Charm Decays within the Standard Model and Beyond

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Abstract. Charm decay studies provide unique Standard Model tests and may open up new physics perspectives. Significant improvements in our knowledge of these decays are being gained through a variety of experimental approaches. In parallel, new theoretical developments strive towards more precise evaluations of the matrix elements needed to relate these data to fundamental quark-level quantities. The complex interplay between theoretical and experimental progress is reviewed, as well as important contributions provided by charm meson data to our understanding of b-meson decay phenomenology.

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INTRODUCTION

Charm meson decays are important tools to explore different facets of the Standard Model and offer unique opportunities to search for new physics signatures. 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 [1]. Later, higher energy machines, either fixed target experiments operating at hadron machines or higher energy e^+e^- colliders, entered this arena. 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 [2] at CESR, has collected a sample of 281 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 fb^{-1} at the $\psi(3770)$ and a similar size sample at an energy optimal to study D_S decays, near 4170 MeV. The BES-II experiment, at BEPC, has published results based on 33 pb^{-1} accumulated around the $\psi(3770)$. It has an ongoing upgrade program both for the detector (BESIII) and the machine (BEPCII), designed as a charm factory with 10^{33}cm^{-2}s^{-1} peak luminosity [3].

The charm mass ($\mathcal{O}(1.5)$ GeV) makes it an ideal laboratory to probe non-perturbative QCD. 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. Once full QCD calculations (for example, unquenched lattice calculations) have demonstrated that hadronic uncertainties are well understood, 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 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 violating phases in D decays, beyond the 10^{-3} level generally predicted within the Standard Model [4].

The charge-changing transitions involving quarks feature a complex pattern, that is summarized by a 3×3 unitary matrix, the Cabibbo-Kobayashi-Maskawa (*CKM*) matrix [5]. It is described by four independent real parameters, that are fundamental constant of nature, just as basic as G, Newton's constant, or α_{EM} and thus need to be measured by experiments. Charm and beauty decays play a key role, but hadronic matrix elements need to be evaluated to extract quark-mixing 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 [6], bears the promise of precise predictions on some key observables [7]. 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 [7]. This formalism is striving to predict some "golden" physical quantities with few percent errors. Several processes relevant for the study of quark mixing fall in this category. Important examples include the leptonic decay constants $f_{B_{(s)}}$ and $f_{D_{(s)}}$ and semileptonic decay form factors. Checks on theory predictions for key "golden quantities" are under way [2, 3] and may provide some insight on the theory inputs for the corresponding quantities in beauty decays.

THE DECAY CONSTANT f_{D^+}.

The decay $D^+ \to \ell^+ \nu$ proceeds by the c and $\overline{d}$ quarks annihilating into a virtual W^+, with a decay width [8] given by:

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

where M_{D^+} is the D^+ mass, m_ℓ is the mass of the final state lepton, $|V_{cd}|$ is a *CKM* matrix element that we assume to be equal to $|V_{us}|$, and G_F is the Fermi coupling constant. Due to helicity suppression, the rate goes as m_ℓ^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 detect a statistically significant $D^+ \to \mu \nu$ signal [9], and subsequently published an improved measurement of f_{D^+} [10]. 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.[1] They reconstruct the D^- meson in one of six different decay modes and search for $D^+ \to \mu^+ \nu$ in the rest of the event. The

[1] Throughout this paper charge conjugate particles are implied unless specifically noted.

