Charm decays and D^0–$\bar{D}^0$ mixing

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The LEP1 data sample (4 million hadronic Z decays) recorded by the ALEPH detector is analysed to study charmed particle decays. The measurements of the hadronic branching ratios $D^0 \to K^-\pi^+$, and of the purely leptonic decays $D_s \to \tau\nu$ and $D_s \to \mu\nu$ are presented. The L=1 charmed mesons D^{**} and D_s^{**} are reconstructed in several exclusive decay channels and their production rates are measured. The contributions from charm quark fragmentation and from b hadron decays are disentangled. A study of decays $D^{*+} \to D^0\pi^+$, with D^0 decaying $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ is shown. The relative branching ratio $\mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+)$ is measured and the contribution to $D^0 \to K^+\pi^-$ decay given by D^0–$\bar{D}^0$ mixing is extracted with a study of D^0 proper time distribution.

1. THE BRANCHING RATIO $D^0 \to K^-\pi^+$

The branching ratio for the decay $D^0 \to K^-\pi^+$ enters several D meson analysis and many measurements involving B hadron decays.

A precise measurement of this quantity is obtained by fully reconstructing the signal events in the cascade $D^{*+} \to D^0\pi_s^+, D^0 \to K^-\pi^+$ and comparing them with an inclusively selected sample of $D^{*+} \to D^0\pi_s^+$ decays [1]. Both the exclusive and the inclusive selections make use of the low momentum (soft) pion π_s to tag the D^* decay. The branching ratio is then extracted from the formula

$$\mathcal{B}(D^0 \to K^-\pi^+) = \frac{N_{D^0 \to K^-\pi^+}}{N_{D^{*+} \to D^0\pi_s^+}} \times \frac{\epsilon^{incl}}{\epsilon^{excl}} \qquad (1)$$

where $N_{D^{*+} \to D^0\pi_s^+}$ is the number of events selected in the inclusive analysis, $N_{D^0 \to K^-\pi^+}$ is the number of events exclusive reconstructed in the decay chain $D^{*+} \to D^0\pi_s^+, D^0 \to K^-\pi^+$, ϵ^{incl} and ϵ^{excl} are the respective selection efficiencies. Each of the two samples is divided in six subsamples selecting the π_s in momentum bins of width 0.5 GeV/c.

1.1. Exclusive analysis

Tracks with momentum in the range between 1 and 4 GeV/c are taken as π_s candidates. Two oppositely charged tracks are added to form a D^0 candidate assigning the kaon mass to the track with charge opposite to the π_s and the pion to the other one. The combinations are retained if the decay angle of the kaon in the D^0 rest frame θ_K^* satisfies $|\cos\theta_K^*| \leq 0.8$ and if 1835 MeV/c^2 $<| M(K\pi) |<$ 1865 MeV/c^2. Number of candidates is counted in the region 0.1435 GeV/c^2 $<| M(K\pi\pi_s) - M(K\pi) |<$ 0.1475 GeV/c^2.

1.2. Inclusive analysis

The signal relies on observed π_s transverse momentum relative to the D^{*+} line of flight. Soft pion candidates are selected as in the exclusive analysis. The axis of the nearest jet to the π_s is taken as D^{*+} direction. $N_{D^{*+}\to D^0\pi_s^+}$ is calculated with a fit to the p_T^2 distribution. Background distribution is parameterised with an inverse polynomial function. Signal distribution is given by a sum of three contributions: $Z \to c\bar{c}$, $Z \to b\bar{b}$ and gluon splitting. The shapes are taken from Monte Carlo, while the relative fractions are estimated using previous measurements [2,3] and the value of $R_b = \Gamma_{Z\to b\bar{b}}/\Gamma_{Z\to \mathrm{had}}$ and $R_c = \Gamma_{Z\to c\bar{c}}/\Gamma_{Z\to \mathrm{had}}$ fixed to Standard Model values.

1.3. Conclusions

The branching ratio is calculated according to eq. 1 for each π_s momentum bin. The results are combined giving $\mathcal{B}(D^0 \to K^-\pi^+) = (3.90 \pm 0.09 \pm 0.12)\%$, at present the best single measurement result [7].

