Determination of Charm Hadronic Branching Ratios and New Modes

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Recent results from CLEO-c, BABAR, and Belle on measurements of absolute branching fractions of D and D_s mesons are reviewed.

1. Introduction

Precise measurements of the absolute branching fractions for D and D_s meson decays are important as they serve to normalize most B and B_s decays as well as many charm decays. Recent measurements from CLEO-c, BABAR, and Belle for the measurements of the absolute hadronic branching fractions of D and D_s mesons are presented here.

Results from the CLEO-c experiment at the Cornell Electron Positron Storage Ring based on 281 pb^{-1} recorded at the $\psi(3770)$ are presented here for studies of D^0 and D^+ decays. In addition, CLEO-c has analyzed 195 pb^{-1} of e^+e^- annihilation data near $E_{\rm cm} = 4170$ MeV for studies of D_s decays. These samples provide very clean environments for studying decays of D and D_s mesons. The $\psi(3770)$ produced in the e^+e^- annihilation decays to pairs of D mesons, either D^+D^- or $D^0\bar{D}^0$. In particular, the produced D mesons can not be accompanied by any additional pions. At $E_{\rm cm} = 4170$ MeV D_s mesons are primarily produced as $D_s^+D_s^{*-}$ and $D_s^{*+}D_s^-$ pairs.

The results from BABAR and Belle use their large samples of e^+e^- data collected by these experiments. The different analyses presented here use integrated luminosities up to 0.55 ab^{-1}. For example, Belle has used 0.55 ab^{-1} to study $D_s^+ \to K^+K^-\pi^+$ in exclusive production of $e^+e^- \to D_s^* D_{s1}$. BABAR has studied $D_s \to \phi\pi$ using a sample of $B \to D^{(*)}D_{s(J)}^{(*)}$ decays. These examples illustrate that charm produced both in the continuum and in B meson decays are useful for studies of charm at the B-factories.

First I will discuss the determination of the absolute D^0 and D^+ branching fractions. New results from CLEO-c and BABAR are discussed here. Then results for D_s branching fractions from CLEO-c, Belle, and BABAR are presented. Last a few inclusive and rare hadronic decay modes are discussed.

2. Absolute D hadronic branching fractions at CLEO-c

This analysis makes use of a 'double tag' technique initially used by Mark III [1]. In this technique the yields of single tags, where one D meson is reconstructed per event, and double tags, where both D mesons are reconstructed, are determined. The number of single tags, separately for D and $\bar{D}$ decays, are given by $N_i = \epsilon_i \mathcal{B}_i N_{D\bar{D}}$ and $\bar{N}_j = \bar{\epsilon}_j \mathcal{B}_j N_{D\bar{D}}$ where ϵ_i and $\mathcal{B}_i$ are the efficiency and branching fraction for mode i. Similarly, the number of double tags reconstructed are given by $N_{ij} = \epsilon_{ij}\mathcal{B}_i\mathcal{B}_j N_{D\bar{D}}$ where i and j label the D and $\bar{D}$ mode used to reconstruct the event and ϵ_{ij} is the efficiency for reconstructing the final state. Combining the equations above and solving for $N_{D\bar{D}}$ gives the number of produced $D\bar{D}$ events as

$$N_{D\bar{D}} = \frac{N_i \bar{N}_j}{N_{ij}} \frac{\epsilon_{ij}}{\epsilon_i \bar{\epsilon}_j}$$

and the branching fractions

$$\mathcal{B}_i = \frac{N_{ij}}{N_j} \frac{\epsilon_j}{\epsilon_{ij}}.$$

In this analysis CLEO-c determine all the single tag and double tag yields in data, determine the efficiencies from Monte Carlo simulations of the detector response, and extract the branching fractions and $D\bar{D}$ yields from a combined fit to all measured data yields.

