Non-leptonic D^0, D^+, and D_s^+ Branching Fractions

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Introduction

Non-leptonic charm decays provide insights into both electro-weak and strong dynamics. This includes the study of long-distance hadronic effects, the approximate symmetries of strong interactions, and precision tests of the Standard Model.

In these proceedings we summarise recent results in non-leptonic branching fraction measurements of D^0, $D^{\pm}$, and $D_s^{\pm}$ mesons, including measurements of relative and absolute branching fractions in inclusive and exclusive modes, radiative decays, and measurements of direct CP violation. Other aspects of hadronic charm decays are covered elsewhere in these proceedings [1, 2, 3, 4, 5, 6, 7, 8, 9].

Charm decays to two pseudoscalars

CLEO-c has recently published the results of branching fractions of D^0, D^+, and D_s decays to two pseudoscalars, based on an analysis of CLEO-c's full data set [10], with $818\,\mathrm{pb}^{-1}$ at $\psi(3770)$ corresponding to $3{\cdot}10^6$ $D^0\bar{D}^0$ pairs and $2.4{\cdot}10^6$ D^+D^- pairs; and $586\,\mathrm{pb}^{-1}$ at $\sqrt{s} = 4170\,\mathrm{MeV}$ corresponding to $5.3{\cdot}10^5$ $D_s^{\pm}D_s^{\mp *}$ pairs. Many of the resulting branching fraction measurements are more precise than the previous world average [12], and some decay modes have been seen for the first time. These results are summarised in Tab. 6 on page 7. In the table, as in the rest of this paper, the mention of one decay process always implies also the charge-conjugate process, and if a number is given with two uncertainties, the first refers to the statistical and the second to the systematic uncertainty. Bhattacharya & Rosner [11] have analysed these results in terms of the diagrammatic approach [13, 14, 15, 16]. The decay amplitudes are expressed in terms of topological quark-flow diagrams; the diagrams used in this analysis are given in Fig. 1. These are not to be confused with Feynman diagrams. The amplitude represented by each diagram includes the contributions from the weak and the strong interaction, to all orders, including long-distance effects. Flavour symmetries of the strong interaction are used to express different D^0, $D^{\pm}$ and $D_s^{\pm}$ two-body decay amplitudes in terms of the same set of six diagrams. Note that, because the amplitudes associated to each diagram include final state interaction, the amplitudes established from two body decays do not predict amplitudes for decays to three or more particles in the final state. The expressions for Cabibbo-favoured (CF) decays in terms of these diagrams are given in Tab. 3. The singlet contributions to these decays are deemed to be negligible. The table compares the measured branching fractions with the result from the best-fit to the quark flow diagram formalism for two solutions. One where the octet-singlet mixing angle θ_η is fixed to $\theta_\eta = \arcsin(1/3) = 19.5^o$, and another, where θ_η is allowed to vary, giving $\theta_\eta = 11.7^o$. The latter case has as many parameters as there are CF decay rates used as constraints, so the agreement between the prediction from the formalism given in the fifth column of Tab. 3, and the measured CF amplitudes given in the second, is exact by construction. A further solution, with $|T| < |C|$, is also discussed in the paper [11]. Figure 2 shows the construction of the amplitudes from the rates given in Tab. 3 for the case for the $\theta_\eta = 11.7^o$ case. The numerical values are

$$\begin{aligned} T &= 3.003 \pm 0.023 \\ C &= (2.565 \pm 0.030)\, \exp\left[i(-152.11 \pm 0.57)^\circ\right] \\ E &= (1.372 \pm 0.036)\, \exp\left[i(123.62 \pm 1.25)^\circ\right] \\ A &= (0.452 \pm 0.058)\, \exp\left[i(19^{+15}_{-14})^\circ\right] \end{aligned}$$

These results are then used to predict the decay amplitudes of singly Cabibbo suppressed (SCS) and doubly Cabibbo suppressed (DCS) two body decays by assuming that the

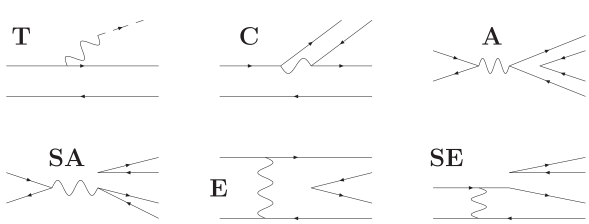

Figure 1: Quark flow diagrams used in the analysis of CLEO-c's $D \to PP$ data [10] by Bhattacharya & Rosner [11]: **T**ree, **C**olour-suppressed tree, **A**nnihiliation, **S**inglet-emission with **A**nnihilation, **E**xchange, and **S**inglet-emission with **E**xchange.

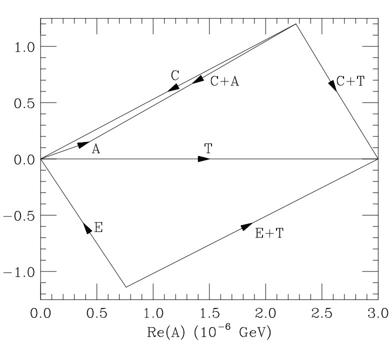

Figure 2: Construction of topological amplitudes in the complex plane based on CLEO-c's recent measurements [10] of for the solution with $\theta_\eta = 11.7^o$, reproduced from [11].

Figure 3: Branching ratios and quark-flow diagram amplitudes for Cabibbo-favored decays of charmed mesons to a pair of pseudoscalars with 2 different values of θ_η, reproduced from [11].

