CHARM DECAYS WITHIN THE STANDARD MODEL AND BEYOND

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The charm quark has unique properties that make it a very important probe of many facets of the Standard Model. New experimental information on charm decays is becoming available from dedicated experiments at charm factories, and through charm physics programs at the b-factories and hadron machines. In parallel, theorists are working on matrix element calculations based on unquenched lattice QCD, that can be validated by experimental measurements and affect our ultimate knowledge of the quark mixing parameters. Recent predictions are compared with corresponding experimental data and good agreement is found. Charm decays can also provide unique new physics signatures; the status of present searches is reviewed. Finally, charm data relevant for improving beauty decay measurements are presented.

1 Introduction

The charm quark has played a unique role in particle physics for more than three decades. Its discovery by itself was an important validation of the Standard Model, as its mass and most of its relevant properties were predicted before any experimental signature for charm was available. Since then, much has been learned about the properties of charmed hadronic systems.

Experiments operating at the $\psi(3770)$ resonance, near threshold for $D\bar{D}$ production, such as MARK III at SPEAR, performed the initial exploration of charm phenomenology. Later, higher energy machines, either fixed target experiments operating at hadron machines or higher energy $e^+e^-$ colliders, entered this arena, with much bigger data samples. In recent years, we have seen a renewed interest in studying open charm in $e^+e^-$ colliders with a center-of-mass energy close to $D\bar{D}$ threshold. The CLEO-c experiment at CESR, has collected a sample of $281 \text{ pb}^{-1}$ at the $\psi(3770)$ center-of-mass energy. This experiment is poised to accumulate a total integrated luminosity of the order of $1 \text{ fb}^{-1}$ at the $\psi(3770)$ and a similar size sample at an energy optimal to study $D_S$ decays. The BES-II experiment, at BEPC, has published results based on $33 \text{ pb}^{-1}$ accumulated around the $\psi(3770)$. It has an ongoing upgrade program both for the detector (BE-SIII) and the machine (BEPCII), designed as a charm factory with $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ peak luminosity.

Several features distinguish charm. Its mass ($\mathcal{O}(1.5) \text{ GeV}$) makes it an ideal laboratory to probe QCD in the non-perturbative domain. In particular, a comparative study of charm and beauty decays may lead to more precise theoretical predictions for key quantities necessary for accurate determination of important Standard Model parameters. On the other hand, once full QCD calculations have demonstrated control over hadronic uncertainties, charm data can be used to probe the Yukawa sector of the Standard model. Finally, charm decays provide a unique window on new physics affecting the u-type quark dynamics. For example, it is the only u-type quark that can have flavor oscillations. Moreover, some specific new physics models predict enhancements on CP violation phases in $D$ decays, beyond the $10^{-3}$ level generally predicted within the Standard Model.

The charge-changing transitions involving quarks feature a complex pattern, that is summarized by a $3 \times 3$ unitary matrix, the Cabibbo-Kobayashi-Maskawa ($CKM$) ma-
trix:

\[ V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \]

These 9 complex couplings are described by 4 independent parameters. In the Wolfenstein approximation, the CKM matrix is expressed in terms of the four parameters \( \lambda, A, \rho, \) and \( \eta \), and is expanded in powers of \( \lambda \):

\[ \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A \lambda^3 (\rho - i \eta) \\ -\lambda & 1 - \lambda^2/2 & A \lambda^2 \\ A \lambda^3 (1 - \rho - i \eta) & -A \lambda^2 & 1 \end{pmatrix}. \]

The parameters \( \lambda, A, \rho, \) and \( \eta \) are fundamental constants of nature, just as basic as \( G \), Newton’s constant, or \( \alpha_{EM} \).

B meson semileptonic decays (determining \( |V_{ub}|/|V_{cb}| \)) and neutral B flavor oscillations provide crucial constraints to determine the CKM parameters \( \rho, \eta \). In both cases, hadronic matrix elements need to be evaluated to extract these parameters from the experimental data. Due to the relatively small masses of the \( b \) and \( c \) quarks, strong interactions effects are of a non-perturbative nature. Lattice QCD calculations seem the ideal approach to tackle this problem. However, a realistic simulation of quark vacuum polarization has eluded theorists for several decades, thus limiting lattice QCD results to the so-called “quenched approximation.” A new unquenched approach, based on a Symanzik-improved staggered-quark formalism, bears the promise of precise predictions on some key observables.

The main ingredients of the new approach are: improved staggered quarks representing sea and valence quarks, chiral perturbation theory for staggered quarks and heavy quark effective theory (HQET) for the heavy quarks. This formalism is expected to deliver predictions soon on some “golden” physical quantities with errors of a few %. They are matrix elements that involve one hadron in the initial state and one or no stable hadrons in the final state, and they require that the chiral perturbation theory is “well-behaved” for the specific mode under consideration. Several processes relevant for the study of quark mixing fall in this category. Important examples include the leptonic decay constants \( f_{B(\ell)} \) and \( f_{D(\ell)} \) and semileptonic decay form factors. Checks on theory predictions for key “golden quantities” are under way and may validate the theory inputs for the corresponding quantities in beauty decays.