This analysis uses three D^0 decays ($D^0 \to K^-\pi^+$, $D^0 \to K^-\pi^+\pi^0$, and $D^0 \to K^-\pi^+\pi^-\pi^+$) and six D^+ modes ($D^+ \to K^-\pi^+\pi^+$, $D^+ \to K^-\pi^+\pi^+\pi^0$, $D^+ \to K_S^0\pi^+$, $D^+ \to K_S^0\pi^+\pi^0$, $D^+ \to K_S^0\pi^+\pi^-\pi^+$, and $D^+ \to K^-K^+\pi^+$). The single tag yields are shown in Fig. 1. The combined double tag yields are shown in Fig. 2 for charged and neutral D modes separately. The scale of the statistical errors on the branching fractions are set by the number of double tags and precisions of $\approx 0.8\%$ and $\approx 1.0\%$ are obtained for the neutral and charged modes respectively. The branching fractions obtained are summarized in Table I.

CLEO-c has presented updated results for these branching fractions[4] since these results were presented. The new results, including $\mathcal{B}(D^0 \to K^-\pi^+) = (3.891 \pm 0.035 \pm 0.059 \pm 0.035)\%$, are consistent with the preliminary results presented here. The last error is the uncertainty due to final state radiation.

3. Measurement of $\mathcal{B}(D^0 \to K^-\pi^+)$ at BABAR

BABAR has used a sample of 210 fb^{-1} of e^+e^- data collected at the $\Upsilon(4S)$ resonance to study the

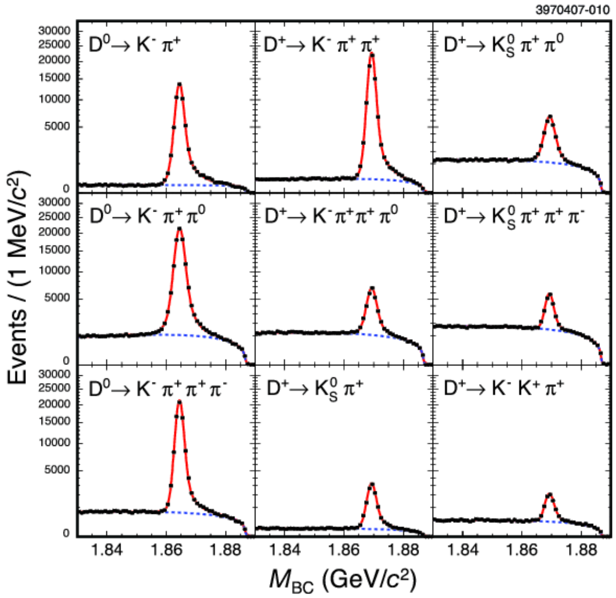

Figure 1: The fits for the single tag yields. The background is described by the ARGUS threshold function and the signal shape includes the effects of beam energy spread, momentum resolution, initial state radiation, and the $\psi(3770)$ lineshape.

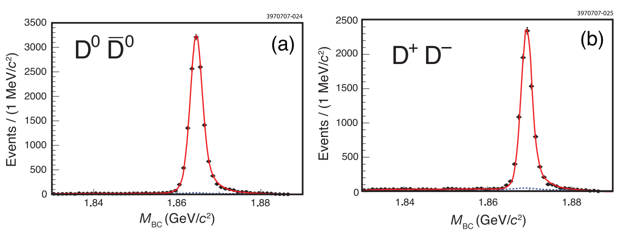

Figure 2: The fit for the double tag yields combined over all modes for charged and neutral modes separately.

Table I Preliminary branching fractions from CLEO-c. Uncertainties are statistical and systematic, respectively.

Mode	Fitted Value (%)	PDG (%)
$\mathcal{B}(D^0 \to K^-\pi^+)$	$3.87 \pm 0.04 \pm 0.08$	3.81 ± 0.09
$\mathcal{B}(D^0 \to K^-\pi^+\pi^0)$	$14.6 \pm 0.1 \pm 0.4$	13.2 ± 1.0
$\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$	$8.3 \pm 0.1 \pm 0.2$	7.48 ± 0.30
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	$9.2 \pm 0.1 \pm 0.2$	9.2 ± 0.6
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+\pi^0)$	$6.0 \pm 0.1 \pm 0.2$	6.5 ± 1.1
$\mathcal{B}(D^+ \to K^0_S\pi^+)$	$1.55 \pm 0.02 \pm 0.05$	1.42 ± 0.09
$\mathcal{B}(D^+ \to K^0_S\pi^+\pi^0)$	$7.2 \pm 0.1 \pm 0.3$	5.4 ± 1.5
$\mathcal{B}(D^+ \to K^0_S\pi^+\pi^+\pi^-)$	$3.13 \pm 0.05 \pm 0.14$	3.6 ± 0.5
$\mathcal{B}(D^+ \to K^+K^-\pi^+)$	$0.93 \pm 0.02 \pm 0.03$	0.89 ± 0.08

