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Experimental study of the orientation of three-jet events in e^+e^- annihilation at PETRA

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Abstract. The full TASSO data have been used to study the orientation of three-jet events in e^+e^- annihilation. The polar angle distributions of the normal to the three-jet plane as well as the polar angle distribution of the most energetic jet have been measured as a function of the thrust cut-off used to select the three-jet sample. The data corrected for radiation and detector effects are compared to QCD predictions and fair agreement is found. As a consistency check we also present measurements of the azimuthal correlations between the lepton and hadron planes. A significant azimuthal dependence is found, consistent again with the QCD predictions.

1 Introduction

Hadron production in e^+e^- annihilation is described in terms of the production and subsequent decay of a $q\bar{q}$ pair. Evidence for the quark fermionic nature came originally from measurements of the polar distribution of the jet axis in multihadronic final states at SPEAR [1]

$$e^+e^- \rightarrow q+\bar{q} \rightarrow \text{two hadron jets} \tag{1}$$

At PETRA energies, deviations from the dominant two-jet topology were observed [2] and interpreted as evidence for vector gluon bremsstrahlung [3] of the $q\bar{q}$ pair

$$e^+e^- \rightarrow q+\bar{q}+g \rightarrow \text{three hadron jets} \tag{2}$$

Many observables have been measured by the TASSO Collaboration, including the Ellis-Karliner angular distribution [4], energy-energy correlations [5], jet masses [6], three-jet [7] and multijet production cross-sections [8] and many others [9], all of which render strong support to QCD as the underlying theory for strong processes. QCD supplemented with various fragmentation schemes [10, 11, 12] give an adequate description of the gross features exhibited by the hadronic final states at PETRA and PEP energies [13, 14].

There are however some predictions derived in QCD which have not yet been tested, because of lack of statistics. One of these predictions refers to the orientation of three-jet events with respect to the beam axis [15, 16] and thus represents the natural extension of the simple $(1+\cos^2\vartheta)$ prediction for the polar distribution of the thrust axis [17] for two-jet events.

Let us denote by σ_U and σ_L the cross-sections for transverse unpolarized and longitudinally polarized photons into $q\bar{q}g$ final states in a coordinate system with the z-axis in the three-jet plane (helicity frame) and let us denote σ_I and σ_T the transverse/longitudinal and the $+/-$ interference terms. In the helicity frame the doubly differential angular cross section reads [15]

$$\begin{aligned}\frac{d^2\sigma}{d\cos\vartheta\, d\chi} &= (1+\cos^2\vartheta)\,\sigma_U + 2\sigma_L \sin^2\vartheta \\ &\quad + 2\sigma_T \sin^2\vartheta \cos 2\chi \\ &\quad - 2\sqrt{2}\sigma_I \sin 2\vartheta \cos\chi \end{aligned} \tag{3}$$

where ϑ and χ are the polar and azimuthal angles describing the relative orientation of the lepton and hadron frames [15]. See Fig. 1 for a pictorial representation.

In this paper we concentrate on the experimental determination of the longitudinal σ_L and transverse σ_T interference contributions and their comparison with QCD predictions.

The longitudinal/transverse composition of the 3-jet cross-section can be obtained from the polar distribution of the thrust axis after integration over χ. One has

$$\frac{d\sigma}{d\cos\vartheta} \propto 1+\alpha(T)\cos^2\vartheta \tag{4}$$

with the parameter α dependent on the particular thrust value T of the event. In fact one expects $\alpha(T)\rightarrow 1$ when $T\rightarrow 1$ and $\alpha(T)\rightarrow 0.2$ when $T\rightarrow \frac{2}{3}$ i.e. the kinematical limit for planar three-jet events. We would like to remark that the differences between the QCD prediction for $\alpha(T)$ and that obtained in scalar gluon theories are at most of $O(20\%)$. In terms of the various cross-sections the anisotropy parameter α can be written as

$$\alpha(T) = \frac{\sigma_U - 2\sigma_L}{\sigma_U + 2\sigma_L} = \frac{1-2\dfrac{\sigma_L}{\sigma_U}}{1+2\dfrac{\sigma_L}{\sigma_U}} \tag{5}$$

where we have supressed the thrust argument in σ_U and σ_L.

