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ELEMENTARY PARTICLES AND FIELDS
Experiment

General Features of Single-Spin Asymmetry in Inclusive Pion Production in Fixed-Target Experiments

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Abstract—The results of various experiments that measured a single-spin asymmetry in inclusive pion production are analyzed in the energy range between 13 and 200 GeV. The experimental fact that the single-spin asymmetry begins increasing at one universal value of the pion energy in the c.m. frame is established.

INTRODUCTION

In the PROZA-M experiment, which was performed at the Institute for High Energy Physics (IHEP, Protvino), the single-spin asymmetry A_N in $\pi^- + p_\uparrow \to \pi^0 + X$ and $\pi^- + d_\uparrow \to \pi^0 + X$ reactions at a beam energy of 40 GeV was measured in the central region for values of the Feynman scaling variable in the range $|x_\mathrm{F}| < 0.15$ [1]. It was found that, at transverse momenta in the region $p_T < 1.6$ GeV/c, the asymmetry in question is compatible with zero, but that, for $p_T > 1.6$ GeV/c, the asymmetry grows linearly in absolute value, reaching -40% at $p_T \approx 2.5$ GeV/c (see Fig. 1, left panel). If the asymmetry is approximated by a linear function, the corresponding straight line intersects the abscissa at a transverse-momentum value of $p_T^0 \approx 1.7$ GeV/c [1]. The asymmetry in $\pi^- + p_\uparrow \to \pi^0 + X$ reactions was also measured in the region of polarized-target fragmentation [2] (see Fig. 1, right panel). It was discovered that, for $-0.8 < x_\mathrm{F} < -0.4$, the asymmetry is significant at p_T values in the range between 1 and 2 GeV/c, but that, at low values of $|x_\mathrm{F}|$ and p_T, the asymmetry is compatible with zero. It turned out that the asymmetry begins growing at a c.m. neutral-pion energy of $E_0^{\mathrm{c.m.}} \approx 1.7$ GeV [2]. In [3], it was found that the asymmetry in $p + p_\uparrow \to \pi^0 + X$ reactions at 70 GeV behaves similarly. Thus, one can assume that the asymmetry does not arise up to a threshold value, whereupon it grows linearly, eventually reaching saturation at some level, if for no other reason than its boundedness (recall that the asymmetry cannot exceed 100%).

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On the basis of the aforesaid, the energy dependence of the asymmetry can be described as

$$A_N = \begin{cases} 0 & \text{for } E < E_0, \\ k \cdot (E - E_0) & \text{for } E \geq E_0. \end{cases} \quad (1)$$

where E is the c.m. energy of the product neutral pion and E_0 is the threshold energy. Neutral pions are detected within a rather narrow angle around the beam axis, whence it follows that, in each experiment, the energy dependence of the asymmetry reflects in fact the transverse-momentum (p_T) dependence (an experiment in the central region) or the x_F dependence (an experiment in the region of polarized-target fragmentation). The above saturation is reached at high values of p_T or x_F, where the experimental errors are rather large, so that these points do not change the result significantly. Since there is no criterion that would make it possible to pinpoint the locus where the asymmetry begins approaching saturation, all of the points were used in the fitting procedure.

For the energy E_0, from which the asymmetry begins growing, a fit on the basis of (1) leads to a value of $E_0^{\mathrm{CMS}} = 1.67 \pm 0.11$ GeV in the central region and a value of $E_0^{\mathrm{CMS}} = 1.76 \pm 0.16$ GeV in the region of polarized-target fragmentation. It should be noted that actual experimental errors are somewhat greater since no account was taken of inaccuracies in determining the energy and since integration with respect to the transverse momentum and with respect to x_F is performed for each point. By way of example, we indicate that, at an energy of 200 GeV, a change of 0.01 in the mean value of the variable x_F leads to a change of 0.1 GeV in the position of the cusp.

