Angular distribution of the production of symmetric hadron pairs in $\pi^- p$ collisions at 40 GeV

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The angular distribution of the cross sections for the production of symmetric hadron pairs with effective masses from 2.4 to 5.4 GeV/c^2 at $\sqrt{s}=8.7$ GeV has been measured on a two-arm spectrometer. The experimental data are compared with theoretical predictions of a model based on QCD.

Measurements of the cross section for the production of symmetric pairs of hadrons with large transverse momenta P_T in hadron collisions can be used to study the dynamics of the parton–parton interaction, for the following reasons. First, it is generally accepted that hadrons with large P_T are produced through hard scattering of their constituents: quarks, gluons, and possibly diquarks. Second, it has been shown experimentally[1] that at values of $x_T=2P_T/\sqrt{s}$ greater than 0.2 the leading hadron in the jet carries the bulk of the momentum of the jet (80–90%). Third, the angular distribution of symmetric pairs of this sort is essentially undistorted by the existence of an internal transverse momentum P_T of the partons in the colliding hadrons.[2] In addition, the fragmentation process has the result that a hadron with large P_T usually contains a scattered parton. The quantum numbers of such a hadron should thus partially reflect the flavor of the fragmenting parton.[3] At relatively low energies we can expect large effects from the violation of scaling and diquarks.[4,5]

In this letter we are reporting experimental data on the distribution of the invariant differential cross sections for the production of h^+h^- pairs, where $h=(\pi, K, p)$, in $\pi^- p$ collisions with respect to θ, which is the angle through which the pair is scattered in its proper frame. The angular distribution of the cross sections for the production of symmetric hadron pairs and two-jet events in pp and $p\bar{p}$ collisions have been measured in several places.[1,6–10] However, these are the first results on $\pi^- p$ collisions. There are basically two reasons for this circumstance: the relatively low intensity of π^- beams (in comparison with p beams) and the difficulties in detecting such rare events as the creation of symmetric hadron pairs with large P_T.

The measurements were carried out on a two-arm rotatable spectrometer, described in detail in Ref. 11. The energy in the c.m. frame of the $\pi^- p$ collisions was 8.7 GeV. The beam of π^- mesons, with an intensity up to 10^8 π^-/s, was incident first on a hydrogen target 40 cm long and then on an absorber. The position of the beam on the target and the beam intensity were measured by multichannel ionization chambers with solid electrodes. An absolute calibration of the chambers was carried out at a reduced beam intensity with the help of scintillation and Čerenkov counters in the beam. The error of this calibration was 10%. The main spectrometer was a two-gap magnet in which the angle between the axes of the gaps was 320 mrad. This arrangement resulted in the detection of pairs of particles which were produced in the target and which separated at an angle close to 180° in the c.m. frame of the nucleon–nucleon interaction at $\sqrt{s}=11.5$ GeV. The coordinates of the particle trajectory beyond the magnet were measured by drift chambers. The particles were identified (π, K, and p) by spectrometers which analyzed the rings of Čerenkov radiation[12] with the help of the known momentum, which was calculated from the deflection of the particle's trajectory in the field of the magnet. To suppress the count from electromagnetic showers, a lead absorber 30 cm thick was placed at the end of each arm of the spectrometer. Beyond this absorber was a scintillation counter in a trigger circuit. One arm of the spectrometer was triggered by a coincidence of the signals from four scintillation counters, while two arms were triggered by a coincidence of single trigger events.

The entire spectrometer could be rotated in the horizontal plane around the center of the target, through an angle up to 60 mrad. Measurements were taken at two values of the angle between the beam axis and the spectrometer axis: 0 and 60 mrad.

The analysis of the experimental data included a geometric reconstruction of the tracks, a determination of the momenta and angles at which the particles left the target, and an identification of the species of the particles from the radii of the Čerenkov radiation rings in the Čerenkov-ring spectrometers. Background events were then subtracted, and corrections were made for the efficiencies for the detection of the particles of the various species. Cross sections were calculated with the help of a Monte Carlo simulation of the experiment.

Hadron pairs satisfying the following requirements were selected for the analysis of the angular distribution of the cross sections:

1) $P_{T1,2} > 1$ GeV/c, where P_{T1} and P_{T2} are the transverse momenta of respectively the h^- and h^+.

2) $|P_{T1}-P_{T2}|<0.6$ GeV/c.

3) $2.4<M_{h^+h^-}<5.4$ GeV/c^2, where $M_{h^+h^-}$ is the invariant mass of the hadron pair.

4) $160° < |\phi_1-\phi_2| < 200°$, where ϕ_1 and ϕ_2 are the azimuthal angles of the hadrons.

