$), the antiproton beam contamination (<2%), and the background in the data sample (<5%). We estimated the upper limit of this error to be $\delta A_N^{\mathrm{sys}} \leq 0.085 A_N$ for each x_F and/or p_T data point, which is considerably smaller compared to the statistical uncertainties.

The analyzing power A_N is given in Table I and shown in Fig. 1 as a function of x_F for the π^- and π^+ data over a p_T range of 0.2–1.5 GeV/c. The data exhibit an almost mirror symmetric dependence in x_F in which the magnitude of A_N increases for both π^- and π^+ mesons with increasing x_F, but the sign of A_N is positive for the π^- data and negative for π^+ data. Figure 2 and Table II show the same asymmetry as a function of p_T averaged over the x_F interval of 0.2–0.9. These data show a threshold effect about $p_T \sim 0.5$ GeV/c, above which A_N increases in magnitude for both π^-'s and π^+'s (see Fig. 3, $p_T \geq 0.5$ GeV/c), and below this p_T value, A_N is significantly smaller and compatible with zero.

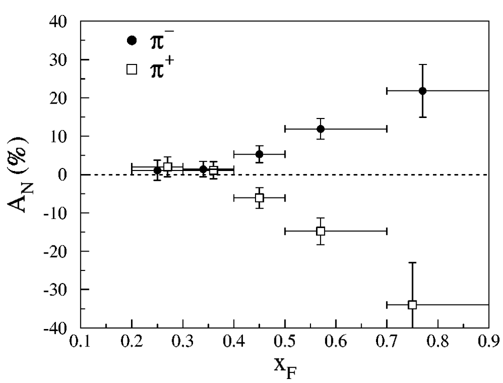

FIG. 1. A_N data as a function of x_F for π^- (full circles) and π^+ (open squares) integrated over p_T. For clarity the first two π^- (π^+) data points are offset by −0.01 (+0.01) units in x_F.

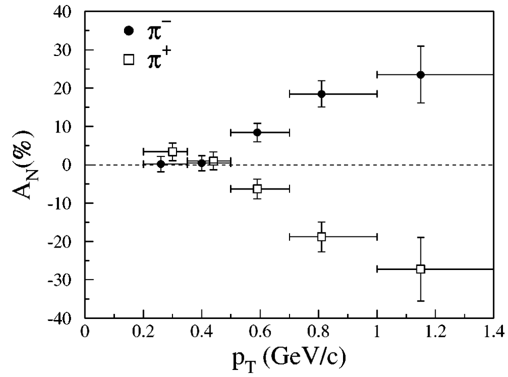

FIG. 2. A_N data as a function of p_T for π^- (full circles) and π^+ (open squares) in the x_F range of 0.2–0.9. For clarity, the first two π^- (π^+) data points are offset by −0.02 (+0.02) GeV/c.

Large values of A_N have been observed in inclusive pion production experiments with polarized proton beams by E704 [4] and previous experiments at lower energies [8]. The A_N results for charged pions presented in this work are compared in Fig. 3 with π^0 data obtained with the same polarized antiproton beam [5] over the overlapping p_T range. For π^0 data, A_N has the same sign as for π^- data and is about half as large. In $\bar{p}\uparrow + p \rightarrow \pi^+ + X$, A_N appears to be similar to that in $p\uparrow + p \rightarrow \pi^- + X$, while, for $\bar{p}\uparrow + p \rightarrow \pi^- + X$, A_N is slightly smaller compared to $p\uparrow + p \rightarrow \pi^+ + X$ data in the same kinematical region.

In summary, the analyzing power for π^- production increases from 0 to about +0.25 with increasing x_F above $p_T \sim 0.5$ GeV/c while, for π^+ production, A_N decreases from 0 to about −0.35 with increasing x_F above the same p_T. It appears that A_N depends primarily on x_F, and reaches large values above a p_T threshold of about 0.5 GeV/c.

These results could be explained qualitatively as an effect similar to that proposed to explain the hyperon polarization [7], in which $q\bar{q}$ pairs produced in fragmentation

TABLE II. A_N data for $\bar{p}\uparrow + p \rightarrow \pi^- + X$ and $\bar{p}\uparrow + p \rightarrow \pi^+ + X$ as a function of p_T. The reported errors are statistical (first error) and systematic (second error).

$p_T(\mathrm{GeV/c})$	A_N (%)	$\langle x_F\rangle$	No. of events
	$\bar{p}\uparrow + p \rightarrow \pi^- + X$		
0.2–0.35	0.2 ± 2.0 ± 0.1	0.35	14 279
0.35–0.5	0.4 ± 2.0 ± 0.1	0.39	14 047
0.5–0.7	8.4 ± 2.3 ± 0.7	0.44	11 630
0.7–1.0	18.5 ± 3.1 ± 1.5	0.50	6123
1.0–1.5	23.5 ± 7.1 ± 2.0	0.59	1203
	$\bar{p}\uparrow + p \rightarrow \pi^+ + X$		
0.2–0.35	3.4 ± 2.3 ± 0.3	0.32	10 465
0.35–0.5	1.0 ± 2.3 ± 0.1	0.36	10 676
0.5–0.7	−6.3 ± 2.6 ± 0.5	0.41	9101
0.7–1.0	−18.8 ± 3.6 ± 1.5	0.47	4672
1.0–1.5	−27.2 ± 8.0 ± 2.3	0.55	953