Thus, we see that, in $\pi^- + p_\uparrow \to \pi^0 + X$ reactions, the asymmetry begins growing at the same value of the c.m. neutral-pion energy in two different kinematical regions. However, this result does not provide

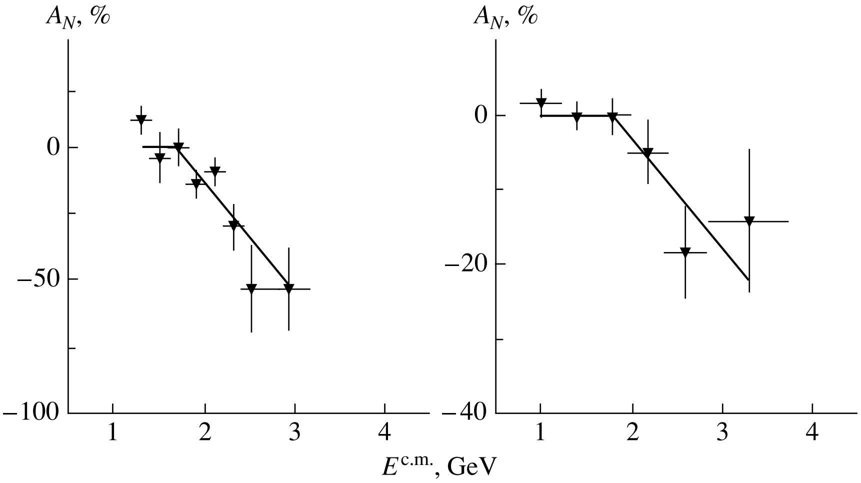

Fig. 1. Asymmetry A_N in $\pi^- + p_\uparrow \to \pi^0 + X$ reactions at a beam energy of 40 GeV as a function of the c.m. neutral-pion energy in (left panel) the central region [1] and (right panel) the target-fragmentation region [2].

a solution to the problem of determining the kinematical variable with respect to which the behavior of the asymmetry is universal. The majority of the existing theoretical models consider the asymmetry as a function of $x_{\rm F}$ or p_T, depending on the kinematical region where the measurements being analyzed were performed.

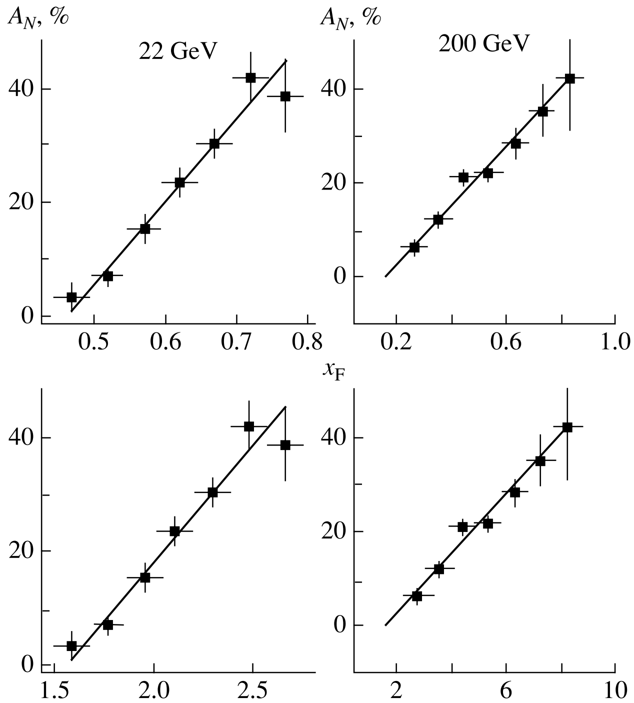

Fig. 2. Single-spin asymmetry A_N as a function of (upper panels) $x_{\rm F}$ and (lower panels) c.m. energy for the polarized-beam-fragmentation region of $p_\uparrow + p \to \pi^+ + X$ reactions in the (left panels) E925 experiment at 22 GeV [4] and (right panels) E704 experiment at 200 GeV [5].