2. LEPTONIC DECAYS OF D_s MESONS

The rate of the leptonic D mesons decays depends on to the quark-antiquark wave function at the origin, which is described by decay constant f_{D_s}. The $B - \bar{B}$ mixing rates are proportional to square of the corresponding decay constants, that at present can not be measured directly. The large uncertainties affecting the calculation of f_B do not allow to translate the precise measurement of the mass difference between the B_d^0 mass eigenstates into tight constrains on the V_{td} element of the CKM matrix. A f_{D_s} precise measurement is a valid check of the theoretical calculation of meson decay constants and can be used as constraint for lattice QCD and QCD sum-rules evaluations. Preliminary measurements of $\mathcal{B}(D_s \to \tau\nu)$ and $\mathcal{B}(D_s \to \mu\nu)$ are presented [4].

2.1. $D_s \to \tau\nu$ analysis

The candidates are searched in the decay chain $e^+e^- \to c\bar{c}$, $c \to D_s$, $D_s \to \tau\nu$, $\tau \to e\bar{\nu}_e\nu_\tau$ or $\tau \to \mu\bar{\nu}_\mu\nu_\tau$. Each event is divided into two hemispheres according to the plane orthogonal to the thrust axis. Hemispheres with an identified lepton and large missing energy are retained. Electron identification is based on the shower shape in the Electromagnetic Calorimeter and on the specific ionization loss measured into the TPC (dE/dx), while muon identification relies on digital patterns in the Hadronic Calorimeter and hits in muon chambers.

Sets of high rapidity and low rapidity tracks are defined in each hemisphere. The confidence levels that these sets originate from the interaction point are then calculated. Cuts are applied on the confidence level for the low rapidity tracks in each hemisphere to reduce the $b\bar{b}$ background, and on the high rapidity tracks to suppress $c\bar{c}$ background.

D_s energy and momentum are determined requiring four momentum conservation and imposing the mass constraint $[E^2_{D_s} - P^2_{D_s}]^{1/2} = M_{D_s}$. The background is reduced requiring $E_{D_s} > 25\,\mathrm{GeV}$.

Several variables are linearly combined to create two discriminating variables U_c and U_b to separate signal from $c\bar{c}$ and $b\bar{b}$ backgrounds respectively. From the signal extracted from a two-dimensional unbinned maximum likelihood fit to the U_c vs U_b distribution $\mathcal{B}(D_s \to \tau\nu) = [4.93 \pm 1.43(\mathrm{stat.}) \pm 2.05(\mathrm{syst.}) \pm 1.62(\mathrm{BR})]$ and $[4.87 \pm 0.93(\mathrm{stat.}) \pm$

1.63(syst.) $\pm$ 1.37(BR)] are measured in the muon channel and in the electron channel, respectively. The errors labelled BR are due to the error on $\mathcal{B}(\mathrm{D}_s \to \phi\pi)$ measurement, that enters in the calculation of normalisation term $P(c \to \mathrm{D}_s)$ [5,6]. The two results are combined, giving $\mathcal{B}(\mathrm{D}_s \to \tau\nu) = [4.9 \pm 0.9(\mathrm{stat.}) \pm 1.6(\mathrm{syst.}) \pm 1.4(\mathrm{BR})]$.

2.2. $\mathrm{D}_s \to \mu\nu$ analysis

The selection strategy is similar to the strategy in $\mathrm{D}_s \to \tau\nu$ analysis. Loose requirements in the muon identification algorithm are used. The missing neutrino is reconstructed performing a two-constraint kinematic fit, in which the missing mass is constrained to be zero and muon and neutrino momenta and the interaction point are constrained to lie in the same plane. The $\mathrm{b\bar{b}}$ and $\mathrm{c\bar{c}}$ backgrounds are reduced with the same techniques. Two discriminant variables U_c and U_b are defined analogously to the $\mathrm{D}_s \to \tau\nu$ analysis. The signal is measured from a fit to slices of $M(\mu\nu)$ in 36 bins (6×6) in the (U_b, U_c) plane. The branching ratio in the muon channel is measured to be $\mathcal{B}(\mathrm{D}_s \to \mu\nu) = [0.64 \pm 0.08(\mathrm{stat.}) \pm 0.21(\mathrm{syst.}) \pm 0.15(\mathrm{BR})]$, where again the error labelled BR comes from the uncertainty on $\mathcal{B}(\mathrm{D}_s \to \phi\pi)$.