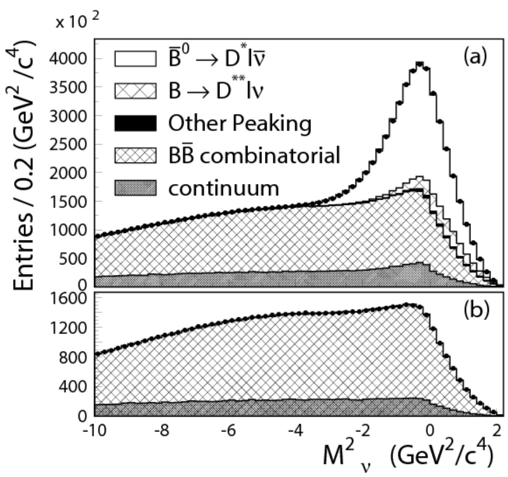

Figure 3: The distribution of the missing mass squared, M_ν^2, for (a) right sign events and (b) wrong sign events. The wrong sign events show that the simulation of the background shape is good. (From Ref. [3].)

decay $D^0 \to K^-\pi^+$ decay [3]. They use semileptonic B decays, $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ followed by $D^{*+} \to D^0\pi^+$, where they use the lepton in the B decay and the slow pion from the D^* to tag the signal. As the energy release in the D^* decay is very small the reconstructed slow pion momentum can be used to estimate the four-momentum of the D^* — the slow pion and the D^* have approximately the same velocity. BABAR extracts the number of $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ decays using the missing mass squared, M_ν^2, against the D^* and the lepton. The M_ν^2 distribution is shown in Fig. 3. A clear signal is observed for $M_\nu^2 > -2.0$ GeV^2. However, there are substantial backgrounds that need to be subtracted due to combinatorial backgrounds in $B\bar{B}$ events and continuum production. Table II summarizes the event yields for the inclusive $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ reconstruction in the column labeled 'Inclusive'. BABAR finds $2,170,640 \pm 3,040$ $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ decays followed by $D^{*+} \to D^0\pi^+$.

The next step in this analysis is to use this sample of events and reconstruct the $D^0 \to K^-\pi^+$ decay. To extract a clean signal BABAR studies the mass difference $\Delta M \equiv m_{K\pi\pi_s} - m_{K\pi}$ where π_s indicate the slow pion from the D^* decay. The mass difference is shown in Fig. 4. The yields for this 'Exclusive' analysis are given in Table II. Using simulated events BABAR determine an efficiency of $(39.96 \pm 0.09)\%$ for reconstructing the $D^0 \to K^-\pi^+$ final state. Combining this with the data yields given above BABAR determines

$$\mathcal{B}(D^0 \to K^-\pi^+) = (4.007 \pm 0.037 \pm 0.070)\%.$$

This is slightly larger than the branching fraction CLEO-c obtained, but within errors they are consistent.

Table II Event yields for the inclusive $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ reconstruction and the exclusive analysis where the $D^0 \to K^-\pi^+$ final state is reconstructed in the BABAR analysis to determine the branching fraction for $D^0 \to K^-\pi^+$ decay.

Source	Inclusive	Exclusive
Data	$4,412,390 \pm 2100$	$47,270 \pm 220$
Continuum	$460,030 \pm 2090$	$3,090 \pm 170$
Combinatorial $B\bar{B}$	$1,781,720 \pm 680$	$8,190 \pm 50$
Peaking		$1,630 \pm 80$
Cabibbo suppressed		550 ± 10
Signal	$2,170,640 \pm 3,040$	$33,810 \pm 290$

