PROPERTIES OF CHARM JETS PRODUCED IN e^+e^- ANNIHILATION NEAR 34 GeV

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$D^{*\pm}$ production via $e^+e^- \to D^{*\pm}X$ was studied at CM energies near 34 GeV. The charged particles produced in the hemisphere opposite to that of the D^* were used to investigate the fragmentation of charm jets. All spectra studied show a close similarity between the charm jet and the average jet obtained by summing over all quark flavours. The spectra of particles produced in the D^* hemisphere were used to study separately first rank and higher rank fragmentation.

The detection of D^* mesons in e^+e^- annihilation at high energies [1–4] offers the possibility of studying with little background the characteristics of charm jets. In a recent publication [3] we have presented a measurement of the fragmentation function of charmed quarks into $D^{*\pm}$ mesons and put limits on the axial vector coupling g_A^c of charm quarks. In this paper, the D^* events were used to study the properties of charm jets.

The data were obtained at the DESY storage ring PETRA with the TASSO detector. Hadronic events from e^+e^- annihilation were selected as described in ref. [5]. The criteria most important for the present study were that to be accepted an event had to have at least 5 charged particle tracks and the momentum sum $\Sigma p \equiv \Sigma|p_i|$ of charged particle momenta had to satisfy $\Sigma p > 0.265\ W$ where W is the total CM energy. A total of 22 356 hadronic events from e^+e^- annihilation were accepted for W between 30.0 and 36.7 GeV, the average being $\bar{W} = 34.4$ GeV.

The $D^{*+} \to \pi^+ D^0$ candidates were detected in the $D^0 \to K^-\pi^+$ and $D^0 \to K^-\pi^+ +$ missing π^0 (denoted by $S^0 \to K^-\pi^+$) decay channels. For brevity we shall indicate only the particle states. The analysis includes also the antiparticle states. As described in ref. [3], for each event all possible $(K^-\pi^+)$ and $(K^-\pi^+)\pi^+$ mass combinations ($M_{K^-\pi^+}, M_{K^-\pi^+\pi^+}$) were formed assuming each particle in turn to be a kaon or a pion. The particles forming the $(K^-\pi^+)$ system were each required to have a momentum $p > 0.8$ GeV/c, and the lone π^+ (not coming from D^0 decay) to have $p > 0.3$ GeV/c. By requiring the fractional energy of the $K^-\pi^+\pi^+$ system $x = 2E_{K^-\pi^+\pi^+}/W > 0.5$ and the mass difference $\Delta M = M_{K^-\pi^+\pi^+} - M_{K^-\pi^+} < 0.150$ GeV, signals due to D^0 and S^0 production were observed. In total $82 D^{*\pm}$ candidates were obtained in the mass range $1.50 < M_{K^-\pi^+} < 1.984$ GeV with an estimated background of 16 ± 6 events.

At our CM energies D^* production can originate from the fragmentation of primary charm quarks, but also from the decay of beauty hadrons (B). The contamination with D^{*+}'s from $B \to D^{*+}X$ decay was estimated by making the following assumptions:

Beauty quark production, $e^+e^- \to b\bar{b}$, contributes to the total hadronic cross section in the ratio $R_{b\bar{b}}/R_{total} = 1/11$ and always produces events of the type $e^+e^- \to B\bar{B}X$. The B has a mass of 5.2 GeV and decays only via $B \to D^*X$ with equal branching ratios for the $D^{*+}X$ and $D^{*0}X$ channels. The D^*'s are isotropically distributed in the B-rest system with the same momentum spectrum as measured for D^0's in the decay $B \to D^0X$ [6]. The B energy spectrum is hard and given by the fragmentation function of ref. [7] with $\epsilon = 0.03$, a value which is in agreement with the experimental results given in ref. [8].

With these conservative assumptions we expect 4% of the D^{*+} mesons detected at $x > 0.5$ to come from B decay. The D^{*+} events therefore represent a rather pure sample of charm quark production where the D^* contains the primary c quark.