Meson	Decay mode	$\mathcal{B}$ [10] (%)	Rep.	Predicted $\mathcal{B}$ (%) $\theta_\eta = 11.7°$	$\theta_\eta = 19.5°$
D^0	$K^-\pi^+$	3.891±0.077	$T+E$	3.891	3.905
	$\overline{K}^0\pi^0$	2.380±0.092	$(C-E)/\sqrt{2}$	2.380	2.347
	$\overline{K}^0\eta$	0.962±0.060	$\frac{C}{\sqrt{2}}\sin(\theta_\eta+\phi_1) - \frac{\sqrt{3}E}{\sqrt{2}}\cos(\theta_\eta+2\phi_1)$	0.962	1.002
	$\overline{K}^0\eta'$	1.900±0.108	$-\frac{C}{\sqrt{2}}\cos(\theta_\eta+\phi_1) - \frac{\sqrt{3}E}{\sqrt{2}}\sin(\theta_\eta+2\phi_1)$	1.900	1.920
D^+	$\overline{K}^0\pi^+$	3.074±0.097	$C+T$	3.074	3.090
D_s^+	$\overline{K}^0K^+$	2.98±0.17	$C+A$	2.980	2.939
	$\pi^+\eta$	1.84±0.15	$T\cos(\theta_\eta+\phi_1) - \sqrt{2}A\sin(\theta_\eta+\phi_1)$	1.840	1.810
	$\pi^+\eta'$	3.95±0.34	$T\sin(\theta_\eta+\phi_1) + \sqrt{2}A\cos(\theta_\eta+\phi_1)$	3.950	3.603

SCS (DCS) amplitudes are the CF amplitudes, scaled by a factor $\lambda = \sin\theta_c$ ($\lambda^2 = \sin^2\theta_c$) where θ_c is the Cabibbo angle. The predictions for decays involving kaons and pions only are mostly in reasonable agreement with measurement although the approach considerably overestimates $\mathcal{B}\left(\mathrm{D}^0 \to \pi^+\pi^-\right)$ and underestimates $\mathcal{B}\left(\mathrm{D}^0 \to \mathrm{K}^+\mathrm{K}^-\right)$. For SCS decays involving η and η', there are indications for a non-negligible contribution from the singlet annihilation diagram.

A detailed description of this approach and its result can be found in [11] and [13, 14, 15, 16]. A comprehensive review of hadronic charm decays and their analysis using this and other methods can be found in [17].

$\mathbf{K^0}$, $\mathbf{\bar{K}^0}$ interference

As pointed out by Bigi & Yamamoto [18], the decay rates of $\mathrm{D}^0 \to \mathrm{K_S}\pi^0$ and $\mathrm{D}^0 \to \mathrm{K_L}\pi^0$ are not the same because of the interference of the CF component $\mathrm{D}^0 \to \bar{\mathrm{K}}^0\pi^0$ with the DCS $\mathrm{D}^0 \to \mathrm{K}^0\pi^0$ component which enters with a different sign for decays to $\mathrm{K_L}$ and $\mathrm{K_S}$:

$$A\left(\mathrm{D}^0 \to \mathrm{K_S}\pi^0\right) = A\left(\mathrm{D}^0 \to \bar{\mathrm{K}}^0\pi^0\right) + A\left(\mathrm{D}^0 \to \mathrm{K}^0\pi^0\right)$$
$$A\left(\mathrm{D}^0 \to \mathrm{K_L}\pi^0\right) = A\left(\mathrm{D}^0 \to \bar{\mathrm{K}}^0\pi^0\right) - A\left(\mathrm{D}^0 \to \mathrm{K}^0\pi^0\right)$$

The amplitudes $A\left(\mathrm{D}^0 \to \bar{\mathrm{K}}^0\pi^0\right)$ and $A\left(\mathrm{D}^0 \to \mathrm{K}^0\pi^0\right)$ are related by an interchange of u and s quarks. Assuming U-spin symmetry of the strong interaction, the decay rate asymmetry is given given by [18]:

$$\begin{aligned} A_{K_{S,L}\pi^0} &= \frac{\Gamma\left(\mathrm{D}^0 \to K_S\pi^0\right) - \Gamma\left(\mathrm{D}^0 \to K_S\pi^0\right)}{\Gamma\left(\mathrm{D}^0 \to K_S\pi^0\right) + \Gamma\left(\mathrm{D}^0 \to K_S\pi^0\right)} \\ &= 2\tan^2\theta_c = 0.109 \end{aligned}$$

A measurement of $A_{K_{S,L}\pi^0}$ therefore provides a test of U-spin symmetry, which is important for example for extracting the CP-violating parameter γ from $\mathrm{B_s} \to \mathrm{KK}$ and $\mathrm{B_d} \to \pi\pi$ decays [19, 20]. The reconstruction of $\mathrm{D}^0 \to \mathrm{K_L}\pi^0$ is challenging because it involves two neutral particles. CLEO-c uses its CsI calorimeter to identify the π^0. The four-momentum of the practially invisible $\mathrm{K_L}$ is reconstructed using beam constraints, benefiting from the very clean environment at CLEO-c where the $\mathrm{D\bar{D}}$ pairs produced absorb the entire beam energy, with no underlying event. The resulting missing mass-squared distribution is shown in Fig. 4. The assymmetry, measured in $281\,\mathrm{pb}^{-1}$ of data, is [21]:

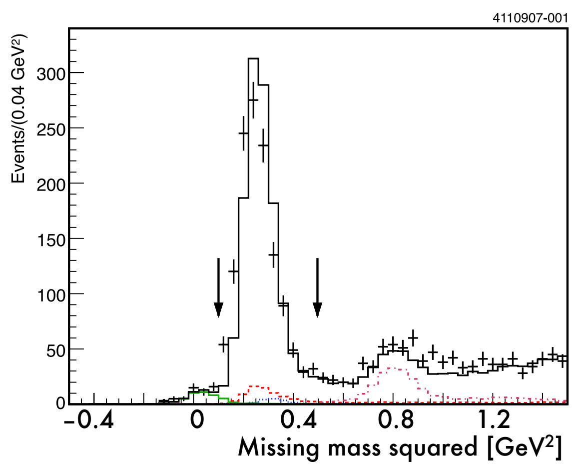

Figure 4: The missing mass distribution in the reconstruction of $\mathrm{D}^0 \to \mathrm{K_L}\pi^0$ at CLEO-c [21]. The points with error bars are data, and the solid line is a Monte Carlo simulation. The dashed, colored lines represent simulations of the peaking backgrounds. The difference in the peak position is understood and due to a minor discrepancy in the calorimeter simulation at large photon energies.

$$A_{K_{S,L}\pi^0} = 0.108 \pm 0.025 \pm 0.024,$$

which is in excellent agreement with the prediction by [18] based in U-spin symmetry. Theoretical prediction for the related asymmetry

$$A_{K_{S,L}\pi^+} = \frac{\Gamma\left(\mathrm{D}^+ \to K_S\pi^+\right) - \Gamma\left(\mathrm{D}^+ \to K_S\pi^+\right)}{\Gamma\left(\mathrm{D}^+ \to K_S\pi^+\right) + \Gamma\left(\mathrm{D}^+ \to K_S\pi^+\right)}$$

are more difficult as there is no such clean symmetry. Using SU(3), Gao predicts [22] $A_{K_{S,L}\pi^+} \approx 0.04$. Based on

Table 2: Recent results for radiative D^0 decays. The CLEO-c results shown in this table are preliminary.

Channel	$\mathcal{B}$ranching Fraction	
$\overline{K}^*\gamma$	$(3.22 \pm 0.20 \pm 0.27) \cdot 10^{-4}$	(BaBar [26])
	$(4.37 \pm 0.37 \pm 0.52) \cdot 10^{-4}$	(CLEO-c prel [27])
$\phi\gamma$	$\left(2.6^{+0.70}_{-0.61}\ {}^{+0.15}_{-0.17}\right) \cdot 10^{-5}$	(BELLE [24])
	$(2.73 \pm 0.30 \pm 0.26) \cdot 10^{-5}$	(BaBar [26])
	$(2.21 \pm 0.95 \pm 0.28) \cdot 10^{-5}$	(CLEO-c prel [27])
$\gamma\gamma$	$< 8.93 \cdot 10^{-6} (90\% CL)$	(CLEO-c prel [27])
$\rho\gamma$	$< 3.63 \cdot 10^{-5} (90\% CL)$	(CLEO-c prel [27])
$\omega\gamma$	$< 3.00 \cdot 10^{-5} (90\% CL)$	(CLEO-c prel [27])

the diagrammatic approach, Bhattacharya & Rosner [11] predict $A_{K_{S,L}\pi^+} = -0.005 \pm 0.013$. Both are consistent with CLEO-c's measurement [21] of

$$A_{K_{S,L}\pi^+} = 0.022 \pm 0.016 \pm 0.018.$$

Decays to vector-mesons and η

BaBar analysed $467\,\mathrm{fb}^{-1}$ of data corresponding to about 1 billion D mesons. Preliminary results for the decay $D^0 \to V\eta$, where $V = \omega, \phi, K^{*0}$, have been presented at the APS April meeting 2009 [23]. The $\omega\eta$ and $K^{*0}\eta$ mode have been observed for the first time. These results, and a previous measurement by BELLE [24], are summarised in Tab. 1. The measurements are compared to predictions by Bhattacharya & Rosner [25], who use the same diagrammatic approach that has been discussed earlier. This yields two solutions, of which solutions A is preferred. While Bhattacharya & Rosner [25] show in their paper that the predictions based on the diagrammatic approach agree well for many D^0 to vector-pseudoscalar decays, there are significant differences for two of the decays shown in Tab. 1.

Radiative decays

In 2008, BaBar reported the first observation of the decay $D^0 \to \bar{K}^{*0}\gamma$ [26], and an improved measurement of $D^0 \to \bar{K}^{*0}\gamma$. CLEO-c has since been able to confirm the observation of $D^0 \to \bar{K}^{*0}\gamma$. In contrast to radiative B decays, radiative charm decays are dominated by long-distance contribution. One way to describe radiative decays is the Vector Meson Dominance (VMD) approach. The radiative decay is assumed to proceed predominantly via an off-shell ρ^0 that then annihilates into a photon, giving the following relationship between the decay amplitudes [28]

$$A(D^0 \to V\gamma) = (e/f_\rho) A(D^0 \to V\rho^0)$$

where $A(D^0 \to V\rho^0)$ needs to be calculated taking into account that the ρ is off-shell. This predicts for the ratio of decays rates:

$$\frac{\mathcal{B}(D^0 \to \phi\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)} \approx \frac{\mathcal{B}(D^0 \to \phi\rho)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\rho)}$$

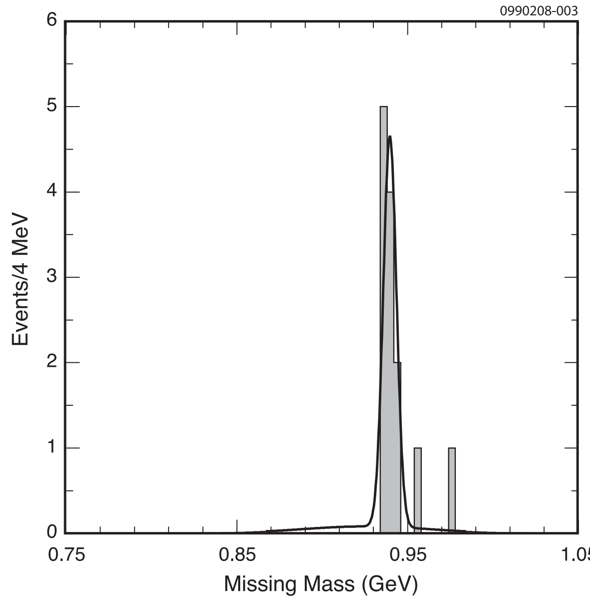

Figure 5: The missing mass of the n in $D_s^+ \to p\bar{n}$ decays, at CLEO-c [30].