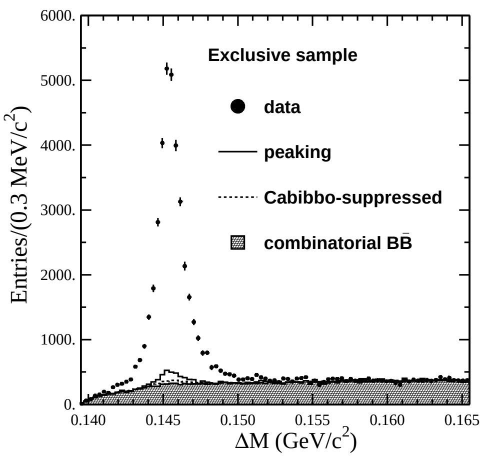

Figure 4: The ΔM distribution for the reconstructed $D^0 \to K^-\pi^+$ candidates in events with a $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}$ tag. (From Ref. [3].)

4. Absolute branching fractions for hadronic D_s decays at CLEO-c

This analysis uses a sample of 195 pb^{-1} of data recorded at a center-of-mas energy of 4170 MeV. At this energy D_s mesons are produced, predominantly, as $D_s^+ D_s^{*-}$ or $D_s^- D_s^{*+}$ pairs. CLEO-c uses the same tagging technique as for the hadronic D branching fractions; they reconstruct samples of single tags and double tags and use this to extract the branching fractions.

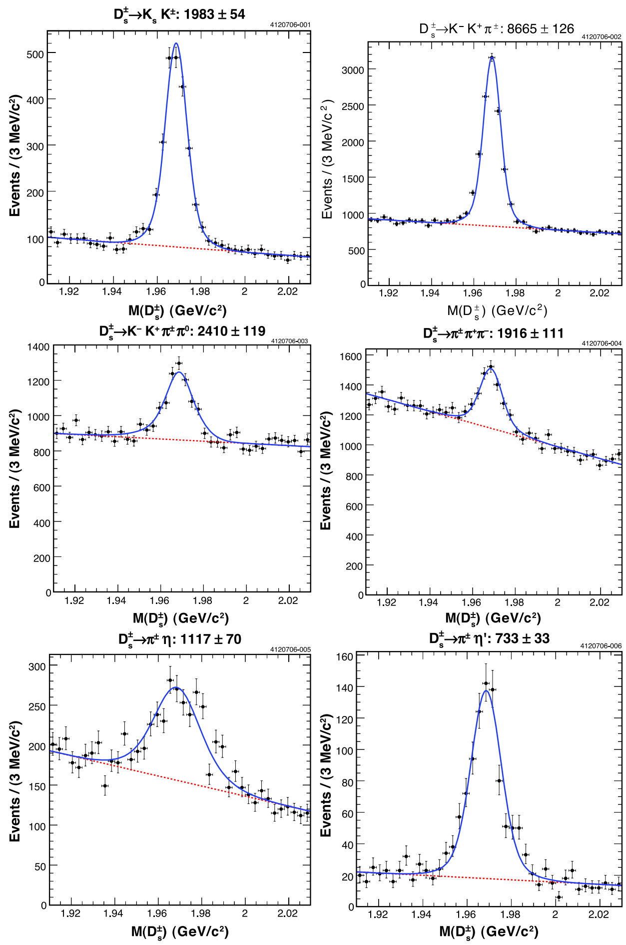

Figure 5: Single tag yields for D_s modes used in the CLEO-c analysis.

CLEO-c studies six D_s final states ($D_s^+ \to K_S^0 K^+$, $D_s^+ \to K^+K^-\pi^+$, $D_s^+ \to K^+K^-\pi^+\pi^0$, $D_s^+ \to \pi^+\pi^-\pi^+$, $D_s^+ \to \eta\pi^+$, and $D_s^+ \to \eta'\pi^+$). The single tag event yields are shown in Fig. 5. The double tag yields are extracted by a cut-and-count procedure in the plot of the invariant mass of the D_s^+ vs. D_s^-. This plot is shown in Fig. 6. Backgrounds are subtracted from the sidebands indicated in the plot and a total of 471 double tag events are found.

