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Determination of the Charm Fragmentation Function in Deep-Inelastic Scattering at HERA

H1 Collaboration

Abstract

The charm fragmentation function has been measured with D^*-production close to the kinematic threshold in deep-inelastic scattering using the H1 detector at HERA. Two different methods have been used for the definition of the observable fraction z of the energy of the D^*-meson with respect to the charm quark. The energy of the charm quark is approximated in one method by the energy of the jet including the D^*-meson and in the other method by the energy of a suitably defined hemisphere of the D^*-meson. Results of fits of Peterson and Kartvelishvili fragmentation functions, included in a model with leading order matrix elements and matched parton showers, string fragmentation and particle decays, as implemented in the Monte Carlo programs RAPGAP and PYTHIA, are presented and compared to results from e^+e^- annihilation. The two methods give the following ranges for the fragmentation parameters: $0.014 < \epsilon < 0.036$ (Peterson) and $4 < \alpha < 6.8$ (Kartvelishvili).

1 Introduction

The production of charm quarks is expected to be well described by perturbative QCD (pQCD) calculations due to the hard scale provided by the heavy charm mass. The hadronization of a charm quark into a jet of particles consisting of a charmed meson and other mesons is however not calculable in pQCD. The transition of a charm quark into a charmed meson is usually described by a phenomenological and non-perturbative fragmentation function, which is expected to be universal. In this paper we investigate the transition of a charm quark into a $D^{*\pm}$ meson.

In deep-inelastic scattering (DIS) the dominant process for $D^{*\pm}$ production has been shown to be the production of a $c\bar{c}$-pair in photon-gluon fusion [1]. In DIS it can be calculated by the convolution of three terms, the gluon density in the proton, the photon-gluon fusion matrix element and higher order QCD corrections to it, and the fragmentation function of charm into a $D^{*\pm}$ meson.

One considerable source of uncertainty in comparing pQCD calculations in next-to-leading order (NLO) with data is due to the choice of fragmentation function and their parameters. Many different functions have been proposed. Widely used parametrizations are the one by Peterson et al. [2]:

$$D_{\mathrm{Q}}^{\mathrm{H}} = \frac{N}{\mathrm{z}[1-(1/\mathrm{z})-\epsilon(1-\mathrm{z})]^2} \tag{1}$$

and the one by Kartvelishvili et al. [3]:

$$D_{\mathrm{Q}}^{\mathrm{H}} = N\mathrm{z}^{\alpha}(1-\mathrm{z}) \tag{2}$$

The free parameters ϵ_Q and α determine the "hardness" of the respective fragmentation function. In these parametrizations z describes the fraction of the charm quark's energy carried by the corresponding heavy meson. Exact definition depends on the implementation [1].

Parameters of non-perturbative fragmentation functions have been fit to data, mainly from e^+e^- annihilation experiments [4–8]. A preliminary measurement of the charm fragmentation function in photoproduction of $D^{*\pm}$-mesons at HERA has been presented by ZEUS [9].

In this analysis the production of charm is tagged by reconstructing a $D^{*\pm}$ meson, close to the kinematic threshold, from the decay into $K^{\mp}\pi^{\pm}\pi_s^{\pm}$, with the $K^{\mp}\pi^{\pm}$ originating from the decay of the D^0 meson. The definition of the variable z describing the fragmentation of a charm quark into a $D^{*\pm}$ meson in DIS is more ambiguous than for example in e^+e^- annihilation, where typically it is defined as $\mathrm{z} = E(D^*)/(\sqrt{s}/2)$. In this analysis we investigate two different definitions, the hemisphere method with $\mathrm{z} = (E+p_{\mathrm{L}})_{D^*}/\sum_{\mathrm{hem}}(E+p)$, in close analogy to the measurements in e^+e^- experiments, and the jet method with $\mathrm{z} = (E+p_{\mathrm{L}})_{D^*}/(E+p)_{\mathrm{D^*jet}}$. Both are defined in the γ^*p-frame. They are described in detail below.

[1] In different models and analyses, several different assumptions can be found. The charm quark may be considered to be fragmenting independently or it may be part of a color string. The fragmentation variable z may be defined in various frames, and the mass of the charm quark may be neglected in the definition or not.

2 Experimental method and definition of observables

There are many observables sensitive to the non-perturbative fragmentation function, both in e^+e^- and ep collisions. In the case of e^+e^-, the natural choice is to measure the dependence of D^* meson production cross section as a function of the variable z, defined as $\mathrm{z} = E(D^*)/(\sqrt{s}/2)$. This definition has the clear advantage that $d\sigma/d\mathrm{z}$ is proportional to the non-perturbative fragmentation function in case of no gluon radiation,

In the case of ep interactions the situation is more complicated. In this analysis we therefore study the dependence of the D^* cross section on two variables, both of them defined in such way that, under the assumptions of no gluon radiation and of independent fragmentation, $d\sigma/d\mathrm{z}$ is directly proportional to the non-perturbative fragmentation function.

