ENERGY–ENERGY CORRELATIONS IN e^+e^- ANNIHILATION INTO HADRONS

PLUTO Collaboration

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Measurements of energy–energy correlations in hadronic final states produced in e^+e^- annihilation at c.m. energies between 7.7 and 31.6 GeV are presented. The data are compared to perturbative QCD predictions. Good qualitative agreement above 20 GeV c.m. energy is found. The importance of non-perturbative effects is discussed, as well as the detailed behaviour of the correlation near 180°.

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The quark–parton model is known to describe the gross features of e^+e^--annihilation like the total cross section and the dominance of two-jet final states to a high degree of accuracy. It is therefore difficult to measure the small deviations from this simple model predicted by QCD.

As a sensitive measure of gluon effects, energy–energy correlations have been proposed [1–4], which are defined as follows

$$f(\theta) = \frac{d\Sigma}{d\theta} = 2 \sum_{a,b} \int \frac{d^3\sigma}{dz_a \, dz_b \, d\theta_{ab}} z_a z_b \, dz_a \, dz_b \,, \qquad (1)$$

where z_a, z_b are the fractional energies ($E_{a,b}/E_{cm}$) carried away by hadrons a and b, and θ_{ab} is the angle between their directions of flight [‡1].

QCD predicts that at sufficiently high energies the correlation around 90° is dominated by single hard gluon bremsstrahlung and is therefore proportional to the quark–gluon coupling constant α_s [3,4]. At small ($0° < \theta < 60°$) and large ($120° < \theta < 180°$) angles QCD predicts a very peculiar exponential dependence on α_s. It can be derived in the leading log approximation (LLA) as a result of summing up a series of multiple gluon emission contributions [5,6]. In this approach the effects due to the final conversion of partons (quarks and gluons) into hadrons [1,5,6] are expected to decrease rapidly with energy, and are neglected. In order to take them into account at subasymptotic energies, Monte Carlo methods have been developed [7]. It should be noted that the LLA framework is quite different from the more conventional one [8] in which the conversion of the quarks into hadron jets is completely attributed to uncalculable long-distance interactions and parameterized by empirically determined fragmentation functions. QCD is then only used to calculate the emission of a single hard gluon which subsequently undergoes its own hadronization process [9,10].

A first measurement of the energy–energy correlation was reported in an earlier publication [2], in which the distribution (1) was computed separately for the two different cases, i.e. where hadrons a and b belonged to the same or to opposite jets. In that analysis the association of a track with a particular jet was determined by a plane perpendicular to the jet axis. This led to possible ambiguities for particles near 90° to this axis and also complicates the interpretation of the correlation data in the large angle (60°–120°) region. The present analysis avoids these difficulties by computing the energy–energy correlation (1) in the full angular range, i.e. without any reference to a jet axis.

For the present study we use the data already published [2] together with more recent data collected at 12 GeV, and from a scan in the energy region between 30.0 and 31.6 GeV [11]. The relevant properties of the detector have been described before [2]. In order to minimize background and corrections, events with less than four charged prongs, and with a jet axis closer than 41.4° to the beam were rejected. The sum (1) was extended over charged particles only for reasons of better measurement accuracy. Using a jet simulation program [8,9], we correct for neutrals as well as for losses in the reconstruction of charged tracks. This procedure automatically ensures the proper normalization of the corrected correlation (1). The correction also includes effects of initial state radiation, detector resolution and of the track analysis and selection.

We have checked that the corrected distributions are insensitive within the quoted statistical errors, typically 10%, to changes in the selection criteria, the definitions of the weights (replacing E_{cm} by $E_{visible}$ in the expression for $z_{a,b}$), and also to changes in the fragmentation parameters of the Monte Carlo simulation. From these considerations we estimate the systematic errors to be smaller than the statistical ones. The method of determining the statistical errors with ignored statistical intercorrelations between different angular bins has been checked by conducting a series of Monte Carlo "experiments" with the same number of events as observed, evaluating the distribution of the results for each bin, and comparing the actual to the expected variance. Unless explicitly noted, both agree.

In fig. 1 the resulting energy–energy correlations are shown in the range of energies between 7.7 and 31.6 GeV. The data below 12 GeV are from earlier experiments at DORIS [12]. At the lowest energies the data show little structure, but with rising energy the peaks at around 50° and 150° move away from the valley at 90° and become more pronounced. This behaviour reflects the increasing development of two distinct jet structures. Above 20 GeV these peaks have moved towards small values of θ and $180 - \theta$, and

‡1 The normalization to 2 instead of 1 was chosen here in accordance with refs. [3,4].

