

Hadronic Charm Decays and D Mixing

Sheldon Stone

Department of Physics, Syracuse University, Syracuse, New York 13244-1130

I discuss new results on absolute branching ratios of charm mesons into specific exclusive final states, Cabibbo suppressed decay rates, inclusive decays to $s\bar{s}$ mesons, limits on $D^0 - \bar{D}^0$ mixing, CP violation and T violation. Preliminary results from CLEO-c now dominate the world average absolute branching fractions. For the most important normalization modes involving D^0 and D^+ , the averages are $\mathcal{B}(D^0 \rightarrow K^-\pi^+) = (3.87 \pm 0.06)\%$, and $\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+) = (9.12 \pm 0.19)\%$. For the D_S^+ CLEO-c measures $\mathcal{B}(D_S^+ \rightarrow K^-K^+\pi^+) = (4.54^{+0.44}_{-0.42} \pm 0.25)\%$. Using this rate, I derive an effective branching ratio $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+) = (3.49 \pm 0.39)\%$, that is appropriate for use in extracting other branching fractions that have often been measured relative to this mode. This number is compared with other determinations.

1. Introduction

Studies of charm decays are pursued for several different reasons. First of all, there is the possibility of directly observing new physics beyond the Standard Model (SM), since the effects of CP violation due to SM processes is highly suppressed allowing new physics contributions to be more easily seen than in b decays where the SM processes typically have large effects [1]. $D^0 - \bar{D}^0$ mixing also is interesting because it could come from either SM or New Physics (NP) processes, and could teach us interesting lessons.

Another important reason for detailed charm studies is that most b 's, $\sim 99\%$, decay into charm, so knowledge about charm decays is particularly useful for b decay studies. Especially interesting are absolute branching ratios, resonant substructures in multi-body decays, phases on Dalitz plots, etc.. Other heavier objects such as top quarks decay into b quarks and Higgs particles may decay with large rates to $b\bar{b}$, again making charm studies important. Furthermore, charm can teach us a great deal about strong interactions, especially decay constants and final state interactions.

2. Experimental Techniques

Charm has been studied at e^+e^- colliders at threshold, first by the Mark III collaboration and more recently by BES and CLEO-c, at higher e^+e^- energies, and at fixed target and hadron collider experiments [2].

The detection techniques are rather different at threshold than in other experiments. The $\psi(3770)$ resonance decays into $D\bar{D}$; the world average cross-section is 3.72 ± 0.09 nb for $D^0\bar{D}^0$ production and 2.82 ± 0.09 nb for D^+D^- production [2]. D_S^+ production is studied at 4170 MeV, where the cross-section for $D_S^{*+}D_S^- + D_S^+D_S^{*-}$ is ~ 1 nb [3]. The underlying light quark “continuum” background is about 14 nb. The relatively large cross-sections, relatively

large branching ratios and sufficient luminosities, allow experiments to fully reconstruct one D as a “tag.” Since the charge and flavor of the tag is then uniquely determined, the rest of the event can be examined for characteristics of the other “known” particle. To measure absolute branching ratios, for example at the $\psi(3770)$, the rest of the event is fully reconstructed, as well as the tag.

At the $\psi(3770)$ D meson final states are reconstructed by first evaluating the difference in the energy, ΔE , of the decay products with the beam energy. Candidates with ΔE consistent with zero are selected and then the D beam-constrained mass is evaluated,

$$m_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - \left(\sum_i \vec{p}_i\right)^2}, \quad (1)$$

where i runs over all the final state particles.

Examples of single and double reconstruction are presented in Fig. 1(a) that shows the m_{BC} distribution for a $D^+ \rightarrow K^-\pi^+\pi^+$ or $D^- \rightarrow K^+\pi^-\pi^-$ final states. These “single tags” show a large signal and a very small background. Fig. 1(b) shows a “double” tag sample where both D^+ and D^- candidates in the same event are reconstructed.

Other experiments make use of the both the approximately picosecond lifetimes of charm to identify detached vertices, and the decay $D^* \rightarrow \pi D$, which also serves as a flavor tag in the case of $D^{*\pm} \rightarrow \pi^\pm D^0$ transitions.

3. Absolute Charm Meson Branching Ratios and Other Hadronic Decays

3.1. Absolute D^0 and D^+ Branching Ratios

In charm meson decays, usually a single branching ratio sets the scale for determinations of most other rates, that are measured relative to it. For D^0 and D^+

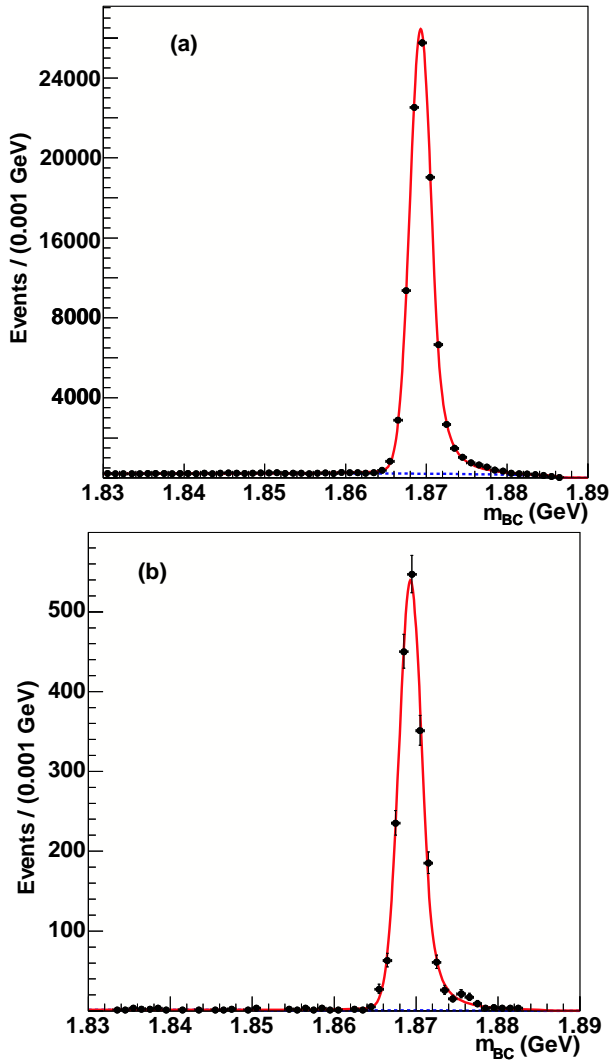


Figure 1: (a) The m_{BC} distributions for candidates from either $D^+ \rightarrow K^- \pi^+ \pi^+$ or $D^- \rightarrow K^+ \pi^- \pi^-$ modes. (b) The m_{BC} distribution for candidates for candidates from $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^- \rightarrow K^+ \pi^- \pi^-$ modes. The solid curves are a fits to the signals plus the backgrounds, that are indicated by the dashed shapes. The signals are asymmetric due to radiation of the electron beams.

these modes are $K^- \pi^+$ and $K^- \pi^+ \pi^+$, respectively.¹ CLEO-c, on the other hand uses a different technique where the branching ratios of several modes are determined simultaneously and all absolutely. Consider an ensemble of modes i , that are both singly reconstructed and also doubly reconstructed, where all combinations of modes may be used. I denote the number of observed single tag charmed particles as N_i , anti-charmed particles as N_j , and double tags as N_{ij} .

¹In general, mention of a mode will also imply consideration of the charge-conjugate state.

