ENERGY - ENERGY ANGULAR CORRELATIONS IN e^+e^- - COLLISIONS (PLUTO - COLLABORATION)

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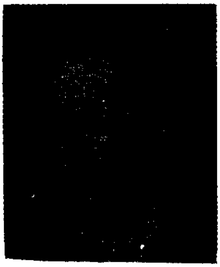


ABSTRACT: Energy-Energy correlations are presented as an alternative method to determine the strong coupling constant α_s. The data are compared to QCD predictions in the forward, backward and central region. The analysis of the backward and central region leads to values of α_s and Λ consistent with those obtained from different experiments.

1. Introduction

For experimental investigations of Quantum Chromo Dynamics it is important to apply different methods of analysis, and check whether they arrive at the same answer. Within the popular theory of strong interactions, QCD, the only unknown parameter which has to be determined is the strong coupling constant α_s. Such methods should be as 'orthogonal' as possible on each other. In e^+e^- annihilations α_s can be determined from the total cross section [1], from three-jet studies by applying three-jet analyses [2] or jet multiplicities determined by cluster methods [3], from the investigation of energy-energy correlations [4] and other channels. With increasing statistics to be collected at PETRA-energies one can hope that finally the results for α_s converge. In fact one already finds fair agreement [2,3]. At present, however, there is still a lack of precise theoretical interpretation of these results, mainly due to effects of higher order in α_s. Such corrections have different behaviour in different channels, which is a main motivation to apply 'orthogonal' methods. Of course, the final convergence of the results rests on a sufficient understanding of these higher order modifications.

The analysis of energy-energy correlations was first proposed to the PLUTO-collaboration [5] by Dokshitzer and D'yakonov [6]. Such correlations do not rely on topological analyses. Calculations are available for the forward (same side), and for the backward (opposite side) correlations [7]. These predictions are obtained by summing the soft gluon cascade to infinite order perturbation in the leading logarithm approximation (LLA). Thus we expect them to hold in places where fragmentation is negligible, which is true for high center-of-mass energies W. Since the predictions are derived on the parton level they involve only α_s, or due to the running nature of the strong coupling constant, the cutoff parameter Λ directly. α_s is parametrized for this and the following discussions by the formula

$$(1) \qquad \alpha_s(W^2) = \frac{12\,\pi}{(33 - 2\,N_f)\,\ln\,(W^2/\Lambda^2)}\ , \quad W \equiv \sqrt{s}$$

The number of flavors N_f is set to 4 for $W \leq 10$ GeV and to 5 above. Energy-energy correlations were also calculated [8] to first order perturbation for the central region around 90^o. We are thus able to compare experimental data with predictions in the complete angular range of two-particle angles, $0 \lesssim \Theta \lesssim 180^o$. The parametrization of these predictions by Λ alone allows α_s to be checked over a wide range in the energy scale. From the PLUTO-experiments at DORIS and PETRA this scale ranges from W = 7.7 to 30 GeV. Moreover, since the predictions for the forward and backward correlations depend on $\alpha_s\ (q^2_\perp)$ with $q_\perp = 2W\sin\Theta/2$, the effective range of the argument is extended down to about 1 GeV.

2. Data taking and definition of correlations

For details of the PLUTO-detector the reader is referred to references [9] (DORIS version) and [10] (at PETRA). Charged tracks are measured in the central detector within a solid angle of 92% of 4π. Their momenta are analysed in the homogenous magnetic field of 1.65 Tesla. For the attributed particle energy all particles are treated as pions. Neutral energy is detected by shower counters over 97% of 4π. Both charged and neutral particle correlations have been studied and found to agree well, but only the charged correlations finally entered into the analysis because of better angular precision. The technique of the data analysis is given in detail in the references [4]. The correlation function, f (Θ), is defined by the following formula

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

where $z_{a,b} = E_{a,b}/W$ are the fractional energies of particles "a" and "b" of an event. The sum is extended over all N particles of an event, like the one shown in Fig. 1a.

