TWO-PARTICLE CORRELATIONS IN e^+e^- ANNIHILATION

PLUTO Collaboration

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We present measurements of two-particle angular correlations in hadron jets produced in e^+e^- annihilation between 7.7 and 31.6 GeV c.m. energy. The data are compared to predictions of high order perturbative QCD calculations.

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e^+e^- annihilation into hadrons has proven to be a very powerful tool for probing the properties of quarks, and for testing QCD, the promising theory of strong interactions. Above 5 GeV c.m. energy, the process is well described by the production of two quarks and their subsequent fragmentation into two hadron jets [1]. Indications of gluons, the quanta of QCD, have been observed in the decay of the $\Upsilon(9.46)$ at DORIS [2], and in deviations from the two-jet topology at the highest energies of PETRA [3]. Still more experimental information is needed about jets, however, not only to "prove" QCD, but also to test the validity of different computational approaches and approximations.

As one possible and theoretically important test, particle–particle angular correlations in jets have been proposed [4,5]. The correlations are defined as the energy-weighted distributions of particle–particle angles

$$\frac{1}{\sigma}\frac{d\sigma}{d\theta} = \frac{1}{\sigma}\sum_{ab}\int dz_a dz_b\, z_a z_b \frac{d^3\sigma}{dz_a dz_b d\theta}\,, \qquad (1)$$

where z_a and z_b are the energies of particles a and b, normalized to the beam energy, and θ is the angle between their flight directions. The distributions divide into two classes, same-side and opposite-side, depending on whether a and b belong to the same or to opposite jets. The two classes probe different aspects of jet fragmentation. While the same-side distributions describe a weighted angular spread of one jet, the opposite-side distributions indicate whether specific correlations between the jets are important. Predictions for opposite-side correlations are given in refs. [5,7–11], for the same side in refs. [6,7,9,10]. All the predictions have in common that they derive from perturbative QCD alone the evolution of parton (quark, gluon) cascades, but ignore the at present incalculable effects of the conversion of partons into hadrons and problems of quark confinement. This allows, on one hand, to test QCD independently of hadronization models. It restricts, however, the kinematical range to which the predictions can be applied. It should also be noted that the derivations involve specific computational approximations like "leading log" which may in addition limit the range of applicability.

We have measured same-side as well as opposite-side correlations of charged particles in e^+e^- annihilation at c.m. energies of 7.7, 9.4, 13, 17, 22, 27.4, 30 and 31.6 GeV. The data were taken with the magnetic detector PLUTO at the storage rings DORIS and PETRA. The PLUTO detector is sensitive to charged particles within 87% of the full solid angle. The angles of particle tracks are measured to better than 0.3°. Details of the experimental setup, the selection and the yield of hadronic events have been presented in ref. [12].

We proceed in the event analysis as follows:

(i) Find the jet axis [2] for the only purpose of de fining the side to which every particle belongs.

(ii) Plot the opening angle of every pair a, b of charged particles with weight $z_a z_b$ in the same- or opposite-side distribution, depending on whether a and