They are related to the number of $D\bar{D}$ events (either charged or neutral) through their branching ratios \mathcal{B}_i as

$$N_i = \epsilon_i \mathcal{B}_i N_{D\bar{D}} \quad (2)$$

$$N_j = \epsilon_j \mathcal{B}_j N_{D\bar{D}} \quad (3)$$

$$N_{ij} = \epsilon_{ij} \mathcal{B}_i \mathcal{B}_j N_{D\bar{D}}, \quad (4)$$

where ϵ_i and ϵ_{ij} are the reconstruction efficiencies in single and double tag events for each mode. (In practice the differences in each mode between single and double tag events are small, and $\epsilon_{ij} \approx \epsilon_i \epsilon_j$.) Solving these equations we find

$$\mathcal{B}_j = \frac{N_{ij} \epsilon_i}{N_i \epsilon_{ij}} \quad (5)$$

$$N_{D\bar{D}} = \frac{N_i N_j \epsilon_{ij}}{N_{ij} \epsilon_i \epsilon_j} \quad (6)$$

CLEO-c has recently updated their absolute branching ratio measurements using a 281 pb⁻¹ data sample, an approximately 5 times larger data sample than used by them for their previous publication [4]. The new preliminary results are shown in Table I [5]. (In this table when two errors follow a number, the first error is statistical and the second systematic; this will be true for all results quoted in this paper unless specifically indicated.)

Table I D^0 and D^+ Branching Ratios comparing preliminary CLEO-c results with the PDG [6].

D^0 Decays	$\mathcal{B}\%$ CLEO-c	PDG
$K^- \pi^+$	$3.839 \pm 0.035 \pm 0.060$	3.91 ± 0.09
$K^- \pi^+ \pi^0$	$14.46 \pm 0.12 \pm 0.38$	13.2 ± 1.0
$K^- \pi^+ \pi^+ \pi^-$	$8.29 \pm 0.07 \pm 0.21$	7.48 ± 0.30
D^+ Decays		
$K^- \pi^+ \pi^+$	$9.11 \pm 0.10 \pm 0.17$	9.2 ± 0.6
$K^- \pi^+ \pi^+ \pi^0$	$5.95 \pm 0.07 \pm 0.17$	6.5 ± 1.1
$K^0 \pi^+$	$3.092 \pm 0.044 \pm 0.074$	2.83 ± 0.18
$K^0 \pi^+ \pi^0$	$14.40 \pm 0.18 \pm 0.58$	10.7 ± 2.9
$K^0 \pi^+ \pi^+ \pi^-$	$6.366 \pm 0.052 \pm 0.184$	7.1 ± 1.0
$K^- K^+ \pi^+$	$0.930 \pm 0.016 \pm 0.029$	0.89 ± 0.08

Systematic uncertainties now are the dominant error source in the CLEO-c results. The largest error, common to all decay modes, is that on the ΔE cut that ranges between $\pm 1.0\%$ and $\pm 2.5\%$ depending on the final state. Modes with K_S or π^0 have additional $\pm 1.1\%$ and $\pm 2\%$ errors, respectively. A comparison with the PDG values excluding all CLEO-c results is shown pictorially in Fig. 2.

The world average values for the normalizing modes are now dominated by the CLEO-c results. They are

$$\begin{aligned} \mathcal{B}(D^0 \rightarrow K^- \pi^+) &= (3.87 \pm 0.06)\% \quad (7) \\ \mathcal{B}(D^+ \rightarrow K^- \pi^+ \pi^+) &= (9.12 \pm 0.19)\%, \end{aligned}$$

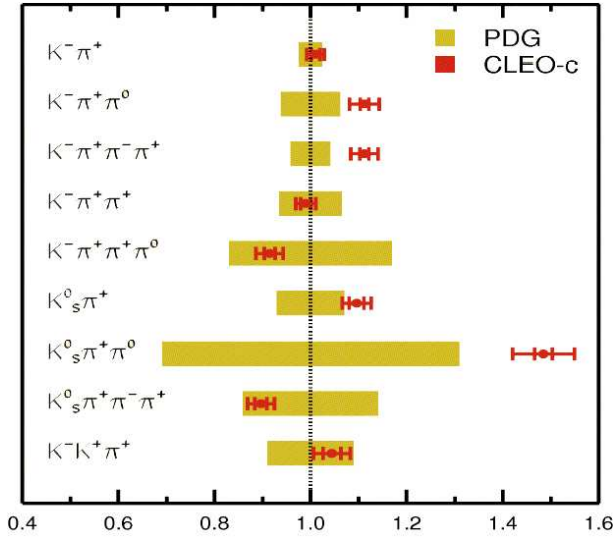


Figure 2: Ratio of preliminary CLEO-c results (281 pb^{-1}) to those of the PDG. The smaller error bars on the CLEO-c results indicate statistical errors and the larger ones systematic errors, shown linearly.

and are now determined with 1.5% and 2.1% relative accuracy, respectively.

3.2. Analysis Procedures for D_S^+ Studies at 4170 MeV

At 4170 MeV D_S mesons are produced mainly in the two processes $e^+e^- \rightarrow D_S^{*+}D_S^-$ or $D_S^+D_S^{*-}$. If we do not detect the photon and reconstruct the m_{BC} distribution making a loose ΔE cut using Eq. 1, we obtain the distribution from Monte Carlo shown in Fig. 3. The narrow peak occurs when the reconstructed D_S does not come from the D_S^* decay. Thus, the method used so successfully on the $\psi(3770)$ no longer works as well.

The alternative method used by CLEO-c is to require that the energy of the D_S is reasonably close to the energy expected in $D_S^*D_S$ events, and then examine the invariant mass. Some such distributions from data are shown in Fig. 4. Note that the resolution in invariant mass is excellent, and the backgrounds not very large, at least in these modes. These mass distributions along with others are used for the CLEO-c inclusive D_S analysis described later.

The $K^+K^-\pi^+$ mode is particularly interesting. I show in Fig. 5 the invariant mass distributions (a) independent of any selections on two-body mass, and for requirements on either K^+K^- mass (b) within ± 20 MeV of the ϕ mass, or (c) in the $f_0(980)$ region from 925 to 1010 MeV in K^+K^- mass, or (d) in the $K^-\pi^+$ mass region within ± 100 MeV of the $K^*(890)$ mass.

Both E687 and FOCUS have done Dalitz plot anal-

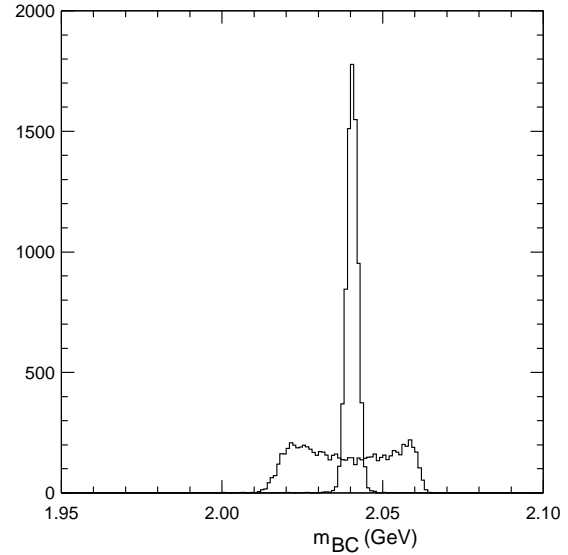


Figure 3: The beam constrained mass m_{BC} from Monte Carlo simulation of $e^+e^- \rightarrow D_S^+D_S^{*-}$, $D_S^+ \rightarrow \phi\pi^+$ at 4170 MeV. The narrow peak is from the D_S^+ and the wider one from the D_S^- . (The distributions are not centered at the D_S^+ or D_S^{*+} masses, because the reconstructed particles are assumed to have the energy of the beam.)

yses and extracted the fit fractions and phases for this decay mode. The Dalitz plot from FOCUS is shown in Fig 6, and the results listed in Table II along with the E687 results [7, 8]. The final state is quite complicated. Besides the large $\phi\pi^+$ and $K^{*0}\pi^+$ components there is a significant amount of $f_0(980)$ which interferes with the other components as well as smaller amounts of two other resonances. In particular, the f_0 has an overlap with the ϕ .