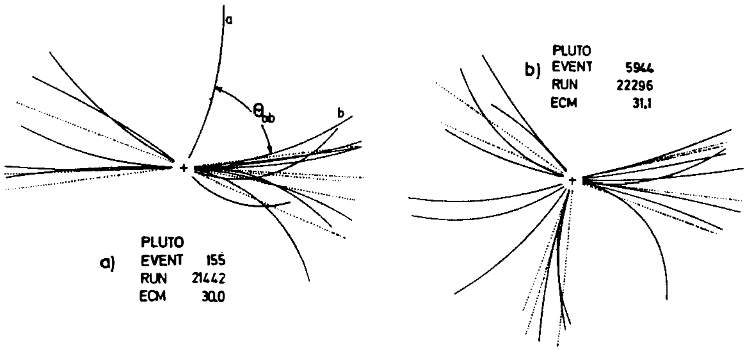
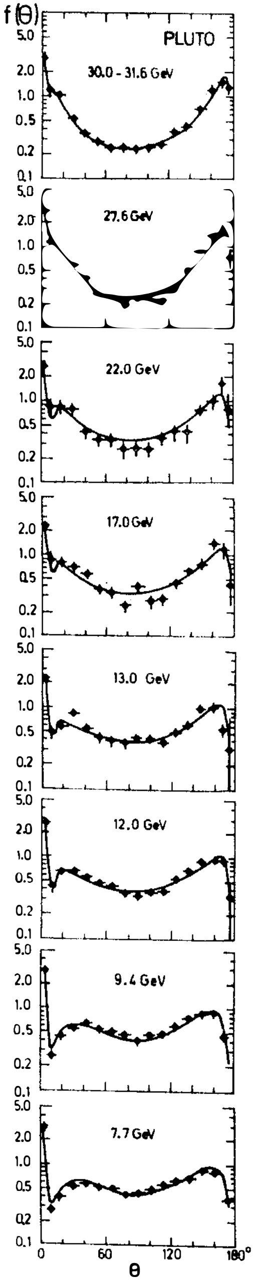


Fig. 1 (a) A typical 2-jet event is shown in a projection transverse to the beams. The curved full lines are charged, the dotted straight lines are neutral tracks. (b) Shows a typical three jet, one of which is interpreted as gluon jet.



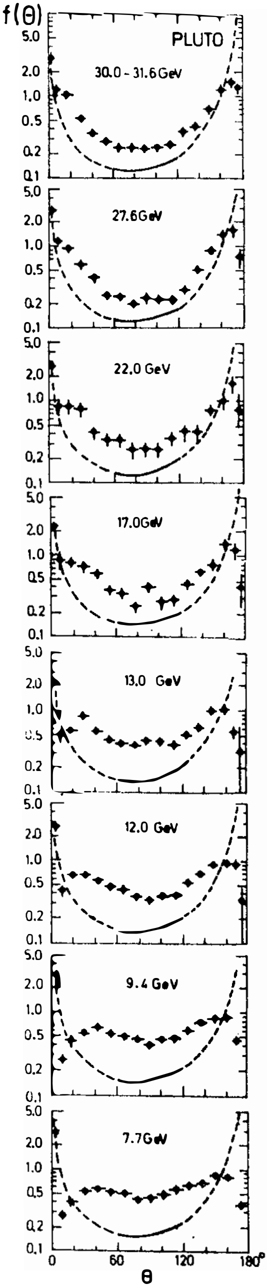
Experimentally, the function is evaluated by combining particle "a" with all other particles "b", including b = a, by plotting the product of their normalized energy, $z_a \cdot z_b$, at their relative angle in space, Θ_{ab}, and summing over b = 1,N as well as a = 1,N:

$$f(\Theta) = 2 \sum_a \sum_b z_a \cdot z_b \cdot \delta(\Theta_{ab} - \Theta) \qquad (3)$$

The double sum includes self-correlation and permutations and equals unity if integrated over Θ. For historical reasons we normalize it to 2. The resulting distribution f (Θ) represents the probability for spacing Θ, weighted with the energy flows. Theoretically, the spacing in the two-particle angles is attributed to multiple emission of soft gluons (small angles) or to the emission of a hard gluon (large angles).