The transverse-interference contribution σ_T can be obtained from an azimuthal measurement. Upon integrating (3) over $\cos\vartheta$ one obtains

$$\frac{d\sigma}{d\chi} \propto 1+\beta(T)\cos 2\chi \tag{6}$$

where

$$\beta(T) = \frac{\dfrac{\sigma_T}{\sigma_U}}{1+\dfrac{\sigma_L}{\sigma_U}}. \tag{7}$$

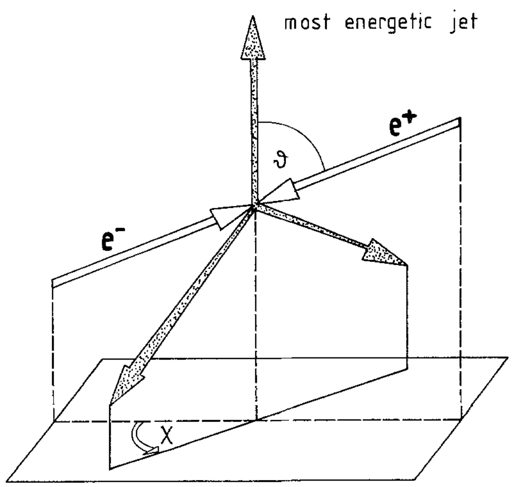

Fig. 1. This picture illustrates the definition of the polar and azimuthal angles ϑ and χ used to define the orientation of three-jet events, taken from [16]

Alternatively the transverse-interference contribution σ_T can be obtained by measuring the polar angle ($\bar{\vartheta}$) dependence of the normal to the three-jet plane. One finds [18]

$$\frac{d\sigma}{d\cos\bar{\vartheta}} \propto 1 + \bar{\alpha}(T)\cos^2\bar{\vartheta} \tag{8}$$

where

$$\bar{\alpha}(T) = -\frac{1}{3}\frac{\sigma_U + \sigma_L - 3(\sigma_L - 2\sigma_T)}{\sigma_U + \sigma_L - \frac{1}{3}(\sigma_L - 2\sigma_T)}. \tag{9}$$

A measurement of $\bar{\alpha}(T)$ together with the knowledge of $\frac{\sigma_L}{\sigma_U}$ from the measurement associated to (4) and (5) allows one to determine $\frac{\sigma_T}{\sigma_U}$.

Note that the $O(\alpha_s)$ prediction $\sigma_L = 2\sigma_T$ [15] gives $\bar{\alpha}(T) = -\frac{1}{3}$ which is identical to the value found for the trivial $O(\alpha_s^0) q\bar{q}$ pair production case with subsequent azimuthally uniform hadronisation as is evident from (9) with $\sigma_L = \sigma_T = 0$. However, if $\frac{\sigma_L}{\sigma_U}$ is found to be non-zero for a thrust range below the two-jet limit $T=1$, a measurement of $\bar{\alpha}(T)$ close to $-\frac{1}{3}$ significantly tests the QCD prediction $\sigma_L = 2\sigma_T$. Two remarks are in order

- the $O(\alpha_s^2)$ corrections to this measure have been found very small i.e. $O(0.1\%)$ and resolution insensitive [18].
- the prediction $\sigma_L = 2\sigma_T$ does distinguish between vector and scalar gluon theories in the $q\bar{q}g$ final states mediated by Z_0 exchange but not in those mediated by γ exchange.