In the present study, the results obtained by measuring the single-spin asymmetry in inclusive charged- and neutral-pion production in all fixed-target experiments with polarized particles at beam energies between 13 and 200 GeV are analyzed for various kinematical regions subjected to the condition that the transverse momentum p_T is in excess of 0.5 GeV/c.

1. SINGLE-SPIN ASYMMETRIES IN INCLUSIVE PION PRODUCTION

1.1. Single-Spin Asymmetries in the Inclusive Production of Positively Charged Pions

The single-spin asymmetry A_N in the inclusive production of positively charged pions was measured at the Brookhaven National Laboratory (BNL) for beam energies of 13.3, 18.5, and 22 GeV; at IHEP for a beam energy of 40 GeV; and at the Fermi National Accelerator Laboratory (FNAL) for a beam energy of 200 GeV.

For the polarized-beam-fragmentation region of $p_\uparrow + p \to \pi^+ + X$ reactions, we will first analyze the results of two experiments that covered the same region of the kinematical variables p_T and $x_{\rm F}$ at significantly different beam energies of 22 and 200 GeV (E925 [4] and E704 [5], respectively). In both experiments, the asymmetry in question reaches 40% for $p_T > 0.7$ GeV/c and $x_{\rm F} > 0.7$. At the same time, the asymmetry begins growing at markedly different values of the variable $x_{\rm F}$. If the experimental data are approximated by formula (1) in terms of the variable $x_{\rm F}$, we find that the point at which this occurs is $x_{\rm F}^0 =$

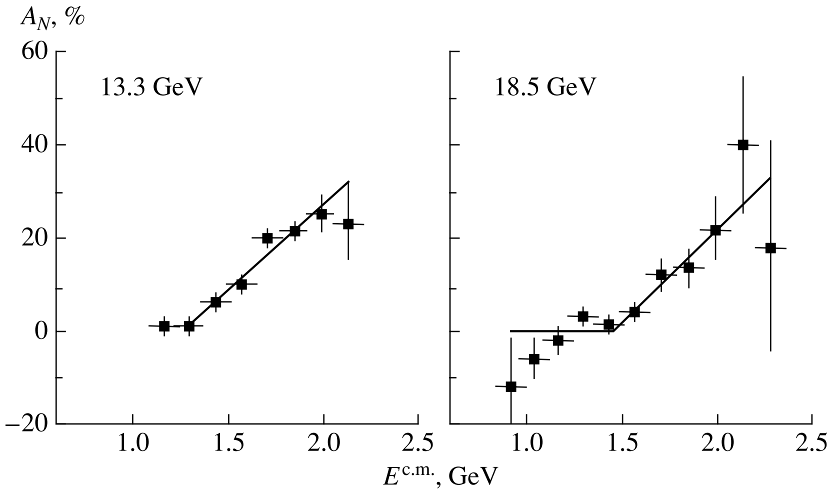

Fig. 3. Single-spin asymmetry A_N as a function of $E^{\text{c.m.}}$ in $p_\uparrow + p \to \pi^+ + X$ reactions at a beam energy of (left panel) 13.3 and (right panel) 18.5 GeV for $x_\text{F} \approx 0.2$ [7].

0.46 ± 0.01 in the E925 experiment and $x_\text{F}^0 = 0.16 \pm 0.02$s in the E704 experiment (see Fig. 2, upper panels). According to almost all of the existing theoretical models, the asymmetry in the region of polarized-beam fragmentation depends predominantly on x_F (see, for example, [6]), but this is at odds with experimental data.

In the Introduction and previously in [2], it was indicated that, in $\pi^- + p_\uparrow \to \pi^0 + X$ reactions, the absolute value of the asymmetry begins growing at the same value of the c.m. neutral-pion energy in two different kinematical regions (specifically, in the region of polarized-particle fragmentation and in the central region at $x_\text{F} \approx 0$). For each experiment, we then find the dependence of the asymmetry on the c.m. energy $E^{\text{c.m.}}$ (see Fig. 2, lower panels). The point at which the asymmetry begins growing is $E_0^{\text{c.m.}} = 1.57 \pm 0.04$ GeV for the E925 experiment and $E_0^{\text{c.m.}} = 1.68 \pm 0.22$ GeV for the E704 experiment, these two values being in agreement with each other within the errors. Surprisingly, these results also agree with those that were previously obtained for neutral pions.