The 2-jet event shown in Fig. 1a therefore tends to populate the regions near 0^o and 120^o. The 3-jet event of Fig. 1b on the other hand will also contribute to the central region around 90^o. The correlation data are displayed for 8 energies from 7.7 GeV to 31.6 GeV in Fig. 2. Already at the lowest energy we observe two broad peaks which mark the onset of jet formation as observed 6 years before at SPEAR and DORIS by analysing sphericity. With increasing energy W the central valley deepens and the peaks become more pronounced and move towards small angles. This behaviour reflects the dominance of 2-jet formation, although - according to the definition of correlations - the two jets are not separated in the peaks. The sharp forward peak is of technical nature, it results from self correlation. An important observation is, that the function is not symmetric with respect to 90^o. This

Fig. 2. Correlation function f (Θ) vs. Θ for 8 different center of mass energies in rising order. The data are compared with Monte Carlo predictions using Λ = 0.2 GeV (full line).



effect is due at low energies to statistical fluctuations which die away with $1/W^2$, and at high energies to the emission of single hard gluons.

The data are well described by the Field Feynman Monte Carlo [11], modified for hard gluon bremsstrahlung by Hoyer et al. [12] for W > 10 GeV (full curve), using Λ = 0.2 GeV. This value corresponds to α_s = 0.164 at W = 30 GeV, which is within the range of present PETRA results [2,3].

3. Central region, $60^0 \leq \Theta \leq 120^0$

Basham et al. (BBEL) [8] have calculated energy-energy correlations in first order perturbation, the result of which can be given in the following form:

$$(4) \quad f(\Theta,W) = \frac{\alpha_s(W^2)}{\pi} \cdot g(\Theta) + \frac{C}{W \cdot \sin^2\Theta} + O(1/W^2)$$

The expression is accurate up to order $(1/W^2)$, as indicated. The first term is pure QCD, and represents a three particle (parton) distribution. Fig.3 (full curve) shows however, that fragmentation cannot be neglected in the central region. To account for this effect, the authors have calculated the second term, which uses two phenomenological parameters: $C = b \cdot \langle p_\perp \rangle$, where b is the coefficient for the logarithmic rise of the total multiplicity with energy ($\langle n_{tot} \rangle \sim a + b \cdot \ln W$), and $\langle p_\perp \rangle$ is the average transverse momentum in e^+e^- - events. Roughly, the value for C is expected to be 3.3 x 0.35 ≈ 1.2 GeV. Actually, one can obtain the constants C and Λ from a fit by exploiting the fact that the two terms of the expression (4) have different energy dependence

Fig. 3 Same data as in Fig. 2. The full line is the QCD-term alone as calculated in ref. [8] for the valid central region. The dashed lines extrapolate the prediction into the forward and backward regions.

(1/ln W and 1/W). The Θ-dependence is eliminated by integrating the expression over the region of validity ($60^o \leq \Theta \leq 120^o$). The resulting integrated correlation data are shown in Fig. 4 as function of $E_{cm} = W$. The solid line presents the fitted function, the dotted line indicates the first term only. The results of the fit are $C = 1.0 \pm 0.2$ in good agreement with the previous estimate and $\Lambda = 0.5 \pm 0.2$ GeV ($\alpha_s = 0.20 \pm 0.02$ at 30 GeV) a result which is not only in good agreement with the other PETRA-values for α_s, but also has the same statistical accuracy.

Basham et al. [7] have also proposed to study the asymmetry, which we have already observed to be present in the data. This carries us one important step further, although we loose accuracy in the data. Because of the $\sin^2\Theta$ - dependence, the fragmentation term drops out, when we take the difference

$$A(\Theta,W) = \frac{\alpha_s(W^2)}{\pi} \left\{ g(\pi-\Theta) - g(\Theta) \right\} + O(1/W^2) \qquad (5)$$

The asymmetry in energy-energy correlations therefore tests pure QCD up to order $(1/W^2)$. The data are shown in Fig. 5 for a combined set of low and high energies. The full curve represents the prediction [7] for $\Lambda = 0.2$ GeV which agrees reasonably