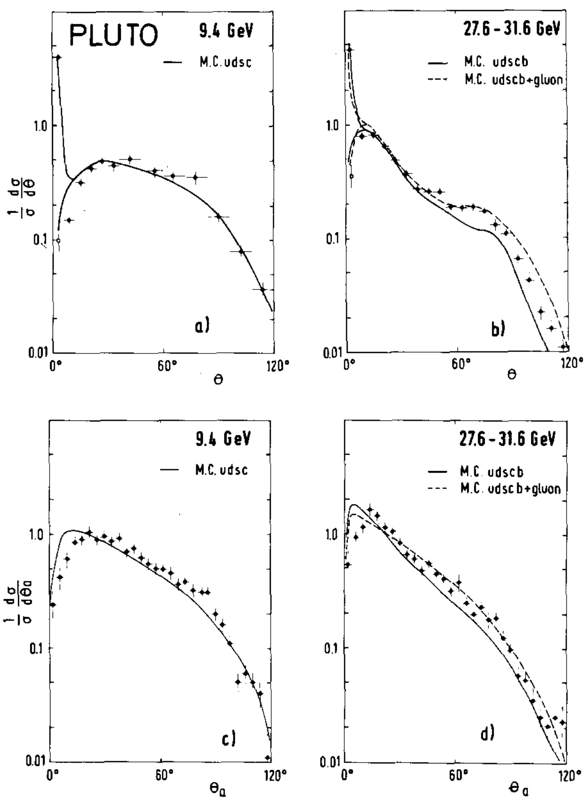

Fig. 1. Angular correlations before corrections for same side (a), (b) and opposite sides (c), (d). The full (dashed) curves give Monte Carlo predictions without (with) hard gluon emission. At small angles the data and predictions branch in (a), (b), depending on whether self-correlations are included (full points) or not (open points). In (c) and (d) the abscissa is the accolinearity angle $\theta_a = \pi - \theta$.

b belong to the same or to opposite sides [‡1]. For the proper normalization of the same-side distribution, all self-correlations (b = a, $\theta = 0$) have to be included in eq. (1).

(iii) Correct the data for detector resolution and acceptance, and for photon radiation in the initial state. According to our Monte Carlo simulation of the measurement and analysis, the corrections are small, typically 10% or less.

(iv) Normalize the distributions to unity in order to account for the neutral particles. We have checked that the normalized correlations change very little if the neutral particles are included in the analysis as well. For reasons of better measuring accuracy, however, only the charged ones have been used.

Figs. 1a and 1b show two examples of same-side correlation, before the corrections (iii) have been applied. At zero angle the distributions are dominated by the correlation of every particle with itself. For illustration, the open points give the part due to pairs of different particles only. The main part of the correlation is well reproduced by a Monte Carlo based on a Field–Feynman jet model [13], including heavy quarks, and a simulation of initial state radiation, the detector, and the analysis. Within this description, QCD effects have only minor influence on the correlation. Single gluon emission calculated according to ref. [14] is negligible at 9.4 GeV, but helps to reproduce the tail of the distribution at higher energies (dashed curve in fig. 1b) [‡2].

In figs. 1c and 1d we have plotted the opposite-side

[‡1] The errors are calculated assuming all entries in the plot to be independent.

[‡2] A similar agreement can be obtained by ad-hoc increasing the mean p_T of the fragmentation model by 50%. The far tail of the same-side correlation, $\theta > 90°$, is built up by pairs of particles which both lie outside the central cone of the jet, and may be useful for testing fragmentation processes in much greater detail than intended here.

