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Study of Charm Production in Z Decays

The ALEPH collaboration

Abstract

In the whole LEP I data sample (4 millions of Z decays) recorded by the ALEPH detector, charmed hadrons have been reconstructed and are used to measure the production rates of $\mathrm{D}^{*\pm}$, $\mathrm{D}_{\mathrm{s}}^{*\pm}$, $\mathrm{D}^{\pm}$, D^{0}, $\mathrm{D}_{\mathrm{s}}^{\pm}$, and Λ_{c} in $\mathrm{Z} \rightarrow \mathrm{c\bar{c}}$ decays. The fractional energy spectrum of $\mathrm{D}^{*\pm}$ is measured and interpreted as a sum of three contributions : charm hadronization, b hadron decays and gluon splitting into a pair of heavy quarks. Summing all the production rates allows a determination of the fractional decay width R_c of the Z into $\mathrm{c\bar{c}}$ pairs to be carried out.

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1 Introduction

The purpose of this paper is to study the production of charmed hadrons : measure the production rates of $D^{*\pm}$, $D_s^{*\pm}$, D^0, $D^\pm$, $D_s^\pm$ mesons and Λ_c baryons, and the $D^{*\pm}$ production spectrum. These measurements are intended to shed light on the production mechanism. The analysis presented here is an extension to the whole LEP I statistics of those presented in previous publications [1, 2]. Several improvements have been made possible by this seven-fold increase in statistics and the use of the vertex detector. A better rejection of the combinatorial background allows the $D^{*\pm}$ mesons to be reconstructed down to $X_E \equiv E/E_{beam} = 0.1$, thus reducing substantially the extrapolation uncertainty and yielding sensitivity to the gluon splitting contribution. The separation between $b\bar{b}$ and $c\bar{c}$ events has been improved by means of an algorithm based on the measurement of the impact parameter of charged tracks and the effective mass of those least fitted to the primary vertex [3].

The Λ_c and $D_s^\pm$ reconstruction down to X_E=0.2 is carried out with enough statistics to measure their X_E spectrum. A signal of $D_s^{*\pm}$ is observed, from which the production rate is measured. By adding the contributions from all fundamental states containing c quarks, a measurement of $R_c = \Gamma(Z \to c\bar{c})/\Gamma(Z \to hadrons)$ is obtained.

This study is of physical interest for studying the fragmentation process through the $D^{*\pm}$ spectrum measurement. It is also of practical relevance for many analyses where charm quarks are involved.

The data used here were recorded between 1991 and 1995 at or near the Z peak. The tracking and calorimetry were required to be in good functionning conditions. Hadronic Z decays are selected with an efficiency of $97.4 \pm 0.3\%$ and a $0.7 \pm 0.1\%$ contamination from $\tau^+\tau^-$ pair production and photon-photon interactions, as detailed in ref. [4].

2 The ALEPH detector

A detailed description of the ALEPH detector and its performances can be found in Refs. [5, 6] and [7]. Only a brief review is given here.

Charged particles are detected in the central part, consisting of a two-layer silicon vertex detector with double-sided (r-ϕ and z) readout, a cylindrical drift chamber and a large time projection chamber (TPC), which together measure up to 33 coordinates along the charged particle trajectories. Tracking is performed in a 1.5 T magnetic field provided by a superconducting solenoid. The combined system yields a $1/p_t$ resolution of $6 \times 10^{-4} (\mathrm{GeV}/c)^{-1}$ and the impact parameter resolution is 25 μm in both the r-ϕ and z views for high momentum tracks. The TPC also provides up to 338 measurements of ionization (dE/dx) allowing particle identification to be performed. For this purpose, for tracks having at least 50 energy deposition measurements, and for the three particle types x (x= p,K or π), the variable χ_x is defined as $(I_{meas} - I_x)/\sigma_x$, where I_{meas} is the measured value of dE/dx, I_x is the expected value for particle type x and σ_x is the expected uncertainty. An important role of the tracking device, especially its vertex detector component, is to help in the b tagging. To this end, a lifetime-mass algorithm has been designed to provide a variable discriminating between b quarks and lighter quarks. This algorithm is described in ref. [3].

The electromagnetic calorimeter is a lead/wire-chamber sandwich operated in proportional mode. It is read out in projective towers of typically 15×15 mrad^2 size segmented in three longitudinal sections. The hadron calorimeter is an iron/streamer-tube sandwich, read out in projective towers.

3 Reconstruction of Charmed Hadron Decays

D^0 mesons are selected through their decay mode $D^0 \to K^-\pi^+$. A track with a momentum greater than 2.5 GeV/c, assigned the kaon mass, is combined to a track of opposite sign with a momentum greater than 1.5 GeV/c and assumed to be a pion. The contribution due to wrong mass assignment of the two tracks from the D^0 is reduced using, when available, dE/dx measurement: the dE/dx of the kaon track has to be closer to the expectation for a kaon than that for a pion, i.e., with notation of section 2, $|\chi_K| < |\chi_\pi|$ is required. The pair formed by the two tracks is retained if its fractional energy $X_E = E/E_{beam}$ is greater than 0.5 and if a common vertex with a χ^2 probability greater than 1% is found. The projected decay length significance is calculated as $(\delta_\ell.\frac{\mathbf{p}}{|\mathbf{p}|})/\sigma$, where δ_ℓ is the difference between the positions of the D^0 vertex and the main vertex, and $\mathbf{p}$ is the momentum of the D^0 candidate. Candidates with a D^0 projected decay length significance greater than 1 are kept in the final sample. The invariant mass distribution is shown in Fig 1.

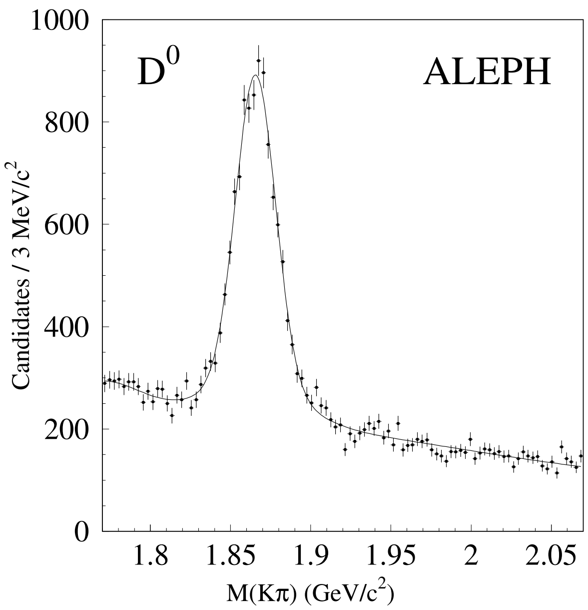

Figure 1: D^0 invariant mass distribution, with the fit result.

The $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$ decay mode is reconstructed as follows : triplets of charged tracks with total charge ± 1 are considered. The pion mass is assigned to the two particles with the same sign, and the kaon mass to the remaining one. The total energy of the triplet is required to be greater than $0.1 \times E_{beam}$. A combination is kept if one of the $K^\pm\pi^\mp$ combinations is within 30 MeV from the D^0 mass. For such a combination, the mass difference $M(K\pi\pi) - M(K\pi)$ is calculated and required to be within 1.6 MeV from the $D^{*\pm} - D^0$ mass difference. The combinatorial background level is a steeply falling function of X_E. Thus background rejection has to be enhanced as one goes to lower X_E. To this end, the scalar nature of the D^0 and its finite lifetime are used as follows. The D^0 being a scalar, the distribution the cosine of its decay angle, $\cos\theta^*$, is uniform, whereas the background peaks at $\pm 1.$ in this variable. For $X_E < 0.45$, it is required that $-0.8 < \cos\theta^* < 0.9$. The decay length significance is required to be positive for $0.3 < X_E < 0.4$ and greater than 1 for X_E less than 0.3. In addition, the probability of the χ^2 for the vertex fit is required to be greater than 1% for $X_E < 0.15$. The efficiency of the decay length cut depends on the origin ($b\bar{b}$ or $c\bar{c}$) of the D^*, as the b hadron flight displaces further the D^0 vertex. An iterative procedure is used to calculate the fraction of b bin by bin in X_E, as described in next section, and to correct the efficiency accordingly. The mass-difference distribution in four X_E ranges is shown in Fig. 2.

