Analyzing power of inclusive production of π^+, π^-, and K_S^0 by polarized protons at 13.3 and 18.5 GeV/c

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We have measured the analyzing power in π^+, π^-, and K_S^0 production by a polarized proton beam at 13.3 and 18.5 GeV/c. The data cover the central and the beam fragmentation region, in the transverse-momentum range up to 2 GeV/c. The results indicate that sizable effects are present at high x_F and also persist into the hard-scattering region for K_S^0 and π^+. A zero value of the analyzing power was observed for π^- production.

In recent years, measurements of single-spin-dependent observables in the production or scattering of hadrons have been acquiring an increasing interest due to the implications they have for our knowledge of QCD. In particular, the production of mesons or jets at high transverse momenta p_T has been the object of several theoretical investigations, since unexpected nonvanishing spin effects have been observed in inclusive meson production off a polarized target.[1,2] The measured quantity is the spin-dependent asymmetry of the production cross section or analyzing power A, which is defined as

$$A=\frac{1}{P_B\cos\phi}\frac{N_\uparrow(\phi)-N_\downarrow(\phi)}{N_\uparrow(\phi)+N_\downarrow(\phi)}\ , \qquad (1)$$

where $N_\uparrow$ ($N_\downarrow$) is the number of mesons produced for beam spin up (down), normalized to the beam flux, and ϕ is the mean angle between the beam polarization direction and the normal to the meson production plane. P_B is the average beam polarization. According to this definition, the analyzing power is positive when more particles are produced to the *left* for beam polarization *up*.

In the central region the argument against seeing such effects is based on an underlying asymmetry at the quark level[3]

$$A(q_\uparrow q\rightarrow qx)=\alpha_s\frac{m_q}{\sqrt{s}}f(\theta) \qquad (2)$$

that leads to almost vanishing values, being proportional to the constituent-quark mass m_q divided by the available center-of-mass energy $\sqrt{s}$. This, however, represents only one of the possible higher-twist processes that can contribute.[4] For example, a recent calculation by Sivers[5] provides a new approach within QCD hard scattering that can lead to single-spin production asymmetries. The mechanism involved is a "trigger-bias" effect that arises if one takes into account the orbital motion of the constituents in a polarized proton. In this case, analyzing power values of a few percent can be expected up to transverse momenta of 10 GeV/c. This mechanism is based on an asymmetry in the parton x,k_T distributions and does not require an asymmetry in the parton-parton hard-scattering cross section.

At the other end, in the soft-scattering region, a simple phenomenological approach based on spin-orbit coupling in the fragmentation and recombination of valence and sea quarks provides a satisfactory description of the observed pattern of spin effects in meson and hyperon production.[6–8] These models, however, give no quantitative estimate of the quark polarization. An extensive study of production processes of different mesons over an extended kinematic region is clearly necessary to better understand these phenomena.

We present here the results of analyzing power measurements performed in inclusive charged-pion and K_S^0 production with a polarized proton beam incident on a beryllium target (polyethylene for part of the pion data) at beam energies of 13.3 and 18.5 GeV/c at the Brookhaven Alternating Gradient Synchrotron (AGS). The data were taken during two different AGS polarized-beam runs separated by about two years. About 36×10^4 π^- and 4×10^5 π^+ were collected in the first run, and 102×10^3 K_S^0 represent the combined samples of both runs. The kaon data from the first run have been published in Ref. 8. The average value of the vertical beam polarization component was 0.63 (0.36) at 13.3 (18.5) GeV/c in the first run, and 0.44 during the second one, for a beam momentum of 18.5 GeV/c. The setup used for the measurements is extensively described in Ref. 8, along with the beam characteristics and the event reconstruction methods. Briefly, charged-track reconstruction was provided by the Brookhaven multiparticle spectrometer[9] and pions were identified by a gas threshold Čerenkov counter and companion hodoscope segmented into matching modules. For the 13.3 GeV/c running where the pions were taken parasitically to the Λ triggers, the Čerenkov counter was set to a threshold selecting pion momenta above 2.1 GeV/c. For the 13.3-GeV/c runs dedicated to the pion triggers, the threshold was raised to 3.0 GeV/c. For the 18.5-GeV/c run, the pion momentum threshold was 3.2 GeV/c.

Kaons were identified through the reconstruction of an effective mass calculated under the $K_S^0\to\pi^+\pi^-$ hypothesis. No pion identification was used, in order to avoid biases in kinematic acceptance. The mass peak has a resolution σ of 7 MeV/c^2. The background underneath the peak accounts for 3.7% of the events, and it is mainly due to poorly reconstructed kaons and Λ's.

