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Analysis of the Energy Weighted Angular Correlations in Hadronic e^+e^- Annihilations at 22 and 34 GeV

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Abstract. Measurements of energy weighted angular correlations in electron positron annihilations at c.m. energies of 22 GeV and 34 GeV are presented. The data are compared with perturbative QCD predictions. The theoretical predictions which refer to the partons describe the data reasonably well, depending on the approximations chosen. The effective strong coupling constant, α_s, has been determined with a method which is expected to be insensitive to fragmentation effects. Nontheless, the values obtained show a strong variation depending on the fragmentation model assumed. At large acollinearity angles QCD calculations going beyond the Leading Double Log approximation appear to be quite successful in describing the data. The agreement is improved when the smearing effect of heavy resonance decays is taken into account.

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Introduction

In the process of e^+e^- annihilation into a quark-antiquark pair one expects a measurable increase of colour-radiative effects with increasing center of mass energies. It has been proposed to identify and measure these perturbative QCD effects by evaluating the energy weighted angular correlation between final state hadrons in e^+e^- annihilation [1, 2].

A first experimental study of the energy weighted angular correlation and a comparison with theoretical models for energies between 7 and 31 GeV have been published earlier by the PLUTO collaboration [3]. A new analysis of the central region at the c.m. energy of 29 GeV has been recently reported from PEP (SLAC) [4].

In this paper we report on the measurement and investigation of the energy correlation function $F(\Theta)$ at two center of mass energies (22 and 34 GeV). $F(\Theta)$ is given by the semi-inclusive differential cross section for two hadrons in e^+e^- annihilation:

$$F(\Theta)=\frac{1}{\sigma_{\text{tot}}}\sum\int\int z_a z_b\, dz_a\, dz_b \frac{d^3\sigma(e^+e^-\to a+b+X)}{dz_a\, dz_b\, d\Theta} \qquad (1)$$

where Θ is the angle between the two hadrons a and b of the final state, z_a and z_b are the relative energies of a and b with respect to the center of mass energy E_{CM}, σ_{tot} is the total hadronic annihilation cross section. The sum is to be taken over all hadrons in the final state.

Experimentally the correlation function is computed as,

$$F(\Theta)=\frac{1}{N}\Sigma_a\Sigma_b z_a b_b \frac{1}{\Delta\Theta}\int_{\Theta-\Delta\Theta/2}^{\Theta+\Delta\Theta/2}\delta(\Theta_{ab}-\Theta')\,d\Theta' \qquad (2)$$

where N is the total number of hadronic events, $\Delta\Theta$ is the experimental bin width in Θ, z_a and z_b are the energies of a and b relative to E_{visible}, the energy of the charged particles. (This is to preserve the normalisation of the correlation function.)

All multihadronic one photon annihilation events are used in computing $F(\Theta)$. No selection of special classes of events (i.e. three jet events) is required in this analysis.

We have compared the measured correlation function with theoretical calculations [1, 2, 5–10], and deduced values for the strong coupling constant α_s in first order QCD, and for the QCD scale parameter Λ in the Leading Log Approximation.

In order to compare with the theoretical predictions, three regions for the angle Θ are to be distinguished:

– The central region around $\Theta \simeq \pi/2$, where the dominant process is expected to be the emission of a single hard gluon. The partonic final state consisting of a superposition of $q\bar{q}$ and $q\bar{q}g$ has been calculated using perturbative QCD of order α_s [2]. For the comparision with the data a phenomenological fragmentation term has been added.

– The small angle region (Θ close to 0) and the large angle region (Θ close to π), i.e. same side and opposite side correlations, which are expected to be dominated by multiple color radiative effects in the parton cascade. In these regions we compared the measured correlations directly with the QCD predictions which are based on the Leading-Log (LLA), Leading-Double-Log (DLLA) and Next-to-Leading-Double-Log (NDLLA) approximations [1, 5–10]. With the exception of [9], these studies assume that the computed parton distribution for $F(\Theta)$ will not be modified in a significant way by the hadronization process, which can be identified as the step where the last partons in the cascade turn into *primordial* hadrons.