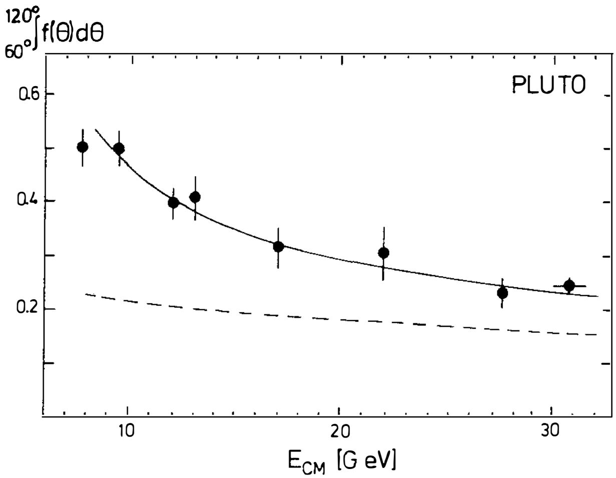


Fig. 4 Shows the correlation function integrated over Θ as function of the center of mass energy. The solid line represents the fit of the full prediction taken from ref. [8], the dashed line is the QCD part (first term of Equ. (4), the difference is the contribution from fragmentation to the cross section (second term of Equ. (4)) in the central region.

well with the data. The present sample, based on ~3000 nb^{-1}, is not sufficient for an accurate measurement (a fit yields $\Lambda = 0.5^{+1.5}_{-0.5}$ GeV, $\alpha_s = 0.2 \pm 0.1$ at 30 GeV), but it is easy to see that the recent increase of luminosity at PETRA by a factor 8 will soon allow for precise results. We have checked, that the inherent asymmetry present at low energies, vanishes like $1/W^2$ with rising energy by applying the Field-Feynman Monte Carlo also to W = 30 GeV. Also this correction (from fragmentation) can be studied with more accuracy if more statistics are available.

4. Forward region (same side correlation)

The data are again shown in Fig. 6. We compare them with a calculation by Konishi et al. [7a] (jet calculus), using their formula (15) for quark jets. The solid line, $\Theta < 60^0$, gives the prediction for Λ = 0.2 GeV. It clearly disagrees with the data even at the highest energies. The prediction would require $\Lambda \approx 2$ GeV to represent the measurements, but this value is not in agreement with the postulate, that different channels should yield similar results. Agreement between data and theory is much better in the backward region:

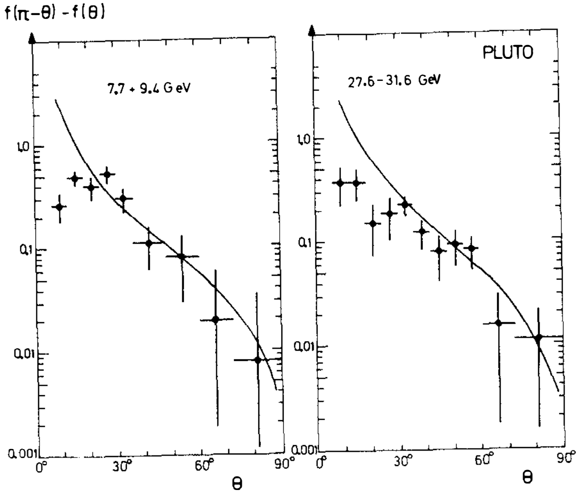
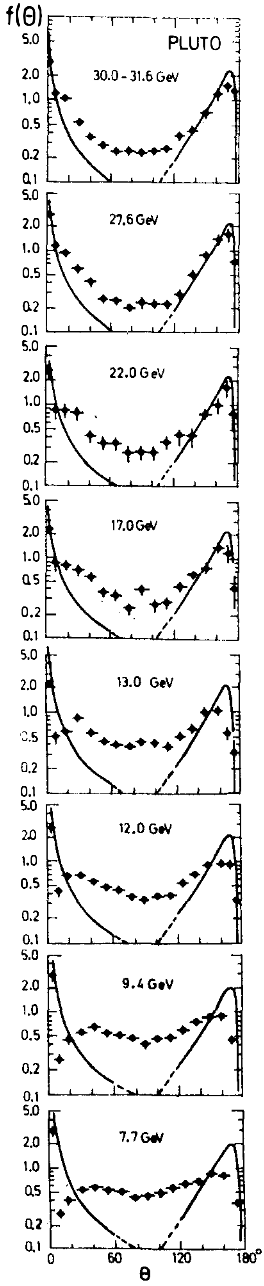


Fig. 5 The correlation asymmetry in the central region is given for a set of low and high energies, and compared to the prediction [8], using Λ = 0.2 GeV.