This is in fact the case:

$$\frac{\mathcal{B}(D^0 \to \phi\gamma)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\gamma)} = (6.27 \pm 0.71 \pm 0.79) \cdot 10^{-2} \quad [26]$$

$$\frac{\mathcal{B}(D^0 \to \phi\rho)}{\mathcal{B}(D^0 \to \bar{K}^{*0}\rho)} = (6.7 \pm 1.6) \cdot 10^{-2} \quad [12]$$

However, using $(e/f_\rho) = 0.06$ [29], one would also expect

$$\frac{\mathcal{B}(D^0 \to V\gamma)}{D^0 \to V\rho^0} \approx 0.0036$$

but the measured ratio for $V = \bar{K}^{*0}$ as well as $V = \phi$ is

$$\frac{\mathcal{B}(D^0 \to V\gamma)}{\mathcal{B}(D^0 \to V\rho^0)} \approx 0.02 \quad \text{for V=}\bar{K}^{*0} \text{ or } \phi$$

which is about a factor of 6 larger than expected from the VMD approach.

$D^0 \to p\bar{n}$

The first observation of a meson decaying to two baryons has been made by CLEO-c in the mode $D_s^+ \to p\bar{n}$, which is also the only kinematically allowed baryonic decay of a light charm meson (D^0, D^+, or D_s). CLEO-c reconstruct the anti-neutron from the missing mass with virtually no background, as shown in Fig. 5. CLEO-c measures the follwing branching fraction [30]:

$$\mathcal{B}(D_s^+ \to p\bar{n}) = \left(1.30 \pm 0.36^{+0.12}_{-0.16}\right) \cdot 10^{-3}$$

This decay mode is dominated by long-distance effects as those shown in Fig. 6. Chen, Cheng and Hsio [31] estimate these as $\mathcal{B}(D_s^+ \to p\bar{n}) \approx \left(0.8^{+2.4}_{-0.6}\right) \cdot 10^{-3}$ in agreement with CLEO-c's observation - short-distance contributions from the annihilation diagram are about 3 orders of magnitude smaller.

Table 1: Recent results for $D^0 \to V\eta$. The BaBar results shown in this table are preliminary.

Channel $D^0 \to$	Prediction/10^{-3} [25] Sol A	Sol B	Measured $\mathcal{B}/10^{-3}$/	
$\phi\eta$	0.93 ± 0.09	1.4 ± 0.1	0.14 ± 0.04	(BELLE [24])
			$0.21 \pm 0.01 \pm 0.02$	(BaBar-prelim [23])
$\omega\eta$	1.4 ± 0.09	1.27 ± 0.09	$2.21 \pm 0.08 \pm 0.22$	(BaBar-prelim [23])
$K^{*0}\eta$	0.038 ± 0.004	0.037 ± 0.004	$0.048 \pm 0.010 \pm 0.004$	(BaBar-prelim [23])

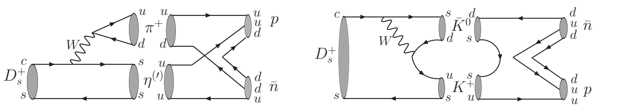

Figure 6: Long distance effects dominate the decay $D_s^+ \to p\bar{n}$.

Absolute Branching Fractions

Absolute Branching fraction measurements are particularly important for those decays frequently used as normalisation modes. BaBar, BELLE and CLEO-c published measurements of absolute branching fractions, using different techniques:

- BaBar obtains a normalisation by reconstructing $D^* \to D\pi$ using only the slow pion in this decay chain, and information from the rest of the event, but not the D itself [32].
- CLEO-c produces charm mesons always in pairs, either $e^+e^- \to \psi(3770) \to D\bar{D}$ for D^0 or $D^{\pm}$, or $e^+e^- \to D^{\pm}D^{*\mp}$. One charm meson provides the normalisation for the decay rates of the other [34, 35]. Figure 8 shows the invariant mass distribution of D_s pairs at CLEO-c. In the D^0-$\bar{D}^0$ system, there are complications and very interesting physics arising from quantum correlations which are discussed elsewhere in these proceedings [1].
- BELLE uses the process $e^+e^- \to D_s^{*+}D_{s1}^-(\to \bar{D}^{*0}K^-)$, again, one charm meson provides the normalisation for the other [33].

Figure 7 illustrates the significant increase in precision achieved in recent years for the most important normalisation modes. The full set of CLEO-c's absolute D_s branching fractions measurements are given in Tab. 3, reproduced from [35].