Table II Final state composition of $D_S^+ \rightarrow K^+K^-\pi^+$.

	Focus		E687	
	Fraction(%)	Phase(°)	Fraction(%)	Phase(°)
$K^{*0}(892)$	44±1	0(fixed)	48±5	0(fixed)
$K_0^*(1430)$	6±1	114±5	9±3	152±40
$\phi(1020)$	45±1	148±4	40±3	178±20
$f_0(980)$	16±1	135±4	11±4	159±22
$f_j(1710)$	4±1	106±6	3±2	110±20

3.3. Absolute D_S^+ Branching Ratios

Measurement of the D_S absolute branching ratios proceeds in a similar manner as used for the D^0 and D^+ rates using a 56 pb^{-1} data sample at 4170 MeV and 20 pb^{-1} at nearby energies. The single tags are reconstructed using invariant mass with a loose cut on the D_S energy. The photon or π^0 from the D_S^*

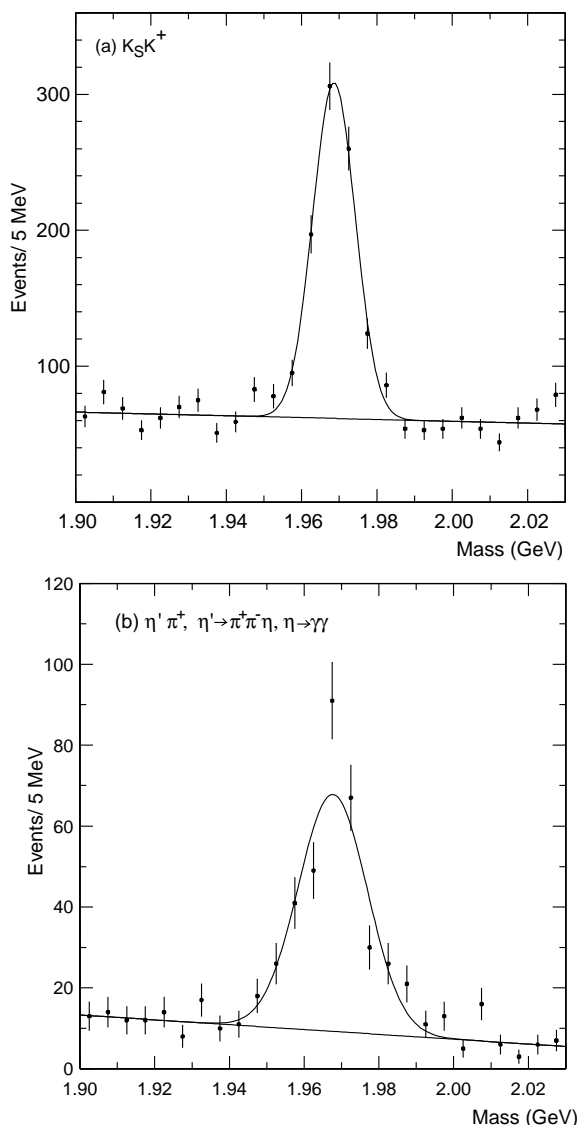


Figure 4: Invariant mass of (a) $K_S K^+$ combinations from CLEO-c, requiring the total energy to be consistent with the beam energy, and (b) $\eta' \pi^+$ mass combinations, where $\eta' \rightarrow \pi^+ \pi^- \eta$, $\eta \rightarrow \gamma \gamma$. The curve is a fit to a Gaussian signal function plus a linear background.

decay is ignored. The modes used and the number of single and double tags are listed in Table III. The invariant mass of the D_S^- candidates versus the D_S^+ candidates in a single event are plotted in Fig. 7(a), while the differences in invariant mass are shown in Fig. 7(b). These plots demonstrate very good signal to background in these modes in double tags.

The preliminary CLEO-c absolute branching ratios results are shown in Table IV. The measurements in the all charged modes have about an $\pm 11\%$ error and are already the best in the world. The accuracy will improve markedly by the end of this summer, as the data sample will increase by a factor of 2.6 and more modes will be added.

Table III The D_S decay modes used in this analysis and the reconstructed number of single tag and double tag events.

Single Tags				
	$K_S K^\pm$	$K^- K^+ \pi^\pm$	$K^- K^+ \pi^\pm \pi^0$	$\pi^+ \pi^- \pi^\pm$
D_S^+	442 ± 25	1607 ± 54	333 ± 38	265 ± 29
D_S^-	346 ± 23	1736 ± 55	376 ± 38	274 ± 28
Double Tags				
	$K_S K^-$	$K^- K^+ \pi^-$	$K^- K^+ \pi^- \pi^0$	$\pi^+ \pi^- \pi^-$
$K_S K^+$	4	5	7	3
$K^- K^+ \pi^+$	2	36	14	13
$K^- K^+ \pi^+ \pi^0$	3	12	5	4
$\pi^+ \pi^- \pi^+$	2	8	0	not used

Table IV The D_S absolute branching fraction results (preliminary) from CLEO-c using 76 pb^{-1} of data near 4170 MeV.

Mode	$\mathcal{B}(\%)$ CLEO-c	$\mathcal{B}(\%)$ PDG
$K^0 K^+$	$2.56^{+0.26}_{-0.24} \pm 0.14$	3.6 ± 1.1
$K^- K^+ \pi^+$	$4.54^{+0.44}_{-0.42} \pm 0.25$	4.3 ± 1.2
$K^- K^+ \pi^+ \pi^0$	$4.83^{+0.49}_{-0.46} \pm 0.46$	-
$\pi^+ \pi^- \pi^+$	$1.02^{+0.11}_{-0.10} \pm 0.05$	1.00 ± 0.28

3.4. The $D_S^+ \rightarrow \phi \pi^+$ Absolute Branching Ratio

Table IV does not include a result for $D_S^+ \rightarrow \phi \pi^+$. The reason CLEO-c gives for its absence is that the definition of what constitutes a ϕ is somewhat ambiguous, due to the interferences in the $K^+ K^- \pi^+$ Dalitz plot discussed above. Most measurements reported for D_S decays in the PDG, however, are normalized to this rate, making it important to have an estimate of the effective branching ratio. The value can vary depending on the experimental resolution and what selection criteria on the ϕ mass are applied by different analyses. The observed shape of the $K^+ K^-$ mass distribution in the ϕ region is convolution of the Breit-Wigner natural width of the ϕ ($\Gamma = 4.3 \text{ MeV}$) with the detector resolution, which often is simply described by a single Gaussian. Since, mass resolutions of most experiments are somewhat similar, the number that I derive here may be of some use. The $\phi \pi$ candidate mass distribution shown in Fig. 5(b) uses a $\pm 20 \text{ MeV}$ cut around the ϕ mass and is 97% efficient. Taking the measured CLEO-c branching fraction for $D_S^+ \rightarrow K^+ K^- \pi^+$ given in Table IV, and the ratio of the number of events found by fitting Figs. 5(b) and 5(a) for D_S events, I find $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi \pi^+) = (3.73 \pm 0.42)\%$. If the mass cut is