The X_E range between 0.1 and 1.0 is divided into 18 bins 0.05 wide. The background is subtracted bin by bin in X_E : for each bin the mass difference distribution is formed and an analytical form is fitted outside the D^* peak. The efficiency-corrected X_E distribution is shown in Fig. 3.

The D^+ meson is reconstructed in the decay mode $D^+ \rightarrow K^-\pi^+\pi^+$. Combinations of three tracks are formed, with the same mass assignment as for the D^{*+} reconstruction. To fight the high background inherent to this decay, the kaon track candidate is required to have a momentum greater than 2.5 GeV/c and an associated dE/dx satisfying $\chi_K + \chi_\pi < 1$. One of the two pion tracks must have a momentum greater than 1.5 GeV/c, while the second is required to be greater than 0.75 GeV/c. The invariant masses of the two possible combinations of the kaon candidate with one of the pion candidates are calculated: $M(K\pi_1)$ and $M(K\pi_2)$. D^+ candidates consistent with the decay $D^{*+} \rightarrow \pi_s^+ D^0 \rightarrow \pi_s^+ K^-\pi^+ X$ are removed by a cut $\Delta M \equiv M_{K\pi\pi} - \mathrm{Max}[M(K\pi_1)\ ,\ M(K\pi_2)] > 0.15 GeV/c^2$. Triplet of tracks with a total energy greater than $0.5 \times E_{beam}$ and forming a common vertex with a χ^2- probability greater than 1% are retained. The reconstructed vertices of the D^+ candidates are required to have a projected decay length significance greater than 1.5. The invariant mass distribution is shown in Fig 4.

The $D_s^\pm$ is reconstructed in the decay chain $D_s^\pm \rightarrow \phi\pi^\pm$ with a subsequent decay $\phi \rightarrow K^+K^-$. The kaon momenta have to exceed 1.5 GeV/c and the pion one 2.5 GeV/c. A dE/dx cut $|\chi_x| < 2.5$ (with notations of section 2) is applied to all three particles to ensure compatibility with the hypothesis. The kaon candidates are required to have the dE/dx information available and fulfilling $\chi_K + \chi_\pi < 1.0$. If $|M_{KK} - M_\phi| < 5$ MeV/c^2 and $p_\phi > 4.0$ GeV the candidate is kept and the two kaons are fitted with the pion to a $D_s^\pm$ as the ϕ has almost no lifetime. Candidates with $\chi^2_{D_s^\pm fit} > 5$ are rejected. The cut on $|cos(\lambda^*)| > 0.4$, where λ^* is the angle between the kaon and the pion in the ϕ rest frame, is motivated by the P-wave nature of the ϕ decay and strongly suppresses the background. The mass distribution of the $D_s^\pm$ candidates is shown in Fig. 5.

The Λ_c is searched for in the decay mode $\Lambda_c \rightarrow pK^-\pi^+$. To form a Λ_c candidate three tracks are required with at least one vertex detector hit and momenta greater than 5.0 GeV/c for the proton, 3.0 GeV/c for the kaon and 1.0 GeV/c for the pion candidates, respectively, whith a total energy in excess of $0.2 \times E_{beam}$. The dE/dx

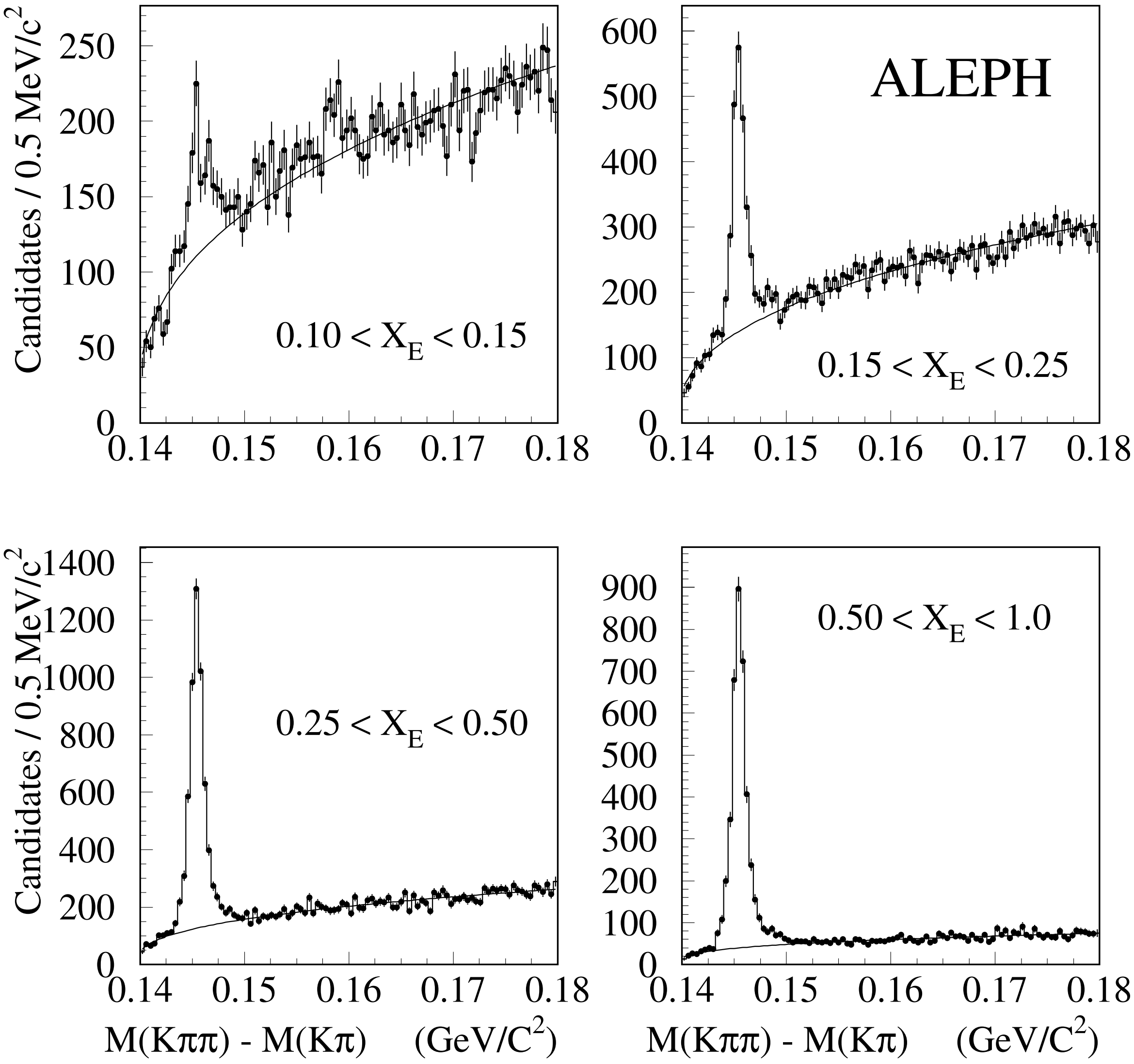

Figure 2: Distribution of the $D^0\pi$ - D^0 mass difference. The background fit is also shown.