The tests proposed in [18] have not yet been performed because it is necessary to measure simultaneously

- the polar distribution of the normal to the three-jet plane $\bar{\vartheta}$
- the polar distribution of the thrust axis for three-jet events ϑ

as a function of a thrust cut-off T_c in order to be able to establish that the parameter $\bar{\alpha}$ extracted from the former is independent of the thrust cut-off chosen and close to $-\frac{1}{3}$ while the parameter α extracted from the latter becomes substantially smaller than 1 when the thrust cut-off approaches the lower kinematical limit. It is when one approaches this limit that one runs out of statistics.

As a final consistency check, we also measure the azimuthal distribution in (6), from which we will determine the parameter $\beta(T)$. The QCD prediction $\sigma_L = 2\sigma_T$ leads to a relation between $\alpha(T)$ and $\beta(T)$ which reads

$$\beta(T) = \frac{1}{2}\frac{1-\alpha(T)}{3+\alpha(T)} \tag{10}$$

whose validity is easy to test.

2 Experimental details

The experiment was performed with the TASSO detector operating at the storage ring PETRA. Details of the detector can be found elsewhere [19]. The data used for this analysis were taken in the period 1980–1986 at centre of mass energies given in Table 1. Hadronic events were selected using the information on charged particle momenta measured in the central detector. The selection criteria are described in detail in [20]. Basically, charged tracks are required to have a momentum transverse to the beam $p_{xy} > 0.1$ GeV/c and a polar angle measured with respect to the beam direction such that $|\cos\vartheta| < 0.87$. The r.m.s. momentum resolution including multiple scattering is $\frac{\sigma_p}{p} = 0.017(1+p^2)^{1/2}$, with p in GeV/c. The main criterion for multihadron events is based on the momentum sum of the accepted charged particles, $\sum_j p_j > 0.265\sqrt{s}$.

Table 1. Number of events and energy range of the data samples used in this analysis

$\sqrt{s}$ range (GeV)	$\langle\sqrt{s}\rangle$ (GeV)	No of events
11.6–12.4	12.0	169
12.4–14.4	14.0	2530
21.0–23.0	22.0	1782
24.0–26.0	25.0	215
29.0–32.0	30.5	808
32.0–35.2	34.8	48558
35.2–38.4	37.5	2621
38.4–46.8	43.5	5913

Only charged particles were used in our analysis. In order to ensure a large acceptance of charged particles in jets we demanded that $|\cos\theta_{tb}| < 0.85$ with θ_{tb} the polar angle of the thrust axis. In order to select three-jet events we used the triplicity algorithm [21]. In this context, particles in each event are grouped into three jets in such a way that the sum of their longitudinal momenta along the corresponding jet directions is maximized. If we denote by E_i and θ_{ij}, with $i, j = 1, 2, 3$, the jet energies and angles between the reconstructed jet directions we demanded

- $E_i > 2$ GeV
- 1 rad $< \theta_{ij} < 2.5$ rad
- $\theta_{12} + \theta_{13} + \theta_{23} > 6.0$ rad.

A total of 1888 events below a thrust cut-off of 0.85 were found, 1502 below one of 0.8 and 932 below one of 0.75. According to Monte Carlo studies these selection criteria provide us with samples where the contamination from two-jet events is below 5%. We also would like to point out that our data sample is dominated by the high-energy runs $\sqrt{s} \geq 29$ GeV, before as well as after three-jet selection cuts. In fact, the sample at and above 29 GeV represent about 99% of the total three-jet. Therefore we are in a position to neglect quark mass effects possibly affecting the predictions discussed in the introduction.