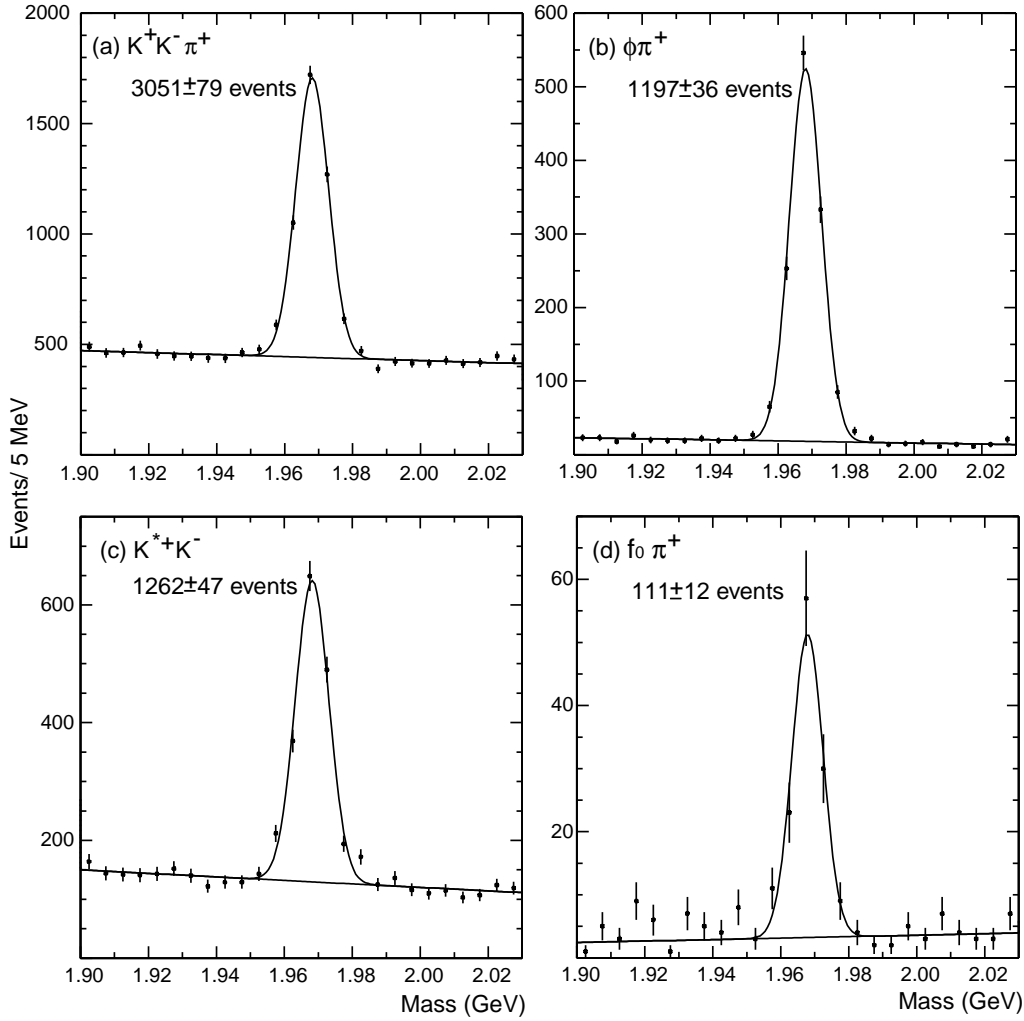


Figure 5: Invariant mass of $K^+K^-\pi^+$ combinations from CLEO-c, requiring the total energy to be consistent with the beam energy. (a) No requirements on two-body mass. (b) K^+K^- mass in the ϕ region. (c) $K^-\pi^+$ mass in the K^* (890) region. (d) K^+K^- mass in the f_0 (890) region.

lowered to ± 10 MeV with a 91% efficiency,

$$\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+) = (3.49 \pm 0.39)\%, \quad (8)$$

where the 7% reduction is presumably due to elimination of a large part of the background f_0 (980). I choose to quote this number as the effective branching ratio.

There are several previous measurements of this rate and one theoretical prediction. CLEO and BaBar use partial and full reconstruction of the decay $\bar{B}^0 \rightarrow D^{*+}D_S^{*-}$. To reduce systematic errors CLEO does the analysis two ways by partially reconstructing either the D_S^{*-} decay or the D^{*+} decay. They determine $\frac{\mathcal{B}(D_S^+ \rightarrow \phi\pi^+)}{\mathcal{B}(D^0 \rightarrow K^-\pi^+)} = 0.92 \pm 0.20 \pm 0.11$ [9]. Using the D^0 branching ratio from Table I results in $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+) = (3.5 \pm 0.8 \pm 0.4)\%$.

BaBar, on the other hand, compares the partial reconstruction of the $D_S^{*-} \rightarrow \gamma X$ decays with the fully

reconstructed decay $D_S^{*-} \rightarrow \gamma D_S^-$, $D_S^- \rightarrow \phi\pi^-$ [10]. They find $\mathcal{B}(D_S^+ \rightarrow \phi\pi^+) = (4.8 \pm 0.5 \pm 0.4)\%$.

At this conference Marsiske presented another result from BaBar. Here they use full and partial reconstruction of $\bar{B}^0 \rightarrow D^{*+}D_{S,J}^-$ (2460) where the $D_{S,J}^-(2460) \rightarrow D_S^+\gamma$ or $D_S^{*+}\pi^0$. They find $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+) = (4.8 \pm 0.4 \pm 0.5)\%$ [11], almost identical to their previous result.

The BaBar values of 4.8%, however, are quite large and almost incompatible with a previous limit. Muheim and Stone published a theoretical prediction and an experimental upper limit of 4.8% at 90% C. L., based on summing all the measured modes, most of which were measured with respect to $\phi\pi^+$ [12]. Updating the limit using current ratios of branching fractions it becomes a slightly less restrictive 5.2% at 90% C. L. (Their prediction for $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$ is $(3.6 \pm 0.6)\%$.) Finally there is a result from BES based

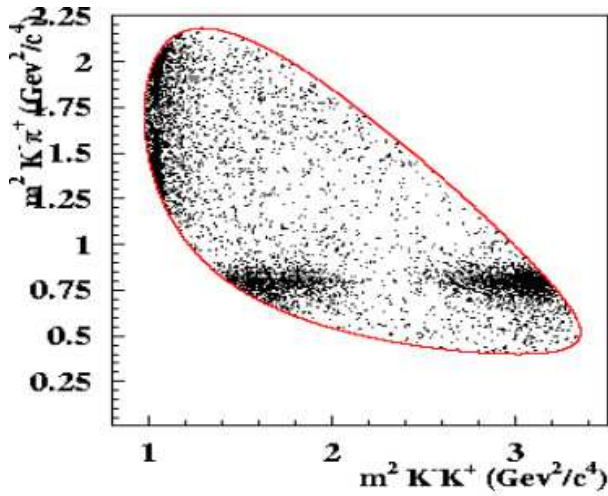


Figure 6: Mass-squared of K^+K^- versus mass-squared of $K^-\pi^+$ in $D_S^+ \rightarrow K^+K^-\pi^+$ events from Focus.

on 2 events of $(3.9_{-1.9}^{+5.1+1.8})\%$ [13].

I choose not to make an average of these values as there is more evidence that shows the BaBar results are too large. This will be discussed in the next section.

3.5. Inclusive Charm Meson Decays to $s\bar{s}$ Mesons

CLEO-c has investigated the decays of charm mesons into lighter particles that have large $s\bar{s}$ quark content. These include the η , η' and ϕ . These rates are determined using events where one D is fully reconstructed and the other decays into the meson of choice. Their preliminary results are listed in Table V.

Table V D^0 , D^+ and D_S^+ inclusive branching ratios into η , η' and ϕ mesons. The D meson decays used 281 pb^{-1} of data at the $\psi(3770)$, while the D_S decays were measured using 71 pb^{-1} at or near 4170 MeV.