For all other experiments, we immediately analyzed the dependence of the asymmetry on the total pion energy in the c.m. frame in terms of the function in (1) (recall that the authors of the original studies examined the asymmetry as a function of the transverse momentum p_T or the scaling variable x_F).

1.1.1.Measurements at BNL for beam energies of 13.3 and 18.5 GeV. In the BNL experiments performed at polarized-proton-beam energies of 13.3 and 18.5 GeV, the asymmetry was studied at $\langle x_\text{F} \rangle = 0.2$ as a function of transverse momentum. The respective results, borrowed from [7], are given in Fig. 3. The asymmetry begins growing from the point $E_0^{\text{c.m.}} = 1.26 \pm 0.04$ GeV at 13.3 GeV and from the point $E_0^{\text{c.m.}} = 1.46 \pm 0.08$ GeV at 18.5 GeV.

1.1.2. Measurements at IHEP at 40 GeV. The asymmetry in the inclusive production of positively charged pions was also measured in the FODS experiment (Protvino) [8]. The authors of [8] concluded that, in approximating their data by a straight line, the asymmetry takes zero value at $x_T = 0.37 \pm 0.02$, which, at $x_\text{F} \equiv 0$, corresponds to a c.m. energy of $E_0^{\text{CMS}} = 1.62 \pm 0.10$ GeV ($x_T = ep_T/\sqrt{s}$). Unfortunately, the values of x_F are not given in [8] for each transverse-momentum interval. At the same time, it was indicated there that the mean value of x_F changed from 0.02 to 0.1. The value of $x_\text{F} = 0.1$ for each longitudinal-momentum interval means the vanishing of the asymmetry at $E_0^{\text{c.m.}} = 1.66$ GeV. To a high precision, we therefore obtain $E_0^{\text{c.m.}} = 1.64 \pm 0.15$ GeV.

1.2. Single-Spin Asymmetries in Inclusive Neutral-Pion Production

The asymmetry in inclusive neutral-pion production was studied at CERN in $pp_\uparrow$ scattering at 24 GeV, at IHEP in $\pi^- + p_\uparrow \to \pi^0 + X$ reactions at 40 GeV and in $pp_\uparrow \to \pi^0 + X$ reactions at 70 GeV, and at FNAL in $p_\uparrow p$ and $\bar{p}_\uparrow p$ interactions at 200 GeV. The results obtained from an analysis of the asymmetry in $\pi^- + p_\uparrow \to \pi^0 + X$ reactions at 40 GeV are considered below.

1.2.1. Measurements in $p + p_\uparrow \to \pi^0 + X$ Reactions. The asymmetry measured in [9] for $p + p_\uparrow \to \pi^0 + X$ reactions at an energy of 24 GeV is displayed in Fig. 4 (left panel). The asymmetry in question grows from $E_0^{\text{c.m.}} = 1.70 \pm 0.07$ GeV.