The polar distributions of the normal to the three-jet plane and the polar distribution of the most energetic jet were measured for these three samples. We also mea-

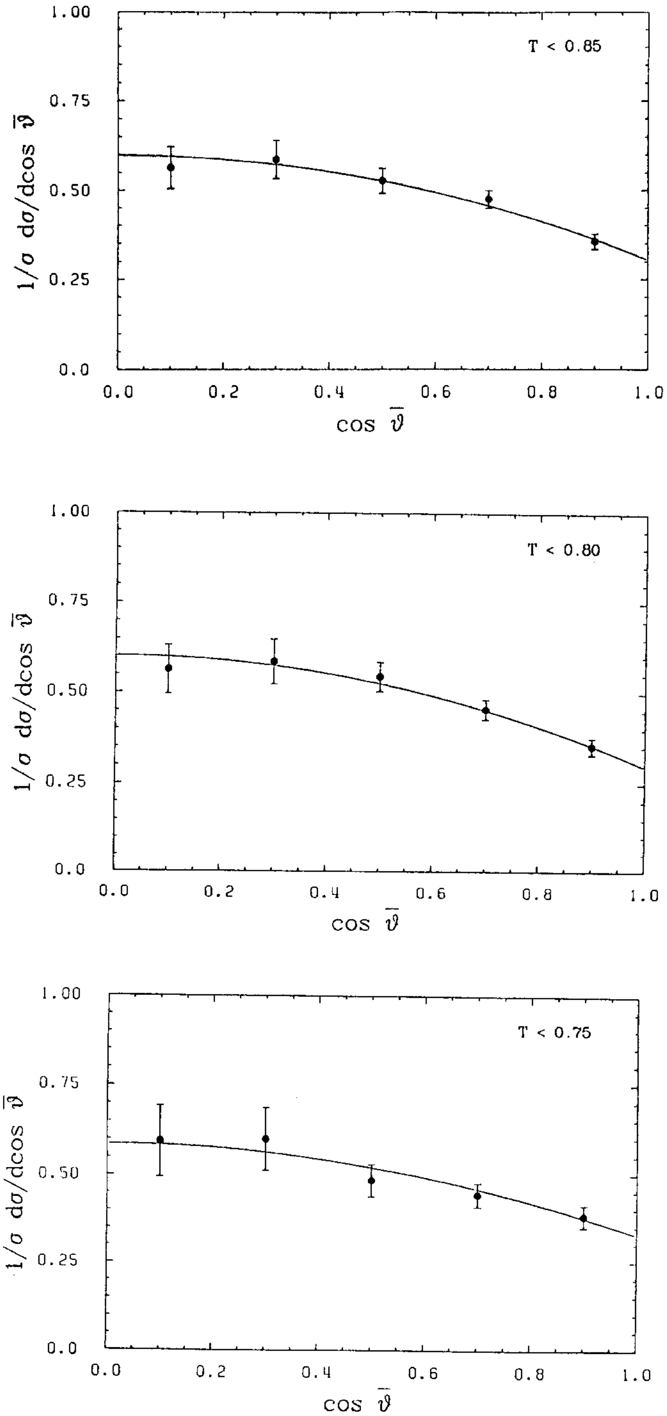

Fig. 2. The polar angle distributions of the normal to the three-jet plane for three different thrust cut-offs. The solid curves represent the results of the fits described in the text

