Indication on the universal hadron substructure: Constituent quarks

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(Received 18 October 2003; published 27 April 2004)

The universality of single-spin asymmetry in inclusive π-meson production is discussed. This universality can be related to the hadron substructure, constituent quarks.

DOI: 10.1103/PhysRevD.69.077503 PACS number(s): 13.88.+e, 12.90.+b

Polarization experiments give us a unique opportunity to probe the nucleon internal structure. While spin averaged cross sections can be calculated within acceptable accuracy, the current theory of strong interactions cannot describe large spin asymmetries and polarization. Polarization is a precision tool for measuring the electroweak parameters, spin dependent structure functions, etc. After establishing the fact that the nucleon spin is not described by simple summing of the quark spins, the study of gluonic and orbital momentum contributions to it is very important and intriguing.

Unexpectedly large values of single-spin asymmetry (SSA) in inclusive π-meson production are a real challenge to current theory because perturbative quantum chromodynamics predicts small asymmetries decreasing with transverse momentum. Various models have been developed to explain results from E704 (Fermilab), PROZA-M and FODS (both Protvino), and several BNL experiments. Most of the models analyze experimental data in terms of x_{F} and/or p_T. To investigate the dependence of SSA on the secondary meson production angle, measurements in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ were carried out at the PROZA-M experiment (Protvino) at the 40 GeV pion beam in two different kinematic regions: at the Feynman scaling variable $x_{\mathrm{F}} \approx 0$ [1] and in the polarized target fragmentation region [2]. The papers [2,3] reported that the asymmetry of inclusive π^0 production in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ begins to increase at the same center of mass system energy $E_0^{c.m.s.} \approx 1.7$ GeV. The result is presented in Figs. 1 and 2. Nevertheless, from this statement we cannot draw a conclusion whether or not the SSA behavior depends on the beam energy.

The π^+ asymmetry in the E704 experiment (200 GeV proton beam) [4] and in the E925 experiment (BNL, 22 GeV) [5] begins to increase at different values of x_{F} ($x_{\mathrm{F}}^0 \approx 0.18$ for E704 and $x_{\mathrm{F}}^0 \approx 0.46$ for E925). It was also found that the asymmetry for these two experiments begins to increase at the same longitudinal or full energy in the center of mass system, $E_0^{c.m.s.} \approx 1.6$ GeV. It happened, surprisingly, to be the same energy as for the PROZA-M experiment. The comprehensive analysis of all fixed target polarized experiments of inclusive π-meson production was done in [3]. The result of the analysis is presented in Fig. 3.

The main conclusion is that the asymmetry begins to increase at the same center of mass energy $E_0^{c.m.s.} = 1.5$ to 2.0 GeV for most of the experiments in the energy range between 13 and 200 GeV. The analysis was done only for those experimental data where the average transverse momentum p_T was greater than 0.7 GeV/c to exclude very soft interactions. The asymmetries at $p_T < 0.7$ GeV/c are significantly lower and do not exceed a few percent. We did not include the experiments when the asymmetry was close to zero. The conclusion is valid for all π^+ and π^0 asymmetries. We have to mention that π^- production seems to contradict this. We can explain this by the fact that π^- mesons at small x_F can be produced not only from the valence d quark but also from other channels. The interference of different channels is also responsible for asymmetry cancellation in π^0 and π^- production in the central region. In the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ in the central region we found significant asymmetry, in contrast to the $p_\uparrow + p \to \pi^0 + X$ reaction. If in the $p_\uparrow + p \to \pi^0 + X$ reaction the asymmetry is cancelled because of different channel interference from polarized and nonpolarized protons, in $\pi^- p_\uparrow$ collisions the valence u quark from a polarized proton combined with the valence $\overline{u}$ quark from π^- gives the main contribution to π^0 production, while other channels are suppressed.

