Angular distribution of parton–parton scattering found from the production of hadron pairs in *pp* collisions at $\sqrt{s} = 11.5$ GeV

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The angular distribution of the cross section for the production of symmetric hadron pairs with effective masses from 2.95 to 4.7 GeV/c^2 has been measured on a two-arm spectrometer. The experimental data are compared with predictions of a model based on QCD.

The angular distribution of the cross section for parton–parton scattering in hadron collisions is an important characteristic of the strong interaction. Research on this distribution is confronted with the fundamental obstacle that quark-partons, gluons, and possibly heavier entities (e.g., diquarks) do not exist in a free state. The angular distributions of the cross sections for parton–parton scattering have been studied experimentally at CERN[1–4] and FNAL.[5] In the experiments of Refs. 3–5, the momenta of the scattered partons were reconstructed by the most direct method: from the kinematics of the jets in two-jet events. In Refs. 1 and 2, these momenta were reconstructed from the momenta of the hadrons which were detected. The angular distribution of the cross sections can be described well by the QCD parton model in first-order perturbation theory.

Separation of hadron jets at the energy of Serpukhov accelerator is an extremely complex problem. However, if one detects not the jets but symmetric identified hadron pairs with large values of P_T, then the angular distribution should not be greatly altered. The reason is that it has been shown experimentally[1] that a hadron carries off most of the momentum of the jet (70–90%) because of "trigger bias" at values of $x_T = 2P_T/\sqrt{s}$ greater than 0.2, and the direction of this hadron approximates the direction of the fragmenting parton. By detecting symmetric pairs of hadrons, one can avoid an effect of the internal transverse momentum of the partons, k_T, in the colliding hadron on the angular distribution of the cross sections.[6] Furthermore, fragmentation has the result that the hadron with the large value of P_T usually contains the scattered parton. The quantum numbers of such a hadron should thus reflect, at least partially, the flavor of the fragmenting parton,[7] while it is very difficult in practice to extract information on the nature of the parent of the jet. At relatively low energies one might expect strong scaling violation and strong effect of the diquarks.[8,9]

In this letter we are reporting a study of the production of h^+h^- pairs, where $h=(\pi,K,p)$, in pp collisions as a function of θ^*, the scattering angle of the pair in the c.m. frame of the colliding protons.

The measurements were carried out on the two-arm rotating spectrometer described in detail in Ref. 10, at an energy of 11.5 GeV in the c.m. frame of the pp collision. A proton beam with an intensity up to 10^9 p/s was incident 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 and by chambers with solid electrodes. An absolute calibration of these chambers was carried out in a beam of reduced intensity, by placing scintillation and Čerenkov counters in the beam. The error in this calibration was 10%. The spectrometer is based on a two-gap magnet with an angle of 320 mrad between the axes of the gaps. This configuration makes it possible to detect pairs of particles which are produced in the target and which separate at an angle close to 180° in the c.m. frame of the pp collision at $\sqrt{s}=11.5$ GeV. The coordinates of the trajectory of the particle beyond the magnet are measured by drift chambers. The particles (π's, K's, and p's) are identified by spectrometers which work with the rings of Čerenkov radiation[11] at a known momentum, calculated from the deflection of the trajectory of the particle in the field of the magnet. The count from electromagnetic showers is suppressed by placing a lead absorber 30 cm thick at the end of each spectrometer arm. Behind this absorber is a scintillation counter connected in a trigger circuit. One arm of the spectrometer is triggered by a coincidence of the signals from four scintillation counters, while both arms are triggered by a coincidence of individual trigger signals.

The entire spectrometer can be rotated up to 60 mrad around the center of the target in the horizontal plane. Measurements were carried out for three values of the angle between the beam axis and the spectrometer axis: 0, 30, and 60 mrad.

The analysis of the experimental data included a geometric reconstruction of the tracks, a determination of the momenta of the particles and the angles at which they were emitted from the target, and an identification of the particle species on the basis of the radius of the ring of Čerenkov radiation in the Čerenkov-ring spectrometer. Background events were then subtracted, and corrections were made for the detection efficiencies for the particles of the various species. The results of a simulation of the experiment by the Monte Carlo method were used to calculate the cross sections.

