Analyzing-Power Measurement in Inclusive π^0 Production at High x_F

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The analyzing power A_N in inclusive π^0 production has been measured with use of the new 185-GeV/c Fermilab polarized proton beam. We obtain the value $A_N=0.10\pm0.03$ for π^0's in the kinematic region $0.2<x_F<0.8$ and $0.3<p_T<1.2$ GeV/c. In certain models of particle production this suggests that the spin of the proton is carried by its valence quarks.

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It is well known from earlier experiments that polarization effects are present in high-energy hyperon and meson production. Hyperons produced with proton or meson beams at high values of Feynman x show large polarization,[1] the production of mesons (π^+,π^-,K_S^0) by a polarized proton beam at lower energies[2,3] show nonvanishing values of analyzing power, and ρ mesons produced in meson-nucleon collisions[4] show significant spin alignment. Since these effects appear at low values of transverse momenta ($p_T\sim1$ GeV/c) and are therefore due to soft processes, a perturbative QCD calculation cannot be performed. However, the observed pattern of measurements is reasonably well reproduced by a model[5] that describes these production processes through the recombination of beam fragments with sea quarks. In this framework, spin-dependent asymmetries are introduced, by means of small parameters, in the quark and diquark production and scattering amplitudes. Spin observables are then calculated with use of static SU(6) wave functions, under the assumption that the spins of the beam-particle fragments are preserved in the scattering and recombination processes. Analyzing-power measurements test all the characteristics of the model, since not only the existence of a polarization mechanism is involved, but also the spin-flavor structure of the wave functions and the conservation of spin during fragmentation and recombination. In addition, such an effect might allow a relatively simple monitoring of the beam polarization for other experiments.

The polarized beam for the experiment was produced at Fermilab by selecting protons arising from the weak decay of Λ hyperons produced in a primary target. Protons emitted at an angle near $\pm90°$ in the Λ rest frame are transversely polarized with respect to their path in the laboratory; those emitted near 0° are longitudinally polarized. Therefore, it is possible to determine their polarization by tagging their trajectories. Along any direction in space, the polarization distribution has values from -0.64 to 0.64.[6] The secondary beam line is shown in Fig. 1, together with the experimental setup. The performance of this beam-production scheme is presented in detail in Ref. 7. After the primary target T1, the selection of Λ-decay protons was achieved with a sweeper system SW, deflections in magnetic fields, and the elimination of neutrals in beam dump ND.

A deflection along the vertical direction observed in hodoscopes M1–M3 allowed momentum determination. Together with the transverse position information of hodoscopes P1–P3, this allowed a full reconstruction of the kinematics, as required to determine the beam polarization. The tagged transverse polarization component was in the horizontal plane. Vertical polarization at the π^0 target was obtained through rotation by means of a spin rotator ("Siberian snake") SN, consisting of eight dipoles.[8] To suppress systematic errors the polarity of the spin rotator, and therefore the correlation between each beam ray incident on the target and its polarization sign, was reversed every ten Tevatron spills. For the present measurement we used only protons with tagged polarization magnitudes between 0.30 and 0.55, representing 47% of the total beam flux, with an average nominal polarization magnitude of 0.44. This value, along with the validity of the polarized beam-production scheme, and the performance of the spin-rotator system were confirmed by an absolute measurement of the Coulomb dissociation of beam protons into proton-π^0 pairs (inverse Primakoff effect).[7] For protons with a tagged polarization magnitude between 0.35 and 0.55 the measured polarization was 0.40 ± 0.12. We selected a proton beam with average momentum of 185 GeV/c and $\pm 9\%$ momentum spread.

The threshold Cherenkov counters C1 and C2 identified pions, about 13% of the beam. Because the mean beam phase space was 2 mrad cm, each beam-particle track was reconstructed by means of segmented hodoscopes placed at each end of the rotator magnet system, to accurately determine the transverse momentum of the produced pions. With one pair of X,Y hodoscopes, S1, placed 23.8 m upstream of the target, and a second pair, S2, placed 2.45 m upstream, we obtained a precision in the reconstruction of the angle of incidence of 0.1 mrad.

The layout of the experiment consisted of an electromagnetic calorimeter GC placed on one side of the beam axis B, 50.5 m downstream of the target T2, with a surface area of 0.5 m^2, for the detection of the $\pi^0 \to \gamma\gamma$ decay products. The calorimeter had two sequential sections: upstream were 124 lead-glass modules (6.35×6.35 cm^2, $13X_0$), which provided the necessary position resolution; downstream was a lead-scintillator sandwich ($\sim 20X_0$). The modules were stacked in the shape of a semicircle, placed symmetrically with respect to the horizontal plane, to have a homogeneous acceptance for pions with the same transverse momentum. The inner, straight edge of the detector was at a distance of 30 cm from the nominal beam axis, to reduce noise and enhance the acceptance for high transverse momentum π^0's. The Pb-scintillator calorimeter allowed the total absorption of the γ energy from the observed $\pi^0 \to \gamma\gamma$ decay. This detector was segmented vertically into five rectangular parts each viewed by four photomultiplier tubes to allow separation of the contributions to the energy deposition coming from different showers.