2.1 The hemisphere method: $\mathrm{z}_{\mathrm{hem}}$

An illustration of the hemisphere method can be seen in Fig. 1.

If one looks at charm production via boson-gluon fusion in the $\gamma^* p$ frame, almost all charm and anticharm quarks move in the direction of the incoming photon. This is caused by the fact that while the photon enters with its full energy into the hard subprocess, the proton interacts via its gluons, which typically carry only a small fraction of the proton's momentum. Assuming no gluon radiation, the charm and anticharm quarks are balanced in transverse momentum.

This fact allows to divide the event into two hemispheres, one containing the fragmentation products of the charm quark, the other of the anti-charm quark. To do that, first the projections of momenta of particles on a plane perpendicular to the $\gamma^* p$ axis are calculated. Then the two-dimensional thrust axis is found. With a line perpendicular to the thrust axis the projected event is divided into two hemispheres, one of them containing the D^* and usually other particles. For them we can define:

$$\mathrm{z}_{\mathrm{hem}} = \frac{(E + p_{\mathrm{L}})_{D^*}}{\sum_{\mathrm{hem}}(E + p)} \ , \tag{3}$$

where in the denominator the energies and three-momenta of all particles with momentum projections in the D^* hemisphere are summed. To suppress contributions from the proton remnant and initial state radiation, particles pointing in the proton direction are discarded.

2.2 The jet method: $\mathrm{z}_{\mathrm{jet}}$

In this method the energy and direction of the charm quark is approximated by reconstructing the jet which contains the D^* meson. One then arrives at the following definition:

$$\mathrm{z}_{\mathrm{jet}} = \frac{(E + p_{\mathrm{L}})_{D^*}}{(E + p)_{\mathrm{jet}}} \tag{4}$$

The jets are found in the $\gamma^* p$-frame using the inclusive $k_\perp$ cluster algorithm [10], taking the mass of the D^*-meson into account. The D^*-jet is required to have $p_{\mathrm{t,jet}} > 3$ GeV. This rather low jet transverse momentum requirement is due to the fact that most of the $c\bar{c}$-pairs are produced near the kinematic threshold.

The two methods tend to differ in case of additional gluon radiation. The hemisphere method sums up contributions from gluons with both low and high p_{T} with respect to the charm quark direction, in analogy with the method used in e^+e^-. The comparison of both methods provides test of our understanding of parton radiation.

3 Data Selection and Analysis

The analysis is carried out with data taken in 2000, when HERA collided positrons of energy 27.6 GeV with protons at 920 GeV. The integrated luminosity is 39 pb^{-1}. The scattered positron is measured in the backward SpaCal calorimeter and is required to have an energy above 8 GeV. The virtuality of the photon, reconstructed from the measured energy and polar angle of the positron, is required to lie in the range $2 < Q^2 < 100$ GeV^2. To ensure hadronic activity in the central region of the detector, the inelasticity of the event, calculated from the scattered positron kinematics, is required to lie in the region $0.05 < y < 0.7$. The z-coordinate of the event vertex, reconstructed from central tracks, has to lie within 35 cm of the mean position for ep collisions. The difference between the total energy E and the longitudinal component of the total momentum p_z, as calculated from the scattered positron and the hadronic final state is restricted to $E - p_z > 35$ GeV. This requirement suppresses photoproduction background, where a hadron is misidentified as a scattered positron.

As already mentioned, the decay channel $D^* \to D^0\pi_s \to K\pi\pi_s$ is used to reconstruct the D^*-meson. The selection criteria for the charged particles, the transverse momentum cuts on the decay products, and the particle identification using dE/dx, are very similar to those used in previous H1 analyses [1] and are given in Table 1. In order to obtain good experimental

D^0	$p_\mathrm{t}(K,\pi) > 0.25$ GeV
	$p_\mathrm{t}(K) + p_\mathrm{t}(\pi) > 2$ GeV
	$\lvert M(K,\pi) - M(D^0)\rvert < 0.07$ GeV
D^*	$p_\mathrm{t}(\pi_s) > 0.12$ GeV
	$\lvert\eta(D^*)\rvert < 1.5$
	$p_\mathrm{t}(D^*) > 1.5$ GeV

Table 1: Kinematic requirements to select D^* candidates.

resolution and background rejection in the reconstruction of a D^* meson candidate, the well known mass difference [11], i.e. $\Delta M_{D^*} = m(K\pi\pi_s) - m(K\pi)$, is used. It is shown in Fig. 2 (left side) together with the "wrong charge D" background (right side), which results from $K^\pm\pi^\pm$ combinations in the accepted D^0 mass range. The wrong charge distribution provides a good description of the right-charge D^0 combinatorial background away from the D^* peak.