	$\eta(\%)$	$\eta'(\%)$	$\phi(\%)$
D^0	$9.4 \pm 0.4 \pm 0.6$	$2.6 \pm 0.2 \pm 0.2$	$1.0 \pm 0.1 \pm 0.1$
D^+	$5.7 \pm 0.5 \pm 0.5$	$1.0 \pm 0.2 \pm 0.1$	$1.0 \pm 0.1 \pm 0.2$
D_S^+	$32.0 \pm 5.6 \pm 4.7$	$11.9 \pm 3.3 \pm 1.2$	$15.1 \pm 2.1 \pm 1.5$

We see that ϕ and η' mesons are relatively rare in D^0 and D^+ decays, while they are relative prolific in D_S decays. About 60% of D_S decays have one of these mesons. The η is produced in significant amounts in D^0 and D^+ decays and has a large 32% rate in D_S decays. These results should be useful for hadron collider experiments that use $B_S \rightarrow D_S X$ decay modes.

We can also use these results to check $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$. Actually three independent checks are possible

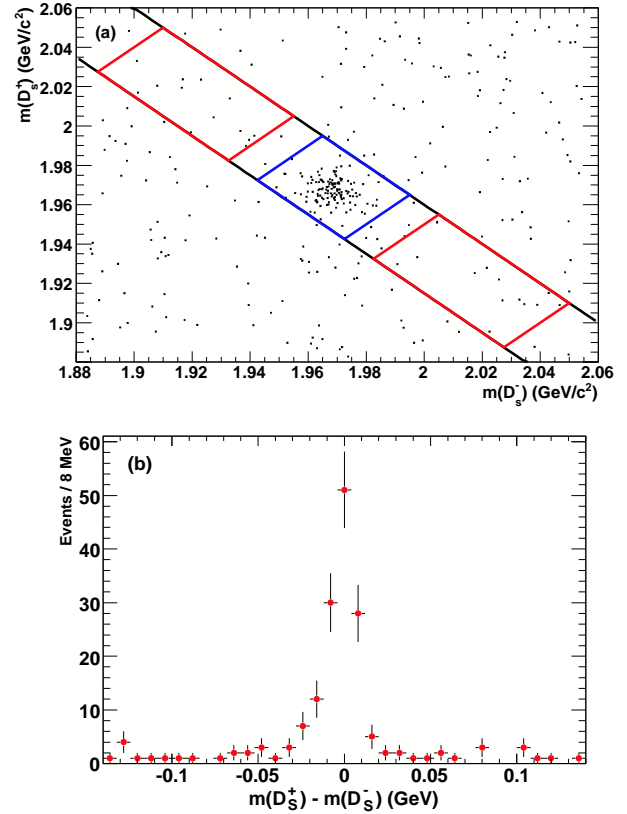


Figure 7: Invariant mass distributions in double tag D_S events. (a) D_S^+ versus D_S^- ; the center rectangle indicates the signal region and the two others indicate the background samples. (b) The difference in D_S^+ minus D_S^- invariant mass.

using each one of these particles. Let us start with the ϕ . I simply count the branching fraction for the decays that include a ϕ meson. These include $\phi\pi^+\pi^0$, $\phi\pi^+\pi^-\pi^0$, $\phi\ell^+\nu$ and $\phi\pi^+$. All of these modes have been measured with respect to $\phi\pi^+$. Summing them relates the inclusive ϕ yield from the already measured modes to $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$ as

$$\mathcal{B}_{\text{SUM}}(D_S^+ \rightarrow \phi X) = (4.2 \pm 0.5) \mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+). \quad (9)$$

In Fig. 8 the inclusive ϕ yield measured by CLEO-c is plotted as a horizontal line and $\mathcal{B}_{\text{SUM}}(D_S^+ \rightarrow \phi X)$ from Eq. 9 is plotted as a function of $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$. The intersection point gives the expected value of $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$, if all the decay modes containing ϕ 's have been measured. More modes would increase the expected inclusive rate and the shaded bands would rotate toward the y axis. Thus, this technique gives an upper limit on $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$. Also shown are the results for the η' and η modes [14]. Averaging the intersection points gives $(3.25 \pm 0.46)\%$, a value that is only meaningful as an upper limit, i. e.

$$\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+) < 3.85\% \quad (\text{at } 90\% \text{ C. L.}). \quad (10)$$

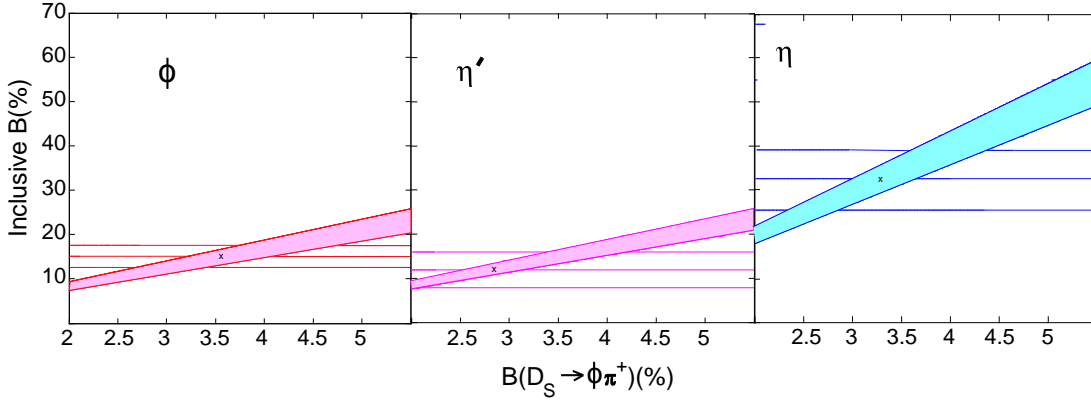


Figure 8: The CLEO-c measurements of the inclusive yields of ϕ , η' and η mesons (horizontal lines) with their $\pm 1\sigma$ errors. Also shown are bands that represent $\mathcal{B}_{\text{SUM}}(D_S^+ \rightarrow \phi X, \eta' X, \text{ or } \eta X)$. These edges of these bands represent the central value $\pm 1\sigma$. The x indicates the most likely exclusive branching ratio assuming all modes have been found.

It is clear that the inclusive measurements favor values for $\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi\pi^+)$ that are consistent with the 3.5% I have derived and are somewhat inconsistent with 4.8%.

3.6. The Real ($D_S^+ \rightarrow \phi\pi^+$) Branching Ratio

In order to compare with theoretical calculations it is useful to extract the value of the real $D_S^+ \rightarrow \phi\pi^+$ branching ratio. This can be done by using the results of a fit to the $K^-K^+\pi^+$ Dalitz plot (e. g. FOCUS) to get the fraction of $\phi\pi^+$. This is not the same procedure that was done in the past of merely cutting on the K^+K^- invariant mass about the ϕ .

The FOCUS Dalitz plot analysis determines the $\phi\pi^+$ fraction as 0.45 ± 0.01 [7]. Multiplying the CLEO number for $\mathcal{B}(D_S^+ \rightarrow K^+K^-\pi^+)$ by this $\phi\pi^+$ fraction (and dividing by $\mathcal{B}(\phi \rightarrow K^+K^-)$ of 0.491), gives

$$\mathcal{B}(D_S^+ \rightarrow \phi\pi^+) = (4.16 \pm 0.41)\% . \quad (11)$$

3.7. New Results on Singly and Doubly Cabibbo Suppressed Decays

In charm decays the c quark can decay into an s quark or a d quark and a virtual W^+ boson. The decays into an s quark are Cabibbo allowed, since their rate is proportional to the CKM element $|V_{cs}|^2$, while those into a d quark are Cabibbo suppressed, since their rate is proportional to $|V_{cd}|^2$, where $|V_{cs}| \sim 0.97$, and $|V_{cd}| \sim 0.23$ [6]. In addition the virtual W^+ can form a Cabibbo favored $u\bar{d}$ pair or a Cabibbo suppressed $u\bar{s}$ pair, as shown in Fig. 9(a). If $c \rightarrow d$ and $W^+ \rightarrow u\bar{s}$ we have a “doubly-Cabibbo suppressed” decay, as illustrated for one channel in Fig. 9(b). CLEO-c has measured a plethora of new

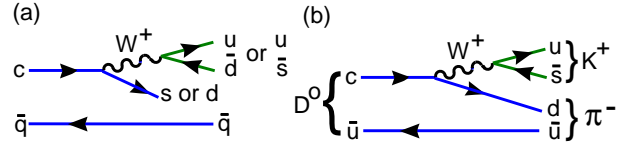


Figure 9: (a) A spectator diagram for D meson decays. If $c \rightarrow d$ or $W^+ \rightarrow u\bar{s}$, the decay is said to be “singly-Cabibbo suppressed.” If both occur in the same decay, we have a “doubly-Cabibbo suppressed” decay. (b) Diagram for the doubly-Cabibbo suppressed decay $D^0 \rightarrow K^+\pi^-$.

singly-Cabibbo suppressed modes [15]. Their measurements are listed in Table VI.