2.3. Conclusions

Preliminary measurements of $\mathcal{B}(\mathrm{D}_s \to \tau\nu)$ and $\mathcal{B}(\mathrm{D}_s \to \mu\nu)$ are presented. The results from the two channels are combined to evaluate the D_s decay constant: $f_{\mathrm{D}_s} = 261 \pm 20(\mathrm{stat.}) \pm 43(\mathrm{syst.}) \pm 35(\mathrm{BR})$. This value is consistent with the previous measurements [7].

3. ORBITALLY EXCITED CHARMED DECAYS

In the heavy quark limit, HQET predicts the $\mathrm{c\bar{q}}$ mesons with L=1 to split in two degenerated doublets according to the angular momentum j of the light quark. One $(j = \frac{1}{2})$ doublet with $J^P = 0^+, 1^+$, usually referred to as $\mathrm{D}^*_{(s)0}$ and $\mathrm{D}^*_{(s)1}$, and one $(j = \frac{3}{2})$ doublet $J^P = 1^+, 2^+$, indicated with $\mathrm{D}_{(s)1}$ and $\mathrm{D}^*_{(s)2}$. It is expected that the decays of these charmed and charmed-strange mesons are dominated by two body decays to $\mathrm{D}^{(*)}\pi$ and $\mathrm{D}^{(*)}\mathrm{K}$, respectively. Only the members of doublets $j = \frac{3}{2}$, that can decay only through D-wave and are therefore narrow, are observed in ALEPH [4,8]. The member of the doublet $j = \frac{1}{2}$ decay through S-waves and are expected to be wide.

3.1. The D^+_{s1} and D^{*+}_{s2} mesons decays

D^{*+}_{s2} state is reconstructed in the decay to $\mathrm{D}^0\mathrm{K}^+$,while D^+_{s1} in the decays to $\mathrm{D}^{*0}\mathrm{K}^+$ and $\mathrm{D}^{*+}\mathrm{K}^0_S$. D^{*+} mesons are reconstructed in the decay channel $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$, and the D^0 mesons are reconstructed in the decays to $\mathrm{K}^-\pi^+$, $\mathrm{K}^-\pi^+\pi^-\pi^+$ and $\mathrm{K}^-\pi^+\pi^0$. Charged kaons and pions are separated using dE/dx. Signal is extracted fitting the mass difference distribution $\Delta M = M(\mathrm{D}^{*+}, \mathrm{K}^0_S) - M(\mathrm{D}^{*+}) - M(\mathrm{K}^0_S) + M_{true}(\mathrm{K}^0_S)$.

The combinatorial background shape is parameterised with a function

$$\frac{dN}{d(\Delta M)} = n \cdot (\Delta M - a)^b \cdot e^{-c(\Delta M - a)} \tag{2}$$

The signal is fitted with a Breit Wigner function convoluted with a Gaussian. D^{*0} mesons decay into D^0 by emitting a pion or a photon. No attempt is made to reconstruct these particles. According to Monte Carlo this doesn't significantly worsen the resolution. In the two decay channels $D_{s1}^{+} \to D^{*0}K^{+}$ and $D_{s2}^{*+} \to D^{0}K^{+}$ signal is determined with an unbinned maximum likelihood to the mass difference distribution $\Delta M = M(D^{0}, K^{+}) - M(D^{0})$. Only the best signal to background ratio channel $D^{0} \to K^{-}\pi^{+}$ is used. The fitting function is the same used in the $D^{*+}K_{S}^{0}$ channel, except for D_{s2}^{*+} decay in which combinatorial background is parameterised with a linear function. In order to determine the production rates $c \to D_{s}^{**}$ and $b \to D_{s}^{**}$ one sample enriched in $c\bar{c}$ and one in $b\bar{b}$ are selected. The properties of long lifetime of b hadrons and harder energy spectrum of D mesons produced in fragmentation of primary c quarks are used. Cuts on the probability of all tracks in the hemisphere of the D_{s}^{**} meson to come from the primary vertex in the hemisphere of the D_{s}^{**} meson, scaled energy of D_{s}^{**} mesons and on the distance of the reconstructed D^{0} vertex to the primary vertex are applied.

