Z. Phys. C – Particles and Fields 29, 175–181 (1985)

Zeitschrift für Physik C Particles and Fields

Experimental Studies on the Heavy Quark Fragmentation Functions

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Received 13 August 1985

Abstract. The influence of perturbative QCD gluon radiation and initial state photon radiation on the experimental determination of the heavy quark fragmentation functions is studied in order to extract $\langle z_c \rangle$, the mean of the charm fragmentation function, from the recent measurements of inclusive D^* production in $e^+ e^-$ annihilation processes. The result is $\langle z_c \rangle = 0.71 \pm 0.014 \pm 0.03$, which is scale invariant in the c.m. energy range of 10 GeV to 34 GeV. This result is interpreted in terms of kinematical calculations on heavy quark fragmentation functions and also compared with results from $\nu - N$-reactions and from investigations of inclusive lepton production in $e^+ e^-$ annihilation. Results of a QCD shower model are in good agreement with the data and offer an alternative description of phenomenological fragmentation functions.

Elementary particle reactions at high energies are commonly described by hard scattering processes of quarks, leptons and gauge-bosons. Whereas leptons and the electroweak bosons appear as free particles in high energy experiments, thus allowing detailed studies of the electroweak forces, quarks and gluons materialise as jets of hadrons. Due to the strong 'confinement' of coloured objects, only phenomenological models exist to describe the fragmentation of quarks and gluons, subsequently named partons, to the observable particles. During the last few years several measurements on the fragmentation of the heavy charm and bottom quarks have been carried out. This article tries to summarise these results in order to specify the parametrisation of the fragmentation process.

In Sect. I, a short overview of the present fragmentation models and the parametrisation of fragmentation functions will be given. The experimental results on heavy quark fragmentation are reviewed in Sect. II, and calculations in order to combine and interpret those measurements are presented. In Sect. III, comparisons to different model calculations are presented.

I. Phenomenological Fragmentation Models

Fragmentation models are used to describe the transition from quarks and gluons to the observable final state of hadrons. Independent jet [1, 2] and colour string [3] models calculate the parton production according to first and second order perturbative QCD down to invariant masses m_{ij} between two partons i and j of $m_{ij} \approx 4$ GeV. The subsequent fragmentation into the observable particles is not calculable by perturbative QCD and is described phenomenologically by the process $Q \to q$ + meson: in the colour-field of the outgoing quark Q a new quark-antiquark pair $q\bar{q}$ is created; $\bar{q}$ and Q combine to a meson and the fragmentation is carried on by the quark q. This process is usually parametrised by a scaling function $f(z)$, where

$$z = (E + p_{\|})_{\text{meson}} / (E + p_{\|})_{\text{quark}} \qquad (1)$$

is the fraction of energy and momentum component parallel to the fragmentation direction, carried away by the meson. In addition, the meson receives a transverse momentum component with respect to the quark axis, which is usually parametrised by a gaussian distribution. Using kinematical arguments, Azimov et al. [4] and later Suzuki [5] and Bjorken [6] pointed out that in the case of a fragmenting heavy quark Q, a larger part of the energy is carried by the meson than in the case of a light quark, leading to harder fragmentation functions $f(z)$ for c- and b-quarks.

Starting from quantum mechanical arguments, Peterson et al. [7] proposed

$$f(z)=1/[z\cdot(1-1/z-\varepsilon_Q/(1-z))^2] \quad (2)$$

for the fragmentation of heavy quarks Q with free parameters ε_Q, which are related to the effective quark masses of the formed meson by

$$\varepsilon_Q=(m_q/m_Q)^2. \quad (3)$$

Other functional forms have been proposed e.g. by the Lund group [3]. In these models as well as in theoretical studies on heavy hadron production (see e.g. [8]), fragmentation functions $f(z)$ are used to simulate that part of the fragmentation which is not calculable by perturbative QCD.