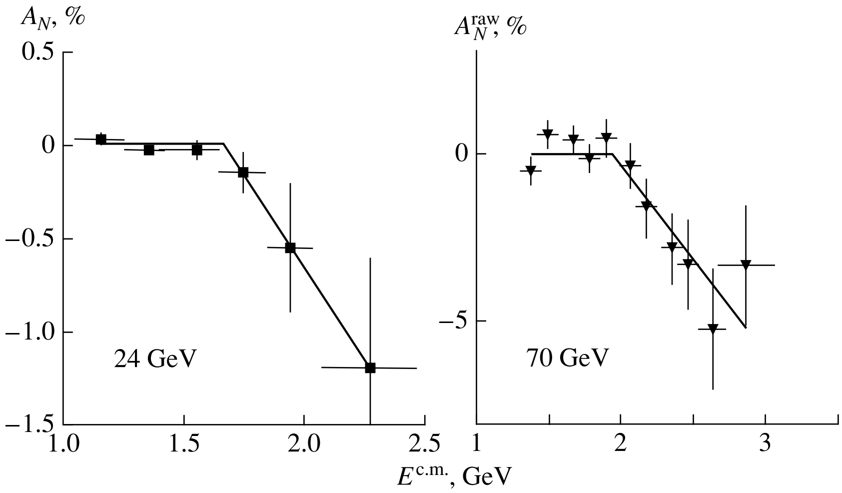

Fig. 4. Single-spin asymmetry A_N in $p + p_\uparrow \to \pi^0 + X$ reactions as a function of $E^{c.m.}$ in (left panel) the central region at 24 GeV [9] and (right panel) the region of polarized-particle fragmentation at 70 GeV [3].

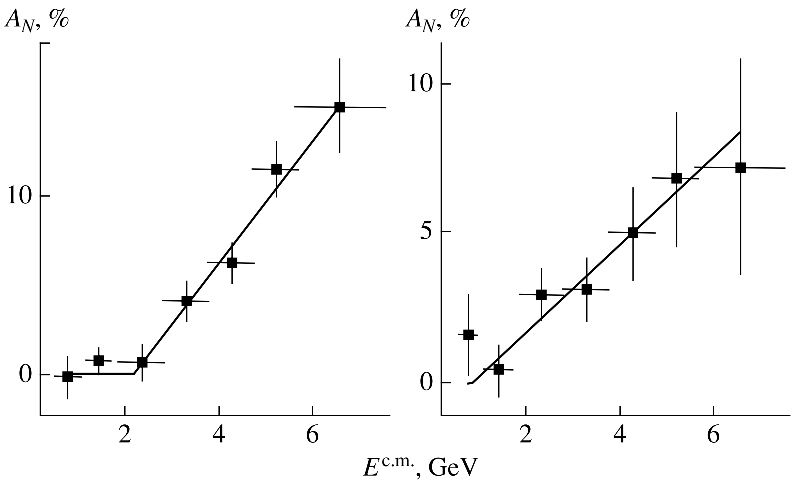

Fig. 5. Single-spin asymmetry A_N for neutral pions from (left panel) $p_\uparrow p$ and (right panel) $\bar{p}_\uparrow p$ interactions at 200 GeV as a function of $E^{c.m.}$ in the beam-fragmentation region (FNAL) [10].

Preliminary experimental results for A_N in $p + p_\uparrow \to \pi^0 + X$ reactions at an energy of 70 GeV were reported in [3]. In the central region, the measured asymmetry is close to zero, whereas, in the target-fragmentation region, the raw asymmetry A_N^{raw} amounted to -3%, which corresponded to a value of -30% for the physically observed asymmetry A_N (see Fig. 4, right panel). The point at which the asymmetry begins growing is $E_0^{c.m.} = 1.93 \pm 0.12$ GeV.

1.2.2. Measurements in $p_\uparrow(\bar{p}_\uparrow) + p \to \pi^0 + X$ reactions at 200 GeV. The asymmetry A_N in $p_\uparrow(\bar{p}_\uparrow) + p \to \pi^0 + X$ reactions at 200 GeV was measured in the E704 experiment [10] (see Fig. 5). The asymmetry begins growing at $E_0^{c.m.} = 2.16 \pm 0.26$ GeV in $p_\uparrow + p \to \pi^0 + X$ reactions and at $E_0^{c.m.} = 0.9 \pm 0.6$ GeV in $\bar{p}_\uparrow + p \to \pi^0 + X$ reactions.

In the central region of $p_\uparrow + p \to \pi^0 + X$ reactions, the asymmetry is compatible with zero over the entire range of the measurements reported in [11].