There are also two new measurements from BaBar [16] one in the singly-Cabibbo suppressed decay mode

$$\mathcal{B}(D^+ \rightarrow \pi^+\pi^0) = (1.22 \pm 0.10 \pm 0.08 \pm 0.08) \times 10^{-3}, \quad (12)$$

which agrees with the CLEO-c result, and one in the doubly-Cabibbo suppressed decay mode

$$\mathcal{B}(D^+ \rightarrow K^+\pi^0) = (0.246 \pm 0.046 \pm 0.024 \pm 0.016) \times 10^{-3}, \quad (13)$$

which is the first observation of this mode. Here BaBar normalizes to the PDG absolute branching ratios [6]. Normalizing to the new world average numbers would substantially reduce the last error.

The di-pion system can have a total isospin of 2, or 0. The decays into the three final states $\pi^+\pi^0$, $\pi^+\pi^-$ and $\pi^0\pi^0$ starting from the $I = 1/2$ D meson states proceed through a combination of $I = 1/2$ and $I = 3/2$ amplitudes [17]. These new $D \rightarrow \pi\pi$ branching fractions allow for a much more precise determination of the phase difference between these two isospin amplitudes. The ratio of the $\Delta I = 3/2$ to $\Delta I = 1/2$ isospin amplitudes and their relative strong phase difference is $A_2/A_0 = 0.420 \pm 0.014 \pm 0.01$ and $\cos \delta_I = 0.062 \pm 0.048 \pm 0.058$ using the CLEO-c results only. The large phase shift, $\delta_I = (86.4 \pm 2.8 \pm 3.3)^\circ$,

Table VI Branching fractions for singly-Cabibbo suppressed D decays from CLEO-c. The sources of the listed uncertainties are statistical, experimental systematic, normalization mode, and CP correlations (for D^0 modes only).

D^0 Modes	\mathcal{B} (10^{-3})
$\pi^+\pi^-$	$1.39 \pm 0.04 \pm 0.04 \pm 0.03 \pm 0.01$
$\pi^0\pi^0$	$0.79 \pm 0.05 \pm 0.06 \pm 0.01 \pm 0.01$
$\pi^+\pi^-\pi^0$	$13.2 \pm 0.2 \pm 0.5 \pm 0.2 \pm 0.1$
$\pi^+\pi^+\pi^-\pi^-$	$7.3 \pm 0.1 \pm 0.3 \pm 0.1 \pm 0.1$
$\pi^+\pi^-\pi^0\pi^0$	$9.9 \pm 0.6 \pm 0.7 \pm 0.2 \pm 0.1$
$\pi^+\pi^+\pi^-\pi^-\pi^0$	$4.1 \pm 0.5 \pm 0.2 \pm 0.1 \pm 0.0$
$\omega\pi^+\pi^-$	$1.7 \pm 0.5 \pm 0.2 \pm 0.0 \pm 0.0$
$\eta\pi^0$	$0.62 \pm 0.14 \pm 0.05 \pm 0.01 \pm 0.01$
$\pi^0\pi^0\pi^0$	< 0.35 (90% CL)
$\omega\pi^0$	< 0.26 (90% CL)
$\eta\pi^+\pi^-$	< 1.9 (90% CL)
D^+ Modes	
$\pi^+\pi^0$	$1.25 \pm 0.06 \pm 0.07 \pm 0.04$
$\pi^+\pi^+\pi^-$	$3.35 \pm 0.10 \pm 0.16 \pm 0.12$
$\pi^+\pi^0\pi^0$	$4.8 \pm 0.3 \pm 0.3 \pm 0.2$
$\pi^+\pi^+\pi^-\pi^0$	$11.6 \pm 0.4 \pm 0.6 \pm 0.4$
$\pi^+\pi^+\pi^+\pi^-\pi^-$	$1.60 \pm 0.18 \pm 0.16 \pm 0.06$
$\eta\pi^+$	$3.61 \pm 0.25 \pm 0.23 \pm 0.12$
$\omega\pi^+$	< 0.34 (90% CL)

shows that final state interactions are important in $D \rightarrow \pi\pi$ transitions. This information could be useful in the study of $B \rightarrow \pi\pi$ decays [18].

4. Searches for New Physics in Charm Decays

New physics could be seen in charm decays by observations of mixing, CP violation [1] or even T violation [19]. Let us first consider $D^0 - \bar{D}^0$ mixing. In the SM mixing is generated by short distance diagrams including the one shown in Fig. 10. Here the heaviest intermediate quark is the b . Since the mixing rate goes as the square of the mass of the intermediate quark, we can see why it is suppressed relative to K^0 mixing (50%) or B^0 mixing (20%), since the top-quark is active in these systems. The CKM couplings also matter. That is why B_S mixing (50%) is larger than B^0 mixing. For D^0 mixing via the b -quark the couplings are $|V_{ub}|$ and $|V_{cb}|$, which are also small.

Mixing due to natural causes in the SM can be enhanced by so called ‘‘long distance’’ effects, which are more-or-less the transition of a D^0 into an on-shell meson pair, e.g. K^+K^- and then another transition

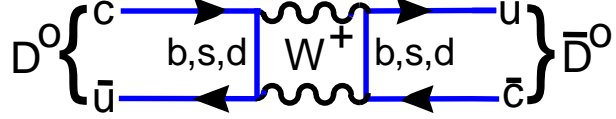


Figure 10: A diagram for $D^0 - \bar{D}^0$ mixing in the Standard Model.

back to a \bar{D}^0 . Mixing is characterized by the mass difference, Δm , and width difference $\Delta\Gamma$, between $CP+$ and $CP-$ eigenstates, where the width Γ is related to the lifetime, τ_{D^0} , as $\Gamma \cdot \tau_{D^0} = \hbar$. New Physics effects in loops, for example new particles, would tend to cause $x \equiv \Delta m/\Gamma \gg y \equiv \Delta\Gamma/2\Gamma$. Predictions though of the magnitude of SM and NP effects are murky. Fig. 11 from Petrov, an update to a plot originally shown by Nelson, shows various expectations [20].

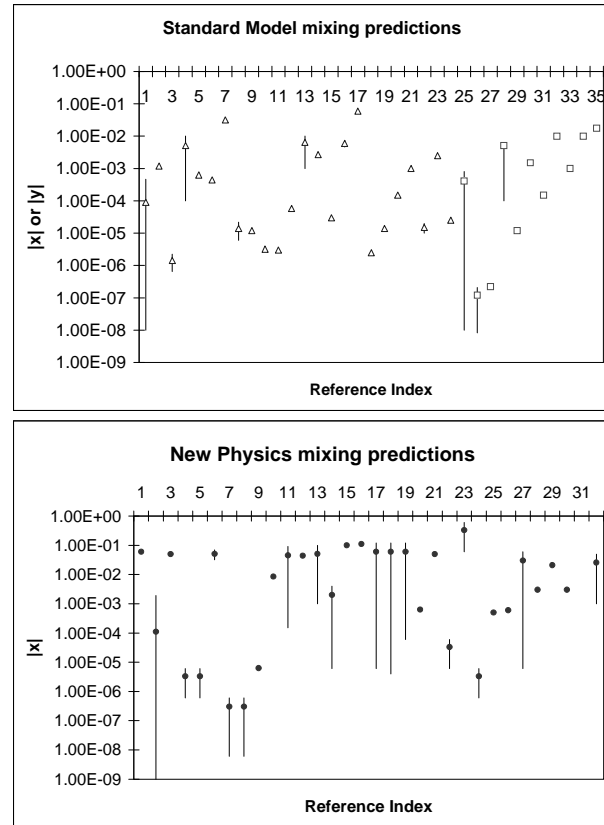


Figure 11: Predictions for x and y in the Standard Model (top) and for x in New Physics models (bottom) indexed as to reference number given in [20].