A further class of models is based on QCD leading log calculations for the development of parton showers down to invariant masses of ~ 1 GeV [9, 10]. At the end of such a cascade, gluons are split into quark-antiquark pairs, which are combined to colour singlet clusters. These clusters then decay into the final particles according to a simple phase space scheme. Within the framework of QCD shower models, the phenomenological fragmentation process of the perturbative QCD models [1–3] now is described by multiple gluon emission down to small invariant masses, together with the formation and decay of colour singlet clusters, and no further parametrisation in terms of fragmentation functions and p_T-distributions is necessary.

II. Experimental Evaluation of the Heavy Quark Fragmentation Functions

The production of heavy charm and bottom quarks in the fragmentation process is expected to the suppressed due to their large masses [3]. Thus, heavy mesons contain either the primary quark of the hard scattering process itself or its weak decay product and are the most useful sources of information on fragmentation functions. Experimental results on the fragmentation of heavy quarks are available from $\nu-N$-scattering and e^+e^- annihilation processes (for a review, see [11]). In general, two different kinds of analyses have been performed: the reconstruction of heavy mesons from their hadronic decay products, and the measurement of inclusive electrons and muons, which are interpreted as the semileptonic decay products of heavy particles.

The most direct method of evaluating fragmentation functions is to measure in e^+e^- annihilations the energy- or momentum- spectra of reconstructed heavy mesons. Such measurements of the charmed D^*-meson have been performed by several experiments around c.m. energies of 10 GeV [12, 13], 29 GeV [14–17] and 34 GeV [18, 19]. The measured quantities are

$$x_E=E_{\text{meson}}/E_{\text{beam}} \quad (4)$$

or

$$x_p=p_{\text{meson}}/\sqrt{E^2_{\text{beam}}-m^2_{\text{meson}}} \quad (5)$$

which, in general, are different from z for the following reasons:

a) Due to perturbative QCD gluon radiation, E_{quark} at the beginning of the fragmentation process is less than E_{beam}, leading to $x\leqq z$.

b) Initial state photon radiation also diminishes E_{quark}.

c) At high c.m. energies, c-mesons as decay-products of primary bottom quarks are expected to populate the small-x region.

The magnitude of these effects is illustrated in Fig. 1 for the D^*-meson, as calculated with the Lund model at $\sqrt{s}=34$ GeV. The dashed line represents a fragmentation function $f(z)$ of the Peterson-type with $\varepsilon_c=0.05$, which in the absence of radiation effects would be identical to the measurable x_E-spectrum except for threshold effects at low x. The softening of this spectrum due to QED and QCD radiation is also shown, as well as the expected D^*-spectrum from the decay of b-particles.

The published x-spectra of D^*-mesons are acceptance-corrected and can therefore be directly compared with QCD model calculations, that also in-

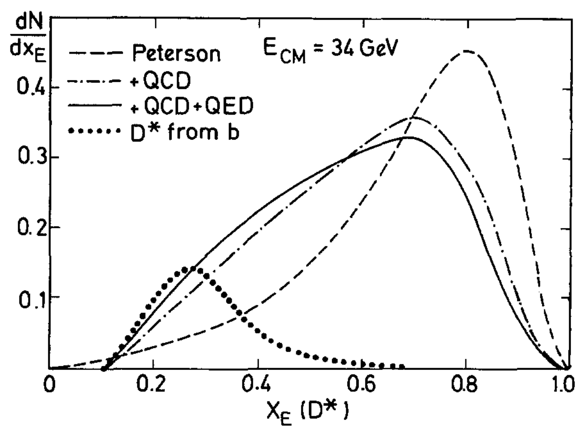

Fig. 1. Softening of the energy-spectrum of D^*-mesons due to QED initial state photon and QCD gluon radiation, calculated for the process $e^+e^-\to c\bar{c}$ at $\sqrt{s}=34$ GeV using the Lund model and a fragmentation function $f(z)$ of Peterson et al. Also indicated is the expected spectrum of D^*-mesons from b-quark decays

clude initial state photon radiation. In order to extract the fragmentation function $f(z)$ for c-quarks or the mean $\langle z_c \rangle$ of that function, several fragmentation models [1–3, 10] and fragmentation functions have been used to study the transition from $\langle z_c \rangle$ to $\langle x \rangle_{D^*}$, due to the effects a, b and c described above.