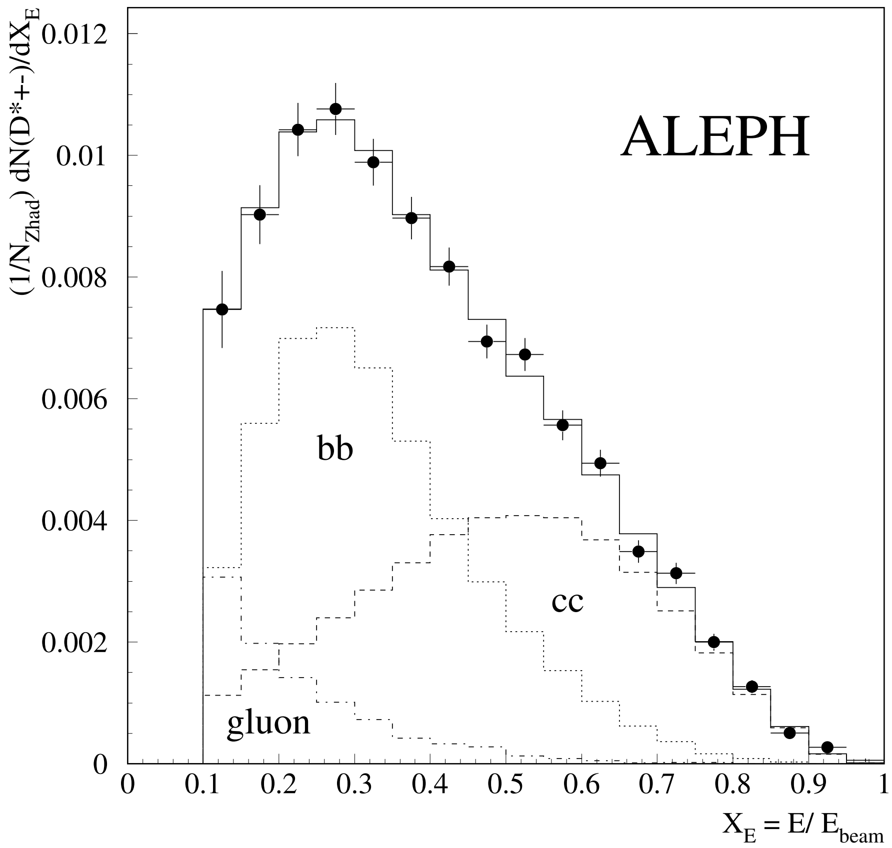

Figure 3: Distribution of X_E for the $D^{*\pm}$'s. The data (points with error bars) are compared to the fit described in the text. The three contributions: $b\bar{b}$ (dotted line), $c\bar{c}$ (dashed line) and gluon splitting to heavy quarks (dashed-dotted) are shown.

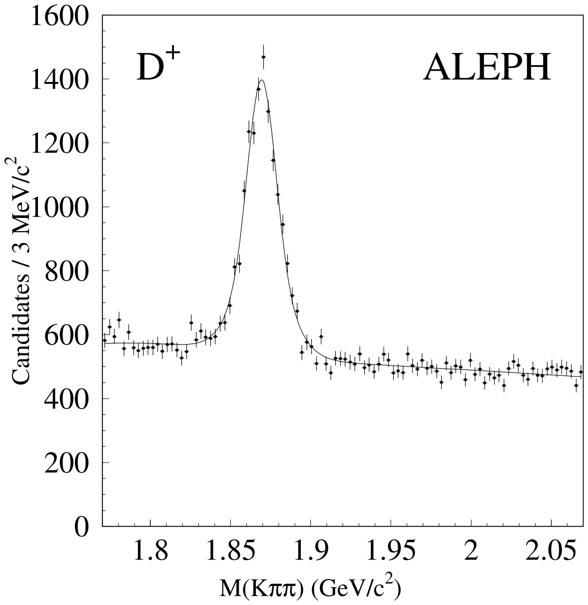

Figure 4: D^+ invariant mass distribution with the fit result.

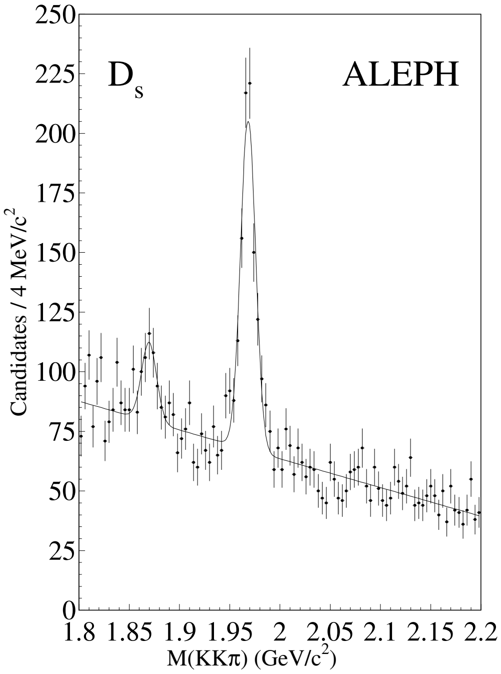

Figure 5: $M(\mathrm{KK}\pi)$ distribution.

is used for the particle identification : $|\chi_x| < 2.5$ is required for the given particle hypothesis. In addition two pion veto cuts are applied: $\chi_\pi < -2.0$ for the proton candidate and $\chi_\pi < -1.0$ for the kaon candidate.

After a χ^2 fit of the tracks to a common vertex the χ^2- probability has to be greater than 1%. The mass distribution of the Λ_c candidates is shown in Fig. 6.

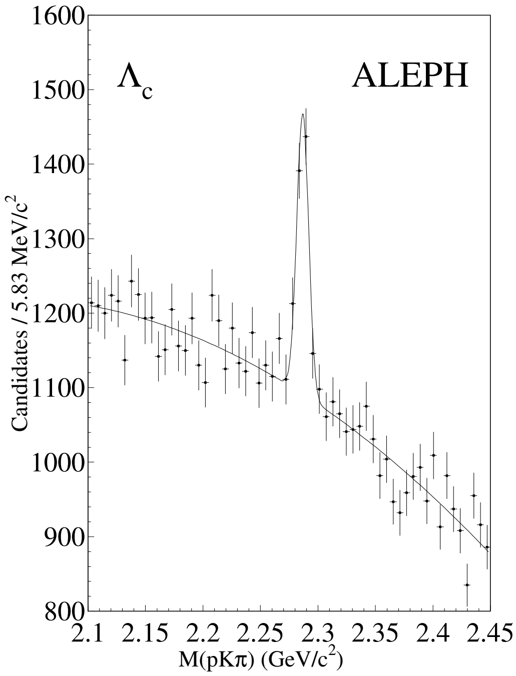

Figure 6: $M(p\mathrm{K}\pi)$ distribution.

The $\mathrm{D}_\mathrm{s}^{*\pm}$ meson is reconstructed in the decay channel $\mathrm{D}_\mathrm{s}^{*\pm} \to \mathrm{D}_\mathrm{s}^{\pm}\gamma$, followed by $\mathrm{D}_\mathrm{s}^{\pm} \to K^+K^-\pi^\pm$ through either the $\phi\pi^\pm$ or the $K^{*0}K^\pm$ decay mode.