3.2. The D_1 and D_2^* mesons decays

D_{2}^{*+} state is reconstructed in the decay $D_{2}^{*+} \to D^{0}\pi^{+}$, D_{2}^{*0} in the decays $D_{2}^{*0} \to D^{*+}\pi^{-}, D^{+}\pi^{-}$ and D_{1}^{0} in the decay $D_{1}^{0} \to D^{*+}\pi^{-}$.

D^{*+} and D^{0} mesons are reconstructed in the same channels as in D_{s}^{**} analysis. Charged D mesons are reconstructed in the decay $D^{+} \to K^{-}\pi^{+}\pi^{+}$. The background is reduced applying cuts the angle between the sphericity axis of the $D^{0/+}$ system and the $D^{0/+}$ direction in the $D^{0/+}$ rest frame, on kaon momentum and on the measured dE/dx. A b/c contribution are separated analogously as in the D_{s}^{**} analysis. Signal is extracted from the mass difference distribution $\Delta M = M(D^{(*)}, \pi_{s}) - M(D^{(*)})$. The combinatorial background shape is parameterised with the function 2, in which the parameter a is fixed to nominal value of pion mass. The signal is fitted as described in Sec. 3.1.

3.3. Conclusions

From the observed number of D_{s}^{**} mesons in the c and in the b enriched samples, assuming that $D_{1} \to D^{*}\pi$ and $D_{2}^{*} \to D^{(*)}\pi$ only and that $D_{s1} \to D^{*}K$ only and $\mathcal{B}(D_{s2}^{*+} \to D^{0}K^{+}) = 45\%$, the production rates from c and b quarks are:

$$
\begin{aligned}
c \to D_{1} &= (3.2 \pm 0.9)\%, c \to D_{s1} = (0.77 \pm 0.22)\% \\
c \to D_{2}^{*} &= (9.4 \pm 1.9)\%, c \to D_{s2}^{*} = (1.3 \pm 0.5)\% \\
b \to D_{1} &= (4.6 \pm 1.4)\%, b \to D_{s1} = (1.1 \pm 0.4)\% \\
b \to D_{2}^{*} &< 3.9\%(95\%CL), b \to D_{s2}^{*} = (2.2 \pm 0.9)\%
\end{aligned}
$$

4. THE $\mathcal{B}(D^{0} \to K^{+}\pi^{-})/\mathcal{B}(D^{0} \to K^{-}\pi^{+})$ AND D^{0}–$\bar{D}^{0}$ MIXING

Both mass and width differences between weak eigenstates of the D^{0}–$\bar{D}^{0}$ system can cause mixing. The rate of such a mixing is predicted from the Standard Model to be orders of magnitude below the current experimental limits, while may approach them in extensions of the Standard Model. A search for D^{0}–$\bar{D}^{0}$ mixing is performed using the decay chain $D^{*+} \to D^{0}\pi_{s}^{+}, D^{0} \to K^{+}\pi^{-}$. The $K^{+}\pi^{-}$ system can be produced by a D^{0} both in a direct Doubly Cabibbo Suppressed Decay (DCSD) and by an oscillation followed by a Cabibbo Favoured Decay $\bar{D}^{0} \to K^{+}\pi^{-}$. The contribution of each component is obtained from a study of D^{0} proper time distribution. Assuming small mixing and neglecting