2 The decay constant \( f_{D^+} \).

CKM unitarity tests include constraints from \( B^0_{(s)} \bar{B}^0_{(s)} \) oscillations. The theoretical inputs, are \( \sqrt{B_f f_{B_s}} \), \( \sqrt{B_s f_{B_s}} \), or \( \xi = \sqrt{B_f f_{B_s}}/\sqrt{B_s f_{B_s}} \), where \( B_f \) represents the relevant “bag parameter”, the correction for the vacuum insertion approximation, and \( f_{B_s} \), represents the corresponding decay constant. It is thus important to validate the theoretical uncertainties, and a proposed strategy is to use the corresponding observables in \( D \) decays for this purpose. The decay \( D^+ \to \ell^+ \nu \) proceeds by the \( c \) and \( \bar{u} \) quarks annihilating into a virtual \( W^+ \), with a decay width given by:

\[ \Gamma(D^+ \to \ell^+ \nu) = \frac{G_F^2}{8\pi} f_D^2 m_\ell^2 M_{D^+} \left( 1 - \frac{m_\ell^2}{M_{D^+}^2} \right) \left| V_{cd} \right|^2, \]

where \( M_{D^+} \) is the \( D^+ \) mass, \( m_\ell \) is the mass of the final state lepton, \( \left| V_{cd} \right| \) is a CKM matrix element that we assume to be equal to \( \left| V_{us} \right| \), and \( G_F \) is the Fermi coupling constant. Due to helicity suppression, the rate goes as \( m_\ell^2 \), consequently the electron mode \( D^+ \to e^+ \nu \) has a very small rate in the Standard Model. The relative widths are \( 2.65 : 1 : 2.3 \times 10^{-5} \) for the \( \tau^+ \nu, \mu^+ \nu \) and \( e^+ \nu \) final states, respectively.

CLEO-c was the first experiment to have a statistically significant \( D^+ \to \mu \nu \) signal, and has now published an improved measure-
They use a tagging technique similar to that developed by the MARK III collaboration,1 where one D meson is reconstructed in a low background hadronic channel and the remaining tracks and showers are used to study a specific decay mode. The relatively high single tag yield makes this technique extremely useful. They reconstruct the $D^-$ meson in one of six different decay modes and search for $D^+ \rightarrow \mu \nu$ in the rest of the event. The existence of the neutrino is inferred by requiring the missing mass squared $(MM^2)$ to be consistent with zero. Here:

\[ MM^2 = (E_{\text{beam}} - E_{\mu^+})^2 - (\vec{p}_D - \vec{p}_{\mu^+})^2, \]

where $\vec{p}_D$ is the three-momentum of the fully reconstructed $D^-$. Events with additional charged tracks originating from the event vertex or unmatched energy clusters in the calorimeters with energy greater than 0.250 GeV are vetoed. These cuts are very effective in reducing backgrounds. Efficiencies are mostly determined using data, while backgrounds are evaluated either with large Monte Carlo samples or with data. Fig. 1 shows the measured $MM^2$, with a 50 event peak in the interval $[-0.050 \text{ GeV}^2, +0.050 \text{ GeV}^2]$, approximately $\pm 2\sigma$ wide. The background is evaluated as $2.81 \pm 0.30 \pm 0.27$ events. This implies:

\[ B(D^+ \rightarrow \mu^+ \nu_\mu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}. \]  

(5)

The decay constant $f_{D^+}$ is derived from Eq. 3 using $\tau_{D^+} = 1.040 \pm 0.007 \text{ ps}$,11 and $|V_{cs}| = 0.2238 \pm 0.0029^{+0.12}_{-0.11}$ yielding:

\[ f_{D^+} = (222.6 \pm 16.1^{+2.8}_{-3.4}) \text{ MeV}. \]

(6)

The same tag sample is used to search for $D^+ \rightarrow \epsilon^+ \nu_e$. No signal is found, corresponding to a 90% c.l upper limit $B(D^+ \rightarrow \epsilon^+ \nu_e) < 2.4 \times 10^{-5}$. These measurements are much more precise than previous observations or limits.13 The very small systematic error is achieved through very careful background and efficiency studies, involving large Monte Carlo and data samples.

Fig. 2 summarizes the present experimental data10,13 and the various theoretical predictions for the decay constant.14–21 The latest lattice QCD result, performed by the Fermilab lattice, MILC and HPQCD collaborations, working together,22 is the first to include three quark flavors fully unquenched and was published shortly before the CLEO-c updated result. It is consistent with the CLEO-c result with a 37% confidence level.

3 Semileptonic decays

The study of D meson semileptonic decays is another important area of investigation. In principle, charm meson semileptonic decays provide the simplest way to determine the magnitude of quark mixing parameters: the charm sector allows direct access to $|V_{cs}|$ and $|V_{cd}|$. Semileptonic decay rates are related to $|V_{cs}|^2$ via matrix elements that describe strong interactions effects. Traditionally, these hadronic matrix elements have been described in terms of form factors cast as a function of the Lorentz invariant $q^2$, the
invariant mass of the electron-\(\nu\) pair. Experimental determinations of these form factors are performed through the study of the differential decay width \(d\Gamma/dq^2\).

### 3.1 Goals in semileptonic decays

If we assume that \(V_{cs}\) and \(V_{cd}\) are known, experiments can determine the form factor shape as well as their normalization. Form factors have been evaluated at specific \(q^2\) points in a variety of phenomenological models,\(^{23}\) where the shape is typically assumed. More recently, lattice QCD calculations\(^{24}\) have predicted both the normalization and shape of the form factors in \(D \to K\ell\nu\) and \(D \to \pi\ell\nu\). Note, that we can form ratios between leptonic and exclusive semileptonic branching fractions that can provide direct theory checks without any \(CKM\) input.

On the other hand, if we use validated theoretical results as inputs, we can derive direct measurements for \(V_{cs}\) and \(V_{cd}\); the most accurate determinations of these parameters presently require some additional input information, such as unitarity. Thus we could extend the unitarity checks of the \(CKM\) matrix beyond the first row.