In the $\mathrm{D}_\mathrm{s}^{\pm}$ reconstruction, tracks are taken as kaon candidates when the dE/dx measurement satisfies $|\chi_K| < |\chi_\pi|$, and as pion candidates when $|\chi_K| > |\chi_\pi|$. To select the $\mathrm{D}_\mathrm{s}^{\pm}$ mesons decaying in $\phi\pi$, pairs of opposite-sign kaon candidates and such as $|M_{KK} - M_\phi| < 8$ MeV$/c^2$, are required to form a vertex with a pion candidate having a probability greater than 1%; every track must have at least one hit in the vertex detector. A value of $|\cos(\lambda^*)|$ greater than 0.4 is also required. $\mathrm{D}_\mathrm{s}^{\pm}$ candidates decaying in K*K are selected when a kaon and a pion candidate with opposite charges fulfill $|M_{K\pi} - M_{K^*}| < 25$ MeV$/c^2$ and $|cos\lambda^*| > 0.6$.

Photons coming from the $\mathrm{D}_\mathrm{s}^{*\pm}$ decay detected in the electromagnetic calorimeter are selected when they have an energy greater than 0.6 GeV and do not form a π^0 candidate. Photon conversions in the detector are identified by searching for electron tracks that are geometrically consistent with the conversion hypothesis; to increase the efficiency on converted photons, also electron-positron pairs where one track is not detected are identified, as described in [8]; candidates with an energy of at least 0.3 GeV are taken into account.

To be able to measure separately the production rate of $\mathrm{D}_\mathrm{s}^{*\pm}$ mesons in $\mathrm{c\bar{c}}$ and $\mathrm{b\bar{b}}$ events, two different subsamples of $\mathrm{D}_\mathrm{s}^{*\pm}$ candidates are selected. One subsample is enriched in $\mathrm{b\bar{b}}$ events and consists of $\mathrm{D}_\mathrm{s}^{*\pm}$ candidates with a $\mathrm{D}_\mathrm{s}^{\pm}$ momentum 8 GeV $< P_{D_s} <$ 20 GeV, a kaon momentum $P_K > 1.5$ GeV$/c$, a pion momentum

$P_\pi > 1$ GeV$/c$, a fitted decay length $\delta\ell > 500$ μm, and a photon energy $E_\gamma < 3$ GeV. In the other subsample, enriched in c$\bar{\text{c}}$ events, the requirements are $P_{D_s} > 20$ GeV$/c$, $P_K > 2.5$ GeV$/c$, $P_\pi > 1.5$ GeV$/c$, $D_\ell > 0$, and $E_\gamma < 5$ GeV. In figure 7 the $M(D_s^*) - M(D_s)$ distributions with calorimetric photons and conversions are plotted.

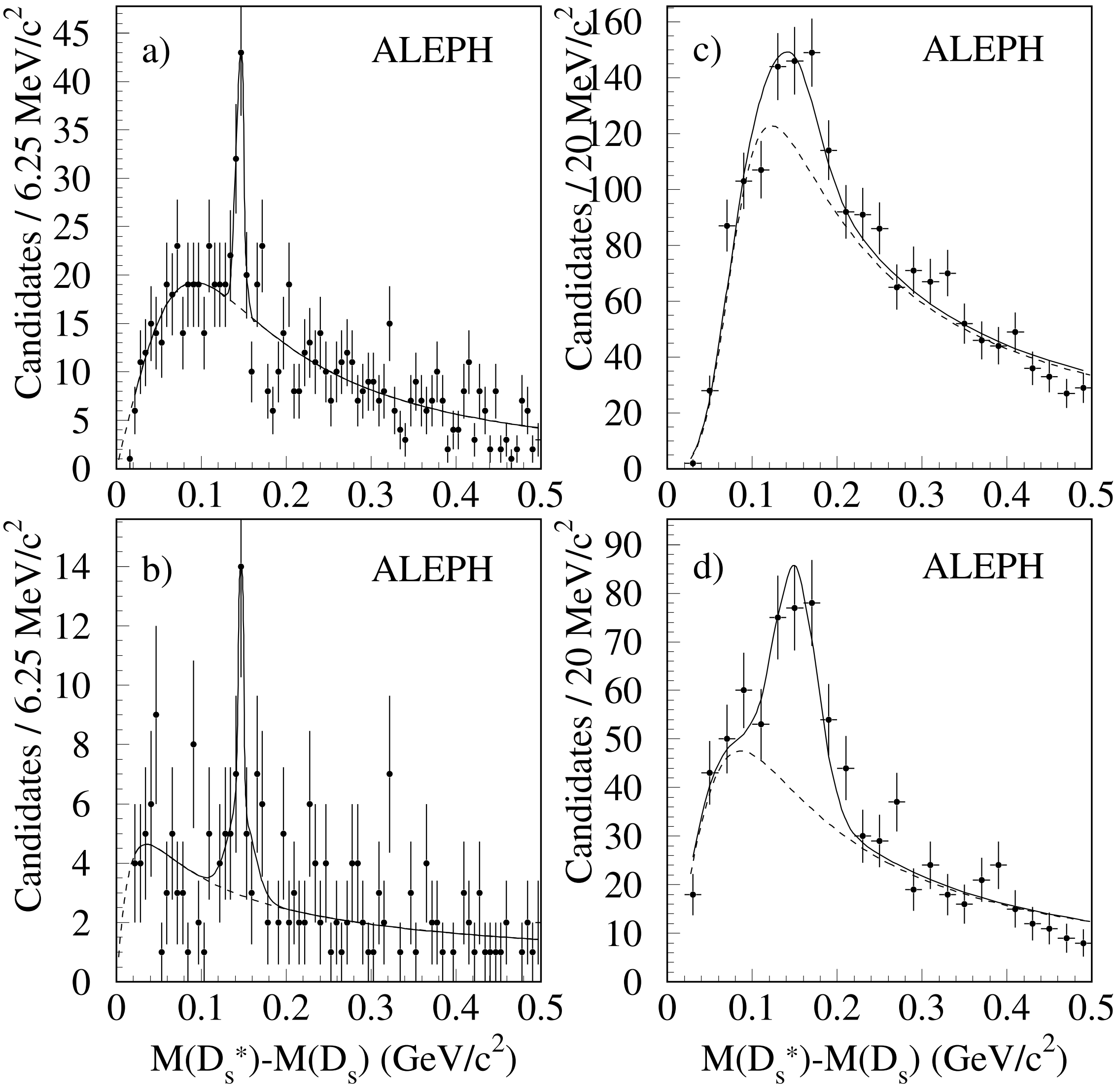

Figure 7: $M(D_s^*) - M(D_s)$ distributions with conversions in the b$\bar{\text{b}}$-enriched sample (a) and in the c$\bar{\text{c}}$-enriched sample (b), and with calorimetric photons (c), (d).

4 Study of the D$^{*\pm}$ Spectrum

The D$^{*\pm}$ spectrum measured as described in section 3 is now interpreted as the sum of three contributions : hadronization of a charm quark produced in a Z $\rightarrow$ c$\bar{\text{c}}$ decay,

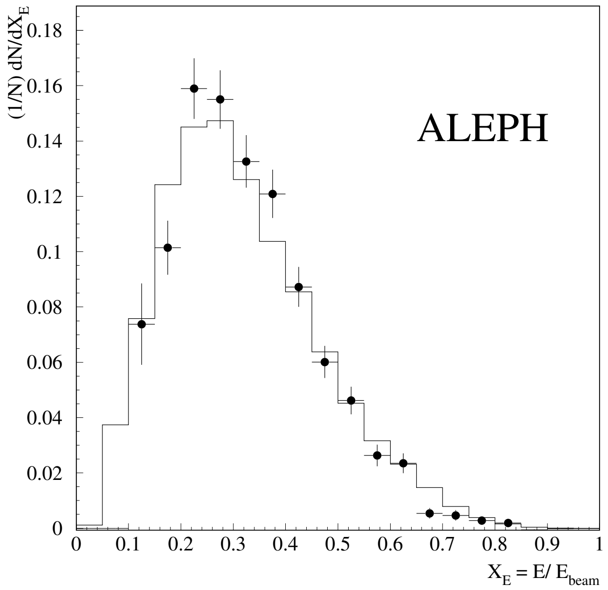

Figure 8: Distribution of X_E for the D$^{*\pm}$'s from the b$\bar{\rm b}$ source compared with the Monte Carlo prediction. The data (points with error bars) are obtained by applying the lifetime-mass btag on the hemisphere opposite to the D$^{*\pm}$, and corrected for efficiency. The remaining charm contribution is subtracted.

decay of a beauty hadron from a Z $\rightarrow$ b$\bar{\rm b}$ decay, and gluon splitting into a pair of heavy quarks which hadronizes or decays into a D$^{*\pm}$. The X_E distribution of the three contributions are taken from the Monte Carlo simulation. The c$\bar{\rm c}$ contribution uses the Peterson fragmentation scheme. The b$\bar{\rm b}$ contribution has been compared with data where a high purity b-tagging is performed in the opposite hemisphere. It is found to be in agreement (Fig. 8).