To analyze the angular distribution of the cross sections we selected hadron pairs meeting the following requirements:

1. $P_{T1}+P_{T2}>2.2$ GeV/c, where P_{T1} and P_{T2} are the transverse momenta of the first and second hadrons;

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

3. $160°<|\phi_1-\phi_2|<180°$, where ϕ_1 and ϕ_2 are the azimuthal angles of hadrons.

The absolute value of the longitudinal momentum in the c.m. frame of the pp collision was $\leqslant 1$ GeV/c for all pairs meeting these three conditions.

The angular distribution of the production of hadron pairs in pp collisions according to the QCD model in first-order perturbation theory is

$$\frac{d\sigma}{dz} / \frac{d\sigma}{dz}\Big|_{z=0} = 0.5\{(1-z)^{-n} + (1+z)^{-n}\}, \qquad (1)$$

where n is a parameter, and $z = \cos\theta^*$. The angle through which the hadron pair is scattered, θ^*, in the c.m. frame is calculated from

$$\cos\theta^* = \frac{\sin\left(\frac{\theta_1+\theta_2}{2}\right)}{\sin\left(\frac{\theta_1-\theta_2}{2}\right)},$$

where θ_1 and θ_2 are the polar angles of the first and second hadrons in the c.m. frame of the colliding protons. The value of the parameter $\vec{n}$ for the squares of matrix elements for the processes $qq \to qq$, $qg \to qg$, and $gg \to gg$ is about 2 in this approximation.

The experimental data for particles of all species were described by expression (1) as a function of the effective mass. Values of the parameter n and of χ^2 per degree of freedom are listed in Table I.

TABLE I.

Pair	Mass (GeV/c^2)	n	χ^2/DOF
$\pi^+\pi^-$	2,95	$2,65 \pm 0,18$	0,42
	3,40	$3.05 \pm 0,14$	0,42
	4,00	$3,16 \pm 0,24$	0,53
	4,70	$4,13 \pm 0,63$	0,47
π^+K^-	2,95	$2,65 \pm 0,18$	1,36
	3,40	$3,17 \pm 0,48$	0,08
	4,00	$3,49 \pm 0,73$	0,08
	4,70	$6,13 \pm 1,76$	0,78
$K^+\pi^-$	2,95	$2,32 \pm 0,41$	0,99
	3.40	$2,97 \pm 0,23$	1,08
	4,00	$3,50 \pm 0,39$	0,37
	4,70	$5,44 \pm 0,94$	0,22
K^+K^-	2,95	$2,12 \pm 0,74$	0,67
	3.40	$2,71 \pm 0,36$	0,87
	4,00	$2,37 \pm 0,76$	2,47
$p\pi^-$	2,95	$3,69 \pm 0,21$	1,04
	3.40	$3,71 \pm 0,11$	0,29
	4,00	$3,90 \pm 0,16$	1,55
	4,70	$4,10 \pm 0,37$	1,32
$\pi^+\bar{p}$	3.40	$3,42 \pm 0,46$	1,20
	4,00	$4,45 \pm 0,74$	1,00
pK^-	2,95	$4,33 \pm 0,73$	1,54
	3.40	$3,77 \pm 0,23$	1,60
	4,00	$3,55 \pm 0,39$	2,53
	4,70	$4,31 \pm 0,28$	0,18
$p\bar{p}$	4,00	$3,64 \pm 0,65$	0,69

In an effort to compare the experimental data with the model of hard elastic scattering of partons in a theory with a vector gluon (QCD), the angular distribution of the cross sections for $\pi^+\pi^-$ pairs was calculated for a pair mass of 4 GeV/c^2 in lowest-order perturbation theory of QCD.[12] These calculations were carried out with the help of the following values for the parameters of the model: The QCD parameter Λ was taken to be 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; the average transverse momentum of the hadrons in the jet was $\langle k_T \rangle_{q\to h} = 400$ MeV/c; and the regularizing parameter, used to eliminate the divergences at small momentum transfer, was $m^2 = 1$ GeV^2.