The study of charm semileptonic decays may contribute to a precise determination of the \(CKM\) parameter \(|V_{ub}|\). A variety of theoretical approaches have been proposed to use constraints provided by charm decays to reduce the model dependence in the extraction of \(|V_{ub}|\) from exclusive charmless \(B\) semileptonic decays. In particular, if HQET is applicable both to the \(c\) and \(b\) quarks, there is a \(SU(2)\) flavor symmetry that relates the form factors in \(D\) and \(B\) semileptonic decays.\(^{25}\) For example, a flavor symmetry relates the form factors in \(D \to \pi\ell\nu\) are related to the ones in \(B \to \pi\ell\bar{\nu}\), at the same \(E \equiv \mathbf{v} \cdot \mathbf{p}_\pi\), where \(\mathbf{v}\) is the heavy meson 4-velocity and \(\mathbf{p}_\pi\) is the \(\pi\) 4-momentum. The original method has been further refined;\(^{26}\) the large statistics needed to implement these methods may be available in the near future.

### 3.2 Semileptonic branching fractions: the data

BES-II\(^{27}\) and CLEO-c\(^{28}\) have recently presented data on exclusive semileptonic branching fractions. BES-II results are based on 33 \(pb^{-1}\); CLEO-c’s results are based on the first 57 \(pb^{-1}\) data set. Both experiments use tagged samples and select a specific final state.
Table 1. Summary of recent absolute branching fraction measurements of exclusive $D^+$ and $D^0$ semileptonic decays.

| Decay mode | B(%) [CLEO-c] | B(%) [BES] | B(%) [average] |
|------------|--------------|------------|----------------|
| $D^0 \rightarrow K^- e^+ \nu_e$ | 3.44 ± 0.10 ± 0.10 | 3.82 ± 0.40 ± 0.27 | 3.54 ± 0.11 |
| $D^0 \rightarrow \pi^- e^+ \nu_e$ | 0.262 ± 0.025 ± 0.008 | 0.33 ± 0.13 ± 0.03 | 0.285 ± 0.018 |
| $D^0 \rightarrow K^*^- e^+ \nu_e$ | 2.16 ± 0.15 ± 0.08 | | 2.14 ± 0.16 |
| $D^0 \rightarrow \rho^- e^+ \nu_e$ | 0.194 ± 0.039 ± 0.013 | | 0.194 ± 0.039 ± 0.013 |
| $D^+ \rightarrow K^0 e^+ \nu_e$ | 8.71 ± 0.38 ± 0.37 | | 8.31 ± 0.44 |
| $D^+ \rightarrow \pi^0 e^+ \nu_e$ | 0.44 ± 0.06 ± 0.03 | | 0.43 ± 0.06 |
| $D^+ \rightarrow K^{*0} e^+ \nu_e$ | 5.56 ± 0.27 ± 0.23 | | 5.61 ± 0.32 |
| $D^+ \rightarrow \rho^0 e^+ \nu_e$ | 0.21 ± 0.04 ± 0.01 | | 0.22 ± 0.04 |
| $D^+ \rightarrow \omega e^+ \nu_e$ | 0.16_{-0.06}^{+0.07} ± 0.01 | | 0.16_{-0.06}^{+0.06} |

The averages reported here include all the branching fractions reported in the PDG 2004 for $D \rightarrow X e^+ \nu_e$ and the CLEO-c and BES-II data. Indirect measurements are normalized with respect to the hadronic and average semileptonic branching ratios included in this report.

For signal events, $U$ is expected to be 0, while other semileptonic decays peak in different regions. Fig. 3 shows the $U$ distribution for 5 exclusive $D^+$ decay modes reported by CLEO-c, which demonstrate that $U$ resolution is excellent, thus allowing a full separation between Cabibbo suppressed and Cabibbo favored modes. Table 1 summarizes the recent measurements from CLEO-c and BES-II, as well world averages obtained from the results presented in this paper and the previous measurements of $B(D \rightarrow X e^+ \nu_e)$ reported in the PDG 2004.

CLEO-c uses the two tagging modes with lowest background ($D^0 \rightarrow K^+ \pi^-$ and $D^- \rightarrow K^+ \pi^- \pi^-$) to measure the inclusive $D^0$ and $D^+$ semileptonic branching fractions. Table 2 summarizes the measured semileptonic branching fractions, and it also includes the sum of the branching fractions for $D$ decay into all the known exclusive modes. The CLEO-c data have been used in this comparison, as they dominate the present world average: the exclusive modes are consistent with saturating the inclusive semileptonic branching fraction at a 41% confidence level in the case of the $D^+$ and 18% confidence level in the case of the $D^0$.

The preliminary inclusive branching frac-
tions can be translated into inclusive semileptonic widths $\Gamma^\ell_D$ and $\Gamma_0^\ell_D$, using the known $D$ lifetimes.\textsuperscript{11} These widths are expected to be equal, modulo isospin violations, and indeed the measured ratio $\Gamma^\ell_D/D^\star/D_0^\star = 1.01 \pm 0.03 \pm 0.03$; thus isospin violations are limited to be below $\sim 4\%$.

| Mode | $B$ (%) |
|------|--------|
| $(D^0 \to X\ell\nu_e)$ | $6.45 \pm 0.17 \pm 0.15$ |
| $\Sigma f_i B((D^0 \to X_i\ell\nu_e)$ | $6.1 \pm 0.2 \pm 0.2$ |
| $(D^+ \to X\ell\nu_e)$ | $16.19 \pm 0.20 \pm 0.36$ |
| $\Sigma f_i B((D^+ \to X_i\ell\nu_e)$ | $15.1 \pm 0.50 \pm 0.50$ |

Table 2. Comparison between exclusive\textsuperscript{28} and preliminary inclusive\textsuperscript{29} results from CLEO-c.