The signal is extracted using a simultaneous fit to right and wrong charge distributions. The signal is fitted by a Gaussian distribution and a background given by a power function of the form $N/(\alpha+1)(x-m_0)^{\alpha}/(M-m_0)^{\alpha+1}$. The fit boundaries are given by m_0 and M and the two free parameters N and α determine the shape and normalization of the background. First, the total event sample is fitted, using six free parameters (three for the Gaussian, two for the right and wrong charge normalization and one for the background shape, common for right and wrong charge background). The number of $D^{*\pm}$ thus obtained is 2390 ± 77 in the total sample. For differential distributions, the signal and background are fitted for each bin, in this case using a five parameter fit (the position of the signal peak is fixed from the fit to the full statistics). This procedure has been used for all physics results.

The corresponding distributions of the kinematic variables of the DIS phase space, the positron's scattering angle and energy, $\theta_{\rm e}$ and $E_{\rm e}$, the photon's virtuality, $Q^2_{\rm e}$, the Bjorken scaling variable, $x_{\rm e}$, and the $\gamma^* p$ center-of-mass energy, $W_{\rm e}$ are calculated from the 4-vectors of the incoming and scattered positron and the incoming proton. The distributions of $Q^2_{\rm e}$ and $x_{\rm e}$ are shown in Fig. 3. The background subtracted distributions are compared to the QCD-based model predictions for D^* production in DIS, using the Monte Carlo (MC) RAPGAP 3.1 [12] interfaced with PYTHIA 6.2 [13] to generate direct and resolved photon initiated events, which are then passed through the full detector simulation and reconstruction package of H1.

Besides identifying the scattered positron and reconstructing the D^*, of which the three decay tracks are then removed from the event record and replaced by D^*, the rest of the hadronic energy, made up of charged particle tracks and calorimetric energy clusters, is reconstructed by appropriately combining track and cluster information, based on their respective resolutions and geometric overlap, to obtain so called hadronic objects.

The data were corrected to hadron level using the bin-by-bin method. To determine correction coefficients the RAPGAP 3.1 MC and the full detector simulation and reconstruction package of H1 were used. Radiative corrections were calculated using HERACLES 4.63 [14] which is interfaced with RAPGAP. To achieve a good description of the data, the MC was reweighted in the z-position of the event vertex. It was further improved by reweighting the transverse momentum and pseudorapidity of the charm quark fragmenting into a D^*-meson. The uncorrected distributions of z are shown in Fig. 4. The data are reasonably well described by the QCD model and detector simulation. The z-distributions, corrected for detector effects and QED radiation are shown in Fig. 5.

The following sources of systematic errors were taken into account:

- the energy of all clusters was scaled up and down by $\pm 4\%$ in the liquid argon calorimeter and $\pm 7\%$ in the SpaCal.
- the nominal resolved photon component of 33 % as predicted by the model was changed to 10 and 50 %.
- the cuts on dE/dx were switched-off.
- different reweighting procedures were applied to MC.
- different procedures for signal extraction were tried.

- the nominal contribution for beauty production was taken according to the prediction of the RAPGAP MC; to estimate the syst. error it was increased by a factor of 2.
- the energy of the scattered positron was varied by ± 3 % for an energy of 8 GeV and by 1% for 27 GeV. For intermediate energies the size of the variation was linearly dependent on energy.
- the polar angle of the scattered positron was varied by more than its uncertainty.

All systematic errors were added to the statistical errors in quadrature. Most of the systematic errors are uncorrelated, with the exception of the effect of the hadronic energy scale for both methods and of the effect of the resolved component in the hemisphere method. In the extraction of the fragmentation parameters, using the QCD model based on RAPGAP and PYTHIA, this has been taken into account.

The influence of various systematic errors on the z distributions is summarized in the Table 2.

sys. source	z(hem) error	z(jet) error
E_e	0.8%	0.7%
Θ_e	0.3%	0.5%
E_{HFSclus}	$\sim$ 5%	$\sim$ 4%
Res. frac	$\sim$ 5%	$\sim$ 2%
Bckgr. subtr.	3.1%	1.7%
dE/dx cut	3.2%	4.3%
beauty	$\sim$ 3%	1.3%

Table 2: The influence of various systematic errors on the z distributions.

4 Results

The normalized D^*-meson cross section $\frac{1}{\sigma}\frac{d\sigma}{dz}$, corrected for detector and QED radiative effects, is shown in Fig. 5 for the hemisphere and the jet method.[2] Both, statistical and systematic errors are shown, the statistical errors being dominant.

The normalized cross sections are used to extract the parameters of the Peterson and Kartvelishvili non-perturbative fragmentation functions, using the RAPGAP 3.1 and PYTHIA 6.2 MC. For steering the production of excited heavy states[3] and other hadronization parameters a set tuned [15] by ALEPH to their data has been used. For fragmentation the Lund string model as implemented in PYTHIA was used with the respective fragmentation functions. The fraction of

[2]Note that σ refers to the visible cross section including lower cut in z given by the boundary of the respective figure.