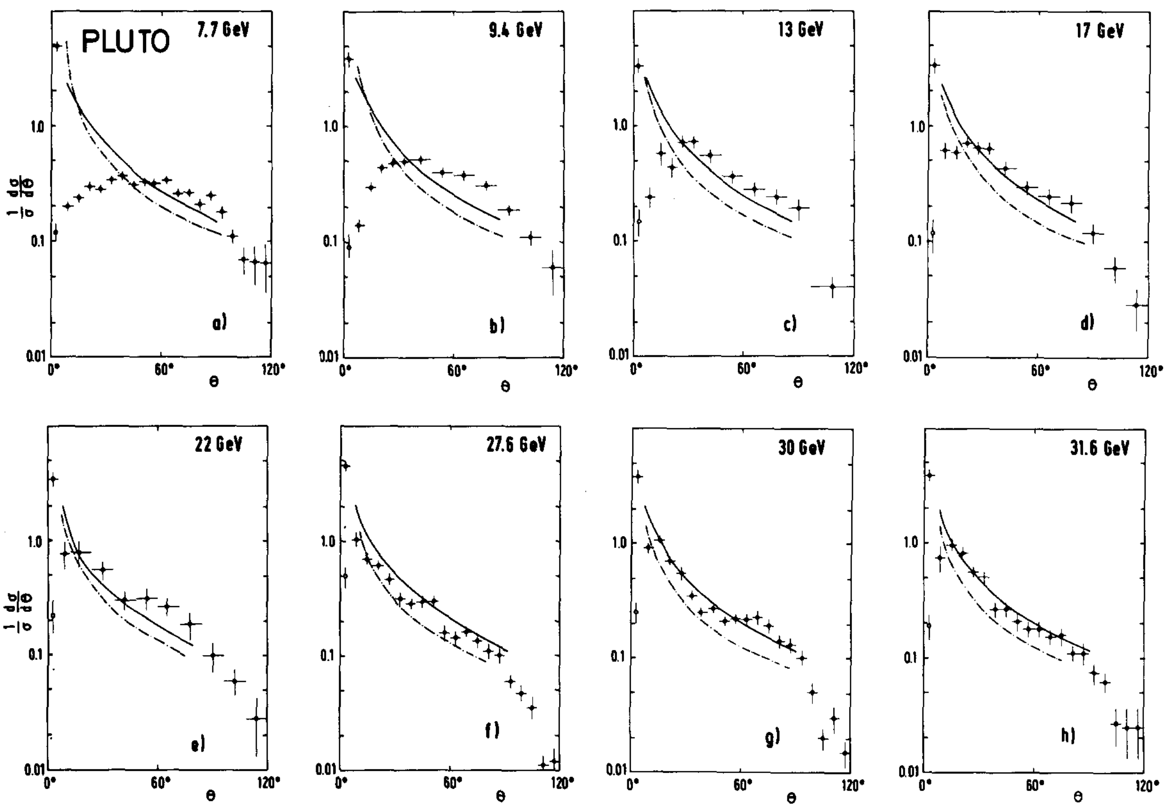

Fig. 2. Same-side correlations for different energies. The dashed–dotted and full curves give the prediction of refs. [6] and [7], all with Λ = 500 MeV.

correlation, also before corrections, versus the acollinearity angle $\theta_a = \pi - \theta$. The model description again is not very sensitive to effects of single gluon emission. It describes the observed distribution reasonably well, except for the smallest acollinearity angles, where the data are lower than expected. An interpretation of this deviation will be given below.

Fig. 2 shows the corrected same-side correlation for all energies between 7.7 and 31.6 GeV. With increasing energy the width of the distribution shrinks. In contrast, the prediction of Konishi et al. [6] (dashed curve) depends only weakly on the energy, a typical feature of QCD results. The prediction describes the correlation of partons in leading-log approximation, and is valid for the range $\Lambda/E_{cm} \ll \theta/2 \ll 1$, with $\Lambda \approx 500$ MeV being the QCD scale, the only free parameter. The full curves show a similar evaluation of the parton correlation by Dokshitser and D'yakonov [7], differing from ref. [6] mainly at the smallest angles and in the resulting normalization. The measured distributions disagree with the predictions at low energies, but approach them rapidly as the energy increases. It thus appears that above 17 GeV the angular spread of the jets can be largely accounted for by quark–gluon dynamics which are calculabe from QCD alone, if higher orders of perturbation are taken into account. This seems to be a more satisfactory description than given by the phenomenological Field–Feynman type jet models discussed above [13, 14].

Fig. 3 shows the corrected opposite-side correlations for all energies, together with the original QCD prediction derived by Dokshitser et al. (DDT) [5]. It is calculated in the leading-log approximation, and valid for $\mu/(E_{cm}\langle z\rangle) \lesssim \theta_a/2 \ll 1$, where $\mu = 300$ MeV is the typical momentum of a quark inside a hadron, and $\langle z\rangle \approx 0.2$ the mean fractional energy of the hadrons. Again the width of the measured correla-