The high-x_F π^0 trigger consisted of energy deposition in the lead glass of more than 30 GeV in anticoincidence with a charged-particle veto counter upstream of the lead glass. We required the interaction to be initiated by a beam particle with momentum and polarization tagged successfully, in coincidence with a beam telescope BT placed immediately upstream of the target, and in anticoincidence with the two threshold beam Cherenkov counters C1 and C2. The calorimeter stability was monitored continuously with a light-emitting diode light source coupled to the modulus via quartz fiberoptics. Before each accelerator spill (repetition rate of about one 20-sec spill/min) light-emitting diode data as well as one pedestal measurement were acquired. Three refer-

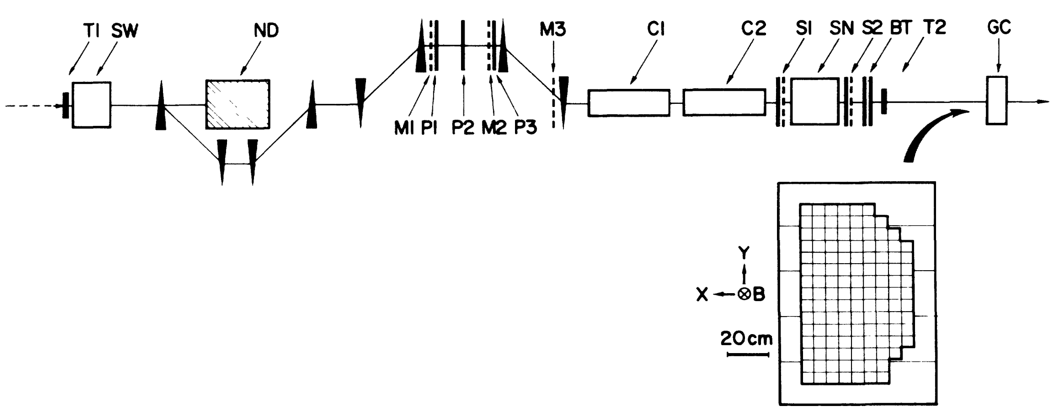

FIG. 1. Elevation view (not to scale) of the secondary beam line and the experimental arrangement, and front view of the electromagnetic calorimeter.

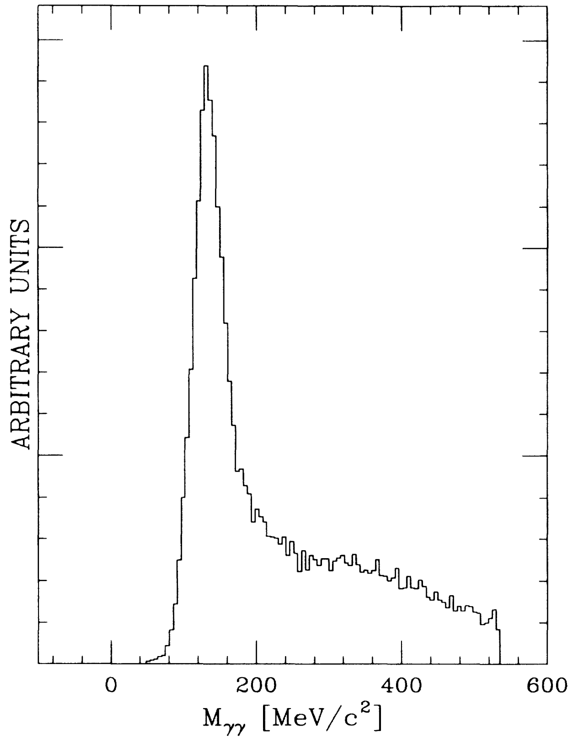

FIG. 2. $\gamma\gamma$ invariant mass.

ence light sources of ^{241}Am-doped scintillator viewed by photomultipliers were used for an absolute monitoring of coherent gain shifts in the whole system.

A total of 285000 triggers was collected, for a beam flux of 1.17×10^{10} protons. Half the data were obtained with a 10-cm-thick polyethylene target, and half with a 7-mm scintillator target. The average beam rate of 10^7 particles per Tevatron spill produced typically 300 triggers, 7% of which reconstructed to a π^0. The reconstructed mass resolution was typically ±17 MeV/c^2 (see Fig. 2), as expected from the finite position resolution of the lead glass and the overall energy and sampling resolution of the calorimeter.