The transverse momentum coming from heavy resonance decays introduces a smearing effect in $F(\Theta)$ at the present c.m. energies. We tried to remove this effect from our data by making a correction to the level of primordial hadrons using the Monte Carlo technique. The correction factor has been evaluated from the ratio of $F(\Theta)$ obtained from the primordial hadrons to that obtained from the final state particles for each Θ bin. The correction to the level of the primordial hadrons depends on the details of the Monte Carlo simulation. It may introduce a systematic uncertainty up to 10–15%.

Data and Corrections

The CELLO detector, which was set up in one of the interaction regions of the e^+e^--storage ring PETRA (at DESY/Hamburg), was used to collect data corresponding to integrated luminosities of 2.52 (pb)$^{-1}$ and 7.88 (pb)$^{-1}$ at center of mass energies of 22 GeV and 34 GeV respectively. The relevant features for the analysis presented here are a magnetic field of 1.32 T and cylindrical proportional and drift chambers coaxial with the beam axis. The solid angle covered is 91% of 4π. Further technical details of the CELLO detector are described elsewhere [11]. The multihadron data sample for this analysis was obtained by applying the same criteria as for our earlier evaluation of the total cross section [12]. It consists of 2600 multihadron events at $E_{\text{CM}}=34$ GeV and 2000 events at $E_{\text{CM}}=22$ GeV.

The uncorrected experimental distribution of $F(\Theta)$ for charged hadrons is shown in Fig. 1. The two-peaked correlation shape is the dominant feature of $F(\Theta)$ at all energies investigated. Apart from

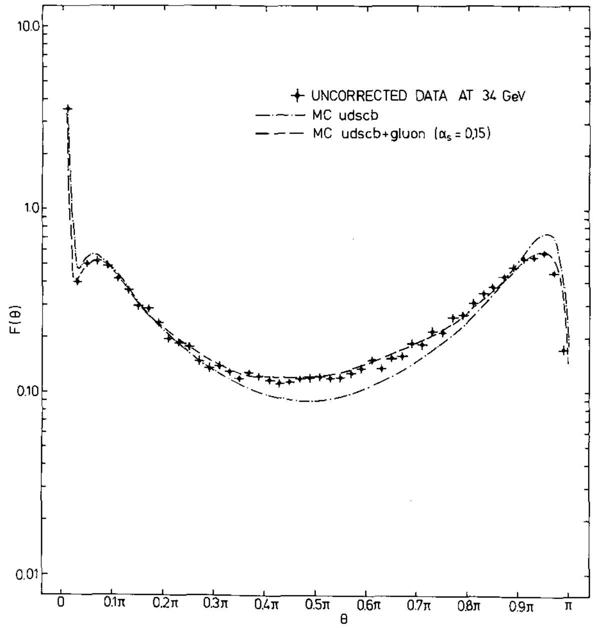

Fig. 1. Uncorrected $F(\Theta)$ at 34 GeV. Dashed-dotted line: Monte Carlo simulated data $q\bar{q}$, dashed line: Monte Carlo simulated data $q\bar{q}+q\bar{q}g$

the spike at $\Theta=0$ which is due to self correlation, the observed distribution shows a small asymmetry with respect to $\Theta=\pi/2$ and peaks at $\Theta=0.30$ and 2.92 radians at 22 GeV and at $\Theta=0.14$ and 2.98 radians at 34 GeV. A comparison with Monte Carlo simulated events of the type[1]:

$e^+e^- \to q\bar{q}+q\bar{q}g+\text{fragmentation}$

yields a remarkable agreement with the data in most angular regions, whereas simulated data corresponding to only $q\bar{q}$ production are in clear disagreement with the experiment. In the Monte Carlo procedure [13-16], $q\bar{q}$ and $q\bar{q}g$ states ($q=u, d, s, c, b$) are generated, which fragment into primordial hadrons and emerge as 'stable' final particles through various decay channels.

For the tracking of the simulated hadrons through the detector the technical features of CELLO were incorporated in great detail. Analyses including the measured neutrals are presently in preparation [17]. Preliminary studies show that our Monte Carlo simulated neutral component is in fair agreement with what we measure with our Liquid Argon calorimeter. Therefore, we presently use Monte Carlo simulated events to correct $F(\Theta)$ for the neutral component by computing the ratio of $F(\Theta)$ of charged + neutral prongs to that of charged prongs only.