The properties of charm quark jets were studied using the charged particle information. The D^{*+} events were subdivided into two hemispheres by a plane perpendicular to the thrust axis. The group of particles in the hemisphere containing the D^{*+} will be referred to as the D^*-jet, the group in the opposite hemisphere will be called the charm quark jet or c-jet. Note that with this procedure, particles from one quark emitted

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backwards in the laboratory system will be associated with the other quark [‡1]. The particle distributions for the c-jet were compared to those from all events which represent a sum over the five quark flavours u, d, s, c and b contributing approximately in the ratio of their charges squared. These events were also subdivided into two hemispheres. The particle groups in either hemisphere will be referred to as the average jets. Note that 4/11 of all average jets are expected to come from charm production.

All distributions shown below were corrected for detector, acceptance and radiative effects. The corrections were determined by a Monte Carlo technique [5]. Using independent jet fragmentation [9–11], events were generated in second order QCD [12] according to $e^+e^- \to q\bar{q}$ for the average events and $e^+e^- \to c\bar{c}$ for the charm events including in both cases the contributions from gluon and additional $q\bar{q}$ emission. The corrected distributions include the charged particles from the decay of particles with lifetimes less than 3×10^{-10} s. Thus, e.g. the charged particles from non-observed K^0_S and Λ decays were corrected for while those from K^0_L were removed. Additional corrections were applied to the c-jet distributions to subtract the hadronic background under the D^* signal. The conclusions drawn below from the comparison of charm jet and D^*-jet distributions with those of the average jet were found to be insensitive to the corrections applied.

The average charged multiplicity is found to be $\langle n_{CH} \rangle = 7.5 \pm 0.5$ (stat.) ± 0.3 (syst.) for c-jets and $6.7 \pm 0.02 \pm 0.3$ for the average jet. The scaled momentum distribution $1/N_{jet} \cdot dN/dx_p$, where $x_p = 2p/W$, is displayed in fig. 1a. Within errors no difference is observed between the distribution for the c-jet and the average jet.

For the study of the longitudinal ($p_\parallel$) and transverse (p_T) momentum distributions the jet axis (= thrust axis) was determined using *all* charged particles in an event. In order to calculate the correction factors from the Monte Carlo generated events the "true" axis was determined from the charged and neutral particles, while the "true" distributions were computed with the charged particles alone.

The rapidity, $y = 0.5 \ln(E + p_\parallel)/(E - p_\parallel)$, was calculated using the thrust axis and assigning the pion mass to all particles in the jet. The normalized yield, $1/N_{jet} \cdot dN/dy$, is shown in fig. 1b. The number of particles produced per unit of rapidity in the central region ($y < 1$) is 2.3 ± 0.2. The c-jet distribution is in agreement with that for the average jet. The same conclusion is reached for the p_T^2 distribution shown in fig. 1c. The sphericity, $S = \frac{3}{2}(\Sigma p_T^2)/(\Sigma p^2)$, and thrust, $T = \Sigma |p_\parallel| / \Sigma p$ were calculated for particles in a single jet, but using the respective axes determined from the *whole* event. No significant differences between c-jet and average jet are observed from the sphericity and thrust distributions (figs. 1d,e).

The sphericity, thrust and p_T^2 distributions are sensitive to gluon bremsstrahlung. The observed agreement between the charm jet and the average jet is indicative that gluon bremsstrahlung is also present in charm events and with similar strength. This will be studied in a forthcoming paper.

In fragmentation schemes such as that of Field and Feynman [9] the D^{*+} meson containing the primary c quark is emitted in the first rank process, $c \to D^{*+} + d$. Consequently, the other particles produced in the D^{*+} hemisphere stem from higher rank fragmentation (and to a small extent from hard gluon fragmentation). We have studied production of particles accompanying the D^{*+} in the D^*-jet. The D^{*+} as well as its decay particles are not included in the distributions. The energy available in the D^* hemisphere after subtracting that of the D^{*+}, $E_{res} = W/2 - E_{D^*}$, is on average $\langle E_{res} \rangle = 6.2 \pm 0.4$ GeV. Thus it is instructive to compare the particle production on the D^* side not only with that of the average jet produced at the same CM energy ($W = 34.4$ GeV) but also with that of the average jet produced at the "residual" energy $W = 2\langle E_{res} \rangle$. We shall use for the comparison our data measured at $W = 14$ GeV [5,13].