[3]Older determinations fo fragmentation parameters typically do not take into account higher excited charm mesons. Since abour 30% of the D^*-mesons in the kinematic range of this analysis come from excited states, their inclusion has a significant effect. It reduces the value for ϵ and increases the one for α.

resolved photon interactions contributing to D^* production in our range of Q^2 was taken to be 33 % as predicted by RAPGAP/PYTHIA.

The normalized cross section as a function of $\mathrm{z_{hem}}$ and $\mathrm{z_{jet}}$ on hadron level was generated for various values of the respective fragmentation parameter and the resulting χ^2 between data and model prediction as a function of the fragmentation parameter was calculated. To calculate the χ^2 the full correlation matrix was used, taking statistical and uncorrelated systematic errors as well as correlations into account. The shape of the χ^2 distribution (with $\chi^2_{\min} + 1$) was used to determine the $\pm\, 1\sigma$ error of the extracted parameter.

The normalized cross sections together with the model predictions and the dependence of χ^2 on the fragmentation function parameter are shown in Fig. 6 for the Peterson and in Fig. 7 for the Kartvelishvili parametrization. The extracted parameters [4] are summarized in Table 3.

Parametrization		Hemisphere Method	Jet Method	Range
Peterson	ε	$0.018^{+0.004}_{-0.004}$	$0.030^{+0.006}_{-0.005}$	$0.014 < \epsilon < 0.036$
Kartvelishvili	α	$5.9^{+0.9}_{-0.6}$	$4.5^{+0.5}_{-0.5}$	$4 < \alpha < 6.8$

Table 3: The extracted fragmentation parameters for Peterson and Kartvelishvili parametrizations.

If the QCD based Monte Carlo model provides a correct description of all aspects of D^*-production, then the jet and hemisphere methods should both lead to the same extracted fragmentation parameter. The discrepancy ($< 3\sigma$) between the parameters may signal inadequacies in one or more aspects of the model. Therefore at this stage we suggest the following ranges for the fragmentation parameters:$0.014 < \epsilon < 0.036$ (Peterson) and $4 < \alpha < 6.8$ (Kartvelishvili).

The measured $\mathrm{z_{hem}}$ distribution is compared to OPAL [6] and CLEO [4] data on Fig. 8. The results of this analysis are in rough agreement with the recent data from CLEO at a similar center-of-mass energy of the $c\bar{c}$-system.

5 Conclusion

The fragmentation function of charm quarks into $D^{*\pm}$-mesons has been measured in ep collisions using two different experimental methods. The resuls are compared with the prediction of the QCD based Monte Carlo model RAPGAP/PYTHIA, which include leading order massive matrix elements for charm production matched to parton showers in the leading-log approximation, the Lund string hadronization model and the widely used non-perturbative fragmentation functions by Peterson et al. and Kartvelishvili et al., respectively. The respective parameters have been extracted from the data with either the energy of the D^*-hemisphere or of the D^*-jet to approximate the energy of the charm quark fragmenting into a $D^{*\pm}$-meson. The two methods

[4]The different reweighting procedures (see sect. 3) lead to an additional systematic error contributions only in the case of down-error (up-error) for Peterson (Kartvelishvili) for the Hemisphere Method.

give the following ranges for the fragmentation parameters: $0.014 < \epsilon < 0.036$ (Peterson) and $4 < \alpha < 6.8$ (Kartvelishvili). The data are compared to recent measurements in e^+e^- annihilation. They are in rough agreement with the recent data from CLEO at a similar center-of-mass energy of the $c\bar{c}$ pair.

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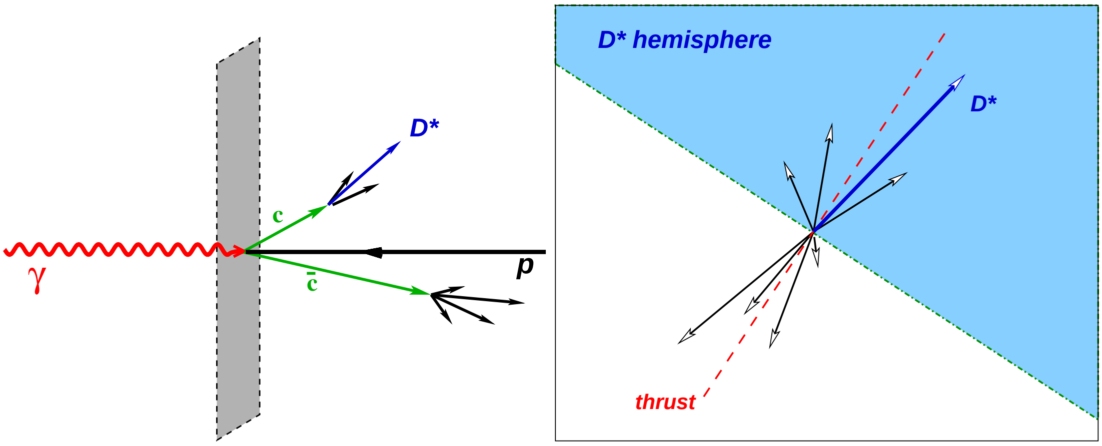

Figure 1: Illustration of the hemisphere method: a) a $c\bar{c}$ pair in the $\gamma^* p$ frame and b) in a plane perpendicular to photon momentum.