In addition, the data have been corrected for acceptance and initial state radiation.

The overall correction to the observed distribution, $F(\Theta)$, depends little on the angle Θ, contributing 10% on average. Corrections increase for Θ near 0 and π, reaching a factor of 2 at the two extreme angular bins. The average uncertainty in Θ of $\simeq 1°$ is negligible compared to the bin size chosen. The momentum resolution for charged particles is $\Delta p = 0.025\,p^2$ (p in GeV/c). To calculate the relative energy weight z, we assumed the prongs to have pion masses. This assumption distorts the $F(\Theta)$ distribution by less than 2 percent. A similar uncertainty arises from the use of E_{visible} (energy of the observed charged hadrons) instead of E_{CM} in the computation of the energy weights.

Results

We show, in Figs. 2a, b, the corrected experimental energy weighted correlation distributions of the final state hadrons for $E_{\text{CM}}=22$ GeV and 34 GeV. The plots also show theoretical QCD predictions. In Figs. 2c, d we plotted the corresponding distributions corrected to the level of primordial hadrons.

In the angular region Θ around $\pi/2$, the (partonic) first order QCD calculation due to Basham et al. (BBEL) [2] yields

$$F(\Theta)_{\text{QCD}} = \frac{\alpha_s}{\pi}\, g(\Theta) \tag{3}$$

where $g(\Theta)$ is independent of the energy. For any reasonable α_s the perturbative QCD result lies clearly below the data. Fragmentation effects in the $q\bar{q}$ production can be taken into account according to a simple model [2] by adding a term

$$F(\Theta)_{\text{FRAG}} = c\langle p_t\rangle / \{E_{\text{CM}} \sin^2\Theta\} \tag{4}$$

where $\langle p_t\rangle$ is the average transverse momentum in the fragmentation process and c is defined by the derivative of the multiplicity $d\langle n\rangle/d\{\log(E_{\text{CM}})\}$. Fitting the sum of the two terms to the data we obtain reasonable agreement in the angular range $0.24\pi < \Theta < 0.76\pi$ for the following parameters:

E_{CM}	α_s	$c\langle p_t\rangle$ (GeV)	χ^2/d.f.
22 GeV	0.22 ± 0.01 (stat)	1.15 ± 0.04 (stat)	23.6/24
34 GeV	0.21 ± 0.01 (stat)	1.20 ± 0.05 (stat)	30.2/24

1 We have used the Monte Carlo of Hoyer et al. [14] with Feynmann-Field [13] fragmentation and heavy quark decays as described by Ali et al. [15] with the following parameters: $A_q=0.77$; $A_g=1.0$; $\sigma_q=0.30$ GeV; Pseudoscalar Fraction $=0.5$; $\alpha_s=0.16$ at $E_{\text{CM}}=22$ GeV; $\alpha_s=0.15$ at $E_{\text{CM}}=34$ GeV