For the case of an underlying $f(z)$ of the Peterson-type, Fig. 2a shows the relation between $\langle z_c \rangle$ and $\langle x_p \rangle_{D^*}$ at $\sqrt{s}=29$ GeV as a function of the parameter ε, calculated with the Lund model. For these calculations, model parameters have been used which provide the best overall description of the experimental data at 34 GeV [20]. In particular, the strong coupling parameter Λ_{QCD} in second order QCD was set to 500 MeV, and the perturbative QCD cutoff parameter $y_{min}=m_{ij}^2/s$, the scaled minimum invariant mass squared between two partons i and j, was set to 0.015 at 29 GeV and 34 GeV c.m. energy and to 0.04 at 10 GeV.

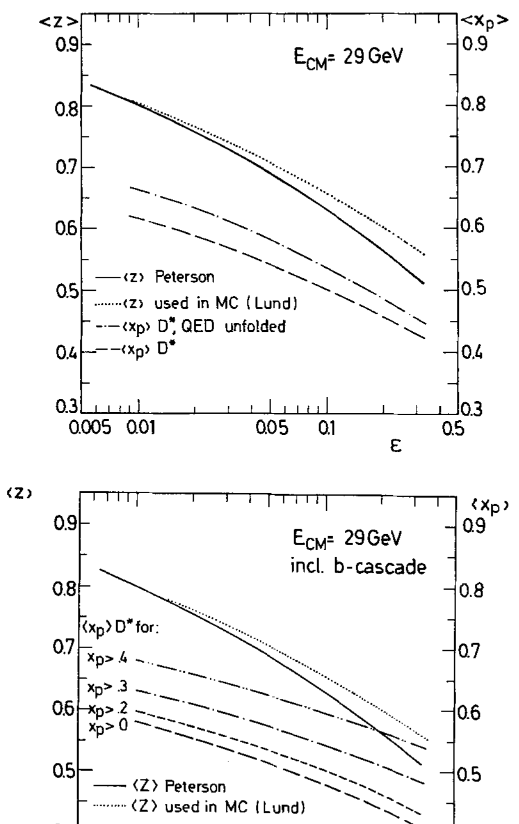

Fig. 2. a Relation between $\langle z_c \rangle$ and $\langle x_p \rangle$ of D^*-mesons as a function of the parameter ε of the Peterson fragmentation function $f(z)$, calculated with the Lund model at $\sqrt{s}=29$ GeV including QED and QCD radiation effects. **b** Same as **a**, but including also D^*-mesons from b-quark production and assuming several experimental lower limits in x_p

In Fig. 2a, the full line represents the mean of the Peterson function $f(z, \varepsilon)$. The final $\langle z \rangle$ of the produced D^*-mesons deviates from the function used in the fragmentation part of the model and is given by the dotted line. Such a shift occurs in all perturbative QCD models and is due to various technical and physical requirements:

– Independent jet models [1, 2] do not conserve energy and momentum during the fragmentation process. This has to be artificially compensated at the end of the whole process, in general leading to $\langle z \rangle_{final} \geqq \langle z \rangle_{initial}$.

– In colour string models [3], the fragmentation proceeds along the colour-flux lines stretched between quarks and gluons, rather than along the quark- and gluon- directions. In addition, z is interpreted as $z'=(E+p_{\|})/(E+\mathbf{p}_{\|})_{rs}$, where $(E+\mathbf{p})_{rs}$ is the total energy plus parallel momentum component of the unfragmented, residual system. The last two particles of the system are then kinematically constrained. The advantage of this procedure is that energy and momentum are conserved at each point of the fragmentation chain. The final z of a particle, however, is shifted with respect to the initially chosen z', due to the boosts between different coordinate systems and the difference in the definition of z.