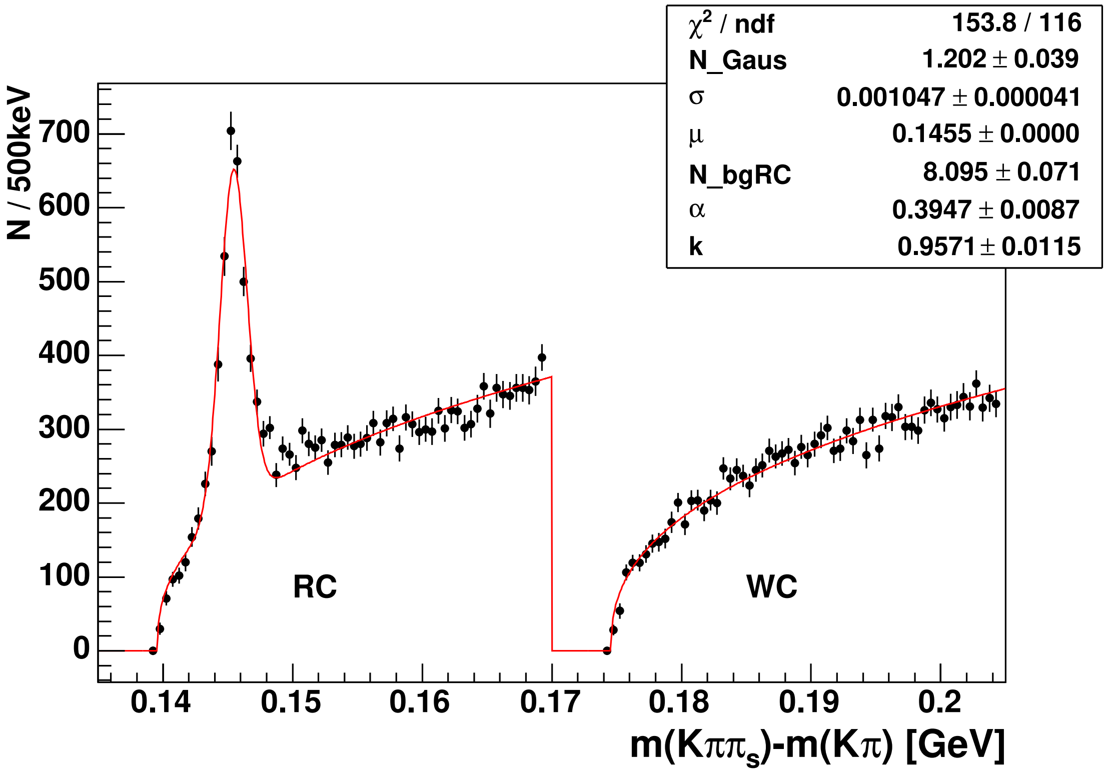

Figure 2: Distributions of $\Delta M_{D^*} = m(K\pi\pi_s) - m(K\pi)$ for right charge (RC) and for wrong charge (WC) D^0 combinations. In order to fit both distributions in the same plot, the latter has been shifted by 0.035 GeV horizontally.