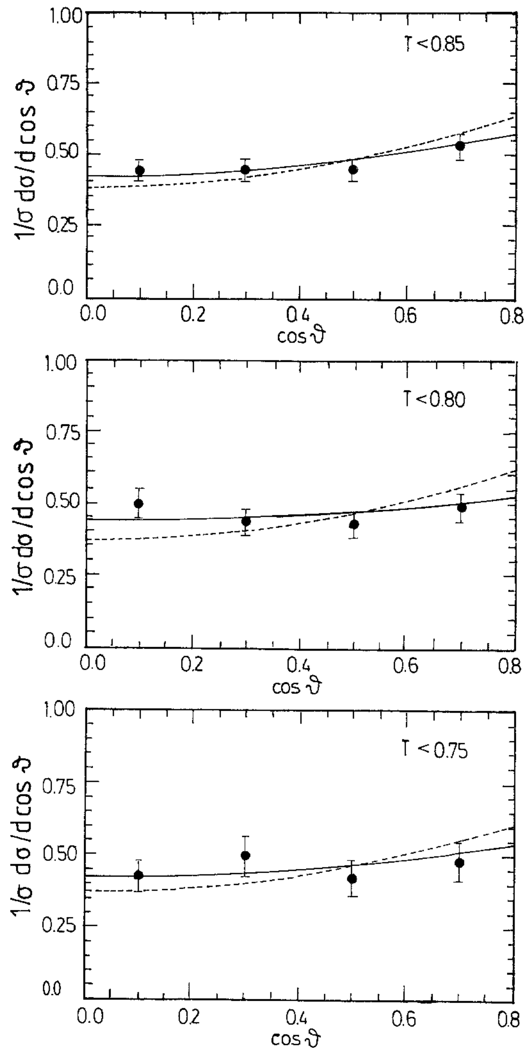

Fig. 3. The polar angle distributions of the jet axis for a sample of three-jet events at various thrust cut-offs. The solid line represents the result of a fit to (12) with the anisotropy parameter α free. The dotted line represents the results of a fit to the expression $(1+\cos^2 \vartheta)$ which is the expectation for two-jet events

sured the azimuthal correlation between the lepton and hadron planes, see Fig. 1. The data were corrected for initial state radiation, detector effects and residual two-jet background in the three-jet sample using standard Monte Carlo techniques. For this purpose low (second) order QCD Monte Carlo models of both the independent and string type were used. Correction factors were calculated by comparing the distributions obtained from Monte Carlo generated events before and after incorporating initial state radiation, detector effects and selection criteria. From the former, two-jet events were excluded but the distributions were obtained from the reconstructed jet directions and not from the original parton four-momenta. Monte Carlo studies show that the systematic uncertainties due to this procedure are negligible for the normal to the three-jet plane as already reported in [18] as well as for the polar distribution of the fastest jet. However they induce additional azimuthal correlations between the lepton and hadron plane which can be quantified in an increase of the parameter β in (6) of roughly 0.10 relative to the parton level prediction.

The final corrected distributions are displayed in Figs. 2, 3 and 4. Finally we would like to point out that the corrected distributions are estable within our statistical errors upon reasonable changes in the cuts used to select three-jet events, upon changes in the jet reconstruction algorithm used, as well as upon changes in the Monte Carlo used for correction. In fact Monte Carlo

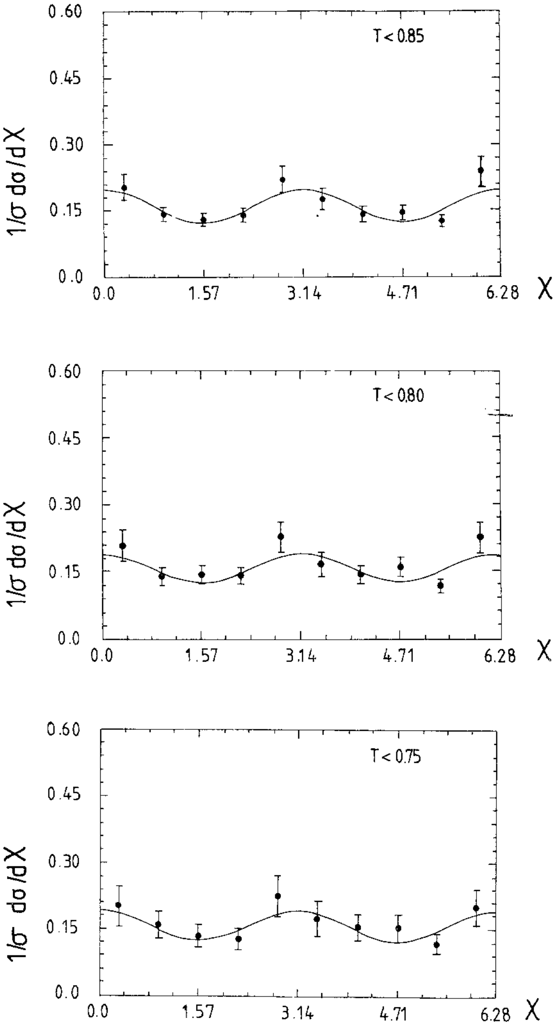

Fig. 4. The azimuthal correlation between the lepton and hadron planes for three-jet samples at various thrust cut-offs. The solid line represents the results of a fit to the QCD form $1+\beta\cos 2\chi$