We have determined the analyzing power A_N for π^0 production taking the average of the results obtained with two spin-rotator polarities evaluated separately. For positive rotator sign, A_N is given by

$$A_N = -\frac{1}{P_B \cos\phi}\frac{N_\uparrow(\phi)-N_\downarrow(\phi)}{N_\uparrow(\phi)+N_\downarrow(\phi)}. \quad (1)$$

The azimuthal angle ϕ is defined as that between the beam-polarization direction and the normal to the π^0 production plane. $N_{\uparrow,(\downarrow)}$ is the number of π^0's produced for beam spin tagged as positive (negative), normalized to the beam flux. P_B is the average beam polarization. The negative sign in front of the equation is due to the fact that the detector was placed to the right of the beam. For negative rotator polarity A_N is given by expression (1) reversed in sign. The data were binned into four regions of Feynman x. The results are presented in Fig. 3 and Table I, together with the average values of x_F and p_T for each bin. The average analyzing power we observe for $\langle x_F\rangle=0.52$ and $\langle p_T\rangle=0.8$ GeV/c is 0.10 ± 0.03. Systematic effects on the result are negligible. Their magnitude, which is determined as the contribution to the measured analyzing power that does not reverse sign under reversal of rotator polarity, is 0.03 ± 0.03. The error in the absolute magnitude of the beam-polarization determination, which is the same for all data points, has not been included. The analyzing power of the events constituting the background was also determined to be consistent with zero. The background underneath the π^0 peak was fitted and the measured asymmetry scaled accordingly.

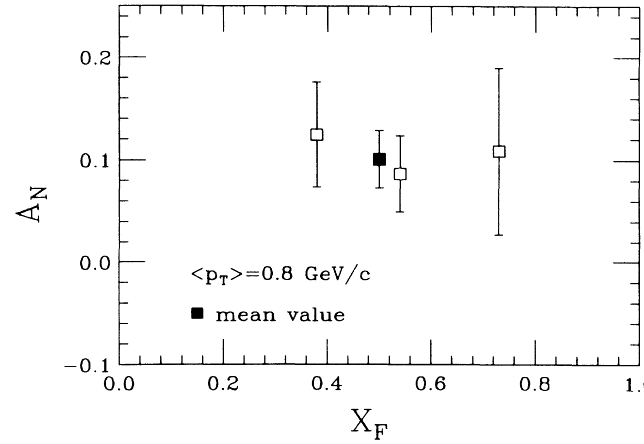

FIG. 3. The analyzing power A_N for π^0 production by polarized protons.

We have evaluated the prediction for the analyzing power following the assumptions of Ref. 5, and for pion production we obtain

$$A_N(\pi^+) = \frac{2}{3}\frac{(\epsilon+\epsilon')}{(1+\epsilon\epsilon')},\quad A_N(\pi^0) = \frac{1}{3}\frac{(\epsilon+\epsilon')}{(1+\epsilon\epsilon')},$$
$$A_N(\pi^-) = -\frac{1}{3}\frac{(\epsilon+\epsilon')}{(1+\epsilon\epsilon')}, \quad (2)$$

where ϵ and ϵ' reflect the different spin-orbit couplings of slow sea partons and fast valence quarks, respectively. They can be extracted from polarization measurements

TABLE I. Analyzing power of π^0 produced with a polarized proton beam.

$\langle x_F\rangle$	$\langle p_T\rangle$ (GeV/c)	A_N
0.28	0.41	0.020 ± 0.191
0.38	0.66	0.125 ± 0.051
0.53	0.78	0.087 ± 0.037
0.73	1.02	0.109 ± 0.081

of Λ production from proton[3,9] and kaon[10] beams. The predictions are expected to be valid at high x_F, where the ratio of π^+ to π^- production follows the u- and d-quark structure functions.[11] The resulting prediction is

$$A_N(p \rightarrow \pi^0) = A_N(\bar{p} \rightarrow \pi^0) = 0.19 \pm 0.02 .$$

(The error contains only the statistical errors on the polarization-measurement results used, not, however, the uncertainties of the model.) We have also taken into account indirect π^0 production through ρ-meson decays, and we calculate a slight increase in the expected value for A_N. Other data on hyperon production[12,13] indicate that inclusion of a spin-spin term in the model[5] improves the agreement with the data.

Our nonvanishing result for $A_N(\pi^0)$ suggests that fast quarks remember the transversity of the incident proton. In addition, despite the simplicity of the phenomenological description we find an agreement in sign and in order of magnitude between measurement and the expectation of the parton-recombination model,[5] based on the results of polarization measurements in hyperon production. The same is true for lower-energy data on charged-pion production.[2]

We were also able to perform a very short measurement using a polarized antiproton beam, originating from $\bar{\Lambda}$ decays. We collected 4300 π^0 triggers for a beam flux of 8.5×10^7 antiprotons; in this case we obtain $A_N = -(0.26 \pm 0.19)$ for $\langle x_F \rangle = 0.38$ and $\langle p_T \rangle = 0.6$ GeV/c.

Our results encourage us to extend these measurements to other mesons and hyperons to provide a more complete picture of the mechanisms involved in these processes, especially since the relationship of the spin of the nucleons to that of the underlying constituents has recently been questioned.[14]

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