### 3.3 Form factors for $D \to K(\pi)\ell\nu$

Recently, non-quenched lattice QCD calculations for $D \to K\ell\nu$ and $D \to \pi\ell\nu$ have been reported.\textsuperscript{24} The chiral extrapolation is performed at fixed $E = \hat{v} \cdot \hat{p}_D$, where $E$ is the energy of the light meson in the center-of-mass $D$ frame, $\hat{v}$ is the unit 4-velocity of the $D$ meson, and $\hat{p}_D$ is the 4-momentum of the light hadron $P$ ($K$ or $\pi$). The results are presented in terms of a parametrization originally proposed by Becirevic and Kaidalov ($BK$):\textsuperscript{30}

\[
f_+(q^2) = \frac{F}{(1 - \hat{q}^2)(1 - \alpha q^2)}, \quad f_0(q^2) = \frac{F}{1 - \hat{q}^2 / \beta^2}, \tag{8}
\]

where $q^2$ is the 4-momentum of the electron-\nu pair, $\hat{q}^2 = q^2 / m_D^2$, and $F = f_+(0)$, $\alpha$ and $\beta$ are fit parameters. This formalism models the effects of higher mass resonances other than the dominant spectroscopic pole ($D_\pi^\star$) for the $K\ell\nu$ final state and $D^\star^\star$ for $\pi\ell\nu$.

The form factors $f_+(q^2)$ govern the corresponding semileptonic decays. The lattice QCD calculation obtains the parameters shown in Table 3.

The FOCUS experiment\textsuperscript{32} performed a non-parametric measurement of the shape of the form factor in $D \to K\mu\nu$. Fig. 4 shows the lattice QCD predictions for $D \to K\ell\nu$ with the FOCUS data points superimposed. In addition, they studied the shape of the form factors $f_+(q^2)$ for $D \to K\mu\nu$ and $D \to \pi\mu\nu$ with two different fitting functions: the single pole, traditionally used because of the conventional ansatz of several quark models,\textsuperscript{33} and the $BK$ parametrization discussed before. Table 4 shows the fit results obtained from FOCUS and CLEO III,\textsuperscript{31} compared to the lattice QCD predictions. Both experiments obtain very good fits also with simple pole form factors, however the simple pole fit does not yield the expected spectroscopic mass. For example, FOCUS obtains $m_{\text{pole}}(D^0 \to K\mu\nu) = (1.93 \pm 0.05 \pm 0.03) \text{ GeV/c}^2$ and $m_{\text{pole}}(D^0 \to \pi\mu\nu) = (1.91^{+0.30}_{-0.15} \pm 0.07) \text{ GeV/c}^2$, while the spectroscopic poles are, respectively, $2.1121 \pm 0.0007 \text{ GeV/c}^2$ and $2.010 \pm 0.0005$. This may hint that other higher order resonances are contributing to the form factors.\textsuperscript{31} It has been argued,\textsuperscript{35} that even the $BK$ parametrization is too simple and that a three parameter form factor is more appropriate. However, this issue can be resolved only by much larger data samples, with better sensitivity to the curvature of the form factor near the high recoil region.

By combining the information of the measured leptonic and semileptonic width, a ratio independent of $|V_{cd}|$ can be evaluated: this is a pure check of the theory. We evaluate the ratio $R = \sqrt{\Gamma(D^+ \to \mu\nu) / \Gamma(D^0 \to \pi e^+\nu_e)}$. We assume isospin symmetry, and thus $\Gamma(D \to \pi e^+\nu_e) = \Gamma(D^0 \to \pi^- e^+\nu_e) = 2 \Gamma(D^+ \to \pi^0 e^+\nu_e)$. For
the theoretical inputs, we use the recent unquenched lattice QCD calculations in three flavors,\textsuperscript{22,24} as they reflect the state of the art of the theory and have been evaluated in a consistent manner. The result is:

$$ R_{sl}^{th} = \sqrt{\frac{\Gamma_{th}(D^+ \rightarrow \mu \nu_{\mu})}{\Gamma_{th}(D \rightarrow \pi e \nu_e)}} = 0.212 \pm 0.028, $$

(9)

The quoted error is evaluated through a careful study of the theory statistical and systematic uncertainties, assuming Gaussian errors. The corresponding experimental quantity is calculated using the CLEO-c $f_D$ and isospin averaged $\Gamma(D \rightarrow \pi e \mu \nu_e)$; we obtain:

$$ R_{sl}^{exp} = \sqrt{\frac{\Gamma_{exp}(D^+ \rightarrow \mu \nu_{\mu})}{\Gamma_{exp}(D \rightarrow \pi e \nu_e)}} = 0.249 \pm 0.022. $$

(10)

The theory and data are consistent at 28\% confidence level, that represents a good agreement.