The dashed line in Fig. 2a shows the final $\langle x_p \rangle_{D^*}$, also as a function of the parameter ε_c used in the fragmentation function $f(z)$, including both photon and gluon radiation. The influence of the initial state photon radiation with respect to the final $\langle x_p \rangle_{D^*}$ is indicated by the dashed-dotted line.

Further calculations have been done to study the influence of b-decays and to extrapolate all measurements to the full x-range. As a result, Fig. 2b shows the expected final $\langle x_p \rangle_{D^*}$ as a function of the parameter ε, including D^* from b-decays, for full acceptance and for typical experimental lower limits in x.

In order to extract $\langle z_c \rangle$ from all measured values of $\langle x \rangle_{D^*}$, similar calculations have been done at c.m. energies of 10 GeV and 34 GeV for both observables x_p and x_E. The available experimental values for $\langle x \rangle_{D^*}$, determined from the published D^*-spectra, are shown in Fig. 3a, together with the statistical errors and the measured range of the observables. Each value was corrected for perturbative QCD radiation, the full x-range and, if not done in the original publication itself, for b-decays and QED radiation, thus extracting the corresponding value of $\langle z_c \rangle$. The final results of $\langle z_c \rangle$ are illustrated in Fig. 3b and show a good agreement between all experiments. Also shown are the combined results

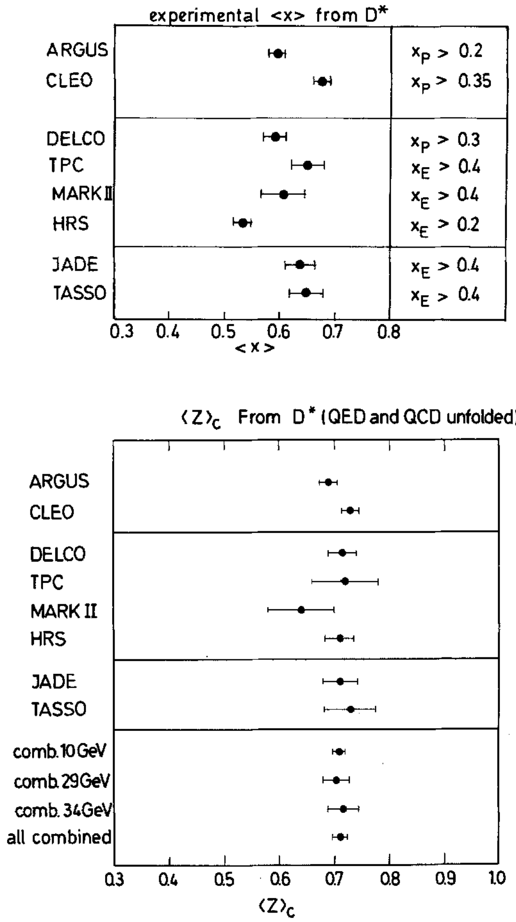

Fig. 3. a Experimental results on $\langle x\rangle$ of D^*-mesons, together with the measured ranges of the observables. **b** $\langle z\rangle$ for c-quark fragmentation, calculated from the experimental $\langle x\rangle$ of D^*-mesons after corrections for QED and QCD radiation, full x-range and decay of b-quarks

for each energy range, which indicate that $\langle z_c\rangle$ is constant between c.m. energies of 10 GeV and 34 GeV. The overall combined value of $\langle z_c\rangle$ from the D^*-analyses is