From these yields CLEO-c determines the branching fractions listed in Table III. CLEO-c is not quoting branching fractions for $D_s^+ \to \phi\pi^+$ as the ϕ signal is not well defined. In particular, the ϕ resonance interferes with the f_0 resonance. CLEO-c reports preliminary results for partial branching fractions for $D_s^+ \to K^+K^-\pi^+$ in restricted invariant mass ranges of m_{KK} near the ϕ resonance. In particular, for a 10 MeV cut around the ϕ mass the partial branching fraction of $(1.98 \pm 0.12 \pm 0.09)\%$ is found while for a 20 MeV cut the corresponding branching fraction is $(2.25 \pm 0.13 \pm 0.12)\%$.

Since these results were presented CLEO-c has

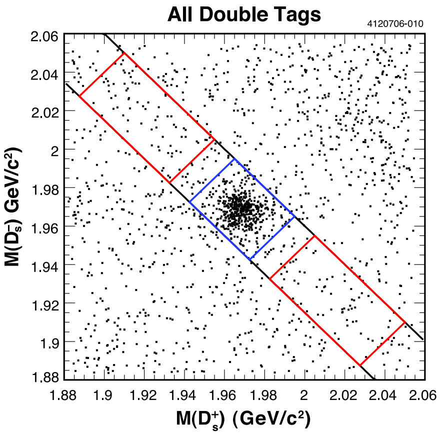

Figure 6: Double tag yields for D_s modes used in the CLEO-c analysis.

Table III Preliminary branching fractions for D_s decays determined in the CLEO-c analysis.

Mode	Branching Fraction (%)
$\mathcal{B}(D_s^+ \to K_S^0 K^+)$	$1.50 \pm 0.09 \pm 0.05$
$\mathcal{B}(D_s^+ \to K^+K^-\pi^+)$	$5.57 \pm 0.30 \pm 0.19$
$\mathcal{B}(D_s^+ \to K^+K^-\pi^+\pi^0)$	$5.62 \pm 0.33 \pm 0.51$
$\mathcal{B}(D_s^+ \to \pi^+\pi^-\pi^+)$	$1.12 \pm 0.08 \pm 0.05$
$\mathcal{B}(D_s^+ \to \eta\pi^+)$	$1.47 \pm 0.12 \pm 0.14$
$\mathcal{B}(D_s^+ \to \eta'\pi^+)$	$4.02 \pm 0.27 \pm 0.30$

updated this analysis to include 298 pb^{-1} of data recorded at the $E_{\rm cm} = 4170$ MeV [4]. In addition to the six mode used in the analysis described above CLEO-c also uses $D_s^+ \to K^+\pi^+\pi^-$ and $D_s^+ \to K_S^0 K^-\pi^+\pi^+$. Among the updated results is the branching fraction $\mathcal{B}(D_s^+ \to K^+K^-\pi^+ = (5.67 \pm 0.24 \pm 0.18)\%$, in good agreement with the preliminary result presented above.

5. Belle study of $D_s^+ \to K^+K^-\pi^+$

Using 0.55 ab^{-1} of e^+e^- data recorded with the Belle detector at KEKB the Belle collaboration has studied the process $e^+e^- \to D_s^{*+}D_{s1}^-$ followed by $D_{s1}^- \to D^{*0}K^-$ and $D_s^{*+} \to D_s^+\gamma$[5]. The final state is reconstructed in two ways; either by partially reconstructing the D_{s1} or the D_s^*.

Belle obtains the branching fraction $\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = (4.0 \pm 0.4 \pm 0.4)\%$. This is somewhat lower than the CLEO-c result presented in the previous section.