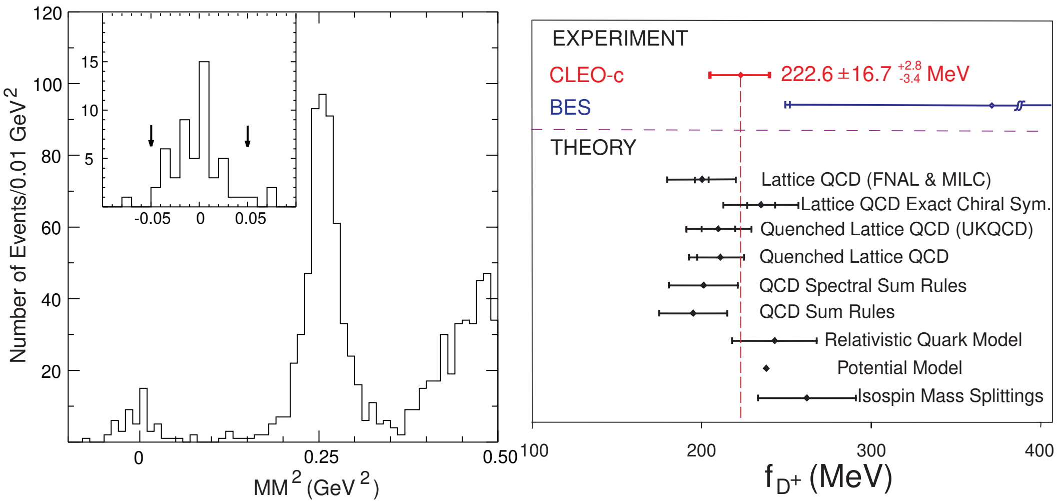

FIGURE 1. (left) CLEO-c MM^2 using D^- tags and one opposite charged track with no extra energetic clusters.[10] The insert shows the signal region for $D^+ \to \mu^+\nu_\mu$ enlarged; the defined signal region is shown between the two arrows; (right) the measured f_{D^+} compared with theoretical predictions. The theory value labelled FNAL-MILC is presented in Ref. [22]. The next points correspond to Refs. [14]-[21] in the same order.

existence of the neutrino is inferred by requiring the missing mass squared (MM^2) to be consistent with zero, where $MM^2 = (E_{beam} - E_{\mu^+})^2 - (-\vec{p}_{D^-} - \vec{p}_{\mu^+})^2$, and $\vec{p}_{D^-}$ 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 GeV^2, +0.050 GeV^2], approximately $\pm 2\sigma$ wide. The background is evaluated as $2.81 \pm 0.30 \pm 0.27$ events. Their result is $\mathscr{B}(D^+ \to \mu^+\nu_\mu) = (4.40 \pm 0.66^{+0.09}_{-0.12}) \times 10^{-4}$.

The decay constant f_{D^+} is derived from Eq. 1 using $\tau_{D^+} = 1.040 \pm 0.007$ ps [11], and $|V_{cd}| = 0.2238 \pm 0.0029$ [12], yielding $f_{D^+} = (222.6 \pm 16.7^{+2.8}_{-3.4})$ MeV. The same tag sample is used to search for $D^+ \to e^+\nu_e$. No signal is found, corresponding to a 90% cl upper limit $\mathscr{B}(D^+ \to e^+\nu_e) < 2.4 \times 10^{-5}$. These measurements are much more precise than previous observations or limits [13].

Fig. **??** summarizes the present experimental data [10], [13] and the various theoretical predictions for the decay constant [14-22]. 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 simultaneously with the CLEO-c updated result. Their result, $f_{D^+} = (201 \pm 3 \pm 17)$ MeV, is consistent with the CLEO-c measurement with a 37% confidence level.

SEMILEPTONIC DECAYS

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 $|V_{cx}|^2$ 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-ν pair. Experimental determinations of these form factors are performed through the study of the differential decay width $d\Gamma/dq^2$.

If we assume that V_{cs} and V_{cd} are known, either from *CKM* unitarity or other experiments, semileptonic data 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 π 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.

TABLE 1. CLEO-c branching fractions and new World averages.

D^+ Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) Avg	D^0 Mode	$\mathcal{B}$ (%)	$\mathcal{B}$ (%) Avg
$\bar{K}^0 e^+\nu_e$	$8.71\pm0.38\pm0.37$	8.31 ± 0.44	$K^- e^+\nu_e$	3.44±0.10±0.10	3.54±0.11
$\pi^0 e^+\nu_e$	$0.44\pm0.06\pm0.03$	0.43 ± 0.06	$\pi^- e^+\nu_e$	0.262±0.025±0.008	0.285±0.018
$\bar{K}^{*0} e^+\nu_e$	$5.56\pm0.27\pm0.23$	5.61 ± 0.32	$K^{*-} e^+\nu_e$	2.16±0.15±0.08	2.14±0.16
$\rho^0 e^+\nu_e$	$0.21\pm0.04\pm0.01$	0.22 ± 0.04	$\rho^- e^+\nu_e$	0.194±0.039±0.013	0.194±0.41
$\omega e^+\nu_e$	$0.16^{+0.07}_{-0.06}\pm0.01$	$0.16^{+0.07}_{-0.06}$			

Semileptonic branching fractions

BES-II [27] and CLEO-c [28] have recently published data on exclusive semileptonic branching fractions. BES-II results are based on 33 pb^{-1}; CLEO-c's results are based on 57 pb^{-1}.