$$\langle z_c\rangle = 0.71 \pm 0.014 \pm 0.03.$$

The systematic error of 0.03 accounts for differences in the fragmentation models and the fragmentation functions used for calculating the corrections. No difference in the corrections is obtained using the colour string model or independent jet models, as long as model dependent values for the parameter $\Lambda_{\rm QCD}$ (see e.g. [20]) and the above-mentioned internal shifts in z are taken into account properly. Uncertainties imposed by the unknown branching ratios from b-particles to D^*-mesons are small, since the influence of D^*-mesons from b-decays on the measurable $\langle x\rangle_{D^*}$-spectrum decreases with increasing experimental lower x-limits and is negligible for $x > 0.4$. Also the correction on $\langle x\rangle$ due to initial state photon radiation decreases from $\sim 5\%$ for full x-acceptance to less than 2%, if only $x > 0.4$ is measured. Different functional forms of the fragmentation functions [3, 7] in the model calculations result in systematic uncertainties in $\langle z_c\rangle$ of less than 0.02. The variation of the parameter $\Lambda_{\rm QCD}$ by ± 200 MeV for each type of model adds a systematic error of ± 0.015, and another ± 0.02 is accounted for by changing the perturbative QCD cutoff parameter $y_{\min}$ by a factor of 2.

With the combined result of $\langle z_c\rangle = 0.71$ some interesting kinematical considerations can be done. To get this $\langle z_c\rangle$ with the function of Peterson et al. (2), $\varepsilon = 0.04$ must be taken. Interpreting ε according to (3) as the squared ratio of the constituent quark masses and assuming the mass of the charm quark to be 1.5 GeV/c^2, one obtains for the mass of the light u and d quarks $m_{u,d} = 0.3$ GeV/c^2. These values are a reasonable guess for the effective quark masses and show that the experimentally observed charm fragmentation is compatible with kinematic arguments as used in [7]. Similar results have been obtained by Azimov et al. [8], who carried out theoretical calculations on heavy hadron production and QCD radiative effects.

Other charmed particles, e.g. the F-meson as a combination of c and s quark or charmed baryons, are expected to fragment softer than D-mesons, because the more massive s-quark or diquark decelerates the c-quark more than a u- or d-quark does. Again applying (2) and (3) for $m_q \equiv m_s = 0.5$ GeV/c^2 and $m_Q \equiv m_c = 1.5$ GeV/c^2 leads to $\varepsilon = 0.11$. Thus $\langle z\rangle$ of F-mesons is expected to be $\sim 10\%$ less than those for D-mesons. Indeed, the published data on F-mesons production [21–25] seem to indicate a softer fragmentation, but the statistical significance is still rather poor. In addition one has to keep in mind that an unknown fraction of F-mesons coming from F^*-decays also softens the measured spectrum.

Following the line of (2) and (3) and taking a b-quark mass of $m_b = 5$ GeV/c^2, results in $\varepsilon_b = 0.004$, and for primary B-mesons a fragmentation function with $\langle z_b\rangle \sim 0.85$ is expected. This value is also quite consistent with measurements of inclusive leptons, as discussed below.

So far, direct measurements of heavy particles are possible only for charmed mesons. Indirect information on both the charm and the bottom fragmentation is available from measurements of inclusive lepton spectra in e^+e^- annihilation [26–31]. Those measurements are not directly comparable to the results obtained from D^* production, for the leptons originate from an unknown mixture of primary mesons and baryons and their decay products, hence the resulting fragmentation functions are expected to be softer than those of the lightest primary D^* and B mesons. The results of the different inclusive lepton analyses are presented using various fragmentation variables, defined as follows:

$$x_E = E_{\text{hadron}}/E_{\text{beam}}, \quad (6)$$

$$x'_E = 2 \cdot E_{\text{hadron}}/\sqrt{s}_{\text{hadronic system}}, \quad (7)$$

$$z_E = E_{\text{hadron}}/E_{\text{quark}}, \quad (8)$$

$$z = (E + p_{\|})_{\text{hadron}}/(E + p_{\|})_{\text{quark}}. \quad (1)$$

Both initial state photon radiation and hard gluon bremsstrahlung are unfolded in the variables z and z_E. The variables x_E and x'_E are comparable to the observables used in the direct heavy meson analyses (4), x'_E being corrected for photon radiation. That implies the relation $\langle z \rangle \approx \langle z_E \rangle \geqq \langle x'_E \rangle \geqq \langle x_E \rangle$, and it is not very meaningful to calculate the average value of all published results. In addition, the correction of these results to a common basis, as presented for the direct D^*-analyses, is quite difficult due to the different fitting procedures and model calculations done by the various experiments.