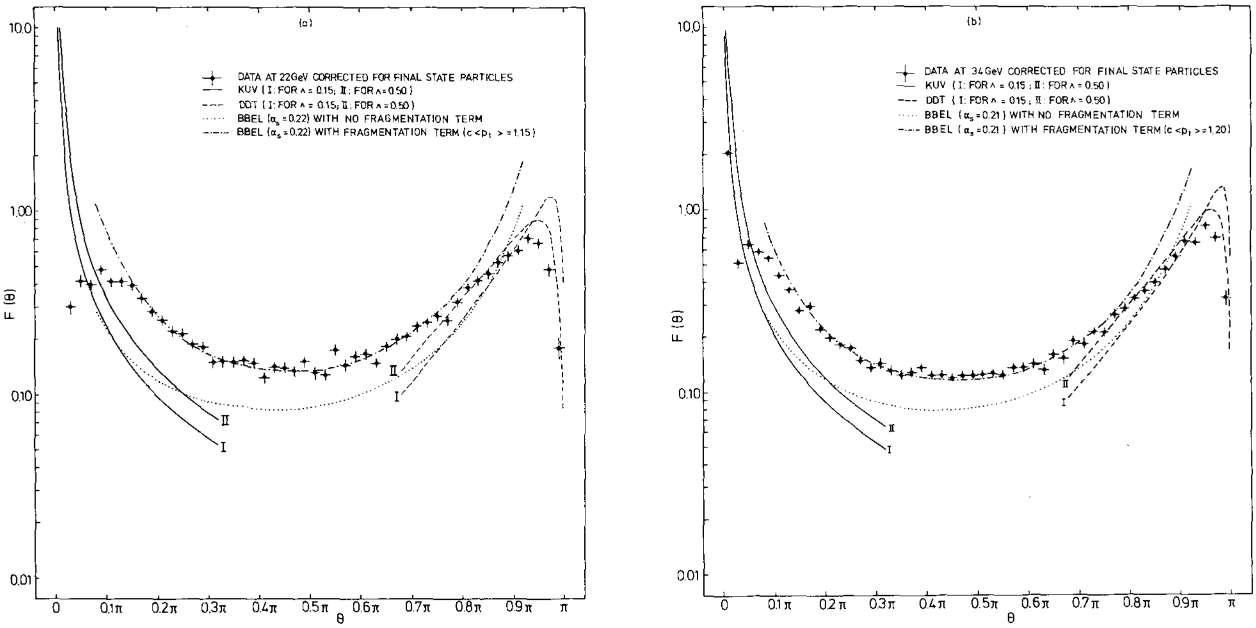

Fig. 2. a $F(\Theta)$ corrected to the level of final state particles at 22 GeV. Full line: QCD prediction of KUV, dashed line: QCD prediction of DDT, dashed-dotted: QCD prediction of BBEL with fragmentation term, dotted line: QCD prediction of BBEL without fragmentation term. **b** $F(\Theta)$ corrected to the level of final state particles at 34 GeV. Full line: QCD prediction of KUV, dashed line: QCD prediction of DDT, dashed-dotted: QCD prediction of BBEL with fragmentation term, dotted line: QCD prediction of BBEL without fragmentation term