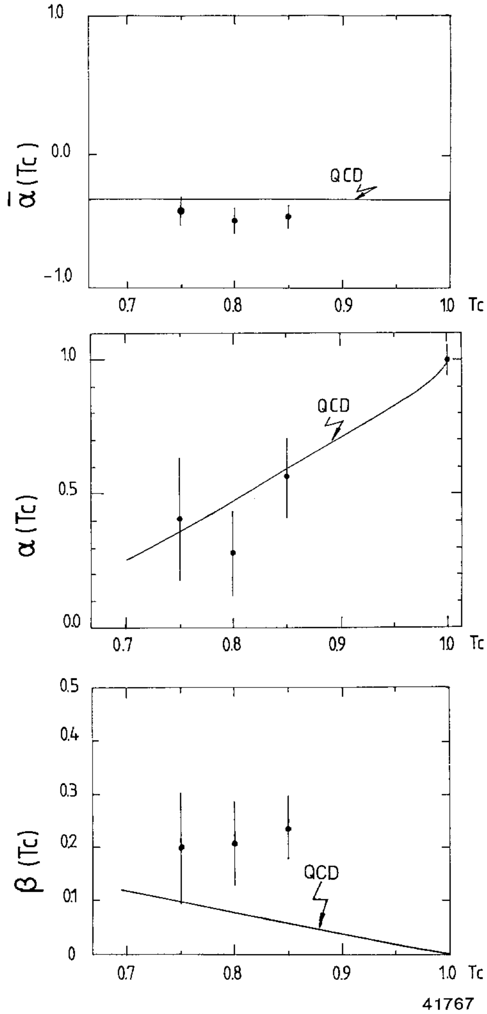

Fig. 5. Values for the anisotropy parameters α, $\bar{\alpha}$ and β as a function of the thrust cut-off applied to select three-jet events. The solid curves represent the corresponding QCD predictions

studies show no differences between low order and parton shower Lund models.

3 Results

The polar angle distributions of the normal to the three-jet plane, defined by the cross-product of the two fastest reconstructed jets, corrected for initial state radiation and detector effects are presented in Fig. 2. The data were fitted to the expression

$$\frac{1}{N}\frac{dN}{d\cos\vartheta}=\frac{1}{2(1+\frac{1}{3}\bar{\alpha})}(1+\bar{\alpha}\cos^2\vartheta) \tag{11}$$

and a value for the parameter $\bar{\alpha}$ was extracted as a function of the thrust cut-offs discussed in the previous section. The values obtained are listed in Table 2 and displayed in Fig. 5a together with the QCD prediction [18], namely $\bar{\alpha}=-\frac{1}{3}$ independent of the thrust cut-off. Good agreement between experimental results and the theoretical expectation is found. For the sake of illustration we quote the probability of the fit to the $T<0.8$ sample to be 95%. If $\bar{\alpha}$ were fixed to the predicted value $\bar{\alpha}=-\frac{1}{3}$ the resulting probability of the fit is 22% while fixing $\bar{\alpha}=0$ results in a probability of 10^{-5}.

Note that in Fig. 5 the data points are not all independent, since each thrust-cut data set contains all the events in the more tightly-cut sets. The correlation coefficient between a data point with error σ_1 derived from n_1 events and a data point, which includes all these data plus additional events, having an error σ and a total of n events is equal to $\frac{n_1\sigma_1}{n\sigma}$.