1.3. Single-Spin Asymmetries in the Inclusive Production of Negatively Charged Pions

Similar investigations were performed for $p_\uparrow + p \to \pi^- + X$ reactions at energies of 22 GeV [4] and 200 GeV [5]. The asymmetry begins growing at $E_0^{c.m.} = 1.95 \pm 0.02$ GeV in the E925 experiment [4] and at $E_0^{c.m.} = 2.9 \pm 0.2$ GeV in the E704 experiment [5] (see Fig. 6).

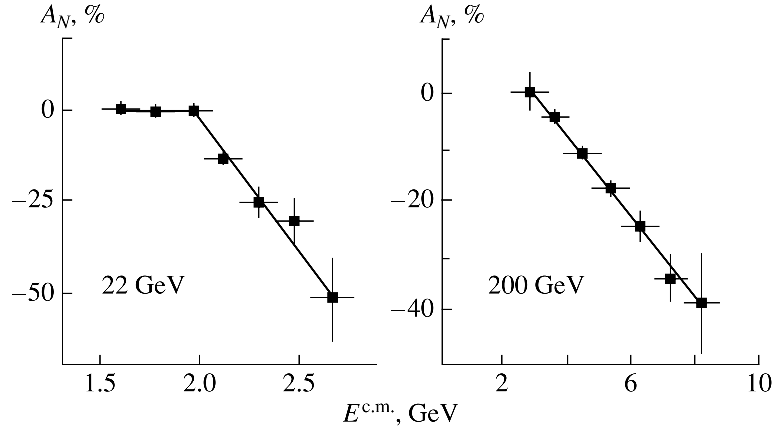

Fig. 6. Single-spin asymmetry A_N as a function of $E^{\rm c.m.}$ for the target-fragmentation region of $p_\uparrow + p \to \pi^- + X$ reactions at a beam energy (left panel) 22 GeV [4] or (right panel) 200 GeV [5].

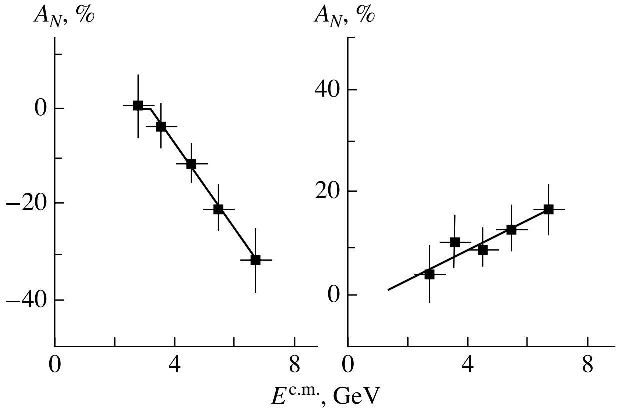

Fig. 7. Single-spin asymmetry A_N for (left panel) positively charged pions and (right panel) negatively charged pions from $\bar{p}_\uparrow p$ interactions at an energy of 200 GeV [12] as a function $E^{\rm c.m.}$.

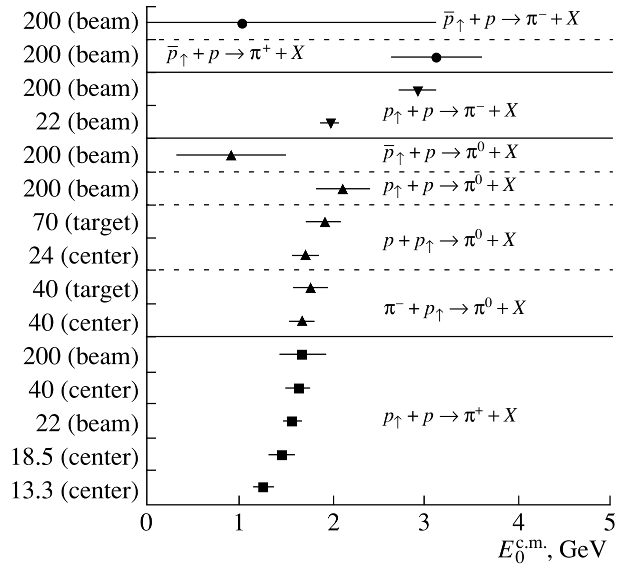

Fig. 8. Points at which there appears an asymmetry: (center) experiments in the central region (at $x_{\rm F} \approx 0$), (target) experiments in the target-fragmentation region, and (beam) experiments in the beam-fragmentation region. The respective energies are given in GeV.