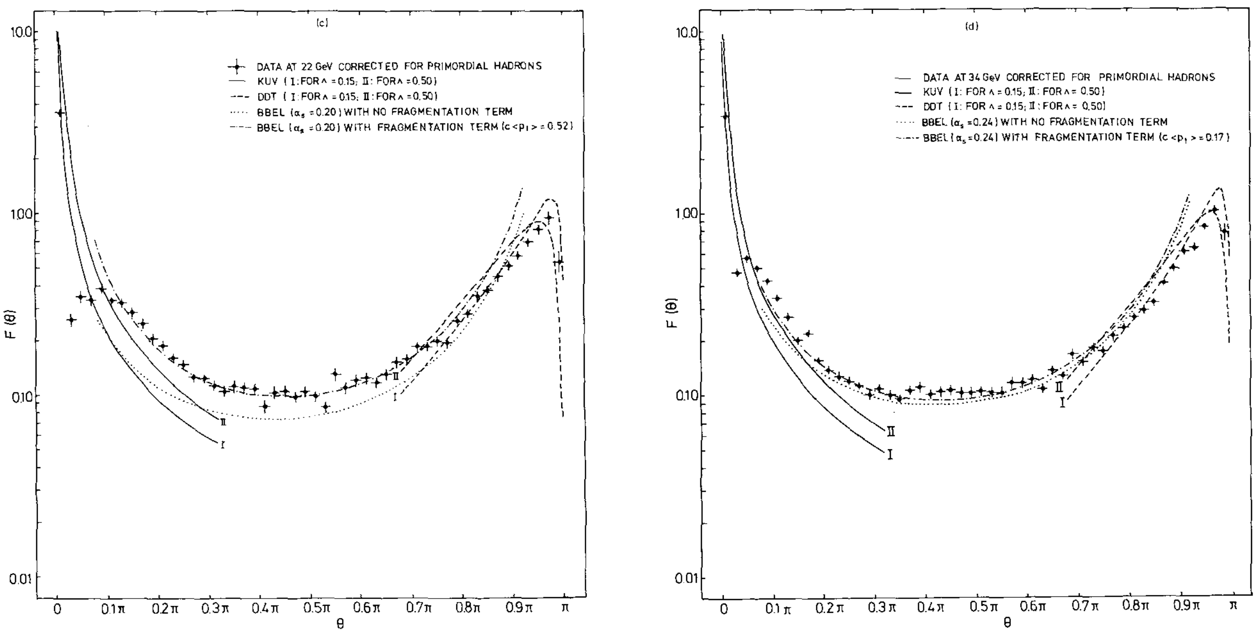

Fig. 2. c $F(\Theta)$ corrected to the level of primordial hadrons at 22 GeV. Full line: QCD prediction of KUV, dashed line: QCD prediction of DDT, dashed-dotted: QCD prediction of BBEL with fragmentation term, dotted line: QCD prediction of BBEL without fragmentation term. **d** $F(\Theta)$ corrected to the level of primordial hadrons at 34 GeV. Full line: QCD prediction of KUV, dashed line: QCD prediction of DDT, dashed-dotted: QCD prediction of BBEL with fragmentation term, dotted line: QCD prediction of BBEL without fragmentation term

The non-perturbative effects are of similar magnitude as the partonic QCD result, and $\alpha_s(E_{CM})$ and $c\langle p_t\rangle$ are strongly anticorrelated as given by the fit.

It has been suggested [2] to use the asymmetry distribution:

$$\mathrm{AS}(\Theta)=F(\pi-\Theta)-F(\Theta) \tag{5}$$

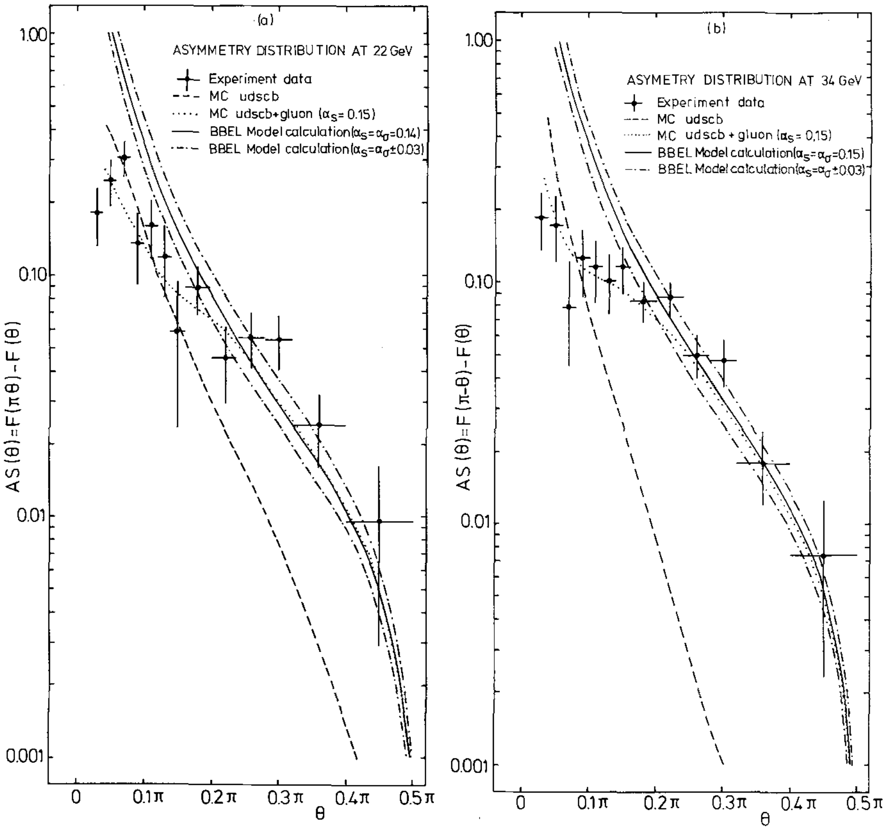

Fig. 3. a Asymmetry distribution AS(Θ) at 22 GeV corrected to the level of final state particles. Full line: QCD predictions of BBEL, dashed line: Monte Carlo ($q\bar{q}$) results, dotted line: Monte Carlo ($q\bar{q}g$) results. **b** Asymmetry distribution AS(Θ) at 34 GeV corrected to the level of final state particles. Full line: QCD predictions of BBEL, dashed line: Monte Carlo ($q\bar{q}$) results, dotted line: Monte Carlo ($q\bar{q}g$) results

for the determination of α_s, since, in first order QCD, AS(Θ) isolates the contribution from single gluon emission. In addition, (4), which is even under the interchange $\Theta \leftrightarrow \pi - \Theta$, suggests that the contribution from fragmentation effects will be greatly reduced.