The absolute value of the longitudinal momentum in the c.m. frame of the π^-p collisions was less than 1 GeV/c for all pairs which satisfied the conditions just listed.

Table I shows values of the invariant differential cross sections for the production of hadron pairs of various species as a function of $\cos\theta$. The cosine of the scattering angle of the pair in its proper frame is found from

TABLE I. Angular distribution of the invariant differential cross sections for the production of symmetric hadron pairs.

Species	Mass, GeV/c^2	$\cos\theta$	$E_1E_2\frac{d^6\sigma}{d^3p_1d^3p_2}$, pb/GeV^4
$\pi^+\pi^-$	3.5	−0.44	26.9±3.0
		−0.37	19.2±1.5
		−0.30	17.4±1.8
		−0.12	8.6±1.2
		−0.04	10.6±0.5
		0.04	10.1±0.4
		0.12	11.2±1.3
		0.30	17.5±1.7
		0.37	27.1±2.1
		0.44	50.1±4.6
π^+K^-	3.5	−0.45	5.72±1.95
		−0.37	2.87±0.71
		−0.30	2.77±1.01
		−0.13	1.36±0.38
		−0.04	1.93±0.20
		0.04	1.60±0.21
		0.12	2.56±0.67
		0.29	2.85±0.61
		0.37	4.14±0.81
		0.44	3.45±2.24
$K^+\pi^-$	3.5	−0.44	5.50±2.34
		−0.37	5.95±0.92
		−0.29	5.67±1.10
		−0.12	5.13±0.84
		−0.04	3.45±0.29
		0.04	3.66±0.28
		0.13	4.38±0.93
		0.30	6.39±1.61
		0.37	11.1±1.5
		0.45	23.2±3.5
K^+K^-	3.5	−0.45	7.83±2.09
		−0.37	1.70±0.81
		−0.30	3.06±0.94
		−0.12	3.49±0.66
		−0.04	2.65±0.27
		0.04	2.52±0.25
		0.12	2.40±0.64
		0.29	4.74±1.19
		0.37	5.18±1.20
		0.45	7.82±2.68

TABLE I. (*Continued.*)

Species	Mass, GeV/c^2	$\cos\theta$	$E_1E_2\frac{d^6\sigma}{d^3p_1d^3p_2}$, pb/GeV^4
$p\pi^-$	3.5	0.47	5.74 ± 1.49
		-0.38	2.73 ± 1.21
		-0.30	2.64 ± 1.88
		-0.16	1.71 ± 0.44
		-0.05	0.82 ± 0.23
		0.05	1.73 ± 0.31
		0.15	1.47 ± 0.41
		0.27	4.82 ± 0.86
		0.37	4.58 ± 1.62
		0.44	6.31 ± 2.61
$\pi^+\bar{p}$	3.5	-0.43	24.0 ± 5.7
		-0.37	21.1 ± 3.3
		-0.27	21.6 ± 2.0
		-0.15	21.7 ± 1.4
		-0.05	15.9 ± 0.8
		0.05	14.5 ± 0.8
		0.15	26.6 ± 1.8
		0.31	51.7 ± 8.3
		0.38	68.3 ± 5.8
		0.47	12.3 ± 8
$p\bar{p}$	3.8	-0.46	6.13 ± 2.19
		-0.37	6.36 ± 1.32
		-0.28	4.30 ± 1.31
		-0.13	2.53 ± 0.67
		-0.05	2.80 ± 0.33
		0.05	3.38 ± 0.36
		0.13	3.62 ± 0.67
		0.28	5.85 ± 1.44
		0.37	10.0 ± 2.0
		0.46	24.4 ± 3.4

$$\cos\theta=\frac{\sin\left(\frac{\vartheta_1-\vartheta_2}{2}\right)}{\sin\left(\frac{\vartheta_1+\vartheta_2}{2}\right)},$$

where ϑ_1 and ϑ_2 are the polar angles of the h^- and h^+ hadrons, respectively, in the c.m. frame. The errors shown for the cross sections in Table I are exclusively the statistical errors of the measurements and the errors of the calculation of the acceptance of the apparatus obtained by the Monte Carlo method. The error of the absolute

TABLE II. Parameters used in the approximation of the angular distribution of the cross sections of symmetric hadron pairs by function (1).