In all of the experiments performed for beam energies of 13.3 and 18.5 GeV at BNL [7] and 40 GeV at IHEP [8], the asymmetry for negatively charged pions from $p_\uparrow + p \to \pi^- + X$ reactions is compatible with zero in the central region.

1.4. Single-Spin Asymmetries in $\bar{p}_\uparrow + p \to \pi^\pm + X$ Reactions at 200 GeV

The asymmetry A_N in $\bar{p}_\uparrow + p \to \pi^\pm + X$ reactions at 200 GeV is given in Fig. 7. For positively and negatively charged pions, the points at which the asymmetry begins growing are $E_0^{\rm c.m.} = 3.1 \pm 0.5$ GeV and $E_0^{\rm c.m.} = 1.0 \pm 2.2$ GeV, respectively; however, the measurement errors are large.

2. DISCUSSION OF THE RESULTS

The entire body of the results discussed above is summarized in the table and in Fig. 8. Both the fitting-procedure uncertainties and the resolution in kinematical variables are taken into account in the errors. Also given in the table are χ^2/N values and the slope of $k \cdot (\sqrt{s} - E_0^{\rm c.m.})$, this slope characterizing the asymptotic asymmetry at the phase-space boundary if it is still described by a linear function and if there is no saturation. The results of experiments that yielded zero asymmetry are not quoted in the table.

We note that, in the inclusive production of neutral and negatively charged pions in $p_\uparrow p$ interactions, the asymmetry is zero in the central region. This circumstance can be explained as follows. In the fragmentation region, a negatively charged pion is produced

Compendium of the results for the point $E_0^{\text{c.m.}}$ at which the asymmetry begins growing in various experiments ($E_{\max}^{\text{c.m.}} = \sqrt{s}/2$; for experiments with a polarized target, the asymmetry is taken with an opposite sign)

Reaction	Energy, GeV	$E_0^{\text{c.m.}}$, GeV	χ^2/N	$k \cdot (E_{\max}^{\text{c.m.}} - E_0^{\text{c.m.}})$, %	References
$p_\uparrow + p \to \pi^+ + X$	13.3	1.26 ± 0.1	0.9	52 ± 6	[7]
$p_\uparrow + p \to \pi^+ + X$	18.5	1.46 ± 0.15	0.85	63 ± 16	[7]
$p_\uparrow + p \to \pi^+ + X$	21.92	1.57 ± 0.1	0.9	68 ± 6	[4]
$p_\uparrow + p \to \pi^+ + X$	40	1.64 ± 0.15			[8]
$p_\uparrow + p \to \pi^+ + X$	200	1.68 ± 0.25	1.1	52 ± 5	[5]
$\pi^- + p_\uparrow \to \pi^0 + X$	40	1.67 ± 0.15	1.5	107 ± 26	[1]
$\pi^- + p_\uparrow \to \pi^0 + X$	40	1.76 ± 0.2	0.7	36 ± 14	[2]
$p + p_\uparrow \to \pi^0 + X$	24	1.7 ± 0.15	0.6	334 ± 165	[9]
$p + p_\uparrow \to \pi^0 + X$	70	1.9 ± 0.2	0.85	208 ± 70	[3]
$p_\uparrow + p \to \pi^0 + X$	200	2.1 ± 0.3	0.5	26 ± 5	[10]
$\bar{p}_\uparrow + p \to \pi^0 + X$	200	0.9 ± 0.6	0.5	13 ± 4	[10]
$p_\uparrow + p \to \pi^- + X$	21.92	1.95 ± 0.1	0.5	-87 ± 11	[4]
$p_\uparrow + p \to \pi^- + X$	200	2.9 ± 0.2	<0.1	-51 ± 6	[5]
$\bar{p}_\uparrow + p \to \pi^+ + X$	200	3.1 ± 0.5	<0.1	-59 ± 16	[12]
$\bar{p}_\uparrow + p \to \pi^- + X$	200	1.0 ± 2.2	0.1	25 ± 15	[12]