CP-violating terms, the time evolution for $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ decay has the following form

$$N_{\mathrm{D}^0\to\mathrm{K}^+\pi^-}(t) \propto \left[R_{\mathrm{DCSD}} + \sqrt{2R_{\mathrm{mix}}R_{\mathrm{DCSD}}}\,t/\tau\cos\phi + R_{\mathrm{mix}}\frac{1}{2}(t/\tau)^2\right]e^{-t/\tau}\ , \tag{3}$$

where τ is the D^0 lifetime ($\tau = 0.415$ ps), R_{DCSD} is the ratio $\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^+\pi^-)/\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+)$, R_{mix} is the ratio $\mathcal{B}(\mathrm{D}^0 \to \bar{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-)/\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+)$ and $\cos\phi$ is the phase angle parameterising the interference between the two processes.

4.1. Measurement of $\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^+\pi^-)/\mathcal{B}(\mathrm{D}^0 \to \mathrm{K}^-\pi^+)$

Each pair of oppositely-charged tracks are combined with the two mass assignments $\mathrm{K}^-\pi^+$ and $\pi^-\mathrm{K}^+$. The signal is identified by selecting candidates in the region $\mid M(\mathrm{K}\pi) - M_{\mathrm{D}^0} \mid < 30$ MeV$/c^2$. If both hypotheses satisfy the mass cut the event is rejected. The decay angle of the kaon in the D^0 rest frame θ^*_{K} is required to satisfy $\mid \cos\theta^*_{\mathrm{K}} \mid \leq 0.8$. Only combinations in which the two tracks form a common vertex and each track have at least one VDET hit are kept. The dE/dx of each track is used to suppress misidentification of a pion with a kaon and vice versa. An extra pion π_s is added to build D^* candidates. The background is suppressed requiring $E_{\mathrm{D}_s}/E_b > 0.5$, where E_b is the beam energy. The right-sign ($\mathrm{K}^-\pi^+\pi^+_s$ combinations) and wrong-sign ($\mathrm{K}^+\pi^-\pi^+_s$ combinations) signal candidates are counted selecting events in the window 0.1435 GeV$/c^2 <\mid M(\mathrm{K}\pi\pi_s) - M(\mathrm{K}\pi) \mid < 0.1475$ GeV$/c^2$ (fig. 1). After combinatorial background has been subtracted the number of signal events found in the right-sign sample and in the wrong-sign sample are $N_{\mathrm{RS}} = 1038.8 \pm 32.5(\mathrm{stat.}) \pm 4.3(\mathrm{syst.})$ and $N_{\mathrm{WS}} = 21.3 \pm 6.1(\mathrm{stat.}) \pm 3.4(\mathrm{syst.})$, respectively. The number of physics background events in the wrong-sign sample is estimated using