### 4 The CKM Matrix

An important goal of the next generation of precision experiments is to perform direct measurements of each individual parameter. This will enable us to perform additional unitarity checks with precision similar to the one achieved now with the first row.\textsuperscript{12} In particular, $V_{cs}$ and $V_{cd}$ are now determined with high precision, but using unitarity constraints.\textsuperscript{11}

The most recent results from LEP II, using the $W \rightarrow \ell \nu$ branching fraction, and additional inputs from other CKM parameter measurement is $V_{cs} = 0.976 \pm 0.014$.\textsuperscript{36} The unitarity constraint implies $V_{cd} \sim V_{us} = 0.2227 \pm 0.0017$.\textsuperscript{12}

If we use the theoretical form factors as inputs, we can extract $|V_{cs}|$ and $|V_{cd}|$ from the branching fractions reported in this paper. The results, obtained using the form factors from the unquenched lattice QCD calculation\textsuperscript{24} and the isospin averaged semileptonic widths from CLEO-c\textsuperscript{28} are:

$$ |V_{cs}| = 0.957 \pm 0.017 (exp) \pm 0.009 (th) $$

(11)

$$ |V_{cd}| = 0.213 \pm 0.008 (exp) \pm 0.021 (th) $$

(12)

A unitarity check derived uniquely from these measurements yields:

$$ 1 - |V_{cs}|^2 - |V_{cd}|^2 - |V_{cb}|^2 = 0.037 \pm 0.181 (tot). $$

(13)

The mean $V_{cd}$ and their errors have been derived from careful application of the theoretical quantities and their stated statistical and systematic errors.

These determinations are not yet competitive, but it will be interesting to see the results of future estimates, when the accuracy is comparable to the one achieved in the first row.

| Table 4. Measured shape parameter $\alpha$ compared to lattice QCD predictions. |
|---------------------------------|
| $\alpha(D^0 \rightarrow K \ell \nu)$ |
| lattice QCD\textsuperscript{24} | 0.5 ± 0.04 ± 0.07 |
| FOCUS\textsuperscript{12} | 0.28 ± 0.08 ± 0.07 |
| CLEOII\textsuperscript{33} | 0.36 ± 0.10\textsuperscript{+0.03}_{-0.07} |
| Belle\textsuperscript{34} | 0.40 ± 0.12 ± 0.09 |

| $\alpha(D^+ \rightarrow \pi \ell \nu)$ |
|---------------------------------|
| lattice QCD\textsuperscript{24} | 0.44 ± 0.04 ± 0.07 |
| CLEOII\textsuperscript{33} | 0.37\textsuperscript{+0.20}_{-0.31} ± 0.15 |
| Belle\textsuperscript{34} | 0.03 ± 0.27 ± 0.13 |

Figure 4. Shape of the form factor for $D \rightarrow K \ell \nu$.\textsuperscript{7} MILC-Fermilab calculation compared with the non parametric data from FOCUS.
5 Charm as a probe for New Physics

The study of charm decays provides a unique opportunity for indirect searches for physics beyond the Standard Model. In several dynamical models, the effects of new particles observed in c, s and b transitions are correlated. Possible new physics manifestations involve three different facets: $D^0\bar{D}^0$ oscillations, $CP$ violation and rare decays.

5.1 $D^0\bar{D}^0$ oscillations

Two main processes contribute to $D^0\bar{D}^0$ oscillations. The short distance physics effects are depicted by higher order Feynman diagrams, such box or loop diagrams that influence the mass difference $\Delta M$. These diagrams are sensitive to new physics, through the interference with contributions with similar topology including exotic particles in place of the $d, s, b$ quarks present in the Standard Model loop. In addition, there is a coupling between $D^0$ and $\bar{D}^0$ induced by common final states such as $K\bar{K}, \pi\pi$ and $K\bar{K}$. As the intermediate states are real, one conjectures that only the difference in lifetime $\Delta \Gamma$ is affected by this coupling. Thus, $\Delta \Gamma$ is expected to be dominated by Standard Model processes.

$D^0\bar{D}^0$ mixing has been studied with a variety of different experimental methods, several of which suffer from a variety of additional complications.

The first approach, which has been pursued by a variety of experiments, is the study of the “wrong-sign” hadronic decays such as $D^0 \rightarrow K^+\pi^-$. These decays occur via two paths: oscillation of $D^0$ into $\bar{D}^0$, followed by the Cabibbo favored $\bar{D}^0 \rightarrow K^+\pi^-$, or doubly Cabibbo suppressed decays $D^0 \rightarrow K^+\pi^-$. The two channels interfere and thus there is an additional parameter that affects the wrong-sign rate: the strong phase $\delta$ between $D^0 \rightarrow K^+\pi^-$ and $K^-\pi^+$ decays. Moreover it has been argued that $CP$ violation may have non negligible effects too. Thus experiments typically perform a variety of fits for the modified variables $x' \equiv x \cos \delta + y \sin \delta$ and $y' \equiv -x \sin \delta + y \cos \delta$, under different $CP$ violation assumptions. Table 5 summarizes the results of the most generic fit, allowing for a $CP$ violating term.

A second class of measurements involves the study of $y_{CP}$: namely the normalized lifetime difference of $D^0\bar{D}^0$ $CP$ eigenstates. In presence of $CP$ violation, $y_{CP}$ is a linear combination of $x$ and $y$ involving the $CP$ violation phase $\phi$. Table 6 summarizes experimental data on $y_{CP}$. The average is positive, although still consistent with 0.

The study of semileptonic $D$ decays allows the determination of another combination of mixing parameters. Experiments study the ratio $r_M$ defined as:

$$r_M = \frac{\int_0^\infty P(D^0 \rightarrow X^\ell \bar{\nu})}{\int_0^\infty P(D^0 \rightarrow X^\ell \nu)} \approx \frac{x^2 + y^2}{2}. \tag{14}$$

Table 7 summarizes the sensitivity achieved.