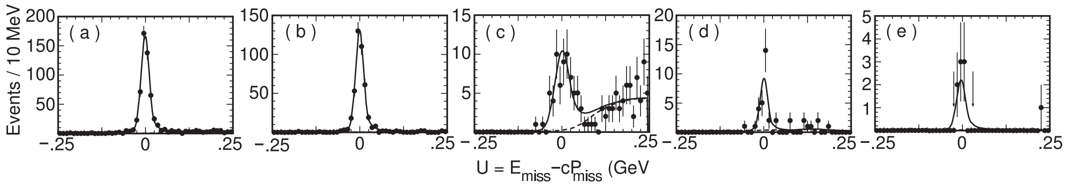

FIGURE 2. Fits (solid lines) to the U distributions in CLEO-c[28] data (dots with error bars) for the five D^+ semileptonic modes: (a) $D^+ \to \bar{K}^0 e^+ \nu_e$, (b) $D^+ \to \bar{K}^{\star 0} e^+ \nu_e$, (c) $D^+ \to \pi^0 e^+ \nu_e$, (d) $D^+ \to \rho^0 e^+ \nu_e$, (e) $D^+ \to \omega e^+ \nu_e$. The arrows in (e) show the signal region. The background (in dashed lines) is visible only in (c) and (d).

The variable $U \equiv E_{miss} - |c\vec{p}_{miss}|$, where E_{miss} and $\vec{p}_{miss}$ represent the missing energy and momentum of the D meson decaying semileptonically, is used to select signal events. This variable is a non Lorentz invariant version of MM^2. Fig. 2 shows the U distribution for 5 exclusive D^+ decay modes reported by CLEO-c, with clear signal peaks near U=0 in all the five channels. Table 1 summarizes the recent data, as well world averages obtained from the results presented in this paper and the previous measurements of $\mathscr{B}(D \to X_i e^+ \nu_e)$ reported in the PDG 2004 [11].

CLEO-c uses the two tagging modes with lowest background ($\bar{D}^0 \to K^+\pi^-$ and $D^- \to K^+\pi^-\pi^-$) to measure the inclusive D^0 and D^+ semileptonic branching fractions [29]. They obtain $\mathscr{B}(D^0 \to X\ell\nu_e) = 6.45 \pm 0.17 \pm 0.15$ and $\mathscr{B}(D^+ \to X\ell\nu_e) = 16.19 \pm 0.20 \pm 0.36$. The corresponding sums of exclusive branching fractions are: $\Sigma_i \mathscr{B}((D^0 \to X_i\ell\nu_e) = 6.1 \pm 0.2 \pm 0.2$ and $\Sigma_i \mathscr{B}((D^+ \to X_i\ell\nu_e) = 15.1 \pm 0.50 \pm 0.50$: the measured exclusive modes are consistent with saturating the inclusive widths, although there is some room left for higher multiplicity modes.

The preliminary inclusive branching fractions can be translated into inclusive semileptonic widths Γ_{D^+} and Γ_{D^0}, using the known D lifetimes [11]. These widths are expected to be equal, modulo isospin violations, and indeed the measured ratio $\Gamma^{sl}_{D^0}/\Gamma^{sl}_{D^+} = 1.01 \pm 0.03 \pm 0.03$: thus isospin violations are limited to be below $\sim 4\%$.

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

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

$$f_+(q^2) = \frac{F}{(1-\tilde{q}^2)(1-\alpha\tilde{q}^2)};\ f_0(q^2) = \frac{F}{1-\tilde{q}^2/\beta}, \tag{2}$$

where q^2 is the 4-momentum of the electron-ν pair, $\tilde{q}^2 = q^2/m^2_{D^*_x}$, and $F = f_+(0)$, α and β are fit parameters. This formalism models the effects of higher mass resonances other than the dominant spectroscopic pole ($D_S^{\star+}$ for the $K\ell\nu$ final state and $D^{\star +}$ for $\pi\ell\nu$ [31].

Table 2 shows the fit results obtained from FOCUS [32], CLEO III [33], and Belle [34], compared to the lattice QCD predictions [24]. In addition, all these experiments perform a single pole fit, traditionally used because of the conventional ansatz of several quark models [23], and the BK parametrization discussed before. These 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 $m_{pole}(D^0 \to K\mu\nu_\mu) = (1.93 \pm 0.05 \pm 0.03)$ GeV/c^2 and $m_{pole}(D^0 \to \pi\mu\nu_\mu) = (1.91^{+0.30}_{-0.15} \pm 0.07)$ GeV/c^2, while the spectroscopic poles are, respectively, 2.1121 ± 0.0007 GeV/c^2 and 2.010 ± 0.0005. This may hint that other higher order resonances are contributing to the form factors [31]. It has been argued [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.

TABLE 2. Measured shape parameter α compared to lattice QCD predictions.