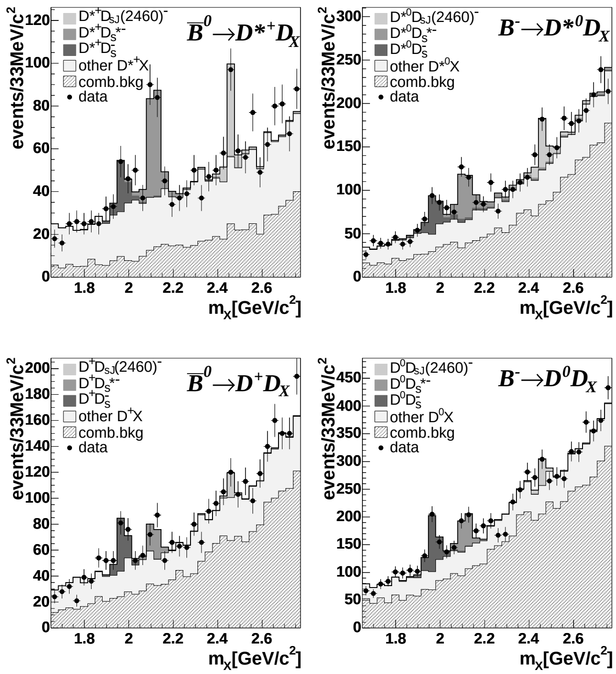

Figure 7: The recoil mass against a D or D^*. (From Ref. [7].)

6. BABAR studies of $D_s \to \phi\pi$

An earlier BABAR study has used $B \to D^*D_s^*$ decays and a technique of partially reconstructing either the D^* or the D_s^* to measure the $D_s \to \phi\pi$ branching fraction[6]. They quote $\mathcal{B}(D_s^+ \to \phi\pi^+) = (4.81 \pm 0.52 \pm 0.38)\%$ based on a sample of 123×10^6 $B\bar{B}$ decays. More recently BABAR[7] has presented preliminary results based on 210 fb^{-1} of data where they use a tag technique in which one B is fully reconstructed. In events with one fully reconstructed B candidate BABAR reconstructs one additional $D^{(*)}$ or $D_{s(J)}^{(*)}$ meson. Then they look at the recoil mass against this reconstructed candidate. The recoil masses are shown in Figs. 7 and 8.

From these modes BABAR extracts $\mathcal{B}(D_{sJ}(2460)^- \to D_s^{*-}\pi^0) = (56 \pm 13 \pm 9)\%$ and $\mathcal{B}(D_{sJ}(2460)^- \to D_s^{*-}\gamma) = (16 \pm 4 \pm 3)\%$ in addition to $\mathcal{B}(D_s^- \to \phi\pi^+) = (4.62 \pm 0.36 \pm 0.50)\%$.

7. Inclusive measurements of η, η', and ϕ production in D and D_s decays

Using samples of tagged D and D_s decays CLEO-c has measured the inclusive production of η, η', and ϕ mesons by looking at the recoil against the tag[8]. The results are summarized in Table IV. The knowledge of inclusive measurements before this CLEO-c

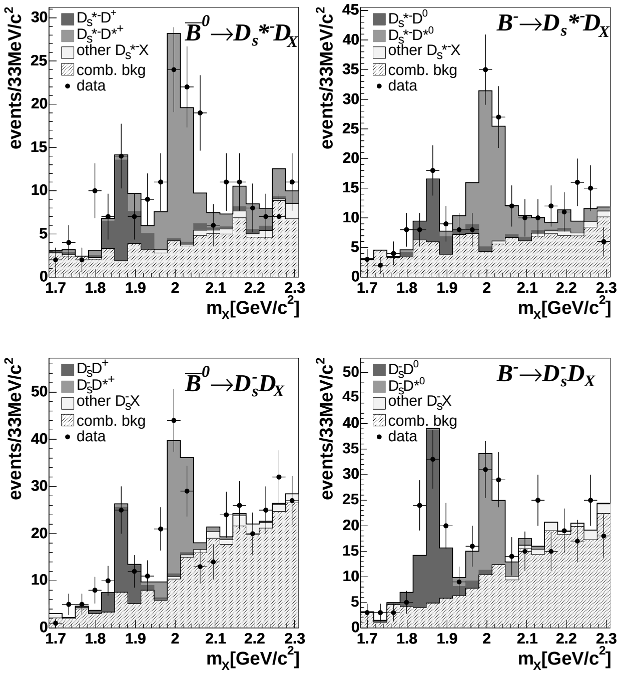

Figure 8: The recoil mass against a D_s or D_s^* (From Ref. [7].)