Table 5. $D^0 \rightarrow K^+\pi^-$ analysis. Only results of the fits allowing for $CP$ violation are included.

| Experiment | Fit Result ($\times 10^4$) |
|------------|-----------------------------|
| CLEO38     | $0 < x'^2 < 0.82$           |
| CLEO43     | $-58 < y' < 10$             |
| FOCUS39    | $0 < x^2 < 8$               |
| FOCUS39    | $-112 < y' < 67$ -          |
| Belle41    | $0 < x'^2 < 0.89$           |
| Belle40    | $-30 < y' < 27$             |
| BaBar41    | $0 < x'^2 < 2.2$            |
| BaBar41    | $-56 < y' < 39$             |

Table 6. Summary of $y_{CP}$ results.

| Experiment | $y_{CP}$ (%) |
|------------|--------------|
| FOCUS44    | $3.4 \pm 1.4 \pm 0.7$ |
| CLEO43     | $-1.2 \pm 2.5 \pm 1.4$ |
| Belle, untagged45 | $-0.5 \pm 1.0 \pm 0.8$ |
| Belle, tagged46    | $1.2 \pm 0.7 \pm 0.4$  |
| BaBar47    | $0.8 \pm 0.4_{-0.4}^{+0.5}$ |

Table 7 summarizes the sensitivity achieved.
Table 7. Summary of mixing limits (95 % cl) from $D^0$ semileptonic decay studies.

| Experiment | $R_M$ | $\sqrt{x^2 + y^2}$ |
|------------|-------|-----------------|
| CLEO       | 0.0091| 0.335           |
| BaBar      | 0.0046| 0.1             |
| Belle      | 0.0016| 0.056           |

by present experiments to $r_M$.

Finally, a very interesting analysis method has been implemented by the CLEO experiment: they have studied the channel $D^0 \rightarrow K_S^0 \pi^+ \pi^-$. Cabibbo favored final states, such as $K^+ \pi^-$, and doubly-Cabibbo suppressed channels, such as $K^+ \pi^-$ interfere. They generalize the methodology that they used to identify the resonance substructure of this decay$^{51}$ to the case where the time-dependent state is a mixture of $D^0$ and $D^0$.$^{52}$ In this case, the parameters $x$ and $y$ affect the time-dependent evolution of this system. This time-dependent Dalitz plot analysis can be used to extract the mixing and $CP$ violation parameters. They obtain ($-5.4 < x < 9.3)$% and ($-6.4 < y < 3.6)$%. It is interesting to note that this constraint has sensitivity comparable to other limits obtained from a much larger data sample.

5.2 $CP$ violation

Within the Standard Model, $CP$ violation effects in $D$ decays are expected to be negligible small, as they are introduced by box diagrams or penguin diagrams containing a virtual $b$ quark: thus they involve a strong $CKM$ suppression ($V_{cb} V_{ub}^*$). In contrast with the $D^0 \bar{D}^0$ mixing case, where the vast theoretical effort devoted to pin down the Standard Model predictions did not yield a clearcut result, there is a wide consensus that observing $CP$ violation in $D$ decays at a level much higher than $\mathcal{O}(10^{-3})$ will constitute an unambiguous signal of new physics. There is a vast array of studies that can be undertaken,$^4$ exploring $CP$ violation effects on mixing observables, searching for direct $CP$ violation effects in $D^0$, $D^+$ and $D^+_S$ decays and, finally, studies of $D \bar{D}$ pairs near threshold, that exploit the quantum coherence of these states.

In general, experimental sensitivity is $\mathcal{O}(1)$%.$^4$ Recent results from BaBar,$^{53}$ Belle$^{54}$, and CLEO$^{55}$ have explored $CP$ violation in 3-body $D$ decays. Babar obtains $A(D^+ \rightarrow K^- K^+ \pi^+) = (1.4 \pm 1.0 \pm 0.8)$%. CLEO obtains $A(D^0 \rightarrow \pi^+ \pi^- \pi^0) = (1 \pm 8^{+9}_{-7})%$. Belle obtains $A(D^0 \rightarrow K^+ \pi^- \pi^0) = (-0.6 \pm 5.3)$% and $A(D^0 \rightarrow K^+ \pi^- \pi^-) = (-1.8 \pm 4.4)%$.

A complementary approach involves the study of observables that are sensitive to $T$ violation,$^{56}$ such as triple product correlations in 4-body decays of $D^0$ and $D^+$. This technique has been pioneered by FOCUS,$^{57}$ through the study of triple product correlations in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$, $D^+ \rightarrow K_S^0 K^- \pi^+ \pi^-$, $D^0_5 \rightarrow K_S^0 K^- \pi^+ \pi^-$. Their present sensitivity is at the level of several percent, dominated by the statistical error. A significant improvement in the sensitivity of this technique is expected in future measurements.

6 Charm as a facet of beauty

The study of $b$ decays has been one of our richest sources of information about the Standard Model, as well as a very powerful constraint on new physics.

As the dominant tree level diagram includes the $b \rightarrow c$ transition, the precision of our knowledge of the $D$ decay phenomenology affects quantities associated with $B$ decays in a variety of ways. For example, the accuracy of the determination of $D$ hadronic branching fractions has an obvious impact on the absolute determination of $B$ hadronic branching fractions. Moreover, the study of specific $CP$ violation observables can be made more precise through ancillary information coming from $D$ decays. Finally, a precise
knowledge of the particle yields in $D$ decays, allow a more precise modelling of inclusive $B$ decays.

6.1 $D$ absolute branching fractions

Absolute measurements of $D$ meson branching fractions affect our knowledge of several many $D$ and $B$ meson decays, from which CKM parameters are extracted.

CLEO-c has employed tagged samples to obtain new values for the branching fractions $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and other modes. This powerful technique, combined with careful efficiency studies based on data, resulted in an accuracy comparable to the one of present world averages. They obtain:

$$B(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.09)\%,$$

and

$$B(D^+ \to K^-\pi^+\pi^+) = (9.5 \pm 0.2 \pm 0.3)\%$$

Corrections for final state radiation are included in these branching fractions.