The experimental asymmetry distributions (5) together with the theoretical results [2] are plotted in Figs. 3a, b for the two energies. By fitting the theoretical asymmetry function to the data in the range $\Theta_{min} = 0.16\pi < \Theta < 0.50\pi$, we obtain the following values for α_s:

E_{CM}	α_s	χ^2/d.f.
22 GeV	0.14 ± 0.02(stat)	8.1/5
34 GeV	0.15 ± 0.02(stat)	6.1/5

Fixing the values of α_s to those we derived from the asymmetry, we refitted the $F(\Theta)$ distributions in the angular region $0.24\pi < \Theta < 0.76\pi$. This yields a somewhat larger value for $c\langle p_t \rangle$.

E_{CM}	$c\langle p_t \rangle$	χ^2/d.f.
22 GeV	1.73 ± 0.04(stat)	31.0/25
34 GeV	1.95 ± 0.05(stat)	40.0/25

AS(Θ) corrected to the level of primordial hadrons does not lead to a significantly different value of α_s. For the primordial hadrons, however, the value of $c\langle p_t \rangle$ is reduced from 1.8 to 1.0, which is consistent with the values of c and $\langle p_t \rangle$ used in the Monte Carlo procedure. In addition, a larger range of Θ can be well fitted to the sum of the two terms (3) and (4).

In first order QCD, α_s is given by $12\pi/\{(33-2N_f)\ln(Q^2/\Lambda^2)\}$ where N_f is the number of flavours. For $N_f = 5$, and $Q^2 = E_{CM}^2$, our α_s values lead to $\Lambda \simeq 0.15$ GeV.

The determination of α_s from AS(Θ) is subject to a number of systematic uncertainties:

(i) Acceptable fits are obtained for $0.12\pi < \Theta_{min} < 0.28\pi$. This variation in the lower limit of the fit leads to an uncertainty in the values of α_s of ± 0.04.

(ii) Any incomplete cancellation in the fragmentation process of $q\bar{q}$ may introduce contributions to AS(Θ) not accounted for by (4) [2]. Using various fragmentation schemes [13–16, 18] we observe a significant asymmetry for the $q\bar{q}$ sample only at small Θ. Subtracting the effect from the experimental distribution and refitting AS(Θ) lowers the value of α_s by 0.01 to 0.03 depending on the model chosen.

(iii) The dynamics of the fragmentation of $q\bar{q}g$ can also contribute to AS(Θ). Comparing AS(Θ) for simulated data at the parton and at the primordial meson level, we find that the evaluated value of α_s

should be increased by 0.01 to 0.06, depending on the fragmentation model.

Although α_s can be determined by this method with a statistical error ± 0.02 we are led to conclude that this determination suffers from substantially larger systematic uncertainties. (For other determinations of α_s from jet topologies see [19].)

For the large acollinearity region (Θ close to π), where only hadron pairs in opposite jets contribute, the data have been compared with the theoretical calculation of Dokshitser et al. (DDT) and with more recent evaluations [1, 5, 7–10]. The original DDT approach is based on summing, in all orders, the diagrams contributing LLA and DLLA terms. As a result, an effective semi-inclusive quark form factor $T_F(\Theta, Q^2)$ is introduced, which accounts for the dominant processes occurring in the quark-gluon cascade. The primordial hadrons emerging are assumed to carry essentially the momenta of the related last parton in the cascade. We have evaluated the corresponding DDT formula as improved by Parisi and Petronzio [7] (for the exact quotes see the appropriate reference) for two different values of the QCD scale parameter Λ (in Leading Log approximation), which is the only free parameter in these calculations.

The results of DDT with $\Lambda = 0.5$ describe the data reasonably well both in shape and order of magnitude for both energies (Figs. 2a, b). The agreement in the region of the peak improves with increasing energy.

The agreement with the data improves considerably if we evaluate $F(\Theta)$ for primordial hadrons instead of the final state particles. As shown in Figs. 2c, d, the distribution of primordial hadrons favors clearly a lower value of Λ around 150 MeV.