A frequently-used normalisation mode for D_s branching ratios is the decay $D_s \to \phi\pi$. This, however, is problematic because of interference effects in the $K^+K^-\pi^+$ Dalitz plot, in particular from $f(980)$ [37, 38, 39]. CLEO-c therefore publishes the absolute branching fraction for $D_s^+ \to K^+K^-\pi^+$, including the entire phase space. However, when using this as a normalisation mode, it can be advantageous to select events with a K^+K^- invariant mass near the ϕ mass, in order to reject background. To accommodate this, CLEO-c also publishes branching fractions for parts of the $D_s^+ \to K^+K^-\pi^+$ phase space corresponding to different cuts around the ϕ mass, but without making any statement about the contribution of $D_s^+ \to \phi\pi$ this includes. The absolute D_s branching fractions for different decay modes from this analysis [35] are given in Tab. 3.

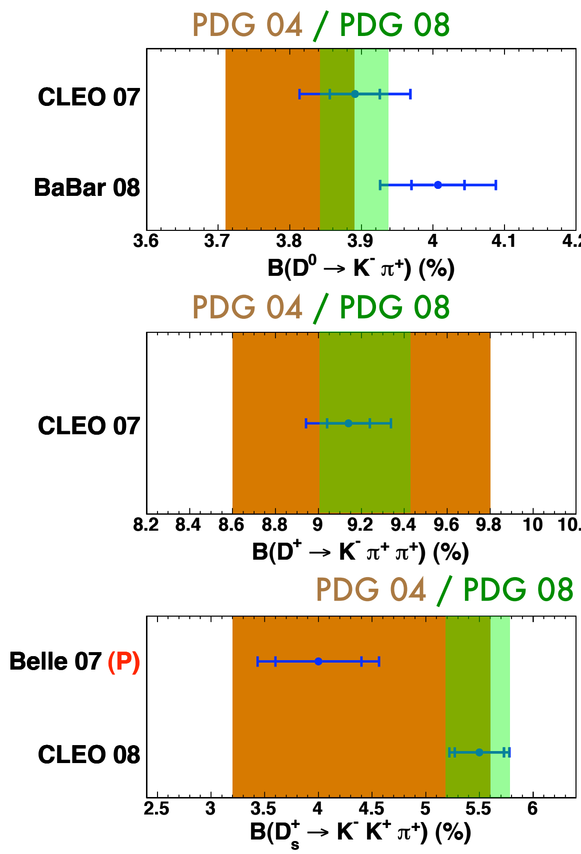

Figure 7: Impact of recent absolute Branching ration measurements on the PDG average. The brown bar represents the PDG average in 2004, while the semi-transparent green bar (that partially overlaps with the brown bar) represents the status in 2008. Recent measurements by BaBar [32], BELLE (preliminary [33]) and CLEO-c [34, 35] are represented by blue lines with error bars.

Table 3: Results from CLEO-c's recent measurement of absolute $\mathrm{D_s}$ branching fractions [35], the world average branching fractions before CLEO-c's measurement [36], ratios of branching fractions to $\mathcal{B}(\mathrm{D_s^+} \to K^-K^+\pi^+)$, and charge asymmetries $\mathcal{A}_{CP}$. Uncertainties on CLEO-c measurements are statistical and systematic, respectively. Table reproduced from [35]

Mode	CLEO-c result $\mathcal{B}$ (%) [35]	PDG 2007 fit $\mathcal{B}$ (%) [36]	$\mathcal{B}/\mathcal{B}(K^-K^+\pi^+)$	$\mathcal{A}_{CP}$ (%)
$K_S^0 K^+$	$1.49 \pm 0.07 \pm 0.05$	2.2 ± 0.4	$0.270 \pm 0.009 \pm 0.008$	$+4.9 \pm 2.1 \pm 0.9$
$K^-K^+\pi^+$	$5.50 \pm 0.23 \pm 0.16$	5.3 ± 0.8	1	$+0.3 \pm 1.1 \pm 0.8$
$K^-K^+\pi^+\pi^0$	$5.65 \pm 0.29 \pm 0.40$	—	$1.03 \pm 0.05 \pm 0.08$	$-5.9 \pm 4.2 \pm 1.2$
$K_S^0 K^-\pi^+\pi^+$	$1.64 \pm 0.10 \pm 0.07$	2.7 ± 0.7	$0.298 \pm 0.014 \pm 0.011$	$-0.7 \pm 3.6 \pm 1.1$
$\pi^+\pi^+\pi^-$	$1.11 \pm 0.07 \pm 0.04$	1.24 ± 0.20	$0.202 \pm 0.011 \pm 0.009$	$+2.0 \pm 4.6 \pm 0.7$
$\pi^+\eta$	$1.58 \pm 0.11 \pm 0.18$	2.16 ± 0.30	$0.288 \pm 0.018 \pm 0.033$	$-8.2 \pm 5.2 \pm 0.8$
$\pi^+\eta'$	$3.77 \pm 0.25 \pm 0.30$	4.8 ± 0.6	$0.69 \pm 0.04 \pm 0.06$	$-5.5 \pm 3.7 \pm 1.2$
$K^+\pi^+\pi^-$	$0.69 \pm 0.05 \pm 0.03$	0.67 ± 0.13	$0.125 \pm 0.009 \pm 0.005$	$+11.2 \pm 7.0 \pm 0.9$

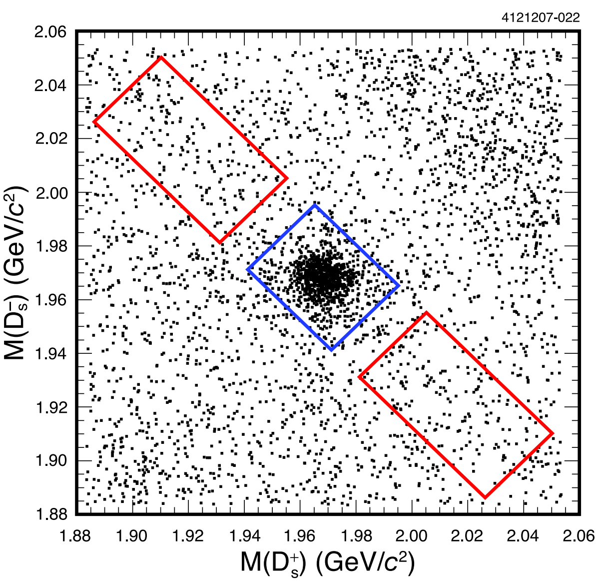

Figure 8: Invariant mass of $\mathrm{D_s}$ pairs reconstructed at CLEO-c [35].