Species	A	B	n	χ^2/DOF
$\pi^+\pi^-$	0.59 ± 0.03	0.41 ± 0.02	3.21 ± 0.12	2.12
π^+K^-	0.56 ± 0.08	0.44 ± 0.07	2.77 ± 0.37	0.77
$K^+\pi^-$	0.67 ± 0.05	0.33 ± 0.04	3.26 ± 0.22	1.61
K^+K^-	0.67 ± 0.10	0.33 ± 0.08	2.21 ± 0.42	1.64
$p\pi^-$	0.73 ± 0.03	0.27 ± 0.02	3.62 ± 0.11	7.7
$\pi^+\bar{p}$	0.67 ± 0.33	0.33 ± 0.07	4.07 ± 0.38	1.58
$p\bar{p}$	0.71 ± 0.07	0.29 ± 0.05	3.65 ± 0.25	0.95

normalization of the cross sections is estimated to be 15%. It results primarily from the absolute calibration of the monitors and the error in the determination of the momentum and the various corrections. The systematic error in the determination of $\cos\theta$, due to the size of the π^- beam at the target and the error in the geodesic calibrations of the apparatus, does not exceed 0.02.

Table I reveals an asymmetry of the angular distributions for forward and backward scattering for essentially all species of pairs. This asymmetry can be attributed to a difference between the structural constituents of the colliding π^- mesons and protons.

The angular distribution of the production of hadron pairs in π^-p collisions which follows from first-order perturbation theory in the QCD model is

$$\frac{d\sigma}{dz} \Big/ \frac{d\sigma}{dz}\bigg|_{z=0} = A(1-z)^{-n} + B(1+z)^{-n}, \quad (1)$$

where n, A, and B are parameters, and $z = \cos\theta$.

The experimental data for pairs of all species are described as a function of $\cos\theta$ by function (1). Table II shows values of the parameters n, A, and B and also the values of χ^2 per degree of freedom. The values of n, A, and B are seen to differ for the pairs of different species. This circumstance is evidence of a difference in the mechanisms for the production of the different hadron pairs.

In the calculations,[13] which were carried out before these measurements, the angular distribution of the cross sections for the production of symmetric $\pi^+\pi^-$ pairs was calculated in the lower-order perturbation theory of QCD. Those calculations used an effective mass of 4 GeV/c^2 for the pair, with an energy $\sqrt{s} = 8.7$ GeV in the c.m. frame of the π^-p collisions. Those calculations used the following values for the parameters of the model: The QCD parameter Λ was 0.4 GeV/c, the average transverse momentum of the partons in the colliding protons was $\langle k_T \rangle_{h \to q} = 800$ MeV/c, and the average transverse momentum of the hadrons in the jet was

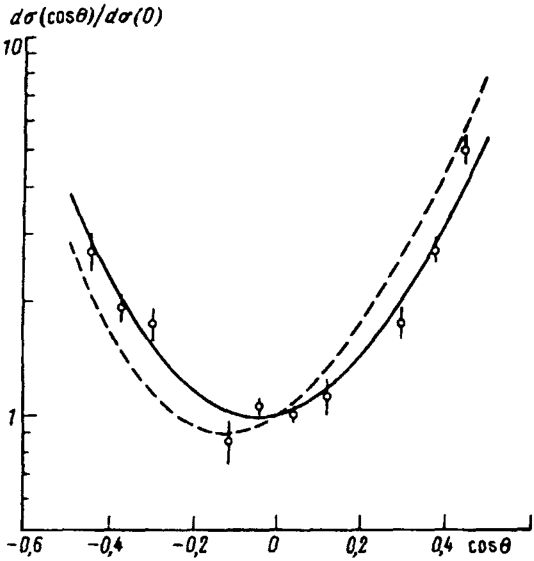

FIG. 1. Angular distribution of the differential invariant cross sections for the production of $\pi^+\pi^-$ pairs. Solid curve—Approximation of the experimental data with an average mass of 3.5 GeV/c^2 by function (1) ($n=3.12\pm0.21$); dashed curve—results of a QCD calculation in Ref. 13 with a mass of 4 GeV/c^2 ($n=3.45$).

$\langle k_T\rangle_{q\to h}=400$ MeV/c. A regularization parameter $m^2=1$ GeV^2 was added to $\hat{s}$, $-\hat{t}$, and $-\hat{u}$ to eliminate some divergences at small values of the momentum transfer in the parton cross sections.

Figure 1 shows the angular distribution of the production of $\pi^+\pi^-$ pairs with a mass of 3.5 GeV/c^2 found from the experimental data, along with a theoretical curve from Ref. 13. We see in this figure that the theoretical results agree qualitatively with the experimental results. The degree of quantitative agreement depends on the choice of parameters of the theoretical model, on the approximations used in the model, and on the choice of fragmentation function.

The results found here agree well with previously published measurements[10] of the angular distribution of the cross sections for the production of symmetric hadron pairs in pp collisions at $\sqrt{s}=11.5$ GeV.

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