	$\alpha(D^0 \to K\ell\nu)$	$\alpha(D^0 \to \pi\ell\nu)$
lattice QCD [24]	$0.5 \pm 0.04 \pm 0.07$	$0.44 \pm 0.04 \pm 0.07$
FOCUS [32]	$0.28 \pm 0.08 \pm 0.07$	
CLEOIII [33]	$0.36 \pm 0.10^{+0.03}_{-0.07}$	$0.37^{+0.20}_{-0.31} \pm 0.15$
Belle [34]	$0.40 \pm 0.12 \pm 0.09$	$0.03 \pm 0.27 \pm 0.13$

By combining the information of the measured leptonic and semileptonic widths, a ratio $R_{sl} = \sqrt{\frac{\Gamma(D^+ \to \mu^+\nu_\mu)}{\Gamma(D \to \pi e\nu_e)}}$, independent of $|V_{cd}|$, can be evaluated: this is a pure check of the theory. 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 [22, 24], as they reflect the state of the art of the theory and have been evaluated in a consistent manner. The theory ratio is $R^{th}_{sl} = \sqrt{\frac{\Gamma^{th}(D^+ \to \mu^+\nu_\mu)}{\Gamma^{th}(D \to \pi e\nu_e)}} = 0.212 \pm 0.028$. The quoted error is evaluated through a careful study of the theory statistical and systematic uncertainties, assuming Gaussian errors. The corresponding experimental R^{exp}_{sl} is calculated using the CLEO-c f_D and isospin averaged $\Gamma(D \to \pi e^+\nu_e)$: $R^{exp}_{sl} = \sqrt{\frac{\Gamma^{exp}(D^+ \to \mu^+\nu)}{\Gamma^{exp}(D \to \pi e\nu_e)}} = 0.249 \pm 0.022$. The theory and data are in good agreement, though the errors are still at the 10 percent level.

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 [36]. 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: $\mathscr{B}(D^0 \to K^-\pi^+) = (3.91 \pm 0.08 \pm 0.09)\%$, and $\mathscr{B}(D^+ \to K^-\pi^+\pi^+) = (9.5 \pm 0.2 \pm 0.3)\%$ Corrections for final state radiation are included in these branching fractions.

CHARM AS A PROBE FOR NEW PHYSICS

The study of charm decays provides a unique opportunity to search for physics beyond the Standard Model. In several dynamical models, the effects of new particles observed in c, s and b transitions are correlated [4, 37]. Possible new physics manifestations involve three different facets: $D^0\bar{D}^0$ oscillations, CP violation and rare decays.

$D^0\bar{D}^0$ 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 ΔM. 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 $K\pi$. 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 haw been studied with a variety of different experimental methods, several of which suffer from a variety of additional complications. The strongest hint for $D^0\bar{D}^0$ mixing is the lifetime difference between the CP-even and CP-odd states [38]:

$$y_{CP} = \frac{\Gamma(CP\text{ even}) - \Gamma(CP\text{ odd})}{\Gamma(CP\text{ even}) + \Gamma(CP\text{ odd})} = (0.9 \pm 0.4)\% \tag{3}$$

Unfortunately, the result is still consistent with 0 and even the central value, should the error decrease significantly, could not be interpreted as a sign of new physics because of hadronic uncertainties [39].

An illustration of the intricacies of $D^0\bar{D}^0$ mixing measurements is the study of the “wrong-sign" hadronic decays such as $D^0 \to K^+\pi^-$, which has been pursued by a variety of experiments [40, 41, 42, 43]. These decays occur via two paths: oscillation of D^0 into $\bar{D}^0$, followed by the Cabibbo favored $\bar{D}^0 \to K^+\pi^-$, or doubly Cabibbo suppressed decays $D^0 \to K^+\pi^-$. The two channels interfere and thus there is an additional parameter that affects the wrong-sign rate: the strong phase δ between $D^0 \to K^+\pi^-$ and $K^-\pi^+$ decays. Moreover it has been argued [44] 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 3 summarizes the results of the most generic fit, allowing for a CP violating term.

Experiments operating at threshold can provide unique insights into this complex problem by measuring the strong phase δ through measurements that exploit the quantum correlations between the D and $\bar{D}$ produced through the $\psi(3770)$ resonance [45].

TABLE 3. $D^0 \to K^+\pi^-$ analysis. Only fit results allowing for *CP* violation are shown.