Table IV Inclusive branching fractions

Decay	$\mathcal{B}$ (%)
$D^0 \to \eta X$	$9.5 \pm 0.4 \pm 0.8$
$D^- \to \eta X$	$6.3 \pm 0.5 \pm 0.5$
$D_s^+ \to \eta X$	$23.5 \pm 3.1 \pm 2.0$
$D^0 \to \eta' X$	$2.48 \pm 0.17 \pm 0.21$
$D^- \to \eta' X$	$1.04 \pm 0.16 \pm 0.09$
$D_s^+ \to \eta' X$	$8.7 \pm 1.9 \pm 1.1$
$D^0 \to \phi X$	$1.05 \pm 0.08 \pm 0.07$
$D^- \to \phi X$	$1.03 \pm 0.10 \pm 0.07$
$D_s^+ \to \phi X$	$16.1 \pm 1.2 \pm 1.1$

measurement was poor, besides limits only $\mathcal{B}(D^0 \to \phi X) = 1.7 \pm 0.8$ was measured. As expected the η, η', and ϕ rates are much higher in D_s decays.

8. The doubly Cabibbo suppressed decay $D^+ \to K^+\pi^0$

Both CLEO-c and BABAR have studied the doubly Cabibbo suppressed decay $D^+ \to K^+\pi^0$. CLEO-c[9] has reconstructed candidates in a 281 pb^{-1} sample of e^+e^- data recorded at the $\psi(3770)$. BABAR[10] has used a sample of 124 fb^{-1} recorded at the $\Upsilon(4S)$. CLEO-c and BABAR finds branching fractions in good agreement with each other, $\mathcal{B}(D^+ \to K^+\pi^0) = (2.24 \pm 0.36 \pm 0.15 \pm 0.08) \times 10^{-4}$ and $\mathcal{B}(D^+ \to K^+\pi^0) = (2.52 \pm 0.46 \pm 0.24 \pm 0.08) \times 10^{-4}$ respectively.

9. Modes with K_L^0 or K_S^0 in the final states

It has commonly been assumed that $\Gamma(D \to K_S^0 X) = \Gamma(D \to K_L^0 X)$. However, as pointed out by Bigi and Yamamoto[11] this is not generally true as for many D decays there are contributions from Cabibbo favored and Cabibbo suppressed decays that interfere and contributes differently to final states with K_S^0 and K_L^0. As an example consider $D^0 \to K_{S,L}^0\pi^0$. Contributions to these final states involve the Cabibbo favored decay $D^0 \to \bar{K}^0\pi^0$ as well as the Cabibbo suppressed decay $D^0 \to K^0\pi^0$. However, we don't observe the K^0 and the $\bar{K}^0$ but rather the K_S^0 and the K_L^0. As these two amplitudes interfere constructively to form the K_S^0 final state we will see a rate asymmetry. Based on factorization Bigi and Yamamoto predicted

$$\begin{aligned} R(D^0) &\equiv \frac{\Gamma(D^0 \to K_S^0\pi^0) - \Gamma(D^0 \to K_L^0\pi^0)}{\Gamma(D^0 \to K_S^0\pi^0) + \Gamma(D^0 \to K_L^0\pi^0)} \\ &\approx 2\tan^2\theta_C \approx 0.11. \end{aligned}$$

Using tagged D mesons CLEO-c has measured this asymmetry and obtained

$$R(D^0) = 0.122 \pm 0.024 \pm 0.030$$

which is in good agreement with the prediction.

Similarly, CLEO-c has also measured the corresponding asymmetry in charged D mesons and obtained

$$\begin{aligned} R(D^+) &\equiv \frac{\Gamma(D^+ \to K_S^0\pi^+) - \Gamma(D^+ \to K_L^0\pi^+)}{\Gamma(D^+ \to K_S^0\pi^+) + \Gamma(D^+ \to K_L^0\pi^+)} \\ &= 0.030 \pm 0.023 \pm 0.025. \end{aligned}$$

Prediction of the asymmetry in charged D decays is more involved. D.-N. Gao predicts [12] this asymmetry to be in the range 0.035 to 0.044, which is consistent with the observed asymmetry.

10. Summary

Recently there has been a lot of progress on the determination of absolute hadronic branching fractions of D and D_s mesons. Here recent results from CLEO-c and the B-factory experiments, BABAR and Belle, were reported. CLEO-c uses the extremely clean environment at threshold for these measurements while the B-factory experiments use their very large data samples to explore partial reconstruction techniques to determine the absolute hadronic branching fractions.

Acknowledgments

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