5. Backward region (opposite side correlation)

The solid line in Fig. 6 for $\Theta > 120^{\circ}$ compares the data with the prediction from Parisi, Petronzio [7b] for $\Lambda = 0.2$ GeV. It is typical for all the predictions on the parton level, that their variation with energy is small (~1/ln W), whereas the data vary strongly (~1/W) as a consequence of subsequent hadronization, which acts as a smearing effect. This behaviour is best displayed in the backward region. The mismatch of the prediction at low energies turns into a close agreement with the data for energies above 20 GeV, where fragmentation becomes negligible. Other authors have fitted their theory to the PLUTO data [4], like Halzen and Scott [13] or Marquardt and Steiner [14], both of which find $\Lambda = 0.5$ or $\alpha_s = 0.20$ at 30 GeV.

The concept of multiple soft gluon emission in the backward region takes also care of the divergence in single gluon emission, when Θ approaches π (see Fig.3, dashed line). The suppression of the correlation cross section for small acollinearity angles was first pointed out by Dokshitzer et al. [6]. We have combined the high energy data from 27.6 to 31.6 GeV and plotted $d\Sigma/d\cos\Theta$ vs. $\cos\Theta$ in Fig. 7, in order to be free from the trivial kinematical zero due to phase space. The data show that indeed the cross section stays constant for $\cos\Theta \to 1$, as does the prediction [7b] (full line). The divergent cross section for single gluon emission is also indicated (dashed line). This result is another experimental verification for the basic idea that a cascade of soft gluon bremsstrahlung dominates the small angle regions.

Fig. 6 Same data as Fig. 2. The full lines are the predictions [7a] for $\Theta < 90^{o}$ and [7b] for $\Theta > 90^{o}$ for the same side and opposite side correlations.

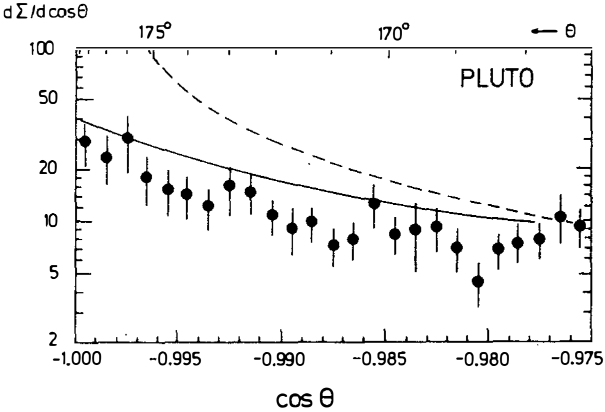


Fig. 7 Shows the correlation cross section $d\Sigma/d\cos\Theta$ vs $\cos\Theta$ near $\Theta = \pi$. The full curve is the prediction of Ref. 7b), the dashed curve displays the divergent behaviour of single gluon emission in the backward region, Ref. 8).

6. Summary

What can we learn from energy-energy correlations in e^+e^--collisions? First we can state that the predictions, which are valid on the parton level, in fact approach the data with increasing energy. The approach is very rapid in the backward direction, such that the cutoff constant Λ can be extracted directly from the comparison at 30 GeV. In the central region, the contribution of the fragmentation is still too large to be neglected at 30 GeV, but can be separated through its strong energy dependence. In this way, the analysis both of the backward and the central region leads to a strong coupling constant which agree with each other, and with the results of the 3-jet analysis as well. The prediction in the forward region does not fit well into this picture. In the central region, fragmentation effects cancel in the correlation asymmetry up to order $1/W^2$. This quantity therefore provides a clean test of QCD, but it needs much more statistics than is presently available. The correlation cross section approaches a constant value for small acollinearity angles, which is an important proof for the concept of multiple soft gluon emission at small angles.

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