Inclusive $\mathrm{D_s}$ branching fractions and exclusive $\mathrm{D_s} \to \omega\mathrm{X}$

In 2009, CLEO-c published a measurement the inclusive branching fractions of $\mathrm{D_s}$ in modes [40], such as $\mathrm{D_s^+} \to \pi^+\mathrm{X}$, $\mathrm{D_s^+} \to \pi\mathrm{X}$, etc, where X stands for any combination of particles. The results are reproduced in Tab. 7 on page 8. While most inclusive branching fractions measured are compatible with the sum of known exclusive rates [41], this was initially not the case for the inclusive branching fraction $\mathcal{B}(\mathrm{D_s} \to \omega\mathrm{X})$, where X stands for any combination of particles. CLEO-c measures this to be $(6.1 \pm 1.4)\%$, far more than the only known exclusive ω mode at the time, $\mathcal{B}\left(\mathrm{D_s} \to \pi^+\omega\right) = (0.25 \pm 0.09)\,\%$ [12].

Since then, CLEO-c has searched for the missing exclusive decay modes to ω, and found them [42]. The missing exclusive modes are mainly those were X is two or three pions. The full results are given in Tab. 4.

Table 4: Branching fractions and upper limits for exclusive $\mathrm{D_s}$ decays involving ω, reproduced from [42].

Mode	$\mathcal{B}_{\mathrm{mode}}(\%)$
$\mathrm{D_s^+} \to \pi^+\omega$	$0.21 \pm 0.09 \pm 0.01$
$\mathrm{D_s^+} \to \pi^+\pi^0\omega$	$2.78 \pm 0.65 \pm 0.25$
$\mathrm{D_s^+} \to \pi^+\pi^+\pi^-\omega$	$1.58 \pm 0.45 \pm 0.09$
$\mathrm{D_s^+} \to \pi^+\eta\omega$	$0.85 \pm 0.54 \pm 0.06$ < 2.13 (90% CL)
$\mathrm{D_s^+} \to \mathrm{K}^+\omega$	< 0.24 (90% CL)
$\mathrm{D_s^+} \to \mathrm{K}^+\pi^0\omega$	< 0.82 (90% CL)
$\mathrm{D_s^+} \to \mathrm{K}^+\pi^+\pi^-\omega$	< 0.54 (90% CL)
$\mathrm{D_s^+} \to \mathrm{K}^+\eta\omega$	< 0.79 (90% CL)

Direct CP violation

CP violation in charm decays provides one of the most sensitive probes for New Physics, and we are only now reaching the sensitivity to exploit this opportunity. In this article, we restrict ourselves to the discussion of direct CP violation; CP violation in the interference between mixing and decay is discussed elsewhere in these proceedings [3, 4, 5, 6, 7, 8, 9].

CP violation in the charm decays in the SM is expected to be small, at a level $< 10^{-3}$ [43, 44, 45]. However, new Physics can significantly enhance CP asymmetries, especially in the case of singly Cabibbo suppressed decays, which are sensitive to new contributions from QCD penguin operators. This could yield direct CP violating effects of $\mathcal{O}(10^{-2})$ [46, 47].

The most precise measurements of direct CP asymmetries

$$A_{CP} \equiv \frac{\Gamma\left(\mathrm{D} \to \mathrm{f}\right) - \Gamma\left(\bar{\mathrm{D}} \to \bar{\mathrm{f}}\right)}{\Gamma\left(\mathrm{D} \to \mathrm{f}\right) + \Gamma\left(\bar{\mathrm{D}} \to \bar{\mathrm{f}}\right)}$$

Table 5: Direct CP violation measurements in $D^0 \to \pi\pi$ and $D^0 \to \pi$pi, and the average by the Heavy Flavour Averaging Group, status January 2009 [48].

Year	Experiment	A_{CP} $D^0 \to \pi\pi$	A_{CP} $D^0 \to KK$
2008	BELLE [49]	+0.0043±0.0052±0.0012	-0.0043±0.0030±0.0011
2008	BaBar [50]	-0.0024±0.0052±0.0022	+0.0000±0.0034±0.0013
2005	CDF [51]	+0.010± 0.013 ±0.006	+0.020± 0.012 ±0.006
2002	CLEO [52]	+0.019± 0.032 ±0.008	+0.000± 0.022 ±0.008
2000	FOCUS [53]	+0.048± 0.039 ±0.025	-0.001± 0.022 ±0.015
1998	E791 [54]	-0.049± 0.078 ±0.030	-0.001± 0.022 ±0.015
1995	CLEO [55]		+0.080± 0.061
1994	E687 [56]		+0.024± 0.084
HFAG average [48]		+0.0022± 0.0037	-0.0016± 0.0023