Both SM and NP predictions range over the entire plot which will make it difficult to claim a NP effect. Nevertheless, it will be interesting to see or limit the size of x and y , especially since tight limits will constrain NP models, and observable mixing, whatever the source, could be a path for NP to generate CP

violation.

4.1. $D^0\bar{D}^0$ Mixing Using Wrong-Sign $K^-\pi^+$ Decay

The $D^{*\pm} \rightarrow \pi^\pm D^0$ decay provides a useful tag of the initial quark content, i. e., whether we start with a D^0 or a \bar{D}^0 . The π^+ tags D^0 , and the π^- tags \bar{D}^0 . While the normal Cabibbo favored decay is $D^0 \rightarrow K^-\pi^+$, it is possible to get $D^0 \rightarrow K^+\pi^-$, a “wrong-sign” decay, via mixing. Unfortunately, this clean signature is complicated by doubly-Cabibbo suppressed decays, as shown in Fig. 9(b). The two processes interfere. Fig. 12 diagrammatically shows the two decay paths.

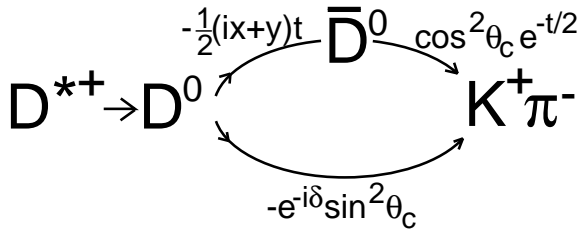


Figure 12: Amplitudes for D^0 decay into $K^+\pi^-$ either via mixing followed by a Cabibbo favored decay (top path), or doubly-Cabibbo suppressed decay (bottom path).

The interference causes the measured x and y to be rotated through an angle δ , the phase difference between the doubly-Cabibbo suppressed and Cabibbo favored processes. The wrong-sign decay rate then as a function of time is

$$R_{\text{ws}} = e^{-\Gamma t} \left(R_D + \sqrt{R_D} y' \Gamma t + \frac{1}{4} (x'^2 + y'^2) (\Gamma t)^2 \right), \quad (14)$$

where R_D is the doubly-Cabibbo suppressed decay rate and Γ is the decay width. By measuring the time dependence of the decay rate it is possible to sort out the mixing from the doubly-Cabibbo suppressed decay. Several measurements have been made resulting in the upper limits listed in Table VII on x'^2 and y' .

Table VII Limits on x'^2 and y' , both at 95% C. L. for cases where CP violation is allowed and also where it is not allowed. (Note that the limits are on x'^2 not x').

Exp.	$x'^2 (\times 10^{-3})$		$y' (\times 10^{-3})$	
	CPV	No CPV	CPV	No CPV
CLEO[21]	0.82	0.78	$-58 < y' < 10$	$-52 < y' < 2$
FOCUS[22]	0.80	0.83	$-120 < y' < 67$	$-72 < y' < 41$
Belle[23]	0.72	0.72	$-28 < y' < 21$	$-9.9 < y' < 6.8$
BaBar[24]	2.2	2.0	$-56 < y' < 39$	$-27 < y' < 22$

The limits are somewhat more restrictive on y' when CP violation is not permitted, while those on x'^2 hardly change. While no experiment claims an effect, it is interesting that the Belle result is consistent with no mixing only at 3.9% C. L. [23].

4.2. Other Mixing Studies

There are several other methods that have been used to search for mixing. The lifetime difference between mass eigenstates provides another measurement of y , usually called y_{CP} . In presence of CP violation, y_{CP} is a linear combination of x and y involving the CP violation phase ϕ . Table VIII summarizes experimental data on y_{CP} . The average is 0.90 ± 0.42 , which is consistent with zero.

Table VIII Summary of y_{CP} results.

Experiment	$y_{CP}(\%)$
E791[25]	$0.8 \pm 2.9 \pm 1.0$
FOCUS [26]	$3.4 \pm 1.4 \pm 0.7$
CLEO [27]	$-1.2 \pm 2.5 \pm 1.4$
Belle, untagged [28]	$-0.5 \pm 1.0 \pm 0.8$
Belle, tagged [29]	$1.2 \pm 0.7 \pm 0.4$
BaBar [30]	$0.8 \pm 0.4^{+0.5}_{-0.4}$

Mixing measurements have also been made in semileptonic decay modes where doubly-Cabibbo suppressed decays are absent. Here the mixed rate $R_M = (x^2 + y^2)/2$ is directly measured. Table IX summarizes the present experimental limits.

Table IX Summary of mixing limits (90 % C.L.) from D^0 semileptonic decay studies.

Experiment	R_M	$\sqrt{x^2 + y^2}$
FOCUS [31]	0.0078	0.12
BaBar [32]	0.0042	0.096
Belle [33]	0.0010	0.044

Fig. 13, prepared by D. Asner for an upcoming PDG review summarizes the overall situation on $D^0 - \bar{D}^0$ mixing from the above measurements.

Another way of searching for mixing is to use Dalitz plot analyses of three-body decay modes. CLEO has done a full time dependent analysis of the $D^0 \rightarrow K_S \pi^+ \pi^-$ mode [34]. The essential feature here is that the CP+ D_1 state has a different time dependence than the CP- D_2 state

$$\begin{aligned} D_1(t) &\sim \exp[-i(m_1 - i\Gamma_1/2)t] \\ D_2(t) &\sim \exp[-i(m_2 - i\Gamma_2/2)t]. \end{aligned} \quad (15)$$

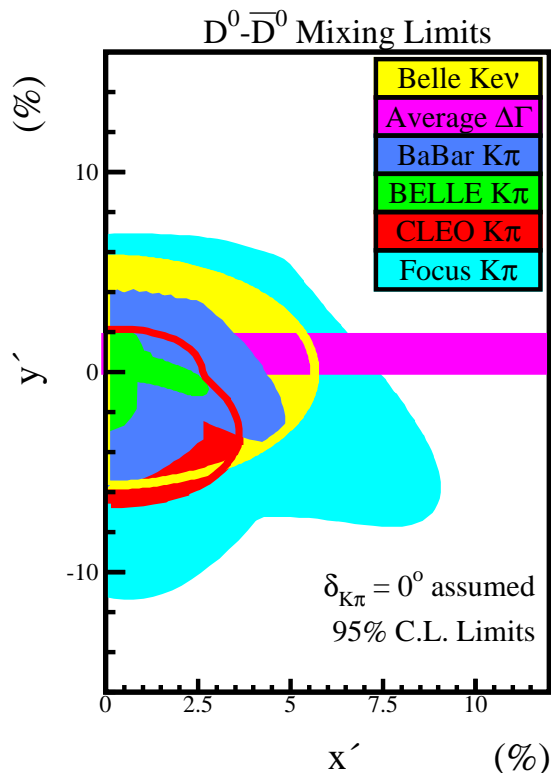


Figure 13: Limits at 95% C. L. on x' and y' from various measurements described in the text. Here $\Delta\Gamma$ refers to the width difference between $CP+$ and $CP-$ eigenstates found by measuring the lifetime difference.