The mean values of the fragmentation variables resulting from inclusive lepton analyses are listed in Table 1. The average $\langle z_b \rangle$ from MAC, MARK-J and TASSO is $\langle z_b \rangle = 0.80 \pm 0.06$ and agrees well with the value 0.85, calculated above from the ratio of quark masses as an expectation for primary B-mesons. The results for the charm fragmentation are compatible with the combined $\langle z_c \rangle$ from the D^*-analyses, except the value from [30].

Measurements on charm fragmentation have also been made in $\nu - N$-scattering experiments by the CDHS [32] and E531 [33] collaborations. CDHS studies D-meson production in dimuon neutrino events. The fitted fragmentation variable is:

$$z_\nu = E_D/E_c, \quad (9)$$

E_D and E_c being the energies of the D-meson and of the charm quark in the rest frame of the hadronic system. This variable is similar to the ones used in e^+e^- analyses, and the result of $\langle z_\nu \rangle = 0.68 \pm 0.08$ agrees quite well with those measurements.

E531 reconstructs charmed mesons and baryons directly and presents a spectrum of the variable

$$x_\nu = E_{\text{hadron}}/(E_\nu - E_\mu) \quad (10)$$

with $\langle x_\nu \rangle = 0.59 \pm 0.03 \pm 0.03$, where the energies of the incoming ν and outgoing μ are defined in the laboratory frame. The variable x_ν is not directly comparable to z_ν nor to the variables used in e^+e^- annihilation. This is pointed out in more detail by T.D. Gottschalk in [34], who expects $\langle x_\nu \rangle \approx 0.8 \cdot \langle z_\nu \rangle$. Thus, the two results on c-fragmentation from $\nu - N$-scattering are compatible with each other and with the measurements in e^+e^- annihilation, but again it is not meaningful to calculate the average of all the published results due to the differences in particle contents, energy range and definitions of variables that enter all the analyses.

III. Comparison with Fragmentation Models

Up to now, no experimental result on the fragmentation functions of heavy quarks has been sensitive enough to allow reconstruction of the detailed shape of those functions, and all perturbative QCD models

Table 1. Results on heavy quark fragmentation from inclusive leptons in e^+e^- annihilation and from $\nu - N$-scattering

Exp.	Lepton	Fitted variable	Mean for charm	Mean for bottom
MAC	μ	z	–	0.8 ± 0.1
MARK-II	e	z_E	–	$0.75 \pm 0.05 \pm 0.04$
DELCO	e	x'_E	0.69 ± 0.06	0.78 ± 0.05
TPC	e	x_E	–	$0.74 \pm 0.05 \pm 0.03$
TPC	μ	x_E	$0.60 \pm 0.06 \pm 0.04$	$0.80 \pm 0.05 \pm 0.05$
MARK-J	μ	z	$0.46 \pm 0.02 \pm 0.05$	$0.75 \pm 0.03 \pm 0.06$
TASSO	e	z	$0.57^{+0.10+0.06}_{-0.09-0.05}$	$0.84^{+0.15+0.15}_{-0.10-0.11}$
TASSO	μ	z	$0.77^{+0.05+0.03}_{-0.07-0.11}$	$0.85^{+0.10+0.02}_{-0.12-0.07}$
CDHS	dimuons	z_ν	0.68 ± 0.08	–
E531	hadrons	x_ν	$0.59 \pm 0.03 \pm 0.03$	–