in SCS decays exist for the modes $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$. Results for these two modes, and averages, are listed in Tab. 5. Other direct CP violation measurements have been published by BaBar [57, 58], BELLE [59, 60], CLEO [10, 35, 61, 62, 63, 64, 65, 66, 67], FOCUS [68, 69], E791 [70], and E687 [56]. This includes the recent CLEO-c results listed in Tab. 6. A comprehensive list of results and averages can found on the HFAG website [48]. No evidence for CP violation in the charm sector has emerged yet. It is interesting to note that the CDF result [51] in Tab. 5 was obtained with only approximately 2% of CDF's current dataset. A simple scaling of the statistical error suggests that, if CDF repeated this analysis with the full dataset, the statistical precision of this single measurement could match the current world-average. The challenge will of course be to control systematic uncertainties at a similar level, and there are other reasons why this simple scaling is too naive, such as the reduction in trigger efficiency for charm events at higher luminosities. But even with these caveats, this illustrates the importance and promise of charm physics at hadron colliders. Most of CDF's charm data have yet to be analysed, and even larger samples will soon be available at LHCb [71], with the prospect of a rich charm physics programme with high sensitivity to New Physics.

Conclusions

Since the last CHARM conference in 2007, large new data samples have become available and have been analysed, resulting in dramatic improvements of the precsion of non-leptonic decay rates of charm mesons, and the discovery of many new decay channels. These are important parameters in their own right, provide tests of symmetries of the strong interaction such as U-spin and SU(3), and are set to provide important input for the analysis of B decays, as most B mesons decay to charm. One of the most sensitive probes for New Physics is CP violation in the charm sector, which is predicted to be $< 10^{-3}$ in the SM. While at CHARM 2007, the most precise measurements of direct CP violation achieved a precision at the percent level, today this has reached the permil level. So far, however, there has been no evidence for CP violation.

Dedicated charm experiments have unique capabilities, especially when running at the charm threshold, but are by no means the only source of charm physics. Many recent measurements have exploited the vast charm samples at the B factories and CDF. This is an encouraging trend in view of the start of data taking at LHCb. LHCb will collect unprecidented charm samples. CDF has shown that precision charm physics is possible at a hadron collider, and has, for most analyses, only used a fraction of its dataset. On the other hand, there will also be new results from the charm threshold with its unique properties: BES III is about to take data at the $\psi(3770)$, and CLEO-c's dataset continues to be analysed. So the prospects for charm physics are bright, with continued analyses of e^+e^- data, new results from the charm threshold, and enourmous datasets collected at hadron colliders.

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Table 6: Branching fractions in $D^0 \to PP$ modes measured using CLEO-c's full dataset, reproduced from [10]. The table shows the branching ratio relative to the normalization modes $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, and $D_s^+ \to K_S^0 K^+$; the resulting Branching Fractions; and charge asymmetries $\mathcal{A}_{CP}$. Uncertainties are statistical error, systematic error, and the error from the input branching fractions of normalization modes. (For D^0, the normalization mode is the sum of $D^0 \to K^-\pi^+$ and $D^0 \to K^+\pi^-$, see [10] for details.)