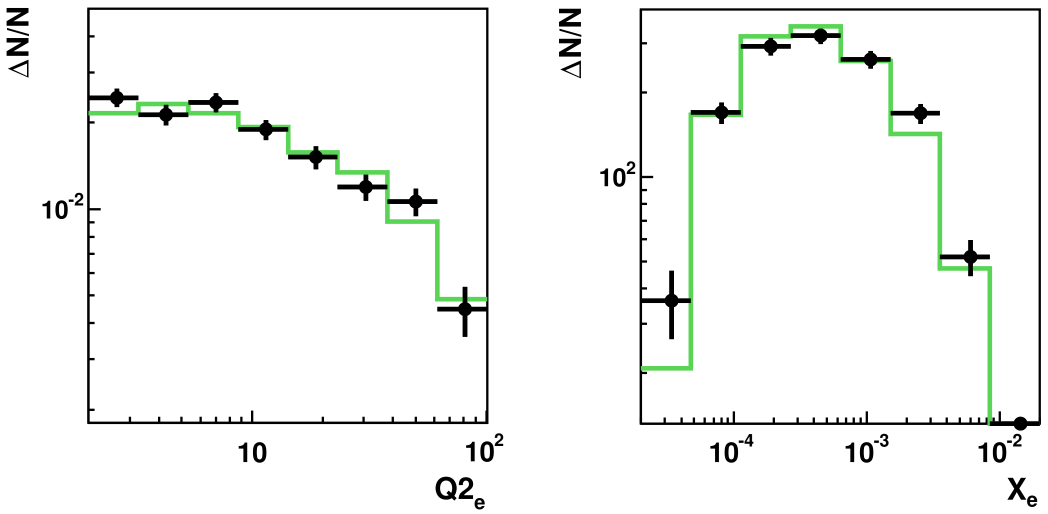

Figure 3: Distributions of Q_e^2 and the Bjorken scaling variable x_e for events with a $D^{*\pm}$-meson.

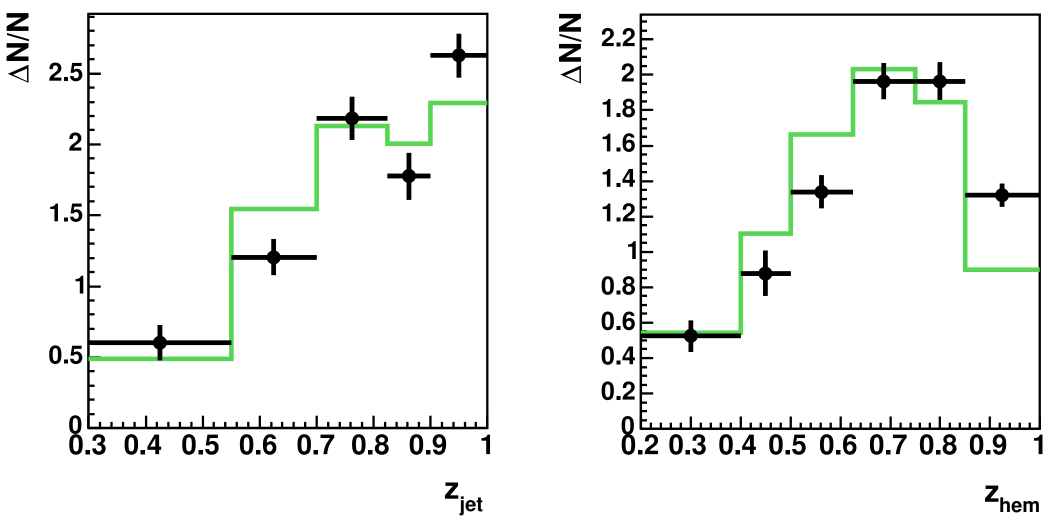

Figure 4: Measured D^*-meson z-distributions for the jet method (left) and the hemisphere method (right) on reconstructed level, compared to the prediction of RAPGAP.

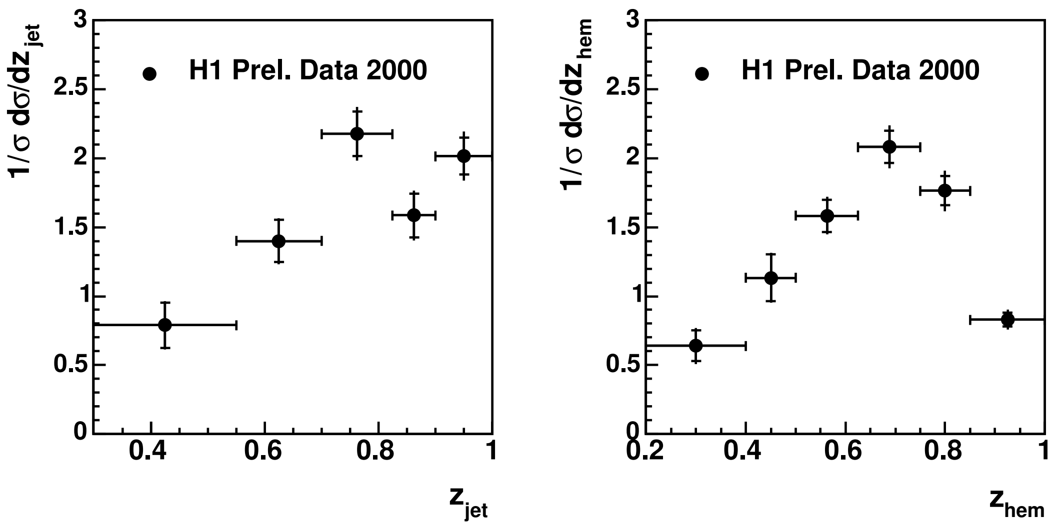

Figure 5: Measured D^* meson z-distributions for the jet method (left) and the hemisphere method(right) corrected for detector effects.