The average number of charged particles produced in addition to the D^{*+} is $\langle n_{CH}^{res} \rangle = 4.4 \pm 0.6 \pm 0.4$. Within errors we found the same multiplicity per hemisphere for hadronic events produced by e^+e^- annihilation at a CM energy of $W = 14$ GeV, $\langle n_{CH} \rangle = 4.45 \pm 0.03 \pm 0.2$ (per hemisphere).

‡1 Using the Field-Feynman fragmentation scheme [9] for events of the type $e^+e^- \to q\bar{q}$, the fraction of charged particles emitted into the backward hemisphere was found to be 6.5%; 4.8% have momenta $p < 0.4$ GeV/c, 1.7% have $p > 0.4$ GeV/c. Furthermore, within errors the number of backward going particles was found to be the same for the D^*-jet and the c-jet.

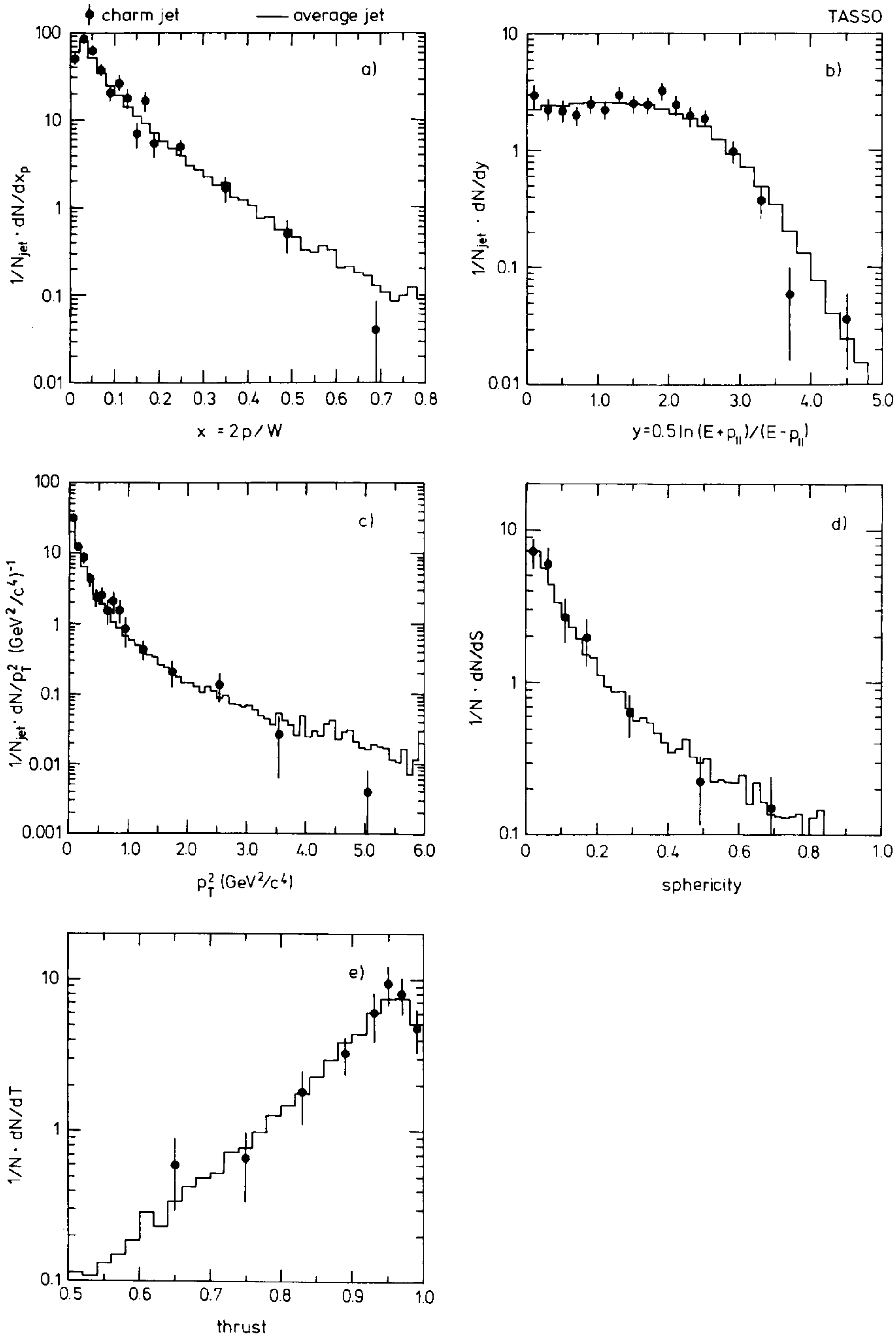

Fig. 1. Charged particle spectra of charm-jets (black dots) compared with those for the average jet (histogram). (a) Normalized yield $1/N_{\text{jet}} \cdot dN/dx_p$ as function of the scaled momentum $x_p = 2p/W$. (b) Normalized yield $1/N_{\text{jet}} \cdot dN/dy$ as function of the rapidity y. (c) Normalized yield $1/N_{\text{jet}} \cdot dN/dp_T^2$ as function of the transverse momentum squared. (d) Normalized sphericity distribution $1/N \cdot dN/dS$ of charm jets. (e) Normalized thrust distribution $1/N \cdot dN/dT$ of charm jets.