In this scheme the asymmetry behavior in $\overline{p_\uparrow} p$ interactions in π^+ and π^- production should be inverted in comparison with the $p_\uparrow + p \to \pi^0 + X$ data. The result from the E704 experiment [6] is consistent with this model. The

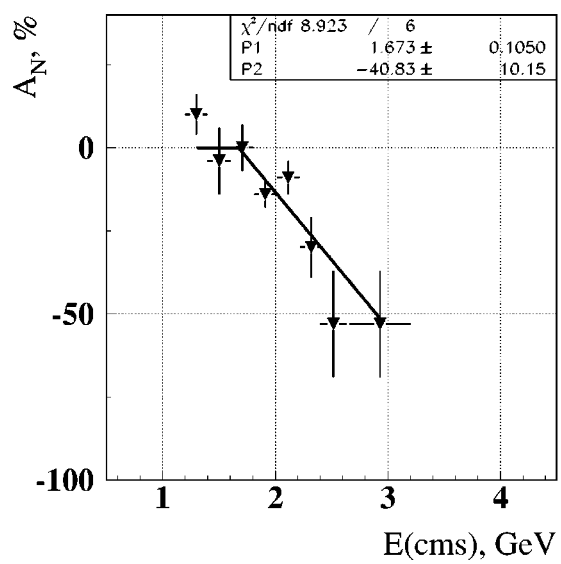

FIG. 1. The dependence of the single-spin asymmetry A_N on π^0-meson center of mass energy in the reaction $\pi^- + p_\uparrow \to \pi^0 + X$ in the central region at 40 GeV [1].

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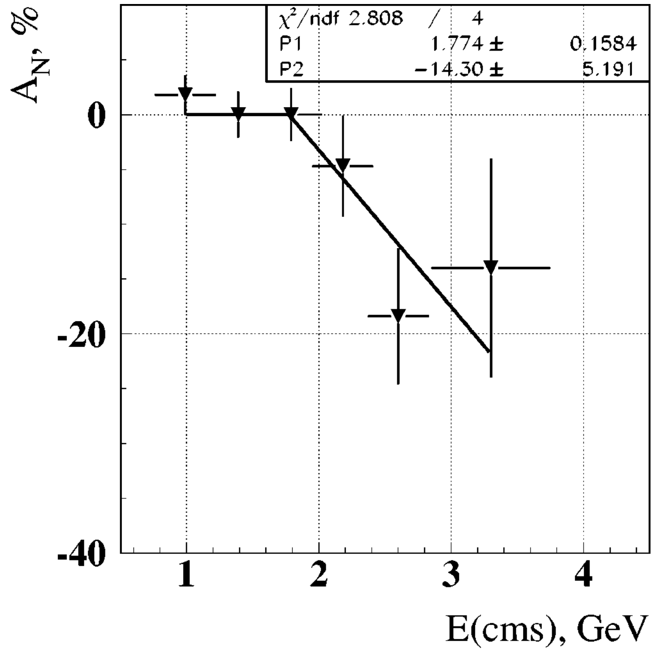

FIG. 2. The dependence of the single-spin asymmetry A_N on π^0-meson center of mass energy in the reaction $\pi^- + p_\uparrow \rightarrow \pi^0 + X$ in the polarized target fragmentation region at 40 GeV [2].

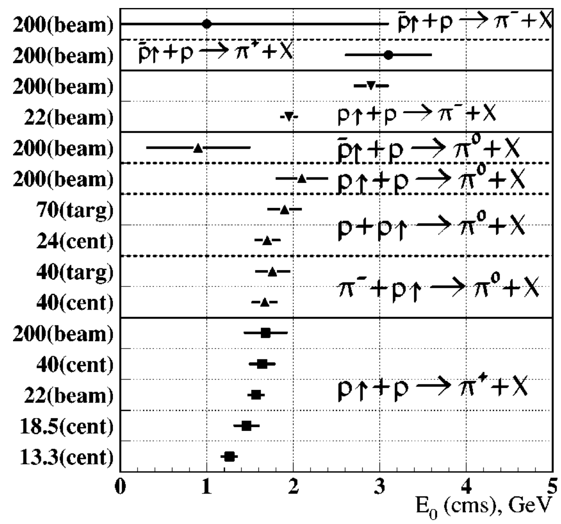

FIG. 3. Center of mass energy values where the pion asymmetry begins to increase for different experiments. The energy along the Y axis is in GeV; "cent" corresponds to experiments in the central region ($x_f \approx 0$), "targ" to the polarized target fragmentation region; "beam" to the polarized beam fragmentation region.