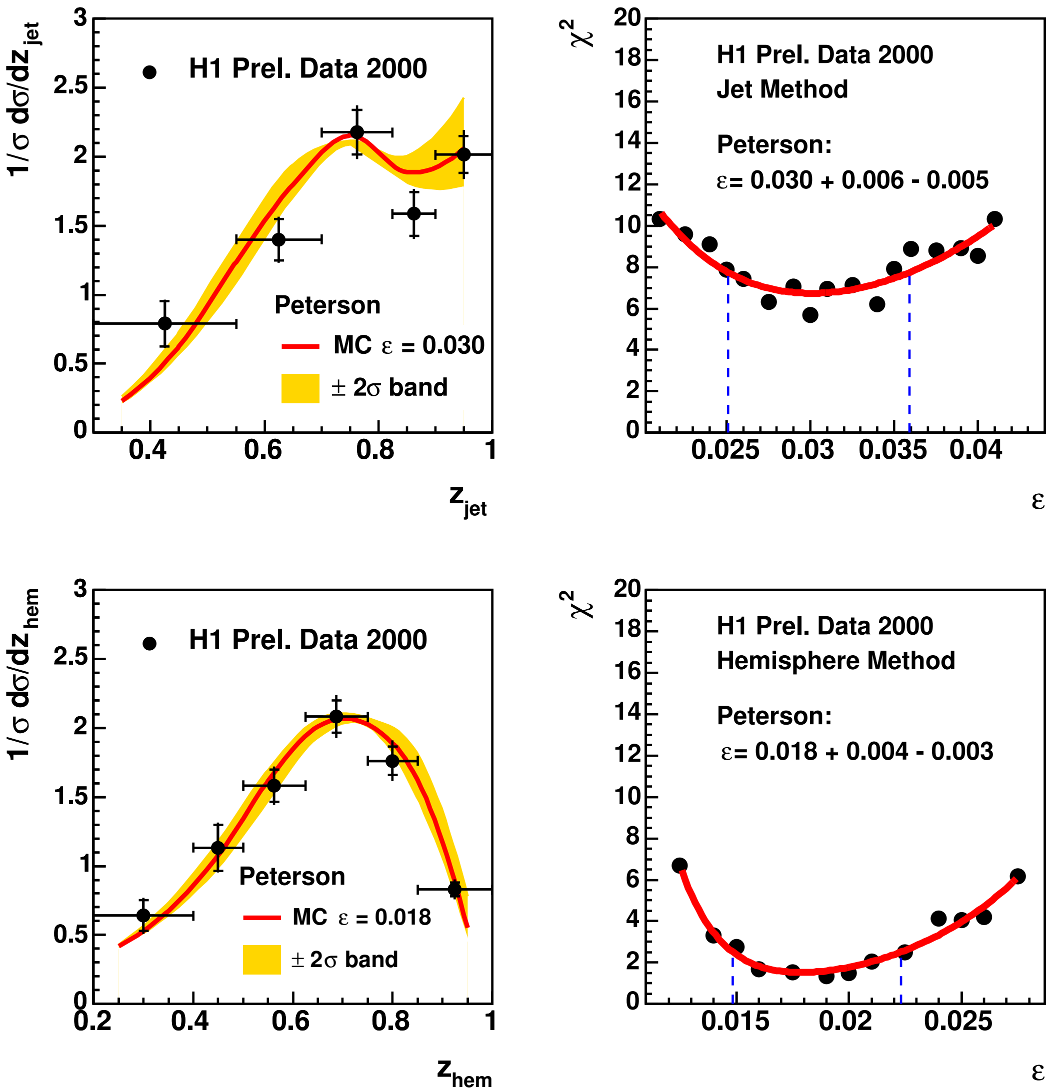

Figure 6: Measured D^* z-distributions for jet method (upper) and hemisphere method (lower) compared with the RAPGAP model prediction using the Peterson parametrization for the non-perturbative fragmentation function.