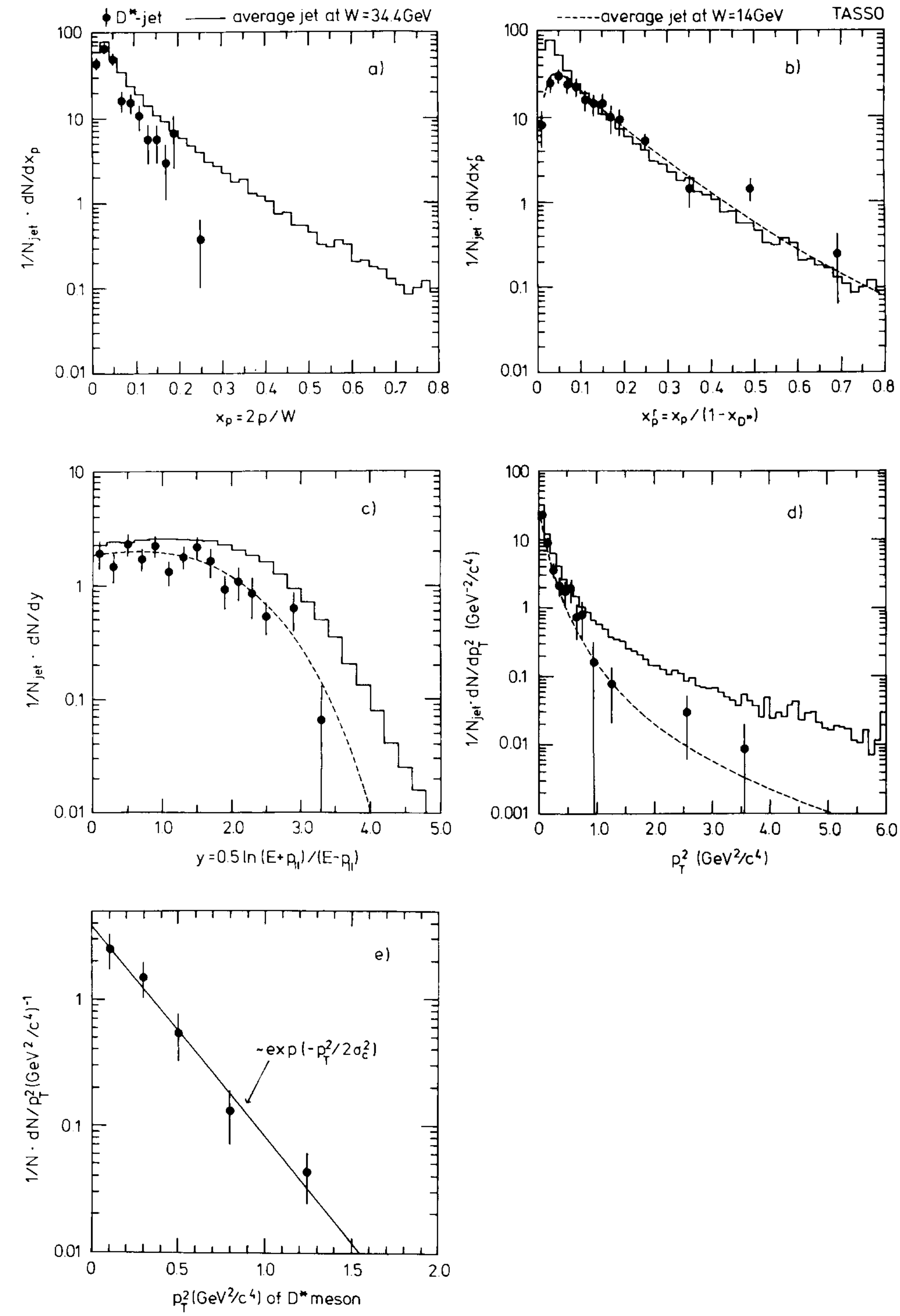

Fig. 2. (a)–(d) Spectra of charged particles accompanying D^{*+} mesons (black dots), compared with spectra for the average jet as $W = 34.4$ GeV (histograms) and at the "residual" W of 14 GeV (dashed curves) [5,13]. (a) Normalized yield $1/N_{jet} \cdot dN/dx_p$ as function of the scaled momentum $x_p = 2p/W$. (b) Normalized yield $1/N_{jet} \cdot dN/dx_p^r$ as function of the (renormalized) scaled momentum $x_p^r = x_p/(1 - x_{D^*})$. (c) Normalized yield $1/N_{jet} \cdot dN/dy$ as function of the rapidity y. (d) Normalized yield $1/N_{jet} \cdot dN/dp_T^2$ as function of the transverse momentum squared. (e) Normalized distribution $1/N \cdot dN/dp_T^2$, where p_T^2 is the transverse momentum squared of the D^* meson relative to the charm quark direction. The straight line shows the result of the fit to the form $1/N \cdot dN/dp_T^2 \sim \exp(-p_T^2/(2\sigma_c^2))$ (see text).

The scaled momentum distribution of the charged particles is shown in fig. 2a. Not surprisingly, the spectrum is soft compared to that observed for the average jet at $W = 34.4$ GeV (histogram). Since on average more than half of the available energy is carried away by the D^{*+}, we show in fig. 2b the distribution of the renormalized scaled momentum, $x_p/(1 - x_{D^*})$. The shape of this spectrum is similar to the x_p distribution of the average jet at $W = 34.4$ GeV except for the region below $x_p/(1 - x_{D^*}) = 0.07$ where roughly a factor of two more particles are produced in the average jet. However, the D^*-jet spectrum agrees well with the x_p spectrum of the average jet produced at the "residual" energy $W = 14$ GeV (dashed curve in fig. 2b). Note that the scaling violations observed in the inclusive particle spectra at low x_p [5] result mainly from phase space effects.

Fig. 2c shows the y distribution of the charged particles. The height of the plateau is ~20% lower than for the average jet at $W = 34.4$ GeV. The average number of particles per unit of rapidity produced in the central region ($y < 1$) is 1.9 ± 0.2. Close agreement is observed with the y distribution of the average jet produced at the "residual" energy, $W = 14$ GeV (dashed curve in fig. 2c). The particle yield in the central region in this case is 2.00 ± 0.03.

The p_T^2 distribution of the charged particles in the D^*-jet is shown in fig. 2d. The fall-off towards high p_T^2 values is somewhat steeper than observed for the average jet at $W = 34.4$ GeV but agrees with that of the average jet produced at the "residual" energy, $W = 14$ GeV (dashed curve in fig. 2d).