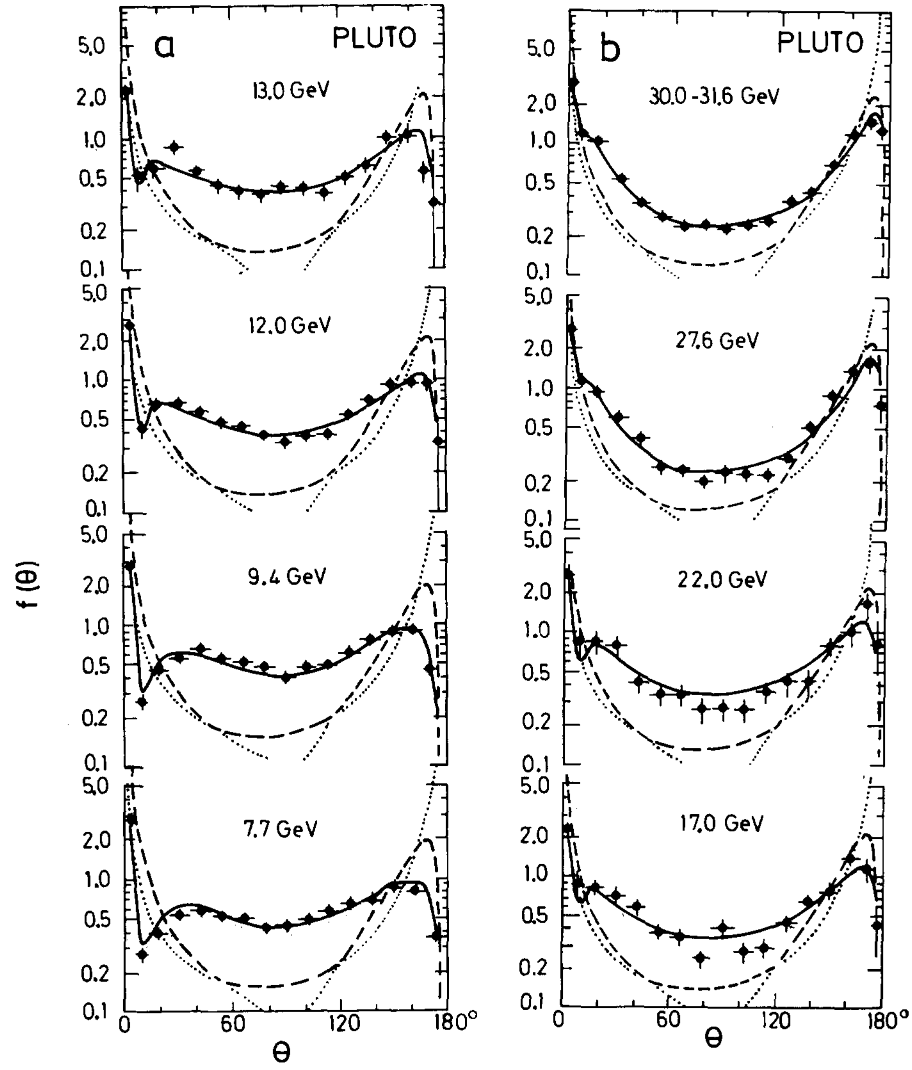

Fig. 1. Energy–energy correlations for different c.m. energies. Full lines show expectations from fragmentation models ($q\bar{q}$ below 10 GeV, ref. [8]; $q\bar{q}g$ above, ref. [9], with Λ = 200 MeV). Dashed lines give pure QCD predictions according to ref. [5] (0°–50°), refs. [3,4] (50°–120°) and ref. [18] (120°–180°). The value Λ = 200 MeV has been taken in all of them. The dotted lines represent the continuation of these predictions out of the regions defined above.

within errors the data have become nearly energy independent. This behaviour is well reproduced by the Monte Carlo simulation, as indicated by the full curves in fig. 1, provided gluon bremsstrahlung is incorporated at high energies [8,9].

As a possible alternative description of these data we also show in fig. 1 as dashed curves the predictions from a model [6,13] which uses the leading log same side predictions [5] for the angular range $\theta \lesssim 50°$, first order calculations [3,4] in the central region $50° \lesssim \theta < 120°$ and leading log opposite side predictions [‡2] in the backward regime $120° < \theta$. These predictions depend on only one parameter namely the strong coupling constant α_s or the QCD scale parameter Λ. The value Λ = 200 MeV has been taken, corresponding to

‡2 Predictions have been taken from eq. (3.3) of ref. [18].