asymmetry of π^+ production begins to increase at the same value $E_0^{c.m.s.} \approx 2.9$ GeV as for π^- in the reaction $p_\uparrow + p \rightarrow \pi^0 + X$, and the asymmetry in the reaction $\overline{p_\uparrow} + p \rightarrow \pi^- + X$ begins to increase at small values of $E_0^{c.m.s.}$.

We may conclude that the meson asymmetry produced by the valence quark begins to increase at the same universal energy $E_0^{c.m.s.}$.

The universality obtained for the value of $E_0^{c.m.s.}$ can be interpreted as the manifestation of the presence of the universal substructures in hadrons. Such substructures can be the constituent quarks if one assumes [7] that origin of the SSA is related to the internal orbital angular momentum of quark-antiquark pairs inside the hadronlike object which a constituent quark represents.

The concept of the constituent quark [8,9] has been used extensively since the very beginning of the quark era, and has been successful in explaining many aspects of hadron properties and their interactions. Experiments at Jefferson Lab [10] have demonstrated a new type of scaling and provided further experimental evidence for the presence of constituent quarks inside hadrons.

Constituent quarks acquire their masses due to spontaneous chiral symmetry breaking in QCD. The operator that transforms current quarks into constituent ones has an energy dependence, and the scale of this energy dependence is determined by $\Lambda_\chi \simeq 4\pi f_\pi$, where f_π is the pion decay constant. The constituent quark appears as a quasiparticle, i.e., as a current valence quark surrounded by a cloud of quark-antiquark pairs of various flavors, i.e., they are structured hadronlike objects (cf. [9]).

In the model [7] the SSA is due to the orbital angular momentum of quarks inside the constituent quark: the spin of the constituent quark, e.g., the U quark, is given by the sum

$$J_U = 1/2 = S_{u_v} + S_{\{\bar{q}q\}} + L_{\{\bar{q}q\}}.$$

It is estimated in [7] that $L_{\{\bar{q}q\}} \simeq 1/3$. This was done on the basis of deep-inelastic scattering data, and a similar estimate can be obtained using the simple relation $L_{\{\bar{q}q\}} \simeq r_Q \langle k_\perp \rangle$, where $r_Q \simeq 1/\Lambda_\chi$ and $\langle k_\perp \rangle \simeq 0.2$–$0.3$ GeV/c. The significant asymmetries in the model appear to show up beyond $p_\perp > \Lambda_\chi \simeq 1$ GeV/c, and this is in agreement with experimental data. Thus, orbital motion of the quark matter inside a constituent quark will lead to significant asymmetries provided the distances are small enough ($r \leqslant 1/\Lambda_\chi$) and the energy is high enough for constituent quark dissolution.

The scale Λ_χ determines not only the transverse size of the constituent quark but also its "ionization energy." This is the minimal energy that is needed for constituent quark excitation and its dissolution. In the model [7] where the SSA is related to the internal orbital momentum of the constituent quark, it will be nonzero only when the constituent quark is "ionized." The value of $E_0^{c.m.s.}$ is then related to that energy, and this means that $E_0^{c.m.s} \propto \Lambda_\chi$. Of course, it would be interesting to get an explicit relation between $E_0^{c.m.s.}$ and Λ_χ, but in order to derive such a relation the problem of the hadronization mechanism needs to be solved first.

Thus, provided the above discussion is somewhat relevant to the real physical situation, we can conclude that the revealed scaling dependence of the asymmetry can be interpreted as another indication in favor of a hadron structure with constituent quarks.

We are grateful to N.E. Tyurin for interest in this work and fruitful discussions. This work was partially supported by Russian Foundation for Basic Research grant 03-02-16919.

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