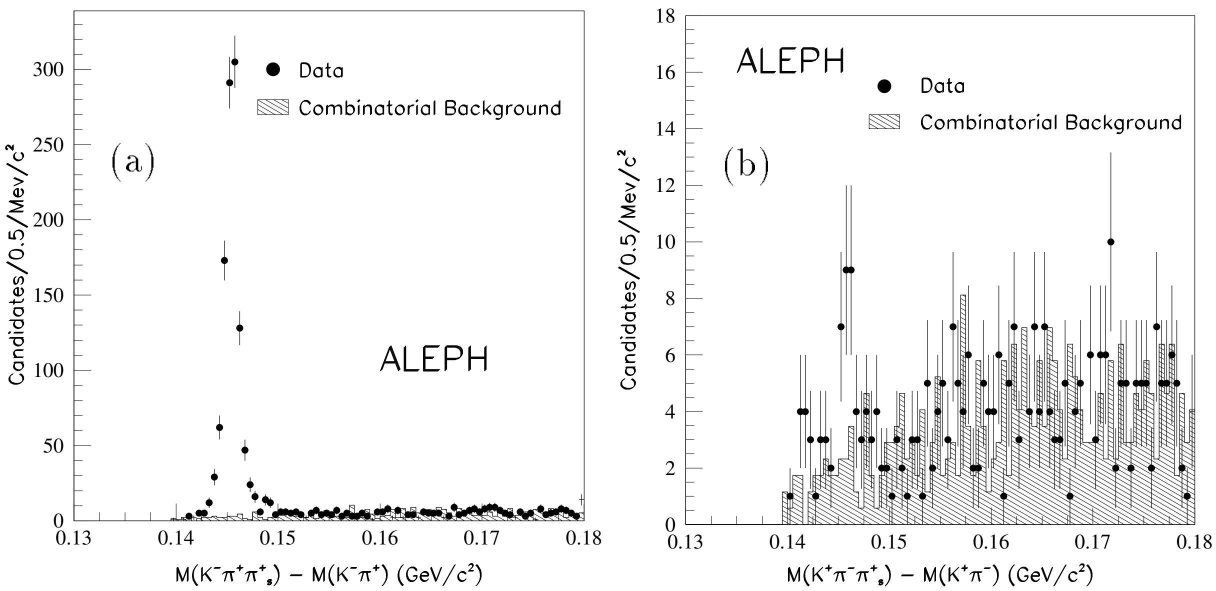

Figure 1. Mass difference distribution for $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+_s$, $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ candidates (a) and $\mathrm{D}^0 \to \mathrm{K}^+\pi^-$ candidates (b)

real and Monte Carlo data to be 2.2 ± 1.0; this is subtracted from the selected sample leading to a signal of $N_{D^0 \to K^+\pi^-} = 19.1 \pm 6.1(\mathrm{stat.}) \pm 3.5(\mathrm{syst.})$. The physics background contamination in the right-sign sample is negligible.

4.2. Proper time study

The proper time of a D^0 candidate is calculated from the distance between the primary vertex projected along the direction of flight of the D^0 and the reconstructed momentum and mass of the candidate. Results are obtained with a binned maximum likelihood fit. Details of the probability density function used are in [10].

Setting the interference term to zero ($\cos\phi = 0$) the result of the fit to the proper time distribution of the wrong-sign sample is $N_{\mathrm{DCSD}} = 20.8^{+8.4}_{-7.4}(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})$, $N_{\mathrm{mix}} = -2.0 \pm 4.4(\mathrm{stat.}) \pm 1.1(\mathrm{syst.})$. The negative value of N_{mix}, outside a physical region, implies that no mixing is observed. Constraining N_{mix} to be positive the number of Doubly Cabibbo Suppressed Decay events is found to be $N_{\mathrm{DCSD}} = 18.4^{+6.2}_{-5.8}(\mathrm{stat.}) \pm 3.2(\mathrm{syst.})$, which translates to $R_{\mathrm{DCSD}} = \left(1.77^{+0.60}_{-0.56}(\mathrm{stat.}) \pm 0.31(\mathrm{syst.})\right)\%$. An upper limit of $R_{\mathrm{mix}} < 0.92\%$ at 95% CL. is obtained.

The effect of interference is studied by fitting the data with fully constructive ($\cos\phi = +1$) and fully destructive interference ($\cos\phi = -1$), finding, at 95% CL, $R_{\mathrm{mix}} < 0.96\%$ and $R_{\mathrm{mix}} < 3.6\%$, respectively.

4.3. Conclusions

The decays $D^{*+} \to D^0\pi_s^+$ with $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$ are reconstructed. The relative branching ratio of the two decay modes is found to be $\mathcal{B}(D^0 \to K^+\pi^-)/\mathcal{B}(D^0 \to K^-\pi^+) = (1.84 \pm 0.59(\mathrm{stat.}) \pm 0.34(\mathrm{syst.}))\%$.

From the study of the proper time distribution the mixing and DCDS components are , giving $R_{\mathrm{DCSD}} = \left(1.77^{+0.60}_{-0.56}(\mathrm{stat.}) \pm 0.31(\mathrm{syst.})\right)\%$, $R_{\mathrm{mix}} < 0.92\%$ at 95% CL. The results are in good agreement with the previous measurements [11–13].

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