To describe the production mechanism, three parameters are fitted to the data : the fraction f_g of D$^{*\pm}$ from gluon splitting, the fraction f_b of b$\bar{\rm b}$ events in the remaining (non gluon splitting) sample, and the Peterson *et al.* fragmentation parameter ε_c[9]. The fit is carried out in two steps. Firstly a two-dimensional fit of the 2-dimensional distribution of (X_E,$\mathcal{B}_{tag}$), where $\mathcal{B}_{tag}$ is the tagging variable described in ref [3] is performed in order to constrain f_b. There ε_c is fixed to a value of 30×10^{-3}, and X_E is required to be larger than 0.25 in order to reduce the gluon splitting contribution to a negligible level. The (X_E,$\mathcal{B}_{tag}$) plane is segmented into 62 bins of variable size in such a way that they all contain enough statistics for a χ^2 fit to be performed. The minimal χ^2 of 71.3 for 61 degrees of freedom is obtained for $R_b\ P(b \rightarrow {\rm D}^{*\pm})/R_c\ P(c \rightarrow {\rm D}^{*+}) = 1.15 \pm 0.06$. The fitted distribution of the $\mathcal{B}_{tag}$ variable is shown in Fig 9, compared with data.

In a second step, fixing f_b to the corresponding value, a fit to the efficiency-corrected X_E distribution is performed using the function

$$(1-f_g)(f_b\frac{1}{N_{\rm b\bar{b}}}\frac{dN^{\rm b\bar{b}}}{dX_E}+(1-f_b)\frac{1}{N_{\rm c\bar{c}}}\frac{dN^{\rm c\bar{c}}}{dX_E})+f_g\frac{1}{N_{g\rightarrow \rm c\bar{c}}}\frac{dN^{g\rightarrow \rm c\bar{c}}}{dX_E}.$$

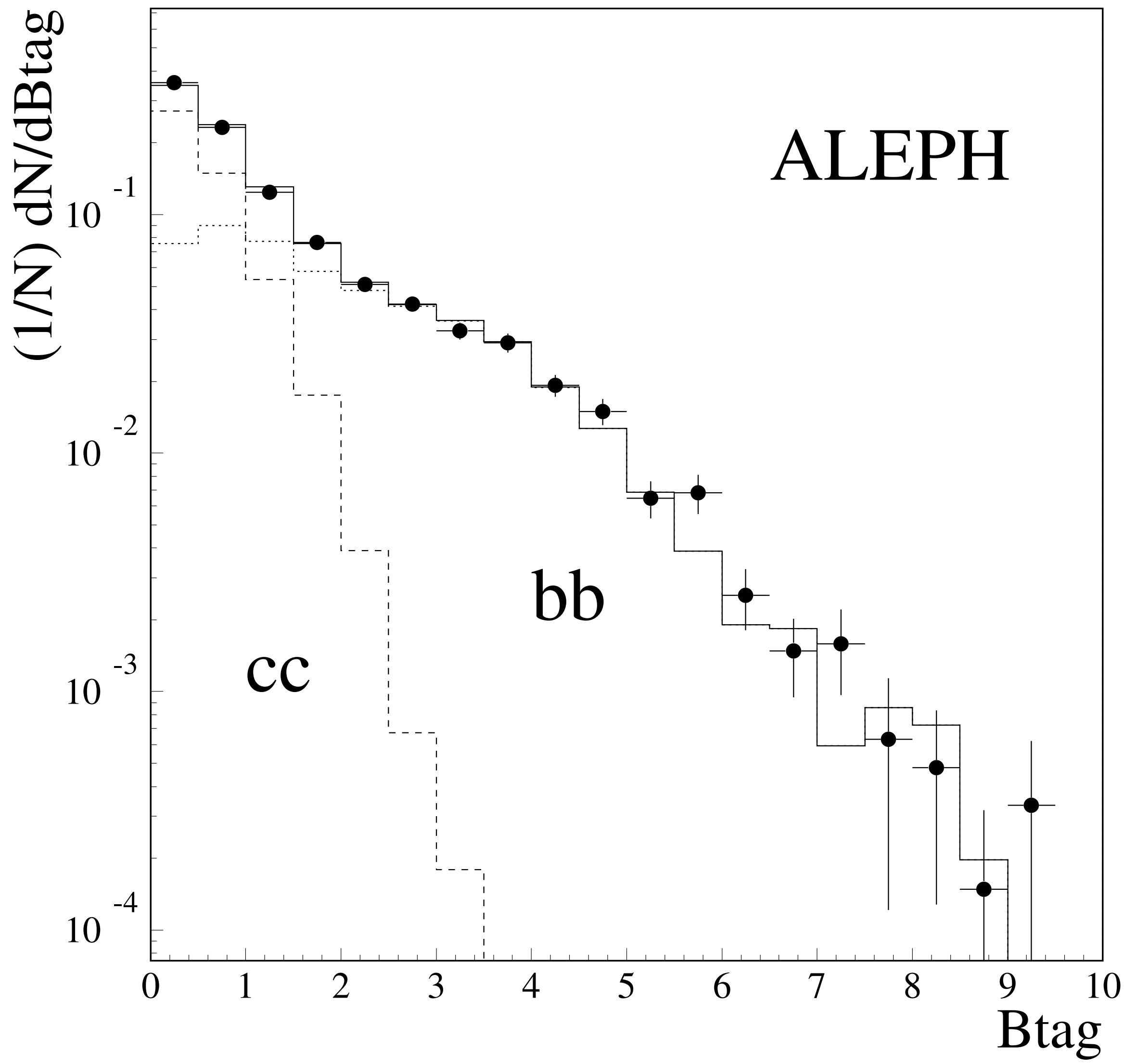

Figure 9: Distribution of X_E for the $D^{*\pm}$'s. The data (points with error bars) are compared with the projection onto the $\mathcal{B}_{tag}$ axis of the fit described in the text. The two contributions: $b\bar{b}$ (dotted line) and $c\bar{c}$ (dashed line) are shown.

As the efficiency at low X_E depends on the $b\bar{b}/c\bar{c}$ fraction, due to the decay-length cut, the fitting procedure is iterated and the efficiencies at low X_E are re-evaluated. The result of the fit is shown in Fig. 3 and its χ^2 is 11.9 for 14 degrees of freedom (the last three bins are grouped together in the fit). The fitted value of f_g can be converted to an average number of gluon splitting events per Z hadronic decay of

$$\bar{n}_{g\to c\bar{c}} = (4.7 \pm 1.0 \pm 1.1)\%.$$

The systematic error only reflects the propagation of the X_E-dependent uncertainties on the reconstruction and selection efficiency, as discussed in the next paragraph, and assumes the JETSET Monte Carlo shape for the gluon splitting and the Peterson parametrization for the heavy quark fragmentation functions [9].