More recent theoretical calculations [8–10] have gone beyond the Leading Double Log Approximation, an important feature being a more complete integration over the transverse momentum of the gluons. In order to allow a more detailed comparison especially in the angular range Θ close to π,

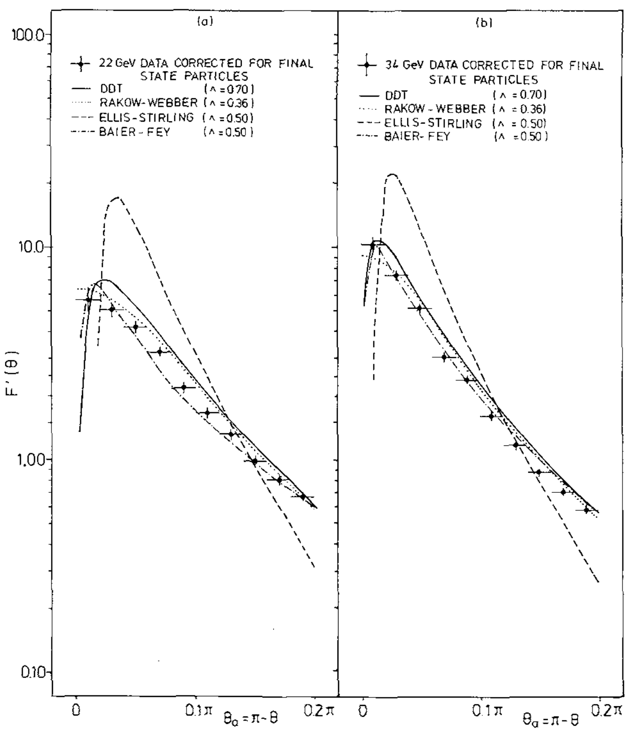

Fig. 4. a $F'(\Theta)$ distribution at 22 GeV, corrected to the level of final state particles, compared with several QCD predictions: Full line: DDT Formula [5] ($\Lambda = 0.70$ GeV), dashed line: Ellis and Stirling [8] ($\Lambda = 0.50$ GeV), dotted line: Rakow and Webber [10] ($\Lambda = 0.36$ GeV), dashed-dotted line: Baier and Fey [9] ($\Lambda = 0.50$ GeV). **b** $F'(\Theta)$ distribution at 34 GeV, corrected to the level of final state particles, compared with several QCD predictions: Full line: DDT Formula [5] ($\Lambda = 0.70$ GeV), dashed line: Ellis and Stirling [8] ($\Lambda = 0.50$ GeV), dotted line: Rakow and Webber [10] ($\Lambda = 0.36$ GeV), dashed-dotted line: Baier and Fey [9] ($\Lambda = 0.50$ GeV)