Whereas in Ref. 8 we studied and presented polarization effects in the production of hyperons in the beam fragmentation region, these data for meson production also cover the central region and transverse momenta up to 2 GeV/c. To allow a better comparison between different incident momenta, we will present our data as a function of x_F (Feynman x) and $x_T=2p_T/\sqrt{s}$. Hence, the c.m.-system production angle between produced particle direction and beam direction is uniquely defined by x_F and x_T.

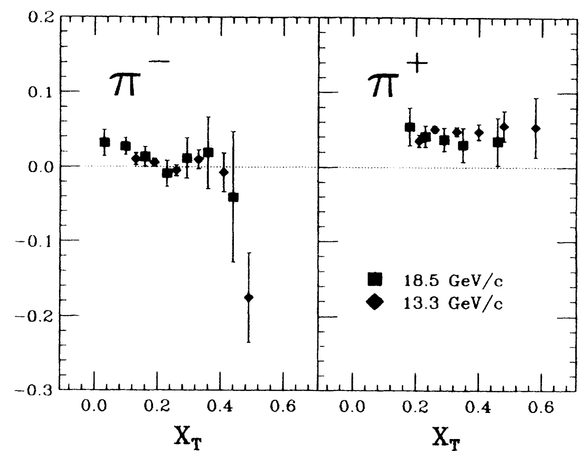

FIG. 2. A results for π^- and π^+ production as a function of x_T.

The results for pion production are shown in Fig. 1 as a function of x_F, and in Fig. 2 as a function of x_T. We observe no energy dependence. The analyzing power for π^- production are consistent with zero over the whole kinematic range, with a possible negative trend for values of x_T larger than 0.4. For π^+ production, A rises with x_F, with an average value of about 0.05.

For kaon production we have plotted the results as a function of x_F in Fig. 3 and as a function of x_T in Fig. 4. We observe increasingly negative values for positive x_F, whereas in the central and target-fragmentation region the analyzing power shows rather constant values, around -0.08. Examining the data as a function of x_T for different bins of x_F, we find that the measured values are the superposition of a constant effect present throughout the kinematic range, and another "component" whose magnitude increases with x_T and is only present in the beam fragmentation region. In the same kinematic region, our measurements of A in Λ and Σ^0 production[8] gave values consistent with zero.

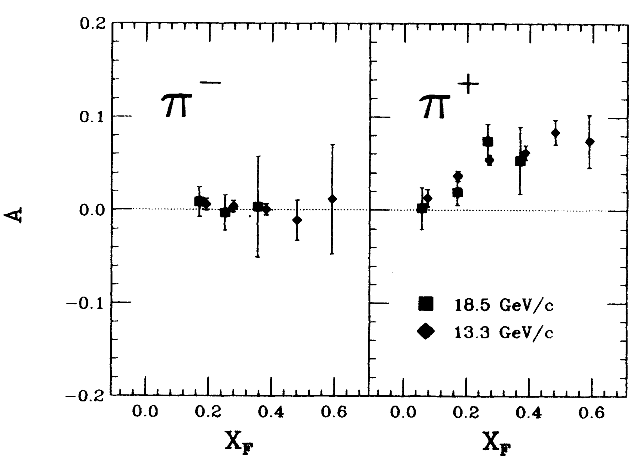

FIG. 1. Analyzing power A results for π^- and π^+ production as a function of Feynman x.

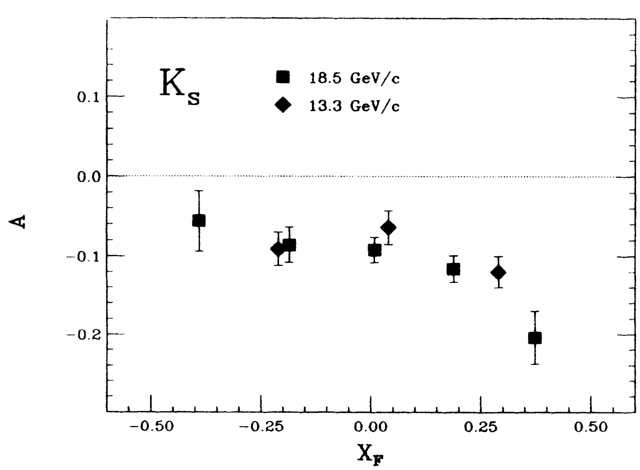

FIG. 3. Analyzing power results for K_S^0 as a function of Feynman x for the two beam energies.