$\alpha_s = 0.165$ at $E_{cm} = 30$ GeV [‡3], as suggested by the measurement of the rate of three jet events [14–17]. The following observations can be made:

(i) At low energies the angular spread of jets is much wider than accounted for by perturbative QCD calculations. This can be considered as an indication that fragmentation effects play a dominant role at these energies.

(ii) As the energy increases the data in the backward direction rapidly approaches the perturbative QCD results.

(iii) In contrast, the predictions in the forward and central regions remain about a factor 2 too low. The latter effect could be cured by inserting a larger value for the coupling constant. However, the energy dependence of the central plateau (integrated from 60° to 120°) as shown in fig. 2 argues against such an ad hoc procedure. This data can be well described by the sum of a pure first order QCD term [3]:

$$d\Sigma^{QCD}/d\theta = [\alpha_s(E_{cm})/\pi] g(\theta) \quad (2)$$

with $g(\theta)$ being an energy-independent function, and a fragmentation term [4]:

$$d\Sigma^{QF}/d\theta = (C\langle p_T\rangle/E_{cm})\sin^{-2}\theta \,, \quad (3)$$

where C is a constant entering in the parametrization of the average multiplicity as $\langle n\rangle = B + C \ln E^2_{cm}$ and $\langle p_T\rangle$ is the mean transverse momentum of the hadrons in a quark jet.

This can be seen from fig. 2 where the QCD term (2), shown as the dotted line, corresponds to $\Lambda = 200$ MeV as previously discussed, and the fragmentation term (3) has been evaluated using $C\langle p_T\rangle = 1.2$ GeV, as derived from jet studies [14–17] and the high energy rise of the multiplicity [20]. If both the QCD and the fragmentation terms are fitted then the following values are obtained for the two free parameters: $\alpha_s = 0.20 \pm 0.02$ at $E_{cm} = 30$ GeV and $C\langle p_T\rangle = 1.0 \pm 0.2$. We should also point out that the simple fit described above reproduces fairly well the detailed angular dependence of the correlation function (1) in the region 60°–120° over our entire c.m. energy range.

In refs. [3,4] it was also suggested that a clear signature of hard gluon bremsstrahlung would be the observation of a forward–backward asymmetry in the energy–energy correlation (1). In order to investigate this point we show in fig. 3 the asymmetry $f(180-\theta) - f(\theta)$ for the combined samples 7.7–9.4 and 27.6–31.6

‡3 The formula $\alpha_s(E_{cm}) = 12\pi/[(33 - 2N_f)\ln(E^2_{cm}/\Lambda^2)]$ has been used with N_f denoting the number of flavours.

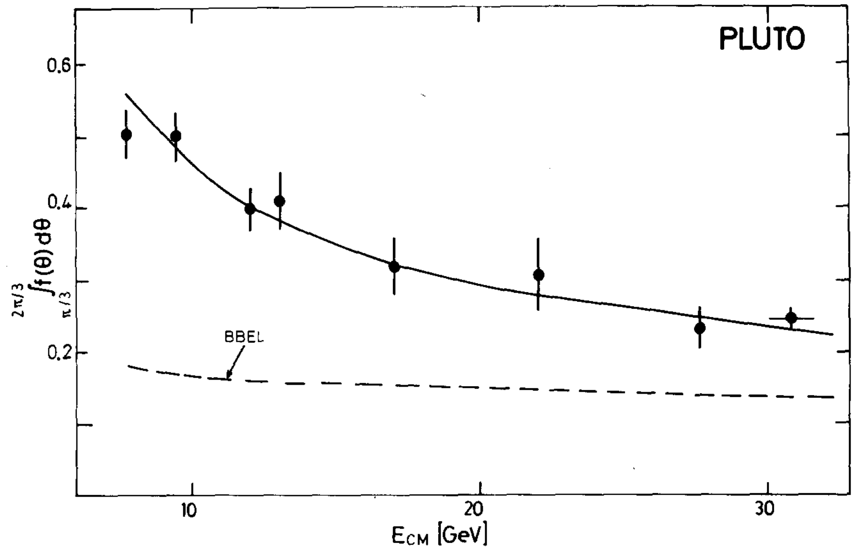

Fig. 2. The energy–energy correlation integrated in the region 60° – 120° as a function of c.m. energy. The error bars are based on the extended statistical analysis explained in the text. The full curve represents the sum of a pure first order QCD term (ref. [3], dashed line), and a fragmentation term according to ref. [4].