The fitted value $\varepsilon_c = (33.9 \pm 3.7) \times 10^{-3}$ can be converted into a measurement of the average fractional energy of the $D^{*\pm}$ in $Z \to c\bar{c}$ events of

$$\langle X_E(D^*)\rangle_{c\bar{c}} = 0.4878 \pm 0.0046 \pm 0.0061.$$

The quoted systematic uncertainty is dominated by the choice of parametrization of the fragmentation function, as was done in ref [1].

Using the Monte Carlo shape for the very small extrapolation to the entire X_E range (i.e. from 0.1 to the threshold at 0.044), the number of $D^{*\pm}$ per hadronic Z decay is found to be

$$\bar{n}_{D^{*\pm}} = (5.114 \pm 0.066(\text{stat.}) \pm 0.070(\text{syst.})) \times 10^{-3}.$$

The 0.5% uncertainty from the finite Monte Carlo statistics is included in the statistical uncertainty. This result is slightly larger than in previous publications, as it includes the gluon splitting contribution.

Systematic errors on these quantities arise from various sources. The uncertainty on the efficiency has been estimated on a cut by cut basis. The uncertainty from the mass and mass-difference cuts have been assessed by varying the fitted mass and mass difference within errors. This gives a 0.5% and 0.3% contribution to the relative error on the efficiency. The Prob(χ^2) cut efficiency has been compared between data at high X_E and Monte Carlo, and found to differ by 8.3%. This is taken as the uncertainty on the efficiency of this cut, applied only to the first X_E bin, and results in a 0.6% uncertainty on the overall normalization. To assess the uncertainty from the cut on decay length significance, the resolution on this quantity has been varied by 10%. The resulting relative change in efficiency is found to be $(1.6 \pm 0.6)\%$ for the $\delta\ell/\sigma > 0$ cut and $(0.06 \pm 0.90)\%$ for the $\delta\ell/\sigma > 1$ cut. Taking a 1.6% uncertainty in the range $0.3 < X_E < 0.4$ and 0.9% for X_E below 0.3, the resulting uncertainty on the overall normalization is 0.4%. As a check, the whole analysis has been repeated with the decay length significance cut relaxed by 1 unit and the cut in χ^2 probability for the D^0 vertex removed. The final number of events changes by 1%. Assuming an uncertainty of 10% on the probability of nuclear interaction in the detector, based on a study of tau pairs where the pion from one of the taus undergoes such an interaction in the detector, an 0.7% relative error on the efficiency is estimated from this source. To study the efficiency on background subtraction, the analytical shape of the background has been modified and the fit range lowered. This results in a 0.2% overall error on the absolute normalization, localized in the first three X_E bins where the background is large (for instance, the uncertainty reaches 4.5% in the first bin). Summing linearly the errors from the $P(\chi^2)$ cut and from the $\delta\ell/\sigma$ cut, as they both pertain to vertexing and are thus strongly correlated, and summing in quadrature all the contributions, summarized in table 1, the overall normalization uncertainty is 1.4%.

Source	$\delta\epsilon/\epsilon$
ΔM cut	0.3%
$M(\mathrm{K}\pi)$ cut	0.5%
$P(\chi^2)$ cut	0.6%
$\delta\ell/\sigma$ cut	0.4%
nuclear interactions	0.7%
Backg. subtraction	$\delta N/N = 0.2\%$.
Total systematics	1.4%

Table 1: Relative systematic errors in percent on the $\mathrm{D}^{*\pm}$ production rate measurement. Some of them are strongly X_E dependent (see text). The two vertexing uncertainties are considered as fully correlated and added linearly.

Some of these systematic effects are X_E dependent. They have been propagated to the gluon splitting measurement and the average X_E measurement leading to the systematic error quoted above.

As a check of stability of the result, the fit has been repeated with f_b being left free. The fitted parameters are perfectly consistent with the result of the whole procedure, but the uncertainty on f_b is increased by a factor of 1.7.

5 Measurement of the $\mathrm{D}_\mathrm{s}^{*\pm}$ production rate

The selection efficiency of the $\mathrm{D}_\mathrm{s}^{*\pm}$ mesons is evaluated on the Monte Carlo (table 2). The efficiencies are relative to a mix of $\mathrm{D}_\mathrm{s}^{\pm} \longrightarrow \phi\pi^{\pm}$ and $\mathrm{D}_\mathrm{s}^{\pm} \longrightarrow K^{*0}K^{\pm}$ decays in the proportion predicted by the branching ratios in [11].

	conversions		calorimetric photons	
	$Z \to c\bar{c}$ (%)	$Z \to b\bar{b}$ (%)	$Z \to c\bar{c}$ (%)	$Z \to b\bar{b}$ (%)
$c\bar{c}$-enriched	0.38 ± 0.04	0.115 ± 0.020	2.72 ± 0.12	0.85 ± 0.07
$b\bar{b}$-enriched	0.100 ± 0.016	0.29 ± 0.03	0.57 ± 0.05	1.60 ± 0.09

Table 2: Selection efficiencies for $\mathrm{D}_\mathrm{s}^{*\pm}$ mesons (the errors are statistical only).

The number of events in the data samples was evaluated by fitting the $\mathrm{D}_\mathrm{s}^{*}$ spectrum with the sum of two gaussians for the signal and a background function. In the case of the calorimetric photons, the means of the two gaussians and the ratio of their area is taken from Monte Carlo. The parametrization of the background has been constructed to reproduce the Monte Carlo. From the fit the number of events in the $c\bar{c}$-enriched sample is $N_c = 27 \pm 7$ (139 ± 4) and in the $b\bar{b}$-enriched is $N_b = 32 \pm 9$ (106 ± 37) with converted (calorimetric) photons. The production rates $f(c \to \mathrm{D}_\mathrm{s}^{*\pm})$ and $f(b \to \mathrm{D}_\mathrm{s}^{*\pm})$ can be calculated by solving two equations as eq. (1) corresponding to the two data samples:

$$
\begin{aligned}
N_{\mathrm{D_s^*}} &= 2N_{q\bar{q}} \times BR(\mathrm{D_s^{*\pm}} \to \mathrm{D_s^{\pm}}\gamma) BR(\mathrm{D_s} \to \phi\pi) BR(\phi \to K^+K^-) \\
& [R_c f(c \to \mathrm{D_s^*})\epsilon_c + R_b f(b \to \mathrm{D_s^*})\epsilon_b] \qquad (1)
\end{aligned}
$$

where $N_{q\bar{q}}$ is the number of hadronic events in the data sample, ϵ_c (ϵ_b) the selection efficiency on $\mathrm{D_s^*}$ mesons generated in $c\bar{c}$ ($b\bar{b}$) events, $f(c \to \mathrm{D_s^*})$ ($f(b \to \mathrm{D_s^*})$) the probabilities of a c (b) quark giving rise to a $\mathrm{D_s^*}$ meson. A similar formula can be written for the $\mathrm{D_s^+} \longrightarrow K^{*0}K^+$ channel. The results from the whole data sample are:

$$
\begin{aligned}
f(c \to \mathrm{D_s^{*\pm}}) &= 7.5 \pm 2.2 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 1.8(\mathrm{BR})\% \\
f(b \to \mathrm{D_s^{*\pm}}) &= 10.2 \pm 3.1 \text{ (stat.)} \pm 0.5 \text{ (syst.)} \pm 2.5(\mathrm{BR})\%
\end{aligned}
$$

the systematic error is due to the uncertainty in the selection efficiencies, and the last error is due to the final state branching ratios taken from [11].