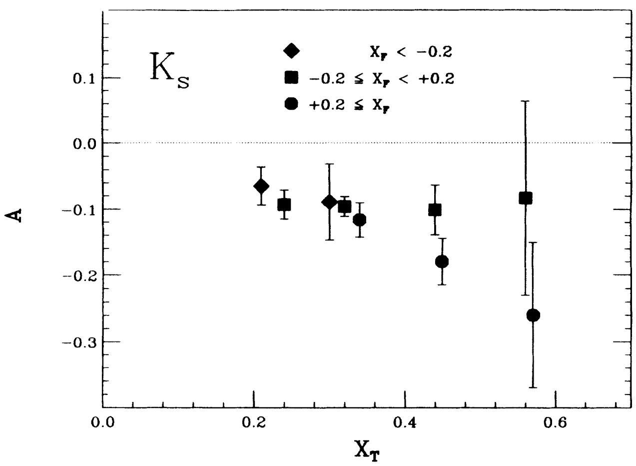

FIG. 4. A results for K_S^0 produced with a 18.5-GeV/c beam as a function of x_T and for different bins of x_F.

As mentioned, hints of a nonvanishing analyzing power in the central region have already been seen in a few other experiments. In $p+\vec{p}\rightarrow\pi^0+X$ at 24 GeV/c using a polarized target[1] at the CERN Proton Synchrotron a similar transverse-momentum range was covered at small x_F. The value of A reaches about 0.5 for $p_T\simeq 2$ GeV/c (to be compared to our data, the sign for A measured off polarized targets at $x_F\simeq 0$ as published has to be reversed). A measurement of π^0 production with $|x_F|<0.1$ performed at Serpukhov with a 40-GeV/c π^- beam on a polarized proton target gave A of the order 0.3 in a similar p_T range.[2]

Preliminary results for the central region taken at the Brookhaven AGS (Ref. 10) show values consistent with zero for the analyzing power in π^- production over the whole kinematic range. For π^+ production, the effects are positive. Values around 0.07–0.10 are observed for $x_T\simeq 0.6$ in the central region, rising to about 0.3 for $x_T\simeq 0.8$.

Also some soft-scattering data are available for comparison. Charged-pion and kaon production has been measured using an 11.75-GeV/c polarized proton beam at the Argonne Zero Gradient Synchrotron.[11] The π^+ data show a strong x_F dependence. A rises from slightly negative values at low x_T and x_F to values around 0.4 for $x_F\geq 0.8$. The high-x_F results for π^- production show a considerable structure, but are consistent with becoming zero for transverse momenta higher than 0.7 GeV/c.

Examining our data together with all the results above we observe a statistically good agreement in the region of overlap. Broadly speaking the pion data are characterized as follows: the analyzing power for π^+ production is always positive whereas for π^- it vanishes in the central region. In π^+ production a strong x_T dependence is present in the central region, whereas A seems to depend on x_F in forward production.

The behavior of the K_S^0 data is very different: no x_T dependence is observed in the central region, whereas in forward production it is clearly present. These data show a nonzero analyzing power that persists throughout the central region down into the fragmentation region of the unpolarized target.

A satisfactory interpretation of all these results is still unavailable. For the beam fragmentation region, inaccessible heretofore to perturbative QCD calculations, a phenomenological model in terms of parton fragmentation and recombination along with a trigger-bias effect[6] first used to explain polarization in Λ production successfully reproduces the observed regularities in π^+, π^0, and K_S^0 production at high Feynman-x values.[8,11,12] This is not the case for the π^- data, however, which still leaves an open question. This model cannot be extended into the central region because there the dynamics of the production cannot be described in terms of the recombination of fast beam fragments having spin correlated to that of the incident particle.[13] It is difficult to imagine that a spin transfer could occur from the polarized beam to the backwards produced kaons. Therefore, an explanation of the present kaon data in these terms is impossible.

However, the central-region data cover a kinematic range where perturbative methods may begin to be applicable. For a long time, the existence of a nonzero analyzing power was considered improbable by most theorists.[3] As mentioned earlier, other mechanisms have recently been investigated[5] that can produce nonvanishing effects. Here the same magnitude and sign are expected for the analyzing power in the production of the different mesons. In this model the analyzing power arises from the orbital motion of the quarks coupled to the spin and thus the sign is independent of the quark mass. While the central region π^+ and π^0 results[1,2] are in agreement with this expectation, the difference in sign between the analyzing power of pions and that of K_S^0's in our data contradicts this expectation. The sign difference for A between K_S^0's and pions might indicate that the strange sea quarks in the proton are polarized with opposite transversity to the nonstrange ones.

The interpretation of all these results is also affected by the controversial question of just where hard scattering begins, since many believe that larger values of transverse momentum are required than reached in measurements to date. Higher-energy measurements, such as those upcoming in Fermilab Experiment E704 at 200 GeV/c beam momentum, will certainly provide clues which might better our understanding of these phenomena.

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