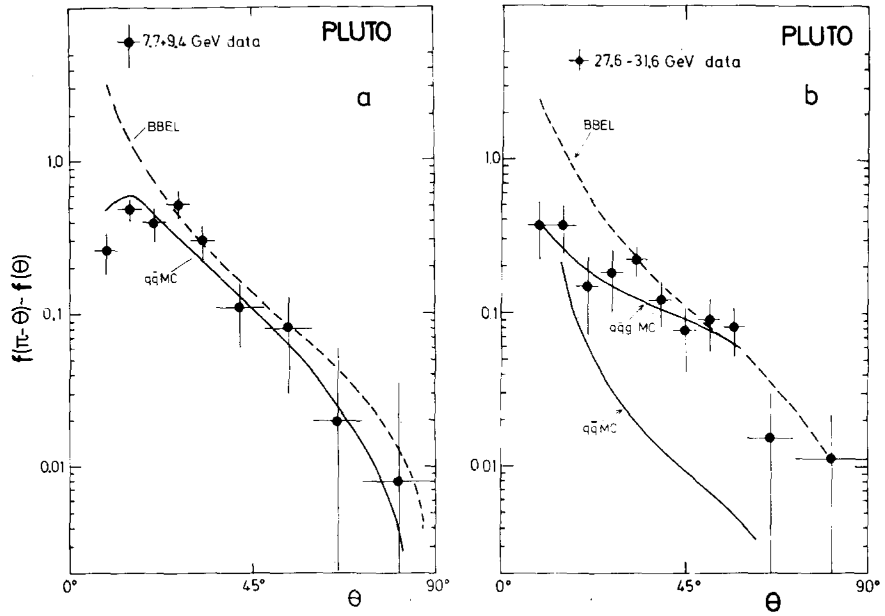

Fig. 3. The forward–backward asymmetry in the energy–energy correlation for the combined samples 7.7–9.4 and 27.6–31.6 GeV. Solid curves represent the expectations from fragmentation models as in fig. 1. The dashed curve stands for the pure first order QCD prediction.

GeV along with a comparison to the corresponding Monto Carlo expectations (full curves) as well as to the pure QCD predictions. Within the errors the observed asymmetry is energy independent and consistent at large angles with the first order QCD predictions (dashed curves). One notes, however, that the $q\bar{q}$ model which describes the low energy data fairly well contains an asymmetry of a similar magnitude. We have checked that the asymmetry present in this model, which we interpret as induced by fluctuations in the multiplicity and transverse momenta of final state hadrons, dies away with energy for $\theta \gtrsim 30°$ as $1/E_{\mathrm{cm}}^2$. Therefore, the asymmetry observed at high energies can be considered as a genuine manifestation of hard gluon bremsstrahlung. This is also expressed in the fact that the $q\bar{q}g$ simulation which describes the asymmetry over the full angular range agrees with the pure QCD prediction at high energies and large angles (fig. 3b). By fitting the asymmetry data to the analytical QCD prediction or to the Monte Carlo expectations one can also determine the strong coupling constant α_s. The values obtained are consistent with those previously discussed, however, the errors affecting this determination are bigger.

It has been suggested [21] that energy–energy correlations and in particular the asymmetry around 90° are also sensitive to the spin of the gluon. In fact the prediction [21] for a scalar gluon theory with $\alpha_s^{sc} = 0.20$ is far too small to fit our data. However increasing α_s^{sc} to ≈ 0.7 removes the discrepancy, so that a meaningful test can only be done either if α_s^{sc} is known beforehand, or if much finer details of the correlation can be measured and safely predicted.

One feature of the energy–energy correlation which deserves special attention is the turnover exhibited by the data at angles near 180°. The suppression of small acollinearity angles originally predicted from first principles in ref. [1] has been extensively discussed in the literature [19]. The experimental observation of this suppression is considered by many as a clean test of QCD [1,18]. Fig. 4 shows the energy–energy correlation (1) in the region near 180° plotted as a function of $\cos\theta$ so as to be free from the trivial kinematical zero due to phase space. The data approach a finite limit for $\cos\theta \to -1$ as generally expected for a fragmentation process. They are somewhat lower than calculated for the quark fragmentation ($q\bar{q}$ MC) alone, but fairly well described by the inclusion of hard gluon