6 Measurement of Fundamental States Production Rates

6.1 Study of the $\mathrm{D^0}$ and $\mathrm{D^+}$ production

The number of $\mathrm{D^0}$ and $\mathrm{D^+}$ present in the samples are extracted from a fit to the invariant mass distributions (fig 1,4), where the signal is parametrized by two gaussians with a common mean and the combinatorial background by a polynomial function. Resonant background contributions, such as $\mathrm{D^0 \to K^-K^+}$, $\mathrm{D_s^{\pm}} \to \phi\pi$, $\mathrm{D_s^{\pm} \to K^*K}$, and $\mathrm{D^0 \to K^-\pi^+}$ where the two mass assignements are reversed, are taken into account in the fit. The fractions of $\mathrm{D^0}$ and $\mathrm{D^+}$ originating from the process $\mathrm{Z \to c\bar{c}}$ are measured by applying, on the hemisphere opposite to reconstructed D mesons, the lifetime-mass tag [3] selecting b hemispheres with 99% purity. The charm fraction in the D meson samples is given by $f_c = \frac{\epsilon_{\mathrm{b\bar{b}}} - f_{b-tag}}{\epsilon_{\mathrm{b\bar{b}}} - \epsilon_{\mathrm{c\bar{c}}}}$ where f_{b-tag} is the fraction of D mesons surviving the b-tag cut. The b-tag efficiency for beauty $\epsilon_{\mathrm{b\bar{b}}}$ is taken from data using a double-tag and $\epsilon_{\mathrm{c\bar{c}}}$ the b-tag efficiency for charm is obtained from Monte Carlo simulation [3]. Both efficiencies are corrected for the selection bias induced by requiring the presence of a high momentum D meson in the opposite hemisphere. The charm fractions in $\mathrm{D^0}$ and $\mathrm{D^+}$ are found to be respectively: $f_c(\mathrm{D^0}) = 0.787 \pm 0.019$; $f_c(\mathrm{D^+}) = 0.797 \pm 0.020$, where the quoted error is statistical.

A small fraction of D mesons are produced via the gluon splitting process into heavy quarks $g \to \mathrm{Q\bar{Q}}$ (Q=c,b). Its size has been deduced using the measurement [12] $\bar{n}_{g\to c\bar{c}} = (2.27 \pm 0.5)\%$, the theoretical prediction $\frac{\bar{n}_{g\to b\bar{b}}}{\bar{n}_{g\to b\bar{b}} + \bar{n}_{g\to c\bar{c}}} = 0.132 \pm 0.047$[13], and the ratio $\frac{\xi_{g\to D}}{\xi_{q\to D}}$ deduced from simulation for the selection efficiency of a D meson from gluon splitting and direct quark.

The efficiencies for selecting $\mathrm{D^0}$ and $\mathrm{D^+}$ are deduced both from data and a Monte Carlo simulation. The number of fitted D mesons, together with the charm fractions and the gluon splitting contamination are reported in Table 3.

From the numbers in this table, the following branching fractions are obtained:

$$
\mathrm{R_c} \times f(c \to \mathrm{D^0}) \times B(\mathrm{D^0 \to K^-\pi^+}) = (0.370 \pm 0.011) \times 10^{-3}
$$

	N. candidates	Charm fraction	Efficiency	$g \to Q\bar{Q}(\%)$
D^0	7871 ± 129	0.787 ± 0.019	0.200 ± 0.004	.6
D^+	7409 ± 153	0.797 ± 0.020	0.191 ± 0.004	.6

Table 3: D^0 and D^+ selection: number of candidates; fraction of $c \to D$ mesons in the sample; efficiency of $c \to D$ meson reconstruction; fraction of D mesons from gluon splitting. All quoted errors are statistical.

$$R_c \times f(c \to D^+) \times B(D^+ \to K^-\pi^+\pi^+) = (0.368 \pm 0.012) \times 10^{-3}$$

Different sources of systematic uncertainty have been investigated and are given in table 4. The first three errors are related to the detector performances. The fraction of tracks

Source	D^0 (%)	D^+ (%)
Track quality	.5	.7
dE/dx	.9	.4
vertexing	3.1	2.3
charm fraction	.7	.7
gluon splitting	.2	.2
fragmentation	3.7	3.7
charm physics	1.6	2.1
fitting funct.	1.5	1.5
MC stat.	2.0	2.0
Total systematics	5.8	5.6

Table 4: Relative systematic errors in percent on the D^0 and D^+ production rate measurements.

with dE/dx information has been compared on data and Monte Carlo with a sample of candidates selected in the side-band regions of the D^0 and D^+. The Monte Carlo has been corrected for differences and the uncertainty on the ratio data/MC has been taken as a systematic error. The dE/dx calibration and resolution has been studied on data for a pure kaon sample from the decay mode $D^{*+} \to D^0\pi_s^+$, $D^0 \to K^-\pi^+$. Data/MC differences have been taken into account to obtain the dE/dx cut efficiency and the associated systematic error is related to the uncertainty on the data/MC differences. The fraction of D mesons forming a common vertex with a χ^2-probability greater than 1% is obtained from data, from the fraction of selected candidates under the D meson mass peak, corrected by the fraction of background candidates estimated on sideband regions. The resolution on the decay-length measurement has been checked on D^0 and D^+ sideband samples, where most of the candidates carry no lifetime information. The difference found between data and Monte Carlo has been taken as a systematic error for the decay length significance cut together with the error coming from D^0 and D^+ lifetime uncertainty. The fraction of tracks not reconstructed due to nuclear interaction in the $D^0 \to K^-\pi^+$ (resp $D^+ \to K^-\pi^+\pi^+$) decay, is estimated from Monte Carlo to be 5 % (resp. 7 %) , with a systematic error of 10 %. The main systematic error on the determination of the charm fraction comes from the correction factor applied to the b-tag efficiencies. Due to gluon emission, the selection of an energetic D meson in the first hemisphere increase the efficiency for the b-tagging in the hemisphere opposite to the D meson. A comparison between data and Monte Carlo of the spectrum of the most energetic jet in the hemisphere opposite to the D meson has been performed to check the simulation of gluon emission. The error on the correction factors come from the limited Monte Carlo statistics and from the possible difference between data and Monte Carlo in gluon emission, inducing a relative error on the charm fraction of 0.7%. The relative systematic error due to the uncertainty on the raw b-tag efficiencies is very small, of the order of 0.2%. The systematics related to the charm fragmentation and the simulation of the decay chain leading to a D^0 and D^+ is evaluated by varying the fragmentation function and the fraction of charmed vector, pseudoscalar and excited meson (10 to 30%) states produced in the charm hadronization. The Peterson fragmentation function was varied to reproduce the measured $D^{*\pm}$ X_E spectrum for different fractions of produced D meson states. Different kinds of fit have been performed to assess the systematic error coming from the fit results. For the signal function, the mean and width of the narrow gaussian distribution is left free, while the relative normalization and width of the second gaussian is fixed according to Monte Carlo simulation. The fixed parameters have been varied within 5% and the fit was repeated with other background parametrizations (second-order polynomial, exponential). Another method, fitting the background outside the mass peak and counting the number of candidates above the mass peak was also applied.