6.2 $D \to K_S\pi^+\pi^-$ Dalitz plot analysis and the determination of the CKM phase $\gamma$.

The decay $B^\pm \to DK^\pm$ has been the subject of intense theoretical effort to devise optimal strategies to measure the CKM angle $\gamma$. The original proposal by Gronau, London and Wyler uses $D$ decays to $CP$ eigenstates. Subsequently Atwood, Dunietz and Soni critiqued this approach and proposed a method based on $D$ decays to flavor eigenstates. Finally, there is one method that has received a lot of attention recently, the extraction of $\gamma$ from a Dalitz plot analysis of $B^\pm \to D^{(*)}K^\pm \to K^\pm K_S\pi^+\pi^-$. Charm factories can help this measurement in a variety of manners: they can provide information on $D^0\bar{D}^0$ mixing, and measure the strong phase $\delta$ between the Cabibbo favored and doubly-Cabibbo suppressed $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^-\pi^+$, and perform unique $D$ Dalitz plot studies.

The Dalitz plot technique illustrates the contributions that CLEO-c and, later, BESIII can provide to reduce the uncertainty in this determination of the angle $\gamma$. This method is attractive because it involves a $D$ decay with a relatively large branching fraction. Moreover this three body final state comprises a very rich resonance substructure, that leads to the expectation of large strong phases. Recently both BaBar and Belle reported measurements on $\gamma$ (BaBar) − $\phi_3$ (Belle) with this method. They obtain:

$$\phi_3 = 77_{-13}^{+17} (\text{stat}) \pm 13^\circ (\text{sys}) \pm 11^\circ (\text{mod})$$

$$\gamma = 70^\circ \pm 26^\circ (\text{stat}) \pm 10^\circ (\text{sys}) \pm 10^\circ (\text{mod})$$

In both cases, the error labeled “mod,” refers to uncertainties on the resonance substructure of the $K_S\pi^+\pi^-$ Dalitz plot. Both collaborations find that to achieve a good fit they need to include two ad-hoc $\pi\pi$ s-wave resonances that describe about 10% of the data. The study of $CP$ tagged Dalitz plots allows a model dependent determination of the $D^0$ and $\bar{D}^0$ phase across the Dalitz plot. Using data samples where the $CP$ eigenstate ($S_\pm$) of the $D$ can be tagged, CLEO-c is studying the Dalitz plots $S_-K_S\pi^+\pi^-$, $S_-K_S\pi^+\pi^-$, as well as flavor tagged $K_S\pi^+\pi^-$ Dalitz plots. A simultaneous fit to these three Dalitz plots can validate Dalitz plot models and reduce the model dependence of these results significantly. Alternatively, a model independent result can be obtained from a binned analysis of the three $CP$ or flavor tagged Dalitz plot. This work is under way and should eventually reduce the model dependence to a couple of degrees.

7 Conclusions

Charm decays provide a rich phenomenology for a variety of important studies that improve our knowledge of several facets of the
Standard Model, and probe for signatures of new physics.

The experimental study of beauty and charm decays is prospering through vibrant experimental activity taking place in several ongoing experiments. The next few years will see an opening up of our vistas on these decays with the upcoming turn on of LHC and of a dedicated charm and beauty experiment at a hadron collider, LHCb. This experiment bears the promise of precision studies that are poised to explore thoroughly all the possible new physics manifestations alluded to in this paper.