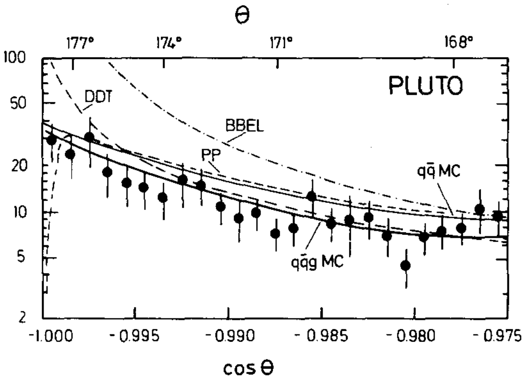

Fig. 4. Opposite side energy–energy correlation in the region near 180° for the combined sample 27.6–31.6 GeV. The full curves are obtained from the fragmentation models already discussed. The dashed lines give different QCD predictions according to ref. [1] ("DDT"), refs. [3,4] ("BBEL") and ref. [18] ("PP").

radiation ($q\bar{q}g$ MC). The "pure" QCD predictions in leading-log-approximation (DDT, PP) are lower than the diverging first order calculation ("BBEL"), in qualitative agreement with the data. They approach different limits as $\theta \to 180°$. It is not clear at present how far these details can be considered as final or are still affected by next-to-leading corrections or confinement effects.

In conclusion the measured energy–energy correlation shows a transition from an almost flat distribution at low energies, probably dominated by fragmentation effects, to a pronounced two jet topology at 30 GeV. It is well described at all energies by a Monte Carlo quark fragmentation model provided first order QCD corrections are taken into account. In an equivalent analytical model, the height and asymmetry of the central region are well described by a simple superposition of a fragmentation term and a first order QCD distribution. Height and width of the forward and backward peaks can alternatively be described by the spread of quark–gluon cascades as calculated in higher order QCD. The predictions are too low in the forward region but give a fair description of the backward peak.

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[1] Yu.L. Dokshitzer, D.I. D'yakonov and S.I. Troyan, Phys. Lett. 78B (1978) 290.
[2] PLUTO Collab., Ch. Berger et al., Phys. Let. 90B (1980) 312.
[3] C.L. Basham, L.S. Brown, S.D. Ellis and S.T. Love, Phys. Rev. Lett. 41 (1978) 1585.
[4] C.L. Basham, L.S. Brown, S.D. Ellis and S.T. Love, Phys. Rev. D19 (1979) 2018.
[5] K. Konishi, A. Ukawa and G. Veneziano, Phys. Lett. 80B (1979) 259.
[6] Yu. Dokshitzer, D.I. D'yakonov and S.I. Troyan, Phys. Rep. 58C (1980) 269.
[7] K. Kajantie and E. Pietarinen, Phys. Lett. 93B (1980) 269;
G.C. Fox and S. Wolfram, Nucl. Phys. B168 (1980) 285.
[8] R.D. Field and R.P. Feynman, Nucl. Phys. B136 (1978) 1.
[9] P. Hoyer, P. Osland, H.G. Sander, T.F. Walsh and P.M. Zerwas, Nucl. Phys. B161 (1979) 349.
[10] A. Ali, E. Pietarinen, G. Kramer and J. Willrodt, Phys. Lett. 93B (1980) 155.
[11] PLUTO Collab., Ch. Berger et al., Phys. Lett. 91B (1980) 148.
[12] PLUTO Collab., Ch. Berger et al., Phys. Lett. 78B (1978) 176.
[13] K. Konishi, A. Ukawa and G. Veneziano, Nucl. Phys. B157 (1979) 45.
[14] PLUTO Collab., Ch. Berger et al., DESY 80/93, Phys. Lett., to be published.
[15] MARK J Collab., D.P. Barber et al., Phys. Lett 89B (1979) 139.
[16] JADE Collab., W. Bartel et al., Phys. Lett. 91B (1980) 152.
[17] TASSO Collab., R. Brandelik et al., Phys. Lett. 86B (1979) 243; 94B (1980) 437.
[18] G. Parisi and R. Petronzio, Nucl. Phys. B154 (1979) 427;
[19] C.Y. Lo and J.D. Sullivan, Phys. Lett. 86B (1979) 327;
P.E.L. Rakow and B.R. Weber, Phys. Rev. Lett. 43 (1979) 1695;
F. Halzen and D.M. Scott, Phys. Lett. 94B (1980) 405;
W. Marquardt and F. Steiner, Phys. Lett. 93B (1980) 480;
S.D. Ellis and W.J. Stirling, Univ. of Washington preprint (May 1980);
R. Baier and K. Fey, Univ. of Bielefeld preprent, BI-TP 80/10.
[20] PLUTO Collab., Ch. Berger et al., Phys. Lett. 95B (1980) 313;
TASSO Collab., R. Brandelik et al., Phys. Lett. 89B (1980) 418.
[21] C.L. Basham and S.T. Love, Phys. Rev. D20 (1979) 340.