predominantly from a valence d quark, whose polarization direction is assumed to be opposite to the proton and u-quark polarization direction this follows from $SU(6)$ symmetry and from data on the structure functions for a longitudinally polarized proton—see, for example, [13], while, in the central region, the production of a negatively charged pion also proceeds via different channels featuring different polarizations of quarks and gluons. It follows that, in the region of polarized-particle fragmentation, the sign of the asymmetry for a negatively charged pion, which originates from a d quark, is opposite to the sign of the asymmetry for a positively charged pion, which originates from a u quark, whereas, in the central region, the asymmetry for a negatively charged pion is smeared because, in the proton, there are one valence d quark and two valence u quarks. In the case of $\pi^- p_\uparrow$ interaction, a large anisotropy for a neutral pion can arise via the formation of such a pion from the valence $\bar{u}$ antiquark of the incident negatively charged pion and a valence u quark of a polarized proton, the contribution of the valence d quark of the proton at high transverse momenta being significantly suppressed in this case with respect to the contribution mentioned immediately above.

The asymmetry in the inclusive production of positively charged pions begins growing at the same value of $E_0^{\text{c.m.}}$ in the range from about 1.5 to 2.0 GeV. The same behavior is observed for neutral pions. However, this is not so for negatively charged pions. This may be due to the fact that positively charged pions are produced from valence u quarks, whose polarization is coincident with the polarization of the proton involved and whose number is greater than the number of other quarks. Recall that we consider only the data for $p_T > 0.5$ GeV/c. As was indicated above, other channels may contribute to the production of negatively charged pions, the relationship between the channel contributions being in principle dependent on x_R ($x_R = 2E^{\text{c.m.}}/\sqrt{s}$)—that is, not only on the c.m. secondary-particle energy, but also on the total energy $\sqrt{s}$ in the c.m. frame. It follows that, in all cases, the asymmetry for a negatively charged pion in $p_\uparrow p$ interaction begins growing at $E^{\text{c.m.}}$ values greater than those for positively charged pions, and this leads to different values at different energies for the point of the emergence of an asymmetry for negatively charged pions. If the above assumption is valid, the asymmetries for positively and negatively charged pions from $\bar{p}_\uparrow p$ interaction must be interchanged with respect to $p_\uparrow p$ interaction. This is precisely the behavior that is actually observed—the asymmetry for a positively charged pion begins growing at the same value of $E_0^{\text{c.m.}}$ as the asymmetry for a negatively charged pion in $p_\uparrow p$ interaction, and the behavior of the asymmetry in $\bar{p}_\uparrow + p \to \pi^- + X$ reactions is similar to the behavior of the asymmetry in $p_\uparrow + p \to \pi^+ + X$ reactions.

We also note that, in eight experiments in the region of polarized-particle fragmentation that were devoted to measuring the asymmetry for charged pions, the values of $k \cdot (E_{\max}^{\text{c.m.}} - E_0^{\text{CMS}})$ were close.

CONCLUSIONS

Data on the single-spin asymmetry in inclusive pion production in fixed-target experiments have been analyzed for beam energies in the range between 13 and 200 GeV. The following experimental fact has been discovered: for a pion that originates from quarks whose number in the hadron involved is greater than the number of quarks belonging to a different sort and whose polarization coincides with the polarization of the hadron, the asymmetry begins growing at the same value of the c.m. pion energy $E_0^{\text{c.m.}}$ and is independent of the primary beam energy.

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