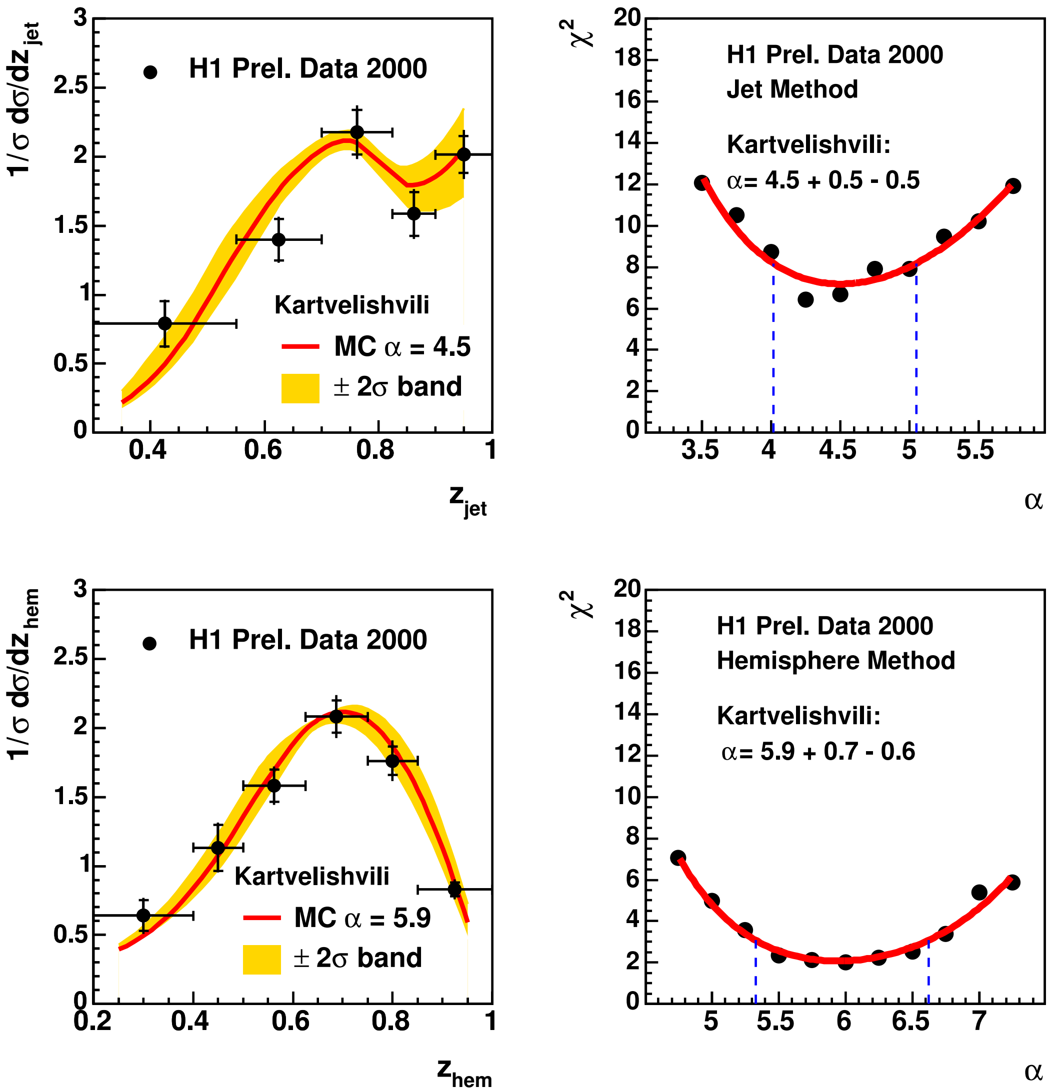

Figure 7: Measured D^* fragmentation function for jet method (upper) and hemisphere method (lower) compared with RAPGAP model prediction using the Kartvelishvili parametrization for non-perturbative fragmentation function.

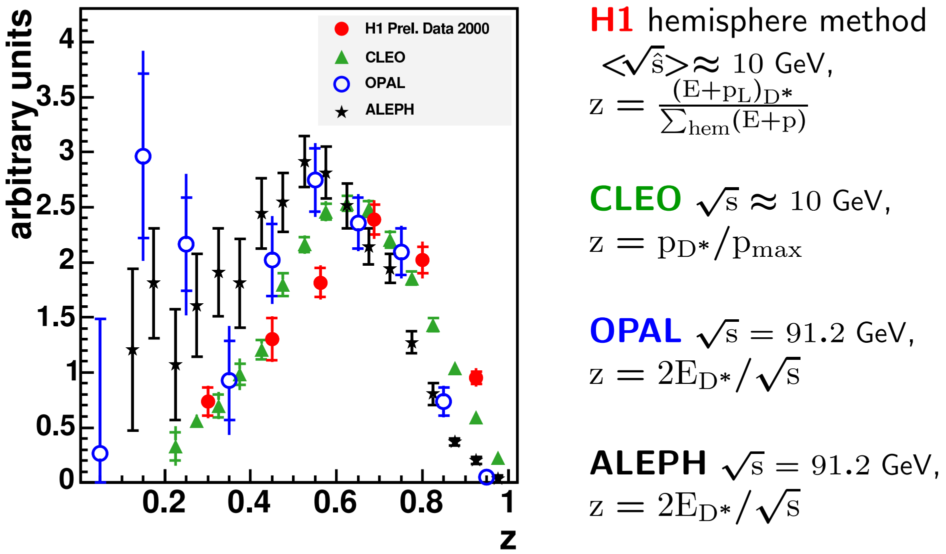

Figure 8: Comparison of the z-distributions from CLEO, OPAL and ALEPH with the one from the hemisphere method from H1.All distributions are normalized to unit area from $z = 0.4$ to $z = 1$.