Mode	$\mathcal{B}_{\rm mode}/\mathcal{B}_{\rm Normalization}$ (%)	This result $\mathcal{B}$ (%)	$\mathcal{A}_{CP}$ (%)
$D^0 \to K^+K^-$	$10.41 \pm 0.11 \pm 0.11$	$0.407 \pm 0.004 \pm 0.004 \pm 0.008$	
$D^0 \to K_S^0 K_S^0$	$0.41 \pm 0.04 \pm 0.02$	$0.0160 \pm 0.0017 \pm 0.0008 \pm 0.0003$	
$D^0 \to \pi^+\pi^-$	$3.70 \pm 0.06 \pm 0.09$	$0.145 \pm 0.002 \pm 0.004 \pm 0.003$	
$D^0 \to \pi^0\pi^0$	$2.06 \pm 0.07 \pm 0.10$	$0.081 \pm 0.003 \pm 0.004 \pm 0.002$	
$D^0 \to K^-\pi^+$	100	3.9058 external input [72]	$0.5 \pm 0.4 \pm 0.9$
$D^0 \to K_S^0\pi^0$	$30.4 \pm 0.3 \pm 0.9$	$1.19 \pm 0.01 \pm 0.04 \pm 0.02$	
$D^0 \to K_S^0\eta$	$12.3 \pm 0.3 \pm 0.7$	$0.481 \pm 0.011 \pm 0.026 \pm 0.010$	
$D^0 \to \pi^0\eta$	$1.74 \pm 0.15 \pm 0.11$	$0.068 \pm 0.006 \pm 0.004 \pm 0.001$	
$D^0 \to K_S^0\eta'$	$24.3 \pm 0.8 \pm 1.1$	$0.95 \pm 0.03 \pm 0.04 \pm 0.02$	
$D^0 \to \pi^0\eta'$	$2.3 \pm 0.3 \pm 0.2$	$0.091 \pm 0.011 \pm 0.006 \pm 0.002$	
$D^0 \to \eta\eta$	$4.3 \pm 0.3 \pm 0.4$	$0.167 \pm 0.011 \pm 0.014 \pm 0.003$	
$D^0 \to \eta\eta'$	$2.7 \pm 0.6 \pm 0.3$	$0.105 \pm 0.024 \pm 0.010 \pm 0.002$	
$D^+ \to K^-\pi^+\pi^+$	100	9.1400 external input [72]	$-0.1 \pm 0.4 \pm 0.9$
$D^+ \to K_S^0 K^+$	$3.35 \pm 0.06 \pm 0.07$	$0.306 \pm 0.005 \pm 0.007 \pm 0.007$	$-0.2 \pm 1.5 \pm 0.9$
$D^+ \to \pi^+\pi^0$	$1.29 \pm 0.04 \pm 0.05$	$0.118 \pm 0.003 \pm 0.005 \pm 0.003$	$2.9 \pm 2.9 \pm 0.3$
$D^+ \to K_S^0\pi^+$	$16.82 \pm 0.12 \pm 0.37$	$1.537 \pm 0.011 \pm 0.034 \pm 0.033$	$-1.3 \pm 0.7 \pm 0.3$
$D^+ \to K^+\pi^0$	$0.19 \pm 0.02 \pm 0.01$	$0.0172 \pm 0.0018 \pm 0.0006 \pm 0.0004$	$-3.5 \pm 10.7 \pm 0.9$
$D^+ \to K^+\eta$	< 0.14 (90% C.L.)	< 0.013 (90% C.L.)	
$D^+ \to \pi^+\eta$	$3.87 \pm 0.09 \pm 0.19$	$0.354 \pm 0.008 \pm 0.018 \pm 0.008$	$-2.0 \pm 2.3 \pm 0.3$
$D^+ \to K^+\eta'$	< 0.20 (90% C.L.)	< 0.018 (90% C.L.)	
$D^+ \to \pi^+\eta'$	$5.12 \pm 0.17 \pm 0.25$	$0.468 \pm 0.016 \pm 0.023 \pm 0.010$	$-4.0 \pm 3.4 \pm 0.3$
$D_s^+ \to K_S^0 K^+$	100	1.4900 external input [73]	$4.7 \pm 1.8 \pm 0.9$
$D_s^+ \to \pi^+\pi^0$	< 2.3 (90% C.L.)	< 0.037 (90% C.L.)	
$D_s^+ \to K_S^0\pi^+$	$8.5 \pm 0.7 \pm 0.2$	$0.126 \pm 0.011 \pm 0.003 \pm 0.007$	$16.3 \pm 7.3 \pm 0.3$
$D_s^+ \to K^+\pi^0$	$4.2 \pm 1.4 \pm 0.2$	$0.062 \pm 0.022 \pm 0.004 \pm 0.004$	$-26.6 \pm 23.8 \pm 0.9$
$D_s^+ \to K^+\eta$	$11.8 \pm 2.2 \pm 0.6$	$0.176 \pm 0.033 \pm 0.009 \pm 0.010$	$9.3 \pm 15.2 \pm 0.9$
$D_s^+ \to \pi^+\eta$	$123.6 \pm 4.3 \pm 6.2$	$1.84 \pm 0.06 \pm 0.09 \pm 0.11$	$-4.6 \pm 2.9 \pm 0.3$
$D_s^+ \to K^+\eta'$	$11.8 \pm 3.6 \pm 0.6$	$0.18 \pm 0.05 \pm 0.01 \pm 0.01$	$6.0 \pm 18.9 \pm 0.9$
$D_s^+ \to \pi^+\eta'$	$265.4 \pm 8.8 \pm 13.9$	$3.95 \pm 0.13 \pm 0.21 \pm 0.23$	$-6.1 \pm 3.0 \pm 0.3$

Table 7: CLEO-c's D_s inclusive yield results from [40]. Uncertainties are statistical and systematic, respectively. The inclusive K_L^0 results are only used as a check for K_S^0. The $D_s^+ \to K_L^0 X$ yield requires a correction before comparing with the $D_s^+ \to K_S^0 X$ yield, as explained in [40]. PDG [12] averages are shown in the last column, when available. Reproduced from [40].

Mode	Yield(%)	K_L^0 Mode	Yield(%)	$\mathcal{B}$(PDG)(%)
$D_s^+ \to \pi^+ X$	$119.3 \pm 1.2 \pm 0.7$			
$D_s^+ \to \pi^- X$	$43.2 \pm 0.9 \pm 0.3$			
$D_s^+ \to \pi^0 X$	$123.4 \pm 3.8 \pm 5.3$			
$D_s^+ \to K^+ X$	$28.9 \pm 0.6 \pm 0.3$			$20\,^{+18}_{-14}$
$D_s^+ \to K^- X$	$18.7 \pm 0.5 \pm 0.2$			$13\,^{+14}_{-12}$
$D_s^+ \to \eta X$	$29.9 \pm 2.2 \pm 1.7$			
$D_s^+ \to \eta' X$	$11.7 \pm 1.7 \pm 0.7$			
$D_s^+ \to \phi X$	$15.7 \pm 0.8 \pm 0.6$			
$D_s^+ \to \omega X$	$6.1 \pm 1.4 \pm 0.3$			
$D_s^+ \to f_0(980) X, f_0(980) \to \pi^+\pi^-$	$< 1.3\%$ (90% CL)			
$D_s^+ \to K_S^0 X$	$19.0 \pm 1.0 \pm 0.4$	$D_s^+ \to K_L^0 X$	15.6 ± 2.0	20 ± 14
$D_s^+ \to K_S^0 K_S^0 X$	$1.7 \pm 0.3 \pm 0.1$	$D_s^+ \to K_L^0 K_S^0 X$	5.0 ± 1.0	
$D_s^+ \to K_S^0 K^+ X$	$5.8 \pm 0.5 \pm 0.1$	$D_s^+ \to K_L^0 K^+ X$	5.2 ± 0.7	
$D_s^+ \to K_S^0 K^- X$	$1.9 \pm 0.4 \pm 0.1$	$D_s^+ \to K_L^0 K^- X$	1.9 ± 0.3	
$D_s^+ \to K^+ K^- X$	$15.8 \pm 0.6 \pm 0.3$			
$D_s^+ \to K^+ K^+ X$	$< 0.26\%$ (90% CL)			
$D_s^+ \to K^- K^- X$	$< 0.06\%$ (90% CL)			

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