The final result on the D^0 and D^+ production rate measurements in $Z \to c\bar{c}$ is

$$R_c \times f(c \to D^0) \times B(D^0 \to K^-\pi^+) = (0.370 \pm 0.011 \pm 0.021) \times 10^{-3}$$

$$R_c \times f(c \to D^+) \times B(D^+ \to K^-\pi^+\pi^+) = (0.368 \pm 0.012 \pm 0.021) \times 10^{-3}.$$

6.2 Study of Λ_c and $D_s^\pm$ production

The c fraction in the $D_s^\pm$ and Λ_c samples are extracted by the same method as for the D^0 and D^+. The background fit includes the Monte-Carlo shape and the proper normalization of contributions from D^0, D^+ to the invariant mass distributions. The efficiency correction follows the same lines as for the D^0 and D^+ case, except that the data are counted in 8 X_E bins between 0.2 and 1, allowing the fit of the X_E distributions to a Peterson-based shape for the purpose of extrapolation down to the threshold. The breakdown of the systematic errors is very similar to the one of previous section.

The following $D_s^\pm$ and Λ_c product branching ratios in $Z \to c\bar{c}$ are obtained:

$$R_c \times f(c \to D^0) \times B(D_s^\pm \to \phi\pi) \times B(\phi \to K^+K^-) = (0.352 \pm 0.057 \pm 0.021) \times 10^{-3}$$

$$R_c \times f(c \to \Lambda_c) \times B(\Lambda_c \to pK\pi) = (0.673 \pm 0.070 \pm 0.026) \times 10^{-3}.$$

Dividing these numbers by the Standard Model value of R_c and the branching fraction for the reconstruction mode, the following fractions are obtained:

$$f(c \to D_s^\pm) = 0.1154 \pm 0.0185 \pm 0.0068 \pm 0.0290(BR)$$

and

$$f(c \to \Lambda_c) = 0.0888 \pm 0.0093 \pm 0.0035 \pm 0.0122(BR).$$

Alternatively, one can use the sum of $R_c \times f(c \to X_c)$ over all the fundamental states of the various hadron species to determine R_c, as is done in section 8.

7 Discussion of the Rate Measurements

In this section the consistency between the rate measurements presented in previous sections is investigated. The effective vector/pseudoscalar ratio is assessed.

Firstly, if we assume that the observed difference between $f(\mathrm{c} \to \mathrm{D}^0)$ and $f(\mathrm{c} \to \mathrm{D}^+)$ is only due to D* production, i.e. if primary D's and D*'s are produced evenly in the two charge states, the following relation must hold:

$$f(\mathrm{c} \to \mathrm{D}^0) - f(\mathrm{c} \to \mathrm{D}^+) = 2\, f(\mathrm{c} \to \mathrm{D}^{*\pm}) \times B(\mathrm{D}^{*\pm} \to \mathrm{D}^0\pi^\pm).$$

This equation is indeed verified, the left-handside divided by the right-handside being 1.02 ± 0.12.

The ratio $P_V = \frac{V}{V+P}$, where V is the fraction of D* (vector) produced and P (pseudoscalar) the fraction of D, after all decays of heavier excited states, can be derived either from the ratio $f(\mathrm{c} \to \mathrm{D}^0)/f(\mathrm{c} \to \mathrm{D}^+)$, or from the $\mathrm{D}^{*\pm}$ and $\mathrm{D}^\pm$ rates. The latter leads to

$$P_V = 0.595 \pm 0.045.$$

It is consistent with the calculations of references [14] (thermodynamical approach) and [15] (string fragmentation approach), both expecting 0.66 for P_V on the basis of phenomenological models, but far from the naive expectation of 0.75 from counting the spin states.

From the analysis of section 5 the vector-to-pseudoscalar ratio $P_V = V/(P+V)$ in the $\mathrm{c\bar{s}}$ sector is 0.64 ± 0.22.

8 $\mathrm{R_c}$ Measurement from Charm Counting

By dividing the values of the product branching fractions found in previous sections by the corresponding decay branching fraction, taken from [11], the following individual charm meson rates are obtained.

$$\mathrm{R_c} \times f(c \to \mathrm{D}^0) = 0.0966 \pm 0.0029 \pm 0.0055 \pm 0.0030(BR)$$
$$\mathrm{R_c} \times f(c \to \mathrm{D}^+) = 0.0404 \pm 0.0013 \pm 0.0023 \pm 0.0027(BR)$$
$$\mathrm{R_c} \times f(c \to \mathrm{D_s^\pm}) = 0.0199 \pm 0.0032 \pm 0.0012 \pm 0.0050(BR)$$
$$\mathrm{R_c} \times f(c \to \Lambda_c) = 0.0153 \pm 0.0016 \pm 0.0006 \pm 0.0021(BR)$$

Estimating the additional contribution from Ξ_c and Ω_c to be 0.0034 ± 0.0017, a value of

$$\mathrm{R_c} = 0.1756 \pm 0.0048(\mathrm{stat.}) \pm 0.0085(\mathrm{syst.}) \pm 0.0068(\mathrm{BR})$$

is found where the systematic uncertainty is a linear sum of the common contributions (nuclear interactions, dE/dx, vertexing, gluon splitting, charm fraction and fragmentation), added quadratically to the other contributions. This is in good agreement with the Standard-Model expectation 0.1719 [16] and the accuracy (6.8%) of this measurement is similar to others [17]. The breakdown of the systematic errors on $\mathrm{R_c}$ is given in table 5.

Source	δR_c
MC statistics	± 0.00220
Charm physics	± 0.00176
Fragmentation	± 0.00606
Charm fraction	± 0.00096
Gluon splitting	± 0.00042
dE/dx	± 0.00161
Nuclear interactions	± 0.00087
Vertexing	± 0.00452
Mass fits	± 0.00178
$B(D^0 \to K^-\pi^+)$	± 0.0030
$B(D^+ \to K^-\pi^+\pi^+)$	± 0.0027
$B(D_s^\pm \to \phi\pi^+)$	± 0.0050
$B(\Lambda_c \to pK^-\pi^+)$	± 0.0021
baryons not decaying to Λ_c	± 0.0017
Total internal	0.0085
Total external	0.0068

Table 5: Systematic errors on R_c broken-down on a source-by-source basis

9 Conclusions

A significant improvement of the knowledge of charm production in Z decays has been achieved. The $D^{*\pm}$ spectrum has been measured and interpreted as a sum of three contributions: hadronization of a charm quark produced in a $Z \to c\bar{c}$ decay, decay of a beauty hadron from a $Z \to b\bar{b}$ decay, and gluon splitting into a pair of heavy quarks which hadronizes or decays into a $D^{*\pm}$. This scheme has been found to describe very well the data, and a fit to the spectrum yielded : the average number of gluon splitting events per Z hadronic decay

$$\bar{n}_{g\to c\bar{c}} = (4.7 \pm 1.0 \pm 1.1)\%,$$

the average fractional energy of the $D^{*\pm}$ in $Z \to c\bar{c}$ events

$$\langle X_E(D^*)\rangle_{c\bar{c}} = 0.4878 \pm 0.0046 \pm 0.0061,$$

and the ratio of $D^{*\pm}$ production from b decays to that from c hadronization

$$R_b\ P(b \to D^{*\pm})/R_c\ P(c \to D^{*+}) = 1.15 \pm 0.06.$$

The production rates of the main charmed fundamental states have been measured accurately. The effective ratio of Vector/(Vector+Pseudoscalar) production rates in charmed mesons has been found to be 0.595 ± 0.045, confirming the rather low value found earlier [1], but consistent with recent semi-phenomenological models. In the charm-strange sector, a value of $P_V = 0.64 \pm 0.22$ is found.

Summing the contributions of all the fundamental charmed states, and including a contribution from baryons not decaying to Λ_c, a measurement of R_c has been achieved:

$$R_c = 0.1756 \pm 0.0048(\text{stat.}) \pm 0.0085(\text{syst.}) \pm 0.0068(\text{BR}).$$

The improvement with respect to previous analyses is due to a better rejection of the combinatorial background and to a better b/c separation, both coming from the use of the vertex detector.

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