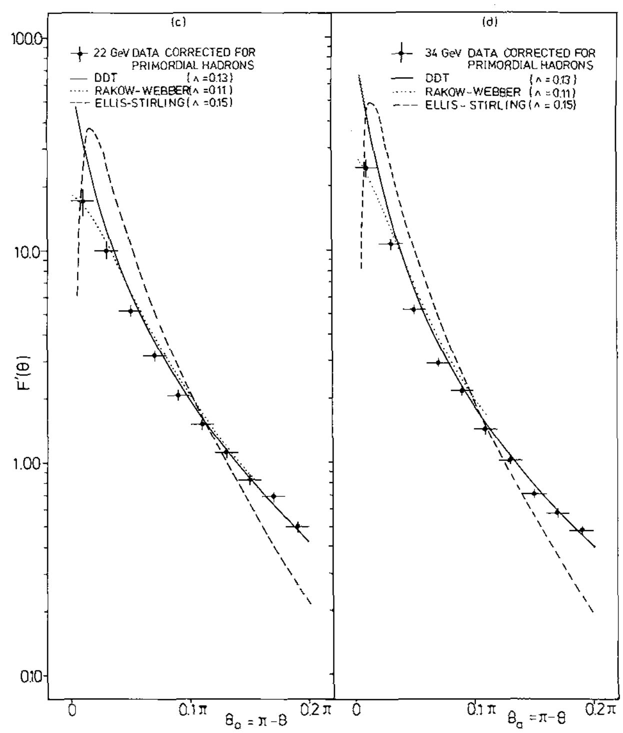

Fig. 4. c $F'(\Theta)$ distribution at 22 GeV, corrected to the level of primordial hadrons, compared with several QCD predictions: Full line: DDT Formula [5] ($\Lambda = 0.13$ GeV), dashed line: Ellis and Stirling [8] ($\Lambda = 0.15$ GeV), dotted line: Rakow and Webber [10] ($\Lambda = 0.11$ GeV). **d** $F'(\Theta)$ distribution at 34 GeV, corrected to the level of primordial hadron, compared with several QCD predictions: Full line: DDT Formula [5] ($\Lambda = 0.13$ GeV), dashed line: Ellis and Stirling [8] ($\Lambda = 0.15$ GeV), dotted line: Rakow and Webber [10] ($\Lambda = 0.11$ GeV)

where F(Θ) has a (kinematic) zero, we have computed the distribution:

$$F'(\Theta)=F(\Theta)/\sin(\Theta) \quad (6)$$

which, together with the different QCD predictions, is plotted in Fig. 4. The data shown represent distributions of both the final state particles and of the primordial hadrons. In addition to an improved integration over the transverse momentum of the cascade partons, Baier and Fey [9] take the intrinsic non-perturbative transverse momentum of hadrons fragmenting from partons into account. The normalisation of the transverse momentum was obtained from low energy data [3]. The agreement of their prediction with the distribution of the final state particles is quite good. One cannot however compare their calculations with the distribution of primordial hadrons, since one would then need to normalize to the primordial hadrons with low energy data. The calculation of Ellis and Stirling [8] is shown in Fig. 4. Their approach does not constitute an improvement compared to the one of DDT, neither for the final state particles nor for the primordial hadrons. Also the turn over at small values of $\pi - \Theta$ is not supported by the data. The most recent calculation of NDLLA terms was done by Rakow and Webber [10], computing however $F'(\Theta)$ on a pure partonic level without using a phenomenological normalisation. We find a remarkable agreement between the data and their prediction. The energy correlation of primordial hadrons again favors a lower value of $\Lambda \simeq 100$ MeV at both energies. A more precise determination of Λ suffers from systematic uncertainties in generating the primordial hadron spectrum.

For Θ close to 0, where only hadron pairs in the same jet contribute, we compared our data with the work of Konishi et al. (KUV) [6], who computed $F(\Theta)$ in the Leading Log Approximation (LLA). As can be seen in Fig. 2a–d there is poor agreement at both energies between the KUV prediction and the distributions of either final or primordial hadrons. Even for primordial hadrons at 34 GeV an unusually high value of Λ would be needed to accommodate the data[2].

Summary

Analysing the energy weighted angular correlation distribution $F(\Theta)$ for multihadron final states at 22 GeV and 34 GeV, we compared experimental data with absolute predictions made on the basis of pure QCD calculations, which generally depend on only one free parameter: the QCD scale Λ.

We evaluated α_s from the asymmetry distribution AS(Θ) utilising essentially the central region of Θ. This method, proposed by Basham et al. [2] is expected to be independent of the details of the fragmentation process to a large extent. Our α_s values are consistent with those obtained analysing jet topologies [19]. The accuracy of this determination of α_s is limited by the systematic uncertainties, which are associated with the model-dependent assumptions concerning the cancellation of the fragmentation effects.

QCD predictions computed for the small and large Θ region have been compared with our distributions of final and primordial hadrons. Generally it is found that the QCD calculations agree better with the primordial hadron distribution. The primordial distributions favor in all cases lower values of Λ. Whereas $F(\Theta)$ for final particles agree best for Λ values between 360 and 700 MeV, $F(\Theta)$ for primordial hadrons favors Λ's between 100 and 150 MeV. The DLLA calculation for the region Θ close to π is in good agreement with the data, in particular with the distribution of the primordial hadrons. The agreement is remarkably improved in the NDLLA approximation of Rakow and Webber.

For the small Θ region the QCD predictions in the Leading Log Approximation lie considerably lower than the experimental data, improving marginally at the higher energy.

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