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References

1. J. Adler et al. [Mark III] Phys. Rev. Lett. 60, 89 (1988).
2. R. A. Briere et al., CLNS-01-1742
3. W. G. Li [BES], Int. J. Mod. Phys. A 20, 1560 (2005).
4. A. A. Petrov, Nucl. Phys. Proc. Suppl. 142, 333 (2005) [arXiv:hep-ph/0409130].
5. L. Wolfenstein, Phys. Rev. Lett. 51, 1945 (1983).
6. P. Lepage and C. Davies, Int. J. Mod. Phys. A 19, 877 (2004).
7. A. S. Kronfeld et al., arXiv:hep-lat/0509169.
8. J.L. Rosner, in Proceedings of the 1988 Banff Summer Institute, edited by A.N. Kamal and F.C. Khanna (World Scientific, Singapore, 1989) p. 395.
9. G. Bonvicini et al. [CLEO], Phys. Rev. D 70, 112004 (2004); [arXiv:hep-ex/0411050].
10. M. Artuso et al. [CLEO], arXiv:hep-ex/0508057.
11. S. Edelman et al., Phys. Lett. B 592 (2004) 1.
12. U. Nierste, these proceedings.
13. J. Adler et al. [Mark III], Phys. Rev. Lett. 60, 1375 (1998); erratum-ibid, 63, 1658 (1989); J.Z. Bai et al. [BES], Phys. Lett. B 429, 188 (1998); M. Ablikim et al. [BES], Phys. Lett. B 610, 183 (2005).
14. T. W. Chiu et al., [hep-ph/0506266] (2005).
15. L. Lellouch and C.-J. Lin (UKQCD), Phys. Rev. D 64, 094501 (2001).
16. D. Becirevic et al., Phys. Rev. D 60, 074501 (1999).
17. S. Narison, in QCD as a Theory of Hadrons: From Partons to Confinement, Monograph series in Physics, S. Narison, T. Ericson editor; Cambridge Univ. Press (2003) [hep-ph/0202200].
18. A. Penin and M. Steinhauser, Phys. Rev. D 65, 054006 (2002).
19. D. Ebert et al., Mod. Phys. Lett. A17, 803 (2002).
20. Z. G. Wang et al., Nucl. Phys. A 744, 156 (2004); L. Salcedo et al., Braz. J. Phys. 34, 297 (2004).
21. J. Amundson et al., Phys. Rev. D 47, 3059 (1993).
22. C. Aubin et al., arXiv:hep-lat/0506030.
23. S. Stone in Heavy Flavours, ed. A.J. Buras and M. Lindner (World Scientific, Singapore, 1992).
24. C. Aubin et al., Phys. Rev. Lett. 94, 011601 (2005); [arXiv:hep-ph/0408306].
25. N. Isgur and M.B. Wise, Phys. Rev. D 42, 2388 (1990).
26. B. Grinstein and D. Pirjol, Phys. Rev. D 70, 114005 (2004) [arXiv:hep-ph/0404250].
27. M. Ablikim et al. [BES], Phys. Lett. B
608, 24 (2005) [arXiv:hep-ex/0410030];
M. Ablikim et al. [BES], Phys. Lett. B 597, 39 (2004) [arXiv:hep-ex/0406028].
28. T. E. Coan et al. [CLEO], arXiv:hep-ex/0506052; G. S. Huang et al. [CLEO],
arXiv:hep-ex/0506053.
29. Q. He et al., CLEO-CONF 05-3;
LP2005-429 (2005).
30. D. Becirevic and A. B. Kaidalov, Phys. Lett. B 478, 417 (2000); [arXiv:hep-
ph/9904490].
31. S. Fajfer and J. Kamenik, arXiv:hep-ph/0509166; and references therein.
32. J.M. Link et al. [FOCUS], Phys. Lett. B 607, 233 (2005) [arXiv:hep-ex/0410037].
33. G. S. Huang et al. [CLEO], Phys. Rev. Lett. 94, 011802 (2005) [arXiv:hep-
ex/0407035].
34. K. Abe et al. [Belle], arXiv:hep-ex/0510003 (2005).
35. R. J. Hill, arXiv:hep-ph/0505129.
36. http://lepewwg.web.cern.ch/LEPEWWG/lepww/4f/Winter05/
37. Y. Nir, arXiv:hep-ph/9911321.
38. R. Godang et al. [CLEO], Phys. Rev. Lett. 84, 5038 (2000) [arXiv:hep-
ex/0001060].
39. J. M. Link et al. [FOCUS], Phys. Lett. B 618, 23 (2005) [arXiv:hep-ex/0412034].
40. K. Abe et al. [BELLE], Phys. Rev. Lett. 94, 071801 (2005) [arXiv:hep-
ex/0408125].
41. B. Aubert et al. [BABAR], Phys. Rev. Lett. 91, 171801 (2003) [arXiv:hep-
ex/0304007].
42. L. Wolfenstein, Phys. Lett. B 144 (1984) 425.
43. S.E. Csorna et al. [CLEO], Phys. Rev. D 65, 092001 (2002).
44. J. Link et al. [FOCUS], Phys. Lett. B 485, 62 (2000).
45. K. Abe et al. [Belle], Phys. Rev. Lett. 88, 162001 (2002).
46. K. Abe et al.
47. B. Aubert et al. [BaBar], Phys. Rev. Lett. 91, 171801 (2003).
48. C. Cawlfield et al. [CLEO], Phys. Rev. D 71, 077101 (2005) [arXiv:hep-
ex/0502012].
49. B. Aubert et al. [BABAR], Phys. Rev. D 70, 091102 (2004) [arXiv:hep-
ex/0408066].
50. K. Abe et al. [Belle], arXiv:hep-
ex/0507020.
51. H. Muramatsu et al. [CLEO], Phys. Rev. Lett. 89, 251802 (2002) [Erratum-
ibid. 90, 059901 (2003)] [arXiv:hep-
ex/0207067].
52. D. M. Asner [CLEO], Phys. Rev. D 72, 012001 (2005) [arXiv:hep-ex/0503045].
53. B. Aubert et al. [BABAR], Phys. Rev. D 71, 091101 (2005) [arXiv:hep-
ex/0501075].
54. X. C. Tian et al. [Belle], arXiv:hep-
ex/0507071 (2005).
55. D. Cronin-Hennessy et al. [CLEO], Phys. Rev. D 72, 031102 (2005)
[arXiv:hep-ex/0503052].
56. I.I. Bigi, in KAON2001: International Conference on CP Violation, 2001;
[arXiv:hep-ph/0107102].
57. J. M. Link et al. [FOCUS], Phys. Lett. B 622, 239 (2005) [arXiv:hep-ex/0506012].
58. Q. He et al. [CLEO], Phys. Rev. Lett. 95, 121801 (2005) [arXiv:hep-
ex/0504003].
59. M. Gronau and D. Wyler, Phys. Lett. B 265, 172 (1991); M. Gronau and D.
London, Phys. Lett. B 253, 483 (1991).
60. D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. 78, 3257 (1997); D.
Atwood, I. Dunietz and A. Soni, Phys. Rev. D 63, 036005 (2001).
61. A. Giri, Y. Grossman, A. Soffer and J. Zupan, Phys. Rev. D 68, 054018 (2003).
62. B. Aubert et al. [BABAR], arXiv:hep-
ex/0507101.
63. K. Abe et al. [Belle], arXiv:hep-
ex/0504013 (2005).
64. D. Asner, CLEO CONF 05-12 (2005).
65. J. Rosner [CLEO], arXiv:hep-ex/0508024 (2005).