Experiment	Fit Results ($\times 10^3$)	
CLEO [40]	$0 < x'^2 < 0.82$	$-58 < y' < 10$
FOCUS [41]	$0 < x'^2 < 8$	$-112 < y' < 67$
Belle [42]	$0 < x'^2 < 0.89$	$-30 < y' < 27$
BaBar [43]	$0 < x' < 2.2$	$-56 < y' < 39$

The pair is in a $C = -1$ eigenstate, thus some selection rules on their decays apply. For example, both D^0 and $\bar{D}^0$ cannot decay to *CP* eigenstates with the same value. CLEO-c, using 281 pb^{-1} taken at this center-of-mass energy, obtains a preliminary value of $\cos\delta = 1.09 \pm 0.66$ [46]. Future improvements will be achieved by adding more *CP* eigenstate modes, more data, and higher energy data using $D^0\bar{D}^0\gamma$ events, where the $D^0\bar{D}^0$ pair is in a $C = +1$ eigenstate.

A completely new approach been implemented by CLEO: they have studied the Dalitz plot of $D^0 \to K_S^0\pi^+\pi^-$. Cabibbo favored substructures, such as $K^{\star -}\pi^+$, and doubly-Cabibbo suppressed channels, such as $K^{\star +}\pi^-$ interfere. They generalize the methodology that they used to identify the resonance substructure of this decay [47] to the case where the time-dependent state is a mixture of D^0 and $\bar{D}^0$ [48]. 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 $(-4.5 < x < 9.3)\%$ 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 samples.

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 $(V_{cb}V_{ub}^\star)$. 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 clear-cut result, there is a wide consensus that observing *CP* violation in D decays at a level much higher than $\mathscr{O}(10^{-3})$ 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, the current experimental sensitivity is $\mathscr{O}(1)\%$ [4]. Recent results from BaBar [49], Belle [50], and CLEO [51] have explored *CP* violation in 3-body D decays. Babar obtains $\mathscr{A}(D^+ \to K^-K^+\pi^+) = (1.4 \pm 1.0 \pm 0.8)\%$. CLEO obtains $\mathscr{A}(D^0 \to \pi^+\pi^-\pi^0) = (1 \pm 8^{+9}_{-7})\%$. Belle obtains $\mathscr{A}(D^0 \to K^+\pi^-\pi^0) = (-0.6 \pm 5.3)\%$ and $\mathscr{A}(D^0 \to K^+\pi^-\pi^+\pi^-) = (-1.8 \pm 4.4)\%$.

A complementary approach involves the study of observables that are sensitive to T

violation [52], such as triple product correlations in 4-body decays of D^0 and D^+. This technique has been pioneered by FOCUS [53], through the study of triple product correlations in $D^0 \to K^+K^-\pi^+\pi^-$, $D^+ \to K^0_S K^-\pi^+\pi^-$, $D^0_S \to K^0_S K^-\pi^+\pi^-$. 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.

$D \to K_S\pi^+\pi^-$ DALITZ PLOT ANALYSIS AND THE DETERMINATION OF THE *CKM* PHASE γ.

The decay $B^\pm \to DK^\pm$ has been the subject of intense theoretical effort to devise optimal strategies to measure the *CKM* angle γ. The original proposal by Gronau, London and Wyler [54] uses D decays to *CP* eigenstates. Subsequently Atwood, Dunietz and Soni [55] 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 [56], the extraction of γ from a Dalitz plot analysis of $B^\pm \to D^{(\star)}K^\pm \to K^\pm K_S\pi^+\pi^-$. Charm factories can help this measurement in a variety of ways: they can provide information on $D^0\bar{D}^0$ mixing, measure the strong phase δ 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 γ. 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 [57] and Belle [58] reported measurements on γ (BaBar) $-$ ϕ_3 (Belle) with this method. They obtain (in degrees) $\phi_3 = 77^{+17}_{-19}$ (stat) ± 13 (sys) ± 11 (mod) and $\gamma = 67 \pm 28(\text{stat}) \pm 13(\text{sys}) \pm 11(\text{mod})$.

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 ($\mathscr{S}_\pm$) of the D can be tagged, CLEO-c is studying the Dalitz plots $\mathscr{S}_- K_S\pi^+\pi^-$, $\mathscr{S}_+ K_S\pi^+\pi^-$, as well as flavor tagged $K_S\pi^+\pi^-$ Dalitz plots. A simultaneous fit to these three Dalitz plots can reduce the model dependence to a couple of degrees [59].

CONCLUSIONS

Charm decays provide a rich phenomenology for a variety of important studies on 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 start of a dedicated charm and beauty experiment at a hadron collider, LHCb. This experiment is poised to explore thoroughly all the possible new physics manifestations alluded to in this paper.

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