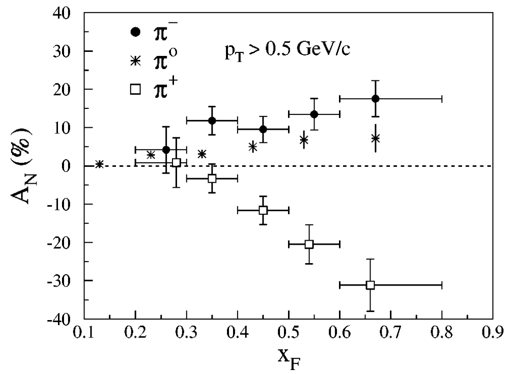

FIG. 3. A_N data as a function of x_F for π^- and π^+ for $p_T \geq 0.5$ GeV/c. A_N data for π^0 in a similar p_T range are also shown [5]. The first π^- and π^+ data points are offset by -0.01 and $+0.01$ x_F units, respectively.

processes become transversally polarized, and, at large x_F, the transverse spin of the (anti)protons is correlated to its (anti)quark constituents. To produce a spin-zero meson, the polarized $(q)\bar{q}$ will couple with the spectator (anti)*up* or (anti)*down* quark from the polarized (anti)proton beam only in an antiparallel configuration. The reflected sign of π^-'s with respect to π^+'s (and between $\bar{p}$ and p beams) might originate from the fact that the up (anti)quark spin is almost fully aligned with that of the (anti)proton for x_F approaching one, whereas that of the down (anti)quark is oppositely aligned. Recent models based on nonperturbative approaches, such as a *soft* π exchange mechanism [9], or resonance-decay interference between real and virtual channels [10], or rotating constituents in the polarized (anti)proton [11], appear to be in good qualitative agreement with the features of the data on the pion production asymmetry measured with both polarized protons and antiprotons.

We are grateful for the assistance of the staff of Fermilab and of all the participating institutions. This work would not have been possible without the ideas and efforts of our colleagues M. M. Gazzaly, R. Rzaev, N. Tanaka, and A. Villari; we regret their passing away and we will miss them all greatly. This experiment was supported by the U.S. Department of Energy, the Istituto di Fisica Nucleare in Italy, the Commissariat à l'Energie Atomique and the Institut National de Physique Nucléaire et de Physique des Particules in France, the former U.S.S.R. Ministry of Atomic Power and Industry, and the Ministry of Education Science and Culture in Japan.

*Present address: Universität Mainz, D-55099 Mainz, Germany.
†Present address: INFN Trieste, I-34100 Trieste, Italy.
‡Present address: Inst. for Cosmic Ray Research, University of Tokyo, Gifu 506-12, Japan.
§Present address: Indiana University, Bloomington, IN 47405.
**Present address: Wakayama Medical College, Wakayama 649-63, Japan.
††Present address: CERN, CH-1211 Geneva 23, Switzerland.
‡‡Present address: Radiation Laboratory, Riken, Saitama 351-01, Japan.
§§Present address: SLAC, Standford, CA 94309.

[1] D. P. Grosnick *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **290**, 269 (1990).
[2] J. Ashman *et al.*, Phys. Lett. B **206**, 364 (1988).
[3] A. Bravar, in *Proceedings of the Adriatico Research Conference on Trends in Collider Spin Physics, Trieste 1995,* edited by Y. Onel, N. Paver, and A. Penzo (World Scientific, Singapore, to be published), and references therein.
[4] D. L. Adams *et al.*, Phys. Lett. B **264**, 462 (1991).
[5] D. L. Adams *et al.*, Phys. Lett. B **261**, 201 (1991).
[6] A. Bravar *et al.*, Phys. Rev. Lett. **75**, 3073 (1995).
[7] T. A. Degrand and H. I. Miettinen, Phys. Rev. D **23**, 1227 (1981); **24**, 2419 (1981); **31**, 661(E) (1985); T. A. DeGrand, J. Markkanen, and H. I. Miettinen, *ibid.* **32**, 2445 (1985); B. Andersson, G. Gustafson, and G. Ingelman, Phys. Lett. **85B**, 417 (1979).
[8] W. H. Dragoset *et al.*, Phys. Rev. D **18**, 3939 (1978); S. Saroff *et al.*, Phys. Rev. Lett. **64**, 995 (1990); B. E. Bonner *et al.*, Phys. Rev. D **41**, 13 (1990).
[9] J. Soffer and N. A. Törnqvist, Phys. Rev. Lett. **68**, 907 (1992).
[10] R. Barni, G. Preparata, and P. G. Ratcliffe, Phys. Lett. B **296**, 251 (1992).
[11] C. Boros, L. Zuo-tang, and M. Ta-chung, Phys. Rev. Lett. **70**, 1751 (1993); Phys. Rev. D **51**, 4867 (1995).