In order to show that, as discussed in the introduction, this test of QCD is unambiguous, we then turned to the polar distributions of the most energetic jet. These

Table 2. Values of the anisotropy parameters for the normal to the three-jet plane and the polar distribution of the fastest jet for $T<T_c$

T_c	$\bar{\alpha}$	α	β
0.85	-0.47 ± 0.07	0.56 ± 0.15	0.24 ± 0.07
0.80	-0.50 ± 0.07	0.28 ± 0.16	0.21 ± 0.08
0.75	-0.43 ± 0.10	0.41 ± 0.23	0.20 ± 0.10

data are shown in Fig. 3. They were fitted to the expression

$$\frac{1}{N}\frac{dN}{d\cos\vartheta}=\frac{1}{2(1+\frac{1}{3}\alpha)}(1+\alpha\cos^2\vartheta) \tag{12}$$

and values for the parameter α were extracted as a function of the thrust cut-offs discussed above. They are listed in Table 2. The polar angular distributions are flatter than the $(1+\cos^2\vartheta)$ distribution exhibited by the total hadronic sample, which is dominated by the two-jet topology and for which $\alpha=1.00\pm0.06$ [9]. For the sake of illustration, in the sample corresponding to $T<0.80$ the probabilities of the fits to (12) with α as a free parameter yielding $\alpha=0.28\pm0.16$ is 0.30 while that obtained when fixing $\alpha=1$ is 0.03.

The values obtained for the anisotropy parameter α listed in Table 2 are also displayed in Fig. 5b, and compared to the QCD predictions. Again good agreement between data and theoretical expectations is observed.

As a final consistency check, we have measured the azimuthal correlation between the lepton and hadron planes. The data, displayed in Fig. 4, show striking departures from the isotropic behaviour expected for two-jet events. These data were fitted to the expression

$$\frac{1}{N}\frac{dN}{d\chi}=\frac{1}{2\pi}(1+\beta\cos 2\chi) \tag{13}$$

and values for the parameter β were obtained as a function of the thrust cut-offs discussed above. They are listed in Table 2. There is a significant azimuthal variation, in fact somewhat stronger than what one would expect from (10). Monte Carlo studies indicate that these azimuthal distributions are more affected by residual fragmentation effects than the polar distributions discussed above. As already discussed in the previous subsection the resulting values for β are 0.10 larger than the QCD predictions. This explains the discrepancy between measured and predicted values which are shown in Fig. 5.

4 Summary

We have presented data on oriented three-jet events at PETRA energies. We have measured the polar distribution of the normal to the three-jet plane for various thrust cut-offs. These distributions are found to be not consistent with isotropy. They are well described by the $(1-\frac{1}{3}\cos^2\bar{\vartheta})$ QCD prediction.

We have also measured the polar angular distribution of the thrust axis for three-jet events, again for various thrust cut-offs. These distributions tend to flatten as the thrust cut-off becomes lower, noticeably deviating from the $(1+\cos^2\vartheta)$ form expected for two-jet events. The error bars are however still too large to be able to distinguish, on the basis of these data only, between QCD and a scalar gluon theory. The measurement of α shows that $\sigma_L\neq0$ for $T<1$ and the measurement of $\bar{\alpha}$ confirms that $\sigma_L=2\sigma_T$. This is the first experimental test in e^+e^- annihilation of the QCD prediction $\sigma_L=2\sigma_T\neq0$. Here again, the data which is dominated by γ exchange cannot distinguish between QCD and scalar gluon theories. Pronounced differences arise however at the Z_0 peak. Data at LEP/SLC will be able in the near future to complete these tests.

As a final consistency check, we have measured the azimuthal correlation betwen the lepton and hadron planes. A significant azimuthal dependence is observed. This is consistent in the lowest thrust cut-off region with the QCD prediction.

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