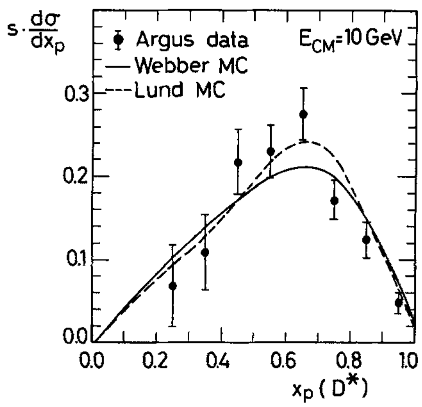

Fig. 4. The experimental D^*-spectrum of the ARGUS collaboration, compared with two different model calculations: the Lund model, using a fragmentation function of Peterson et al. with $\varepsilon = 0.05$, and the Webber model with a simple procedure for charmed cluster decays

using the standard fragmentation functions are able to describe the data if the parameters are adjusted properly. In the case of the commonly used single parameter function of Peterson et al., a good description is obtained with ε in $f(z)$ calculated according to (3). This knowledge of the parametrisation of the heavy quark fragmentation functions may reduce possible systematic errors in a wide spectrum of hadronic analyses, where detailed comparisons of data with model calculations are necessary.

An interesting question is whether QCD-shower models describe the experimentally observed fragmentation of charmed particles. To describe the fragmentation process, no phenomenological fragmentation functions are needed by those models, as described above. The model of Webber et al. [10], which originally did not include the fragmentation of charmed particles due to the weak decay of c-quarks before formation of clusters, has been extended in the following way [35]: Primary c-quarks stay in the QCD-cascade without weak decays and form clusters similar to the light quarks. Each charmed cluster then decays into a D^* plus a π or a K meson. This simple procedure cannot describe the experimental charm particle yields and cross sections, but is well suited to study the fragmentation of D^*-mesons.

The spectrum of the final D^*-mesons predicted by this model, including initial state photon radiation, is compared to the ARGUS data in Fig. 4. Also shown is the final D^*-spectrum calculated from the Lund model and $f(z)$ of the Peterson type with $\varepsilon = 0.05$. Both models agree quite well with the data, indicating that multiple gluon radiation due to leading log QCD plus a simple cluster decay model may well describe the phenomenological fragmentation functions needed to explain data in the framework of perturbative QCD models. At $\sqrt{s} = 10$ GeV, however, the dominant process that determines the final D^*-spectrum of the QCD shower-model is the cluster formation and decay. A good agreement with the data can also be achieved at c.m. energies of 29 and 34 GeV, where both the contributions of QCD gluon radiation and of the cluster decay algorithm are approximately equal in size.

IV. Summary

Calculations have been presented in order to extract $\langle z_c \rangle$, the mean of the charm fragmentation function, from direct measurements of the D^* energy- and momentum- spectra in e^+e^- annihilation. The result is

$$\langle z_c \rangle = 0.71 \pm 0.014 \pm 0.03$$

for a cutoff between fragmentation and perturbative QCD at $y_{\min} = 0.015$. This result is constant in the c.m. energy range of 10 GeV to 34 GeV. It is compatible with kinematic considerations of hard fragmentation functions for heavy quarks, in particular with the interpretation of the parameter ε in the function of Peterson et al. as the squared ratio of the constituent quark masses. Following these considerations, F-mesons and charmed baryons are expected to fragment $\sim 10\%$ softer, which seems to be compatible with recent F-measurements. For primary B-mesons, $\langle z_b \rangle$ is expected to be ~ 0.85. Results on charm and bottom fragmentation from inclusive lepton spectra in e^+e^- annihilation and from $\nu - N$-scattering cannot be directly compared and combined due to the presentation of different observables, but are in general agreement with the presented results from D^*-mesons. QCD-shower models reproduce the experimental data on charm fragmentation and offer an alternative description of phenomenological fragmentation functions by multiple gluon radiation and a simple model for charmed cluster decay.

Acknowlegements. I wish to thank my colleagues from the JADE-collaboration for many discussions and suggestions, in particular J. v. Krogh, E. Elsen, R. Marshall and J. Heintze. Special thanks also to T. Sjöstrand and B.R. Webber for numerous fruitful discussions on the model calculations.

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