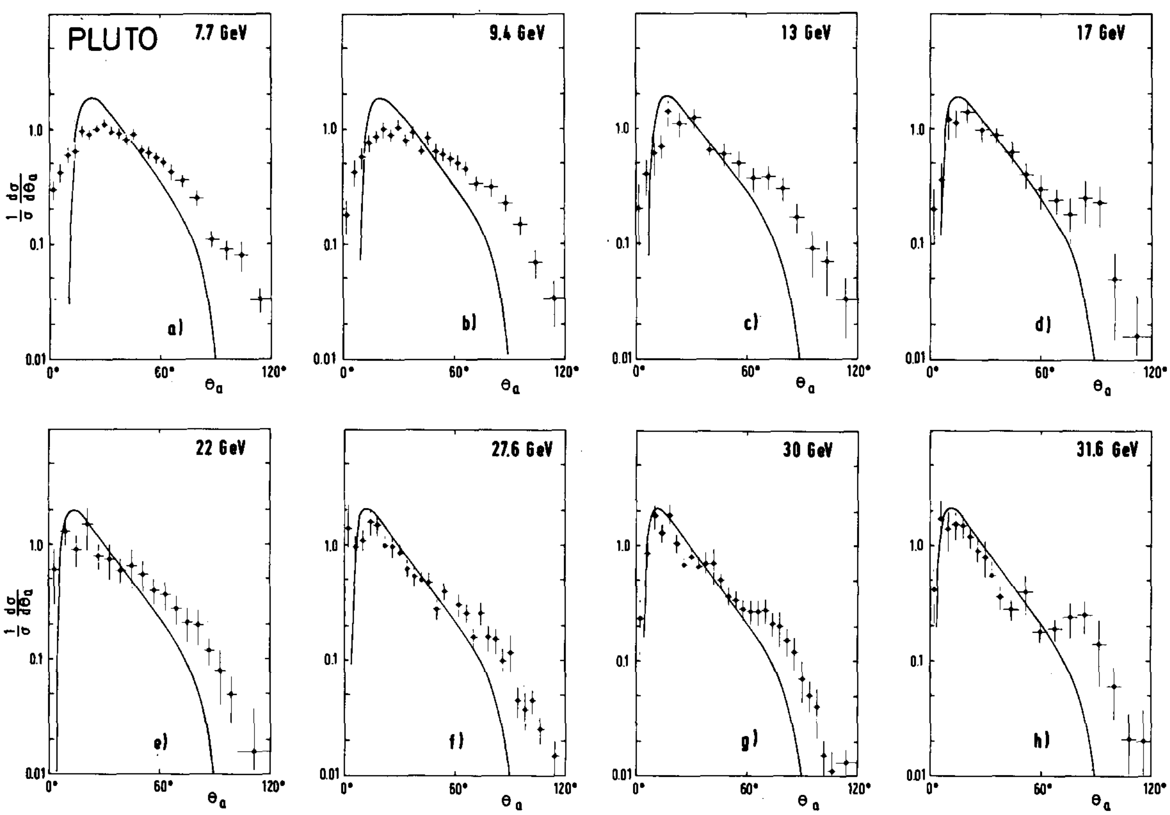

Fig. 3. Opposite-side correlations for different energies versus acollinearity angle $\theta_a = \pi - \theta$. The curves show the prediction of ref. [5] with $\Lambda = 500$ MeV.

tion is larger at low energies, but approaches the QCD prediction as the energy increases. In particular the suppression of small acollinearity angles, which is attributed to multiple gluon emission [‡3], is qualitatively well described. A quantitative comparison with the data aiming at a measurement of Λ appears premature, however, as the predictions of different authors still vary in some details [8,11]. At large angles, $\theta > 60°$, the small-angle approximation of the calculations breaks down. However, those large-angle correlations are dominated by the emission of one single hard gluon, and can be described in first order perturbation.

In conclusion we have measured two-particle correlations in jets produced in e^+e^- annihilation between 7.7 and 31.6 GeV. They are compared to predictions derived from QCD in leading-log approximation. The only adjustable constant, the scale Λ, has been set to 500 MeV. At low energy, the measured distributions are wider than predicted, suggesting that either confinement effects or nonleading contributions cannot be neglected. Towards higher energies, the data rapidly approach the QCD predictions, leading to a good qualitative agreement around 30 GeV. One particular feature of the opposite-side correlation, the suppression of small acollinearity angles, is also well described. This indicates that already at our present energies important features of hadron jets can be explained by perturbative QCD alone, and may in turn be used for quantitative tests of the underlying basic quark–gluon dynamics.

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[‡3] Formally, the suppression tests the variation of the running coupling constant $\alpha_s(4E_B^2\tan^2\theta/2)$ for small values of the argument. The acollinearity effect has also been discussed very recently in ref. [15].

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