Limits extracted are $(-4.5 < x < 9.3)\%$ and $(-6.4 < y < 3.6)\%$ at 95% C.L., without assumptions regarding CP-violating parameters. This result is compared with others in Fig. 13 (again from D. Asner). We note that the CLEO limits are comparable even though they are based on an order of magnitude less luminosity, showing the potential of such analyses.

BaBar at this conference presented an analysis of $D^0 \rightarrow K^+\pi^-\pi^0$ where they use cuts on the Dalitz plot to enhance the Cabibbo favored rate and suppressed the doubly-Cabibbo suppressed rate [35]. This is possible since the Cabibbo favored rate proceeds largely through $K^-\rho^+$, while the doubly-Cabibbo suppressed rate goes into $K^{*+}\pi^-$ and $K^{*0}\pi^0$. For the CP conserving fit they find $R_M = (0.23^{+0.18}_{-0.14} \pm 0.04) \times 10^{-3}$ which translates into $R_M < 0.54 \times 10^{-3}$ at 95% C. L.. They also find that R_M is consistent with no mixing at 4.5% C. L..

4.3. CP/T Violation

Unexpectedly large CP violating asymmetries in the range from $10^{-2} - 10^{-4}$ is a better signature for NP than mixing. There are several ways to study CP vio-

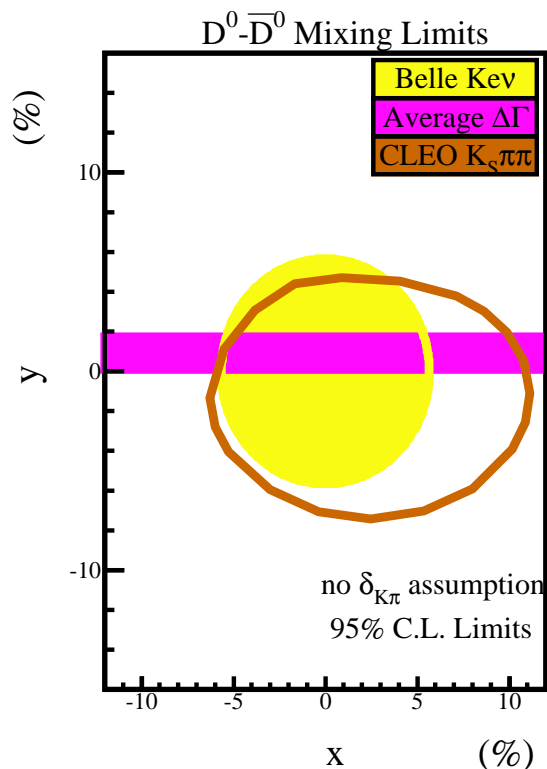


Figure 14: Limits at 95% C. L. on x and y from the CLEO $K_S\pi^+\pi^-$ Dalitz analysis, the average lifetime difference and the Belle semileptonic analysis.

lation in charm decays [36]. We can look for direct CP violation, even in charged decays [37]; we can look for CP violation via mixing; T violation can be examined in 4-body D meson decays, assuming CPT conservation, by measuring triple-product correlations [19]. Finally the quantum coherence present in correlated $D^0 - \bar{D}^0$ decays of the $\psi(3770)$ can be exploited (see the talk by D. Cinabro [38]). Some recent results are shown in Table X. No significant effects have been seen.

4.4. Conclusions

The absolute branching fractions for charm mesons have been measured with unprecedented accuracy. Combining the PDG values with the preliminary CLEO-c results for D^0 and D^+ decays, and using the CLEO-c results for D_S^+ , I find

$$\mathcal{B}(D^0 \rightarrow K^-\pi^+) = (3.87 \pm 0.06)\% \quad (16)$$

$$\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+) = (9.12 \pm 0.19)\% \quad (17)$$

$$\mathcal{B}(D_S^+ \rightarrow K^-K^+\pi^+) = (4.54^{+0.44}_{-0.42} \pm 0.25)\% \quad (18)$$

CLEO-c does not quote a branching ratio for $D_S^+ \rightarrow \phi\pi^+$ mode because of interferences on the Dalitz plot.

Table X Measurements of CP violating asymmetries, A_{CP} (or A_T) in charm decays. BaBar compares D^+ versus D^- rates. The CLEO result is obtained using a Dalitz plot analysis. CDF uses the decay of $D^{*+} \rightarrow \pi^+ D^0$ as a flavor tag, and FOCUS uses triple product correlations to measure T violation.

Exp.	Decay Mode	A_{CP} or A_T (%)
BaBar [39]	$D^+ \rightarrow K^- K^+ \pi^+$	$1.4 \pm 1.0 \pm 0.8$
BaBar [39]	$D^+ \rightarrow \phi \pi^+$	$0.2 \pm 1.5 \pm 0.6$
BaBar [39]	$D^+ \rightarrow K^{*0} K^+$	$0.2 \pm 1.5 \pm 0.6$
Belle [40]	$D^0 \rightarrow K^+ \pi^- \pi^0$	-0.6 ± 5.3
Belle [40]	$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	-1.8 ± 4.4
CLEO [41]	$D^0 \rightarrow \pi^+ \pi^- \pi^0$	$1_{-7}^{+9} \pm 8$
CLEO [42]	$D^0 \rightarrow K^- \pi^+ \pi^0$	-3.1 ± 8.6
CLEO [43]	$D^0 \rightarrow K_S \pi^+ \pi^-$	$-0.9 \pm 2.1_{-4.3-3.7}^{+1.0+1.3}$
CDF [44]	$D^0 \rightarrow K^+ K^-$	$2.0 \pm 1.2 \pm 0.6$
CDF [44]	$D^0 \rightarrow \pi^+ \pi^-$	$1.0 \pm 1.3 \pm 0.6$
FOCUS [45]	$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$	$1.0 \pm 5.7 \pm 3.7$
FOCUS [45]	$D^+ \rightarrow K^0 K^+ \pi^+ \pi^-$	$2.3 \pm 6.2 \pm 2.2$
FOCUS [45]	$D_S^+ \rightarrow K^0 K^+ \pi^+ \pi^-$	$-3.6 \pm 6.7 \pm 2.3$

The $K^- K^+ \pi^+$ or the $K^0 K^+$ modes should be used for normalization. Since most of the D_S decay modes have been measured as ratios to the $\phi \pi^+$ mode, I extract an effective branching ratio

$$\mathcal{B}^{\text{eff}}(D_S^+ \rightarrow \phi \pi^+) = (3.49 \pm 0.39)\%. \quad (19)$$

These rates can be used for many purposes. For example, adding up the number of charm quarks produced in each B meson decay at the $\Upsilon(4S)$ resonance by summing the D^0 , D^+ , D_S^+ , charmed baryon and twice the charmonium yields gives a rate of 1.09 ± 0.04 , where the largest error comes from the D^0 yield.

Many more Cabibbo suppressed and some doubly-Cabibbo suppressed modes have been measured. Large phase shifts have been more accurately measured in the $D \rightarrow \pi\pi$ channel.

There is no definitive evidence for $D^0 - \overline{D^0}$ mixing. The best limits yet are $|y'| < 2.5\%$ and $|x'^2| < 7.2 \times 10^{-3}$ both at 95% C. L. The limit on $|x'|$ of about 8% is just beginning to probe an interesting range. There are two hints that mixing may be soon found. Belle finds consistency with no mixing at 3.9% C. L. in wrong-sign $K^- \pi^+$ decays and BaBar finds consistency with no mixing at 4.5% C. L. in wrong sign $K^- \pi^+ \pi^0$ decays, thus making further searches more interesting. There have not been any observations of CP or T violation.

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