Figure 1 shows the angular distribution of the production of $\pi^+\pi^-$ pairs with a mass of 4 GeV/c^2 found from the experimental data, along with theoretical results from Ref. 12. The dashed line corresponds to a QCD model with a violation of scaling at $\sqrt{s} = 11.5$ GeV, while the dot-dashed line corresponds to QCD without this violation, with $Q^2 = 4$ GeV^2. We see from this figure that the deviation from scaling at the given energy has an important influence on the strength of the angular dependence for π-meson pairs, and the theoretical results agree qualitatively with the experimental

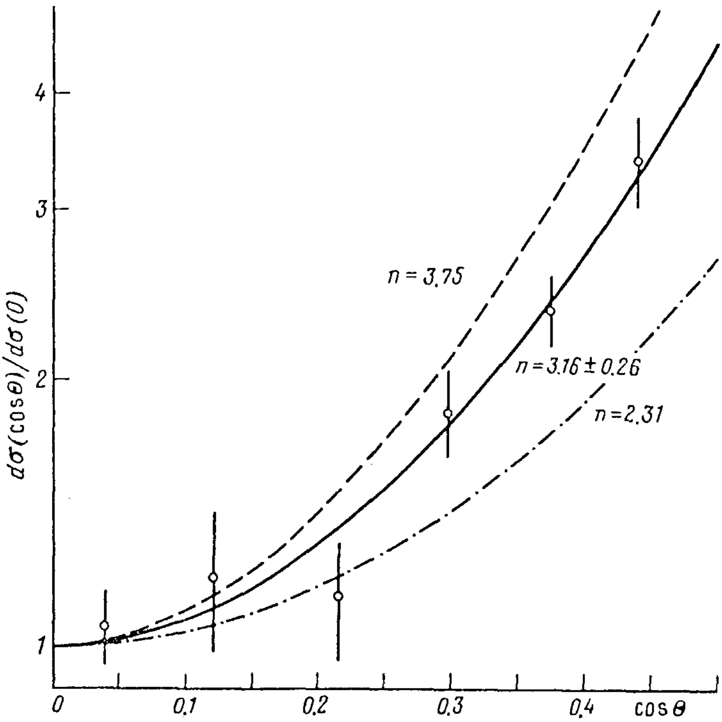

FIG. 1. Angular distribution of the production of $\pi^+\pi^-$ pairs with a mass of 4 GeV/c^2. Solid line—Approximation of the experimental data by expression (1); dashed line—calculation from a QCD model with a violation of scaling; dot-dashed line—calculation from a QCD model without this violation of scaling, for $Q^2 = 4$ GeV^2.

data. The quantitative agreement depends on the values selected for the parameters of the theoretical model, the approximations used in the model, and the choice of fragmentation function.

The angular distribution of the cross section in the case of an Abelian theory with a scalar gluon is considerably weaker,[3,4] ($n \sim 1$), so it could not successfully describe the experimental data which we are reporting here.

A qualitative comparison of the values of the parameter n in the angular distribution for all types of pairs reveals the following:

1. The value of n for pairs containing a proton are systematically higher than the values for meson pairs. For example, we find the average value $\langle n \rangle_{\pi^- p} = 3.77 \pm 0.08$, in comparison with $\langle n \rangle_{\pi^+\pi^-} = 2.97 \pm 0.10$ and $\langle n \rangle_{K^+K^-} = 2.56 \pm 0.30$.

2. For all pairs containing a proton, the value of n is essentially independent of the mass of the pair, while for meson pairs (other than K^+K^-) there is some increase in n with increasing mass.

3. The K^+K^- system stands out among the purely meson pairs in that its value of n is independent of the mass and is closer to 2.

These results are consistent with experimental results reported previously on the angular distribution of the cross sections for $\pi^0\pi^0$ pairs[1] and for two-jet events.[3–5]

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