As mentioned above, the D^{*+} is expected to be produced in the first rank process $c \to D^{*+} + d$. In this case the p_T^2 distribution of the D^{*+} mesons measures directly the p_T^2 distribution of the first rank process. In determining the p_T^2 distribution, the correction to the "true" axis (the direction of the c quark fragmenting into the D^{*+} meson) was calculated from the Monte Carlo generated events. The p_T^2 distribution is shown in fig. 2e; it is well described by the form $dN/dp_T^2 \sim \exp(-p_T^2/(2\sigma_c^2))$. The fit shown by the straight line in fig. 2e yielded $\sigma_c = 0.36 \pm 0.02$ GeV/c. A systematic error of ±0.04 GeV/c has to be added to account for the uncertainty in the determination of the c-quark direction. The value of σ_c agrees with the value $\sigma_q = 0.355 \pm 0.010$ GeV/c obtained by fitting the entire event sample [11] in terms of a QCD model with independent jet fragmentation. Hence, we observe no evidence for a difference in the p_T^2 distribution for the first rank process compared with the p_T^2 distribution summed over all ranks and all quark flavours.

In conclusion, e^+e^- annihilation into hadronic events containing $D^{*\pm}$ was studied near CM energies of 34 GeV. The charged particle production in the hemisphere opposite to the $D^{*\pm}$ provided an unbiased method of analysing the fragmentation properties of charm quarks. The charged multiplicity, the p, p_T and rapidity spectra and the thrust and sphericity distributions were presented for the charm jet and compared with those of the average jet. A priori, one might have expected a difference between the fragmentation properties of heavy quarks such as the charm quarks compared to the light quarks, u, d, s. For instance, charm quarks have a hard fragmentation function [1–4]. However, looking at the particles detected after all decays, we observed a close similarity between the particle spectra of the charm jet and the average jet. We also analysed particle production in the $D^{*\pm}$ hemisphere. Since the $D^{*\pm}$ itself is expected to result from first rank fragmentation, removing the $D^{*\pm}$ allowed us to study particle production from higher rank fragmentation. The particle spectra observed for the higher rank fragmentation match those measured for an average jet produced at the "residual" energy which is the energy of the total D^{*+}-jet minus the energy of the D^{*+}. The p_T^2 properties of the first rank process as observed via the D^{*+} were found to agree with those obtained by averaging over all ranks and flavours.

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References

[1] J.M. Yelton et al., Phys. Rev. Lett. 49 (1982) 430.
[2] C. Bebek et al., Phys. Rev. Lett. 49 (1982) 610; P. Avery et al., Phys. Rev. Lett. 51 (1983) 1139.
[3] TASSO Collab., M. Althoff et al., Phys. Lett. 126B (1983) 493.
[4] S. Ahlen et al., Phys. Rev. Lett. 51 (1983) 1147.
[5] TASSO Collab., R. Brandelik et al., Phys. Lett. 114B (1982) 65.

[6] J. Green et al., Phys. Rev. Lett. 51 (1983) 347.
[7] C. Peterson et al., Phys. Rev. D27 (1983) 105.
[8] M.E. Nelson et al., Phys. Rev. Lett. 50 (1983) 1542;
E. Fernandez et al., Phys. Rev. Lett. 50 (1983) 2054;
MARK J Collab., B. Adeva et al., Phys. Rev. Lett. 51 (1983) 443.
[9] R.D. Field and R.P. Feynman, Nucl. Phys. B136 (1978) 1.
[10] P. Hoyer et al., Nucl. Phys. B161 (1979) 349;
A. Ali et al., Z. Phys. C2 (1979) 33.
[11] TASSO Collab., data reported by G. Rudolph at the EPS Conf. on High energy physics (Brighton, 1983).
[12] K. Fabricius et al., Phys. Lett. 97B (1980) 431; Z. Phys. C11 (1982) 315.
[13] TASSO Collab., M. Althoff et al., paper in preparation.